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WEATHER ANALYSIS
from
SATELLITE OBSERVATIONS

U. S. NAVY WEATHER RESEARCH FACILITY
NORFOLK, VIRGINIA

DECEMBER 1960

WEATHER ANALYSIS

FROM

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National Oceanic and Atmospheric Administration
TIROS Satellites and Satellite Meteorology

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FOREWORD

The report which follows is the second publication issued by the Navy Weather Research Facility on Task 33, "Meteorological Satellite Analysis Techniques". It describes the characteristics of TIROS I, the world's first successful meteorological satellite, shows some of the more obvious cloud-weather relationships revealed by TIROS photography and attempts to give an evaluation of this new meteorological tool in weather analysis and forecasting for naval operations.

This report was prepared and written by Mr. Robert M. Fenn, Task Leader of Task 33, who gratefully acknowledges the assistance furnished by Messrs. Peter A. Bogden and Charles R. Jones, summer student trainees, who prepared the mosaics used in section 4. Acknowledgement is made to the Weather Bureau and to the National Aeronautics and Space Administration for some of the TIROS photographs used in sections 1 and 2. Mr. Vincent J. Oliver, of the U.S. Weather Bureau Office of Forecast Development contributed the display shown in figure 4.5 of section 4.

The description of procedures at the Ft. Monmouth read-out site during the operational period of TIROS I was contributed by LCDR R. E. Frank, USN.

Charles A. Palmer Jr

CHARLES A. PALMER, JR.
Commander, U. S. Navy
Officer in Charge
Navy Weather Research Facility

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1. PROJECT TIROS I, THE NASA METEOROLOGICAL SATELLITE EXPERIMENT

1.1 Introduction

Modern meteorology took a significant step forward with the introduction of the air mass and frontal system of forecasting, first introduced by the Norwegian school of meteorologists during World War I. The Navy adopted the new system in 1932.

World War II provided the impetus for further development in meteorology. The establishment of many new stations, the improvement of observational instruments and techniques, and the application of dynamic theory to weather processes, led to the growth of numerical weather prediction techniques during the post-war period. Electronic computers, capable of digesting great masses of observational data, have been applied to the study of atmospheric dynamics. Numerical techniques have greatly increased the demand for observational data, but have not, as yet, solved the forecasting problem.

The usual meteorological equations used in dynamic forecasting can, in principle, forecast the behavior of wind, pressure, density, and humidity. They cannot now predict rain or cloud. Besides the mathematical difficulties involved in solving the equations because of their non-linearity, further limitations are imposed by the necessity of introducing artificial boundary conditions and smoothing out irregularities.

But, the most serious objection to dynamic techniques is that they do not forecast weather, as such. They can produce reasonably accurate prognostic charts but detailed forecasts of most weather elements are likely to depend, for some time, upon judgement, experience, or statistics [37].

Meteorological satellites appear to offer the most practicable means of satisfying the demand for additional observational data, while affording the meteorologist a new look at the weather.

The first meteorological satellite transmitted only cloud cover data. Other satellites planned for the future will be equipped with infrared sensors which will give information on cloud thickness, atmospheric moisture, temperature, albedo, and solar and terrestrial radia-

tion. TIROS I, the meteorological satellite launched 1 April, 1960, circled the earth once every 99 minutes and, during its active life of 78 days, transmitted 22,952 cloud-cover pictures.

The operational success of TIROS I will do much to revive the almost lost art of nephanalysis, which formed the basis for most weather forecasting techniques during the early nineteenth century and, quite probably, for many centuries before that. The importance of the state of the sky was emphasized by the air mass and frontal analysis system introduced in this country during the early thirties. Knowledge of the physical structure of the clouds improved with the phenomenal growth of aviation during and just after World War II. Successful experiments in cloud seeding followed the study of the physical processes involved in cloud formation and dissipation and renewed scientific interest in wholesale weather control.

In numbers of satellites in orbit and in scientific achievements the United States is far ahead of the Russians, but, to quote a leading news magazine, ". . . .However much such way-out wonders may entrance the men who are making space science their life, and however the research vehicles may probe into the . . . . . mysteries of the solar system, they are hardly calculated to set the world's non-scientific citizens to dancing in the streets. Still, there is one research satellite -- which is also a "use" vehicle -- whose function can excite scientist and layman alike: it is TIROS I, the weather-observing spacecraft launched in April of this year [47]."

This report is partly the story of TIROS I and the Navy's part in it. Since all the data received from TIROS were in the form of photographs, it was considered advisable to present the report largely in that form. The aim has been to keep the discussion brief and let the photographs speak for themselves.

1.2 Orbit and Stabilization

TIROS was injected into a nearly circular orbit (eccentricity 0.003) at an altitude varying from 387.7 nautical miles at perigee to 407.2 nautical miles at apogee. It was aimed for an injection inclination of 48.29 degrees relative to the equator. Actual inclination was 48.327 degrees. TIROS was designed to remain stable in its orbit at a spin rate of 9 revolutions per minute or better. Spin rate at injection was 10 rpm which later slowed to 9.5 rpm. Three pairs of control

rockets around the baseplate were available to speed the rotation back to 12 rpm if it had dropped below 9.

1.3 Launch Vehicle

A three-stage Thor-Able rocket shown in figure 1.1 was used as the launch vehicle. The second stage was adapted from earlier Vanguard and Thor-Able rockets and used liquid propellants. It had six small rockets at the top to spin up the third stage, weighed about 4,000 pounds and developed about 7,500 pounds of thrust. The third-stage solid propellant rocket weighed about 500 pounds and put out about 3,000 pounds of thrust. The Air Force Ballistic Missile Division with its contractors, Space Technology Laboratories, Inc., and Douglas Aircraft Corp., was responsible for booster development and for mating booster and payload.

Figures 1.2 and 1.3 show the second stage being set in place and fired from the Atlantic Missile Range, Cape Canaveral, Florida.

1.4 The Satellite Pay-load

The satellite is 42 inches in diameter, 19 inches high, and weighs 264 pounds. Power is supplied by nickel-cadmium batteries charged by 9,200 solar cells. Figure 1.4 shows the satellite being tested at RCA laboratories. (Note the spin-up rockets on the base.) Figure 1.5 shows a cut-away drawing of TIROS I.

TIROS' two TV cameras differ in coverage and resolution. Table 1.1 summarizes the camera characteristics.

Two channels are used to serve each camera. There are two communications receivers, two precision electronic-clock mechanisms (to control sequencing), two magnetic videotape recorders, and two independent beacon systems operating on 108 and 108.3 mc., respectively. Two 330-oz., 2-watt FM telemetry transmitters transmit video information on 235 mc. A single nickel-cadmium battery power supply is used to keep the solar cells charged.

Compressed bandwidth technique holds the bandwidth down to 62.5 kc. Each tape recorder stores up to 32 frames exposed by the cameras during a single orbit. When the satellite comes within range of one of the two ground stations, a command signal starts the tape

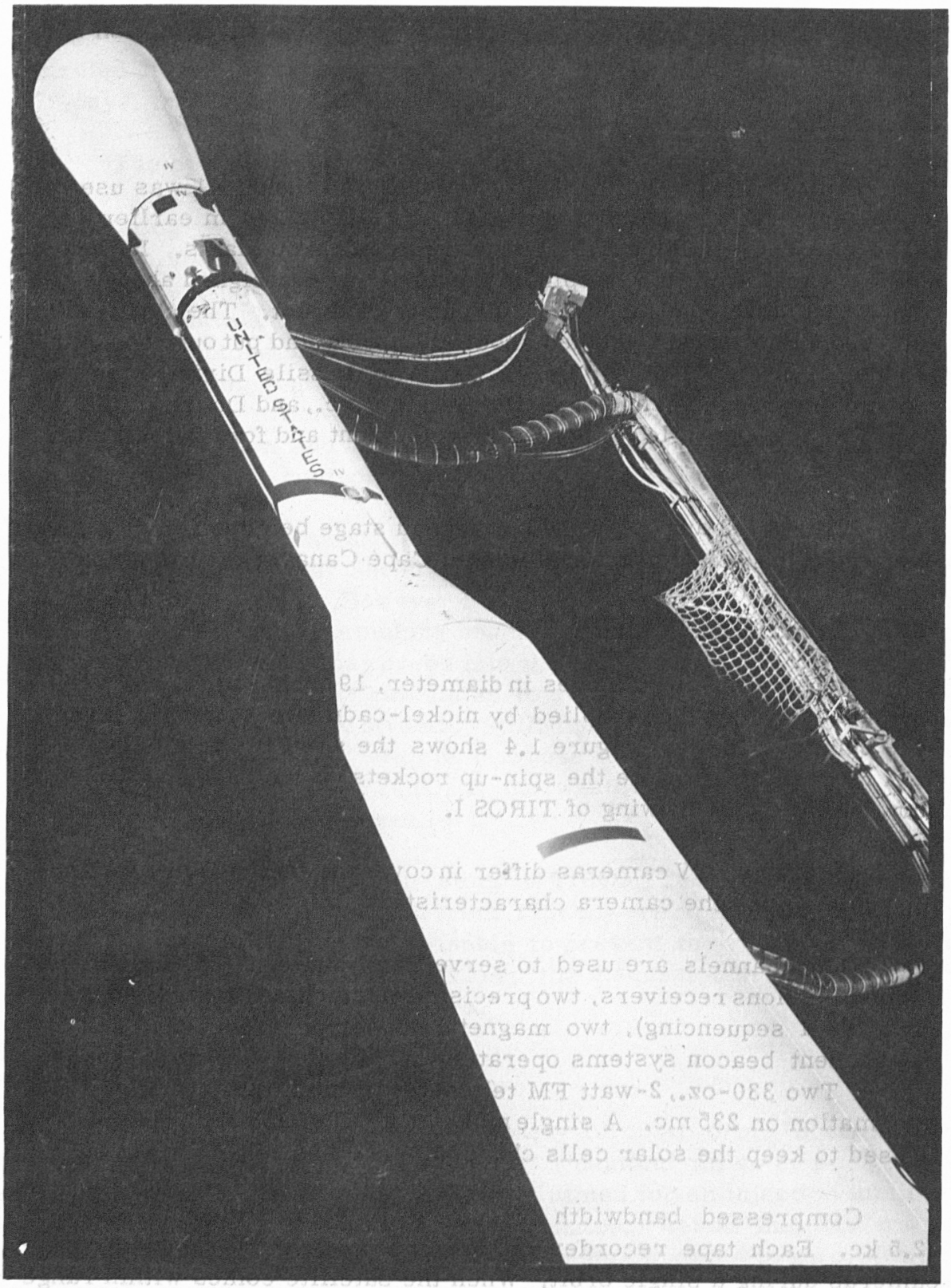

Figure 1.1. Three-stage Thor-Able Rocket, the TIROS I Launch Vehicle.

