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# ATHER SATELLITE SYSTEMS

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Martin Rosenzweig

ACKNOWLEDGMENT

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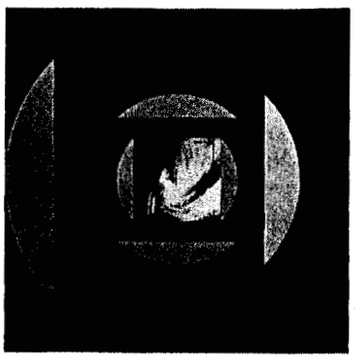
**COVER:** An occluding cyclone at 54° S, 119° E in the South Indian Ocean, as revealed by Tiros VI on Oct. 14, 1962, forms the focus for this month's cover by Martin Rosenzweig. NOMSS, the National Operational Meteorological Satellite System, will bring a new capability to bear in discovering and predicting the course of such potentially destructive weather systems.

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# TIROS Satellites and Satellite Meteorology

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# Keeping a weather eye

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WEATHER BUREAU

## An interview with the editors of this special issue

MORRIS TEPPER, Director of Meteorological Systems, NASA Headquarters
S. FRED SINGER, Director, National Weather Satellite Center, U.S. Weather Bureau
JOHN NEWBAUER, Editor-in-Chief, A/AE

**NEWBAUER: Dr. Singer, Dr. Tepper, I was pleased when you responded favorably to the idea for this issue. Why did you propose the articles to be read here?**

TEPPER: The papers covering NASA work were selected to report on the state of flight projects being conducted in the national meteorological satellite program. They emphasize primarily the engineering aspects of the successful Tiros series and the developing Nimbus series, and then extend to studies for future flight efforts, the nature of supporting research and technology, and some of the scientific results produced to date.

SINGER: My thought was to solicit articles which illustrate the fact that satellites are now being used in an operational system—incidentally, the *first* operational system based on space technology.

The scientific side of the weather satellite program should not be neglected. Thus several articles discuss their use for the study of the atmosphere, as well as for certain nonmeteorological applications, such as snow and ice.

Finally, the global aspects of weather inevitably demand international cooperation; and we have a discussion of the operation of the competent agency, the World Meteorological Organization.

**NEWBAUER: In the next two years we will see new generations of spacecraft to explore in detail the interplay of the sun and its surroundings, as an enormous thermodynamic system. What will this combined work give us as a background for weather control?**

TEPPER: As I see it, both the scientific and meteorological satellites that we are currently developing, will complement one another in the investigation of the great volume of space between the earth and the sun. They will reveal the significant constituents, and their amounts; give us clues as to the dynamic and thermodynamic forces that control the motions; provide information about the energetic particles in this great volume. This information will be necessary, of course, if we are to understand adequately both the phenomena in this three-dimensional volume and their variation as a function of time.

Now, with regard to the use of this information for weather control, I am afraid it's much too early to consider any specifics. But, as we learn how the atmosphere reacts to variations in solar input, we shall discover the clue as to what is required to make the atmosphere behave as we wish, perhaps by our producing the necessary variations of energy input.

SINGER: I concur with Morris, that a firm or better scientific understanding of the operation of the atmosphere has to precede any scientific attempts at weather control. In this connection, the effect of the sun on the earth's atmosphere is particularly interesting. Many people have speculated that changes in the large-scale circulation of the atmosphere are somehow related to the *variable* part of the solar radiation. As you know, the solar "constant" is not quite constant; the output of the sun does vary from time to time; you can certainly see it in the fact that there is a sunspot cycle. This variation is particularly pronounced in the ultraviolet and X-ray region of the sun, and in the corpuscular output of the sun. Now, unfortunately, no one has as yet established a causal connection—a chain of events—that relates a variation of the solar ultraviolet to an actual variation in the atmospheric circulation. To do this only on a *statistical* basis is highly unsatisfactory, I think; one would like to see a direct connection established. As I see it, the data from meteorological satellites which observe the earth's atmosphere in action, coupled with data from scientific satellites, of the type of EGO and POGO, which are able to measure solar ultraviolet and corpuscular radiation, may help scientists to establish this possible causal connection.

**NEWBAUER: You feel, in other words, that it may be possible, perhaps within a decade, to develop a theory for "weather control."**

SINGER: Yes, I think this is perhaps the most exciting aspect, scientific aspect, of the present satellite business, to establish whether and how the sun influences the weather *directly*.

**NEWBAUER: Could a single nation command an effective worldwide weather satellite system by itself?**

SINGER: I certainly think we could; in fact, we are setting up a national meteorological satellite system which also fills global needs; because the satellite itself provides a global observatory. Our meteorological satellite system itself will not depend directly on the contribution of other countries, but in order to use the output of the satellite system for effective forecasting you do have to have many types of data from other nations,



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Morris Tepper and S. Fred Singer, left and center, guest editors for this special issue, discuss questions put by A/AE Editor, John Newbauer.

particularly about surface and atmospheric conditions such as winds, pressures, and temperatures. The satellite itself is not yet able to measure wind, pressure, precipitation. All we have observed so far are infrared radiations from various layers of the atmosphere and, of course, the cloud patterns.

**NEWBAUER: Do we need this information about local conditions over both land masses and the sea?**

SINGER: We need both, and over the oceans particularly—they constitute most of the surface of the earth.

TEPPER: I think it would be pertinent to indicate that one of the articles in this issue (Moody and Widger, page 57) addresses itself to this problem of getting detailed additional information from data-sparse areas by means of automatic observation and telemetering platforms that are periodically interrogated by a satellite. This system is merely in the conceptual stage at this time.

With regard to the possibility of any one country establishing a global meteorological satellite system, it is clear that we can do it. Moreover, other countries with adequate launching capabilities and space technology development can also. The question is, what is the best way of proceeding with the job. I think it's preferable to develop the meteorological satellite system on an international basis. Simple economics dictate that such a system will be quite expensive, and the sharing of the expense by many countries would be very helpful.

From a more technical point of view, I would like to refer to what Fred mentioned a moment ago—that we must have the cooperation of other countries insofar as local observations are concerned and also insofar as the analysis of the available information is concerned. We must have this cooperation in order to fulfill our own responsibilities in meteorology. We must work together if we are to acquire a true understanding of the atmosphere.

**NEWBAUER: How much of a building job does this represent in countries other than our own? Do the means exist in many countries around the world to bring about such a system?**

TEPPER: A meteorological satellite system has many parts to it—launch vehicle, spacecraft, data acquisition, data utilization. It isn't necessary for other nations to participate by contributing to all parts of the system. When it comes to spacecraft development, and when it comes to launching the spacecraft into orbit, there are few countries with these specialized capabilities. Two countries and perhaps a third might be able to produce these aspects of a global system. But there are the other aspects. Data acquisition—the development of a command and data-acquisition station as part of the system is within the reach of many countries. With regard to the receipt of data by ground-communication links the picture is even better. Practically any country can become a partner in this endeavor by installing suitable teletype or radio receivers to accept information from areas covered by satellite. And finally, there is the very exciting development of the Automatic Picture Transmission System with which, by means of relatively inexpensive devices, ranging in cost up to $50,000, it will be possible for countries to receive pictures directly from a satellite. This development is discussed in several articles here.

**NEWBAUER: Once Nimbus appears, how long will it hold the field? With Nimbus do we embark on a program that will preempt engineering study of weather-satellite systems for a fair amount of time?**

TEPPER: Have we come to the end of the road with Nimbus, and with it will we merely keep putting up identical copies? We might look at it this way. Nimbus was developed in response to certain meteorological requirements expressed in terms of types of observations, coverage, frequency of observations, etc. These requirements are continually modified, improved or sharpened, and correspondingly we will have to continue the engineering efforts required to satisfy these variations.

SINGER: We view Nimbus, of course, as the essential building block in the National Operational Meteorological Satellite System, NOMSS, but we don't think this is the end of the road. Even with the existing Nimbus we would like to see more things done. For example, the present Nimbus represents some outstanding engineering advances. It has an extremely interesting attitude-control system, for example, and a very intriguing system of obtaining solar power (see page 42). Experience will tell us whether the present Nimbus does an adequate job for operational meteorological purposes; we think it probably will. But we can also see the need for a launch capability which will handle more weight. What we would like to see, again from a rather operational point of view, is more redundancy of equipment

on Nimbus, in order to get a longer effective operational lifetime. We also have the problem of power to take care of all the equipment that we would like to see aboard Nimbus. The present solar paddles are just adequate, but perhaps in the future we should consider nuclear power as a means of providing the sort of electric power to handle, for example, satellite-borne radars, satellite-borne lasers, or at least satellite-borne microwave receivers.

TEPPER: There is another aspect to consider with regard to the paddle problem. As you know, the early Nimbus will go into a high-noon orbit; but already the requirement is developing for a launch of Nimbus into an orbit other than high noon. This would require the development of another degree of freedom for the motion of the solar paddles, so that the paddles will continue to face the sun throughout the orbit. We are far from having completely solved all the problems for Nimbus itself, let alone those posed by future requirements.

SINGER: Yes, but by that time the best engineering approach may be nuclear power. As you know, space technology has advanced in all areas, and I think that the proper thing for us to do is to take advantage of all these advances in, for example, the area of communication satellites, or in the area of manned space vehicles, or wherever space technology is advancing. I am sure that the Nimbus satellite five years from now will perform differently from the one of today.

TEPPER: I should point out that the synchronous meteorological satellite represents a new concept entirely—one which will require much development effort.

SINGER: As far as the development of subsystems is concerned, described in this issue is the infrared equipment which will be carried on Nimbus; but we can see now, from an operational point of view, the need for much-higher-resolution infrared equipment. A high resolution, for example, will spot forest fires and other conflagrations on the earth. This type of development, I believe, will have to be done and may in fact affect the spacecraft design—it will require, for instance, a great deal more power.

**NEWBAUER: Engineers will have plenty of work to do on meteorological satellite systems for a number of years. How does the field look for students interested in meteorology?**

SINGER: It looks, I think, extremely bright. There has been a renaissance of the atmospheric sciences, not only because of satellites. But with meteorological satellites providing masses of data, there will be created great scope for innovation and research and new ideas in the field of meteorology. A sort of revolution of that type has existed since the first balloon went up. We are stimulating more universities to work with satellite pictures and with satellite infrared data, and we hope that this trend will continue to be strengthened. We need more people who are willing to "come back from outer space" and devote themselves to the earth, which after all is still an important planet.

**NEWBAUER: Will these programs, both scientific and engineering, have a significant effect on industry?**

SINGER: I would like to mention one aspect of industry often neglected. A large volume of data will come back from the meteorological satellites. For example, from Nimbus we will get back something like *5-billion bits a day*. There has to be, of course, a large data-processing center; but I can visualize that many other people may wish to have smaller computers which can speak directly to this large computer center that we are building in Suitland, Md. So I think the data-processing industry as a whole will become very much concerned with the handling of satellite data for various operational purposes. Weather is perhaps one of the outstanding examples where data have to be processed in real time. Such needs exist in other areas as well, but this probably represents the largest volume of data being processed in real time.

**NEWBAUER: What developments might be watched closely with respect to weather satellites; what do you watch closely in affiliated fields?**

SINGER: Well, I'm watching closely manned space stations. We have conducted some meteorological experiments in the Mercury project with cameras having specially designed filters. We use the Mercury program as a kind of test bed for meteorological-satellite sensor design. But, beyond this, it is intriguing to contemplate to what extent a manned space station can perform an operational function in the field of meteorology. I don't think we can answer this question yet, naturally, but I think it is one field that we will certainly want to watch very closely, and encourage if possible.

TEPPER: I don't think we're sure about what can be done here. One point of view is that the meteorologist would not be useful at all aboard a manned space station. At best his function might be to keep the onboard instruments running properly. The inference is that the human being is too limited in his observing capabilities. He is limited to the visible range, while instruments can view a wider range in the electromagnetic spectrum. Moreover, they can be quantitatively calibrated. Another point of view is that a human being has between his ears a unique computer, one yet to be duplicated by a machine. This computer is extremely versatile and adaptable to new conditions. And if we don't realize what may be the potential of the man aboard a space station, we will find out very quickly after a man has been aboard. He will be able to react to situations that we may not have anticipated and considered adequately in terms of instrumentation.

SINGER: A man can, of course, maintain, adjust, and calibrate some of the very elaborate equipment of a future "meteorological observatory." He may even operate an orbiting data-processing center, and do analysis and interpretation. He can instantly focus attention on particular areas of the globe with certain of his sensors. I think the man can do many things that the instrument cannot do; we cannot yet design an instrument to deal with unexpected situations.

**NEWBAUER: The question remains: Can a trained meteorologist identify and interpret weather systems from a station?**

SINGER: For many situations instruments will be better. But I also believe that a man can supply something in addition to the instruments, by covering the situations that haven't been anticipated.

TEPPER: I would agree with that.

**NEWBAUER: Perhaps we can keep a weather eye on space stations, and for the time being satisfy ourselves with the broad view of developing weather satellite systems this issue affords.** ••

# Weather and the future

As satellites extend man's vision into new dimensions, weather forecasting will make major advances as a science, until we see reliable predictions a season ahead. This will have far-reaching economic benefits for all. Following are some estimates of cost-savings, assuming that we can predict weather accurately only *five* days in advance:

- $2^1/_2$ billion a year in agriculture
- $45 million in the lumber industry
- $100 million in surface transportation
- $75 million in retail marketing
- $3 billion in water-resources management

These estimates of savings are for just the United States. Worldwide benefits would be many times as great.

Continued scientific research aimed at understanding the underlying processes that produce weather and determine climate may lead us in the next decade to control weather and modify climate.

This exciting prospect poses a profound challenge to our scientists to gain a thorough understanding of the consequences of any man-made interferences to insure that they are beneficial. For the atmosphere represents an international resource of fundamental importance to all mankind. To use it intelligently, we must understand its workings, predict its behavior, and learn how to modify some of its excesses, as we fulfill our destiny in mastering the space environment.

Vice President of the United States
Chairman, National Aeronautics and Space Council

BACKGROUND TO NOMSS—

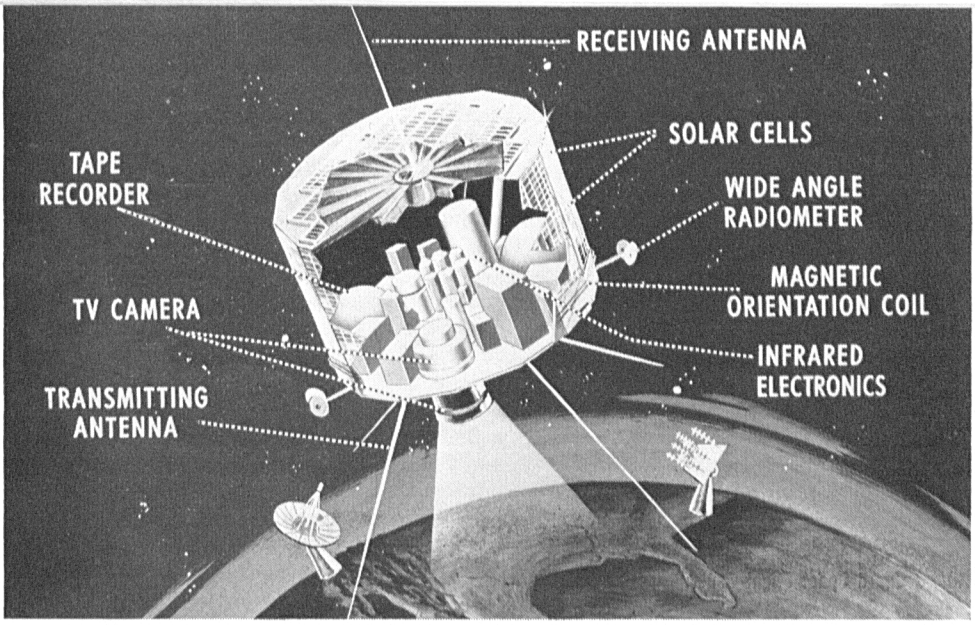
# Space and the weather

## Excerpts from House Report No. 2561, "Space and the Weather," by the House Committee on Science and Astronautics, Dec. 3, 1962

A conference of representatives from the National Aeronautics and Space Administration, the Department of Defense, the Federal Aviation Agency, the Weather Bureau, and others, was called by NASA on October 10, 1960, to begin the planning for a national operating weather satellite system. A Panel on Operational Meteorological Satellites (POMS) was organized under the National Coordinating Committee for Aviation Meteorology (NACCAM), which after several months of extensive study produced a plan that was endorsed and supported by all the interested government agencies, and was incorporated in a report issued in April of 1961. This is widely known as the POMS Report. The following is taken directly from the abstract of the report, as well as its conclusions and recommendations:

> This report of the Panel on Operational Meteorological Satellites, a working group of the National Coordinating Committee for Aviation Meteorology, describes and recommends a plan for the implementation of a national operational meteorological satellite system. The proposed system is designed to phase into operation at the earliest date consistent with the requirements of the various U.S. weather services and the current state of technology. It has a progressively increasing capability to serve the needs of both the United States and the international meteorological community . . .
>
> Over-all management of the system would be assigned to the U.S. Weather Bureau, which would be directly responsible for data acquisition, communications, processing, analysis, and dissemination. Development and procurement of spacecraft and launch vehicles, including the actual conduct of launch operations, would be delegated to NASA. It is contemplated that NASA would also participate in spacecraft control and programming and in data acquisition. Participation of the military services and other user agencies, as required, is expected. . .
>
> *Recommendations*
>
> 1. That the United States undertake to develop a national operational meteorological satellite system at the earliest possible date.
> 2. That this document be accepted as the basis for initial planning and implementation of such a system.
> 3. That funds be made available in early fiscal year 1962 to begin implementation of the system.
> 4. That assignment of management responsibility for the national operational meteorological satellite system be made at the earliest possible date, and that this responsibility be placed with the U.S. Weather Bureau of the Department of Commerce. That appropriate legislative changes be made to permit the Department of Commerce to effectively carry out this responsibility.
> 5. That the U.S. Weather Bureau create a new organizational segment to manage the operational satellite system.
> 6. That the Department of Commerce contract with the National Aeronautics and Space Administration to develop and/or procure for the U.S. Weather Bureau the spacecraft, launch vehicles, and ground-support equipment and to accomplish the launchings. Further, that the NASA shall participate in such postlaunch activities as command and data acquisition, as required by the interrelationship of ground equipment and spacecraft.
>
> These recommendations are designed to support a national policy which centralizes certain types of spaceflight activities within NASA and USAF without precluding operational use of satellite observations by other organizations.
>
> 7. That the satellite-data users participate in the staffing of the operational - system organization through assignment of appropriate personnel.
> 8. That the operational system evolve from the NASA R&D program. That the Aeros satellite be supported for eventual incorporation into the operational system.
> 9. That the Tiros program be extended to provide some measure of operational capability prior to the first Nimbus launch.
> 10. That consideration be given to the eventual replacement of ground communications by satellite data relay.
> 11. That immediate engineering attention be directed to the following long-range problem areas:
>
> (a) Possible replacements for the Thor-Agena B launch vehicle if it is to be made unavailable by early Thor phase-out.
>
> (b) Optimum number and location of command and data-acquisitions stations.
>
> 12. That foreign countries be phased into the program at an early enough date to allow them adequate time to develop their roles . . .

Following the adoption of the POMS Report, Congress in September 1961, appropriated $48 million to the Weather Bureau to "establish and operate an operational meteorological satellite system" (Public Law 87-332).




**Tiros**—still making weather satellite history.

There are several national and world organizations which have contributed substantially to the planning and operational activities of the weather satellite system. A brief description of these organizations and their functions would be helpful. The order of mention here is not intended to indicate their relative importance.

The World Meteorological Organization (WMO) is a specialized agency of the United Nations, and has been in existence since 1950. Actually, it evolved from the International Meteorological Organization which was established in 1878. It is composed of members representing 113 states and territories, and has the following purposes: To promote worldwide cooperation in the establishment of organized weather facilities; to set up methods for the prompt dissemination of information; the establishment of weather measurement and analysis standards; to foster weather research and training programs within and between nations; and to assist in the exchange of knowledge and experience gained in the application of weather information to such activities as communications, agriculture, soil erosion, and so forth.

The National Coordinating Committee for Aviation Meteorology (NACCAM), which is chaired by the Weather Bureau representative, includes members from the Department of Defense, NASA, the Federal Aviation Agency (FAA), and the three Armed Services. It was this organization which formed the Panel on Operational Meteorological Satellites (POMS) and whose function it is to coordinate the operational requirements of the various users of operational weather satellites.

The Joint Meteorological Satellite Advisory Committee (JMSAC) is composed of members representing NASA, the Department of Defense Research and Engineering, the three Armed Services, and the U.S. Weather Bureau. It is the function of JMSAC to assist NASA in the coordination of the research and development program, leading to operational use of the data . . .

The functional responsibilities of the USWB and the NASA under the Nimbus Operational System will be as follows:

*U.S. Weather Bureau:*

(a) Determination of the overall meteorological requirements.

(b) Specification of quantities to be measured by the satellite meteorological instruments.

(c) Processing of data for operational meteorological purposes.

(d) Integration of data into weather analyses.

(e) Use of data and analyses for forecasts.

(f) Dissemination of data, analyses, and forecasts.

(g) Archives (processing, storage, retrieval).

(h) Research and climatological use of data.

*National Aeronautics and Space Administration:*

(a) Design, fabrication, and test of the spacecraft.

(b) Procurement of the launch vehicle.

(c) Maintenance of launch sites.

(d) Construction of command and data-acquisition stations.

(e) Prelaunch preparation of spacecraft and vehicle.

(f) Launch operations, including scheduling.

(g) Tracking and orbit determination.

(h) Programming and command to satellite.

(i) Data recovery at command and data-acquisition stations.

(j) Communication of research data to the National Weather Satellite Center.

Since the output of the R&D Nimbus vehicles will be used by the Weather Bureau in the operational system, the interagency agreement for the National Operational Satellite (NOS) applies to R&D vehicles insofar as data utilization is concerned. These interfaces in meteorological satellite programming are subjects of continuous coordination between NASA and the Weather Bureau. This coordination is provided in a number of ways, both at the working level and at the top management level. One of the ways of effecting close cooperation is the assignment of a Weather Bureau employee as manager of the Nimbus Data Utilization Systems Office in NASA where he works directly with and is responsible to the general Nimbus project manager. This link does not, however, replace the single management organization under which NASA is responsible for R&D of new satellites, while the DOC-WB is responsible for operational meteorological satellites. ••

## Growing with each flight, they showed the potential for operational systems

# Tiros achievements

BY ROBERT M. RADOS, Tiros Project Manager, NASA Goddard Space Flight Center

To assess properly the achievement of Tiros, one must keep in mind the system in its entirety—the spacecraft, the launch vehicle, the data-acquisition facilities, and the data-utilization areas. Each contributed much to the record of success summarized in the table here.

The first Tiros demonstrated the feasibility of providing and using cloud photographs. In addition, it demonstrated the utility of certain types of satellite dynamics and thermal control, the versatility of various electronic and mechanical components, and other capabilities of modern technology. The useful life of Tiros I ended with the burnout of a camera transmitter, caused by a failure of power turnoff relay, which affected the entire satellite system. Seventy-six days (approximately 185 active hours) of successful operation produced almost 23,000 pictures by both cameras, one with a wide-angle and one with a narrow-angle lens, both operating in remote and direct modes. Pictures stored on tape in the satellite and later played back were equally as satisfactory as the direct transmissions. The successful firing of the spin-up rockets was accomplished 57 days after launch and to the designed spin rate.

The analyses of the spin-axis motion of Tiros I resulted in the use of a controlled current loop (magnetic coil) in Tiros II to steer it, taking advantage of the effect of the earth's magnetic field.

Tiros II underscored the feasibility of obtaining and using satellite cloud pictures. More important, it demonstrated successful operation of the infrared experiment and the magnetic attitude-control system. The former initiated extensive studies of the energies radiated and reflected by the earth and its atmosphere. And, of special engineering significance, its infrared subsystem was operated successfully 525 days after launch.

The quality of the pictures from Tiros II's wide-angle lens camera was reduced from that of Tiros I by a deposit on the lens from the exhaust gases of the third-stage rocket. Consequently, more attention was focused on the pictures from the narrow-angle lens system, and this led to valuable insight into the structural detail of both the type of cloud cover and the earth itself. The pictures from Tiros II proved the feasibility of using satellites to observe sea-ice conditions. Amid other accomplishments, Tiros II monitored the weather for the suborbital flight of Astronaut Alan Shepard and the launch of Ranger I.

Tiros III can be considered the first of the quasi-operational weather satellites. This satellite dramatically fulfilled its prime objective of providing hurricane surveillance by observing "Esther" two days before probable detection by conventional observations. On one day—September 11, 1961—Tiros III observed five hurricanes and typhoons on a global scale as well as several tropical and extra-tropical storms. Because of the large quantities of excellent data it delivered, hundreds of operational analyses were developed. The techniques for these analyses were developed through the availability of the data and the improvements in the ground-system communications and facilities afforded by experience from Tiros I and II. In addition to an infrared subsystem, Tiros II contained an omnidirectional radiation sensor designed to give additional insight into the earth's energy budget.

The launch of Tiros IV initiated the continuous meteorological satellite observations which have extended over one year. The Tiros IV established operationally the use of satellites for ice surveillance. It provided support for Astronaut John Glenn's orbital flight, Project Ranger, and the Antarctic resupply.

The accomplishments in the areas of design and development attributed to Tiros I–IV were repeated, and were augmented, by Tiros V and VI. Pri-

**THE TIROS RECORD**

**LAUNCHINGS AND PERFORMANCE**

| Tiros | Launch Date | Useful TV Life | Useful IR Life | Total Pictures | Sensors | Special Accomplishments |
|---|---|---|---|---|---|---|
| I | April 1, 1960 | 77 days | — | 22,952 | Wide and narrow angle TV | Proved feasibility of meteorological satellites |
| II | Nov. 23, 1960 | 76 days | 141 days | 36,156 | Wide and narrow angle TV; two IR systems | IR subsystem successful; magnetic attitude control successful; ice reconnaissance feasible |
| III | July 12, 1961 | 145 days | 81 days | 35,033 | Two wide angle TV; three IR systems | Hurricanes, typhoons observed; photo-facsimile pictures obtained routinely |
| IV | Feb. 8, 1962 | 120 days | 146 days | 32,593 | Wide and medium angle TV; three IR systems | Ice reconnaissance project established; supported Mercury, Ranger, Antarctic resupply, Joint Task Force 8 |
| V | June 19, 1962 | 240* days | — | 46,634 | Wide and medium angle TV | Hurricane coverage |
| VI | Sept. 18, 1962 | 149* days | — | 37,389 | Same as Tiros V | Hurricane coverage |

*Operational as of Feb. 14.

Remarks:

Tiros II Last TV pictures 301 days after launch
Last IR data 525 days after launch

Tiros III Last TV pictures 231 days after launch
Last IR data 208 days after launch

Tiros IV Last TV pictures 266 days after launch
Last IR data 169 days after launch

marily intended to provide hurricane coverage for the 1962 season, these satellites increased coverage by virtue of orbits with 58-deg inclination, as compared with the 48 deg of their predecessors. Increasingly effective use of the attitude-control system, moreover, steered these satellites into a more extensive coverage of areas of vital concern. The use of a simple auxiliary command station in Chile, begun with Tiros IV, further extended the coverage of areas of interest. Tiros V demonstrated the excellence and thoroughness of the vehicle technologists when, through the secondary guidance system, despite random failure of the primary system, an acceptable orbit was achieved. On Feb. 19, 1963, after eight months for Tiros V and five months for Tiros VI, excellent data were being received and used.

Throughout the Tiros program, accomplishments in the data-utilization area have been significant and immediately applicable to the peaceful uses of space. A truly real-time use of Tiros data has been achieved. Meteorological analyses are made within 2–3 hr of data receipt, and the results transmitted not only to the forecast centers of the U.S., but to those of foreign lands as well.

The continuous progress in the Tiros program can be attributed to the engineering and scientific accomplishments and thoroughness of many individuals from government and private industry, working together with a common aim and a will to succeed. Organizations that have contributed prominently to the program include NASA Goddard Space Flight Center, and Wallops Station; Department of Commerce, U.S. Weather Bureau; RCA Astro-Electronics Div.; U.S. Navy, Pacific Missile Range; Allied Research, Inc.; the U.S. Air Force; and the U.S. Army Signal Research and Development Laboratories.

### Suggested Additional Reading

Besides articles in this special issue of *A/AE*, the following reports summarize Tiros performance.

NASA/GSFC Technical Report TR-R-131, "Final Report on the Tiros I Meteorological Satellite System," edited by L. Allison and E. Neil.

RCA/AED Report on "Final Operation Report, Tiros I Meteorological Satellite System," Oct. 1, 1960.

RCA/AED Report on "Post Launch Evaluation Report, Tiros II Meteorological Satellite System," May 31, 1962.

RCA/AED Report on "Post Launch Evaluation Report, Tiros III Meteorological Satellite System," Dec. 21, 1962. ●●

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## Directed from GSFC Technical Control Center, they have grown to include orbital programming, magnetic steering, and plans for selective address

# Tiros operations

BY ERNEST F. POWERS, NASA Goddard Space Flight Center

Operational control for Tiros satellites, exercised by the Technical Control Center (TCC) at NASA Goddard Space Flight Center (GSFC), has grown as a technical challenge as the project evolved from its early R&D role in Tiros I to its present combined mission of furnishing operational meteorological data and supporting research and development in the study of the physics of the atmosphere.

Diagrammed on page 31, TCC is responsible for the monitoring and operational evaluation of spacecraft and Command and Data Acquisition (CDA) station performance and for the direction and coordination of the operational phase of the Tiros mission. In accomplishing these tasks, TCC receives a variety of input data, derives the necessary courses of action, and provides the resultant data to the participating agencies and groups. Examples of the many types of input data include computed orbital information indicating minute-by-minute satellite position over the earth, solar illumination over the orbital track, and station acquisition predictions. TCC also provides a comprehensive summary of spacecraft spin-axis positions, both hindsight and predictive, for purposes of magnetic attitude steering, and the effects of these data on the spacecraft power supply and viewing angles of IR and TV camera sensors.

These data, plus requests from the U.S. Weather Bureau as to where on the orbit Tiros TV pictures are desired, enable TCC to program satellite data command and readout (see page 32). Once the spacecraft has been interrogated and the data received, a summary of all operations, including specific command times and responses as well as signal quality, strength, and duration, is reported to the control center. Selected parameters of the spacecraft telemetry (voltages, temperatures, etc.) are also forwarded after each orbital interrogation, along with the data from the Horizon Sensor and North (Sun Angle) Indicator Subsystems. The necessary computations are then performed immediately.

The next orbital interrogation is not undertaken until a summary analysis of these data has indicated an acceptable performance level of the spacecraft and the CDA station. Any unusual or abnormal response from the spacecraft is immediately analyzed and program changes, if needed, are made for the next interrogation.

The operational condition of the CDA stations is reported in summaries of orbital interrogation and data handling—for example, quality of antenna control, whether by automatic track or by slave to a special antenna programmer console; current capabilities for effective command and noise-free data readout; effective photo processing, attitude prediction and gridding; and meteorological analysis. Special "hot" voice lines link TCC with each of the CDA stations to receive or relay these vital data.

Effective communications for command, control, and data dissemination have contributed much to the high performance level achieved with Tiros. Voice lines, photo facsimile, teletype, and data facsimile all play a part in

the operation. Each represents an alternative method in the conveying of information from point to point, while maintaining a specific use.

Real-time analyses of the Tiros data as conducted by meteorologists at the CDA stations have presented a learning process since the early days of Tiros I. Progress from lengthy hand calculations and detailed map projections and analyses have given way to use of a digital computer and plotter requiring a variety of input data. Using special nomograms and ephemerides, the hand calculations are reduced where possible.

Research with Tiros TV data has been aided by producing a master 35-mm negative from which copies can be made for distribution. The Master negatives reside at the National Weather Records Center, Ashville, N.C. The production of this master negative demands rigid and accurate quality-control procedures from initial film derivation to the CDA stations. The establishment of exacting controls on ground-station TV kinescope settings and levels and dark-room development techniques has seen a major advance in only the past year. The large number of photographs requires automatic film processing and reproduction and a high degree of uniformity in the end product. This has recently been achieved with Tiros data.

The motion of the spacecraft spin axis, which was originally thought to be relatively fixed in space, has been discussed in many technical reports. This axis has been found to have a regular precession of as much as 3–5 deg per day, due primarily to three torques acting upon the satellite.[1,2] Angular motion of the axis arises from, first, a primary torque caused by the interaction of a magnetic dipole along the satellite spin axis with the earth's magnetic field; this magnetic dipole is caused by residual magnetism of the satellite's components along the spin axis and by closed current loops in the spacecraft instrumentation. Then, a secondary torque is caused by a differential in the earth's gravitational field, as related to the fact that the moment of inertia of Tiros about the spin axis being greater than the other principal moments of inertia, the orbital plane precession of approximately 3.6 deg per day around the equator due to the oblateness of the earth, and the spin axis being normally out of the orbital plane. Therefore, whenever the spin axis is out of the orbital plane, a torque is exerted on the spacecraft due to this difference in moments of inertia. Third, a secondary torque arises from eddy currents caused by the satellite rotation about its axis in the earth's magnetic field.[2] Continued research is being conducted at GSFC to examine the effects of this torquing plus effects of aerodynamic torquing on the spacecraft spin axis.

Concerning this work, a theoretical model has been constructed which gives the total torque acting on the satellite over one orbital period, and a GSFC computer program called MGAP (Magnetic Attitude Prediction) utilizes this theoretical model to predict the changes in satellite spin-axis attitude. Knowledge of these changes is extremely important for programming operation of the spacecraft systems in orbit, and for the effective utilization of the Tiros TV and IR data when received at CDA stations.

The need for constant knowledge of spin-axis position has led to two important changes in Tiros operations.

First, a variable-current closed circuit coil was installed on Tiros II and succeeding spacecraft. This coil allowed the creation of an additional calibrated dipole moment along the satellite spin axis. It can be energized by five variations of current of both positive and negative values as well as a zero value.

This coil actually allows *optimum magnetic steering* of the spacecraft spin axis. Motions of up to 10 deg per day can be added to the normal spin-axis precession rate or the precession motion can be retarded to a significant degree. The graph on page 31 shows a record of such action. Although the spin axis is still constrained to stay within the limits of the orbital plane, significant results using magnetic steering have been accomplished, that is, the sun-spin vector angle has been kept to within prescribed limits for proper illumination of the solar cells and the sun rays have been kept out of the field of view of IR sensors.

Secondly, teams have been placed at the CDA stations to provide on-site daily determinations of satellite spin-axis attitude. Through the use of a small digital computer and special grid-plotting equipment, these teams first derive or verify the attitude from the current orbit of Tiros data and then prepare the latitude and longitude grid overlays for the upcoming interrogation. The team at the Wallops CDA station collects and collates all data for determining the best spin-axis attitude for each orbit of the past day, and based upon these values predicts the attitude for the next 36 hr. GSFC makes long-range magnetic attitude predictions using the theoretical model previously mentioned. Excellent correlation exists ($\pm 1.5$ deg) between the observed attitude as computed by the CDA attitude-determination teams and the predicted values issued by GSFC.

An analysis of the many methods of Tiros attitude determination has shown that there is a great deal to be gained from the many sources of attitude derivation. The techniques and procedures used to determine the best attitude from Tiros include the horizon sensor, TV pictures (two types of analysis), and the output of Channel Two (8–12 micron) of the IR scanning radiometer. Although TV pictures continue to be the best source of attitude information, the other data plus predicted magnetic-steering information have given a high degree of confidence to the final attitude values, and hence picture interpretation and analysis.

Another change incorporated on Tiros II, based on experience with Tiros I, was the removal of the digitizing system for the horizon-sensor data from spacecraft to the ground readout sites. This was found to be desirable because the horizon sensor was subject to spurious responses from cloud elements. When read out as an analog signal on the ground, however, the spurious or unwanted responses could more easily be gated out or discarded before the digitization process. This has proven very successful.

Operational procedures for Tiros have evolved to achieve the best spacecraft and CDA station performance. Two changes of rather recent origin should increase the useful life of the Tiros spacecraft. The spacecraft are now interrogated for every orbit possible in order to consume power and prevent battery overcharging. And switching of the vidicons is held to a minimum.

The choice of launch dates and possible launch times for Tiros have been found to depend on many factors, besides availability of a flight-tested, accepted spacecraft. Launch dates are affected by the hemisphere's coverage desired from the television cameras, the orbit inclination, vehicle

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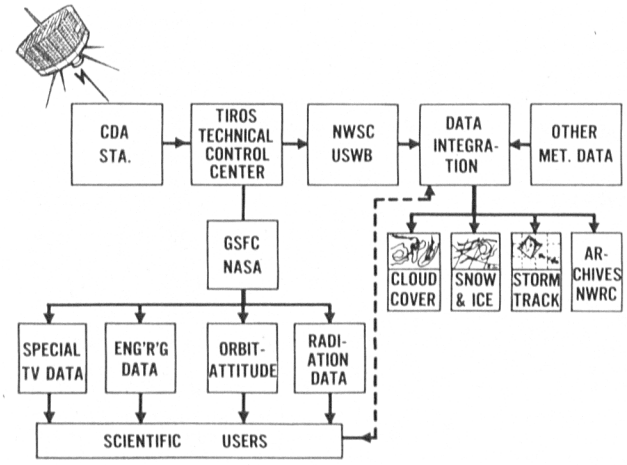
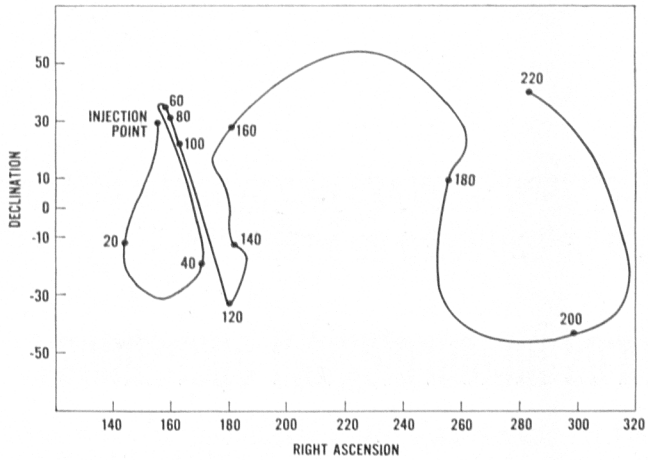
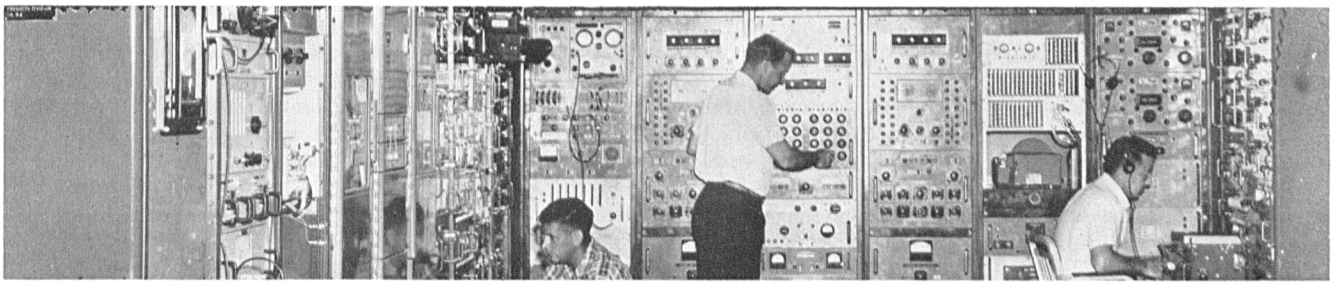



**TIROS DATA FLOW**




**Tiros V Spin-Axis Attitude:** As determined by CDA Station teams for first 220 days in orbit.



**CDA Equipment at Wallops Station.** Center: command-programming, antenna-control, and calibration devices. Right: receivers and recorders for horizon sensor and housekeeping telemetry. Left corner: equipment for reception, recording, display, and photographic reproduction of 235-mc TV data. Extreme left: 237.8-mc IR equipment.

characteristics, direction of launch and season of the year, and the relationship of a planned orbital plane to the orbital plane of a spacecraft already in orbit.

For example, if Tiros is to be launched NE from Cape Canaveral on a Delta vehicle into a 58 deg-inclination, 350-n. mi. orbit, the primary considerations for launch date are desired television coverage at some specific time, for example, hurricane coverage in mid-August and September, and the orbital-plane relationship with that of presently operating spacecraft. However, if Tiros is to be placed into a polar orbit, these same constraints plus such factors as the position of the first verticality, the hemisphere (North or South) which is properly sunlit, and the precise type of polar orbit, for example, sun-synchronous, will demonstrably affect the eventual launch date.

Launch times (launch windows) are chosen so that the normal precession of the satellite spin axis for at least 7-10 days will not cause the sun-spin vector angle (Gamma) to shift beyond the accepted limits of 20–70 deg, or will have allowed the sun's rays to enter the field of view of the IR scanning radiometer (39–51 deg Gamma), and will provide proper solar illumination for TV pictures at the desired times for the selected period. It is the unusual occasion when all of the constraints of date and time are equally well satisfied, and some compromise must be made.

The programming of two satellites (Tiros V and VI) in orbit with orbital planes less than 15 deg apart introduced new areas of concern in the design of Tiros spacecraft and in the conduct of operations. The urgency for a different type of command system to enable selective interrogation was very evident. Operations procedures at TCC and at the CDA stations had to be adjusted so that, if the two spacecraft were to be interrogated within the time frame of the same orbital period, data readout from one spacecraft had to be completed in time to allow proper program setup time for the closely following interrogation. Then the data handling and processing had to be accomplished so that the final data were presented in time to be of value to the users. CDA equipment redundancy and duplicate communications facilities enabled these operations to be performed on a realistic basis. But there is need for a new or modified command system with selective address, and a modification has been designed for inclusion on future Tiros spacecraft.

Finally, experience in Tiros operations indicates that spacecraft interface requirements should never be assumed to be met merely by production of new units to supposedly identical specifications. Of course, any design changes which affect the spacecraft operation must see a complementary change in the CDA station equipment, but the CDA station must be prepared not only to optimize according to the individual spacecraft's calibration, but also must be prepared to make adjustments as new "calibrations" are received in orbit. It is at this point that flexibility and good engineering common sense have paid off in Tiros operations.


