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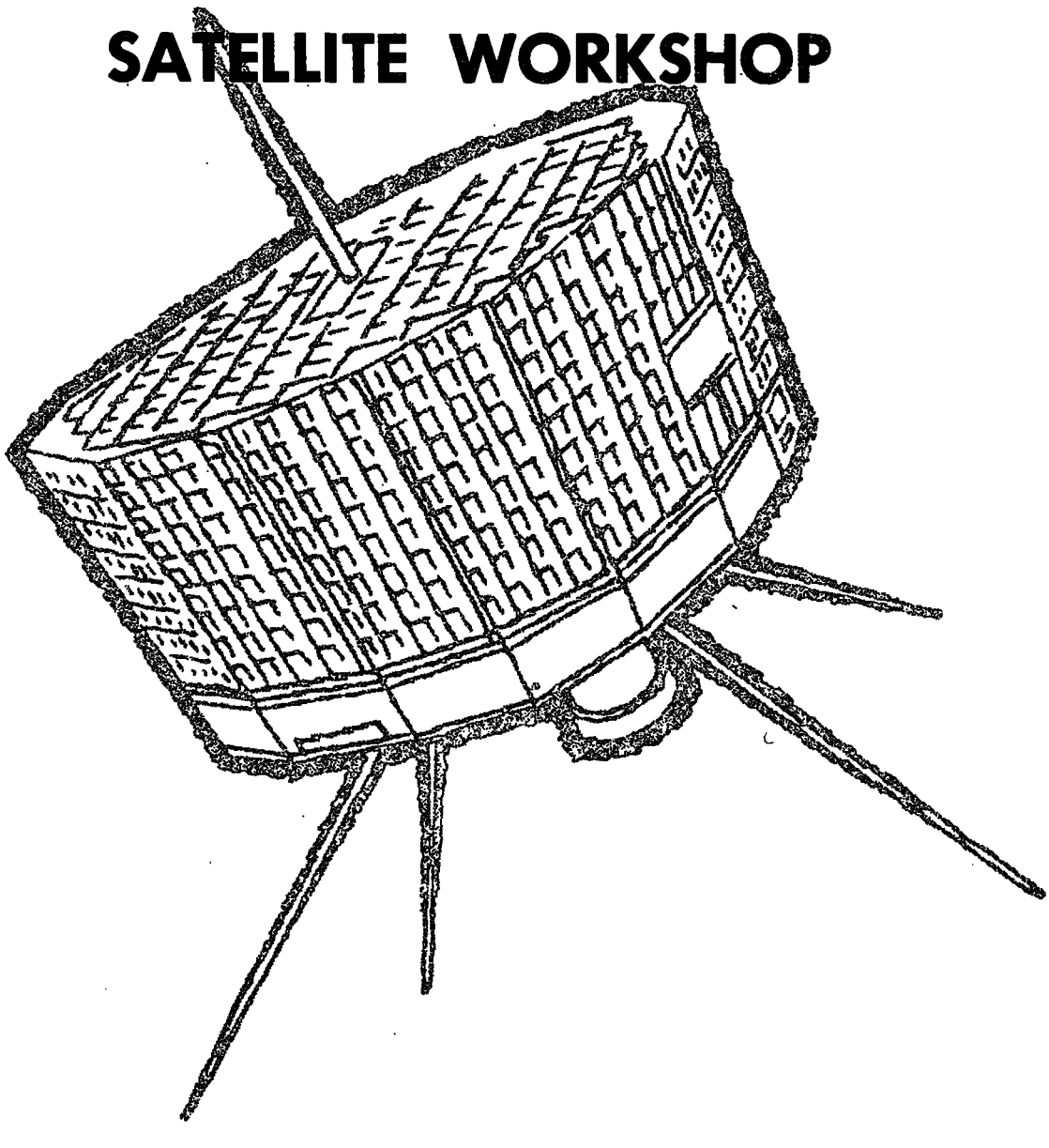
U.S. Weather Bureau

PROCEEDINGS OF THE INTERNATIONAL METEOROLOGICAL SATELLITE WORKSHOP



WASHINGTON, D.C. NOVEMBER 13–22, 1961

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
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PROCEEDINGS OF THE INTERNATIONAL METEOROLOGICAL SATELLITE WORKSHOP

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
and
U.S. DEPARTMENT OF COMMERCE, WEATHER BUREAU

Washington, D.C.

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National Oceanic and Atmospheric Administration
TIROS Satellites and Satellite Meteorology

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The International Meteorological Satellite Workshop, November 13–22, 1961, presented the results of the meteorological satellite program of the United States and the possibilities for the future, so that—

- The weather services of other nations may acquire a working knowledge of meteorological satellite data for assistance in their future analysis programs both in research and in daily synoptic application and guidance in their national observational support efforts.
- The world meteorological community may become more familiar with the TIROS program.
- The present activity may be put in proper perspective relative to future operational programs.

AGENDA

NOVEMBER 13, 14: TECHNICAL SESSION

NOVEMBER 15, 16: FIELD TRIPS

(*a*) NASA Goddard Space Flight Center, Greenbelt, Md., and Anacostia, D.C.

(*b*) NASA Wallops Station, Va.

(*c*) USWB Meteorological Satellite Laboratory and National Meteorological Center, Suitland, Md.

NOVEMBER 17, 20, 21: LABORATORY SESSION—Exercises on Coordinate Analysis, Picture Rectification, Interpretation of Picture Data, and Use of Radiation Data.

NOVEMBER 22: INFORMAL DISCUSSION

(*a*) Presentation of Observational Support Efforts by Foreign Participants

(*b*) Arranged Discussions With NASA and USWB Specialists.

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TECHNICAL SESSION

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1. STATEMENT OF JAMES E. WEBB

Administrator, National Aeronautics and Space Administration

It is a pleasure to welcome you here today on behalf of the National Aeronautics and Space Administration, the civilian agency of the United States which is charged with the responsibility for space research, exploration, and for practical applications.

We are happy to have this opportunity to share with you the work we are doing jointly with the U.S. Weather Bureau in the field of meteorology and to receive your suggestions as to ways and means through which we can all benefit from future cooperative efforts.

The presence here of representatives from more than 30 countries is evidence of the strong interest everywhere in the world of the practical benefits which all nations may now confidently expect to gain from broadly based efforts to apply satellites to weather research and to forecasting.

In addition to welcoming the representatives from the national weather services, I would like to welcome those who represent the organizations which have endorsed this Meteorological Workshop: The World Meteorological Organization, the International Union of Geodesy and Geophysics, the International Committee on Space Research, the International Civil Aviation Organization, the U.S. National Academy of Sciences, and the American Meteorological Society.

The National Aeronautics and Space Administration has joined with the U.S. Weather Bureau to invite you here because we are convinced that the technology of meteorological satellites is nearing the point where it can be applied globally for practical research and for operational forecasting. Moreover, the TIROS experimental series of weather satellites will be replaced in about a year by the more useful and more nearly operational Nimbus series. The Nimbus satellites, for instance, will be focused on the earth at all times from polar orbits. We hope and expect that it will then become possible within a reasonable time for every country which is prepared to do so to receive information directly from these satellites.

I need not emphasize the value of such information for it will offer to all nations for the first time an immediate and comprehensive view of the total cloud cover pattern in its own and in neighboring geographic areas. With such a prospect in view, and consistent with our national space policy, we believe that the technology, the processes, and the operational techniques we have developed for use of such information should be made available to the world's weather services at the earliest possible time.

We are happy indeed that so many of you are here for this purpose and we hope you will give us your suggestions as to how improvements can be made.

This Workshop is but one instance, one example, of the practical benefits which flow from the U.S. policy to share with other nations the scientific and technical knowledge we gain from our space program and to obtain from them the knowledge they have acquired in this field.

The same kind of factual and highly detailed presentations and discussions which will be given during this Workshop are organized also for those interested in our other programs. This was true of the information gained from the suborbital space flights of Astronauts Alan Shepard and Virgil Grissom, and it is true in connection with our preparatory activities for experiments with communications satellites where joint working groups, including a number of interested nations, permit a full and early sharing of plans and information. The United States has recognized from the beginning the interests of other nations in space and the ex-

tensive benefits to be gained by all from international cooperation. Our scientific experiments have been described in great detail in the literature and reported to the world scientific community in ways that are traditional with scientists.

In President Kennedy's first State of the Union address, just 10 days after he took office, he stated that our intention as a nation is to explore all areas of international cooperation or, in his words, "to invoke the wonders of science instead of its terrors." More recently the President has invited all nations to join with us in developing not only a weather prediction program but also a communications satellite program and in carrying out the multitude of experiments which are clearly necessary if mankind is to probe space most effectively and benefit from an expanding knowledge of near space, the moon, and the distant planets.

For all these reasons I am most happy to welcome you to this International Meteorological Satellite Workshop through which, working together, we dedicate our efforts to an early realization of the use of space for practical and peaceful benefits for all mankind whose activities everywhere are so dependent on weather.

2. STATEMENT OF HARRY WEXLER

Director of Research, U.S. Department of Commerce, Weather Bureau

On behalf of the U.S. Department of Commerce, Weather Bureau, I greet colleagues and guests from so many different countries and organizations.

Many of you have traveled great distances to be here, and we greatly appreciate the time, effort, and sacrifice from your duties that this entails. We hope that you will be amply repaid not only by the scientific experience that this Workshop affords, but also by the opportunity to meet and talk with colleagues from other countries.

For the first time meteorologists have an observing device which, like the atmosphere, is global in extent. This device, the meteorological satellite, is the natural evolution of, first, what an observer can see from horizon to horizon and, second, what a radar can "see" over a larger area and through intervening darkness, cloud, or haze.

Meteorologists traditionally have pieced together visual observations and those from instruments and radar to construct synoptic charts over large areas the size of a continent and, more recently, the size of a hemisphere. In so doing, meteorologists have had to interpolate and extrapolate over areas where observations are sparse or missing, particularly over oceans and other uninhabited areas.

The earth-orbiting satellite, by its ability to photograph the cloud cover and measure the outgoing radiation patterns, takes advantage of the synthesis of observations that Nature herself has already performed in arranging clouds and airmasses in certain orderly patterns, large and small, which meteorologists can interpret in terms of storms, fronts, and other atmospheric entities.

It is in the depicting of these natural weather maps that the earth-orbiting satellites have made their first contribution to meteorology by assisting synoptic analysis and weather prediction. Notice I said "first contribution," because the operational and research exploitation of these new vehicles has just begun and their communications potential is still untapped.

The greatest impact of satellite data will undoubtedly be felt in the Southern Hemisphere, 80 percent covered by oceans, from which observational information is sparse, and also in the tropics, where cloud patterns may well become the principal working tools of meteorologists in an area where the sharp synoptic patterns of fronts, cyclones, and anticyclones of high latitudes are generally not found. However, even outside the tropics, satellites can depict overall patterns and details not discernible by even the densest networks; satellites will also contribute to studies involving regional and global energy budgets and transports.

Such a global-observing device should bind even closer the meteorologists of the world, who for over a century have held meetings to facilitate the exchange of observing techniques and weather observations among the various nations.

In 1878 these meetings, which began as early as 1853, were formalized by the establishment of the International Meteorological Organization which existed until 1950, when it was transformed into the World Meteorological Organization under the United Nations.

Dr. Reichelderfer, Chief of the U.S. Weather Bureau and the first president of the World Meteorological Organization, regrets very much that he is not in Washington today to greet you personally, and he asked me to convey his greetings and best wishes to you. I would like, also, to extend another greeting, from Professor Van de Hulst, of the Netherlands, president of the Committee on Space Research (COSPAR),

established by the International Council of Scientific Unions.

COSPAR, whose representative I have the honor to be at this Workshop, was organized 3 years ago to provide continuity in rocket and satellite activities arising as a result of the International Geophysical Year. It has had two very successful symposia on space science, one in 1960 and one in 1961, and will have a third symposium in late April and early May of 1962 in Washington. Associated with this symposium will be a 3-day meeting on meteorological rockets and satellites, and I hope that all of you will come again to Washington next spring to attend these meetings.

To the greetings of Dr. Reichelderfer and Professor Van de Hulst, I add my own. Best wishes for a cordial and fruitful experience in Washington during the next 10 days.

3. STATEMENT OF HUGH L. DRYDEN

Deputy Administrator, NASA

I appreciate this opporunity to add my word of greeting to those of Mr. Webb and Dr. Wexler. We are very happy that you could come to this Workshop. We are looking forward to your contributions toward the most effective use of the satellites in operational weather problems and to the meteorological research in your countries.

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4. STATEMENT OF MORTON J. STOLLER

Deputy Director, Office of Applications, National Aeronautics and Space Administration

It is a great pleasure for me to be able to add my welcome to those you have already received.

This Meteorological Satellite Workshop is the first such meeting since the recent establishment of the Office of Applications as one of the four major technical program offices within the NASA organizational structure. The Office of Applications is responsible for meteorological systems, communications systems, and for the identification and growth of other areas to which the results of NASA's research and development efforts can be directed for the benefit of mankind the world over.

Mr. Webb has already mentioned the efforts of NASA to make our technical results known to all who are interested. We expect that in the application of space science and technology to fields of interest such as meteorology the presentation of new data and techniques may have to take place regularly. I certainly hope that we will have more than just this initial opportunity to discuss with you the details of our meteorological satellite systems.

I hope, too, that we will have an opportunity to work with your colleagues in other scientific and technological areas, principally communications, perhaps navigational systems, to speed the development and improvement of those other services which are of worldwide interest.

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5. STATEMENT OF KAARE LANGLO

Chief, Technical Division, World Meteorological Organization

More than 40 years ago Professor Wilhelm Bjerknes went to his government and asked for $15,000 to expand the network of meteorological stations on the west coast of Norway. The significance of this story is not the receipt of $15,000, but what was achieved with $15,000. With this money 20 additional stations were built. By means of these stations a significant development was made in meteorology by discovering the frontal systems, or the cyclone model, developed by Professor Bjerknes. I mention this because the World Meteorological Organization believes that extending the observational network is essential to our understanding of what happens in the atmosphere. This is why we believe that satellite observations are important, and the World Meteorological Organization will do everything possible to support any associated activities which are dependent on intergovernmental agreements. We started this work before the first satellite was launched, and we are going to continue to do whatever we can to support these activities.

I should like to thank the authorities of the United States for taking the initiative through this Workshop. I am directing these thanks to the NASA authorities and to the Weather Bureau and hope that they will have great success in the work to come. We are hoping that several more of these Workshops can be arranged in the future.

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6. STATEMENT OF U. SCHWARZ

Technical Officer, International Civil Aviation Organization

In the short time that satellite meteorology has been on the scene, it has become apparent that there are likely to be many, both direct and indirect, applications of satellite meteorology to aeronautical meteorology. ICAO has therefore been very happy to endorse the aims of this Workshop.

May I, therefore, extend the best wishes of ICAO to both the organizers and the participants for a very successful meeting.

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7. STATEMENT OF MORRIS TEPPER

Director of Meteorological Systems, National Aeronautics and Space Administration

I would like to join the speakers who preceded me in extending to you a most friendly and cordial welcome. In this Workshop we have endeavored to develop a program which will be both instructive and useful.

We shall try to present to you within the time allotted to this Workshop what we have been planning, what we have been doing with the data, and how we have been doing it. We hope you will listen critically and let us know, either during the Workshop or later, after you have had a chance to study the material and analyze the data yourself, your evaluations and your results so that we may improve our present techniques and procedures.

We hope that this Workshop will be the first of many such International Workshops or symposia to be held in different countries where scientists, working with meteorological satellite data, can collect and interchange ideas and results.

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8. THE CURRENT NASA METEOROLOGICAL SATELLITE PROGRAM

By Morris Tepper, *Director of Meteorological Systems, NASA*

Perhaps by way of introduction it would be well to pose the following question: Why is there a need for meteorological satellite data?

By its very nature, the atmosphere is a global phenomenon. It covers the entire earth, land areas and water areas alike, and extends upward with decreasing density. Moreover, the atmosphere is constantly in motion. This motion is produced and influenced by the complex interaction of many events: the unequal heating by the sun of the land and ocean areas, the latitudinal variation of this heating, the surface irregularity of the landmasses, the rotation of the earth, and others. Atmospheric motions are not simple in character, yet are extremely important because in the lower 10 to 15 miles of the atmosphere practically all the weather that affects man is produced.

The meteorologist recognizes the global character of the atmosphere and well realizes that he must observe, describe, and understand the behavior of the atmosphere over a large portion of the globe if he is to explain and predict with any degree of confidence the weather events that occur in any locality. The requirement for global data increases rapidly with the length of the forecast period.

Thus, over a period of years, there has evolved among meteorologists of all countries the realization that only with the assistance of cooperative international observations will it be possible for any country to fulfill its own national meteorological obligations. The World Meteorological Organization is the vehicle through which active international cooperation in meteorology is achieved. Many hundreds of observations are taken daily by many countries. These observations are made the common property of the entire meteorological community through established rapid international communications channels.

Despite this participation of men in many countries observing the atmosphere and sharing these observations for individual and mutual benefit, it is perforce necessary that these observations be restricted primarily to those regions regularly frequented by man. The atmospheric events in desert, polar, and oceanic areas for the most part remain undetected, and information on their contribution to the global atmospheric motion and to associated weather patterns has been unavailable to meteorologists on a regular basis. It is only when these events move out of the uninhabited areas that their presence becomes known. By this time it may be too late to issue the necessary kinds of warnings for the protection of life and property. For example, some of the most destructive storms are those of tropical origin which form near the equator in those oceanic areas that are practically devoid of weather information. Frequently, the first warning of such a storm is when it strikes an island, ship, or continental shoreline.

Figure 8–1 shows the distribution of observing stations in the world radiosonde network. Each dot represents a station. Note the absence of stations in the oceanic areas and in many land areas as well. Satellites can provide surveillance of these data-sparse ocean regions on a global basis, permitting early detection and accurate tracking of storm systems. Based on such observations, timely warnings can be issued to both populated areas and vessels at sea. In the same manner, accurate identification and tracking of storms in data-sparse regions at higher latitudes would aid in more accurate forecasting of these systems.

More generally, then, since the atmosphere is global in character, knowledge of its behavior in some of the more remote areas is frequently required if suitable prediction of weather for

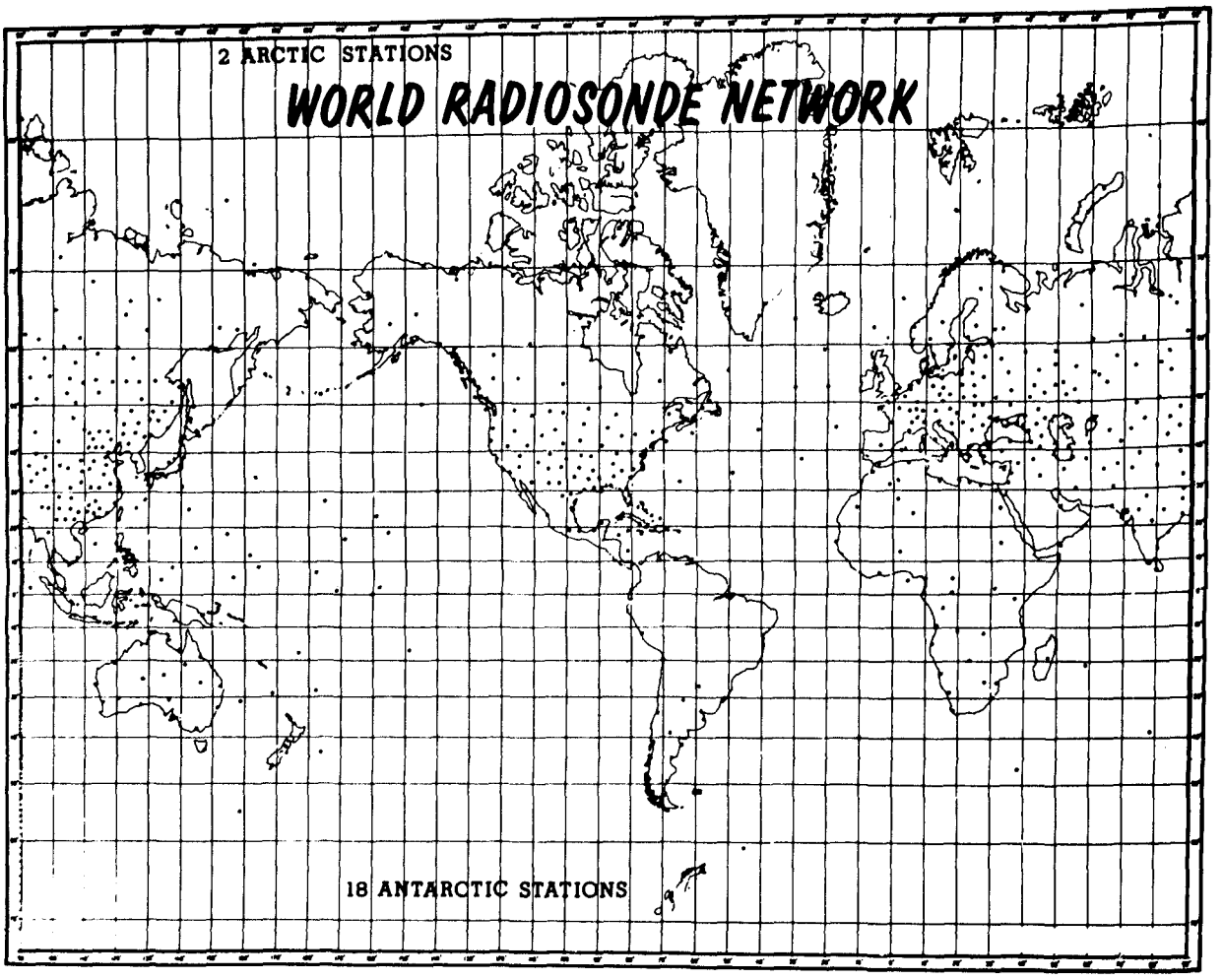


FIGURE 8–1.

a desired location is to be obtained. Even in continental regions where stations seem to be very dense, as shown in several areas of the globe (fig. 8–1), the network of stations is frequently still too coarse to catch the smaller scale weather events, such as local showers, thunderstorms, and severe local storms, including tornadoes. These storms are small in extent and have a relatively short duration. It is almost by chance that they are identified by the existing network.

A meteorological satellite having sensors with good resolution and a capability for continuous surveillance will be able to identify and track the smaller scale phenomena. Thus, it will be possible to give more explicit and detailed short-term forecasts of these severe weather events to the general public and to aviation interests. Furthermore, satellites can provide types of data not possible from other observing systems. Being situated outside the atmosphere of the earth, the satellite can view the sun directly without interference from the filtering action of the atmosphere which accompanies earth-bound observations. In the last analysis, the energy for atmospheric motions comes from the sun. With radiation sensors onboard, the satellite is in a position to measure the net balance between the solar input and the outgoing solar radiation. This net balance represents the energy available for driving the atmosphere. Moreover, this balance may be viewed from onboard a satellite either in a gross manner to acquire the global radiation budget or in detail to study local effects.

The TIROS series of meteorological satellites has demonstrated both the technical feasibility of obtaining the desired data and the practical utility of the data so obtained. TIROS consists of a series of experimental spin-stabilized me-

teorological satellites launched into orbit at an angle of about 50° at a distance of about 400 miles. TIROS I was launched April 1, 1960, and operated until mid-June 1960. TIROS II was launched on November 23, 1960, and was still providing useful television data 9 months later. TIROS III was launched on July 12, 1961, and has had a remarkable history of hurricane and typhoon surveillance. Figure 8–2 is a photo-

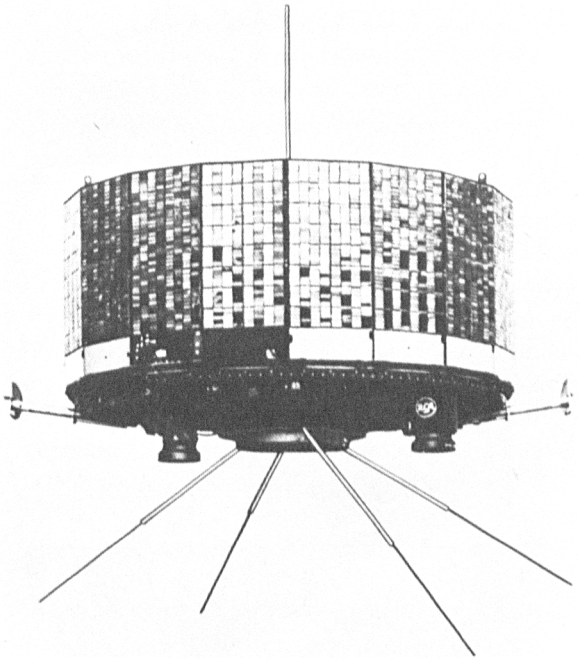


FIGURE 8–2. TIROS III.

graph of TIROS III and shows the outside of the satellite.

Each TIROS satellite carried two television cameras to obtain pictures of cloud cover. TIROS II and TIROS III carry scanning-type five-channel radiometers and black- and white-body radiometers for observing parts of the field of view with a wide-angle camera. TIROS III, in addition, carries a wide-angle radiometer similar to the one carried on the Explorer VII satellite.

Figure 8–3 shows TIROS II situated on top of the Thor-Delta launch vehicle. Although the satellite is exposed in this photograph, it is usually covered before launch with a shroud, a protecting device to assist it in its launch through the atmosphere. The equipment on the right services the rocket and the satellite prior to launch. Of course, it is disengaged at launch time.

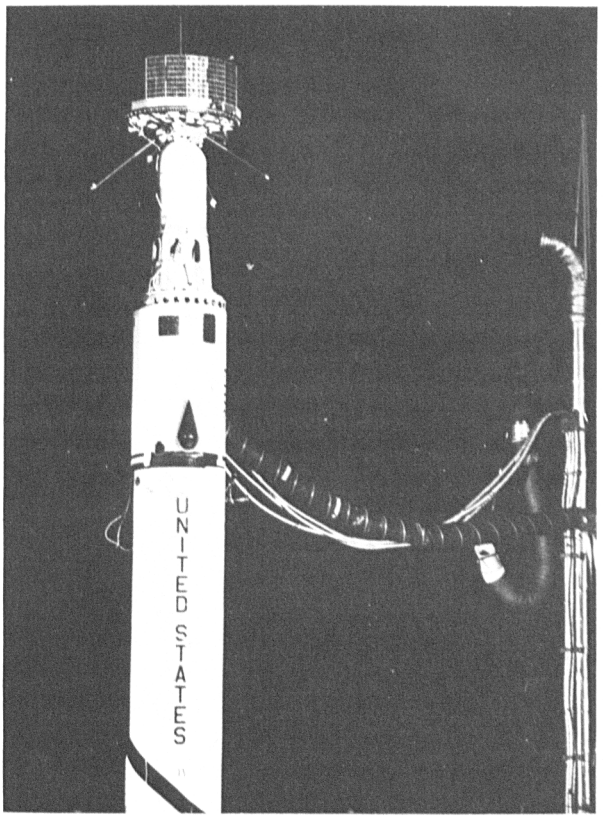


FIGURE 8–3. TIROS II and Thor-Delta launch vehicle (shroud removed).

Figure 8–4 shows TIROS I actually being launched. Here, the shroud is in place protecting the satellite on top of the rocket. The equipment on the right has been disengaged.

Figure 8–5 presents a cutaway view showing the interior of TIROS II.

Figure 8–6 shows the types of meteorological observations that can be deduced from the TIROS infrared radiation measurements. They are listed corresponding to the various channels existing in the TIROS II and III satellites. In paper 10 the components and functioning of the TIROS satellite are described in greater detail.

Following TIROS III it is expected that four additional TIROS spacecraft will be launched, at about 4-month intervals, to provide a continuity of operational meteorological satellites in orbit through the estimated date of the first Nimbus launch. Consideration is also being given to launching some of these last four TIROS spacecraft into higher inclination orbits.

TIROS *demonstrated that a spacecraft and supporting ground system could be developed around special sensors like the cameras and the*

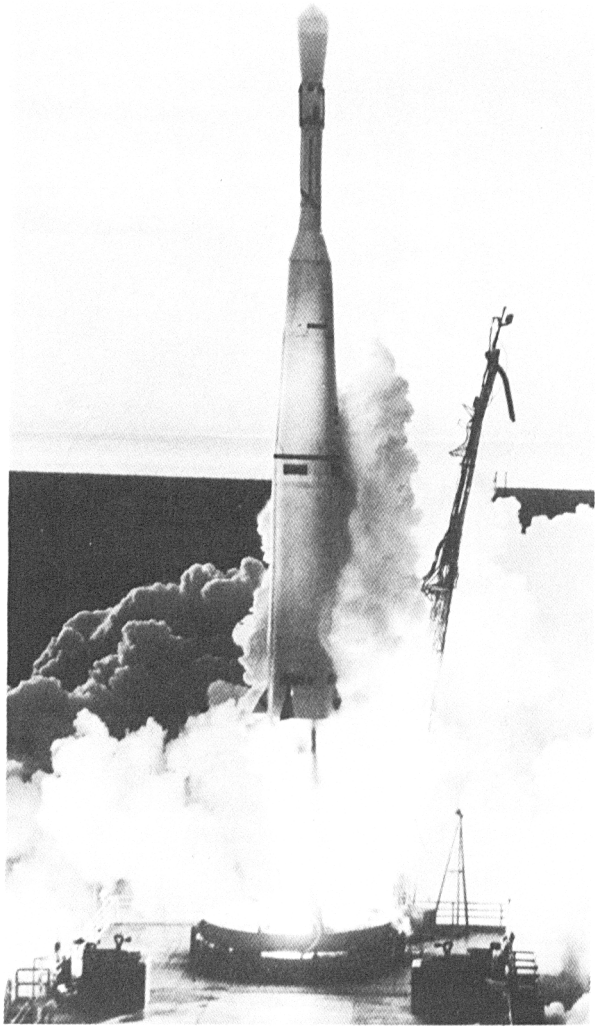


FIGURE 8–4. TIROS I being launched.

radiation detectors and could transmit the measurements of these sensors to the earth with satisfactory fidelity. The almost 23,000 pictures taken by TIROS I and the even greater number of pictures taken by TIROS II and TIROS III, as well as the considerable volume of infrared radiation data, all provide the most convincing testimonial of successful satellite system operation. The brilliance of this performance was only slightly dulled by the fact that the wide-angle camera in TIROS II was somehow defocused during launch and one of the TIROS III cameras failed about 12 days after launch. The resulting pictures from TIROS II, although not of the same quality as those from TIROS I and later from TIROS III, still show clearly the larger cloud and land areas and lack only detail.

Figure 8–7 shows pictures from TIROS I on the left and TIROS II on the right. The top two photographs are of the same land areas, the Gulf of Aden, and the Red Sea. The TIROS I picture is seen to be much clearer and shows considerably more detail, but the TIROS II pictures still show information on a gross scale. A similar degree of clarity exists with regard to the two storms in the Indian Ocean, one observed by TIROS I on the left and the other observed by TIROS II on the right. This remarkable performance of the satellites required the successful operation of many interdependent and delicate subsystems, components, and electronics. In several instances new previously untried technological advances were made. For example, spin rockets were fired on ground command after as much as 10 months in a space environment. There was a partial control of the attitude of the satellite, also on ground command. There was also the operation of lubricated ball bearings in a space environment.

The satellite measurements were found to contain useful meteorological information. With the receipt of the very first pictures from TIROS I, it became apparent that the satellite system was producing photographs of clouds, cloud formations, and cloud patterns. The meteorological research teams at the U.S. Weather Bureau, the Air Force Cambridge Research Laboratories, the Naval Weather Research facilities, and other institutions attacked the problem of interpreting the TIROS pictures in terms of weather information content. These studies indicated excellent correspondence between cloud formations and meteorological patterns, such as low-pressure areas and associated cyclonic storm systems, cold fronts, large areas of stratus cloudiness, convective areas having cellular-shaped clouds, local severe storms, jet-streams, and mountain clouds. As a matter of fact, these findings confirmed previous suggestions based on limited photographs from high-altitude rockets that Nature was drawing her own weather map by means of clouds.

Figure 8–8 shows a mosaic of photographs of cloud cover taken on May 20, 1960. On the top are the pictures taken by the TIROS I satellite. The picture below has superimposed upon it, and rectified according to geography, the location of these clouds, and also the meteorol-

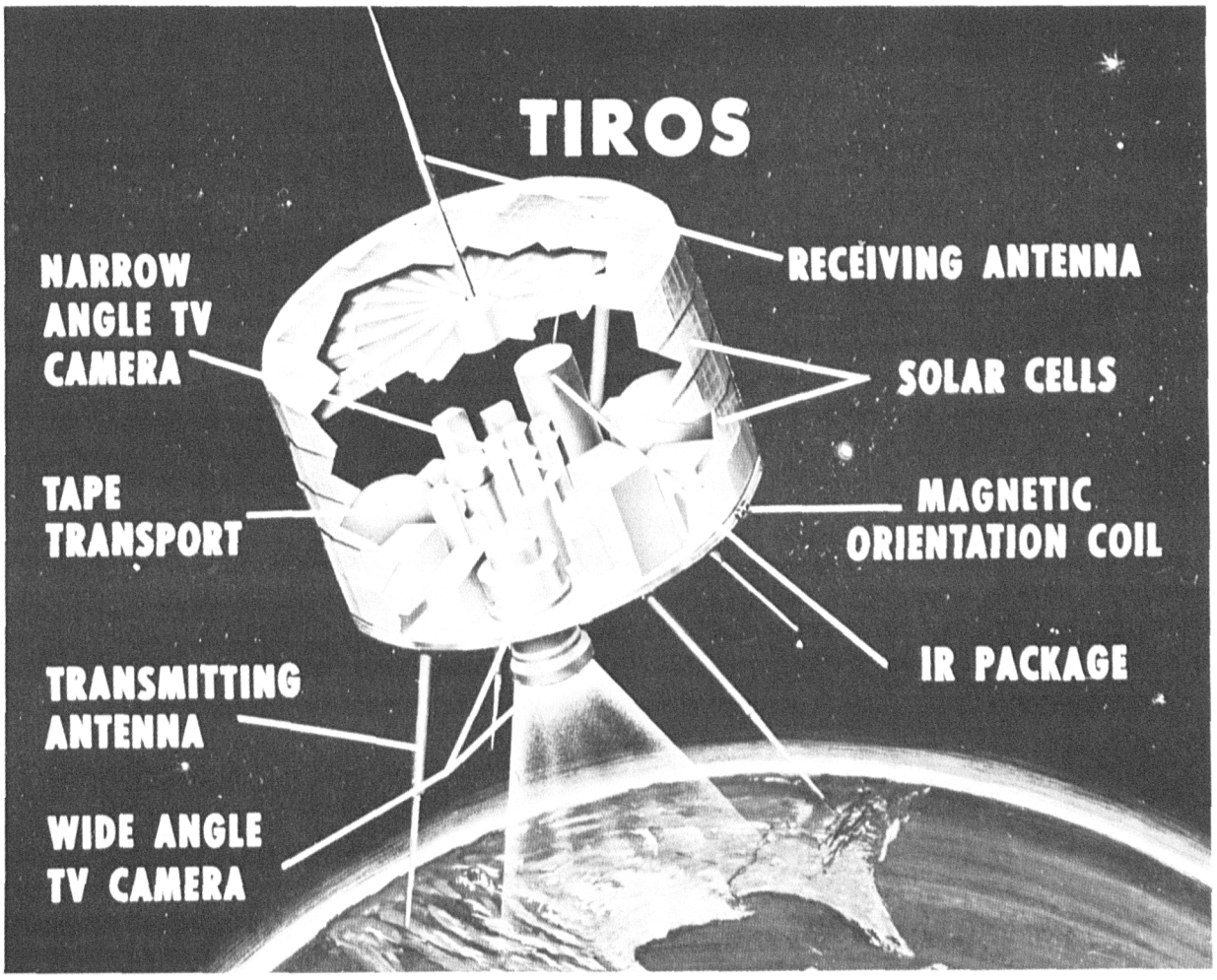


FIGURE 8–5. Cutaway view of TIROS II.

logical fronts, analysis, and pressure pattern of that day. The correspondence between these two is remarkable.

The extraction of meteorological information from TIROS II and TIROS III infrared measurements is proceeding at a slower rate. Signals from the satellite must be converted into meaningful physical measurements which must then be plotted on a map for proper study. Preliminary results have been very satisfying. Areas of satellite low-temperature measurements have been associated with cloudy zones and areas of high temperatures with cloud-free pressure regions.

The TIROS data have made it possible to increase the accuracy of weather analyses, have provided increased information both on the gross aspects of weather and on its detail, have assisted in the interpretation of cloud features and patterns, and have made it possible to infer weather patterns over areas where other data are nonexistent or insufficient. Ample illustrations of both the picture data results and the results of the infrared-radiation measurements are provided in subsequent papers.

It would have been significant enough had TIROS been successful only in providing new and detailed research data about atmospheric processes. This would undoubtedly have led to a more thorough understanding of the weather and the factors that produce it. However, TIROS was important in still another respect. In anticipation of the possible utilization of TIROS data for operational purposes, teams of meteorologists were stationed at the data-acquisition stations to study the incoming data in real time. *Within 60 hours after Tiros I was launched, picture data less than 6 hours old were being interpreted and the analyses forwarded by facsimile transmission to the Na-*

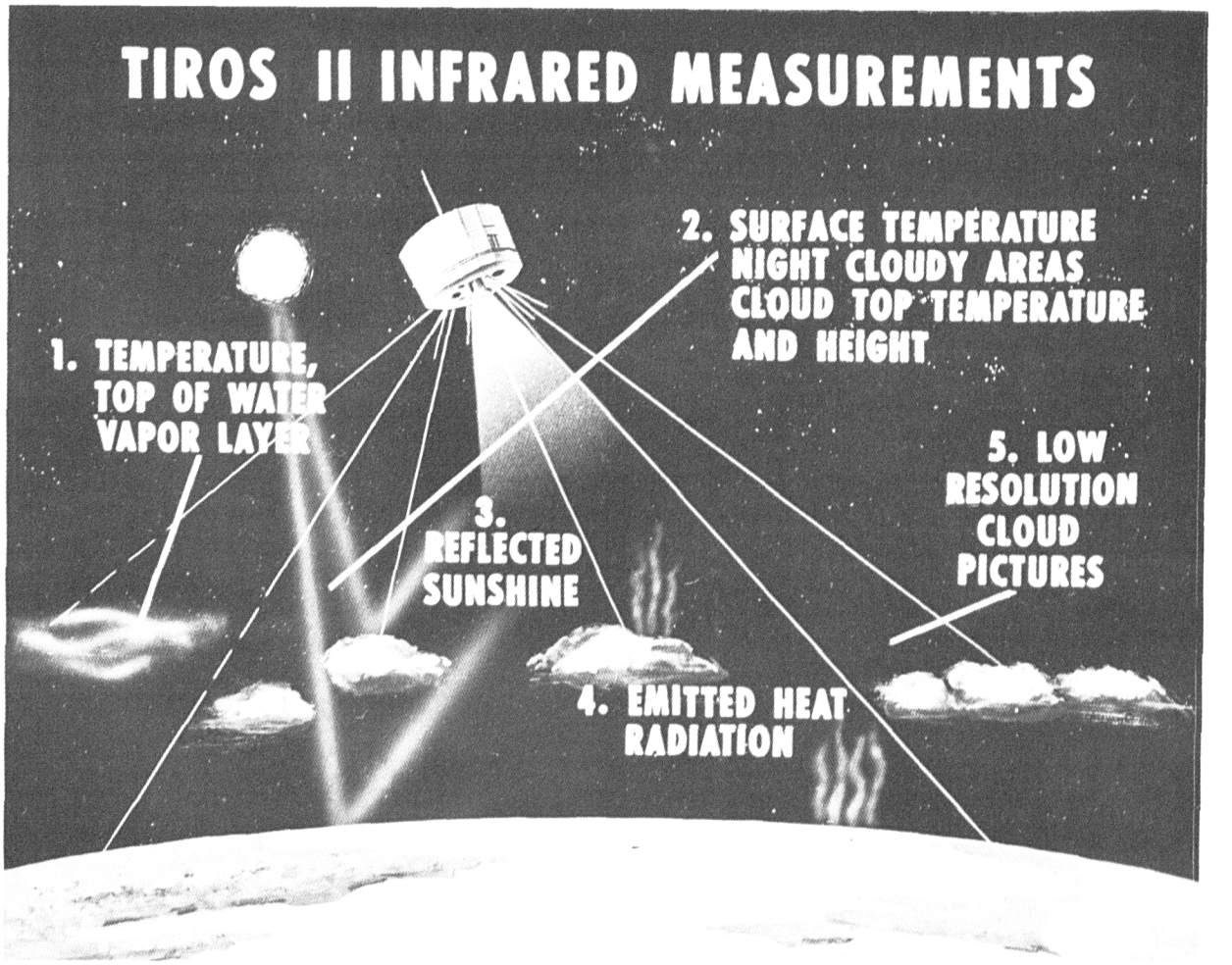


FIGURE 8–6.

tional Meteorological Center of the U.S. Weather Bureau at Suitland, Md. These transmissions were incorporated into the regular anaylses and forecasts of the Weather Bureau. Copies were also relayed to U.S. air and naval services, both in this country and overseas, where they proved to be very useful. In later periods these analyses have been made available to foreign weather services.

In their use of this information the U.S. weather services have indicated that these cloud analyses established, confirmed, or modified surface frontal positions, assisted in the briefing of pilots on accurate weather conditions, were used in direct support of overwater deployment and aerial refueling of aircraft, gave direct support to an Antarctic supply mission, confirmed the position of a Pacific typhoon, verified and amplified local analyses particularly over areas of few reports, and more. There is a full discussion of the utilization of TIROS data for current analyses in paper 15. Because the atmosphere is a global phenomenon and meteorology is an international science, it is well recognized in the U.S. meteorological satellite program that maximum benefits will be derived only through international cooperation and participation. Thus, the TIROS program has been developed to include international participation as follows:

1. The transmission of meteorological analysis to foreign countries.—As described previously, as satellite data are acquired at readout stations, they are analyzed directly by teams of meteorological experts, and their analyses of the data are furnished to the National Meteorological Center whence they are retransmitted to field users, both nationally and internationally.

2. The availability of basic data for foreign research groups.—Copies of the TIROS picture data

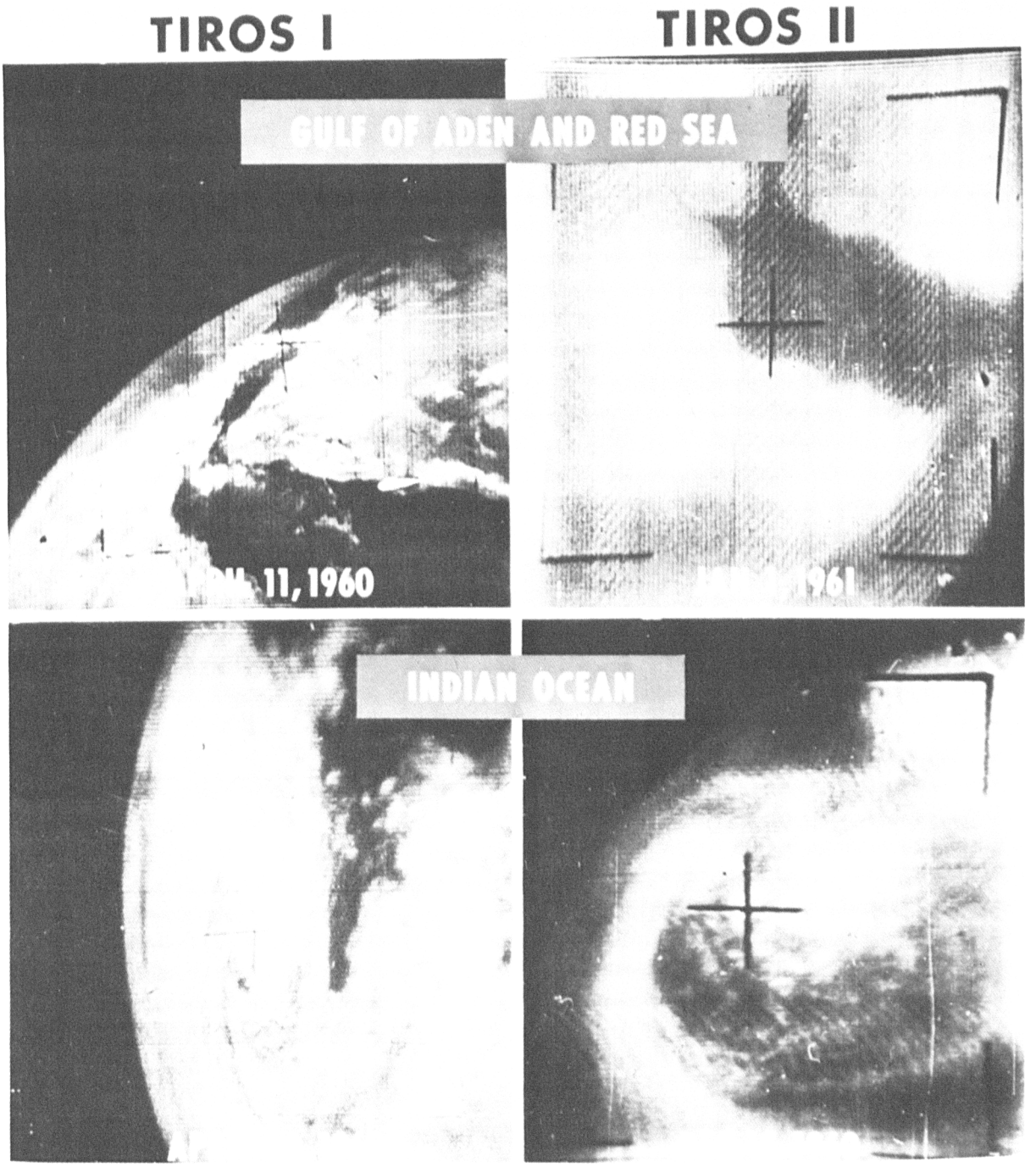


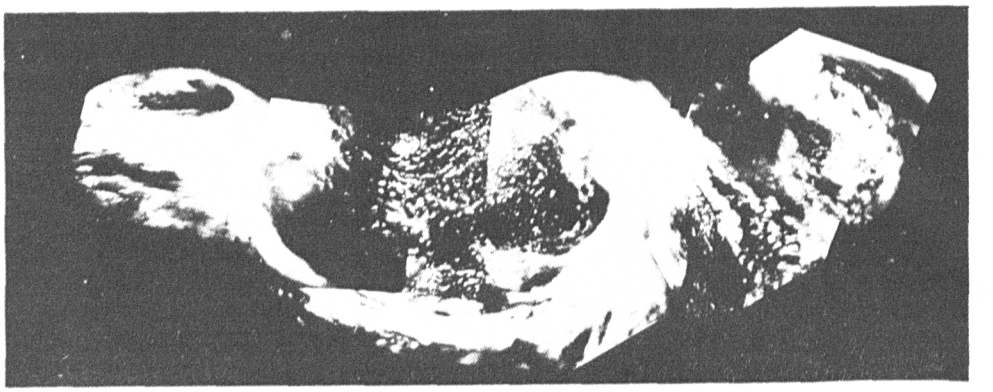
FIGURE 8–7. Comparison of TIROS I and II wide-angle-camera photographs.

may be acquired by any country in the form of 35-millimeter positive transparencies for projection or 35-millimeter duplicate negatives from the National Weather Records Center at Asheville, N.C. A catalog, of which the TIROS I portion has been published (ref. 1), contains maps showing the approximate area viewed in each picture sequence and other useful information required for proper interpretation and analysis of the pictures.

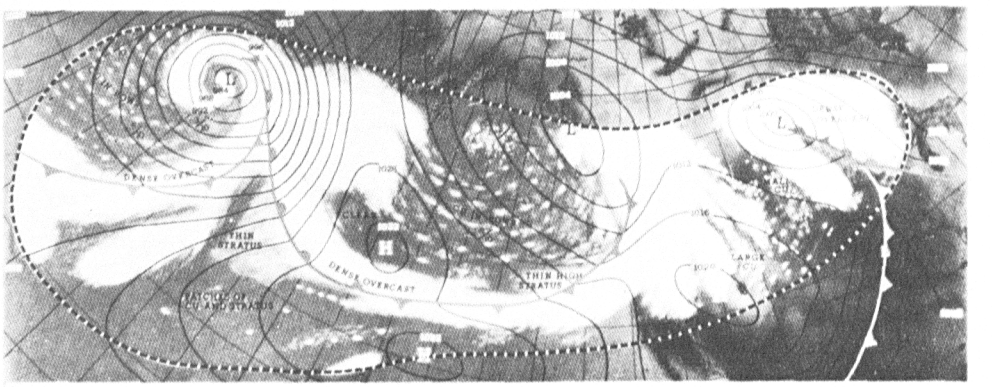
3. Supporting meteorological observations.—Satellite information is more useful when combined with other meteorological observations, for example, special upper air soundings, aircraft observations, rocket observations, special radar coverage, and others.

STORMS AND FRONTS

A Family of Weather Systems



MOSAIC OF TIROS PHOTOGRAPHS



WEATHER MAP, MAY 20, 1960, WITH TIROS CLOUD DATA

FIGURE 8–8.

In connection with TIROS II, the national meteorological services of 21 countries adhering to COSPAR were contacted and were offered the necessary satellite orbital information in the event they wished to make special observations which could be correlated with the satellite observations over their locality. Seventeen countries indicated that they were anxious to participate in this program. This program never fully materialized in view of the degraded pictures of the TIROS II wide-angle camera. However, a similar program, expanded to include invitations to approximately a hundred of the countries adhering to WMO, was initiated in association with TIROS III. Over 30 countries have indicated their intentions to participate actively. It is anticipated that similar programs, probably on a more routine and continuous basis, will be operated in connection with future TIROS launches.

4. International Meteorological Satellite Workshop.—The objective of the Workshop is "to present directly to the foreign weather services the results of the U.S. meteorological satellite activity to date and the possibilities for the future so that the program may be more completely known and understood by the scientific world community, that the present activity may be put in its proper perspective relative to future operational programs; and, finally, that the foreign weather services may acquire a working knowledge of the TIROS data for assistance in their future analyses programs, both in research and in operations and guidance in their own national observational support efforts."

Reference

1. PYLE, ROBERT L., AND MERCER, DONALD M., compilers: *Catalogue of Meteorological Satellite Data—TIROS I Television Cloud Photography.* Key to Meteorological Records Documentation No. 5.31, U.S. Dept. of Commerce, Weather Bur., 1961.

9. THE CURRENT USWB METEOROLOGICAL SATELLITE PROGRAM

By DAVID S. JOHNSON, *Chief, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

A rather comprehensive review of the TIROS meteorological satellite program upon which most of the research activities in the Weather Bureau are based has been given in paper 8.

The research activities in the meteorological satellite program in the Weather Bureau are centralized in the Meteorological Satellite Laboratory. The Laboratory is primarily concerned with meteorological research utilizing satellite observations in order to increase the understanding of the atmosphere and, at the same time, to develop new and improved techniques for analysis and forecasting.

Because of concern with the nature of the observations, the Laboratory also participates in the satellite experiment design and in basic instrument development. The volume of meteorological data obtained by the satellite averages millions of bits of data per day. This causes serious problems of data processing, both for immediate operational use and for any research programs that are carried on subsequently. Therefore, automatic data-processing techniques are being studied to meet research needs and to develop operational techniques.

In addition to the research program, the Laboratory has been deeply involved in an experimental operational use program which, it is hoped, will serve as a forerunner of an operational meteorological satellite system.

The research work of the Laboratory, including the operational meteorological satellite system, will be described in detail in numerous subsequent papers. Therefore, in this very brief presentation, only a few points will be discussed, with emphasis on certain topics which may not be covered in the subsequent papers.

Figure 9–1 is a mosiac prepared from pictures taken by TIROS I extending from the eastern north Pacific Ocean across lower California, Mexico, and the United States, to a point just east of Lake Michigan. These pictures give a view of the type of coverage that is obtained with the TIROS satellites. The mosiac in figure 9–1 is composed of pictures taken by the wide-angle camera. Each picture covers an area of about 700 to 800 miles on a side when the camera is pointing straight down, with a larger area covered as the camera points obliquely at the surface of the earth. In the picture at the far right, for example, the horizon can be seen. The two pictures in the lower right and the picture in the upper left were taken with the narrow-angle camera, which views an area approximately 70 or 80 miles on a side when the camera axis is normal to the surface of the earth.

This gives some idea of the comparative resolution of the two camera systems and what might be classed as normal pictures from both TIROS I and TIROS III. As mentioned in paper 8, the wide-angle pictures in the case of TIROS II were fuzzy and lacked detail.

The high-resolution picture showing Tiburon Island, in the Gulf of California, embraces the outlined area shown in the corresponding wide-angle picture. The distance between the island and the coast is about 1 to 1½ miles; this gives a fair idea of the resolution that can be obtained.

The cloud patterns which exist over the Pacific may be seen in figure 9–1. In general, it has been found that the cloud systems seen by TIROS are highly organized, but this is not always the case. For example, the cloud systems in the pictures on the left are rather chaotic. But even in their chaos they have some organization; note the rolls along the edge of the stratiform cloud. In the last two pictures on the right, clouds associated with a cyclonic vor-

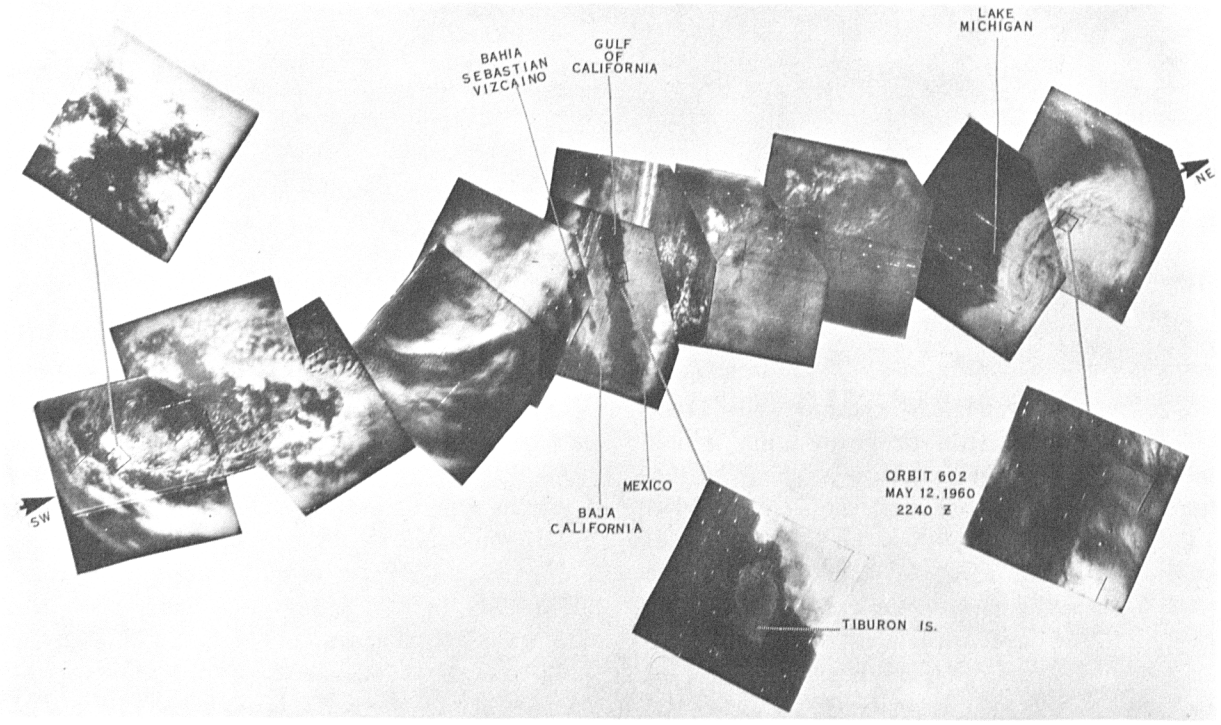


FIGURE 9–1. TIROS I mosaic of clouds over northeastern Pacific to Lake Michigan.

tex located just east of Lake Michigan may be seen.

A bank of stratus over the eastern north Pacific Ocean just off Baja California and the southern California coast is shown in figure 9–2. Generally, stratus exists in the eastern portion of anticyclone patterns and is often found in data-sparse areas; this is a particularly good example. Thus, there is an opportunity, with meteorological satellites, to collect data which can be used for studies of large areas of semipermanent stratus and their associated trade-wind inversion, particularly when radiation data which can be used to infer the temperatures of the tops of the stratus are available on a regular basis.

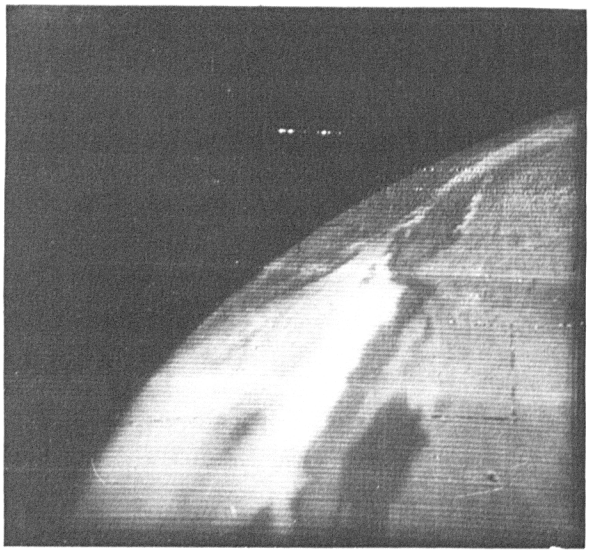


FIGURE 9–2. Stratus off west coast of Baja California.

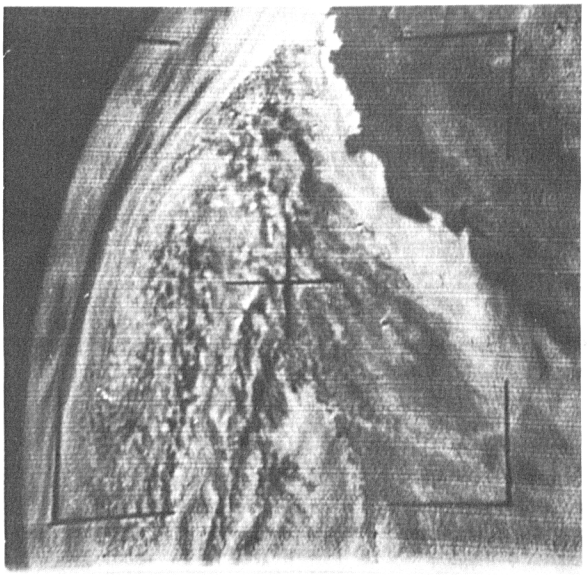


FIGURE 9–3. California coast.

Figure 9–3 is a photograph of an area including the California coast. Note the darker Y-shaped area which is San Francisco Bay. The water, of course, has the lowest albedo in the picture. Monterey Bay is visible below and to the right of San Francisco Bay. The dark spot just to the right of the center of the vertical portion of the upper right fiducial mark is Lake Tahoe, on the border between California and Nevada. The San Joaquin and Sacramento Valleys and a stratus deck along the coast of California not penetrating inland except at the Golden Gate can also be seen. Note also in this picture a rather weak spiral vortex associated with a dissipating storm system some distance off the California coast over the eastern Pacific Ocean.

Tiros III has been nicknamed by the press as the "Hurricane Hunter" satellite; figure 9–4 shows one picture of a hurricane which resembles to a considerable degree the hurricane symbol which is frequently used by meteorologists. This particular picture shows hurricane Betsy. Tiros III has been particularly notable in its coverage of hurricanes and typhoons, as well as

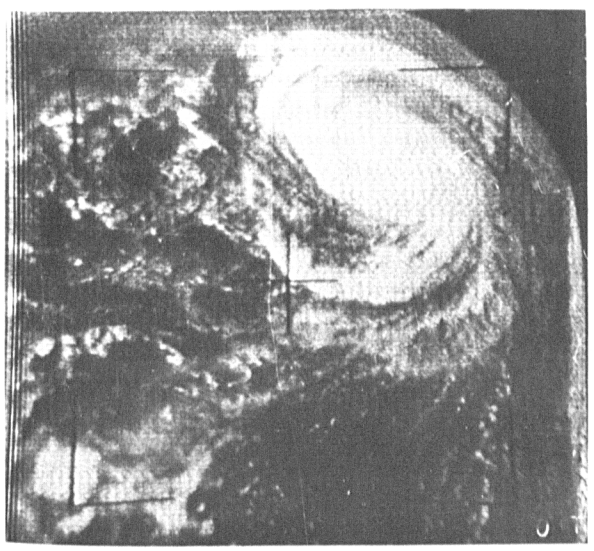


Figure 9–4. Hurricane Betsy.

weaker tropical storms and easterly waves. It may be of interest to note the bright cloud mass in the lower left corner of figure 9–4. Although the weather associated with this mass has not been checked by conventional meteorological data, similar masses in a number of other pictures have been noted and the weather associated with them has been reported by conventional means. These bright discrete cloud images appear to be associated with mature cumulonimbus cloud masses and are often indicative of severe local storms. Thus, when this type of image appears in a particular picture, the possibility of a severe local storm should be considered. This connection between severe local storms and hurricanes was particularly notable in the case of hurricane Carla after it moved in over the United States from the Gulf of Mexico.

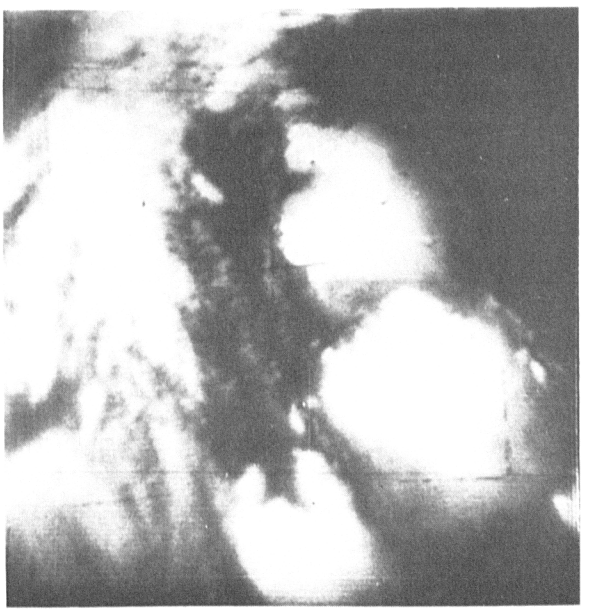


Figure 9–5. Isolated cloud masses over northeast Colorado.

Three cumulonimbus cloud masses over northeastern Colorado as photographed by Tiros I are depicted in figure 9–5. Note that the three isolated cloud images are brighter than the other clouds. Surrounding each of these masses is a relatively clear area, suggestive of rather substantial subsidence. In this particular case the ground observations indicated severe winds, which damaged crops, associated with these three cumulonimbus masses; hailstones as large as 2 centimeters in diameter were observed. More details on this type of phenomenon will be given in subsequent papers.

Figure 9–6 is a picture of mountain wave clouds downwind of the Andes over Argentina; this picture illustrates another particularly useful application for satellite pictures which view such a large area at one time. The Andes can

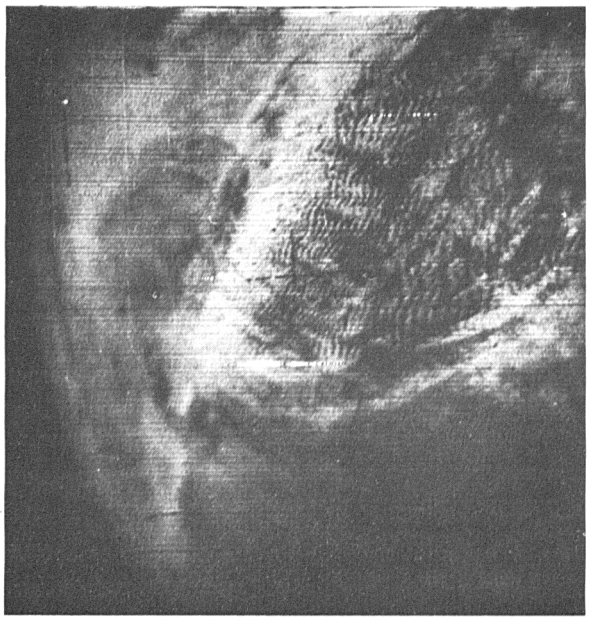


FIGURE 9–6. Mountain wave clouds east of Andes.

be seen just to the left of the center of the picture with the wave patterns extending downwind toward the east. There are two different scales of perturbations visible: the relatively short wavelength, particularly clear near the mountains, and the longer wavelength on which the short wavelength is superimposed. The extent of the wave pattern as indicated by the cloud distribution is of the order of 200 to 300 miles downwind of the mountain ridge.

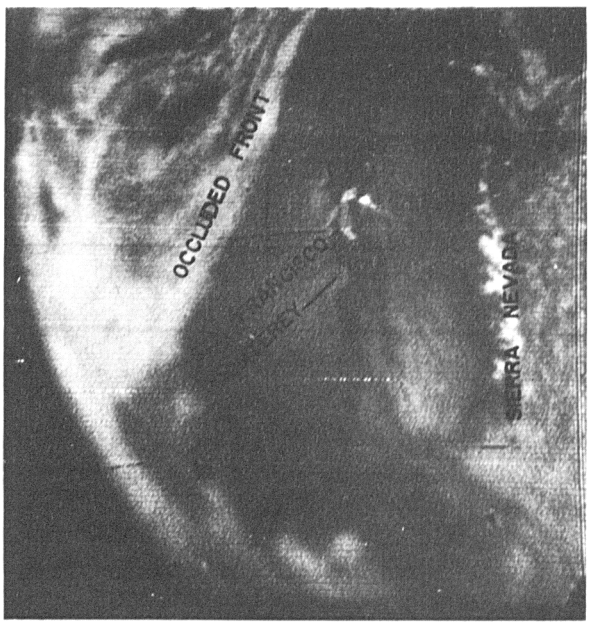


FIGURE 9–7. Snow cover over Sierra Nevada.

Figure 9–7 illustrates an example of what might be called a borderline meteorological application, the depiction of snow cover. Again, the State of California is pictured with the San Francisco Bay clearly indicated by the specular reflection of the image of the sun. The center of the image of the sun is in the Sacramento River estuary just northeast of San Francisco Bay; the Sierra Nevada mountain range which is mostly snow covered is easily seen. It is oftentimes difficult to discern with certainty in any one picture the difference between snow and clouds. By examining the same area on a series of days, the areas which are definitely snow covered can be differentiated from those which are cloud covered. The cloud system over the eastern Pacific off the west coast of California is associated with an occluded cyclone.

Another fringe application, as far as meteorology is concerned, is ice detection; figure 9–8 illustrates this application. TIROS II was particularly useful in that many narrow-angle pictures were obtained such as these of ice in the Gulf of St. Lawrence area. The figure shows two mosaics of the same area in the Gulf of St. Lawrence extending from west of Anticosti Island to the west coast of Newfoundland. The pictures, taken 6 days apart, make it possible to note the changes in the ice pattern during that period.

Note in the mosaic for March 23, the lead of open water parallel to the northeast coast of Anticosti Island and also the cracks which are beginning to appear in the rather extensive icepack to the east. This area where the cracks appeared and where the ice is darker than elsewhere, which is believed indicative of relatively thin ice, was open water 6 days later, as shown in the mosaic of March 29. The floes range in size from about 1 to 8 kilometers in diameter, and the fields, the solid large areas of ice, are larger than 8 kilometers in diameter.

Some examples of sun glint, which was briefly mentioned in the discussion of figure 9–7, are shown in figure 9–9. The two pictures at the lower right were taken about a minute apart by TIROS I over the Aral Sea. In the left picture of the Aral Sea, the sea, as would normally be expected, is darker than the surround-

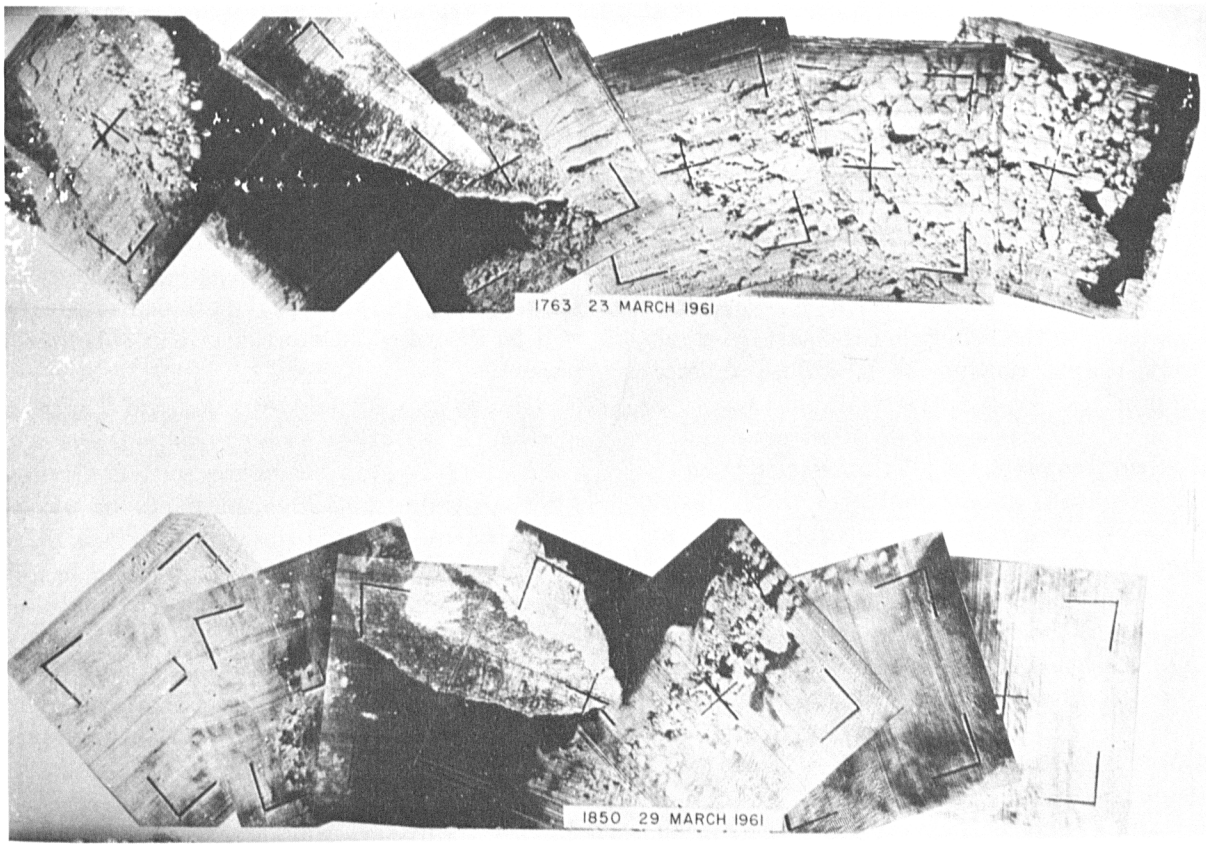


FIGURE 9–8. Mosaics showing ice on the Gulf of St. Lawrence.

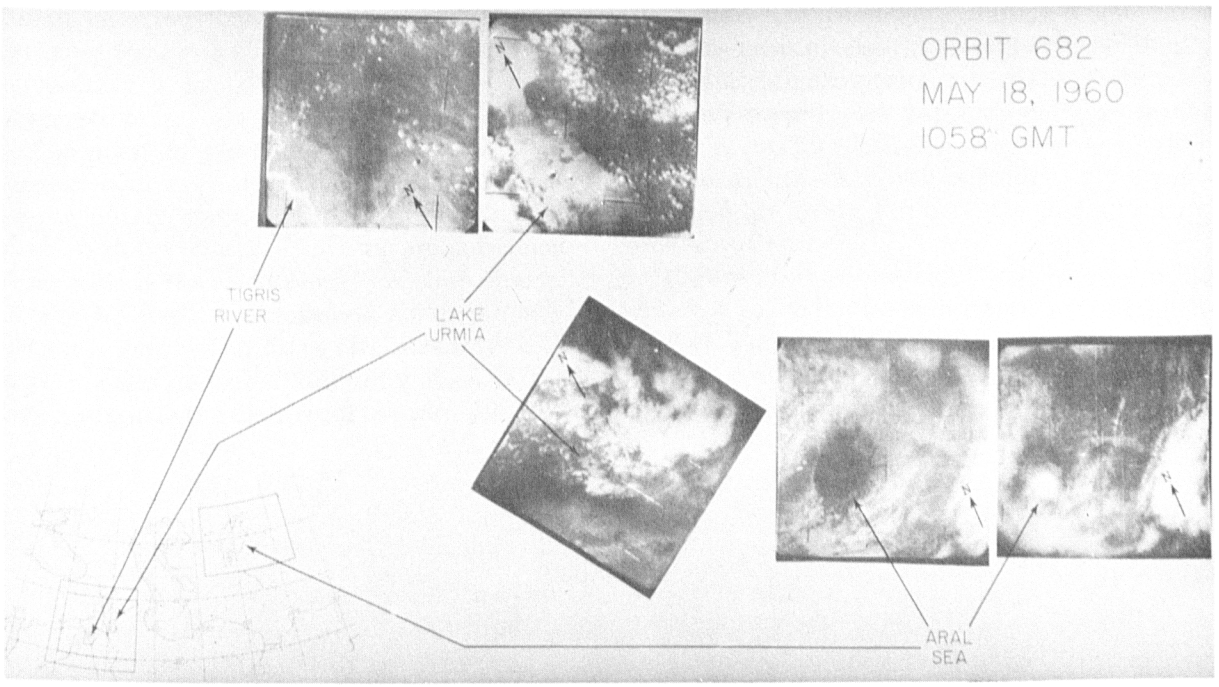


FIGURE 9–9. Sun glint as seen from TIROS.

ing land or cloud because of its very low albedo. In the picture to the right the image of the sun is reflected by the sea, and the sea is very bright. The conclusion in this particular case, confirmed by supporting observations, is that since the water surface is very smooth, a mirror image of the sun is being seen on the surface. In the upper part of figure 9–9 is a view of Lake Urmia in which the specular reflection is diffuse and rather uniform over the entire lake surface. This leads to the belief that the surface is relatively rough, serving as a diffuse reflector. Thus, there is much interest in the possibility of using the image of the sun, or reflectivity, under clear-sky conditions as an indicator of the ocean surface conditions.

In conclusion, the Meteorological Satellite Laboratory is also active in the interpretation of the radiation measurements which require a great deal more data processing and study before any results can be presented. These results, to date, and some of the problems involved will be discussed in more detail in subsequent papers.

10. THE TIROS SATELLITES

By W. G. Stroud, *Chief, Aeronomy and Meteorology Division, Goddard Space Flight Center, National Aeronautics and Space Administration*

This Workshop provides the opportunity to evaluate the performance of the Tiros meteorological satellite system as part of the NASA studies of the atmosphere and its motions. In addition, the three satellites launched have varied in degree of success. The usual difficulties that an experimental physicist or meteorologist may have in conducting atmospheric experiments have been encountered. However, these have been exaggerated by the unusual laboratory (space) in which the experiments are being conducted.

There has been no question for some time of the value of meteorological satellites. But the technology of the launch vehicles, the telemetry problem, that is, the problem of communicating the data from the satellite to the ground, and all the other practical considerations, including funds, have only recently permitted the realization of the desires of meteorologists and geophysicists to bring the entire earth under observation.

The point of view taken by NASA is that Tiros represents a series of experiments rather than a purely operational tool or the final answer in the problem of making measurements from outside the atmosphere. A close analysis of the infrared and reflected solar radiation data obtained by the Tiros satellites reveals the experimental nature. Not only does it take time to receive the data from the satellite but it also takes time to interpret these data in terms of the atmospheric phenomena.

The experimental Tiros system can really be broken down into four major elements: The launch vehicle; the spacecraft or satellite; the data acquisition, that is, the problems of acquiring the data from the satellite by the ground stations; and the data utilization, that is, the procedures by which the data are used. This paper is concerned with only the first three of these elements.

The launch vehicle.—The Thor-Delta used to launch the satellite is a three-stage vehicle: liquid, liquid, and solid; that is, the first two stages are liquid and the third stage is solid. It has been used to launch Tiros I, II, and III. The Tiros I launch vehicle was slightly different in terms of guidance and sequencing, but it had the same propulsive units. These three vehicles have placed the satellites in nominally 400-nautical-mile orbits with 100-minute periods and roughly 48° inclination. This means that the satellite latitude excursion is between 48° north and 48° south latitudes, corresponding roughly to the limits of the globe brought under observation.

Figure 10–1 shows the Thor booster being inserted in the launch stand prior to the launching of Tiros II. The first-stage Thor has a thrust of about 150,000 pounds. It is interesting that the Thor vehicle used to launch Tiros I

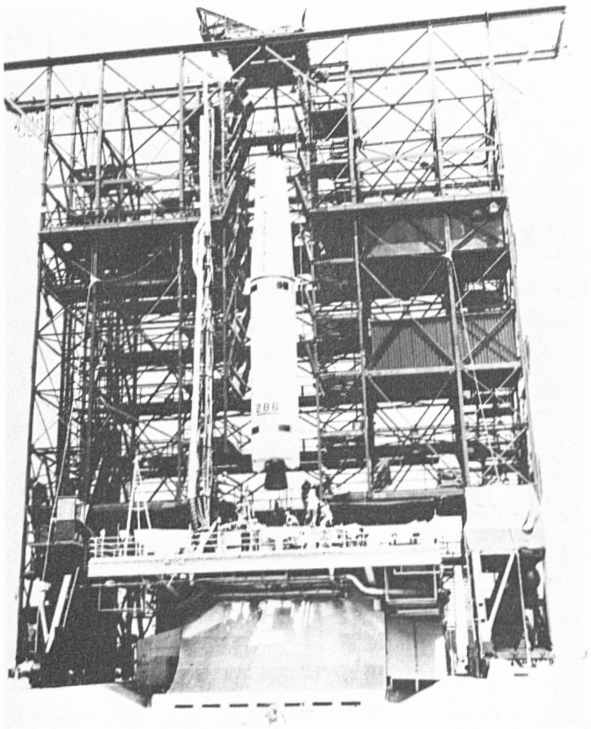


FIGURE 10–1. Placement of the Thor booster on the launch stand for the TIROS II launch from Cape Canaveral.

was extensively used as a training vehicle by the military services; finally, it was obtained by NASA and modified to the form used for the TIROS launches. This modified Thor successfully performed in the launch of the TIROS I satellite itself.

Figure 10–2 shows the vehicle on the launch stand. The launch vehicle stands about 90 feet high, it is about 8 feet in diameter, and at lift-off it weighs a little over 100,000 pounds. An impressive feature of the launch vehicle is the rate at which it consumes oxygen. It consumes oxygen during the boost phase at the same rate as about 6 million people.

Table 10–I summarizes the satellite orbital parameters resulting from the successful launch-vehicle performances:

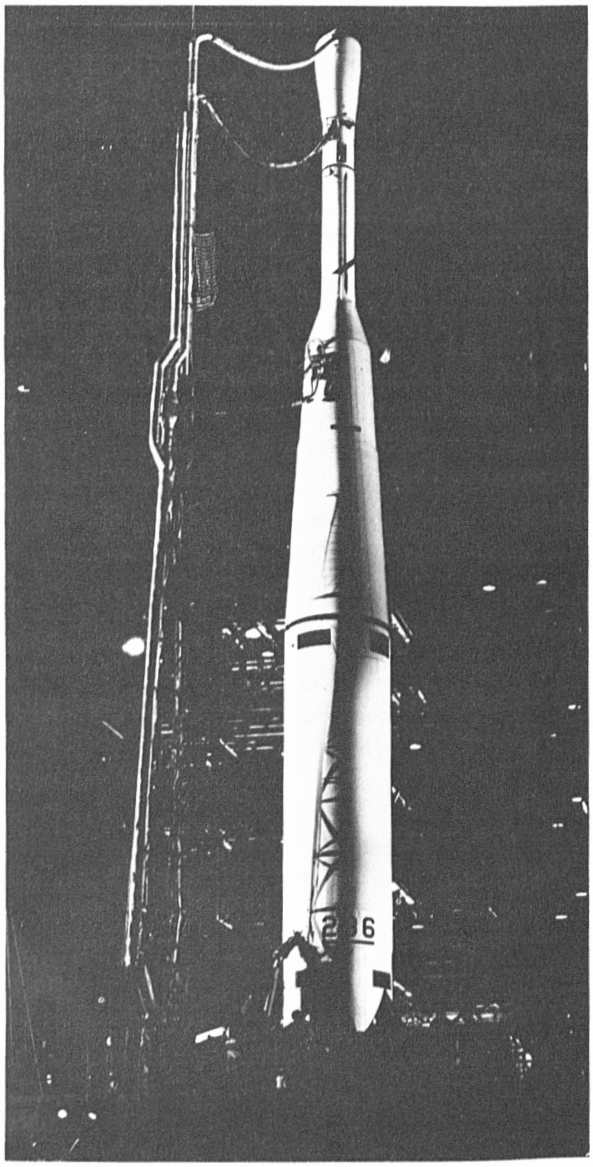


FIGURE 10–2. The Thor-Delta launch vehicle standing ready for launch in the early morning of November 23, 1960.

TABLE 10–I.—*Orbit Information*

	TIROS I	TIROS II	TIROS III
Period, min	99. 24	98. 26	100. 4
Average height, statute miles (km)	450 (720)	420 (676)	475 (760)
Apogee, statute miles (km)	461. 3 (740)	451. 5 (726)	509. 8 (820)
Perigee, statute miles (km)	436. 0 (702)	387. 8 (624)	457. 1 (736)
Eccentricity	0. 00287	0. 00727	0. 00593
Inclination, deg	48. 392	48. 530	47. 898

The spacecraft.—Figure 10–3 shows a familiar view of the satellite which is 42 inches in diameter and about 19 inches high. The satellite weighs about 280 pounds and contains a vast complex of optical, sensory, electronic, magnetic, and mechanical devices that serve the

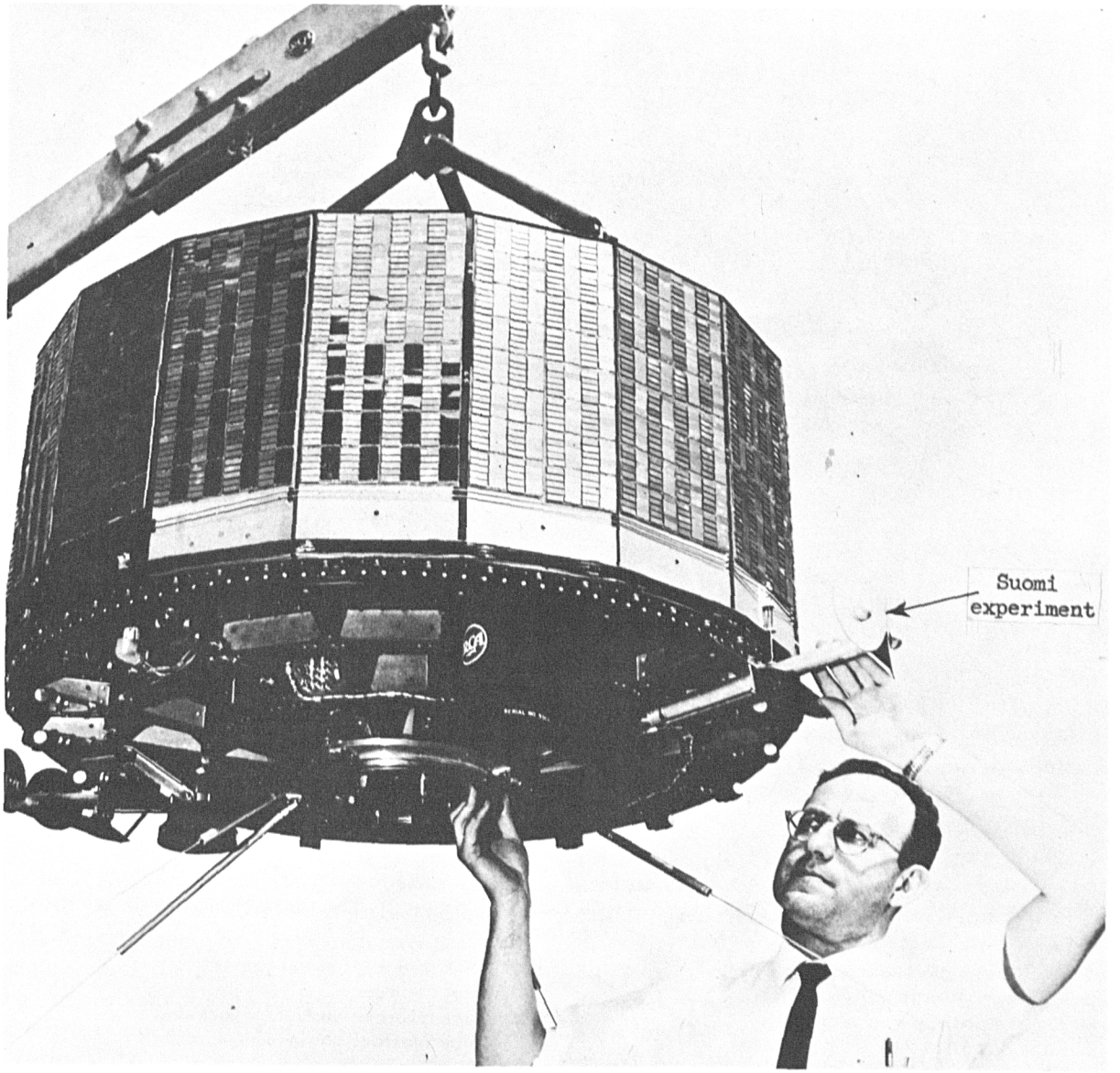


FIGURE 10–3. The TIROS satellite in the TIROS III configuration showing the base plate with cameras looking downward. The top is covered with solar cells.

following functions: to detect, to store, and to transmit the data; to control the various functions; to provide memory (a clock) inside the satellite; to control the spin rate of the satellite because it is spin stabilized; to control the power; and to control the attitude to a certain extent. The attitude of the TIROS satellite is the most critical problem.

Figure 10–4 shows a top view of the internal package. The main interest here is in the sensor systems. The tops of the television cameras can be seen in the figure: two wide-angle television systems (Nos. 5 and 30) and one of the big tape recorders (Nos. 3 and 19) on which the picture information is stored. The infrared radiation system (No. 12) and instruments

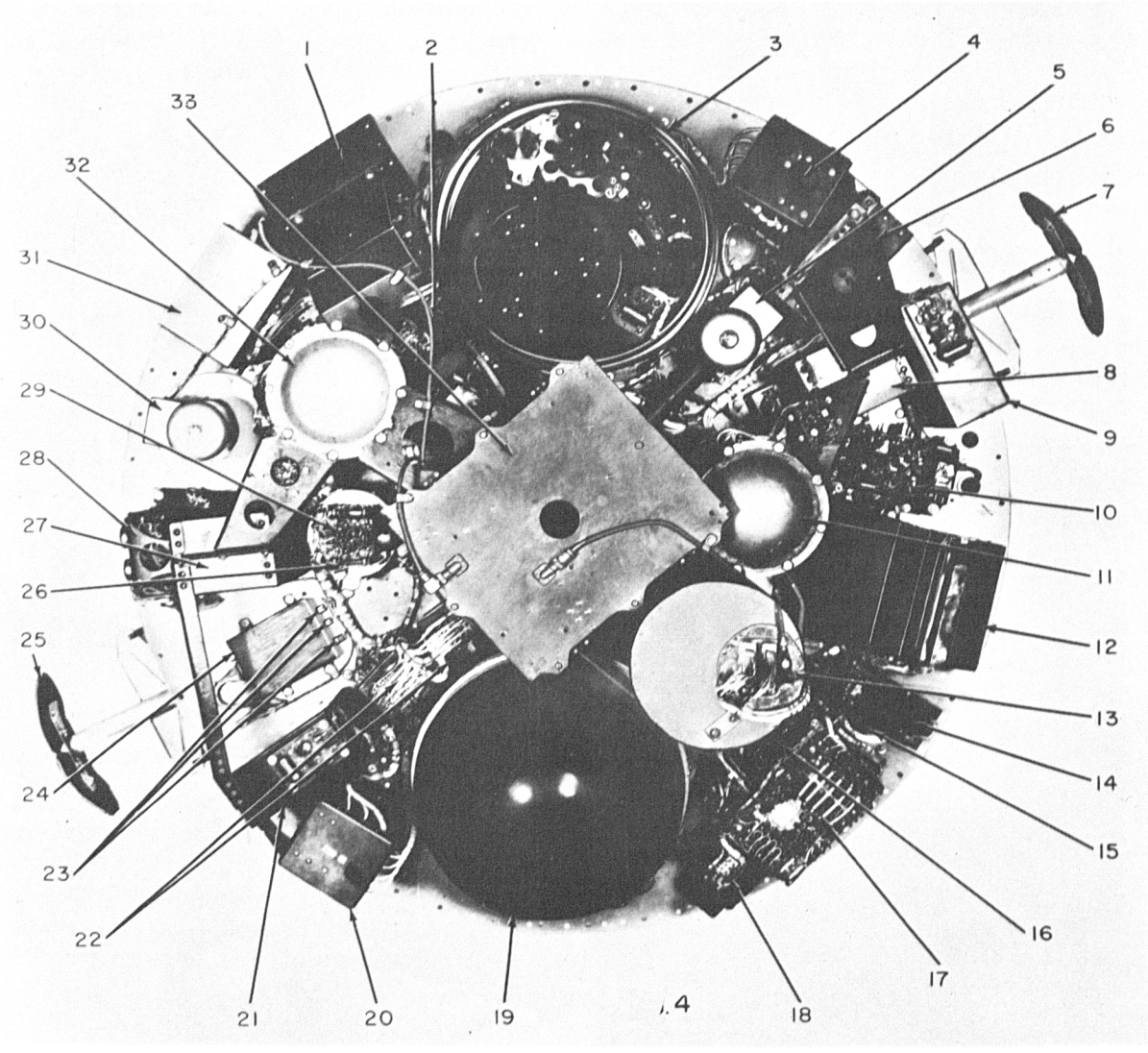


FIGURE 10–4. A top view of the TIROS satellite with the cover removed. The various components are listed as follows:

1. TV camera electronics package.
2. TV transmitter power converter.
3. Tape recorder (cover removed).
4. Tape recorder electronics package.
5. TV camera.
6. Tape recorder power converter.
7. Omnidirectional radiometer.
8. TV camera control package.
9. Tape recorder power converter.
10. Heat measuring equipment control panel and (below) command receivers.
11. Electronic clock.
12. Scanning radiometer.
13. Heat measuring experiment electronics (and tape recorder) package.
14. Horizon detector.
15. Nonscanning radiometer.
16. Voltage regulators.
17. Battery protection panel and despin timer (below) and TV transmitter (below).
18. TV transmitter power converter.
19. Tape recorder.
20. Tape recorder electronics package.
21. Tape recorder power converter.
22. Main telemetry switches.
23. Temperature sensors.
24. Omnidirectional radiometer electronics package.
25. Omnidirectional radiometer.
26. Beacon transmitters.
27. Auxiliary control package.
28. Voltage regulator.
29. Attitude control switch.
30. TV camera.
31. Synchronous generator and (below) TV transmitter.
32. Electronic clock.
33. Antenna diplexer and (below) batteries.

for storing and transmitting the infrared information data are shown (No. 13). Shown also are: one of the infrared radiation scanners (No. 12), the various clocks for keeping time on the satellite (Nos. 11 and 32), and the beacons for keeping track of the satellite (No. 29). The satellite radiates at 108 megacycles at all times and the ground stations (minitrack network) keep track of it.