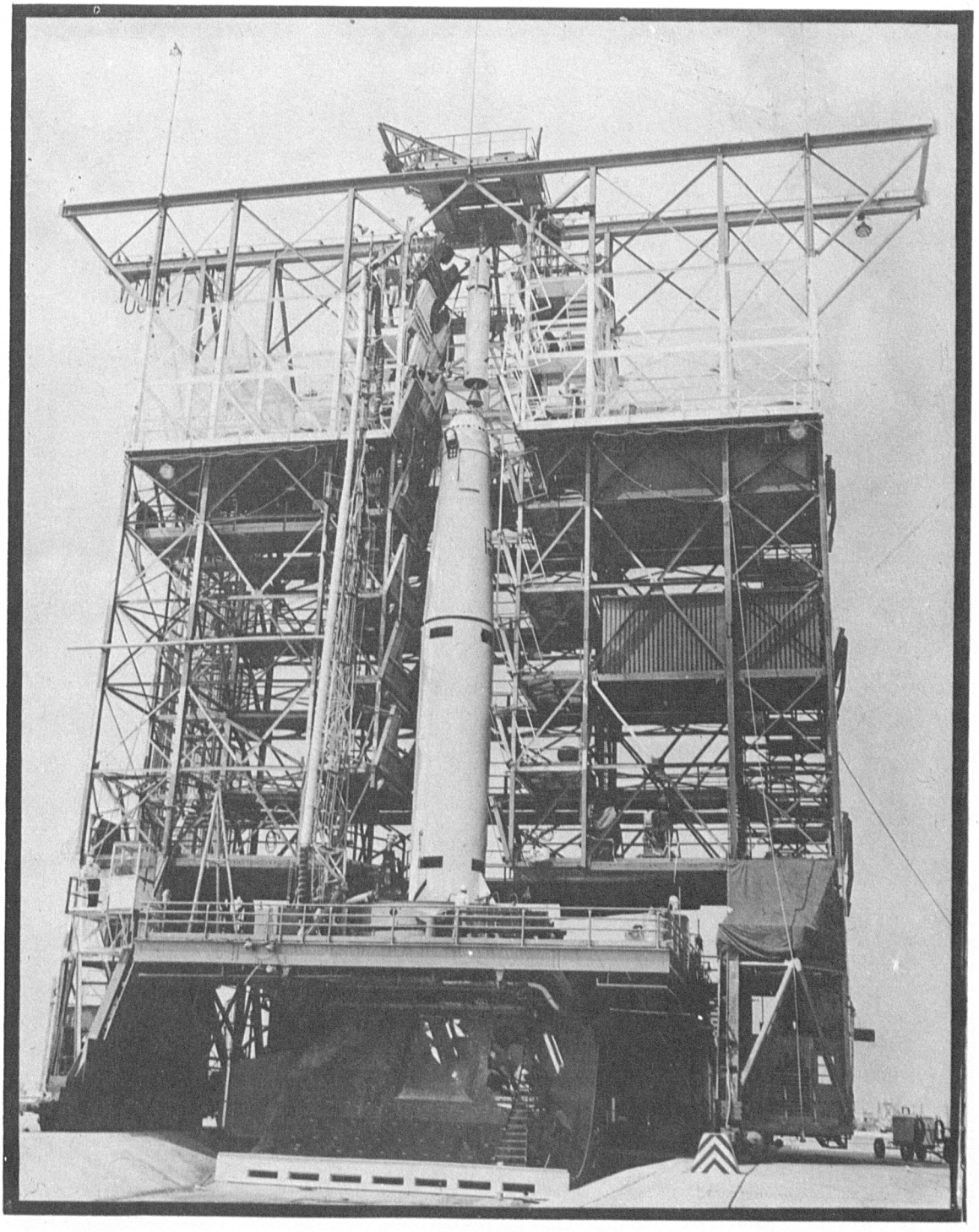

Figure 1.2. Second Stage of Thor-Able Rocket Being Set in Place Preparatory to Launching TIROS I.

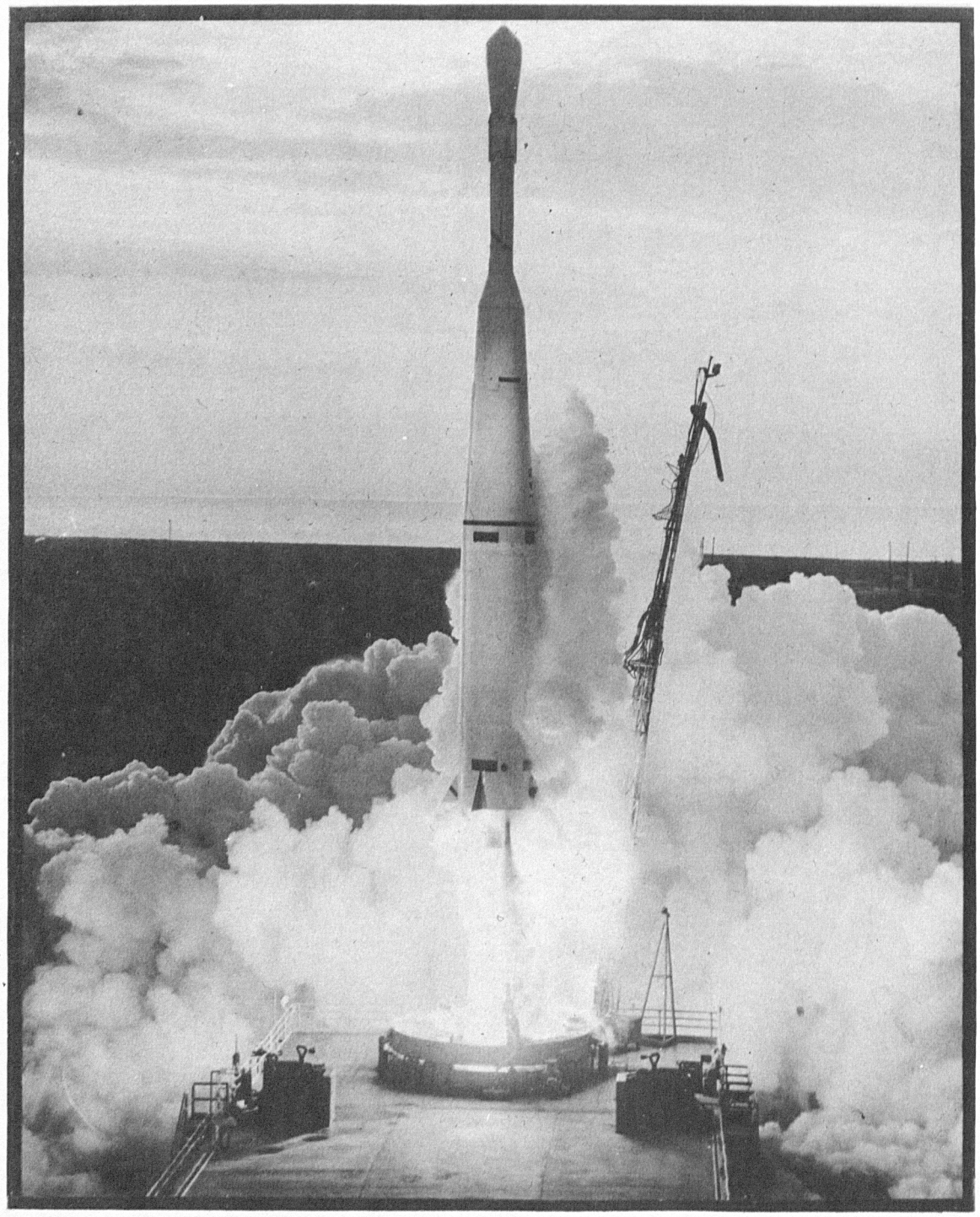

Figure 1.3. Launching of TIROS I, Cape Canaveral, Florida, 0510 EST, 1 April 1960.

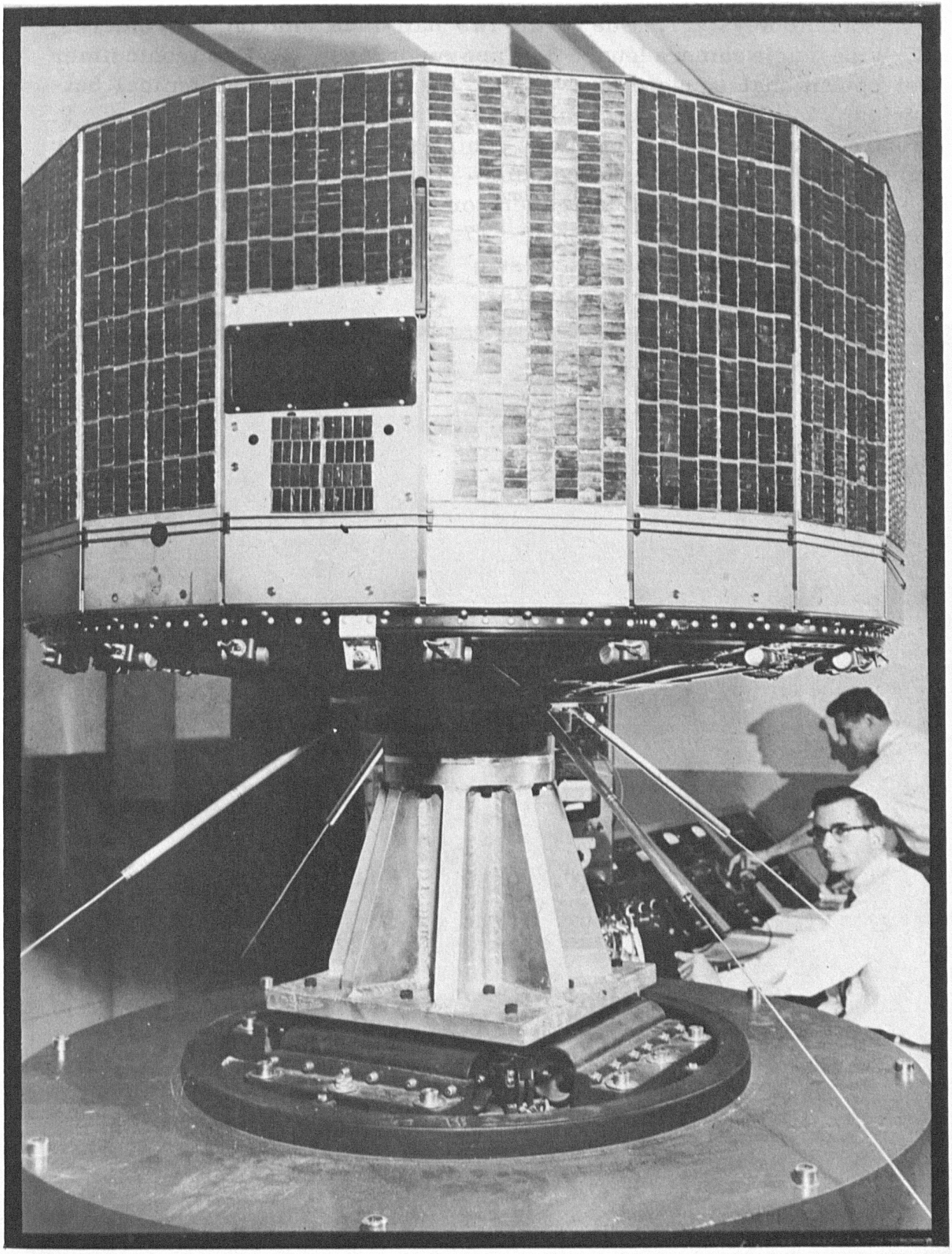

Figure 1.4. TIROS I on Test Stand during Preliminary Test Stage.

Photo keys: 1. One of the two half-inch Vidicon TV cameras; 2. Wide-angle camera lens; 3. Tape recorders; 4. Electronic timer for operational sequencing; 5. TV transmitter; 6. Chemical batteries; 7. Camera electronics; 8. Tape recorder electronics; 9. Control circuits; 10. Auxiliary controls; 11. Power converter for tape motor; 12. Voltage regulator; 13. Battery charging regulator; 14. Auxiliary synchronizing generator for TV; 15. Transmitting antennas; 16. Receiving antenna; 17. Solar sensor to measure position of satellite with respect to sun; 18. Solar cells; 20. De-spin mechanism; 21. Spin-up rockets.