## Acknowledgment

The author wishes to thank Herbert I. Butler, Associate Chief for Projects, GSFC Aeronomy and Meteorology Div., for his assistance and contributions.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Sustained coverage and synoptic interpretations can be expected as a result of—

# Tiros meteorological operations

BY LT. COL. JAMES B. JONES, USAF, and LEE M. MACE
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Prior to the launch of Tiros I, meteorologists were privileged to study a few cloud observations recorded by cameras sent aloft on rockets.[1,3] These observations provided a view of the weather on a grand scale, and even recorded cloud patterns associated with entire weather systems. Most of the details of cloud structure and organization were of interest initially to the research meteorologist. On one rocket film sequence, however, a significant storm system was seen which had *slipped unobtrusively* through the conventional weather observing network: The operational forecaster began to awaken to the potential value of a weather observer in space.

It is not surprising, therefore, that while the Tiros program was still in the experimental phase a substantial effort had been devoted from the beginning to exploit the data for *immediate operational use.* This portion of the Tiros program addressed itself essentially to the questions:

1. Do the photographs contain information of immediate operational value?
2. Can cloud features be located within the limits of accuracy required for operational support?
3. Can pertinent information be abstracted in a form which can be easily distributed and used?
4. Can the elapsed time between observation and distribution to the forecaster be held within acceptable limits?

As the data-utilization experiment evolved, all these questions have been answered affirmatively to a large degree.

The experiment has developed thus far through three phases: *exploratory,* extending from the launch of Tiros I and ending with the demise of Tiros II; *evolutionary,* covering the period from the launch of Tiros III to a point somewhere between the launches of Tiros V and VI; and *interim operational,* emerging during the period following the launch of Tiros V. Our discussion here considers these phases as these developed.

In March 1960, meteorologists selected from the U.S. Weather Bureau, the military weather services, and from military and industrial research organizations reported for duty at the Tiros readout stations in New Jersey and Oahu, Hawaii. As if to add a touch of historical significance, the New Jersey team set up shop in the old Marconi building—near the Evans Signal Laboratory of Fort Monmouth—from which some of the first trans-Atlantic wireless messages were transmitted in the early 1900's. The Oahu team, operating in leaky Jamesway huts on remote Kaena Point, were pioneers in the physical as well as the scientific sense.

Concurrently, a small group of Weather Bureau scientists and technicians was organized within the Meteorological Satellite Section (now the National Weather Satellite Center) to provide technical guidance and support to these two field units. Initially, this group assumed the role of proxy for all the data users and selected areas containing significant weather systems to be photographed by Tiros, and provided early evaluation of the analyses prepared at the ground stations from the cloud photographs.

These three teams of meteorologists—at Kaena Point, in the Marconi Building, and in Washington, D.C.—began the search for answers to questions posed at the beginning of this article.

The question concerning immediate operational value of information contained in the satellite photographs was answered early in the Tiros I operation with an unqualified "yes." By the time Tiros I had ceased to function in mid-June of 1960, it was generally recognized that a satellite could provide operationally useful information in the form of routine storm surveillance in both the tropical and extra-tropical regions and detailed observations of cloud distribution and organization from vast areas of the globe otherwise devoid of meteorological information.

The remaining aspects of operational utility—location accuracy, timeliness, and acceptable data formats—could not be evaluated by simple inspection of the photographs. A careful analysis was necessary to assess the accuracies which could be achieved, and a customer survey was needed to evaluate the latter two factors.

Of paramount importance to the

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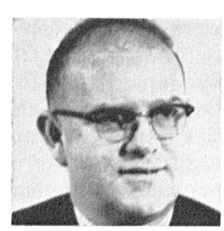
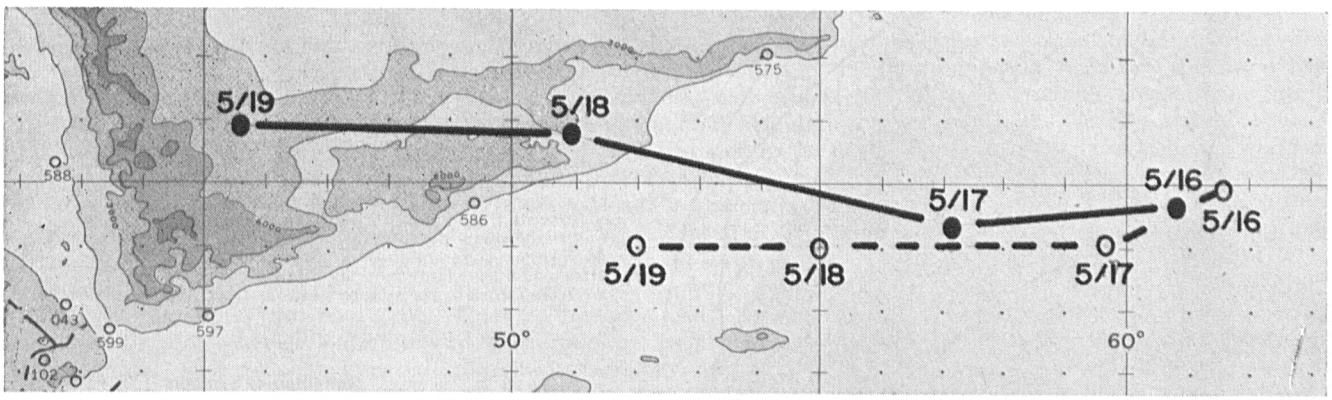


**LEE M. MACE**
is Chief of the Programming and Processing Section of the Weather Bureau's National Weather Satellite Center. Since beginning weather-satellite work, he has been concerned with the operational phases of the Tiros program—interpretation of satellite pictures and distribution of the data to operational users. He formerly was an aviation weather forecaster.



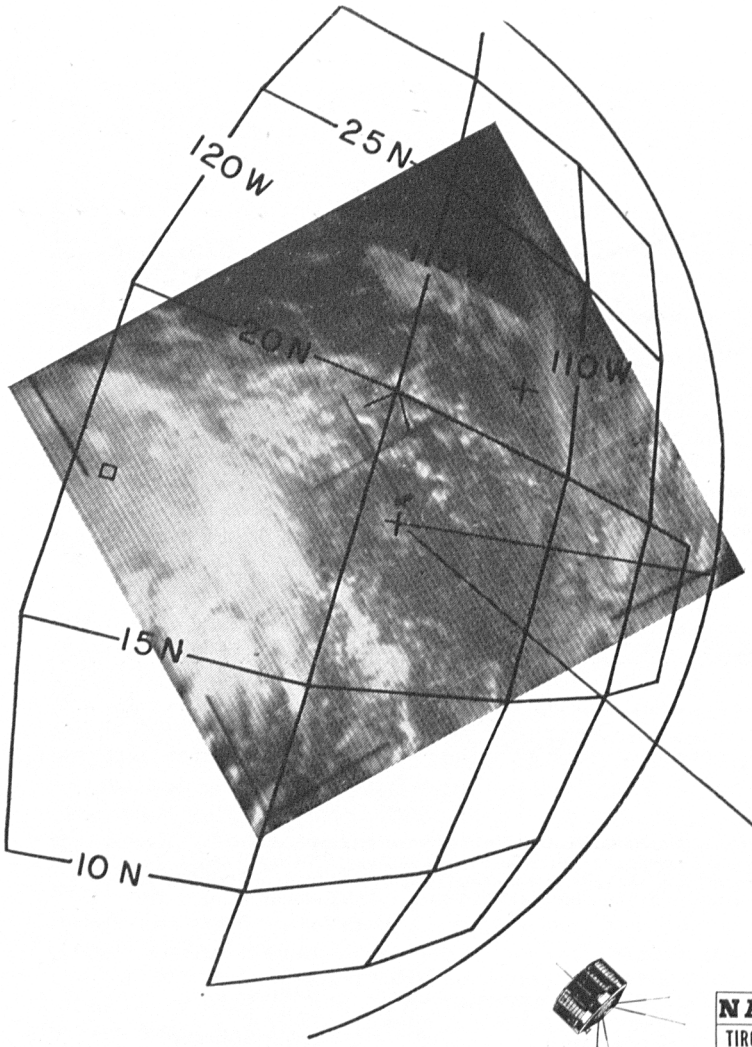

**Tiros Storm Surveillance Capability** from data-sparse regions can be seen in this map of a tropical cyclone moving across the Arabian Sea. Solid line shows storm track based on Tiros observation; dashed line shows storm track for conventional sources. These conventional observations proved inadequate even for accurate post-analysis of this dangerous storm.

**FIRST TIROS NEPH**

**First Tiros Nephanalysis Distributed** for use and evaluation by meteorologists in the United States and Europe. The NEPH was prepared at Ft. Monmouth from Tiros I pictures (Orbit 43 of April 4, 1960) by analysts J. H. Conover of AFCRL and Lt. Col. J. B. Jones, USAF.

**Definition of Symbols**

| | | | |
|---|---|---|---|
| CLR | Clear Skies | + | Dense or heavy |
| Sctd or O | Scattered cloud cover | THN or — | Thin |
| O | Broken cloud cover | UNK | Unknown |
| Ovc or O | Overcast skies | PROB | Probably |
| V | Variable | Ci | Cirrus cloud form |
| | | CUFM | Cumuliform clouds |




**Computer-Produced Grid,** like the one at left, made by Bendix G-15 equipment at satellite stations, represents a major step in evolution of data-utilization experiments. Based on prediction of where the satellite will be at the time a picture is taken, the grid represents the section of the globe as seen from Tiros—i.e., the grid is a perspective-map section. The grid is properly oriented on the photograph, after which the significant cloud features are transferred to a standard weather map base for distribution.

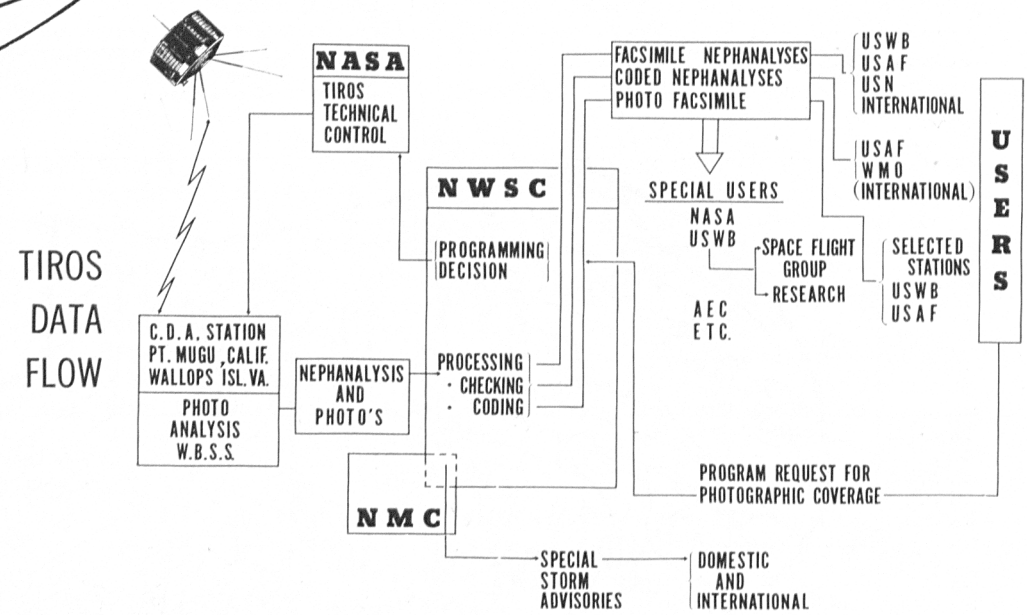
**Definition of Symbols**

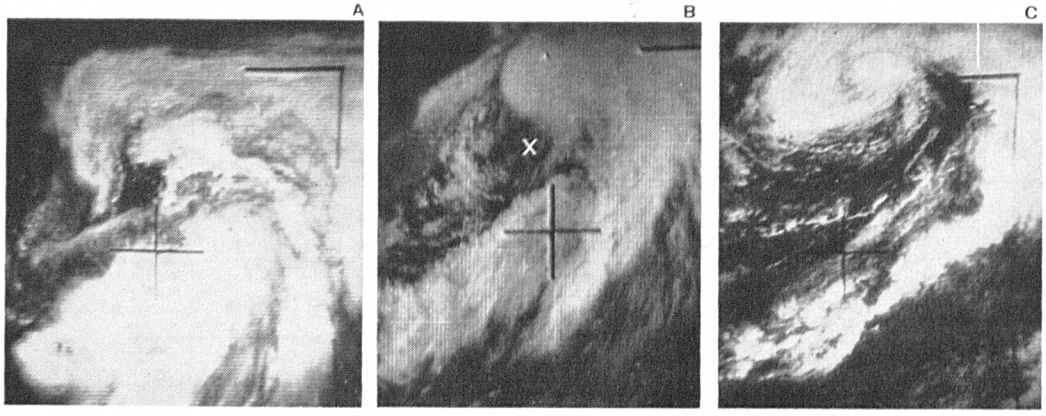
Satellite subpoint

Principal point and principal line at grid time.

Principal point position 1 min after grid time.

Principal point and line indicating position of the sun relative to the principal point.




**ALMA's HISTORY**

Photo "A" shows tropical storm Alma on August 27, 1962, off the East Coast of the United States. This photo provided the only detailed information about the extent of cloudiness associated with Alma.

Photo "B," taken on August 28, shows intrusion of dry air toward center, signified by relatively clear area at X. This Tiros picture provided clue that the storm would begin to weaken.

Photo "C," taken August 29, shows intrusion of the dry "clear" air into the center of the storm circulation and beginning of storm weakening, as forecast from "B."

accurate geographic location and orientation of the satellite photographs is a precise knowledge of the satellite location and attitude relative to the earth at the time each picture is taken. Intimately involved are the following: determination and prediction of satellite location and attitude as a function of time, fidelity of the satellite programming equipment in the ground station and on the satellite, and, finally, the intangible—care and skill exercised by the meteorologist in analyzing the photographs. Format (gridded photographs, schematic depiction of the cloud features, alphanumeric coding) and timeliness depend on more mundane considerations. Map scale and projection, acceptable conventions for schematic depiction, availability and cost of communications, and specific requirements of the data users are some of the more important factors.

Tools and procedures employed by the teams of analysts during the exploratory phase were simple, straightforward, and flexible. Brute-force techniques rather than sophistication were the order of the day while the meteorological community was becoming familiar with the capabilities and idiosyncracies of the Tiros system.

To expose the field forecaster to a variety of conventions for the schematic depiction of the cloud features, the analysts were encouraged to exercise individual artistic and meteorological skills while transcribing "significant" cloud features from the photographs to a map. These schematic representations of the cloud amount and large-scale organization, known as nephanalyses—NEPHS for short—were distributed to field weather stations over regular communication circuits for evaluation. The field forecaster was asked to comment on the accuracy, timeliness, format, correspondence with conventional data, and operational situations in which the analyses had been useful.

The first Tiros NEPH distributed for evaluation was transmitted from Fort Monmouth to Washington on the third day of the Tiros I operation. Depicting cloud patterns observed on the 43rd orbit, it was relayed to field weather stations in the U.S. and Europe for evaluation.

Before the exploratory phase ended, evaluations from field weather stations had firmly established the operational utility potential of the satellite and had begun to identify and define limits of accuracy, detail, and time delay tolerable in several broad operational areas.

Introduction of significant changes to operational policy and procedure began with the launch of Tiros III. Weather Bureau data-processing stations were established as part of the Tiros ground stations—now located at Wallops Island, Va., and Point Mugu, Calif.—and were manned by a permanent cadre of Weather Bureau meteorologists and technicians, many of whom had previous Tiros experience. This permanent staff was augmented by meteorologists from the Air Weather Service and the Naval Weather Service assigned on temporary duty. Similarly, a Programming and Processing Section was organized as a permanent unit within the NWSC to maintain the necessary liaison between the operational meteorologist in the field and the Tiros program. These permanent units replaced the temporary teams of meteorologists and technicians previously assigned to cover only the functional period of a given satellite. Organizational changes were completed with the assignment by NASA of computation and photoprocessing units to work on site in each of the data-processing stations to support the operational experiment.

Emphasis during this phase was now placed on development and refinement of procedures designed to make the NEPHS of more value to larger numbers of users. One of the more important procedures to evolve was that of advising the operational meteorologist on areas to be photographed routinely during the next 24–48 hr and areas where photographs could be taken some 7–10 days hence. The weather men in the field responded by asking for satellite coverage over areas of specific meteorological interest. These requests were given priority in preparing the picture-taking instructions for transmission to the satellite.

At the Weather Bureau data-processing stations, programs and procedures were developed which led to preparation of perspective map sections—latitude/longitude grids for specific pictures to be acquired during a given pass—a few hours before the satellite pictures were acquired. These replaced the more generalized tools—perspective grid, transfer grid, and special map projection—used during the exploratory phase of the experiment. This innovation reduced the manipulations required of the analyst by a factor of 3 or 4, and resulted in a substantial reduction in analysis time. NEPHS could be made available to meteorologists in the National Meteorological Center (NMC) within 2–4 hr after pictures were taken by the satellite.

To expedite further the delivery of information concerning special-interest phenomena, such as tropical storm activity, a special bulletin service was inaugurated. With this service, it has been demonstrated that specific information on the location and dimensions of potentially destructive weather phenomena can be sent to weather offices throughout the world within 1–2 hr after the weather feature has been photographed by the satellite.

Other significant tests initiated during this period and continuing today include the selective distribution of actual photographs by photo-facsimile to a 10-station network and international transmission of the NEPHS by radio facsimile.

Weather services at home and abroad continued to submit evaluations of the operational utility of the satellite data. Some examples of the users' reactions are quoted or paraphrased below.

A meteorologist at the NMC attributes the *detailed* information available in a series of Tiros *photographs* with the following operational assist. Tiros V had tropical storm Alma under surveillance once daily during Aug. 27–29, 1962. On each of these three days, selected photographs of the storm were sent by photo-facsimile to the NMC within 30 min to an hour after the storm had been observed by the satellite. Between August 27 and 28, the meteorologist noted significant changes in the distribution of cloudy and clear areas near the storm center. These changes were among the factors which led to a forecast that the storm would gradually lose intensity. During the subsequent 24–48 hr the storm weakened as forecast.

A communique from the Australian Meteorological Service indicates to some extent the international scope of the operational experiment. "Your response to our recent request for preferred coverage over tropical cyclone waters to the northwest and northeast of Australia was most gratifying and it has already been fruitful in tracking a cyclone in the former area from 10 to 15 January."

On May 4, 1962, a Pan American Airlines pilot scheduled for the New York to Dakar run received as part of his weather briefing a Tiros NEPH showing the cloud distribution along his route. He was asked by the Weather Bureau's Meteorologist-in-Charge at Idlewild to evaluate the NEPH while enroute to Dakar. The pilot's evaluation, quoted below, underscores the operational value of the weather satellite, particularly over areas where weather information from conventional sources does not exist.

"Enclosed is the Tiros weather map

given me upon my departure IDL, Flight 150/04. I was asked to comment as to its accuracy.

"The area, on our track, from IDL to 60° West is shown to have been overcast. Actually, it was clear from IDL to 65° West and then broken from 65° W to 60° W. From 60° West to Dakar, the map was so accurate as to be almost unbelievable. The map position of the cold front was not only located exactly, but with a 150 mile scan on radar its northeast-southwest positioning was clearly defineable. The cloud types and amounts were completely correct.

"Continuing on the flight from DKR to ROB, it too was letter perfect with the exception of our finding some 2/8 CB's off the coast. This is probably due to the morning buildup, rather than the possibility of the CB's shown at 20° W extending that far northeast.

In my estimation we have found the answer, let's send up more Tiros."

This feedback of the customers' reactions has been beneficial to Tiros and to future programs as well.

In recent months, meteorologists have asked that Tiros be continued on an interim operational basis until NOMSS can be fully implemented. This request may foretell a gradual change in status of the program. Regardless of official designation—experimental or operational—emphasis during this next phase will shift from pure description to the synoptic interpretation of the cloud pictures. Objective remains the same: Make available to the meteorologist more of the latent data in the satellite picture.

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# TOSS: Tiros operational satellite system

BY A. H. GLASER, Aracon Laboratories
and F. E. CHRISTENSEN,
National Weather Satellite Center

## Two Tiros satellites with opposed orbits would provide TV data with more than twice the operational value of a single Tiros and make possible continuous picture coverage of the northern hemisphere

As the papers by Rados (page 28) and Powers (page 29) and Jones and Mace (page 32) have indicated, Tiros I provided the meteorological community with a view of the earth and its weather on a scale never before achieved. The revelation of the organization of cloud systems as seen from the satellite immediately suggested that an operational weather satellite system would be valuable and feasible. Tiros II provided additional operational experience. With its narrow angle camera, Tiros II demonstrated the possibility of extending operations to include such things as snow and ice reconnaissance (see Singer and Popham, page 89).

Beginning with Tiros III, two cameras suitable for operational meteorological purposes have been incorporated in each satellite. This permits extension of the picture taking capability of Tiros to 64 pictures per orbit, or very nearly the maximum permitted by the basic orbital geometry. In the event of the failure of one camera system, the remaining camera continues to provide coverage over operationally significant parts of the orbit.

Because of the unanticipated longevity of one Tiros V camera, the Tiros experimental system became very nearly an operational system for an extended period. Teams of experienced meteorologists, satellite engineers and operators, an electronic computer, and photographic technicians were placed on duty 24 hrs a day at the Wallops Island and Point Mugu Command and Data Acquisition stations as well as at Tiros Technical Control in Greenbelt and in the Tiros Data Center in the National Weather Satellite Center in Suitland, Md. Special communications lines were established from the CDA Stations to the Data Center, and several times daily weather satellite data were disseminated to the world over existing weather communications facilities.

In spite of this apparently operational system-in-being, it must be emphasized that the Tiros of today is an experiment, as is the operational system that has grown up around it. These experiments have amply demonstrated the operational utility of the Tiros satellite and have led to demands for the establishment of a truly operational satellite system.

The next step toward implementation of the eventual National Operational Meteorological Satellite System (NOMSS) calls for picture coverage of much of the earth's surface on a programmed basis each day. An interesting proposal for achieving this objective, using two Tiros satellites in orbits in phase apposition, has been entitled TOSS, for Tiros Operational Satellite System. This program has just been implemented by the Weather Bureau and NASA.

To appreciate the significance of this orbital arrangement, examination of the characteristics of Tiros and its orbit is required.

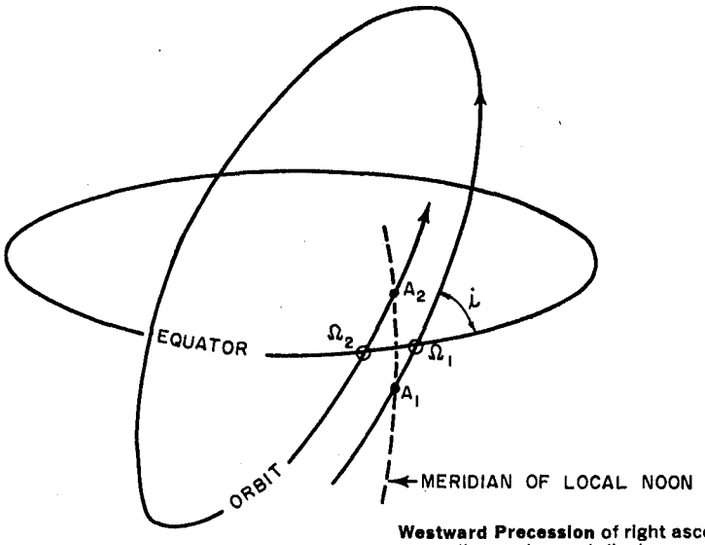
Tiros moves in a nominally circular direct orbit at an altitude near 740 km and at an inclination of 58 deg. A total of 64 pictures taken at 30-sec intervals can be stored on magnetic tape in the satellite between interrogations. The 64-picture sequence covers an area approximately 13 by 120 deg of great-circle arc.

If the earth were spherical and made up of homogeneous spherical layers, it would attract an exterior body as though its mass were concentrated at its center. The orbit of a satellite controlled only by the attraction of such an ideal earth would be perfectly described by Kepler's laws and the plane of its orbit would be fixed in space. Such an ideal motion is only a first approximation since a satellite is influenced by numerous perturbing forces. For an earth satellite these forces are caused by:

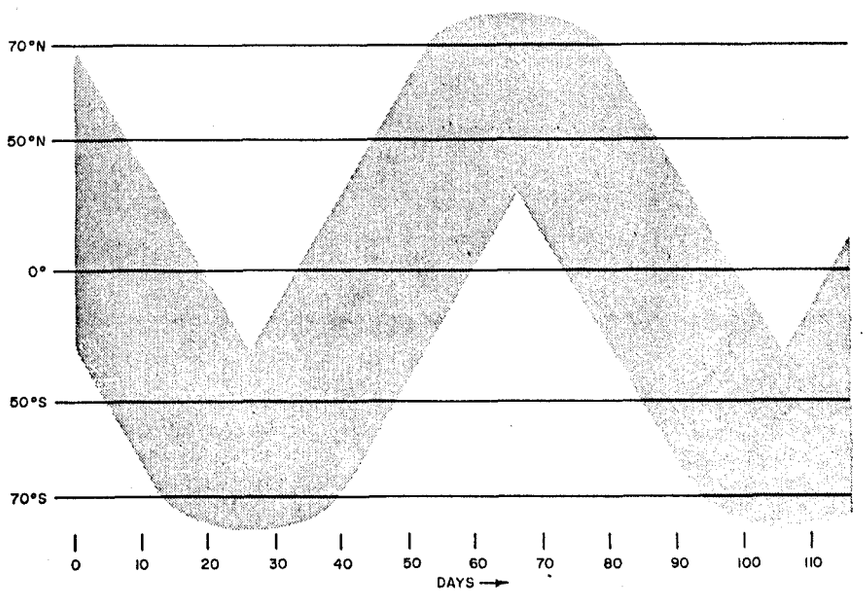
1. The slight equatorial bulge of the earth.
2. The interaction of electric and magnetic fields of the earth and the satellite.
3. Atmospheric drag.
4. The non-homogeneity of the earth.
5. The influence of other celestial bodies.
6. The satellite's motions.

The perturbing effects of the first two of these causes on the Tiros orbit are large in comparison with the others. Atmospheric drag can have a large effect on a near-earth satellite or on a satellite whose perigee is close to the earth. The Tiros orbit, being circular and of sufficient height above the earth's surface, is not greatly influenced by atmospheric friction. It should also be noted that orbital inclination is not modified by drag and the effect on orbital regression is small and exerted only through decreased satellite height.

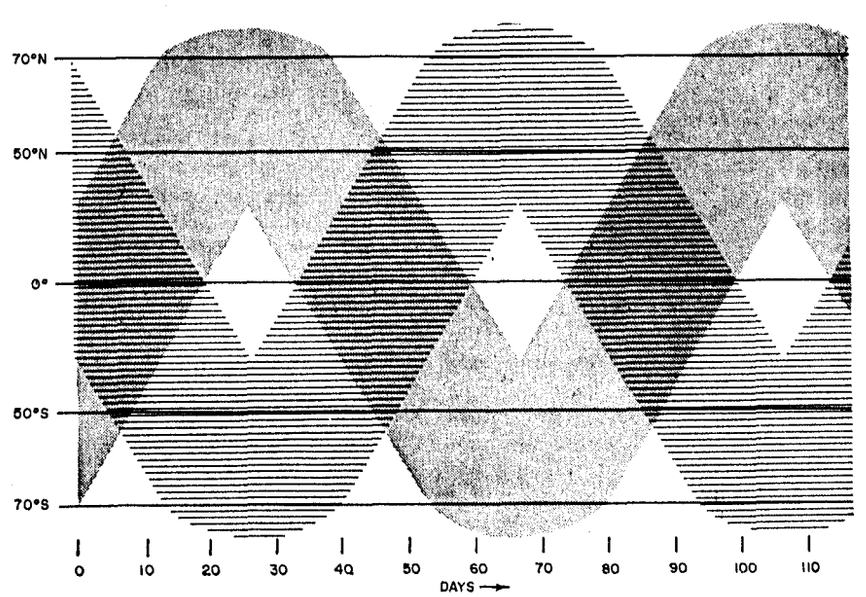
The effect of the earth's oblateness on the Tiros orbit is large and, on first examination, would appear to seriously impair the effectiveness of a space oriented weather satellite. Because of this oblateness, the right ascension of the nodes of the Tiros orbit precesses westward at the rate of 3.6 deg per day. In addition, the orbital motion of the earth causes the right ascension of the sun to be displaced eastward at the rate of 1.0 deg per day. These combined effects, coupled with a fixed space orientation of the satellite spin




**Westward Precession** of right ascension of ascending nodes and displacement of spin-axis vertical point,; $\Omega_1$ and $\Omega_2$ = consecutive ascending nodes; $A_1$ and $A_2$ = consecutive spin-axis vertical points; and i = orbital inclination.




**Day-to-Day Change** of latitudinal belt observed by a single Tiros (above) and with two Tiros in the Toss configuration (below).




axis, in the absence of other forces, would cause the camera to look downward over daylight areas of the earth for about 40 days followed by a similar period of looking at the earth in darkness.

Fortunately, the interaction of the magnetic fields of the earth and Tiros has a perturbing effect on the Tiros orbit of similar magnitude to that exerted by the earth's oblateness. This force has no effect on the orientation of the line of nodes. It does cause the satellite spin axis to be displaced in such a manner that the point of verticality of the camera axis is displaced eastward along the satellite track. Furthermore, the magnitude of this force can be altered by changing the amount of current flowing through the magnetic attitude control device (See page 29).

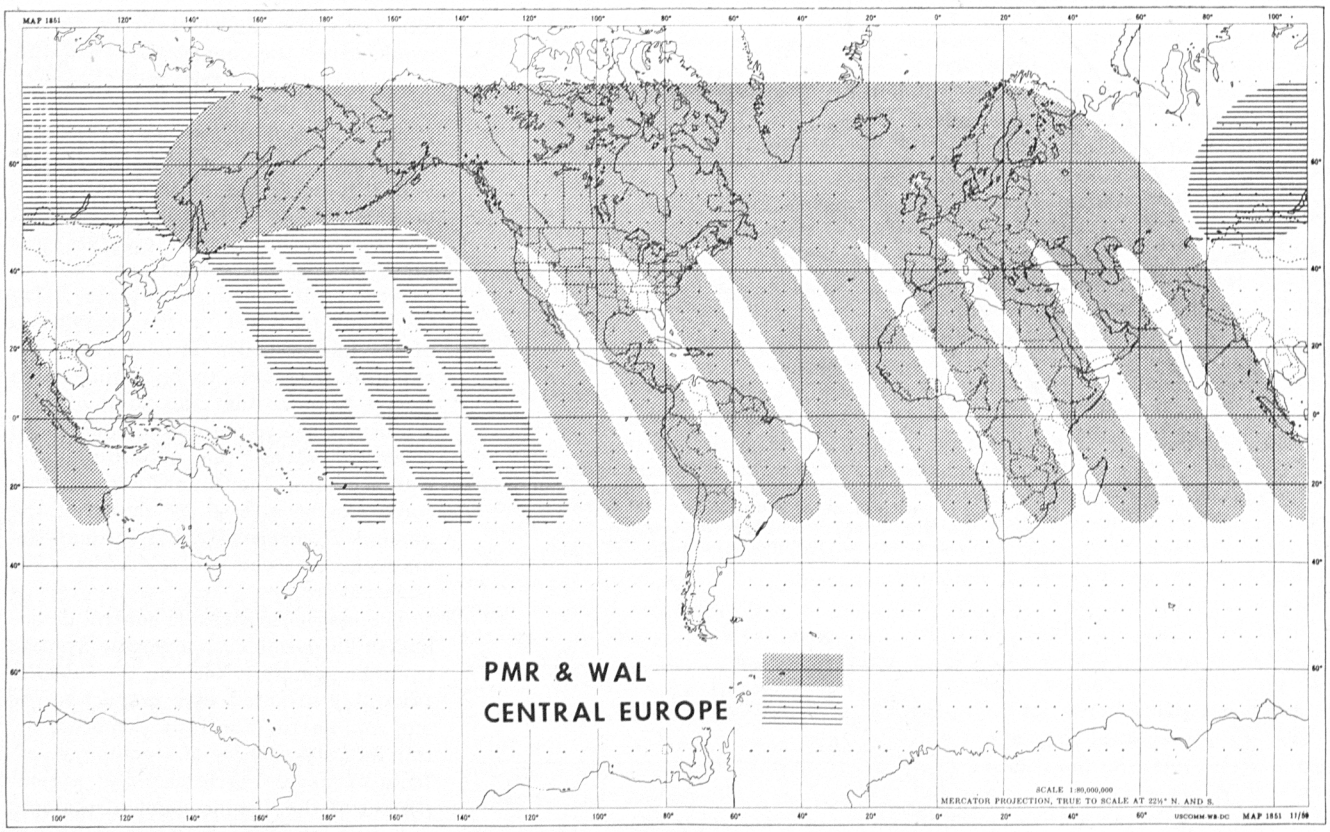
The magnetic attitude control device makes it possible to exercise control over the spin axis, keeping the satellite favorably oriented with respect to the sun and earth. The illustration at the top left shows how the combined effects of nodal regression and a component of the displacement of the spin axis keep the camera looking down at the daylight portion of the earth.

The illustration also points up the major operational weakness of the Tiros experiment. Favorable illumination for picture taking is maintained only by sacrificing the choice of latitude of the area covered.

The progressive change of the latitudinal belt that can be photographed by a single Tiros is shown at left. It can be seen that, for a considerable portion of the precession cycle, pictures in the northern hemisphere are not possible.

Certain operating constraints limit picture taking even further. To assure sufficient input to the solar cells and the maintenance of proper temperatures, the spin axis (parallel and opposite to the camera axis) should be at least 15 deg from the sun. To keep the sun from striking the camera lens or the horizon sensors, the spin axis should be no more than 65 deg from the sun. This means that the Tiros spin axis cannot always stay in the orbital plane, and in particular the cameras should look poleward, away from the sun, when the sun is most nearly at right angles to the orbit, that is, at the time of maximum poleward extension of the picture-taking area.

As a result, surface illumination can become insufficient for any useful picture taking for a period of about one week during the spin-axis cycle that occurs near the winter solstice. Since the total cycle takes about 80 days, this should happen to each satellite




**Tiros Coverage:** Single Tiros and three CDA stations give the photographic coverage described by the toned areas in the map above for the first day of orbital flight.

only once a year in each hemisphere.

The presentation in the illustration immediately suggests a solution to the latitudinal coverage deficiency of the Tiros experiment. A second Tiros, in similar orbit, but with the right ascension of its ascending node 180 deg from that of the first, would provide coverage to fill in the gaps. This arrangement of Tiros orbits, known as phase apposition, is the basic concept behind the TOSS proposal.

The illustration on page 39 shows how the coverage provided by the two satellites would combine to provide photographic coverage during daylight over most of the earth. The low-latitude gaps appearing in the coverage pattern can be minimized by judicious use of the magnetic attitude control device.

With this orbital configuration, TOSS would provide television data having operational value considerably *more than twice* that of a single Tiros. Daily picture coverage is nearly doubled and, more important, *continuous northern hemisphere* picture coverage is possible. In order to achieve the desired 180-deg phase apposition, the launch of the second satellite must be timed so that the right ascension of its descending node coincides with the right ascension of the ascending node of the first satellite. With the orbital parameters previously described, the precession cycle is 80 days. Therefore, a launch separation of 40 days satisfies the desired apposition.

The success of TOSS is dependent upon maintenance of adequate separation of ascending nodes. Indeed, if the orbital planes of the two satellites drift into near coincidence, the operational value of the system is reduced to that of a single satellite. The possibility of such an event can be investigated by referring to an approximate equation for the displacement of the nodes of a near-earth satellite:

$$\dot{\Omega} = 86400\ (6\mu)\ (a/r)^2\ (GM/r^3)^{1/2} \cos i,$$

where $\dot{\Omega}$ = change in right ascension in degrees per day; $\mu$ = quadrupole strength of the earth's gravitational field, $0.273 \times 10^{-3}$; $a$ = radius of the earth, 6378.388 km; $r$ = orbital radius; $G$ = gravitational constant, and $M$ = mass of earth, i.e., $GM$ is $3.986329 \times 10^5$ km$^3$ sec$^{-2}$, and $i$ = orbital inclination.

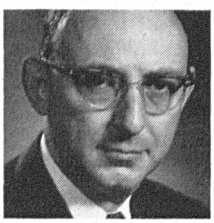
Thus we have $\dot{\Omega} = -20.8158 \times 10^{18}\ r^{-7/2} \cos i$ as the displacement of the nodes in degrees per day (positive eastward), with $r$ expressed in kilometers.

Logarithmic differentiation yields:

$$\Delta\dot{\Omega} = -\dot{\Omega}\ (\Delta i \tan i + 7/2[\Delta r/r])$$

with $\Delta i$ in radians.[1]

Using this equation, the deviation of the ascending nodes from the desired 180-deg apposition caused by



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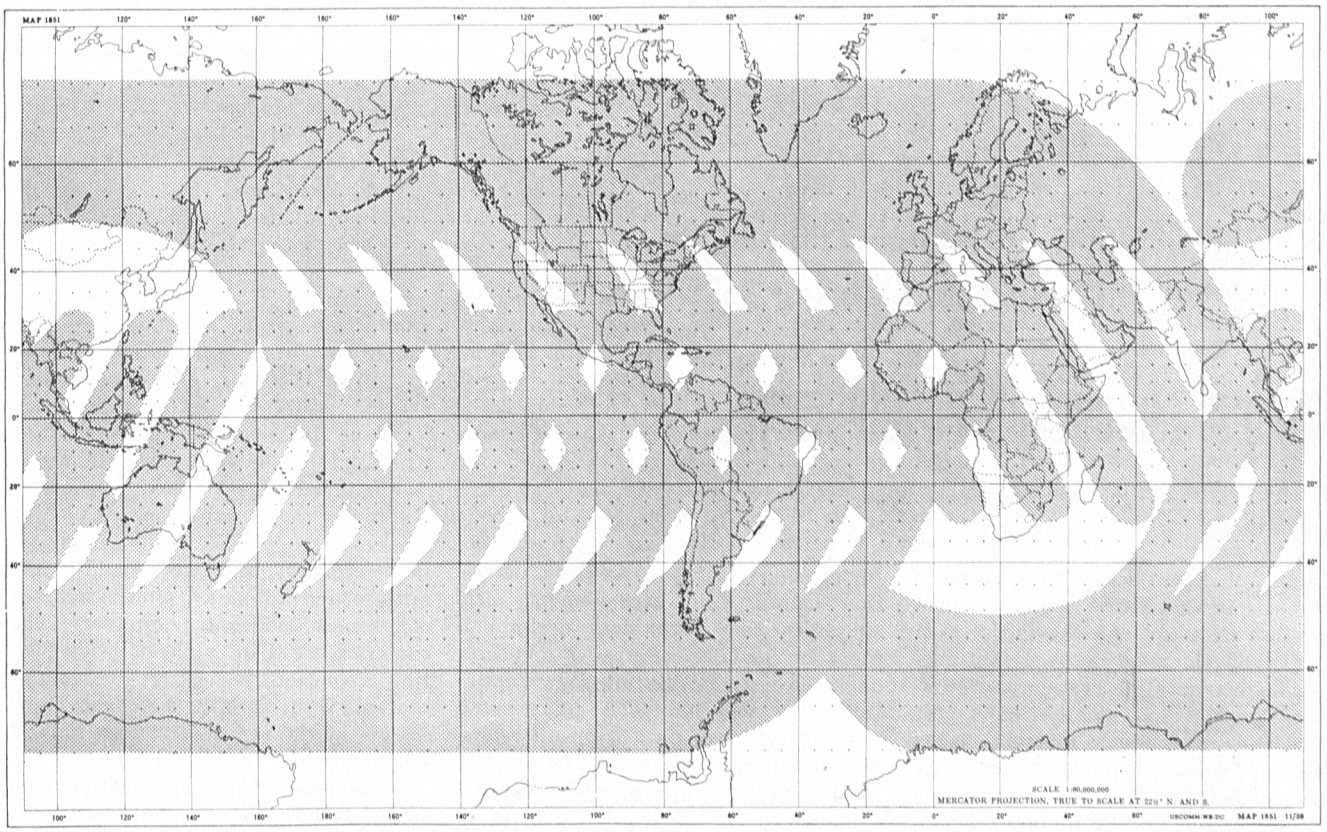
**F. E. CHRISTENSEN** is a meteorologist in the National Weather Satellite Center, having begun his USWB career following USAF service in World War II. He has filled Bureau posts in several areas and prior to joining the Center was Chief Flight Meteorologist for the facility responsible for instrument calibration and data quality.




**Toss Coverage:** Two Tiros in the Toss configuration give the coverage described by the toned areas in this map. Map depicts one satellite 40 days after launch and a second on the day of orbital flight.

individual errors in height and inclination can be calculated. Characteristic extreme differences between two Tiros satellites in height and orbital inclination may be $\Delta r = 40$ km and $\Delta i = 0.5$ deg; the respective contributions to $\Delta\dot{\Omega}$ are 12.8 deg per six months and 9.1 deg per six months. Assuming these maximum individual contributions are in the same sense, the orbital planes would have shifted from apposition by some 20 deg in six months, the expected lifetime of the later Tiros satellites. Examination of the illustration on page 39 shows that such a shift will have only a slight effect on the coverage available at any time from both satellites.

In addition to the latitudinal restraint on geographical location of pictures, a longitudinal restraint is imposed by the requirement that each orbit to be interrogated pass within acquisition range of the command and data acquisition (CDA) stations. Present Tiros CDA stations are located at Wallops Island, Va., (WAL) and Point Mugu, Calif. (PMR). These are very nearly optimum locations for two stations located in the continental U.S., but they are able to interrogate only nine of the 14.4 passes of each Tiros per day. This results in a data gap in the Pacific Ocean when pictures are being taken on the southbound portion of the orbit, and a gap in the Atlantic Ocean for the northbound leg.

The addition of a single CDA station removed 180 deg of longitude from the central U.S. would permit interrogation of every orbital pass during the day. A glance at a map indicates that logistic, communication, and political considerations might preclude the use of such a location.

A CDA station in western Europe would permit three daily interrogations in addition to those acquired by the U.S. stations. The contribution of a European CDA station to the daily photographic coverage of the earth possible with a single Tiros at a particular time in the precession cycle, as well as with a TOSS Configuration, using a third CDA station, are shown on this spread. The illustrations amply demonstrate the operational advantage of a third station. An additional CDA station in Japan would remove the gap completely and provide valuable backup to the other stations.

The Nimbus CDA station now under construction at Gilmore Creek near Fairbanks, Alaska, will have the capability of interrogating Tiros. Under a single Tiros operation, this station will be able to acquire approximately four passes daily, one of which could not be acquired by the other U.S. stations. In addition to its potential for support of a TOSS program, the ability to interrogate Tiros will provide a valuable opportunity to simulate the Nimbus Operational System.