Table 10–II summarizes the camera systems.

TABLE 10–II.—*Camera Parameters*

	Wide angle	Narrow angle
Field of view, deg	104	13
Area coverage from average height of satellite and zero nadir angle, sq miles (km)	750 (1,200)	75 (120)
Lens speed	f/1.5	f/1.8
Shutter speed, milliseconds	1.5	1.5
Lines per frame	500	500
Resolution per raster line pair, zero nadir angle, miles (km)	1.5 to 2 (2.5 to 3)	0.2 to 0.5 (0.3 to 0.8)

In TIROS I and II a wide-angle camera which took a picture with a scope of about a thousand miles on a side and a narrow-angle camera which took a picture with a scope of about 75 miles on a side were used. The lens speeds are given, the number of frames, and the video bandwidth.

There is another view of the satellite in figure 10–5 which gives some reference to the various-sized boxes that are used in it. The key tape recorder (No. 1) used stores 32 pictures. In any orbit of the satellite, 32 pictures can be taken and stored in the satellite for any one camera. Other boxes for control functions are shown as No. 2. Also shown are the antennas for both the 235-megacycle transmission of the data to the ground (No. 3) and the 108-megacycle transmitter (No. 4) which are used for tracking and for telemetry, the telemetry solving the problem of keeping track of how well the satellite is operating; for example, the telemetry indicates whether the voltages are proper throughout the satellite, if all the power is being acquired from the solar cells that should be acquired, what the power balance is in the satellite, and so on. All this information must be obtained if the performance is to be properly evaluated.

There are three aspects of the camera systems that are different from the usual systems. One is the "sticky" nature of the vidicon surface that is used. This is not a normal image orthicon or television system. The surface of the television vidicon tube is exposed to the image of the earth in 1.5 milliseconds; then, the electron beam reads the picture off in about 2 seconds, that is, converts the picture information, which is the distribution of charges on the photograph surface, to electrical signals. Thus, the time required in this operation (a time compression of almost 1,000 to 1) permits a reduction in the radiofrequency bandwidths required to transmit the data to the ground. This characteristic of the vidicon is quite unusual and has been used most advantageously; a video bandwidth of about 62.5 kilocycles is used in contrast to the normal television systems where the video bandwidths are of the order of 4 megacycles.

The second aspect of the camera system is that of resolution versus contrast, that is, what can be seen in the pictures. The resolution, in terms of the number of lines in the wide-angle camera system, as an example, can be deduced from the fact that the angle field of view of the lens is about 104° which is projected onto a 500-line vidicon. The vidicon produces a 500-line scan. This yields a television resolution of about 1.5 or 2 miles with the camera pointing straight down from a nominal 400-mile altitude. That does not mean that two objects on the ground which are roughly 2 miles apart can be resolved, because the optical resolution is twice the television resolution. Even if full advantage could be taken of the resolution, there is another factor which enters the ability to determine what is in a picture; this is the contrast. The quality of the TIROS I pictures was a pleasant surpise because the contrast be-

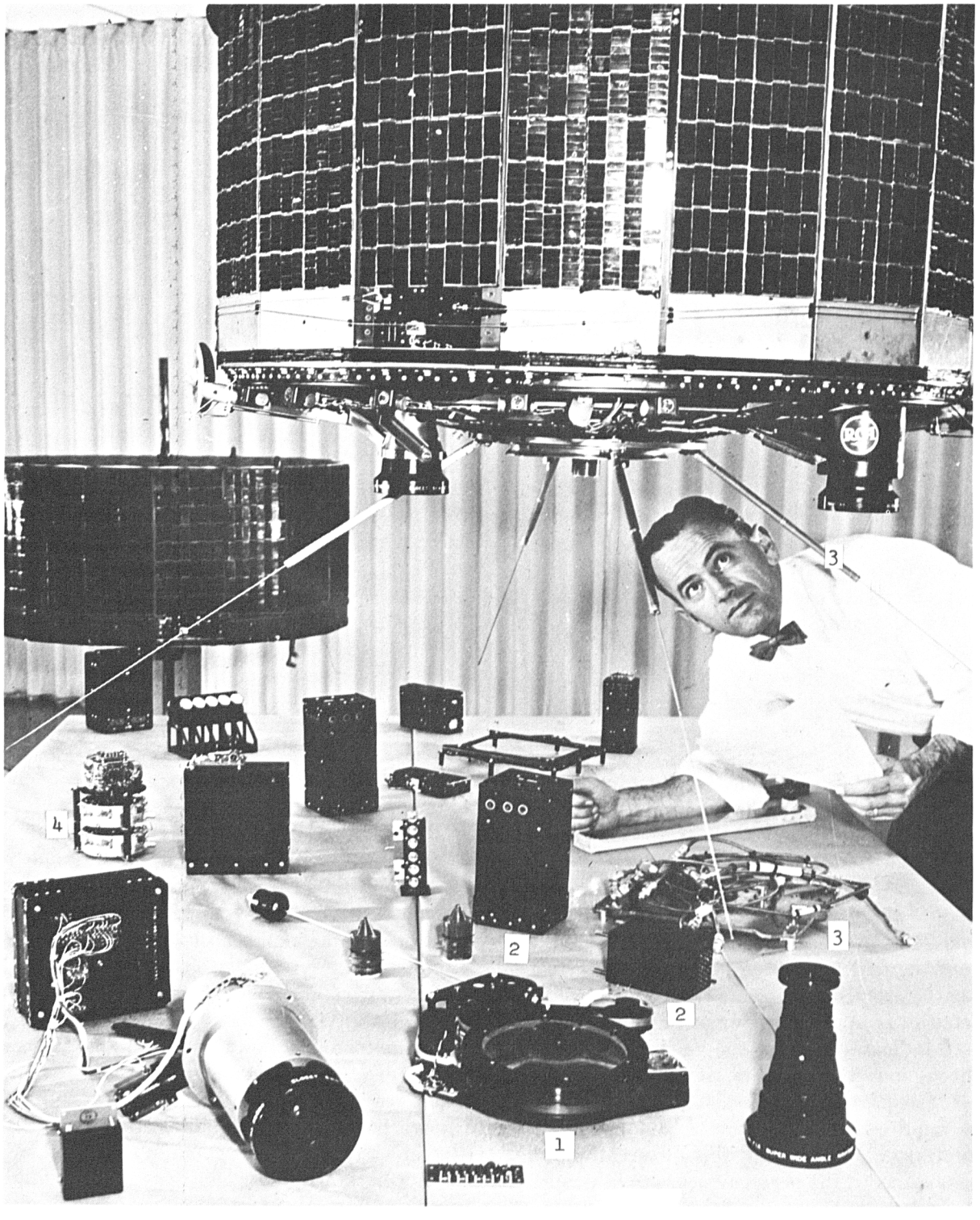


FIGURE 10–5. View of the TIROS satellite showing some of the major components. Each component is carefully qualified before being mounted on the base plate and electrically integrated. Numbers indicate: 1, key tape recorder; 2, control functions; 3, antenna for 235-megacycle transmitter; 4, 108-megacycle transmitter.

tween the clouds and the surface was so high. It is easy to recognize that the background is black and the clouds are light in tone.

The high dynamic range of the vidicon surface, high dynamic range in the sense that it responds to wide variations in light intensity, also helps to provide pictures of good contrast although basically the system does not produce photographic quality information. It was not intended to and is rather limited in this sense. But the combination of adequate resolution and good contrast provides pictures which are of "quality" in appearance.

The third aspect in the camera system is the attitude of the satellite. The satellite is spin stabilized. This means that orientation of the spin axis is nominally constant, pointing to a fixed point in space. As the satellite travels around the earth, the cameras in a fixed position at the rear are pointed at the earth only a quarter of the time. The problem encountered with respect to the attitude is that in Tiros I the spin axis did not stay fixed in space as expected; there was a reaction between the residual magnetic moment of the spinning satellite and the magnetic field of the earth. Also, since the satellite was not a spherical mass, there was a nonuniform interaction between the earth's gravitational field and the satellite. Both of these torques, the magnetic coupling between the satellite and the earth's field and the nonuniform distribution of gravity, tend to move the spin axis of the satellite. Figures 10–6 to 10–8 show how the spin axis has performed in terms of the astronomically defined right ascension and declination.

Figure 10–6 shows how the spin axis moved in Tiros I; the change in declination with right ascension is fairly smooth. The numbers indicate days after launch. A theory was developed for this variation based on the coupling of the magnetic moment of the satellite with the mag-

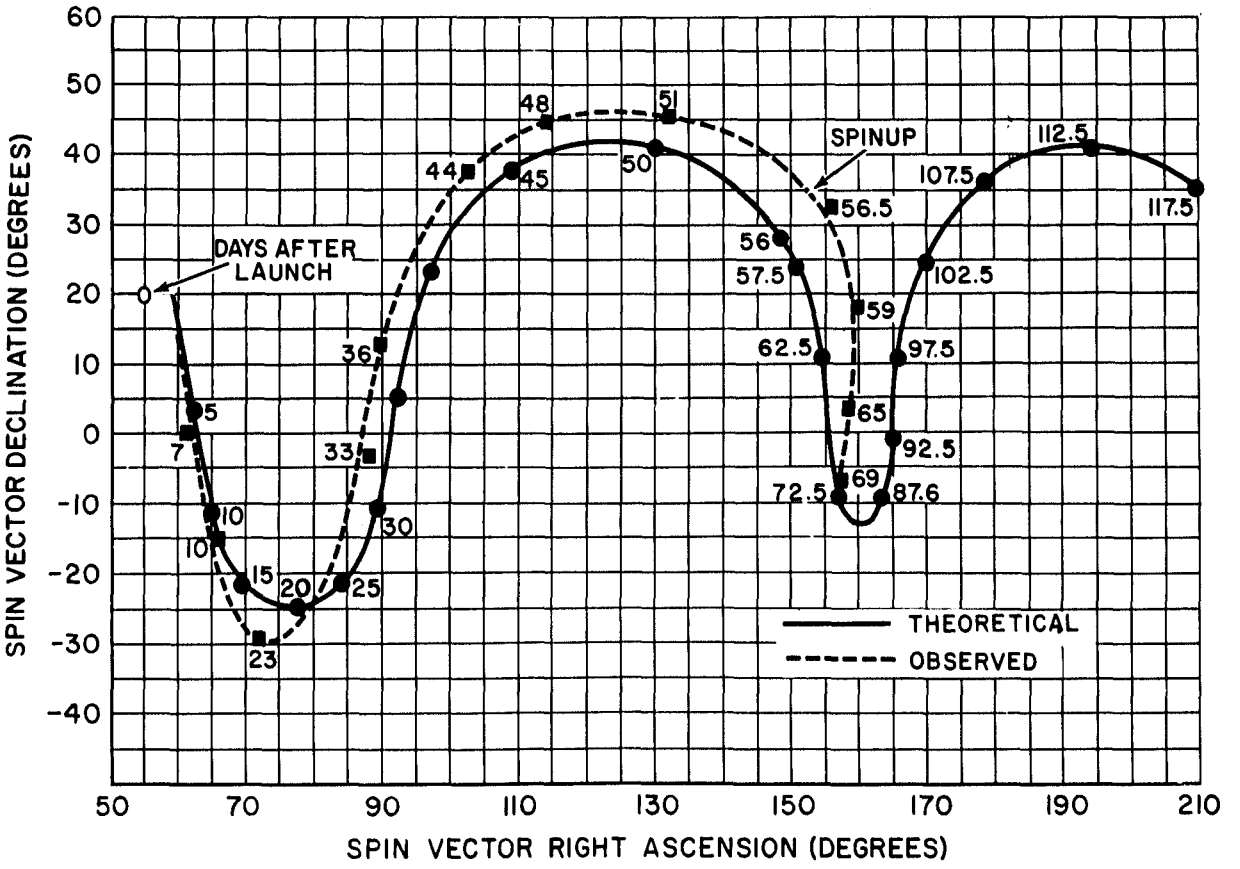


FIGURE 10–6. Motion of the spin axis of TIROS I under the influence of the earth's magnetic field and the gravitational torque.

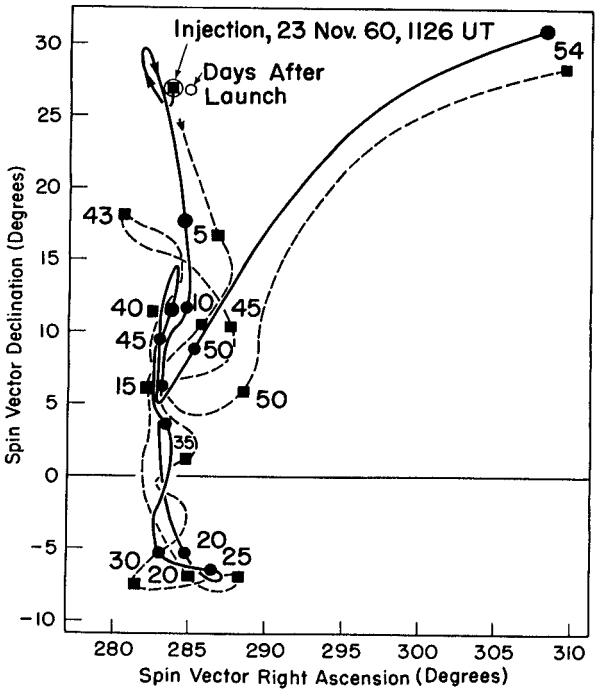


FIGURE 10–7. Motion of the spin axis of TIROS II.

netic field as well as the gravitational field; the theoretical fit is the dashed line. It is satisfactory in terms of the accuracies desired.

On the basis of this information a change was introduced in TIROS II and TIROS III; an electromagnetic coil was wrapped around the periphery of the satellite which permitted variation in the magnetic moment of the satellite both in magnitude and direction, so that, to a certain extent, as shown in figure 10–7 for TIROS II, the motion can be changed or controlled. The solid curve indicates the way in which the spin axis is controlled. The strange convolutions of the motion derive from two things. In TIROS II there was trouble with the programing and, occasionally, for some unknown reason, the magnetic coil switch ended up in the wrong position; thus, the magnet moment was of an undesired amount. Secondly, the motion of the spin axis is not controlled so much as the rate of change is varied to prolong the picture taking or power acquisition.

Figure 10–8 shows the variation for TIROS III up to 81 days. Again, the same kind of irregular motion is seen when the motion is slowed. Look at the small changes roughly between 60 and 65 days, contrasted with the changes from 75 to 80 days. There the attitude was changed rather quickly.

The next aspect of the spacecraft system to be discussed is the infrared radiation system (ref. 1). The name is not quite proper; it should be the reflected solar and emitted radiation. However, it has come to be called infrared radiation because most of the channels in this system are devoted to an exploration of the longer wave, the thermal radiation coming from the earth.

Figure 10–9 gives an indication of the geometry of the radiometer. The fact that the satellite is spin stabilized and the spin axis is essentially constant in direction led to a configuration for the radiometer onboard the satellite in which the axis of the scan system is at 45° to the spin axis of the satellite. The spin axis of the satellite can be visualized as being parallel to the chopper disk. The chopper disk rotates rather rapidly at 40 cycles per second, compared with the spin rate of the satellite which is about 10 revolutions per minute. This means that as the satellite scans the surface of the earth, spinning this chopper disk gives, alternately, a view of space and a view of the surface of the earth. The relative positions of the spin axis and the scan beam itself provide full coverage of the earth with the radiation system; that is, in the 100-minute period, 100 minutes of data can be obtained. It should be realized that even when the spin axis is pointing directly toward the earth the scanner, at 45°, still sees the earth, tracing out a circle on the surface of the earth. This complicates the data reduction but does permit the acquisition of data over each full orbit.

Figure 10–10 is a picture of the radiometer showing the five channels which look out through the slots visible in the photograph. The basic housing is for the preamplifiers. Because of the low signal levels, very high amplification (60 decibels) is needed.

Figure 10–11 is a block diagram of the system which shows the channels concerned. The physical meaning of these will be discussed in subsequent papers. The 6- to 6.5-micron channel measures the water vapor; the 8- to 12-micron channel measures atmospheric radiation; the 0.2- to 6-micron channel measures the albedo of the earth; the 8- to 30-micron channel measures essentially the total emitted thermal

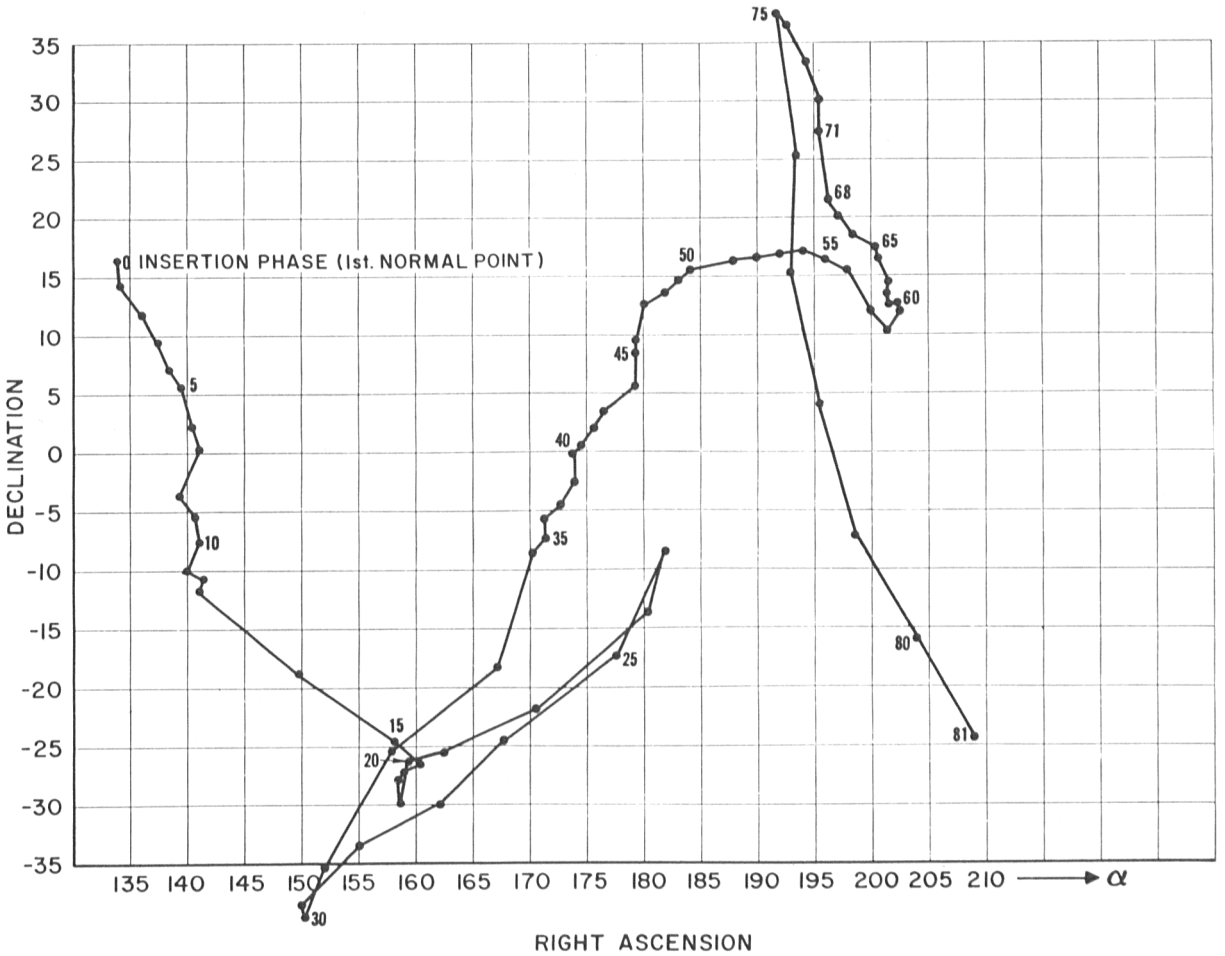


FIGURE 10–8. Motion of the spin axis of TIROS III.

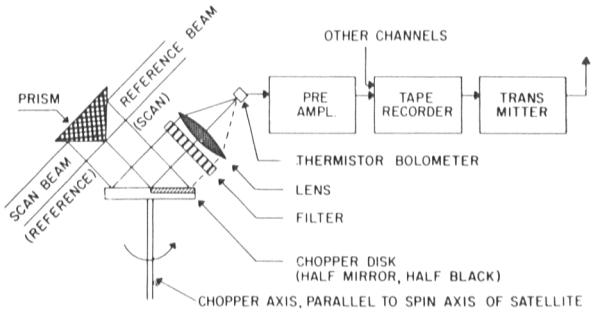


FIGURE 10–9. Schematic diagram of the scan radiometer used in TIROS II and III. Each of the five spectral channels is identical.

radiation (the earth being considered a 270° K black body). The 0.55- to 0.75-micron channel corresponds to the spectral sensitivity of the vidicons in the television system and was included to provide a comparison between the data obtained by the scan techniques and the picture data.

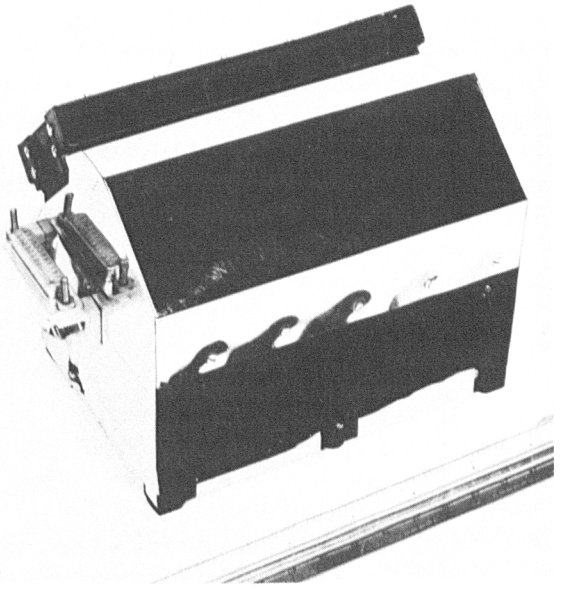


FIGURE 10–10. A photograph of the five-channel scan radiometer used in TIROS II and III.

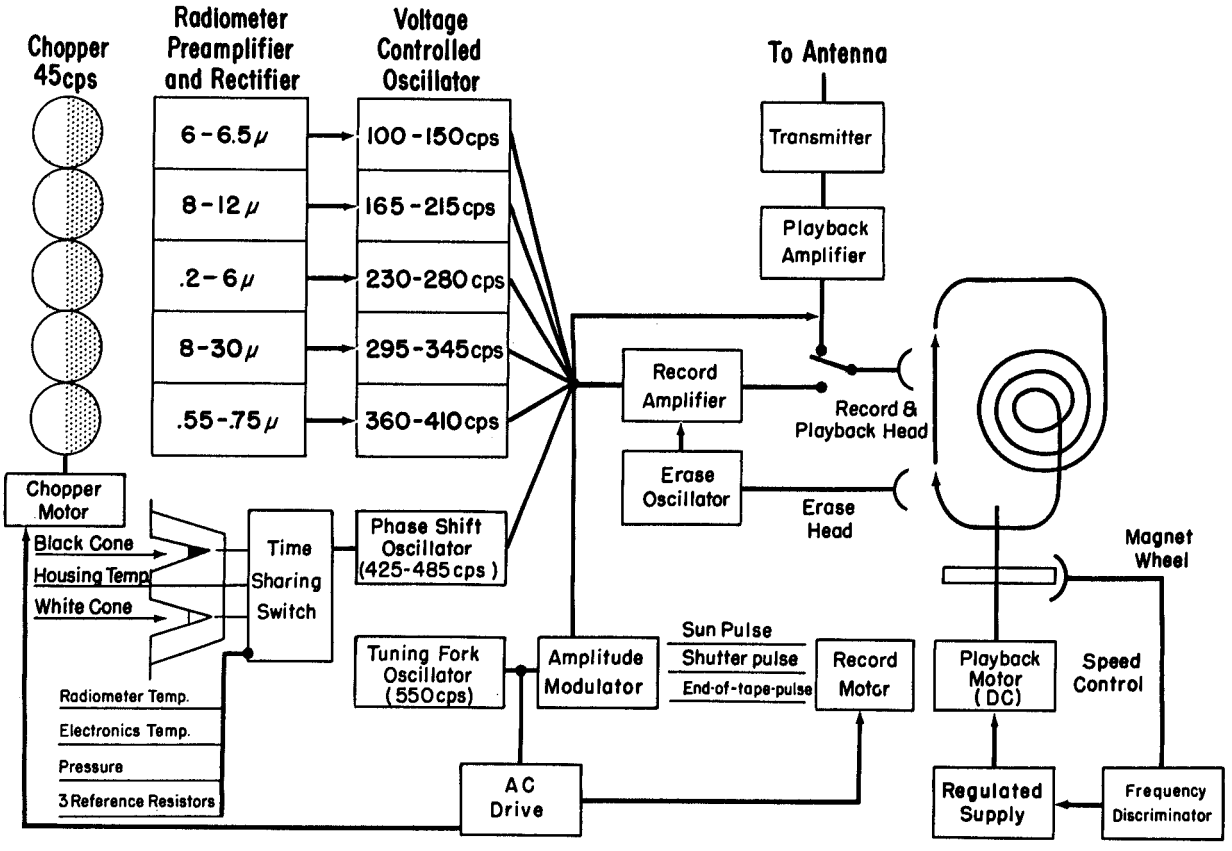


FIGURE 10–11. Block diagram of system.

Another radiation experiment involved two small cones, one black to measure the total emitted radiation and reflected radiation, and one white which would absorb just the thermal radiation, the infrared end of the spectrum. The field of view of these cones corresponds to the field of view of the wide-angle camera system and looks at the same area as the wide-angle camera; that is, this cone arrangement points to the rear of the satellite in the same direction as the camera system. This provides a direct measure of the heat balance of the area of the earth viewed in any one of the pictures.

Among the basic sensory systems is the Suomi experiment (ref. 2), the sensors for which are shown in figure 10–3. The University of Wisconsin group has prepared an experiment, which was flown on Explorer VII, consisting of two small hemispheres backed by mirrors. One is a black body, the other, a white body; the black body absorbs all radiation and the white body absorbs only the long-wave radiation. There are two of these, one on either side of the satellite. They are also used on the TIROS III satellite. The rest of the system is a block diagram of the procedure by which radiation is detected and the results stored directly on the continuous-loop magnetic tape recorder. If the information is not read out, that is, if the tape recorder is not commanded to play back the information at one of the data-acquisition stations, the satellite keeps recording the data but erases the immediately preceding information. In other words, the last 100 minutes of infrared data are always stored onboard the satellite. This provides a real advantage in the data-acquisition problem because of the locations of the stations for acquiring the data from the satellite. The data from all 14 orbits or 14.5 orbits that the satellite makes in any one day are not acquired; on the average, probably only 7 or 8 orbits of data per day are acquired from the satellite. There is a clock in the satellite infrared system as well as the transmitter at 235 megacycles for playing back the stored information in only 3.3 minutes, a time determined

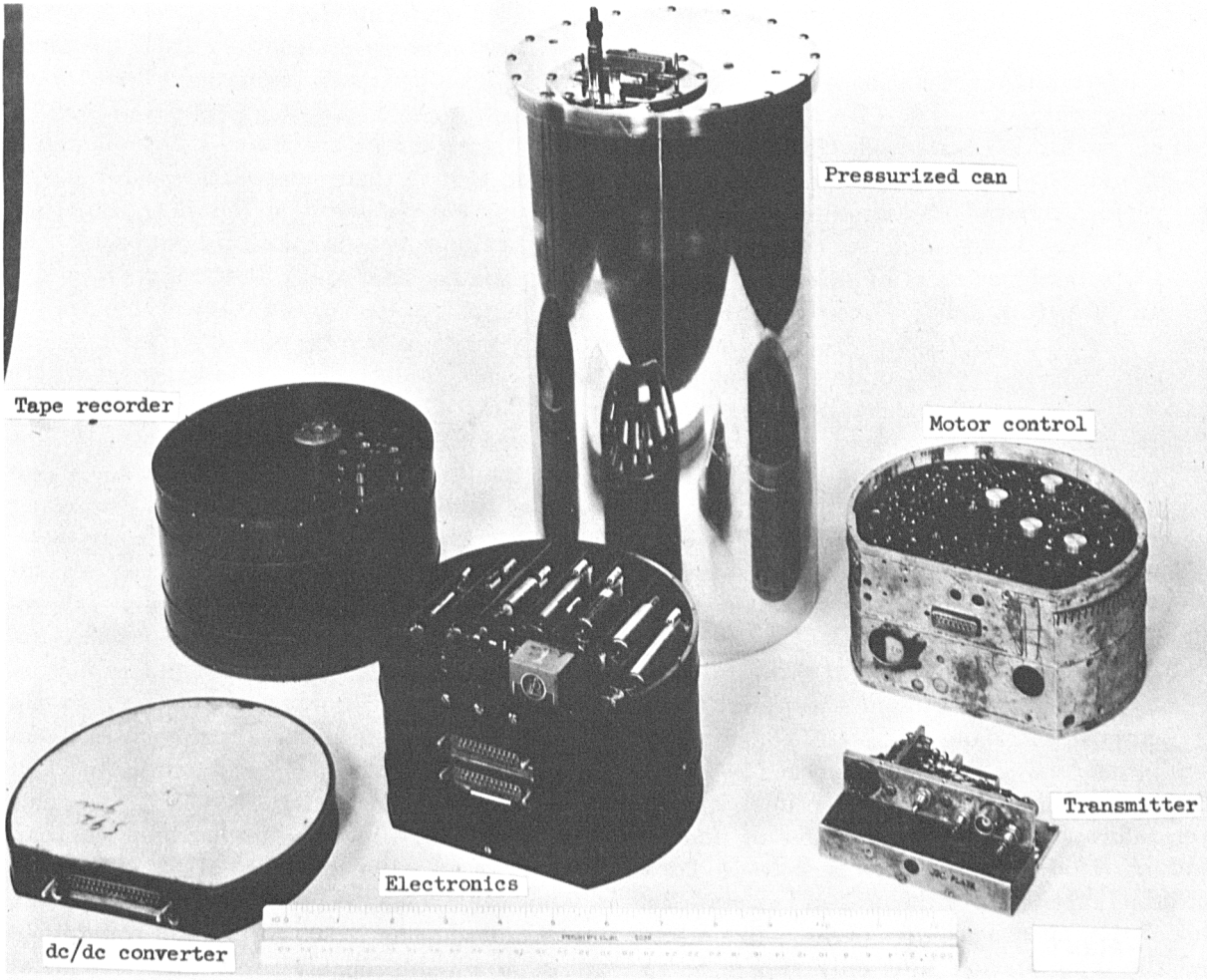


FIGURE 10–12. The mechanical and electronic assembly of the telemetry system for the radiation measurements on TIROS II and III.

by the period that the satellite is over the data-acquisition site. The mechanical assembly of the system is shown in figure 10–12.

The radiation system has performed well; the interpretation of the data received will be discussed in subsequent papers. The radiation system was included only in TIROS II and TIROS III, whereas the camera systems have been in all three satellites, although in the TIROS III satellite there were two wide-angle cameras compared with one wide-angle and one narrow-angle camera in both TIROS I and TIROS II.

The problem of acquiring data from the satellites is a real one in terms of the complexity of the ground stations and the fact that there are limited areas and limited places in which these stations can be put. The two stations now being used and which have been used throughout the TIROS programs are on the east and west coasts of the United States. During TIROS I one of the stations was in Hawaii but was moved to San Nicholas Island, a small island off the coast of California; the other station is Wallops Station off the east coast of Virginia.

The large antennas used in receiving data have been either one of the large parabolas, a 60-foot-diameter parabola, or an equivalent multiple-helix device having about a 30-decibel gain at the 240-megacycle frequency at which the information is acquired. Both of the antennas are capable of automatically tracking the satellite, an important aspect in acquiring the data because of the relatively narrow beam width. This places difficult requirements on the mechanical properties of the antennas, which have been one of the largest single operational problems, particularly the continuous opera-

tion and maintenance of these large dishes in high winds.

The operation of the station is handled in the following way. The TIROS Technical Control Center, which is located at Goddard Space Flight Center, receives all the information on the performance of the satellite and on the operational problems, that is, what the wind levels might be in terms of operating one of the big antennas, what the communications problems are, and so on, and from which areas it would be desirable to obtain meteorological data. The Weather Bureau indicates where picture information is desired. The ground stations then provide the programs to be sent to the satellite; these programs direct the satellite either to take pictures immediately, if this is possible, or to take pictures at some predetermined time, after the satellite has passed the data-acquisition site.

On the average, about seven orbits of data can be obtained by the ground stations each day. This means that about 450 pictures and about 7 radiation tapes can be obtained each 24 hours. The station locations are not optimal, as has been indicated. It is just a matter of finding land at the right places. There could be a better arrangement for the present two stations. One of the stations acquires perhaps five orbits and the other station adds only two or so to this. However, there are many occasions when they can be used for backup.

The ability to send commands to the satellite and to provide the programed information to take a picture so many hours or so many minutes from now comes from the control panel shown in the center of figure 10–13. The decks of racks of electronics on the right side of the figure are for the telemetry data, the housekeeping information that is needed to determine voltages throughout the satellite and the performance of the various boxes and control units on the satellite itself.

The key element in the immediate use of picture data at the station is the fact that as the picures are received at the ground (consoles on the left) they are displayed directly on the photokinescope and photographed on 35-millimeter film, so that within roughly half an hour after the satellite pass it is possible to process the film and to have the meteorologist at the station looking at the photographic data obtained by the satellite. This is true whether the data have been directly transmitted from the satellite or whether the pictures have been taken over some remote area such as Australia.

The picture data are stored on the magnetic tape so that if there has been an error in the receiving of the data on the photokinescope and the film, the tape can be played back. The film data are used right at the station, and a copy is transmitted to the Navy Photographic Center where it is processed and distributed to all research users. All the radiation data are stored directly on magnetic tape. The radiation data are returned to Goddard Space Flight Center at NASA where they are rather elaborately processed. The problem of processing radiation data will be discussed in paper 16.

A brief summary of what has been accomplished in the TIROS satellite system is presented as follows: The vehicle performance has been excellent. The nearly circular orbits desired have been attained; there has been no loss of the satellite, which is the first concern, from the launch vehicle itself. There have been problems with each of the satellites; in some respects, each of the satelites has been less than perfect.

TIROS I, which was launched April 1, 1960, transmitted some 23,000 pictures in roughly 78 days, of which probably two-thirds were meteorologically significant. The radiation experiments, either the scan type or the wide field, were not onboard the first TIROS. There were two major failures in the system. One was that between orbits 22 and 572 the narrow-angle camera did not work. It began functioning again after 572 orbits. It turned out that if a camera had to fail, the narrow-angle camera was the more expendable since the wide-angle camera has always produced the more useful meteorological data. Finally, the satellite died because a relay failure destroyed the battery system completely draining the units so that the charge could not be maintained. However, the TIROS I satellite still transmits its beacon when it is in the sunlight, and the minitrack networks keep track of it.

TIROS II, which was launched on November 23, 1960, is still transmitting. It is not, apparently, working in the sense of producing data. It has produced over 35,000 pictures and roughly 1,600 orbits of radiation information.

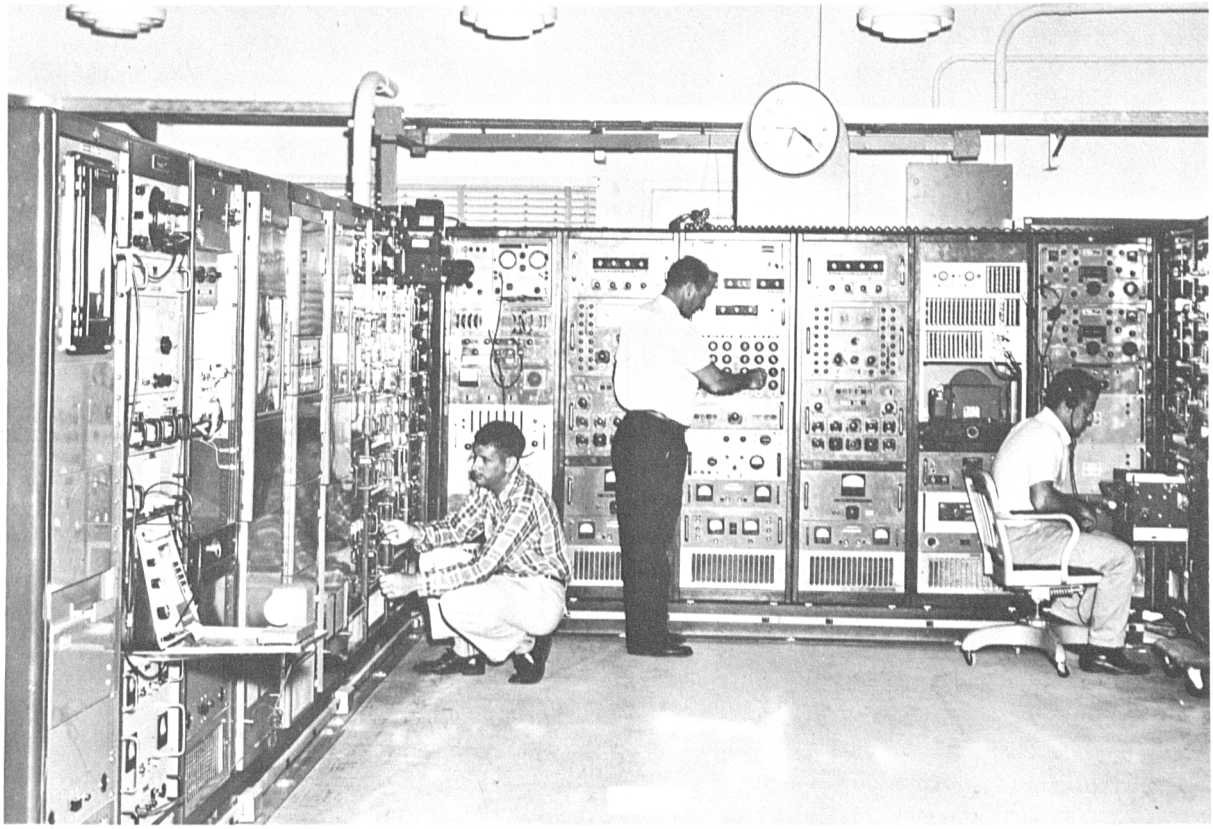


FIGURE 10–13. An inside view of the command and data acquisition station. Here the commands for the satellite are prepared for transmission and the telemetry TV picture and radiation data are received and recorded.

The failures were threefold. The radiation data stopped being acquired after roughly 1,600 orbits when the chopper motor, the motor that drives the chopper disk, stopped on April 22, 1961, after some 5 months of operation. The balance of that system, however, is still working. Some of the radiation data are still obtained from the nonscanning system, and the performance of the electronics and the tape recorder can still be evaluated. The major failure in TIROS II was caused by the fact that the wide-angle lens was apparently coated with the exhaust gases from the third-stage rocket. What was lost in the pictures as a result was, essentially, contrast. The resolution was unchanged. The pictures, however, were usable and many nephanalyses were produced from the pictures. The third failure experienced in TIROS II, also in the detector system, was the decay of two of the interference filters in the scan radiometer. This occurred after several months of operation. The 6- to 6.5-micron channel, which has a relatively narrow interference filter, failed. Again, it is not certain whether failure was caused by exposure to space or exposure to the ultraviolet when the scan system went through the corona of the sun or even by the reflected ultraviolet radiation from the surface of the earth.

TIROS III was launched on July 12, 1961. The latest summary available as of the 13th of November 1961 shows that data have been acquired through orbit 1,782; 31,378 pictures have been taken by TIROS III, and approximately 800 orbits of radiation data have been acquired. With almost a hundred thousand pictures and a thousand orbits or so of good radiation data, reducing these data will be a difficult task.

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11. CLOUDINESS ASSOCIATED WITH LARGE-SCALE SYNOPTIC SYSTEMS IN TEMPERATE LATITUDES

By S. Fritz, *Chief Scientist, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

The most striking patterns which have been found in the Tiros satellite pictures are the large-scale vortex cloud systems, associated cyclones, their frontal systems, and other details about the patterns. Anticyclonic cloud patterns are also sometimes identifiable. A few cases that have been studied in areas in the Pacific Ocean, the United States, and the Atlantic Ocean will be presented; some Southern Hemisphere cases will also be presented.

Figure 11–1 shows a series of pictures of Northern Hemisphere cyclones taken by Tiros I. Briefly, these pictures show cyclones in various stages of development. Picture 1 is a rather young cyclone, picture 2, is a cyclone a little further in its development, picture 3 is a rather old cyclone and further advanced in its occluded stage, and finally the most developed storm is seen in picture 4, in which only a part of the storm can be seen.

The appearance of these cyclones varies. Sometimes a white cloud mass is seen; it is white because the solar energy is being reflected to the satellite. In the pictures very dark re-

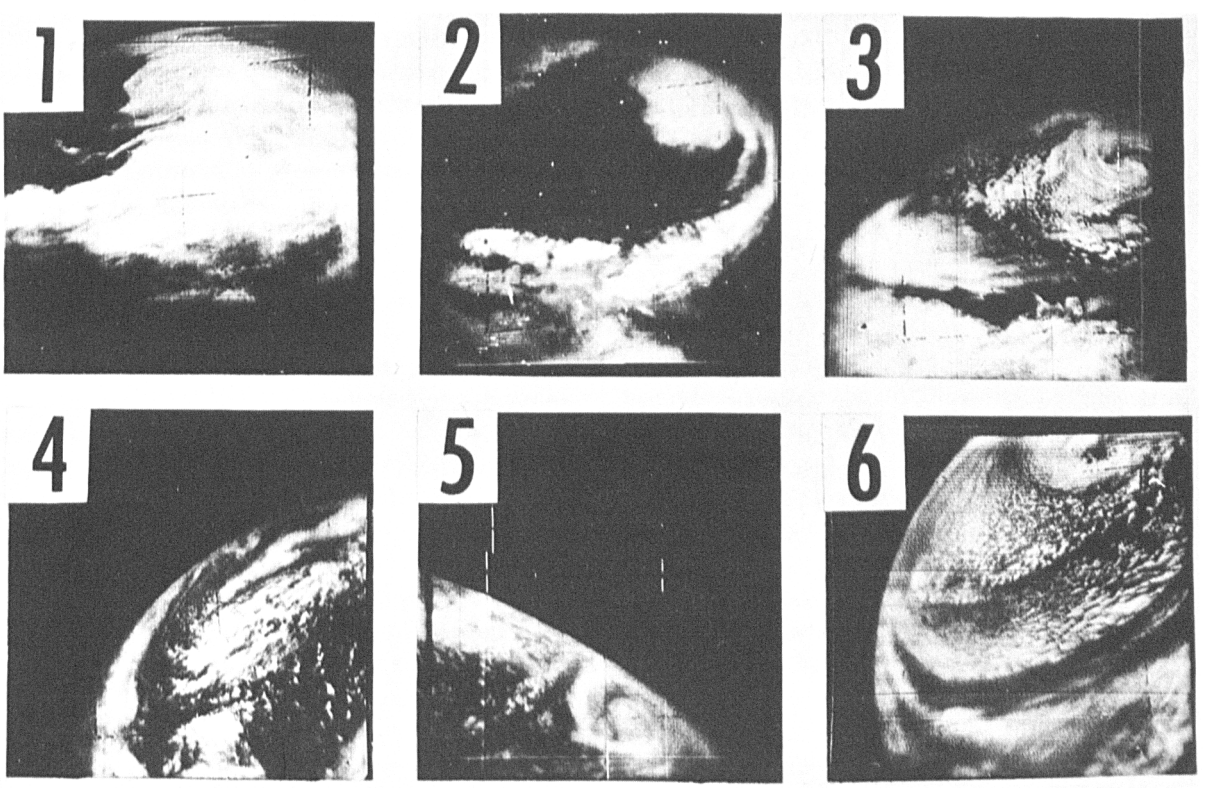


Figure 11–1. Northern Hemisphere cyclones.

gions are also seen, which represent, for the most part, cloudless regions and can be assumed to be cold air that is invading the area occupied by white clouds.

Sometimes, as in picture 6 of figure 11–1, a strip of cloudless air is actually embedded in the main cloud system. In addition, the streakiness of the clouds in the spiral array can be seen. The extent of streakiness in the atmosphere is perhaps a little surprising in comparison with what was expected before TIROS. The atmosphere displays a great deal of streakiness. Darker strips are embedded in the more or less overcast bright regions, as in pictures 2 and 3, and are also seen in cloud streets, some of which will be shown subsequently. The outlines of the cyclonic patterns are thus seen in at least these two ways: cold air coming into the cloudy area and streakiness in the upper cloud system.

Consider, now, how such information may be used. There are ways of locating geographically the various cloud elements that are seen in the pictures. For example, in the case of the cyclones, the theoretical center of the spiral pattern can be located. It is also fairly clear that in some regions of the world the mere location of cloud systems will be of considerable help; such areas are, for example, the regions that bound South America both to the east and to the west, the region that surrounds Africa, and the region to the south of Australia. These are regions from which there are very few reports; there are no islands, very few ships, and very few airplanes. Thus, they are areas of almost complete meteorological silence. The mere knowledge of the location of a system in those regions can be of great use for forecasting.

It should be recognized that the satellite is not a forecaster. It can only observe. Every forecast system has as its beginning some information about the initial state of the atmosphere. The satellite serves as a very important observing tool which can provide information about atmospheric conditions at the beginning of a forecast period. In silent areas, knowledge of the existence and location of a storm, information which except for TIROS might not be known, is very important. This same argument would also hold in the tropical regions where often very little information can be obtained regarding the existence or the location of severe storms, such as hurricanes or typhoons.

In other areas of the world, for example, in the Atlantic Ocean area, in the Pacific Ocean to a lesser extent, or in the North American, European areas, the existence of the larger storms is generally known, although sometimes, by using satellite pictures, it is possible to position the storm more accurately. If a big storm exists in those areas, conventional reports will establish its existence. Some improvement can be made in locating new formations—waves on a front, for example—which might be poorly documented even over ocean shipping lanes. Also, there are cases in which, even in well-covered areas, smaller systems may escape detection and the satellite can help.

Since clouds are produced by physical processes, much information on the present state of the atmosphere, such as the distribution of moisture, the presence of vertical motion, a general indication of wind pattern, and other factors, should be obtainable from the cloud pictures.

On the whole, it is believed that, on the large scale, clouds are produced essentially by upward motions in the presence of the proper humidity field. Thus, the clouds indicate the vertical motions and the humidity field which gave rise to the particular pattern. In the more recently tried forecasting methods, namely numerical weather prediction, equations of motion are modified to fit a particular model and an attempt is made to forecast the future state of the atmosphere. In order to begin the forecast, the conditions of the atmosphere at the beginning of the forecast period must be known. Of primary use in the initial horizontal flow field, that is, the horizontal motions that exist at the beginning of the forecast period. Even in the somewhat elementary models, the vertical motion field, the field of the upward and downward motions of the atmosphere, is computed on the basis of a knowledge, or on an estimate, of the horizontal motions that exist at the beginning of the forecast period.

It is known that in many regions, even in the better observed ocean areas, such as the Atlantic or the Pacific Ocean, the upper air information which must go into such vertical-motion estimates is inadequate. There are an insufficient number of upper air stations. In the Pacific Ocean there are very few. Although there are more in the Atlantic, the number of reports

available is still too small to give a reliable picture of the vertical motion. Nevertheless, computations of the vertical motion are made in these ocean areas on the basis of the information that is available at the beginning of the forecast period. A check on the vertical motion is available if the theory that clouds are produced by upward vertical motions is accepted. Then, the computed vertical motion can be compared with the cloud pictures. If the computed motions do not agree with the cloud pictures, corrections must be made either in the model or in the estimate of the initial flow field.

Perhaps present knowledge does not allow changing the models, but, by accepting the numerical models which are in use, it may be possible to change the initial conditions in such a way as to make the vertical motion field or humidity field agree with the cloud pictures. These cloud observations are now basic; it is hoped that all regions of the world will be observed at least once a day by late 1962 or early 1963.

There are at least two approaches being made to explain the physical nature of clouds. One of these two approaches is a study being conducted by Capt. E. C. Kindle of the U.S. Air Force to develop a numerical method of forecasting the location and extent of cloudiness. The cloud pictures are fitted to the appropriate time step of the computed forecast fields of horizontal flow and vertical motion. This procedure gives a humidity field. By using this field, forecasts are made ahead for a short period, say 4 hours. Then, if cloud pictures are available, these are compared to the forecast humidity field. If the actual cloud pictures do not agree with the forecast of what the clouds should be, on the basis of the computation made using the humidity data together with the motion field, only the initial humidity field is changed to get agreement at the cloud observation time. Once agreement at the cloud observation time is achieved, the computations are continued for several hours more, and then an attempt is made to forecast the cloud field in the future. Thus, the method is a way of obtaining consistency between the motions of the humidity field and the cloud pictures.

In the Meteorological Satellite Laboratory, this problem is being attacked in another way. The humidity field is not changed, but it is assumed that the clouds are an indication of the vertical motion field. The vertical motion field can be computed in several different ways. The results from the numerical prediction system that is used in the Weather Bureau are accepted. An attempt is made to see whether the vertical motion field that is computed from the equations of horizontal motion and the horizontal flow field at the beginning of the forecast period agrees with the cloud observations from the satellite. If it does not agree, ways are being studied to change the initial horizontal flow field—particularly in ocean areas—in such a way that the vertical motion field would agree with the cloud pictures.

The solution is not yet known because this investigation is just beginning. However, it seems that there is a lot more information to be obtained from the large-scale cloud pictures than just the positions of synoptic patterns. With proper research and investigation into the basic nature of the physics that produce the cloud systems, there is hope of having an important input into numerical weather prediction methods.

In the earliest phases of cyclonic systems it is expected that cyclones will often form as waves on preexisting fronts. However, as far as is known, there are no good pictures from the TIROS series of a wave on an extensive frontal system. Figure 11–2, which is a composite of pictures from an Atlas rocket that was fired in 1959, shows what a wave may look like. Puerto Rico, Haiti, Cuba, the eastern coast of the United States, and a part of the western Atlantic Ocean are shown in the figure. The wave on the frontal system never did develop very much. The frontal system has definitely been distorted to the north in the manner which would have been expected from the Norwegian frontal theories on wave development.

There is another feature which is interesting and which is occasionally seen in TIROS pictures. This is the cloud pattern which sometimes outlines anticyclonic areas. In the region of an anticyclone, massive stratiform clouds or continuous layer clouds are not expected; however, small cumulus clouds are often arrayed in lines. These lines often lie close to the wind direction, although how close is sometimes a question. Sometimes they do outline the larger scale anticyclonic flow.

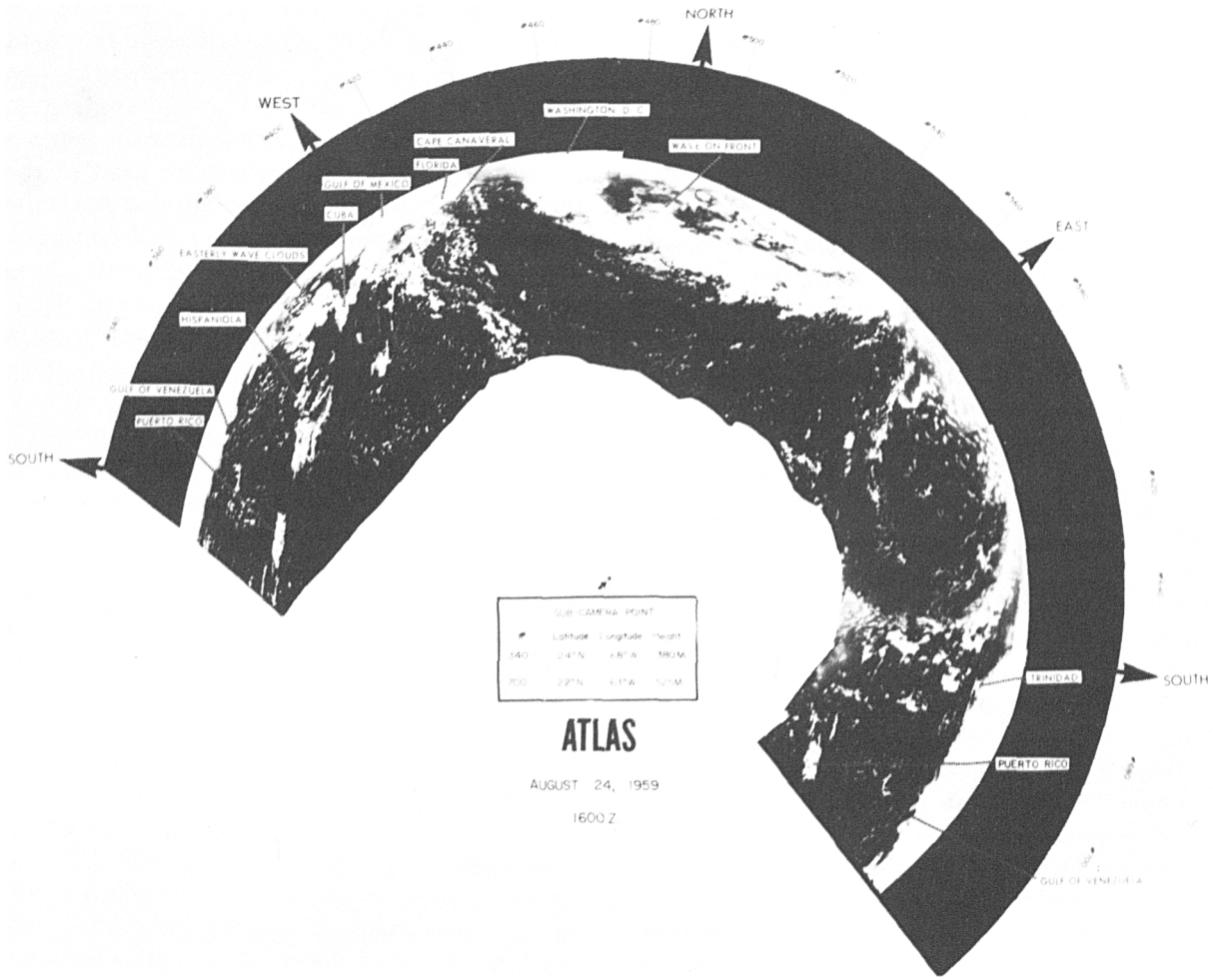


FIGURE 11–2. Mosaic assembled from nineteen frames of Atlas moving pictures. Height range, 380 to 525 nautical miles.

In figure 11–3 a weather map of a cyclone along the eastern coast of the United States, the region around Boston and Cape Cod, is shown. The important point is that, according to the analysis, there is an open-wave cyclone which has not yet occluded; there is also a cloud system showing the circulation. It might be noted that along the coast on the day these pictures were taken there were no clouds reported from the ground or from the satellite; thus, the coastline should be visible. However, the visibility of coastlines is a study in itself. Some coastlines are very difficult to see, whereas other coastlines are very marked. In this case the cloud-free region can be seen, but the coastline is not discernible because the contrast between the land and water is too small.

In figure 11–3, the weak frontal cloud system corresponding to the cold front can be seen. It looks as if it is tapering out at the southern end. The cold air is intruding but has not gone very far into the cloudy air mass. In a good print perhaps some traces of a circulation in the cloud could be seen, but it would be difficult. Mainly, a rather large nondescript cloud mass is seen as well as the dark area representing the cold air which has only begun to enter the main cloud region. This pattern, then, might be characteristic of a young cyclone which is more or less at the beginning of its occlusion process but which has not quite started occluding.

Figure 11–4 does not have anything to do with cyclones. This figure is from TIROS II. The pictures were not so clear as those from TIROS I, but a good deal of information can be obtained from them. This photograph shows the east coast of the United States, including

Boston, Cape Cod, Long Island, and Chesapeake Bay, with Washington to the west of the bay. The land is very white and the coastline is sharp. An area along the coast is rather dark and then a white area appears again. The

FIGURE 11–3(a). Three overlapping TIROS pictures showing extratropical cyclone centered about 120 miles east of Cape Cod, April 1, 1960.

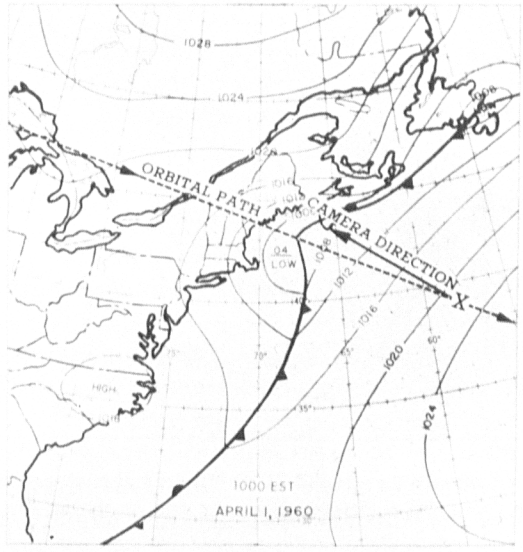


FIGURE 11–3(b). Sea-level weather map, 1000 EST, April 1, 1960. Point X denotes approximate location of satellite and the arrow indicates camera direction when pictures were taken.

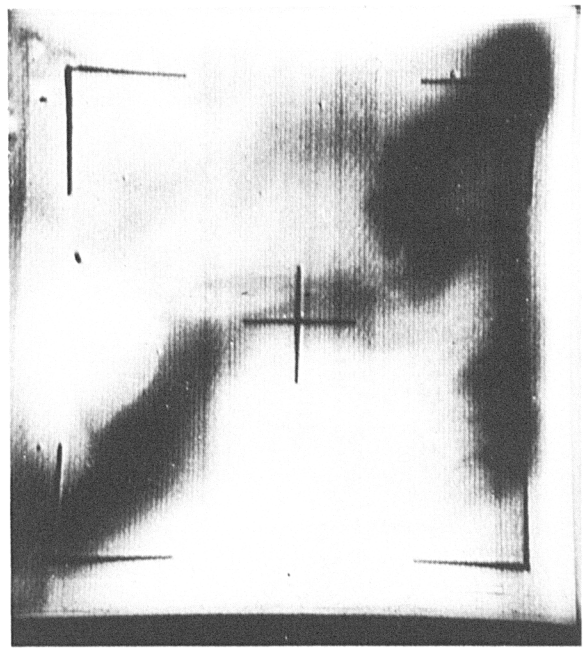


FIGURE 11–4. Photograph taken by TIROS II of snow-covered east coast of United States.

reason that the coast is so well defined is that this picture was taken 2 days after a snowstorm along the east coast of the United States; the land was thus very bright because of the snow. There were practically no clouds over the land area. However, as the air moved out over the warm water, a large-scale cloud mass parallel to a very large section of the coast and at an appreciable distance downwind was produced.

Figure 11–5 shows a cyclone over the middle portion of the United States (studied in detail in ref. 1). This chart was made both from the conventional information and from the satellite picture. The main point to note is the rather large cloud system extending far to the north; this system may be somewhat deceptive in the pictures of figure 11–6. The cloud extends from south of the cyclone center to the north. Also note the shaded areas on this map, which represent radar reports indicating precipitation, and sferics reports indicating thunderstorm activity. These occur at various locations along the front. Figure 11–6 shows the TIROS cloud pictures associated with figure 11–5. Near the horizon the distances are very much foreshortened. A very short distance near the horizon in these pictures represents a very large dis-

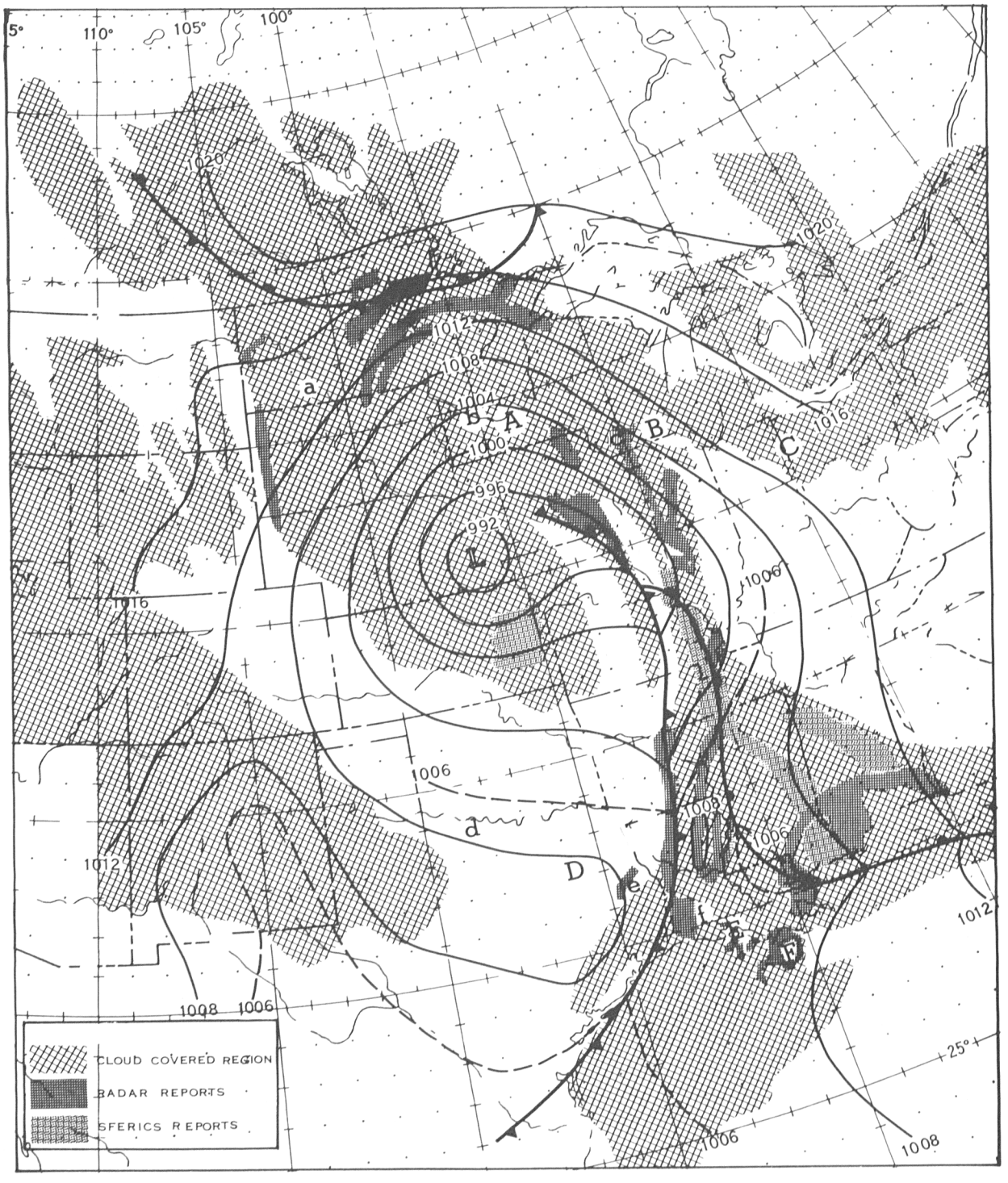


FIGURE 11–5. Sea-level chart, 2100 GMT, April 1, 1960, with cloud cover area and radar and sferics reports. Capital letters refer to photographs taken by the satellite from the positions shown by the matching lower-case letters.

tance on the earth, so that the correct shape of the cloud system cannot be seen. These pictures must be rectified in order to obtain cloud shapes similar to those of figure 11–5. Shown here is the major cloud system associated with the cyclone center and the cold front which extends from the center toward the southern part of the United States. Of note, in connection

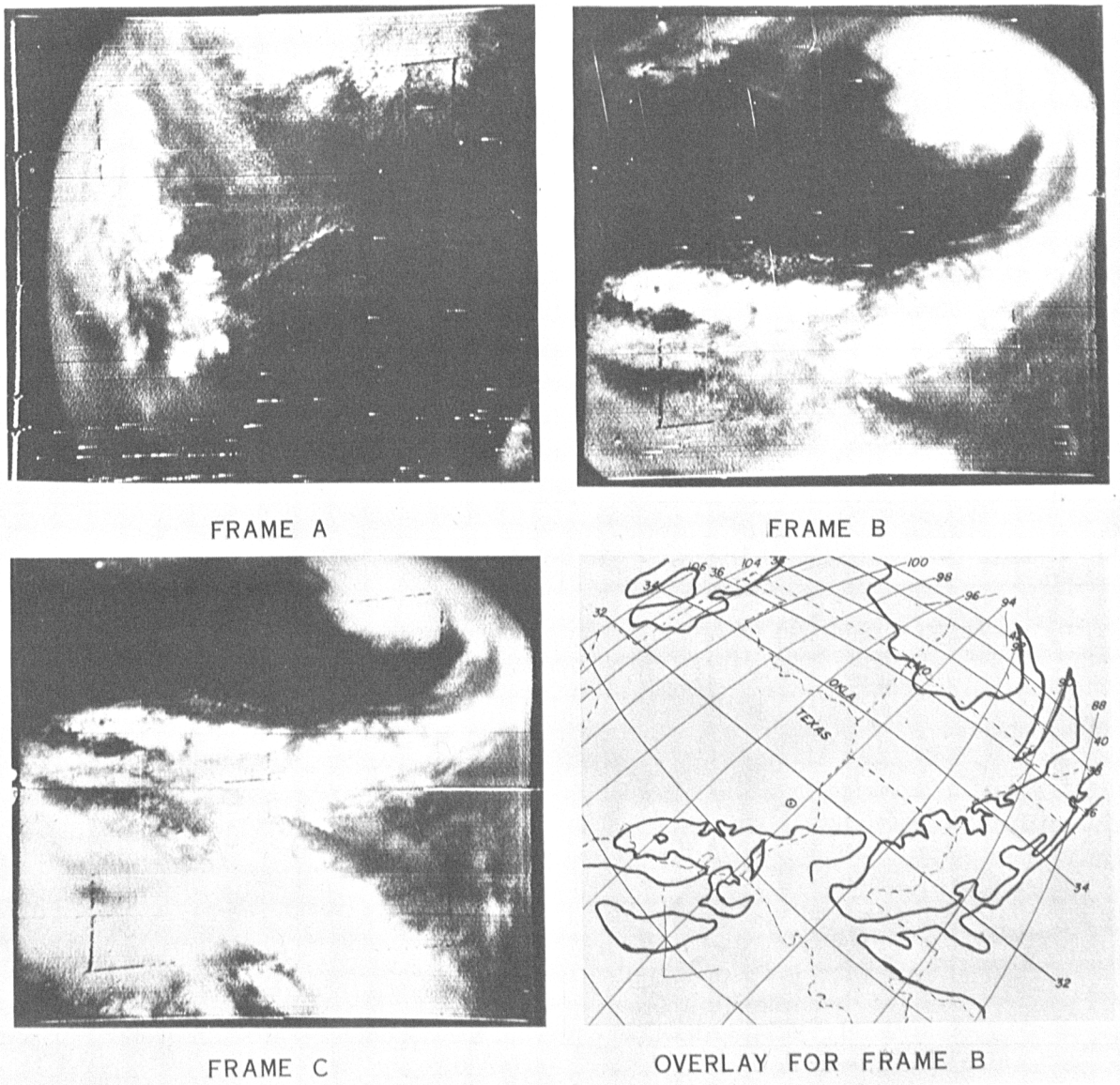


FIGURE 11–6. TIROS wide-angle cloud photographs taken over points A, B, and C of figure 11–5. Grid overlay for frame B.

with the thunderstorms and precipitation along the front, are the gradations in brightness (corresponding to the shaded areas in fig. 11–5) which can be seen in the general area of cloud cover. Another point of consideration is that, if two separate pictures taken at two different places and two different times are examined and the difference in brightness is compared, there is little that can be inferred regarding the vertical developments of the cloud because the brightness of a cloud depends on so many factors.

However, it appears that to a certain extent in a region of general cloudiness, that is, where the area is rather bright everywhere but not uniformly bright, the brighter areas may represent clouds of actual vertical development; that is, clouds of the cumulus congestus and cumulonimbus types tend to be brighter. With reference to the larger scale patterns, the cold air can be seen coming in from the west and northwest, invading the cloud area, frame B, and cutting further into it in frame C. In this case the system has progressed a little further toward the occlusion process; thus, this storm would represent a somewhat older stage of development than the one seen in figure 11–3. There-

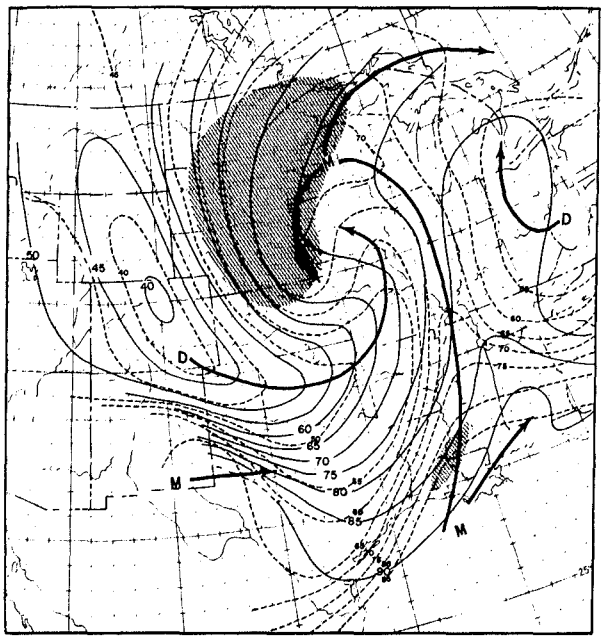


FIGURE 11–7. Isentropic chart for 300° K. Solid lines indicate pressure; dashed lines indicate condensation pressure; 0000 GMT, April 2, 1960; shading indicates approximate area of saturation; pressure given in 10's of millibars.

fore, it would be expected that cold air would continue to flow in behind the frontal system, and perhaps warm moist air would flow into the region along the frontal system.

Figure 11–7 shows an isentropic chart, which is a good way to represent atmospheric conditions. The isentropic chart is a representation which is used to show the airflow in three dimensions. In other words, the air is flowing up along a particular surface or down along a particular surface in the atmosphere. This chart shows the position where the cold front was, just before coming into the cyclonic center. The isentropic surface has its highest point at 400 millibars; in the south the surface is low at 900 millibars. Thus, the moist air flowing from south to north along the line *M* is being lifted upward along the isentropic surface. This chart would indicate an agreement with the previous ideas that the cloud which represented the cold front (fig. 11–5) was indeed an area of upward flow of warm moist air and that the cold dry air coming in from the west and southwest was actually air coming down toward the surface, subsiding and cutting into the cloudy region.

As is well known, fronts are enormously complicated. British meteorologists have found that in many fronts, in addition to the clouds which are not by any means uniform or standard from one front to another, there are dry areas. In addition, they find that in every front there are varying types of cloud systems. Thus, it could be assumed that in all major frontal systems, the air has had a history of upward motion coming from an area where the air was moist.

The difficulty in studying cloud pictures is that, although the cloud development is instantly recorded, the cloud has gone through some history during its development. It is possible that although the cloud was produced in the expected way, namely by upward motion of moist air, the cloud may, by the time it is observed, have been transported to a region where the motion is downward, or perhaps just horizontal, and might persist for some time. Thus, it cannot be certain that a cloud, observed at an instant in its development, represents upward motion.

An apparent finding made in one of the studies at the Meteorological Satellite Laboratory is that if there is a cyclonic system which is still growing, in other words, if, at the upper levels (500 millibars and above), a closed isobaric system or closed contour system has not formed, the cloud does represent very well the major regions of upward motion. In those cases it probably would be justifiable to assume that the cloud does represent a region of rising moist air.

Figure 11–8 shows a storm (studied in detail in ref. 2) which is a little further in development. In this case, also, although observational coverage is perhaps better than it is in some of the Southern Hemisphere oceans, details are found which are not usually obtained from conventional reports. This figure represents a composite of pictures taken in the region of the Gulf of Alaska. The cyclone is represented by an array of clouds surrounding a smaller cloudless area at *A*. It looks as though the cold air has come around all the way into the cloud area and the spiral is more pronounced than the one shown in figure 11–6, suggesting a still further state of occlusion process of an older storm. The surprising item is the presence of the small vortexlike cloud

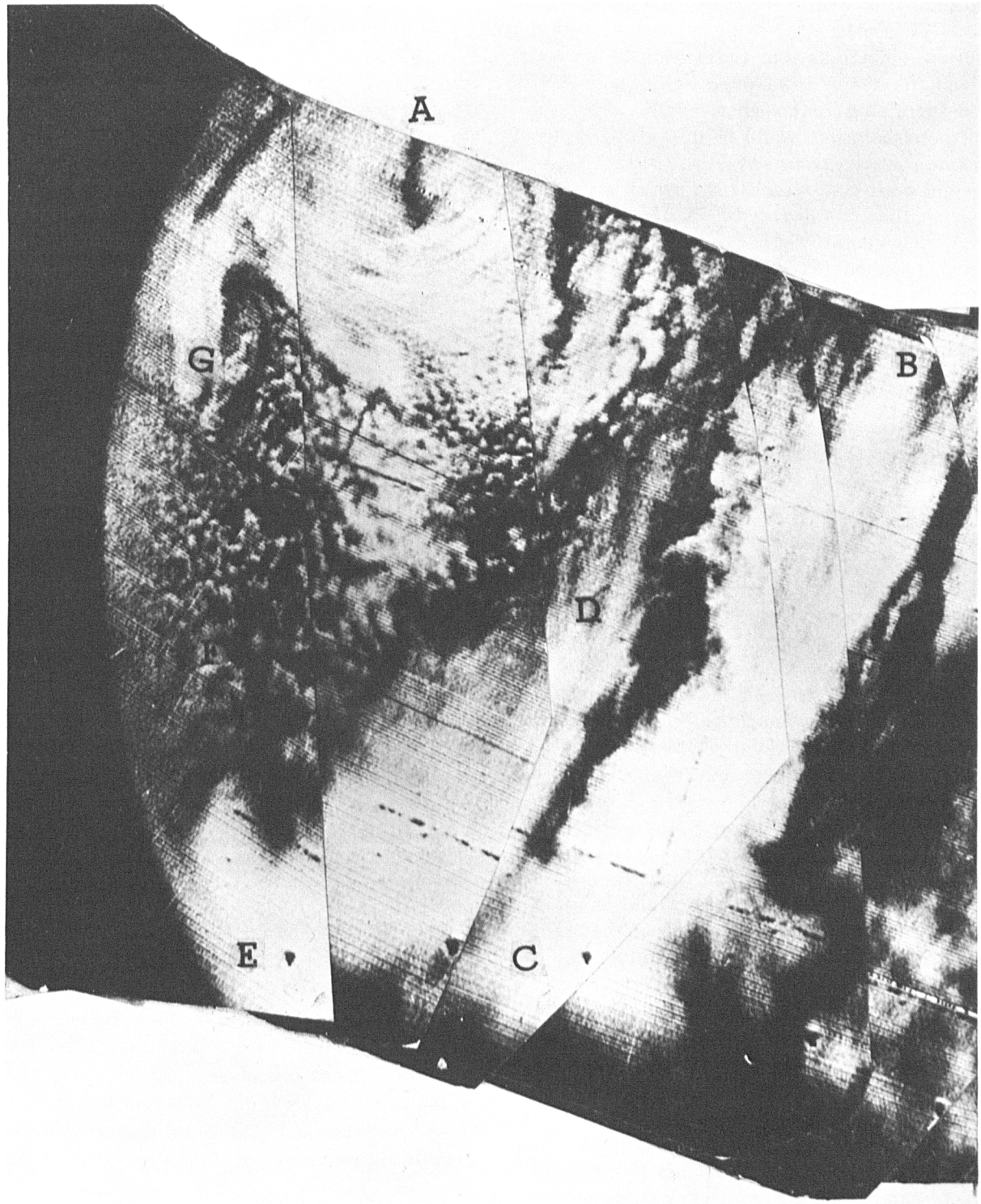


FIGURE 11–8. Composite picture of Gulf of Alaska storm and adjacent synoptic features. Pictures were taken at approximately 2200 GCT, April 1, 1960.

system at G which is behind or to the west of the major cyclonic cloud system. There was no indication of this on any of the maps. The Gulf of Alaska area is by no means well reported. There is one radiosonde in an area about the size of the United States, so it is not too surprising that such a small-scale system in the circulation would be missed. It is presumed that the system at G is the remainder of an old occlusion, still part of an older frontal system, the exact history of which is not known.

Associated with the major cyclone is the main frontal system BC and the cloud DE which is separated from the main frontal system. Then, there are the more broken-up clouds at F, arrayed, in part, in sort of a circular pattern. If the main cloud surrounding A is closely examined, the streaks mentioned previously are seen. The impression is that this streaky cloud is lying above the broken-up clouds; in that case, the streaky cloud would represent the altostratus or cirrus overcast above the lower cloud deck. One opinion is that this pattern represents, in this case, the cloud system in the cold air which is capped by a rather low-level inversion, say, an inversion below the 700-millibar level. The cellular types of clouds at F will be discussed in subsequent papers.

What is interesting also in this picture is the cloud DE. The synoptic pattern that was associated with this cloud represented the cyclone and the cold front. On the cold front was a wave which was shown as very weak. Cloud DE was analyzed as being associated with a wave system that is rather faraway. Had this picture been studied at the time the analysis was made, perhaps that wave would have been given more emphasis; it turned out that in the next 24 hours the wave did develop and become a major cyclone.

Figure 11–9 (fig. 1 of ref. 2) is the synoptic pattern associated with the storm shown in figure 11–8. The heavy broken line is the orbital path of the satellite. The pictures were taken at the positions indicated by dots. The frontal system is seen in the foreground. The wave in the southwest is outside the region of the picture.

Figure 11–10 (fig. 5(b) of ref. 2) shows part of the cyclonic system in the Gulf of Alaska and the associated surface chart. Note the frontal system. This frontal system, lying

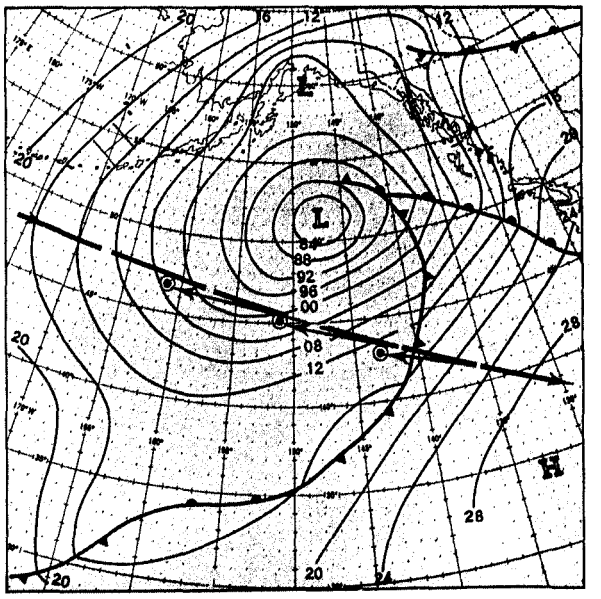


FIGURE 11–9. Sea-level analysis with track of satellite indicated by heavy line. Circled dots indicate principal points of pictures and arrows show orientation of camera for each picture. 0000 GCT, 2 April 1960.

more or less through the clouds, was substantiated by some surface reports. Therefore, the location of the frontal system was known. In the case of the Midwest storm shown in figure 11–5, the clouds were on the edge of the front; that is, the clouds were almost entirely to the east of the cold front, in warm air. In figure 11–10 the cloud system straddles the front and the cloud may actually be in cold air to a large extent. Apparently, this situation was found often by the British meteorological flight, namely, that the clouds could be in either place although, predominantly, they were in the warm air.

This, perhaps, is another fruitful field for study of the detailed dynamics and structure of frontal systems in relation to their cloud patterns. Why, for example, do these various systems exist and how can they be used to find the solutions needed to problems in forecasting and in basic understanding. From various studies it has been learned that these frontal systems usually represent regions of rather sharp temperature gradients and it appears that this is true also in these cases (figs. 11–5 and 11–10). When the system gets very old, the temperature contrast is by no means as great as it is in a younger system.

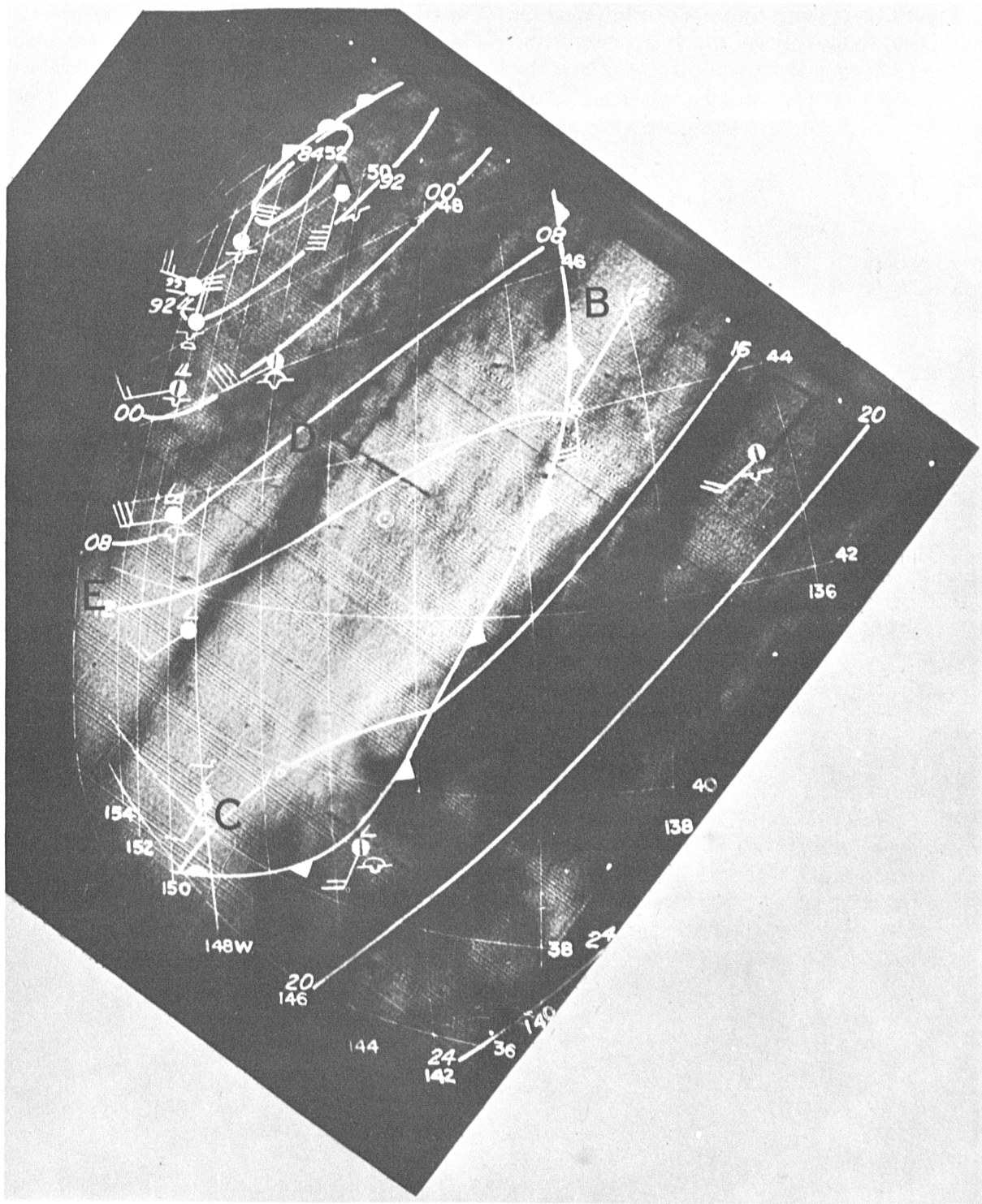


FIGURE 11–10. Picture of cloudiness south and southeast of the Gulf of Alaska cyclone. 2° latitude-longitude grid; principal point indicated by circled dot; surface analysis and data for 0000 GCT, April 2, 1960 superimposed.

Figure 11–11 shows the upper air information and also dashed lines which represent the regions of vertical motion. In this case the vertical motion was computed to be upward, which would be in agreement with the cloud system. But, because of the break in the cloud,

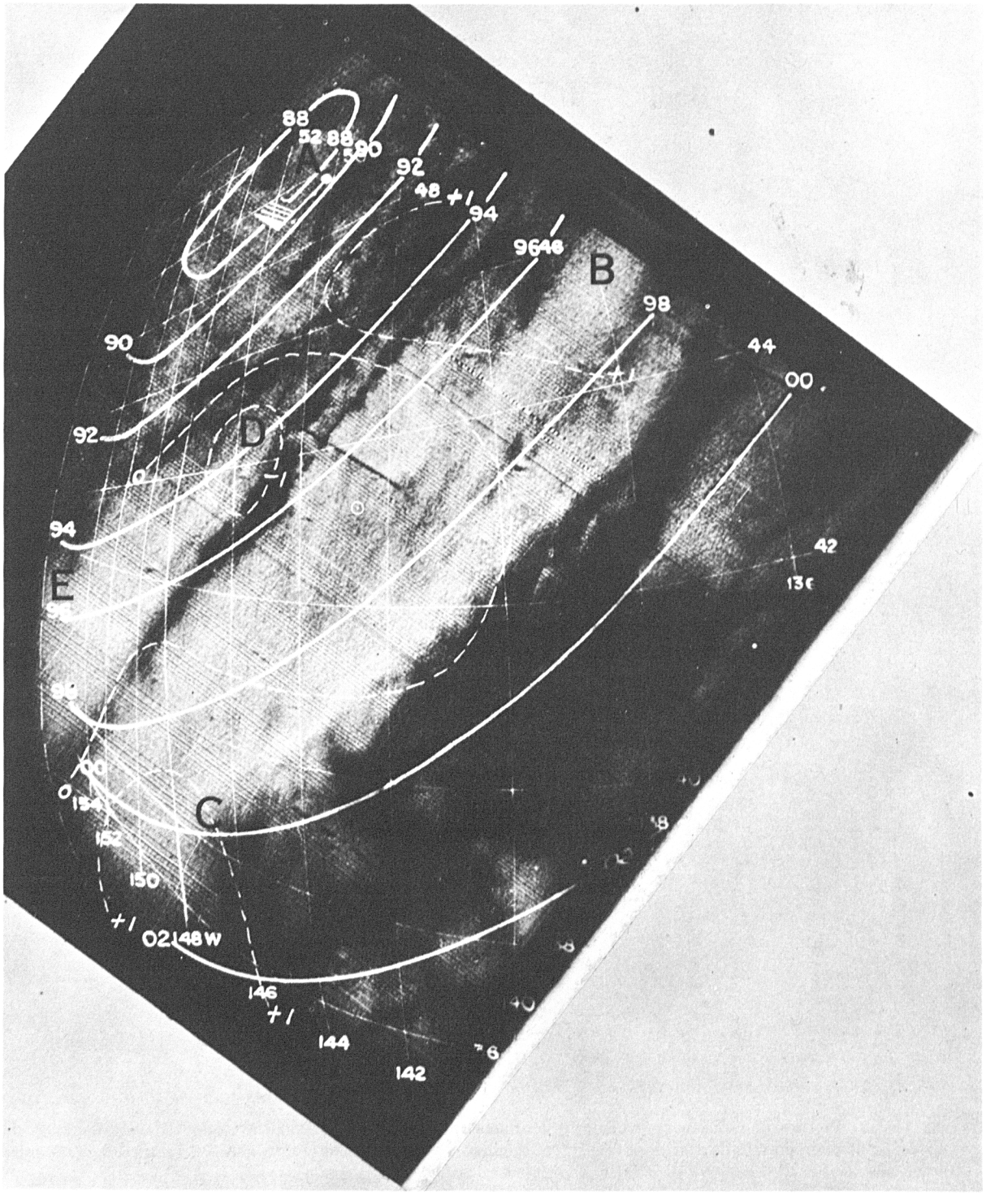


FIGURE 11–11. Same cloud area as in figure 11–10. 2° latitude-longitude grid; principal point indicated by circled dot; 700-millibar contours and 600-millibar vertical motion (dashed) in cm./sec.; data for 0000 GCT, April 2, 1960.

it was suspected that perhaps the vertical motion actually had two centers rather than just one. This break in the clouds would be in the region where the upward motion was absent or even downward. Thus, again, some detail in the estimate of the initial conditions might be obtained.