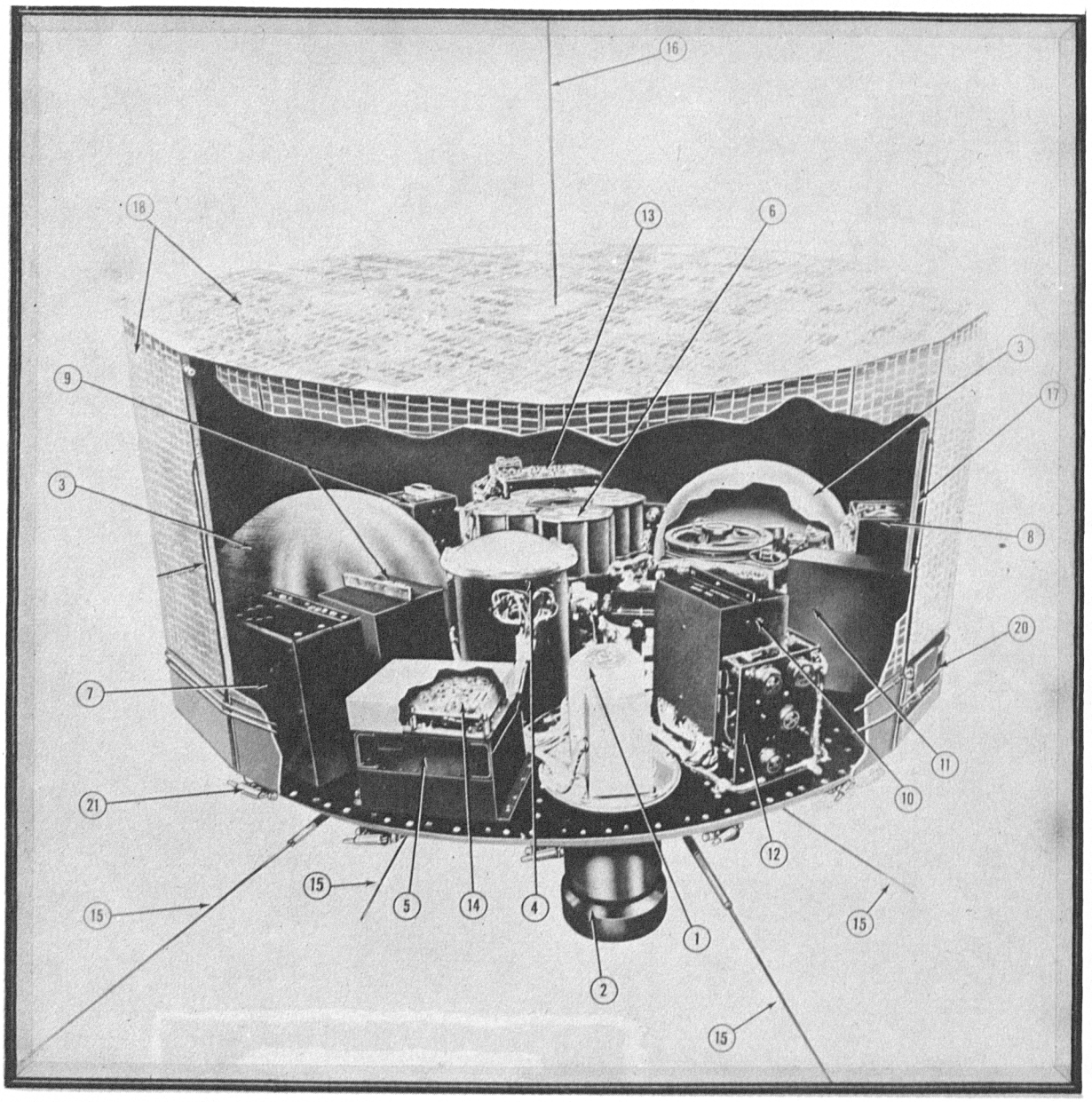

Figure 1.5. Cut-away Drawing of TIROS I.

TABLE 1.1

Item	Camera	
	Wide	Narrow
Lens field	104	12.7 degrees
Lens aperture	f/1.8	f/1.5
Shutter speed	1.5	1.5 millisec.
Lines per frame	500	500
Frame readout	2	2 sec.
Video Bandwidth	62.5	62.5 kcs.
Area viewed from Vertical (approx.)	750 (562,500)	65 miles sq. (4225) sq. mi.
Shades of grey (design)	8	8
Shades of grey (practice)	5-6	5-6

readout to the transmitters for transmission to the earth.

1.5 Picture Quality

During its active life of 78 days TIROS I transmitted 22,952 cloud-cover pictures. The photographs in this section are indicative of the quality of photography obtained from both the wide- and narrow-angle lens TV cameras.

The series shown in figures 1.9 through 1.12 is composed of the first photographs received from TIROS I, approximately seven hours after launch. The pictures were received at the Ft. Monmouth read-out site and transmitted to NASA headquarters by wire-photo. Photographs 4, 6, 8, 10, 11, 12, 14, 16, 17, and 25 were made by the low resolution (wide-angle lens) camera; other views were made by the high resolution (narrow-angle) TV camera. The satellite was over the eastern United States and its cameras were pointed downward and toward the west.

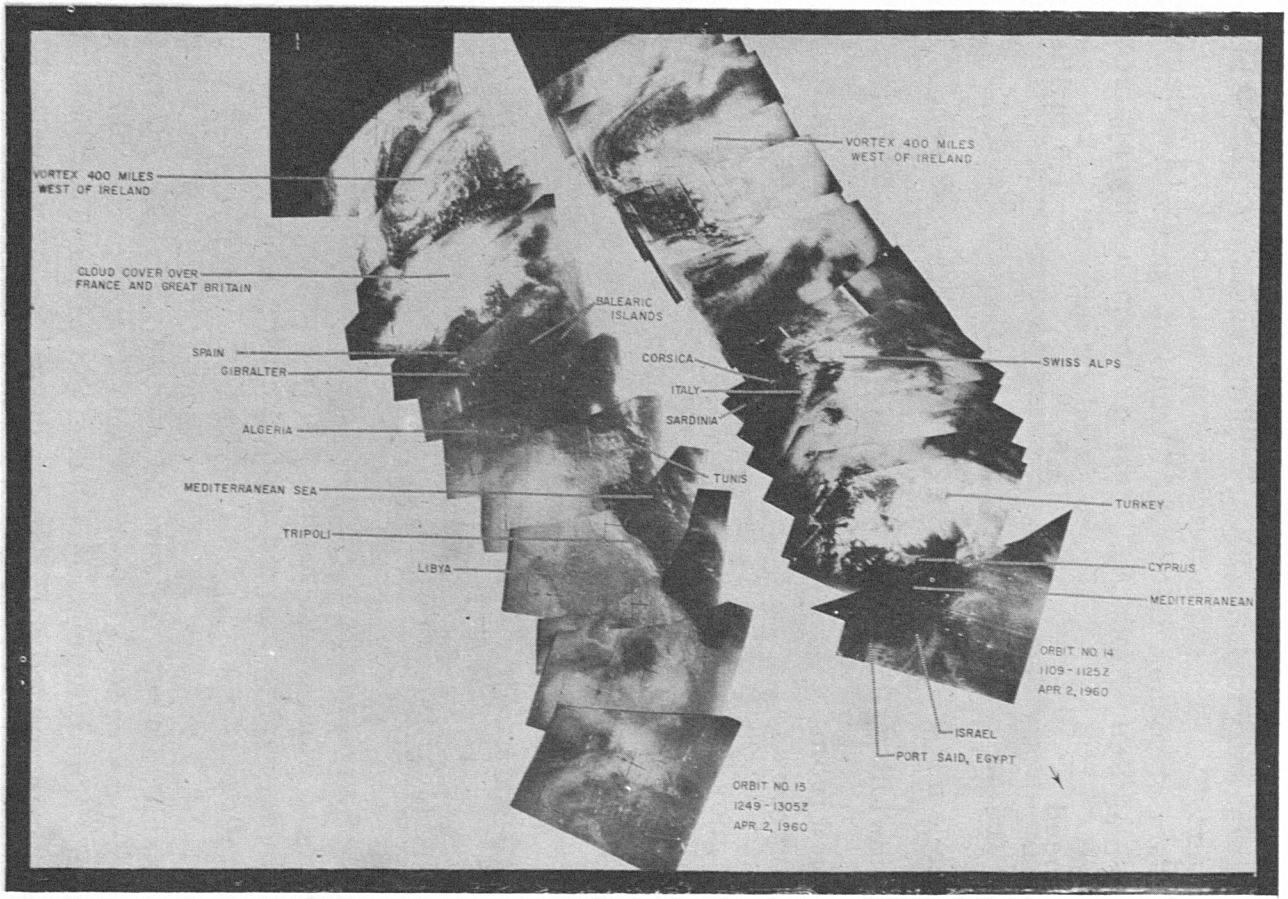

Figure 1.6. The Two Mosaics Shown Here Were Constructed from 30 Frames Taken during the 14th and 15th Orbits on 2 April 1960, Covering an Area More Than 4,000 Miles Long. The Clouds Show an Organized Pattern Associated with a Large Mature Cyclonic Vortex about 450 Miles West of Ireland. (Photo Courtesy of U. S. Weather Bureau.)

Figure 1.7. The Western Coast of French West Africa Stands Out Sharply in this Wide-Angle Shot Taken on the 31st Orbit, 4 April 1960. Area of the Picture Extends from Cape Blanco to St. Louis, French West Africa. Received at Kaena Pt., Hawaii.

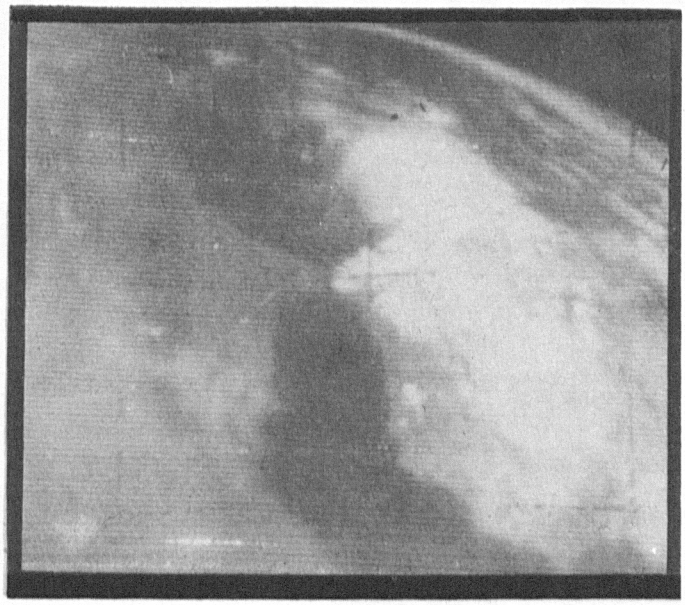

Figure 1.8. TIROS Photograph from the 45th Orbit over North Africa, Looking Downward and to the West. The Strait of Gibraltar Lies in the Center of the Photograph; Spain to the Right. Portugal is Covered by Clouds. On the Left Side of the Picture is the Moroccan Coast and the Western Part of the Mediterranean Coast of Algeria. The Dark Area in the Foreground is the Mediterranean Sea. The Atlantic Ocean Lies in the Background.