A full TOSS operation, complete with adequate ground data-processing and communications facilities, as well as a reserve supply of satellites and boosters to assure continuity, would satisfy many present requirements for satellite meteorological observations. Setting up such a system would be a giant step toward the formation of a fully operational NOMSS, which must await the development of an operationally dependable Nimbus satellite.

TOSS, as an interim system, is based on existing proved components and techniques and can supply vital weather data requirements of the U.S. and foreign meteorological services.

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## Although lagging the initial schedule, it now sees first spacecraft being assembled

# Nimbus spacecraft development

BY HARRY PRESS and JACKSON V. MICHAELS, NASA Goddard Space Flight Center

The Nimbus project is the follow-on to Tiros in the NASA meteorological satellite program. As the initial step in the development of a global meteorological satellite system, the Nimbus concept specifically calls for worldwide coverage on a regular basis and an increased payload capability to provide a platform for an increased number of sensors. Preliminary design of the Nimbus spacecraft was completed in 1960.[1,2]

More than two years have now elapsed, and it will be appropriate to describe the approach used in the system, to present a brief history of the development, and to assess achievements to date in the light of the original design objectives.

Nimbus' basic objective has been to develop a meteorological satellite system that will provide basic data on worldwide atmospheric processes for real-time use in weather forecasting and for research studies. To accomplish this objective, the Nimbus system was conceived as an earth-stabilized satellite in a near-polar orbit, as shown on page 44, capable of full global observation on a daily basis, with the earth's rotational movement providing longitudinal coverage and the orbital motion of the spacecraft providing latitudinal coverage. The initial choice of an 80-deg retrograde 600-n. mi. orbit, with a local-noon equatorial crossing, ideally suits these requirements, permitting optimum picture-exposure times and keeping the orbital plane in the earth–sun line for prolonged periods. As the illustration shows, this arrangement also simplifies the mechanical design of the solar paddles, because it requires only one axis of rotation for orientation with the sun. The polar orbit allows readout of data from all orbits by two ground stations, to be located in Fairbanks, Alaska, and Eastern Canada.

An additional objective, fundamental in the approach to the Nimbus system, was a spacecraft design of inherent flexibility that would permit evolution of the individual subsystems and sensors with minimum interface and redesign problems. The Nimbus spacecraft, shown on page 43, includes a completely separable control system and a sensory ring incorporating a large number of standard-size bays to accept individual subsystem modules of fixed size and standard interface requirements. Contained within the sensory ring are the power-supply electronics and battery modules and the clock-command and pulse-code-modulated (PCM) telemetry subsystems. These three subsystems, together with the controls package and the solar paddles, compose the minimum Nimbus spacecraft ensemble.

Performance of the Nimbus spacecraft is monitored by a 672-channel telemetry subsystem having still further growth potential. The original spacecraft configuration contained fully redundant Advanced Vidicon Camera Subsystems (AVCS), consisting of six cameras, two four-track tape recorders, and two S-band transmitters and antennas, plus associated electronics and control circuitry. The cameras use 1-in. vidicons with 800-line resolution, providing picture resolutions of 1.5 mi. at the corners and 0.5 mi. at the zenith, at an altitude of 600 n. mi.

In addition, the configuration contained fully redundant Automatic Picture Transmission Subsystems (APTS), similar in performance to the AVCS, but designed for continuous real-time picture transmission, rather than for storage and data readout to a central data-acquisition station. Every 208 sec along the orbit path during daylight hours, APTS will provide pictures to relatively inexpensive ground stations equipped with facsimile recording devices, thus effectively bringing broad real-time cloud-cover data to almost every element of the worldwide meteorological community.

Remaining subsystems of the original configuration were a five-channel Medium-Resolution Infrared Radiometer (MRIR), similar to that flown in the Tiros spacecraft, and a High-Resolution Infrared Radiometer (HRIR), designed to be the night-time cloud-cover complement of AVCS and responsive to the 3.4- to 4.2-micron region of the infrared spectrum. Included, too, was a Low-Resolution Infrared Radiometer (LRIR), designed to examine the earth's heat budget. Inability to achieve required performance goals caused the elimination of

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**JACKSON V. MICHAELS**
Numbus Spacecraft Systems Manager at Goddard, previously headed the Technical Staff of the Army Signal R&D Labs' Astro Electronics Div., engaged in technical planning for Courier, Score, Tiros, and Advent. He has taught courses in space technology, and is co-author of the book "Introduction to Space Communication Systems," to be published by McGraw-Hill.

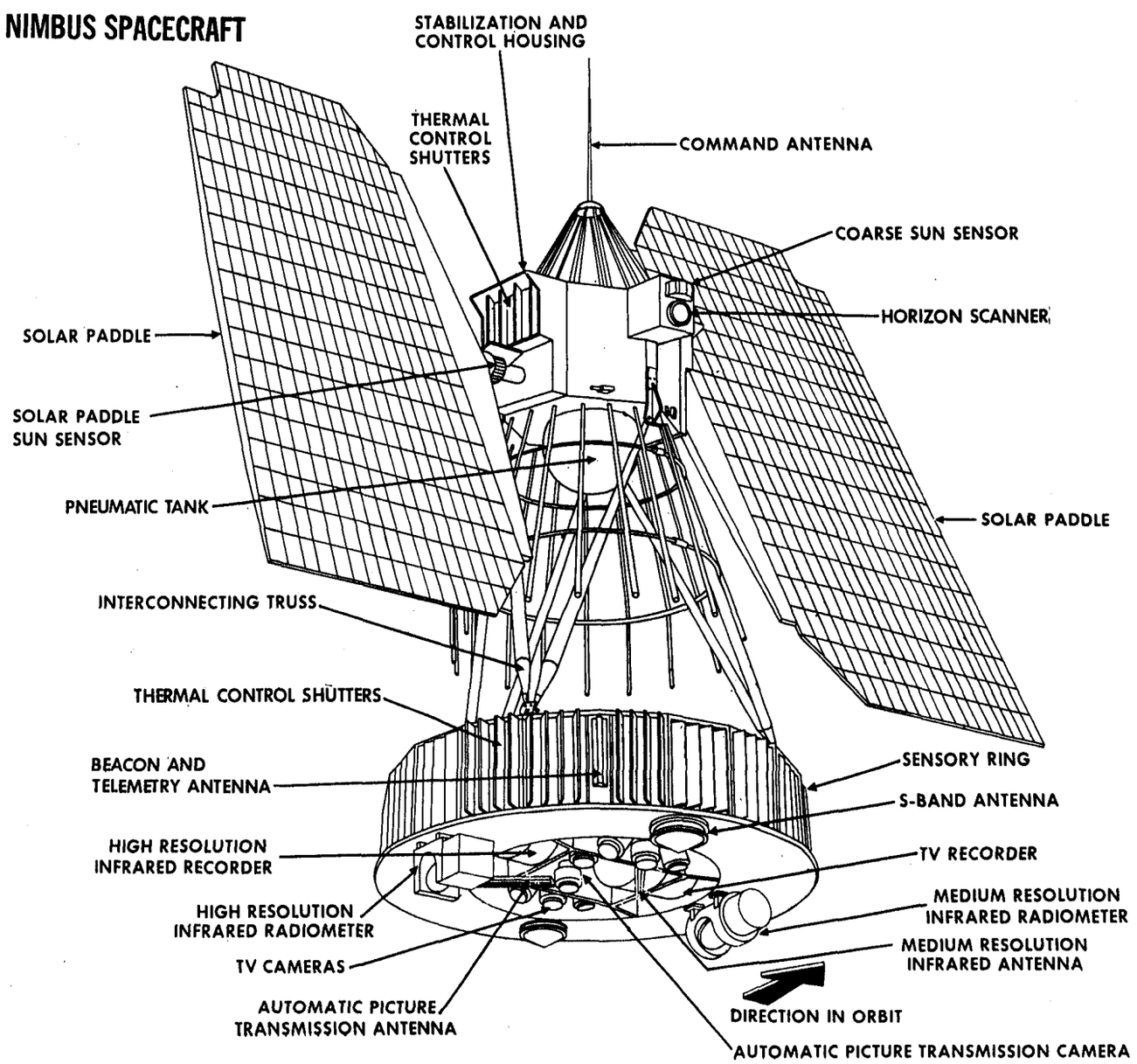
the LRIR subsystem early in the program.

The equally basic design objective of long life (six months in orbit) dictated the use of conservative design practices, extensive subsystem redundancy, and intensive subsystem and spacecraft qualification. A high margin of safety is generally secured during prototype development by qualification under conditions more severe than the actual launch and space environments. Flight hardware is qualified under the nearest possible simulation of the anticipated flight levels. Before subsystem integration, all thermal and mechanical system conclusions are validated by checking and testing full-scale thermal and mechanical models to prototype qualification levels.

With the completion of the initial design in 1960, there was defined a basic management approach to the system development, consisting of the government (specifically, NASA's Goddard Space Flight Center) assuming the role of prime contractor and system manager, with the responsibility for selecting industrial contractors to develop and fabricate the subsystems, and for providing technical and managerial direction of the subsystem development efforts. A project manager and four system managers (for the spacecraft, launch vehicle, data-acquisition, and data-utilization systems) were appointed to head the over-all project effort.

The modular aspect of the Nimbus concept allowed development of the subsystems to proceed concurrently with preparatory spacecraft development. Substantial advanced mechanical and thermal analyses, and corroboration of these analyses by full-scale model testing, were conducted with good results. However, the price paid for this flexibility has been the need for close supervision of subsystem development and tight control of interfaces.

In late 1960 and early 1961, individual contracts were let for parallel development of each of the subsystems, calling for detailed design, breadboard development, and prototype and flight-hardware construction. The contracts also covered extensive subsystem environmental qualification testing in regard to humidity, acceleration, vibration, and vacuum-thermal conditions.



In addition to development of the individual subsystems, a contract was let for integration and testing of the complete spacecraft. This contract covered construction of the basic spacecraft housing structure, integration of the various subsystems into a full prototype and into flight spacecraft, over-all spacecraft system performance testing, and, finally, a vigorous spacecraft environmental-qualification testing program. Noteworthy is the development of a system which simulates, within the confines of a vacuum chamber, the operation of the spacecraft in orbit (see page 46). During vacuum-thermal qualification, the full Nimbus spacecraft floats on a film of air, tracking an artificial horizon with communication only by radio to the checkout equipment outside the chamber.

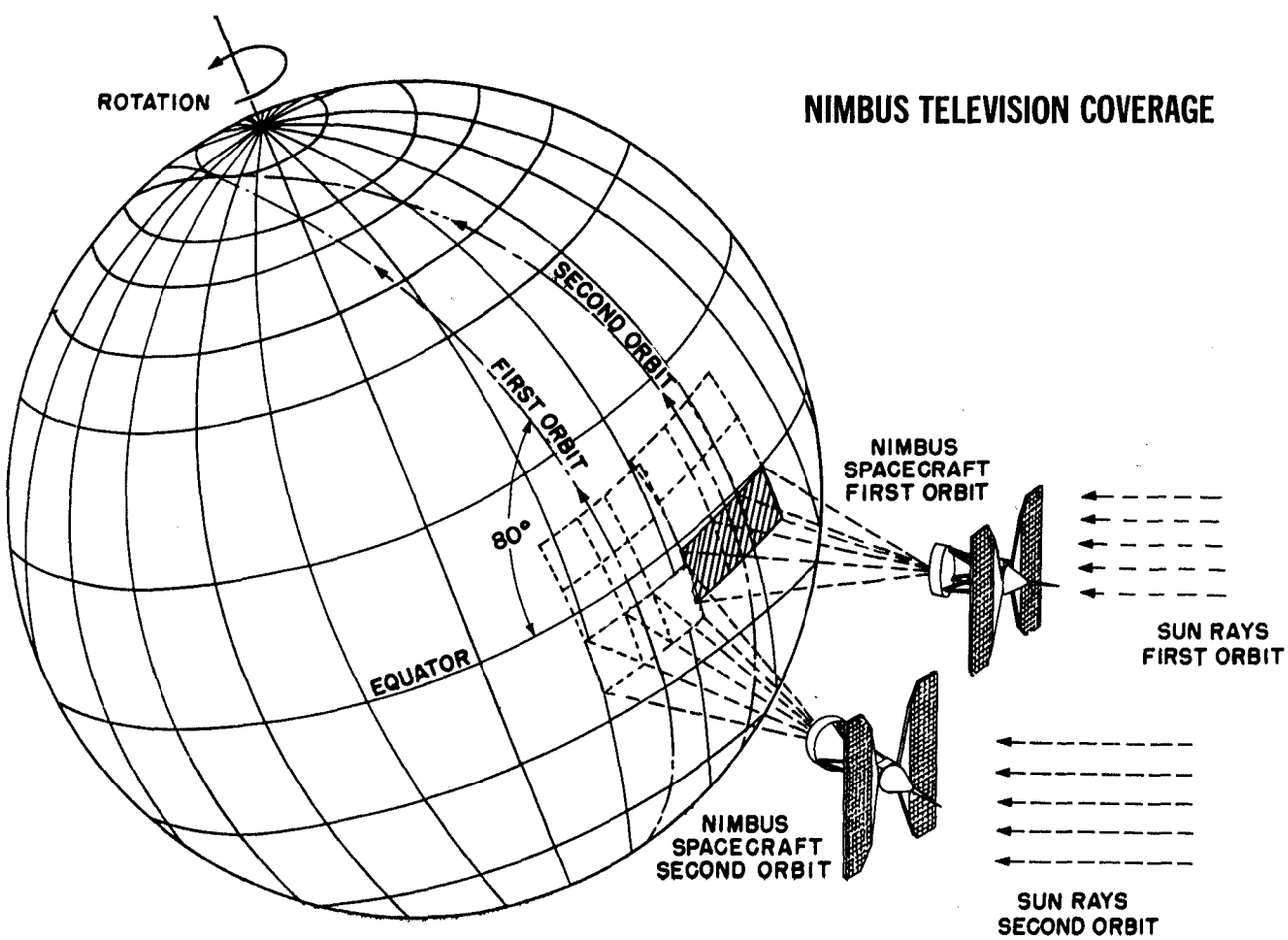
Initial plans called for the sequential development and construction of the initial flight spacecraft at six-month intervals, in what was envisioned as an orderly research and development activity. It was thought that the first spacecraft development cycle would require about 1 1/2 years, one year being allotted to subsystem development and 6–9 months to spacecraft integration and qualification. This time schedule turned out to be overly optimistic.

The progress of Nimbus was accelerated rapidly when, in May 1961, the President presented a special message to Congress requesting an accelerated Nimbus program "to give us at the earliest possible time a satellite system for worldwide weather observation." Later that year, the Congress appropriated additional funds to the Weather Bureau to implement this objective. This new requirement essentially resulted in revisions and accelerations of the program aimed at an earlier worldwide operational capability. Additional spacecraft funds were included, as well as funds for additional ground stations, in order to assure a worldwide weather-observation capability. NASA, working in conjunction with the Weather Bureau, moved rapidly to supplement the existing R&D program to meet this objective.

Nimbus spacecraft development has encountered significant delays due to technical difficulties in the development of a number of major subsystems. Although these delays have been time-consuming and expensive, the problems were not insurmountable. The table on page 45 compares major system performance achievements with the initial design objectives. In most cases design objectives have been attained. The achievement of an AVCS with the desired resolution and high linearity (1/2%), using a wide-band frequency-multiplexed system, is a significant accomplishment in storage systems. The development of APTS is also considered a major advance in real-time meteorological systems. In two cases—stabilization accuracy and the HRIR resolution—some compromise of design values was found necessary, but this should not seriously affect early flight missions, and the design values will be subject to later improvement.

All major subsystems have been built and fully qualified in prototype hardware, with two exceptions. Flight hardware also nears completion. The two exceptions are the stabilization and control subsystem and the solar paddles. Each of these has posed serious development problems.

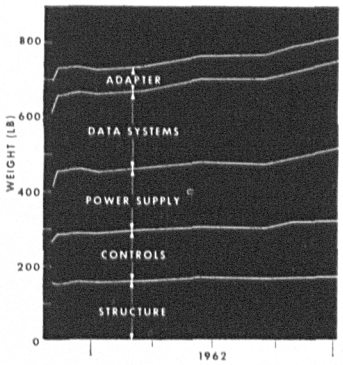
In the control subsystem, a major redesign of the infrared horizon-scanning system used for attitude sensing was required to achieve reliable attitude data. The redesigned system has been built and has performed satisfactorily in tests, although sensor ac-



**PRESENT NIMBUS PERFORMANCE**

| | DESIGN OBJECTIVE | ACHIEVEMENT |
|---|---|---|
| WEIGHT | 650 LB | 750 LB |
| STAB. ACCURACY | ± 1% | ± 2% |
| POWER (MAX) | 450 WATTS | 400 WATTS |
| AVCS (RES) | ½ MILE | ½ MILE |
| PCM TELEMETRY | 672 CHANNELS | 672 CHANNELS |
| HRIR (RES) | 2 MILES | 5 MILES |
| MRIR (RES) | 30 MILES | 30 MILES |
| COMMANDS | 128 | 128 |
| APTS (RES) | 1½ MILE | 1½ MILE |

**NIMBUS 'A" WEIGHT HISTORY**




**NIMBUS AND TIROS COMPARED**

| | TIROS | NIMBUS |
|---|---|---|
| GEOMETRY | PILLBOX | DUMBBELL |
| WEIGHT (lb) | 300 | 650 |
| ORBITAL ALTITUDE (nautical miles) | 380 | 600 |
| ORBITAL INCLINATION | 48° EQUATORIAL | 80° POLAR, RETROGRADE |
| STABILIZATION | SPIN-STABILIZED | 3-AXES EARTH ORIENTED |
| EARTH COVERAGE | 10 TO 25% | 100% |
| CAMERA RESOLUTION | 500 LINES/FRAME | 800 LINES/FRAME |
| TV RESOLUTION (miles) | 1 | 1/2 |
| MAXIMUM POWER AVAILABLE (watts) | 20 | 400 |
| IR SENSORS (resolution, miles) | MRIR (30) | MRIR (30)<br>HRIR (5) |

curacy does not yet provide the full pointing accuracy desired.

Development and construction of the solar paddles was also seriously delayed by a decision in late 1962 to change from the initial p-on-n solar cells to more-radiation-resistant n-on-p cells. This decision arose from the unexpected creation of an artificial radiation belt at Nimbus flight altitude by a high-altitude nuclear-explosion test in mid-1962. New and satisfactory cells are now being procured and integrated into Nimbus.

As mentioned previously, a major weight problem was encountered in spacecraft development. The design objective was a weight of 650 lb for the spacecraft, to permit compatibility with the medium-sized Thor-Agena booster. Although every effort was made to meet this objective, it was readily apparent by mid-1961 that the full Nimbus spacecraft with the planned redundancy would exceed design weight by a substantial amount, and would exceed the launch vehicle capability. It was accordingly concluded that the early development flights would not include the desired redundancies.

A modified Nimbus configuration was defined in late 1961 and programmed for the early flights. Subsequent subsystem development gave rise to additional weight increases, so that the basic spacecraft now weighs about 750 lb, but can still be launched by the Thor-Agena to an altitude of 500 n. mi.

In the present configuration, the spacecraft contains one three-camera AVCS, one single-camera APTS, and the HRIR, in addition to the minimum spacecraft elements described previously. Although the original payload goals appear optimistic in light of subsequent developments, the weight history at the top indicates that the sensory subsystems account for about 20% of the total weight, constituting a reasonable payload efficiency. Structure, which includes wiring harnesses, thermal controls, and antennas, is less than 25% of the payload. Later flights, which plan to incorporate full redundancy, will require a launch vehicle of increased capability.

In parallel with the spacecraft development, the Nimbus project is also developing a Command and Data Acquisition (CDA) system to provide near real-time readout of data from all orbits. As indicated earlier, full orbital coverage can be achieved with two high latitude stations, one at Fairbanks and the other in Eastern Canada. The construction of the Fairbanks station is well underway and the station should be operational by early fall in ample time for the initial flight. The station will include an 85-ft tracking antenna with auto-track capability as well as an extensive data processing system for data evaluation and data transmission over wide band microwave links to the GSFC and to the Weather Bureau. The sensory data will thus be available for direct application to weather forecasts. The construction of the second CDA station in Eastern Canada has been delayed. Meanwhile, NASA plans to use the antenna system at Rosman, N.C., as a second and backup station for the initial flight.

In summary, the development of the Nimbus spacecraft has proceeded at a slower pace than initially planned, but the technical problems are now almost completely solved and the first flight spacecraft assembly is underway. A great deal has been learned about the technical problems implicit in a meteorological satellite with the capability of Nimbus, and the problems inherent in the management approach taken. Initial flights should prove the validity of Nimbus design concepts and our ability to realize them in flight systems. This flight experience, moreover, should provide the decisive tests on which to base the growth of a national meteorological satellite system.

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# Nimbus testing

BY HERBERT I. BUTLER
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GSFC Aeronomy and Meteorology Div.

The Nimbus test program will determine the ability of the spacecraft design to meet all performance requirements and demonstrate the dependability of the flight hardware. Flight equipment will be identical in every respect to prototype. The program consists of two levels of environmental tests:

*Prototype Tests*—To demonstrate a conservative margin of safety in the complete spacecraft and its subsystems. All tests and test levels are more severe than those anticipated in flight.

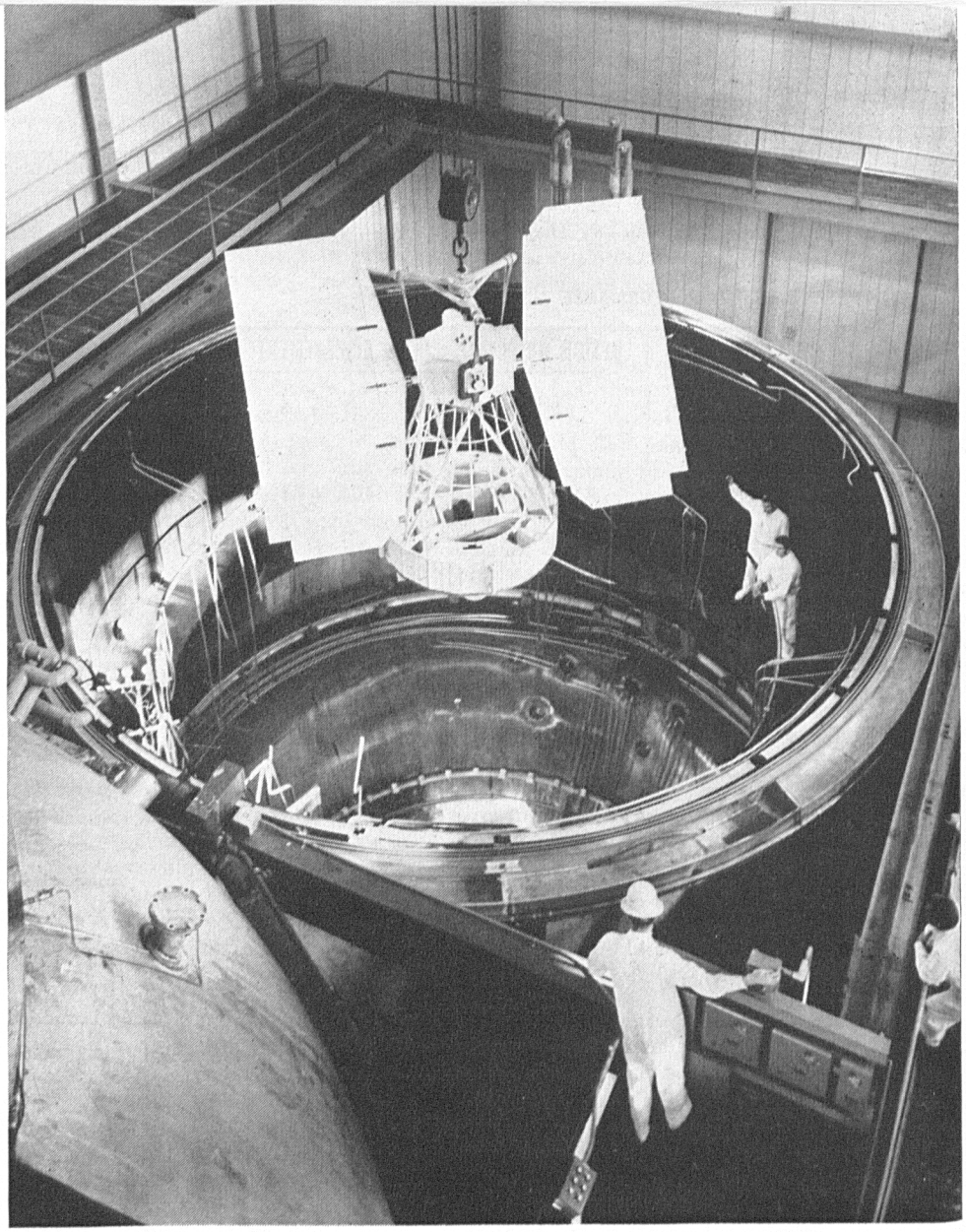
*Flight Acceptance Tests*—Designed to demonstrate the successful reproduction of prototype-proven concepts. Test levels are the best possible simulations of those anticipated in flight.

Testing follows this order:

1. Humidity. While nonoperative, the major spacecraft subsystems will be subjected to a test-chamber temperature of 40 C with a relative humidity of 95% for 50 hr. This is an *earth*, not a space requirement. The humidity in Pennsylvania, where the spacecraft is assembled, and in California, where it will be launched, often exceeds 95%.
2. Vibration. The spacecraft will be attached to an adapter to simulate its actual mounting on the Agena B launch vehicle, and vibrated in each of three orthogonal directions.
3. Acceleration. The spacecraft, in an operational condition normal for powered flight, will be attached to a mounting adapter, as in the vibration test, and accelerated in three orthogonal directions.
4. Vacuum Thermal. Attached to a mounting adapter, the spacecraft will be lowered into the chamber and placed under vacuum, while in the operational mode, for an extended period of time. Failure of any subsystem or assembly will require withdrawal of the spacecraft, replacement of the unit, and reinsertion of the spacecraft into the chamber for the full period.

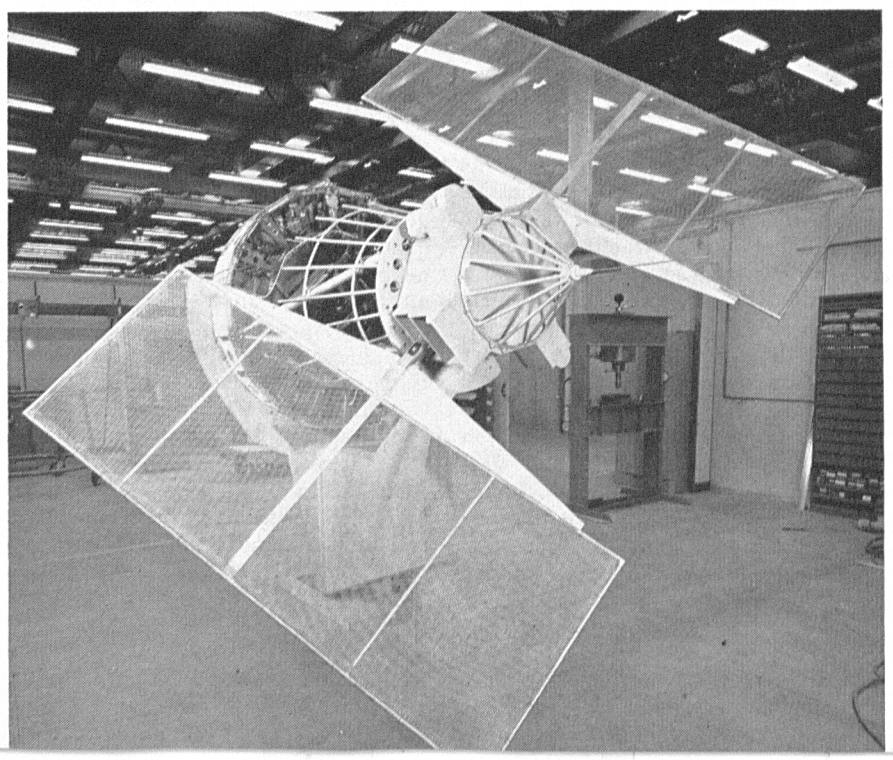
The prototype receives all four tests. Flight hardware receives only vibration and vacuum-thermal tests.

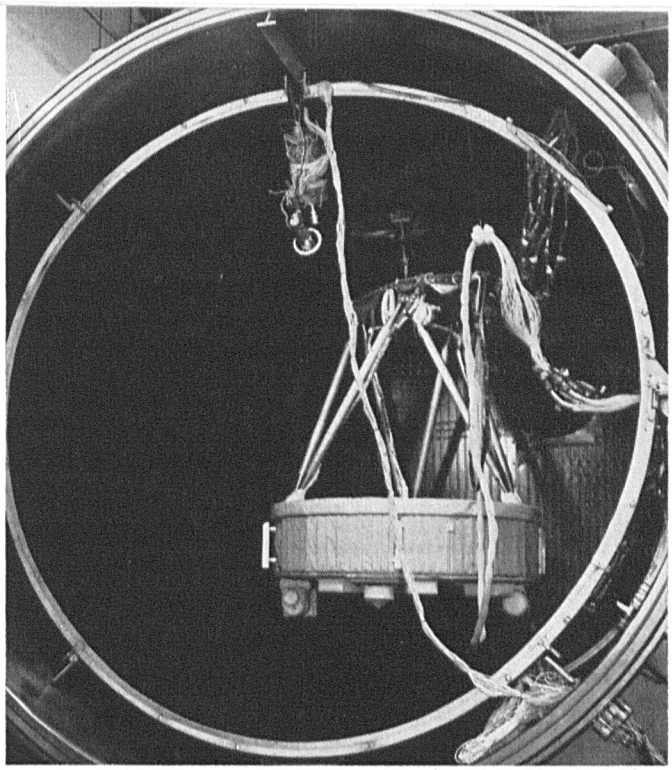
The test program is currently in the prototype phase. Structural design has been proven by extensive test of a full-scale vibration model. The stabilization and controls system has been successfully "flown" for many hours on an air bearing using a variety of model earth conditions. Most of the sensory-ring subsystems have been fully qualified in independent performance and environmental tests prior to integration in the ring, and complete systems tests have been conducted using pre-prototype engineering models. In the next few months, environmental tests will be conducted on the prototype sensory-ring assembly, the stabilization and controls system, and then the completely assembled prototype.



**Vacuum Thermal Chamber** 39 ft in diam can house a fully assembled Nimbus and orbital-motion simulation system. Orbital operation of the complete system will be simulated for a prolonged test period.

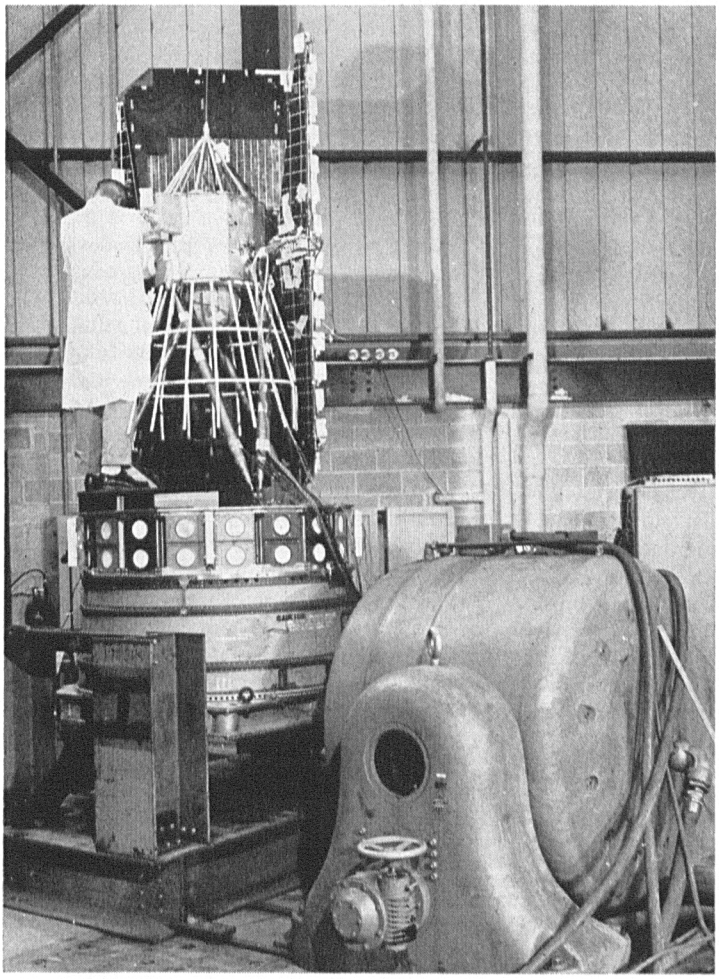
**Nimbus Antenna Test Model** used in the design phase to measure the antenna performance and pattern generation. The mesh paddles appear as a solid ground plane at the RF frequencies used by the spacecraft.



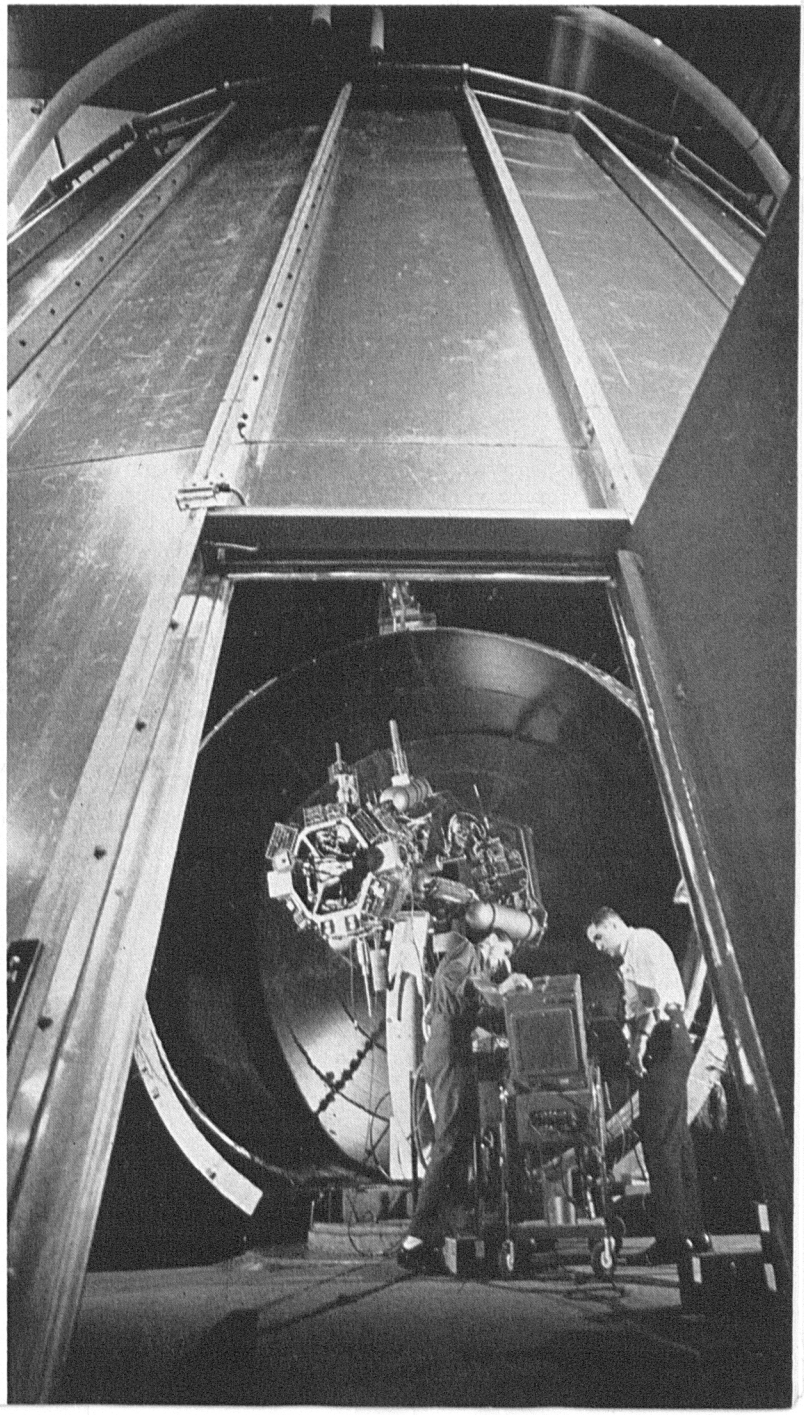


**Nimbus Thermal Design Model** being installed in the 10- by 24-ft vacuum thermal chamber. Attached to a mounting adapter, the spacecraft will be lowered into the chamber and placed under vacuum, while in the operational mode, for an extended period of time. Failure of any subsystem or assembly requires withdrawal of the spacecraft, replacement of the unit, and reinsertion of spacecraft into chamber for full period.

*Photos Courtesy of GE Missile and Space Div.*



**Vibration Model of Nimbus Structure** being installed on shaker. Tests have been completed to verify the basic design, before qualification testing of prototype and flight hardware.



**Pre-prototype Control System** mounted on an air bearing for performance evaluation. Cold water, flowing over the outside of the aluminum tepee, provides a uniform sky to simulate the space signal for the horizon scanners.

New electronic and magnetic systems have been developed to handle huge quantities of data during each Nimbus orbit

# Data storage for meteorological satellites

BY M. I. SCHNEEBAUM and R. A. STAMPFL
NASA Goddard Space Flight Center

Huge quantities of data will be stored and readout from advanced weather satellites, such as Nimbus. Data storage thus becomes a critical feature of design. This paper discusses some of the advanced research being conducted by the Goddard Space Flight Center (GSFC) in the field of electronic and magnetic data storage of video information in meteorological satellites.

Electrostatic storage is the basis for two unique TV systems being developed by RCA for GSFC. Two basic processes characterize these systems:

1. An optical image is converted to an electrical charge pattern that can be stored for relatively long periods of time (writing process).

2. The transformation at will of this charge pattern into a video signal (reading process).

The storage vidicon is the heart of the Automatic Picture Transmission System (APTS) which will be flown on Nimbus. This system provides wide-angle cloud-cover pictures from a satellite and transmits them in real time on a narrow-band channel to a local ground station for recording on facsimile equipment.

The storage vidicon resembles a conventional vidicon except for the addition of a thin, high-resistance polystyrene storage layer on the photoconductive surface. A cutaway view of the front end of the vidicon is shown on page 49. The tube is operated by holding the target potential constant and raising or lowering the mesh potential with respect to the target during the prepare, expose and readout sequences. The vidicon photoconductor is optically exposed by means of a mechanical shutter, and is then electronically "developed," that is, the charge image is transferred from the photoconductor layer to the polystyrene storage layer. The readout cycle follows for 200 sec, during which picture information is readout at the rate of 4 lines per sec.

Experimental evidence indicates that the polystyrene surface suffers radiation damage under prolonged electron bombardment, resulting in reduced lateral resistance and loss of storage capability. Research is being conducted to improve radiation resistance of the polystyrene by increasing the purity of the materials. The addition of a flood gun is being investigated to reduce the electron bombardment. In addition, other materials are being investigated.

On readout, the video signal amplitude modulates a 2400 cps subcarrier which in turn frequency modulates a 5-w transmitter as indicated in the block diagram on page 49. The requirement for the system to pass very low-frequency video signals was a difficult problem, solved by pulsing the cathode with a 4800 cps subcarrier. This subcarrier signal causes the readout electron beam to be chopped at the 4800 cps rate. The charge pattern on the polystyrene storage layer amplitude modulates the subcarrier. The video modulated subcarrier is A.C. coupled to a bandpass amplifier and detector.

Video data is continuously transmitted during the daytime portion of the satellite orbit. The system has a linearity of 0.5% and a limiting resolution of 700 TV lines. System linearity was achieved through special yokes, vidicons, and digital sweep circuits. Highlight sensitivity is 0.7 foot-candle sec. Signal-to-noise ratio is 26 db, giving approximately 7 grey scales. A grey-scale calibration wedge, consisting of 11 known levels, is located at the top of each picture, parallel with the horizontal scan. A flash tube illuminates the wedge each time the shutter is activated, giving a calibrated scale on each picture. The angular coverage is 108 deg, which, for a 500-n. mi. altitude satellite, yields approximately 1150 by 1150 n. mi. ground coverage per picture.

The storage vidicon thus permits slow scan readout, and a narrow bandwidth permits use of simple ground-station equipment. The APTS ground station can be assembled from inexpensive, off-the-shelf commercial components. The ground station consists of a helix antenna and a preamplifier mounted on a pedestal, a narrow-band FM receiver, and a commercial facsimile recorder modified for automatic start and stop, employing the airborne subsystem control signals, and thus permitting any local weather station to obtain direct cloud-cover pictures

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heads the Systems Engineering Branch of Goddard's Aeronomy and Meteorology Div., responsible for development of the major subsystems for Nimbus.
He previously headed the Physics Branch of NWP's Engineering Dept., where for 13 years he was engaged in development of aircraft fire control, machine guns, Terrier GSE, and nonmagnetic tools.

**R. A. STAMPFL**
designed and specified the Nimbus spacecraft and its electronic systems, and was previously Project Manager for Tiros II.
A native of Austria, he received his academic training there, earning a Ph.D. in communications from the Vienna Institute of Technology in 1953. He began professional work here with the Army Signal R&D Lab.

of the immediate area whenever the satellite is in view.

With an investment for a ground station of approximately $30,000, meteorological groups throughout the world will receive local real-time cloud pictures at least once a day for immediate use.

A second television system under development for Nimbus which utilizes the electrostatic storage is the Dielectric Tape Camera. The storage medium is a thin flexible tape coated with suitable materials which permits storage of an electric-charge pattern on an outer insulating layer.

The writing process consists of exposure of the tape to an optical image through a lens system in a manner similar to photography. However, in this process, the tape is also exposed to a uniform electron beam that deposits an electric charge on each elemental area of the tape in proportion to the amount of light falling on that area. Optical and electrical exposures both occur from the insulating or dielectric side of the tape.

To convert this charge image to a video signal, the portion of tape on which the image is stored is moved to a location where it can be scanned by the electron beam that performs the readout process. In this process, the polystyrene surface is scanned by the read beam in much the same manner as an image orthicon target is scanned by the electron beam. The result is that in the scanning process, the return beam is modulated by the charge pattern on the insulation.

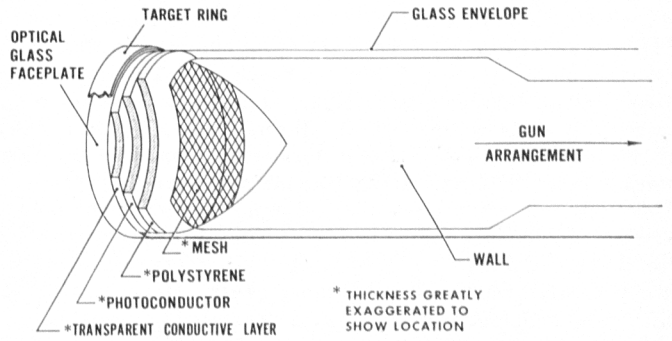
The tape itself is 35 mm wide and consists of three layers on a base material, as shown at the right. The base material is optical quality nylon called "Cronar." These optical properties were important in early development, when the tape was exposed optically through the base material. Research into the basic process indicates that it may be advantageous to make the base from an opaque material since optical exposure can be performed directly on the dielectric material, rather than through the base.