Figure 11–12 shows another storm (discussed more fully in ref. 3) in the Atlantic Ocean which was a rather mature storm. This system is to the west of England. It so happened that this storm system was photographed on two separate orbits, 100 minutes apart. As the satellite goes around the earth, if it passes an area near the northern part of one orbit, on the next orbit it may cross the area again. Note the persistence over a 100-minute interval of some rather small-scale features. Part (*a*) is the northern part of the storm; part (*b*) is the southern part. Part (*a*) was taken early on April 2, 1960, and part (*b*) was taken 100 minutes later on the same day. Land features are labeled to help with the orientation. The Mediterranean part of Spain is mainly cloudless. The lower right of part (*a*) shows snow in the Alps. There were very few clouds in the Alps region at this time, as verified by surface reports. Italy is to the south as marked in the figure. Part (*a*) shows holes in the clouds over the Bay of Biscay, near France and Spain; the clouds in the Atlantic storm extend across Spain.

It was noticed that the cloud system surrounding the storm with the holes over the Bay

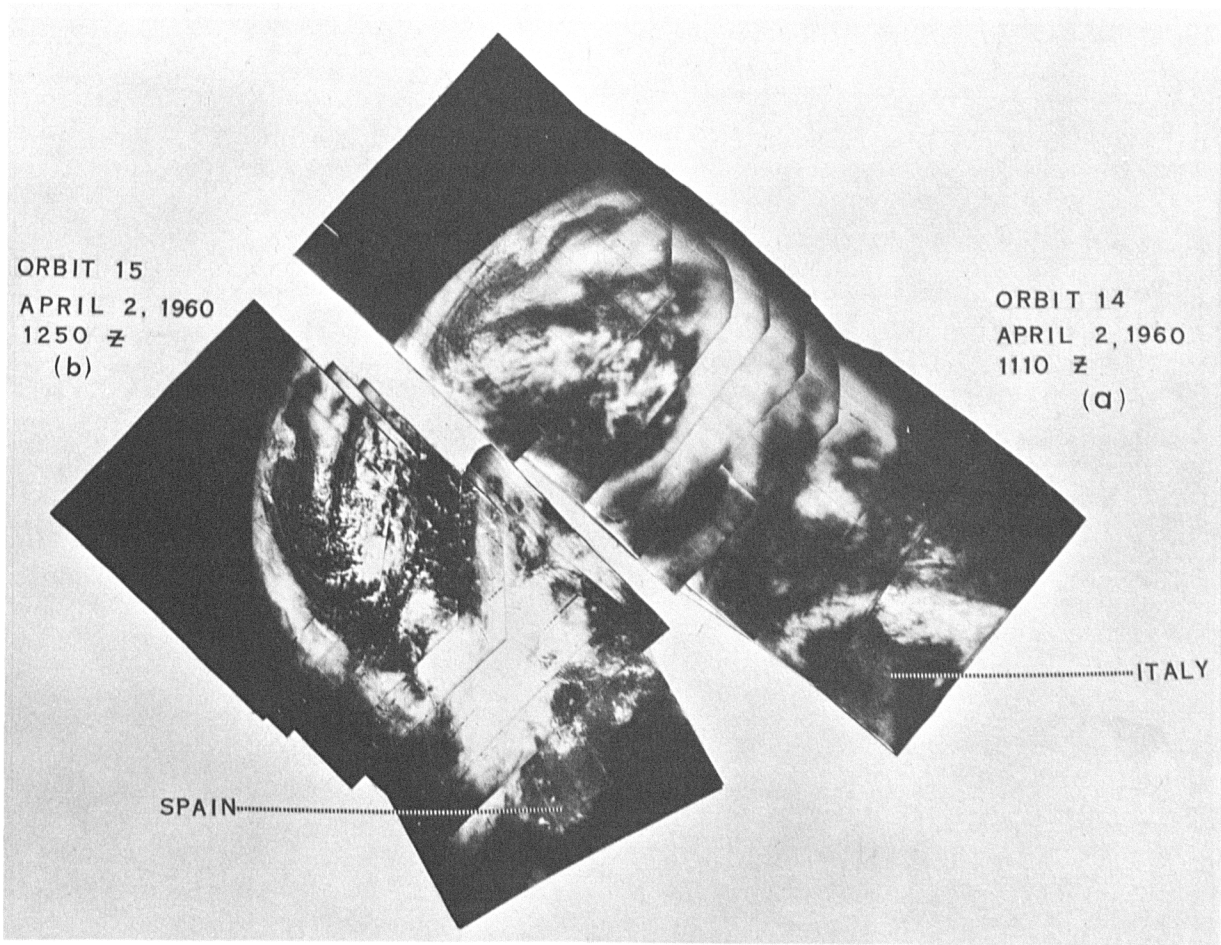


FIGURE 11–12(a). Composite of frames photographed at about 1110 GMT, April 2, 1960, showing stratiform cloud surrounding cumuliform cloud in an Atlantic Ocean vortex.

FIGURE 11–12(b). Composite of frames photographed at about 1250 GMT, April 2, 1960, showing the same Atlantic Ocean storm 100 minutes later.

of Biscay (pt. (*a*)) came into an arrowlike projection. The same formation appeared 100 minutes later. This cloud arrow protrudes from what might be called the wall of the cyclonic cloud. From this region some cloud streaks, rather thin lines, are spreading outward. They are also present 100 minutes later and they seem to be going into the main body of the center of the storm.

The broken-up cumuliform clouds get brighter as they go from the region of northerly flow, where the clouds seem to be much more suppressed in vertical extent, to the region of southerly flow, where they get brighter. It is assumed that they are of higher vertical extent in the region of southerly flow, although the height of the clouds cannot be determined directly from the picture. There is an interesting swirl of clouds north of the Alps on the northeast side of the main cloud formation. The air was actually flowing around cyclonically and then branching off to the east. It may be wondered whether this cloud, which existed over Germany, might not be a representation of a small anticyclonic swirl branching off the main flow.

By various techniques something may be ascertained about the geographical location of the individual cloud elements. Figure 11–13 is a map which shows the storm cloud formation, pictured in figure 11–12, over the British Isles, Ireland, the French coast, and Spain. The cloudless region on the right is over Italy. The satellite traveled along orbit 14, coming across the Alps and Italy, and 100 minutes later it traveled along the orbit 15 track across Spain and North Africa. This map represents the composite information about the storm. Shown

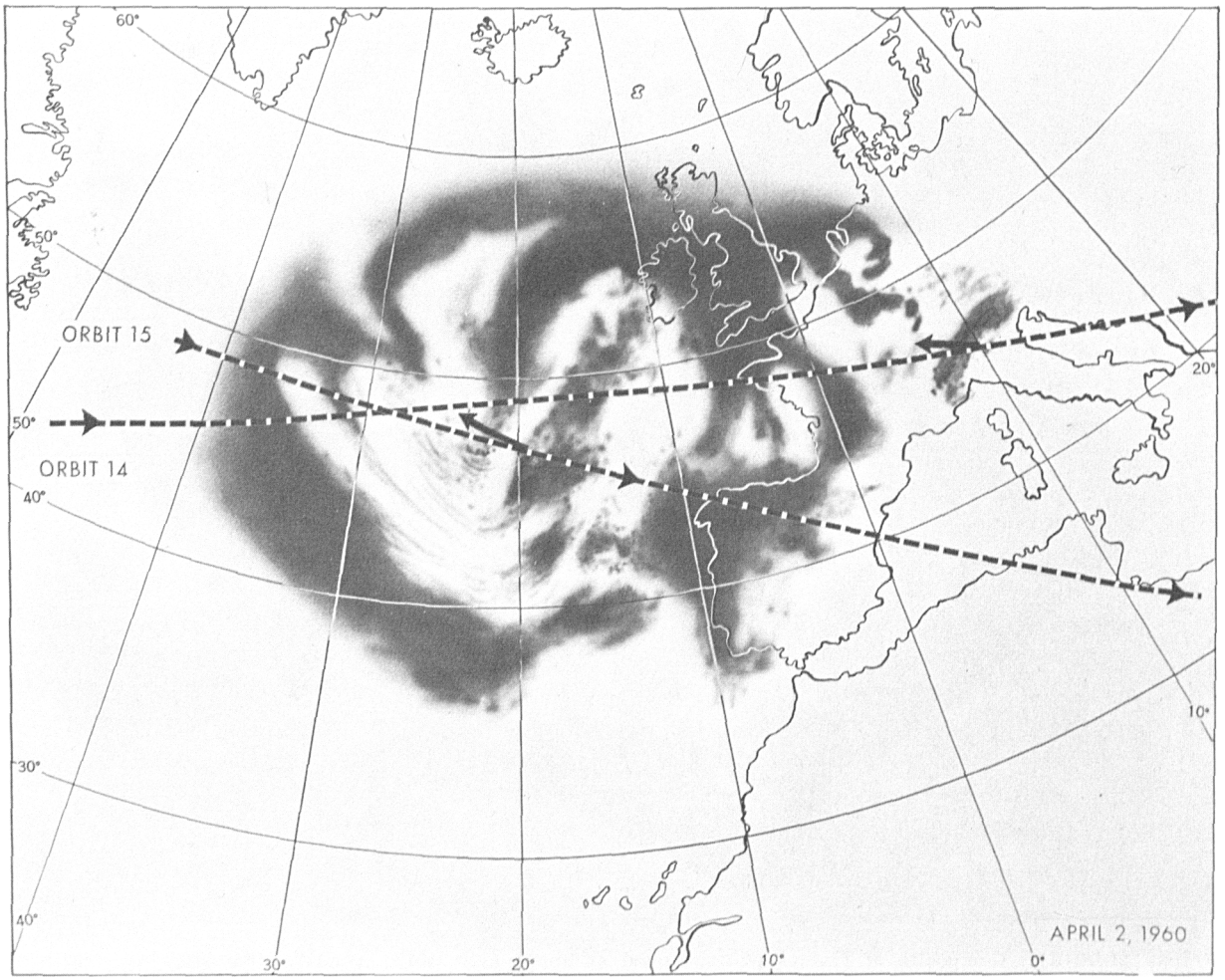


FIGURE 11–13. A sketch of the pictures in figure 11–12 arranged in proper geographic location.

again are the two holes over the Bay of Biscay and the broken cloud pattern. The arrow is mapped at about 50° north and 20° west. It seemed reasonable to suspect that the cold source which was feeding this storm had been cut off because cloud now surrounded the storm completely. It turned out that this region was associated with a very deep cold airmass which extended to the tropopause. In the region to the east and northeast, warm moist air was flowing.

Figure 11–14 is the sea-level chart associated with figure 11–12. The hatched area is the stratiform cloud that surrounded the storm in the pictures. It has been included for purposes of orientation with regard to the synoptic features. The low center is very near the arrow; in the central region all reports showed clouds with vertical development, cumulonimbus, and cumulus congestus, but no overcast conditions. In the region where the frontal system is located, all reports indicated practically overcast conditions, or at least nine-tenths coverage, with various stratiform clouds; these reports merely show that the satellite pictures agree with the surface observer. The details of the pattern could not be obtained in any way other than from the satellite. The major cloud system was known, of course, from conventional observation. The frontal system was very difficult to locate accurately because of the fact that it was a rather old system and the contrast between airmasses was very weak. However, the analysts placed the front more or less in the middle of the cloud system, using the theory that in the older systems the clouds do not fall right on the edge of the front as they do in growing vigorous cold fronts.

Figure 11–15 shows the 500-millibar chart. It shows, as expected, that there was warm moist air flowing around the cyclone. Figure 11–16, which is the isentropic chart, shows the

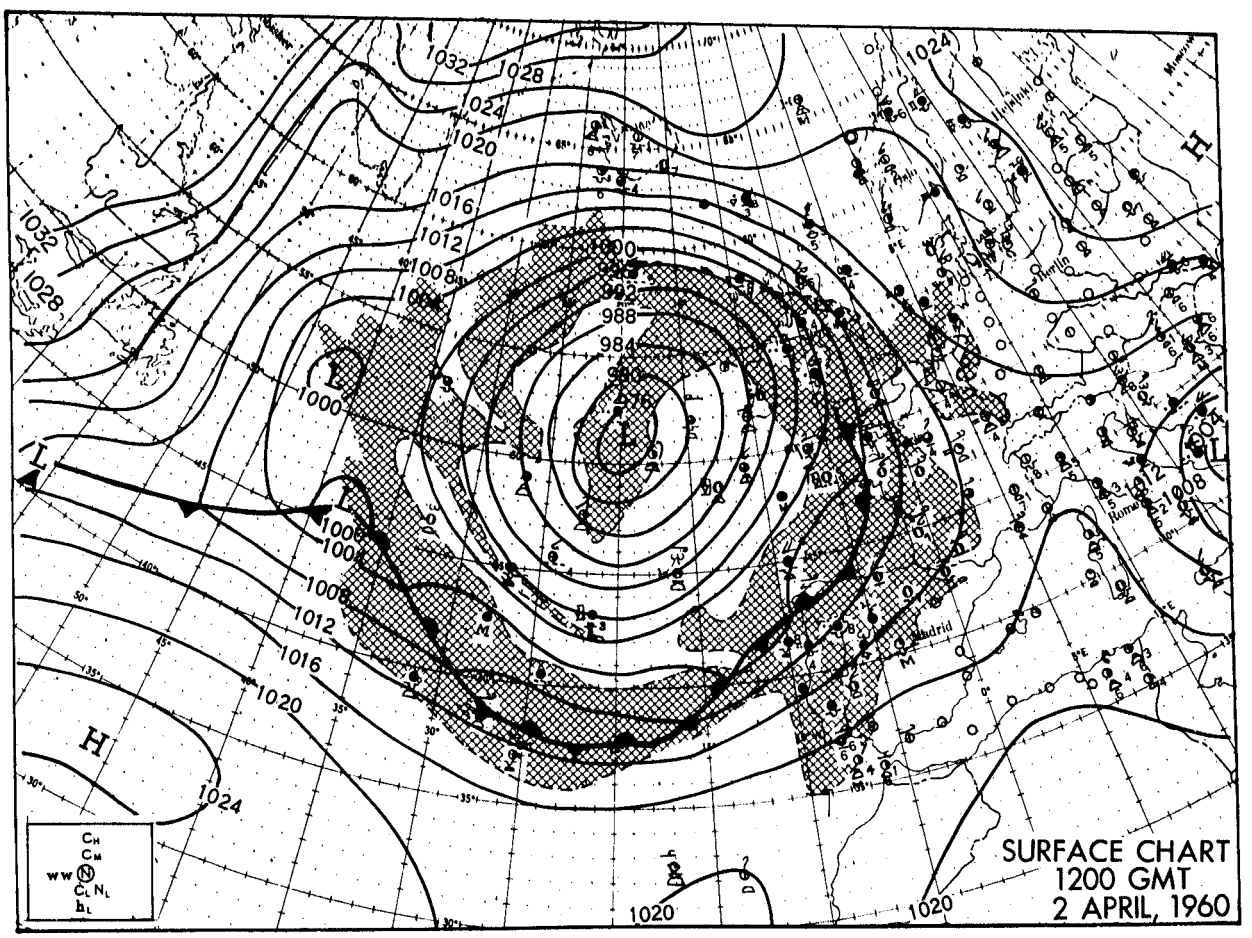


FIGURE 11–14. Sea-level chart for 1200 GMT, April 2, 1960, showing mature cyclone with outline of stratiform cloud area from figure 11–13 superimposed. Surface cloud observations are also shown.

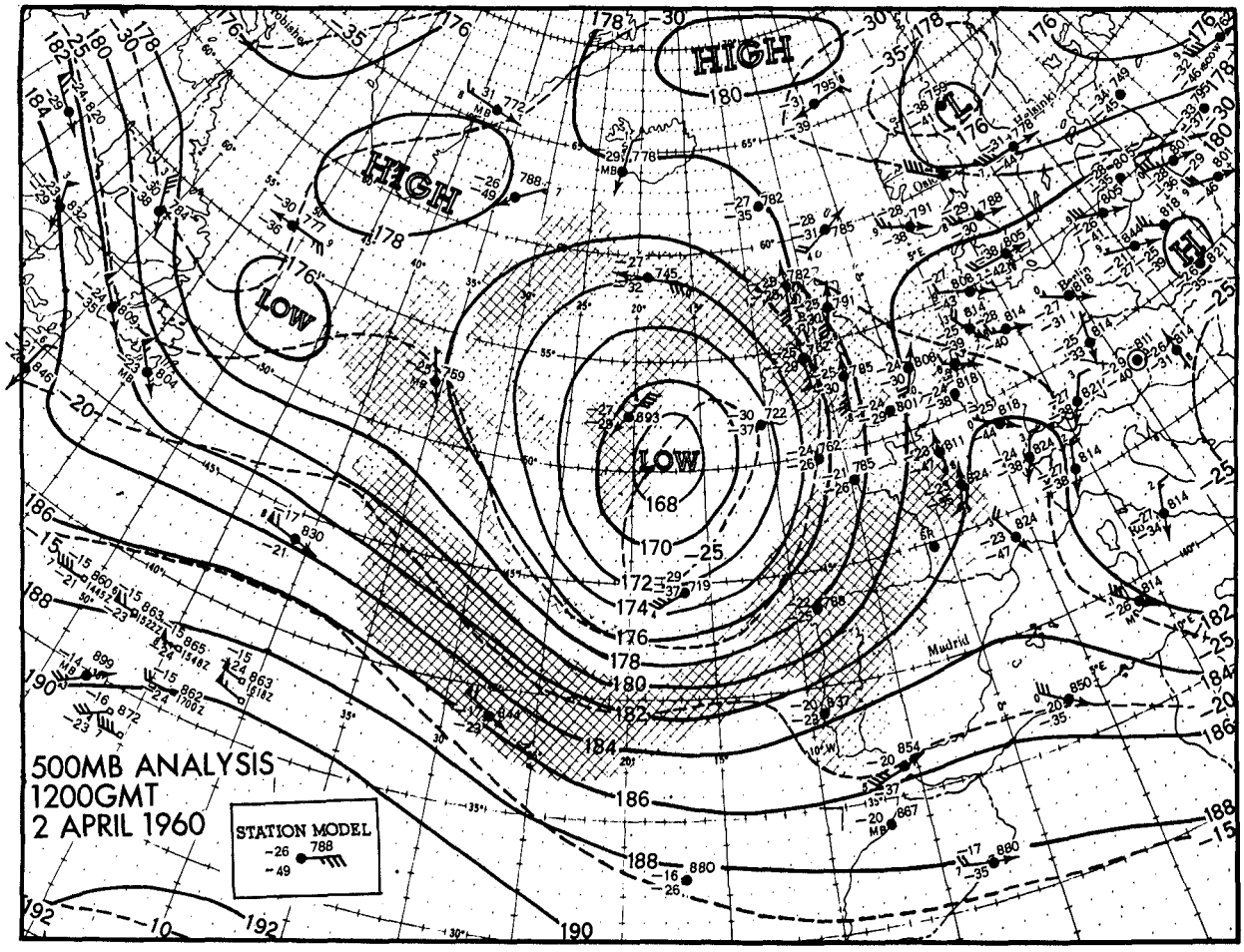


FIGURE 11–15. 500-millibar chart for 1200 GMT, April 2, 1960. Solid lines are 200-foot contours; dashed lines are isotherms; dewpoint temperatures are shown at lower left of each station circle.

airflow more clearly. The warm moist air was flowing up the isentropic surface from the southeast sector of the storm and cyclonically around. To the north reports were received from two ships (ships I and J). The variation of wind with height at these ship locations shows that this warm moist "tongue" flows between the stations. This agrees very well with the pictures of the clouds forming the arrow-shaped projection, with the moist warm air flowing around the cyclone.

In the center of the mass is a very high and cold dome of air, corresponding to the broken region shown in figure 11–12. In the region to the northwest conditions are somewhat more ambiguous and it is uncertain, on the basis of these data at least, that there is a flow of warm moist air. However, the presence of the cloud, unless it is one of those cases where the cloud was formed under one regime and now is gradually moving out into another (which does not seem likely in such an extended frontal system), would indicate a region where the motion is upward but perhaps not so strongly upward as in some of the other regions where it is very clearly indicated.

One other point is worth mentioning. In the region of the cold front, there is a deep cold mass of air which is shown in figure 11–16 and also warm air ahead of the mass. It is known that if air is flowing around the cyclone, and in such a manner that it is flowing around the cold air also, then the thermal wind equation requires that the wind should increase in magnitude with height; that is, the speed of the wind should increase with height.

This would mean that, if the regions where cold air lies next to warm air could be found in cloud pictures, as indeed they can in this case, it would be known that somewhere in the

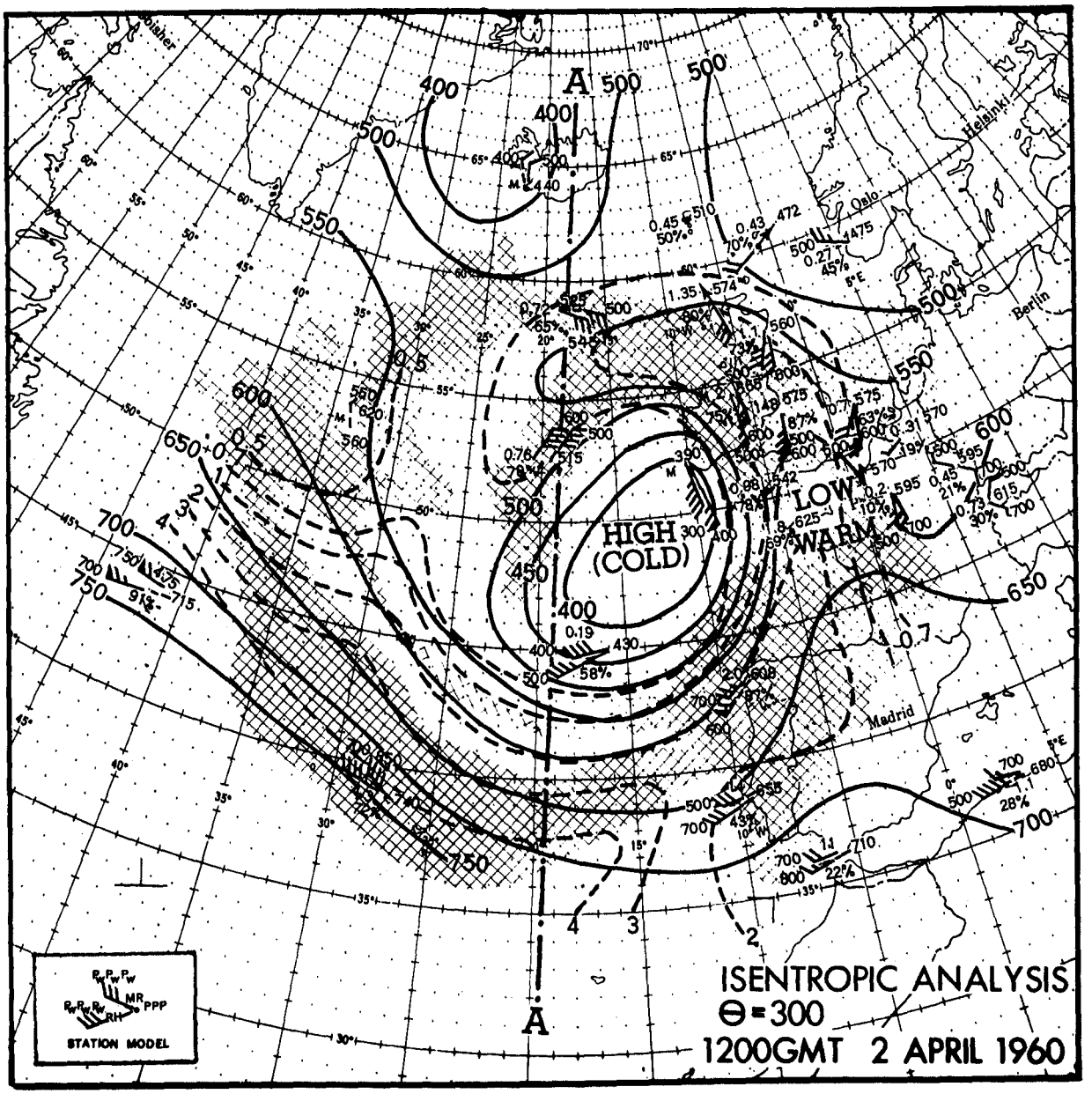


FIGURE 11–16. Isentropic chart (θ=300° K), 1200 GMT, April 2, 1960. Solid lines are isobars on the isentropic surface; dashed lines are lines of constant mixing ratio. Line AA shows the region of the cross section in figure 7 in reference 3. The winds are shown at two pressure levels near the level of the isentropic chart. High and low refer to the elevation of the isentropic surface.

vicinity of the boundary between the cold and the warm air there is a region of strong winds. It may be characterized as the jetstream if the winds become strong enough. Whether the winds were precisely at the boundary would depend on the relative slope of the adjacent airmasses and other factors. However, in the general vicinity of the boundary there is a region of strong winds. This region can be seen in figure 11–16. As would be expected in the case of a cyclone, the winds in the center are rather light. As the boundary between the stratiform cloud and the region where there is very little stratiform cloud and no cumuliform cloud is crossed, a region of high winds would be expected. Actually, there are winds approaching 60 knots across this region; then, the winds decrease in the general anticyclonic region. Several cases such as this have been examined. As might be expected, in a very

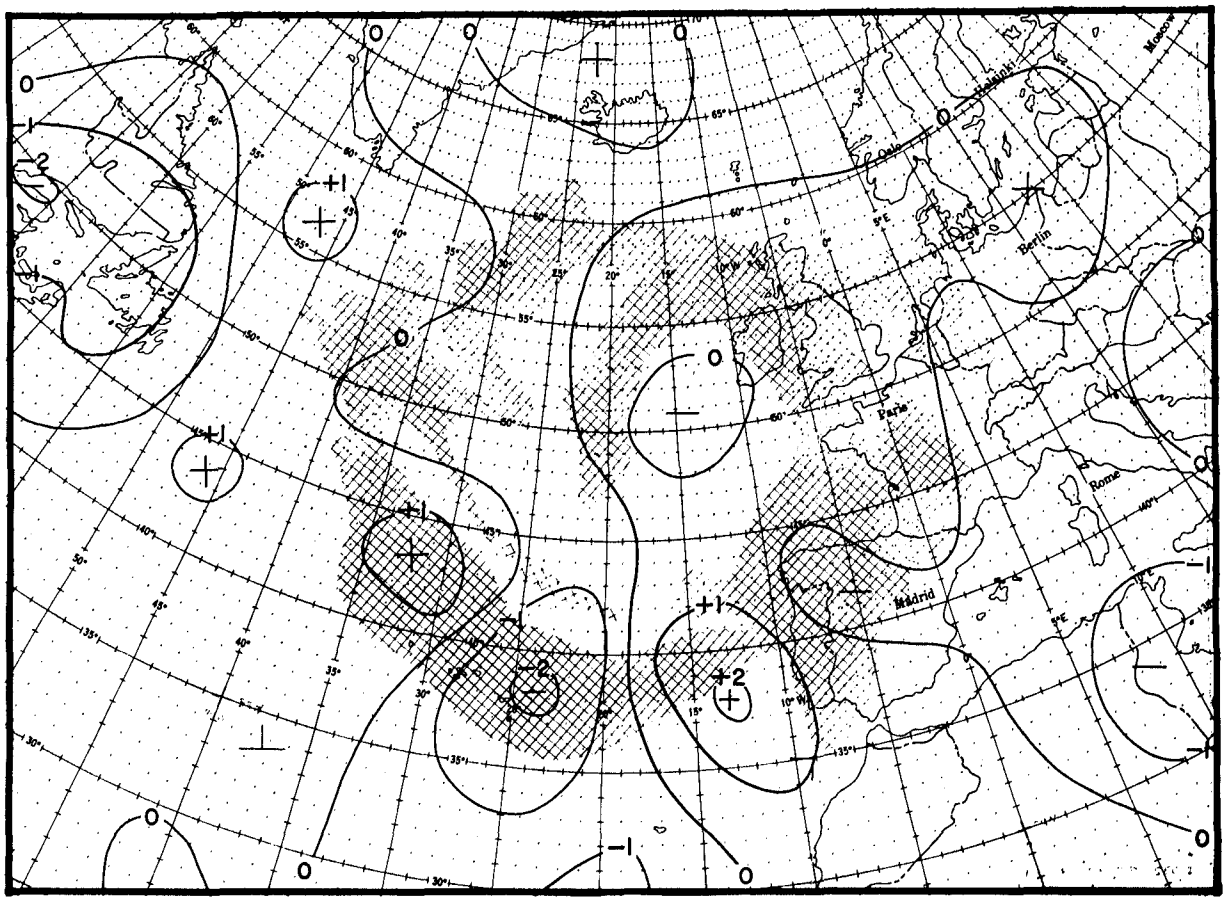


FIGURE 11–17. Vertical motion chart for 600 millibars at 1200 GMT, April 2, 1960, computed by JNWP unit. Units are cm/sec; a plus denotes upward motion; a minus denotes downward motion.

general sense, the region of strong winds aloft can be located.

Figure 11–17 shows the vertical motion field as it was computed by the U.S. Weather Bureau numerical prediction unit on the basis of what was believed to be the horizontal wind field at the beginning of a particular forecast period. In the middle of the region surrounded by stratiform cloud there is a region of downward motion which agrees with the belief that this is not a region of little motion on the isentropic surface. On the other hand, to the right, or west, of the arrow there is still a very weak upward motion. By contrast, there is strong upward motion near 37° north and 13° west. This region, according to the flow in the cloud, would probably represent a larger upward motion than shown. Perhaps more important is that the region centered near 37° north, 25° west, which lies adjacent to the one just mentioned, shows a strong downward motion and is a region where substantial cloudiness still exists. In the absence of any other information this region would probably be considered one of upward motion, not downward motion. Thus, this might be a case which, because of the lack of upper air data, does not permit a good estimate of vertical motion. In this area some improvement could be made in the tools which are available to the forecaster.

Figure 11–18 is a cloud mosaic of TIROS I pictures across the northern Pacific. The frontal systems are plain. The cloud is branching off in an anticyclonic manner to the west of the central occlusion. Also shown is the broken-up cloud field which is associated with the air in the anticyclonic colder air. Where the cloud edge is sharply defined, strong winds would be expected at an upper level, as previously mentioned. There is cold air coming into a region with a strong frontal system. Thus, it would be expected that warm moist air is flowing side by side with colder air, so aloft there should be a region of stronger winds.

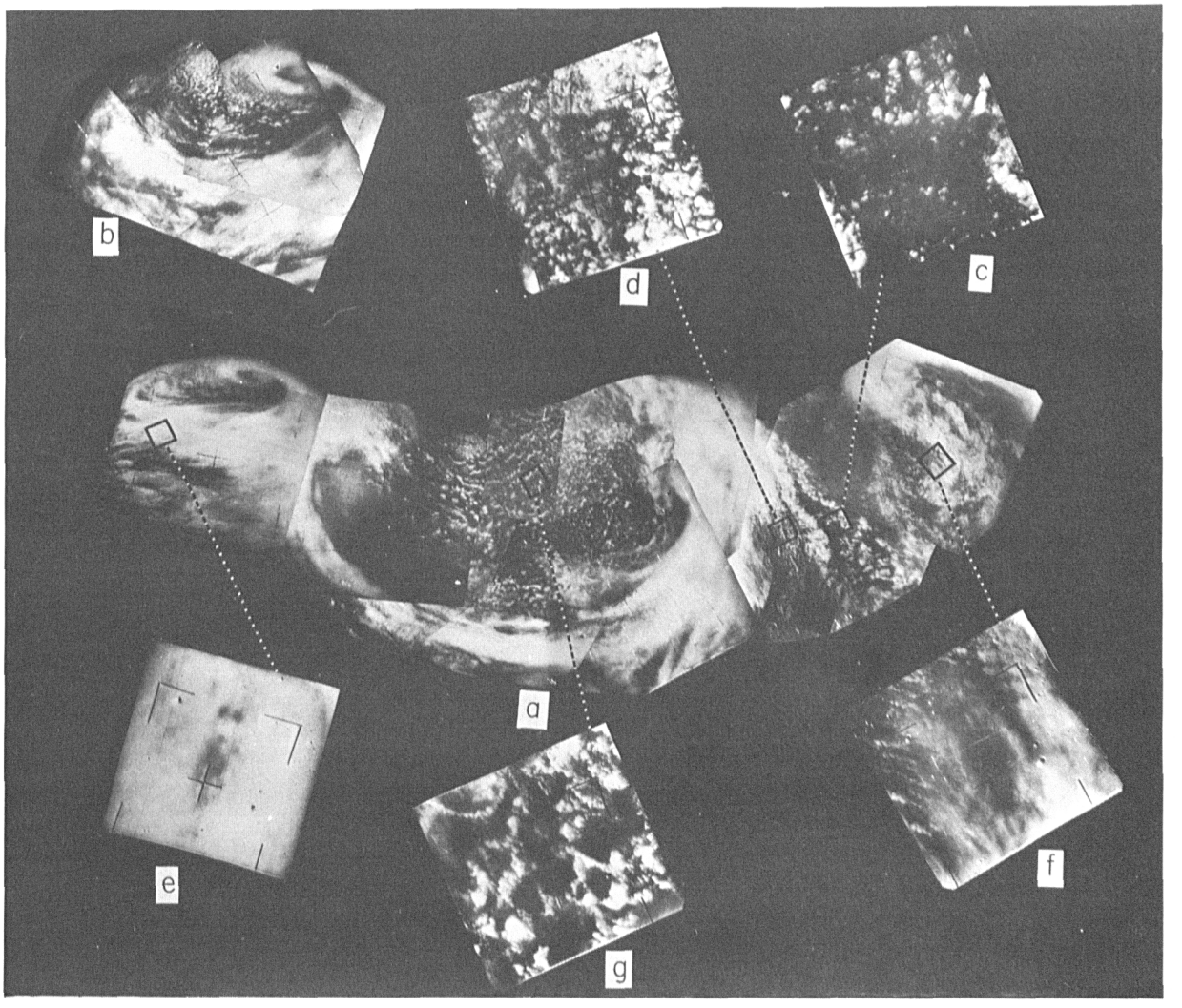


FIGURE 11–18. (a) Cloud mosaic of TIROS I pictures across northern Pacific, May 20, 1960. (b) Cyclone detail (mosaic of wide-angle pictures). (c), (d), (e), (f), and (g) are narrow-angle pictures of mosaic.

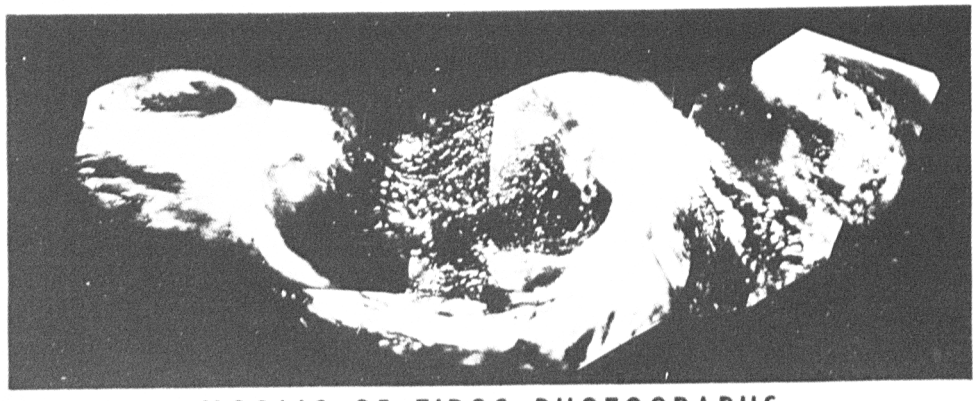
Some details of narrow-angle pictures in this region may be of interest. For example, picture (*g*), taken in the region shown by the connecting square, shows some of the detail of the individual cumulus clouds, which are partially arrayed in circular patterns. There is, especially in this region, lack of agreement regarding the extent to which these clouds are built up. Some meteorologists believe that these clouds are built up to large heights. Others are rather skeptical; but it is a region for which there is very poor upper air data so that the results cannot be verified.

Figure 11–19 gives a better illustration of the region where strong winds might be expected, with contrasting flows of cold and warm air. Although the location of the "jet" cannot be known, it is believed that it could be placed along a line paralleling the sharp edges of the clouds near the cold fronts of the two main systems. Other information may have to be used to decide how to connect portions of the jet. Parts of the jet could probably be identified on the basis of the pictures alone.

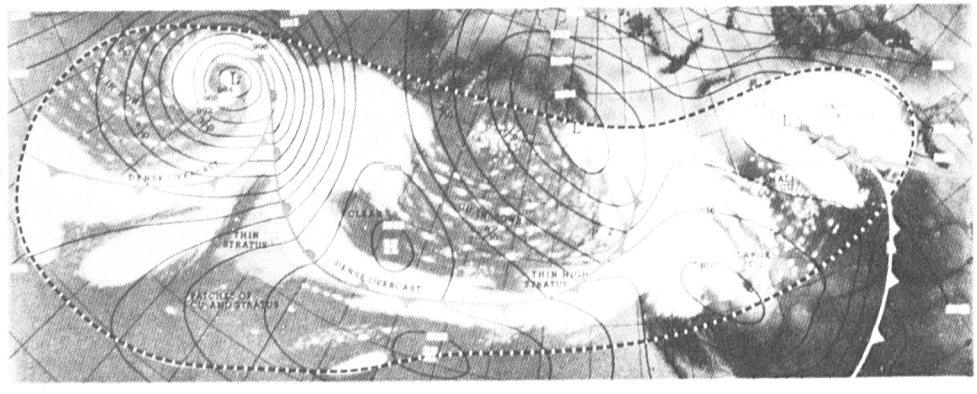
Figure 11–20 shows a system of cyclones in the Southern Hemisphere. Picture 3 shows a stratiform cloud completely surrounding more broken-up cloud; between the two is a cloudless area. This looks very much like the storm in the Atlantic which has just been described (fig. 11–12); it could, therefore, be speculated that this pattern represents a cyclone in a rather mature state of development in the Southern Hemisphere. Picture 6 shows a storm which

STORMS AND FRONTS

A Family of Weather Systems



MOSAIC OF TIROS PHOTOGRAPHS



WEATHER MAP, MAY 20, 1960, WITH TIROS CLOUD DATA

FIGURE 11–19. Cloud mosaic and matching weather map, May 20, 1960.

was discussed in reference 4. The cyclone is defined, to a certain extent at least, by the cold air which has penetrated the mass of the cloud. Actually, the cold air is coming far around the cyclonic pattern. Thus, this is a fairly advanced state of cyclonic development. It was known that this storm was located between South America and Africa. There was one ship report available to the South American analysts; however, the picture was not available when the analysis was made. The ship reported a very low pressure. A storm was therefore placed on the weather map near the ship location. However, the cloud pictures of the storm show that it was far to the east of the ship and that no large cyclonic system was present near the ship position. An examination of the situation revealed that the report and picture could be made consistent by merely changing the first digit of the coded transmission of the barometric pressure from a nine to a zero. Everything falls in place with the storm faraway from the ship and with reports from the ship fitting in rather well with the remainder of the cloud pictures. This is an excellent example of how cloud pictures in a region with practically no conventional information can be of great value in analyzing the synoptic situation.

The ability to derive all the information from cloud pictures is largely undeveloped. What is needed is for the whole meteorological community to accept these cloud pictures as one of the best observations obtainable, especially in areas where there are few conventional observations, to use them to attempt to understand what the cloud patterns mean, and to improve forecasts in the operational service in those areas.

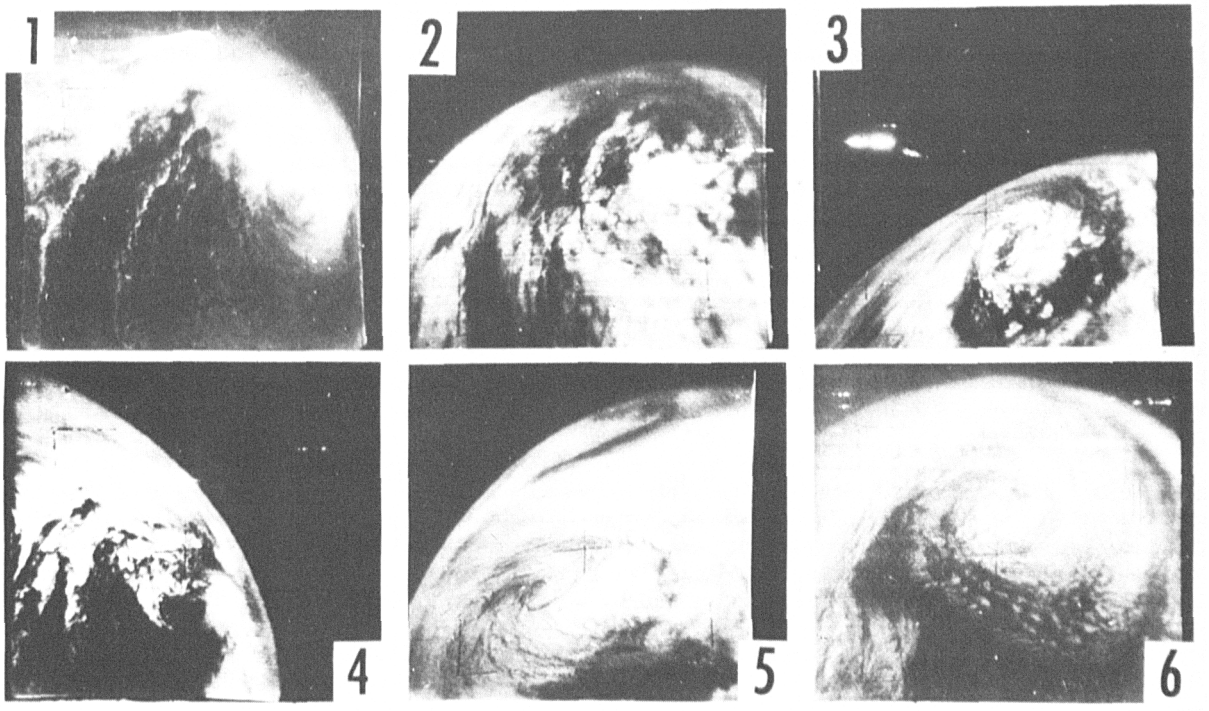


FIGURE 11–20. Southern Hemisphere cyclones as seen from TIROS I.

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Question Period

MCCULLOCH, Canada: I was wondering if some of the pictures, especially figures 11–5 to 11–7, the Midwest storm, might not lend a little support to the Canadian multifront model—to the idea that there may be more than one major frontal system.

FRITZ: It might well be. Certainly, I would investigate that. My recollection is that in the analysis of that storm, we did not detect in the radiosonde data available any distinct airmass difference. Perhaps, we were not looking at it in terms of the particular model that you have in mind. It would be a very good point to study.

PATRICK, Nigeria: Correlation is rather lacking between the field of vertical motion, as computed by the Numerical Weather Prediction Unit (JNWPU) here, and the cloudiness. Do you feel that the field of vertical motion is not giving a correct idea because of a fault in the model approximation or because the correlation of cloudiness with vertical motion, in general, might not be very helpful to practicing meteorologists in supplementing their forecasts?

FRITZ: I think that in areas like the United States, for example, in the central United States where there are ample radiosonde data, that the vertical motion fields, as computed by the JNWPU groups, are in the main adequate. But in an area like the Atlantic, where even though there is probably a greater density of radiosonde information than in any other ocean except the southern Pacific where there are many islands, I think the data are inadequate to compute the vertical motion field well. Over the ocean, especially if there is a cyclone which is still in the state of development, the clouds represent the vertical motion field better than the JNWPU computations. Since that is true, we have a possibility of improving the JNWPU product in those areas. This would not mean that we could do it everywhere, and it would not mean that we could do it with any cloud system. But with a great many cyclonic systems, and in ocean areas, we definitely have a prospect of improving the vertical motion field estimate.

LEVI, Israel: In the same context, with respect to correction of the vertical motion fields from clouds, I feel that it would be rather difficult to get the correct picture knowing that extensive stratocumulus decks, for instance, often cannot be differentiated from extensive altocumulus decks. The considerable difference in height might mislead us quite a lot in that case.

FRITZ: Yes, that is a very important point. I think if we had only the cloud pictures, that would be a rather serious handicap, although perhaps not hopeless. However, we have now another tool which may help: the satellite radiation measurements, which will be discussed in subsequent papers. With the aid of these radiation measurements, we have a possibility of estimating whether the cloud is very high or very low, at least to differentiate between extensive stratus decks, say with a top of 5,000 feet, and extensive altostratus, with a top of 15,000 or 20,000 feet. We have a very good prospect of being able to detect large differences with radiation measurements. When we get to the point where that becomes operational, the objection which you mentioned, which is a very serious one, may, in part at least, be overcome.

PATRICK: Are the bright spots which are shown in the observations due to short waves reflected to the satellite? In certain areas there are desert regions, for example, the Sahara in Africa. Some of the meteorologists in countries toward the south of Africa will be interested in focusing on things like dust haze. In that case will it be possible to distinguish in the pictures between the type of radiation reflected from the dust haze and that from thin clouds, and will dust haze be distinguishable from the ordinary sand in the desert?

FRITZ: Actually, I do not know the answer to your question. Perhaps it would be a very good thing for someone from that area to investigate the TIROS pictures to see what can be done. I have studied a few pictures along the Mediterranean, African coasts in the area of Libya and Tunisia, and I have examined the ground features. In those cases there were no clouds, and one could see very clearly the sand dunes in the land features. The sand dunes themselves have enough contrast with the surrounding terrain so that one can detect them. On the other hand, along the Mediterranean coast, there were small white spots, which looked like small cumulus clouds. It is doubtful that the clouds could be checked from surface data, but there probably were small cumulus cloud streets. Several meteorologists who have looked at those white spots have thought that they were cumulus clouds which you could see against the very bright ground which lies not far from the Mediterranean coast. But what an extensive cloud deck would look like, I am not at all sure.

RASOOL, Institute for Space Studies: I want to ask about the polarization measurements from the top of the clouds. Dust would not make any difference to the albedo, would it?

FRITZ: It might. We do not have any polarization measurements. However, I would suppose, from suggestions that have been put forth about the estimate of cloud tops by measuring polarization, that if the degree of polarization were measured, looking down, an estimate of cloud heights could be obtained. The idea is that the air lying between the satellite and the cloud would polarize the light and that the amount of polarization would depend on the amount of air which lies between the satellite and the cloud. If this would work, then one could distinguish, for example, between a cloud which was high and dust which, I presume, would not be so high. But we do not have any information about that.

RASOOL: Could the droplet size be obtained by polarization?

FRITZ: I do not know.

LANGLO, WMO: Have you thought of any program to compare the cloud observations obtained by conventional means, a network of the densest type as in Europe, with cloud observations from satellites? Have you thought of any program like that of Professor Bergeron who has for many years proposed that the whole method of cloud observations by normal meteorological stations be revised, in the sense that they are not really giving what they ought to give?

FRITZ: We have not considered the European network. I am hoping that the meteorologists in Europe will give the problem serious thought. But we have looked rather closely at the networks in the United States and Mr. Erickson, in paper 12, is going to discuss topics related to your question, namely, what is the relation between what is seen in the satellite picture and what is seen from the surface and, also, what is seen from airplanes. Sometimes, fields of small cumulus clouds as seen by the satellite may appear as haze or a thin cirrus from the ground. This relationship is being studied. Also under consideration are codes for defining the cloud systems pictured by satellites. There definitely is a need for classifying cloud patterns as seen from satellites in terms of the physical processes producing the patterns.

TEPPER: If I may add a few remarks relative to the question: We have in the United States a severe-storm research program which combines a very dense network of surface observations, special upper air observations, and an intensive aircraft and radar program. In conjunction with this research program, the satellite data will be used to define cloud systems.

12. INTERPRETATION OF CLOUD TYPES

By C. O. Erickson, *Research Meteorologist, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

Care must be used in interpreting the images seen in satellite pictures as specific types of clouds. Figure 12–1 is used as an introduction to the recognition problems that result from picture degradation caused by resolution and optical factors inherent in a system such as the Tiros vidicon equipment.

Figure 12–1 is a photograph that has been artificially treated to simulate a television picture at three different levels of resolution. The original photograph, from which these three are derived, was taken from a V–2 rocket over the Southwestern United States at an altitude of about 146 miles. The three pictures in the figure represent that same scene as it would appear if transmitted by television scan lines whose width at the ground averages for the photographs from left to right, ¼ mile, 1 mile, and 2 miles, respectively. The difference in the photographs is pronounced. For a line width of ¼ mile, the small- and medium-sized cumulus clouds in the photograph are clearly visible. For a line width of 1 mile, these same clouds are blurred. For a line width of 2 miles, only the gross features are visible and the individual cloud elements can no longer be seen.

The resolution factor is somewhat analogous in the Tiros pictures, which are transmitted to earth by television. The width of the scan lines is not the same over different portions of the picture. In the area of the subpoint, where the camera is pointing straight down, the width of the scan lines is between 1 and 1½ miles. Toward the horizon the line width is of the order of several miles, owing to the large angle of incidence and the greater distance of the satellite from the surface of the earth.

The average overall resolution of wide-angle Tiros pictures is perhaps 3 miles. This means that the smaller cloud features, which can be seen from the ground and which serve to identify the cloud type to the ground observer in conventional observations, often cannot be seen in Tiros pictures. Such features would include the altocumulus, stratocumulus, and small fair-weather cumulus clouds, all of which generally seem to be less than 1 mile in size.

A field of small fair-weather cumulus, as mentioned in paper 11, sometimes looks as if it might be a thin stratus deck. Bulging cumulus clouds, the Low 2 type in the international code, cumulonimbus, and thunderstorms are larger and more visible, and they tend also to cluster together. These types are visible in Tiros pictures, both because they are larger individually and because they often form clusters. In other words, cumuliform appearance is often on a larger scale than is visible from the ground. The same sort of thing occasionally is true in stratocumulus over the oceans where the apparent size of the elements in cloud patterns seen in the satellite pictures is of the order of 10 to 30 miles or more, whereas the ordinary stratocumulus rolls that are observed from the ground are of the order of half a mile or so.

It has been found that the brightness of clouds is an aid to interpretation only in a very general sense because of the many factors that influence brightness in the Tiros pictures. Some very general rules have been formulated and they are perhaps what might have been expected. Extensive bright cloud masses, those of the order of hundreds of miles across, usually are composed of dense stratiform cloud. Small bright cloud masses in the form of irregular patches often contain cumulonimbus or thunderstorms. Cloud masses of low brightness usually are composed of cirrus or altocumulus or perhaps small cumulus clouds. Thick cirrus is visible in Tiros pictures but thin cirrus apparently cannot be photographed.

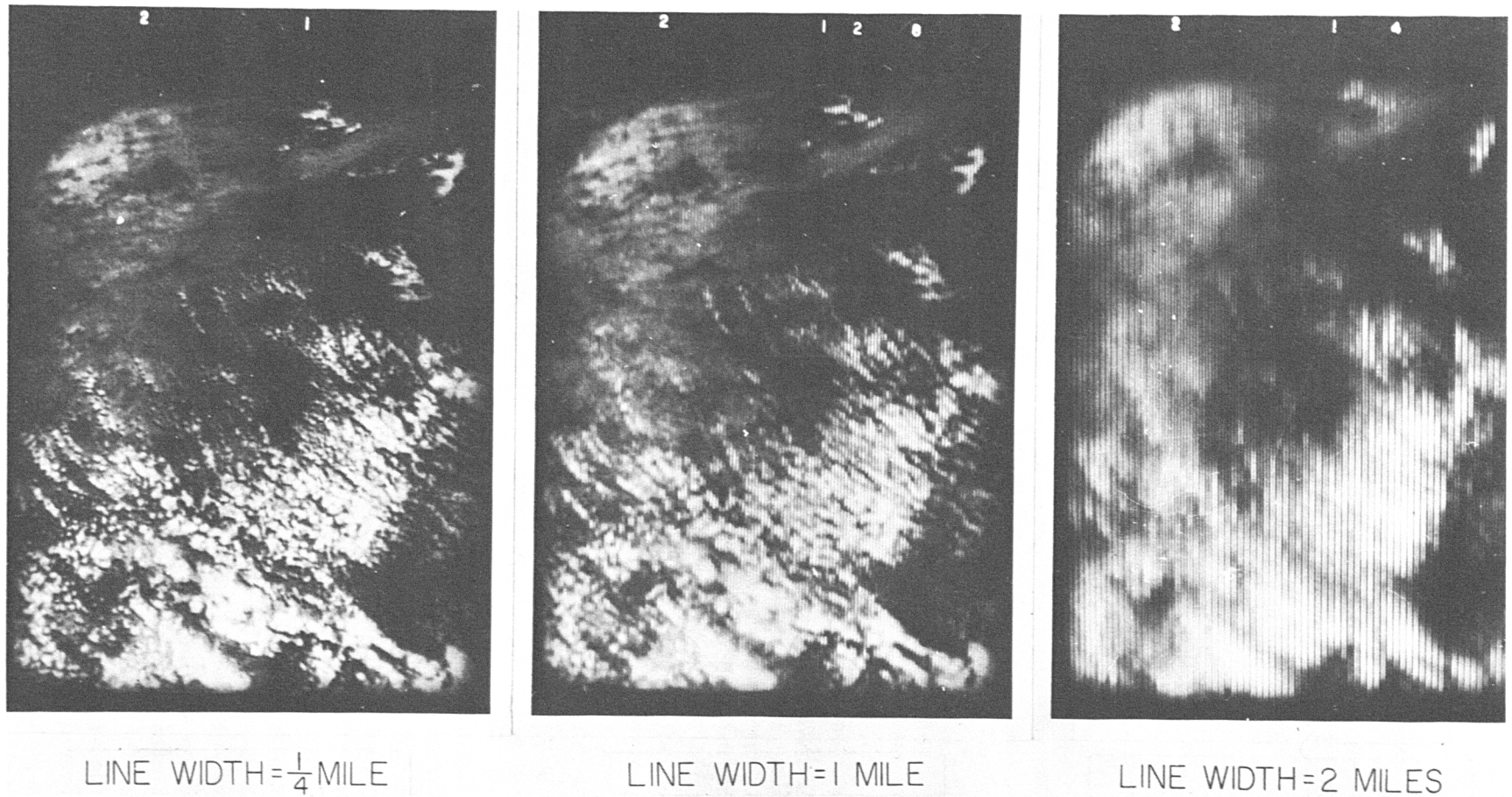


FIGURE 12–1. Simulated image degradation.

Figures 12–2 to 12–8 show some of the different cloud types as they appear in TIROS pictures. In examining these pictures, the fact that there is a certain amount of loss of detail because of reproduction processes should be kept in mind. Figure 12–2 shows Spain and a portion of the western Mediterranean, with Gibralter near the bottom of the picture. The subpoint is somewhere near the lower right corner. The best resolution appears in the fore-

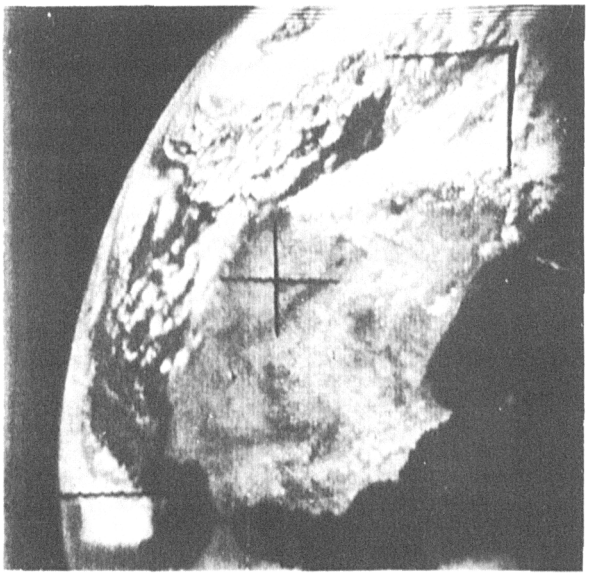


FIGURE 12–2. A TIROS III picture of Spain and neighboring areas taken July 15, 1961.

ground area, where it is about 1 to 1½ miles; there are no clouds in this area. A cumuliform cloud structure over the Atlantic is visible in the picture; this structure probably consists of clusters of large cumulus and cumulonimbus. Ships in that area of the Atlantic were reporting cumulonimbus and showers near the time of this picture. Near the horizon, about all that actually can be determined is that clouds are present. It would be very difficult from the picture alone to say what types they are and exactly what the amount of cloud cover is. It would be very easy to overestimate the cloud cover that is present. Near the top of the picture there is a vortex shown by the cloud pattern which was centered over the British Isles.

Figure 12–3, a photograph of the Florida coast, is a good illustration of the appearance of thunderstorms and cumulonimbus clouds. The bright patches over Florida are cumu-

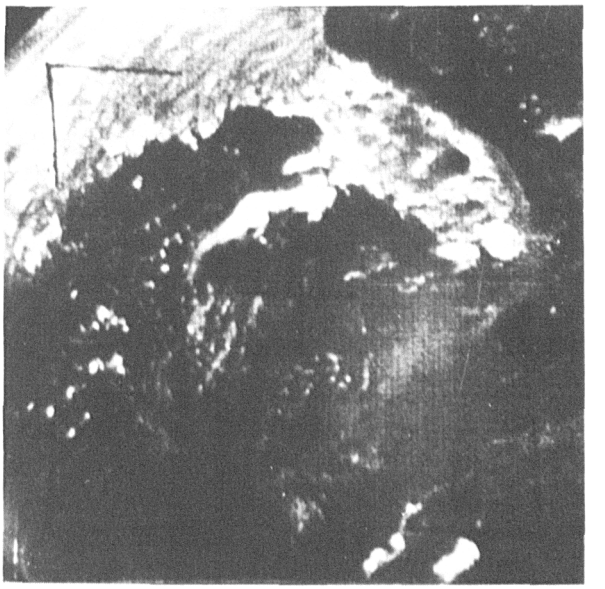


FIGURE 12–3. A TIROS III picture showing thunderstorms over Florida, July 14, 1961.

lonimbus and thunderstorms. There was a squall line west of Tampa at the time of this picture. The smaller patches over the gulf and near the left edge of the picture are rather bright and are probably approaching the cumulonimbus stage but may not yet be thunderstorms. The still smaller clouds slightly to the left of the center crossmark probably are bulging cumulus clouds, perhaps of the Low 2 type, but not thunderstorms. Some cumulonimbus cloud patches on the western tip of Cuba, similar to those over Florida, can also be seen.

Figure 12–4 is a TIROS I picture which has superimposed on it the State boundaries (dashed lines) of the portion of the east central United States which is covered by the picture. Also superimposed on the picture is the surface synoptic analysis at 2000 GMT which was just 5 minutes before the time of this picture. Within the warm sector of the cyclone (approximately the center of the picture) there is a very wide range of cumulus sizes. The clouds over Kentucky actually are Low 2 type clouds or bulging cumulus. If they were all the fair-weather type of cumulus, a cumuliform structure would probably not be visible at all. The larger white patches over the western portions of Pennsylvania and Maryland are well-developed thunderstorms. Practically every station in that area was reporting a thunderstorm near the time of this picture. As a matter

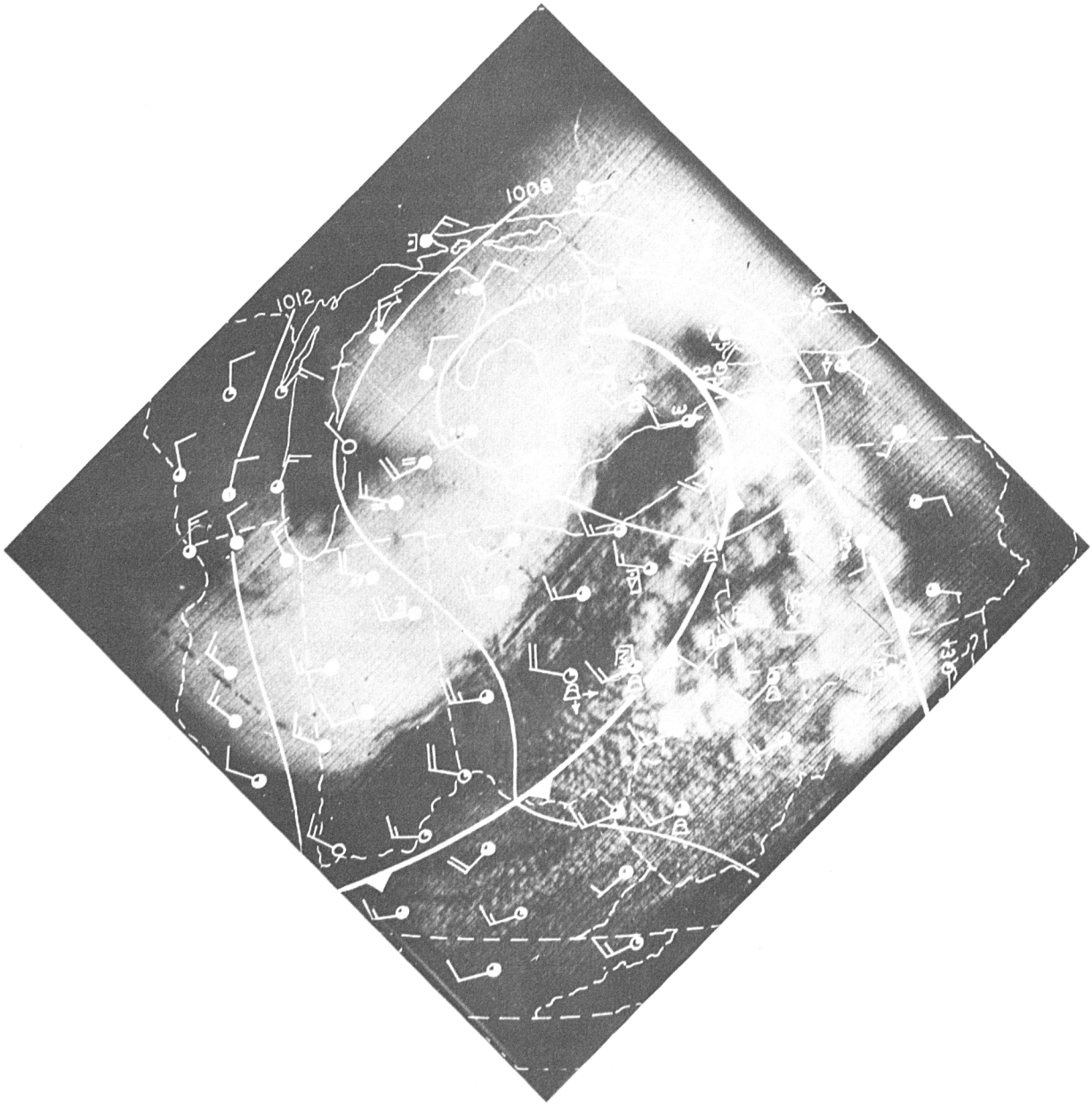


FIGURE 12–4. A TIROS I picture, with superimposed surface analysis, showing a wide range of cumuliform sizes. Pass 673, May 17, 1960, 2005 GMT.

of fact, about 3 or 4 hours later funnel clouds were observed over portions of Maryland and Virginia. To the north and west of the low center is a large stratiform cloud mass. North of the low center there are at least two layers, and perhaps more. To the southwest, over Indiana, there is only one stratocumulus deck. The number of layers cannot be determined from the picture alone.

Figure 12–5 is a TIROS I picture with a map of the Great Lakes region superimposed on it. The smaller photograph on the left is a narrow-angle picture taken at nearly the same time as the wide-angle picture; it is of the dashed-line area over Wisconsin. The narrow-angle picture shows some small cumulus clouds and some cirrus. In the same area on the wide-angle picture the difference between the two is not discernible. However, other portions of the wide-angle picture reveal certain characteristics. Since this picture was taken during May at 3 p.m., the waters of the Great Lakes are much

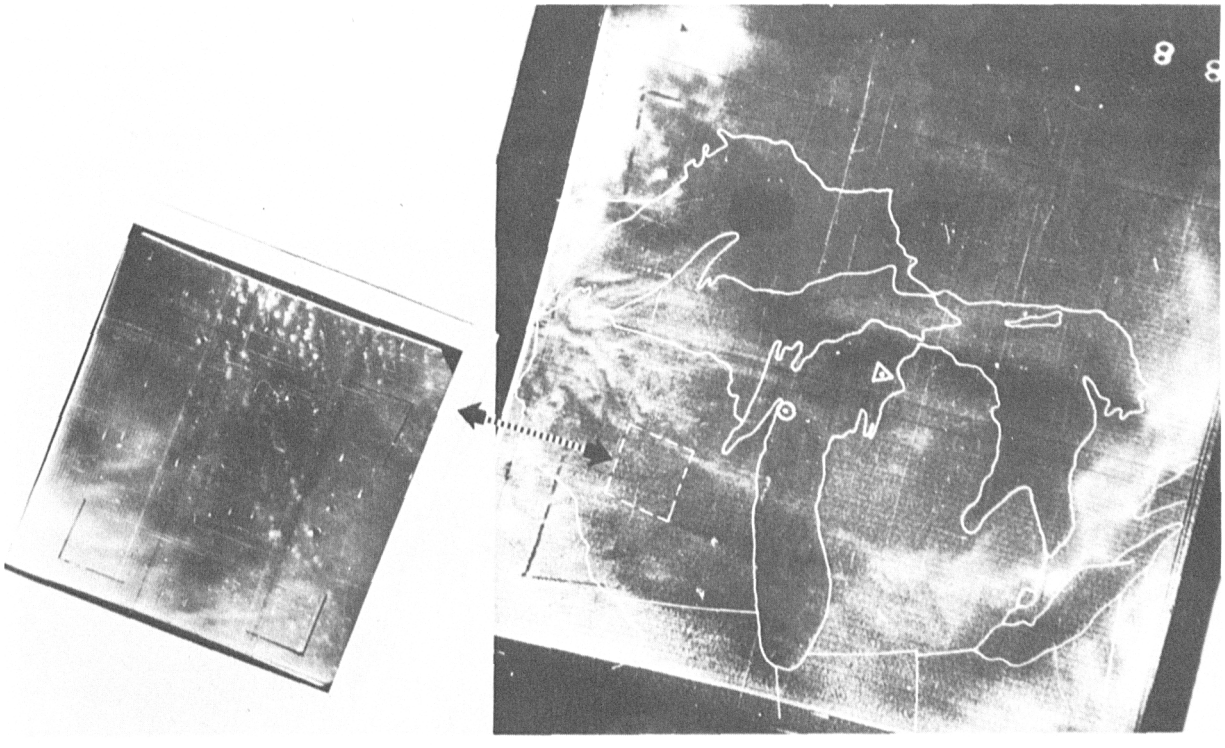


FIGURE 12–5. A combination wide- and narrow-angle picture from TIROS I showing cumulus and cirrus near the Great Lakes, May 18, 1960.

colder than the land. It, therefore, might be deduced that the clouds over southern Ontario, being over land and not over water, are low-level cumulus clouds. This deduction was found to be correct, although the individual cloud elements reported from ground stations cannot be seen because they are too small to be resolved. On the other hand, it might be deduced that the clouds extending over the waters of the western end of Lake Superior are not cumulus. Again, this analysis is correct; these clouds are cirrus. There is a rather fibrous appearance to these clouds sometimes observed in cirrus but not present in cumulus.

In figure 12–6 the outline of the Great Lakes region is again superimposed on a TIROS I picture. The clouds in the region L are cirrus and again extend over the tip of Lake Superior. The clouds indicated by M are cumulus. In this particular case these clouds are very near the subpoint, which is marked by a small dot within a triangle; cumuliform structure can be seen, even though the clouds are reported as Low 1 cumulus by ground observers. In area N exactly the same type of clouds occur as at M, but the resolution of the picture at N is not so good because it is farther from the subpoint; the clouds look as if they may be a thin stratus deck. Actually, the clouds at N are cumulus; again, this analysis can be inferred from the fact that the clouds exist only over the land and end abruptly at the shore of the lake.

Figure 12–7 is a picture of the California coast taken by TIROS III. There is a thick layer of stratus off the coast. Farther out in the Pacific the clouds are mostly of the stratocumulus type, and a slight cyclonic whirl can be seen in the cloud mass. The cloud elements in the figure appear to be of the order of perhaps 10 to 30 miles in size which is typical of elements in stratocumulus over the ocean as seen from the satellite.

Figure 12–8 illustrates the variations in focus over the wide-angle picture area of TIROS I. In the picture on the left, the best focus is over Arkansas and the poorest focus is over Kentucky. In the picture in the center, the best focus is over Indiana and northern Kentucky, and in the picture on the right, the best focus is over Ohio and northern Kentucky.

Notice the clouds over Kentucky. These three pictures were taken only 1 minute apart.

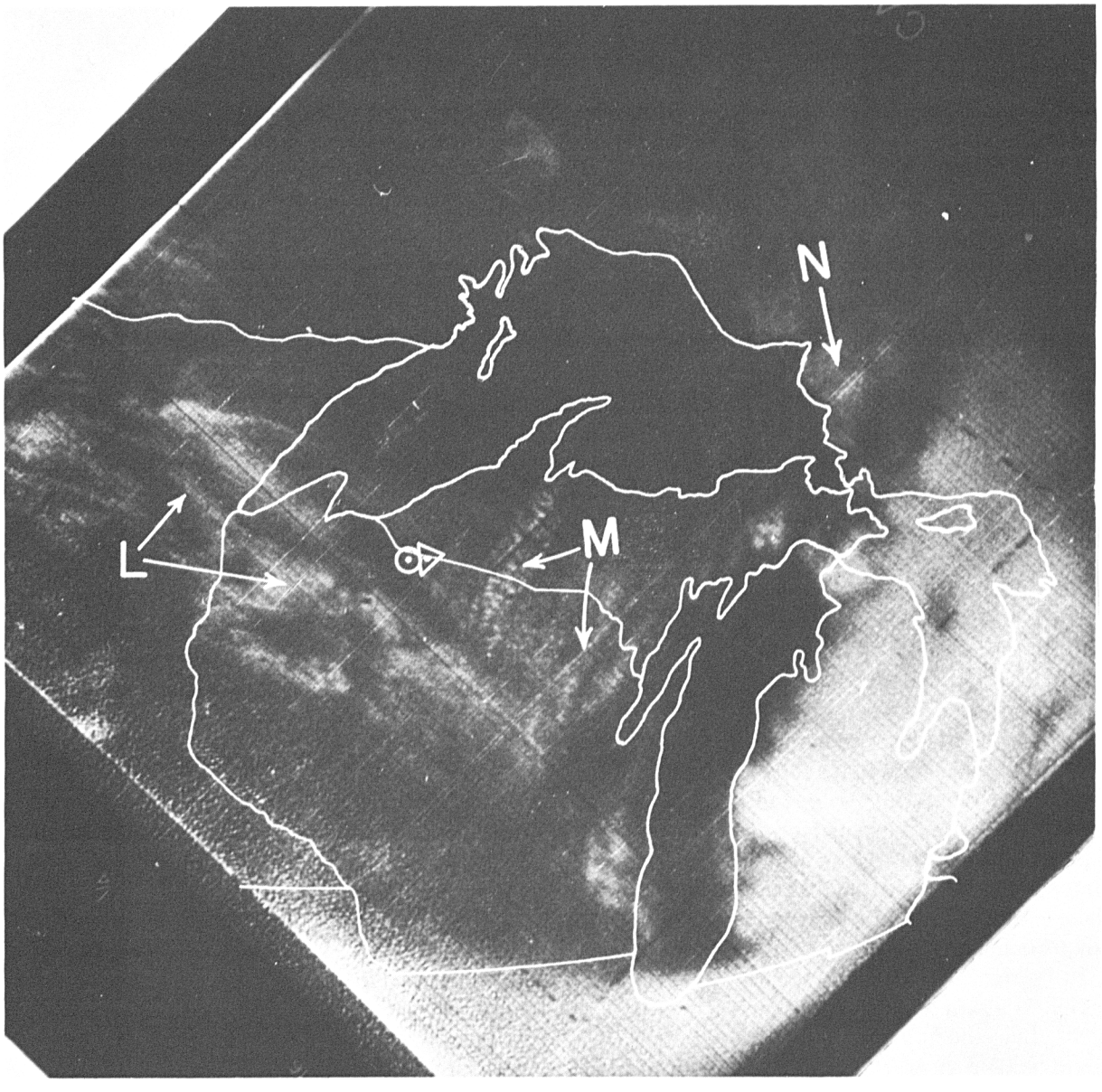


FIGURE 12–6. Cumulus and cirrus clouds near the Great Lakes, May 17, 1960.

There is a lot of detail in the center and right pictures where this region appears in the area of good focus. There is very little detail in the left picture where the same region is in the area of poorer focus. This is a characteristic of TIROS I pictures only; the pictures from TIROS III seemed to have a more uniform focus over the entire field of view. In the central picture, the cloud mass over southern Tennessee is a region of small fair-weather cumulus and it looks like a thin stratus deck. The elements are not resolved at all. Over Kentucky the elements are larger, mostly Low 2 type, and can be seen clearly.

Figure 12–9 shows a comparison of the picture quality from TIROS I, II, and III. The photograph from TIROS I is on the left, from TIROS II in the center, and from TIROS III on the right. The picture from TIROS II is not so good as those from TIROS I and III. The picture from TIROS III shows details more clearly than does the picture from TIROS I, particularly the horizon in the upper left portion of the pictures which is a little more sharply defined in the TIROS III picture than it is in the TIROS I picture. These early pictures from TIROS III were of excellent quality, and it is hoped that future TIROS satellites will have pictures as good in quality as these.

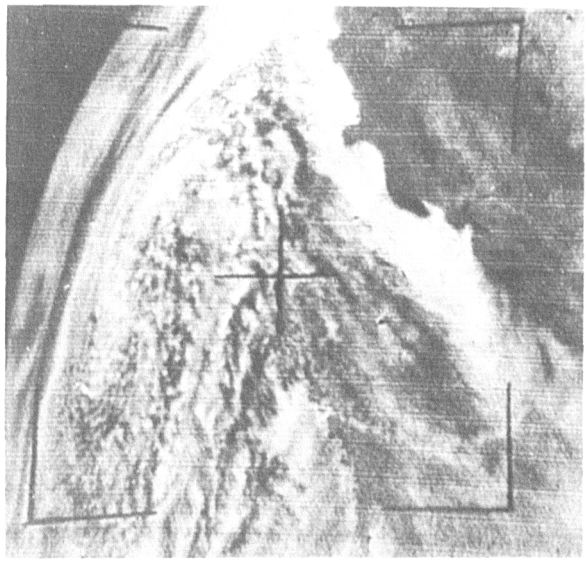


FIGURE 12–7. Stratus and stratocumulus clouds off the California coast, July 14, 1961.

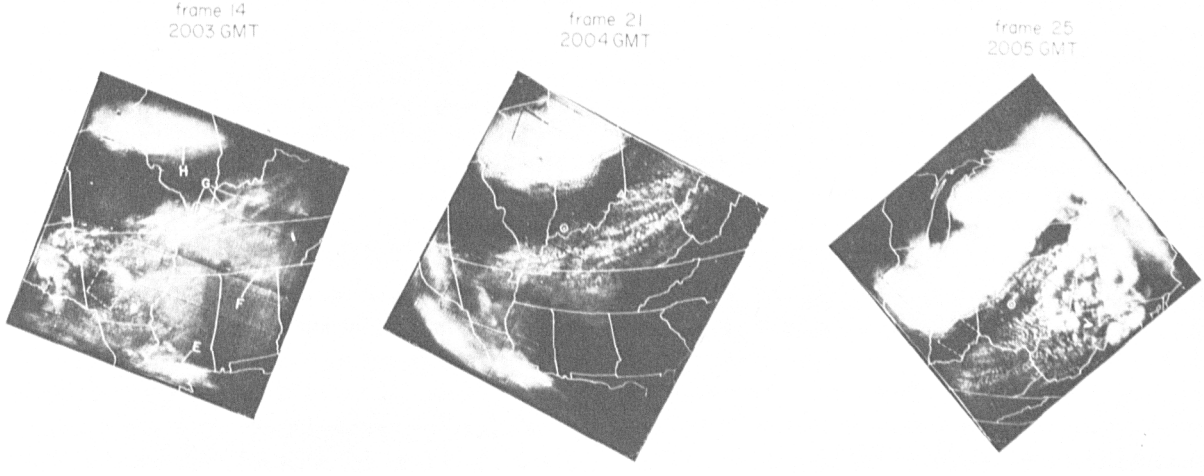
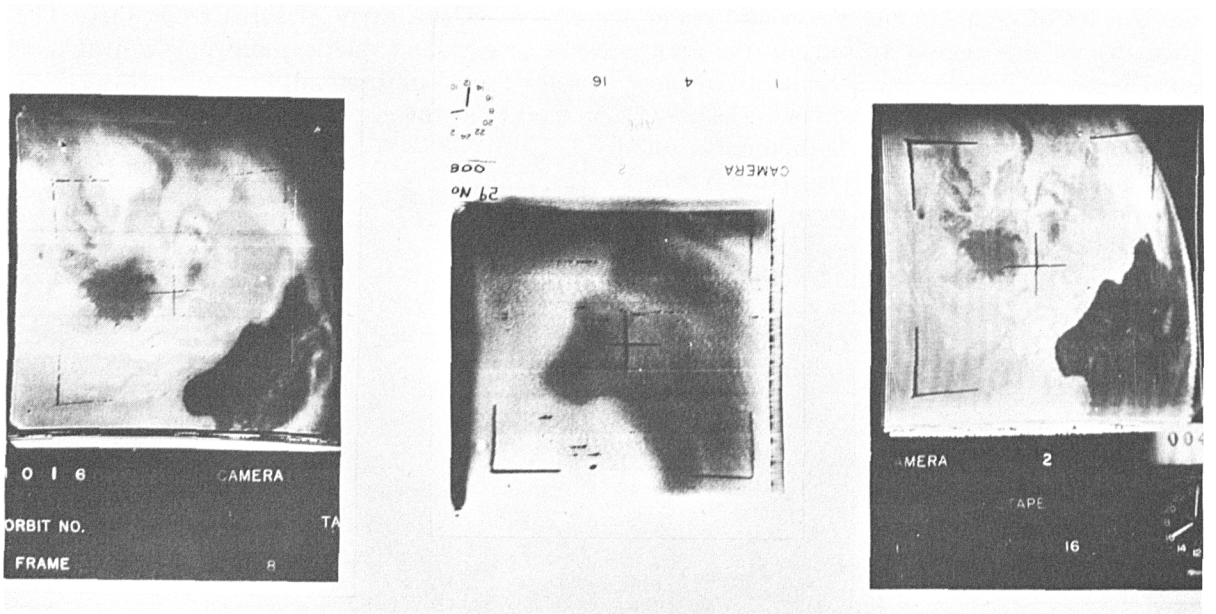


FIGURE 12–8. Comparison of three successive pictures from TIROS I showing the variation in focus over the picture area. Pass 673, May 17, 1960.



TIROS I	TIROS II	TIROS III
Pass 016, frame 8 Apr. 2, 1960	Pass 088, frame 21 Nov. 29, 1960	Pass 046, frame 17 July 15, 1961

FIGURE 12–9. Comparison of picture quality from TIROS I, II, and III. Area shown is Libyan coast, North Africa.

Question Period

BRUINENBERG, Netherlands Antilles: In the picture of Florida, were the thunderstorms, especially the one between Miami and Key West, indeed as large as the picture indicates, that is, 50 or 60 miles in diameter? Is it the anvil which is so bright, or is it the main body of the thunderstorm? There were much smaller clouds in the lower left-hand corner of the picture and farther away from the subpoint. Are these cirrostratus?

ERICKSON: I cannot comment specifically on this picture. But I would think, judging from others of the same type, that the cirrus spreading out from the storm does create an enlarged impression of the image and that the cloud towers are not really so large as they appear. There is another factor in that the cumulonimbus cells often tend to cluster together and two or three or more of these may merge. In well-developed thunderstorms this often seems to be the case, and perhaps it was the case in this picture.

RUDDER, Trinidad: In this paper it was stated that the thin cirrus is not photographed by the TV cameras in the satellite. Is it known whether this cloud is completely transparent, or does it affect the clarity or definition of the picture?

ERICKSON: There have been areas in which thin cirrus was definitely reported from ground stations and from aircraft and yet it could not be detected in the satellite pictures. I cannot comment further on this.

13. TROPICAL CLOUDINESS, SEVERE STORMS, AND CONVECTIVE CELLS

By L. F. HUBERT, *Chief, Synoptic Meteorology Section, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

The utility of the satellite observations has already been pointed out in preceding papers. In this paper the areas of interest will be the tropics and severe storms at midlatitudes.

The television observations of the meteorological satellite are particularly useful for synoptic analysis in the tropics, an area of sparse data. In the tropics the number of reporting stations is restricted mainly because of geographic factors. One of the many synoptic systems not yet completely understood because of the lack of sufficient data is the phenomenon called a shear line or convergence line. This system occurs in the tropics when the polar front advances from the higher latitudes into the subtropics and finally all the way into the tropics. When the polar front loses its airmass discontinuity characteristic, there still remains a shear line, so called because it actually is the locus of a line of cyclonic shear in the horizontal wind field. The significant part is not that there is some abstract quantity (a derivative of velocity) along this line, but the fact that there really is weather: cloud buildups, showers, and continuous cloud cover which would make a difference in many types of air operations or terminal conditions at airfields.

This shear line, or convergence band, is difficult to describe because of the fact that as it pushes farther and farther south it becomes more and more like a stationary front and finally lies motionless, perhaps coming to rest between the few observing stations scattered over the tropical oceans. The result can be that it may remain undetected for rather long periods by any conventional island network, until an aircraft or ship crossing the shear line encounters a good deal of weather.

A study of a convergence system that existed in the south Pacific Ocean on May 11 and 12, 1960, and was observed by TIROS I gives an illustration of the type of observations and the basic data for research that the satellite provides. Figure 13–1 is a map of the area and a synoptic analysis. The tip of Australia is on the lower left side of the map. By tropical standards this chart shows a very good network of surface observations, most of which are island stations. Unfortunately, many of these stations are on quite rugged terrain, so that the surface wind is sometimes influenced by the local terrain. Where there were two conflicting observations the type of station exposure and the terrain were taken into account and a reasonable meteorological choice was made between them. Figure 13–1 is the best estimate of the surface flow pattern (a layer from about the surface to a few thousand feet above).

The general easterlies in the tropics and anticyclone patterns in the subtropics are shown. There is good documentation of a small anticyclonic eddy embedded in this general anticyclone, with a second anticyclone to the west. The covergence of the trade winds and the winds from the south in both of these anticyclones results in a line of directional convergence along the heavy black line on the chart. This, in streamline analysis terms, is called a convergence asymptote, the flow approaching a central line asymptotically. From the surface observations alone a nephanalysis was made and it was found that there were indeed a few more middle clouds in the area of the convergence asymptote. In the tropics this would be an indication of some type of disturbance or a convergence. Whenever there is a disturbance in the tropics, there almost always

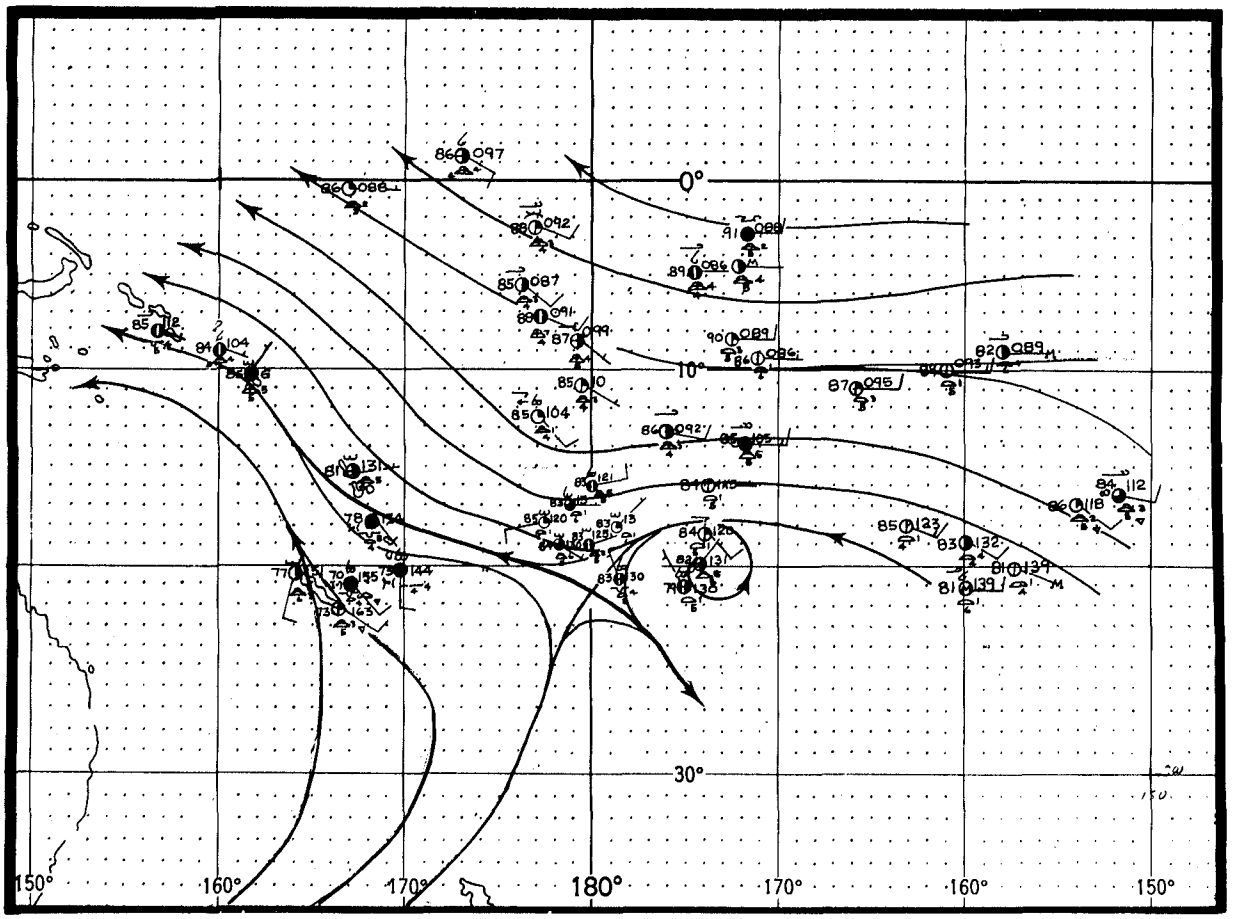


FIGURE 13–1. Surface streamline analysis for 0000 GMT, May 11, 1960.

is an attendant overnormal amount of middle cloudiness. This middle cloudiness is often the only clue to that disturbance. From the analysis of the surface map in this case it was determined that there was perhaps some disturbance. A more specific analysis than that could not be obtained.

Figure 13–2 shows an analysis 24 hours later in which the anticyclonic cell is still evident, as is the main convergence band.

Figure 13–3 is a composite of pictures made in two TIROS passes over this area at about 0000 GMT, on May 11, 1960. The picture mosaics gave the coverage in the irregular area outlined on this composite. The two mosaics were made from photographs taken only about 100 minutes, or one pass, apart. Therefore, any of the large-scale systems, which could be expected to last for many hours, should be visible on both sets of pictures. It can be seen that the major band of clouds appears on both sets of composite pictures. Close to the equator there is very little cloudiness. The main cloudiness is the large convergence band of the subtropics. The pictures shown in figure 13–4 were obtained 24 hours later and show the persistent convergence band. Figure 13–5 is a schematic representation of this photography. In it the foreshortening in the satellite pictures has been removed and the cloud coverage is presented on a Mercator map. The white and gray areas represent clouds. The heavy dark line through the white area is the convergence asymptote where most of the cloudiness and weather would be expected. The main band of clouds is about 3,000 miles in extent from near the Solomon Islands south into the south Pacific. It varies in width from 200 miles to approximately 500 to 600 miles or more.

Figure 13–6 shows the nephanalysis 24 hours later. The convergence band is in about the same position. The picture is evidence that the band seen in figure 13–5 persisted for 24 hours.