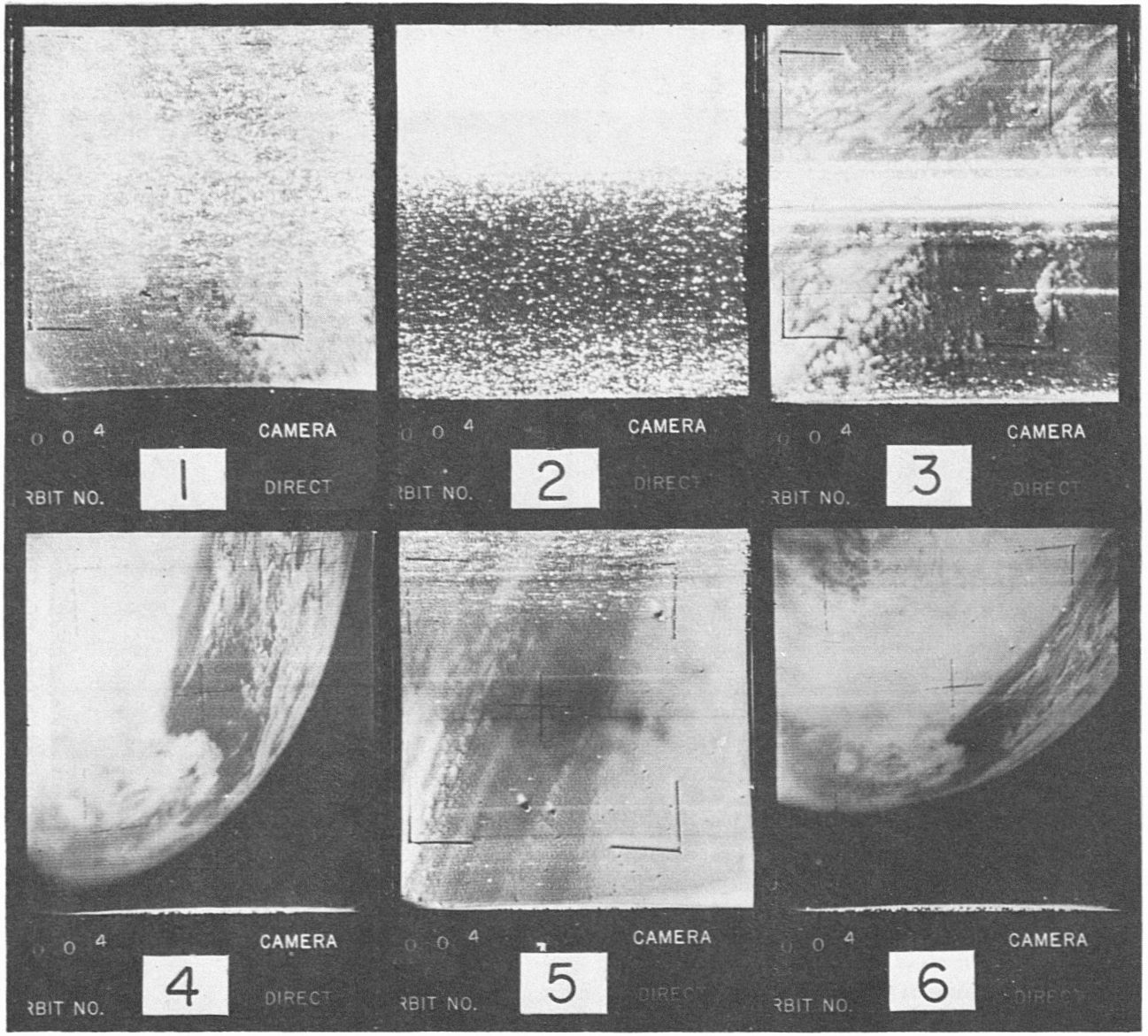

Figure 1.9. First Pictures from TIROS.

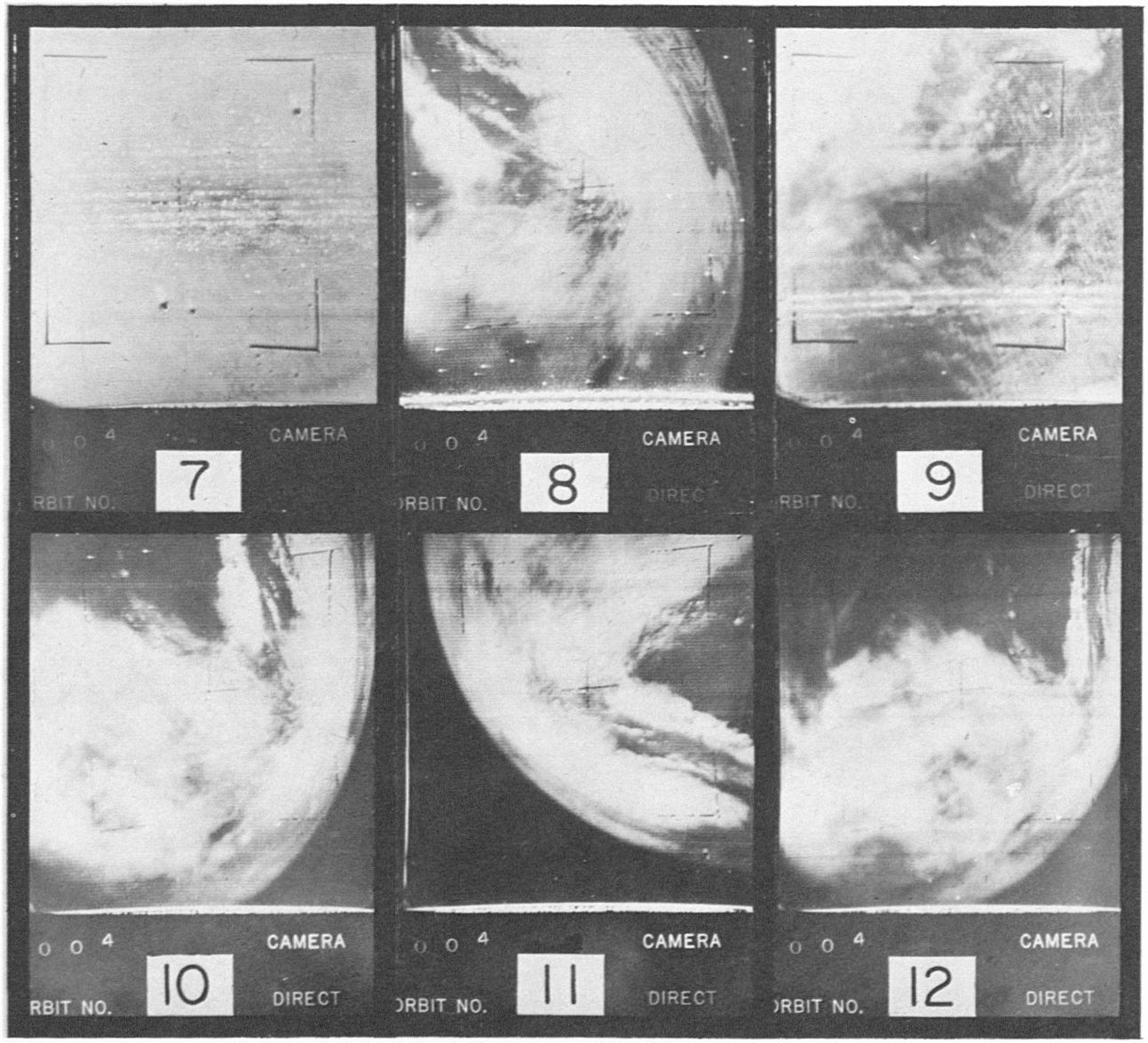

Figure 1.10. Series Showing a Deepening Wave Cyclone Off the New England Coast Described in Section 2.

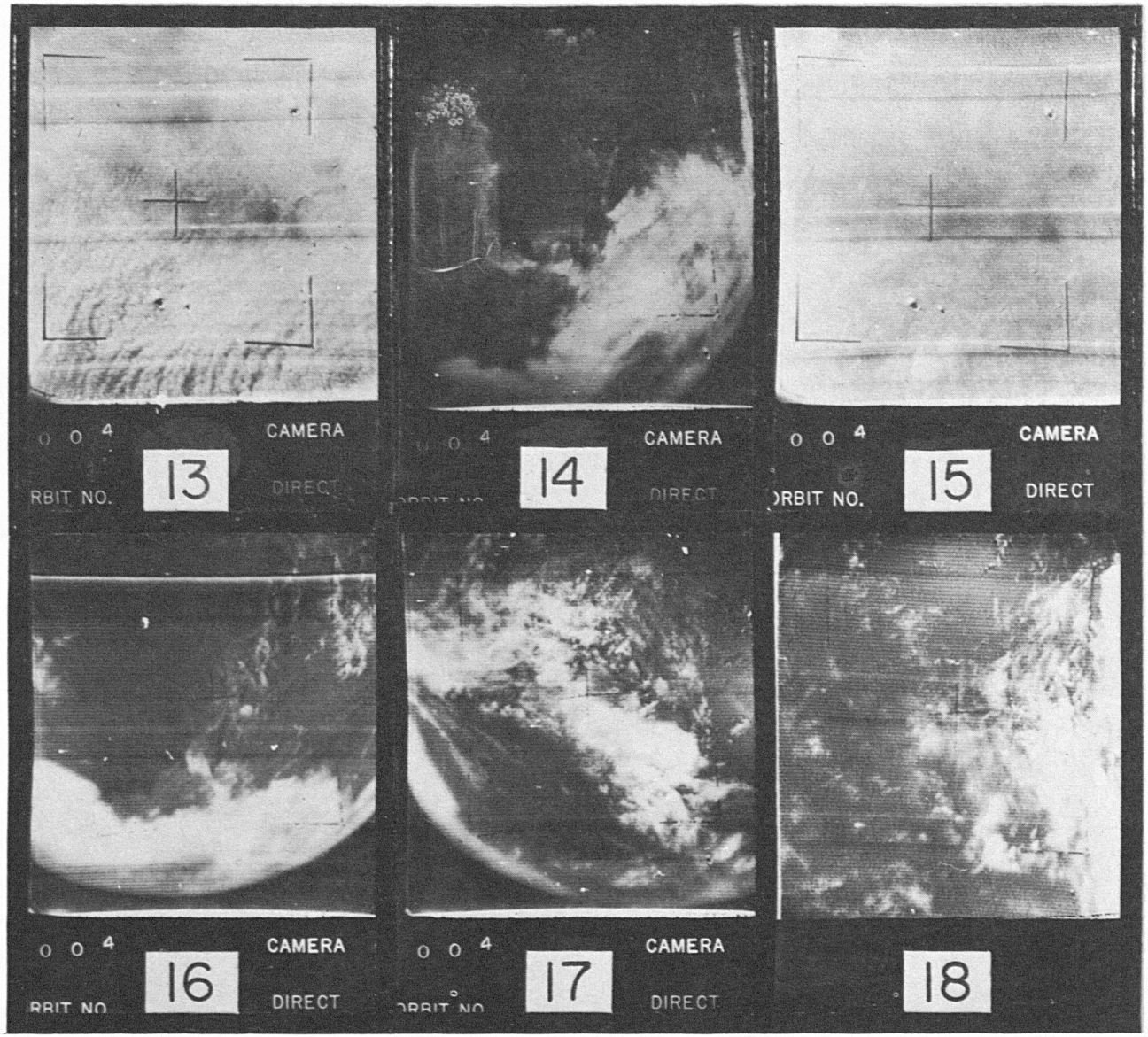

Figure 1.11. First Cloud Cover Pictures Received from TIROS.