Three layers are superimposed on this base in sequence using vacuum deposition techniques. These layers are deposited on a continuous basis, with the tape moving at a constant rate of speed. Lengths as long as 50 ft have been processed on this laboratory tape machine.

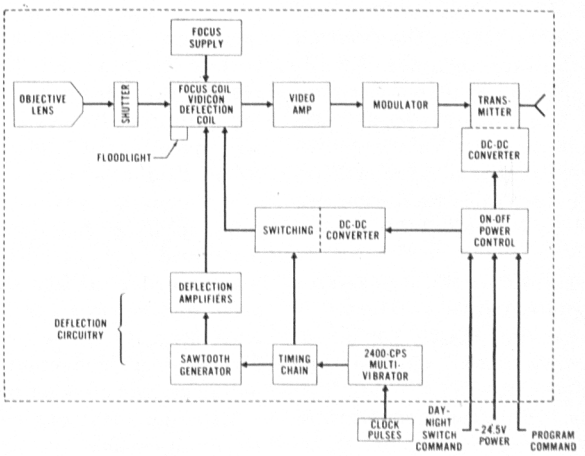
The first layer is a gold-and-copper combination approximately 0.01 microns thick which forms a transparent conducting coating that serves as the electrical connection to one side of the photoconductive layer.

The photoconductive layer is simi-

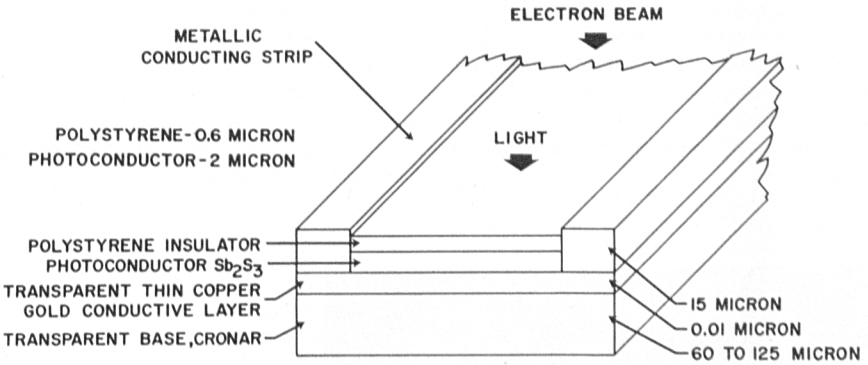
**POLYSTYRENE STORAGE VIDICON**



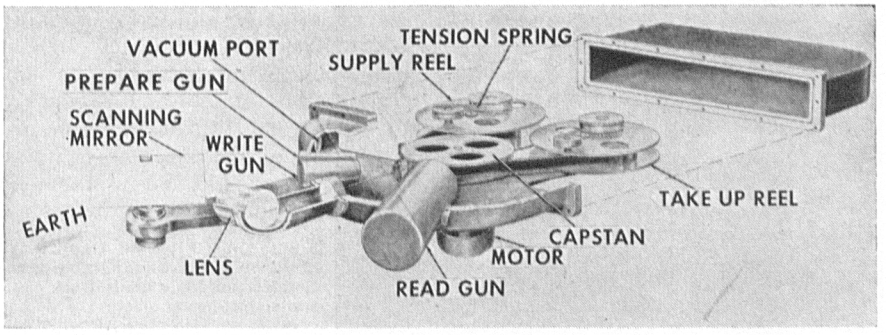

**APTS DIAGRAM FOR SATELLITE**




**DIELECTRIC-TAPE CONSTRUCTION**




**DIELECTRIC-TAPE CAMERA**



lar to the photosensitive layer of commercial vidicons, and the spectral response of the system is determined by this layer. The material used at present is arsenic trisulphide.

The final layer is an extremely thin uniform coating of polystyrene approximately 0.6 microns thick. This is the insulating layer that acts as a capacitor for holding the electric charges forming the charge pattern equivalent to the optical image.

A laboratory camera has been developed which has demonstrated the feasibility of utilizing the dielectric tape principles for observing the storing cloud-cover pictures from a satellite. The tape camera performs the combined function of observation and storage, replacing both the vidicon camera and the tape recorder. An advanced model is now under development which will closely approximate the flight configuration. This is shown on page 49. A number of problems remain to be solved, since the entire enclosure must be evacuated for proper operation.

The electrostatic camera possesses the following inherent capabilities:

1. Higher packing density per pound than the conventional camera/tape recorder configuration.
2. Limiting resolution comparable with the best image orthicons. 1200–1500 TV lines is currently achievable, with a target of 2500 TV lines in the foreseeable future.
3. Slit camera type operation, which permits wide angular coverage with low distortion.
4. Sensitivities comparable to currently available airborne vidicons, and low light sensitivities of the order of 0.01 ft-candle sec.
5. Variable resolution readout capability.

The present camera configuration can store on tape two complete orbits with horizon-to-horizon coverage with 0.2 mi. ground resolution.

The present Tiros and initial Nimbus spacecraft contain conventional vidicons with magnetic tape as the storage medium. The same is true of the infrared scanning system.

Simple calculations indicate that $10^7$ infrared information bits and $5 \times 10^8$ TV informations in 96 pictures must be stored per orbit. These data are presented in analog or binary coded form. Data storage without mechanical movement is, of course, attractive. However, development of large memories with size, weight, and power comparable to magnetic tape recorders does not appear feasible within the next few years. For this reason, the imrpovement of magnetic-tape storage devices is constantly being investigated in-house at Goddard Space Flight Center.

A medium capacity endless-loop tape recorder has been successfully developed for satellite applications. The recorder utilizes 120 ft of 1/4-in. tape, and records for 1 1/2 hr. Playback is at 30 times the record speed. The recorder consumes 2 w of power on record and 10 w on playback.

Recorder development has emphasized flexibility so as to serve as many applications as possible. Momentum compensation has also been of prime importance. Stabilized spacecraft are controlled by small torques so that even the small unbalanced momentum generated by the recorders become major disturbances. Long-life applications require a sealed pressurized container; the lower section of the container houses drive-amplifiers for 100-cps synchronous motors, a pressure transducer, and auxiliary electronics. Inherent ruggedness of these units makes direct mounting on the container feasible with standard encapsulation employed.

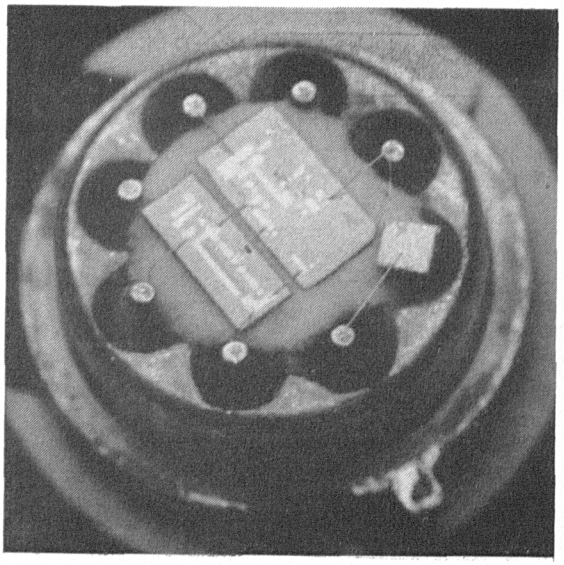
An analog version of the recorder has the endless-loop cartridge in the center of the container, partly covered by plugs, and the record and playback motors in the form of two cylinders to one side. A single capstan drives the tape across the head, held firm by a pressure pad. By single substitution, an eight-track digital head is mounted with the electronic record and playback amplifiers alongside.

Since the tape drive is a delicate mechanism, it must be mounted so as to survive the large range of vibration environments encountered in different structures. In general, resonance of these structures occurs at low frequencies, so the mount itself can be designed for resonance at higher frequencies. The tape drive is mounted between two plates tied to two shelves of the container by means of miniature dampers, and up to 20 $g$'s rms of random noise vibration can be applied, or an equivalent sinusoidal sweep, without failure.

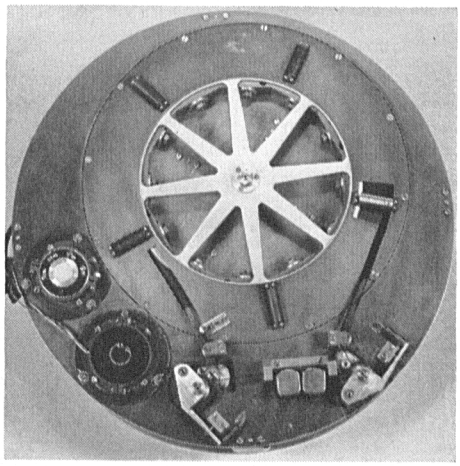
The record and playback amplifiers for analog units are inherently more reliable than the drive mechanism. Conventional analog amplifiers are being used. Digital amplifiers, however, lend themselves more readily to design by integrated circuits. The high reliability of these circuits when silicon planar transistors are used, and their small size, makes it practical to include an eight record/playback amplifer package in the recorder since it can be built with a volume equal to that of the recorder head. Such circuits can be operated at power levels of one microwatt per stage so that thermal dissipation of an assembly is negligible. Thus, these circuits run at low temperatures and are extremely reliable.

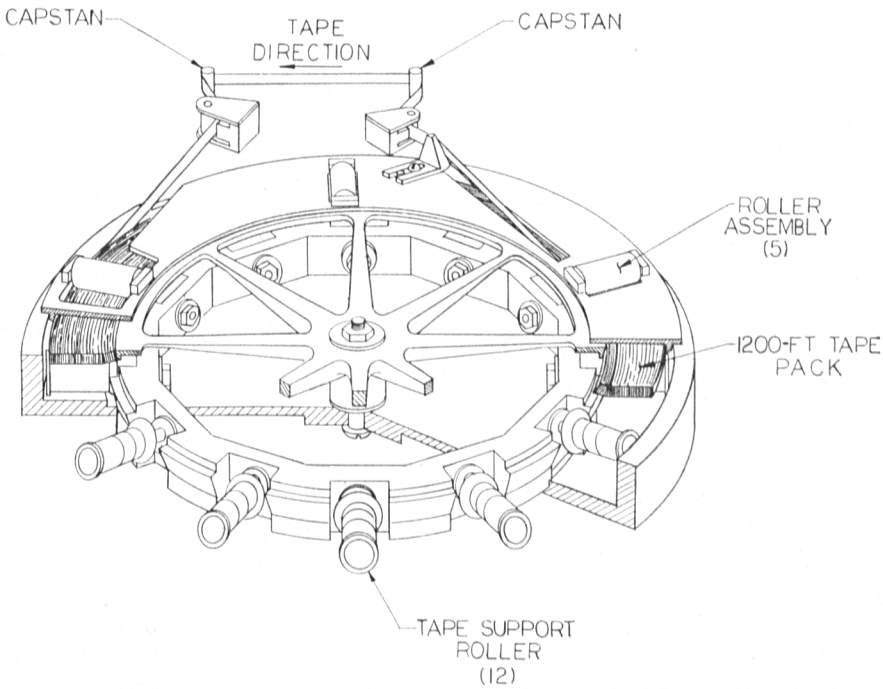
Each record amplifier consists of four transistors which can be mounted with its associated resistors in a standard transistor can. Conventional non-return-to-zero recording is used in which zeros and ones magnetize the tape in opposition. Separate erase is thus not needed. A microphotograph of the amplifier is shown at the left. The small square is a field-effect transistor preamplifier; the next larger square a silicon crystal with load and coupling resistors etched on the surface which serves as the next transistor stage. The longest crystal contains two direct coupled transistors and associated circuitry.

Similarly, playback amplifiers have been developed where the head output is amplified and the wave-shape re-



**Single Digital Record Amplifier** is shown in this microphotograph. Small square is a field-effect transistor; larger silicon crystals contain other circuitry.






**1200-ft-tape Endless-loop Recorder** now looks as shown in the photo at top, a laboratory model. The drawing below shows details of its endless-loop cartridge.

constructed by a multivibrator so that conventional or microminiature logic circuitry can process the pulse train. The power levels and small volume of these circuits permit selective redundance at small cost in terms of weight and volume.

Redundant logic circuitry can readily be designed to achieve long-life recorders. A contribution toward this end is the development of an analog-to-digital converter sufficiently small and of sufficiently low power that digital recorder techniques become comparable with analog.

Analog-to-digital converters can also be built according to any of the standard techniques using integrated circuits for the logic. The speed required for the conversion often determines the techniques used. A compromise between complexity and speed in an analog-to-digital converter leads to a design where the input signal is compared sequentially to a number of binarily related voltages, setting appropriate flip-flops. Readout can be serial or parallel as desired, since the flip-flops hold their positions until recycled. For most meteorological applications, seven bits or 128 levels is adequate. For infrared sensing, it is sufficient to operate this converter at a 40 microsec per bit rate, with total conversion requiring 280 microsec. Logic for such a converter has been microminiaturized and operates at less than 5 microwatts for this logic, with an additional 50 microwatts needed for the error amplifier and weighing network.

The requirement for large storage capacity led to the development of an endless-loop recorder having 1200 ft of 1/4-in. tape. Playback speed is 30 ips, and record speed is either 30 cps or 3 3/4 cps. The unit will record analog video whose subcarrier is frequency modulated. Initially, infrared scanner signals will be recorded. Later models will record TV frames when a fast start and stop is perfected.

The advantages of endless-loop recorders over more conventional two-reel types lie in their convenient readout capability. Since the tape moves in the same direction for record and playback, no recycling time is lost and a complicated high-speed recycle mechanism is not needed. Readout can be commanded at arbitrary times and, since erase can be performed immediately prior to record, only the oldest information will be erased regardless of how many readouts are performed within a given time.

A view of a laboratory-model recorder and a cross-section of the tape cartridge are shown at the left. Loops of a few hundred feet or shorter can be pulled without additional guide. The differential velocity between tape layers demands good tape lubrication, particularly in view of wide temperature requirements and attendant tension changes. These side effects became predominant when long loops were designed. Regular mylar magnetic tape cannot be used in untreated form. Preshrinkage at high temperatures creates good dimensional stability so that drive forces stay within tolerable limits. Tape lubrication has a direct influence on speed constancy, and the lubricant must be perfectly smooth. Low flutter and wow can only be achieved in long loops when tape support rollers are used, thus helping to overcome the velocity differential between the inner and outer radius.

Better performance has been achieved with long loops than with short ones, with flutter and wow of 0.17% rms up to 1000 cps and 0.102% rms up to 300 cps measured on a laboratory model. The general layout of the tape drive is an outgrowth of the short loops. Around the spoked wheel, retained by rollers, is the tape loop which is driven by two capstans from the innermost portion of the tape to the outer. As in other recorders, Mylar belts are used for speed reductions and a clutch engages the capstans to the record or playback drive chain, respectively.

The same drive principle can be applied to multiple track 1/4- and 1/2-in. tapes and to digital recorders, thereby generating a family of equipment for a variety of meteorological satellite requirements. ••

Problem: how to process 250 million bits of information for each Nimbus pass and then distribute data to weather centers within 105 min

# Nimbus data in operational meteorology

BY DAVID S. JOHNSON, W. FERGUSON HALL, and CHARLES L. BRISTOR
National Weather Satellite Center

The use of satellite data in operational weather analysis and forecasting in the near future will be based primarily on current applications and the results of research now in progress, as discussed by Jones and Mace on page 32 and Fritz on page 70. The operational value of satellite observations will be enhanced substantially when data from the entire earth become available on a routine basis. The need for regular observational coverage at frequent intervals cannot be overemphasized.

Progress is being made in inferring positions of the jet stream, streamline patterns, convergence zones, and positions of storms and fronts from satellite cloud pictures. This information will have direct applicability to hemispheric analyses produced by the National Meteorological Center (NMC) of the Weather Bureau, particularly over the vast areas of the earth where few conventional observations are now available. Techniques are being investigated whereby satellite cloud and radiation observations can be incorporated into numerical analysis and prediction schemes. Less than 20% of the earth's atmosphere is adequately observed by conventional techniques. The satellite offers a means of filling these great data voids.

The ability of weather satellites to identify and track storms, including devastating hurricanes and typhoons, has been amply demonstrated by the Tiros series. As a result, Congress has appropriated funds to the Weather Bureau to establish and operate the National Operational Meteorological Satellite System (NOMSS) to provide worldwide observations on a regular basis. When this system becomes operational, storm detection and tracking can be performed on a regular basis for the entire globe to the benefit of all mankind. Detailed investigations of severe storms, moreover, can be performed by reconnaissance aircraft guided by these satellite observations.

Variations in the atmospheric heat budget as a function of space and time can be measured for the first time over the entire earth by satellite-borne radiometers. Preliminary research results indicate that these data are correlated with the large-scale, general circulation of the atmosphere and the important energy movements and transformations which govern our weather.[1] This work holds considerable promise of improving long-range forecasting. The determination of atmospheric heat sources and sinks, another important consideration in extended forecasting, will be aided by satellite measurements of surface characteristics, including ice- and snow-covered areas and surface temperatures on a global basis.

Many types of atmospheric phenomena, structure, and thermodynamics appear to be associated with specific cloud types and patterns as seen in satellite pictures. Based on the many research studies conducted during the past three years, work is now underway to catalog classes of satellite cloud images in terms of the atmospheric conditions in each class.

The uses of meteorological satellite data beyond the next few years will expand with available new types of measurements[2-7] and increased understanding of atmospheric processes.

The plan for a National Operational Meteorological Satellite System (NOMSS) is based on the use of the Nimbus satellite now under development by NASA Goddard Space Flight Center (GSFC) (see page 42). With one Nimbus satellite in operation, every point on the earth's surface will be observed twice a day, once in daylight and once at night. This will represent a significant advance over Tiros in observational coverage. The Tiros satellite can observe only about 18% of the earth on any one day, and the area viewed changes constantly from day to day. A fully operational system must provide global observations on a regular basis.

The development of NOMSS is guided by the requirements for meteorological data in satisfaction of the needs of civil and military organizations. The table on page 53 presents a summary of the current requirements. While the early version of NOMSS will not satisfy all these requirements, research and development now in progress and planned for the future will attempt to improve the system to fulfill as many of these requirements as possible. This may necessitate development of additional types of spacecraft (see page 57).

The major elements of NOMSS will

**DAVID S. JOHNSON** who was one of the founders of the USWB Meteorological Satellite Lab in the fall of 1958, is Deputy Director of the Bureau's National Weather Satellite Center.

**W. FERGUSON HALL** has been Chief of the Systems Branch of the Weather Bureau's Satellite Center since 1961, having previously headed FAA's Meteorological Data Processing Section.

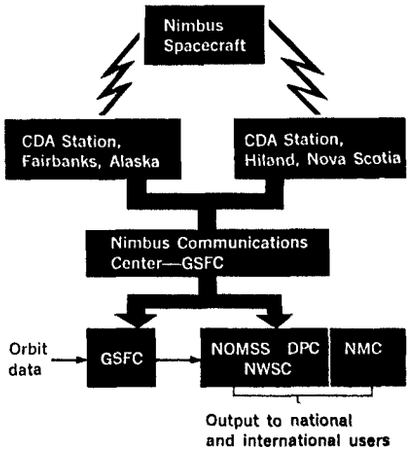
**CHARLES L. BRISTOR** has been associated with the U.S. Weather Bureau for 25 years—a career broken only by World War II service in the USAF and for graduate study.

## REQUIREMENTS FOR METEOROLOGICAL OBSERVATIONS

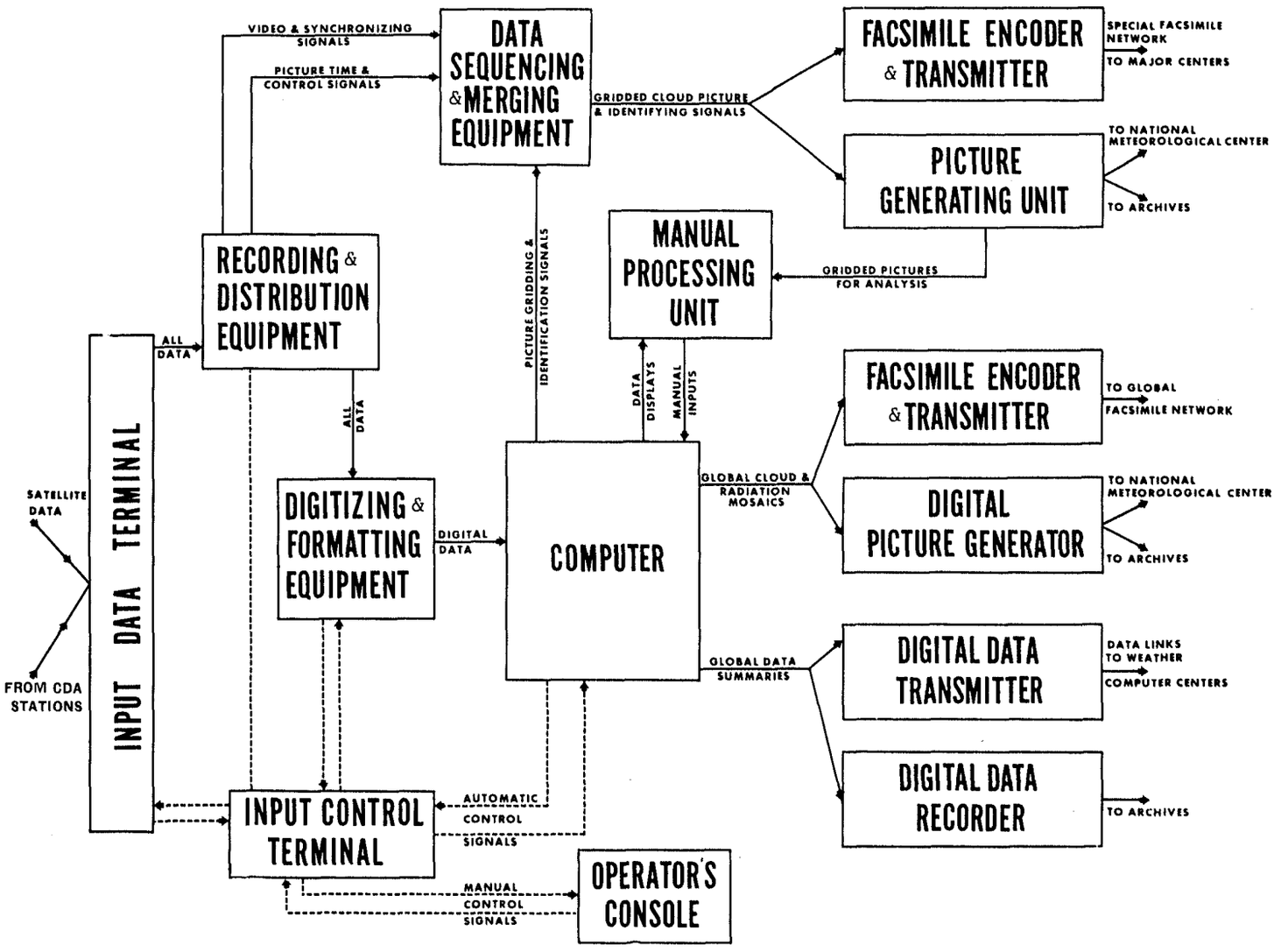
| Observation[a] | Resolution: Horizontal D | Resolution: Horizontal A | Resolution: Vertical D | Resolution: Vertical A | Accuracy D | Accuracy A | Observation Frequency D | Observation Frequency A |
|---|---|---|---|---|---|---|---|---|
| **(a) For broadscale (hemispheric) analysis** | | | | | | | | |
| Cloud cover | ½ mi. | 3 mi. | 1000 ft | 5000 ft | — | — | 4/day | 1/day |
| Surface temp. | 4 mi.² | 30 mi.² | — | — | <1 C | <3 C | 4/day | 1/day |
| Atmospheric temp. | 4 mi.² | 30 mi.² | <500 ft | <2500 ft | <1 C | <5 C | 2/day | 1/day |
| Atmospheric moisture | 4 mi.² | 30 mi.² | <500 ft | <2500 ft | <10% | <20%[b] | 2/day | 1/day |
| Density | 4 mi.² | 30 mi.² | <500 ft | <2500 ft | <1% | <1% | 2/day | 1/day |
| Atmospheric heat bal. | 30 mi.² | 30 mi.² | — | — | <5% | <20% | 2/day | 1/day |
| Precipitation | 4 mi.² | 30 mi.² | <1000 ft | <5000 ft | 0.1 in./hr. | 0.2 in./hr | — | — |
| Winds | 100 mi.² | 1000 mi.² | <2000 ft | <5000 ft | <5 kt | <15 kt | 4/day | 1/day |
| Surface pressure | 30 mi.² | 500 mi.² | — | — | <1 mb | <5 mb | 2/day | 1/day |
| **(b) For mesoscale (regional) analysis** | | | | | | | | |
| Cloud cover | 0.1 mi. | 0.5 mi | 100 ft | 1000 ft | — | — | 1/hr | 2/day |
| Surface temp. | 1 mi.² | 4 mi.² | — | — | <½ C | <1 C | 1/hr | 2/day |
| Atmospheric temp. | 1 mi.² | 4 mi.² | <200 ft | <500 ft | <½ C | <1 C | 1/hr | 2/day |
| Atmospheric moisture | 1 mi.² | 4 mi.² | <200 ft | <500 ft | 5% | 10%[b] | 1/hr | 2/day |
| Precipitation | 1 mi.² | 4 mi.² | <500 ft | <1000 ft | 0.1 in./hr | 0.1 in./hr | — | — |
| Surface pressure | 4 mi.² | 30 mi.² | — | — | <0.5 mb | <1 mb | 1/hr | 2/day |

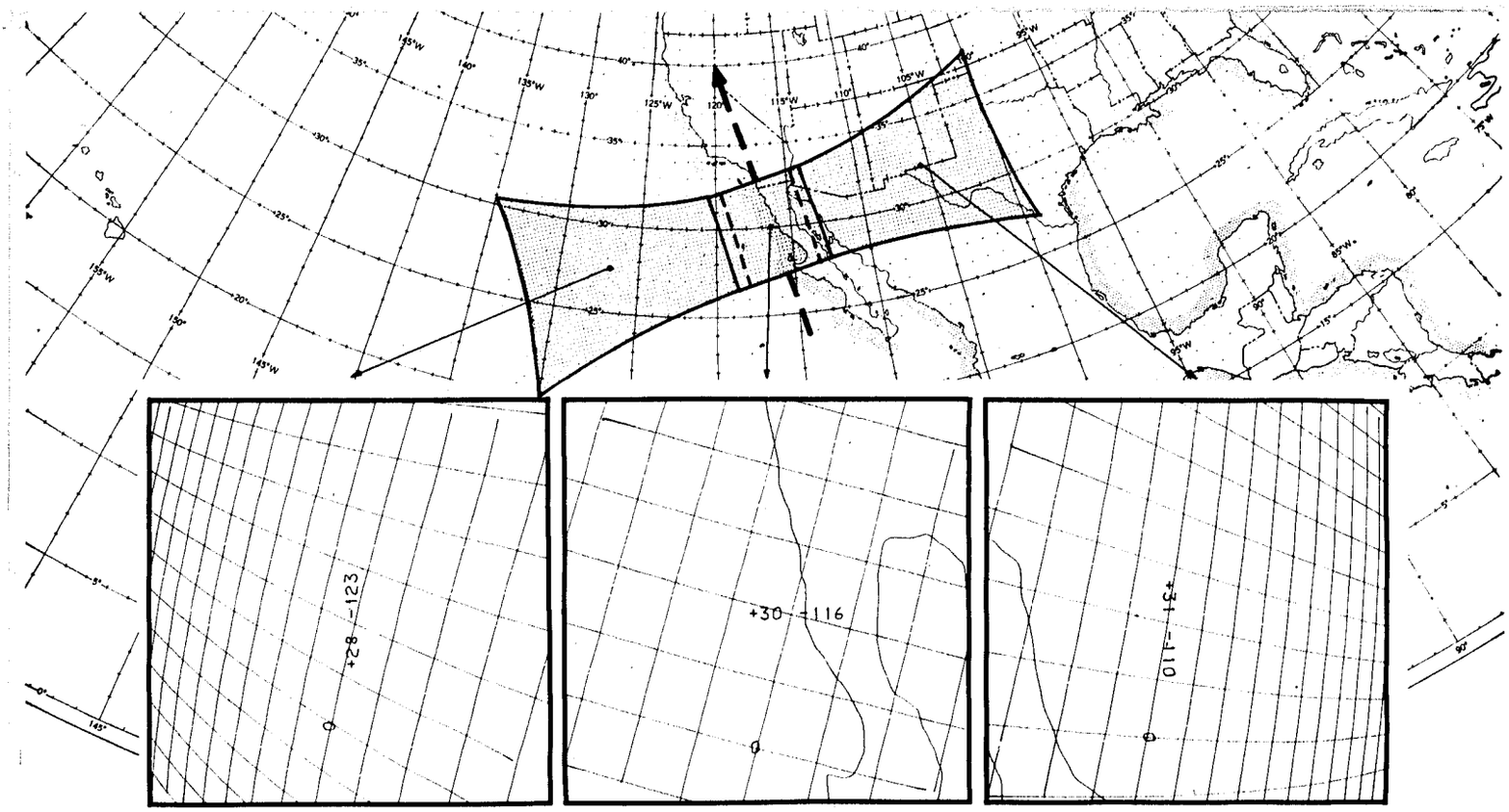
[a] D=desirable; A=acceptable.
[b] Relative humidity.

## NIMBUS DATA FLOW




## NOMSS DATA PROCESSING SYSTEM






**Nimbus AVCS (Three Camera) Coverage,** showing typical mapping of one picture set and, in bottom boxes, corresponding computer-generated latitude and longitude grids. These grids will be merged with the cloud pictures automatically in the NOMSS Data Processing Center.

be the spacecraft (and launch vehicles), data acquisition, engineering monitoring and control, meteorological data processing, and data dissemination, the latter described by the flow chart on page 53. What follows concerns NOMSS data processing and data dissemination.

Two principal command and data acquisition (CDA) stations, located at Fairbanks, Alaska, and Hiland, Nova Scotia, will be used to acquire data from the Nimbus satellite. When Nimbus is launched in a 750-n.mi. orbit, as ultimately planned, these two stations will acquire data from all orbits. Communication channels with bandwidths of 96 kc/s will be used to transmit the data to Washington, D.C., for further processing for meteorological purposes at the National Weather Satellite Center (NWSC) as well as for engineering evaluation and monitoring at GSFC.

Approximately one-quarter billion bits of meteorological data will be obtained from each orbit of the early Nimbus satellite. Received at one of the two CDA stations, from a given orbit, these data must be transmitted to Washington, processed, and then disseminated to forecast centers within one orbital period (approximately 105 min) in order for the system to be ready to receive the data from the next orbit. This schedule also is compatible with the needs of meteorology; for operational purposes, the value of weather data rapidly diminishes with time after the observation has been made. The goal in the early phases of NOMSS is to make the processed satellite observations available to the user within 3 hr after the observations have been made. System design is predicated on these requirements.

The NOMSS Data Processing Center (DPC) is being established at NWSC, Suitland, Md. The selection of this site was based on several factors. DPC is being designed to handle data acquired at both CDA stations, so precluding the need for redundant installations at each station; and it is located adjacent to the NMC, where conventional weather observations from all over the world are collected and hemispheric analyses and forecasts are prepared. Both satellite and conventional meteorological observations will thus be available for interpretation and analysis by the two centers on an integrated basis.

DPC design has been based on the use of high-speed computers to obtain maximum flexibility.[8,9] In this manner, just as with the modular design of the Nimbus spacecraft, new types of observational data and new output products can be accommodated with a minimum change in the equipment required for processing. Also, data can be provided in digital form, suitable for use by other weather computers involved in numerical weather analysis and prediction. The basic computer to be used in DPC is an IBM 7094. Smaller computers are used for certain specialized tasks in the system.

The chart on page 53 shows the major elements of the data-processing system. The over-all automatic operation of the center is controlled by the computer through the "Input Control Terminal." Manual over-ride can be initiated from the "Operator's Console." All of the data from the CDA stations required for data processing for meteorological purposes is received through the "Input Data Terminal" via wideband communication links. In addition, satellite ephemeris data will be received from GSFC.

Three general classes of data will be received in the Center from the first Nimbus satellites: (1) Video signals from the advanced vidicon camera system, (2) signals from the high-resolution infrared radiometer (HRIR, a mechanical scanning radiometer operating in a water-vapor "window" to provide night-time cloud-cover information and surface temperatures), and (3) telemetry data required to process and use the meteorological data, such as picture-taking times, attitude error signals, and voltages and temperatures which affect camera and radiometer calibrations. All these data move from the data terminal to the "Recording and Distribution Equipment." The data are also recorded should reruns be necessary.

Cloud-picture information will be processed in both analog and digital form. Before receiving data from a given orbit, the basic orbital param-

eters will have been received by the computer through the NASA Nimbus Technical Control Center (NTCC). The first data to be received at the data-processing center from the CDA station following each interrogation of the satellite will be the telemetry information mentioned above. These data will enter the computer, which will then generate information to be used in placing latitude and longitude grids as well as landmarks on the cloud pictures in analog form. The computer also uses these data for rectifying and for preparing a mosaic of the cloud data.

Following this preliminary processing of telemetry and orbital data, the picture video and synchronizing signals will be received from the CDA station. To produce pictures in analog form, the signals are directed to the "Data Sequencing and Merging Equipment" for two main operations. The video data are transmitted over the wideband link at one-eighth the speed they were received from the satellite at the CDA station. In the data-sequencing process, the data rate is returned to normal speed and placed in proper order for display. Secondly, the picture gridding and identification information generated by the computer is merged with the video signals. This combined output is fed to the "Picture Generating Unit," composed of a cathode-ray-tube display device, camera, and rapid film-processing unit. The pictures thus produced—an example of which appears on page 54—are available for use in the NMC and for additional manual processing and interpretation associated with the satellite data-processing system.

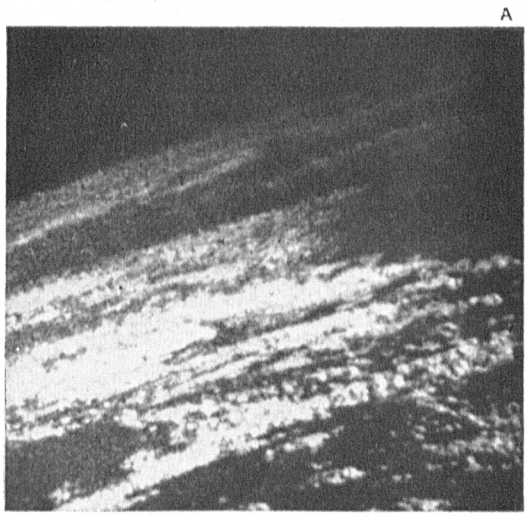
Certain of these pictures will be transmitted to major forecast centers. For example, photographs of hurricanes and tropical storms will be transmitted to the Hurricane Forecast Center in Miami, Fla. Under consideration is the use of a special "Facsimile Encoder and Transmitter" which would directly convert the picture information in electronic form to a form suitable for facsimile transmission without the necessity of rescanning the photographs produced by the "Picture Generating Unit."

In parallel with these operations, video signals also will be digitized and placed in proper format for entry into the computer. The computer, utilizing the telemetry data and orbital elements previously received, will rectify the video data from an entire orbit and produce a mosaic in map form. Experimental results of digitizing and mapping cloud pictures are shown at bottom. Several formats for this type of output are under consideration. Production of full-resolution, rectified photo mosaics is very costly in terms of computer time and memory capacity. It therefore appears impractical to do such processing operationally.

A more practical use of the computer involves reduction of the millions of bits of picture information to a more manageable volume. This will be done by summarizing picture elements into rectified grid squares. Single digit descriptors will express the per cent cloud cover, average brightness, and the pattern of those picture elements within each grid square. With the IBM 7094, a minimum grid length of 15 mi is possible—sufficient for broadscale and certain mesoscale applications.

These digital mosaics will be presented in analog form to the "Manual Processing Unit" where meteorologists, utilizing the individual high-resolution pictures produced by the "Picture Generating Unit," will superimpose on the mosaics meteorological interpretations, such as atmospheric stability, wind flow, storm centers, fronts, etc. In accomplishing this task, the meteorologists also will have available the analyses of conventional meteorological data produced by the NMC. The analyst will utilize projected images with the interpretative information being automatically fed back to the computer during the analysis phase. Thus the final computer output will represent an automatic merging of the computer and manual analy-

A



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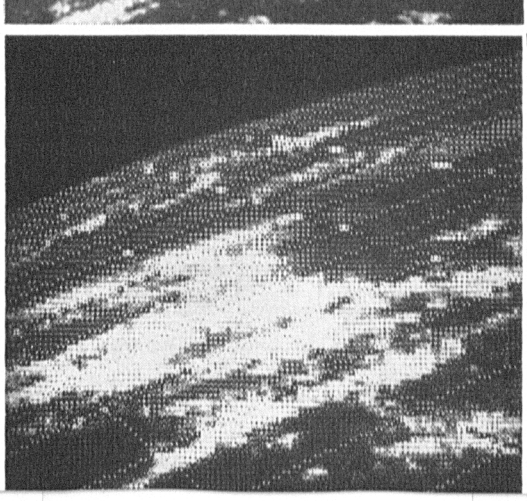

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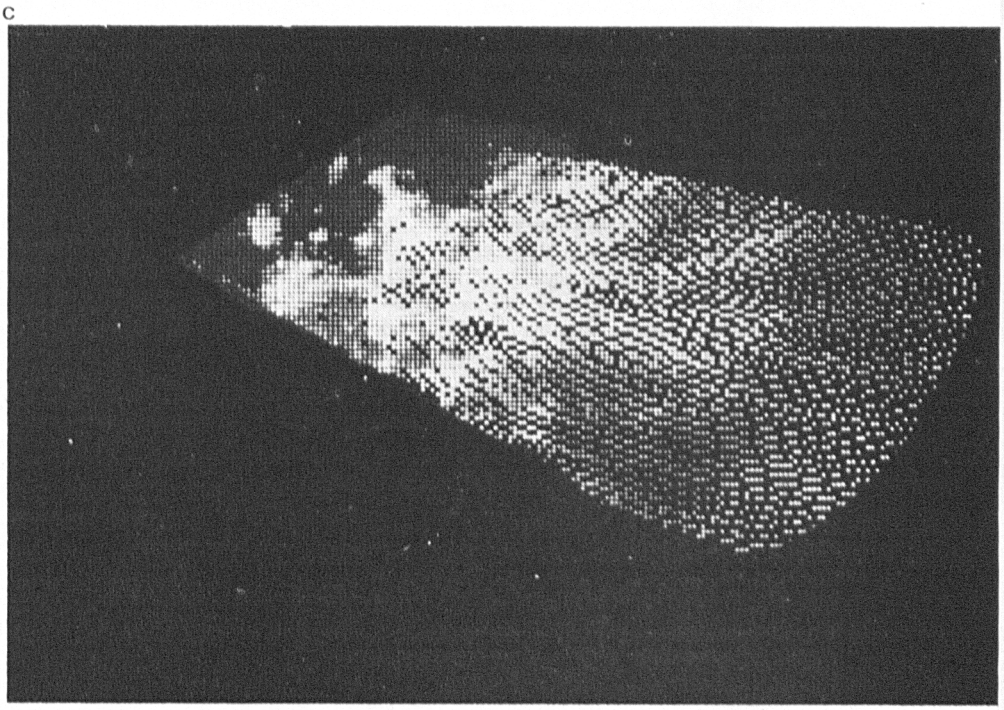

**Experimental Digitizing and Mapping of Cloud Pictures.**
(A) Copy of original photo taken by a rocket-borne 16-mm camera at an altitude of 85 mi.
(B) 100-scan-line digitization of original picture with superimposed latitude and longitude lines. (C) Same digital information computer rectified to a Mercator map projection. Foreshortening toward the horizon in the original picture results in larger spacing of scan spots in the right-hand portion of picture. To present a more pleasing picture to the eye, filler spots can be added by computer.

ses. These outputs then will be available through the "Digital Picture Generator" for use in the NMC and for archiving. They also will be converted directly to facsimile format by the "Facsimile Encoder and Transmitter" for transmission to other weather centrals.

The mosaics, summarized by grid squares, will be available in digital form for point-to-point relay to other computers through the "Digital Data Transmitter." Additional computer products designed to meet specific needs will be generated in digital form for use by other weather computers as well as for research and climatological studies.

The preceding description of the operation of the data-processing system has been in terms of the cloud pictures to be obtained by the Nimbus advanced vidicon camera system (AVCS). The early Nimbus satellites also will produce high-resolution infrared radiation (HRIR) data to be used in determining cloud distribution and surface temperatures at night. These data will be processed in a manner quite similar to that used for the AVCS data, except for a change in the synchronizing signals and in the amount and type of telemetry data required for location and rectification of the radiometer scans, and in determining the equivalent black-body radiation temperature of the earth's surface in clear areas or of cloud tops in cloudy areas.

The temperature information will be utilized in estimating cloud-top heights and producing surface-temperature maps. The temperature analysis will be performed by the computer utilizing climatological temperature data and current radiosonde observations, and will produce output maps of these parameters as well as superimposing estimated cloud top height information on the cloud mosaics.

The flexibility of the data-processing system provides for the processing of a wide variety of signal formats, both analog and digital. Changes can be accomplished in most cases by altering computer programs and changing settings on the associated auxiliary equipment. For example, the NWSC Meteorological Satellite Laboratory is developing an infrared spectrometer for use on future weather satellites which will produce a series of radiation measurements in the 15-micron carbon dioxide band.[2,10,11] Computer programs have been developed which can be used to determine the vertical profile of temperature beneath the satellite and above about 20,000 ft in the atmosphere from the measurements received from the satellite-borne spectrometer. GSFC is developing a system for future use on meteorological satellites which will digitize the data measured by their multichannel, medium-resolution infrared radiometer. The data-processing system can be adapted readily to receive these data and produce meteorological analyses from them.

A special photographic laboratory is now being constructed as part of the DPC for NOMSS. This laboratory, equipped with specialized equipment for high-speed, high-quality film processing and copying, will provide film and print copies required in the operational analysis and forecasting activities of the DPC and NMC, and will also prepare master films for deposit in the National Weather Records Center, Ashville, N.C. This Center serves as the national archive for meteorological data and will be responsible for providing copies of the satellite data to research workers throughout the world.