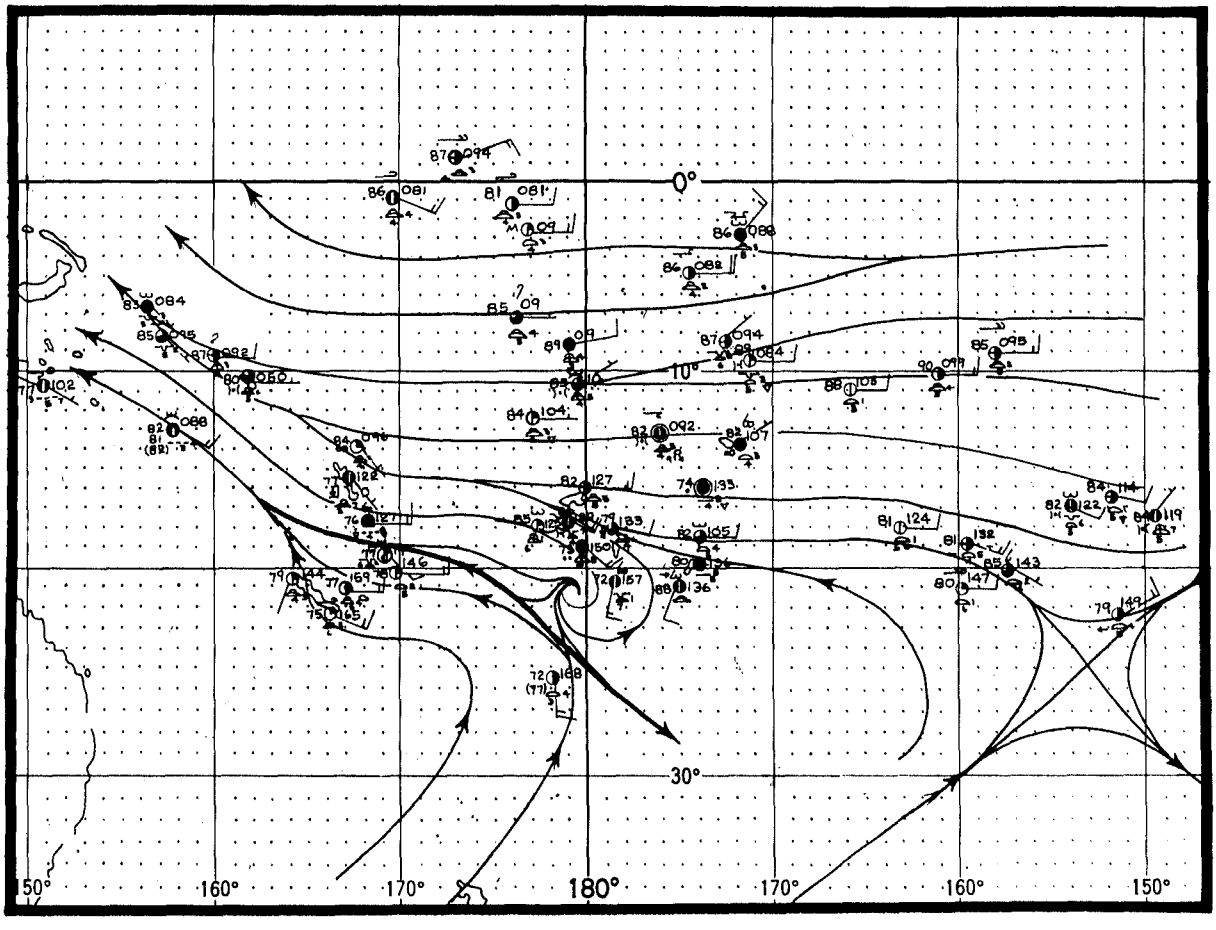


FIGURE 13–2. Surface streamline analysis for 0000 GMT, May 12, 1960.

In addition to the convergence band, the observations were studied in detail. The observations on May 12 showed more cloudiness in the tropics than those of May 11. That the analysis shows no clouds north of the equator does not indicate lack of cloudiness; there were no pictures north of that latitude. Where there was picture coverage, it can be seen that there was no well-organized intertropical convergence zone as would normally be expected in May. This demonstrates that even negative information can be very useful to the tropical analyst who attempts to obtain all possible information from conventional data. The analyst will examine wind reports for minor changes. If a wind in the tradewind belt changes just 20° or 30° from the southeast in the Southern Hemisphere or from the northeast in the Northern Hemisphere it may be symptomatic of a fairly severe disturbance some distance from the station.

It happened that in analyzing this series the standard meterological observations were analyzed in detail without using the picture data. One station suddenly reported a strong south wind. To a tropical analyst, this is an indication that some type of disturbance, such as a trough line, may be developing. Hours were spent searching the reports farther downstream 6 hours, 12 hours, 24 hours, and 36 hours later in an attempt to locate that wave. It also would take an operational analyst hours to search reports in an attempt to explain such a wind shift. It so happened that this wind shift could not be explained. Perhaps there was an error in the observation. Nothing was found downstream. It probably was either a local effect or something that had no synoptic significance.

If an analyst had these pictures available, a glance at them would perhaps have solved the question immediately, another instance of the

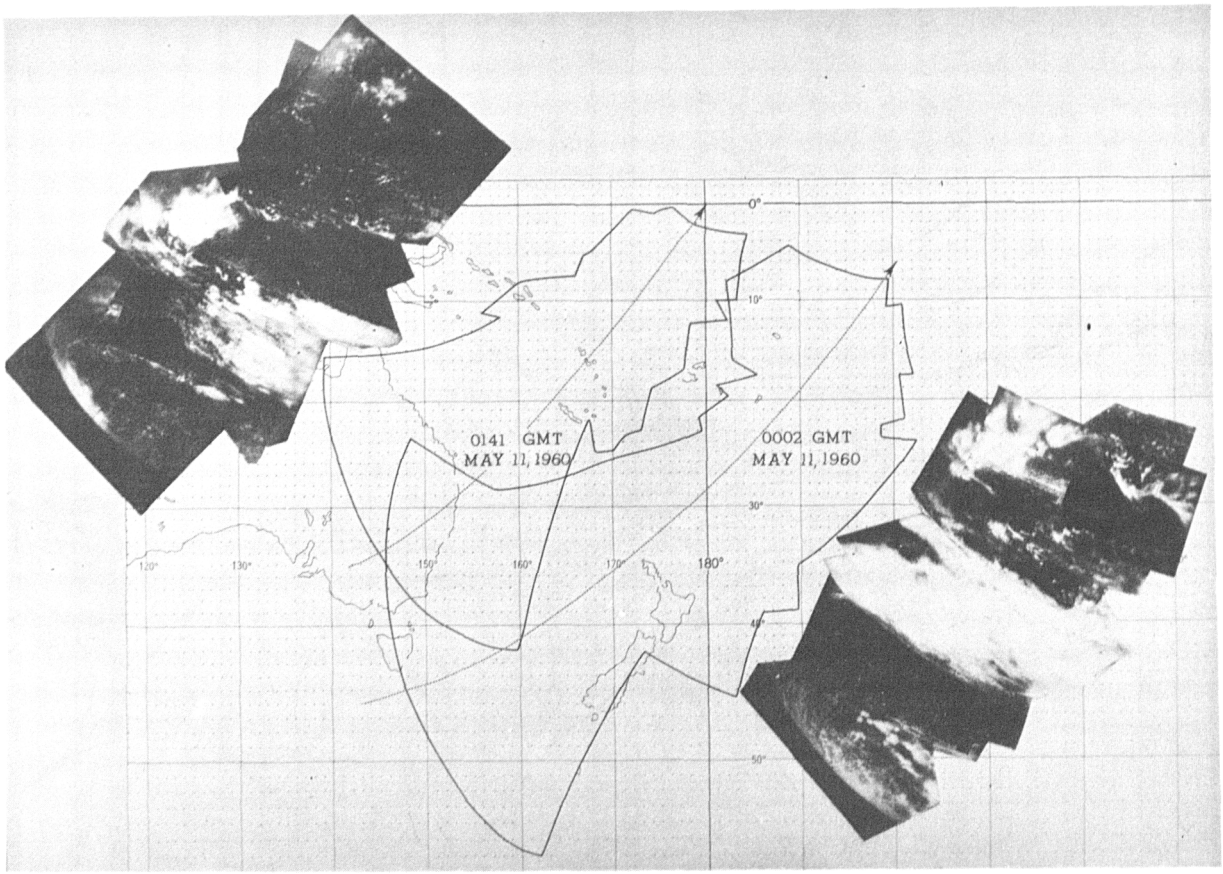


FIGURE 13–3. *Composite picture taken near 0000 GMT, May 11, 1960.* Dotted lines show satellite track; irregular outline is boundary of pictured area.

utility of these observations in operational analysis. In research where every particle of information is extracted from the data, pictures represent a good deal of additional data; thus, work can be shortened and more confidence placed in the results.

Figures 13–3 and 13–4 showed frames put together as a mosaic. Figure 13–7 shows two individual frames, which are more useful for doing analysis. On these frames are latitude-longitude lines. By means of a computer, or other means discussed in the Workshop papers, it is possible to construct a grid of latitude and longtitude lines which can be superimposed on any individual frame or sequence of frames. Gridded pictures such as these are the basic analysis tool; although the mosaics give an idea of the appearance of the whole area, the details of individual pictures must be examined in order to conduct research. Note that in this figure it is possible to observe the hole in the cloud cover, centered at 24° south, 172° east, which corresponds to the shallow anticyclonic cell pointed out in the discussion of figure 13–1.

During the useful lifetime of TIROS I, a large number of cyclonic storms in various stages of development were photographed, as was one typhoon in the southwest Pacific. On the basis of the experience with TIROS I, it was predicted that it would be possible to see, quite early in their development, all tropical storms in the picture-taking swaths of succeeding TIROS satellites. Figure 13–8 shows a tropical storm in the eastern Pacific which has not quite reached the hurricane stage. It is generally accepted that most tropical disturbances, such as hurricanes, form on some preexisting disturbance, and that these preexisting disturbances generally have a good deal of middle cloudiness. Theoretically, the middle cloudiness should mask lower clouds so that it would not be possible to see the patterns starting to organize in the lower levels. In spite of these theories it was believed that most storms would be seen in

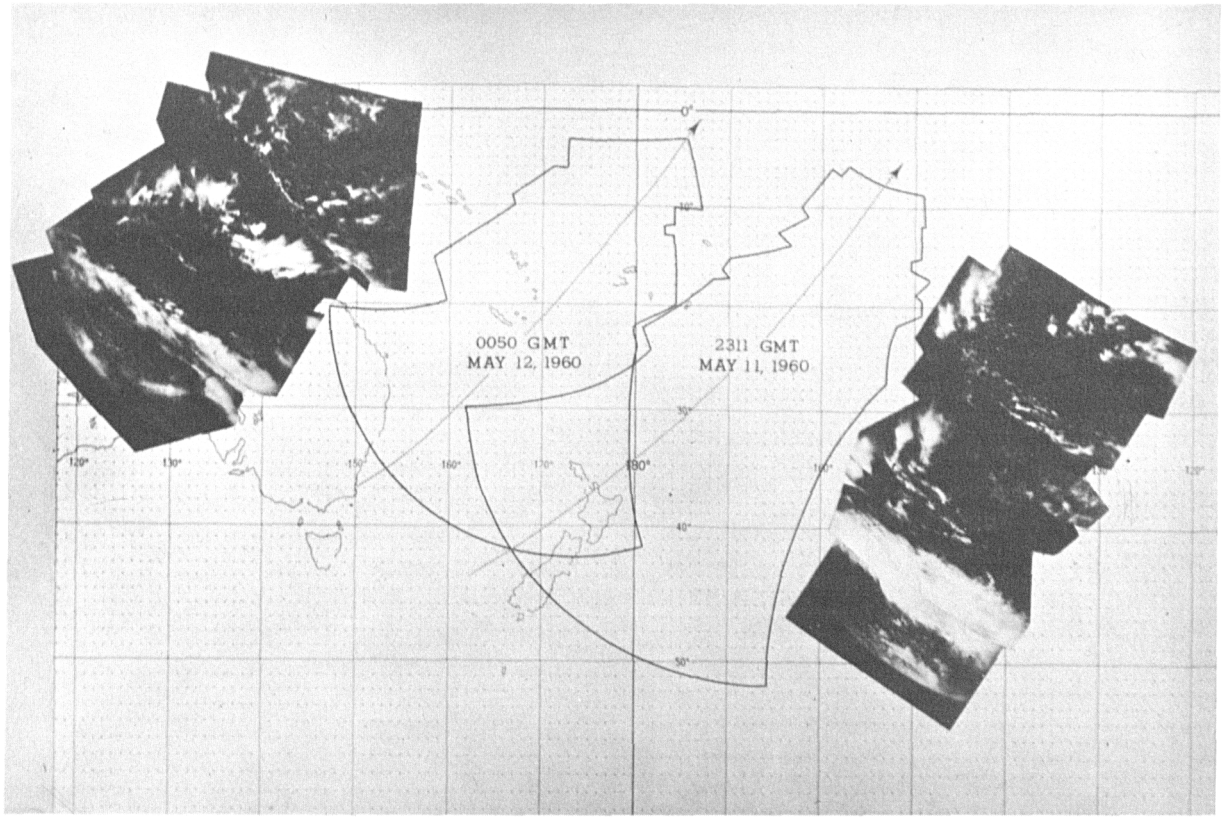


FIGURE 13–4. Composite picture taken near 0000 GMT, May 12, 1960. Dotted lines show satellite track; irregular outline is boundary of pictured area.

the formative stage. So far the forecast appears to be fairly accurate; as far as is known, every vortex located has been seen early in its development. Spiral patterns have been found that look like those in figure 13–8. Apparently these patterns develop within half a day.

Every spiral pattern observed is not a hurricane. Off southwest California, there are many of these vortices, many of which never do become hurricanes or even very severe tropical storms. Therefore, care must be taken upon observing a vortex in an area of a hurricane development not to identify it prematurely as a hurricane. However, such a vortex should be watched because in 12 to 24 hours it could turn into a hurricane.

It may be speculated that the reason these patterns are seen so quickly is that, as soon as the wave disturbance initiating the storm becomes organized into a vortex, the middle cloudiness which would obscure it is very quickly organized into the system of the vortex itself. The dynamics of this type of circulation are such that vertical motions organize rapidly around the vorticity maximum, which would tend to organize all associated cloudiness into the overall pattern of the storm. It appears that these vortices will be identified in the satellite pictures very quickly from now on. Certainly every little eddy in the surface layers will not be visible; but as soon as these eddies get to the stage where they bear watching, it is probable that a very large percentage will be detectable so long as the pictures are good. A vortex in its formative stage would not be identifiable at all near the horizon of a picture. Such a vortex must be near the subpoint where the whole cloud field can be viewed. As the TIROS series ends and the Nimbus series begins, a much greater coverage will be attained, and it is probable that almost all the hurricanes of the world will be seen.

Figure 13–9 shows a composite picture of hurricanes Debbie and Esther, together with a nephanalysis of the composite. In the southern part of the nephanalysis the vortex symbol represents hurricane Esther. On the mosaic the two storms look very close together because

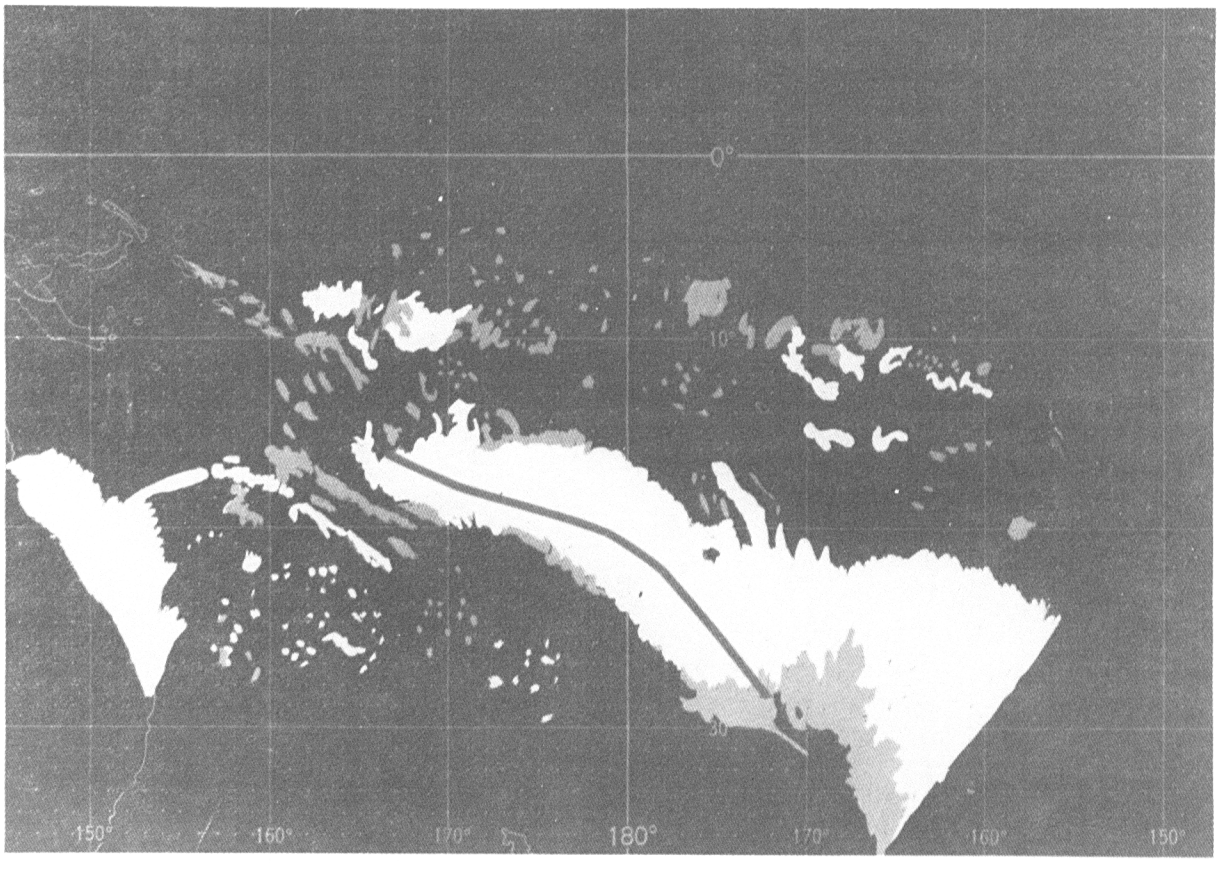


FIGURE 13–5. Schematic representation of clouds pictured in figure 13–3. Heavy dark line in cloud areas is convergence asymptote transferred from figure 13–1; May 11, 1960.

the area of each picture is so large. However, hurricane Esther is at 15° north whereas hurricane Debbie is at 31° north; they are thus separated by at least 15° of latitude, plus a certain amount of longitude.

Familiar features may be seen by noting details in this mosiac. The cloud patterns form spiral arms that seem to be penetrating hurricane Debbie. The same spirals can be seen in the picture of hurricane Esther. In a relatively small area these separate circulations approach each other closely; the spiral arms of the two storms appear to come within a hundred miles of each other. Hurricane Liza (fig. 13–8) and its counterpart, hurricane Madeleine also showed the same characteristic; the cloud patterns seemed to be very close together. It is not known whether the cloud patterns of the two storms shown in figure 13–9 represent clouds at the same level. One pattern may be high and one pattern may be low. This suggests that there is a series of these vortices along a line, like the Von Kármén vortices, which were described a generation ago.

Similar patterns have been observed with a single hurricane; in these cases there seemed to be a primary vortex, the hurricane, linked to another minor circulation downstream, perhaps along the trough line. Many of the vortices which appeared in pictures had not been detected by conventional meteorological analyses. This, then, is an area for further investigation to answer questions such as, "Is there a train of vortices?" Every once in a while such a train of vortices will suddenly appear and sometimes intensifies as a circulation. What is the reason for intensification? The suggestions and studies so far indicate that it must have something to do with the upper troposphere. Perhaps these small vortices exist in the low atmosphere, move along only as small tropical storms until a change takes place aloft, and then suddenly they become large storms.

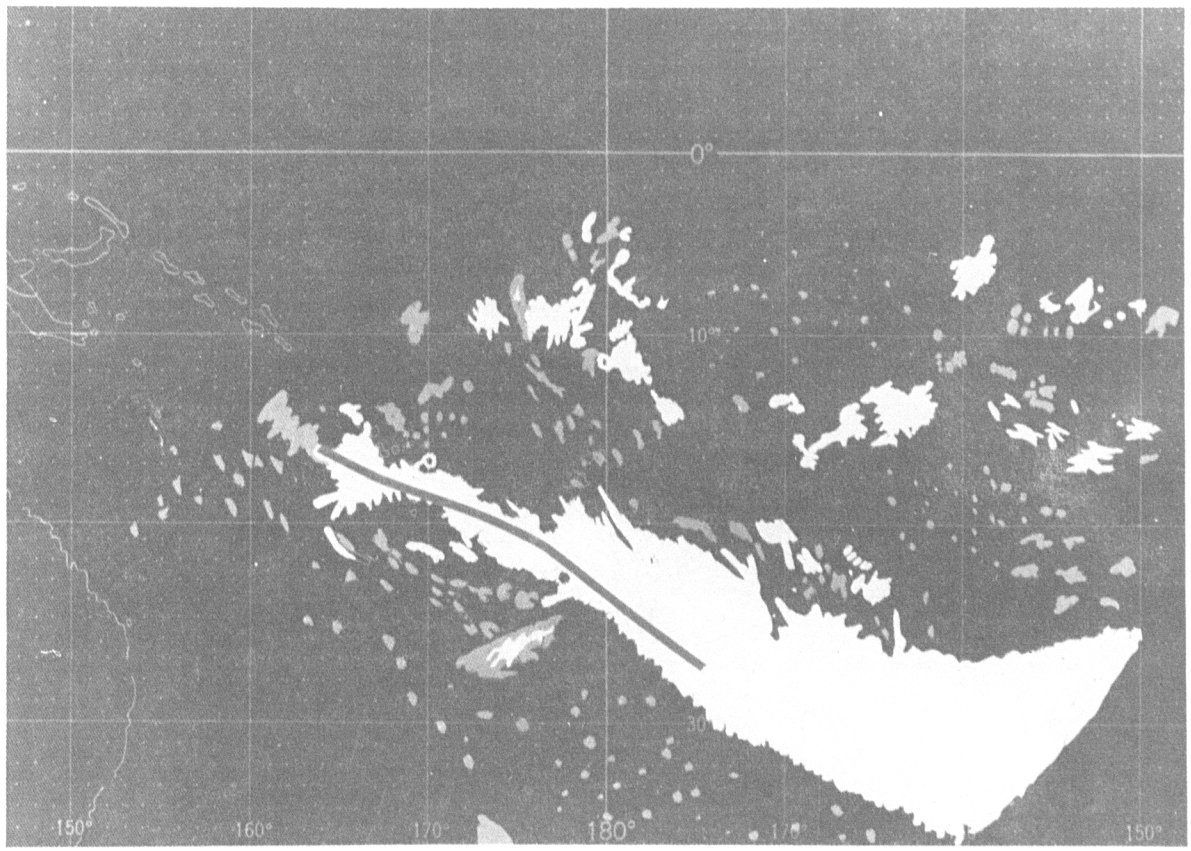


FIGURE 13–6. Schematic representation of clouds pictured in figure 13–4. Heavy dark line in cloud areas is convergence asymptote transferred from figure 13–2; May 12, 1960.

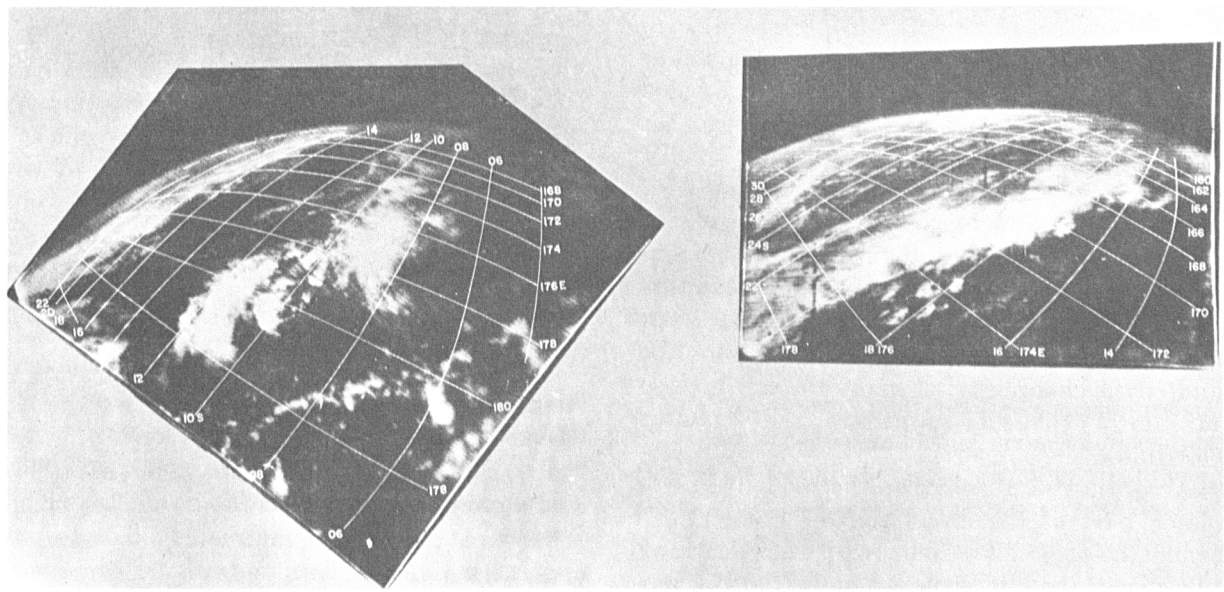


FIGURE 13–7. TIROS I frames taken near 0000 GMT, May 12, 1960, with superimposed location grids.

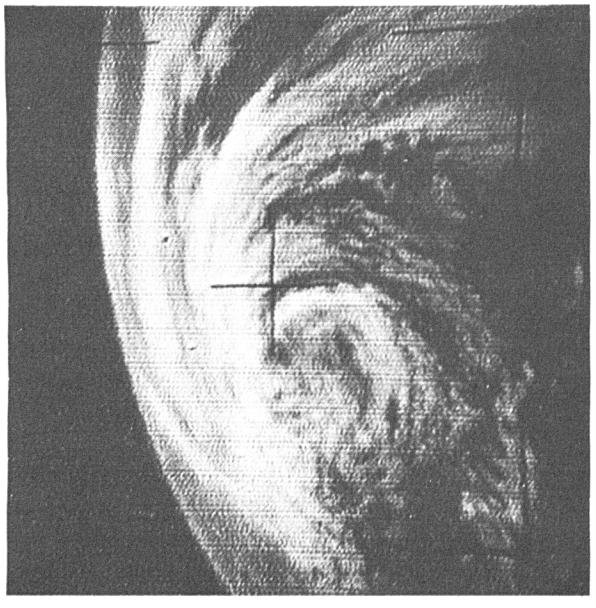


FIGURE 13–8. Tropical storm Liza. Center at 24.5° north, 136.5° west, July 23, 1961.

In pursuing this research, it will be possible, when infrared measurements, interpretable as cloud-top temperatures, are available to differentiate between the high and middle cloud systems, which are indicators of events in the upper troposphere. When this is possible then the incomplete picture of hurricanes now extant will be complete. A good deal of information can then be added to the knowledge of the kinematics and the dynamics of these storms.

Another item to be noted in preliminary investigations is that apparently the storms have a cloudless ring or a semicircle around them. This appears to be an area of subsidence that has evaporated the cloud to form an almost cloudless moat around the storm. This area is very sharp. What seems at first glance to be a curiosity may very well turn out to be a significant clue to the dynamics of the circulation of the storm. It is very interesting to note that not only does this moat evaporate the middle and cirrus cloudiness but many times it goes so far down that it suppresses the cumulus cloudiness.

According to theoretical thermodynamics a major part of the circulation of a hurricane cannot be a closed system, with subsidence on the edge of the hurricane, an indraft at the surface, and an updraft at the core. However, there well may be an important branch of the hurricane circulation that is closed. When this has been thoroughly documented and explained, it may reveal a phenomenon not possible to observe until the existence of the satellites.

Figure 13–10 shows a severe convective storm area over the United States (ref. 1). The reason this particular figure was chosen is because it shows the bright cloud on the left, which is one of the charateristic large patterns mentioned in paper 12. This "square" overcast area near Oklahoma City when rectified (see fig. 13–11) and put on a map looks more like a rhombus than a square. The very dense cloudiness at the top of the picture occurs behind the front. In the area of bright cloud in figure 13–10, to the right of the "square" cloud transverse rolls or wave clouds can be seen. The prevailing wind was from the southwest and these wave clouds lay across the wind, suggesting a gravity oscillation.

In the area of very large cloudiness tornadoes were reported within a few hours after the picture was taken. Aircraft flew some probes and reported a mushy type of hail near the cloud tops which extended to and above the tropopause which was at 55,000 feet. Along a line to the west of the "square" cloud (fig. 13–10) a cloudless dark area can be seen bounding a cloudy (light) area. This is known among analysts who work in this geographic area, as the dewpoint front, because in this particular locality in the United States there are very often masses of quite dry air and very moist air separated by a very sharp gradient. The NNE–SSW line between San Angelo and Fort Worth (in fig. 13–11) represents that discontinuity. There are almost no clouds NE of the "square" cloud, suppressed cloudiness to the SE of the "square" cloud, and cumulus and cumulus congestus to the east of the "square" cloud. Should these dewpoint fronts be readily identifiable in satellite pictures, another analysis use of satellite data will have been gained.

Some of the popular newspaper and magazine articles indicated that TIROS is now a tornado-forecasting tool and that a "square" cloud indicates a tornado. This is not quite true. The significance is not the fact that the cloud is "square," but that it is isolated. The bright area, a large group of clouds about a hundred miles on a side, stands out because it is completely isolated from the other clouds. It has been suggested by researchers investigating tor-

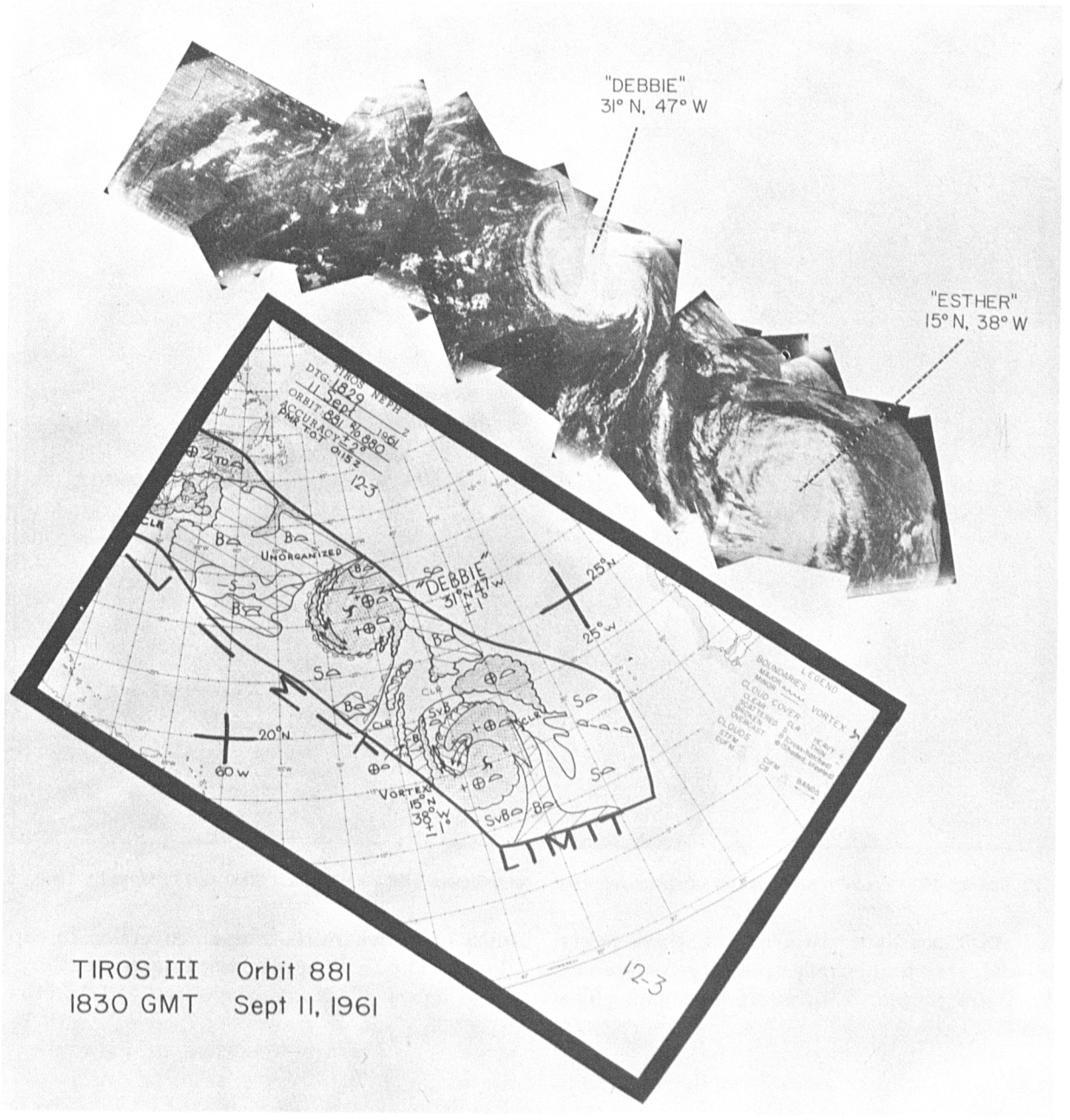


FIGURE 13–9. Cloud mosaic of hurricanes Debbie and Esther and operational nephanalysis made from these pictures. 1830 GMT, September 11, 1961.

nadoes that at least part of a tornado area is bounded by an almost cloudless area. The development is as follows. First occur the small fair-weather cumuli. As these develop into cumulus congestus they cluster together and a few grow large at the expense of adjacent clouds which are suppressed, leaving a large cloud mass surrounded by a relatively cloud-free area.

TIROS, for the first time, documented the fact that this process apparently goes even further, that the cumulus congestus masses collect into very large isolated groups which generate very severe storms. There must be a good deal of subsidence to satisfy the equation of continuity: the fast indraft into the storm, the vertical motions, and the subsidence around the edge. There are many other cases of this particular type, some of which were presented in paper

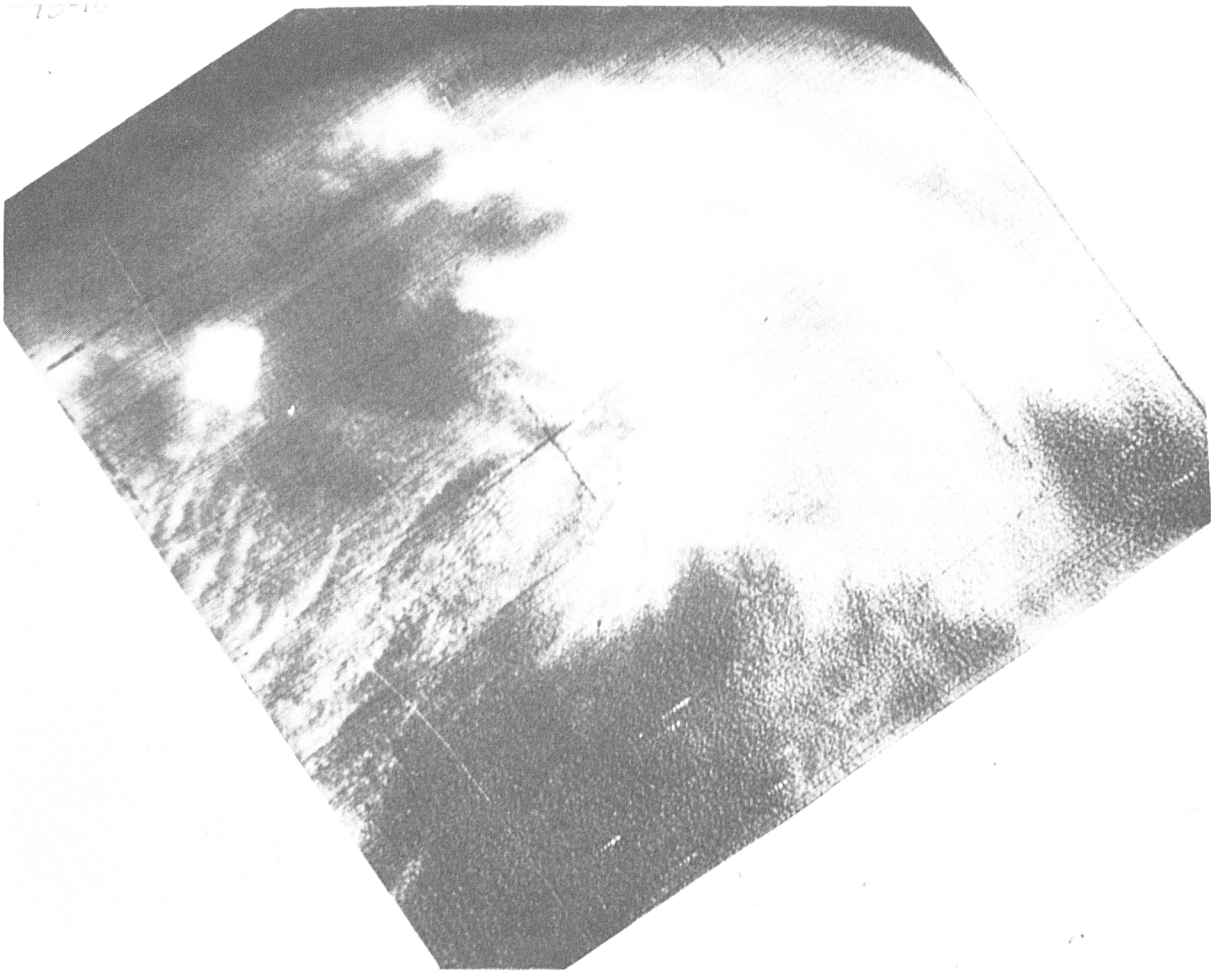


FIGURE 13–10. TIROS I photograph of "square" cloud over Texas and Oklahoma. 2000 GMT, May 19, 1960.

12. As TIROS data are acquired, these fairly isolated, very highly reflective, large patches of cloud are indeed features to be noted. The question has been asked: "Was this bright patch a cirrus shield or the cumulonimbus towers?" The high middle clouds and even the low clouds were probably joined, so the patch was a conglomerate. The fact that it is so isolated indicates that it is a severe convective storm.

Figure 13–12 shows a completely different type of cloudiness having the mottled appearance of a broken deck. The significance of this cloud pattern is that although it may occur where there are showers, it is, in general, indicative of very definitely limited convection. As mentioned in paper 11, the opinions concerning this type of cloudiness are not unanimous even in the U.S. Weather Bureau. However, the majority opinion is that these clouds must occur where there is an inversion to cap them. This will be discussed subsequently.

In figure 13–12(a) convective cells in the form of rings or crescent-shaped cells can be seen. The average diameters of these rings are of the order of 30 to 50 miles. A few individual cells with diameters of 90 miles have been seen. In many cases the diameters were only 10 miles. In some cases rings can be distinguished. In other cases there are only cusps or semicircles; many times the clouds have a mottled appearance. When a mottled appearance is noted, rings are often found. The significance appears to be twofold. For operational use, the convective cells reveal a great deal about stability and processes in the atmosphere. Academically, for research, the cellular pattern appears to be very significant because now, for the first time, organization of

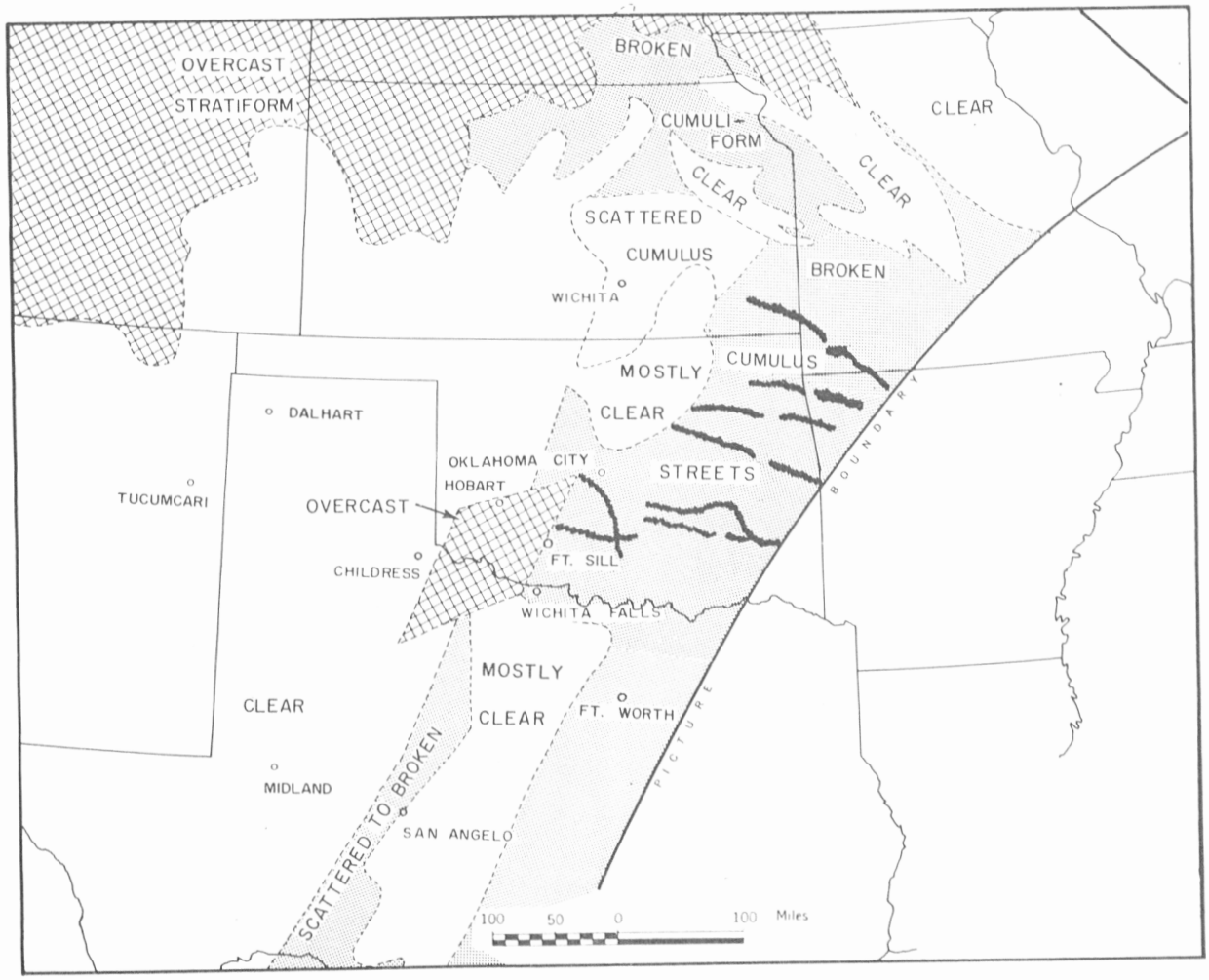


FIGURE 13–11. Schematic analysis of figure 13–10.

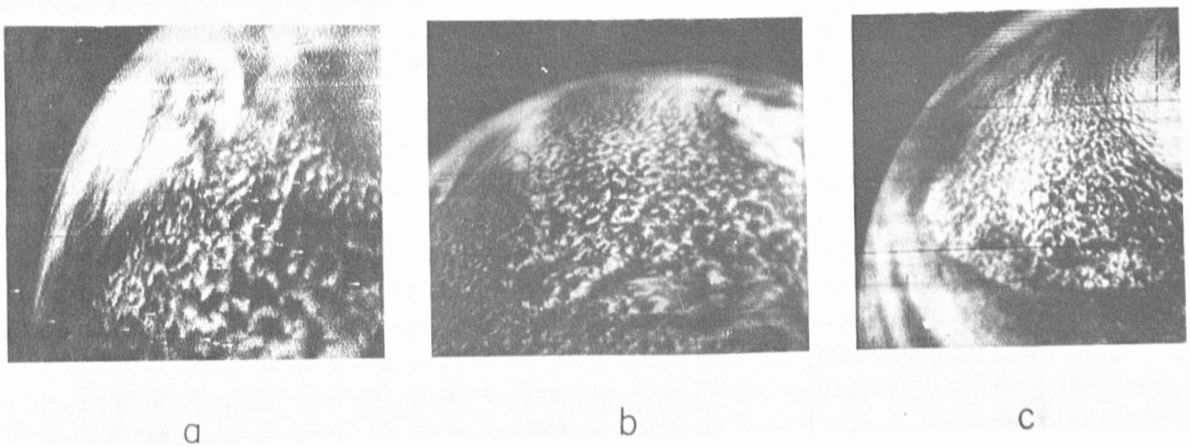


FIGURE 13–12. TIROS photographs of convective cells. (a) 650 nautical miles NE of Bermuda, 1612 GMT, April 4, 1960. (b) Central Pacific, 2341 GMT, April 1, 1960. (c) 750 nautical miles NE of Hawaii 2230 GMT, April 4, 1960.

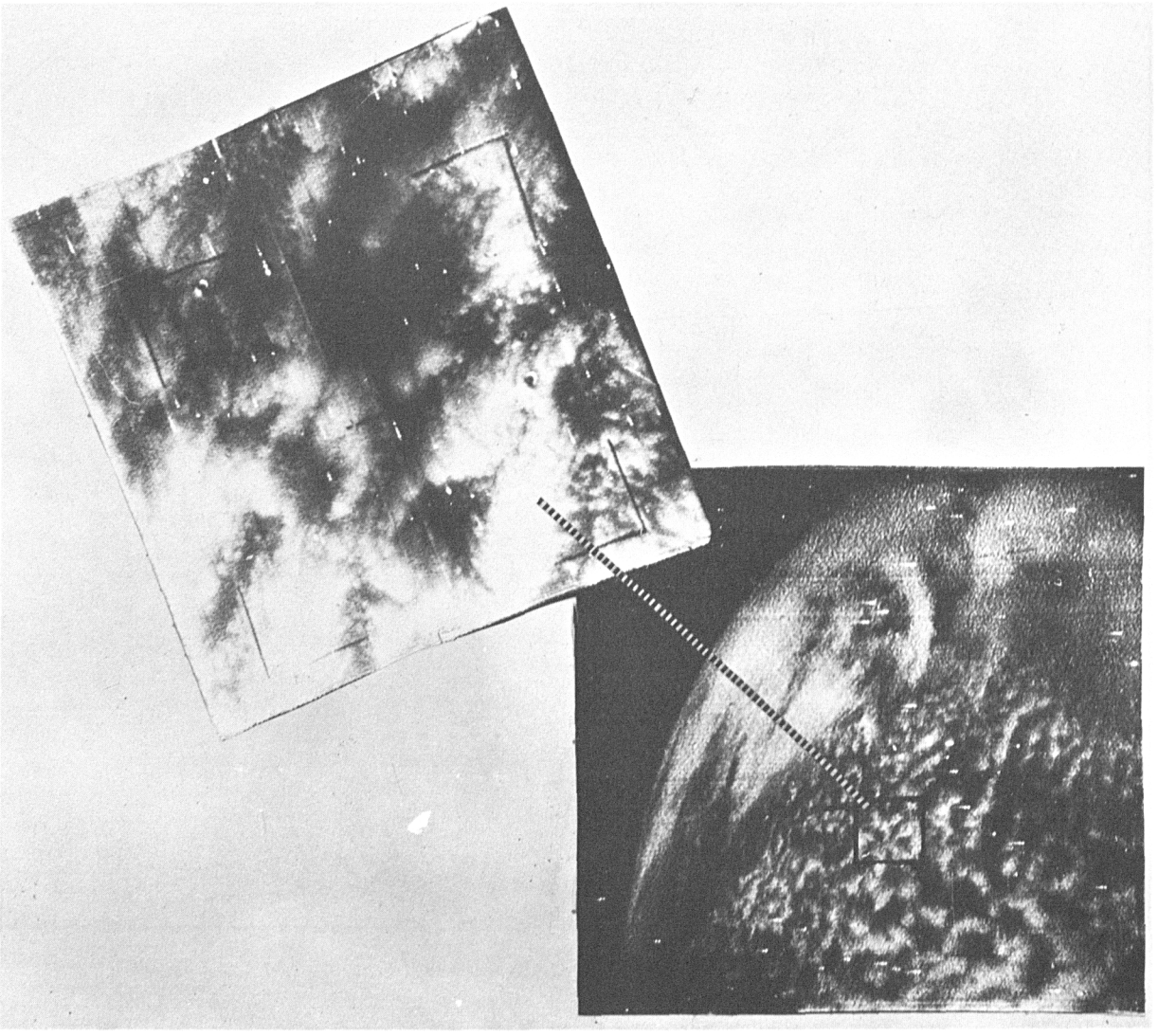


FIGURE 13–13. Enlargement of figure 13–12(a) and a narrow-angle view of convective cells.

a type that is similar to but not the same as that which has been produced in the laboratory is observed in the atmosphere. When a thin cloud layer in the atmosphere is heated from below, or cooled from above, convection cells should occur in the form of irregular polygonal patterns, as in the laboratory experiments.

There are significant differences between laboratory results and what was observed in the TIROS pictures. Part of the difference is probably due to the fact that each of these cells is not an individual convective cell such as those obtained in the laboratory. The observed cloud patterns are made up of a good many individual cumulus elements.

Figure 13–13 shows a narrow-angle picture of the area outlined in the accompanying wide-angle picture. What looks like a ring on the wide-angle picture is really quite a complicated pattern. Each "ring" is made up of many cumulus elements. Each one is using latent heat to get its bouyancy and create its own small circulation, as each individual cumulus cell must. However, this pattern is superimposed on the 30- to 50-mile cellular pattern which was first discovered in TIROS pictures and which could not be seen from the surface of the earth because of the large scale. The smaller scale patterns, those 10 miles in diameter, have been observed by aircraft. The knowledge of the large-scale pattern gained through TIROS has never been available to researchers before.

Disregard temporarily the very small scale detail of this pattern and note the scale of

convection of the 30- to 50-mile-diameter rings; observe the locations of these clouds. It has already been mentioned that many times these larger cells occur in cold air over the ocean as a cold front pushes southward. The warmer water surface drives the convection, and in the few cases documented by ship radiosonde, low-level inversions have been found at 5,000 to 6,000 feet. Convection cells are also found in anticyclones over the oceans. In anticyclones the downward vertical motion of the dynamic high forms a subsidence inversion. If conditions are favorable for driving this convection from below, such as cooling from the top of the cloud layer or warming from the surface, convection will occur in these anticyclones but will be confined below the subsidence inversion.

Figure 13–14 shows the synoptic surface chart at the time the picture in figure 13–13 was taken. The center of the picture is marked by the circled dot. This field was studied in reference 2. Very fortunately, aircraft had released dropsondes in this area; thus, the stability was measured. Figure 13–15 shows the character of the atmosphere in this particular synoptic pattern, together with the subsidence inversion. Provided such patterns have been docu-

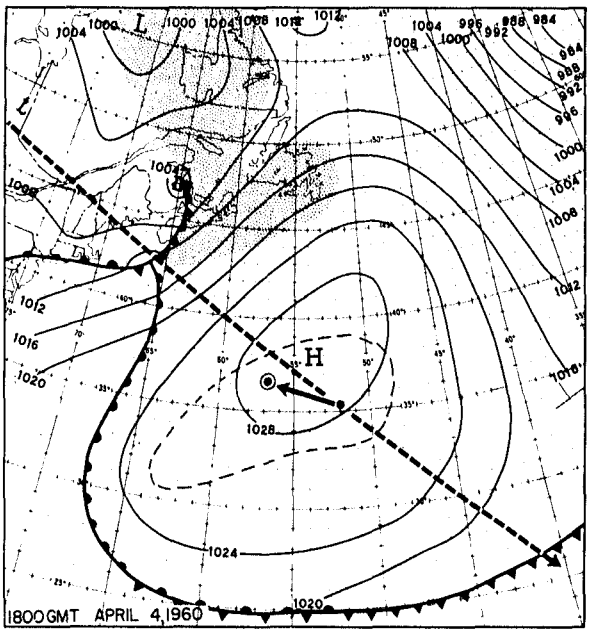


FIGURE 13–14. Surface analysis 1800 GMT, April 4, 1960, and center of picture, figure 13–12(a), indicated by circled dot.

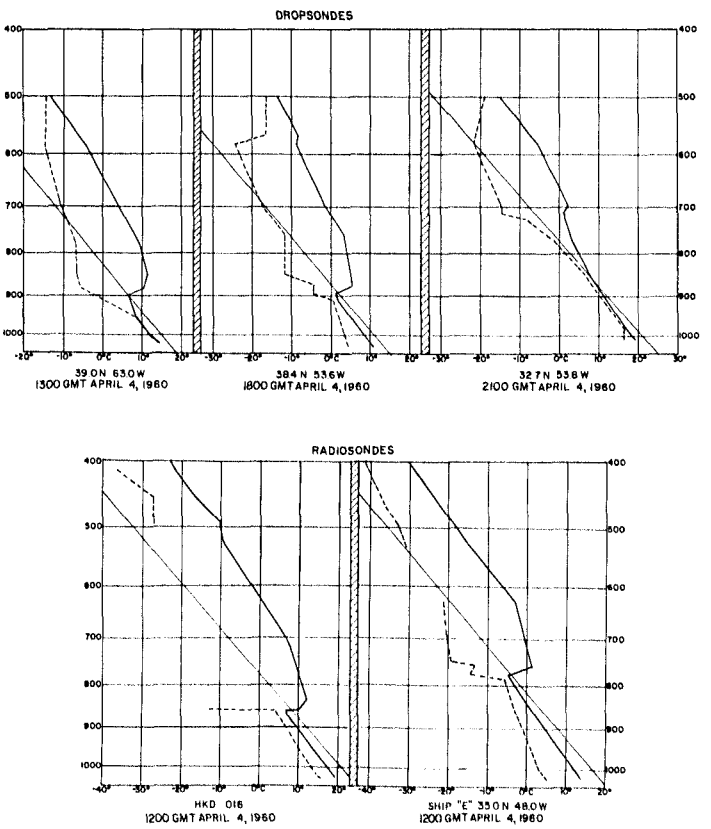


FIGURE 13–15. Radiosondes and dropsondes near time of map shown in figure 13–14.

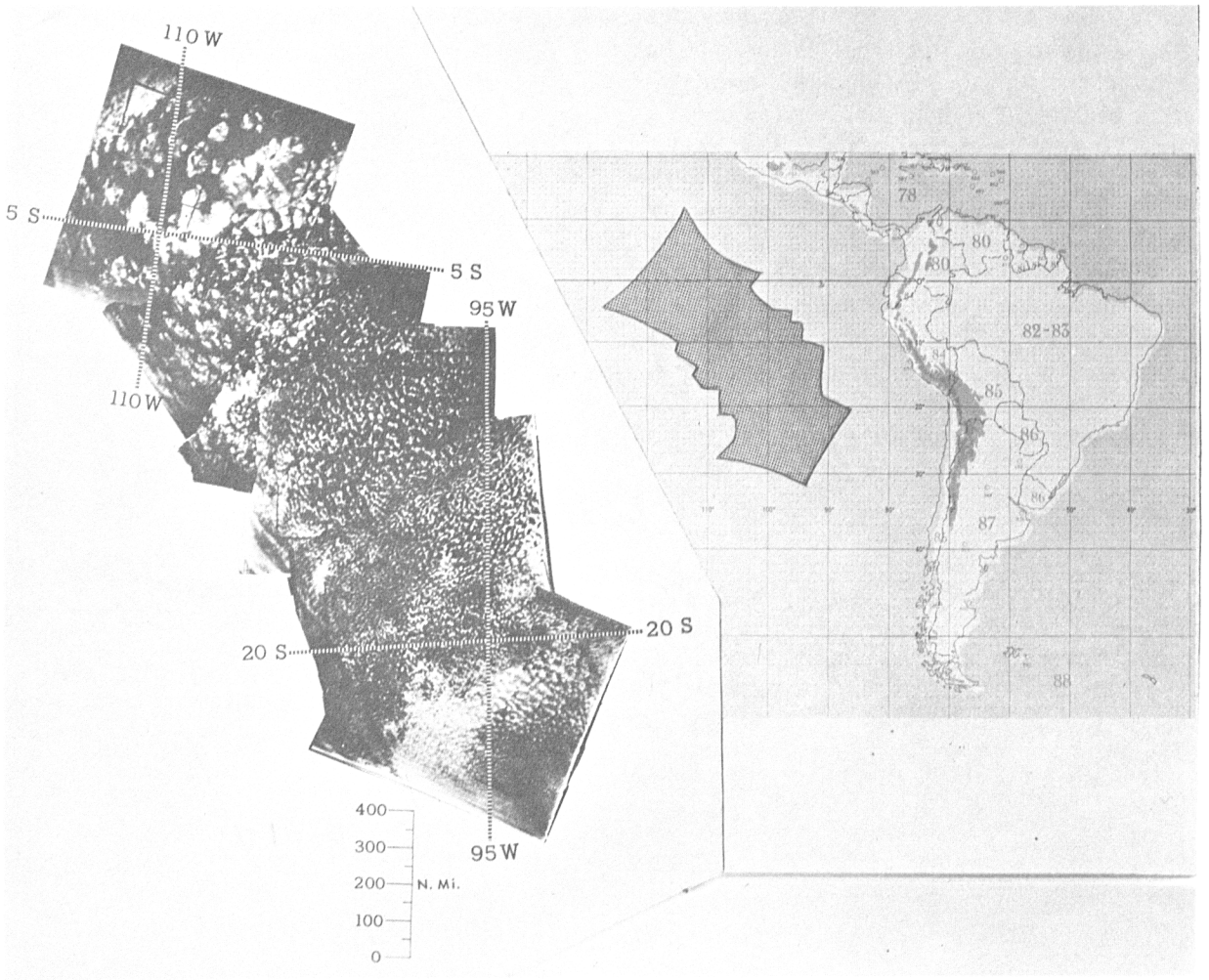


FIGURE 13–16. Convective cells pictured by TIROS III, 1840 GMT, July 22, 1961.

mented and associated with particular types of soundings, a satellite picture showing this kind of pattern will yield a good deal of information about the stability of the atmosphere in the layers where the convection is occurring. If infrared measurements indicate that the cloud tops are confined to 8,000 feet and below, then it will be known that a condition such as one shown in figure 13–14 exists and that there are no similar cells at a much higher level.

The pictures shown in figure 13–16 have no corroborating meteorological evidence. The shaded area, which is in the south Pacific just off South America, defines the region covered by the mosaic of pictures from TIROS III. This pattern is the same type of pattern as those shown in figures 13–12 and 13–13. Unfortunately, a certain amount of detail is lost in the reproduction of these photographs. The original pictures clearly show rings and semicircles in this area. This is the position of a south Pacific anticyclone. It is reasonable to assume that there is subsidence in this pattern which would put an upper limit on the convection. Certainly, subsidence must exist in the anticyclone but, as the equator is approached, the convection is such that the subsidence should be found at much higher levels; the clouds themselves should penetrate the inversion and finally destroy it. This picture is a good illustration of the change of character of these small mottled cells. At about 5° south, the pattern changes into the type which represents the large clustered clouds in several layers; possibly some cumulonimbus is present but in general, there is a very different type of cloudiness

here than farther south. A study of the detail indicates that the whiteness, or brightness, of these clouds is a little more marked toward the equator (fig. 13–16). It may be that the change of character of the cloudiness pattern represents the depth to which the convection is taking place and, therefore, what is seen in these pictures may be, speculatively, waves on the associated inversion surface.

A great deal of time has been spent emphasizing that convection is limited in depth by an inversion. It is not meant to be implied that every time convection is limited in this way, this type of cell will occur, nor is it meant that the inversion makes the cells. Rather, from the early indications, it can be speculated that there is a layer which does not have a great deal of directional or speed shear in the vertical. The winds do not increase or decrease greatly with height, nor do they change in direction with height in the convective layer. Thus, a layer is being forced into convection, very similar to the way in which it would be in the laboratory. Under those conditions it appears that these convective cells will occur. As soon as a great deal of shear is superimposed, the pattern breaks down into lines and streakiness. Thus, the inversion by itself is not the important factor.

Of apparent significance is the fact that this pattern indicates a convective layer which is not subjected to a great deal of shear. As such, there is no reason why this pattern cannot occur in the middle cloudiness as well as in the low cloudiness. However, it may be a more common condition of the low layers. This pattern is frequently seen behind cold fronts and in highs because the conditions leading to convective cells are frequently satisfied behind such fronts and in highs. There is certainly no reason to believe that they cannot occur elsewhere, and, eventually, they may be observed elsewhere. If they are not observed and the infrared data indicate high cloudiness, this implies that somehow the regime must be unstable and at the same time not subjected to a great deal of wind shear.

References

1. Whitney, Linwood F., Jr., and Fritz, Sigmund: *A Tornado-Producing Cloud Pattern Seen from Tiros I.* Bull. Am. Meteorological Soc., vol. 42, no. 9, Sept. 1961, pp. 603–614.
2. Krueger, Arthur F., and Fritz, Sigmund: *Cellular Cloud Patterns Revealed by Tiros I.* Tellus, vol. 13, no. 1, Feb. 1961, pp. 1–7.

Question Period

Patrick, Nigeria: I wonder whether you are coordinating the information from radar, the width-to-height ratio of thunderstorms. This definitely would give you an idea of the stability of the atmosphere. That might be much more helpful to you in formulating whatever new theory you want.

Hubert: Unfortunately, as I indicated, most of these very definite patterns have been observed over the oceans, and radar information is very difficult to obtain in those areas. I think that as we obtain more and more pictures, then certainly we will use radar and any other tools we can to study the stability of these patterns.

Mustafa, Sudan: The great similarity in both cloudiness and pattern of hurricanes Debbie and Esther and the alinement of the spiral bands where the storms are close together was very fascinating. I think on the meteorological scale they could be considered as being at almost the same point. This might suggest that possibly hurricanes do form in families. I wonder if some evidence has been found as to whether this is so.

Hubert: The indications so far are that they may indeed, but we have only started studying this. There are at least two series in Tiros III where there are pictures of the same storm and of the surrounding areas over several days. I think that as we study these we will be able to document this association. I think that your suggestion is correct, that there are families of vortices.

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14. PICTURE GRIDDING

By C. L. Bristor, *Chief, Computation Section, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

The purpose of this paper is to describe the activities of the Weather Bureau in generating prospective geographic locator grids by high-speed computer.

Gridding by a high-speed computer represents a compromise between speed and accuracy in order that large numbers of pictures may be provided with satisfactory locator information in a reasonable length of time. The present effort began about 2½ years ago, before Tiros I was launched. Several of these gridding programs were produced for operation on an IBM 704 electronic data-processing machine; since then, two of these programs have been adapted for and are being used on the IBM 7090 computer. This paper presents a brief discussion of these two programs, the input information required, and the results.

The output of the computers is discussed first. One program involves a latitude and longitude computation at each of a population of grid points superimposed on the image plane. Since the cameras onboard Tiros are spinning at the same rate as the vehicle, the square picture frame may appear in any roll aspect with respect to the horizon. Accordingly, the latitude and longitude grid is computed for a circular image area which contains the picture square regardless of the roll position. The original grid of points extends over this entire area, and those points which happen to be above the horizon are automatically eliminated.

The charts produced by the IBM printer have half-inch mesh grids (figs. 14–1 and 14–2). The latitude and longitude are expressed to tenths of degrees. The contour shading is merely a system of filler numbers. The numbers have no meaning except to delineate the latitude contours. The horizon line is at the top edge.

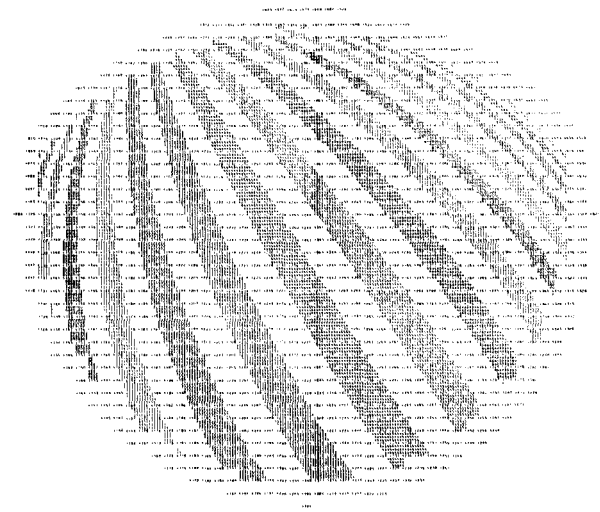


Figure 14–1. Longitude grid produced by IBM printer.

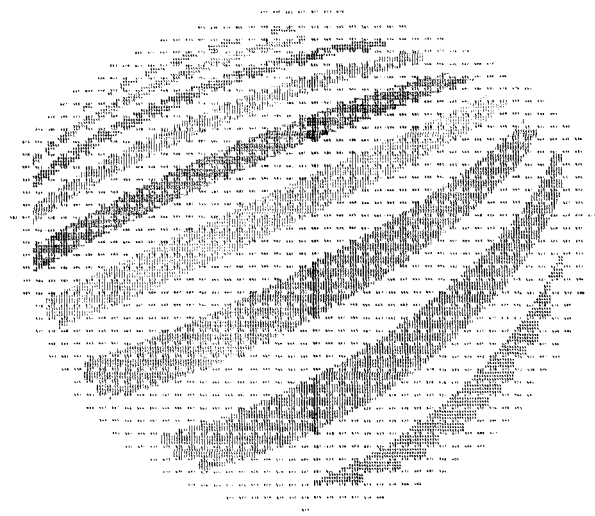


Figure 14–2. Latitude grid produced by IBM printer.

There is an alternate program which produces grid lines drawn by a mechanical device. This device (an electronic curve plotter), in turn, is controlled by a magnetic tape generated by the alternate digital computer program.

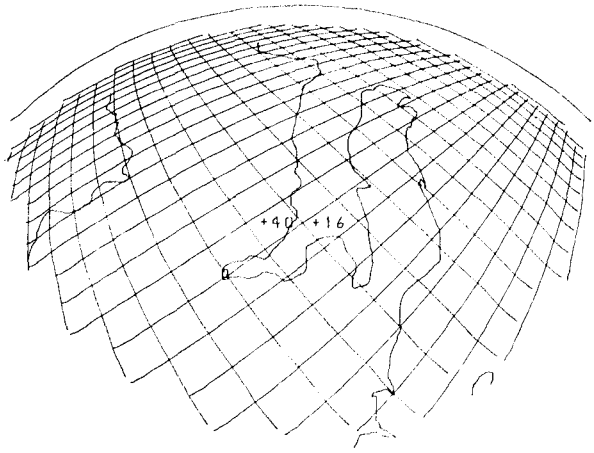


FIGURE 14–3. Example of grid drawn by data plotter.

Figure 14–3 shows a sample of this type of grid. The grid is composed of 1° latitude and longitude lines. As much labeling as possible has been purposely eliminated in order to accelerate the drawing process. In the lower right corner the first number is the orbit number 700. The picture frame number is 38. The code digits refer to, first, the identifying readout station; second, the mode of readout (whether the picture is recorded in a direct mode or from tape); and, third, the camera, camera 1 or camera 2.

A latitude-longitude intersection point is selected near the center of the gridded area with appropriate labels on either side. The left-hand side is the latitude of this intersection, 40° north; the right-hand side is the longitude, 16° east. In order to identify which direction is north, a zero digit has been placed at an intersection south of this point. In other words, an arrow may be imagined along the meridian with the zero being the tail and the arrow pointing toward the north to the labeled point of intersection. Thus, orientation can be established and, given the latitude-longitude interval, all the lines in the grid can be labeled. The horizon line is at the top. Some of the latitude-longitude lines that are crowded in the foreshortened region near the horizon have been purposely eliminated.

The grids also contain some geography. Some 18,000 words of memory in the computer are devoted to latitude and longitude points along the major coastlines of the world. The gridding is still somewhat crude in this regard, since coastal points are specified to the nearest 0.1°. However, these coastlines are useful in placing the grids on the photographs.

A discussion of the input requirements of the program and how it operates follows. No attempt will be made to describe the geometry and mathematics of the program. Fundamental input includes the latitude and longitude of the subsatellite point and the height of the vehicle above the surface of the earth. This information is generated as a function of time by the NASA TIROS Technical Control Center. Thus, if the shutter activation time is known the position of the satellite may be obtained. Other input of primary importance is the attitude of the satellite which can be discussed with the aid of figure 14–4. The attitude is defined in

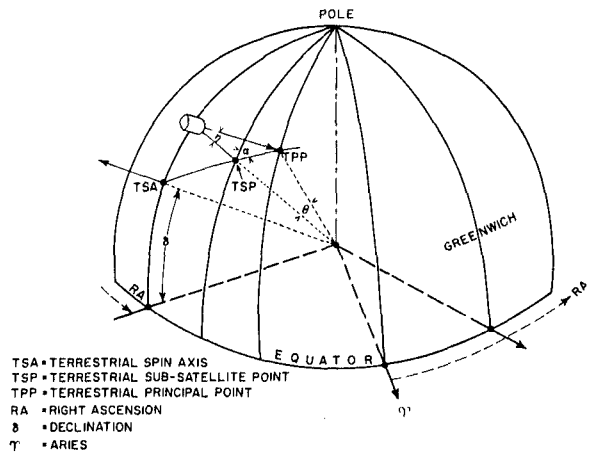


FIGURE 14–4. Attitude definition diagram.

terms of celestial coordinates and the convention has been to reference the attitude to Aries. The coordinates are normally in terms of right ascension and declination. By using the geocentric vector pointing toward Aries, the attitude of the satellite can be defined by a line parallel to the axis of the satellite extending through the center of the earth. This line can be defined by its declination (δ) from the Equator and by its right ascension (RA) measured from Aries (♈) around the equator to the east. Obviously, if the time is known, the right ascension and declination can be converted into the equivalent latitude and longitude of the terrestrial spin axis (TSA) point. Since the geocentric axis is erected parallel to the spin axis, the attitude of the satellite can be expressed in terms of the nadir angle be-

tween the subpoint vector and the principal axis of the satellite, this angle being equal to the geocentric angle between the subpoint and the spin axis point. The attitude can be expressed in terms of the azimuth of the great circle arc which extends from the spin axis point (TSP) through the subpoint; the azimuth is measured from north around to this great circle.

There are, then, several opportunities for expressing the attitude: in terms of the celestial coordinates or the latitude and longitude of the spin axis point, in terms of the nadir angle and the azimuth angles, or even in terms of the latitude and longitude of the terrestrial principal point (TPP) where the optic axis of the camera intersects the earth.

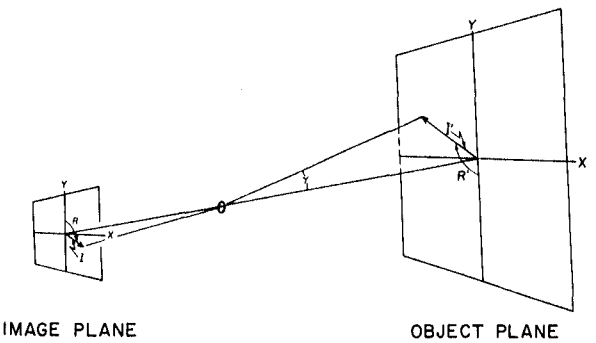


FIGURE 14–5. Object-image plane diagram. The symbols are defined as follows: I, distance from center to object, image plane; I', distance from center to object, object plane; R, radial angle, image plane; R', radial angle, object plane; γ, angle defining object length.

With the help of some sketches the method of computation can be followed. Figures 14–5 and 14–6 will help explain the linkage between image location and earth location. In the case of the printed output program this amounts to tracing a point on the image plane through the lens system to the earth intersection of the ray in object space. If it is desired to transfer an x, y image point through the distortion system of the lens and the electronic system of the satellite, conversion must be made into the polar coordinates, denoting a radial angle R on the image plane and the length of the vector from the center (I in fig. 14–5). With these two parameters the distortion tables can be used, either the symmetric alone or both symmetric and asymmetic, to obtain object space parameters. The symmetric distortion expresses an amplification of the vector length, and the asymmetric expresses an amplification and also a rotation. In any case the object ray is obtained which now can be expressed in terms of a radial angle R' and a new length I' on the surface of an image parallel object plane. Alternately, object length may be expressed by the angle Y formed at the satellite between the optic axis and the ray in question.

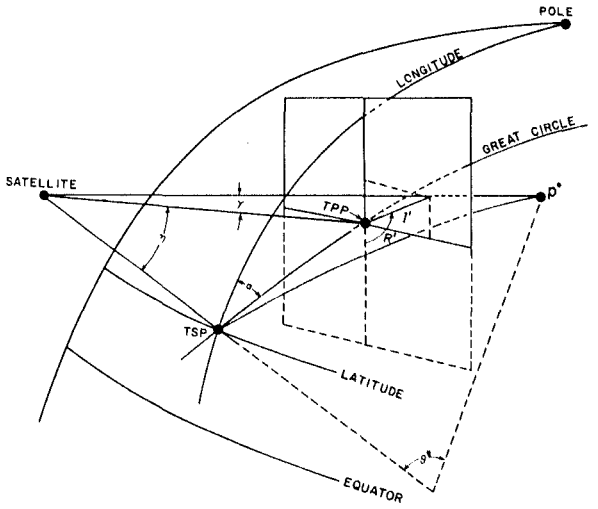


FIGURE 14–6. Object space geometry. Symbols are defined as follows: I', object distance; p^*, point of intersection of ray with earth; R', radial angle; TPP, principle point, TSP, subsatellite point; α, azimuth angle; γ, angle (in object space) defining object length; η, nadir angle; θ^*, geocentric angle related to nadir angle.

Figure 14–6 indicates the radial angle R' and the angle Y in object space. The satellite is indicated along with the subsatellite point TSP and the principal point TPP. The object plane is shown intersecting the surface of the earth where the optic axis of the camera reaches the earth; part of the object plane penetrates into the earth and the other part appears above the surface of the earth. The satellite vertex angle of a right triangle Y is formed by the satellite, the principal point, and the point of intersection of the ray in question and the object plane. Without going into too much detail, it can merely be stated that the angle Y and the radial angle R' on the object plane may be transformed into different component angles. Actually, two such transformations are carried out. The original angle pair can be converted into orthogonal components of the angle Y with one component

in the plane of the subpoint and the optic axis. These component angles are further projected so that the result is a final nadir angle involving the ray in question, the subpoint vector, and a final azimuth angle α on the surface of the earth from the meridian around to the great circle to the point in question.

With these two angles known, figure 14–4 can be restudied. Instead of the principal point, an arbitrary point can now be imagined on the image plane—a point for which the nadir and azimuth angles have been determined in line with the preceding discussion. The conversion to latitude and longitude can now be visualized. The nadir angle is converted to an equivalent geocentric angle which becomes the lower side of the triangle Pole-TSP-TPP. By using the geocentric angle θ as a side, the azimuth angle as a vertex, and the given colatitude of the subpoint as another side, this spherical triangle can be solved in the general sense and the latitude and longitude of any point that is selected on the image plane can be obtained.

The line-drawn code that produced figure 14–3 has been used to gride some thousand or more pictures from TIROS I, and it is expected to be used in the future to grid some 7,000 or 8,000 TIROS III pictures. It runs on the 7090 computer in approximately 10 seconds, and the line-drawn output takes approximately 2 minutes, depending upon the amount of earth-viewed area. These codes are being amended to take into account asymmetric distortions. To date, the input information required to generate the asymmetric component has been lacking, but this feature will be operational on a trial basis for the archival gridding of TIROS III pictures. Some modifications are also expected toward using this code in a more streamlined fashion for operational activities. It is planned to revise it for a similar type of gridding for the Nimbus series and also for placing grids on pictures which are being recorded by an electronic photofacsimile device. It is intended also to use certain portions of these programs for the digital processing and rectification of pictures.

Brief mention may be made of a similar gridding code that is in use on very small computers at Wallops Island and at Point Mugu. The gridding process need not be done by a large computer. It depends on the speed and flexibility desired.

15. USE OF TIROS PICTURES IN CURRENT SYNOPTIC ANALYSIS

By JAY S. WINSTON, *Chief, Planetary Meteorology Section, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

It was generally agreed, even before the first TIROS satellite was launched, that the cloud pictures obtained would have operational utility. Thus, plans were made to try to utilize the TIROS pictures on an operational basis, and meteorologists were assigned to the two readout stations to be on hand to view the pictures as they were transmitted and to try to make interpretations or nephanalyses of these pictures; communications were set up to send the information back to forecast centers. The purpose of this paper is to describe briefly the manner in which these data are acquired and processed for operational use. In addition, some of the operational applications of the data are reviewed.

Figure 15–1 shows in diagrammatic form the functions involved in the operational program. At the TIROS Technical Control Center (TTCC), which is located at the Goddard Space Flight Center, Greenbelt, Md., the commands to the satellite are determined. These commands determine when and where pictures will be taken within the limitations of attitude and sunlight on a particular day on particular orbits. This control center depends on orbital and attitude predictions made by the NASA Computing Center, which in turn bases its predictions on tracking information from the minitrack network and on attitude information from the readout stations.

A further input comes from a programing unit of the Meteorological Satellite Laboratory, located at Suitland, Md., which contributes programing ideas on what the meteorologist would desire on a particular day, based first of all on the limitations of sunlight and satellite attitude and then on meteorological considerations. These meteorological considerations are based primarily on operational needs, but occasionally also on what is most desirable from the research point of view.

Programs are made up by the TIROS TCC each day and are transmitted to the two data acquisition (readout) stations, one at Wallops Island, Va., and the other at the Pacific Missile Range, Point Mugu, Calif. As the satellite comes within visual range of a data acquisition station on a given orbital pass, a command is given to the satellite to take pictures. If it is daytime at the readout station, these pictures may be taken immediately; this is the "direct mode" of picture taking. More frequently, the satellite is programed to take pictures remotely, that is, along the orbit over some other part of the earth, out of range of the readout station. The next time the satellite comes within range these data are transmitted to the ground receiving station. The picture data signals are immediately fed onto a television tube where a camera instantaneously photographs each television picture. The film for a set of pictures obtained on one interrogation of the satellite is developed and printed as a strip of film positives in about 15 to 20 minutes. These film positives are presented to the meteorologist who actually looks at each picture projected by a photoenlarger with latitude-longitude grids superimposed. These grids are prepared in advance of the receipt of pictures and are usable as long as there is no marked deviation from the prescribed picture-taking program for that day. A nephanalysis is then made on a standard meteorological base map from the set of pictures obtained on each orbital pass.

The nephanalyses are transmitted by facsimile to Suitland from the readout station and also by teletypewriter in coded form. These nephanalyses are examined by meteorologists of the Operations Unit of the Meteorological Sat-

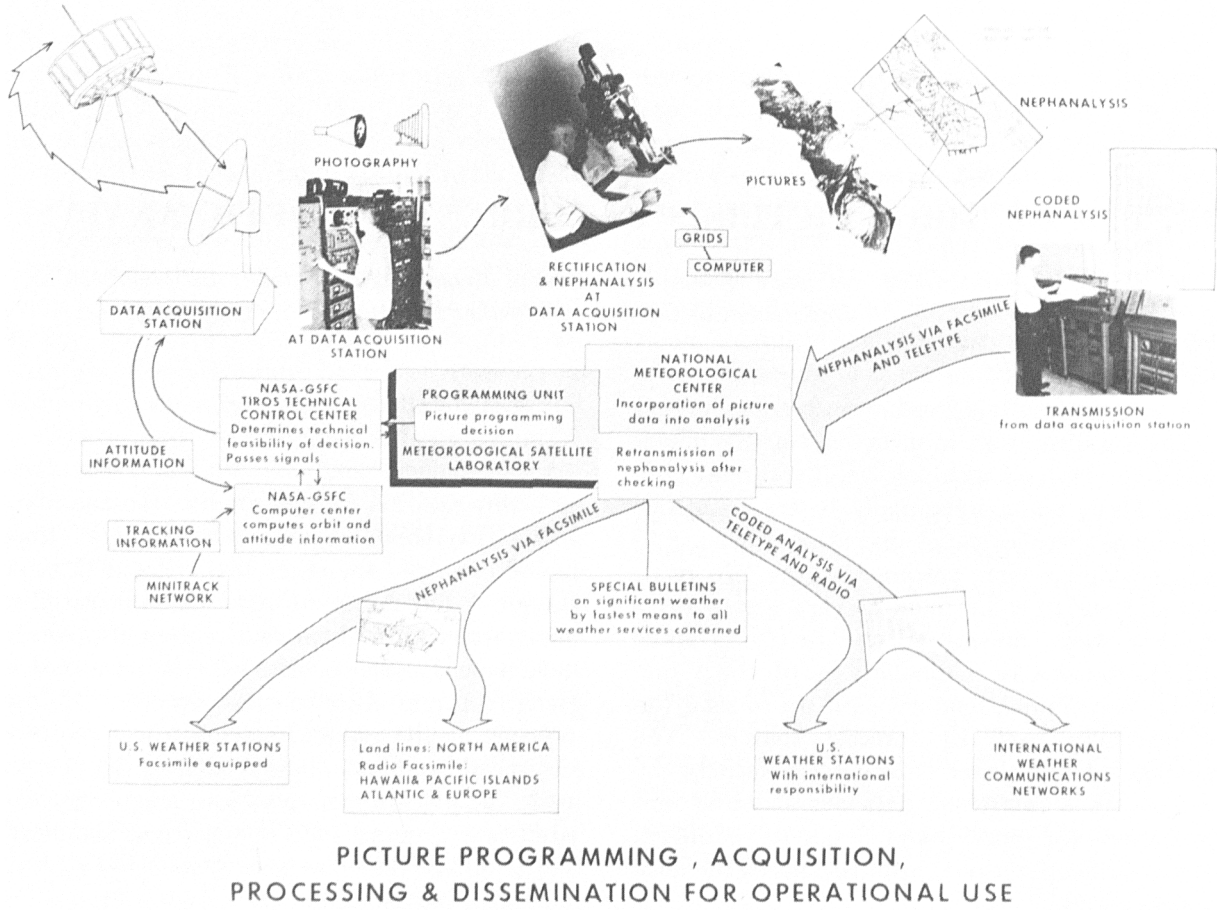


FIGURE 15–1. Picture programing, acquisition, processing, and dissemination for operational use.

ellite Laborary. If it is felt that the quality of a nephanalysis is good and has sufficient accuracy, it is transmitted, as soon as time is available on facsimile, to forecast offices or units of the U.S. Weather Bureau, the Air Force, and the Navy in the continental United States, Hawaii, the Pacific Islands, the Atlantic, and Europe. Coded nephanalyses are also sent out on the international weather teletypewriter networks.

One special thing that has been tried with TIROS III, in the case of tropical vortices in particular and any other important feature that is of interest, has been to provide for more rapid dissemination of the information to forecasters who would be most interested. In cases where, for example, a previously undetected vortex or a vortex in a significantly different position from the existing analysis is seen in a TIROS picture, the meteorologist at the readout station makes a direct call to Suitland, even before the nephanalysis is ready, and gives some of the details of its location and the extent and nature of cloudiness around it. Such information has formed the basis for special bulletins on significant storm information which have been sent to the meteorological offices concerned. For instance, during September 1961, several messages were sent to Japan, the Philippines, and other forecast services in the western Pacific when typhoons or other vortices were viewed by TIROS III.

Figure 15–2 is a composite of nephanalyses obtained during 1 day of operations, starting at about 1800 GMT, August 16, 1961, over the eastern Atlantic and continuing westward to the east coast of Asia until about 0730 GMT, August 17. Pictures were taken on the southwest-to-northeast leg of the orbit. Note the missing orbit in the central Atlantic and the gap between eastern Asia and western Europe. The coverage in figure 15–2 is essentially the

optimum that can be obtained in a given day with TIROS and with the readout stations located in Virginia and California.

During the operation of TIROS III an attempt was made to test an experimental operational program. Meteorologists were on duty at Suitland whenever TIROS pictures were being received. These meteorologists studied the nephanalyses, and occasionally a few selected pictures obtained via photofacsimile, in relation to the surface and upper air maps prepared by the National Meteorological Center (NMC). When there was information of special interest, immediate consultations were held with NMC analysts and forecasters. As a result many modifications were made in the map analyses and sometimes the satellite data were available before some of the conventional Northern Hemisphere data.

Several types of modifications were made. The most spectacular changes during September 1961 involved tropical vortices. Hurricanes were very well detected by TIROS III. Two of the most significant findings are shown in figure 15–3. On September 10, 1961, in a single set of pictures TIROS III viewed hurricane Debbie and a new vortex farther southeastward. The latter turned out to be the first Atlantic hurricane discovered by TIROS—hurricane Esther. Figure 15–3 is the picture that was obtained on that day; from the picture a well-defined vortex would probably be suspected, althought it would be uncertain whether a hurricane was indicated at that time. The conventional data were so sparse that, without these pictures, a disturbance would not have been suspected.

Consider hurricane Debbie more carefully. Debbie had already been discovered crossing the Cape Verde Islands several days earlier. After it left the Cape Verde Islands it was essentially lost since there were no ship reports

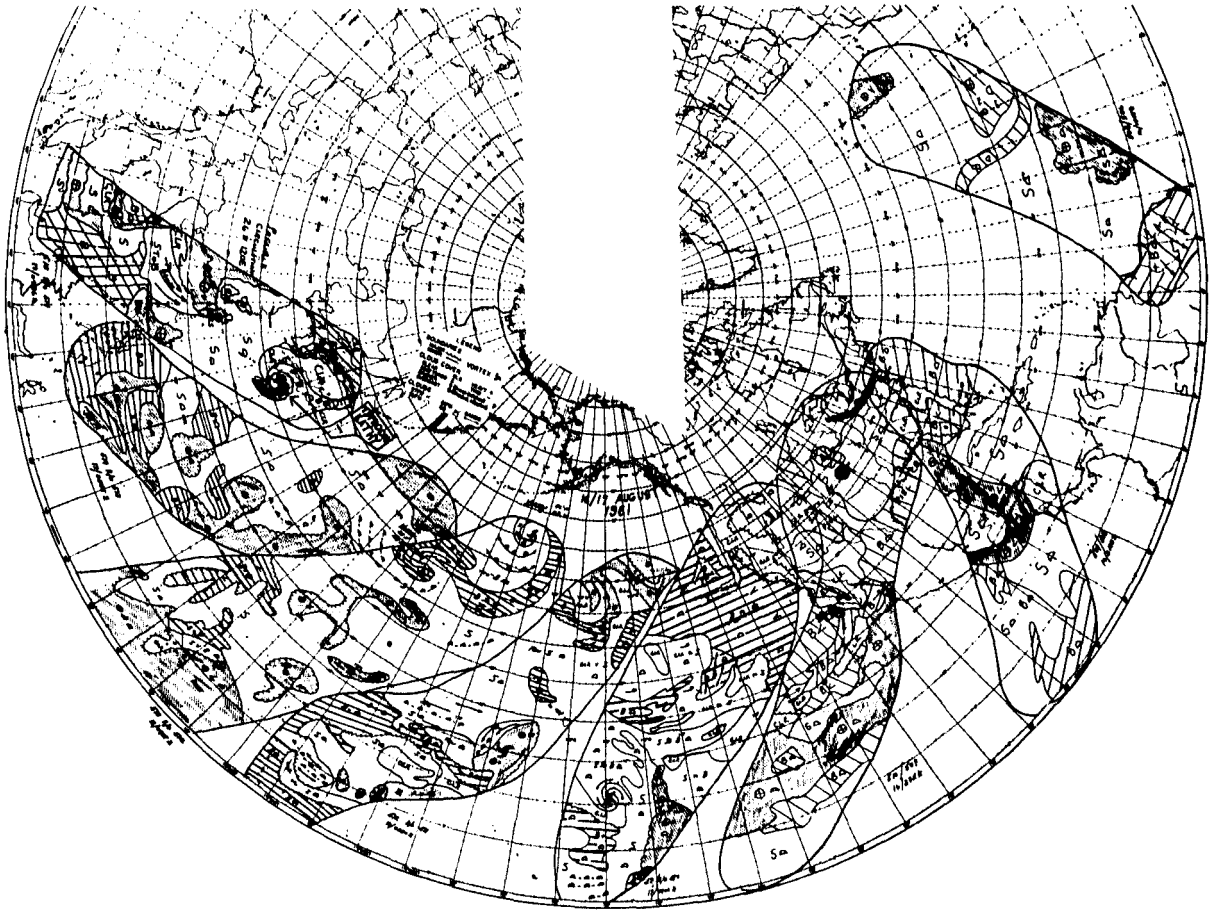


FIGURE 15–2. Composite of nephanalyses derived from TIROS III pictures in 1 day of operations, August 16–17, 1961.