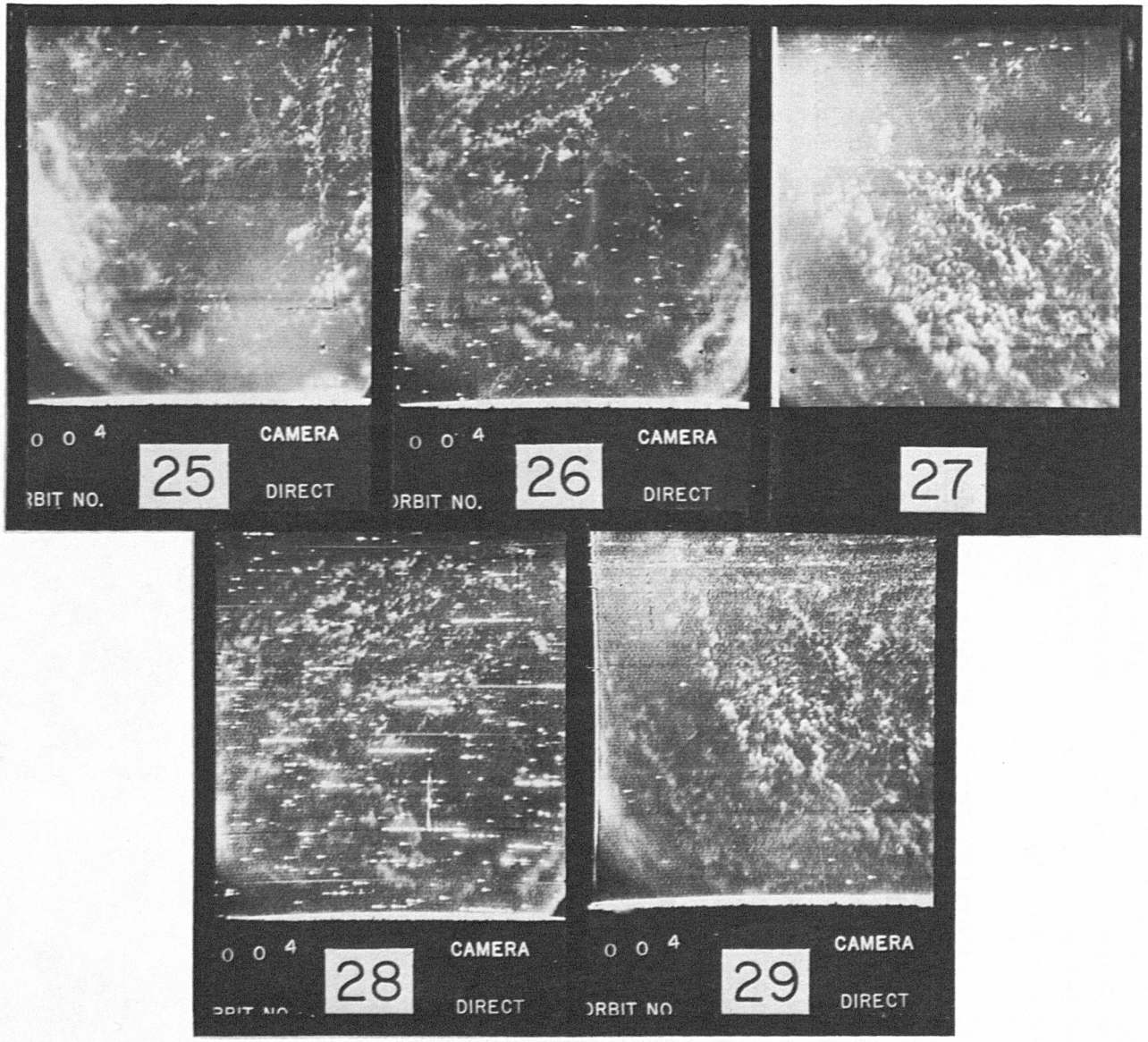

Figure 1.12. Frames 25-29, Orbit 4.

2. CLOUD-WEATHER RELATIONSHIPS REVEALED BY TIROS I

It is still too early to assess the value of TIROS photography in weather analysis and forecasting. The most spectacular shots and those which have received wide publicity were of large tropical and extra-tropical cyclones.

2.1 Cloud Systems - Middle Latitudes

Of the cloud systems described in an earlier report [32], three were observed on a single orbit over the North Pacific. On this same orbit four special cloud forms were photographed. All are shown in the illustrations which follow.

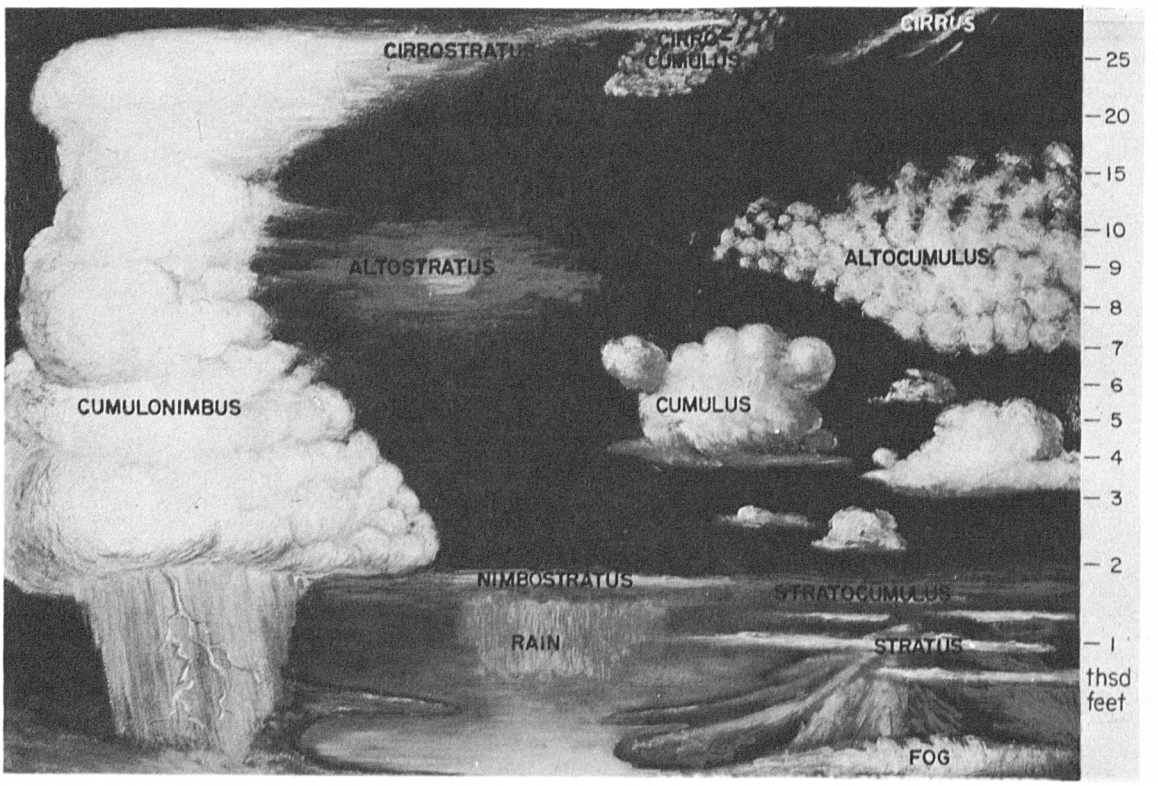

Figure 2.1. Cloud Families.

2.1.1 Extratropical Cyclones

The most common as well as extensive cloud systems observed by TIROS were those associated with cyclonic storms. The observed cloud patterns appeared to be most closely related to events in the lower troposphere. The following pages contain some of the more interesting cyclone portraits.

2.1.1.1 Deepening Wave off the U. S. East Coast (fig. 2.2A)

The structure of the cyclonic storm is shown in this mosaic of three overlapping TIROS pictures. The accompanying surface analysis was made by the National Weather Analysis Center, U.S. Weather Bureau, Suitland, Md. Cyclonic flow is indicated by the cloud mass near the center. A weak cold front is shown by the fibrous cloud trailing southward. The dark area to the south shows cloudless skies in the cold air behind the front.

2.1.1.2 Cyclone over the Mississippi Valley (fig. 2.2B)

This storm, centered over southeastern Nebraska was viewed by TIROS on the same day. The cold front and occlusion agree well with synoptic models. Cold, dry air moving in behind the cold front is clearly shown by the absence of clouds in the dark area to the west. East of the front, advection of mT air is apparent in the cloudiness of the warm sector. Thunderstorms occurred in the bright areas near the Gulf of Mexico.

2.1.1.3 Cyclone over Eastern Pacific (fig. 2.3)

This shows a storm located about 800 miles west of Southern California, in an area usually occupied by the Pacific subtropical anticyclone. The cloud system was composed of wide concentric bands separated by narrow clear zones as shown in figure 2.3A. Some of the bands appear to be composed of series of smaller cloud elements, as shown in figure 2.3B, the narrow-angle shot.

2.1.1.4 Southern Hemisphere Cyclone (fig. 2.4)

This is a single-frame photograph showing the clockwise circulation around a low in the Southern Hemisphere.

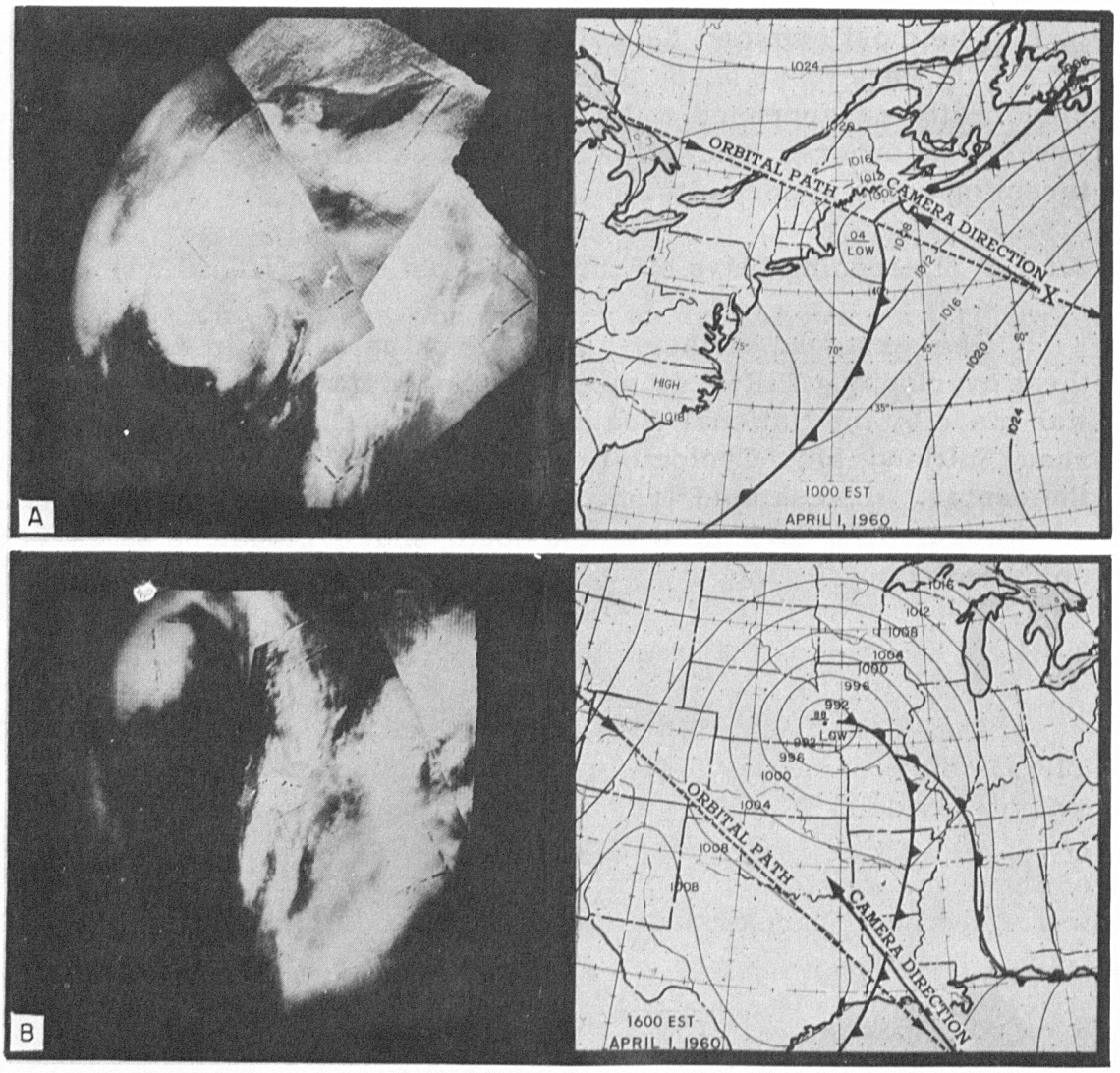

Figure 2.2. Two Mosaics from 4th and 5th Orbits Showing (A) a Deepening Wave Cyclone Off the U. S. East Coast and (B) an Occluded Cyclone Over the Mississippi Valley. (Photographs courtesy of NASA and the U. S. Weather Bureau.)