Two formats are planned for archival storage of pictures from the Nimbus AVCS. In the microfilm system, all sets of pictures, with superimposed latitude and longitude grids, from one orbit will be contained on a single film sheet. Approximately 10 days of pictures will be stored on each reel of Nimbus archival roll film. In addition to a legible legend for each picture, a machine-readable code block will be included to permit automatic search and retrieval of selected pictures.

Frequent mention has been made of the NMC where hemispheric and North American analyses and prognoses are prepared using both conventional observations and satellite data. These analyses and prognoses are used by military and civil weather centers scattered throughout the hemisphere in producing forecasts for specific applications and areas. With the additional data to be available from NOMSS, serious problems will exist in transmitting rapidly the products from NMC and NWSC to the major forecast centers. Therefore, a systems study is now in progress to develop the design of an optimum communications system whereby this information can be transmitted expeditiously to the forecast centers. Preliminary indications are that 14-kc/s channels will be used between Suitland and the major forecast centers in North America. Narrower bandwidth feeder circuits probably will be used between major forecast centers and local weather stations.

Limitations in conventional communications overseas present a serious obstacle to providing adequate dissemination of these data to other countries as well as U.S. bases beyond the limits of North America. Radio facsimile broadcasts will be continued, but present bandwidths will limit the amount of useful information that can be conveyed. Serious consideration must be given to the future use of satellites as a means of transmitting weather information as a part of a global weather system.

The Automatic Picture Transmission System (APTS) (see page 48) under development for use on the Nimbus satellite represents a first step in using the satellite itself to convey weather information directly to weather forecast centers wherever they may be. Similar developments, applicable to other types of measurements, as well as the products of world weather centers such as NMC, will be a logical extension of the current meteorological satellite program. Such possibilities offer the possibility of realizing ultimately a truly global weather system of tremendous benefit to all mankind. It can be said with certainty that today's evaluation of the future importance of satellites in meteorology will turn out to be vastly underestimated.

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# POTENTIAL METEOROLOGICAL SATELLITE SYSTEMS

As NASA proceeds with the development of the Nimbus spacecraft, to implement the National Operational Meteorological Satellite System, the Tiros Operational Satellite System (TOSS) will provide useful operational coverage. In the meantime, various new systems are being studied with a view to augmenting eventually, if necessary, Nimbus. The following three papers discuss important approaches to possible new systems.

Potential Systems—1

## Data collection by satellites

BY ALTON B. MOODY, NASA Office of Applications
and WILLIAM K. WIDGER JR., Aracon Laboratories

As meteorological observing tools, satellites such as Tiros and the forthcoming Nimbus have many capabilities and potentials unequaled by other available or foreseeable techniques. These include—

1. Global coverage, including particularly remote areas such as the ocean expanses, polar regions, and uninhabited land areas, where conventional observing would be too costly.

2. Ability to provide detailed pictures of distinctive cloud patterns, such as the spiral banding associated with most cyclonic storm systems, which Tiros revealed (see page 70). So spectacular are these pictures, and so great is the correlation between these patterns and common meteorological features, such as fronts and pressure centers, that it has been said truly, "Nature uses the clouds to draw its own weather maps, which the satellite permits us to see and use."

3. Ability to measure, for the first time, basic net-radiation gains and losses of the atmosphere, which are the primary energy inputs to and exhausts from the atmospheric engine. Other radiation measurements in specific spectral regions, provide information on surface temperatures and cloud-top heights (see page 76). In the future, at least gross data on the vertical structure of variable atmospheric components and of temperature are expected to be measurable using narrow bands in the infrared or ultraviolet (see page 85).

Although these capabilities are impressive, meteorological satellites—at least without ancillary platforms within the atmosphere able to make ambient measurements—have very distinct and significant limitations. In particular, there are no ways presently foreseeable to make measurements, with useful accuracy, of the dynamic and static parameters most commonly employed in primary existing forecasting techniques—such as pressure, wind direction or velocity, and detailed vertical distributions of temperature in the free atmosphere. Nor can these be adequately inferred from data the satellites reap so well.

These deficiencies can be overcome, however, if the global weather satellites are coordinated with the necessary ambient sensors immersed in the atmosphere. This concept was first suggested in the mid-1950's, probably initially by Wexler.[1] Later, Mook and Johnson proposed a radar-beacon transponder system for interrogating remote automatic weather stations.[2] More recent investigations have suggested the feasibility of less sophisticated satellite equipment for this purpose, as well as raised doubts as to the feasibility and value of the other applications of a satellite weather radar.[3]

Ambient meteorological measurements in remote areas appear technically feasible using such systems as:

1. Fixed-position, land-based automatic weather stations, such as Amos,[4] which can make most of the observations normal to a standard synoptic station.

2. Fixed-position or free-floating automatic marine weather stations, such as Mamos[5] or Nomad,[6] which can concurrently take other much-required oceanographic observations.

3. Constant-level balloons, for free atmosphere winds and temperatures, as first suggested by Lally.[7]

Recent studies indicate it should be within the state of the art to use satellites such as Nimbus to interrogate such stations regardless of their location, collect their data, locate their positions, and then transmit these data for reduction, analysis, and use when the satellite passes over existing or planned space data-acquisition facilities. Furthermore, should such a capability be developed, it could be applied to similar non-meteorological operations—seismic and geomagnetic observations, cosmic-ray balloon

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**WILLIAM K. WIDGER JR.**
has just become Director of Satellite Meteorology at Aracon Laboratories, Allied Research Associates, Inc., Previously, from 1951 to 1960, he was a research meteorologist and then Chief of the Satellite Meteorology Branch at AFCRC, and subsequently NASA Project Officer for Tiros and Nimbus. He received a Sc.D. in meteorology from MIT in 1949.



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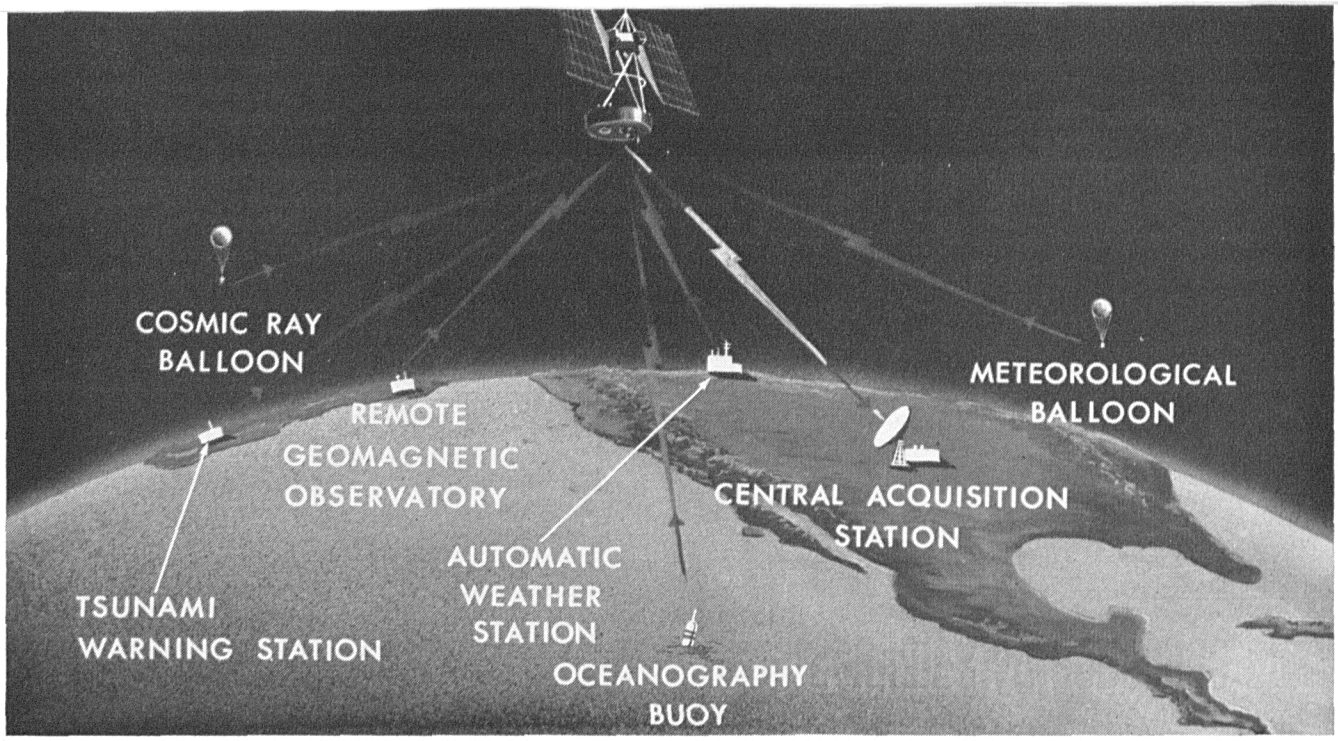


**Real-Time Measurement** of atmospheric conditions on global scale would be possible through satellite data-collection system of kind shown.

flights, iceberg tracking, air-sea rescue, or returned space-capsule location, and possibly even migrations of banded birds. Sketch above depicts some of these possible applications.

Requirements for satellite position location and data collection would then fall into four categories:

1. Moderate telemetry requirements, without location, as for fixed automatic land stations.
2. Moderate telemetry requirements, with location, as for free-floating marine stations.
3. Low telemetry requirements, with location, and with severe restrictions on observing-platform electronics, as for constant-level balloons.
4. High telemetry requirements, perhaps with location, as for stored as well as real-time data from the observing platform.

Thus far, it is not apparent whether these diverse requirements can best be solved with a single or separate satellite telemetry systems.

Sensing-platform interrogation, data collection, and storage in the satellite, and subsequent readout, have never appeared to present undue problems. Existing observing platforms, provided with suitable discrete address transponders compatible with the satellite subsystems, should meet these requirements. Accurate position location did seem a problem, however, because of the difficulties of employing accurate directional antennas on satellites, until David Cubbage of NRL proposed using range intersections, rather than bearing intersections, for this purpose.[8] Because of the slight curvature of a subsatellite point locus, ambiguity as regards position location left or right of the subsatellite locus is eliminated except for points relatively close to the locus. In these cases, position can usually be established on the preceding or succeeding orbit. Studies to date suggest significant advantages to satellite data collection and position location—considering technical factors, logistics, and economics—as compared to the alternative of a worldwide ground-based RDF net.

The application most thoroughly studied to date involves constant-level balloons, and has often informally and unofficially been referred to as Strobe (Satellite Tracking Of Balloons and Emergencies), with the word, "Emergencies," referring to the location of personnel in air-sea rescue distress situations as a compatible by-product of the system. This balloon concept, developed by a working group of the Joint Meteorological Satellite Advisory Committee (JMSAC), would utilize small, long-lived, superpressure balloons, with no ballasting and with two-dimensional, very low density, microminiaturized electronics for power, transponder, and temperature measurements. Winds would be calculated from successive locations and the elapsed time between them. Global data could be provided by several hundred such balloons, with new ones launched as older ones fail.

A major consideration is that these balloons must present no hazard to aircraft.

Another consideration, is that of obtaining *international concurrence* to transit through the airspace of all areas. Expected balloon lifetimes should permit at least two global circuits of a balloon before its failure.

Somewhat less fully investigated are applications for marine data gathering and for remote land-based weather stations.

Studies are underway or are planned that should develop the best present estimates of the total requirements for applications of satellite data collection and positioning, and the optimum engineering approach to satisfying these requirements.

Present thinking suggests that, should such a capability be approved, development and operation of the platforms, sensors, transducers, etc., would be the responsibility of those desiring to acquire and utilize the data that could thereby be made available, much of it on a scale and frequency never before feasible.

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Potential Systems—2

# Towards the synchronous meteorological satellite

BY WILLIAM W. JONES, NASA Goddard Space Flight Center

In the development of a truly global weather observation system, the synchronous meteorological satellite will be particularly attractive to the meteorologist.

Many atmospheric phenomena have relatively short lifetime and can only be detected by continuous surveillance. Yet, they are of extreme interest to the meteorologist, due either to their own importance (thunderstorms, hail, tornadoes, and other severe local storms) or their indications of larger weather systems. For instance, small, fair-weather cumulus clouds may define patterns associated with large-scale meteorological systems.

The top sketch on page 60 indicates diagrammatically some properties of various scales of atmospheric systems. The vertical axis gives a measure of the typical size of a weather system on a linear scale, and the horizontal axis gives the lifetime of the weather system on a logarithmic scale. Notice that cyclonic storms are quite large and last many days. Hurricanes are smaller and of shorter duration. Tornadoes are very small and have extremely short duration, on the order of minutes.

Tiros proved the invaluable use of artificial satellites in scientific study of the earth's atmosphere and in the practical analysis and forecasting of weather. However, it gave observations of both large- and small-scale meteorological systems essentially on a random basis.

Nimbus will provide the first step toward a global meteorological observation system by systematically taking cloud-cover pictures over the entire earth once every 12 hr. But, here again the meteorologist will not be able to observe the short-lifetime meteorological system with sufficient frequency nor will he be able to observe identical areas of a large-scale system more than once every 12 hr at best.

Two Nimbus satellites would provide local observations every 6 hr, but this would improve matters only slightly. Severe storms, thunderstorms, and tornadoes with lifetimes less than 5 hr could develop and dissipate entirely between two successive observations in a two-satellite Nimbus system.

The only economically feasible means of continually viewing the earth's weather processes is by use of a synchronous meteorological satellite. This is particularly true with respect to very short lifetime weather phenomena.

The sketch on page 60 shows an initial concept of a synchronous meteorological satellite. Launched into a synchronous equatorial orbit, it would appear to hover over the satellite subpoint, thus providing a means of continuously observing the earth's cloud cover over approximately 60 deg of latitude and longitude to either side of the satellite subpoint. In addition, since it remains essentially "stationary" to any observer within line of sight of the spacecraft, it allows relaying observations and other meteorological data directly to users.

As a first step in developing such a satellite, the Goddard Space Flight Center is conducting a number of study programs on both the complete system and long-lead-time subsystems, such as sensors, controls, and communications.

It is the purpose of this study to find the most reasonable and reliable systems for bringing maximum areas of the earth under constant observation, define the critical scientific and engineering problem areas, and identify the advances in technology required for successful achievement of the mission.

The final report from this study will form a matrix of sensor-oriented parametric data for each of the satellite subsystems. Thus, selection of a particular sensor characteristic, such as resolution, in the matrix will deter-

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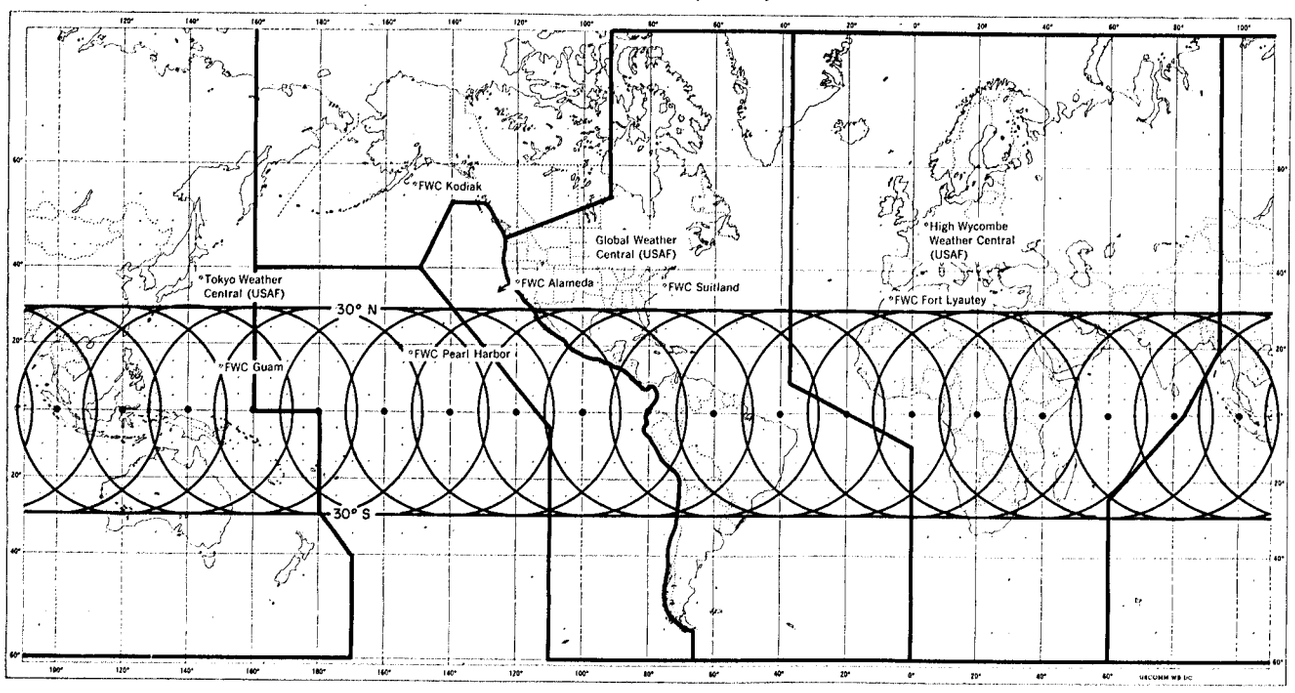
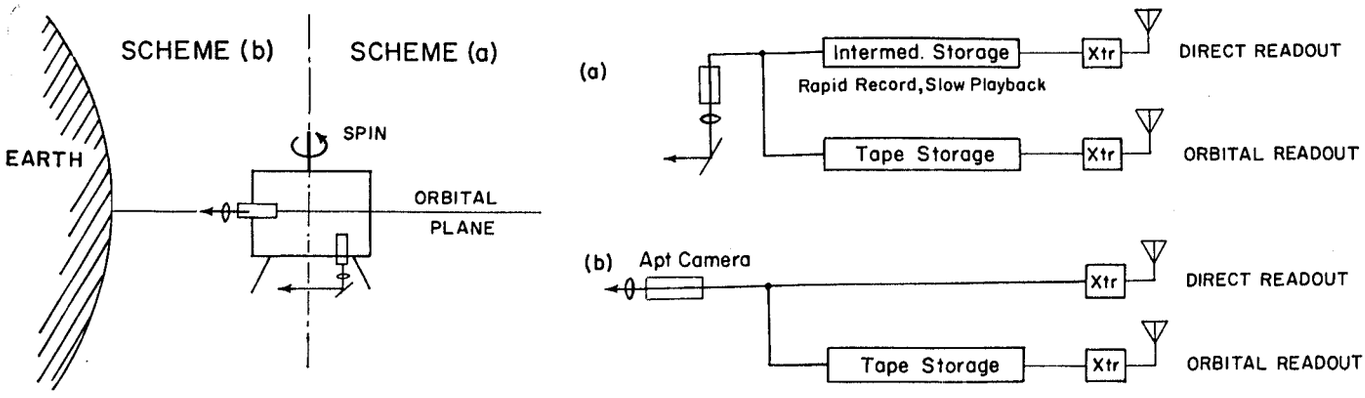
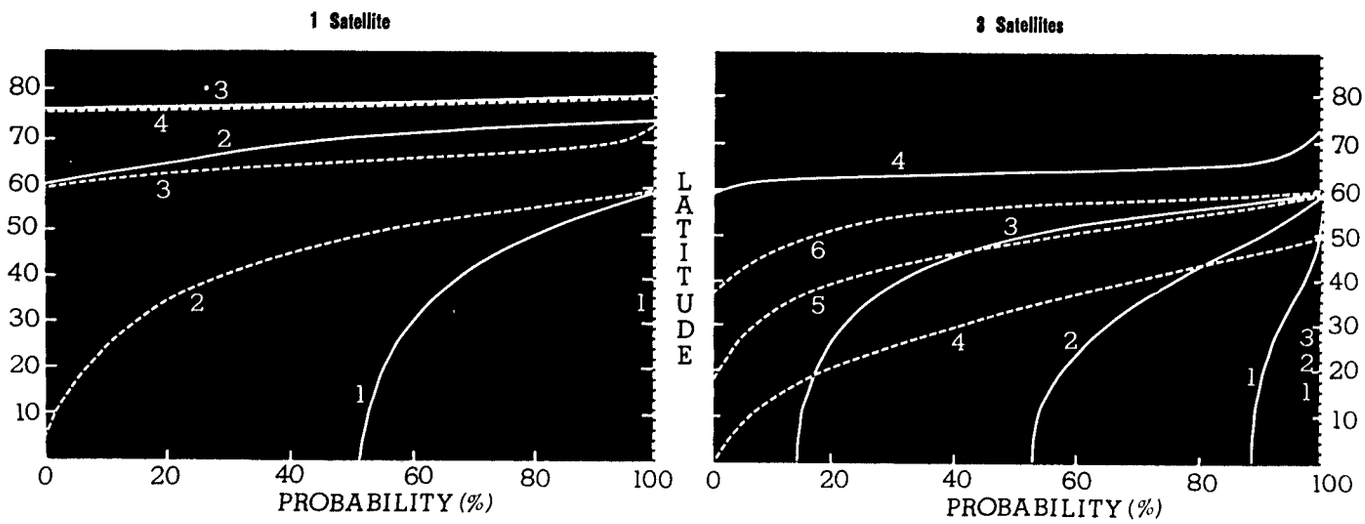
## COVERAGE FROM A DIRECT READOUT EQUATORIAL WEATHER SATELLITE (DREWS)




## MEANS FOR ACHIEVING DIRECT READOUT




## "PEEKS" PER DAY




Note: "Peek" is picture with receiving station in view. Conditions assume APT system in polar-orbiting satellite at 500-n.mi. altitude.

Code: ——— Picture 840 n.mi. wide; resolution 0.85-1.5 n.mi./TV line.
- - - Picture 1622 n.mi. wide; resolution 1.2-6.3 n.mi./TV line.

extremely high-resolution picture which includes his local meteorological situation and the lower resolution cloud analyses which allow him to make a long-range forecast.

In addition, it should be realized that many users cannot be reached by the established communication channels. Ships at sea, possibly large transoceanic aircraft, and other entities, for example, polar expeditions, usually have severe problems in maintaining communications with a home base.

As testing of the Nimbus APT system is initiated during the latter portion of 1963, the meteorological community should evaluate the system's performance and potential in terms of the choices of operational system parameters which must be made. Perhaps the most important of these is the *orbit inclination* of the satellite, because this will determine the areas viewed. Along with this and of nearly equal importance is the satellite *altitude*, which will affect both the size (coverage) of the picture and the distance at which a picture can be received (assuming line-of-sight limitations). A third important parameter is the *resolution* obtained in the picture. It would seem that the resolution gets worse as altitude increases; but, in fact, the relation is more complicated. For very low altitudes the "effective" resolution at the picture edge becomes quite bad. Consequently, there is an optimum altitude range of about 1000–2000 n.mi., as the table below shows.

Compatibility of the APT system with existing facsimile equipment is also a matter of some concern. The APT readout system is designed to operate on a rate of 240 scans per minute, which is not compatible with the widely used facsimile recorders or the existing networks. Thus, an additional facsimile recorder will be needed at each readout station, and a manual step may be needed to retransmit pictures over existing systems. This is an important matter which must be resolved as the APT system is placed in operation. If a slower scan rate were adopted, for instance, 120 scans per minute, the picture cycle time would increase from 3 min and 28 sec to 6 min and 48 sec. This would cause a greater separation between successive pictures unless the satellite *altitude* were increased to enlarge the viewing area and, at the same time, to increase the contact interval with the satellite transmitter. Again reference can be made to the table below.

The frequency and area of coverage available to a given ground station depend upon the latitude of that station and the number of satellites utilized. The table on page 64 shows this dependence for a near-polar orbit using the Nimbus APT system. Note especially the last column giving the average number of pictures per day *containing* the readout station; this situation, which can be of great operational importance, is defined as a "peek."

A station serving the Antarctic Support Force, for example, is near enough to the Pole to interrogate each satellite during every orbit. A single satellite, then, has the capability of furnishing to a station at 80 deg south latitude cloud pictures of all but a minute portion of the polar cap through a series of 13 picture-passes taken in a single day. (This high degree of coverage in the Antarctic is possible only during the summer months between September and April when there is adequate daylight at those latitudes.)

Stations in equatorial regions have, even under the ideal situations illustrated, a much reduced probability of coverage. This result of geodesy, providing extensive overlap in polar regions, leaves wide gaps at the equator. Additionally, the requirement exists for more frequent coverage in equatorial regions than in polar regions. This area is approximately 80% ocean, and hence contains comparatively few observation stations. The tropics are responsible, too, for developing and influencing weather conditions in higher latitudes and serve as the source of much of the globe's weather. The dynamics of tropical meteorology are such that frequent coverage of these areas is most useful in order to make meaningful analyses.

Better coverage at the equator can be gained by increasing the number of satellites in polar orbits or by broadening the field of view of the camera lenses (at the expense of resolution) to provide the necessary picture frequency and distribution. Both of these solutions provide excessive redundancy at the poles. As we shall see, the addition of an equatorial satellite may be preferable.

Bottom graphs on page 62 describe the situation, giving as a function of latitude, the probability of $n$ or more "peeks"/day, and presenting results for one polar satellite, and three polar satellites in different orbital planes. The graphs show two different camera situations—a medium angle lens giving a picture width of 840 n.mi. (Nimbus APT), and a picture width of 1622 n.mi., so adjusted that pictures from successive passes just touch at the equator.

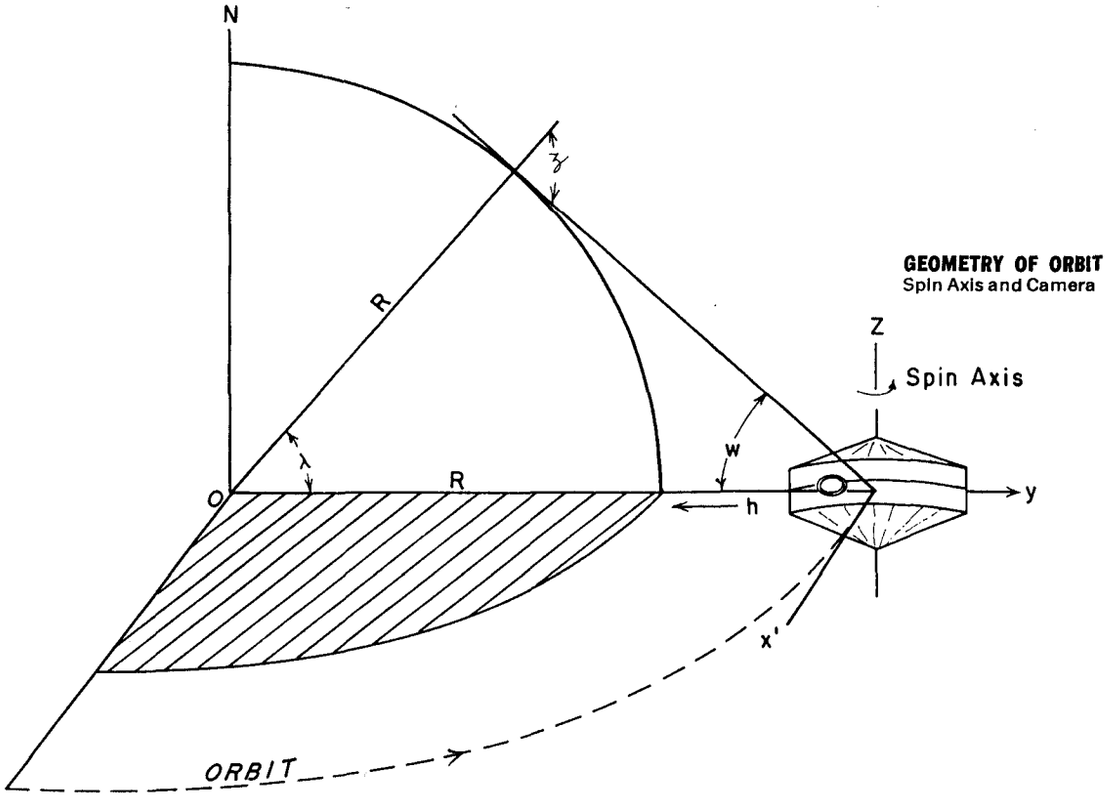
In connection with these questions, we have re-examined with some care the matter of resolution. The usual definition of resolution is the dimension on the earth's surface corresponding to one line in the TV raster at the satellite's vidicon. This definition, however, will always give the *best* resolution, and is often misleading. Depending on the application, other definitions of resolution may be more realistic. In particular, one needs to take into account the fact that the clouds have a finite thickness. A much more severe criterion of resolution is the ability to resolve a 5-mi. break in the clouds with a cloud deck reaching up to 6 mi.

Using this definition of resolution, it turns out that the effective dimension which can be covered with an APT camera from a Nimbus-like orbit is only 500 instead of 840 n.mi. It is interesting to see, from the table on page 65, how this affects various operational considerations. It is evident that the DROS system in polar orbit gives very adequate coverage at intermediate and high latitudes, but very poor coverage at the equator. This situation may be improved by combining with a number of satellites in near polar orbits, one satellite in an orbit rather acutely in-

**COVERAGE AS FUNCTION OF SATELLITE HEIGHT**

| Height, n.mi. | 500 | 1000 | 1500 | 2000 | 2600 |
|---|---|---|---|---|---|
| Camera field of view, [a]∠deg. | 76.24 | 66.43 | 59.98 | 53.11 | 47.49 |
| Resolution (width of 1 TV line),[b] n.mi. Center | 0.83 | 1.45 | 1.93 | 2.32 | 2.69 |
| Corner | 1.28 | 2.07 | 2.55 | 2.90 | 3.21 |
| Length/breadth of pix, n.mi. | 584 | 1001 | 1318 | 1567 | 1805 |
| Picture area, sq n.mi. × $10^5$ | 3.4 | 10.0 | 17 | 24 | 32 |
| Orbits per day | 13.9 | 11.5 | 9.9 | 8.6 | 7.3 |
| Pix interval,[c] min. | 2.8 | 5.8 | 8.9 | 12.3 | 16.4 |
| Frequency per day, for a station to be in picture, if interval is programmed as above: | | | | | |
| Equator | 0.376 | 0.532 | 0.604 | 0.621 | 0.612 |
| 20°N/S | 0.400 | 0.566 | 0.643 | 0.661 | 0.651 |
| 40°N/S | 0.490 | 0.694 | 0.786 | 0.810 | 0.798 |
| 60°N/S | 0.750 | 1.061 | 1.205 | 1.239 | 1.221 |
| 80°N/S | 2.158 | 3.054 | 3.467 | 3.564 | 3.513 |

[a] Chosen to give Z = 45° at picture edge.
[b] Square picture format scanned by 800-line raster.
[c] Time between successive pictures to maintain total coverage along swath (no overlap of area).




clined to the equator. The ideal, of course, would be a pure equatorial orbit, which currently, is difficult to achieve.

Such an equatorial satellite may be equipped for direct readout only, storage and delayed readouts, or combinations of the two approaches. Since most of the area in question is water, some form of storage of information collected in those areas appears necessary. Since the Tropic Belt includes many islands and other areas with very limited, if existing, communications, direct readout of pictures from such a satellite is mandatory, if resident meteorologists are to benefit. Direct readout is also required for maritime users.

**DIRECT READOUT COVERAGE:**

From 600-n. mi. Nimbus orbit

| Latitude | Avg. daylight passes/day to acquire pix[a] | "Peeks" per day[b] |
|---|---|---|
| 0 | 1.55 | 0.516 |
| 10 | 1.58 | 0.524 |
| 20 | 1.65 | 0.549 |
| 30 | 1.79 | 0.595 |
| 40 | 2.25 | 0.674 |
| 50 | 2.57 | 0.803 |
| 60 | 3.12 | 1.032 |
| 70 | 4.54 | 1.509 |
| 80 | 8.42 | 2.982 |

[a] Based on minimum receiver antenna elevation angle at 10 deg and 3 1/2-min readout time. The average number of pictures per pass is about three.

[b] Average number of pictures covering a readout station

The map on page 62 illustrates the coverage from a hypothetical Direct Readout Equatorial Weather Satellite (DREWS) at 2000 n.mi. altitude, viewing the region between 30 deg north and 30 deg south latitude once every 3 hr. Although some definition would be lost because of the higher altitude, major cloud features should be well defined, and this would nicely supplement a polar-orbiting system and compensate for its deficient coverage below 30 deg latitude. In fact, the probabilities for Cases (1), (2), and (3) of the table on page 65 would become 100% up to 30 deg latitude.

Can the operating altitude of polar satellites be optimized? The graphs on page 65 illustrate both orbital period and coverage as a function of orbital altitude.

Picture definition drops when local zenith angle, $z$, exceeds 65 deg. In certain operational situations 45 deg may be more realistic. Some of the tradeoffs are well illustrated for the case $z = 45$ deg. Satellite altitude is the independent variable; the camera field of view is adjusted to make $z = 45$ deg at the picture edge. Note that the resolution becomes more uniform over the picture as height increases. Note also the increasing picture interval; it becomes compatible with a 120 lines per min facsimile between 1000 and 1500 n.mi.

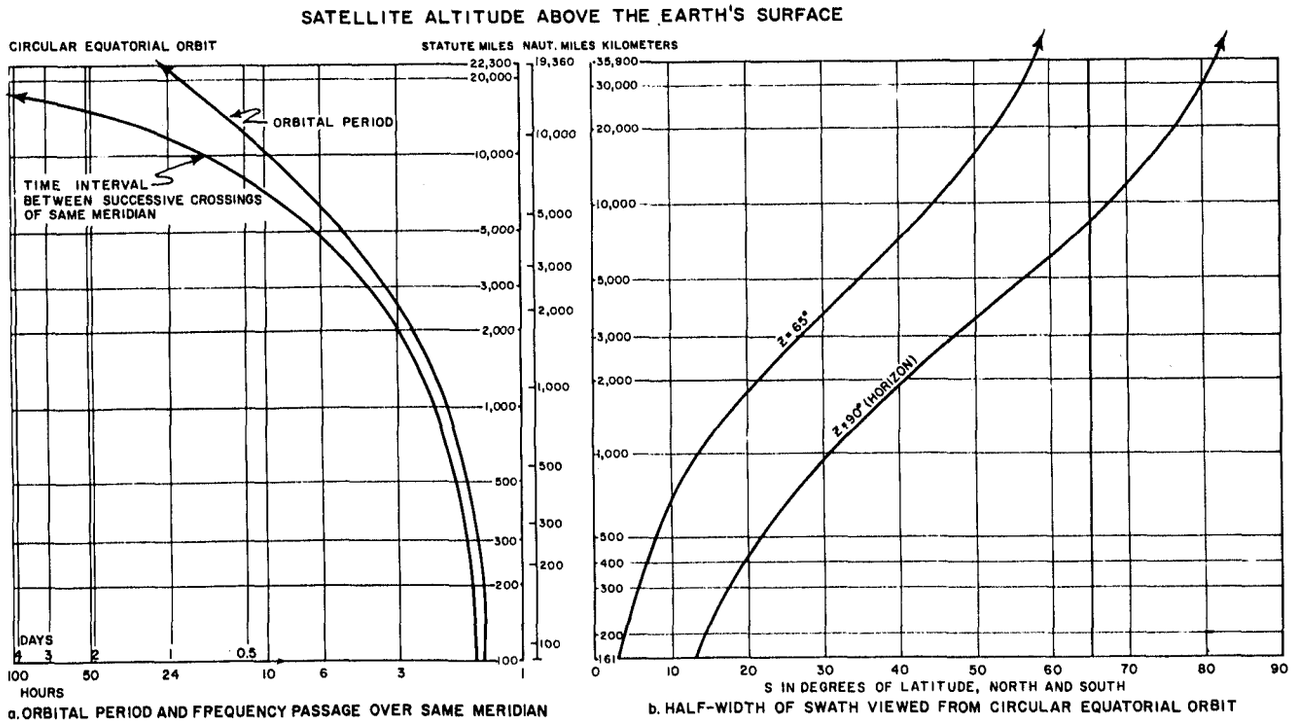
The table on page 63 shows that increased coverage cannot be obtained with a wider-angle lens, but either through a multiple camera system (as the Nimbus AVCS system) or by increasing the altitude, with a slight resulting loss in definition at the picture center. Most interestingly, it shows that the optimum coverage is obtained in the vicinity of 1700-n.mi. altitude.

These last few paragraphs illustrate best, perhaps, the concern of the authors and the reason for this article. It appears that another ingredient beyond experimental data, design criteria, and highly technical knowledge is needed to establish the direct-readout weather satellite system. This is the certain knowledge as to how it will be used, which can only be obtained as a response from the entire meteorological community.

As mentioned earlier, direct-readout pictures are taken with a camera pointing vertically down when the satellite is over the illuminated portion of the earth. Picture taking is controlled by an internal clock, and therefore operates automatically; no command or interrogation is necessary, and this in turn results in a further simplification of the ground equipment. It also makes it possible for many stations to gain access to the satellite's transmission at the same time. The transmission can, therefore, be considered to be a true "broadcast."

For the data to be useful operationally, it must be used rapidly and with a minimum of processing. This makes

**ORBITAL PERIOD AND COVERAGE OF POLAR SATELLITES**




a. ORBITAL PERIOD AND FREQUENCY PASSAGE OVER SAME MERIDIAN

b. HALF-WIDTH OF SWATH VIEWED FROM CIRCULAR EQUATORIAL ORBIT

the verticality of the camera extremely important. In principle, there are three methods:

1. Active stabilization, for example, as in Nimbus.
2. Completely passive stabilization, for example, through the use of the gravity-gradient torque.
3. Command stabilization or semi-passive methods, involving the use of a spinning satellite.

The Nimbus stabilization system is discussed in the paper on page 42. If one is thinking of a direct-readout system containing only an APT camera, then it does not appear worthwhile to provide an active stabilization system for such a light and small satellite.

Gravity-gradient stabilization on the other hand seems ideally suited for a direct-readout satellite, since it gives the required orientation, namely, toward the center of the earth, without any further commands or corrections. In practice, however, there are several problems.

A mechanism must be provided to damp out the librations. The Applied Physics Laboratory of Johns Hopkins Univ. has developed a damping spring which appears to do this job very simply.[3] The spring has an energy dissipation factor of about 50% and can damp the libration in a matter of 15 days. Before the gravity-gradient torque is applied, however, the satellite is de-spun by means of a "Yo-Yo." The remainder of the spin is damped out in about two days by magnetic hysteresis rods, and then an internal magnetic field is turned on by command and produces rough alignment with the geomagnetic field in about seven days. When the satellite is roughly in the desired orientation, a 60-ft boom is extended by command, and the gravity-gradient torque begins to operate. The complete system will soon be demonstrated on the Transit 5A satellite. Indications are that the quieting period will be less than the values quoted.

A matter which has not yet been completely investigated is the nature and magnitudes of all the perturbing torques. The main torque very likely is the magnetic torque on the vidicon focusing coils. Preliminary estimates indicate that these torques are all small compared to the gravity-gradient torque or that they can be compensated. It will also be necessary to compensate torques arising from internal motions, such as the TV camera shutter, tape recorders, relays, etc.

Since the gravity-gradient torque can produce only alignment along the local vertical, there can still be a rotation about that axis. A system must be developed, therefore, which indicates compass directions, preferably right on the picture.

An alternative approach, used in the DREWS design, makes use of satellite spin to gain gyroscopic stability against perturbing torques. If the spin axis is perpendicular to the orbital plane, and if the camera optical axis is perpendicular to the spin axis (that is, if the camera axis is within the orbital plane), then once during every spin period the camera axis will be looking vertically down on earth. If the picture is snapped at that instant only, then a "vertical" picture will be obtained every time.[4]

The picture-taking operation can be made automatic and timed by means of a horizon sensor which also looks within the orbital plane and determines the times of "first look" and "last look" at the horizon. By bisecting this interval, we arrive at the vertical orientation. A refinement,[5] designed to avoid "jitter" due to clouds on the horizon, is to average over many spin periods and also to use the carbon di-

**PICTURE-WIDTH EFFECTS ON OPERATIONS[a]**

| Operational case | Probability[b] | Effective picture width 840 n.mi. | Effective picture width 500 n.mi. |
|---|---|---|---|
| (1) At least one peek per day | $(1-q^4)$ | 89% | 67% |
| (2) At least one peek at a particular time | p | 52% | 31% |
| (3) Three peeks per day | $p^3$ | 14% | 3% |

[a] Three DRO satellites in Nimbus-type orbits, e.g., 9 a.m., Noon, 3 p.m.

[b] Here p is the probability of obtaining a peek at the equator; p will always be less than 100% if successive passes do not overlap at the equator; q is (1-p).

oxide bands at 15 microns, which give an effective horizon well above the usual cloud layer.

As can be seen from the diagrams in middle of page 62, there are a variety of ways in which a direct-readout satellite can be achieved. The simplest approach might be Scheme A, a modification of the existing Tiros, involving the addition of a mirror, horizon sensor, triggering scheme for the TV shutter, and additional tape recorder for intermediate storage. Scheme A involves the proven Tiros camera. In Scheme B, the camera itself is mounted perpendicular to the spin axis and is identical with the APT camera developed for Nimbus.

The alignment of the spin axis perpendicular to the orbital plane poses a more severe problem. While the effect of perturbing torques will be small, it can nevertheless become appreciable after a certain period of time and result in a considerable deviation of the spin axis from the desired direction.

Three methods can be applied: The first would be to keep the perturbing torques as small as possible. The main disturbance is a magnetic torque; and by proper compensation of the vehicle this torque can be minimized. In addition, the rapid rotation will cancel one component of the torque by averaging it out. Furthermore, for an equatorial orbit it can be shown that the first-order magnetic torque will be zero, because of additional cancellation owing to the spin-axis and magnetic-field vector keeping a nearly constant angular relationship as the satellite moves around the equator.[5] But the second-order effect can still be appreciable after a certain length of time.

The second approach, therefore, is to accept whatever torques are left over and correct the attitude of the vehicle occasionally by command. Magnetic torquing has proven quite successful with Tiros (see page 29) and with other satellites as well. In this scheme, an internally mounted coil energized on command creates a magnetic moment in the satellite, and this in turn produces a torque by interacting with the earth's magnetic field.

A third approach, and perhaps the most effective one in the long run is to find a restoring torque which will keep the spin axis perpendicular to the orbital plane. A clue to the existence of such a torque is given by the fact that the spin angular momentum is parallel to the orbital angular momentum of the satellite. The latter, however, is something like $10^{12}$ times as large as the former.[5] Since the orbital angular momentum defines the orbital plane, the proper alignment can be maintained if some method of weak mechanical coupling can be introduced. A possible approach, which is semipassive and uses an internal gyro, but no commands, has been suggested by the MIT Instrumentation Laboratory. It will be interesting and important to establish whether this approach can, in fact, work in a practical satellite.