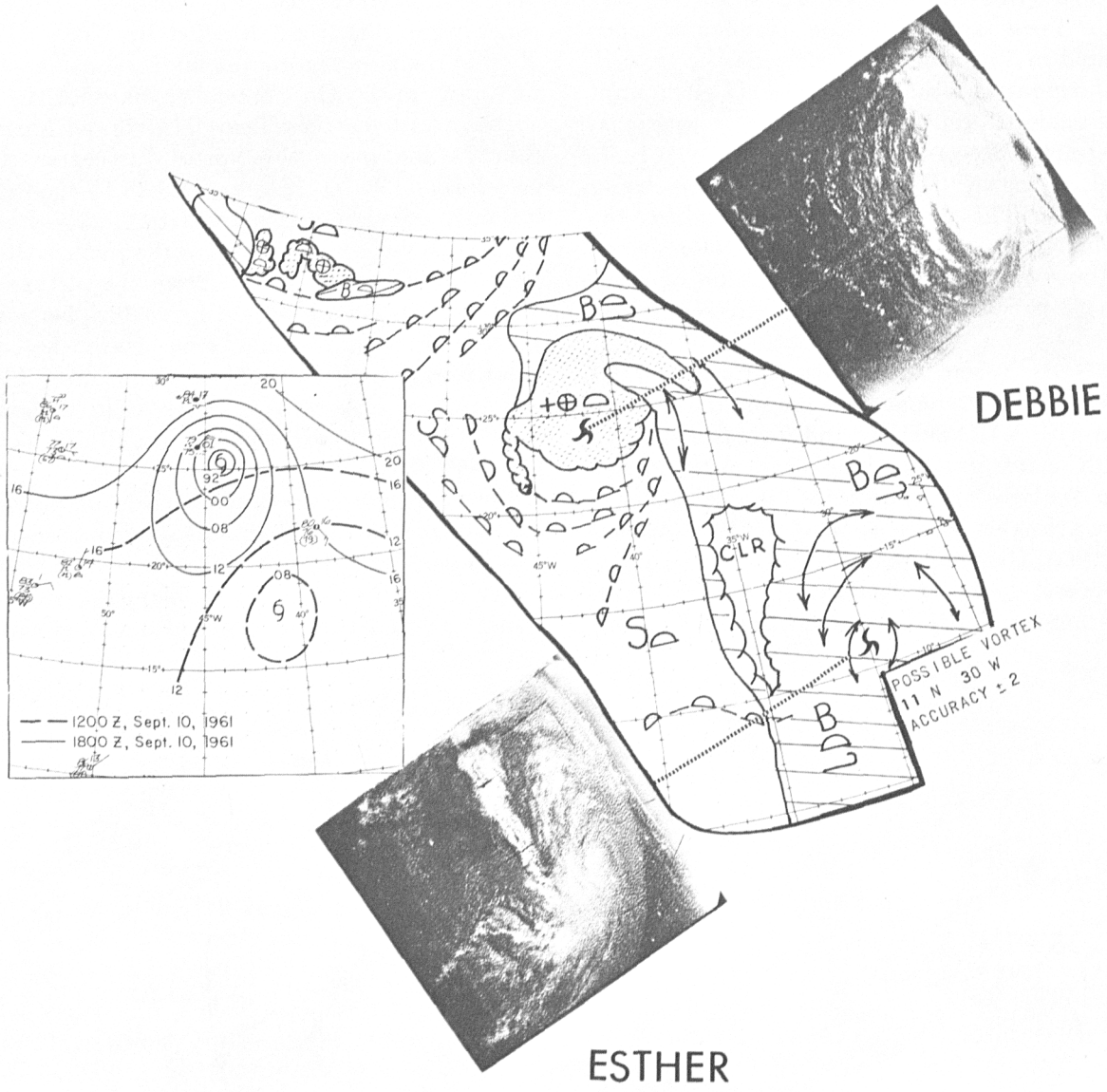


FIGURE 15–3. Nephanalysis, selected TIROS pictures, and section of National Meteorological Center surface analysis on September 10, 1961, when hurricane Debbie was relocated and hurricane Esther was first discovered.

in the vicinity. The map analyses carried it generally westward purely on the basis of continuity. By 1200 GMT, September 10, the official position of Debbie was as shown in figure 15–3 and it was carried as a rather weak tropical storm. The TIROS picture shown was taken at about 1800 GMT. As far as could be determined from this picture the center of the vortex was at about 24° north, 42° west, a position considerably different from the position which had been the result of several days of extrapolation. At about the same time a ship report near the storm became available. With this ship report showing strong northeast winds, rain, and low pressure (i.e., indications of a good vortex), and the excellent TIROS picture, the center was relocated. Thus, between the official NMC surface maps for 1200 GMT and 1800 GMT there was a shift of about 7° or 8° of latitude in the position of Debbie. This is a rather outstanding example of the aid that the pictures can give in a sparse-data area.

Debbie was then followed with TIROS pictures and conventional data for several days

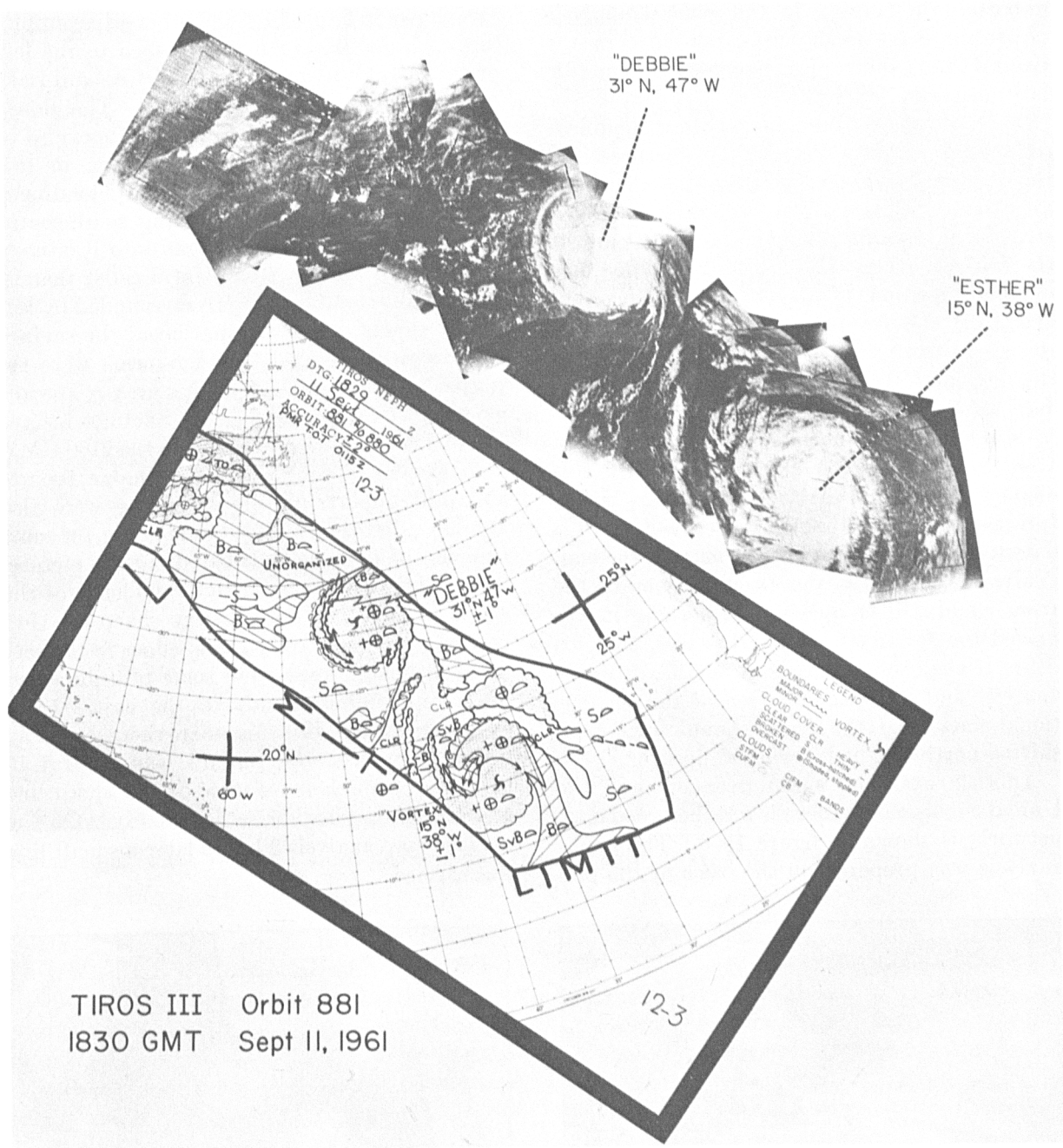


FIGURE 15–4. Nephanalysis and mosaic of pictures on September 11, 1961, showing hurricanes Debbie and Esther about 24 hours after they were recorded by the pictures shown in figure 15–3.

after September 10. Pictures and a nephanalysis of Debbie about 1 day later, 1830 GMT, September 11, are shown in figure 15–4. By this time, of course, there was aircraft reconnaissance into the center and the storm was under very good surveillance. Esther was once again viewed on this same pass. It was now about as big in appearance as Debbie and appeared to be a very well defined storm. By this time aircraft had been dispatched to the storm. Within about 12 to 18 hours afterwards aircraft penetrated the storm and it was officially recognized as a hurricane and named "Esther." The location of vortices is one of the more spectacular accomplishments of the TIROS satellites. It is obvious that the satellite is very

important in helping in the general analysis of storms over ocean areas, not only in the tropics and subtropics but also in middle latitudes.

There have also been more minor modifications made on the basis of TIROS pictures. In the nephanalysis shown in figure 15–5 there was an overcast of stratiform clouds and broken stratiform cloudiness along the east coast of the United States on August 23, 1961. The original position of the front (the original sketch of the frontal position by an analyst drawing this surface map) is indicated. After the nephanalysis arrived at NMC and the surface data were reexamined, the analyst decided to shift the front northwestward as a warm front in the position shown. Whether this change resulted in any major change in the forecast in this case is not known, but there is a desirable gain of greater precision in the map analysis. Of course, the exact location of the front could still be questioned; perhaps it was moved too far northward. However, the evidence is clear, on the basis of the TIROS nephanalysis and on reexamination of the conventional data, that the front should have been shifted northwest of its original position.

Another example, again over or near the United States where there is a rather good data network, is shown in figure 15–6. The nephanalysis was prepared on the basis of the picture shown in figure 15–6 and other adjacent pictures. Lake Michigan can be seen to the left of the center crossmark in the picture and Lake Superior is also partially visible. The clouds north and east of Lake Superior appear to be associated with the stationary front in this region. The rather solid belt of cloudiness, 100 to 200 miles wide, extending south-southwestward from upper Michigan into Kentucky appeared to contain cumuliform cells; that is, very bright cloud areas were surrounded by less bright clouds. An examination of the surface reports revealed that thunderstorms were reported at many stations in this area. The analyst in this case could, in all likelihood, have justifiably placed a squall line on the 2100 GMT map from the data at hand. Radar reports and pilot reports of this cloudiness were also available, but they all arrived at about the same time as the nephanalysis based on this picture. The picture gave very definite evidence of the shape of this line, with a very sharp clearing behind it and relatively sharp edges to the east of it, although there were some protuberances of cumulonimbus clouds to the east. Thus, even over an area like this where there are many synoptic reports, the picture was helpful in giving a comprehensive view of the squall line and fixing its position rather closely. On the surface map analysis 3 hours later a squall line was carried.

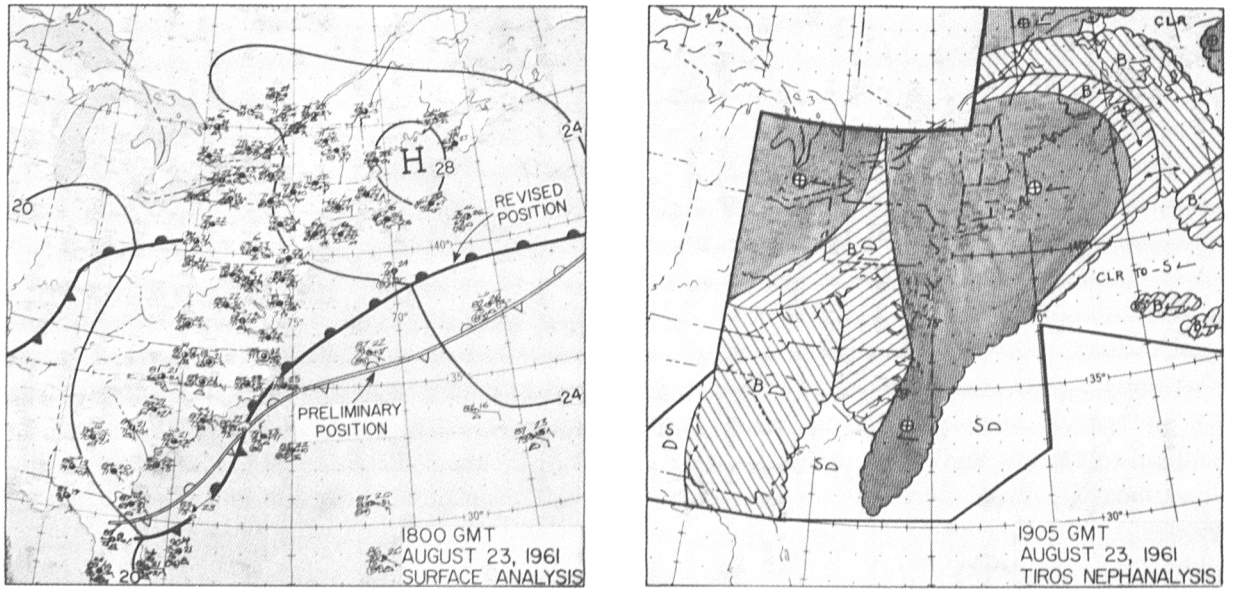


FIGURE 15–5. Revision of warm-front position off the east coast of the United States on August 23, 1961, on the basis of the TIROS nephanalysis.

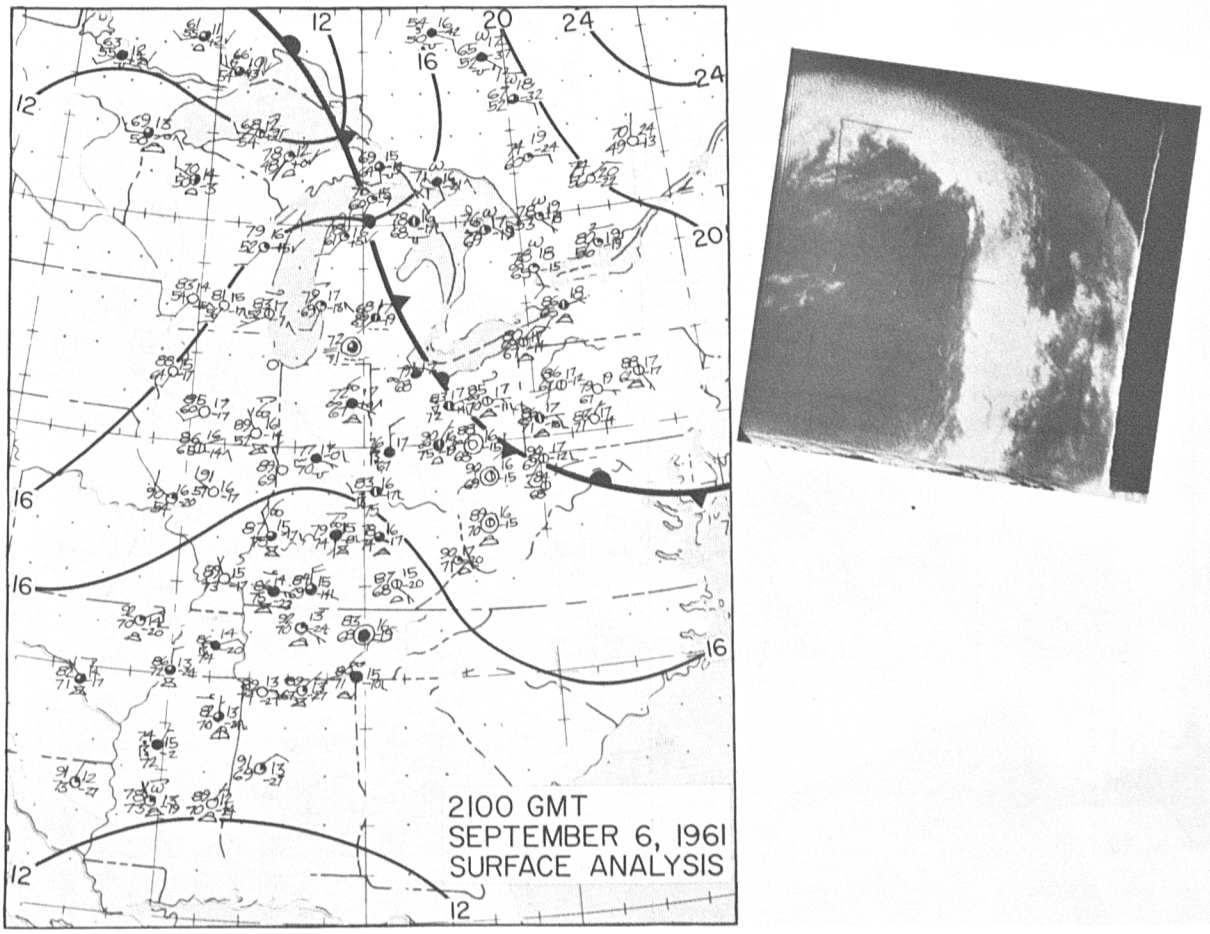


FIGURE 15–6. TIROS view of a squall line extending from the Great Lakes region toward the lower Mississippi Valley.

These, then, are some of the uses to which the data have been applied at NMC. Other probably worthwhile uses of the data for improving numerical weather prediction are being examined in research at the Meteorological Satellite Laboratory. Also, in the numerical prediction group at NMC, examination of TIROS nephanalyses relative to the numerically computed vertical motion data has been made during daily map discussions. As yet, there really has been no modification in the computed vertical motion fields on the basis of the TIROS cloud information. In addition to the NMC, several other U.S. analysis and forecast centers have made modifications in their map analyses many times.

The discussion thus far has concerned only map analysis. There are also, however, very direct forecast applications of the picture data, particularly for aviation operations where a knowledge of cloudiness is important, especially over ocean areas. A few examples where satellite picture data would be of importance are as follows. Figure 15–7 is from a case study of TIROS I pictures of a cyclonic vortex in the Atlantic Ocean near Bermuda (ref. 1). This chart shows a nephanalysis obtained from ship reports in the area and also the TIROS nephanalysis. The important point here is that the conventional nephanalysis shows clear to scattered cloudiness throughout the area around the vortex, whereas the TIROS nephanalysis shows details of heavy broken to overcast cumuliform cloudiness and bands of cloudiness around the low center. Thus, the TIROS observations give a great deal more information about the cloudiness around this cyclone than could be obtained from all the ship observations, even though this is an area from which numerous ship reports are received. Such increased cloud informa-

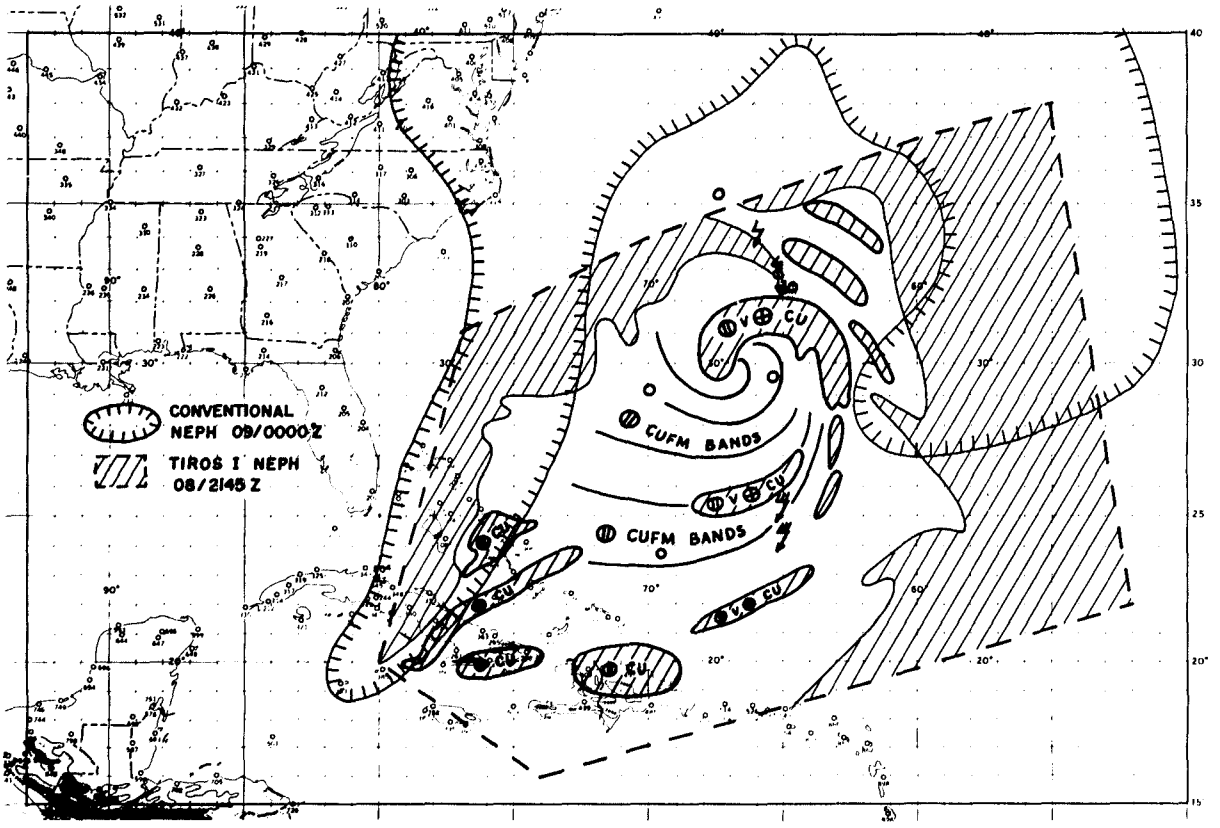
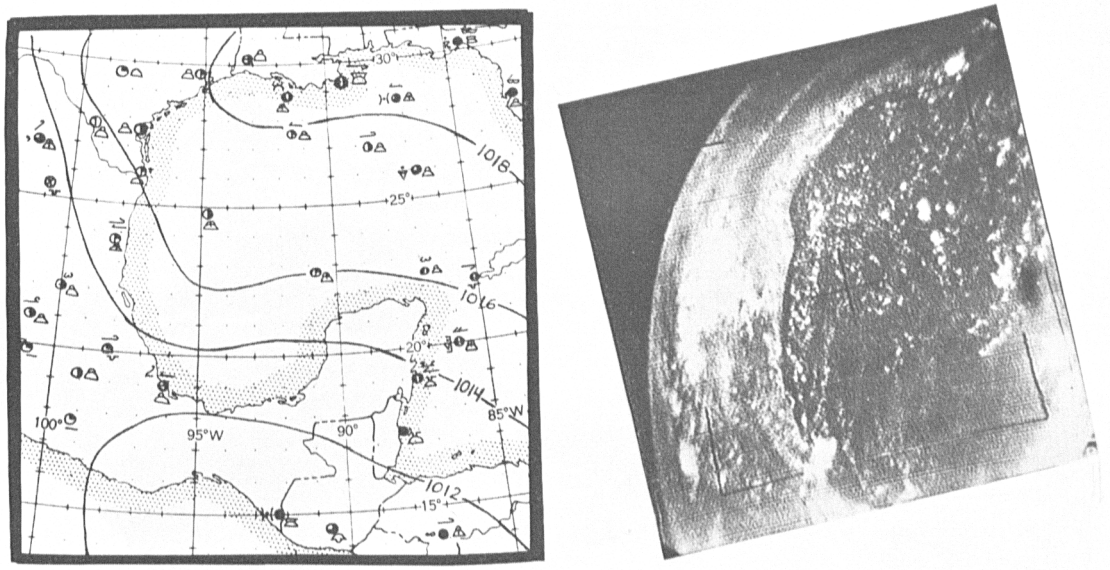


FIGURE 15–7. Comparison of conventional nephanalysis (May 9, 1960, 0000Z) with TIROS I nephanalysis (May 8, 1960, 2145Z).

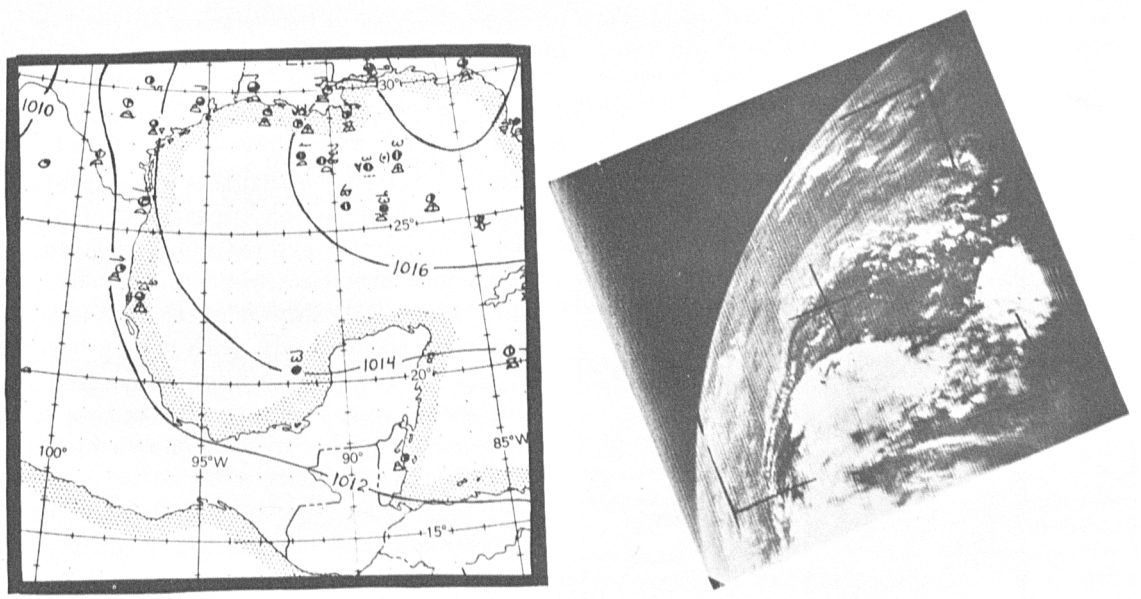
tion can be of great importance for aircraft operations for many hours after pictures are obtained.

Figure 15–8 shows TIROS III pictures of cloudiness over the Gulf of Mexico on 2 days, July 18, 1961, 1800 GMT, and July 20, 1961, 1800 GMT. In general, the surface map analyses for these 2 days do not show any vast differences. However, there was an easterly wave near Yucatan on July 18, whereas on July 20 there was general southeast anticyclonic flow through much of the gulf region. From the ship reports, the surface map analysis, or even the upper air analysis many meteorologists would probably have been unable to deduce that there was any difference in cloud cover over the Gulf of Mexico on these 2 days. On July 18 the picture shows that most of the area could be characterized as covered by scattered cumuliform cloudiness with a few widely scattered cumulonimbus clouds. Two days later the area cloudiness was greatly increased; there were remnants of the strong easterly wave that was over Yucatan 2 days earlier. A large area of bright cloudiness had moved into the gulf. Much of this undoubtedly consists of rather thick middle clouds but also cumuliform elements seem to be embedded in the cloudy area. This broken to overcast cloudiness covers a very large area, a major portion of the Gulf of Mexico. This is a graphic example of what can be obtained from TIROS pictures and how conventional data often fail to give true weather conditions.

Figure 15–9 is a picture of Florida with cumuliform cloudiness and cumulonimbus cells over much of Florida. The most important feature to be noted is the apparent extension of cumulonimbus activity westward from about the Tampa area. This cumulonimbus activity, which might be interpreted as a squall line, extends a few hundred miles westward from the west coast of Florida into an area of very few ship reports, and where the surface flow is anticyclonic but weak. If an aircraft were proceeding west-east in this area it would be rather foolish for the pilot to fly in the squall line; it would be obvious from the picture that the flight



JULY 18, 1961 1800 Z



JULY 20, 1961 1800 Z

FIGURE 15–8. Widely differing cloud cover over the Gulf of Mexico as viewed by TIROS III, July 18 and 20, 1961.

could be conducted about 50 miles north or south of this line and all the turbulence in the extensive cumulonimbus clouds could be avoided.

Figure 15–10 is a sample of a nephanalysis from the mid-Pacific, extending from rather low latitudes into middle latitudes. Note the continuous overcast cloudiness extending all the way from 15° to 20° north to 45° to 50° north near the surface high center. The superimposed analysis is the standard NMC analysis for this time showing the subtropical low center and trough to its south. Actually, the interpretation in this case by the meteorologist at the

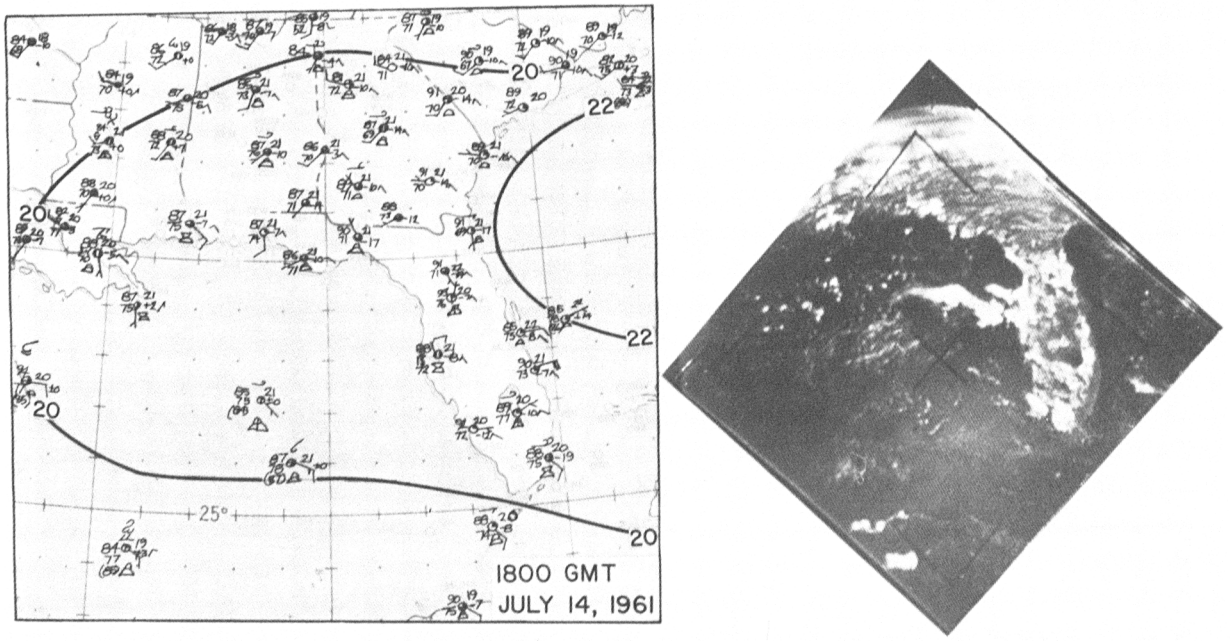


FIGURE 15–9. The capability of the satellite to give a comprehensive view of thunderstorm activity over a large area is illustrated in this picture of the eastern Gulf of Mexico and the Florida peninsula. Of particular interest is the line of thunderstorms extending nearly 200 miles westward from Florida into the Gulf of Mexico, an important synoptic feature which is undetectable from the surface weather map.

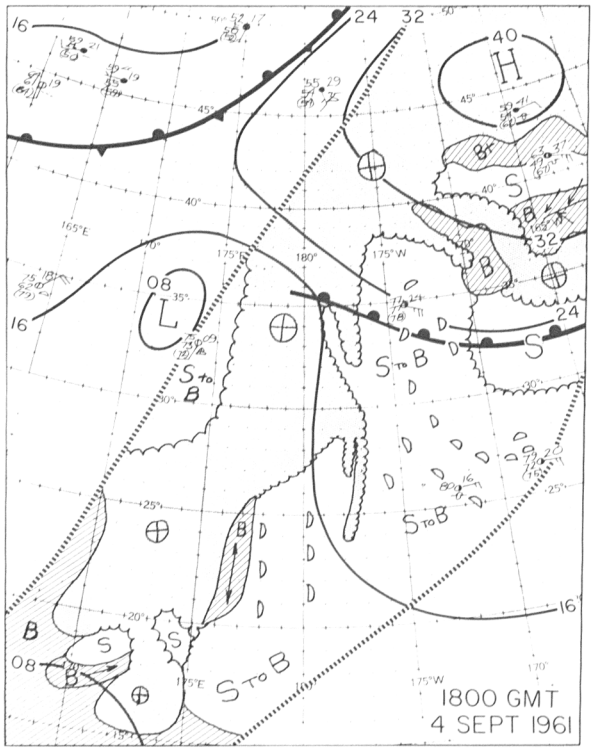


FIGURE 15–10. TIROS III nephanalysis and corresponding sea-level analysis, 1800 GMT, September 4, 1961.

readout station was that this was a frontal cloud band. It had all the appearance of the broad dense cloudiness typical along a front. It is fairly obvious that this could not be called a cold front. A ship near the cyclone center reported tropical air with a southerly flow. Whatever front there might have been in this low would have had to be farther westward.

Essentially, the overcast shown in the nephanalysis must reflect a broad zone of strong convergence and upward motion extending over an area which is not covered by ships. All the ships were on the fringes of the overcast. Of course, it is possible that from previous maps the existence of overcast or broken clouds could have been deduced. However, it would have been impossible to anticipate such a broad zone of overcast cloudiness given the surface map and whatever upper air maps were available, the latter being based on even less data.

In conclusion, reports have been received from Weather Bureau and Air Force forecast offices concerning the uses of TIROS picture data. An example is the report received from the Weather Bureau International Aviation Unit at New York International Airport, where the

weather for the Atlantic air routes is forecast. During the useful life of TIROS III, when nephanalyses were received by facsimile, copies were given to the crews of flights going across the Atlantic. The response, in general, it is reported, has been extremely enthusiastic. These nephanalyses gave the flight crews much more detail of cloud systems than they normally would have had in any other way. Specifically mentioned in this report is the route between New York and Dakar. For other routes across the Atlantic a weather depiction chart obtained from standard observations is normally provided. For the New York to Dakar route, however, preparation of such a chart is not feasible due to the lack of data. When TIROS nephanalyses were available, copies were given to the crews. Although few nephanalyses were available they provided a fine portrayal of the clouds all the way across the Atlantic.

These nephanalyses have been available at Suitland and on facsimile networks on the order of 2 to 4 hours after the observations were made. These data can be given to the pilots within perhaps another hour after receipt at the forecast office. Thus, if a flight happened to depart after 4 hours after a nephanalysis was received it could be the most up-to-date and comprehensive data on cloudiness that could be obtained for that oceanic flight.

Reference

1. JONES, J. B.: *A Western Atlantic Vortex Seen by TIROS I.* Monthly Weather Rev., vol. 89, no. 10, Oct. 1961, pp. 383–390.

Question Period

NANCOO, Jamaica: We come from an area where there is very little information and depend much more on the TIROS pictures than most people. However, the information can be misleading. So we would like to put things in true perspective. Could you say what the order of accuracy is, with regard to the location of these cloud areas?

WINSTON: The accuracy of location is generally shown directly on the facsimile copies of the nephanalyses. The accuracy is generally on the order of ±2° of latitude. This, of course, is not very precise for many purposes. In some cases, where there are landmarks in the pictures on a given orbit, the accuracy generally increases to about ±1° of latitude. When the uncertainty is ±3°, or more, the nephanalyses are generally not transmitted.

D. S. JOHNSON: Could someone comment on whether the accuracy is included in the teletype version of the nephanalysis? It is supposed to be.

A. W. JOHNSON: We have now under consideration a revision of the code before the next TIROS is launched. The problem will be considered carefully when we do revise the code and we will make sure the accuracy is reported.

D. S. JOHNSON: I would like to say in this regard to those of you who have made use of the code in your own countries: If you have comments to make regarding the utility of the code and suggestions as to how it might be made more helpful and useful for you, we would appreciate it very much if you would inform us of your problems with the code.

PALLMAN, El Salvador: The currently used form is that, after the heading, A, B, C, and so forth are used in order to characterize the different types of clouds and, following this, the latitude and longitude positions are given. I would like to make a suggestion: Perhaps for each coded transmission, the identifying groups A, B, C, and so forth, could be repeated. It has happened in the past that because of faulty communications we lose the coded identification of cloud characteristics and have only the positions. Between the time of picture taking by TIROS and the transmission, for instance, through Miami broadcasts, 12 to 15 hours elapse. It is clear that because of this delay the nephanalysis can serve only for a check of clouds over the ocean and there is no chance for direct synoptic application.

Mr. Winston showed photographs comparing cloud distribution over the Gulf of Mexico on July 18 and 20, 1961. It was explained that on the surface map there were no remarkable differences between the distributions of surface pressure on these 2 days. In El Salvador a daily analysis has been made since 1956, not only of surface maps but also of maps of the free atmosphere, at 850, 500, 250, and 100 millibars. We realize that although on the surface map there does not exist a remarkable difference between situations on one or another day, in the free atmosphere remarkable differences can be seen, and in some cases we make use of these differences with respect to certain practices of meteorological analysis. Does there exist already a comparison between cloud-cover distribution shown in TIROS photographs and upper air charts?

WINSTON: You have posed several questions. I will start with the last. The examples which were given in this paper were chosen mainly as a matter of convenience. In most cases the upper air maps could have been given, but most upper air charts have even less data than the surface charts over ocean areas.

I examined the upper air charts for the July 18 and 20 case (fig. 15–8). I do not remember any significant difference in the upper air charts over that area for these 2 days. I do not think there was much indication of an easterly trough over the Gulf of Mexico. It was practically lost, so far as I can remember. So the upper air data would have been no better than the surface data in this particular case.

We do not mean to give the impression that we use only surface maps in our investigations. In all our investigations we are attempting to correlate the pictures with the surface and upper air charts in a coordinated fashion. We hope that perhaps the greatest use of these pictures, at least in connection with numerical weather prediction, might be in relocating upper air troughs and other features of the midtroposphere charts.

In regard to the other questions, for instance the coding of the teletype messages, I think these ideas should be taken under advisement. We try to improve these codes, when possible, as weaknesses become evident.

D. S. Johnson: The points raised by Dr. Pallman about the code and the delay in communications can perhaps be discussed by Mr. A. W. Johnson.

A. W. Johnson: On the matter of the code, the major change that is contemplated is a condensation of the code to eliminate the repetition of the letters A, B, C, and so forth, and to indicate simply the number of times that these letters will occur in succession. I will discuss this code more fully in a subsequent paper. The code will be distributed through the WMO. A certain amount of international agreement must be secured before it is implemented. Although we are reluctant to have still another new code for the next Tiros while there is a possibility that further revision might be necessary, the problem of short communications time has made it necessary to condense the present code. Thus, there will be a new code for Tiros IV which we hope will be internationally adopted.

We are very disturbed about the inadequacies of international meteorological communications and have some proposals to make. We are able to get the product to Suitland rather promptly. Mr. Winston and others have shown that it is of operational use in the analysis center. So we feel it is necessary, on the premise that the nephanalyses may be useful internationally, to find a better means of distribution from Suitland. It is this problem that we are discussing with Mr. Davies and Dr. Langlo of the WMO and with communications agencies in the United States and in the Southern Hemisphere. I think the case of the 12-hour delay is not a usual one. The information is scheduled at periodic intervals on a Weather Bureau (WBR) broadcast from Miami.

Molinero, Honduras: It is true that, to shorten the code, the number of times the letter *A* for example would appear along a latitude line could be given. That would be very useful where the condition is overcast. But if there are scattered clouds, I do not think the system would be effective because the report would read two times the letter *A* and once the letter *B* and so forth; thus, this device would not serve to shorten the transmission.

In Honduras the coded Tiros nephanalyses are considered very useful. However, one of the biggest problems has been the irregularity in receiving these analyses. The code is received when our area is included in the Tiros observations. We use the data at our own latitudes, from about 50° west. An easterly wave could probably be identified during July through December when such waves are very common. The very rough weather associated with the easterly waves makes identification relatively easy. Just once or twice the code received from Miami lacked the heading, but that was not very common.

I have used these codes many times and find that the lack of cloud-type identification makes it very difficult to determine the difference between an overcast of cumulonimbus or an overcast of cumulus, fair-weather cumulus, or stratus.

16. PHYSICAL MEASUREMENTS AND DATA PROCESSING

By William Nordberg, *Atmospheric Structures Branch, Goddard Space Flight Center, NASA*

Of main concern in this discussion are the radiation experiments, in general, on the Tiros satellites. There are three aspects to the radiation experiments. The first one is the instrumentation used on the Tiros satellites. Since the instrumentation has already been discussed, in part, in paper 10, only a brief discussion will be given herein. The second aspect of the radiation experiments is the calibration of the instruments. Work is still being done to try to calibrate these instruments more precisely, which means to relate the input into these instruments more precisely to the output telemetered to the ground stations. The third aspect of the radiation experiments is the problem of data reception, processing, analyzing, and interpretation. There is much work to be done on this phase of the experiments.

It may be worth while to summarize briefly the various publications and the work done by researchers in the field of radiation experiments.

Reference 1 is a basic paper in which the instruments and some of the preliminary data received from Tiros II are described. The electronic aspects of the Tiros radiation experiments are discussed in reference 2. Charts or maps of the Tiros radiation data are available (ref. 3) and these will be described briefly herein. Some initial efforts to interpret the data from Tiros III in terms of various situations which have been reviewed are given in reference 4.

Figure 16–1 is a photograph of the Tiros II satellite. This figure is presented to show the viewing ports of the radiation sensors onboard the satellite. There are two radiation instruments onboard. One is a so-called five-channel scanning radiometer, sometimes referred to as a high-resolution or medium-resolution radiometer. The radiometer, as used in these experiments, measures both reflected and infrared radiation from the earth, reflected in visible regions and emitted in infrared regions. These radiations have been observed in five more or less spectrally defined regions; thus, the instrument is called the five-channel radiometer.

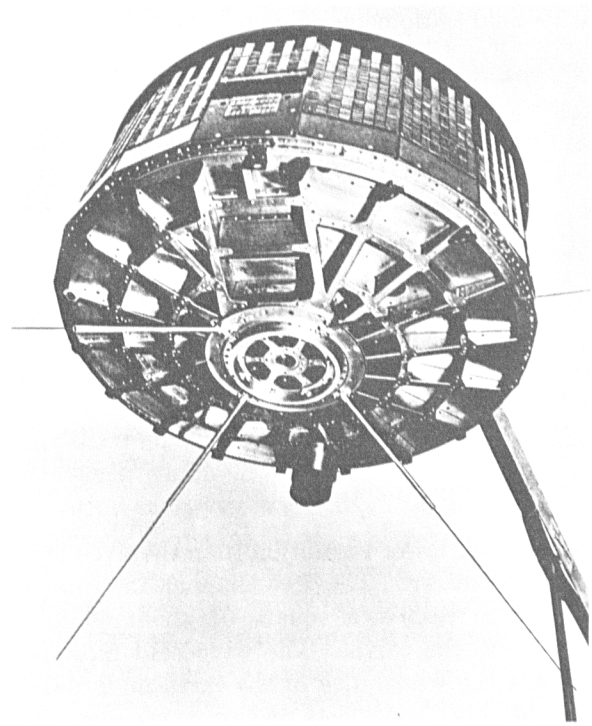


Figure 16–1. Tiros II meteorological satellite launched November 23, 1960. The medium-resolution scanning radiometer looks through rectangular apertures in the side and base plate. The low-resolution radiometer looks through the round aperture in the base plate almost diametrically opposed to the protruding wide-angle television lens.

It is mounted in the pillbox-shaped satellite on the side so that one viewing port looks out toward the bottom of the satellite (usually referred to as the floor side), whereas the other looks out toward the side (usually referred to as the wall side). The distinction between the

sides is important because one serves as the reference side, and the other, as the signal side. Sometimes, the floor side looks at the earth; then, *it* is the signal side. Sometimes, the wall side looks at the earth; then *it* is the signal side. The reference side looks constantly into outer space and compares the outer space signal which is obviously zero or which has very little radiation in it against the one that it receives from the surface of the earth.

The other radiation instrument onboard is a wide-field radiometer, shown in figure 16–2. It

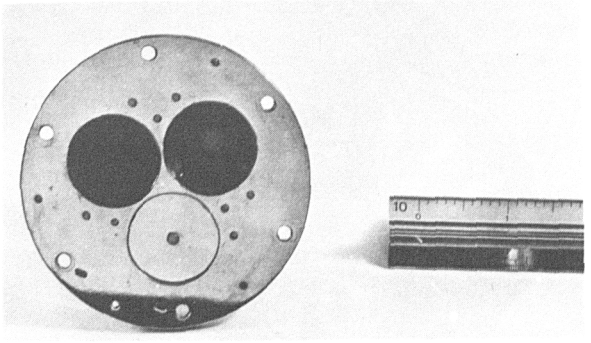


FIGURE 16–2. Exterior view of the low-resolution radiometer showing the black detector (left) and the white detector (right).

has a much lower resolution than the five-channel radiometer. The five-channel instrument is able to resolve a square of about 60 kilometers on the earth. The wide-field radiometer sees the whole disk of the earth underneath the satellite; it consists of two cones, one with a detector painted white, which is sensitive only to infrared radiation and which reflects visible radiation, and one with a detector painted black. This latter one is sensitive to the total radiation received. The exact workings of this instrument will be discussed subsequently.

The five-channel or scanning high-resolution radiometer is shown in detail in figure 16–3. The viewing ports for the individual five spectral regions of the wall side can be seen on the bottom.

Figures 16–4 and 16–5 define and describe the spectral regions in which the five-channel instrument is sensitive. Figure 16–4 shows the sensitivity of channels 3 and 5 to reflected radiation from the earth. Channel 3 is sensitive from about 0.2 micron to about 6 microns. Channel 5 is sensitive from about 0.5 micron to about 0.8 micron. The reason why these two

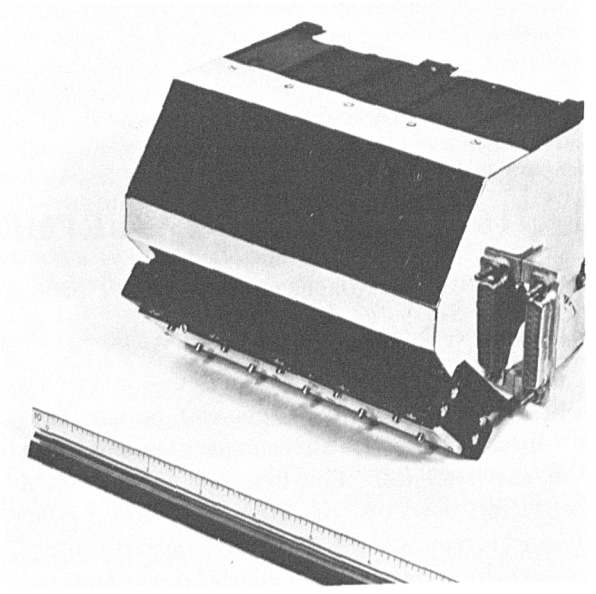


FIGURE 16–3. Exterior view of the medium-resolution radiometer showing the view apertures in one direction of the five channels. The prismatic cross section of the reflector is seen on the right of the line of appertures.

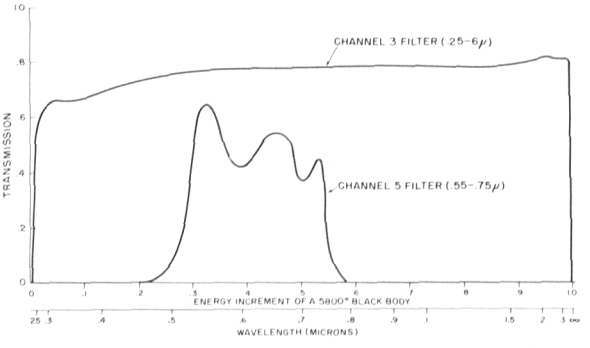


FIGURE 16–4. Filter transmission characteristics of channels 3 and 5 of the medium-resolution radiometer.

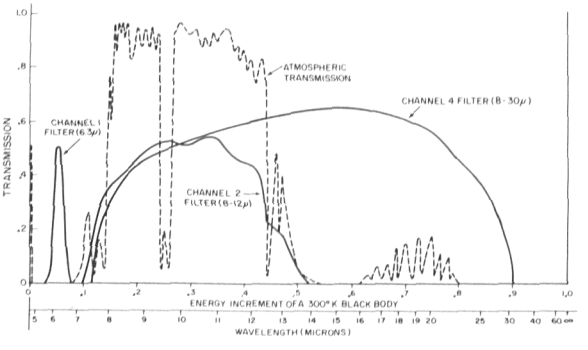


FIGURE 16–5. Filter transmission characteristics of channels 1, 2, and 4 of the medium-resolution radiometer. The dashed line is the approximate transmission characteristic of 1 atmosphere.

regions were chosen is the following. Channel 3 was intended to encompass the total reflected sunlight from the earth. Channel 5 was intended to be sensitive near the actual maximum spectral intensity of sunlight. There is also a more practical reason for selecting this narrow spectral region; the spectral sensitivity of this channel is very close to the spectral sensitivity of the television cameras onboard the same satellite. The spectral curves (figs. 16–4 and 16–5) are somewhat stylized in the sense that they do not show some of the erratic response occurring outside these bands. The reason is that the curves were drawn before an exact and precise knowledge of the spectral response of this instrument was obtained. This erratic response was detected only after rigorously calibrating these instruments in the laboratory. Channel 5, which already has a complicated response curve in the 0.5- to 0.8-micron range, also has a small but noticeable response farther out in the 1-micron region. This makes the processing and analyzing of the data accordingly more complicated.

Figure 16–5 shows the infrared channels or the three channels sensitive to emitted radiation from the earth. Channel 1 has a very narrow peak in the 6.3-micron region. The dashed lines show the transmission characteristic of the atmosphere. In the 6.3-micron region there is practically no transmission; this is due to the absorption by water vapor in the atmosphere. Maximum atmospheric transmission occurs in the spectral region in which channel 2 is sensitive except for the dip at approximately 9.5 or 9.6 microns, which is due to the absorption of ozone in the upper atmosphere. However, the total energy in this atmospheric transmission dip is rather small compared with the total energy in the spectral region for which this filter is sensitive. This region starts at about 8 microns and extends to about 13 microns. After these curves were drawn, more precise calibration indicated that there is a slight response of this channel at about 16 microns. It was hoped that this channel would be a perfect "window" channel; however, as the spectral calibration has shown, there is some response outside this window. There is, then, a minimum transmission through the atmosphere in the channel 1 region and a maximum transmission in the channel 2 region.

In the third remaining infrared channel, channel 4, a spectral range as broad as possible, extending from about 7 microns to about 30 microns, is chosen; here, it is intended, to receive the total thermal energy emitted from the earth.

With the complicated spectral responses described it is a difficult task to obtain a measure of radiation from the electrical energy measured at the output of each channel. A relationship between received radiation and measured output voltages must therefore be established experimentally. This is done in the following ways. The infrared channels of the instrument are exposed to black-body targets whose radiation temperatures are known precisely. The output of the radiometer is recorded with varying target temperatures. This means that a 1-to-1 correlation between the total energy emitted from the target and the output of the instrument can be established. When the satellite is in orbit the earth takes the place of the black-body target, and the electrical output from the instrument after demodulation can be expressed in terms of black-body target temperatures which in turn can be converted to radiation energy received from the earth. This approach, however, does not render a satisfactory picture of the radiation emitted from the surface of the earth or the atmosphere because the radiation measured within the highly nonuniform spectral response of the instrument (fig. 16–5) must be correlated with the total radiation emitted from a given altiude region of the atmosphere of the earth in a given direction. A method to obtain such a correlation is described in paper 17.

Figure 16–6 shows the installation in the laboratory for experimentally calibrating the visible channels. In the visible channels, the reflected-light channels, the problem is somewhat different from the thermal-calibration problem. A 1-to-1 correspondence between the radiation from the target and the output of the instrument cannot be obtained as simply as in the case of the infrared channels. A well-calibrated source which illuminates a diffusing screen, simulating a reflecting cloud surface (fig. 16–6), must be used. The distance of the screen can be varied and, therefore, the intensity of the diffuse emitter or diffuse reflector, which is a special type of paper, can be varied. This

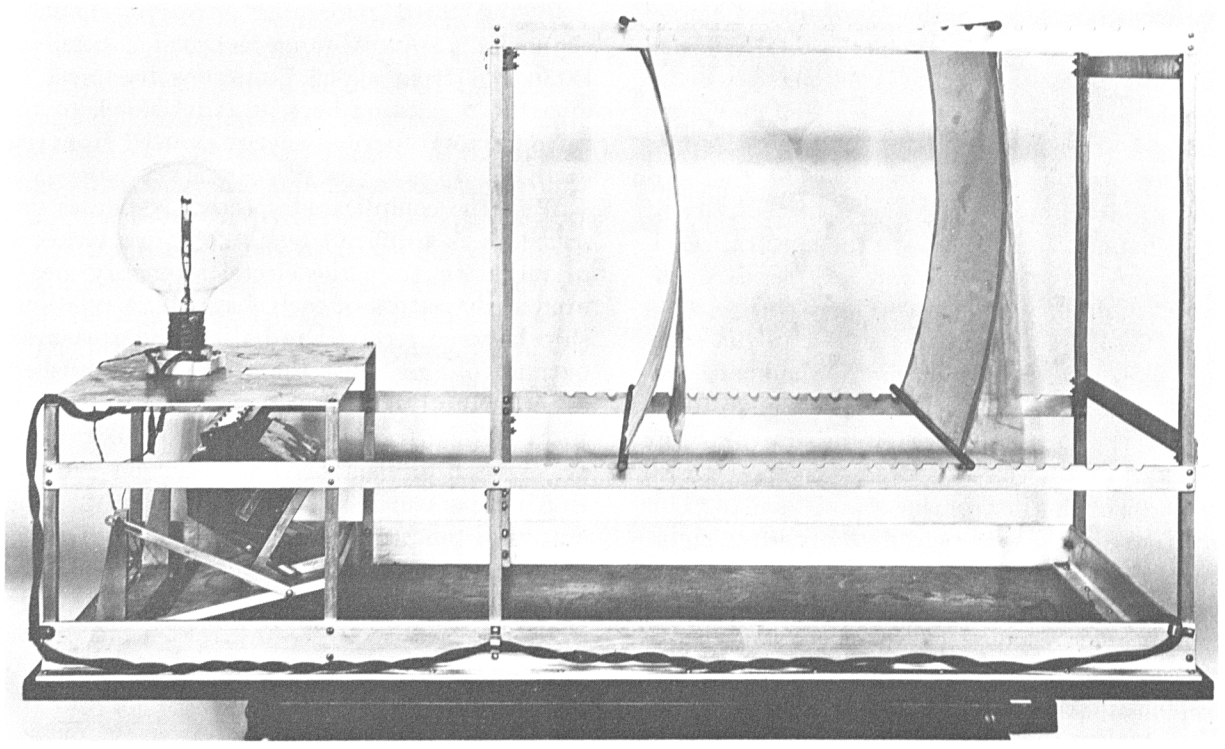


FIGURE 16–6. Calibration installation for the two visible-light channels of the TIROS five-channel radiometer. A 1.5-kilowatt calibrated tungsten bulb shown in the left side of the light stand illuminates a diffuse paper target mounted in the right side of the stand. The radiometer is mounted underneath the tungsten bulb and shielded from direct light.

diffuse reflector then illuminates the radiometer and the output of the two visible channels is monitored as a function of the distance of the screen from the bulb; namely, as a function of the total intensity or brightness of the screen. Again, a 1-to-1 correspondence could be obtained if the paper screen truly simulated reflected solar radiation. However, this is not the case. This source used in the laboratory at its brightest has a color temperature of about 3,000° K. The sun has a temperature almost twice this value. The spectral characteristics of the laboratory source and the sun are therefore vastly different.

In order to convert the output to the albedo seen by the instrument, the exact spectral characteristic of the source, the exact spectral response of the instrument, and the exact spectral characteristic of the sun must be known. For the latter a black-body radiator of 5,800° K is assumed for channel 3; a black-body radiator of 6,000° K is assumed for channel 5. These assumptions may be made confidently. The exact spectral response of the instrument and of the source are very difficult to obtain. As a source a carefully calibrated bulb is used as a "primary standard." The spectral response of the instrument is measured by comparing it with the response of detectors of uniform spectral sensitivity.

In TIROS II these calibration problems had not been solved as completely as in TIROS III, and most of the data received, particularly most of the visible energy data, were only relative measurements. In TIROS III the calibration has been perfected and there is more certainty about the absolute measurement of energies reflected from the earth in the visible part of the spectrum. Measurement, of say, the transmission of a filter or of any optical component in the five-channel radiometer by just using the various monochrometers and spectrophotometers available is not very simple. The problem is not only to produce monochromatic radiation and have the radiometer respond to it but also the calibration must be performed with a detector of greater precision than the one contained in the radiometer; such

detectors are very difficult to find because of the required uniformity of response over the broad spectral regions over which the instrument must be calibrated. This, again, is particularly true for the infrared channels.

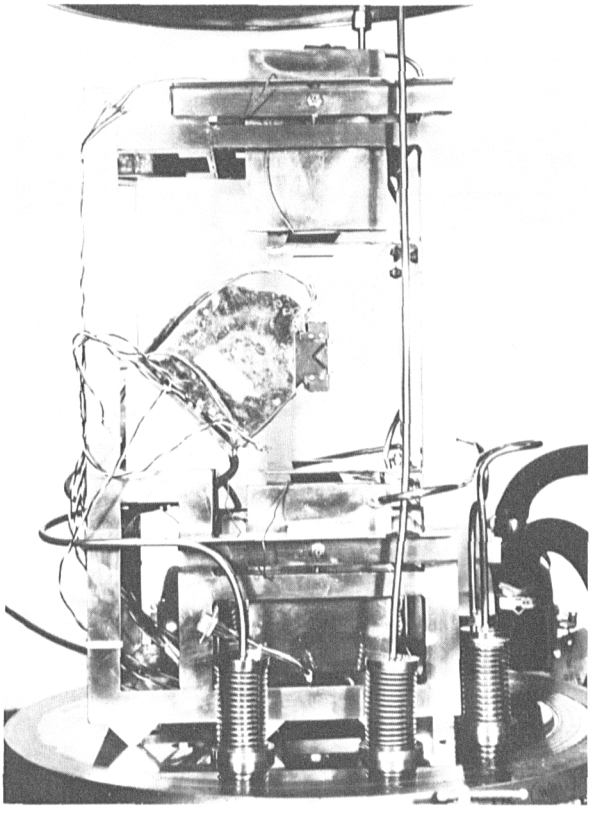


FIGURE 16–7. Laboratory installation used for calibrating infrared portion of the TIROS five-channel radiometer. The radiometer is mounted in the center. Identical black-body targets are mounted on top and bottom. All the equipment shown fits inside a Bell jar which is evacuated to a maximum pressure of 10^{-6} mm Hg.

Figure 16–7 shows the facility used in the calibration of the thermal channels, the infrared channels. The radiometer is mounted in the center of the apparatus with one viewing port looking up and the other viewing port looking down. There are two black-body targets, one above the radiometer and one below. The slots visible in the two targets are actually the conical black bodies into which the instrument looks. If both of these targets are embedded, say, in liquid nitrogen, then the three infrared channels see practically no radiation through both viewing ports. This simulates the situation the satellite encounters in outer space when neither wall nor floor side are looking at the earth. The output of the instrument should then be zero. When the temperature of one of these black-body targets, for instance the top, is increased to a range which is comparable to the equivalent black-body temperatures of the earth, the output of the instrument will increase; the increasing voltage can then be measured as a function of the increasing black-body temperature of this target. Then, the process is reversed; the top target is kept at liquid nitrogen temperatures and the bottom one is heated. The response of the instrument is not exactly the same, although theoretically it should be. This difference in response between the "wall" and the "floor" sides is an important part of the calibration and very cumbersome to handle in the data reduction.

Figure 16–8 gives a picture of the results. The black-body temperatures are plotted on the abscissa; these temperatures range from liquid nitrogen temperatures (−196° C) up to about 40° C. If the floor side is chosen to be the scanning side and looks at a target of variable temperature, the wall side will constantly look at a liquid nitrogen target. As the temperature is increased, the voltage increases from zero up to a saturation level of approximately 12 volts. Thus, a curve of voltage against black-body temperature of the target is obtained; the temperature of the satellite is an additional parameter in obtaining these curves. Two different temperatures for the instrument are shown in this figure, 25° C and 45° C. As the temperature of the instrument varies, nearly parallel curves will result. After the output has been obtained as a function of these two parameters, namely, the temperatures of the instrument and the target, the energy which is available under the filter function curves (fig. 16–5) may be computed for a given black-body temperature.

Figure 16–9 shows this relation. This curve is obtained by using Planck's law for a given black-body temperature and integrating it over the filter function of the instrument. This is where the complication occurs. If this filter function were perfectly rectangular, it would be elementary to compute the relationship between the black-body temperature and the energy received by the radiometer. The complex nature of the filter function not only complicates the computational process of this in-

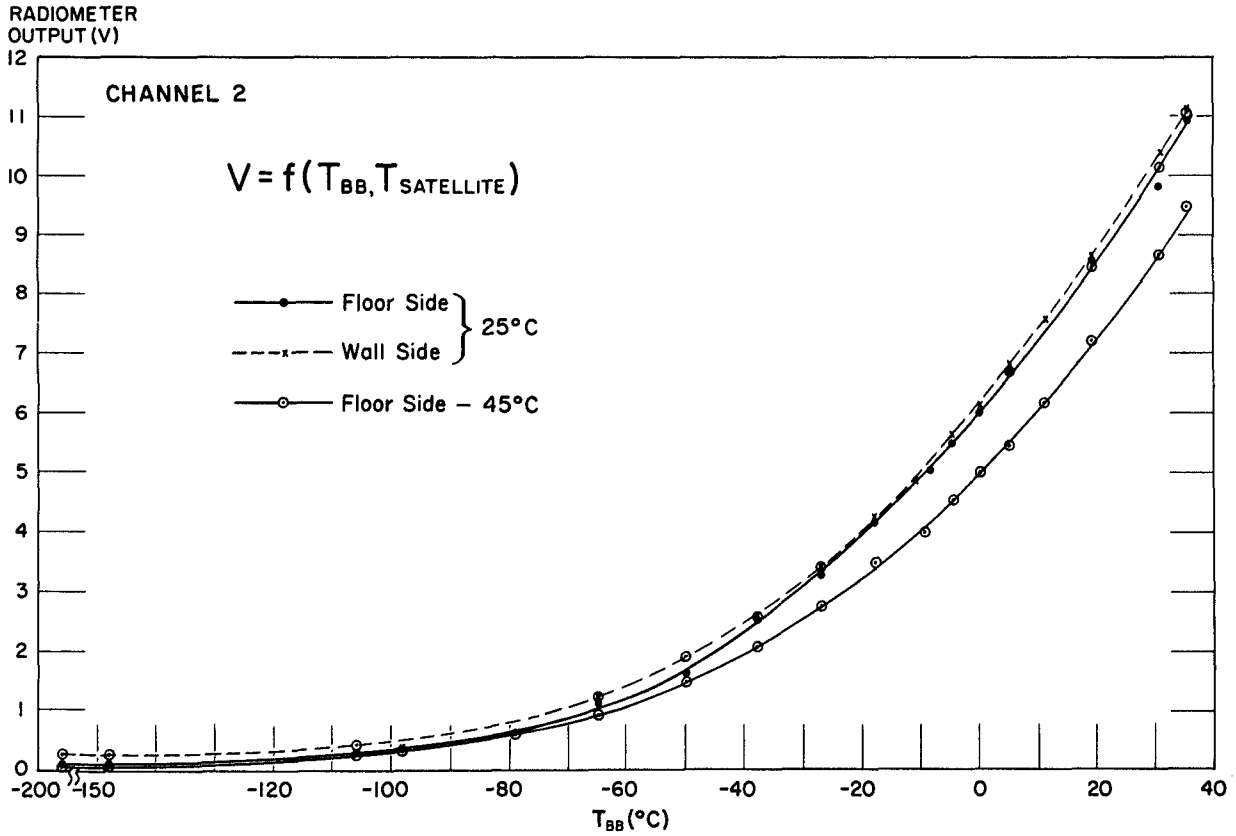


FIGURE 16–8. Typical curve showing the relationship between the voltage output of channel 2 of the scanning radiometer and the temperature of a black-body target viewed by the scanning beam of the radiometer. The reference beam at the same time is looking at a black-body target at liquid nitrogen temperatures.

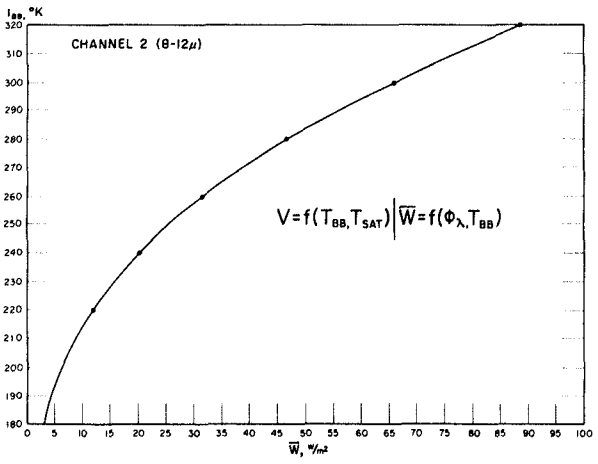


FIGURE 16–9. Curve showing the relationship between black-body temperature T_{BB} and energy W received by the radiometer. This relationship is obtained by integrating the theoretical black-body energy curve over the spectral range to which the radiometer is sensitive.

tegration but also makes it necessary to find a mathematical correlation between the energy received under the filter function and the energy emitted by the earth within the spectral range of interest. As mentioned previously, such a correlation will be discussed in paper 17

Figure 16–10 presents a group of equations showing the functioning of the wide-field radiometer. The temperatures of the black and white sensors are proportional to the energies radiated to the sensors by the target, which will be the earth, and by the housing of the sensor itself, as well to the heat conduction from the housing to the sensor. This energy relation is simply a proportionality expressing the balance of incoming and outgoing energies at each detector. In these equations there are four constants of proportionality for each the black and the white cone which must be determined in the laboratory. First, each cone is calibrated with thermal radiation in the infrared only

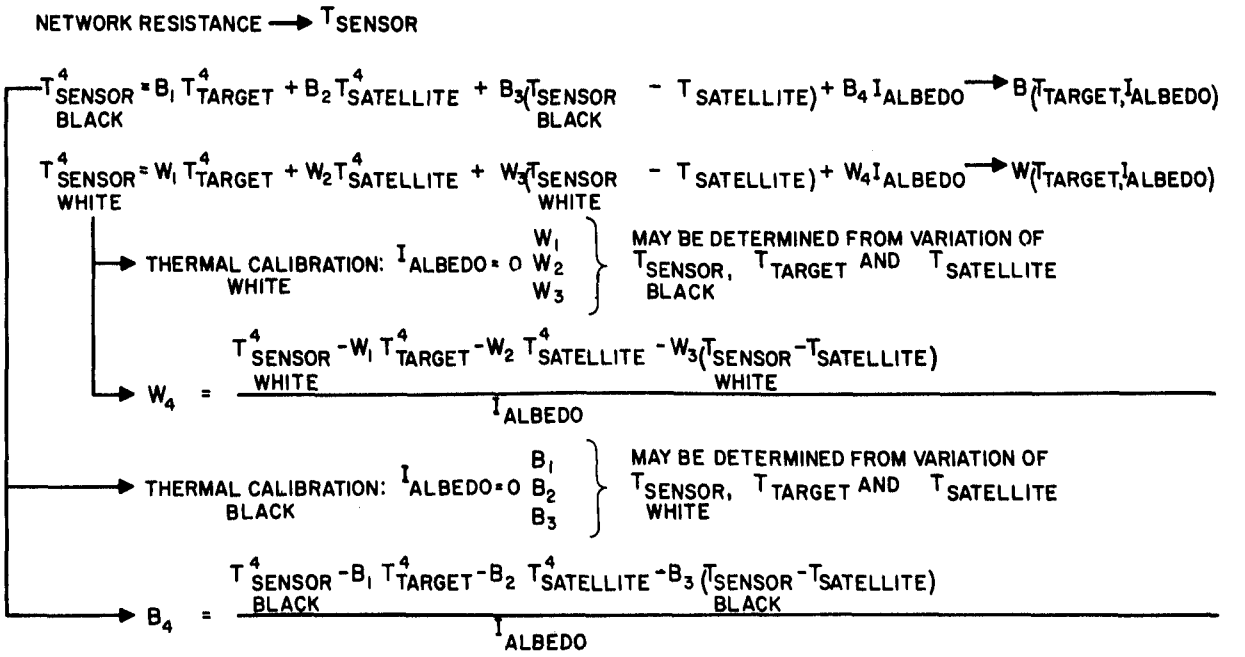


FIGURE 16–10. Equations showing the functioning of the wide-field radiometer.

which affects the first three terms on the right-hand side of the two equations at the top of figure 16–10. Since all lights are turned off, there is no energy from the visible targets which means that I_{ALBEDO}, the intensity of albedo, is zero. The three constants, B_1, B_2, and B_3 for the black sensor, or W_1, W_2, and W_3 for the white sensor, are determined by putting the instrument through a range of various sensor temperatures, target temperatures, and satellite temperatures. By a least-squares solution these constants are determined.

After B_1, B_2, B_3 and W_1, W_2, W_3 have been determined, the lights are turned on. The brightness of the light targets corresponds to a given albedo intensity I_{ALBEDO}. The temperatures of both the black and white sensors, the satellite, and the thermal target are measured. The constants B_4 and W_4 are then obtained by the arithmetic process shown in figure 16–10.

In the satellite the temperatures of the black and white sensors of the satellite itself are measured and telemetered to the ground. With the knowledge of constants B_i and W_i (i=1 . . . 4), the two unknowns, namely, the temperature of the equivalent black-body temperature of the earth T_{TARGET} and the intensity of the albedo I_{ALBEDO} can be determined.

Figure 16–11 is a record of the signals received from the satellite. It shows seven channels. The bottom channel is simply a timing channel. It shows sun pulses which the satellite picks up by scanning the sun, and as the satellite moves into the shadow of the earth these sun pulses disappear. This record is very close to either sunrise or sunset and, therefore, the visible channels receive no light. The top five traces show the signals obtained from the high-resolution radiometer, traces 3 and 5 being the visible channels. The infrared channels (traces 1, 2, and 4 from the top of the figure), however, receive very strong signals; one of these channels will be shown subsequently on an enlarged record. The signals from the wide-field radiometer (trace 6) are of interest here. They are seen in a commutated fashion. In the groups of three dots the outside ones represent the temperature of the black sensor and the center one represents the temperature of the white sensor. These two temperatures are at different levels, naturally, because of their different spectral sensitivity. The voltages for each of these dots are measured and then the equations presented in figure 16–10 are solved for albedo intensity and for equivalent black-body temperature of an area of the earth viewed underneath the satellite. This area is several hundred miles in radius.

Figure 16–12 gives an idea of the typical geometry. In one position (top of picture) the

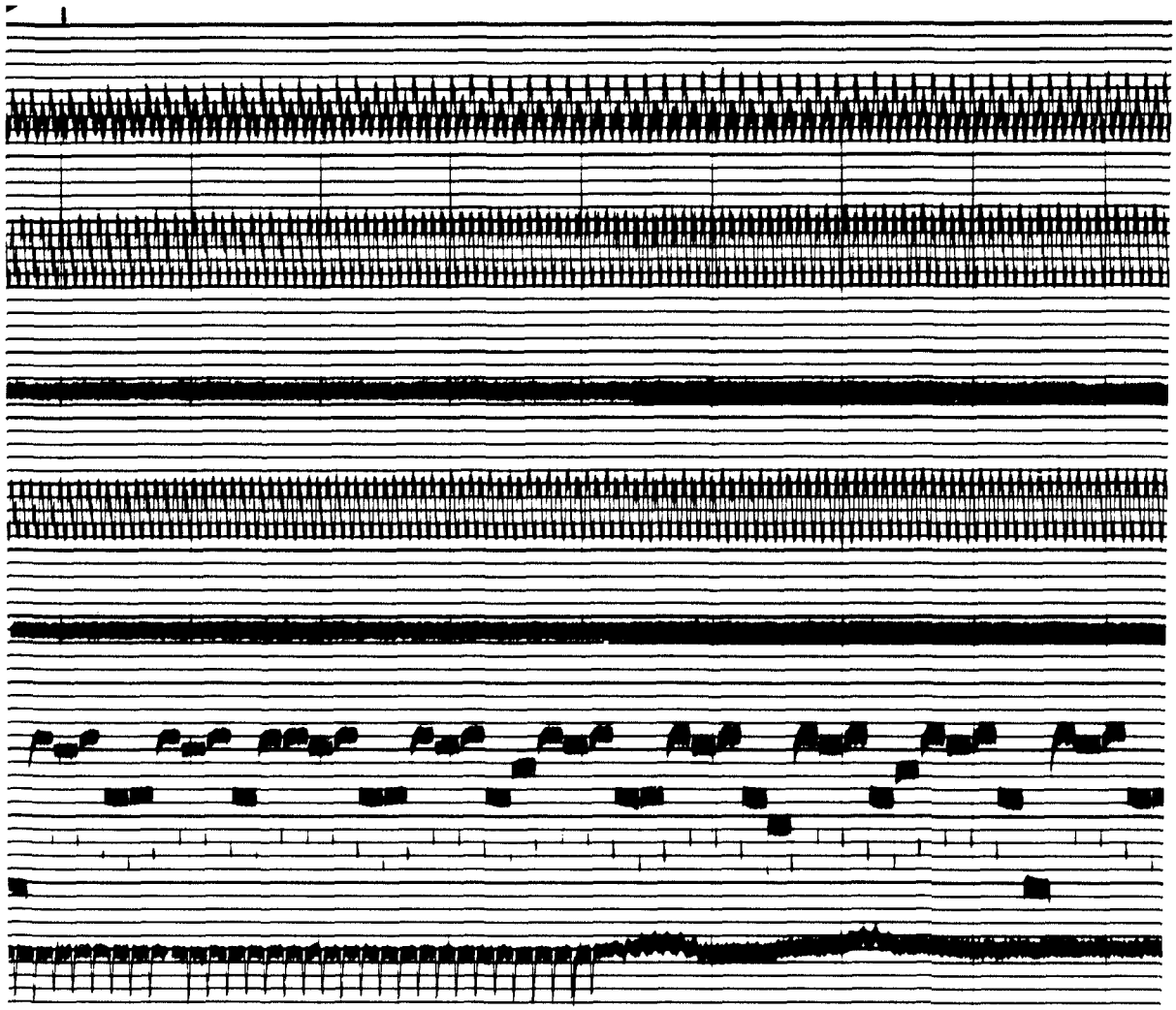


FIGURE 16–11. A typical record of data transmitted from the TIROS radiation experiments. The top five traces show the responses of the five-channel radiometer. Traces 1, 2, and 4 from the top correspond to the three infrared channels; traces 3 and 5 correspond to the visible channels. The bottom channel is a timing reference. The second channel from the bottom is commutated into various segments and contains the information transmitted from the wide-field radiometer as well as "housekeeping" parameters of the satellite, such as temperature and pressure.

bottom of the satellite, the floor side, looks straight down upon the earth; therefore, the wide-field or low-resolution radiometer views an area directly under the satellite. The five-channel or medium-resolution radiometer, which in this case scans through the floor side, describes a circle as the satellite spins; the traces scanned may be seen in the figure. The other beam looking out through the wall side of the satellite will see outer space. Since no radiation is received in this beam, this is the reference side. Then, as the satellite progresses in orbit, about halfway around the earth it will come to a position where not the floor or the bottom but the side of the satellite looks down on earth, whereas the spin axis of the satellite is parallel to a tangent to the surface of the earth. At this point the wide-field radiometer ceases to view the earth (the bottom case in fig. 16–12). It sees outer space and the signal is useless except for reference because there is no radiation. The five-channel radiometer, however, continues to scan as the satellite spins. The floor beam which looks out through the floor of the satellite at 45° to the spin axis will scan the earth over one portion of the spin

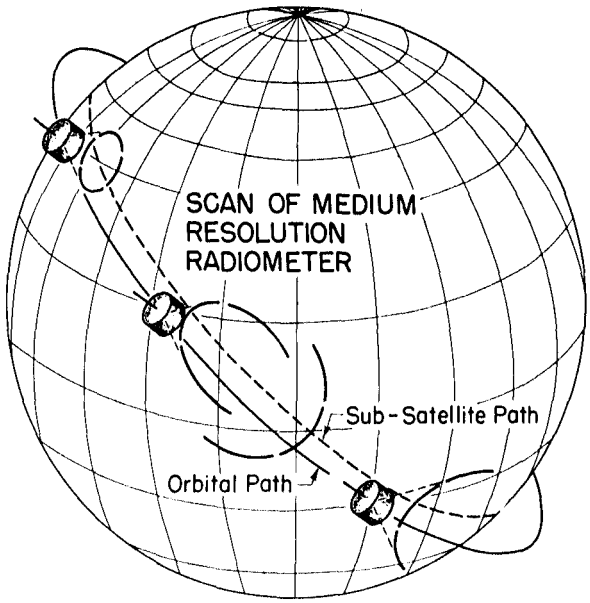


FIGURE 16–12.—Geometry of the scanning motion of the five-channel radiometer.

cycle, and over the other portion it will look into outer space. After this beam has turned to scan outer space, the other beam which looks out through the wall will start to scan the earth. There are, then, alternative sweeps between the wall side and the floor side during one satellite revolution.

Figure 16–13 shows a typical pattern. This pattern was derived from the 8- to 12-micron channel. It was taken under the condition where the satellite was "sideways;" in other words, the earth was being viewed alternately by the floor beam and the wall beam. The lowest signal level in figure 16–13 results when both beams are looking into outer space. As one side starts to see the earth the signal rises suddenly to a fairly high level. The steep transients at the beginning of the scan and at the end occur as the horizon is scanned. Between horizons the beam scans the earth and considerable detail can be seen. The variation of the signal amplitude is due to changes in the emission from the earth.

In terms of the black body, the minimum temperatures would correspond to about 250° K to 260° K. It is approximately 4 to 5 volts in terms of output of the instrument. The maximum temperatures correspond to very warm spots. Apparently, the instrument is viewing areas of clear skies and senses equivalent black-body temperatures very close to the surface of the earth of the order of 280° K to 290° K, or about 10 volts.

These data can be reduced by converting the signal traces point by point from voltages shown in figure 16–13 to black-body temperatures by means of applying all the knowledge obtained from the calibration curves; then, a map may be plotted by going back to the orientation of the satellite which can be determined from various data provided by the tracking stations. This procedure would be very lengthy. If points were read at reasonable intervals, say, if a scan were divided into 50 points or so for each of the six channels, one orbit would yield several hundred thousand data points. TIROS II has radiated data during a thousand or so orbits. TIROS III is now in its 1,700th orbit. If all the data points from TIROS II and III were combined, there would be approximately a billion data points. Thus, the problem of reducing these data is staggering.

A more sophisticated method of reading, scaling, and presenting the data must be used. This is what is called data reduction. It will be demonstrated that by using high-speed computers, this problem can be solved. The next step is to analyze the data. As a result of the data-reduction process the data are presented to the world meteorologists in various forms ranging from plotted maps to magnetic tapes since various applications in the analysis will call for different forms of presentation. It will apparently take many scientists to exhaust all the material presented in the TIROS radiation maps.

Figures 16–14 and 16–15 give an idea of the data reduction and presentation. The focal point in the diagram shown in figure 16–14 is the radiation data program. Various types of information are fed into this program which is placed in a 7090 electronic data processing machine at the Goddard Space Flight Center at Greenbelt. Included are the radiation data stored on tape in the satellite and transmitted on command playback; these data are recorded at a ground station at the Goddard Space Flight Center and then demodulated. The data are converted into voltage signals and then into actual digital signals on tape. This procedure, thus far, requires the preparation of about three magnetic tapes. The analog signals

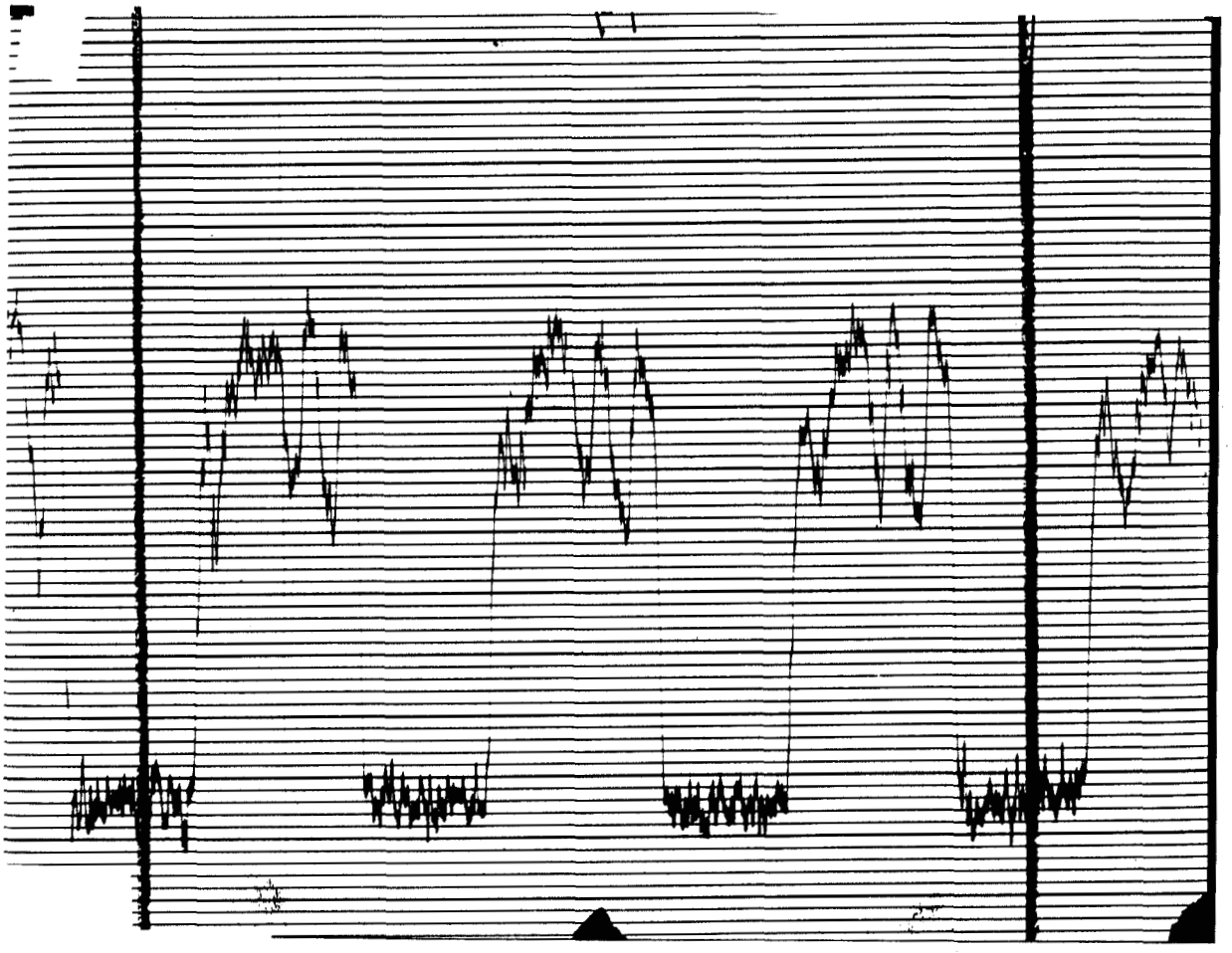


FIGURE 16–13. Oscillogram showing three consecutive sky-earth scans of channel 2 of the medium-resolution radiometer. The amplitude is approximately proportional to the radiant energy received.

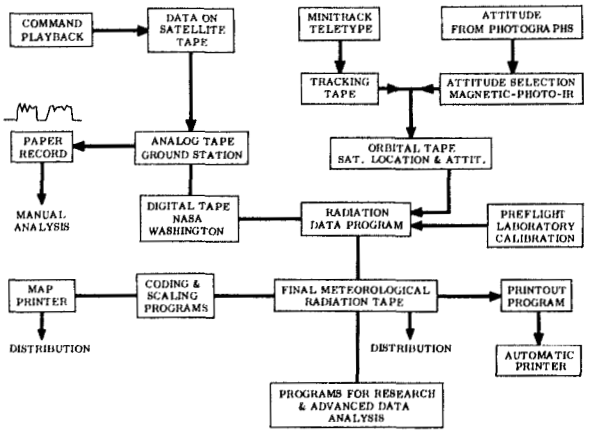


FIGURE 16–14.—Schematic diagram of the flow of radiation data during its course of processing.

can be tapped off before the digital tape is prepared and just for checking purposes one or two scans can be studied every day to see that the satellite is still working properly and to conduct a manual data analysis.

Then, the digital tape is fed into the radiation program. At the same time the tracking information which goes through an orbital program is obtained from the minitrack stations. The 7090 computer also prepares these magnetic tapes and feeds them into this program. In addition, attitude information of the satellite or the orientation of the satellite, which can be obtained by various methods, is fed in. A brief introduction to the methods of attitude information is given in paper 10 in which it is shown, how the magnetic field and gravitational effects on the orientation of the spin axis of the satellite are used to determine the attitude of the satellite. These effects can be calculated and, therefore, the attitude of the satellite can be predicted or calculated if the

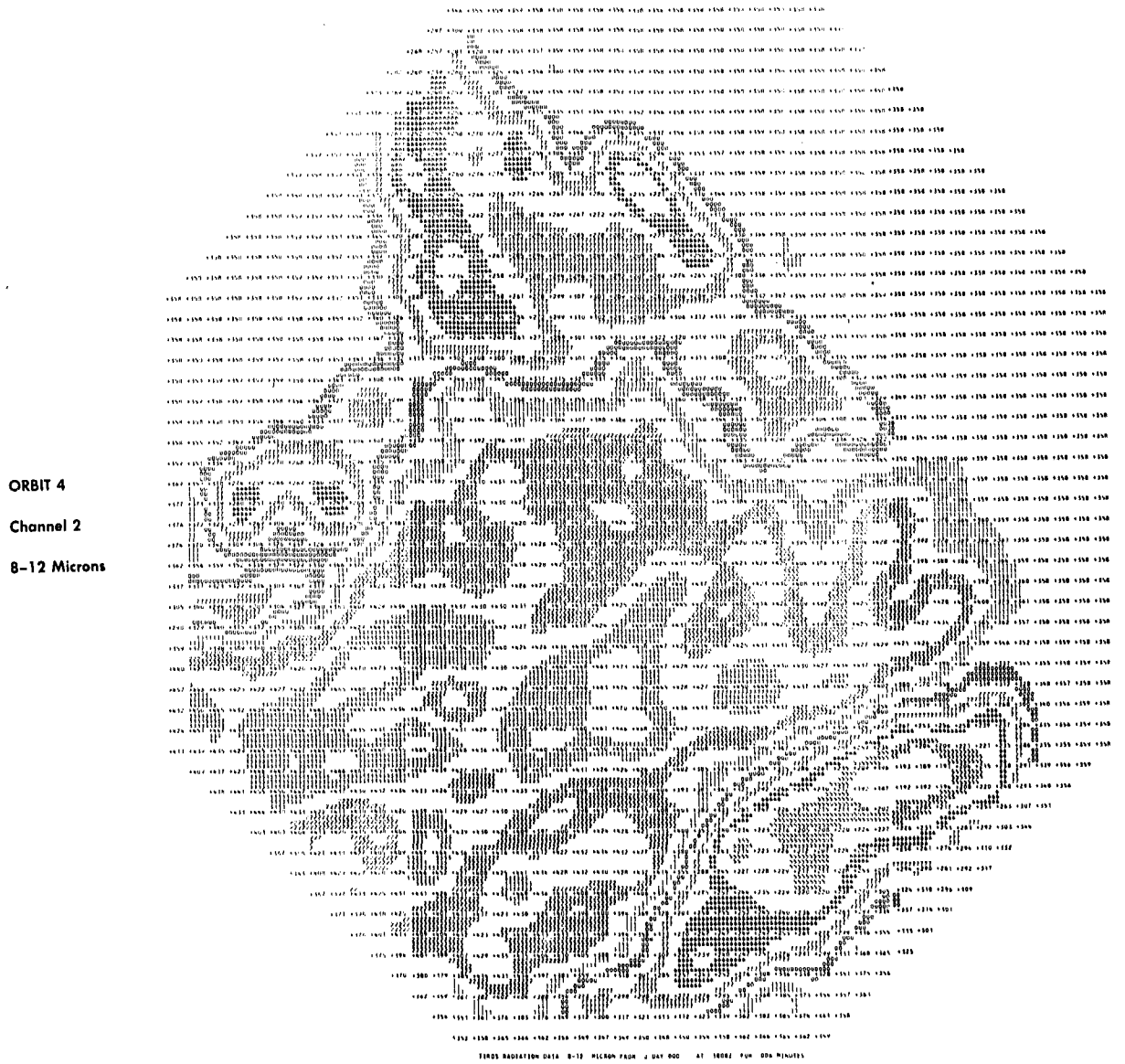


Figure 16–15. Typical map produced by automatic printer through processing shown in figure 16–14. The numbers accompanied by a plus prefix indicate the radiated emittance of the surface of the earth in watts per square meter in a wavelength region viewed by infrared channel 2. A grid overlay must be used to determine the geographic coordinates.

necessary auxiliary information is available. The infrared sensors, as they scan the horizon, can provide attitude information independently. The television photographs can also aid in providing the orientation of the satellite if they show landmarks.

All this orientation information feeds into an attitude program, which in turn, provides an imput to the radiation data program, which then combines all this information and puts out a final magnetic tape. All these stages go through magnetic tapes. Nobody has to punch cards or perform any similar manual chore. Actual patterns of radiation can be obtained from the final meteorological radiation tape by playing it back through a digital computer. The computer is needed in order to print a list of the radiation data as a function of time, location, and angular relationships. A computer program called the printout program performs this listing. At the same time maps may be plotted with another program which performs the scaling and coding necessary to print the data in a geographic grid pattern.

The final meteorological radiation tapes, rather than just being printed or mapped, can also be used for more advanced studies. The radiation maps need not be printed out if interest centers on the total heat budget of the earth. In that case, for instance, the data would be retained on tape and calculations would be programed and performed in the computer on the energy available in the various spectral regions, the radiative transfer of this energy through various model atmospheres, all the complex integrations, and so forth. Only the final data need to be printed. How many programs there could be in order to digest the data presented in this so-called final tape is left to the imagination.

Figure 16–15 shows one sample of the maps plotted from the first 50 usable orbits of TIROS II. The numbers indicate radiation emitted in channel 2, which is the 8- to 12-micron channel, for a given orbit over a certain area of the earth. The radiant emittances from the surface of the earth are expressed in watts per square meter. The geographic location can be established by using an overlay which shows the geographic features of the particular area and then by determining the locations where these points fall. These data are presented and described in reference 3. The particular pattern shown in figure 16–15 was taken with Lake Michigan roughly in the center of the picture. In that area radiation emitted from the earth was about 40 watts per square meter. A photograph taken during this same orbit and pass by the satellite shows that there was a frontal passage over the eastern United States accompanied by an overcast, which was apparently very high with dense clouds because they are bright. This decreases the total radiation emitted over that area of the United States (far right portion of fig. 16–15) by about half of what it is over the cloudless areas to the west.