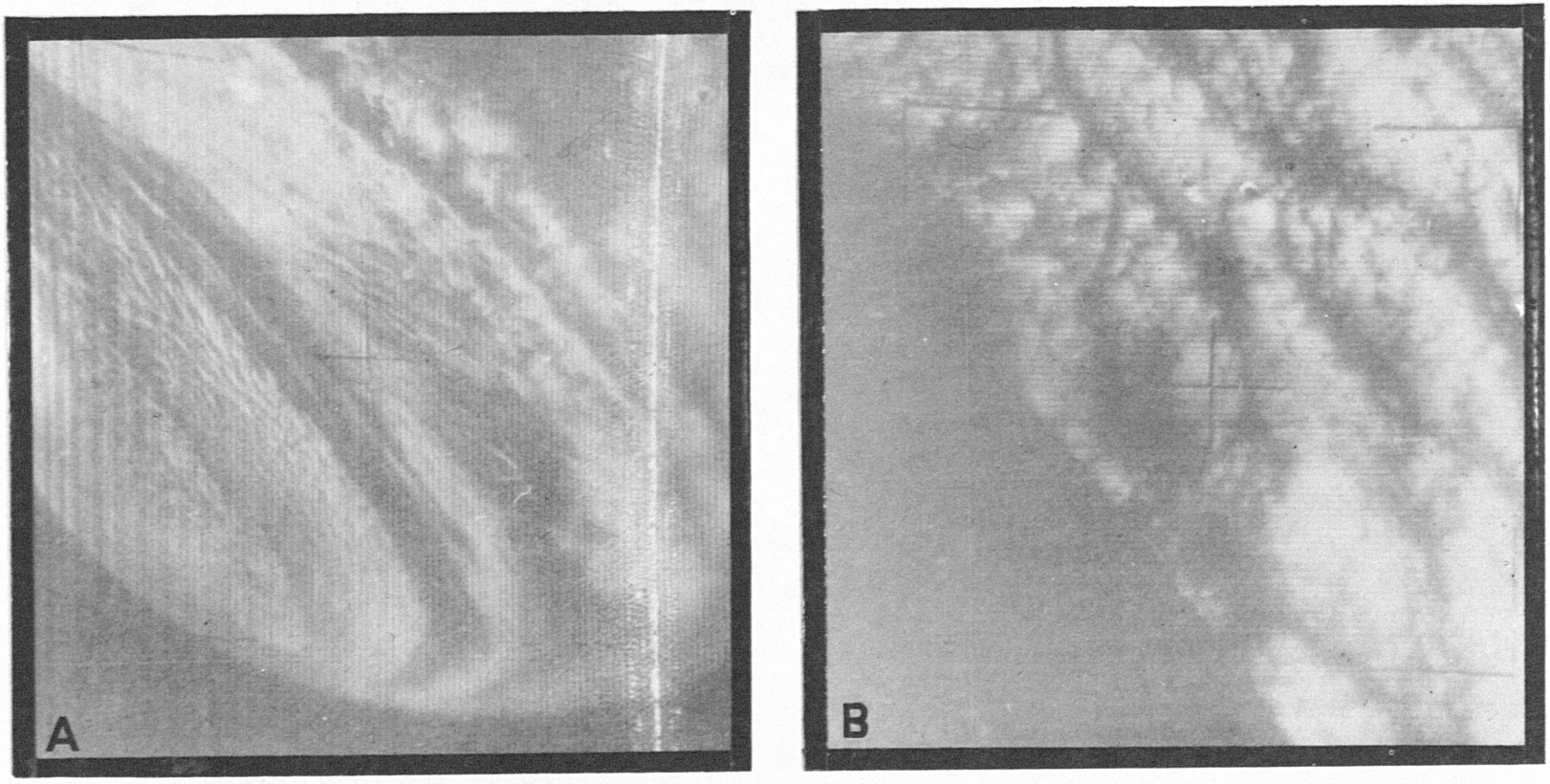

Figure 2.3. Wide and Narrow Angle Lens Shots of Pacific Cyclone from Orbit 50.

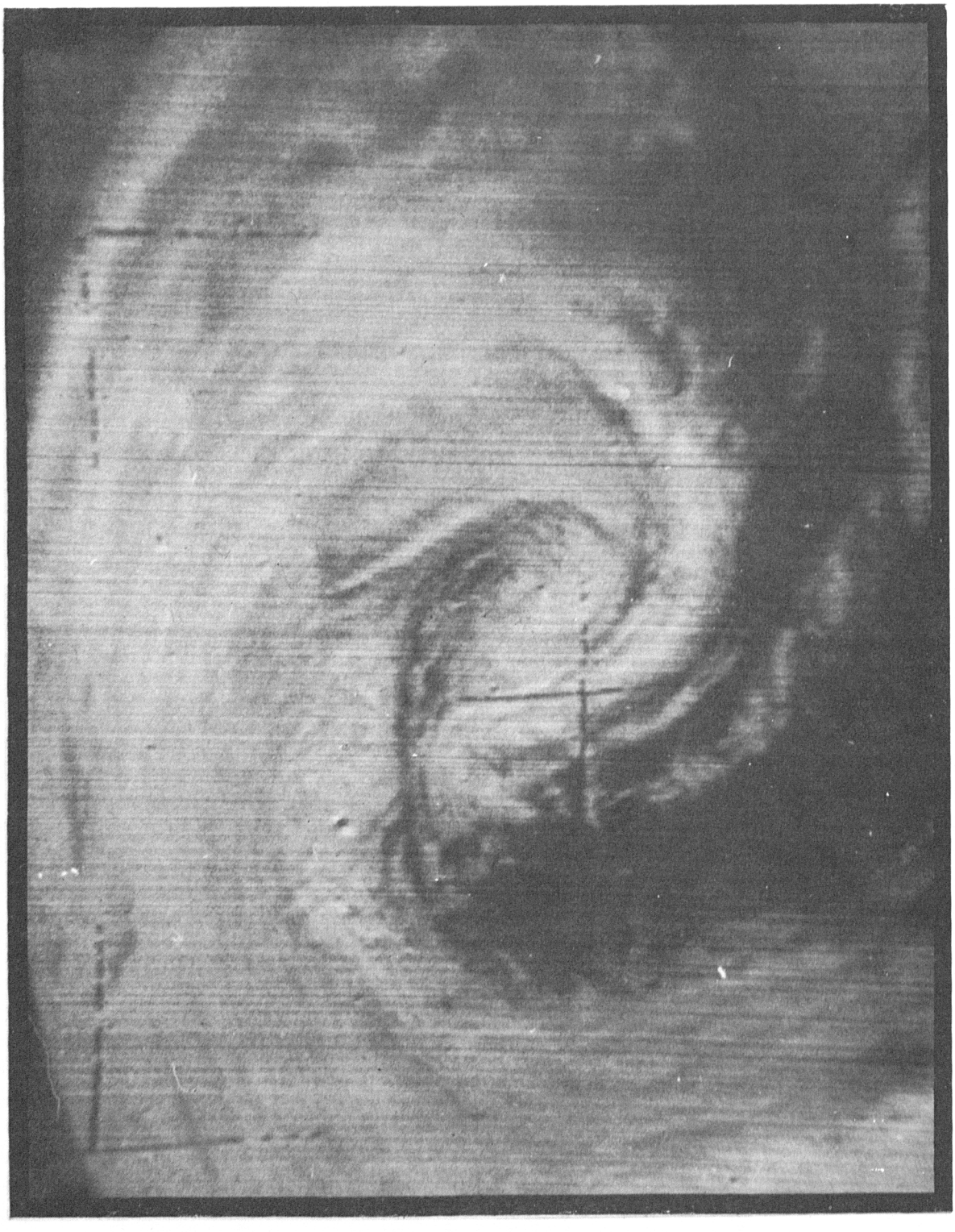

Figure 2.4. Southern Hemisphere Extratropical Cyclone. Note the Cloud Streets.

2.1.2 Fronts

Cloud masses associated with fronts are not always continuous, even over the oceans, as has been amply demonstrated by radar observations and high-altitude cloud photographs. Clouds caused by the lifting of warm air at or near the front may be absent or obscured by an upper cloud deck. In many cases, particularly in the case of an abrupt wind shift, the front may be marked by an abrupt change in cloud type. An example of the cloud structure associated with a weak cold front is shown by figure 2.6. In figure 2.5 the lower frontal clouds are almost completely obscured by a cirriform cloud layer.

2.1.2.1 Segment of a Well-defined Front over the North Pacific (fig. 2.5)

This segment of a cold front over the Pacific on 19 May, paralleled the jet stream. The jet axis was located about 200 miles to the north of the surface front.

2.1.2.2 Segment of a Weak Quasi-stationary Front (fig. 2.6)

This frame shows the clouds associated with the same cold front in an area where it had become stationary and weakened. Scattered ship reports indicated stratocumulus clouds at lower levels. Altocumulus and cirrus are visible in the photograph.

2.1.3 Anticyclones

Large cloud-free areas are almost universally dominated by anticyclonic systems. In the continental United States and adjacent waters the center of the clear area is usually slightly southeast of the center of the High, with widespread cloudiness, often stratocumulus, at the southeastern edge.

Figure 2.7 shows an almost vertical shot of the semi-permanent sub-tropical anticyclone off the southern coast of California. The clear area is slightly southeast of the High center. Clouds to the southeast are mainly stratus and stratocumulus, but cirriform clouds dominate to the north and west.