It appears, then, that there are a variety of ways of achieving, from a technical point of view, a capability for a direct-readout satellite. In all likelihood, several of these approaches will be pursued, at least in the developmental stage, before an operational system is settled on.

In conclusion we would be remiss if we did not mention the important international aspects of a Direct Readout Satellite System. At this time, when only the United States and the Soviet Union have plans for implementing a full-scale operational satellite system, involving elaborate spacecraft, expensive central readout stations and data-processing facilities, it is heartening to realize that the other countries of the world, especially the newer nations, can participate by investing in a direct-readout ground station.

The capability to observe local weather should be particularly important for the tropical countries. These countries suffer from the absence of a well-developed meteorological service, as well as a lack of weather stations and a good communication system. Moreover, they are heavily dependent on agriculture, which depends critically on the weather. The tropical countries also have such problems as locusts, whose migration, in turn, depends on the local weather (see page 89).

Altogether, we should expect more than good will to result from the implementation of direct-readout satellites as a contribution to the improvement of the weather services of all of the nations of the world.


### Acknowledgments

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# Research with satellite cloud pictures

BY SIGMUND FRITZ, U.S. Weather Bureau

## Experiment and theory come to bear on the nature of the hydrodynamic and thermodynamic processes implicit in the cloud pictures that Tiros produced

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There are already several review articles which summarize the results obtained from meteorological satellites.[1] In brief, clouds have been found to be highly organized, and the satellite pictures reveal atmospheric phenomena on all scales.

The satellite pictures often suggest that certain dynamical mechanisms are acting to produce cloud patterns. Here a few types of cloud patterns will be compared with laboratory experiment and theory to emphasize the hydrodynamical implications of the satellite pictures.

It should be noted, however, that any of the implied dynamical processes can only give necessary, and not sufficient, conditions for the production of cloud patterns. For example, the presence of enough water vapor, operated upon by a condensation mechanism, is always required also.

*Cellular Clouds.* The so-called cellular cloud pattern is frequently found in satellite pictures. Krueger and Fritz[2] discussed a few cases located over the Atlantic and Pacific Oceans. The Tiros picture shown at the top, from their paper, shows a cellular cloud pattern. Especially in the lower right quarter of the photo, the pattern suggests semicircular arcs of cloud, with clear areas in the center—a pattern similar to that found in the laboratory by Graham[3] and Avsec.[4]

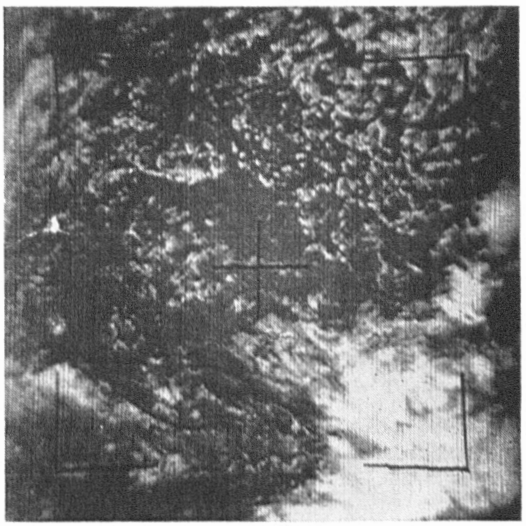
The clouds in this picture were imbedded in an atmospheric layer in which the temperature decrease with height was close to the adiabatic lapse rate. This relatively unstable layer was capped by a marked inversion, that is, an increase of temperature with height, at levels, which varied from 3000-9000 ft over the area.

In the laboratory these patterns are deformed from hexagonal Bénard cells by the superposition of vertical shear of the horizontal wind on the hexagonal pattern.[3] But there are important differences between the laboratory results and the results revealed by Tiros pictures. Among the most intriguing is scale.

In the laboratory, the characteristic ratio of width of the cells, $w$, to the height, $h$, is $w/h = 3$. By contrast, for the cells in the picture at top here $w/h = 30$, or about a factor of 10 larger. This value is computed from the fact that the cellular diameters in the picture range from 20 to 50 mi. If we take the height of the inversion as the depth of the fluid, then $h$ varied from about 0.6 to 1.5 mi.

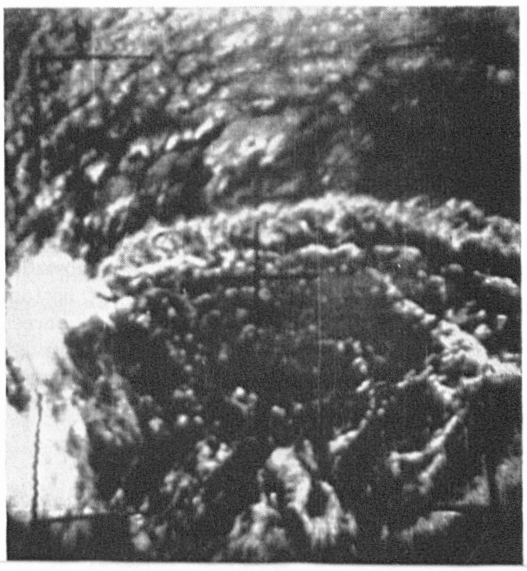
Several studies have attempted to explain or elucidate the conditions associated with the "flatter" cells observed by Tiros. For example, Fritz, Lipps, and Moore, working individ-

**Cellular Cloud Pattern** appears at lower right in this Tiros I picture taken 650 n. mi. northeast of Bermuda at 1612 GMT, April 4, 1960. From Krueger and Fritz.[2]



**Cloud Mass from Precursor Hurricane Anna,** as shown by Tiros III on July 16, 1961, shows only weak organization of cloud patterns, if any.

**Same Cloud System a Day Later** shows a pronounced organization of cloud lines, compared to picture above, with lines curving sharply into overcast.



ually or in groups, considered among other things the distribution of cooling or heating in the cells.[5]

In the cells, clouds are produced where the motion is upward. In the cloudless portions of the cells, the motion is probably downward, at least near the upper boundary (at the inversion). Moreover, at least two heating or cooling mechanisms occur when the cloud is present. First, stratocumulus clouds are good radiators of thermal energy to space; they approximate black-body radiators at the temperature of the cloud "top." Evaporation from the cloud "top" may also contribute to cooling there. On the other hand, as the clouds condense they release the heat of condensation, and so act as heat sources.

Thus the clouds act as heat sinks at the top of the upward moving air. They also act as heat sources throughout the part of the cloud where condensation is occurring, also in the upward moving air.

In most cases examined, the cell size became *smaller* rather than larger, when these effects were added to the simpler classical problem. The main exception to this occurred when the air was *heated* near the top boundary in the upward flowing part of the cell. This suggests that condensation may be a factor in producing large cells. Even then, the effect on the cell size is probably small. Roy and Scorer also evaluated the effect of cooling throughout the cell and found the effect on cell size to be small.[7]

Thus, to find the explanation for the "large" cells seen by Tiros I, still other factors must be investigated.

Theoretical studies of Bénard cells usually employ molecular quantities for the coefficients of viscosity and heat diffusion. However, it is common to use the concept of "eddy" coefficients in studies of turbulent flow in real fluids. Priestly[6] and Roy and Scorer[7] have applied these to explain the flatter cells. Say that $K_x$ and $K_y$ denote the "eddy" coefficients for the horizontal direction and $K_z$ for the vertical direction. Priestly then reasoned as follows: Assume that the cells rotate about horizontal axes, as in the case of Bénard cells. The upward flowing air, which produces the clouds, penetrates a short distance into the stable air above the base of the inversion. The airflow returns in the stable inversion and then descends where the air is cloudless. Since $K_z$ acts to suppress velocity and temperature differences between the horizontally moving air at the top and bottom of the cell, $K_z$ must operate across the stabilizing barrier of the inversion; therefore $K_z$ is small. However for $K_x$ and $K_y$ there are no corresponding suppressions. From analogy with conditions in the boundary layer and in the general circulation, Priestly considers that $K_x/K_z = 100$ is plausible, and this leads to about a tenfold flattening of the cells, in agreement with Tiros observations.

Roy and Scorer also emphasize the variation of $K_x$ and $K_y$ as compared to $K_z$.[7] They note that $K$ is greater in the turbulent cloudy areas than in the cloudless areas. They also consider that the cell motion acts as though the horizontal transfer of heat by eddies were large. With these assumptions they consider both isotropic and non-isotropic turbulence, and find that in either case a flattening of the cells occurs. They also show the ratio $w/h = 30$ can be achieved by various combinations of viscosity and heat conduction coefficients.

On the other hand Sasaki, mainly because of the difficulty of assigning numerical values to $K$ (for eddies) objectively, prefers to consider $K$ negligible.[8] He noted, however, that horizontal and vertical gradients of potential temperature existed in the area of the Tiros picture at the top of page 70, and that instability can be produced when the gradients exceed certain critical values. According to Sasaki's criterion, the horizontal and vertical temperature distributions, as given by radiosondes in the area of the cells correspond to cells which are even flatter than the ones observed by Tiros.

In summary, then, the insertion of variable values for $K_x$ and $K_y$, which are larger than $K_z$, into a modified classical theory, can produce significantly flattened cells. Also baroclinic instability, introduced by horizontal temperature gradients, can apparently also produce flat cells independent of $K$. Eventually, all the significant factors will need to be combined into a unified theory.

*Tropical Vortex.* Another occurrence which needs explanation was observed by Tiros during the formative stages of the tropical cyclone, which later became Hurricane Anna of 1961.[9]

On July 16, 1961 the cloud mass from which Anna developed was located near 10° N, 39° W, as shown in the middle picture on page 70. Although there may have been some organization present in the cloud patterns between latitudes 10° N and 20° N, it was, if present, weak. But by 1449 GMT on July 17, a marked change had occurred. The main cloud had moved to about 12° N., 43° W, and, by contrast, showed a pronounced organization of cloud lines, as the bottom picture on page 70 reveals, curving sharply into the overcast area from the east and north. The direction of such cloud lines usually lies near the direction of the vector of the vertical shear of the wind; and when the shear vector lies along the wind, as it often does in the tropical Atlantic at low levels, the cloud lines are also related to the wind direction. Thus, the curved, "spiral" cloud array indicates that the vertical wind shear vectors were arranged in a curved pattern, and that probably the wind was also curved cyclonically.

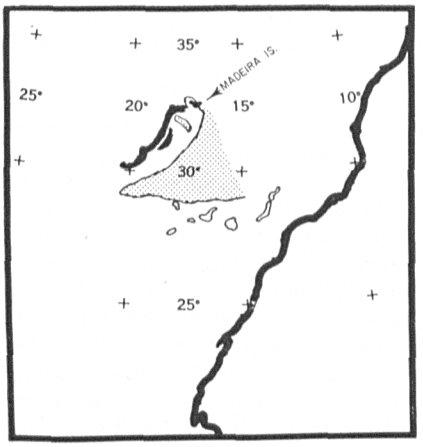
The marked change in cloud pattern suggests a corresponding change in airflow associated with the *onset* of instability. It is therefore interesting to compare these events with an experiment reported by Faller.[10]

Faller used a rotating water tank, from which the water was withdrawn at the center. The water was pumped back into the tank along its perimeter. The tangential velocity, V, increased with radial distance from the center. Under the proper conditions of speed of rotation, $\Omega$, and fluid velocity, V, instability developed in the Ekman boundary layer. (The theory of the Ekman layer is discussed by Haurwitz.[14]) This instability produced convective bands which spiraled toward the center of the tank. The onset of instability in the form of well-ordered spiral rolls was observed to occur at a critical Reynolds number, $R_{ec} = 145$. There was a transition from well ordered rolls to more irregular rolls and fully-developed turbulence at $R_{et} = 177$.

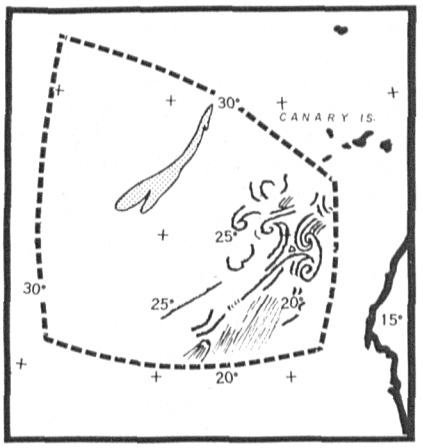
Moreover, Faller found a constant relationship between the spacing of the bands, $L$, and the depth, $D$, of the Ekman layer, namely, $L = 10.9D$.

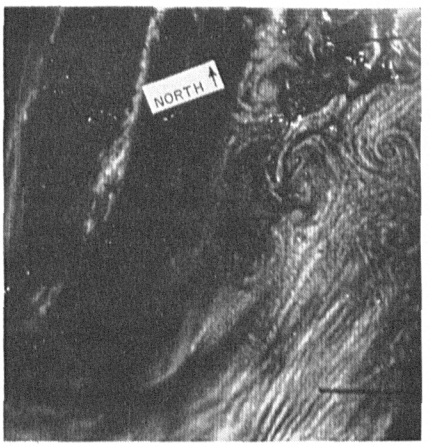
Now, the onset of instability may also occur in hurricane genesis. Hurricanes often begin as small cold-core disturbances in the easterly wind zones of the tropics.[11] In a cold-core disturbance the air is coldest near the center, where the air is rising. Such conditions cannot persist without forcing from the environment. Additional mechanisms must therefore act to produce the warm-core, self-sustaining convection of a hurricane. The heat released by condensation in the clouds can gradually change the cold core into a warm core. A stage in the development may then be reached, when the air is withdrawn vertically from the system rapidly enough, so that the associated low-level inflow may become unstable in the sense of Faller's experiment.

The spacing, $L$, between the cloud lines, in the bottom picture on page 70, was about 20–40 mi. If following



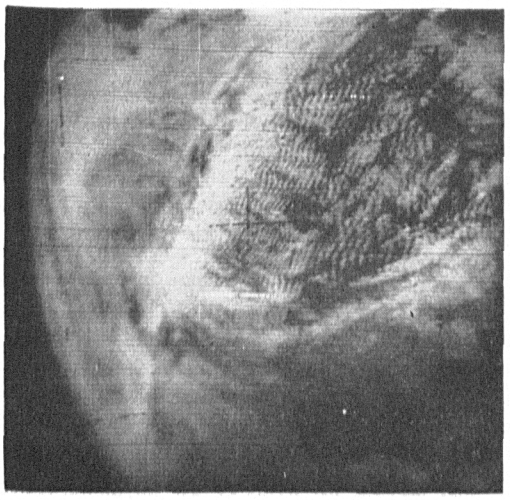
**Cycloidal Cloud Pattern** downstream from Madeira Island, photographed by Tiros V at 1650 GMT on June 21, 1962. The island has dimensions of 20 by 65 km, with mountains extending up to 1800 meters. From Hubert and Krueger.[12]



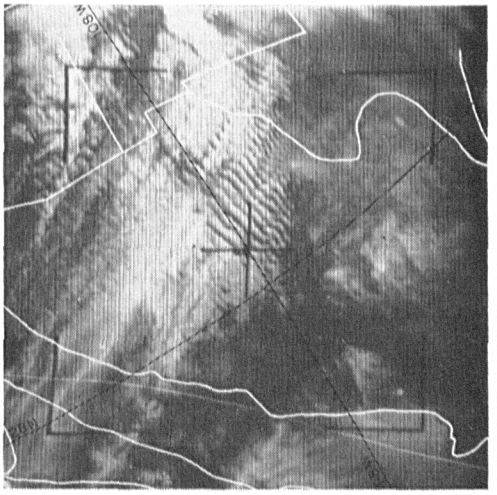




**Complex Eddy Cloud Pattern** downstream from Canary Islands, photographed by Tiros V at 1400 GMT on July 2, 1962. The Canary Islands range in size from about 30 by 12 km to 53 by 78 km and in height from 500 to over 3000 meters. From Hubert and Krueger.[12]

**Wave Cloud Pattern** in the lee of the Andes Mountains, as seen by Tiros I at 1738 GMT on April 18, 1960. *Relatively uniform bright band,* oriented N–S, is over the Andes.



**Wave Cloud Pattern** over northern Mexico and southwestern U.S., with a geographic outline *superimposed. Taken by Tiros VI* at 1706 GMT on Nov. 15, 1962.



Faller we take $R_{ec} = V\ D/_{\nu}\ D = (\nu/\Omega)^{1/2}$ (for an Ekman layer) and utilize the equation $L = 10.9D$, then $V = R_{ec}\ L\ \Omega/10.9$. Here $\nu$ is the coefficient of eddy viscosity. At latitude 15° N, $\Omega$ equals $1.8 \times 10^5\ sec^{-1}$; then, taking $R_{ec} = 145$ and $L = 20$ mi., we find V = 17 knots. From the values of $R_{ec}$ V, and D used here, $\nu \approx 1.5 \times 10^6\ cm^2/sec$.

The wind speed was doubtless about 17 knots, or even higher, in the region of the cloud lines near latitude 16° N. Further, $D \approx 2$ mi., which seems quite reasonable, especially since, on the basis of experience, the appearance of the clouds was characteristic of a pronounced temperature inversion in the lower part of the troposphere.

Thus, the Tiros pictures, such as the one on page 70, are consistent with laboratory results and suggest the onset of instability in the friction layer during the early, formative stages of a tropical cyclone, at least, for this one case of the forerunner of Hurricane Anna.

*Mesoscale Eddies Produced by Islands.* Another class of interesting phenomena are the mesoscale spiral and cycloid patterns produced in the lee of elevated islands under suitable atmospheric conditions. Several examples of these were discussed by Hubert and Krueger.[12] Two of their figures are reproduced at the left. The top one shows a general field of cellular clouds, doubtless under a strong, low inversion, with very little vertical shear of the horizontal wind. But starting in the vicinity of Madeira Island and extending downwind for about 150 mi. is a long cloud pattern arranged more or less like a series of arcs in a cycloid. The general area of the cycloid cloud is surrounded by relatively cloudless air in some places, suggesting that the air was shaded from the main wind by the island, or that subsidence of the air was occurring, or both.

Hubert and Krueger point out that the presence of the inversion favors the production of inertial oscillations in the air. The frictional influence of the islands modifies the balance of forces which existed in the airflow upwind from the islands. And the unbalance of forces produced by the presence of the island introduces inertial oscillations which take the form of cycloids, if the oscillations are stable. Furthermore, the wavelength of the pattern depends on the speed of the mean flow, and on the horizontal shear. They find that the cycloid pattern in the top figure corresponds to a wind speed of 10 knots and a period of between 17 and 24 hr.

The pattern in the lower figure,

however, is rather different from the other. The spiral patterns are much more developed. The cloud patterns suggest that more "eddies" exist, and the appearance is one of greater instability. Also the cloud pattern downwind (to south) of the eddies shows pronounced streakiness, rather than the cellular pattern of the top figure. Such streakiness often suggests a marked vertical shear of the horizontal wind, rather than the absence of shear indicated by the cellular pattern. The eddies suggest a von Karman type of vortex introduced by an obstacle, such as the complex grouping of the Canary Islands. Moreover, the existence of vertical shear can be another destabilizing influence, which may have been present in the bottom but not the top figure.

However, Hubert and Krueger suggest that the eddies in the bottom figure are not von Karman vortices, because the eddies were found too far downstream from the islands, in their view. For example, they calculate that the eddies could have existed for, *at most*, 8 hr even if one considers only the vertical shearing stresses of the horizontal wind. Nevertheless, for a reasonable value of the mean horizontal wind, and the observed distances of the eddies from the islands, they estimate that the eddies had been in existence for 10–20 hr from the time of their formation. However, the numerical value of the eddy stresses which they used are doubtless uncertain by a factor of 2 or 3; and if so, the eddies appearing in the bottom figure could have been mechanically produced by the islands, without the need for additional destabilizing mechanisms.

However, having rejected the view that the eddies of the figure on page 72 are merely mechanically produced by the islands, Hubert and Krueger apply a criterion for instability appropriate to the mean flow in which the eddies are imbedded.

Although they do not arrive at this result, one can show that from their assumptions, $V/R < -f/2$ where $V$ = tangential velocity, $R$ = radius of trajectory curvature, $f$ = Coriolis parameter = $2\,\Omega \sin \phi$, $\Omega$ = angular velocity of the earth, and $\phi$ = latitude. For $V = 15$ knots (7 m/sec) at latitude 25 deg, $R < 145$ mi. (= 230 km) indicates a rather marked anticylone. Moreover, the horizontal shear, $\partial V/\partial R > V/R$.

They also assume that perturbations on the inversion may decrease the depth of the fluid by 30%. If so, it can be shown that $\partial V/\partial R$ could become cyclonic.

If it were practical, it would be interesting to observe the island-produced eddies from their inception, and to note the meteorological conditions required for the onset of the eddies.

*Wave Patterns in Clouds.* Rather regular wave patterns are observed fairly frequently in clouds. They may be formed in several ways. One type of such waves is the pattern produced by flow of wind over and perpendicular to a mountain range.

The Andes Mountains represent a rather narrow, high mountain range, which extends for great distances north and south. Wind from a direction of 250 deg (from the southwest) blows almost perpendicular to the mountain; and when the temperature and wind vary in a certain manner with height, waves will form. These waves become visible when clouds form in the upward moving part of the wave.

Döös[13] has considered such a case based on the Tiros picture at the bottom left on page 72. This shows the Andes Mountain as the rather wide N-S band, caused by rather uniform cloudiness and some snow on the mountain. In the lee of the mountain a remarkably regular and widespread wave pattern appeared in the clouds. The wave pattern extended about 200 mi. downwind from the mountain and for at least 250 mi. in a N-S direction. The measured wavelength of the cloud pattern, although not exactly the same everywhere, was about 7 mi. Fortunately, one of the few radiosonde stations, Puerto Montt, is located just to the west of the mountain. This station showed a fairly uniform wind increasing with height from about 20 knots near the surface to about 100 knots at a height of 30,000 ft. The temperature decreased rather uniformly, from about 10 C near the surface to about −50 C at 30,000 ft, although a slight inversion existed near 13,000 ft. With these distributions, Döös found theoretically that the computed wavelength should also be about 7 mi.—in close agreement with observation.

It should be noted however that more than one wave pattern seems to exist in the picture on page 72. Superposed on the main short wave pattern is another less well-defined wave with a wavelength of about 30 mi. This wave pattern is oriented more NE-SW than the first wave train. It is interesting to note that Döös' theoretical development yields two solutions for a certain, rather arbitrary, choice of parameters. For example, if he takes the average height, $H$, of the terrain near the base of the mountain as 2625 ft (= 0.8 km), he gets two solutions for the wavelength, namely, $L_1$, = 6.8 mi. (11 km) and $L_2$ = 44 mi. (70.3 km). As already noted, $L_1$ agrees well with the wavelength for the picture on page 72. But $L_2$ = 44 mi. seems too high to explain the longer "waves" seen in the picture. It is possible, by adjusting the parameter, $H$, to get closer agreement with $L_2$; but then the agreement with $L_1$ becomes poorer.

However, the pattern of the longer waves in the picture on page 72 is not very well defined, and even the suggested wave begins far from the mountain. Thus, there may be other causes for this poorly defined pattern, such as the influence of irregularities in terrain downwind from the main mountain ridge.

Another example of waves discovered over Mexico and the southwestern U.S. by Tiros VI appears at the bottom right on page 72. This pattern may have been formed by the flow of air over the Sierra Madre Occidental Mountains, but no analysis of the cause has yet been attempted.

*Conclusions and Further Speculations.* From the few examples presented, we see that the cloud pictures from Tiros present challenging problems. Hydrodynamical and thermodynamical processes produce the observed cloud forms when an adequate supply of water vapor is present. The problem is to deduce the nature of these processes and the state of the atmosphere, in as much quantitative detail as possible.

Very regular cloud patterns are produced by the interaction of airflow with a mountain. It is interesting to speculate, however, to what extent one can deduce a consistent set of wind and temperature distributions which could produce regular wave patterns, such as the ones in the pictures on page 72, when other information is not available.

With regard to cellular patterns, numerous pictures from many parts of the world are available. It seems likely that a measure of the horizontal dimensions of the cells, provided by the pictures may offer an estimate of the height of the inversion which we postulate to be present. Moreover, the presence of well-formed cells suggests absence of vertical wind shear.

Instability in the Ekman boundary layer has been invoked as the cause of the appearance of the clouds shown in the picture on page 70. If this is so, we should perhaps expect to find a transition to such a pattern whenever a tropical disturbance changes from a cold-core to warm-core system of sufficient intensity. With the exception of Hurricane Anna, no other examples have yet been investigated for this effect.

Many of the cloud patterns discussed do not occur as often as one might expect if the mechanisms postulated for their cause were the only determining factors. These mechanisms, such as the flow past Madeira Island, or the Canary Islands, in the presence of a strong inversion, probably occur more often than we find the associated patterns in the satellite pictures. But to make the dynamical phenomena visible enough water vapor must be present. Moreover, in many cases there must be regions of local convergence so that upward motions can condense the water vapor. And these convergent zones must themselves be arrayed in a pattern consistent with the airflow postulated.

In spite of all these requirements, it is fascinating to find that the atmosphere does organize itself into a myriad of patterns made visible by clouds. And the need to infer the physical significance of the numerous cloud patterns observed from satellites poses interesting questions.

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Day and night cloud patterns, atmospheric structure, and global heat balance have received intensive study in—

# Research with Tiros radiation measurements

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The advantages of viewing the earth and its atmosphere from an orbiting meteorological satellite have been thoroughly expounded by now and are well known. The Tiros series has demonstrated the usefulness to the meteorologist of observations of large-scale cloud cover and similar features with television cameras. TV observations, while providing a maximum resolution of the areas viewed, nevertheless have two distinct disadvantages: Their response is limited to a rather small portion of the visible spectrum (0.5–0.7 microns) and the absolute intensities of the radiation received by the camera cannot be measured. The greatest asset of TV observations therefore lies in the ability of the cameras to map meteorological features with relatively high resolution.

Much more can be learned, however, about the physical structure of the atmosphere and its meteorological implications by extending observations to other portions of the spectrum, particularly to the infrared, and by obtaining a more precise measurement of intensities of radiation emanating from various regions of the globe. This makes it highly desirable to supplement TV photographs with radiometric observations.

A radiometer generally consists of a photodetector (the nature of which will largely depend on the desired spectral response), an optical filter and, possibly, light gathering lenses or mirrors. It has to be well calibrated in terms of its irradiance, but a variety of spectral regions may be chosen by selecting the proper components, such as transmission filters, reflective coating, etc. All measurements discussed here resulted from rather simple instruments which reflect the state of satellite radiometry of several years ago, when the idea of this type of experiment was first realized.

Today, one might conceive of considerably more advanced, high-resolution radiometric sensors, some operating in the extremes of the electromagnetic spectrum such as microwave radiometers, but their concepts are described elsewhere in this issue (see page 85). To some extent, the design of such future devices will undoubtedly be based on the results reported here.

Radiometric experiments have been generally performed by meteorological satellites for one or a combination of the following three reasons:

1. To map the distribution of cloud patterns both day and night and determine heights of cloud tops. The simplest device to accomplish this is a radiometer operating in a narrow portion of the infrared spectrum where the transmission through clear atmosphere is a maximum (that is, an atmospheric "window"). One of the most effective windows for this purpose lies in the 10–11 micron region. The radiation received at the instrument is assumed to be a known function of the effective temperature only of the emitting surface (ground or cloud top). Since temperature distribution with height in the troposphere is assumed to be known from balloon or climatological data, radiation measurements can not only detect the presence or absence of clouds, but also determine the heights of the cloud tops. Two requirements must be fulfilled by the radiometer: The field of view of the instrument must be reasonably small to provide sufficiently high spectral resolution (0.5 and 3.0 deg are used in present high- and medium-resolution instruments), and the field of view must scan the earth continuously to give adequate coverage.

2. To determine the structure of the atmosphere. Here again, the radiometer must operate within a narrow spectral region near the center of a strong absorption band of one of the atmospheric constituents (6.7 microns for $H_2O$ or 15 microns for $CO_2$). The radiation received is a function of both the temperature and the concentration of the constituent with height. By measuring radiation in the absorption band and comparing it with measurements in a window channel, the temperature structure of the lower atmosphere can be derived if the concentration of the absorbing gas is known (as in the case of $CO_2$), or the total content of the absorber in the viewed column can be determined if the temperature structure is known. Total amounts of water vapor in the column may be determined by this last method. Because of the high spectral resolution necessary, it has not been possible so far to use the former method. Such an instrument is now under development (see page 85).

3. To determine the balance be-

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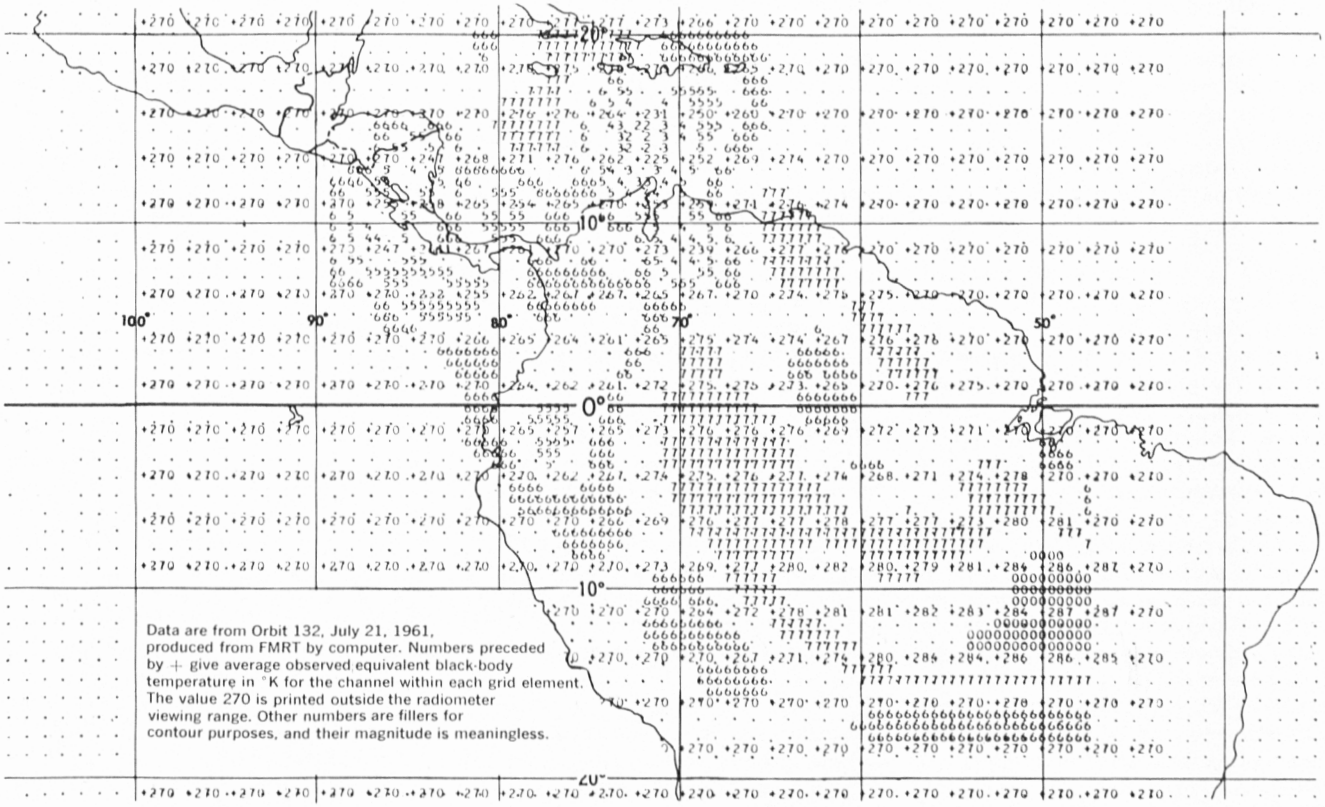
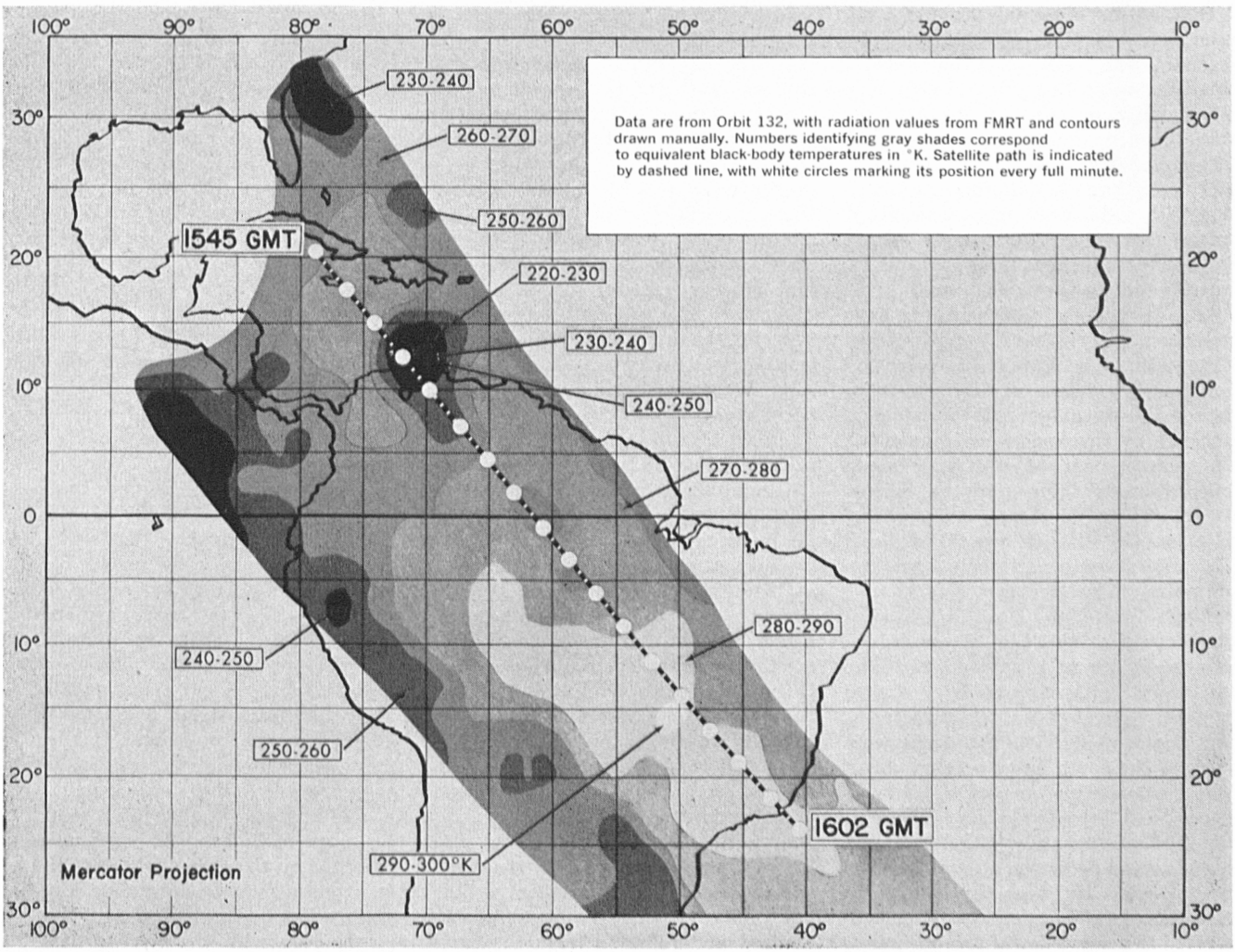
is responsible for carrying out physical measurements in the meteorology program of NASA's Goddard Space Flight Center —including radiation experiments on the Tiros satellites, development of radiation sensors for Nimbus, and sounding-rocket programs for measuring structure of the atmosphere. Dr. Nordberg contributed to the rocket-grenade technique for temperature soundings in the upper atmosphere and conducted this experiment during the IGY. He also participated in development of Vanguard II, first U. S. meteorological satellite.

**TIROS III RADIATION MAPS, 8–12 MICRON CHANNEL**—top, produced by computer; bottom, reduced manually



tween solar energy absorbed and thermal energy emitted by the earth and the atmosphere. This balance is a major factor in determining the energy stored in the atmosphere and available to be transformed into dynamic processes. Measurements for this purpose may be performed by two extremely simple sensors. One must operate in the solar spectrum (0.2–4 microns) to detect reflected solar energy from the earth, and the other in the infrared (5–30 microns) to receive emitted thermal radiation. Spatial resolution in this case is not of the essence, and the field of view may be one order of magnitude larger than for a medium-resolution scanning radiometer.

Each of these three areas holds great importance for meteorology. A complete mapping of cloud distribution and heights is of immense importance to the synoptic meteorologist: a knowledge of global height distributions of temperature and water vapor could eventually find its way into schemes for numerical weather forecasting, and the measurement of radiative energy balance might provide a powerful tool to explore the formation of storm systems.

Of the three areas, the first has been most extensively satisfied by measurements from all meteorological satellites in the past[1-3] and will also be strongly pursued in the near-future with Nimbus experiments.[4] Measurements from Tiros[5-8] and Explorer VII have been highly encouraging with respect to measurement of total energy fluxes, and some results were obtained from Tiros III and IV water vapor in the atmosphere.[9]

In addition, these experiments have produced a wealth of secondary results, such as background information for the better use of horizon scanners,[10] the durability of optical components in the space environments,[11] the development of useful infrared calibration techniques in the laboratory,[12] and the development and use of a magnetic attitude-control device.[13] The experiments and their basic results are reviewed below.

*Experiments to Date.* The first meteorological satellite, Vanguard II, carried as its only payload two PbS photocells with appropriate optical systems, electronics, tape recorder, and telemetering. The photocells were to scan the earth to map cloud cover. The scanning motion was to be produced by the regular spin of the satellite.[14] Unfortunately, the satellite tumbled and no systematic maps could be generated. However, the experiment was successful inasmuch as it demonstrated the capability of this technique and paved the way for the subsequently successful Tiros radiation experiments.

The sensors flown in Tiros II, III, and IV have been fully described elsewhere.[15] Each satellite contains two instruments. One is a nonscanning radiometer with broad response in both the visible and infrared regions and a rather low spatial resolution. Its field of view is approximately 55 deg. The other is a scanning radiometer which scans as the satellite spins. It is of medium spatial resolution, has a 5-deg field of view, and responds to radiation in five different spectral regions determined by optical filters. Three of these regions are in the infrared between 5.9 and 6.7 microns, 8 and 12 microns, and 8 and 30 microns. The other two lie mainly in the visible portion of the spectrum between 0.50 and 0.75 microns and 0.2 and 7.0 microns. These spectral regions are purely nominal since the response of the instrument within these regions is far from uniform. Therefore, the exact spectral response curves must be used when the energy distribution in each channel is calculated. Typical curves for Tiros III have been given elsewhere.[16]

In the 5.9 to 6.7 micron channel, a maximum of absorption due to water vapor is encountered. Energy in this channel is therefore received mainly from the highest altitudes where water vapor may be found in the atmosphere. In contrast, the optical depth is a maximum in the 7.5 to 13.5 channel, since absorption due to any of the atmospheric constituents—except ozone, which covers only a minor portion of this channel—is very small. The 7.0 to 32.0 channel covers almost 80% of the total black-body energy emitted by the earth, while the total solar energy reflected from the earth is contained in the 0.20 to 7.0 channel. The 0.50 to 0.75 channel is of interest because it covers only a narrow spectral region very near the maximum of solar-energy distribution, and is similar in its spectral response to the TV cameras carried on the same satellite.

One of the basic differences between the wide-field and five-channel instruments is that the five-channel radiometer scans the earth during all portions of the orbit, while the wide-field radiometer fully views the earth during less than 1/5 of the orbit. The wide-field instrument measures the radiant emittance of a target by means of a thermistor whose resistance is a function of the absorbed energy flux. This is accomplished over the whole spectrum with two detectors: a black one equally sensitive to radiation emitted and reflected from the earth, and a white one predominantly sensitive to emitted radiation. The portion of solar energy reflected from the earth (the earth's albedo) and the apparent black-body temperature for earth can be determined by comparing the energies received by the black and white detectors. A complete description of this instrument has been given by Hanel.[17]

Very much in contrast to the wide-field radiometer, the sensors in the five-channel instrument are alternately, and in rapid succession, illuminated with two diametrically opposed fields of view, one scanning the earth and the other pointing into outer space. The sensors therefore measure the difference of the energy fluxes in the two directions. Since the flux from outer space is essentially zero, this serves as a reliable reference.

A detailed description of this instrument and its scanning mechanism is contained in.[15] Further instrumental details, such as recording, transmitting, and electrical conversion of the measurements have been described.[18]

In addition, Tiros III and IV each carried radiation sensors of the type used in Explorer VII and described below.[21]

On Explorer VII, incident radiation from the sun, reflected solar radiation from the earth, and emitted radiation from the earth are measured with simple bolometers in the form of hollow silver hemispheres. The hemispheres are thermally isolated from, but in close proximity to, specially aluminized mirrors. The image of the hemisphere which appears in the mirror makes the sensor look like a full sphere. The mirror is made large enough so that no part of the hemisphere bolometer "sees" the satelite itself. The temperatures of the thin silver hemispherical bolometers are measured by glass-coated bead thermistors, mounted so as to provide good thermal contact to the hemisphere. In addition, provision is made to measure the temperature of the mirrors.[21]

It is possible to show that a mirror-backed hemisphere by virtue of the satellite spin acts, as far as the radiation fluxes are concerned, very similar to an isolated sphere in space. Two hemispheres are coated black, which makes them respond about equally to solar and terrestrial radiation. Another hemisphere, coated white, is more sensitive to terrestrial radiation than to solar radiation. A fourth, with a gold surface, is also more sensitive to solar radiation. A black sphere, mounted on the axis of the satellite at the top, is used to determine any deterioration in the mirror surfaces by comparison with the blackened hemi-

spheres. Finally, a small Tabor-surfaced hemisphere equipped with a shade to protect it from direct sunlight can be used to measure reflected sunlight when the axis of the satellite points to the earth's surface.

The information telemetered to the earth's surface is sensor *temperatures*. The radiation fluxes are obtained by using these temperatures in heat-balance equations.

Two scanning radiometers similar in concept to the Tiros experiments will be flown in Nimbus. The radiometers have now reached the prototype stage. One, a high resolution radiometer with a 1/2-deg field of view, will map thermal radiation in an atmospheric window between 3.5 and 4.2 microns.

The other, a medium-resolution radiometer, is a continuation of the Tiros five-channel radiation experiment. Early versions will have about the same wavelength ranges as the Tiros radiometer but will be improved. The spectral range of the 8–12 micron channel will be narrowed to a 1-micron band from approximately 10 to 11 microns, where the window is most transparent. Spectral response of other channels has also been improved.