Many of these maps have been studied. It has been found, for instance (ref. 3), that the infrared radiation emitted from the earth in all channels depends above all on the cloud cover and the water-vapor content of the atmosphere. Clouds and water vapor control in a very remarkable way the total energy leaving the earth and also, naturally, the total energy reflected from the earth.

A very interesting study of three particular cases has been made and is presented in reference 3. The area chosen was over the tropical ocean, off the shore of South America. The sky over this area was cloudless, or as cloudless as can be found. Simultaneous television pictures were available with the data received from the five-channel radiometer and the wide-field radiometer. It was found that the wide-field radiometer agreed very well with the five-channel radiometer in the sense that it showed albedo values comparable to those of the two visible channels. The observed albedo over this ocean area ranges from 5 to 7 percent. This observation was at local noon over a cloudless ocean; the reflected radiation obviously was very low.

The total energy received in the 7- to 30-micron channel, about 80 percent of which is infrared radiation from the earth, shows blackbody temperatures ranging from 250° K to 260° K. This agrees, again, very well with the energies measured by the wide-field radiometer. Thus, the experiment appears to be consistent. However, it is interesting that, even over this clear area, the "window" channel in the 8- to 12-micron region shows temperatures which are about 20° below what is assumed to be the water temperature in that region. Temperatures are about 275° K, definitely under 280° K. This would indicate a great sink of energy. It appears to be somewhat significant since this measurement was taken near an area where just a few days before hurricane Anna had developed.

A more interesting case was found over the desert regions. The area from the Mediterranean into the Indian Ocean was studied for orbit 46 of TIROS III. This case is interesting for the following reason: First, the satellite passes over the Mediterranean Sea, a clear area in a very warm region. Then, it scans the desert, which has very high surface temperatures and low water-vapor content. Over the desert the 8- to 12-micron window channel yields temperatures very close to surface temperatures, around 310° K. This temperature indicates that radiation comes from very near the surface of the earth.

As the satellite traverses the 15th parallel into the tropics, the window-channel temperature drops by about 20° to 25°. It could be

that the surface temperature is somewhat lower in this area. However, a more reasonable explanation is that the water-vapor content increased tremendously in the tropics. This may be determined by looking at the 6.3-micron channel; there, also, the temperature drops by about 30° as the satellite crosses the 15th parallel and passes over tropical Africa. The 7- to 30-micron channel, as well as the wide-field radiometer, shows a very similar behavior. These record about 280° K to 290° K over the African desert and about 260° K over tropical Africa. The albedos in this case show that the desert reflects about 30 percent of the incident sunlight, whereas the vegetated area farther south in Africa reflects about 15 percent of the incident sunlight.

The same values were measured in the first case where the satellite passed over the coastline of South America (albedos of about 15 percent) and in another case studied over the United States (orbit 4, TIROS III). Over Michigan, Indiana, and Illinois with clear skies, about 15 to 16 percent of sunlight reflected. On the same pass farther south, near Kentucky, over dense clouds, as much as 50 to 55 percent of sunlight is reflected. That was one of the brightest large-area clouds found in the TIROS pictures. The maximum albedo values occasionally measured over smaller clouds have been near 65 percent. Albedo values over 70 percent have never been observed.

The radiation data presented here were intended only to give an understanding of the experiment. The meaning of these data in terms of a better understanding of the atmosphere and of an application to large-scale meteorological observation is given in subsequent papers. The potential contained in the TIROS radiation measurements will probably not be exhausted for many years.

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Question Period

MCCULLOCH, Canada: I would like to ask whether there are any plans for investigating the ultraviolet and X-ray ranges with a view toward determining any information on, for example, solar variability and perhaps its relationship to terrestrial weather?

NORDBERG: This question has been posed to us by many people. Particularly, suggestions have been made to monitor continuously the solar intensity in various bands in the ultraviolet and visible portion of the spectrum. We have never considered X-rays. But in the visible and ultraviolet, particularly in those spectral regions that are responsible for creating ozone and for destroying it, we have thought that it would be interesting, for instance, to look at the Hertzberg bands which are responsible for creating ozone, and then, say, at the Hartley or some of the other bands instrumental in destroying ozone. The change in ratio between these bands could cause changes in the ozone distribution and therefore influence the heat budget of the earth. At the moment we are not considering such experiments for meteorological satellites because, for instrumental reasons, they are better suited for the astronomical observatory types of satellites that NASA is planning.

At this time there is a plan to monitor the radiation of the sun over almost the whole spectrum, from very far in the ultraviolet into the visible, on one of the NASA astronomical observatories. If these results show any interesting avenues, it will certainly be worth while to consider the inclusion of such experiments on meteorological and geophysical satellites which are generally designed to look at the earth and are not the best suited vehicles to carry sensors to observe the sun; the solar observatory and astronomical satellites, of course, are designed for that purpose. Maybe there will be good reason to combine the measurements from the two programs.

JAMES, United Kingdom: I would like to ask Dr. Nordberg about the equations he wrote for determining the parameters when calibrating the radiation instruments. Are they satisfactory for a satellite?

NORDBERG: I can give a quick answer to your question. The equations that were written down are for steady state. They do not use a time variation. The time constant of the instrument was measured in the laboratory, and this is another one of these extraneous calibration procedures that we have to go through. It turns out that this instrument, the wide-field radiometer, has a time constant of up to 1 to 1½ minutes. This is not very good if you want to get a fairly high resolution. But, on the other hand, this instrument has not been designed for high resolution. In comparing this instrument with the very fast responding five-channel instrument, the data still agree very well when we consider time and space averages.

If the satellite passes over an area of rapidly changing radiation features, such as in the African case I mentioned, in which the satellite starts out over the Mediterranean Sea, then passes over the desert, and finally passes over tropical areas, the time constant of the wide-field radiometer produces a time lag with respect to the faster responding five-channel instrument.

So it is true; one cannot get a high resolution in time with this instrument just as one cannot get a high resolution in space with this instrument. This is a very crude instrument. Even though it is so crude, it yields a good deal of useful data over the time that it sees the earth.

17. APPLICATION OF TIROS DATA TO RADIATIVE PROCESSES IN THE ATMOSPHERE

By D. Q. WARK, *Chief, Physical Meteorology Section, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

In paper 16 some of the problems in interpreting the data from the TIROS five-channel radiometer are indicated. The following discussion may explain in some detail the meaning of at least one of the readings from the five-channel radiometer.

Specific intensity is the energy crossing a unit area in unit time, and, in this case, per unit frequency interval. This quantity is proportional to the quantity measured by TIROS because the satellite sensor field of view is a very narrow angle; all the radiation within the field of view leaves the earth in approximately the same direction with a certain specific intensity. However, the quantity actually measured is expressed by the following equation:

$$I(\Theta)=\int_0^\infty I_\nu(\Theta)\Phi_\nu d\nu$$

where $I_\nu(\Theta)$ is the specific intensity at frequency ν and at zenith angle Θ, and Φ_ν is the filter function.

In order to determine the relation between this integral and the simple integral of intensity over all wavelengths, data calculated on the basis of 100 model atmospheres, taken from radiosonde observations, were used. The outgoing intensity from the top of the atmosphere was calculated by using these data; then, by empirical methods the relation between the TIROS measured quantity and the true intensity from the earth was determined.

Only channels 2 and 4 are discussed herein. Channel 2 is in the 8- to 12-micron water-vapor window and is intended to measure surface temperatures or temperatures of cloud tops. Channel 4, on the other hand, is intended to measure the total outgoing radiation for purposes of heat balance. However, the filter function is not flat through the entire spectrum as shown in paper 16 and, in fact, does not include the entire infrared spectrum. There is a degree of incompleteness; there is radiation which is not observed at all. Therefore, the calculated values based on 100 atmospheres have been used to find a very important relation which is shown in figure 17–1. Plotted on the abscissa is the specific intensity through the channel 4 filter; that is, equation (1) where the channel 4 filter function has been applied. The ordinate is the integrated specific intensity, unfiltered over all wavelengths. The intensity has been calculated at several angles inasmuch as it is a function not only of wavelength but also of the angle from the local vertical. Figure 17–1 shows mean lines for sec $\Theta=1$, which is the local vertical, sec $\Theta=2$, which is 60° from the local vertical, and sec $\Theta=5$, which is about 78.5° from the local vertical. These mean lines give the relation between the measured value, or a quantity which is proportional to the measured value, and the true specific intensity. The scattering of points about the mean lines is very small, less than 1 percent at any one of these angles. From figure 17–1, then, the intensity at a given angle can be determined.

However, in channel 4 the determination of total flux is desired. Total flux into a hemisphere is defined as the intensity integrated over that entire hemisphere. Thus, in order to distinguish the total flux from a measurement of intensity, the variation of intensity with zenith angle must be known. This variation has also been calculated for the 100 atmospheres, and in figure 17–2 the normalized intensity is shown. In this figure the intensity in a given direction $I(\Theta)$ is divided by the intensity in the local vertical $I(0)$ and plotted against the zenith

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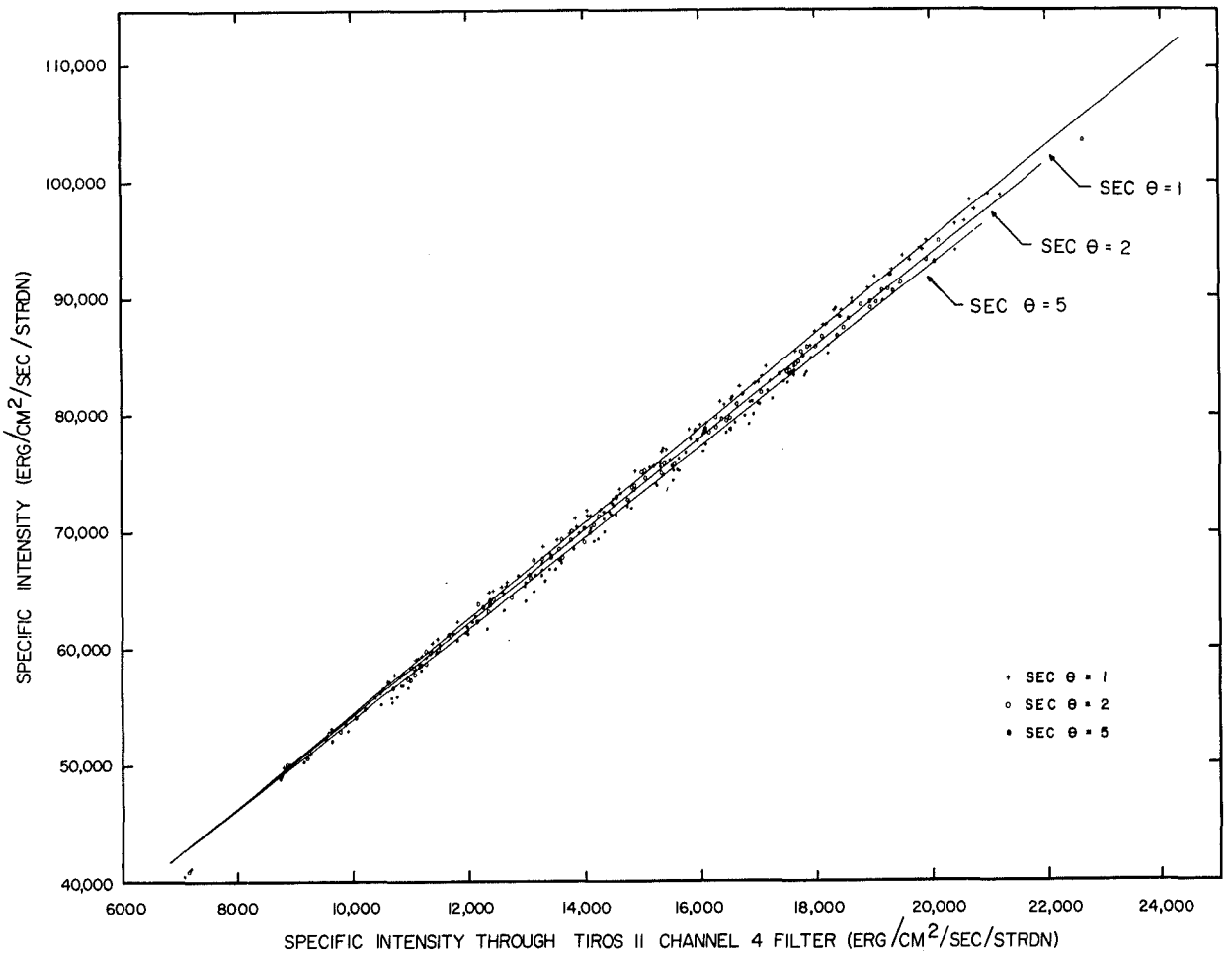

FIGURE 17–1. Total outgoing specific intensity in direction θ from the local vertical plotted against the same quantity after passing through the TIROS II channel 4 filter. The plotted points represent the calculated values for 100 model atmospheres, with sec θ=1, 2, and 5.

angle Θ, the angle from the local vertical. For various atmospheres different relations are obtained. For example, the measurements at 50° for atmospheres 6 and 2 are totally different. Therefore, flux cannot be inferred from a single measurement of intensity. Atmosphere 1 is a winter arctic atmosphere with a surface inversion; atmosphere 2 is a case with high thick overcast cloudiness; atmosphere 3 is a spring arctic case; atmospheres 4 and 5 are moist midlatitude cases; and atmosphere 6 is over Albuquerque, N. Mex., where the moisture was aloft rather than near the surface. The mean value for 100 cases is shown by the heavy line. Methods have been devised whereby the TIROS value of intensity can be used to obtain the proper angular dependence. All the curves in figure 17–2 have about the same shape; the position along the ordinate depends upon the absolute value of intensity. Thus, it is possible to obtain the flux, within very narrow limits, from the measurements recorded by TIROS.

Techniques are being devised to use the measurements from channel 2, the 8- to 12-micron region, to obtain temperatures. But, as shown in paper 16, the temperature value is difficult to obtain because of the absorption by water vapor and by the 9.6-micron ozone band. Thus, although the black-body temperature of the surface is desired, perhaps only 50 to 90 percent of the radiation leaving the surface actually arrives at the satellite. The rest of the radiation received by the satellite originates within the atmosphere, either from the water vapor or from the ozone.

There are other problems which have not

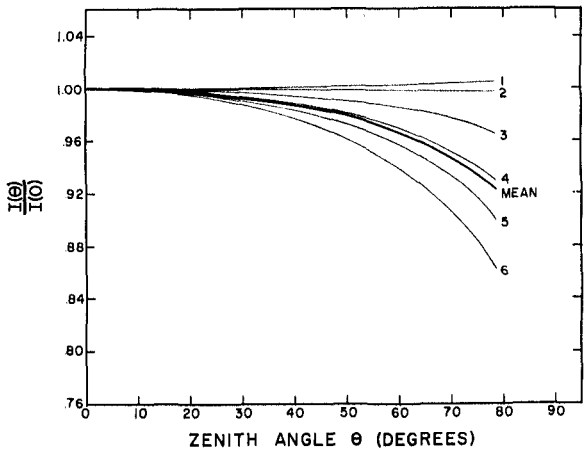

FIGURE 17–2. Limb-darkening for TIROS II channel 4. The ratio of the total specific intensity in the direction θ from the local vertical to that in the local vertical is plotted against θ for values up to sec $\theta=5$. The mean curve is from 100 model atmospheres. The other curves are: (1) Isachsen (79 N., 104 W.), February 21, 1958, clear skies and large surface inversion; (2) El Paso (32 N., 106 W.), March 1, 1958, overcast at 400 millibars; (3) Mould Bay (76 N., 119 W.), April 1, 1958, clear skies and small surface inversion; (4) Green Bay (44 N., 88 W.), October 24, 1958, overcast at 700 millibars; (5) Albany (43 N., 76 W.), August 1, 1958, overcast at 930 millibars; (6) Albuquerque (35 N., 107 W.), July 11, 1958, clear skies and high humidity aloft. This figure indicates the correction to be made for the angle of the outgoing radiation.

been studied as yet. These include the emissivity, or blackness, of the surface being viewed and the radiation from particles which might be in the atmosphere. Also, there is still some uncertainty about the absorption of radiation by water vapor in the atmosphere window. However, the calculations of intensity have been made using the best spectroscopic data available.

Figure 17–3 shows the same relation for channel 2 as that given in figure 17–1 for channel 4. Equation (1), with the channel 2 filter function being used, is again plotted along the abscissa. Because the total intensity over all wavelengths is no longer of interest, the limits of the integrated intensity (the ordinate) have been taken as 814 to 1,325 cm^{-1} by using these limits the channel 2 measurement can be transformed to the total radiation which a black body would have between the limits 814 to 1,325 cm^{-1}. These limits were chosen to give a minimum scatter of the data points; this was done by trial and error. Two cases are shown: sec $\theta=1$, which is in the local vertical, and sec $\theta=5$, at 78.5° from the local vertical. Very little angular effect can be seen.

The contributions from water vapor and ozone are now discussed. Although the problems of emissivity and radiation by particles are not solved, information gained in studying water vapor and ozone is useful in attacking these problems.

Figure 17–4 shows the specific intensity plotted against the ozone correction. This correction is the difference between the specific intensity for the true atmosphere and that for an atmosphere which would contain no ozone. The relation is roughly linear. There is a fair amount of scatter in the data points because the relation between the surface temperature and the ozone content and distribution is not a 1-to-1 relation; also, the ozone-layer temperature affects the intensity. An interesting feature is that the line crosses the abscissa at about 6,000 ergs per square centimeter per second per steradian. The inference is that if the surface were cold enough, it would be colder than the ozone layer. The ozone correction values indicated by this line should be valid within very small limits if the correct amounts and distributions of ozone have been assumed.

In figure 17–5 the water-vapor correction is plotted against the specific intensity between 814 and 1,325 cm^{-1}. This correction is the difference between the specific intensity of the atmosphere and the specific intensity of a water-free atmosphere. The correction is near zero for very low intensities because the water-vapor content is very low for very low surface temperatures; the correction increases sharply as the intensity increases because water-vapor content rises sharply at high temperatures. The curve would probably level off at even higher values of intensity because these would probably be found only over deserts, where the water-vapor content is low.

The scatter of data points is large because the water-vapor content does not have a 1-to-1 relation with the surface temperature. In fact, there are some negative corrections. These are due to inversions, where the water vapor is contained in a layer which is warmer than the surface. Figure 17–5 indicates that the inferred surface temperature must be adjusted from 0°

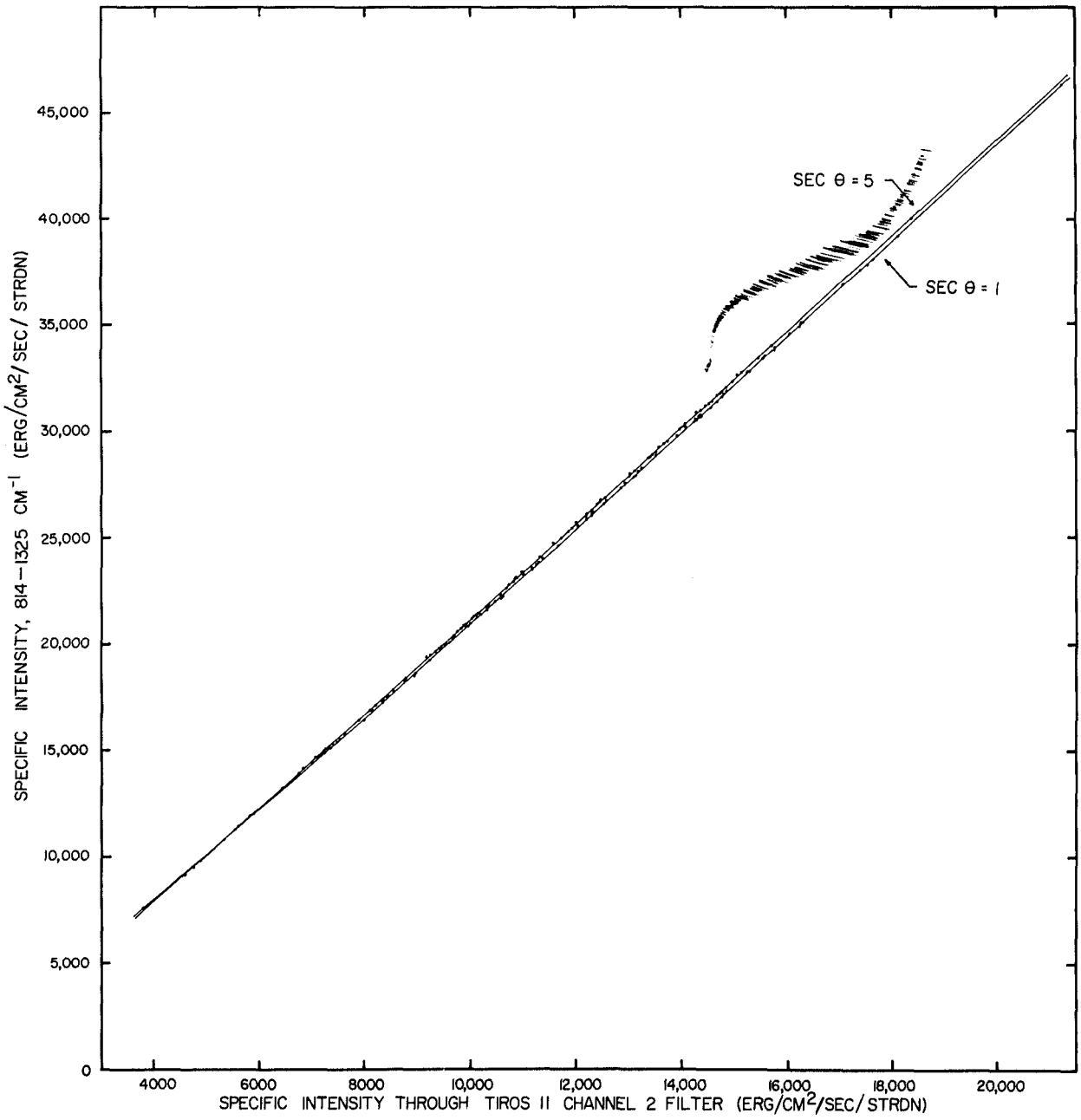

FIGURE 17–3. Outgoing specific intensity over the interval 814 to 1325 cm^{-1} (12.3 to 7.5 microns) in direction θ from the local vertical plotted against the total specific intensity after passing through the TIROS II channel 2 filter.

to more than 10°. In paper 16, it was indicated that there might be corrections of as much as 20°. In this investigation, however, corrections of about 12° to 14° from ozone and water vapor are indicated.

An illustration of how the measurements from TIROS are correlated with the empirical data of figure 17–1 is given in figure 17–6, which shows a weather map of North Africa, the Mediterranean, and southern Europe, for 1200 GCT, November 29, 1960. There is a low-pressure area in Yugoslavia, a front from the heel of the Italian boot to about Tripoli, a high-pressure area over the Iberian Peninsula, and a high-pressure area over Egypt and Libya.

Figure 17–7 shows a TIROS II composite picture over the same area. These pictures were obtained at the same time as the radiation data.

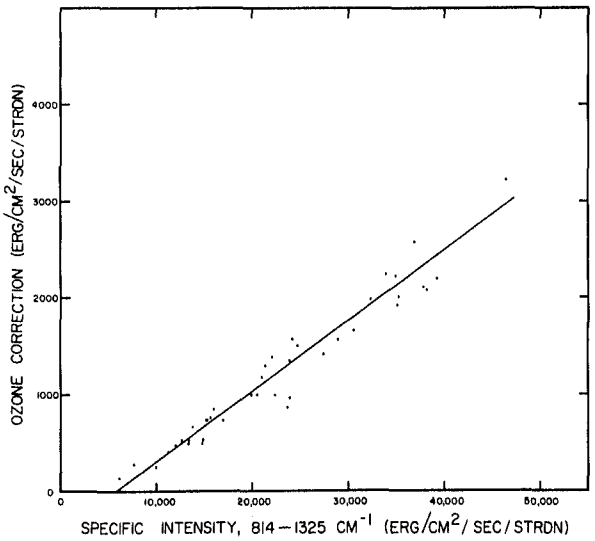

FIGURE 17–4. Ozone correction to be applied to the TIROS II channel 2 data plotted against the 814 to 1325 cm^{-1} interval specific intensity. The points indicate the quantities to be added to obtain the intensities which would be found in the case of an ozone-free atmosphere.

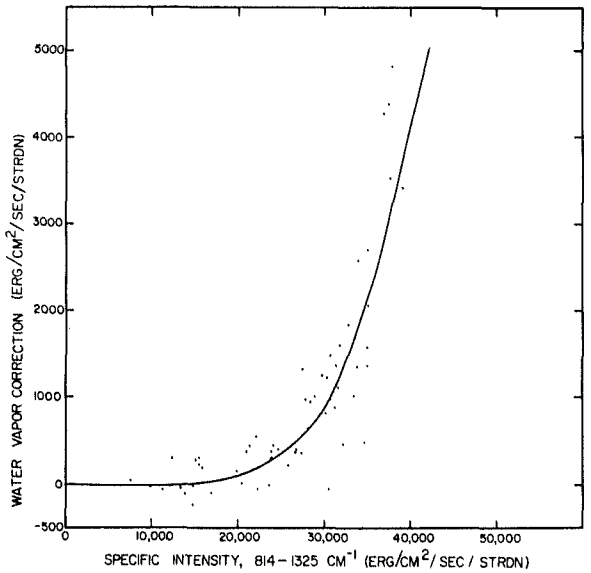

FIGURE 17–5. Water-vapor correction to be applied to the TIROS II channel 2 data plotted against the 814 to 1325 cm^{-1} interval specific intensity. The points indicate the quantities to be added, after the ozone correction, to obtain the intensities which would be found in the case of an atmosphere free of water vapor.

Between Italy and Tripoli, where the front lies, there is only a weak indication of clouds, as though there might have been cirrus or scattered clouds. But, to the west, in the trough over Sardinia and western Algeria, there are very dense clouds. In addition, there is a patch of very dense clouds lying over southeastern Spain. The coast of Africa is outlined from Tunisia to Cirenaica; south of the coast is supposedly cloudless desert, which has high albedo.

In figure 17–8 is shown the upward flux, in langleys per minute, derived from the information in figure 17–8. The flux has not been corrected for limb darkening, that is, the variation of the intensity with angle; figure 17–8, therefore, contains errors of up to 10 percent in some of the absolute values.

Along the front near Tripoli, the value is about 0.32 langley/min; in the trough behind the front, the values decrease to 0.28 langley/min. In addition, it is very interesting to note that southward over the Algerian desert values of upward flux of 0.28 langley/min and even of 0.26 langley/min are obtained, which indicates that the trough behind the front is active well into the desert. In the patch of cloudiness over southern Spain the value is 0.26 langley/min, and the low which lay over Yugoslavia is indicated by the 0.26 value, which is at the edge of the data. The maximum value is about 0.42 langley/min over the Sudan, which is what would be expected over rather warm areas. Values as low as 0.20 in some other cases examined are also consistent with what might be expected. The channel 2 data vary by a factor of about three from the minimum values to the maximum values, which is commensurate with the results from channel 4.

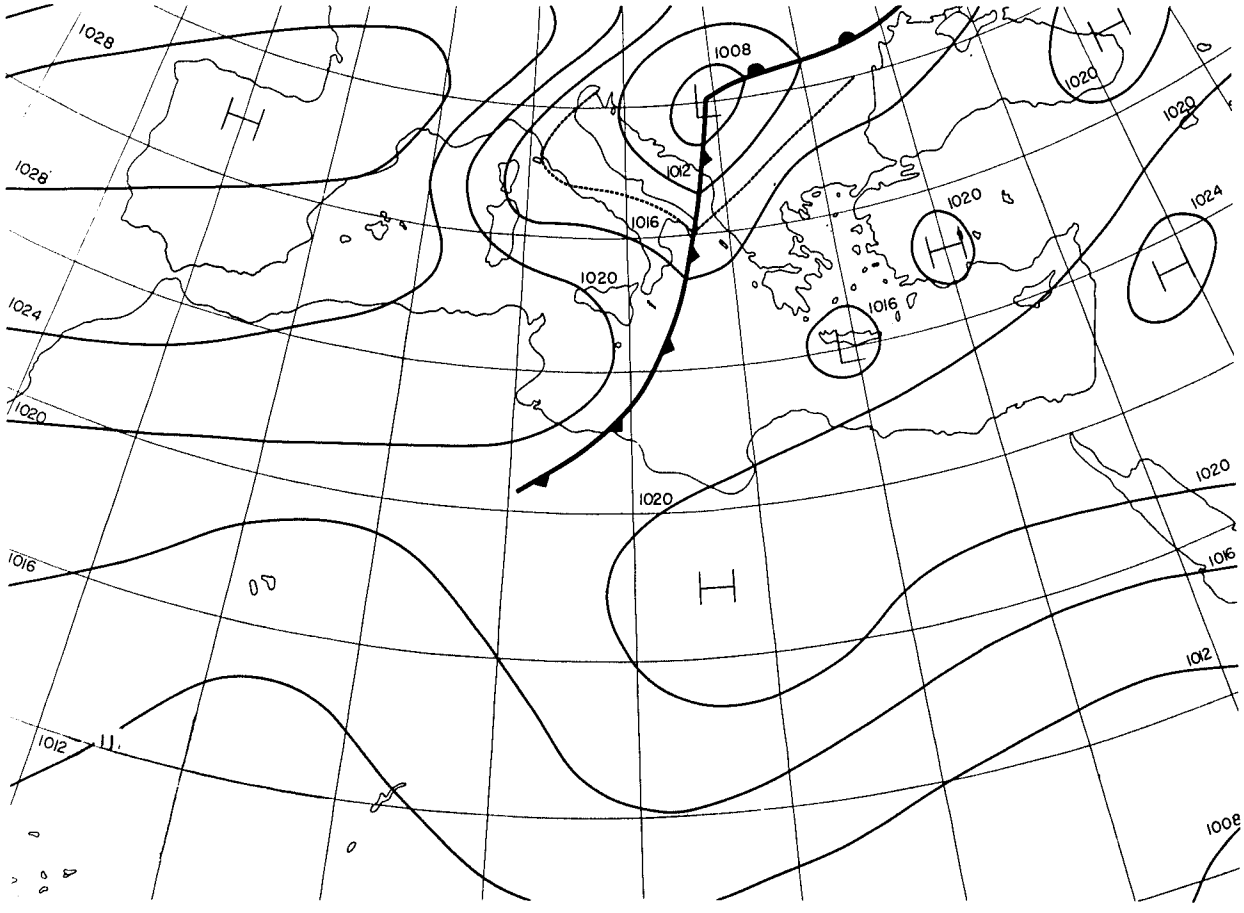

FIGURE 17–6. Surface weather chart for 1200 GCT, November 29, 1960.

FIGURE 17–7. TIROS II nephanalysis and composite of pictures taken from orbit 87 between 0957 and 1013 GCT, November 29, 1960.

FIGURE 17–8. TIROS II radiation chart showing the total upward flux in langleys per minute over the same area shown in the photographs of figure 17–7. No limb-darkening corrections were made.

18. APPLICATION OF RADIATION DATA TO SYNOPTIC ANALYSIS AND TO STUDIES OF THE GENERAL CIRCULATION

By Jay S. Winston, *Chief, Planetary Meteorology Section, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

Some of the maps of radiation data presented in previous papers illustrate applications of these data for synoptic usage. For the most part data obtained in the 8- to 12-micron window region, channel 2 of the Tiros radiometers, will be used synoptically. As data become available from the other channels, the broad infrared and the reflected solar radiation measurements will be more useful for studying the overall heat budget of the earth and its atmosphere and the general circulation.

The synoptic usage is considered first. Figure 18–1 is an example, given in reference 1, of radiation data for the 8- to 12-micron window region obtained in a pass of Tiros II across the Atlantic Ocean. These data are expressed in terms of effective radiating temperature in ° C. The isopleth interval is in terms of radiative intensity; thus, the isotherms are labeled −10°, −17°, −25°, and so forth. There is not an equal thermal difference from one isotherm to another. The wide variations in temperature are of interest in figure 18–1 (the letter *C* indicates cold and the letter *W* indicates warm). Note the very cold values in the northern section of the occlusion in the middle Atlantic where there was a rather intense low and a well-developed upper low center. The warmer values farther south along the front are still a little cooler than some adjacent regions. The warmest area is found to the west of the front. A very cold area is found at the western edge of the data, the forerunner of another wave cyclone developing to the west. The temperature pattern of the frontal system approaching Europe is not nearly so well defined as those of the other frontal systems in the central and western Atlantic. Actually, a warm axis is found near this frontal zone, with lower temperatures extending northward just east of the front and also some cold areas north of the warm front. In general, the relationship is not a very classic one, if it is assumed that cold values signify moderately high clouds and warm values signify clear to scattered clouds or low broken to overcast clouds. The data can thus show differences in frontal structure and, combined with cloud pictures, could be very useful. Unfortunately, no cloud observations are available for comparison with this radiation chart.

Most of the preliminary studies to evaluate these data in detail should be over areas where there are rather good conventional synoptic data. An example of such a study of an orbital pass over the United States is presented in figure 18–2. These data obtained on November 23, 1960, at about 1810 GMT are again for the 8- to 12-micron window region. The temperatures are expressed in terms of ° K. The isotherm interval is 10° K; the dot-dash lines are intermediate 5° K isotherms. These same data in analyzed printout form were presented in paper 16. The present analysis was prepared from the unsmoothed data before the machine printout data were available, so there are differences between this analysis and the machine version which result from differences in smoothing and locating the data points. An important feature of interest is along the frontal zone near the east coast of the United States where very low values of radiation were obtained (fig. 18–2). This front was nearly stationary with wave developments along it. The lowest radiation temperature values tend to be mainly southeast of the front. Note the sharp gradient of temperature to the north and west of the front. Generally, there are high temperatures from

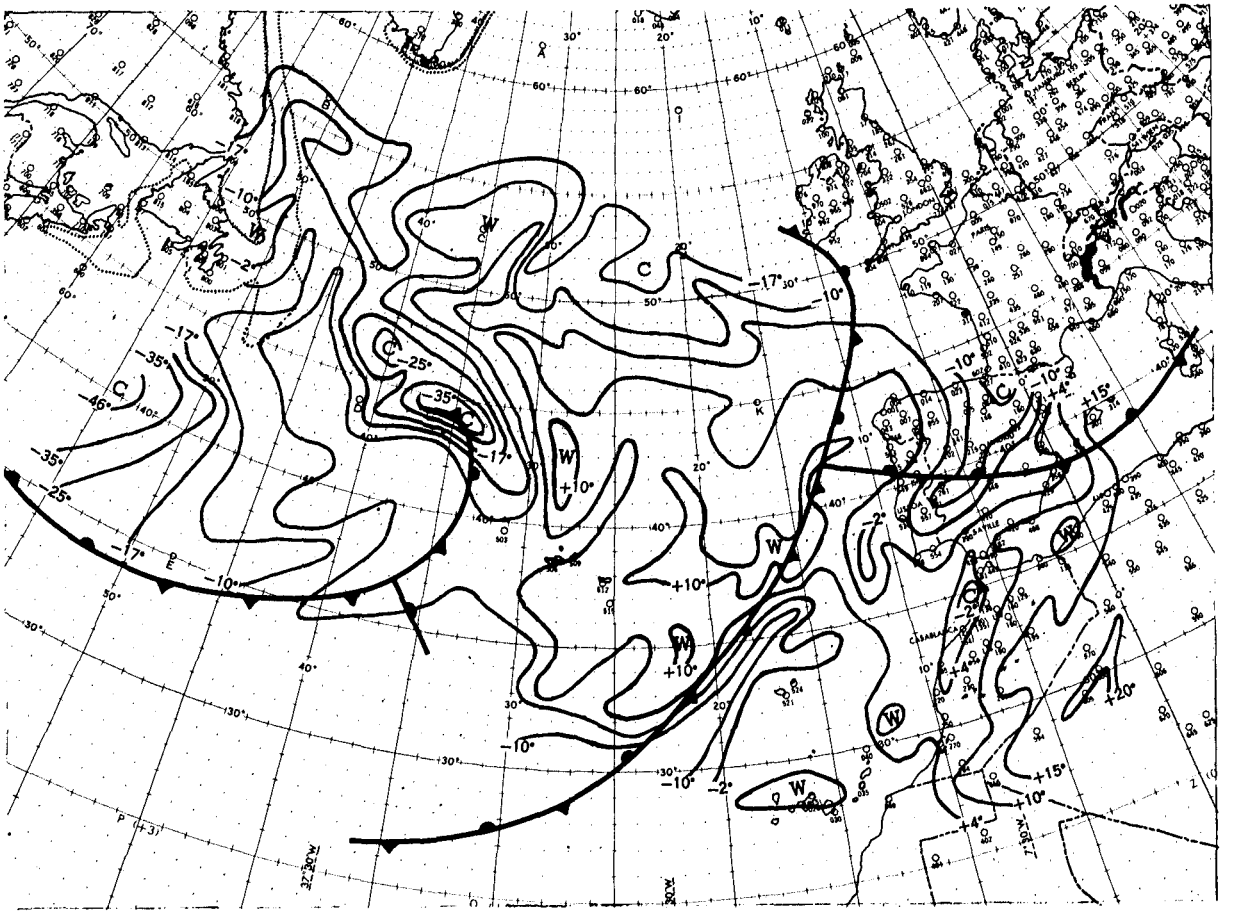

FIGURE 18–1. Radiation data 8- to 12-micron region obtained by TIROS II. Temperature in ° C.

the Appalachian Mountains to the central part of the United States. The temperature gradients throughout this region are relatively small. Farther west over the Great Plains and Rocky Mountains more complicated patterns are found.

Figure 18–3 is a cloud chart based on conventional data only. (TIROS II pictures were available for this time but were rather poor.) This chart was based not only on surface data but also on radiosondes, pilot reports, and vertically pointing cloud radar at one station (Washington, D.C.). It shows not only areas of overcast, broken and scattered clouds, and clear skies but also an analysis of the heights of cloud tops in the broken and overcast areas. Only three contour lines have been drawn: 30,000, 10,000, and 5,000 feet. It is interesting that the very lowest radiation values were in the area where the tops of the upper cloud layer of an extensive multilayered cloud system were more than 30,000 feet. Pilots reported heights of 33,000 feet or more in this area. Furthermore, the area of rainfall nearly coincided with the zone of the highest cloud tops and lowest radiation temperatures (i.e., less than about 250° K).

Note the very abrupt change in cloud height over the region near 39° north and 75° to 80° west from the high cirrostratus above 30,000 feet to a layer of altostratus-altocumulus with tops at about 15,000 feet and then to broken and scattered stratocumulus clouds at about a hundred miles to the northwest. The radiation gradient (fig. 18–2) was extremely strong in this region, showing a very sharp change from low to high values over Pennsylvania, where the clouds become scattered stratocumulus and then the skies clear toward the northwest. In the Midwest (Mississippi and Ohio River Valleys, Great Lakes, and eastern Great Plains) satellite-measured temperatures were within

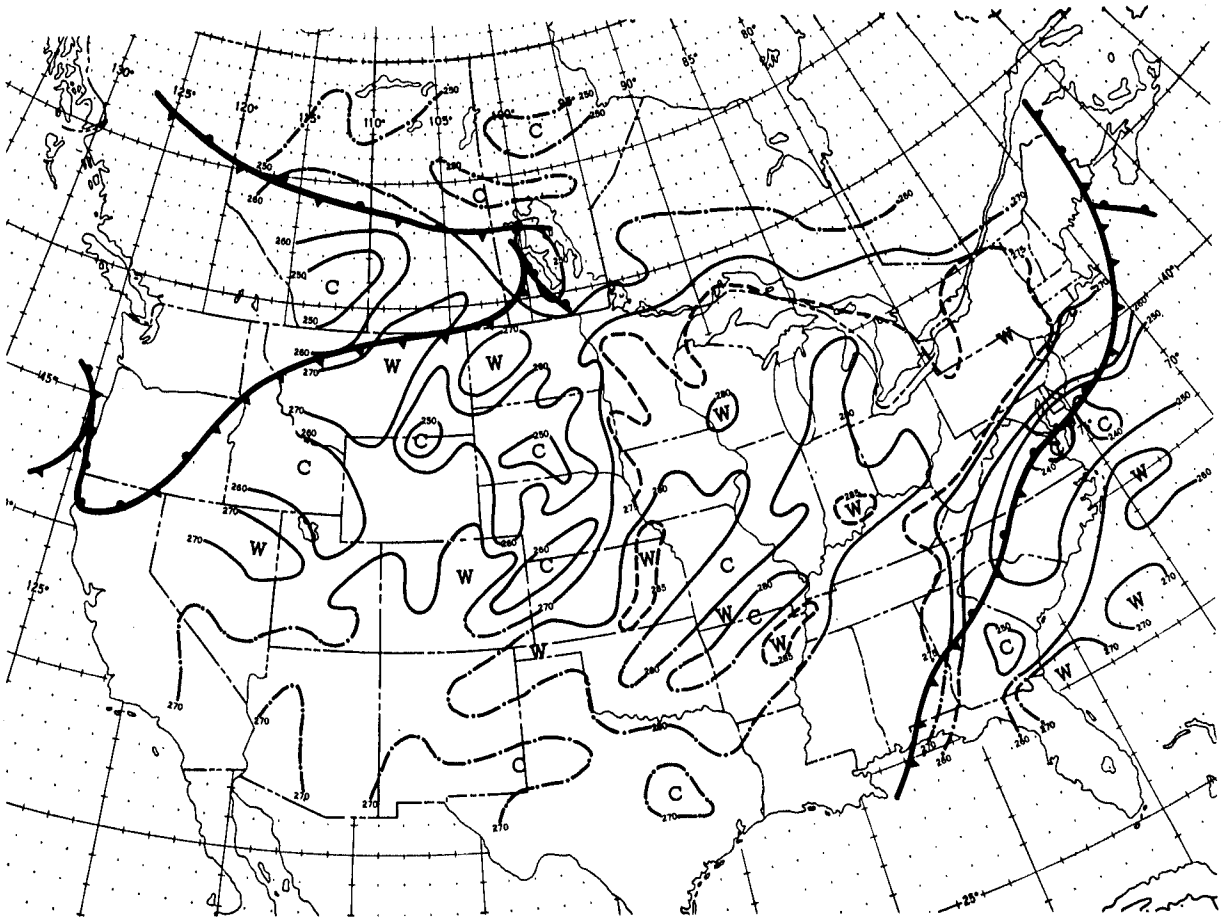

FIGURE 18–2. TIROS II radiation data 8- to 12-micron region, 1810 GMT November 23, 1960. Temperatures in ° K.

about 1° to 5° K of the surface air temperatures for this time of day, near local noon on November 23, 1960. An interesting area over the Great Plains (the Dakotas, Nebraska, and Wyoming) was covered by cirrus and cirrostratus clouds which apparently were rather thin. Underneath this cirrus and cirrostratus was an altostratus cloud layer with tops estimated to be about 18,000 feet. This is the area where two cold centers are shown in figure 18–2. These roughly coincide with the shape of the altostratus cloud area underneath the cirrostratus (fig. 18–3).

Figure 18–4 shows estimates of the heights of the tops of clouds derived in part from the satellite temperature values of figure 18–2 and with the aid of the vertical temperature distribution. The temperature distribution of the standard atmosphere could possibly be used, but on the average a better estimate can be made over most of the Northern Hemisphere by use of isotherm charts prepared daily in the National Meteorological Center for several constant pressure surfaces. In many areas these may be crude estimates, but in other areas they are rather good. Over the United States for this date (November 23) analyzed isotherm patterns were used at several constant pressure surfaces to obtain crude "soundings" at many points within this pattern of satellite temperatures. Entering each sounding with a satellite temperature value from figure 18–2, a height value was obtained for each point. These are the heights shown in figure 18–4. Note that over the high cloud area in the eastern United States heights of 27,500 feet or more were obtained. Between this region and Pennsylvania there is a sharp drop in heights to 5,000 feet or less, which generally agrees with figure 18–3. Southwestward along the frontal zone the heights continue relatively high, but then there is a very sharp decrease to 5,000 to 10,000

feet over the south (Georgia and Alabama). This region is still overcast, as may be seen in figure 18–3, but the overcast consists of stratocumulus clouds with tops around 5,000 to 10,000 feet which agree well with the estimates made from the radiation data. In the area of scattered clouds or clear skies, these height values shown in figure 18–4 essentially do not have much meaning. They generally give rather low values, which are close to the surface of the earth. Over the Dakotas the maximum values are 17,500 feet. In other words, the satellite seems to be "looking" through the cirriform clouds (shown in fig. 18–3) to the tops of the altostratus. The cirrus and cirrostratus are apparently rather thin and are not absorbing and emitting much radiation in the window region.

Returning to the area of high clouds near the east coast, the height estimates from the satellite measurements are only about 22,000 to 28,000 feet, whereas heights of 30,000 to 33,000 feet were estimated from the pilot reports and other data. Since the cirrostratus clouds were rather thick, about 7,000 feet, the heights derived from the satellite temperature values correspond to the lower parts of the cirrostratus (or slightly below their bases). Thus, the cirrostratus clouds were only partially transparent to infrared radiation and were making a substantial contribution to the infrared radiation in the window region as measured by the satellite.

In summary, this case definitely illustrates that the radiation data in the water-vapor window can be very useful for approximate cloud-

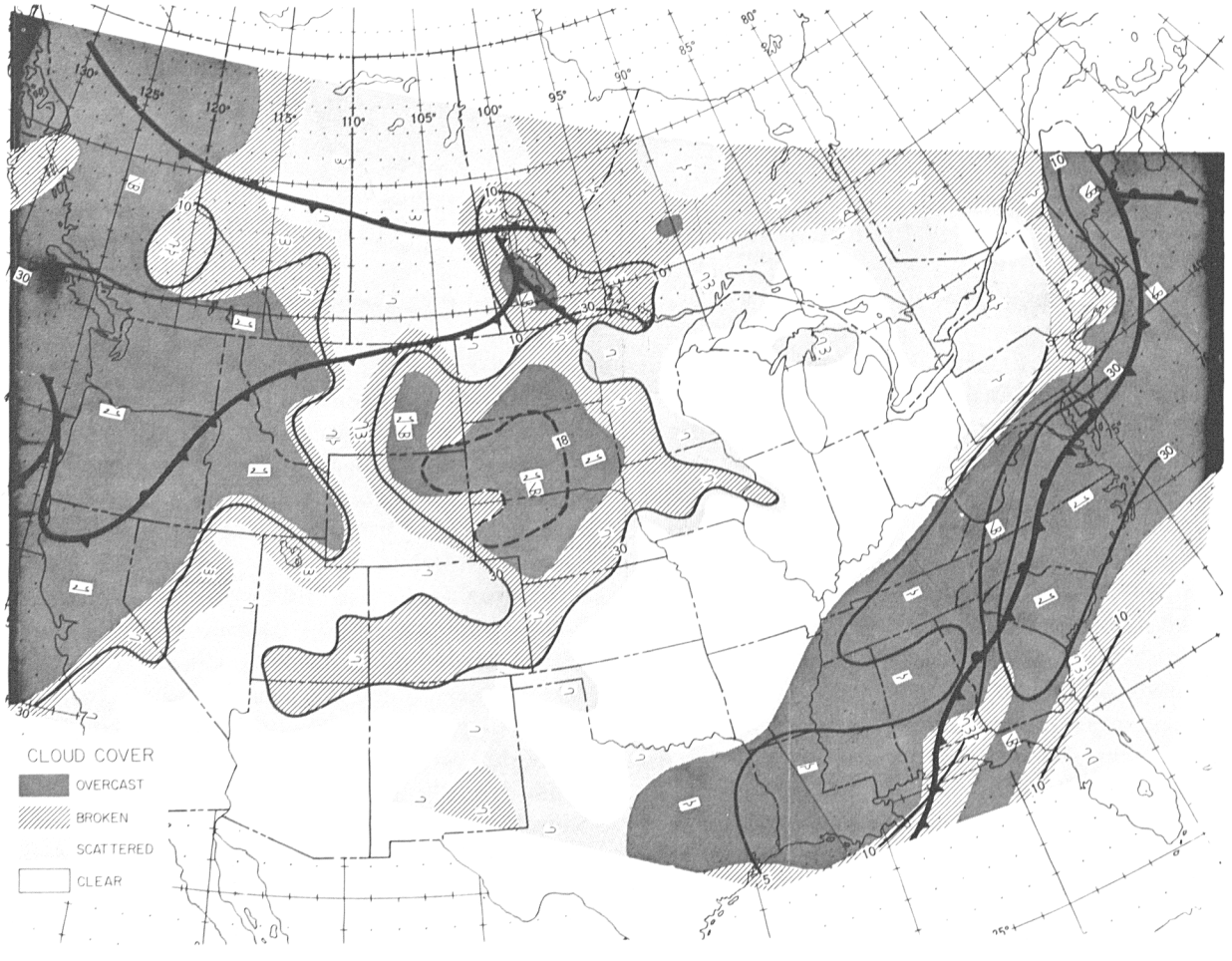

FIGURE 18–3. Cloud cover chart for 1800 GMT, November 23, 1960. Solid lines are contours of heights of cloud tops in thousands of feet.

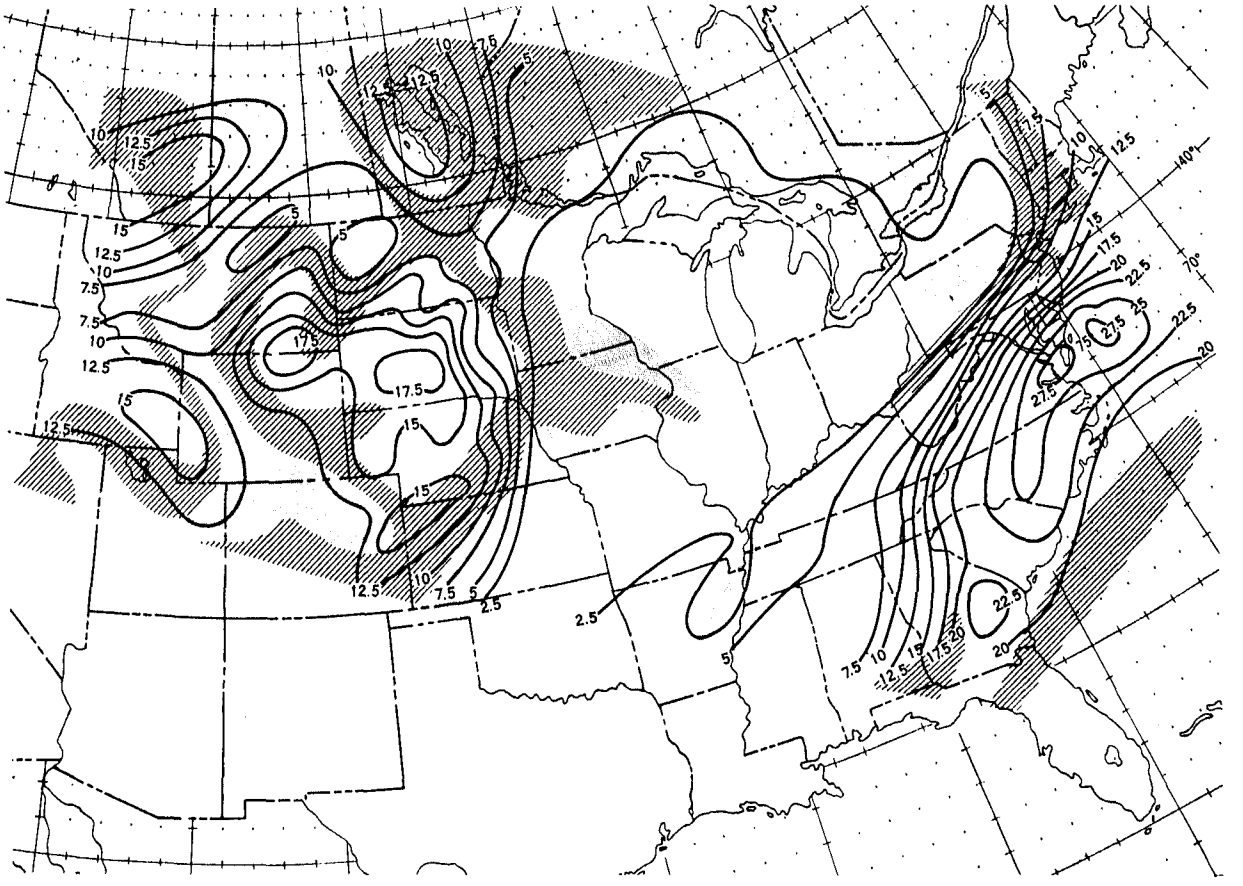

FIGURE 18–4. Heights of cloud tops (thousands of feet), 1800 GMT, November 23, 1960, as estimated from TIROS II radiation measurements. Hatched areas are the broken clouds of figure 18–3; dotted areas are the scattered clouds of figure 18–3.

top determination both night and day. In the daytime these data would be most useful in conjunction with satellite pictures. At night these data would be the only information on cloudiness available and would at least be useful for detecting extensive middle and high cloud systems.

The question of how these radiation data will be used as they are gathered over large areas of the earth and over longer time periods is the basic problem. It is expected that the capability for measuring the global heat budget in more detail will be increased. Then, a knowledge of the behavior of broad-scale heating and cooling will aid in determining how the atmosphere responds on a broad scale to this heating. Work thus far in this area has been to prepare for the time when these heat-budget measurements will be available. Investigations of some energy parameters in the atmosphere have been started. A brief discussion of this work follows.

Figure 18–5 shows a way of characterizing the energy cycle in the atmosphere. (See ref. 2.) This characterization, although applicable to the whole atmosphere in the strictest sense, must for practical purposes be treated as it applies to various portions of the atmosphere. Essentially there are only two basic forms of energy: kinetic energy and potential energy (the latter actually includes the internal energy when the entire atmosphere is considered). It is well known that the amount of potential energy is much larger than the kinetic energy and only very small changes in potential energy can produce all the changes that would ever occur in the kinetic energy. It is more convenient to deal only with that part of the potential energy which is available for conversion into kinetic energy, the available potential energy. Both the kinetic energy and available potential energy may be considered in terms of two components, zonal and eddy. Thus, there

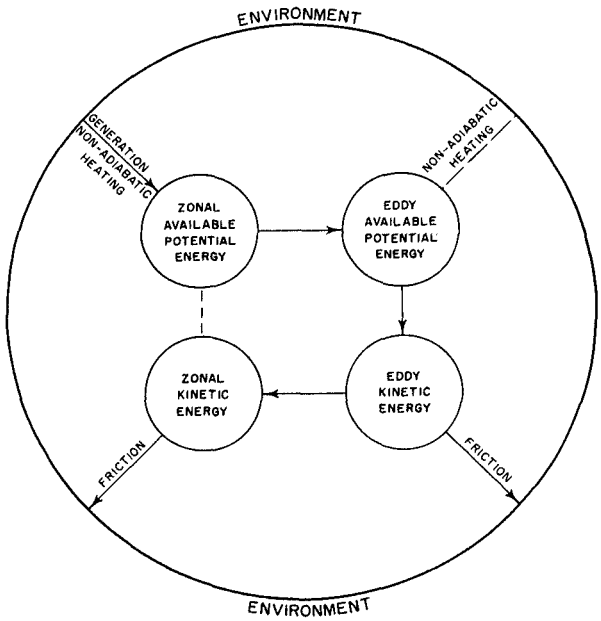

FIGURE 18–5. Proposed energy cycle for the atmosphere of the earth.

are zonal available potential energy, eddy available potential energy, zonal kinetic energy, and eddy kinetic energy. The kinetic energy is well known; it is a function of the square of the wind speed. The zonal component is essentially the kinetic energy of the mean zonal (west-east) flow. The eddy component is the energy of the deviations from mean zonal flow within latitude circles.

The available potential energy is mainly a function of the spatial variance of temperature on isobaric surfaces. The zonal component is a function of the variance of latitudinally averaged temperatures or, essentially, of the strength of the north-south thermal gradient. The eddy component is a function of the variance of temperature within latitude circles; it has a minimum value when the isotherms are parallel to the latitude circles and a maximum value when the isotherms display a wave pattern of large amplitude.

Consider the cycle illustrated in figure 18–5. Generally, if nonadiabatic (diabatic) heating occurs, zonal available potential energy or eddy available potential energy may be generated. Generation (positive generation) occurs when the heating and the temperature field are positively correlated; that is, when the warmer air is heated and the colder air is cooled. Of course, there would also be generation when there is cooling everywhere, as long as there is less cooling where the air is warm and more cooling where it is cold. If the heating is negatively correlated with temperature, that is, cooling of warm air and warming of cold air, then there would be dissipation (negative generation) of available potential energy. In general, at least in the colder season of the year, in the Northern or Southern Hemisphere, there is a tendency for generation of available potential energy.

The heat-budget data obtained from satellites will be of prime importance in determining this generation term. For the first time the net heating of the earth-atmosphere system will be measurable. Although the actual heating of the atmosphere itself must be known in order to determine the energy cycle, the earth-atmosphere heat budget might nonetheless give a gross measure of other heating processes as well as of radiation. In any event it is known that the net difference in radiation (in the winter season heating at low latitudes and cooling at high latitudes) generates zonal available potential energy.

The next stage in the energy cycle following generation of zonal available energy is conversion from zonal to eddy available energy. Essentially, this means that there is a buildup in the temperature gradients within latitude circles at the expenses of the zonal gradients. This is a familiar development in middle latitudes; in simplest terms it is related to the breakdown of a zonal type of flow with fast westerlies into a perturbed circulation of large-scale wave patterns where there are large exchanges of air between high and low latitudes. In fact, the key factor in the conversion from zonal to eddy available energy is the north-south heat transport; that is, the larger the values of heat transport are, the greater is the conversion to the eddy form of available potential energy.

Eddy available potential energy can also be generated by radiation differences within lati-

tude circles; for example, the differential heating between continents and oceans results in increased differences in temperature within the latitude circles. On the other hand, many times the heating is distributed so that there is a dissipation of eddy available energy by the heat sources, mainly in the case of the heating of air in exchange with the surface, for example, heating of cold air masses over warmer ocean currents in the winter.

Following the energy cycle through, once eddy available potential energy starts building, there is an almost simultaneous buildup in eddy kinetic energy. After this there may then be a conversion from eddy kinetic energy to zonal kinetic energy. Then, of course, both forms of kinetic energy are dissipated by friction.

Figure 18–6 shows samples of computations of energy parameters which are calculated from the analyses of Northern Hemisphere midtropospheric charts made at the National Meteorological Center. The parameters represent a substantial depth of the atmosphere over the entire Northern Hemisphere northward from 20° or 30° N. The case illustrated in figure 18–6 involves a very well marked cycle in zonal available potential energy. Note how this zonal available energy built up to a peak value on January 1 and then dropped rapidly in the first week of January. The drop in zonal energy was accompanied by a rise in the eddy available potential energy, which had a rather low value until just about the time the zonal available energy started falling. It appears that there was a conversion from zonal available to eddy available energy at this time.

The behavior of eddy kinetic energy during this cycle in available energy is also interesting. Eddy kinetic energy was relatively small

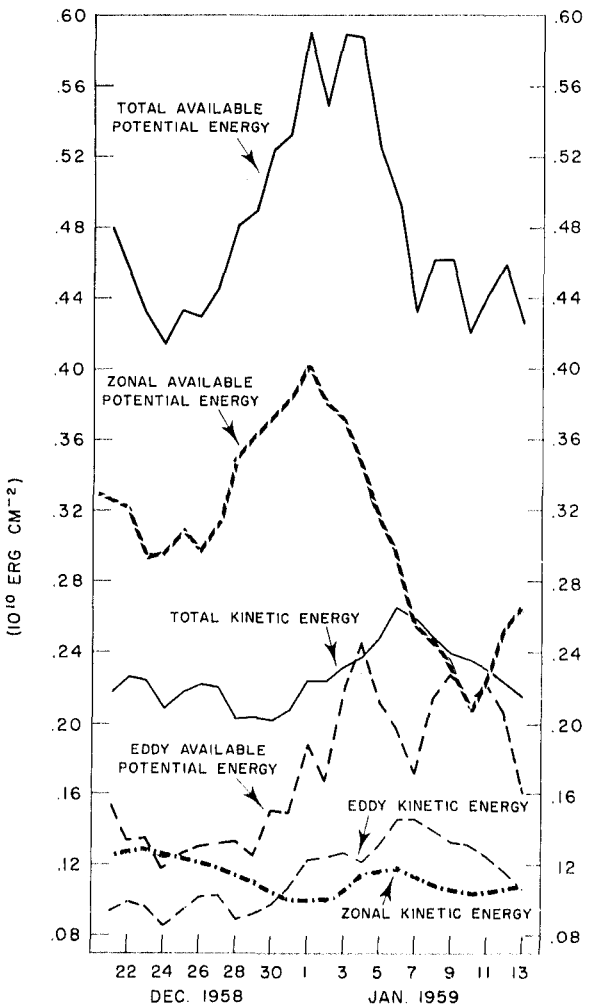

FIGURE 18–6. Time variation of available potential and kinetic energy and the zonal and eddy components of each. December 21, 1958, to January 13, 1959.

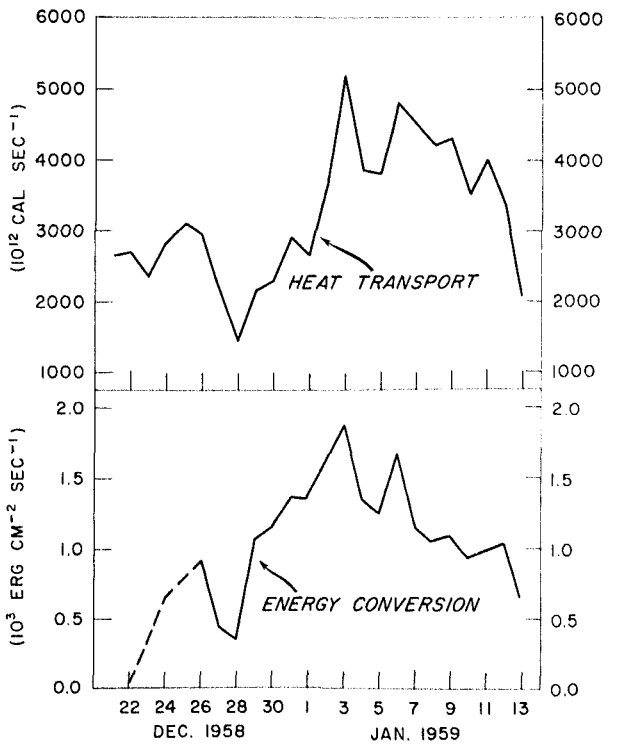

FIGURE 18–7. Total heat transport across all latitudes from 20° N northward and the conversion between available potential and kinetic energy. Same time period as in figure 18–6.

when zonal available energy was increasing, but it rose almost simultaneously with the eddy available energy. It actually reached a peak, however, a day or so beyond the peak in the eddy available potential energy. The zonal kinetic energy during this period showed some drop and then a slight rise, but basically it did not seem to take part to any extent in the general cycle found in the other forms of energy.

It is also of interest to examine briefly the heat transport for the same period (fig. 18–7). The expected relationship is shown: rather low values while the zonal available potential energy was building up, then a rapid rise indicating a large-scale north-south heat exchange which acts to convert zonal available to eddy available energy.

Figure 18–8 shows the available potential energy for the same case partitioned into energy in four specific regions rather than in the zonal and eddy forms. In this case these are wedge-shaped zones extending from about 30° north to the pole. Of most interest here is that the major variation, or cycle, in available potential energy showed up essentially only in zone 1 (over the North American area). Note that the energy values for the other areas did not change much. Thus, a large-scale cycle in available potential energy of the Northern Hemisphere as a whole was dominated by events in one region of the hemisphere—in this case the North American area. This shows the importance of paying close attention to geographical and synoptic-scale influences even in such large-scale studies as of the energetics of the atmosphere over much of the Northern Hemisphere.

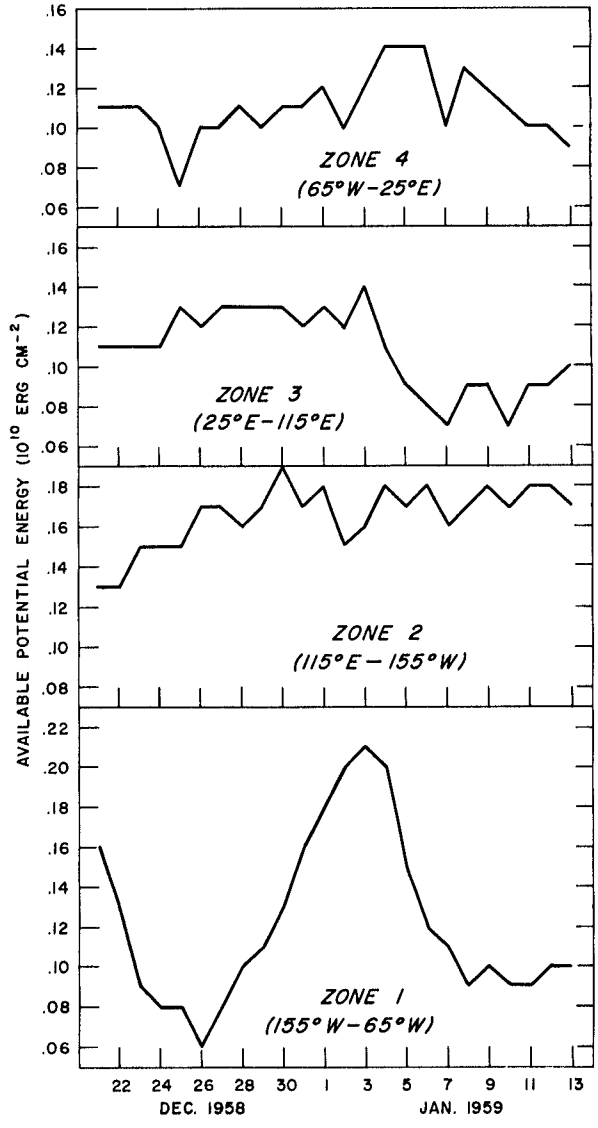

FIGURE 18–8. Time variations of available potential energy in four zones extending northward from 30° N. Same time period as in figure 18–6.

References

1. HANEL, R. A., and WARK, D. Q.: *TIROS II Radiation Experiment and Its Physical Significance.* Jour. Optical Soc. of America, vol. 51, no. 12, Dec. 1961, pp. 1394–1399.
2. WINSTON, JAY S., and KRUEGER, ARTHUR F.: *Some Aspects of a Cycle of Available Potential Energy.* Monthly Weather Rev., vol. 89, no. 9, Sept. 1961, pp. 307–318.

Question Period

SCHMIDT, Netherlands: I should like to ask whether any relationships have been found between latitudinal variations in radiation and intensity variations in the subtropical jetstream.

WINSTON: So far, no. There has been no study of this. This is all for the future.

PATRICK, Nigeria: In this paper, determining cloud heights from radiation data was mentioned. I was wondering whether a phenomenon like fog could actually be determined or whether the method used is not just giving the amount of liquid water content in clouds instead of providing information about the cloud heights.

I think some figures about the heat budget between 30° and the poles were shown. At that point, the conversion of kinetic energy to available potential energy was discussed. I was wondering what must have happened in the midlatitudes where there is indirect circulation. I feel that there kinetic energy is being converted into

available potential energy. Are certain of the conclusions made justified? I feel that the heat budget in the equatorial belt, which is the driving force in winter for the whole general circulation, was neglected.

WINSTON: With regard to the last point, the arrows in the depiction of the energy cycle were for the prevailing direction of conversion as determined from empirical studies at MIT, UCLA, and other places. Where there are no arrows, no prevailing direction is indicated. However, at certain times there can certainly be a flow of energy which is opposite to the prevailing directions. With regard to the indirect meridional cell, I believe the evidence is that this cell does not play an important role in the total conversion between potential and kinetic energy in middle latitudes.

In regard to the tropical and equatorial regions, your comments are quite right. So far our studies have been confined to midlatitudes, from about 20° to 30° northward. We are not doing any measuring of the contributions of the Hadley cell; this is part of the problem which needs more attention.

The other question about fog, I am not sure I know how to answer. Essentially, if fog is present and that is the only cloud, the values should be rather high. If there is fairly moist air, you will not be able to distinguish the surface from the cloud. But if you also have pictures taken at the same time (or measurements from the visual portion of the spectrum), you will be able to tell whether there is or is not a cloud deck. If you are going to make an estimate of height from an effective radiating temperature, the height value will be low. We do not claim that such estimates are going to be accurate to any closer than a few thousand feet. With window measurements alone you could not be sure whether the satellite is viewing the surface of the earth or a cloud top within a few thousand feet of the surface.

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19. DIFFERENTIAL COOLING FROM SATELLITE OBSERVATIONS

By V. E. SUOMI, *Professor of Meteorology, University of Wisconsin*

The use of TIROS photographs and TIROS infrared measurements have been discussed in the preceding papers in this Workshop. These discussions mainly concern the use of TIROS data in storm location—an application which has aroused much interest. In this paper the theories on the energetics of the atmosphere, principally the conversion of available potential energy into kinetic energy, are discussed in an attempt to provide a clearer understanding of what causes weather. Some of these theories are introduced in paper 18 and pertinent figures are presented in reference 1.

The TIROS cameras and infrared devices describe and record conditions at the top of the atmosphere. The problem of meteorological interest, however, is what is happening *within* the atmosphere. Of primary interest is the change of net radiation with height to determine whether the atmosphere is heating or cooling. The mean local cooling or heating for finite layers in the atmosphere is given by

$$\frac{\Delta T}{\Delta t}=\frac{g}{c_p}\frac{\Delta R_{\text{net}}}{\Delta P}$$

where

c_p	specific heat at constant pressure
g	gravity
P	pressure
R	radiation
T	temperature
t	time

The cooling (or heating) rate in °C per day is expressed by

$$\Delta T=5.9\times10^3\frac{\Delta R_{\text{net}}}{\Delta P}$$

where R_{net} is expressed in cal/cm²/min and ΔP is given in millibars.

Ideally, the temperature change in the atmosphere is the desired measurement. Although instruments in the satellite can only measure the energy leaving the top of the atmosphere, the possibilities of obtaining meaningful estimates of this change and of other factors are good.

Figure 19–1 is a photograph of a radiometersonde which is flown on balloons. The triangular object in front of the radiosonde measures the radiation originating in the atmosphere above the balloon; it also measures the radiation which comes from the surface of the earth and the atmosphere below the balloon. With this instrument it is possible to make measurements of net radiation as a function of height in the free atmosphere.

Figure 19–2 presents two typical soundings of net radiation within the atmosphere over Wisconsin (ref. 2). The ordinate is a linear pressure in millibars and is proportional to the mass of the atmosphere. The abscissa is net radiation in cal/cm²/min. The energy of the sunlight is not included because the soundings are taken in darkness. Typically, the net radiation at the surface ranges from about 0.06 calorie to about 0.11 calorie. The total variation at the surface is not great. In the portion of the sounding in which net radiation rapidly increases with height, the energy leaving the top of the layer exceeds that which enters the bottom of the layer and as a result the layer will cool. On the other hand, in the portion of the sounding in which there is little change in net radiation with height, there will be no temperature change with time.

In the layer from the surface to 200 millibars, the cooling on August 17 is 50 percent greater than that on April 22 (fig. 19–2). In a similar manner, adjacent air columns in which the vertical divergence of net radiation differs will cool differentially, thus generating horizontal air temperature differences. The prob-

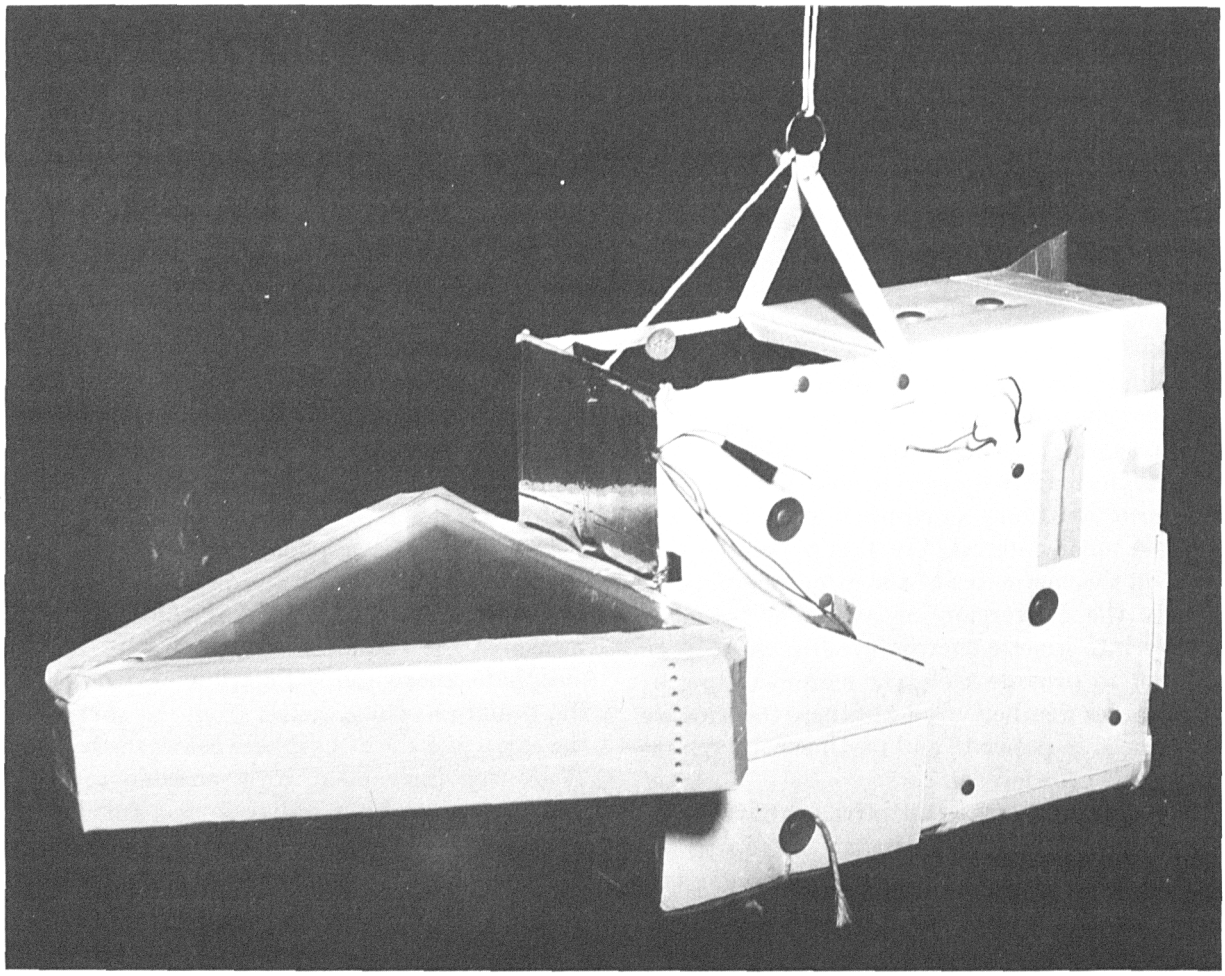


FIGURE 19–1. Radiometersonde consisting of net radiometer attached to U.S. Weather Bureau radiosonde.

lem is how this information can be obtained from a satellite.

At the top of the atmosphere the downward radiation is essentially zero; thus, the upward radiation (which a satellite measures) and the net radiation (which a radiometersonde would measure if it were at that height) are identical. The net radiation of the surface ranges from almost zero to only about 0.11 cal/cm²/min. On the other hand, the net radiation at the top of the atmosphere ranges from about 0.18 cal/cm²/min to as much as 0.44 cal/cm²/min. Most of the variation of net radiation at the top of the atmosphere is caused by the radiative losses from the atmosphere. Figure 19–3 is a scatter diagram of the divergence of net radiation obtained from radiometersondes for the layer from the surface to 100 millibars compared with the outgoing radiation at the 100-millibar level. The radiometer soundings cover a wide range of latitude and weather conditions. The scatter diagram again shows that the strength of the outgoing radiation is an indication of the rate of cooling of the atmosphere.

Figure 19–4 shows a cross section of the atmosphere from Los Angeles, Calif., to International Falls, Minn., with net radiation as a function of height and distance as obtained from radiometer soundings. Differences in the spacing of the isolines of net radiation are related to the rates of cooling or warming of the atmosphere. Differential cooling therefore gives rise to the generation of horizontal temperature differences. Additional details concerning these soundings may be found in reference 3.

Although the illustrations and discussion just presented are brief, they indicate that the divergence net radiation in the free atmosphere un-

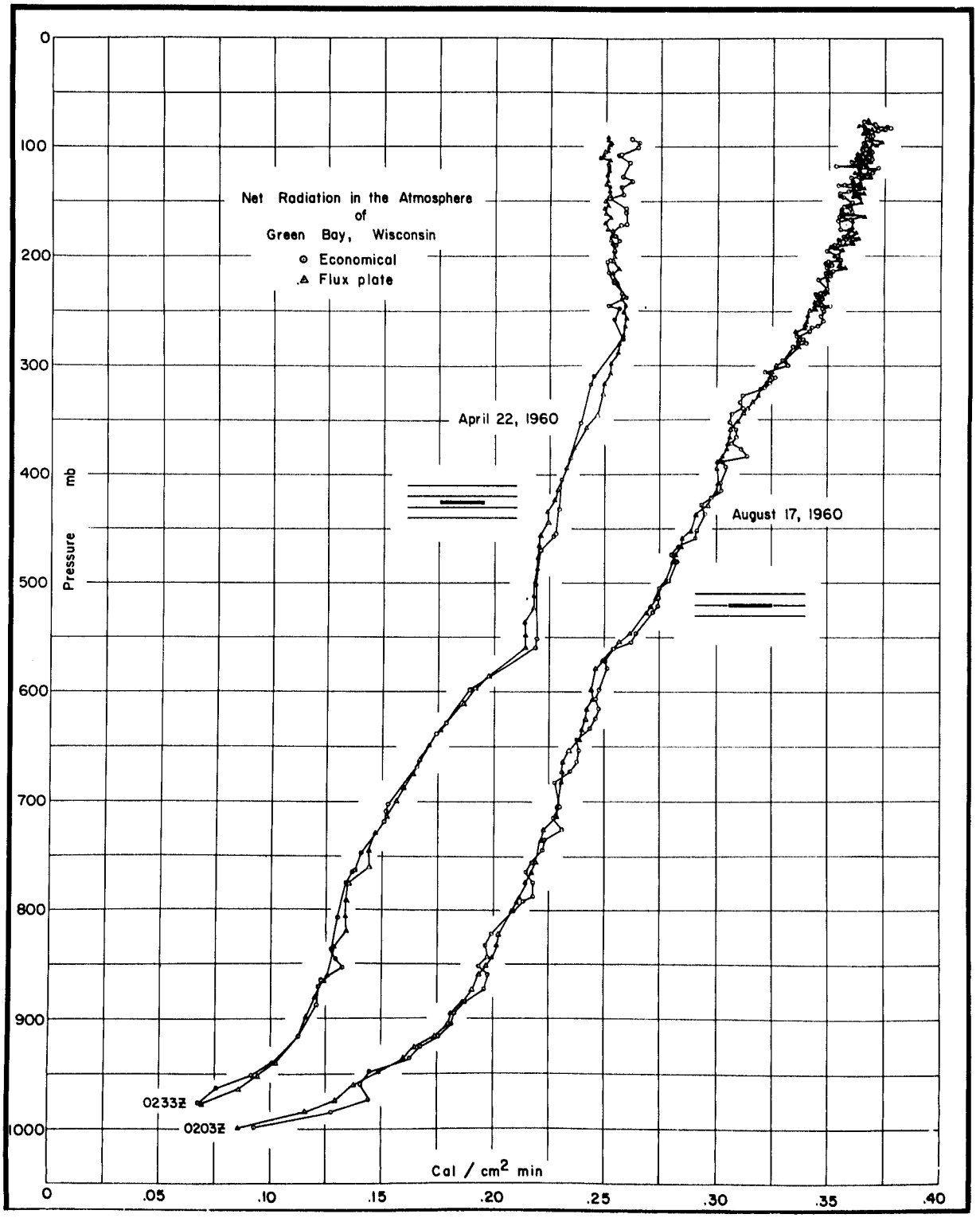


FIGURE 19–2. Radiometer soundings. The two curves for each date were obtained from two different instruments on the same balloon.

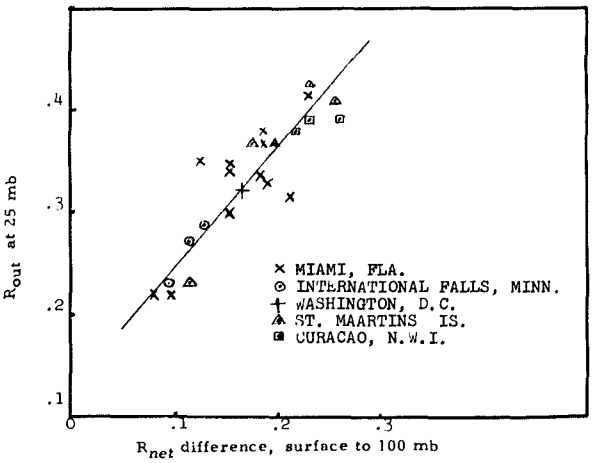


FIGURE 19–3. Relation between outgoing long-wave radiation at 25 millibars and difference in net long-wave radiation between surfaces and 100-millibar level.

dergoes large variations on a horizontal scale comparable to the variations of weather systems. Clearly, horizontal temperature differences over this same scale are being generated or reduced.

The infrared instruments which have been described for TIROS II and III are very elaborate compared with the simple instrument used on Explorer VII. Figure 19–5 is a photograph showing one of the mirrors and the black and white hemispherical bolometers as installed on Explorer VII. The unit appears on the cylindrical center of the satellite pictured, with the white bolometer in line with the axis and the black bolometer to the right of the white bolometer. When the satellite is spinning rapidly, as is Explorer VII, the hemispheres, by virtue of the mirrors, act like spheres in space. The heat conducted down the mounting post and radiated from the inside of the hemisphere to the mirror must also be taken into account. It can be shown that the absolute value of the temperature of either the white or the black sensor is a measure over a wide band of the spectrum of the outgoing radiation from the earth. This discussion will be confined to the performance of the instrument at night.

Figures 19–6 and 19–7 are the Northern Hemisphere surface and 500-millibar weather maps, respectively, for April 4, 1960, obtained from the U.S. Weather Bureau files. Figure 19–8 is a map of long-wave radiation loss from the earth for the same date. The maps are not strictly comparable because the satellite measurements are not synchronous. The similarity between the main features shown on the 500-millibar map, such as the low-pressure troughs in the Mississippi Valley of the United States and in the Pacific between California and Hawaii, and the pattern of outgoing radiation is clearly evident. Figures 19–9 to 19–11 are further examples of outgoing radiation for a series of days in December. The surface fronts are entered on the radiation maps. Figures 19–12 (*a*) and (*b*) (plotted on two maps for clarity) are locations of the daily positions of the centers of high and low pressures and also the daily positions of the centers of high and low values of outgoing radiation. The center of the low for radiation is displaced to the east of the center of low pressure. That the two move together as the days progress is a very striking feature. These illustrations are the first maps of radiation obtained from a satellite on a global scale and further illustrate that the outgoing radiation has significant changes on a scale comparable to that of weather systems. Additional details are available in reference 4.

In the preceding discussion it has been emphasized that the differences in cooling rate can generate horizontal temperature differences (eddy available potential energy). Offhand, the differences in cooling rate would be expected to *reduce* the temperature differences that exist because warm objects tend to lose heat more rapidly than cold objects. Clearly, if eddy available potential energy is to be generated instead of destroyed the warm columns of the atmosphere must cool less rapidly than the cold air columns. *Thus, if differences in cooling rate are to be a source of eddy available potential energy, evidence must be found that warm air columns cool less rapidly than cold air columns.*

Figure 19–13 is a plot of the departure of the cooling rate from its latitude mean for December 1, 1959. The solid line is the departure of cooling from its mean; thus, values above zero indicate relative warming. The dashed line indicates the departure of the thickness of the 1,000- to 100-millibar air column from its mean value along the latitude circle and represents temperature differences. The generation of eddy available potential energy is proportional

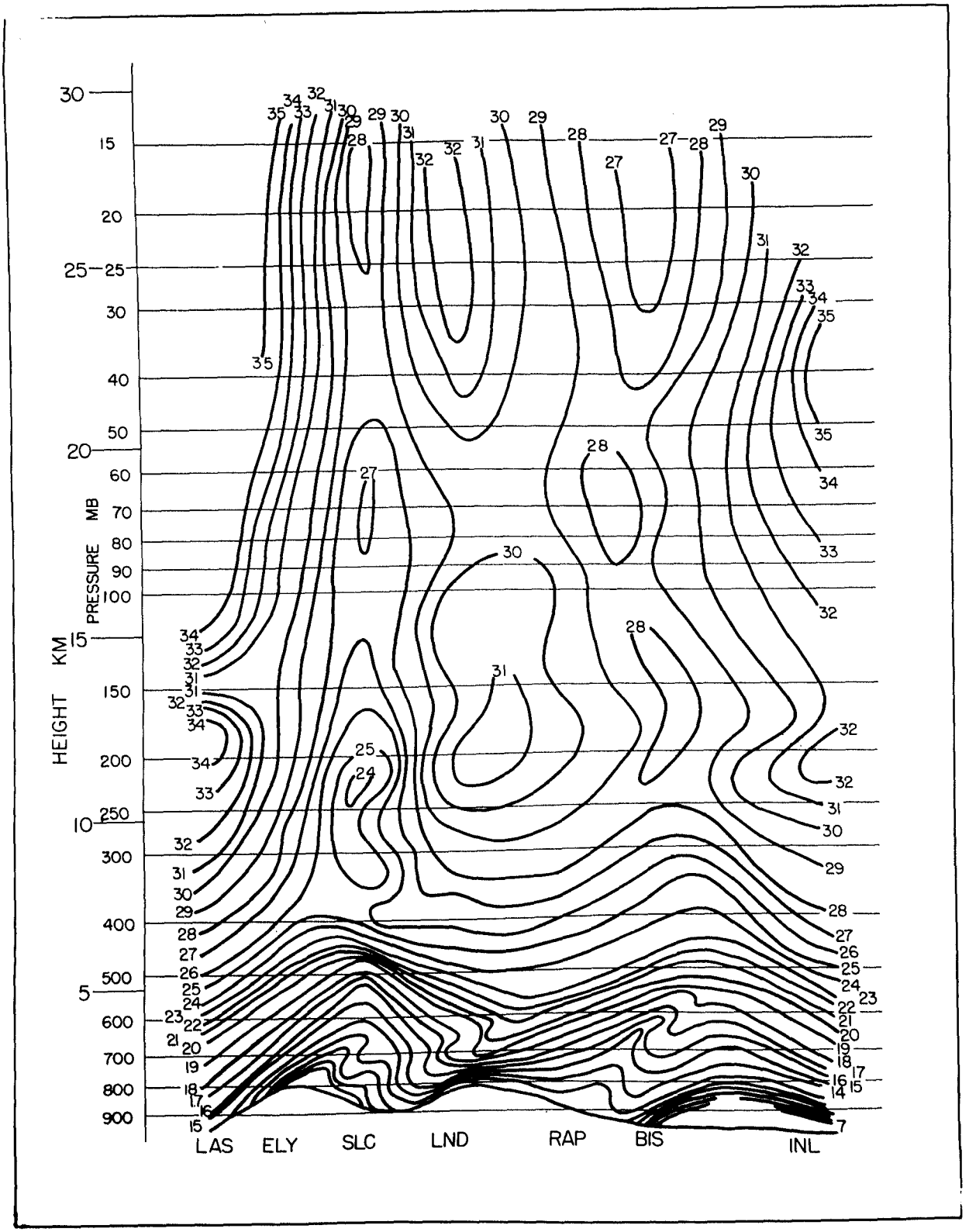


FIGURE 19-4. Isolines of net radiation. Units are 10^{-2} cal/cm²/min. Stations extend from Los Angeles, Calif., to International Falls, Minn.

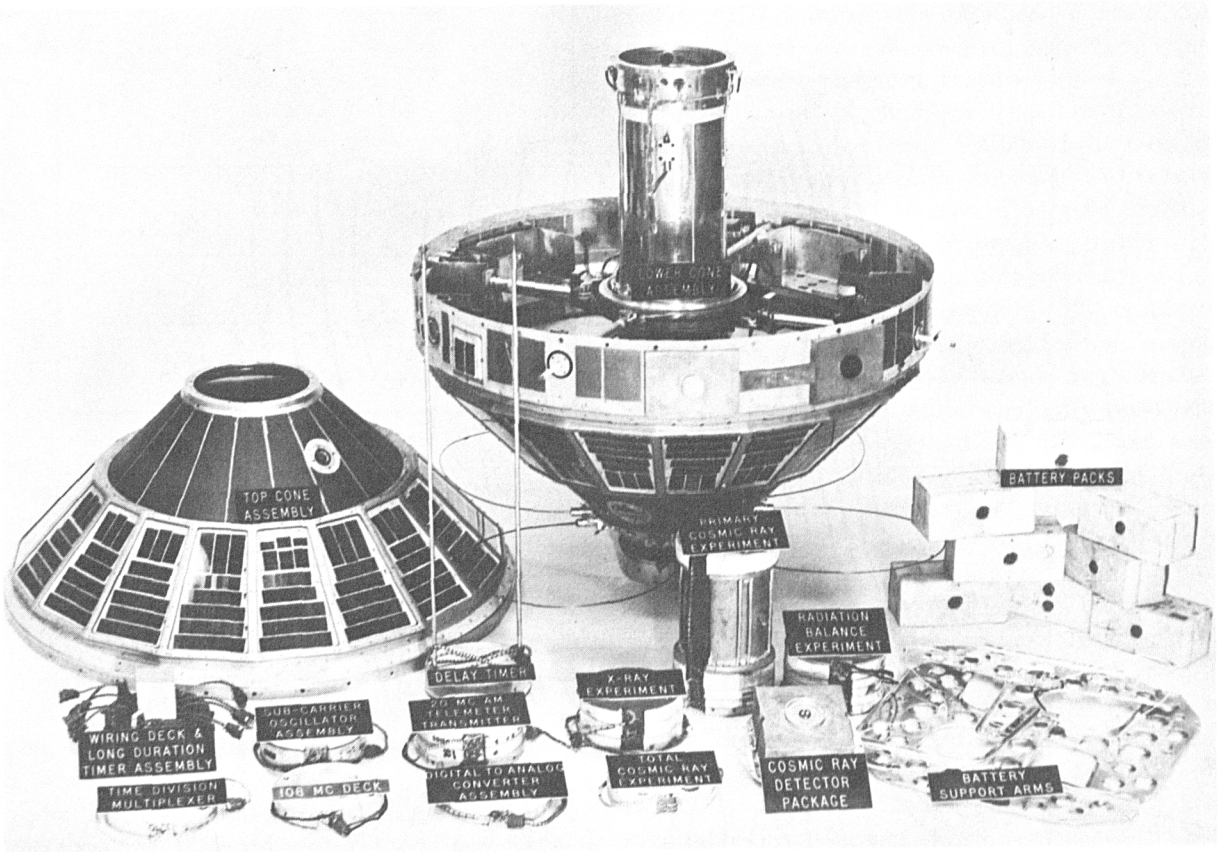


FIGURE 19–5. Disassembled view of Explorer VII payload. *Note bolometer experiment mounted on equatorial ring.*

to the product of these departures given as follows in reference 5:

$$G_e = \frac{P_o}{gAh} \int_A h^* \left(\frac{dQ}{dt}\right)^* dx\, dy$$

where

h	1,000- to 100-millibar thickness
$\frac{dQ}{dt}$	cooling rate
P_o	pressure, 1,000 millibars
g	acceleration of gravity

The asterisk indicates the departure of a quantity from its area A average.