2.2 Tropical Systems

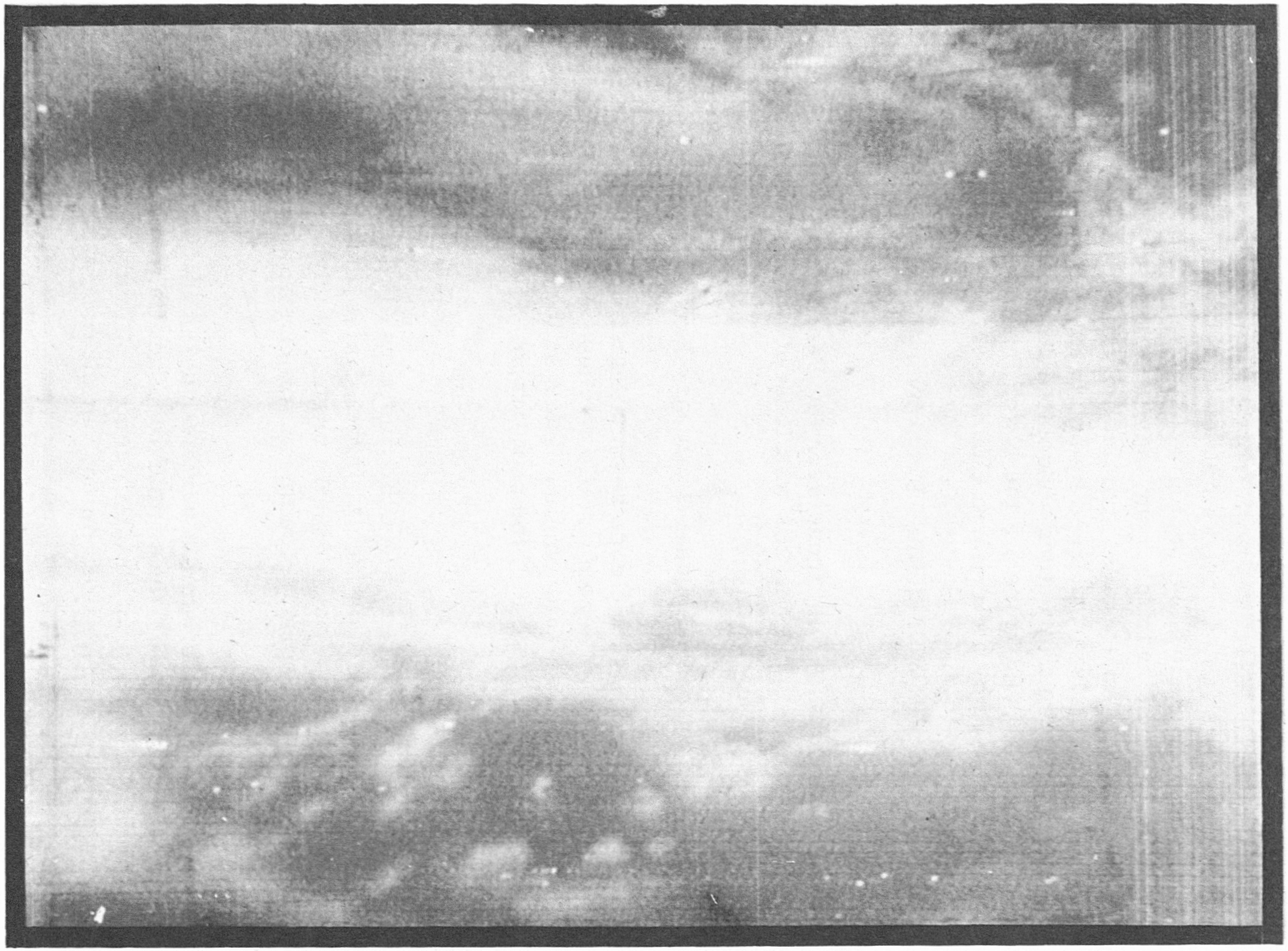

Figure 2.5. Segment of a Well-defined Cold Front over the North Pacific.

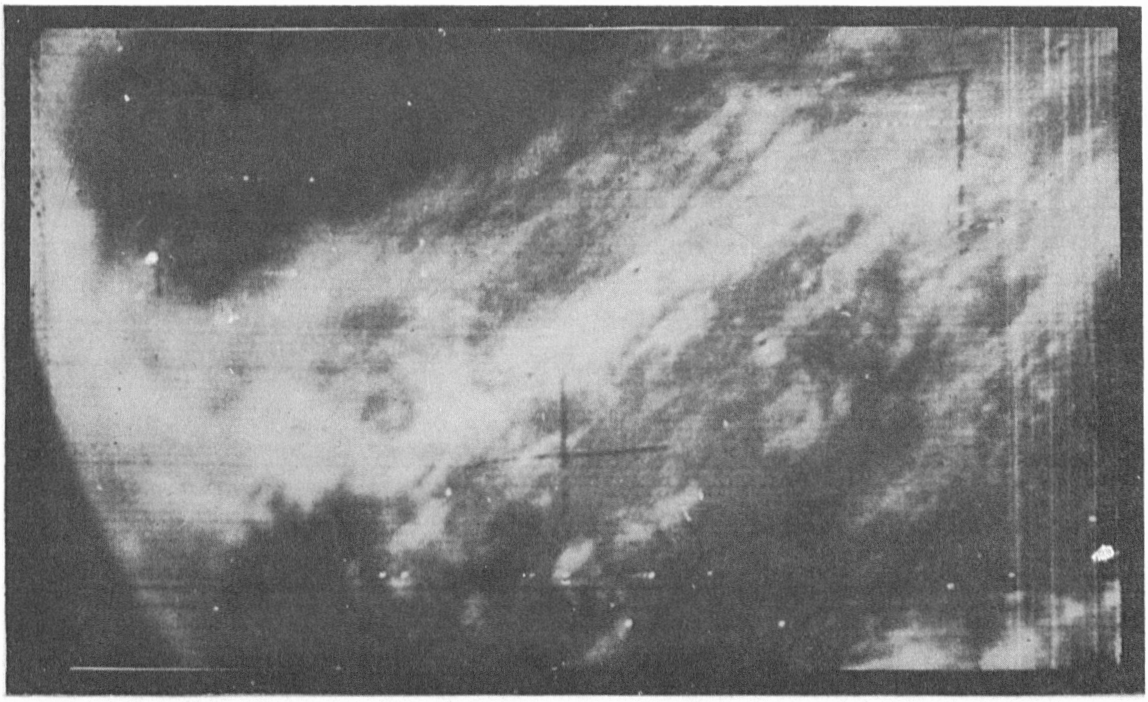

Figure 2.6. Segment of a Weak Stationary Front over the North Pacific, 19 May 1960.

Figure 2.7. Pacific Anticyclone Off the California Coast.

2.2.1 Tropical Cyclone

A small but intense circulation is shown in these photographs of a typhoon over the South Pacific Ocean north of New Zealand on 10 April 1960, figure 2.8. Note the well-marked cloud streets typically associated with such storms.

2.3 Special Cloud Forms

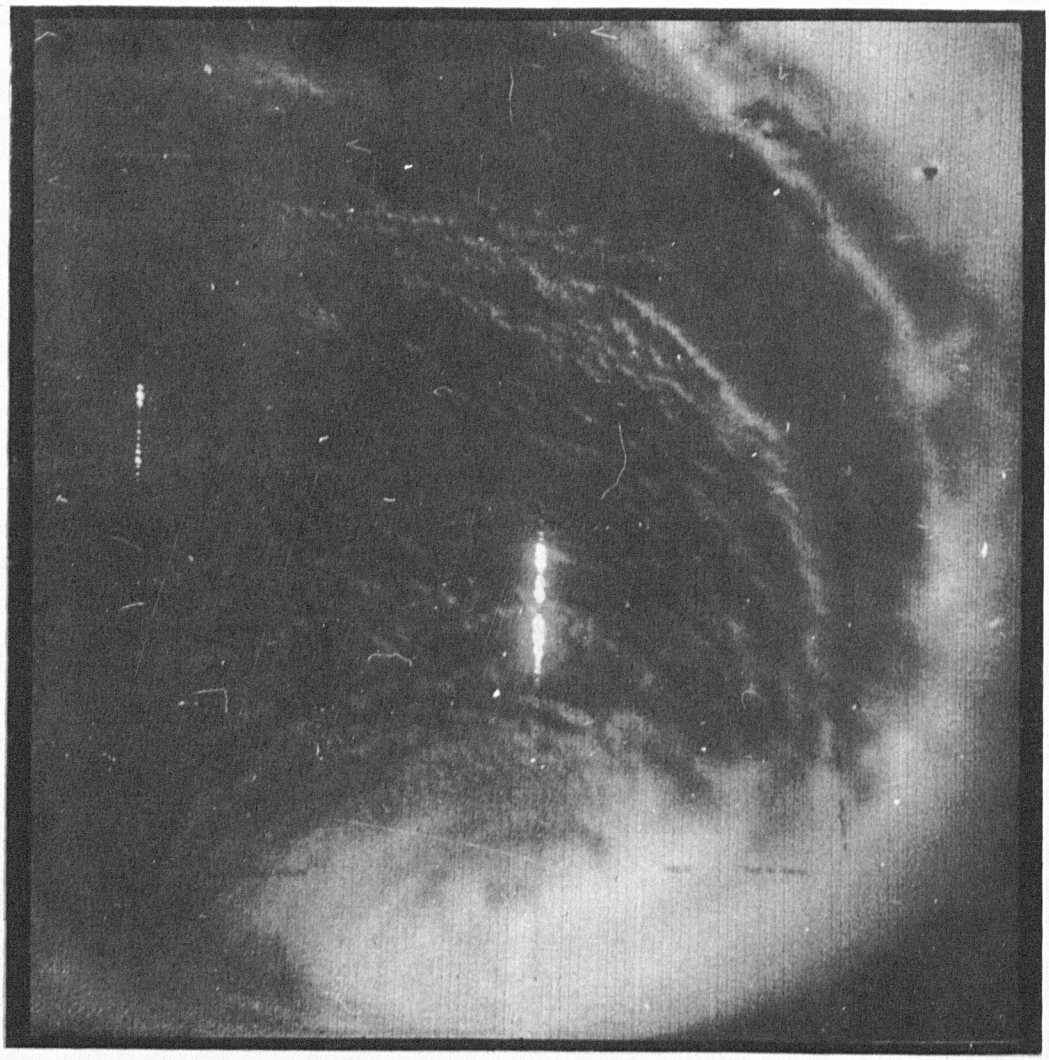

Figure 2.8. Tropical Storm Viewed by TIROS I. This Picture Was Stored on Tape During the 125th Orbit; Read Out at Kaena Pt. on the 128th Orbit.

2.3.1 Banner Clouds

Lenticular clouds, which may range from stratocumulus through cirrus, form downwind from mountain peaks. They are almost a permanent feature over high elevations in the Tropics. Figure 2.9 shows an example of this type of cloud photographed from an airplane. Compare this with the photograph of the Hawaiian Islands, figure 2.10, and with the photograph of a banner cloud over Mt. Whitney, figure 2.11.