The major advance, however, is in the check of calibration during operation in space. Both medium- and high-resolution radiometers will scan the radiometer structure, which has been converted into a black body by deep grooves and a proper coating, and which has a separate telemetering channel to monitor its temperature. Now two points on the calibration curve are available for all thermal (infrared) channels—zero (outer space) and a point close to the maximum of the dynamic range. However, some channels which are insensitive to infrared, such as the 0.25- to 4-micron channel of the medium-resolution radiometer, need other means of checking the calibration. Here the sun provides the calibration signal.

Twice each orbit, the lower surface of Nimbus is exposed to sunlight, just before and just after the spacecraft enters and leaves the earth's penumbra. A metal reflector and a sapphire bead then channel sunlight into the view of the radiometer.

In contrast to Tiros, where scanning motion is provided by satellite spin, Nimbus radiometers generate the scan internally, by a rotating mirror. Scan lines are perpendicular to the velocity vector of the satellite and provide complete coverage of the earth from horizon to horizon without overlaps or gaps in the scan pattern at the subsatellite point. Use of the atmospheric window from 3.5 to 4.2 microns made the application of fast semiconductive detectors possible without going to excessive cooling requirements. In the satellite, a radiative cooling system maintains a detector temperature of approximately −80 C, sufficient for the lead selenide detector cell used in the high-resolution radiometer. The cooler is a surface of high emissivity, 2 1/2 by 4 cm in size. It is thermally in contact with the cell but isolated from the spacecraft, exposed to outer space but never to the sun. This is possible on Nimbus since the orientation of the spacecraft is actively controlled with respect to earth and sun.

Aside from engineering the instruments, there are two major challenges common to all radiometric experiments: Calibration of the sensors and handling the vast amounts of information continually accumulated by the satellite. These challenges are particularly pronounced in the Tiros five-channel radiometer experiment, where each channel must not only be calibrated in terms of its total irradiance but the precise spectral response must also be known since in one orbit the instrument feeds over one million data bits to a digital computer.

The calibration for total irradiance is accomplished with specially constructed black bodies in vacuum for the thermal channels and with precision calibrated tungsten sources for the solar-radiation channels. Calibration for spectral irradiance becomes a major difficulty in the long wave end of the 8–30 micron channel. In the visible channels, this calibration must be performed with great precision because the tungsten calibration target and the reflecting earth have vastly different radiative temperatures (2800 and 6000 K).

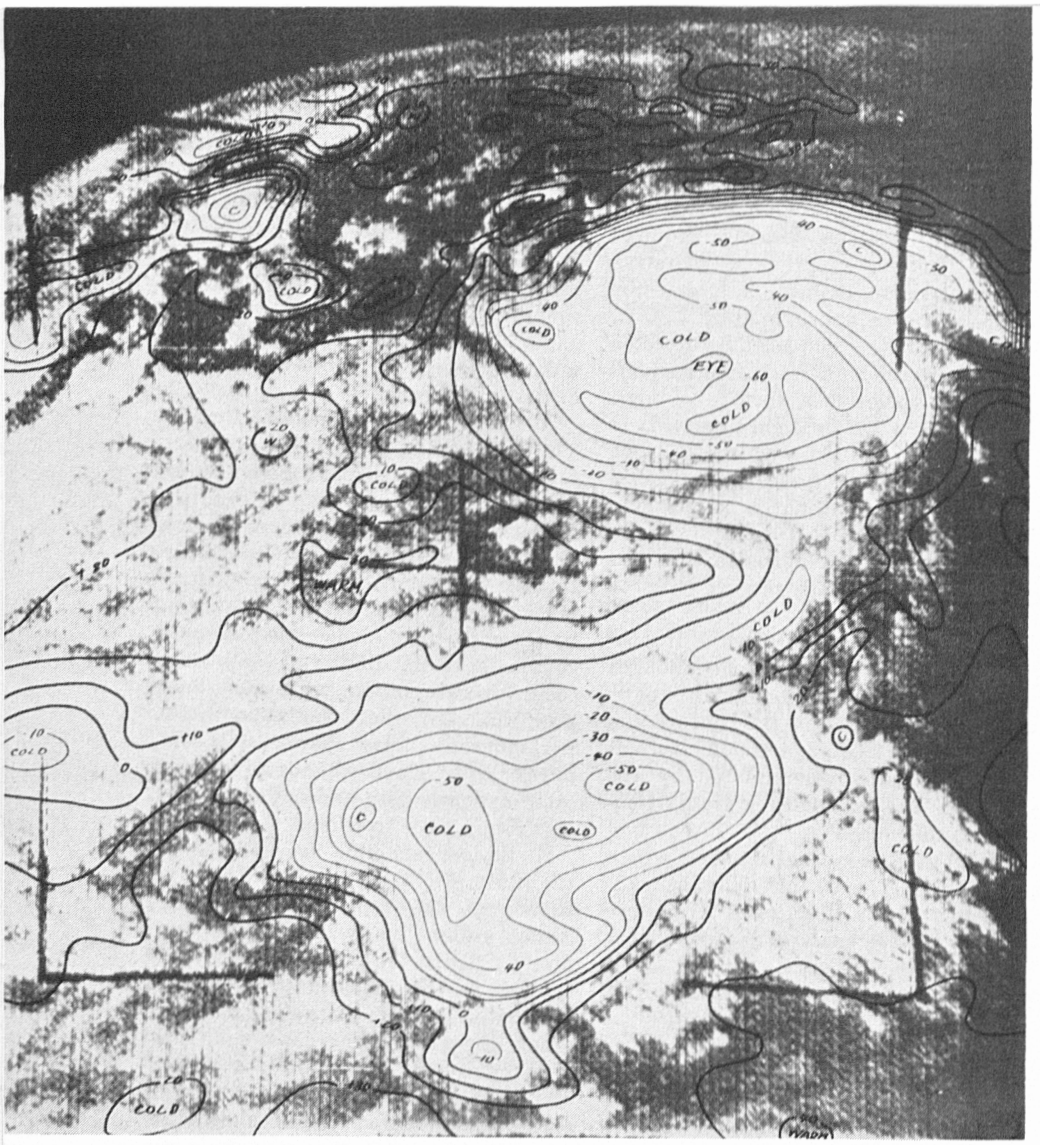
Data are recorded on a magnetic tape containing the radiation intensities in digital form as a function of geographic location, viewing geometry and time. This record, called FMRT (Final Meteorological Radiation Tape), is produced by a highly complex program in an IBM 7090 computer from digitized telemetry records and a knowledge of the calibration of the sensors and the satellite's location and attitude. The latter is especially cumbercome to incorporate since none of the satellites flown so far has been earth-oriented. In utilizing the data that is, in plotting cloud cover maps, deriving energy budgets, or performing other research on radiation data, it is most advantageous to program the problem and operate directly on the FMR tape without intermediate printouts.

For those who do not have easy access to large digital computers data catalogs were published on Tiros II[19] and III[20] which contain a representative sample of data collected, and are intended to show the potential of the radiation measurements. The map on page 77 is a typical example of such a data display. Its significance will be discussed below.

*Review of Experimental Results.* The wide-field radiometers on Explorer VII[8] have already given an indication that patterns of emitted radiation fluxes from the earth can be well correlated with cloud patterns. It was the Tiros five-channel instrument, with its much greater resolution, however, which demonstrated most convincingly its ability to map cloud cover. To date, innumerable cases have been analyzed where radiation in the 8–12 micron window channel was compared with cloud photographs and other synoptic data and the agreement was found to be excellent.

A typical example is depicted in the illustrations on page 77. The map shown in the top illustration was drawn automatically by the computer directly from the FMR tape, and is typical for the results presented in the Radiation Data Catalogs.[19,20] In the other illustration, the same map has been contoured manually for better clarity, with regions of different blackbody temperature ranges shown in different shades of grey, and the path of the satellite subpoint from northwest to southeast also indicated. The region of minimum temperature (200–230 K) near 13° N, 72° W indicates a circular cloud system which, because of its very low temperature, must extend to extreme altitudes. Indeed, this system coincides with hurricane Anna, identified through cloud photographs and aircraft reconnaissance. In a series of similar radiation maps, the storm can be tracked over its entire path almost 4000 km.

Because of the small scale of plotting, the temperatures shown on the maps generally represent averages over several scan spots within one grid element. Therefore the maps do not necessarily show the true minimum temperature measured in the storm center. In fact, careful examination of each scan spot reveals that this temperature ranged between 200 and 210 K. From a climatological temperature profile, shown on page 80, one finds the height of the cloud top for the hurricane at approximately 15 km, while the cloud system just to the southeast of the storm shows minimum temperatures near 230 K and therefore a cloud top height of approximately 11 to 12 km.

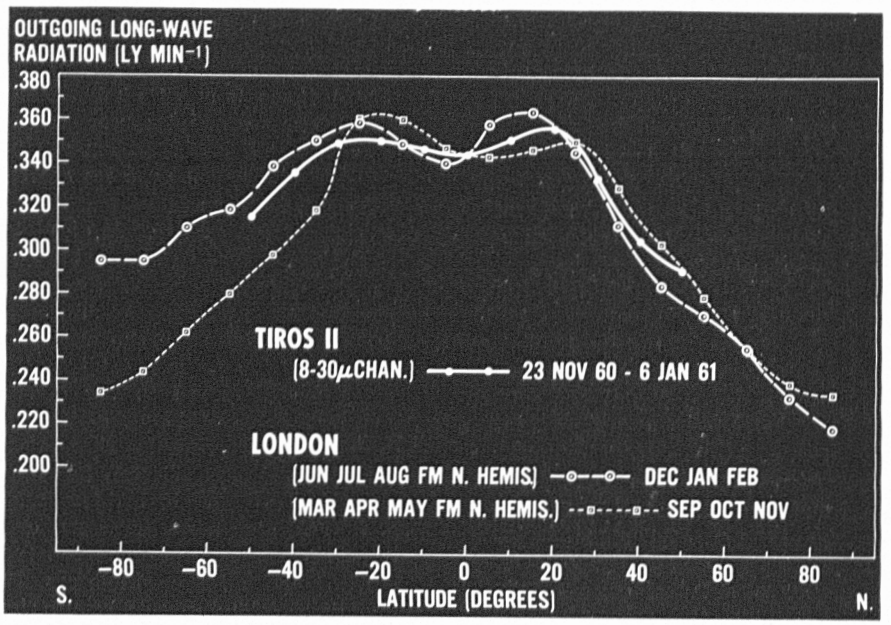



**Hurricane Anna as seen by Tiros III** (Orbit 132) near 13° N, 72° W. Contour lines represent relative radiation intensities from 8–12 micron channel. Radiation contours drawn from raw analog data.

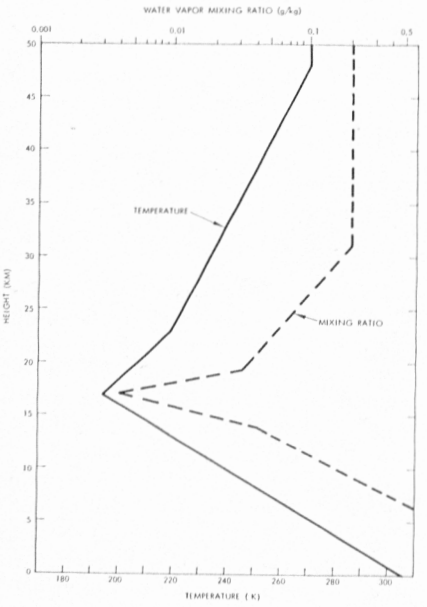
Such height determinations can only be made from radiometer data and are not at all evident from cloud photographs such as the one shown at left here. The illustration shows a Tiros photograph over hurricane Anna taken at the time of the radiation measurements of the two illustrations on page 77. In addition, manually reduced contour lines of radiation values in the 8–12 micron channel prepared from the *analog* telemetering records are superimposed on the photograph. The analysis of these analog radiation data and the contouring of the photograph shown adjacent was carried out by Prof. T. Fujita and his staff at the Univ. of Chicago. His kind permission to reproduce his results in this article is gratefully acknowledged.

The perfect match between radiation and cloud patterns is striking. It is this type of presentation, given on an incomparably larger scale than in the two maps, which demonstrates the full cloud-mapping ability of the radiation sensors. Unfortunately, in the illustration at the left, the radiation intensities were plotted on a relative scale only and the contour numbers shown are arbitrary and not well suited for cloud height determinations.

Additional features apparent in the map on page 77 are the huge clear area (290–300 K) over central South America corresponding to the high-pressure system one would expect to find in this subtropical belt in the winter hemisphere, and the large cloud mass off the coast of Florida. Comparisons such as the one shown in the




**Outgoing Long-wave Radiation** vs. latitude, measured and predicted. Tiros II results (solid curve) are compared with theoretical curves of J. London (dashed curves).




**Temperature and Water Vapor Mixing Ratio** vs. height. Temperatures taken from data on tropical atmosphere. Water-vapor profile fits radiation data over Hurricane Anna.

map on page 80 and the ability of computers to create meaningful maps from the digitized data clearly demonstrate that radiometric observations in an infrared "window" region may well be used for synoptic analysis in future real-time meteorological satellite systems.

It must be strongly emphasized, however, that such systems are still very much in the future. The example given for the determination of cloud-top heights illustrates the principle only and any cloud height measurement with present Tiros instruments is very approximate. Many difficulties of a theoretical nature must still be overcome. For example, no true atmospheric window really exists where the transmission even in clear atmosphere is 100%. Black-body temperature measurements in the 8–12 micron channel by Tiros must therefore be corrected for absorption by water vapor, carbon dioxide, and ozone. A theory to apply such corrections was developed by Wark and Yamamoto.[2] Even after applying these corrections, investigations show that, especially when cloud tops are near the earth's surface, radiation measurements yield temperatures 5–10 K too low.

There could be several reasons to explain this: Clouds which were assumed to radiate as black bodies in this region of the spectrum may have an emissivity considerably less than 1; particles in the atmosphere such as aerosols or thin cirrus clouds, not visible in TV photos, may produce additional absorption not accounted for in the Wark-Yamamoto theory; the theory or assumptions used in the theory may be inadequate; or measurements given by the instrument may be in error. All four reasons are now being investigated.

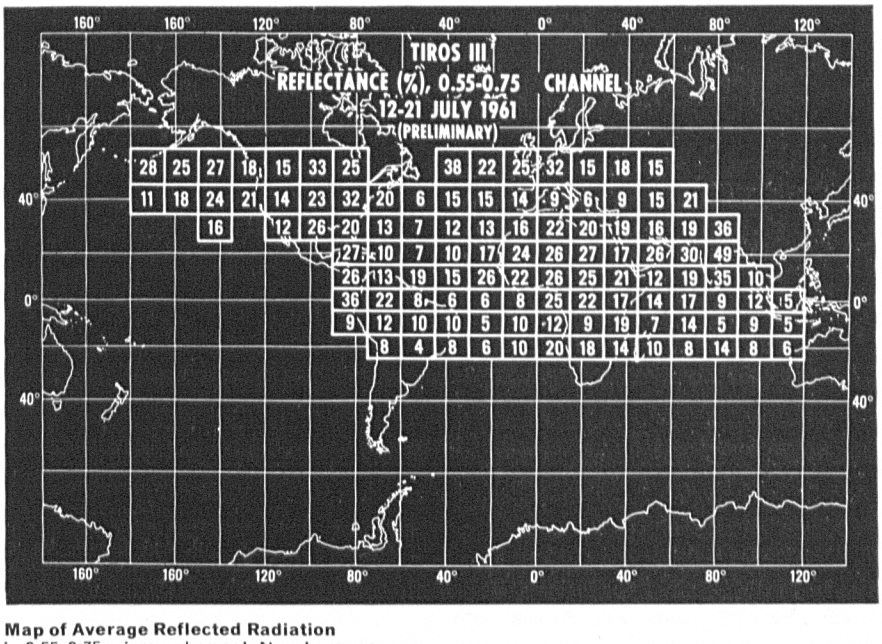
An increasing deterioration in the response of all channels of the radiometer with flight time was found in Tiros II and to a greater extent in Tiros III.[16] However, corrections to account for this change in calibration are already incorporated in the temperature difference stated above. Results of further theoretical investigations and elaboration of the above reasons will certainly provide more precise methods of cloud height determinations from radiation measurements. In addition, these investigations, combined with a more complete scrutiny of all the data available, will shed light on such unknowns as the emissivity of various types of clouds and the screening effect of aerosol or similar particles on the outgoing radiation. Nevertheless, empirical correction factors can be obtained even now from existing data and successful, if approximate, determination of cloud-top heights may be and have been made from Tiros measurements.[23]

Similar considerations govern our ability to derive pertinent information on the structure of the atmosphere from radiation data. An example is given in the illustration on page 80. By comparison of the black-body temperatures measured in the 8–12 micron window channel over hurricane Anna (200–210 K) with simultaneous measurements in the 6.7 microns water vapor absorption channel indicates that the temperatures measured in the latter are approximately 10 K higher. Since we have already determined from the window channel that the cloud tops reached to approximately 15 km (near the tropopause), this temperature difference can only be explained by the presence of considerable amounts of water vapor in the stratosphere above the cloud top.

Bandeen, et al.[9] have found by trial and error a water-vapor distribution which will produce this measured temperature difference. The required water-vapor mixing ratio vs. altitude function is shown in the illustration on page 80. This function is by no means unique but was chosen because it agrees both with present ideas of water-vapor content in the stratosphere[25] and with the radiation measurements. Again, the above case is typical for several situations observed so far over extensive cloud systems in the tropics and is indicative of some of the more subtle information contained in these results.

Attempts to derive estimates of the global heat budget from radiation data have been made and investigations by Winston and Rao,[8] Bandeen and Nordberg,[5] Prabhakara and Rasool,[6] and House[7] have shown that on a large scale the satellite results confirm theoretical estimates by London[24] and others on the global distribution of total emitted long-wave radiation. The satellite investigations are based on Explorer VII measurements[26] and on the 8–30 micron channel from Tiros II and III.[5,6,8] An example is shown in the graph on page 80. Tiros II data shown in this figure have been corrected for the deterioration of the sensor response with time and for total outgoing flux by the method of Wark and Yamamoto.[22]

The Tiros results show clearly, although not to the extent predicted by theory, a minimum of outgoing radiation near the equator. This minimum is due to the extensive cloud cover in the equatorial zone, while the maxima near the two tropics reflect the clear skies and warm temperatures of these regions. The more rapid decrease of outgoing radiation with latitude in the winter hemisphere, due to colder temperatures and intenser cloudiness, as well as the higher maximum near the summer tropic, can be clearly found in the satellite data. Investigation of outgoing radiation on a shorter time scale based on Tiros II measurements, and comparisons with dynamic considerations of the atmosphere, have shown that in some cases minima in outgoing flux go hand in hand with




**Map of Average Reflected Radiation** in 0.55–0.75 micron channel. Numbers are in per cent of incoming radiation, averaged over grid elements and time period shown.

an increase in the zonal kinetic energy which is derived from, and is a measure of, the energy carried by winds along a latitude circle.[5] This first indication of a connection between the gross outgoing radiation measured by satellites on a planetary or continental scale and energy parameters relating to the dynamics of the atmosphere will be further pursued, and is of major importance to an understanding of the forces which create circulation in the atmosphere.

A complete planetary heat budget, however, must include a measure of incoming solar radiation in addition to outgoing long-wave radiation. Measurements from one of the Tiros III solar radiation channels (0.55–0.75 microns) of regional averages of reflected energy over a period of nine days are shown in the illustration on page 81. The numbers express the total energy reflected in percent of incoming solar radiation within the spectral range of the instrument. This incoming radiation was taken to be (108.6 w/sq meter) sin *e*, where *e* is the elevation angle of the sun at the location and time of measurement. The value of 108.6 is derived from a total solar constant of 1395 w/sq meter and the spectral response for this channel.[16]

The illustration shows that radiometric measurements in the visible spectrum again reflect very well the distribution of cloud cover—namely, high average reflectivities near the equator and low ones in the subtropics, except for India, where during this time of the monsoon the highest average reflectances (49%) were observed. The differences in average reflectances between land and water at moderate latitudes only may also be seen in this illustration. Reflectances over the subtropical North and South Atlantic, the Indian Ocean, and the Mediterranean are appreciably lower than over land masses at comparable latitudes. Apparently, in these regions differences in the reflectances of land and water surfaces are noticeable because of the predominantly clear weather. At higher latitudes, like the North Pacific, no difference in reflectance can be detected, apparently because cloud cover is more frequent over water than over land.

In addition to supplementing the cloud cover patterns observed during daytime in the infrared window, which is not well suited to detect low-altitude clouds, the solar radiation channels on Tiros can be used to derive *relative* measurements of the absorption of solar energy and aid in interpretation of long-wave outgoing flux measurements.

The illustration also shows that measured reflectances cannot be interpreted as measurements of planetary albedo, and are therefore not useful to include in quantitative heat budget considerations at this time. Since the solar constant is known quite accurately and the outgoing flux is given in the graph on page 80, we know that, for the sake of equilibrium, the sum of the average planetary albedo and the outgoing radiation must equal the incoming solar radiation. This results in a value of 32 to 36% for the average albedo. The average found from the illustration is 17 to 18%.

This disagreement by a factor of 2 is difficult to explain, particularly since the deterioration in the response of the sensors[16] has already been taken into account. The fact that Tiros measurements for this period cover only a limited region of a zone between 55° N and 25° S may influence the results somewhat, but certainly not to such a large extent.

A more likely explanation may lie in the fact that the values in the illustration are based on isotropy and uniformity with regard to both the angle and wavelength of the backscattered sunlight. There are indications from theoretical investigations[26] that the reflectance toward the direction of the incoming sunlight may be appreciably larger than in other directions. Since in most of the observations used in the illustration, the angle formed by the sun, the target, and the satellite was near 45 deg, it is possible that this might account for the low observed reflectances. A variation in the reflectance with wavelength may also contribute to make the satellite observations appear too low.

These factors are now being investigated both theoretically and by supplementary laboratory and free atmosphere balloon measurements.

*Conclusions.* Thus, maps of cloud patterns revealing meteorological features such as frontal systems, tropical storms, etc., have been produced with adequate resolution and in large quantities from the Tiros radiometric experiments to demonstrate their value to both day and night synoptic analysis. With appropriate, empirically derived, correction factors, one can also obtain approximate measurements of cloud heights, especially over large, uniform, and intense cloud systems. Successful determinations of the global distribution of total emitted long-wave radiation over limited periods of time have been made and agree well with theoretical predictions. Some preliminary correlations were found between outgoing fluxes and dynamic parameters in the atmosphere.

Reflected solar radiation, measured to permit an evaluation of the entire planetary heat budget, follows very closely, as one might expect, the patterns of cloudiness, as well as the distribution of land and water—at least over those regions of the globe covered by Tiros. Quantitative measurements of the earth's albedo, however, have not been possible as yet.

The difficulties which now prevent us from interpreting solar-energy reflectance measurements in terms of albedo and the disagreement found between calculated and measured emitted radiation in the window channel will certainly force us to subject measurements to further interpretations. From these we may find further enlightenment regarding the large-scale scattering, emission, and transmission properties of clouds, the earth's surface, and the atmosphere—parameters which may still lie dormant in a vast amount of data. We believe that, with the successful interpretations of the radiometer measurements mentioned earlier, we have only exploited a small, more obvious portion of the data.

It has also been shown that under certain circumstances the presence of substantial amounts of water vapor in the stratosphere can be implied from simultaneous radiation measurements in two spectral channels. Again, resolution of some of the outstanding theoretical questions will produce more information on water-vapor distribution both in the troposphere and stratosphere.

Tiros radiation measurements have also pointed up the need for an improvement in the stability of optical sensors under prolonged flight environment. Deterioration in sensor response during orbital flight has not been fully explained. This further emphasizes the need for reliable in-flight calibration on future instruments. And, finally, support of satellite experiments with coordinated ground-based or balloon measurements have become even more important.

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IR radiation, ozone distribution, cloud top heights, the solar constant, and "sferics" figure in future satellite experiments

# Physical measurements from meteorological satellites

BY R. A. HANEL, NASA Goddard Space Flight Center
and D. Q. WARK, National Weather Satellite Center

Extensive discussions of the meteorological observations successfully obtained from artificial satellites, including the photographs taken by the Tiros series and the radiometric measurements by Tiros and by Explorer VII, have been given elsewhere. The forthcoming Nimbus series of meteorological satellites will carry similar television and radiometric instruments. In addition, other experiments are being planned and further experiments of meteorological importance are under study.

One of these experiments involves indirect determination of the atmospheric temperature. The radiance of the atmosphere to space in the infrared depends on the transmittance and the temperature, by the well-known principles of radiative transfer. The transmittance of an atmospheric gas depends mainly on its vertical distribution and if, as in the case of carbon dioxide, one can assume a uniform mixture, the transmittance is known as a function of the pressure. From measurements of radiance at several wavelengths with different transmittances, one should be able to deduce the temperature of the atmosphere as a function of pressure.

In 1959, L. Kaplan suggested that the temperature structure of the atmosphere could be deduced from radiance measurements from a satellite in several narrow intervals of the 15-micron carbon dioxide band.[1] At a conference to discuss infrared satellite experiments, it was suggested that the most feasible instrument at the present time for carrying out the suggested measurements would be an infrared grating spectrometer with multiple detectors.

The Weather Bureau and NASA have proceeded with the development of an instrument of suitable bandwidth and radiometric accuracy. The first "breadboard" model has been produced and tested. The spectrometer, with its specially designed wedge-immersed thermistor detectors, has been described in detail elsewhere.[2] The photo on page 86 shows the spectrometer and gives a view of the grating and the detectors. The accompanying diagram shows the layout. An $f/5$ Ebert-type spectrometer of the "under and over" sort, it employs a grating 5 in. square that has a dispersion of about 1.4 $cm^{-1}$ per mm at 15 microns. Exit slits are about 5 $cm^{-1}$ wide, with the detector lenses situated behind the slits. In addition to four intervals in the 15-micron band, there is a fifth detector 7 $cm^{-1}$ wide located in the 11.1-micron "window" whose purpose is to measure the temperature of the surface or cloud tops. A chopper wheel allows alternate views through "space" and "earth" ports.

This breadboard instrument has been used to conduct experiments from the ground, and has been found to perform approximately to the required radiometric accuracy. A report on its performance will be published in the near future. Currently under construction are instruments containing most of the design elements required for a satellite-borne instrument. These will first be tested in high-altitude balloons.

The spectrometer, however, is bulky (16 by 32 in.), heavy (55 lb, exclusive of electronics except the preamplifiers), and a heavy drain on power (10 w). Aboard a satellite, an interferometer would be more satisfactory from every standpoint. Although interferometer development is now considerably behind that of grating spectrometers, there is every promise that they will eventually achieve the spectral resolution and radiometric accuracy needed for indirect temperature soundings.

In the microwave region, the 5-mm band of oxygen might be employed for the same purpose, as suggested by Lilley and Meeks.[3] Discussions of some problems with indirect soundings will be found elsewhere.[4-7]

Microwave radiometry is another area of interest. The infrared region from 3–40 microns is presently the domain of many meteorological satellite experiments. The presence of atmospheric absorption bands of $H_2O$, $CO_2$, and $O_3$ make this region well suited for a variety of investigations. Furthermore, detectors are readily available and instrumental techniques fairly well established. But thermal emission at much longer wavelengths, in the regime of microwaves, also deserves attention. Some atmospheric constituents show a number of rota-

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tional lines there. Oxygen, for example, has a strong line at 2.5 mm and a band of 36 lines at 5 mm, while water absorbs at 0.85 and 13.5 mm.

The microwave range differs from the infrared by a factor of about 100 in the wavelengths. Theoretical concepts for experiments in the region of thermal emission are applicable to both infrared and microwave wavelength regions. However, the physical phenomena, and especially the instrumental techniques used, in both wavelengths make them distinctly different in many respects.

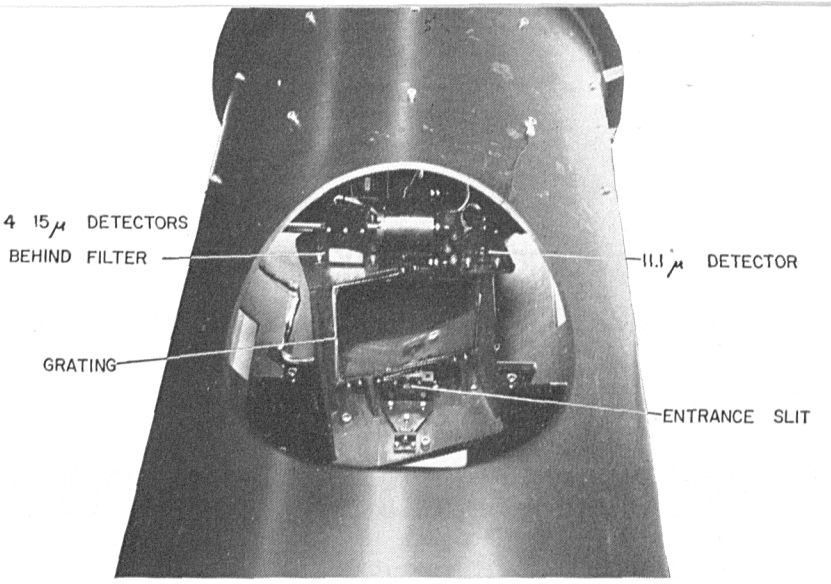
The longer microwaves penetrate clouds much easier than infrared rays. Only Rayleigh scattering must be considered for microwaves, since cloud droplets are very small compared to the wavelength. This is not necessarily so for larger rain drops, so that a method to detect precipitation in clouds may be based on this phenomenon. Furthermore, the high resolving power of microwave receivers and the existence of individual strong lines fairly isolated from others, removes some of the difficulties inherent in interpretation of infrared bands that consist of many overlapping lines of different strength.

These apparent advantages must be contrasted to certain drawbacks. In the infrared, the radiant emittance of a source, say at 250 K, is very sensitive to small temperature changes. The emittance in a narrow band near the 6.3$\mu$ water band, for example, is approximately proportional to the 10th power of the temperature. The same source shows a third power relation between emittance and temperature at 20$\mu$. For microwaves, the signal strength is only linearly proportional to temperature.

The available emittance over useful ranges is orders of magnitudes lower at microwaves than at normally useful ranges in the infrared. This particular shortcoming, however, is compensated by the different operating concept of microwave receivers.

In the far infrared, the thermal detectors in use today register the radiation by means of the heating they undergo in absorbing the radiation. They are, however, affected by noise fluctuations which are the ultimate limitations on their sensitivity. In most instances, the noise is entirely unaffected by narrowband optical filters placed in front of them.

In contrast to this, the tuned circuit (cavity) of the microwave receiver (and other methods which restrict the effective bandwidth) short-circuits all frequencies not within its passband. This very effective reduction in noise makes possible microwave intensity measurements to an accuracy equivalent to a fraction of a degree centigrade.



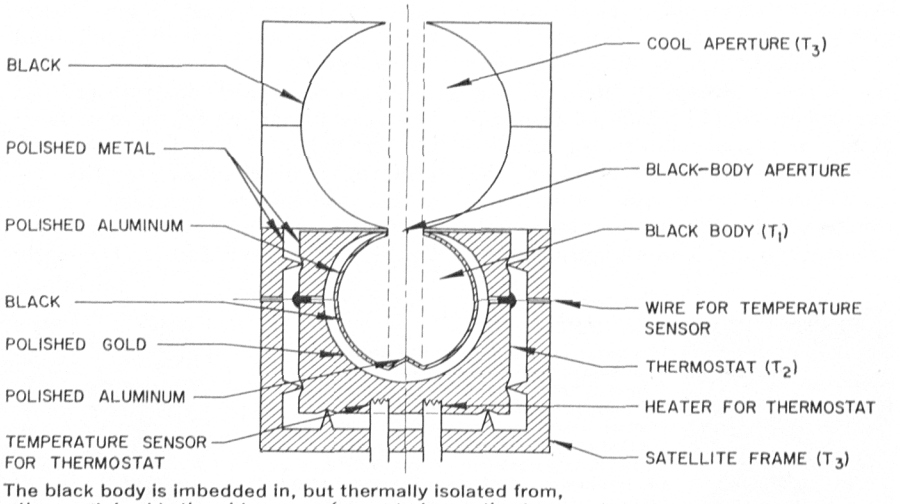

**"Breadboard" Spectrometer** photo above shows entrance slit, grating, detectors, and parts of viewing ports. The diagram on the opposite page shows side view of the spectrometer. The signal is the view out of the paper ("space") chopped against the view into the paper ("earth") as reflected off the mirror at the left, which here appears rotated to view a calibration black body.

Before useful meteorological experiments can be performed in this spectral range, many physical parameters must be considered. Absorption coefficients of atmospheric gases, extinction cross-sections of water droplets and ice crystals, the transmissivity of clouds and the emissivity of various types of terrain, plus state of the art of low-noise receivers, are important design criteria.

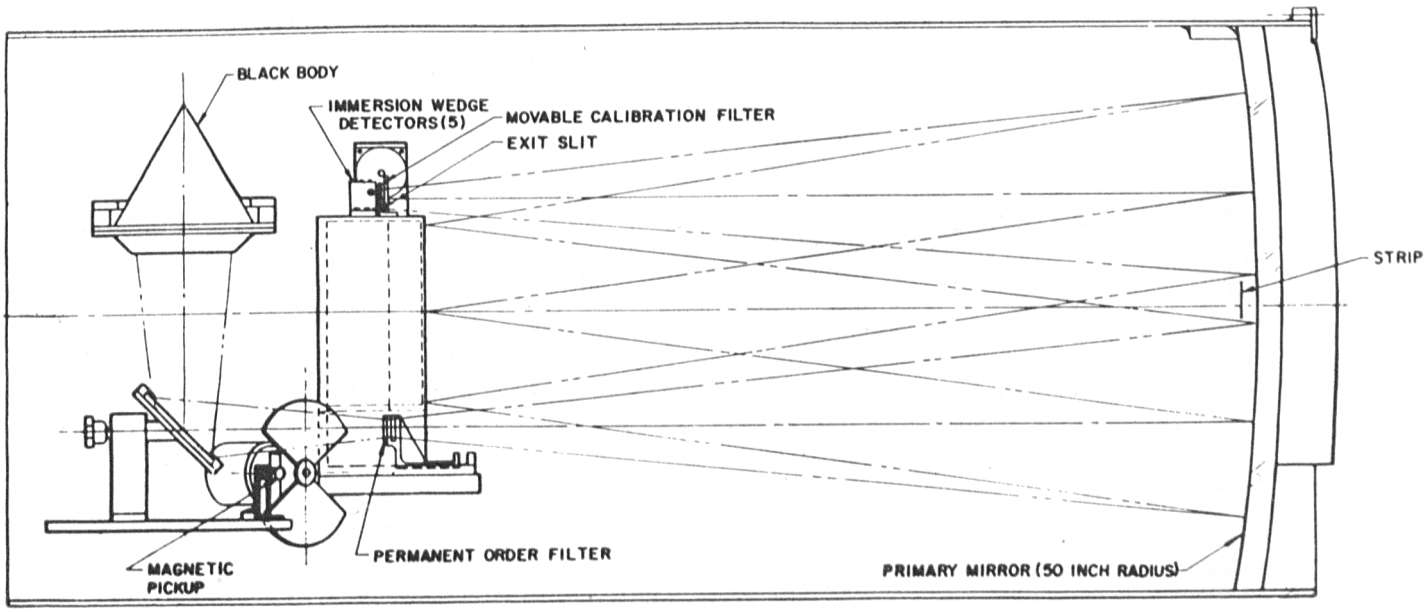
In much the same way that temperature structure can be obtained from a satellite, the distribution of ozone might also be found from measurements in the strong Hartley band in the ultraviolet. Because the transmittance of ozone is known, measurements of scattered sunlight at several wavelengths or of the occultation of direct sunlight by the atmosphere, at a series of positions of the satellite, can be used for the deduction of ozone distribution. Originally suggested by Singer,[8] this topic has been discussed in more detail by Singer and Wentworth,[9] Twomey,[10] and others.

Frith,[11] of the British Meteorological Office, suggested the occultation method; his instrument is to be carried in a satellite in the near future. Another instrument has been flown briefly in a polar orbiting satellite.[12] Each of these instruments employs a filter which admits a rather broad band in the ozone band below 3000 A. They are basically broadbeam receptors, in contrast with vertically viewing spectrometers considered for

**DETECTOR ASSEMBLY**




The black body is imbedded in, but thermally isolated from, a thermostat set to the wide range of expected operating temperatures. The cool aperture forms a black body for convenience.




ozone and temperature experiments.

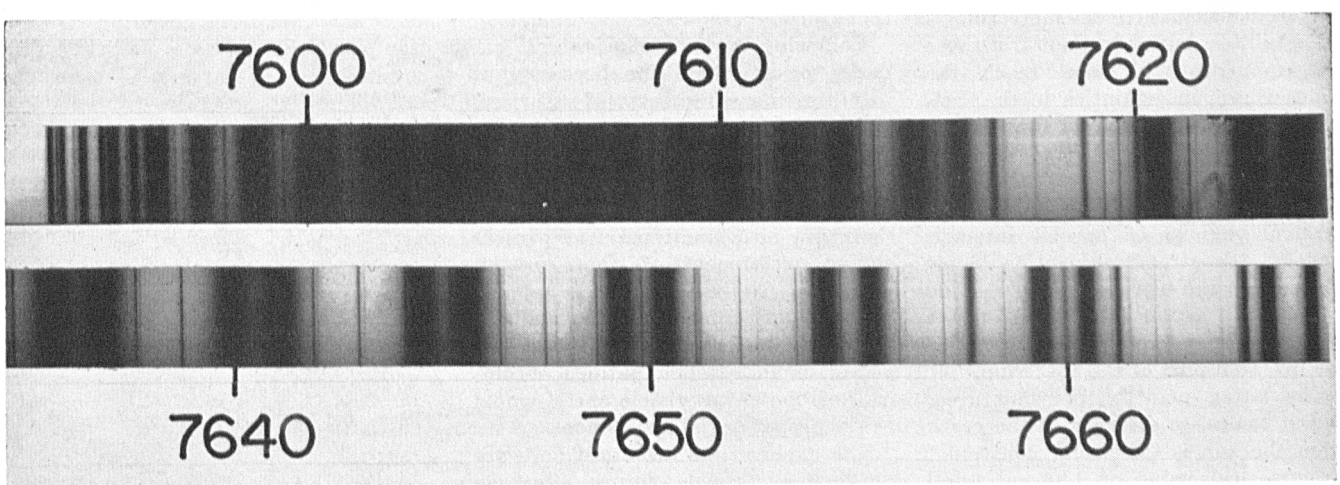
A wavelength scan for vertical viewing of scattered sunlight would require a spectrometer (or interferometer) with a resolution of a few angstroms and a field of view of not more than about 0.04 steradians. Such instruments have been considered, but have not yet been implemented by the Weather Bureau or NASA.

In another area, measurements of reflected sunlight by a satellite instrument can indicate the presence of a cloud, but meteorologists also require a knowledge of the height of cloud tops. Infrared radiometric measurements can be used to determine cloud-top temperatures, but the relation between height (or pressure) and temperature in the atmosphere is highly variable. Another method, largely independent of the temperature variations is available to us.

If a gas has a known mixture in the atmosphere, the transmittance of sunlight from the top of the atmosphere down to a cloud, and back to a satellite, will depend (aside from a slight temperature term) upon the optical path, given by the pressure at the cloud top and the angles of incidence and view. The only unknown is the pressure at the cloud top, which can be deduced from transmittance as measured from the relative radiance in the band and in the nearby continuum.

This experiment was proposed by Hanel,[13] who suggested using the 2-micron band of carbon dioxide. Yamamoto and Wark[14] suggested that the 0.76-micron band of oxygen would be better. While the 1.8-micron band of water vapor overlaps the 2-micron band rather seriously, the oxygen band does not suffer from blending of other atmospheric bands. For high clouds or for low water-vapor content, the situation for the 2-micron band is more favorable, although high spectral resolution would be necessary to take advantage of this band.

The detail of the 0.76-micron band is shown at bottom. In the upper part is the R branch which contains the band head (left), the band center, and 3 lines of the P branch. Below is an additional part of the P branch. This spectrum was obtained with the 150-ft tower telescope at Mt. Wilson. Many details can be seen, including the lines due to the $O^{17}$ and $O^{18}$ isotopes. Using this and other spectra, a study is being conducted to determine all the




**Spectrum of 0.76-Micron Oxygen Band,** obtained with the 150-ft tower telescope at Mt. Wilson. In the upper part is the band head (left); the **R** branch lies between the band head and the band center; three lines of the **P** branch can be seen to the right of the band center. In the lower part are lines farther out in the **P** branch. The very narrow lines throughout are from the isotopic molecules $O^{16}O^{17}$ and $O^{16}O^{18}$. There are also some solar lines.

necessary physical parameters of the band and to calculate transmittance under the range of optical path found in the atmosphere.

The illustration shows that the R branch can become nearly totally absorbing, and therefore the transmittance becomes insensitive to optical path. In the P branch, there remain regions of rather great absorption, but, at the longer wavelengths, there is a region of significant but not overwhelming absorption where sensitive measurements of transmittance might be made. Where the optical path is short (vertical incidence off high clouds), the P branch may become too weak to allow good transmittance measurements, and the R branch could be the preferable region. Thus it would probably be better to monitor several regions of the spectrum to cover all ranges of transmittance to be encountered with changing cloud heights, sun angle and viewing angle. Because filters do not cut off sharply, this experiment might require a spectrometer of low spectral resolution.

There is as yet no active effort to build an instrument to carry out this experiment from a satellite. The study of the band must first be completed in order to set forth the instrumental requirements.

Another interesting experiment would deal with the solar constant.[15] The fraction of solar energy absorbed by the earth and its atmosphere is of great importance for the understanding of meteorological processes. Absorbed sunlight heats the atmosphere and surface, and provides the energy source for evaporation of water and atmospheric circulation. The amount of radiation absorbed by the earth can be determined from a satellite by measuring the incident and the reflected components of the solar flux.

So far, only the reflected component has been measured from meteorological satellites, but refinements in these measurements will soon reach the point where uncertainties in the incident radiation become appreciable, and both components (the incident and reflected flux) must be determined. This holds for certain narrow spectral regions of special interest, such as the strong absorption bands of ozone in the ultraviolet (2200–2800 A), as well as for total solar energy flux integrated from the ultraviolet to far infrared part of the spectrum.

The latter quantity, per unit area, and at the mean distance of the earth from the sun is the "solar constant." A numerical value of 1.94 cal $min^{-1}$ $cm^{-2}$, or 1350 watt $m^{-2}$, is generally accepted today,[16-18] although a more recent survey indicates that 2 cal $min^{-1}$ $cm^{-2}$ is a better estimate.[19] These values were derived from measurements made in recent decades from the earth's surface. Atmospheric extinction, however, necessitates considerable correction of experimental results. The atmosphere is completely opaque to large portions of the ultraviolet and infrared spectrum.