Figures 19–14 to 19–16 show the area values of the generation G_e term for a series of days. This term tends to have positive values in the warm air of the southerly flow ahead of a cyclone where the high cold cloud layer prevents the escape of long-wave radiation. In order to determine if this generation is an important source of eddy available potential energy, figure 19–17 was drawn to show the hemispherical totals for December 1 to 3, 1959, and April 4, 1960. On December 1 the generation was negative, but on December 3, 1959, and April 4, 1960, the generation was strongly positive and more than enough to overcome the average dissipation of surface friction. The amount of eddy generation shown in figure 19–17 is equal to or greater than the amount of zonally generated available potential energy as shown in figure 4 of reference 1 and in paper 18. Thus, there is evidence that in these cases the differential cooling of the atmosphere represents an important new source of energy available to drive weather systems. Clearly, this hypothesis must be verified further by additional analyses and tests. The TIROS II and III infrared data can form the basis of these tests.

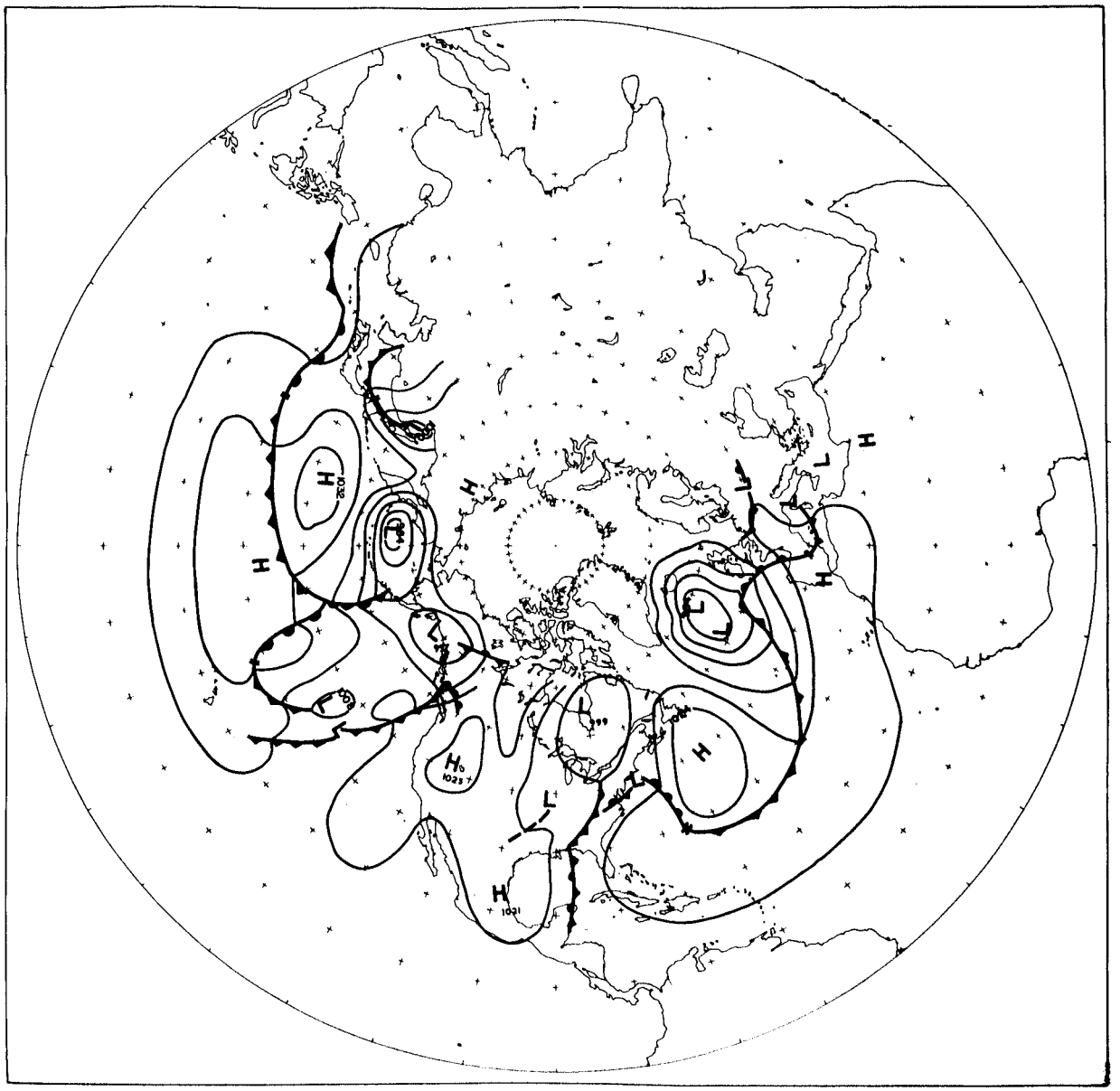


FIGURE 10–6. Surface analysis. April 4, 1960, 1200Z.

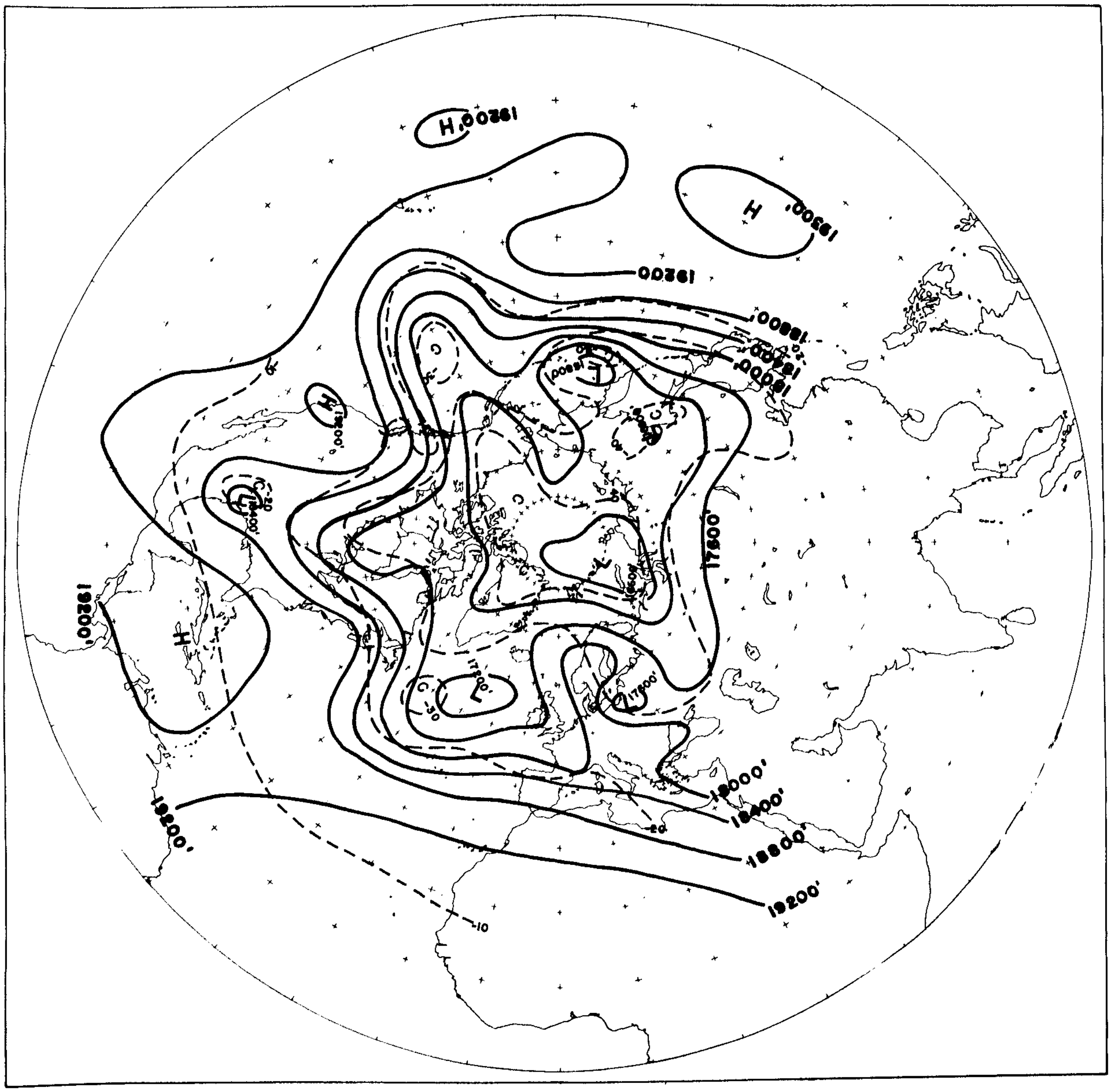


FIGURE 19–7. 500-millibar analysis. April 4, 1960, 0000Z.

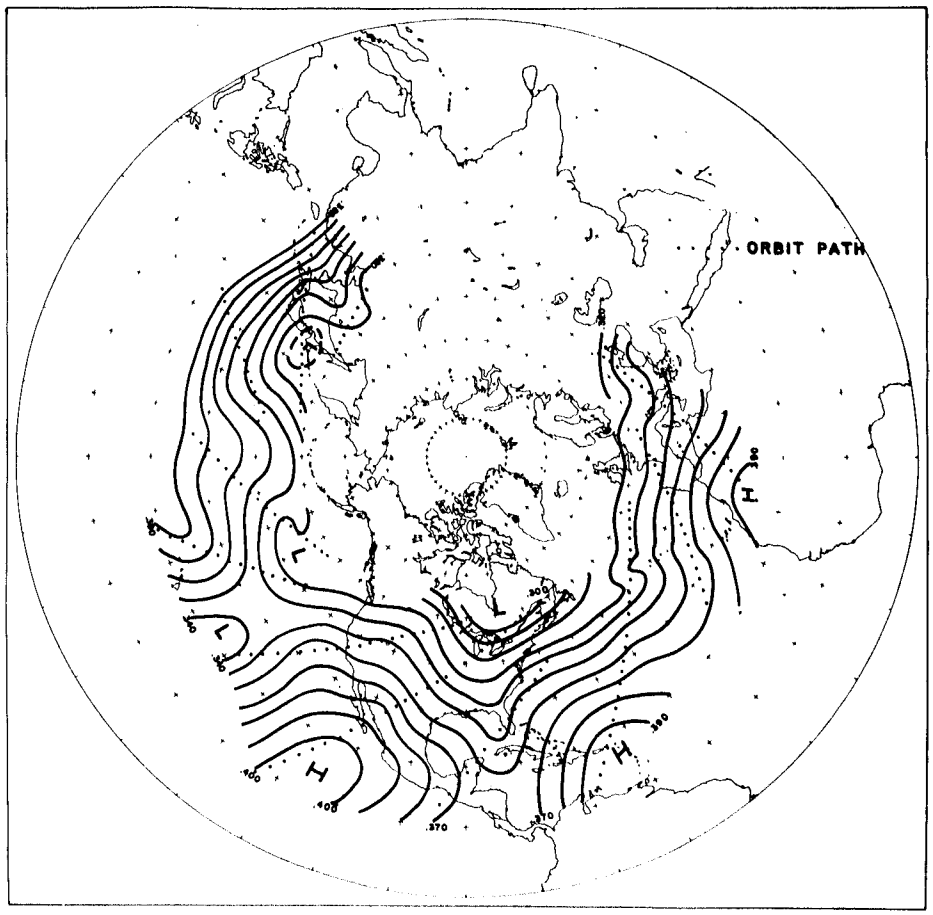


FIGURE 19–8. Long-wave radiation loss in cal/cm²/min. April 4, 1960.

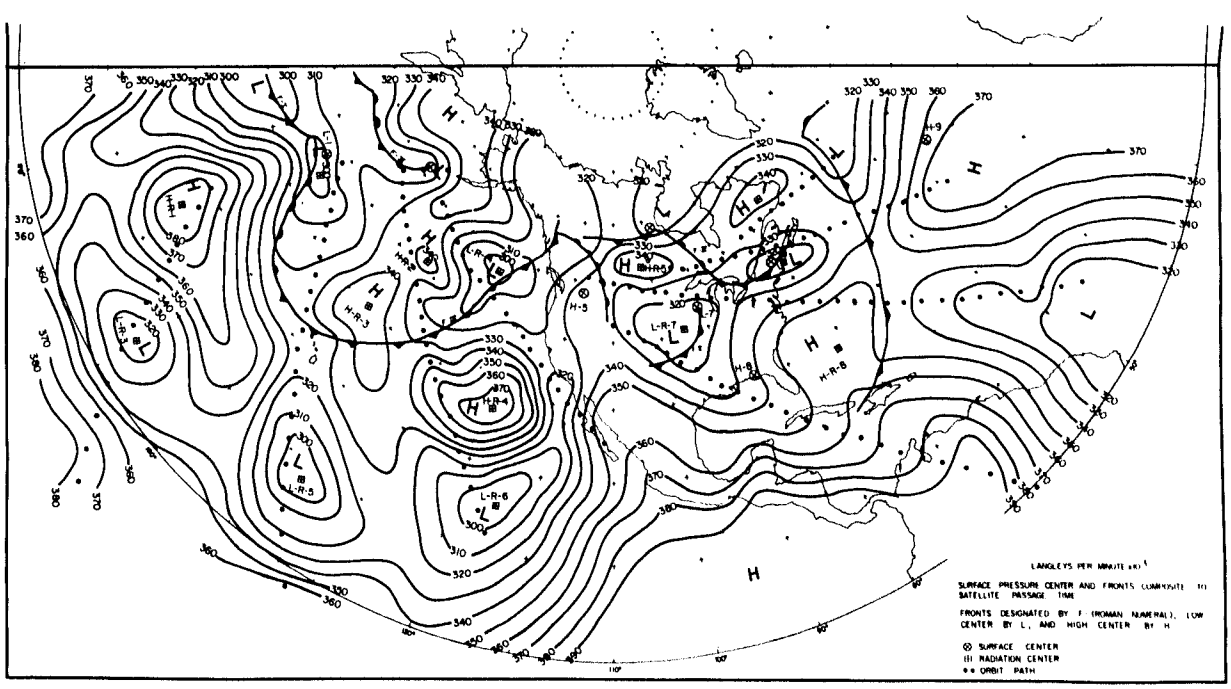


FIGURE 19–9. Long-wave radiation loss map. December 1, 1959.

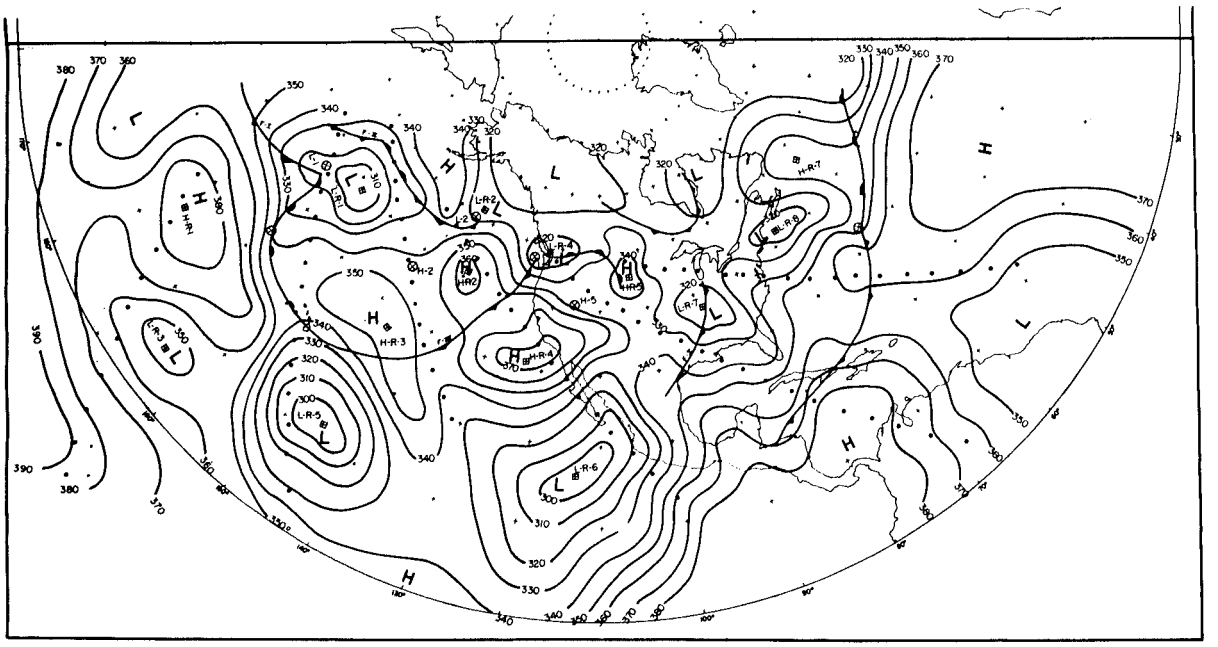


FIGURE 19–10. Long-wave radiation loss map. December 2, 1959. See key, figure 19–9.

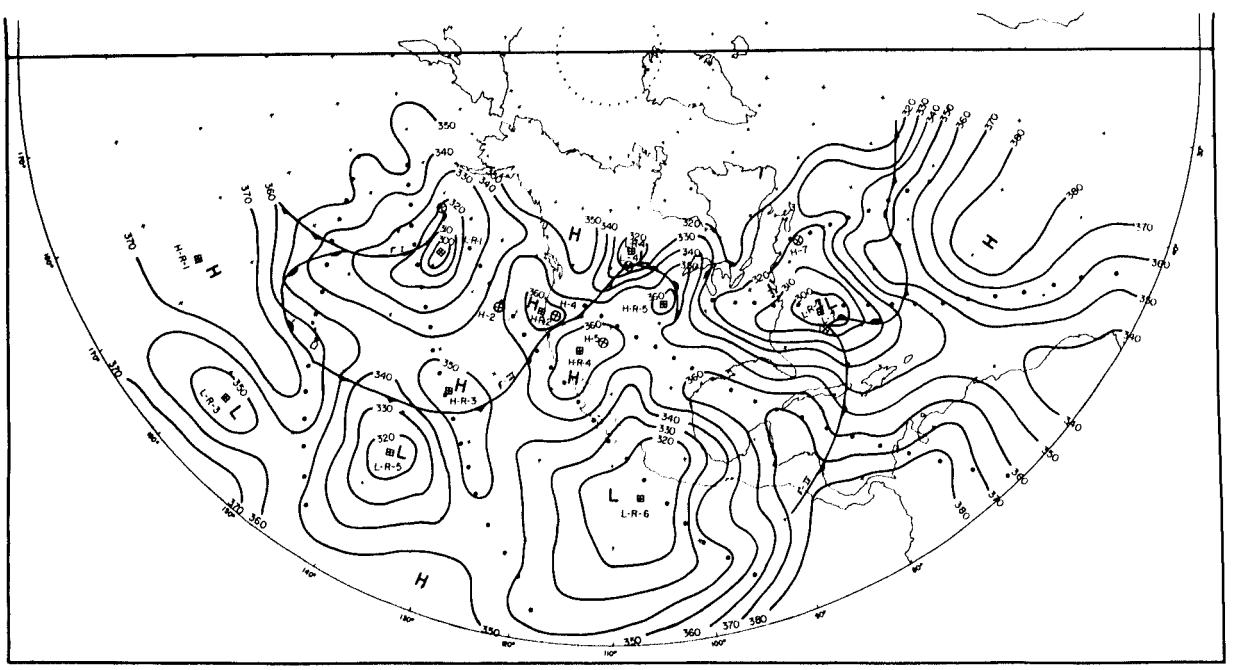
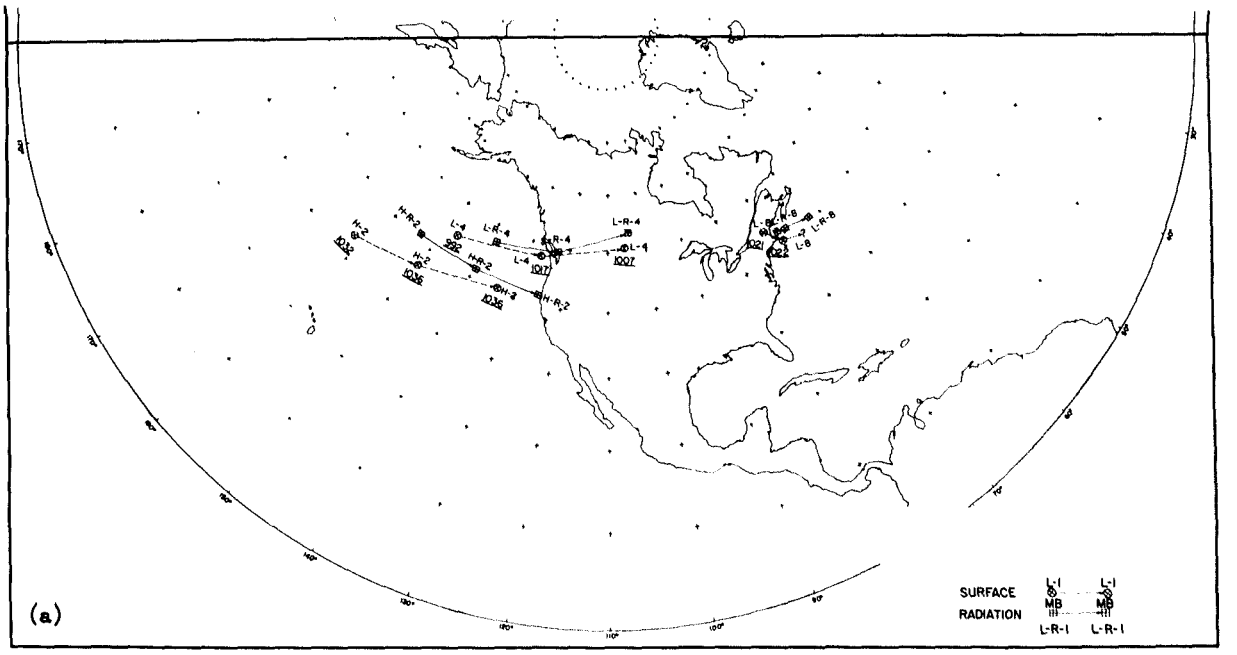


FIGURE 19–11. Long-wave radiation loss map. December 3, 1959. See key, figure 19–9.



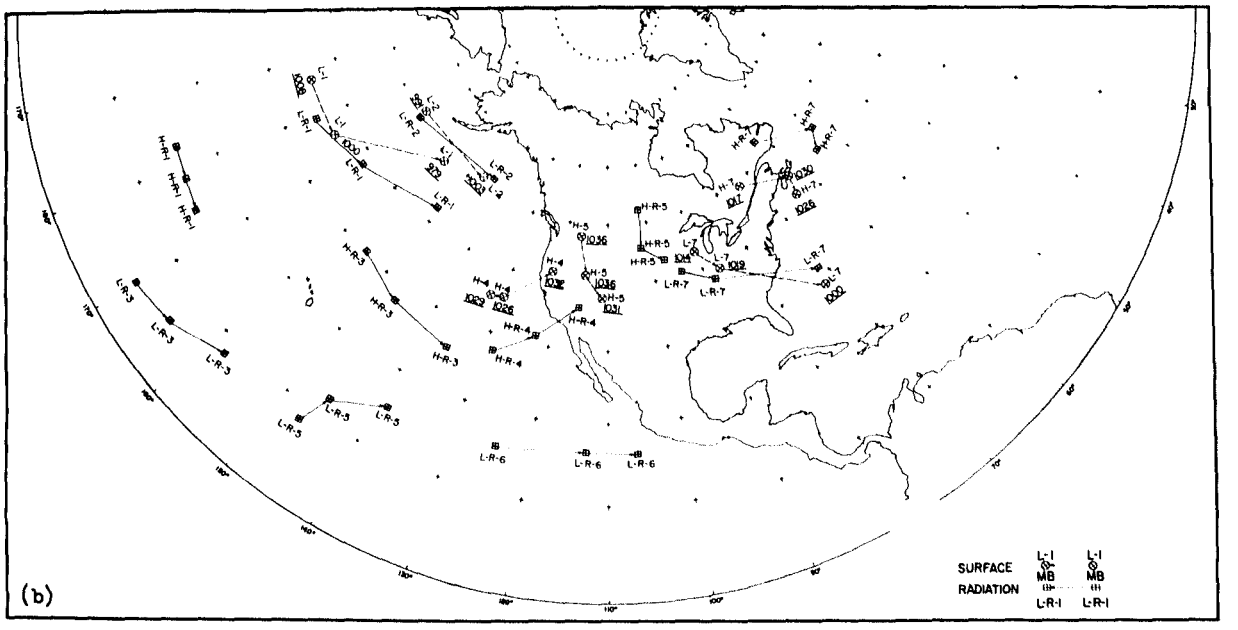


FIGURE 19-12. Surface and radiation center continuity charts. December 1 to 3, 1959. Numbers refer to pressure and radiation centers.

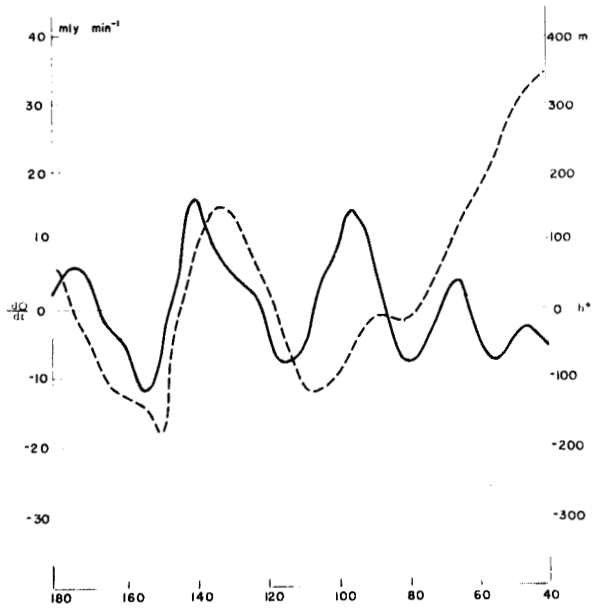


FIGURE 19–13. Departure of cooling rate from its latitude mean. Solid curve is departure of cooling from its mean value; dashed curve is departure of thickness of 1,000- to 100-millibar air column from its mean value along latitude circle; December 1, 1959; 40° north.

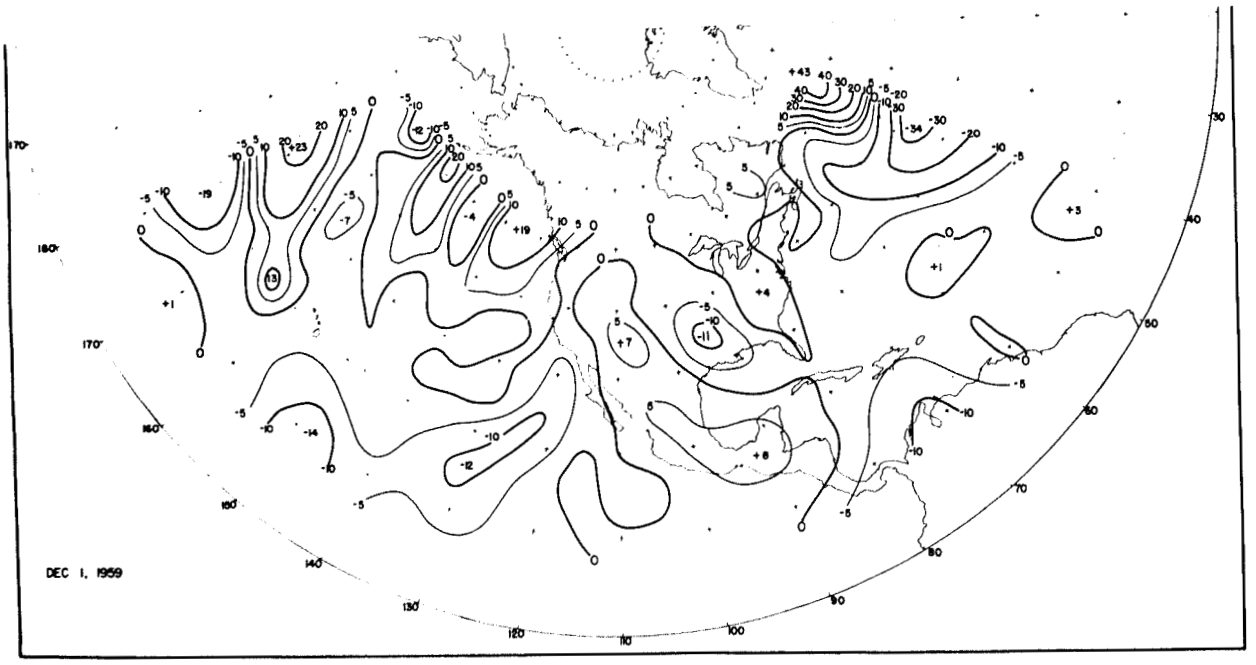


FIGURE 19–14. Generation of eddy available potential energy. Units are 10^3 ergs/cm^2/sec. December 1, 1959.

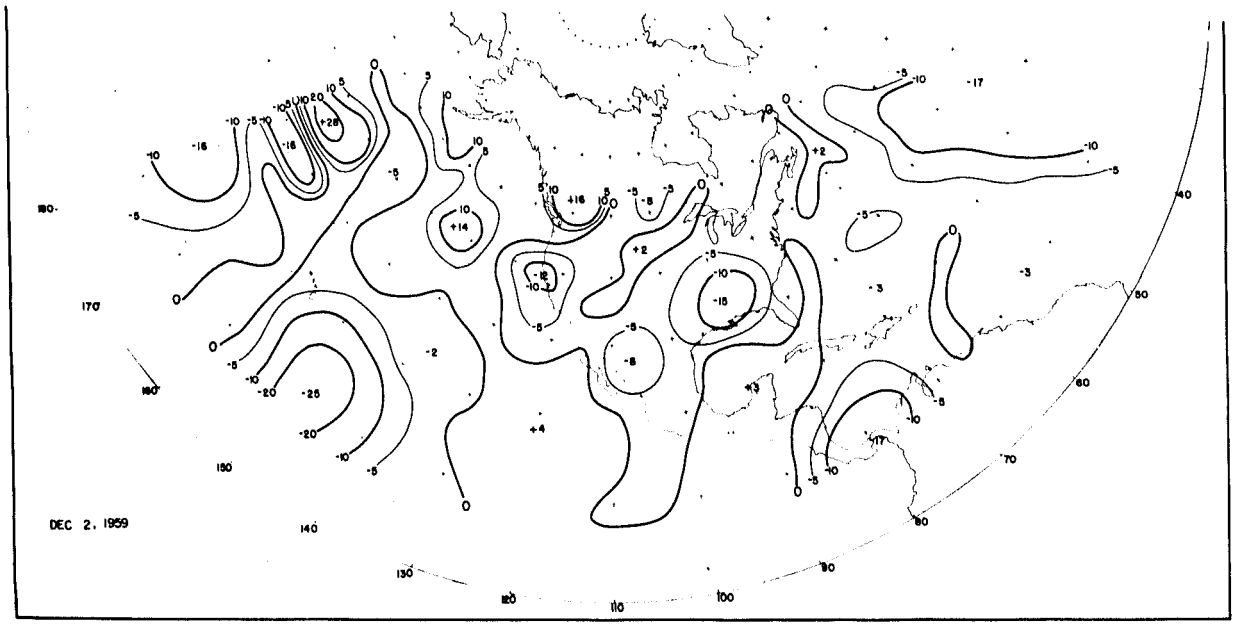


FIGURE 19–15. Generation of eddy available potential energy. Units are 10^3 ergs/cm^2/sec. December 2, 1959.

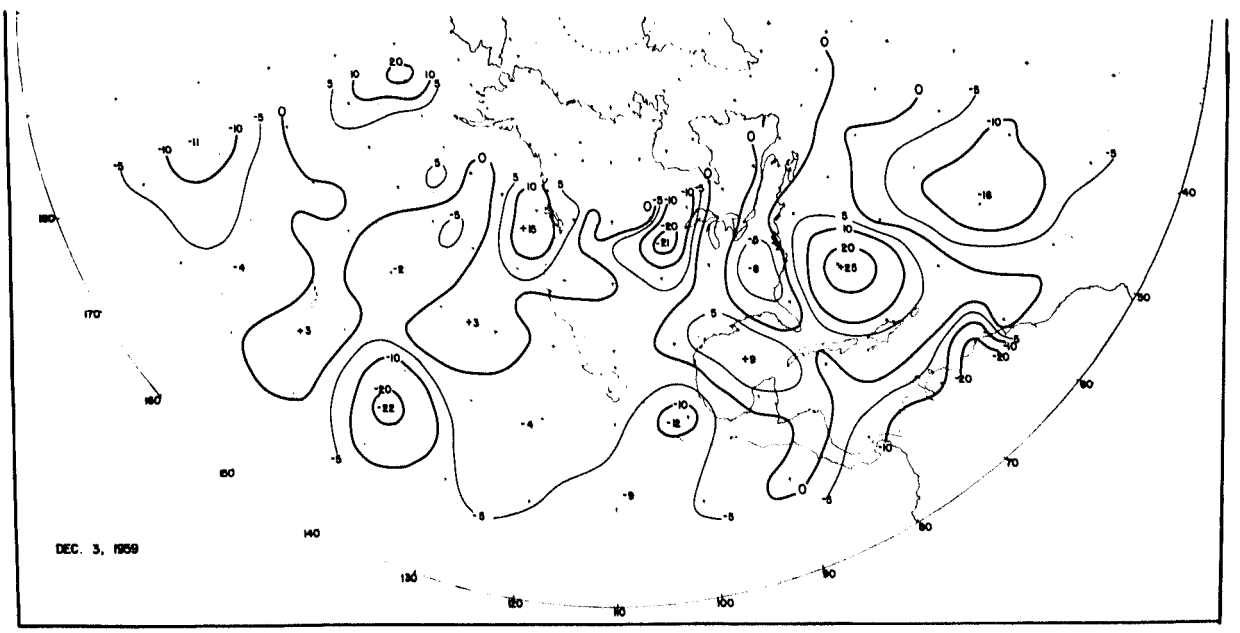


FIGURE 19–16. Generation of eddy available potential energy. Units are 10^3 ergs/cm^2/sec. December 3, 1959.

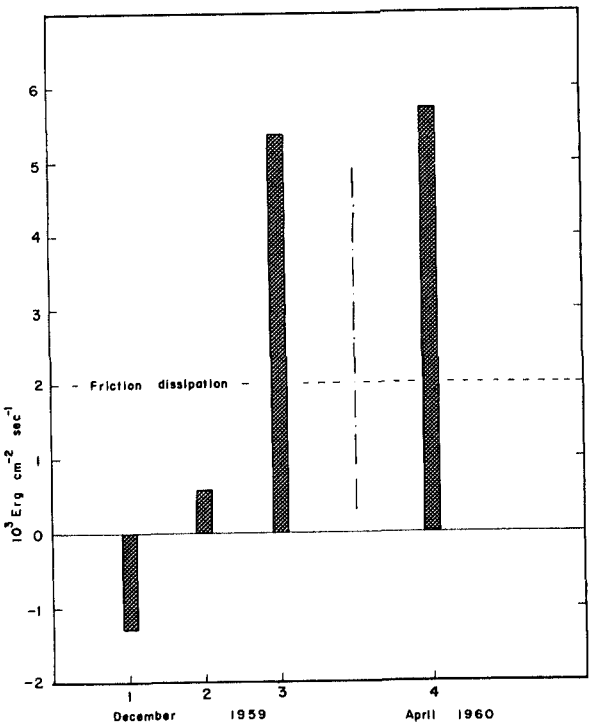


FIGURE 19–17. Time variation of the generation of eddy available potential energy (average over a region of 30° to 50° north, 40° to 180° west).

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4. WEINSTEIN, MELVIN, and SUOMI, VERNER E.: *Analysis of Satellite Infrared Radiation Measurements on a Synoptic Scale.* Monthly Weather Rev., vol. 89, no. 11, Nov. 1961, pp. 419–428.
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Question Period

JOHNS, Canada: Dr. Suomi, were all the charts presented based on satellite data or were some based on radiation and balloon data? I would assume they must have been mainly satellite data from the large coverage.

SUOMI: That is correct. I used the balloon data to show that it is possible to get an estimate of the divergence in the atmosphere by looking at what is coming through the top. It is a crude estimate, to be sure, but I would say it is correct in most cases within 20 percent.

TEPPER, NASA: Dr. Suomi, after having computed the available potential energy in these various cases, what was the subsequent synoptic situation that corresponded to the atmosphere having this available energy?

SUOMI: A cyclone formed off the Atlantic coast on December 3. However, it is too early to say that this is definitive. Let's say that this is just conjecture. We must study more cases. It looks very promising.

20. ARCHIVING OF TIROS DATA

By R. L. PYLE, *Chief, Documentation Section, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

Since the TIROS satellite experiments have been so successful in providing a unique kind of meteorological data, it is rather important that these data be properly preserved and made available conveniently and quickly for use by the meteorological community and by the public at large.

Some of the ways in which these data may be applied in meteorological research studies have been discussed in preceding papers. These beginning efforts indicate the enormous potential value of the data, a potential value that can be fully realized only if many more scientists in all parts of the world are able to work with this new research resource and thereby discover and develop more ways to put it to constructive use. The prerequisite for using these data is that they be readily available to anyone and that the quality be nearly equal to that of the original data.

The main purposes of the archival system are, first, to provide permanent storage for the data; and, second, to be able to provide copies of the pictures with a minimum of degradation, efficiently and promptly, in the desired quantities for all who may wish them. Furthermore, the archives must be able to provide sufficient documentation for the user to locate these pictures accurately in time and in space.

These cloud pictures represent a new kind of meteorological data from the archival point of view. They are not data that can be readily reduced to numbers, entered on punchcards, and processed by machine. They are a kind of data which, at the present time, must be stored in picture form. Thus, when the time comes to make copies for the users, it is not always possible to reproduce full quality in the copy that the user receives. Probably, the major problem faced in this archival system development so far has been in trying to work out schemes by which the full clarity and detail of the pictures can be preserved in the later generations of these pictures which are distributed to users. For operational weather analysis and forecasting, the TIROS pictures must be processed as rapidly as possible so that the information can be made available while it still has some value for the forecaster. However, in preparing the picture data for the research archives, more time can be spent in processing in order to do a more careful job.

The archival procedures which have been developed and which are briefly described herein have been essentially the same for the first three TIROS satellites. The picture signals received from the satellite are recorded at the readout stations on magnetic tape. A few minutes later the tape is played back to display the pictures on a television screen, and a 35-millimeter camera photographs the screen. Since this set of pictures ultimately becomes the basic archival record, special care must be taken to obtain the best possible photographic exposure.

The exposed film is sent to the U.S. Navy Photographic Interpretation Center, where it is processed under very carefully controlled laboratory conditions. This processing consists of developing the film, editing it, and adding title frames to assist the user in locating pictures on the film. From this edited original negative film, a positive film copy is made which then serves as the archival master. This master copy is deposited at the National Weather Records Center of the U.S. Weather Bureau where it is used for making further copies at the request of users.

An important step in the processing is the control of film density. In the original negative there is considerable variation from orbit to orbit in the basic density level of the film. In

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producing the positive archival master the Navy Photographic Interpretation Center uses specialized equipment which automatically compensates for these variations in the density level. This compensation is necessary because the master positive, which is stored at the Weather Records Center, must be of a fairly uniform density throughout in order that automatic printing equipment can be employed to produce copies of these pictures in the quantities now being demanded.

The Weather Records Center stores these archival master films in units of 100-foot rolls. Persons or institutions can order copies from the Center in the form of 35-millimeter positive film for projection and viewing, or negative film from which opaque prints may be made. Both the positive and the negative film copies from the Records Center are made directly from the positive archival master. The positive copies are made by a diazo process and the negative copies are made by a Kalvar process. These methods are used to make copies for distribution to users which are, effectively, second generation photographs since some degradation is unavoidably introduced with succeeding photographic generations.

At the present time complete reels of these pictures must be ordered from the Weather Records Center. It is not now feasible for the Center either to furnish copies of individual pictures or to furnish specialized photographic formats.

For TIROS I, the positive archival master has been produced for all the pictures that were obtained. These are available now from the Weather Records Center. A complete set will comprise 50 100-foot reels of 35-millimeter film.

The archival masters of TIROS II and TIROS III film are now being processed at the Navy Photographic Interpretation Center and it is expected that the National Weather Records Center will be able to furnish copies of these sometime in 1962.

Documentation for the TIROS pictures is provided in the form of printed listings which contain the essential information about the picture sequences and also in the form of maps which show roughly the geographical areas that have been photographed in each of the picture sequences.

For TIROS I this information has been published in a catalog (ref. 1). This catalog will give an idea of the coverage that was obtained by TIROS I and of the type of information which must be known in order to interpret the pictures properly. A similar catalog is being planned for TIROS II, although this catalog will contain listings only. Since it is a great task to compute coverage swaths for the maps, this was not done for TIROS II because picture quality was not sufficiently good to warrant the effort.

Beginning with TIROS III, this catalog material will be published in installments as rapidly after the pictures have been taken as the material can be assembled. For TIROS III the first installment, which describes the pictures taken in July and August 1961, has been printed (ref. 2). Additional installments for September, and possibly October 1961, will be forthcoming as soon as the material is assembled. Eventually the installments will be combined in a single printing similar to the TIROS I catalog.

Documentation is also being developed in the form of latitude-longitude grids that may be superimposed on the picture. In paper 14 a number of the problems and procedures encountered in constructing these grids are described. It should be emphasized that, from the archival point of view, for TIROS I the uncertainties in the satellite attitude and in actual time at which remote pictures were taken have made this gridding a difficult task. Nevertheless, grids have been constructed for approximately 800 TIROS I frames, taken from about 80 different picture sequences. These will be superimposed on the pictures photographically by the Navy Photograph Interpretation Center. The gridded sequences will form a special set of 35-millimeter reels and will be made available through the National Weather Records Center as either positive or negative copies. A list of the sequences which have been gridded for TIROS I will be published.

For TIROS II, because the wide-angle pictures have, in general, less value for research work than those from either TIROS I or III, there are no plans to prepare any gridded pictures for the archives. Individual pictures can be gridded by the method described in paper 14.

For TIROS III, there are plans to grid pictures from virtually every one of the se-

quences that have usable meteorological information. This will amount to several thousands of pictures and is possible only because most of the gridding procedure has been automated.

One part of the procedure which is not automated is the actual photographic superposition of the grids on the pictures to make a single composite picture. This is a tedious job which still must be done manually. Therefore, a change in the form in which the TIROS III gridded pictures will be made available is contemplated. Under the proposed plan, the grids would be placed on a separate strip of 35-millimeter microfilm. The user then would get a copy of the film strip containing the grids and would also get a copy of the ungridded cloud pictures. It is then a simple photographic procedure to make an enlargement of the grid on transparent foil and an enlargement of the picture and match the two. In the Satellite Laboratory it has been found that careful work with cloud pictures usually leads to slight adjustments in the grid placement. As more is learned about a particular sequence, the scientist finds that it is often a handicap, for research purposes, to have the grids fixed inflexibly to the pictures. However, there are other purposes for gridded pictures, including their use for instruction in schools and for informational displays. Therefore, for TIROS III it is planned to take a number of the more interesting sequences, which show hurricanes, dramatic landmarks, and so forth, and make a superimposed gridded picture file available through the Weather Records Center.

So far this discussion has concerned pictures. Most of the information needed to order the pictures is contained in reference 1 which describes the current availability status of all TIROS pictures. Archival procedures are also being planned for the TIROS radiation data. (See refs. 3 and 4.) As already mentioned much information can be gained by working with the magnetic tape itself. The first meteorological radiation tapes which have been properly prepared for use by scientists are now available for copying. They may be obtained through the Weather Records Center of the Weather Bureau. So far, archival tapes are available only for the usable data obtained from 102 of the first 439 orbital passes of TIROS II. There are great problems involved in interpreting the data from these tapes. (See ref. 3.) These tapes are furnished at a cost which is expected to be between $75 and $100 per reel. One reel contains 2,400 feet of magnetic tape and contains the data from 1 orbital day of TIROS II.

For the forthcoming Nimbus satellite system essentially the same type of archival system is planned except that there will be a much greater volume of data which will necessitate more automatic procedures in retrieving the data from the archives. Machine methods will be employed to locate data and probably copies will be furnished more selectively than is possible with current archiving procedures.

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3. STAFF MEMBERS of the AERONOMY and METEOROLOGY DIV., GODDARD SPACE FLIGHT CENTER, NASA, AND THE METEOROLOGICAL SATELLITE LAB., USWB: *TIROS II Radiation Data.* Users' Manual. Goddard Space Flight Center (Greenbelt, Md.), Aug. 15, 1961.
4. STAFF MEMBERS of the AERONOMY and METEOROLOGY DIV., GODDARD SPACE FLIGHT CENTER, NASA AND THE METEOROLOGICAL SATELLITE LAB., USWB: *TIROS II Radiation Data Catalog.* Vol. I, Goddard Space Flight Center (Greenbelt, Md.), Aug. 15, 1961.

Question Period

RUDDER, Trinidad: How will we know when the catalogs of TIROS III gridded or nongridded pictures become available?

PYLE: As more archival films become available, notice will be sent to all of the countries through the World Meteorological Organization. In many cases copies of the catalogs will be sent through WMO to all countries. Announcements will also be put in the COSPAR Bulletin. I think that WMO or the Weather Records Center would be the best contact in the event you have any specific questions about what may or may not be available at any future time.

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21. SUPPORTING METEOROLOGICAL OBSERVATIONS

By A. W. Johnson, *Chief, Operations Branch, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

It has been adequately demonstrated that research on satellite data needs the support of other information obtained by more or less conventional means. It may be of help to those of other countries to describe briefly the procedures employed in the United States to obtain these data.

A special alert message, similar to the alert message received in other countries, goes out over U.S. teletype circuits. This message automatically places a requirement upon the weather stations to take supplementary cloud observations in the area in which the satellite will be active. These are entered on a chart and are mailed to the Meteorological Satellite Laboratory. These observations give an indication of the cloud cover in the area in which the satellite has taken photographs.

Radiometer soundings have also been obtained, both in the United States and in other countries. Sky photographs are taken; a special effort is made to collect pilot reports; rocket soundings are taken. There has been a certain amount of aerial photography, and there has been a very definite effort to take coincident radar observations, including photographs of the radarscopes at the time of passage of the satellite. Special surface radiation measurements have been made, especially in some of the World Meteorological Organization countries. There has been good response from many countries to the suggestion, made in connection with Tiros II and Tiros III, that supporting observations be taken.

There seems to be some question from meteorological services in different countries as to just what observations should be made. The major point of the international supporting observation program is to encourage observations in a particular area for the benefit of that area and to encourage some research, on a global basis, of the sort that has been described in various papers presented during this Workshop. Obviously, it would be desirable to have information on any special efforts which may be made in particular countries; in many cases copies of the information obtained through supporting programs in other countries may be solicited as an aid to particular studies being conducted in the United States.

Nevertheless, the invitation to take part in a special observational program has been extended with the hope that research on this fascinating new source of meteorological information would be stimulated in various countries. The cooperative efforts desired are essentially that various types of conventional observations be taken insofar as possible, coincident with the passage of the satellite.

It may be helpful to describe what information can be obtained from the United States. The archival process and the forms of research data available have been described in paper 20. It should be stressed here that all meteorological information obtained by the United States is freely available both for research and for daily operations. It is available to all countries simply for the asking. In some cases nominal charges are made for the cost of archival film. However, in general, free availability of all information is both fact and policy.

At the readout stations nephanalyses are prepared. This procedure has been described in various papers in this Workshop. The basic information about the satellite and its program and about the codes and communications media over which the information will become available is distributed through the World Meteorological Organization. A special alert message which is generally adequate has been developed.

Unfortunately, this message does not always reach all the countries desiring to participate. This alert message is transmitted daily on schedule and advises of the areas of activity of the satellite; the activity for the immediately following 24 or 48 hours is given, as is the outlook for the next 7 days.

The nephanalysis must be encoded after it has been prepared. The nephanalysis is received by facsimilie at the programing unit in Suitland in 3 to 4 hours after receipt of data from the satellite, depending on the particular situation. The encoded message is then prepared. This is also done at the readout station and transmitted to Suitland by teletype. Then, the coded message is examined to determine if it contains the proper details, is within word-count limits, or needs revision. Most important, message transmission is subject to available communications time. The means available for the distribution of nephanalyses are not at all satisfactory. There are no means of transmitting photographs to other countries; the means for obtaining the photographs promptly at the Weather Bureau are limited. The best transmission medium, perhaps, is facsimile. Almost all the use made of the information on an operational basis in the United States is from nephanalyses transmitted by facsimile. International facsimile is available on a very restricted basis; dependence is therefore placed on transmission of encoded messages by teletype and radio, which is regrettable. It is hoped that eventually there will be an adequate international facsimile system.

Even in the area of teletype, the systems are not good enough. A Northern Hemisphere exchange system which links five major centers was established early in 1961. Those five centers have distribution responsibilities which should insure that the information is available to everyone in the Northern Hemisphere. Even this system has not worked as dependably as was hoped. By comparison with the Southern Hemisphere, however, the problem is solved in the Northern Hemisphere.

There are plans in the WMO to establish a system in the Southern Hemisphere comparable to that in the Northern Hemisphere. There are conflicting opinions as to whether the current proposals will work. In any case there will be, it is hoped, dependable links from each of the Southern Hemisphere continents to some point on the Northern Hemisphere ring, so that there can be at least an exchange with the Southern Hemisphere continents. There is real hope that one of the international aid programs will make possible the implementation of the teletype system described. The best way to disseminate these data is not known. The U.S. Weather Bureau has gone so far as to send commercial telegrams to meteorological services in various countries to inform them of apparently significant events which could not have been known from conventional observations.

For Tiros IV, more than 100 meteorological services of the world are being invited to take part once again in a supporting observational program. Another request to the Secretariat of the WMO to distribute a new code is being considered. Many of the deficiencies in the present code are recognized. Comments and suggestions as to how the code can be improved are encouraged.

It has been suggested that some indicator of confidence should be included in the code. The code which was distributed through the WMO has no such indicator although there have been messages which have included some plain-language remarks indicative of the confidence of the analyst in the material. An attempt will be made to devise some means to include in the next code an indication of the confidence in the data.

Another problem with the code is its length. It has been found that the more experience the readout station personnel acquire, the more complicated are the nephanalyses they are able to prepare. This means that the message becomes inordinately long, with the result that fairly often messages are cut off to fit into communications schedules or other messages are delayed because there is insufficient time in the schedule. Revisions are being made. Condensation of the code is a major revision under consideration. There are possibilities of adopting a code which uses both numbers and letters. This is difficult to transmit on teletype. There are other suggestions that a completely numerical code be used and that some redundancy be included so that at the end of each of the 1° lines of latitude it will be apparent whether the information has been received. There are other suggestions that the same information

that is contained in the heading be repeated at the end of the message (namely, the cloud indicators in the heading) so that if the first part of the message is missed, the information will be available at the end of the message.

These corrections are all being considered very carefully. The Weather Bureau is anxious not to change the code too many times. A new code for every TIROS is undesirable. On the other hand, there are significant deficiencies in the present code; thus, a new code is being proposed through the Secretary General of WMO. It is hoped that the new code will be used and that its adequacies or inadequacies will be reported.

A few remarks may be made concerning the improvement of meteorological communications. The satellite has proven that, meteorologically, communciations networks are inadequate for routine communications with the Southern Hemisphere. It is also true that the satellite provides a type of data difficult to disseminate in the Northern Hemisphere. Ideas and, especially, support are needed. Ways of improving the communications systems can probably be found. There are international sources of funds available which might be used; countries which wish to receive satellite data routinely must be willing to participate in the requesting of those funds. It is hoped that the countries of the world will join in the effort to improve the form of the product from TIROS and other satellites and the means available for distributing it.

Question Period

BRUINENBERG: Netherlands Antilles: Is it possible to have the picture transmitted by radiofacsimile through available means? Many countries cannot be reached by landlines facsimile, but can be reached by cable, which will cause extra delay. It will cause further delay in having the cable decoded. What are the possibilities of having it sent by radiofacsimile, for instance, via military channels which are available?

A. W. JOHNSON: It is possible to send photographs by radiofacsimile. We have not experimented enough with this to know what to expect. I think routine transmission of the nephanalyses by radiofacsimile will be possible soon.

Are you suggesting that the WBR broadcast, which eventually will be a facsimile broadcast, include photographs rather than, or in addition to, the nephanalysis?

BRUINENBERG: When it is in operation I am sure that the facsimile broadcast will be the fastest form available. I am sure that the facsimile nephanalyses will be best, but the nephanalyses should still be transmitted in coded form for people who cannot receive facsimile.

A. W. JOHNSON: In my paper I mentioned that we recognize very well that the best piece of material to give you is the photograph itself. We are hoping that before too many years go by we can reach this point. There have been some discussions with commercial interests on the radio transmission of actual photographs in special cases. These transmissions would not be a routine thing according to present thinking. They would take the place of that which is now being done by telegram; that is, when significant events are seen which we think you do not know about from other means, a telegram is sent. We have studied the sending of actual photographs of what we have seen. This involves devising a gridding procedure; it involves facilities which we, at this moment, do not have but are investigating. This would mean that at our selection, under the present plan, we would send these transmissions to countries that we think should know of the particular unusual phenomenon that we have seen. This does not mean that we are anticipating routine distribution of the type which you are asking about.

SCHWARZ, ICAO: Will it be possible in the near future to include estimates of cloud-top heights derived from the radiation data both in the pictorial representation as well as the code? Will it be possible to include information important to aviation, like special indications of mountain waves visible in TIROS pictures, jetstream clouds, and so forth?

A. W. JOHNSON: Mountain waves are in some instances discernible in the TIROS photographs. It would mean quite a special problem to sort out cases of mountain waves for a particular interest, such as aviation. This could be done, but it is not now in our specific planning. The waves would appear in encoded form in the nephanalysis itself. However, to establish an alert system with respect to a single phenomenon for the benefit of aeronautical interests would cause some very difficult operational problems. We hope that the nephanalysis itself just as it is received on the regular circuits that are available in weather offices will identify phenomena of that type adequately for your use.

The other question involves measuring the heights of cloud tops from satellites. This capability is nonexistent, but research leading toward this capability is underway. Eventually, with the Nimbus satellite and further developments, we hope that cloud-cover information will be available on an operational basis day and night, which means that the radiation information will be the basis for obtaining it. This is well over a year away.

RAHMATULLAH, Pakistan: We are very much interested in getting information, at least in plain language, about cyclonic storms in the Indian Ocean, the Bay of Bengal, and the north Arabian Sea, where the observational network is very sparse. I do not know what arrangements have been made for transmitting nephanalyses over the Asiatic network. Sometimes we tune to Tokyo, but most of our supplemental broadcast data are from New Delhi. Somehow, because of communications difficulties, we have not been able to get any of the nephanalyses so far. Pending completion of arrangements for getting nephanalyses, could it be arranged through the WMO to transmit important nephanalyses warning signals, something like "storms in the north Arabian Sea, watch out," in plain language to the different countries or to the supplemental centers like New Delhi or Tokyo?

A. W. JOHNSON: There are one or two easy ways to answer that question, although I feel it should be answered by Dr. Langlo of the WMO. New Delhi is one of the five principal centers in the Northern Hemisphere exchange system. The messages include an indicator which requires that they be transmitted from New York on the Northern Hemisphere exchange system via Frankfurt to Moscow. Similarly, they go from New York via Tokyo to New Delhi. Each of these centers, by WMO arrangement, has the responsibility for redistribution of material in its area. I do not wish to avoid your question, but your problem, I might suggest, is with New Delhi and not so much with us. We have corresponded with these centers and we have urged them to do the redistribution that is required, and all have agreed to do so. However, your request is not unique. We have similar complaints from other places which do not happen to be principal centers on the ring.

For the rest of your question, the best that we have been able to arrange so far for the particular cases of severe storms in sparse-data areas is to send special commercial telegrams. These would be addressed to Karachi and would advise your service that a storm exists. If there is a storm that concerns East Pakistan, we would still send the message to Karachi, as well as a message to your center in Dacca. We have standing instructions in our offices to watch, especially in sparse-data areas, for tropical storms and to send special telegrams. Messages of this sort have been sent and have been well received. It happens that since we set up the procedure, I do not believe we have had occasion to observe any storm in your area of interest. Therefore, there has not been a message to you. Most of the messages, I think, have been sent to the far western Pacific. Messages have been sent to Japan, the Philippines, and Australia, and to certain U.S. island interests in the Pacific.

LANGLO, WMO: Since WMO has been mentioned in this connection, I should like to say a few words. First of all, I think all of us should thank the United States for what has already been done in distributing these data. I think every country, and the Organization itself, is indeed very grateful to the United States for their great effort in making these data available.

In order to improve distribution of these data, it is most important that each country take the necessary initiative to improve its own telecommunications. Unless each country improves the various means which can be used to transmit these data, very little progress can be made. You cannot expect that the WMO can do everything in this connection. I can assure you that we are trying every possible means of improving these communications. This is not sufficient. We need the full support of every country. For particular difficulties in particular regions I think I have to remind you about the decision of our Executive Committee to refer regional problems to the president of the regional association. I think any difficulties you have in one particular region should be taken up officially with the regional association.

For the future there is no other way than to follow the recommendations of our panel of experts on satellites which, as the first priority, recommended the transmission of the photomosaic pictures, which unfortunately is not possible because the means are not available. The second priority is the transmission by facsimile of the nephanalysis, and as the third measure, there is the coded message.

VAN DER HAM, Netherlands: We are glad for the alert messages, but what we should also like to have in advance is information on the times of ascending nodes, and so on. Would that be possible with the next TIROS satellite?

A. W. JOHNSON: I think it is possible, but is the problem that the alert message is not adequate?

VAN DER HAM: We know the times of photographing only 1 day in advance, and we should like our organization to have an idea of the times of the passage of the satellite, let us say, a week ahead. It was planned for TIROS II that we would get times of passes of the satellite for several days in advance.

A. W. JOHNSON: The alert message is designed to give you quite a few days of planning information. We do not know ourselves, as far in advance as you are asking, just what the photographic program of the satellite is going to be. In order to distribute the orbital information every place, regularly, I would have to know more clearly just why it would be of use. Mr. Stroud, you might want to speak as to whether this is feasible. I had understood that, in general, the alert message had been accepted as adequate for planning, once you knew roughly when the satellite was going to be in orbit. In other words, you can make plans now for TIROS IV, and then can implement them on a daily basis when you get the message from us.

D. S. JOHNSON: There is a 7-day alert which is about as much as anyone can give.

A. W. JOHNSON: It is an outlook type of alert. The actual program is made up only the day before.

STROUD: I think the question has been answered. The problem of directly transmitting all the computed orbital information for 2 or 3 weeks in advance would be a tremendous task.

D. S. JOHNSON: I think the gentlemen would be happy with the time of the ascending node. However, I fail to see how this would satisfy the purpose since you would also have to know which orbit could be contacted

and where pictures would be taken along the orbit. This information cannot be given in advance. This information is contained, I believe, in the 7-day forecast. As Mr. Stroud pointed out in paper 10, there are many changes that occur sometimes even a few hours before acquisition. In general, we try to keep changes to a minimum. Occasionally, there are problems that appear. Thus, I am not sure that only the ascending node information would be of great help to you.

TORRES-MOLINERO, Honduras: If, during the alert period, for example, the satellite is going to pass over Central America, what would be the best means of taking advantage of the passage of the satellite? On the passage of the satellite, we just make common observations; we do not do anything special. I would like to know what we can do to take better advantage of it.

A. W. JOHNSON: The alert is designed specifically to inform those countries which have decided to establish a special observational program that the satellite will be active in their area. If you do not intend to supplement your routine observational program, the alert message will do you no good, except that you might learn from it that on the following day there may be information of interest to you in nephanalysis form. The alert is designed to enable services to begin supplementary observational programs.

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22. NASA METEOROLOGICAL SATELLITE PLANS FOR THE FUTURE

By Morris Tepper, *Director of Meteorological Systems, NASA*

The NASA objectives in planning a meteorological program may be stated as follows:

The first objective is to obtain data essential to (1) improved knowledge and understanding of the atmosphere, and (2) development of weather analysis and forecasting techniques.

The second objective is to develop satellite prototypes and principles of a national operational meteorological satellite system.

The final objective is to conduct basic and applied research and development for continued improvement of the operational system. Contributions toward meeting this objective will, it is hoped, come from many persons in many countries.

Hopefully, these basic objectives will be achieved through a flight program of progressively more sophisticated meteorological satellites and related programs of supporting research and development.

Tiros I, II, and III have been discussed in the preceding papers in this Workshop. Subsequent Tiros launches to a total of at least seven, including those already launched, are scheduled at approximately 4-month intervals. The objective is to provide a continuity of operating meteorological satellites in orbit through the first successful Nimbus launches.

The fourth Tiros is expected to be substantially the same as Tiros III, except that one of the two wide-angle television cameras will be equipped with a lens providing slightly less coverage, about 20 percent decrease, but with correspondingly improved resolution, and, what is more important, much less distortion. Consideration is being given to launching Tiros satellites into orbit at angles of inclination greater than those used at present (about 50°). This will provide meteorological data farther north and south—poleward, of course—and in the winter season, a better chance to study the applications of the data to sea ice analysis.

Figure 22–1 shows the reason for progressing from the Tiros series to the Nimbus series. The Tiros satellites are limited in coverage potential by two features. One, the satellites are in an inclined orbit. In other words, the earth can be viewed essentially between two latitudes, roughly 50° north and 50° south. The polar regions are not accessible to the Tiros view. The second feature of Tiros which is undesirable for an operational system is the fact that it is spin stabilized with respect to space; that is, it presents more or less the same orientation in space throughout its lifetime. In part of its orbit it views the earth; in another it views space. This, too, limits the coverage potential. Nimbus is designed to overcome these two deficiencies. Nimbus will be in polar orbit so that it will view the entire earth as the earth rotates underneath it, and it will be oriented to view the earth at all times.

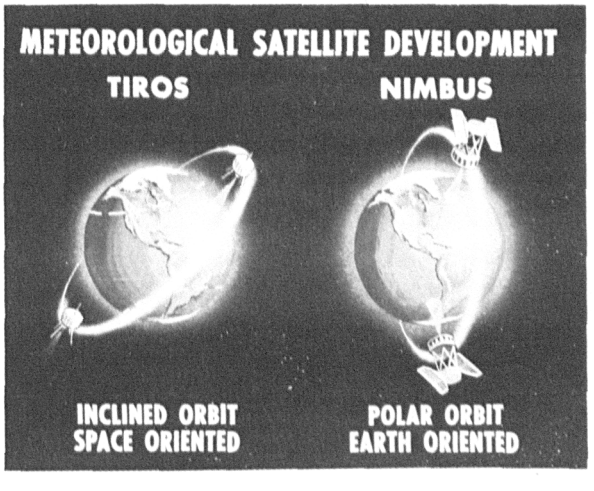

Figure 22–1

The Nimbus family will be a family of satellites with many common components, such as data storage, controls, orientation, stabilization, data transmission, structure, and so on. It will have a flexible capability for improving old and introducing new systems as required. The first satellite in the Nimbus family is due to be launched late in 1962, with subsequent launches at about 6-month intervals. Since Nimbus will be earth stabilized, its cameras and other atmospheric sensors will always face the earth. Moreover, because of the polar orbit, Nimbus will view each area of the earth about twice a day.

Figure 22–2 shows the Nimbus satellite in the early development stage. It will be about 10 feet tall and about 5 feet across at the base. The weight of the first Nimbus satellite will be about 600 pounds. Later versions with more sophisticated sensors are expected to weigh up to 800 pounds, or possibly more. The satellite will have a lower part shaped like a hatbox where the sensor equipment will be located; the upper part is the control section and will orient the satellite properly. The two sections will be connected by struts. The solar platforms, indicated in figure 22–2, will be fastened to a shaft extending from the control section. These platforms, which will be controlled always to face the sun, will be covered with solar cells to provide power. The section on the top of the connecting struts will provide the controls to keep the satellite axis and the sensors always pointing toward the earth. The lower section contains the sensing units.

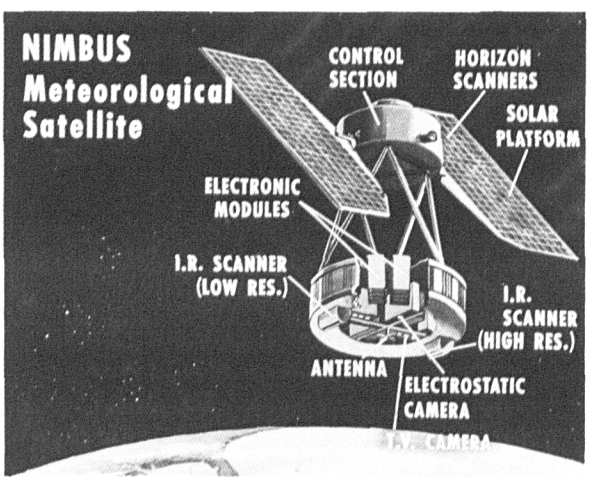

FIGURE 22–2

As presently planned, the Nimbus will contain vidicon cameras with wider coverage and better resolution than those in TIROS and a number of improved radiation sensors. The lower section of Nimbus is being designed on a modular or standardized compartment basis. The electronic modules shown in figure 22–2 can therefore be replaced in later versions of the satellite with improved or new types of equipment without redesigning the entire satellite. In later Nimbus satellites it may be possible to include new types of sensing equipment, such as image orthicon television cameras that can provide cloud data pictures at night, a radar set to provide data on the areas of precipitations, a radiation spectrometer to provide information on the temperature structure in the stratosphere, and a sferics detector to identify thunderstorm areas. An electrostatic-tape camera for a more detailed view of significant weather systems is also under development. Also planned is a device for measuring the solar constant or the total solar energy impinging on the earth. The general characteristics of the Nimbus family are presented in table 22–I.

Even the first Nimbus, although primarily an experimental research and development spacecraft, can be used to provide data for operational purposes. Plans exist for these data to be sent in real time from the data acquisition station in Fairbanks, Alaska. The reason for a station in Fairbanks is the fact that the spacecraft will be in polar orbit and a northern station can acquire more data as the satellite orbits the earth. The ideal locations would be exactly at the poles, of course, or close to them. The data will go from Fairbanks to the National Meteorological Center of the U.S. Weather Bureau at Suitland. There, the data will be analyzed and the resulting weather information distributed to both civilian and military weather stations. From its earliest conception Nimbus has been planned to serve as the basis for the spacecraft of the first operational meteorological satellite system. As the TIROS and Nimbus satellites rotate around the earth they view different portions of the geography of the earth. Thus, the evolution of a weather system can be followed only by studying data obtained in successive passages of the satellite over the same area. Several hours may elapse between passes. The meteorologist is

TABLE 22–I.—*Nimbus Meteorological Satellite*

Spacecraft:	
Size	114 in. high by 56 in. diameter.
Weight	550 to 600 lb.
Power	Solar cell paddles; nickel, cadmium batteries.
Stabilization	Earth-oriented pneumatic jets and inertia wheels; ±1° pitch and roll; ±2° to 3° yaw; rates <0.1° per second horizon scanners; integrating gyro.
Sensors:	
Advanced vidicon subsystem TV cameras.	0.3-mile resolution; nearly horizon-to-horizon coverage.
Radiation detector subsystems	Medium resolution, 5 channels, similar to TIROS. High resolution, night clouds, 125-mile resolution. Low resolution, total and thermal radiation, 400 miles.
Solar constant	±0.2 percent.
(Later spacecraft: electrostatic tape camera; spectrometer; image orthicon cameras; radar.)	
Orbit:	
Inclination	80° retrograde (quasi-polar; constant local time).
Altitude	600 nautical miles (±30 nautical miles; 3 sigma).
Period	108 min.
Launch	Pacific Missile Range.
Command and Data Acquisition: Station	Fairbanks, Alaska.
(Immediate relay of TV cleared data to NMC via 48 kcs line).	

interested in continuously observing developments of a particular storm area. This is particularly true of the short-lived and severe local storms where the entire life history may be a matter of only a few hours. It is also important to be able to follow the development of nascent storms before they explode into fully maturity.

Figure 22–3 shows the Aeros satellite which is now in the planning stage. The Aeros satellite will be launched into a stationary orbit. The orbit is called stationary because, due to its distance from the earth, 22,300 miles, the satellite will be moving at about the same speed as the rotation of the earth. Therefore, it will appear to be stationary over the subsatellite point. The orbit will be equatorial and the Aeros will view events essentially in the temperate and tropical regions. The principal instrumentation to be developed will be a cloud-cover observational system, with vidicon cameras having a variable focus; the wide-angle camera will view a great portion of the earth, and a high-resolution camera will view a smaller portion. It may not be necessary to have two cameras; one may be sufficient. That is a matter of development. The purpose of the high-resolution camera would be to obtain sharper details in a smaller geographic area. Under present plans the first Aeros satellite will be launched between 1964 and 1967.

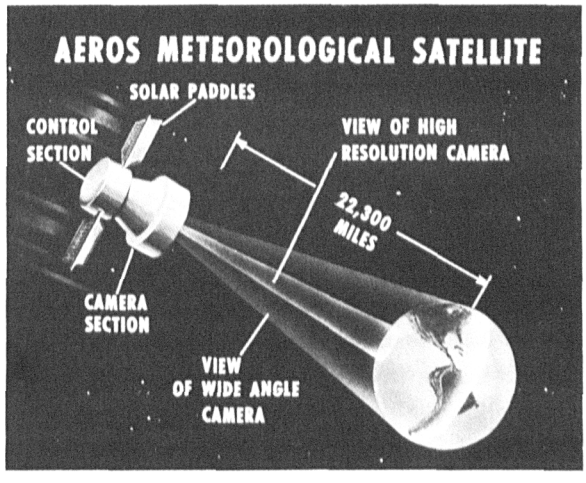

FIGURE 22–3

Following the termination of the currently planned Nimbus series, the launching rate is expected to be about one research and development meteorological satellite a year in addition to the Aeros satellites. This program will be used to develop and test improved or new sensing systems to be incorporated, as they become proved out, into the operational meteorological system.

Figure 22–4 shows several possible systems. The first sketch shows the original concept of

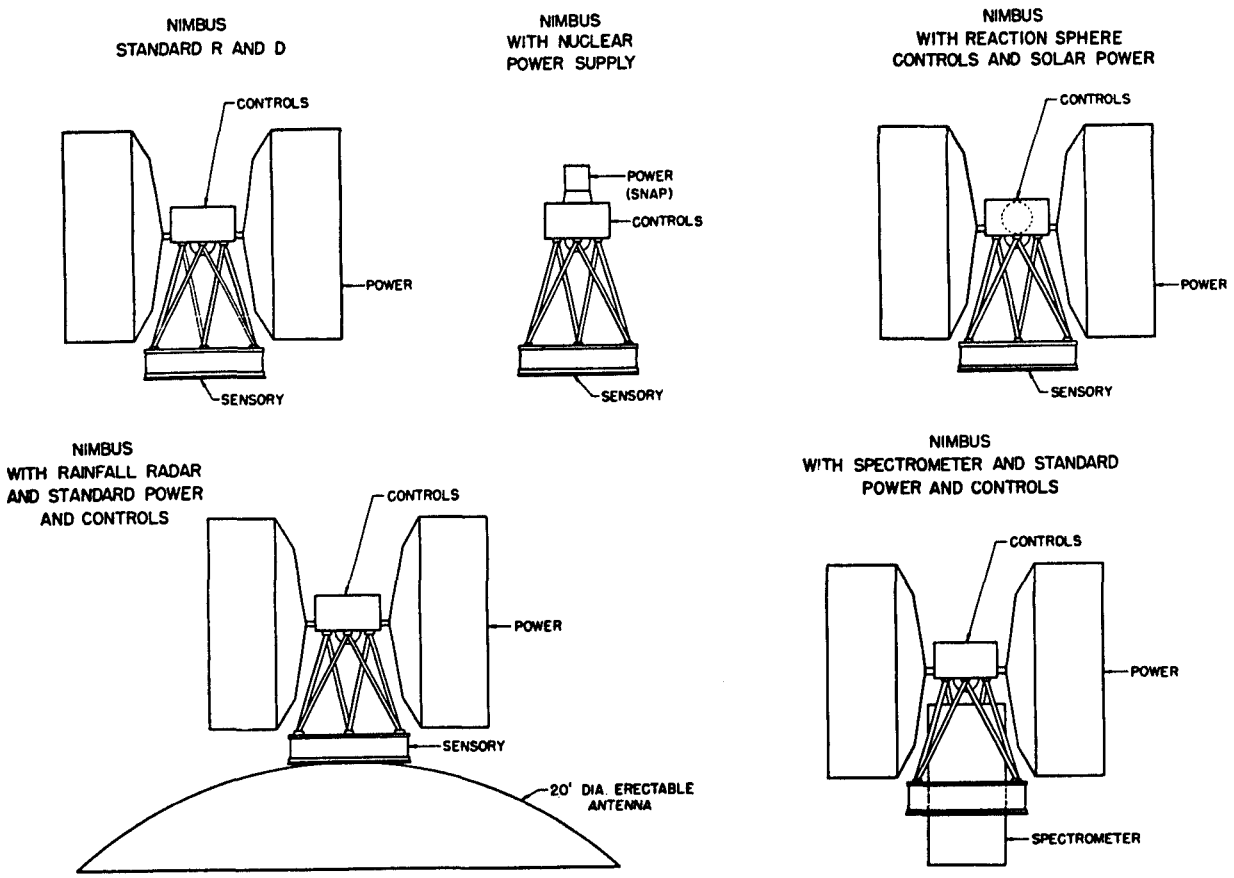

FIGURE 22–4

Nimbus with the controls, the power, and the sensory configuration. A change that might be possible in future developments would be, for example, the incorporation of a nuclear power supply where the present paddles are replaced by a smaller power supply. Another possible change is to incorporate reaction sphere controls instead of the present jets as indicated in the top right sketch. The rest of the configuration is shown to remain the same. Also, the sensors may be changed by including a radar, with a 20-foot erectable antenna as shown in the bottom left sketch. Another possibility would be to add a spectrometer as shown in the bottom right sketch. These changes are all conceptual at present. There are no specific engineering drawings.

The flight program is based on a continuing research and advanced technical development program for developing techniques, components, and prototypes in such areas as improved radiation sensors, studies of atmospheric quantities that can be measured by improved sensors, improved mechanical and electronic components of flight systems, and improved and new meteorological sensors such as those mentioned previously. The most critical areas in these programs deriving from the volume of meterological data and the requirements of the operational meteorologists are the reduction, the processing, the transmission, and the presentation of the meteorological data to the weather forecasters in as near real time as possible.

The determination of signficant meterological content of the satellite output is a key factor in resolving these problems. The meteorologists must determine beforehand the real meteorological content of the data output because only through this type of study will it ever be possible to reduce the volume of information so that it may be transmitted with the existing facilities or even with improved facilities. Thus, if the significant meteorological content of the output is determined, rapid transmission techniques may be refined to make this information available to the field personnel in time for use.

Developments under study in this field include satellite onboard analysis techniques for extracting the useful meteorological information so that all the data do not have to be transmitted. Other developments required are special techniques for data presentation, automatic analysis instrumentation, improved transmission facilities, and advance communications relays. Data compression techniques, in which a good deal of progress has already been made, are used to reduce the bandwidth in the transmission of pictures and should be included in this list.

In addition to the efforts that are required for the development of advanced spacecraft and associated systems, continuing attention is also needed for the solution of another fundamental data problem: The study and analysis of the data in order to provide better analysis and forecasting techniques and improved understanding of atmospheric processes. In this study the primary responsibility rests with the Meteorological Satellite Laboratory of the U.S. Weather Bureau, the research agencies of the military services, the universities, and other research organizations.

The volume of data already acquired by the TIROS satellites and of data expected from future meteorological satellites is enormous. The Weather Bureau and the other weather-data users are analyzing these data in research programs and applying the results to operational weather purposes. Attempts are being made to encourage increasing numbers of investigators to study these data through aggressive contacts with the scientific community in general and with university research groups in particular.

By means of this International Workshop and other similar ones to follow it is hoped that the scientists in countries all over the world will consult one another with regard to their individual data-analysis endeavors. Other international aspects may be listed as follows:

(1) The transmission of nephanalyses.—It is planned to continue the current practice of disseminating internationally the analysis of data.

(2) Non-U.S. command and data acquisition stations.—The fully operational system currently being developed in the United States is dependent on a least one command and data acquisition station on foreign soil. This phase of the program is in its early planning stages.

(3) Ultimate direct readout of the data by foreign countries.—A more direct way of making available to any country the weather information in its immediate area of interest would be by means of a direct readout of satellite transmissions. Under study at present are problems connected with making available to a foreign country acquisition stations programed for nondestruct readout of stored data as well as direct readout of the satellite transmission. This would be a very significant and important development.

At present, when the satellite data are read, the data are destroyed to make room for the subsequent gathering of data. When a nondestruct readout capability is developed, then a country with an acquisition station will be able to interrogate the satellite and obtain the data without destroying these data for another country. Here, another problem will be encountered, however, and that is the power supply. If there are too many interrogations, there might be an excessive power drain on the satellite.

(4) The possibility of international participation in a unified global operational meteorological satellite system.—A truly international operational system can be foreseen with satellites transmitting global observations to a World Meteorological Center and more restrictive data directly to regional, national, and local centers and nations. The World Center would provide global analyses and longer period forecasts, whereas the other centers would concentrate on meteorology of a more local nature.

Question Period

McCULLOCH, Canada: Dr. Tepper, is it safe to assume that the high-resolution camera planned for Aeros could be pointed at any location within the temperate and tropical zones and that the pointing of this camera could be changed from time to time as various areas of interest move?

TEPPER: The answer is yes; this is what we would like to be able to do.

VAN DER HAM, Netherlands: Could you tell to what latitudes the camera of Aeros would be able to move? What northerly and southerly latitudes?

TEPPER: I think that it goes to about the Arctic and Antarctic Circles. Of course, there will be considerable data compression in those areas.

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23. AN OPERATIONAL METEOROLOGICAL SATELLITE SYSTEM

By DAVID S. JOHNSON, *Chief, Meteorological Satellite Laboratory, U.S. Department of Commerce, Weather Bureau*

The philosophy of the proposed operational system and some of the international implications involved are discussed in reference 1.

Shortly after the launch of TIROS I, when it became evident that operational use could be made of data from the first experimental meteorological satellite, there was a growing interest in the United States in the possibility of developing an operational program. In fact, only 60 hours elapsed between the launch of TIROS I and the time first operational use was made of the satellite information.

Subsequent to the launch of TIROS I, a number of discussions regarding an operational system were held in the United States and working groups studied the problem. Based upon the conclusions of these groups, it was decided to proceed with the development of a national operational meteorological satellite system based upon the engineering and development work of the NASA.

The initial phase of the operational program will supplement the previously planned NASA research and development program utilizing the Nimbus spacecraft, which has been described in paper 22. The objective during this first phase is to assure the collection and dissemination, on as nearly a continuous basis as possible, of data which are known to be useful for operational purposes and which can be processed rapidly. The first phase involves increasing the number of launches of the Nimbus satellite over those which had originally been planned and implementing additional ground facilities to obtain global coverage and to process the data for operational use. NASA is constructing a command and data acquisition station at Fairbanks, Alaska, which is nearly complete. However, this single station will not supply global coverage. At least one additional station is required. The operational program will add this station to the network. Also, there will be an acceleration of the development of automatic data-processing techniques, including wideband communication facilities and other facilities required for the rapid processing of the data in order to assure rapid dissemination to meteorologists.

It is hoped, then, that very early in the research and development phase of Nimbus, operational use can be made of the data on a nearly continuous basis. Although this still would be in conjunction with the research and development program, it would provide global coverage as soon as possible and with as few breaks as possible. Obviously, when one satellite ceases operation, a certain amount of time will be required for a second satellite to be placed in orbit and begin operating.

The objective of this program, following the first phase just described, is to assure that one polar-orbiting satellite is in operation at all times. This would then mean that every point on the earth would be viewed at least once in daytime, except for the winter pole, and would be viewed also once at night, every 24 hours.

At an $\approx 80°$ retrograde orbit and at the design altitude, the orbit will precess in such a manner that the orbital plane will continuously contain the earth-sun line if the satellite has been launched to cross the Equator at approximately local noon or local midnight, on the ascending node or descending node, respectively. The time of equatorial crossings would continue throughout most of the lifetime of the satellite. This would then make available the best illumination for the daytime cloud pictures. Another byproduct would be the availability of the specular reflection of the image of the sun on water

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surfaces from which it may be possible to infer sea conditions.

There are no definite plans at the moment for the future expansion of the operational system based on the Nimbus type of satellite. However, there is the possibility of having two such satellites in orbit at the same time, launched so that there would be observations at 9 a.m., 9 p.m., 3 a.m., and 3 p.m. (local times) of each point in the vicinity of the Equator. Of course, these times will shift to some extent as the satellite moves to higher latitudes. Roughly, there would be an observation at least once every 6 hours near the Equator. As the satellite nears the poles, it will see the earth much more frequently. Above 60° there will be very frequent observations.

In regard to frequency of observations, it is interesting to look still farther into the future when orbiting satellites of the Nimbus types and the Aeros stationary type of satellite will be operating simultaneously. With this combination there would be very frequent observations in the polar areas from the Nimbus satellite and nearly continuous observations of the remainder of the earth from the Aeros satellite. These satellites would indeed complement each other insofar as frequency of observations and coverage is concerned. At the present time it is felt that there are a number of experimental measurements which can be made from the Nimbus satellite which would not be made, as far as is now known, from the Aeros satellite. Thus, there are other considerations in the selection of the orbits and the altitudes involved.

In the initial phases of the operational system it is planned to use comunication links with a 50-kilocycle bandwidth between command and data acquisition stations and the National Meteorological Center at Suitland, Md. This bandwidth will allow all the data collected on one orbit to be transmitted to Suitland before the next orbit is received. This is essential; otherwise the volume of data would quickly become overwhelming.

It takes approximately 10 minutes to receive from the satellite all the information that will be stored on Nimbus from one orbit. Then, by extending the time for playback over the wideband communications link, the data can be transmitted over a period of approximately an hour, using 50 kilocycles rather than using a bandwidth of approximately 3 megacycles or more which would be required if the data are to be transmitted at the same rate of speed at which they are transmitted from the satellite to the command and data acquisition station.

There are many factors to be considered in the selection of the number and location of command and data acquisition stations. As indicated in paper 22 there has been no final decision in this regard. One consideration is the problem of communication. It is more severe than such a problem as finding 3-kilocycle bandwidth lines to transmit nephanalyses by facsimile. The magnitude of the problem of this type of communication is already known. However, if maximum use is to be made of data available, wide bandwidth communication lines are essential. This, then, does limit selection of station locations to a considerable degree. There is a possibility of using communications satellites not only for meteorological satellite data but as a solution to the total problem of data transmission confronting meteorologists.

The reason for transmitting the data from the command and data acquisition stations to Suitland is that, particularly with more than one station, it is more efficient to centralize the rather complicated data processing that must be carried out before the meteorologist can make maximum use of these data in real time. Also, the meteorologist must consider not only satellite information but all meteorological data available. The National Meteorological Center serves as a collecting point for all observations; thus, the Center would incorporate not only meteorological satellite data but all meteorological data of which the satellite provides a part. The processing of these data would be carried out as a whole to provide integrated analyses and other products in the varying forms required for a multitude of applications. This also makes one consider how a meteorological service might look, say, 10 to 15 years from now, when there is a fully operational meteorological satellite system, as well as other developments in meteorological sensing such as radar, surface observations, and upper air soundings.

When one considers the fantastic amount of information which confronts the meteorologist

and the great diversity of applications which have to be made, it is obvious that there must be specialization. Some forecasters may concentrate solely on the prediction of severe local storms, others may be concerned with long-range forecasting, and so forth.

As an example of the volume of data, a rough estimate was made that 10^9 bits of data (in computer parlance) will be available from cloud pictures for one orbit of Nimbus. This emphasizes the need for planning very seriously just how this information is to be handled, its application, and how to deal with the total problems of the system.

There certainly will be applications of these data for all varying scales and varying needs. The question arises: How best can the forecasters who are going to make the final application be served when the variety and volume of data that will be available to them are considered?

Certainly, there will be a greater centralization of specialized forecasting where various meteorologists can draw upon portions of the satellite data for specific application. This would apply more to short-range forecasting than to extended-range or hemispheric forecasting.

Reference

1. WEXLER, H., and JOHNSON, D. S.: *Meteorological Satellites*. Bull. Atomic Scientists, vol. XVII, nos. 5–6, May–June 1961, pp. 185–190.

Question Period

SLATER, U.S. Air Force: How many orbits can be read out from the Fairbanks, Alaska, station? You would have about 13 orbits from Nimbus.

D. S. JOHNSON: There are slightly less than 14 orbits per day, and of these, 9 can be read out at Fairbanks. The remainder would be missing.

NANCOO, Trinidad: If the first Aeros satellite is orbited at a speed approximately equal to that of the spin of the earth, unless you have a camera that can take pictures at night do you not think that it would be of more advantage if the satellite were orbiting at a different rate when photographing the light side?

D. S. JOHNSON: This point is well taken. One of the objectives, of course, is continuous surveillance. Much consideration is being given to the development of systems which could observe the clouds at night as well as in daylight. However, to clear up any possible doubts, Aeros will be orbiting with the rotation of the earth so that it will effectively remain above a single point on the Equator.

MCCULLOCH, Canada: What are the geographical limitations of the second command and data acquisition station which you postulate will be needed for Nimbus?

D. S. JOHNSON: That is a difficult question to answer uniquely since there are a number of parameters to be considered. It would be most desirable to consider a station which would be separated 180° in longitude from the Fairbanks station, if the Fairbanks station if to be considered as one of them. However, there is a considerable range beyond this point. You have, considering two stations, two acquisition circles within which you will see the satellite for the minimum 10 minutes required for the acquisition of the data. I believe that the radius of these circles is about 1,200 nautical miles. If the positions of the stations are selected so that these two circles are just tangent, and hopefully then would cover 180° of longitude, you would intercept all the orbits.

There are other possibilities. One is to use two or more stations at a somewhat lower latitude where logistics, communications, and living accommodations are less difficult. One also could consider increasing the orbital altitude of the satellite which would increase the radius of each acquisition circle. There are a number of other permutations such as these, but these are the types of considerations that go into determining the various combinations of locations that could be used. There has even been consideration given to three stations. Of course, only one station would be required if it were poleward of 81°. There are varying points of view about establishing a station at those latitudes.

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24. GENERAL DISCUSSION

JAMES, United Kingdom: First of all, I think we should congratulate NASA and the U.S. Weather Bureau on this incredibly ambitious program. It comes as quite a surprise.

I just wonder if we are all being a little narrow in the field of meteorology we are considering. Perhaps Dr. Tepper might have said more about the research satellites. Anyway, I would just like to mention a few things. Your program is concerned mainly with looking down at the earth, and occasionally up for radiation from the sun. In the only simple experiment we have in the U.K., we look sideways, and there are one or two things which trouble us. I wonder if you have encountered limb darkening.

We are concerned with limb darkening of the radiation of the sun, particularly in the ultraviolet. I know you have to have a very stable vehicle to measure this sort of thing, and I wonder what you have in mind.

Meteorology is a vastly expanding subject, and besides being mathematicians, geographers, and physicists, I cannot help feeling that we should perhaps be geochemists as well. I feel that we should know a lot more about the composition of the atmosphere, how emissions are absorbed, and the quantities of nitrous oxide, oxygen, and ozone in the atmosphere, to name a few.

Finally, I think that we should concern ourselves with the origin, say, of dust which has been reported at high levels. In fact, I will go further and suggest that measurements from a satellite ought to verify or refute Dr. Bowen's suggestion about rainfall and meteor showers.

D. S. JOHNSON: We have been following with great interest the U.K. experiment for ozone determination. Although I will not speak for everyone here, I suspect that this may have something to do with why we have not engaged in this particular investigation. There is plenty to do otherwise and we are very delighted that you people are working on this. I think that Dr. Tepper would like to discuss some of the other experiments in the geophysical program. I believe that you were specifically pointing your question to some of the other areas which I, at least, like to think are still meteorology.

TEPPER: The information that we have presented to you so far is restricted to meteorology and is deliberately narrow. A discussion of the entire geophysical program that is being undertaken in this country today would take a great deal of time. We have a very extensive space science program in which geophysical exploration plays a major role. This program includes not only satellite observations but rocket observations as well, and contains a gamut of observations in the various fields you have mentioned, and many more. We have restricted our presentation essentially to the meteorology of the lower atmosphere. This is why we have excluded from our discussion the geophysical satellites and the rocketsonde program.

FRITZ: Of course, we do know that many measurements are being made of the meteoric dust content, both of sizes and amounts, by various satellites that are already in orbit. The statement Dr. James made is very comprehensive and includes many things which meteorologists have wanted to know for a long time. He mentioned the composition of the atmosphere, for example. We had a meeting in Washington about 2 years ago, to which we invited many infrared radiation experts in the country, Goody, Kaplan, Howard, and Elssaser, to name a few. All those people met to discuss what could be measured by infrared techniques. The obvious things mentioned at the meeting and discussed over a 2-day period, were water vapor, temperature, ozone in the 9.6-micron band, carbon dioxide, and, in general, all the things in the atmosphere which radiate strongly in the infrared. Then, we decided what could be done first.

One of the things which is essential, for example, in water-vapor measurements, if infrared techniques are to be used, is to measure the temperature first, because water-vapor emission depends both on composition and on temperature. As an outgrowth of such discussions, we are actively engaged in a program to measure the temperature of the atmosphere. We now have a "breadboard" model spectrometer which was designed to measure the emission of the atmosphere in the carbon dioxide bands in very narrow wavelength regions. Each of these narrow wavelength regions has a somewhat different absorption coefficient so that we can "look" to different depths in the atmosphere. By sensing in at least four wavelength regions, we will get a vertical profile of temperature from the upper stratosphere to about 1 millibar. This will be done all over the world every day. Thus, we will have essentially a stratospheric isotherm map at constant pressure. If that succeeds, and we have every hope that it will, water vapor might then be measured. If one knows the temperature and chooses the proper wavelengths, one might try to measure water-vapor distribution.

Ozone was mentioned. As you know, the theory of ozone measurement by using solar ultraviolet light scattered back by the atmosphere, has been worked out by several people. Dr. Twomey, of the Weather Bureau, has recently published a thorough discussion of it in the Journal of Geophysical Research, July 1961. I think what is needed now is work on the experimental side.

The limitation here is that nobody is doing it; nobody has come forward to try it. It could be done if we had the precision, and Dr. Twomey thinks that the necessary instrumentation is essentially available.

LANGLO, WMO: I hate to bring up the question of dollars. In many circumstances when you plan for the future, this question is being asked. The sum of $3 million for a readout station was mentioned. My question is, would it be technically feasible to have other types of readout stations in several countries which could make a limited readout for specific data needed for operational purposes?

TEPPER: We appreciate the fact that $3 million or so for a readout station is an expensive proposition and so we have under serious consideration, at present, studies for systems that might lend themselves to a readout station that would be simpler than the one that we have been using.

D. S. JOHNSON: I would like to add that the $3 million is an order-of-magnitude figure.

25. PHOTOGRAPHS OF PARTICIPANTS TAKEN DURING TECHNICAL SESSION

FIGURE 25–1. Workshop participants taking notes during lecture.

FIGURE 25–2. Dr. V. E. Soumi lecturing on uses of infrared data from satellite.

FIGURE 25–3. Question period following presentation by Dr. V. E. Suomi. Standing, left to right, Mr. D. S. Johnson, Dr. Suomi, and Dr. Morris Tepper.

FIELD TRIPS

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26. FIELD TRIP TO NASA GODDARD SPACE FLIGHT CENTER, GREENBELT, MD., AND ANACOSTIA, D.C.

At the TIROS Technical Control Center in Building 3, Greenbelt, Mr. Ernest Powers explained to the participants how the information from the tracking and attitude computers is utilized and combined with inputs from the Weather Bureau in the preparation of control commands to the satellite.

At Anacostia, members of the Aeronomy and Meteorology Division conducted the participants on a tour of the facilities used to support the TIROS project. The procedures and equipment used to test and calibrate the infrared radiometers were demonstrated and explained by Dr. William Nordberg. The complete process of handling the infrared data from the raw analog form as received from the satellite through all the steps of conversion and combination with attitude and ephemeris data to produce the final meteorological magnetic tape was also demonstrated and explained by Mr. William Bandeen and Mrs. Marjorie Townsend. The participants were given samples of the "quick look" pen and ink paper recordings of the data.

A model of the TIROS satellite was demonstrated and some of the more critical characteristics were explained by Mr. Herbert Butler. Particular emphasis was placed on an explanation of some of the limitations and capabilities such as the storage capacity of the tape recorders and the effect of attitude on picture taking.

Dr. R. Stampfl gave a comprehensive review of the Nimbus satellite, making use of a full-scale model, and indicated how many of the limitations of TIROS will be overcome by the broader picture coverage and attitude stabilization of Nimbus.

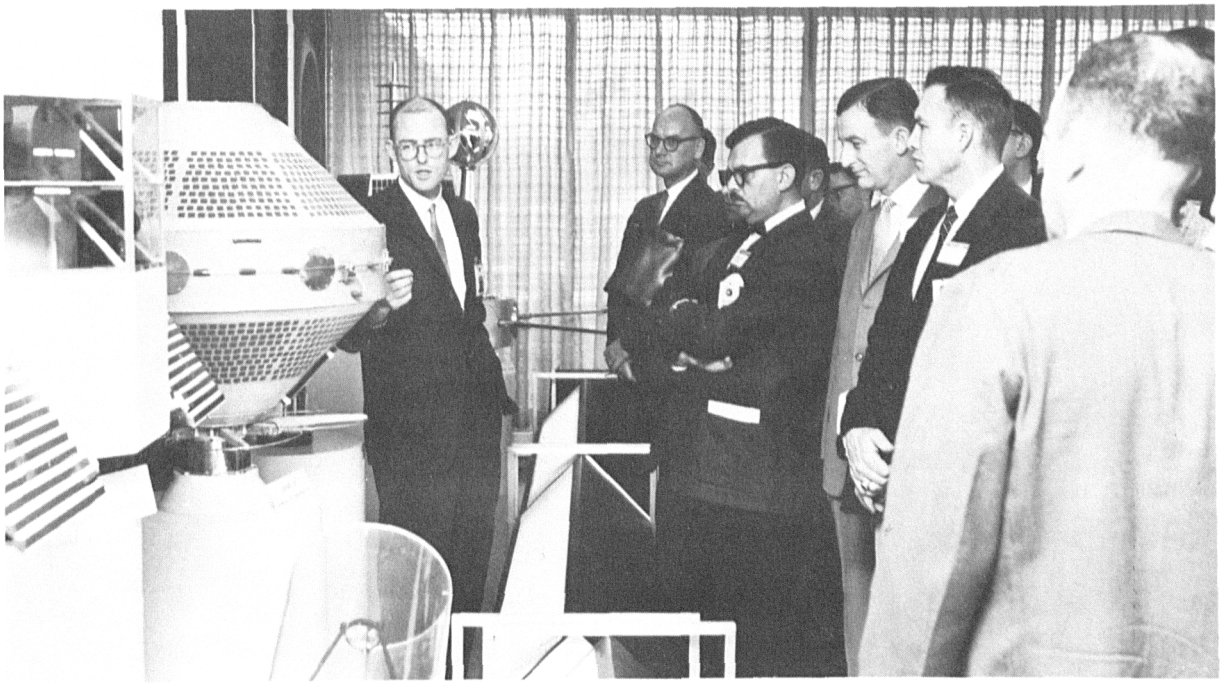

FIGURE 26–1. Dr. John Townsend, Jr., explaining operation of experiments on Explorer VII.

FIGURE 26–2. Mr. Robert Hite explaining rectification of TIROS II radiation data.

FIGURE 26–3. Mr. Harold Hoff explaining operation of 85-foot tracking and data acquisition antenna being installed at Fairbanks, Alaska.

FIGURE 26–4. Mr. Herbert Butler explaining instrumentation on TIROS II.

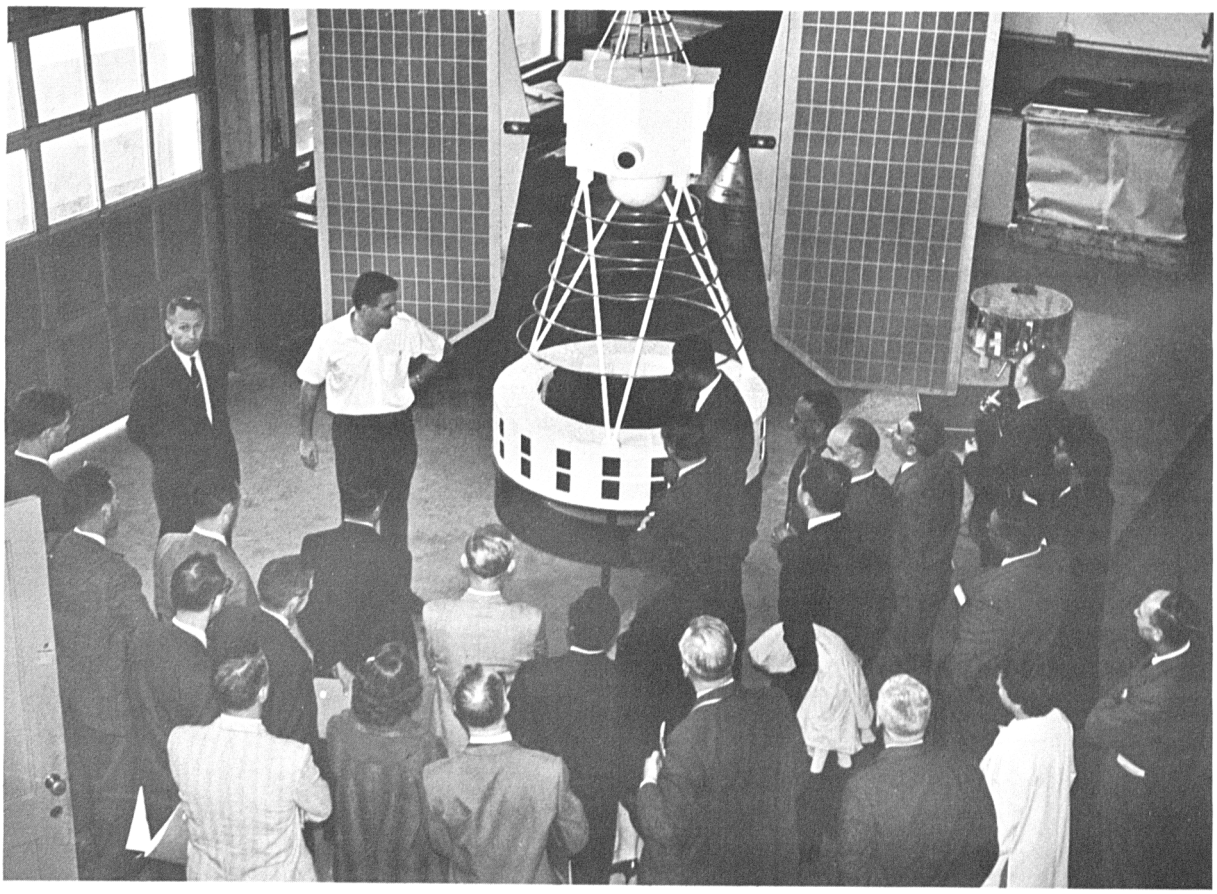

FIGURE 26–5. Dr. William Nordberg explaining features of Nimbus model.

27. FIELD TRIP TO NASA WALLOPS STATION, VA.

The participants were welcomed by Mr. Robert L. Krieger, Director, in the conference room of the Range Control Center and the operation of the center was explained. A presentation on the technical and operational aspects of the Arcas sounding rocket was made. Displays included photographs, basic data and flight sequence charts, and a full-scale inert Arcas rocket system with component parts such as individually packaged aerosonde and 1-meter Mylar sphere payloads.

A complete tour was made of the TIROS weather satellite command and data acquisition station. An explanation was given of the methods of commanding the satellite and receiving data from the satellite. This was followed by a presentation on the methods and techniques of rectification and analysis of the data received, with actual TIROS pictures of cloud cover being used in this demonstration. The TIROS tour was concluded with a discussion of methods of communication and dissemination of weather data through the Weather Bureau communications center at Suitland, Md. Another presentation was made on the method of obtaining scientific data on wind, temperature, and density of the upper atmosphere by using small explosive charges. Charts and hardware were used to illustrate the method and features.

FIGURE 27–1. Mr. John F. Spurling explaining operation of Arcas meteorological rocketsonde.

FIGURE 27–2. Participants viewing data acquisition antenna.

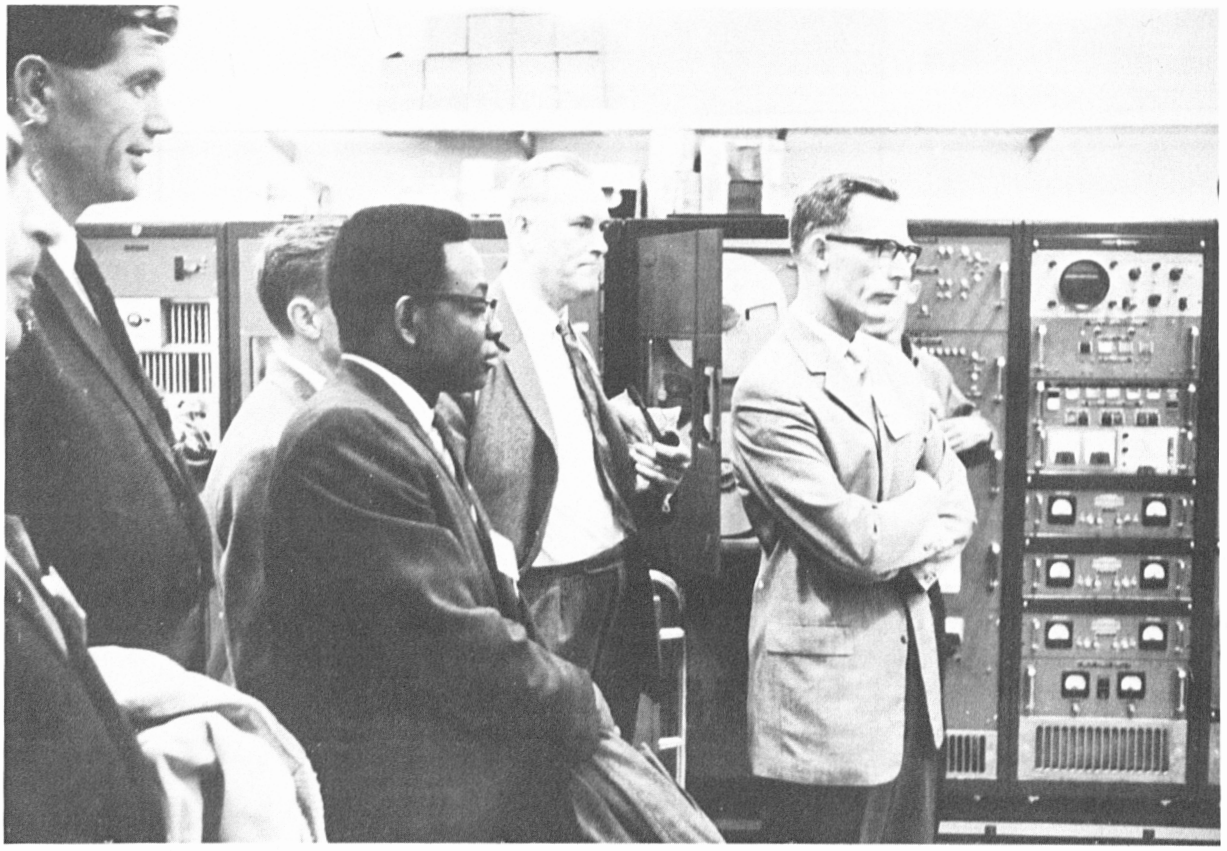

FIGURE 27–3. Participants viewing acquisition of data at meteorological station.

28. FIELD TRIP TO USWB METEOROLOGICAL SATELLITE LABORATORY AND NATIONAL METEOROLOGICAL CENTER, SUITLAND, MD.

The participants visited these installations in two groups. The guided tour of the National Meteorological Center included a welcome by Dr. George P. Cressman, Director. Visits were made to the Analysis and Forecasting Branch, the Numerical Weather Prediction Branch, and the Extended Forecast Branch. Short explanatory talks were presented, and questions were answered. The visit to the Meteorological Satellite Laboratory included displays and explanations of picture mosaics, charts, and instruments being used in various research projects within the laboratory. The mechanics of the program for operational use of the satellite cloud pictures were also explained. Mr. David S. Johnson, chief of the laboratory, welcomed each group.

A brief visit was also made to the Project Mercury (man in space) meteorological support group.

FIGURE 28–1. Dr. G. P. Cressman welcoming participants to National Meteorological Center in analysis room of Extended Forecast Section.

FIGURE 28–2. Participants viewing operation of electronic curve plotter in Numerical Weather Prediction Section.

LABORATORY SESSION

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29. EXERCISES ON COORDINATE ANALYSIS, PICTURE RECTIFICATION, INTERPRETATION OF PICTURE DATA, AND USE OF RADIATION DATA

One full day was spent by the participants learning the basic geometry needed to position TIROS pictures geographically. Working with the necessary grids, graphs, charts, and TIROS photographs the participants produced a geographic grid for a specific TIROS photograph. Immediately after each portion of the procedure was explained to the group, the participants worked through that portion individually. The sessions were led by Mr. L. F. Hubert. Dr. Tetsuya Fujita, of the University of Chicago, who devised the method used, acted as special consultant at the session. Laboratory assistants were available to assist the participants as needed.

One-and-one-half days were spent on detailed photointerpretation and nephanalysis, broad-scale nephanalysis, and synoptic uses of TIROS picture data. As in the sessions on picture rectification, demonstrations by session leaders were followed with individual application by the participants of the procedures demonstrated. Some of the synoptic uses discussed were the correction of conventional analyses by use of satellite data and the estimation of broad-scale flow patterns and surface fronts from nephanalyses.

The exercises on the use of radiation data, which followed the same pattern of lecture-demonstration, then individual work, as the previous laboratory sessions, were held during the final half day of the formal Workshop. The basic TIROS infrared radiation data were discussed. An exercise on the use of the atmospheric "window" data followed, and the analysis arrived at was compared with cloud observations and other conventional data.

FIGURE 29–1. Mr. L. F. Hubert explaining orbital characteristics of TIROS satellites.

FIGURE 29–2. Dr. T. Fujita assisting participants in rectification exercise.

FIGURE 29–3. Maj. J. B. Jones aiding participants in laboratory exercise.

FIGURE 29–4. Mr. C. O. Erickson aiding participants during laboratory session.

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DISCUSSION SESSION

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30. INFORMAL PRESENTATIONS OF OBSERVATIONAL SUPPORT EFFORTS BY FOREIGN PARTICIPANTS

A. VILLEVIELLE, France: I am going to describe to you as briefly as possible the French place in the meteorological research program. This meteorological research program is part of a much larger research program, that of the French Space Committee. This committee is directly under the office of the Prime Minister. The implementation of this program is the responsibility of a newly created agency called the National Center of Space Studies. The CNES, as we call this organization, is rather similar to NASA, and it cooperates directly with the French National Weather Bureau on that part of the research program which deals with meteorology.

Altitude is the criterion used to delineate this meteorological research program. It was decided that the National Weather Bureau would study the high atmosphere up to 100 kilometers. This is approximately the transitional zone between the atmosphere called the homosphere, whose molecular composition is constant, and the atmosphere where the phenomena of diffusion and photodissociation become predominant.

This altitude offers the advantage of being easily reached by several types of sounding rockets, such as the Belier and the Centaure, now being tested. The rocket, however, is not the only type of vehicle being considered since we plan a series of experiments with polyethylene balloons with a maximum ceiling of 40 kilometers. These experiments, which can be systematically repeated because of their low cost, can be used for several research projects, particularly with regard to albedo.

We are endeavoring to develop a system using a parachute that will slow down the return of the payload once it is ejected at the highest point of the trajectory. Tests now underway should enable us to achieve return speeds that will be noticeably lower in the 70- to 40-kilometer zone.

Experimentation proper will cover the following main areas:

(1) Measurement of temperature and pressure in the high atmosphere up to 100 kilometers.

(2) Measurement of the concentration of minor components such as water vapor and methane.

(3) Measurement of wind velocity.

(4) Measurement of the radiation balance of the atmosphere.

With regard to the first item, the importance of such measurements becomes obvious when one notes that the results obtained in this field often differ noticeably. The variation in space and time of the pressure and temperature barometers gages is fundamental in some other scientific research activities. That is why we have undertaken the study of new instruments to measure pressure and temperature whose characteristics are suitable to rocket flight.

Insofar as the second item, measurement of the concentration of minor components such as methane and water vapor, is concerned, absorption methods in the infrared range will be used. The purpose of such measurements is to acquire information on the vertical exchange motions in the high atmosphere and on the diffusion of hydrogen toward the exosphere. With respect to water vapor, a special research program is planned to study mother-of-pearl clouds and eventually to create them artificially. With regard to the third item, the measurement of wind velocity, this comes within an international program whose purpose is to gain better knowledge of general airflow in the atmosphere. Particular emphasis will be placed on jetstream location below the warm stratopause layer and below the minimum temperature of the mesopause.

With regard to the fourth item, the measurement of radiation, this objective is identical to

the purpose behind TIROS, but we look more particularly for the radiation balance measured on the basis of its components in the two wide bands ranging from 0.2 micron to 4 microns, as well as from 4 to 30 microns, corresponding, respectively, to the diffused reflection and the thermal emission of the earth. Albedo measurements will be particularly considered in relation to the various measurements of surface condition, position of the sun, and airmass characteristics, including the clouds.

This is the current meteorological research program using rockets. We are also conducting studies of instruments to be placed in a satellite to be launched in the coming years. These studies deal particularly with the acquisition of data on the satellite attitude and telemetry means and, therefore, go beyond the framework of meteorology.

With regard to the present, the Main Weather Forecasting Bureau of Paris does receive American nephanalyses and daily reads them out and plots them. Upon receiving the TIROS alert messages, the teletype message is sent to our stations in order to set supporting observation programs. These data are recorded and printed and a copy is available for the U.S. Weather Bureau.

A more systematic study of these will be conducted by the Bureau of Space Research when it obtains the radiometric data from TIROS. At that time we will try to check the photographic and radiometric data against the surface and altitude observations of the weather station systems, as well as against special observations conducted by military aerial reconnaissance planes.

JAMES M. MCMONAGLE, Ireland: When we were asked to cooperate in this TIROS project, the chief thing that we thought we would do would be something in the line of cloud observations. We had two methods of approach. One was to use the sypnoptic station network that we have, and the other was to supplement that by photographs from some high-flying jets, of the National Airline, Air Lingus, and also with some Army trainers. Air Lingus agreed very kindly to take meteorological personnel on any of their regular scheduled flights from Shannon to New York if the TIROS pass coincided with the time of flight; these people can photograph the clouds from above, between about 30,000 and 35,000 feet, and obtain information that way. The Air Corps people took photographs when we notified them of the approximate time of the pass.

The TIROS alerts that were issued came in fairly regularly, the time given being the mean time of the picture sequence, and the track given was taken as the suborbital path. We sent an alert message to all the synoptic stations that we have to make a special cloud observation at the time specified in the message. The special observation was to show more than the ordinary synoptic report; it was to show the type of cloud and, more particularly, the direction from which it was invading the sky. They measured the azimuth from the direction of the approach to the top of the cloud sheet, and so on.

We made a pictorial diagram and a circle to represent the horizon circle and sent those in every other day to the central office in Ireland. When we got all these reports in, we tried to draw up a cloud pattern of the cloud type over the country. A big drawback on that is that it was a view of the clouds as seen from below, whereas the TIROS pictures were from above. There may have been some differences in that field. Another factor is that during most of the times of the TIROS passes over Ireland, on a good number of occasions at any rate, there was a fairly moist southwesterly flow that covered Ireland and there was almost a solid sheet of low stratus and stratocumulus. There was not much upper cloud visible. By and large the observations that we made were as we expected the clouds to be. When we received the nephanalyses, they compared very favorably with what TIROS was reporting for the clouds, that is, wet cumuliform or stratiform.

On one or two occasions there were cold fronts moving across the country between two passes of TIROS. The edges were fairly well marked. These were fast-moving fronts, and the TIROS report did follow through the frontal passage. On another occasion there was an area of cumulonimbus activity moving in, particularly in the Dublin area. The first TIROS pass reported clear, and the second pass reported convective cellular. From these pictorial analyses we could trace the cumulonimbus moving in. There were actually three passes on that, spaced by about 3½ to 4 hours, 100 minutes each pass. The whole procedure depended on getting the TIROS

alert message on time and getting it circulated. Generally, the alert message gave the pass for the following day. We usually had it 24 hours ahead, and on some occasions up to 48 hours in advance.

The pictures that the Air Corps took were in fairly good agreement as well. They showed more or less stratiform clouds, and cumulus on some other occasions.

This was the general program carried on from about mid-August to about mid-September. There were, all together, about 48 or more passes covered.

VAN DER HAM, Netherlands: I should like to ask if Ireland used a special code for their special observations. A few times we saw on the network special Tiros observations from Ireland in a code we did not understand.

MCMONAGLE: We did have a special code, but it was for internal use only, and it inadvertently went out on the circuit several times. It was a four-figure code to give the total amount of the particular layer of cloud, as far as we could estimate, instead of cumulative amounts as in the synopsis, and to give the direction from which the cloud was moving and the angle between the horizon and the upper edge of the cloud sheet; it started off with an indicator. It was a simple code. The pictorial message was the main part. The pictorial message was to amplify the code. The code came in immediately after the observation was made. The picture did not come in until 48 or 72 hours later.

C. J. VAN DER HAM, Netherlands: I think, in general, our program was about the same as that reported by Mr. McMonagle. In the first place, we also made special synoptic cloud observations and, therefore, we used the model for the journal of clouds that is found in the International Cloud Atlas of WMO where there is also a column for making a picture of the clouds that you see in the sky and also the direction in which you see them. We did this at 15 stations in the Netherlands. Furthermore, we took all-sky camera photographs. It happened that in one of our universities they have developed a special all-sky camera. It is a camera with some 10 or 15 lens built up together so that an angle of about 210° all around is possible. It was quite enough to take all-sky photographs.

As in Ireland, we had photographs taken from about 30,000 feet by the Air Force, all at the time when TIROS made its observations. We had special radar observations at our airport, Schiphol. There, a sketch was made of radar targets that were visible at the times when TIROS came across.

I shall comment briefly about our experience with nephanalysis. Charts were prepared which showed the difference between nephanalysis and synoptic observations. For instance, there was a case over the British Isles when nephanalysis gave overcast, and in synoptic observations there was no one station reporting overcast, most giving five-eighths to seven-eighths of cloud cover. I think it may be possible that it is difficult to differentiate between broken clouds and overcast, in some cases anyway.

There was also a case where, near the Netherlands, there was a big sheet of clouds, I think it was stratocumulus, just a hundred miles off the coast. In nephanalysis it reached to about 50 miles in length. Thus, these kinds of differences may happen. I know that it is not possible to get an accuracy of more than, perhaps, 1° or 2° of latitude and that may be the reason why we saw this difference. There are a few more cases.

A. W. JOHNSON: This problem of geographical rectification is one which we now known about since we have had this Workshop; 1° or 2° is expected much of the time. On the facsimile transmissions of the nephanalyses, you recall that we do indicate a degree of confidence in the geographic rectification. In the teletype code we are going to have to include something like that in the next version.

MCMONAGLE: It is also possible to code the nephanalysis in 1° squares. In the picture of the particular cloud mentioned, it might have, say, come down to 50° north, but it would have been coded up to cover later, and that would account for 30 or more miles. In other words, the coded version which we got could not give such fine detail.

A. W. JOHNSON: There are these built-in limitations in the code which we are trying to improve on all the time. We may not always have Schiphol Airport defined quite exactly.

D. S. JOHNSON: Were you able in the Netherlands to receive facsimile transmissions of the nephanalyses?

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VAN DER HAM: Yes; we did receive them, but not on a regular basis. I think the teleprints of the nephanalyses were more regular. We could rely on getting them every evening and even during the day. But facsimile was not so regular, perhaps also because we have to receive many other charts on facsimile. So we cannot stand by all day to receive nephanalyses.

A. W. JOHNSON: We have had some samples sent to us from the United Kingdom of facsimile nephanalyses received on the other side of the Atlantic. The quality is erratic, at best.

JOHN F. GABITES, New Zealand: I expect the New Zealand experience in arranging special synoptic observations has been very similar to that of other people, so there is no need to repeat that in detail.

We also arranged to have our synoptic stations record greater detail of the nature of clouds, whether continuous or broken, their location, and where the edges were located.

It is helpful to have a photographic record of the sky conditions. I might perhaps draw attention to the possibility for an all-sky camera that may interest other people as well. You do not always have a good all-sky camera available. This is one that we improvised quickly with an ordinary camera just for the sake of getting a photographic record. There is a simple mounting, in sections, with four dowels, with a wooden block at the top with a hole cut through it, a simple device to held the camera so that it looked downward, and a spherical reflector, which is the hubcap of a motorcar. I assure you that the hubcap of a Morris Minor works very effectively as a mirror. It is just a matter experimenting. If you have a movie camera, so much the better. It is a simple matter to have this camera mounted, to use the self-timer, pull the trigger, and drop down below the view of the camera.

Over the last 20 years or so there has been a shifting of attention in the information reported synoptically. With the influence of aviation, we have increased the length of our code from time to time. We send more figures, but we have tended to degrade the information. I think that with the attention that we now have on cloud systems again, that the time would be opportune to revise the cloud reporting systems in some regard.

All over the world there are observers looking at the sky. They can see some highly significant things. They can see where the cloud is organized, or where it is disorganized. They can see where the organized systems lie in relation to the station or in relation to mountains and other geographical features. But, in general, around the world that information is not reported. We have reports of three-eighths of clouds of a particular sort, or seven-eighths, but in most regions there is no indication where that cloud lies, whether it is organized, or where the gap lies.

During World War II the New Zealand stations used an additional supplementary group which gave some of that information. In the revision of the codes of 1949 we somehow dropped this local group, but we have been feeling the need for something of the sort again and, of late, have been experimenting within New Zealand with a better supplementary group than we had before, one which gives more information. The sort of thing it indicates is whether the low cloud is scattered over the whole sky or whether it is an organized sheet or system. If it is organized, the azimuths between which it lies relative to the station are indicated and, in a very simple fashion, the elevation of the top. Similarly, it indicates whether the middle- and high-cloud systems are organized, whether they have well-defined edges, and so on. At the time I left home we still had a few modifications in mind for our experimental code. We have not brought it, in general, to our stations but I expect we will in 1962. Perhaps by the time of the Committee on Synoptic Meteorology meeting we will have some more extensive experience to report.

I mention this because I believe many other people will have thoughts of some similar way of defining what the sky looks like. I think it would be very helpful operationally in many services where forecasters are faced with rather detailed forecasting in and around terminals if they could know whether the cloud reported is over the sea or over the land, whether it is over the mountains or over the valleys, and whether it is organized. I think perhaps with the interest aroused by TIROS that we might be able to inaugurate some improvements in the method of reporting.

An interest of mine for a long time has been the heat budget, and I have been concerned with estimates of the longwave radiation losses from the atmosphere, which is generally cloudy in some regard. It has been very difficult to make any sort of a census of the clouds. The bases of clouds are reported all over the world; that is, the bases of the low clouds. But in the ordinary synoptic code there is no direct indication of the amounts of the middle- or high-cloud systems. You can make some deductions, perhaps, from the total amount of clouds, but you have no reliable information. On the other hand, the letter code reports amounts and heights of the bases of various individual layers. But whether a layer is reported depends entirely on what is underneath it.

The system of deciding which of the eight groups are to be reported is rather disconcerting, both to the forecaster and also to the research man. It is frustrating to have the record from a station showing a sheet of middle cloud perhaps lasting for some hours, then disappearing for perhaps 2 or 3 hours, and then reappearing in the code merely because there had been some other cloud underneath which took precedence in being reported. We can only guess that the middle cloud sheet was there the whole time, but the letter code is quite misleading in that regard.

We in New Zealand have been contemplating inaugurating a local instruction that all layers of clouds will be reported. This will include a few more groups than the minimum laid down in the existing code. It is not going to increase our communications traffic very much, but it is going to remove a great uncertainty from the minds of both the forecaster and the reseach man using the record of the observations.

Many services, perhaps, have formed a record of reporting that does not suffer from these defects. I think, though, in most regions people are handicapped by the defect in the present code. I am hopeful that with the new interest in clouds there will be some improvement detected.

C. J. Boyden, United Kingdom: We have in the United Kingdom a high-altitude research branch which was formed a little under 2 years ago and which is concerned solely with this kind of problem. I cannot give you details, inasmuch as I am concerned primarily with the synoptic side, of what they are doing, but their main project is the measurement of ozone; I understand that the Scout satellite is expected to be launched next spring. Much of the work for that is being done at Goddard. Scout II will be launched in 1963 if all goes well. The main purpose of these satellites is ozone investigation; in fact, I think the sole object from the the United Kingdom point of view is the problem of ozone.

Before this Workshop I think we all had fairly clear ideas as to the potentials of Tiros, or any later satellites. The usefulness in research is evident. Our views on that have been reinforced during this Workshop.

In the tropics, in the Southern Hemisphere, and in places where there are few observations, Tiros is an immensely powerful tool. My personal view is that in temperate latitudes, say, the European and the American sector, Tiros information is something we are very glad to receive, but only on rare occasions does the information as issued now concerning the cloud pictures help us to modify our analysis and then usually to some minor extent. This is no criticism of Tiros. It is a statement, in other words, of the happy position we are in of having a large number of observations which give us a fairly complete and accurate three-dimensional picture, and only rarely can Tiros improve on that.

My reason for saying this is really related to the problem of communications. We in the United Kingdom receive and always have received Tiros by facsimile. The reception is quite adequate on most occasions. Facsimile is not so reliable as radio teleprinter. But, on most days, we can interpret the picture with little difficulty, although, just a minor point, the major boundary shown by the wavy line is apt to confuse the picture. A plain thick line might be easier to interpret. A collection of "B's," cumulus symbols, squares, and so on can be rather confusing if transmission conditions are bad. But, broadly speaking, we are satisfied with the reception of our picture.

Many countries are dependent on the teleprinter for the coded version of the nephanalysis. I have seen some correspondence recently between Region 4 and Region 6 which shows that many people are perturbed at the quantity of information to be sent. It has been suggested that Tiros messages, the coded messages,

should be given priority over other material. Personally, I would oppose that strongly on the grounds that I have stated. As far as we are concerned, in our region, we would not wish to give a coded TIROS message or any TIROS message priority over the existing material. I think the solution ought to be that the normal method of transmitting nephanalyses should be by facsimile. I do not wholly understand the difficulty. I believe with many services the problem is a financial one. They do not have facsimile and they will not get the money for it.

Would this Workshop not be an opportunity, particularly for the tropical services, to give support to requests for money for facsimile equipment, and should we not regard facsimile as the normal method of transmission of these messages, to be supplemented by the teleprinted message on only rare occasions when something of very great importance had to be transmitted or when conditions were known to be bad?

The difficulty of reception in the Netherlands has been mentioned. I do not know how real that is, but I do recall that when I was in Holland 3 or 4 years ago there was difficulty in receiving Dunstable, even. So, I suspect the trouble might be a local one. We in Dunstable get Washington regularly, a continuous program from Washington. We get Tokyo when we want it. We can receive from all stations and I suspect that facsimile is an underrated method of transmitting material.

There is just one minor point, in conclusion. If we must have these coded messages for the time being as a backup, if for no other purpose, to the radio pictures, I wonder if there would be acceptance of the suggestion that instead of working on a 1° square in the coding, we should go the other way and use a 2° square. Personally, I do not believe that the very high degree of accuracy can be needed. There is, on the initial nephanalyses, a certain tolerance. We are usually told that it is ±2° initially. Some of us suspect it is occasionally a little more than that when it is given as 1° or 2°. The information reaches the user something like 9 or even 11 hours after the photograph is taken, so that the clouds he is looking at have moved on by about 3° or 4° of latitude anyway. And if one could work in 2° squares it would reduce the number of letters to one-quarter of what they are at present and the whole message would be about 30 percent, say, of its present length.

A. W. JOHNSON: Mr. Boyden referred to the suggestion that satellite nephanalyses receive priority on international communications. We have approached the chairman of the Committee on Synoptic Meteorology working group on telecommunications to solicit his advice as to what might be done, and we have suggested that some kind of priority treatment be given to the TIROS messages if the international community desires that this be done.

We feel very deeply that we are going to a great deal of trouble to get this information and that our means of disseminating it are inadequate. We hope that facsimile will be developed to a much greater extent than is now the case on an international basis and certainly in our thinking it is this type of communication that we hope will be the basic type, to be supplemented by the coded message. Much of the world is not quite so far advanced as some of the North Atlantic countries, and facsimile does not exist in many of these places; consequently, we still have to go by the more cumbersome means of coded message.

I am interested in this 2° suggestion. We are going to have a meeting early in December of those of our people most concerned with this kind of activity, and this will be one of the suggestions that we will try to evaluate more exactly.

MCCULLOCH, Canada: It seemed to me that if the code were 2° then the tolerance would be ±4, which might get a little thin at times. The usefulness would be reduced, I feel, quite drastically.

GABITES: I would like to oppose any suggestion of introducing a coarser method of indicating a cloud pattern. I feel that it is not a question of accuracy in positioning to which we should pay so much attention. We know that there will be errors. I feel that if we went to, say, 2° squares then the whole pattern would be so degraded as to become virtually useless.

I think there is great virtue in keeping as much detail in the pattern as is reasonable for operational purposes and accept the fact that the positioning might be a little in error. The recipient often has means of adjusting the posi-

tion. The important thing, I think, is the pattern which is made.

VAN DER HAM: I would agree with Dr. Gabites about those 2° squares. What would be the accuracy of 2° squares compared with 1° squares?

A. W. JOHNSON: It would be reduced to one-third of current accuracy. We certainly will consider this.

RAHMATULLAH, Pakistan: In most of the tropical countries it would be rather late to introduce facsimile transmission and to receive TIROS pictures on facsimile. We will have to depend more or less on some coded analysis. For that purpose the shorter the code is, the more practical it is. At present, the nephanalysis code is so lengthy that it is rather impossible to accommodate it in the transmission schedules and that is one of the reasons why we have not been able to receive and use it routinely.

As regards the code, I have gone through it rather hurriedly. I feel that it can be shortened considerably by some sort of a contrivance. Instead of having AAA, we can write "A–10" after that. In this way somehow we can shorten this code. Whatever can be done to shorten the code certainly will be very useful for areas where the TIROS pictures are of great value.

In most of the desert areas of the Middle East and the ocean areas, there is not much observation. Sometimes, the telecommunication is very poor and we do not get data for 10 hours or so. Sometimes, between Karachi and Beirut there will hardly be any observations for some time due to a telecommunications breakdown or something of that type. In that case TIROS will be of very great help and any shortening of the coded message would certainly be very useful.

BOYDEN: I would like to make one or two small points on the comments. In the first place, if you have 2° tolerance, and then another 2° from the code, it is not quite 4°, it is a little under 3°. I am not a statistician but I think a little under 3° would be the ultimate tolerance.

MCCULLOCH: Under these conditions? Couldn't it be as great as 4°?

BOYDEN: It could be as great as 4°. It really would need to be tested. After all, one is concerned with the orientation of the line. You have a number of points determining that line, and the continuity would help to some extent. In other words, instead of having a small scattering of points you would have a larger scattering of points, but you might be able to define your line fairly well.

MCCULLOCH: We in Canada are not nearly so fortunate as those in the United Kingdom as far as the synoptic network is concerned. At the present time the TIROS photographs are not of too much value to us in our broad Arctic regions.

We feel that we have to take the forward view here. If we take the backward view, we could spend many thousands of dollars completing a comprehensive synoptic network of standard observations across the Arctic. The problems, of course, are quite formidable.

But, looking ahead, we have a new tool. The money involved will be much less. The results I feel could be just as worth while, if not more so. And I think perhaps our situation is similar to that of more countries than is that of the United Kingdom. The older methods of observation, while they have been adequate, are probably not going to be adequate in the future.

VAN DER HAM: I remember, Mr. Johnson, that in your paper you discussed supporting observations in the United States; you said, I believe, that you had cards or a code on which you recoded these evaluations. Could you tell us anything about that?

A. W. JOHNSON: I think you are referring to the cloud sheet that is filled out at the local station level. This is similar to that used in many countries. It is simply a horizon circle, and the observer sketches on that, very roughly, the amount of clouds and, if possible, the type. There is a standard instruction that has gone out. These cards are then mailed to the Weather Bureau. It is not an immediate communication at all. It is a simple series of circles and the card is filled out in response to an alert message which is comparable to the alert message which is received in other countries.

CARACCIOLO, Brazil: I wonder if in your future plans on transmitting TIROS pictures you could investigate the means of transmission also. We have been unable to receive any picture by facsimile in Brazil, and I understand that Argentina has the same problem. Even by teletype, it has been very difficult. We in-

stall all types of antennas and all types of receiving equipment. Right now we are getting a little better transmission from Miami, but none in facsimile. We have facsimile, but we do not receive any transmisisons from the United States or even from Europe.

A. W. JOHNSON: There is at this time no facsimile broadcast from Miami. There are two radio teletype broadcasts. About all that can be said is that in the U.S. budgetary cycle there is a request for funds to establish a broadcast from Miami which it is hoped will serve South America much more adequately than is now the case.

The coded messages have also failed to reach Argentina and Brazil much of the time. It has been agreed to send messages by commercial telegram when they are of particular significance. It has also been agreed to send the nephanalyses on a more or less routine basis to Rio de Janeiro for rebroadcast on Amersud. The effectiveness of this procedure is not yet known.

JALU, France: In Paris, also, the meteorological services have had difficulties with the reception of facsimile. We have no explanation for it. For that reason they would like to know the immediate program of nephanalysis transmission from the U.S. Weather Bureau. During the August to September 1961 observation period, I understand that Paris received the information on about eight orbits a day, and then it went down considerably. It would be useful to the French delegation to have an idea of the forthcoming workload to know how many nephanalyses will be transmitted.

A. W. JOHNSON: TIROS III is not performing as well now as it did at the beginning. There has been a rather serious degradation in the quality of the photographs and it was decided to discontinue the routine distribution of the nephanalyses from TIROS III. There are only special cases which receive distribution now.

The readout stations are still reading the information and they are still preparing nephanalyses to the extent that they are capable of doing so. The areas covered had to be limited and the analyses over land areas had to be discontinued. Only overwater analyses are being transmitted, and these will be in very limited numbers.

In terms of your workload, as soon as the fourth TIROS is launched, provided it is functioning as expected, some time early in 1962 you can expect to receive as many nephanalyses as we can produce. These will be transmitted as they have been in the past on the Washington facsimile transmissions. Unfortunately, there in some difficulty in getting any routine handling of them on those particular transmissions and they have to be inserted in the schedule on a more or less time-available basis. We have the same problem on the radio teletype circuits, but it is expected that they will start coming to you early in 1962.

VAN DER HAM: Have you in the United States any more suggestions, or questions perhaps, about our supporting observations?

A. W. JOHNSON: I do not think so. I have found this discussion this morning very encouraging. In the remarks that were made at the beginning of this Workshop, we tried to emphasize that the supporting observations are as much for your benefit, or more, than they are for our benefit. Obviously, we want to be informed of the program that you are implementing and the research that you do. And we want to assist in that research in any way that we can by providing satellite information that will be useful in connection with your own observations. The supporting observations have been all the way from rocketry, radiometersondes, and aerial photography down to the simple cloud sheets. Any or all of these observations that can be made or any new or different observation which will support TIROS will be welcomed.

CLOSING REMARKS BY KAARE LANGLO, WMO

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31. STATEMENT OF KAARE LANGLO

Chief, Technical Division, World Meteorological Organization

Due to other commitments, I have unfortunately not been able to be with you the last few days, and since I am leaving for Europe tomorrow, I am glad to have this opportunity to speak to you on a matter about which I believe every participant from whatever country or organization feels in the same way as I do. I am not only speaking on behalf of the World Meteorological Organization and of the International Civil Aviation Organization, but I am also speaking on behalf of every meteorologist who wishes to see the science of meteorology given its proper place and recognition among the sciences and who does not wish to see the development of meteorology unduly hampered by its long traditions. During the past days we have been listening to well-prepared, well-presented, and very interesting lectures. We have been instructed in the practical use of satellite data; we have been taken by planes and buses to visit important installations concerned with meteorological satellites and rockets. We are all very impressed with what we have seen and heard and we all wish to express our warm gratitude to everyone who has been connected with these arrangements. But we also wish to say more. We have had the opportunity of participating in free discussions of the problems involved in using satellite data; we have perhaps given the impression that we wish more to be done or we wanted other experiments to be carried out. I should like to make it very clear that such comments should not in any way overshadow our main sentiment: our warm gratitude and appreciation to the United States, to the NASA, and the Weather Bureau for the tremendous efforts that have already been made to advance meteorological science for the benefit of all countries. As you know, the activities of the World Meteorological Organization are to a large extent dependent on the efforts made by its Member States, and it is indeed a pleasure for me to express once again our sincere thanks to the United States for what is has done in the field of satellite meteorology, not only measured in dollars and personnel, but in initiative and enthusiasm which cannot fail to bring our science forward. I would be grateful if the representatives of our host country present here would convey these notes of thanks to all concerned with the organization of this highly successful Workshop on satellite meteorology.

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APPENDIXES

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APPENDIX A

BASIC INFORMATION ON TIROS SATELLITES

The TIROS Satellites

Introduction

TIROS is the short name for Television and InfraRed Observation Satellite. TIROS I, launched April 1, 1960, by the National Aeronautics and Space Administration (NASA), carried television cameras only. TIROS II (launched November 23, 1960) and III (launched July 12, 1961) also carried equipment to sense solar and terrestrial radiation.

The primary instrumentation of TIROS III consists of two television cameras, both basically the same as the wide-angle cameras used in TIROS I and II, and scanning and nonscanning radiation detectors. The satellite instrumentation also includes tape recorders, transmitters, telemetry, and associated electronics for both the television camera and radiation systems, radio beacons, and a power supply of storage batteries and solar cells. There are auxiliary devices to control satellite attitude, wobble, and spin rate, and various switching, timing, and sequencing circuits to control the instrumentation. (See the section entitled "Other Equipment.") Miniaturization and weight-saving techniques compatible with maximum reliability and performance are used.

All the TIROS satellites are generally cylindrical in appearance. The vertical covering of this cylinder, which is 42 inches (107 cm) in diameter and 19 inches (48 cm) high, consists of 18 flat sections. The sides and top are covered with solar cells, the primary power source. The weight of TIROS III is approximately 287 pounds (130 kilograms).

TIROS III was launched in a northeasterly direction from Cape Canaveral, Fla., into a nearly circular orbit at a mean altitude of about 475 statute miles (760 kilometers). The period of revolution of the satellite around the earth is about 100 minutes, so that the satellite travels around the earth about 14.5 times every 24 hours. With plane of the orbit inclined about 48° to the equator, meteorologically useful data cannot be obtained poleward of approximately 55° latitude. The satellite is spin stabilized in space. Initially, its spin axis was normal to the earth at about 20.8° north latitude; this changes to some extent as discussed in the section entitled "Spin Axis Orientation." Both camera axes are parallel to the spin axis, and both cameras look in the same direction. The average orbital figures for TIROS I, II, and III are listed as follows:

	TIROS I	TIROS II	TIROS III
Period, min	99. 24	98. 26	100. 4
Average height, statute miles (km)	450(720)	420(676)	475(760)
Apogee, statute miles (km)	461. 3(740)	451. 5(726)	509. 8(820)
Perigee, statute miles (km)	436. 0(702)	387. 8(624)	457. 1(736)
Eccentricity	0. 00287	0. 00727	0. 00593
Inclination, deg	48. 392	48. 530	47. 898

Photography

On TIROS III, the two television cameras designed to photograph the cloud cover of the earth under daylight conditions are the same in regard to the size of the earth area viewed and the resolution; both are the same in these respects as the wide-angle camera used on TIROS I and II. From an altitude of 475 miles (760 kilometers), these cameras are designed to view areas approximately 750 miles (1,200 kilometers) on a side when the cameras are pointed straight down (zero nadir angle); under these conditions, the cameras provide a resolution of the order of 1.5 to 2 miles (2.5 to 3 kilometers). When the cameras are looking at greater nadir angles, the extent of coverage is increased whereas the resolution decreases according to obvious goemetric factors. The narrow-angle camera used on TIROS I and II viewed areas approximately 75 miles (120 kilometers) on a side when the camera was pointed straight down. The best resolution was on the order of 0.2 to 0.5 mile (0.3 to 0.8 kilometer).

Some details about both cameras are given in the following table:

	Wide angle	Narrow angle
Field of view, deg	104	13
Area coverage from average height of satellite and zero nadir angle, sq miles (km)	750 (1,200)	75 (120)
Lens speed	f/1.5	f/1.8
Shutter speed, milliseconds	1.5	1.5
Lines per frame	500	500
Resolution per raster line pair, zero nadir angle, miles (km)	1.5 to 2 (2.5 to 3)	0.2 to 0.5 (0.3 to 0.8)

The decision to use two wide-angle cameras on TIROS III, rather than one wide-angle and one narrow-angle camera as on TIROS I and II, was based on several factors, most important of which is the provision for redundancy, or back-up, in the event of a malfunction or failure of one of the cameras. Failure of the only wide-angle camera onboard either TIROS I or II would have made use of the narrow-angle camera data difficult or impossible. (Since camera No. 1 on TIROS *did* fail some 12 days after launch, the decision to use two wide-angle cameras has already proven to be fortunate). Furthermore, meteorologically significant cloud systems are most often apparent over the large areas shown in the wide-angle camera pictures. When both wide-angle cameras are operating, more extensive synoptic coverage than would be possible with one wide-angle camera and one narrow-angle camera can be obtained. Sufficient narrow-angle pictures are available to satisfy present research requirements until cameras providing similar resolution over wider areas become available in more advanced types of meteorological satellites.

Radiation sensors

The second series of meteorological sensors on TIROS III consists of three sets of radiation detectors. The first of these consists of a five-channel radiometer which uses the spin of the satellite to generate a scan. This radiometer is oriented with its optical axis at 45° to the spin axis of the satellite and scans the surface of the earth by means of a combination of the rotation of the satellite and its movement along the orbit. The spectral bands of these radiometers and the purpose of each are as follows:

Channel	Band	Purpose
1	6.0 to 6.5 microns	Radiation from water-vapor bands. This is designed to measure the temperature of the water-vapor layer at an average altitude somewhat below that of the tropopause. The altitude to which the measured temperature corresponds varies with the vertical distribution of water vapor.
2	8 to 12 microns	Radiation emitted through the atmospheric "window." The information expected from these measurements includes: (*a*) cloud-cover detection, especially at night and over areas where TV cameras are not operated; (*b*) measurement of cloud-top temperatures and, accordingly, a rough measure of cloud-top heights; (*c*) measurements of surface temperatures or temperature gradients over cloud-free areas.
3	0.25 to 6 microns	Albedo of the earth.
4	8 to 30 microns	Infrared radiation emitted by earth and atmosphere combined.
5	0.55 to 0.75 micron	Radiation in the red part of the visible spectrum. This channel is designed to provide gross visual radiation maps for comparison with the vidicon data and provides a gross visual spectrum reference in areas for which vidicon data are not obtained.

These radiation sensors provide a resolution of about 40 miles (about 65 kilometers) when looking straight down.

The second set of radiation sensors consists of a black and white body, each mounted in the apex of a cone. Each has a 450-mile (720 kilometer) diameter field of view which falls within the field of view of the vidicon cameras. These provide low-resolution data relative to the albedo of the earth and total emitted radiation for heat balance studies. These sensors are essentially the same on TIROS II and III.

The third set of radiation sensors is about the same as one of the experiments on the Explorer VII satellite. These sensors consist of four hemispheres, each about 1 inch (2.5 centimeters) in diameter, mounted on mirror surfaces on rods sufficiently extended from the base of the satellite so that, when in orbit, the hemispheres do not see any part of the spacecraft. One set of these hemispheres, a black body and a white body, is mounted on one side of the satellite with an identical pair exactly opposite it. The net effect of these four hemispheres is that of a white and black sphere of the same diameter isolated in space at the altitude of the satellite orbit. The black body absorbs most of the radiation incident upon it whereas the white body is sensitive mainly to radiation whose wave-length is longer than approximately 4 microns. When the direct solar radiation is subtracted, the data from these sensors can be used to infer the albedo of the earth and the total emitted radiation reaching the satellite. The field of view is from that part of the earth bounded by the horizon as seen from the altitude of the satellite.

Reduction and processing of the TIROS II and III radiation data from the five-channel radiometer are being undertaken as rapidly as possible; these data will be ready for general release in the near future. Studies of limited selected cases demonstrate that the data appear to be of significant meteorological value.

Other equipment

In addition to the two kinds of meteorological sensors previously described, the satellite carries a horizon sensor (to aid in determining spin axis attitude) and a series of sun sensors (for determining the north direction of the pictures, particularly when low nadir angles restrict the horizon visible on the pictures). There is also a magnetic coil for attitude control. (See the section entitled "Spin Axis Orientation.") Other equipment includes tape recorders for data storage, data transmitters, a command receiver, beacon transmitters for tracking and for telemetry of the performance of equipment, storage batteries, solar cells, and necessary associated electronics.

Operations

Tracking and orbit determination are being carried out by the minitrack network and the NASA Space Computer Center. The primary data acquisition stations for TIROS III are located at Wallops Island, Virginia, and Point

Mugu, California. The antennas for the latter station are located on San Nicolas Island, about 60 miles off the California coast. These stations program or command the satellite to perform such operations as:

- Transmission of cloud photographs from either camera while within telemetry range of the station (about 1,200 miles).
- Taking of one series of 32 sequential pictures *per camera* with either or both cameras at specific times in the future (normally when the satellite is remote from a station) and storage of them in the magnetic tape recorded.
- Read-out of the cloud pictures stored on magnetic tape in the satellite.
- Read-out of the radiation data stored in the satellite. This system is arranged to contain the radiation data from approximately the last full orbital pass.

Combinations of any or all of these operations may be performed during a single pass over a station, depending on the time within radio range. Attitude data are continuously transmitted through modulation of the tracking-beacon. The vidicon telemetry signals received at a data acquisition station are recorded on magnetic tape and simultaneously on film through photography of the monitor screen. The radiation data are recorded only on magnetic tape.

Decisions as to the regions of greatest meteorological interest for programing each satellite pass are made by the U.S. Weather Bureau based on consideration of locations suitably illuminated for photography, the attitude of the satellite, interpretation of data obtained on previous passes, and the stated plans of cooperating experimenters in the United States and abroad. These decisions are utilized by the NASA Tiros Technical Control Center in programing commands to the satellite unless changes are required by engineering or experimental considerations.

Spin axis orientation

In the case of Tiros I, interactions between the magnetic moment of the satellite and the magnetic field of the earth produced unexpected changes of the spin axis orientation (ref. 1). Tiros II and III are equipped with a magnetic attitude control coil through which, on command from ground stations, variable amounts of current are permitted to flow. This device makes it possible to exercise some control over the spin axis orientation. Although this cannot significantly change the orientation within a single orbit, it is possible to prolong the periods during which the satellite and its sensors are favorably oriented with respect to the sun and the earth. The maximum rate of change using this device is about 15° per day.

Tiros III: Programing Limitations and a Method for Determining Geographic Coverage

Based on the characteristics of a Tiros satellite, its orbit, and the solar illumination of the earth, it is possible to predict for each day of the orbital cycle of the satellite the approximate geographic area in which it is probable that satellite cloud-cover photographs will be taken. Although technical and programing factors introduce some uncertainty in predicting the areas to be photographed, these predictions can be useful for planning. More accurate photographic programing information was supplied over international meteorological communications networks 7 days in advance and then again 24 to 48 hours in advance. The following geographic limitations may be noted:

(*a*) The probability that photographic data will be obtained decreases poleward of the extreme orbital subpoints of the satellite; that is, no photographic data can be expected poleward of 55° north or 55° south latitude with the normal orbit which is inclined at 48° to the equator.

(*b*) Because of the location of the data acquisition stations, the amount of data obtained over the following countries and areas within 48° north and south latitudes will be severely limited: Afghanistan, southern Argentina, southern Chile and adjacent southeastern Pacific Ocean, Iran, Pakistan, India, and USSR.

The following sections describe the primary reasons for the limitations of the Tiros III coverage and a method for determining the areas of potential coverage for any given date. The

material included has been based on the predicted (or nominal) orbit prior to launch. The actual orbit achieved does not vary substantially from the nominal. Any revisions are provided in the detailed programming data transmitted over meteorological communications circuits.

Latitude limitations

Because of the slight bulge of the earth at the equator, the plane of the orbit of the satellite precesses in right ascension at the rate of a few degrees per day. As a consequence of this rate of precession and the movement of the earth in its own orbit around the sun, a complete cycle of this precession of the plane of the orbit of the satellite relative to the sun is completed in about 9 weeks. This imposes latitude limits on the areas of photographic coverage because of the requirement for solar illumination.

In attempting to visualize these phenomena and their effects on the availability of observations over a given area, it is necessary to recall that for any single day the plane of the orbit remains nearly fixed in absolute space and relative to the sun, while the earth rotates independently within the orbit. Thus, on any single day, considering solar illumination only, the same latitudes at all longitudes could be observed by the cameras at various times during a 24-hour period. However, the locations of the read-out stations place an additional constraint on observable longitudes. (See next section.) The slow precession of the orbit plane causes the illuminated latitudes, as seen from the satellite, to change over a 9-week cycle in the manner described as follows.

The time of each launch is chosen so that initially the northern part of the orbit is on the side of the earth nearest the sun and the TV cameras can obtain data over latitudes from about the equator to 50° north latitude. (The satellite passes over the Southern Hemisphere only at night during these initial orbits.) Gradually, the latitude at which the orbit crosses the noon meridian moves slowly southward until, about 1 week after launch, the descending node (point where the orbit crosses the equator on the southbound leg) is on the same side of the earth as the sun. At this time, photographic observations will be made in the regions approximately between 35° north and 35° south latitude.

Precession of the orbit and southward movement of the illuminated areas under the orbit continue until about 4 weeks after launch; the southern part of the orbit is on the side of the earth nearest the sun and photographic data can be obtained over the area between 20° south and 50° south latitude but not in the Northern Hemisphere over which the satellite passes now only at night. From this point, the precession causes the illuminated portion of the orbit to move northward gradually; about 6 weeks after launch, the ascending node (point where the orbit crosses the equator on the northbound leg) is on the same side of the earth as the sun and again the observable latitudes are primarily in the tropics. Continued precession and northward movement of the illuminated area under the orbit reach the point, about 8 weeks after launch, where the northernmost portion is again over the side of the earth nearest the sun, and photographic observations again are possible between 28° north and 50° north latitude. Precession continues and southward movement of the illuminated area under the orbit begins again. The whole cycle repeats about every 9 weeks throughout the useful life of the satellite.

The consequences are graphically illustrated in figure A–1, on which the shaded area indicates, for each date on the abscissa, the illuminated latitudes. For use in determining the areas of photographic coverage, the data on this graph are displayed in two parts, figures A–2(a) and A–2(b). Figure A–2(a) shows the illuminated latitudes on the southbound portions of the orbits whereas figure A–2(b) shows these latitudes for the northbound portions.

Longitude limitations

Within the illuminated latitude zone there are also longitude limitations upon the areas from which data may be obtained. The locations of the readout stations (Virginia and California) determine the extent of these limitations for the following reasons:

(*a*) The data storage capability of the satellite is limited.

(*b*) The range at which each station can contact the satellite and usefully read-out data is limited to line of sight from the ground to the satellite.

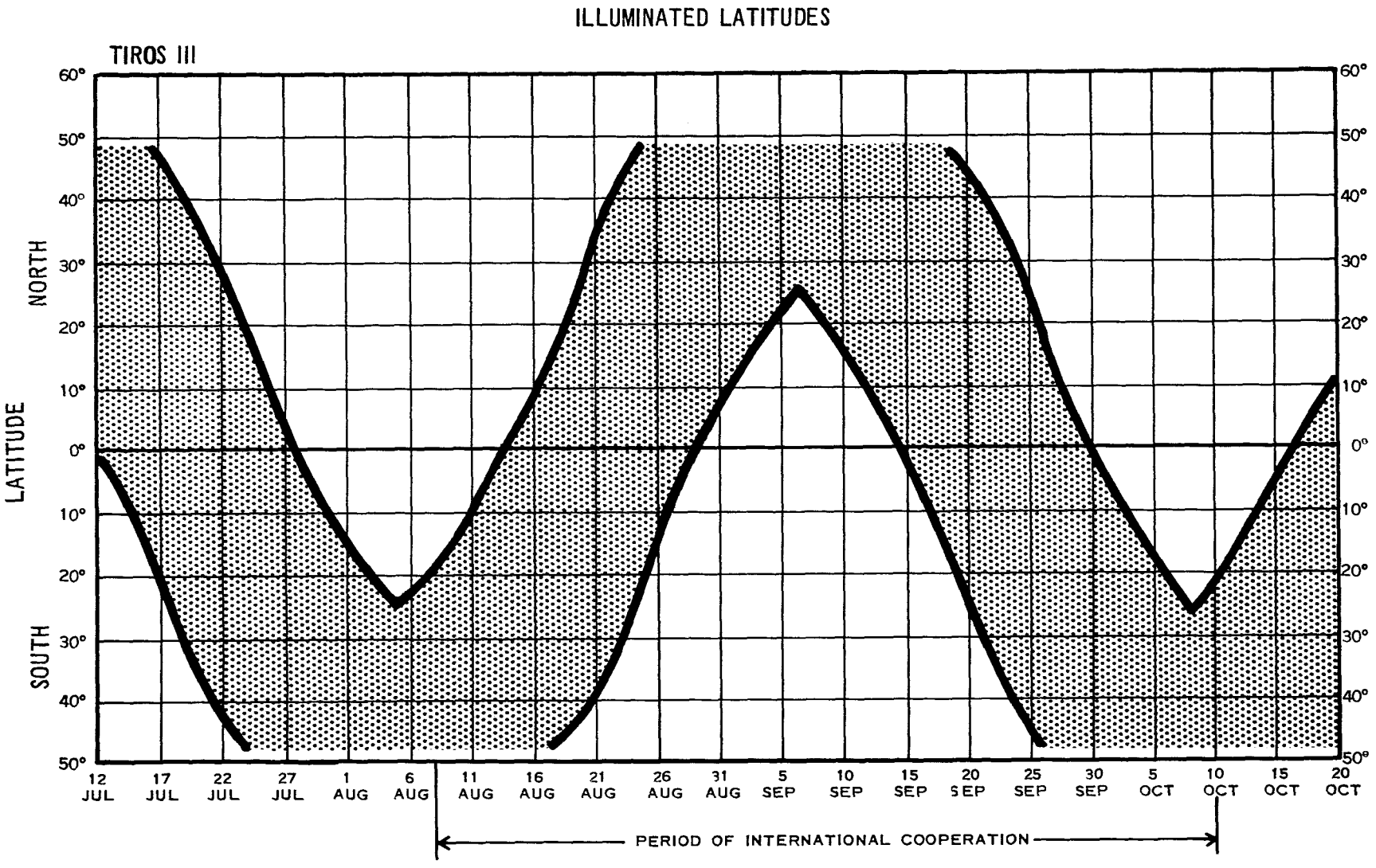

ILLUMINATED LATITUDES
TIROS III
LATITUDE
NORTH
SOUTH
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
12 JUL
17 JUL
22 JUL
27 JUL
1 AUG
6 AUG
11 AUG
16 AUG
21 AUG
26 AUG
31 AUG
5 SEP
10 SEP
15 SEP
20 SEP
25 SEP
30 SEP
5 OCT
10 OCT
15 OCT
20 OCT
PERIOD OF INTERNATIONAL COOPERATION

FIGURE A–1.

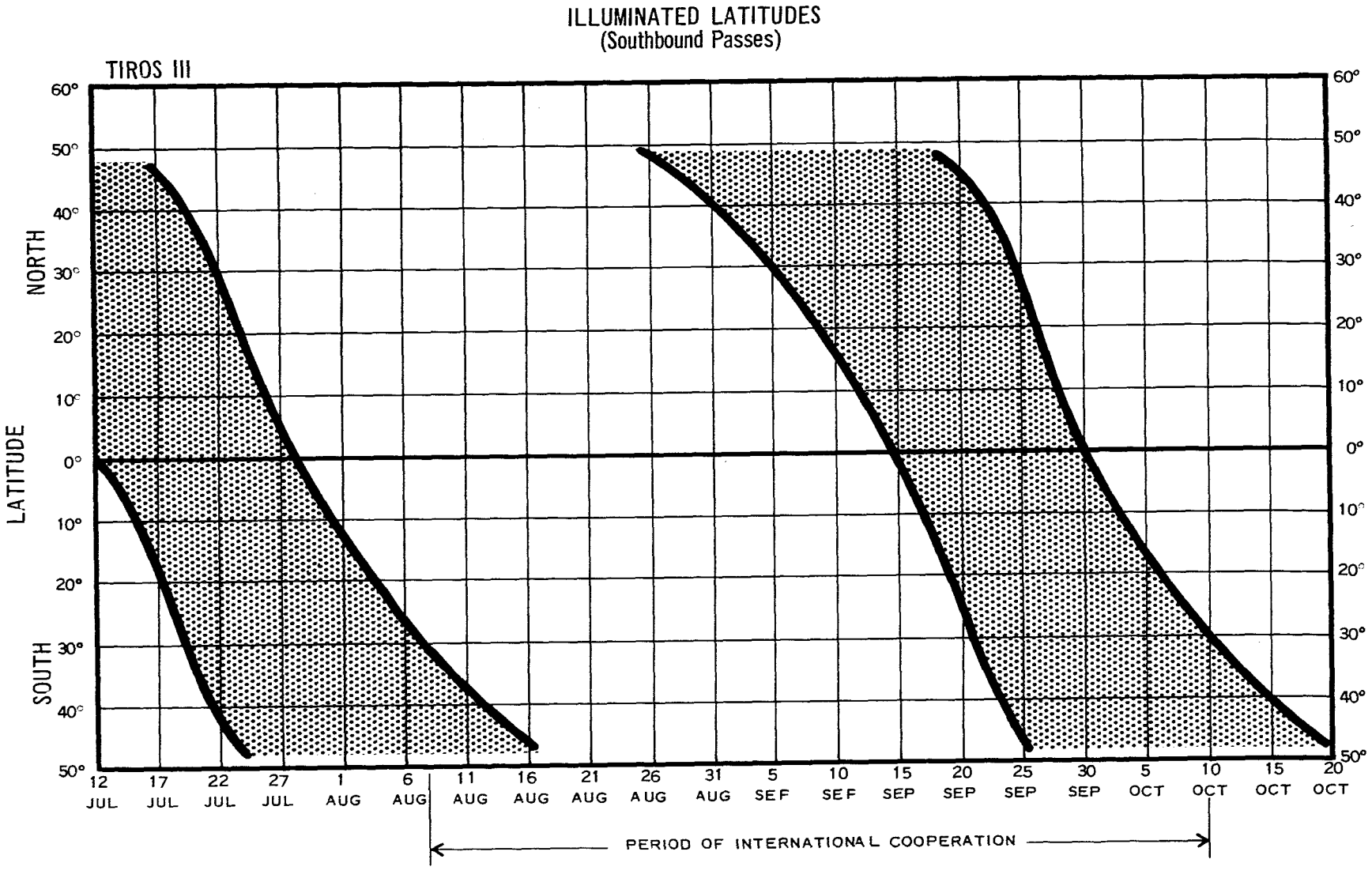

ILLUMINATED LATITUDES
(Southbound Passes)
TIROS III
LATITUDE
NORTH
SOUTH
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
12 JUL
17 JUL
22 JUL
27 JUL
1 AUG
6 AUG
11 AUG
16 AUG
21 AUG
26 AUG
31 AUG
5 SEF
10 SEF
15 SEP
20 SEP
25 SEP
30 SEP
5 OCT
10 OCT
15 OCT
20 OCT
PERIOD OF INTERNATIONAL COOPERATION

FIGURE A-2(a).

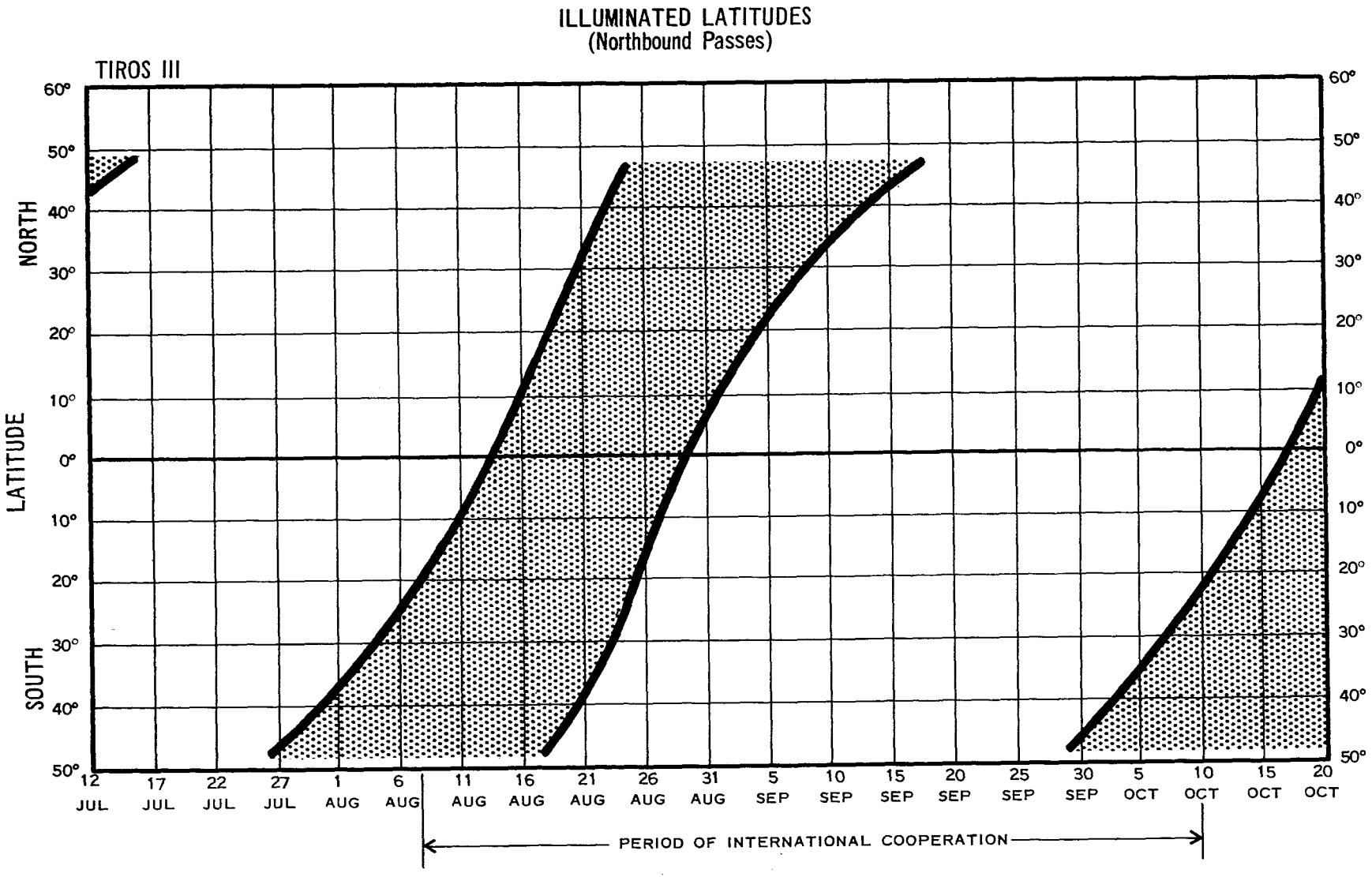

ILLUMINATED LATITUDES
(Northbound Passes)
TIROS III
LATITUDE
NORTH
SOUTH
60°
50°
40°
30°
20°
10°
0°
10°
20°
30°
40°
50°
12 JUL
17 JUL
22 JUL
27 JUL
1 AUG
6 AUG
11 AUG
16 AUG
21 AUG
26 AUG
31 AUG
5 SEP
10 SEP
15 SEP
20 SEP
25 SEP
30 SEP
5 OCT
10 OCT
15 OCT
20 OCT
PERIOD OF INTERNATIONAL COOPERATION

FIGURE A-2(b).

When plotted on a Mercator projection world map, the trace of the orbit subpoint describes a sine-shaped curve, centered on the equator, with a half-amplitude of just under 50° of latitude and a wavelength of approximately 335° of longitude. The 335° wavelength derives from the rotation of the earth under the satellite; the longitude of each ascending node being displaced approximately 25° west of that for the immediately preceding orbit. The range at which each data readout station can contact the satellite and usefully read-out data is a circle with a radius of about 20° of latitude.

Orbits with ascending nodes over the area of the Atlantic Ocean cannot be contacted by either data readout station; in fact, the first orbit following these that can be contacted has an ascending node of about 75° west longitude and can be reached by the Virginia station near the southeastern extremity of its range. (The following discussion relates to a 24-hour period starting with this orbit.) Following this orbit the next seven orbits can also each be contacted by either the Virginia or California stations (or both), the last one being that with an ascending node near 80° east, which is contacted by the California station near the southwestern extremity of its range shortly before its descending node near 115° west. During this 7½-orbit period, station locations impose no limit on the amount of data that can be obtained. The area covered during this 7½-orbit period is defined as Area I and is the most favorable area for photographic coverage.

During the approximately 6½ orbits between the last contact with the California station and the next contact with the Virginia station (about 24 hours after the first contact with the Virginia station, which started the period under consideration), we can obtain:

(a) One sequence of 32 pictures

(b) Solar and terrestrial radiation data for the last 100 minutes before the Virginia station contact

The areas covered during this 6½-orbit period include Areas II and III and are less favorable for photographic coverage.

Remote programing

An additional factor even further limits the data that can be obtained during this 6½-orbit period of time. The satellite clocks, which determine when remote picture sequences will start, can run for a maximum of only three orbits (5 hours) after being started before they initiate the picture-taking sequence. Under normal operating modes, this limits picture data following the last California contact to the area between this contact (just before the 115° west descending node) and 5 hours and 15 minutes later (shortly after the descending node at approximately 165° east longitude). The area covered during this three-orbit (5 hour) period following the last contact with California station is defined as Area II. From this point on, no pictures could be taken under normal operating modes until the first Virginia contact on the orbit with an ascending node between 75° west and 100° west.

To overcome this limitation, a supplemental mode of operation was tried for the first time during the TIROS III experiment. The clocks were set during the last California contact (just before the 115° west descending node) but, if not started then, they could be started by a special signal transmitted from the NASA minitrack station at Santiago, Chile. This experimental mode permitted pictures to be taken from the time an orbit came within range of Santiago (shortly before the ascending node near 30° west longitude) until the next contact with the Virginia station. This special mode was established primarily to increase the opportunities of obtaining tropical storm data over the tropical North Atlantic (it was successfully used to obtain pictures of hurricane Betsy), but can be more widely applied. The area over which pictures can be taken using this special mode (Santiago clock start) is defined as Area III. This special mode of operation can in no way increase the amount of picture data that can be obtained during the 6½-orbit time period (Areas II and III) following the last California contact; it only permits more flexibility in choosing the areas over which the one picture sequence is taken.

The areas (II and III) affected by this limitation of one series of pictures per day are approximately as follows:

(*a*) *On southbound portions of the orbits* (fig. A–3(a)): From a line running approximately from the southern tip of the Kamchatka Peninsula southeast to South Georgia Island (south Atlantic Ocean) westward to a line running from Hungary southeast to near the southern tip of New Zealand.

(*b*) *On northbound portions of the orbits* (fig. A–3(b)): From a line running from Sakhalin Island (north of Japan) southwest to about 50° south, 0° westward to a line running from the English Channel to about 50° south, 165° west.

It should be noted that most of these areas are also covered by orbits in the other phase which are contacted once per orbit by the Virginia or California stations. This is not true, however, for an area over central, southern, and southeastern Eurasia, and for another over the southeastern Pacific Ocean and southern Argentina and southern Chile; consequently, the amount of data that TIROS will be able to obtain over these latter areas will be severely limited.

Use of graphs and maps

To determine when pictures can be taken over any given area, first determine the latitudinal limits of the area. Then, using figure A–2(a), determine when those latitudes are illuminated for southbound passes. From figure A–2(b), make a similar determination for northbound passes. These are the approximate periods when it will be possible to take pictures over this area. Other limitations, discussed subsequently, preclude taking data over all areas at all times. The specific times within these possible areas when pictures were to be taken were more precisely identified by messages sent over international meteorological circuits 7 days and 24 to 48 hours in advance.

In many parts of the world, the period of southbound passes will be more favorable than that of northbound passes, or the reverse. To determine this, use figures A–3(a) and A–3(b). These maps show the geographical limits of Areas I, II, and III for southbound passes (fig. A–3(a)) and for northbound passes (fig. A–3(b)). Area I is the most favorable; next most favorable is Area II. Area III provides the least favorable probability of obtaining pictures from the satellite. It is roughly estimated that the probability of pictures being taken in Area I is about five times greater than in Areas II and III combined. Similarly, it is estimated that the probability in Area II is about twice as great as that in Area III.

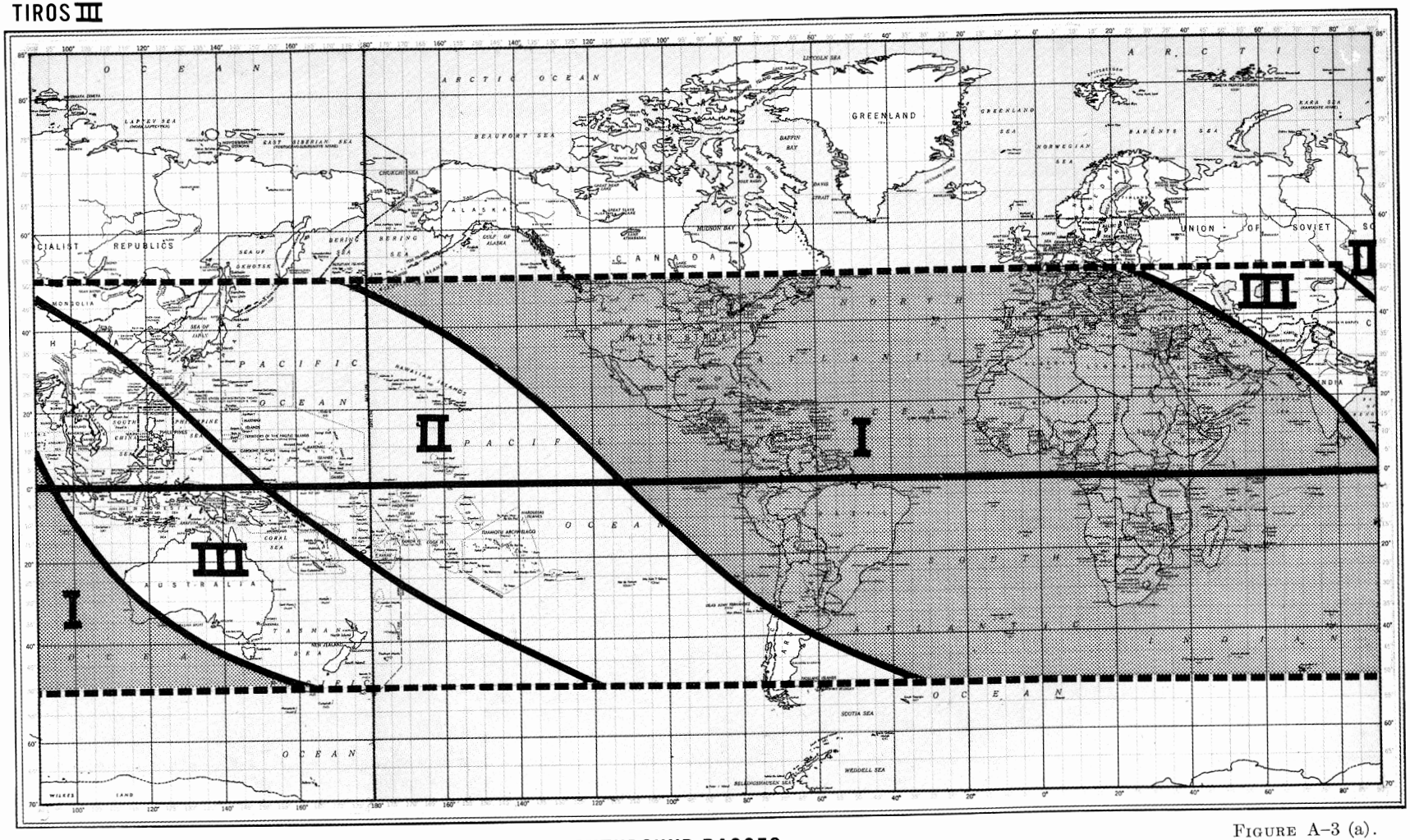
Example

Consider, as an example, the case of that part of Brazil between the Equator and 30° south latitude. On the southbound portions of the orbits, the northern part of the area is under an illuminated portion of the orbit from about September 15 to September 30; the southern part is under an illuminated portion from about September 21 to October 10. On the northbound portion of the orbits, the southern part of the area is under an illuminated portion of the orbit from about August 3 to August 23; the northern part is under an illuminated portion from about August 14 to August 28. However, Brazil is under Area I (most favorable condition) for southbound portions of the orbit while it is under Area III (least favorable conditions) for northbound portions. Accordingly, the most favorable period for TIROS pictures over Brazil would be during the period between about September 18 to October 3 when Brazil is under an illuminated southbound portion of the orbit. Perhaps a lesser effort might be set up for the period between about August 10 to 26; although illumination is satisfactory, Brazil is under those portions of the orbit that can be programmed only using the special Santiago clock-start mode. Consequently, there is much less chance of pictures being obtained over this area during August.

Derivation of maps and graphs

An overlay of the satellite track superimposed on a Mercator projection of the earth was used. The "high noon point" of the satellite orbit (that is, the point in any orbit at which the subsatellite point on the earth crosses the meridian of local high noon) is determined from the difference in right ascension (astronomical longitude) between the sun and the ascending node of the orbit. It is assumed that the minimum nadir angle (zero) occurs at this point—that is, the cameras are pointing straight down—and that the 30-minute illuminated area for a picture-taking sequence (one full 15-minute sequence per camera) will commence 15 minutes

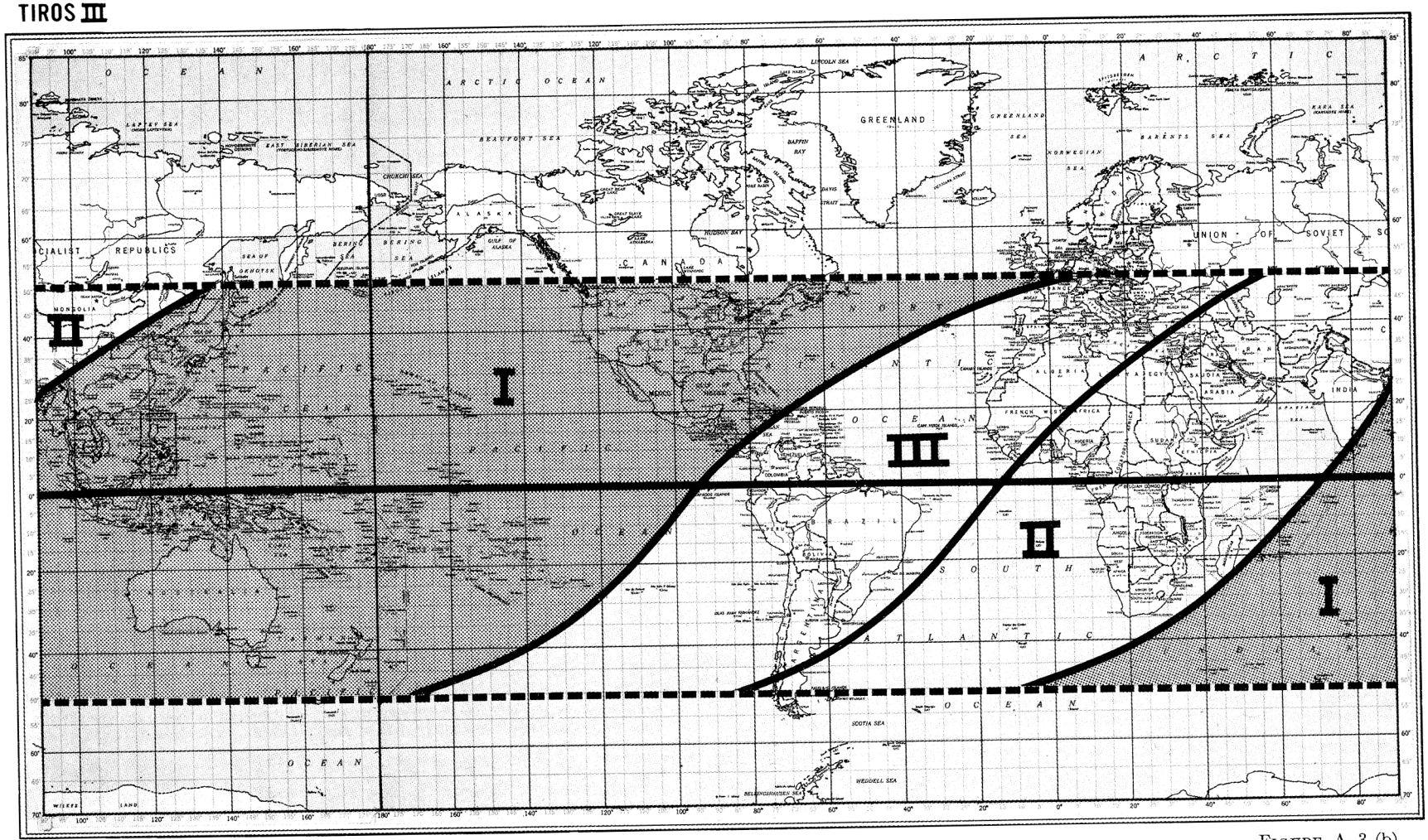
TIROS III



SOUTHBOUND PASSES

FIGURE A–3 (a).

TIROS III



NORTHBOUND PASSES

FIGURE A–3 (b).

before this point on the orbit and be completed 15 minutes after the high-noon point.

There are potential variations in the boundaries in the graphs and maps of 25° in longitude and 6° in latitude. The longitude may vary because of differences in the position of the first and the last orbits during which the satellite can be contacted by the two readout stations each 24-hour period. Both the longitude and latitude may vary, dependent upon camera attitude.

Assumptions

As mentioned previously, the assumption has been made that the minimum nadir angle (zero) occurs at high noon on the orbit and that the photographic sequence of the camera will evenly bracket high noon. In addition, it has been assumed that the satellite spin axis vector is in the orbital plane. In actual operation, the position of the minimum nadir angle will vary and the spin axis vector will generally be somewhat out of the orbital plane. A number of the picture sequences will be taken before or after high noon on the orbit in order to furnish a number of pictures with horizons to facilitate determination of attitude through photogrammetric techniques.

Thus, it will be possible under some conditions to obtain a limited number of pictures north of 48° north and south of 48° south, the extreme orbital subpoints. However, the probability of data being obtained decreases when proceeding poleward of these latitudes.

Other limitations

There follows a discussion of other factors which limit the data which can be obtained from TIROS III:

(*a*) Orbit inclination: Because the orbit of the satellite is inclined at an angle of slightly less than 50° to the equatorial plane, the satellite is unable to gather significant meteorologically useful data poleward of about 55° N. and S. latitude.

(*b*) Spin stabilization: For all practical purposes, the orientation of the spin axis of the spacecraft remains fixed in absolute space over any one orbit (the rate of change of the spin axis orientation due to use of the magnetic control coil cannot exceed about 15° per day). Accordingly, even under the most favorable circumstances with regard to the orientation of the spin axis and the position of the sun, the TV camera is pointed toward illuminated portions of the earth over only about one-third of each orbit. The interaction of the satellite with the magnetic field of the earth keeps the camera pointing approximately to the nadir near the high-noon point of the orbit, regardless of whether this occurs in the Northern or Southern Hemisphere.

(*c*) Magnetic tape storage capacity:

(1) Photographic data: During the period between the programing of the camera for remote (storage) picture operation and the reading out of the data from the tape recorder on the camera, only one set of 32 remote pictures, taken sequentially at 30-second intervals, can be obtained by a camera system. The overall length of the area observed during one sequential strip of 32 pictures is of the order of 6,000 miles (9,600 kilometers), at best. Accordingly, between successive contacts with the data acquisition stations, at best only one such set of 32 pictures can be taken by the camera system.

(2) Radiation data: Because these data are recorded on a continuously running endless loop magnetic tape which completes its cycle in about 100 minutes, data older than 100 minutes are erased as newer data are recorded. Thus, only data observed within 100 minutes before data read-out by a ground station can be obtained.

(*d*) Power: At times the rate of power provided by the solar cells is insufficient to permit the taking of as many TV pictures as would otherwise be available. The extent of this constraint varies with the precession of the orbit plane and the orientation of the satellite spin axis. In addition, available power gradually decreases as the nickel-cadmium storage batteries degrade with age and with repeated charge-discharge cycles.

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APPENDIX B

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