Satellites now present the opportunity to determine the solar constant directly, without the interference of the atmosphere.

The method chosen for a future experiment exposes a black body to the sun, registers the equilibrium temperature of the body, and telemeters the data back to earth. In equilibrium, the incoming solar flux balances the black-body flux from the cavity which is well defined by Stefan-Boltzmann's law. The measurement of energy flux can thereby be reduced to a temperature measurement.

Certain precautions must be taken, concerning mainly the blackness of the body, the degree of isolation achieved, and the accuracy of the temperature sensing devices.

The principle of the instrumentation is shown on page 87. The black cavity is thermally insulated from its surrounding as much as possible. In addition, the net flux between the cavity and its mounting is made negligible by thermostating the housing to approximately the operating temperature of the black body.

One final experiment that might be mentioned involves the measurement of "sferics," or the RF emissions by lightning (from "atmospherics"). The detection and mapping of sferics could be an important contribution to meteorology by indicating areas of strong vertical motion related to tropical storm development and to other violent phenomena bearing on strong winds, heavy rainfall, and turbulence.

Following a discussion among experts to determine the necessity of satellite measurements of sferics,[20] and the instrumental requirements for such an experiment, the Weather Bureau has sought to establish a more firm design requirement. Although there are no commitments at present on an instrument of this sort, it has been suggested that a simple receiver of fairly broad bandpass (probably in the vicinity of 100 mc/s), and with an antenna pattern encompassing the entire visible earth, would be the proper initial experiment.

The experiments discussed here are part of a possible future effort in meteorological observations from satellites. They may eventually be flown as space becomes available, and other experiments, not discussed here, may also be carried on satellites. However, instruments for such experiments must be conceived well in advance of possible flights because of the long lead-time involved.

Some of the Tiros experiments and those planned for Nimbus will be continued on an operational basis. Others may have only limited observational requirements, and can be discontinued after objectives have been achieved. These can then be replaced by others, so that the vital requirements for flexibility in scientific investigation can be realized, and new ideas and concepts continually tested.

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Studies of ice, snow, forest fires, and locust swarms show the potential for extensive work in this field

# Non-meteorological observations from weather satellites

BY S. FRED SINGER and ROBERT W. POPHAM, National Weather Satellite Center

Shortly after the launch of Tiros I in April 1960, the late Harry Wexler, then Chief of the U.S. Weather Bureau's Office of Meteorological Research, requested the Bureau's Meteorological Satellite Section (now the National Weather Satellite Center) to look into the possibility that Tiros pictures taken over Canadian east coast waters showed ice in the Gulf of St. Lawrence. This study indicated that ice was indeed observed, and concluded with the comment that ice reconnaissance from satellites appeared most feasible.[1] Two years later, with the launch of Tiros IV, civilian and military aircraft, ships, and weather stations participated in a joint Canadian-United States program to evaluate the use of satellites for ice reconnaissance and surveillance.

In August 1962, at the request of the Department of Lands and Forests of the Ontario Government in Canada, the National Weather Satellite Center participated in an operational program to determine whether smoke could be detected if a major forest fire occurred. Using the information which that Department and the U.S. Forestry Service later provided, one case where forest-fire smoke was observed and identified in Tiros satellite pictures has been confirmed, and two others are being investigated.

Recently a program has been started to determine the extent to which satellite pictures of snow cover may be used to estimate the amount of runoff which would occur as a result of snow melt. In addition to NWSC, this study includes participation by the U.S. Weather Bureau's Hydrologic Services, the Canadian Hydrometeorological Service, and other Federal, state, and provincial government agencies interested in the conservation of water resources, flood control, and navigation.

On several occasions, Tiros neph-analyses have been used in conjunction with surface weather observations to predict the probable migration of swarms of desert locusts in the Somali Peninsula area.

In developing an operational weather satellite program, the National Weather Satellite Center is primarily concerned with the identification of cloud features seen in satellite pictures and the physical processes which result in cloud formation, movement, and eventual dissipation (see page 70). For this reason, the design of satellite camera, infrared, and microwave sensor systems is necessarily directed toward satisfying meteorological requirements for these specific types of observations. The operational picture interpretation and data-processing techniques used are designed to satisfy the limits for speed and accuracy established by the meteorologist.

While the primary function of an operational meteorological satellite system will continue to be aimed toward obtaining observations of direct meteorological significance, the experiences just described indicate how such a system may very well fulfill the needs of scientists in other fields for broad scale observations on a real-time basis.

It is somewhat difficult, of course, to draw a fine line indicating where the interests of the meteorologist in ice, snow, and forest fires should end and the oceanographers', hydrologists', and foresters' interests should begin. In the sense that ice is generally considered of more immediate economic interest to the oceanographer than to the meteorologist, satellite ice studies are considered "non-meteorological" applications of satellite data. This same reasoning applies to satellite observations of forest fires and snow cover. The relation between meteorological satellite observations of clouds and the migration of locust swarms is somewhat more direct, but locust studies also share this somewhat dubious distinction.

*Ice.* The first satellite photograph of sea ice was obtained within hours after Tiros I was launched on April 1, 1960. Since then, every Tiros vehicle has observed ice in such areas as Hudson Bay and Gulf of St. Lawrence, the Sakhalin Islands off the east Asiatic coast, and more recently in the Antarctic.[2]

Approximately 15-million sq mi., or about 10% of the earth's surface, is covered by sea or land ice. For this reason it has major climatological significance, and necessarily enters into any consideration of the earth's total heat budget. On a smaller scale,

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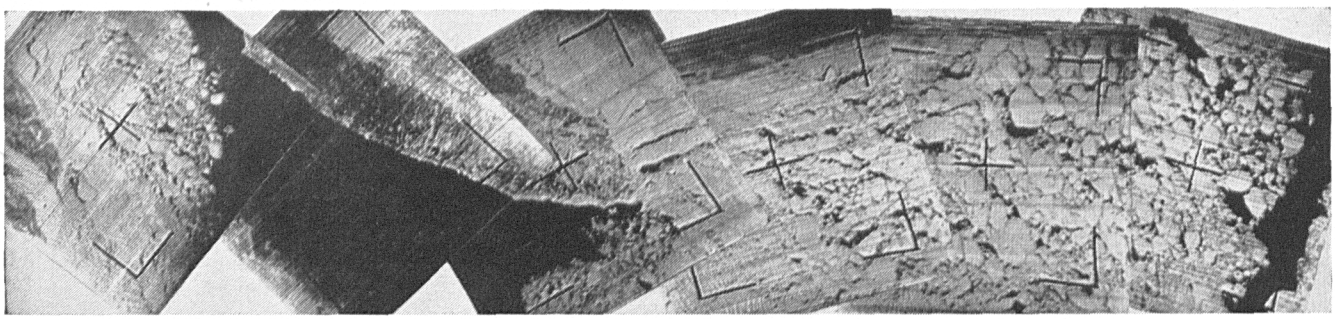
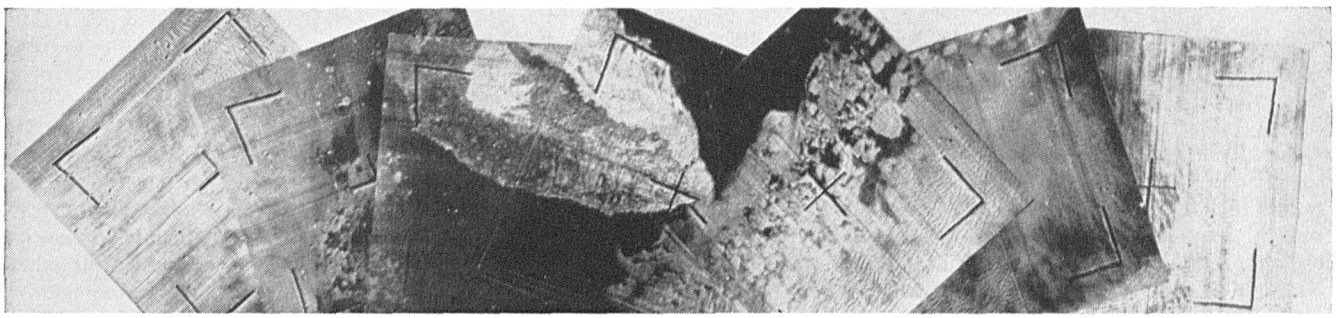
**ROBERT W. POPHAM**
joined the National Weather Satellite Center of the Weather Bureau at Suitland, Md., in 1959. A contributor to the Joint USA/Canadian Ice Reconnaissance Study last year, he is engaged in research for the Bureau with emphasis on ice-reconnaissance studies affecting watershed balances and ice movement affecting shipping. He received his B.S. in meteorology in 1959.



**Ice Pictures Taken by Tiros II** (narrow-angle lens) over the Gulf of St. Lawrence. The top picture, taken March 23, 1961, shows open water south of Anticosti Is., fast ice extending out roughly 3 mi. from its north coast, and a refrozen lead paralleling the fast ice. About 40 mi. north of the coast, the reflectivity of the ice changes abruptly along a well-discernible line. East of the Island, large ice floes and fields are separated from the west Newfoundland coast by open water. The bottom picture, taken March 29, 1961, shows the change in ice conditions north of the Island; open water now exists north of the line where the change in ice reflectivity occurred six days earlier.



ice completely covering numerous small lakes or large bodies of water substantially reduces the amount of water vapor available to the free atmosphere through evaporation. One effect of this is a marked reduction in snow-flurry activity, and frequently a regional transition from a Maritime to a Continental climate.

The possibility of conducting routine satellite ice surveillance to observe the advance and retreat of major ice-pack boundaries is especially important to the climatologist and to the meteorologist concerned with extended weather forecasting. With a polar-orbiting weather satellite such as Nimbus, this information will be readily available.

Of more direct economic significance, however, is the possibility of conducting routine ice reconnaissance from satellites. Since ice constitutes a major hazard to navigation, it has a direct bearing on the wintertime economy of many countries, especially in the northern hemisphere. Almost all the ice observations presently used by forecasters to predict ice conditions for commercial or military vessels, operating in areas such as the Gulf of St. Lawrence or going into the Antarctic ice pack, are obtained from aircraft or ice breakers. In 1961 the U.S. Navy and Coast Guard spent an estimated $400,000 for aerial ice-reconnaissance observations in support of U.S. fleet operations, while an additional estimated $6,650,000 was spent in maintaining and operating ice breakers. In Canada, aircraft and ice breaker operations combined cost an estimated $3,500,000. (The above figures were compiled from data provided by the U.S. Navy and Coast Guard and the Canadian Department of Transport.)

Shown above here are portions of two mosaics prepared from pictures obtained with the narrow-angle (12.7 deg) camera on Tiros II in March 1961. The six-day change in ice conditions around Anticosti Island in the Gulf of St. Lawrence is readily apparent. Several cracks or leads in the ice, as well as many individual ice floes, can be distinguished.

In early 1962, United States and Canadian government agencies participated in a joint program to determine the extent to which satellite ice observations could be used to complement aerial and ship reconnaissance. While much of the information remains to be analyzed, preliminary analyses and discussions with ice analysts indicate that ice information obtained on a routine basis from a Nimbus vehicle could provide much of the data presently collected by aircraft. These discussions also revealed that observations from such a vehicle might have resulted in a total saving to both countries of approximately 40% or $800,000 accruing largely through a reduction in the frequency of long-range flights and the use of smaller, short-range aircraft (possibly helicopters). In addition, savings of about 10% or roughly $900,000 might have been realized through a reduction in the fuel, maintenance, and upkeep costs of icebreakers. There are also many more, but less easily estimated, savings which would be realized by commercial shipping companies.

While the above figures indicate possible savings which might have resulted through the use of satellite ice observations, it would undoubtedly be more realistic to assume that, even with the satellite, the annual cost to those organizations responsible for conducting ice reconnaissance would have remained essentially the same or increased slightly as the demands for ice information increase. However, the increase in total effective area coverage which can be obtained from satellites, and the use of these satellite ice observations to direct ship and aircraft movements, would result in the rapid accumulation of significantly more ice information than had heretofore been possible. The accumulative savings could conceivably be far more than those estimated for 1961.

The persistence of an ice feature is the most feasible operational method of distinguishing ice from clouds, but this method can only be used where there is sufficient background contrast. Thus, stereoscopic methods of distinguishing clouds from the underlying surface are being investigated. The use of infrared and passive microwave sensor systems to identify or penetrate clouds is also being studied.

It is not too difficult to imagine that within the next two to three years a group of ice observers or analysts, highly trained in interpreting satellite photographs, may be located at one or two satellite readout stations, directing ships through major leads in the ice pack, or routing reconnaissance aircraft directly to small leads or openings to investigate ice conditions in more detail.

*Snow.* A major responsibility of the hydrologic services in many countries is determining the extent and depth of snow. Snow melt is a major source of water in many of the states and provinces in western North America. The rate of snow melt is particularly important to civil engineers and hydrologists for water conservation and flood-control purposes.

The photo at bottom shows that very little change occurred in snow conditions in the Canadian Rockies during a 15-day period in April 1962. Comparing the pictures with a map of the area, one can follow the Columbia River for many miles through the mountains.

Using satellites to observe the extent of snow-covered ground and to obtain qualitative estimates of the rate of snow melt constitutes a study just beginning. Snow cover in the St. Lawrence River Valley is currently being studied by NWSC in association with the Joint Photographic Intelligence Centre (JPIC) in Canada, as an extension of the Canadian–United States satellite ice program. A major project involving Tiros VII, as well as a thorough examination of previous satellite observations of snow cover in western North America, will be conducted this spring by several Canadian and United States agencies.

As an exercise in determining how accurately snow cover might be measured in satellite pictures, various methods (gridding and planimetering) were used to calculate the extent of the snow-covered area near the center of Anticosti Island in the Gulf of St. Lawrence. We used a mosaic of aircraft pictures obtained on April 13, 1962, a Tiros IV medium-angle (78 deg) picture of April 3, 1962, and a Tiros II narrow-angle (12.7 deg) picture (see page 90) of March 29, 1961, to make these estimates:

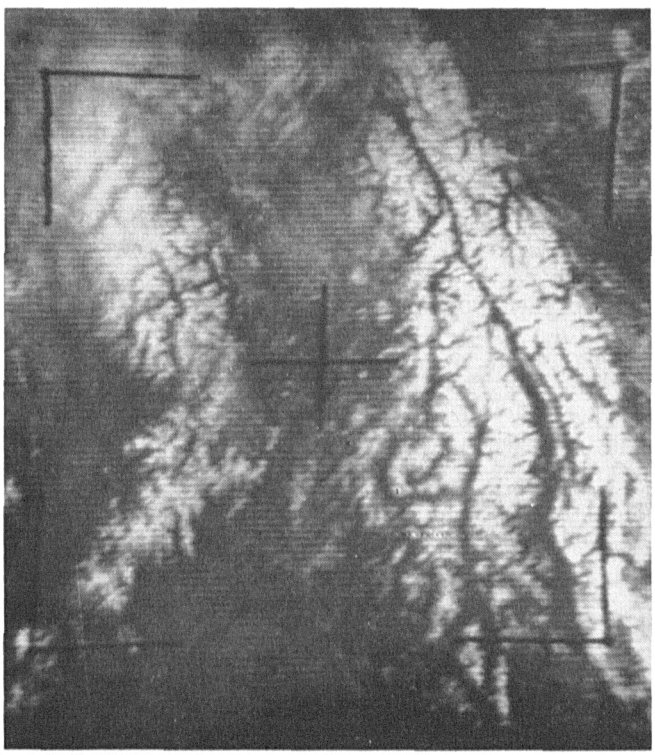
Aircraft mosaic—300 sq mi. ±10.
Tiros IV pictures—300 sq mi. ±40.
Tiros II picture—290 sq mi. ±15 mi.

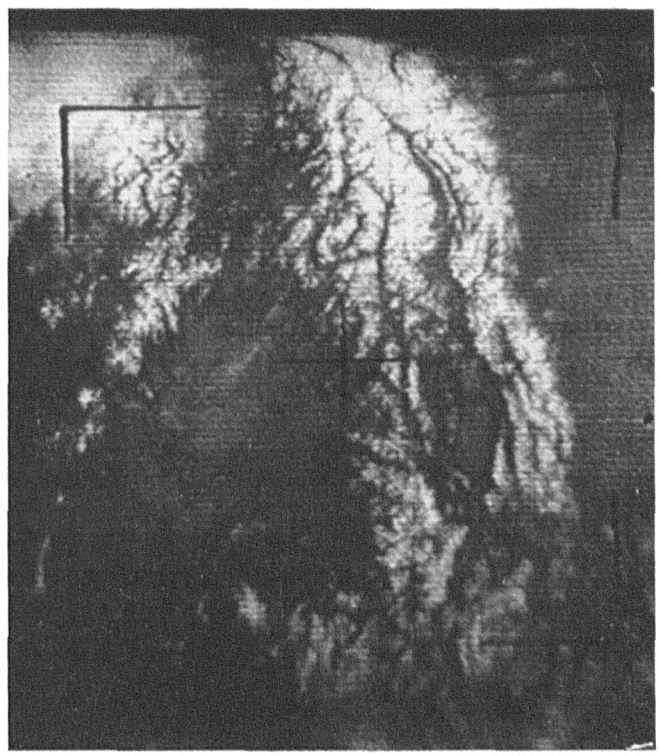
About 220 sq mi. of snow-covered area measured in these pictures was burned over by a forest fire in 1955. The boundary of the burn and the boundary of the snow cover are almost identical along the northern and western sides. The southeast boundary is more diffuse; the snow cover as seen in the pictures extends into a swampy region. The amount of snow-covered swamp outside the burned area was determined to be 70–80 sq mi., bringing the total snow-covered burn-swamp area to 290–300 sq mi.

*Forest Fires.* It has been estimated that some 130,000 forest fires occur each year in the United States alone. Of this number, about 7,000 are started by lightning; the rest are caused either indirectly as a "by-product" of human activities, or through individual carelessness. Our annual expenditure in the United States for detecting and fighting forest fires has been estimated at $150–$200 million, and the annual loss has been estimated at between $50–300 million.

Human observers stationed in fire towers several miles apart provide the most effective method of forest-fire detection. To complement tower observations, aerial reconnaissance has been used with increased frequency in recent years. Electronic devices aboard aircraft are also being used as a means to detect "sleepers"—forest fires which smoulder for several days before breaking out and producing a visible smoke column.

The efficiency of any fire-detection system depends on its ability to main-





**Snow Cover Over Part of the Cascade** and Rocky Mountain ranges, in Canada, as seen by Tiros IV.
In the picture on the left, taken April 11, the dark lines through the Rockies are largely river valleys; the Columbia River and Canoe River valleys can be readily identified.
The right-hand picture, taken April 16, reveals minor changes in snow cover between these two mountain ranges.
Note the over-all dendritic drainage pattern of this entire area, revealed by the distribution of the snow cover.

tain a watch over an area, however large, where fires might occur and to relay information on the fire's location, size, and apparent direction of movement. It is frequently too costly to maintain surveillance over vast forested areas outside the continental United States. In Alaska and Canada, for example, fires often go undetected for many days, and consequently exact a tremendous toll. The use of satellites to complement existing forest-fire detection techniques, therefore, has major economic implications.

In July 1962, the United States Forestry Service provided the National Weather Satellite Center with the coordinates of 19 forest fires. The largest of these burned 66,000 acres. Of the 19, only 11 might have been observed by the satellite. Of these, there were three cases where the area was virtually cloud-free, but no smoke could be identified.

Working with data supplied by the Department of Lands and Forests on fires occurring in mid-1961, National Weather Satellite Center personnel tentatively identified forest-fire smoke in Tiros III pictures obtained on July 12 and 13, 1961. This analysis was confirmed when weather records for that period showed smoke being reported by several weather stations in the area. This is the only confirmed case where smoke from a forest fire has been detected in satellite pictures, but two other cases are being examined. Both of these involve forest fires in California, one in late 1961 (specific date unknown) and one in August 1962. Further studies may reveal forest-fire smoke elsewhere in Tiros pictures. The fact that it has been positively identified in only one case does not mean that they cannot be seen. The 19 cases provided by the United States Forestry Service include only those causing fire damage to Federal government property. Fires involving damage to state-owned lands have not been investigated.

This approach—examining satellite pictures over areas where fires are known to exist—is necessary to establish lines of further research in this area. Assuming that other examples can be found, meteorological conditions existing at the time of the observation should be examined. The background against which the smoke was observed should also be studied along with the type of woods (fuel type) which were burning. Sunlight, and the angle of view from the satellite, should also be considered. Smoke from the 1961 fire in California was identified against a water background, having been blown off the coast by easterly winds.

Early detection of fires is obviously a prerequisite for effective fire control. Improved camera systems and the interpretation techniques may make it possible to observe smoke in satellite pictures on an operational basis, but probably not fast enough for effective fire fighting action. High-resolution infrared radiation scanners and passive microwave sensors planned for future satellites may prove best for early detection of fires.[3]

As part of the analysis of satellite snow-cover observations, pictures taken two winters apart are being examined to determine whether changes in the snow pattern may be related to forest fires which have burned undetected during the intervening period. Locating these areas and estimating the size of the burn appear to be well within our present capabilities.

*Locusts.* At first glance, one might hardly think of discussing locusts in a paper concerning satellites. But the synoptic weather pattern depicted on Tiros nephanalyses, as well as the satellite pictures themselves, have been used on several occasions in conjunction with surface meteorological observations to forecast the migration of swarms of the desert locust—a highly mobile, prolific insect which breeds largely in arid regions, such as the Sudan.

In many countries, locusts have inflicted heavier crop damage during the past decade than ever previously recorded.

The 60 nations subject to attack by this insect spend approximately $15 million annually on its control, under the direction of the Food and Agriculture Organization, supported by the United Nations Special Fund. Through a cooperative arrangement among the member nations, supplies of insecticides are stockpiled in areas likely to be invaded. When swarms are located, they are sprayed from aircraft.

The effectiveness of this method of control depends largely on ability to predict the invasion area. Meteorological factors are important in predicting the breeding areas of the locust swarms, their time of emergence, and their migration.[4] The significance of atmospheric convergence, both on a micro-scale and a macro-scale, in the concentration and migration of swarms has long been noted.[5,6]

Aircraft and ground observations indicate that heavy swarms are comparable in size to water droplet clouds commonly photographed by Tiros. At Hargeisa in the Somali Peninsula, for example, a large swarm covering an area of approximately 130 km$^2$ was observed on Aug. 3, 1960. The vertical extent of flying swarms has been observed to vary from a few meters to several thousand meters, while the spacing between locusts may vary from more than 10 locusts/m$^3$ down to 0.001/m$^3$.[5] However, it is very doubtful if the contrast between the swarm and the surface would enable positive identification. The immediate application of satellites in this field will be largely confined to locating frontal systems and other areas of convergence by analyzing satellite television or infrared observations.

*A Final Note.* Many individuals seem awed by the apparent complexity of satellites, and are frequently reluctant to become involved in satellite-data interpretation until some concrete evidence of its applicability to his field has been demonstrated. Lack of knowledge about how to interpret observations and, occasionally, where to obtain them may have discouraged many who would like to work with satellite data. Neither need be lacking. And we hope the work described here will convince many, as it convinced us, that many other applications, besides the strictly meteorological, will be forthcoming, some quite unanticipated, for a National Operational Satellite System.


### Acknowledgments

In a paper of this nature, to which so many organizations or individuals have contributed both information and ideas, it is obviously difficult to acknowledge completely contributions by each one independently. However, we are particularly indebted to the Meteorological Branch of the Department of Transport in Canada for stimulating and participating in many of the projects involving satellite applications to ice reconnaissance, snow surveillance, and forest-fire detection; to the Anti-Locust Research Centre in London, England, for information and the compilation of data related to locust studies; to the U.S. Navy and Coast Guard for the figures used to estimate 1961 ice-reconnaissance costs; and to the many other United States and Canadian government and private organizations, not mentioned elsewhere in this paper, that have been working closely with NWSC in exploring applications of meteorological satellite observations.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Increasing weather-satellite usefulness will be a major goal of the World Meteorological Organization

# WMO moves into space

BY F. W. REICHELDERFER, Chief, United States Weather Bureau

The world was quick to recognize the international significance of spacecraft and the vital importance of developing astronautics and cognate activities in the ways of peace. Not long after the first satellite was placed in orbit, the UN General Assembly established a Special Committee on the Peaceful Uses of Outer Space; and again in its Resolution 1721 of December 1961 and Resolution 1802 a year later, the Assembly strongly urged all nations to cooperate in exploring and developing the great possibilities in this new sphere.

By implication, these resolutions emphasized also the close relationships and interdependence of astronautics, meteorology, and telecommunications. To these should be added aeronautics, because in the nature of things these four realms of science and technology have much in common, not only in their mutual interest in the atmosphere right from the earth's surface up to its outer limits and out into space, but also in their frequent dependence on international cooperation.

Obviously, not all international matters go through the United Nations or other formal channels of government. Many important activities work directly between private groups or through international institutions outside of governments. Good examples are the programs planned and conducted by the national academies of science and the national research councils of many countries working internationally among themselves, and the international scientific associations like ICSU (International Council of Scientific Unions) with its many affiliates representing the different fields of science. In the field of astronautics the IAF (International Astronautical Federation) is a nongovernmental association of interested national societies. Doubtless everybody experienced in things international is well aware of the advantages of direct and informal action when governments need not be concerned.

But whenever plans or activities depend on funding or other support by governments, or involve recognized government prerogatives, sovereignty, and security, then intergovernment machinery must be brought into the arrangements. Usually there are several approaches to intergovernmental action—bilateral, multilateral, universal.

Currently the U.S. and U.S.S.R. are endeavoring through conferences between designated representatives of the two governments to agree on working arrangements for complementary launchings of satellites and exchange of data from spacecraft. As more nations become active in astronautics, the negotiations and working arrangements will become multilateral, and later the United Nations may establish another specialized agency devoted exclusively to this field of science and technology. The successive stages in organizing international activities in aviation during the past 50 years, leading finally to the UN International Civil Aviation Organization (ICAO), are indicative of probable trends in international procedures.

Of necessity, meteorologists organized their international interests long before the UN was established. Because the general circulation of the atmosphere carries air masses with their endless variations and frequent weather changes rapidly across continents and oceans regardless of national boundaries, exchanges of weather information between countries are very necessary. A meeting of prominent meteorologists from many countries was convened in Brussels in 1853 to agree on standards and exchange of weather reports. In 1878 the International Meteorological Organization was formed to provide broader acceptance of its working arrangements; and IMO continued until 1951 as a nongovernmental international association, although recognized as quasi-official by most governments.

In 1951, the IMO was transformed into the World Meteorological Organization (WMO), incident to the growing emphasis on affiliation of all intergovernment organizations with the United Nations. The IMO, comprising as it did most of the scientist-directors of the best-known meteorological institutes and weather bureaus of the world, held to its nongovernmental status as long as possible, and this emphasis placed by its members on freedom of planning and action in scientific matters without nationalistic restraints is reflected in the form of

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heads the United States Weather Bureau and is U.S. Representative to the World Meteorological Organization, having served as its President from 1951 to 1955, and President of the WMO Regional Association for North and Central America. From 1939–51, Dr. Reichelderfer was U.S. Representative to the International Meteorological Organization.

organization finally adopted for WMO.

The WMO Convention, drafted in Washington in 1947, provided Technical Commissions composed of scientists recognized in one or more of the several branches of meteorology—aeronautical meteorology, climatology, research, etc. When serving in the Technical Commissions, members are expected to represent science and technology for the common good and work toward advancement of meteorology. Subsequently, many panels of scientists were established for *ad hoc* participation in developing special plans, with the understanding that the members, like those of the Technical Commissions, direct their efforts to the aims of WMO.

Telecommunications were also organized for international cooperation long before the UN. The International Telecommunications Union (ITU), now one of the UN Specialized Agencies, and the WMO work closely together. Interwoven interests of ICAO, ITU, and WMO have frequent bearing on services and facilities available for astronautics, especially in its expanding international role. Operations of spacecraft require rapid and reliable telecommunications and benefit from comprehensive reports of atmospheric conditions over most if not all parts of the globe.

Indeed, in a sense, the whole earth is the "terminal airport" for spacecraft. Although launching sites and re-entry or landing places will usually be fairly well fixed, there will be frequent occasions when communications and weather for almost any region or place on earth may be needed unexpectedly and urgently. Present networks of telecommunications and weather-reporting stations do not give adequate world coverage, and under UN Resolution 1721 the WMO has suggested a plan for development of a World Weather Watch. The map on page 95 shows the present coverage in weather reporting for the Northern Hemisphere.

These communications for the international synoptic weather reporting system make up one of the largest "news"-gathering facilities in the world. The principal channels in the system carry a continuous flow of meteorological data. Throughout the world the respective national weather bureaus make their standard observations for weather maps at 0000, 0600, 1200, and 1800 Z. The telecommunications carry the detailed reports to designated collection centers. These reports flow in standard weather codes adopted worldwide through the work of IMO/WMO and refined or modified many times by the Technical Commission for Synoptic Meteorology to accommodate the code forms and specifications to changing requirements and new technologies in aeronautics and other fields of operation. Changing requirements often disclose important differences in the needs of the different countries and between the diverse circumstances in polar regions and tropical, aeronautical usages and agricultural, continental, and maritime, etc.

Each station meteorological report or synoptic weather message contains data for some 18–20 surface weather elements; and if it is a radiosonde station, the single message may have data representing more than 50 different atmospheric conditions or "quantities." The geographical coverage on land and sea, the use of standard technical procedures and uniform reporting codes throughout the world, and the speed of transmission of reports and completion of mapping four times daily in the principal meteorological centers on all continents, now including Antarctica—all show the remarkable coordination achieved by WMO in the international synoptic weather reporting system.

In the National Meteorological Center at Suitland, Md., near Washington, D.C., for example, the map room plots reports from something like 2000 stations, each report consisting of 7 to 12 5-figure groups (more in cases of upper-air sounding stations), each representing at least 10 weather elements. This reporting and mapping repeats every 6 hr. An estimate of the world number of 5-figure groups of weather data transmitted daily indicates a total of at least 15 million code groups.

With such great numbers of weather reports every few hours, one might conclude that the sampling of meteorological quantities in the atmosphere is adequate for the needs of meteorologists and all other practical purposes. Quite the *contrary*. It has been estimated that present observations and soundings of the atmosphere represent only about 1/10th, and for some purposes of research and prediction perhaps less than 1/100th, of those necessary to develop meteorology as a quantitative science.

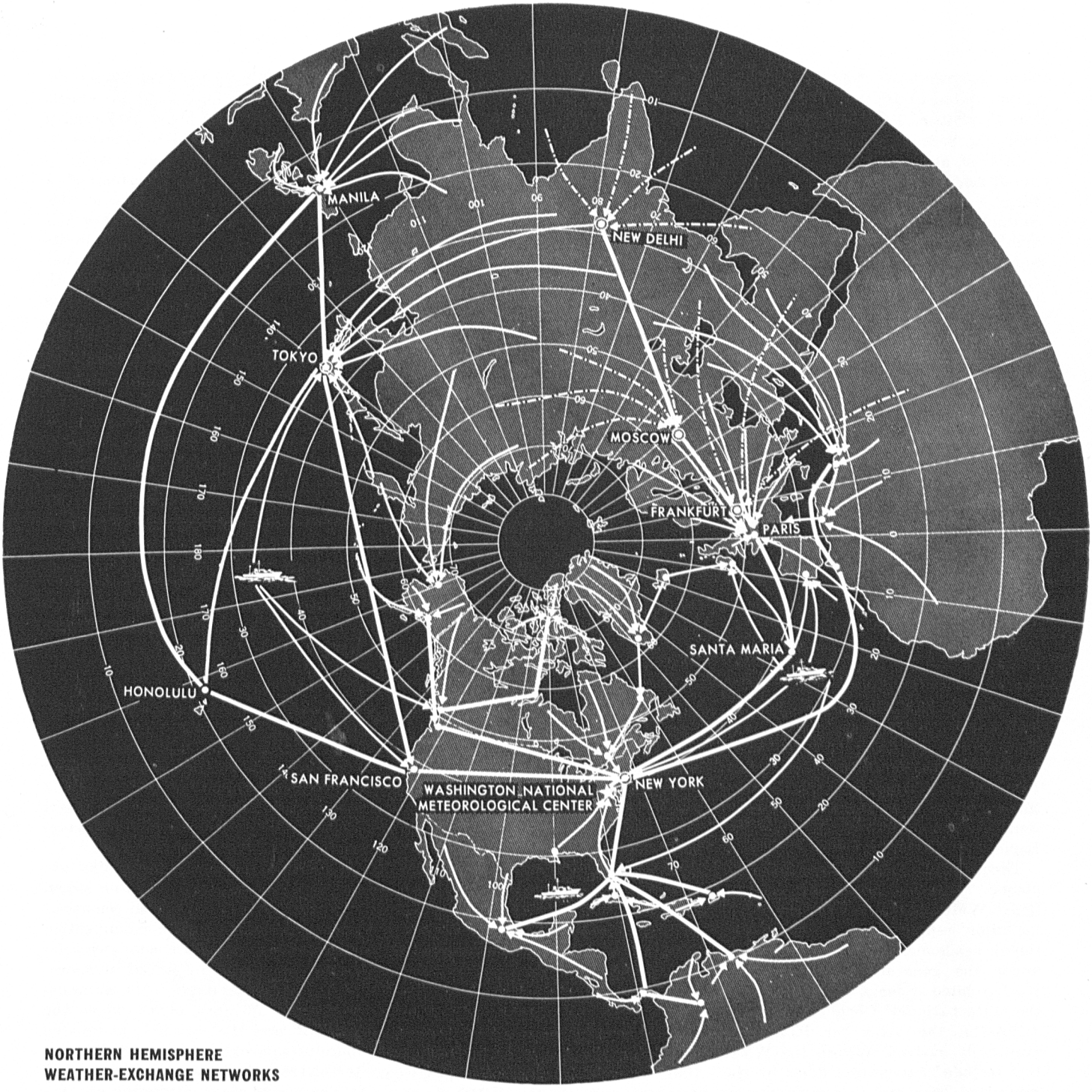
Evidence of the inadequacies for the globe as a whole can be seen in the plan for a World Weather Watch published in the WMO First Report in response to UN Resolution 1721. This plan is mainly the work of the late Harry Wexler of the U.S. Weather Bureau and of Victor Bugaev of the U.S.S.R. A map in the WMO First Report visualizes the severalfold increase needed in upper-air soundings over ocean areas and parts of continents not yet covered. The form of the proposed network for soundings of the atmosphere will likely change considerably as a result of satellites. These will serve to collect meteorological information not only directly by television, as in Tiros cloud photographs, but also indirectly as communication-relay facilities for ocean buoys and constant-level balloons that would constitute a floating grid in the atmosphere.

These ideas foresee very great increases in the various forms of meteorological and communication networks that would encompass the globe, and the services they would provide to aviation, astronautics, and other fields benefiting from weather information. They would certainly call for the international agencies—ICAO, ITU, WMO, and others—to take still greater responsibilities in negotiating suitable working arrangements including uniform practices, coordinated schedules, etc.

The weather communication facilities just outlined are not organized into a world network in the strict sense of comprising a single system. The "system" is now made up of the separate national networks coordinated through the efforts of the WMO into essentially a whole. Undoubtedly, a well-designed over-all world system of weather communications for the common good would entail many changes. It would bring many improvements and show many economies, but it would also give rise to deep problems of national interests and usages in many countries. An integrated, universal design in communications and meteorology leads to the same kind of dilemma as concepts of world government, albeit somewhat less acutely.

Notwithstanding the many advantages that are conceived in proposals for international organizations like WMO to become worldwide service agencies with responsibility for designing, establishing, and operating the facilities that are required in common by all countries, the ICAO, ITU, WMO, and other UN Specialized Agencies are not likely to change in this way but probably will continue to be primarily *coordinating* and promotional bodies, and leave the operating services to the national meteorological agencies of countries.

Actually, the present synoptic networks show remarkably good coordination, although in many respects they represent successive patchwork solutions, often shaped by expediency and limited financing, with gaps in some places and overlaps in others. Some




**NORTHERN HEMISPHERE WEATHER-EXCHANGE NETWORKS**

are made up of teletype or even telegraph and telephone lines, others radio circuits, some radioteletype. Inevitably, today's networks show many weak links at relay points where errors, delays, and omissions occur.

In the United States, for example, practically all of the original weather communication circuits by wire telegraph have been converted to teletype, not only for aviation services but also for general meteorological services. A few short links are by telephone or radio. International transmissions are by teletype, cable, and radio, some over commercial channels, others by government circuits, with different departments providing the facilities in different segments or links of the system. These include the Coast Guard, Federal Aviation Agency, military departments, and Weather Bureau.

Meteorological reporting and communications have grown up in this multiple participant manner because the insatiable requirements for more weather data have gone far beyond the practical scope of a single organization. The reports from remote localities and from ocean areas can be obtained with the desired coverage and frequency only by making use of weather observers and communication circuits established primarily for other purposes, for example, ships at sea.

Clearly, the resulting aggregate offers a challenge to the designer of new systems, and the approach is not simplified by the national and international aspects that cannot be disregarded.

Despite difficulties, the world "system" serves well for many purposes, although not for all. A brief account of the ways in which special projects have been put into operation through the procedures of the WMO will illustrate their effectiveness.

The program of the International Geophysical Year (IGY) in 1957–58 was perhaps the largest worldwide operation ever undertaken in science. It was carried through very successfully, especially in meteorology. How the plan developed is of interest. The proposal to organize an IGY grew from a suggestion that a Third Polar

Year be organized for the 1957–58 period of maximum sunspot activity. The First Polar Year was held during 1882, the Second during 1932–33.

In 1950, at a small informal gathering of scientists in Silver Spring, Md., Lloyd V. Berkner spoke of the untold contributions an IGY could give to man's knowledge and to practical applications of geophysics. The idea doubtless had been discussed many times in scientific meetings, as in the session of the International Union of Geodesy and Geophysics (IUGG) in Brussels in August 1951. That session, however, held to the plan for a Third Polar Year, and in one of its concluding resolutions invited the WMO to send a representative to meetings for planning the Polar Year.

Up to this time, discussion and development of the plan had been largely, if not entirely, in nongovernmental associations. This is indicative of advantages in encouraging free play of creative scientific ideas among individuals outside restraints of official position. In its session during October 1951, the WMO Executive Committee, just one month after IUGG had adopted its Polar Year resolution, took the subject under consideration and concluded that "a Geophysical Year for the whole world would be of greater interest to WMO than a Third Polar Year, having regard to the fact that routine meteorological observations are now made in the North Polar Region."

Through a series of conferences among representatives of IUGG, ICSU, WMO, and many special groups, including representatives of the national academies of sciences, acting under the general guidance of the ICSU-related Special Committee on the International Geophysical Year (CSAGI), the plans for IGY were eventually evolved. Within the WMO this included extensive studies by the interested Technical Commissions and by working groups of members selected to consider particular aspects of the program.

These scientific groups presented their recommendations to the WMO Executive Committee and the WMO Congress (1955), and it was through these official intergovernmental channels that formal agreements were eventually reached among directors of national meteorological services, where the many segments of the IGY program were actually carried out. Funding and technical operations were done almost entirely by the individual nations. International coordination into a cohesive program was through the WMO and its constituent bodies and panels. WMO collaborated with other interested intergovernmental and nongovernmental bodies as appropriate. The entire meteorological program was an impressive demonstration of international accomplishment through voluntary cooperation.

A somewhat different development was the WMO action on UN Resolution 1721 on outer space, making special reference to communications, meteorological satellites, weather forecasting, and atmospheric research. Tiros I was launched April 1, 1960. Designed as an experimental satellite, it immediately became "operational" because its cloud photographs have great practical value for locating storms at sea and for other purposes of weather forecasting. Tiros photographs were displayed during the WMO Executive Committee session of June–July 1960. The response was enthusiastic. All members wanted to obtain Tiros photos daily for use in their national meteorological services.

On his return home, the U.S. Delegate to WMO informed higher offices of government of this international interest, and the possibilities of "weather" satellites serving a universal need among the peoples of the earth and bringing them closer through their common interest in weather and climate. The outlook was presented in personal briefings by the Weather Bureau before members of the Federal Council for Science and Technology and the President's Science Advisory Board.

In September the proposal was referred to a panel for study, and during the next several months it went through successive stages of being shaped into form to be presented by the United States to the General Assembly of the United Nations. After some debate and certain modifications, Resolution 1721 was adopted unanimously by the Assembly in December 1961. In this instance, the program proposal came to the WMO from a higher intergovernmental level, unlike the IGY proposal, which came from a resolution of a nongovernment body, the IUGG. Promptly after adoption of UN 1721, the Secretary General of WMO, after conferring with the President of the Organization, arranged for a team of consultants, one from U.S. and the other from U.S.S.R., to work with the Secretariat in producing a report as requested in the UN Resolution.

The WMO First Report was issued in June 1962. Other bodies of the UN shared responsibilities for other parts of the Resolution; but for the meteorological portion WMO proceeded through the Technical Commissions concerned, principally Aerology and Synoptic Meteorology. The Executive Committee appointed special panels who went on with plans preliminary to action by the WMO Congress in 1963. One of these panels looking to establishment by the Congress of a permanent advisory committee on satellite research and other relevant UN proposals, arranged to include in its membership representatives of other international bodies, ICSU, IUGG, UNESCO, etc. These working groups are proceeding with preliminary plans.

In the meantime, starting with an exchange of letters between President Kennedy and Chairman Khruschev in February 1962, events have moved rapidly toward an agreement on cooperation in space activities between the two countries. In March 1962, Hugh L. Dryden, NASA Deputy Administrator, and Academician A. A. Blagonravov held preliminary talks in New York, followed by a meeting in Geneva, May 29 through June 7, to discuss potential areas of cooperation. On December 5, the United Nations was notified by the U.S. and the Soviet Union of the bilateral agreement for cooperation in outer space in the fields of meteorology, a world magnetic survey, and passive communication satellites. Statement read in part:

"In the field of meteorology, it is important that the two satellite launching nations contribute their capabilities toward the establishment of a global weather satellite system for the benefit of other nations."

The cooperative program falls into two stages—the experimental stage, approximately 1963–64, will consist of the establishment of communication links between the two countries adequate for the transfer of meteorological satellite data. This arrangement will go into effect when the U.S.S.R. and U.S. are able to provide data of approximately equivalent interest from their own satellites.

The second stage, beginning approximately 1964–65, calls for coordinated launchings of a system of operational weather satellites. This second stage, considered the operational phase, calls also for the transfer and wider dissemination of satellite data to other nations, with full consideration of the recommendations of the World Meteorological Organization.

With its demonstrated capacity for international planning and coordination of large new programs, the WMO can be expected to play its proper role in advancing the usefulness of weather satellites, without absorbing unnecessarily the national responsibilities of the member countries and their capacity for better serving the desires of their individual peoples. ••

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