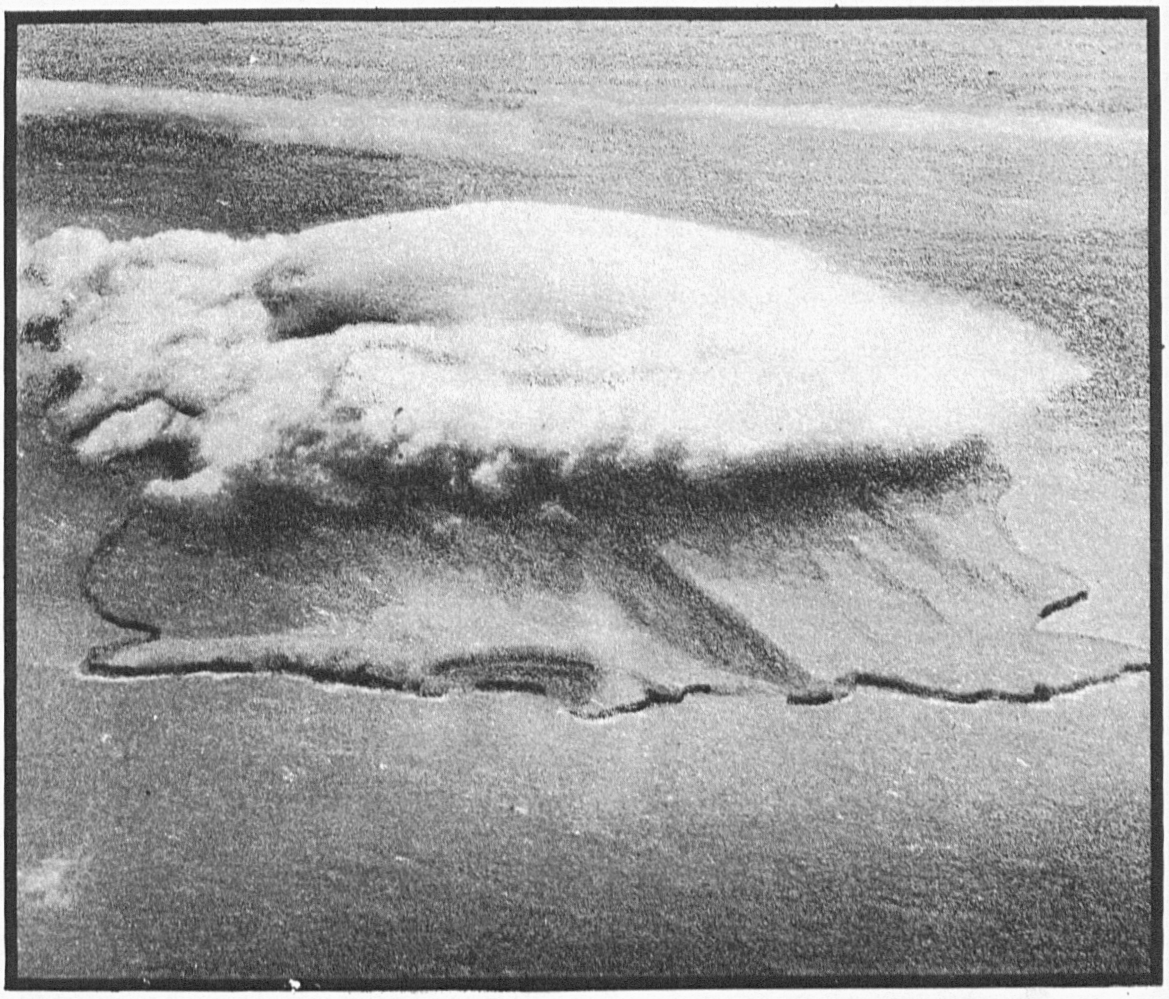

Figure 2.9. Banner Clouds over a Tropical Island in the Pacific.

113 128

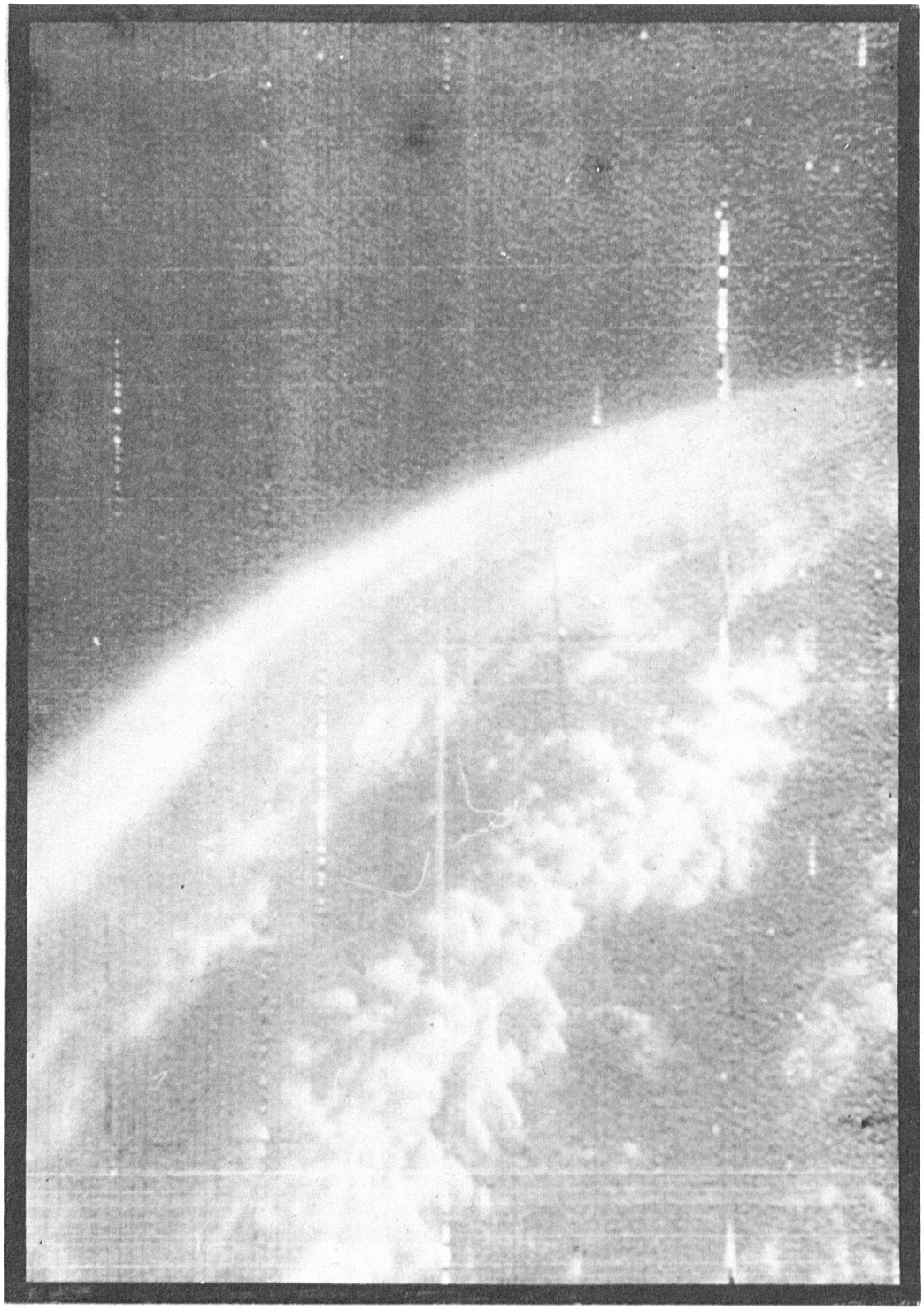

Figure 2.10. Orographic Cumuli over the Hawaiian Islands as seen by TIROS I.

Figure 2.11. Banner Clouds over Mt. Whitney, California and Orographic Clouds over the Sierras and the Western Plateau, 19 May 1960.

2.3.2 Billow Clouds

Billow clouds are broad, nearly parallel, lines of cloud oriented normal to the wind direction and are usually associated with the "mountain wave" effect. Figure 2.12 shows a good example of billow clouds along the Alps. The cloudy area to the south is the Italian Peninsula, the dark areas to the east and west, the Adriatic and Mediterranean Seas. The Islands of Corsica and Sardinia are clearly seen to the west of Italy.

2.3.3 Cloud Streets

The tendency of cumuliform clouds to orient themselves in more or less parallel rows is particularly marked in the tropical trade winds area. This tendency, which has also been observed in radar photographs of hurricanes and extratropical cyclones, appears to be a common feature of all convective phenomena. Figure 2.13 shows cloud streets in the trade wind cumuli near Hawaii.

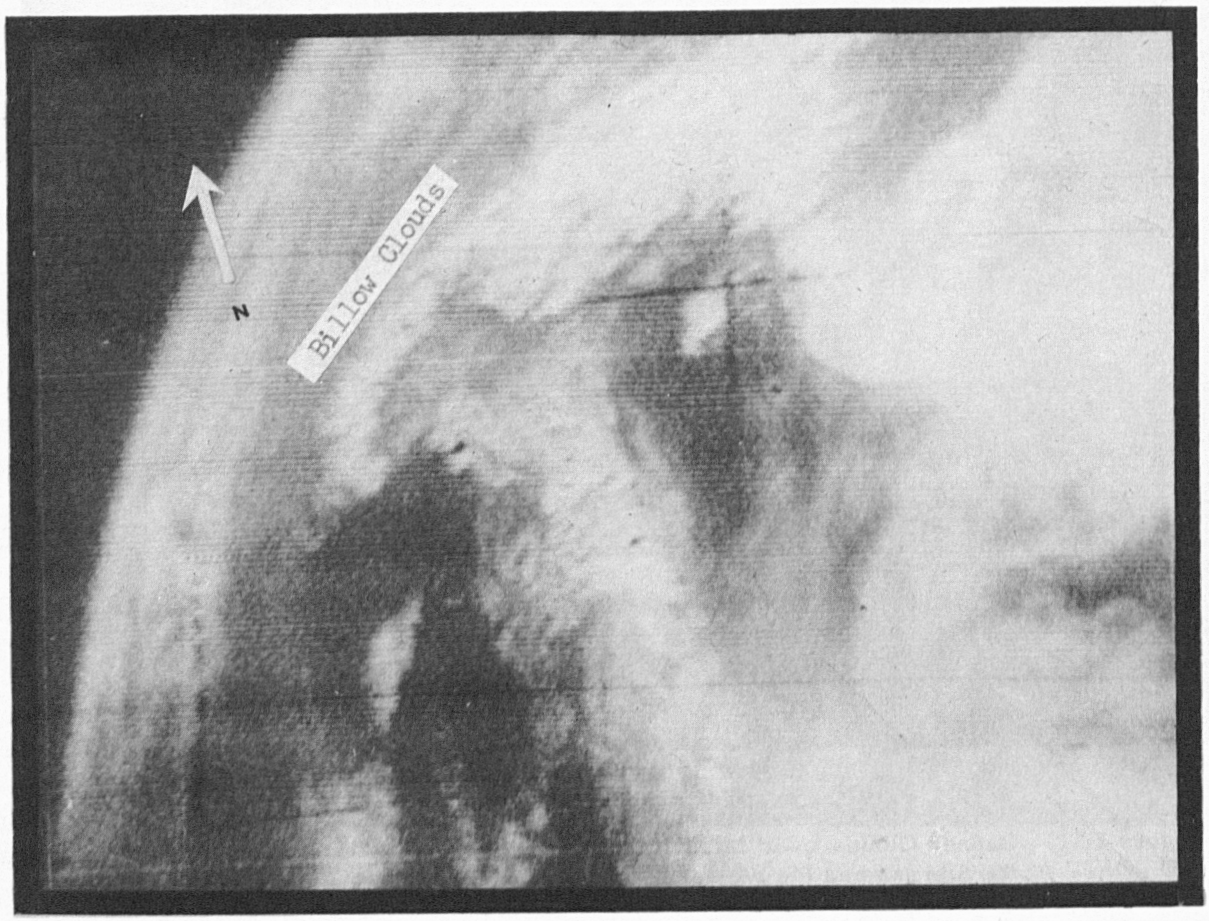

Figure 2.12. Billow Clouds over the Alps.

Figure 2.13. Cloud Streets in Central Pacific Vicinity of Hawaiian Islands.

2.3.4 Jet Stream Clouds

Where cirrus clouds occur in connection with a jet, they are generally located 25 to 50 miles south of the core and form a ribbon extending along the course of the jet stream. TIROS photographs showed some remarkable shots of such jet stream clouds which were accurately

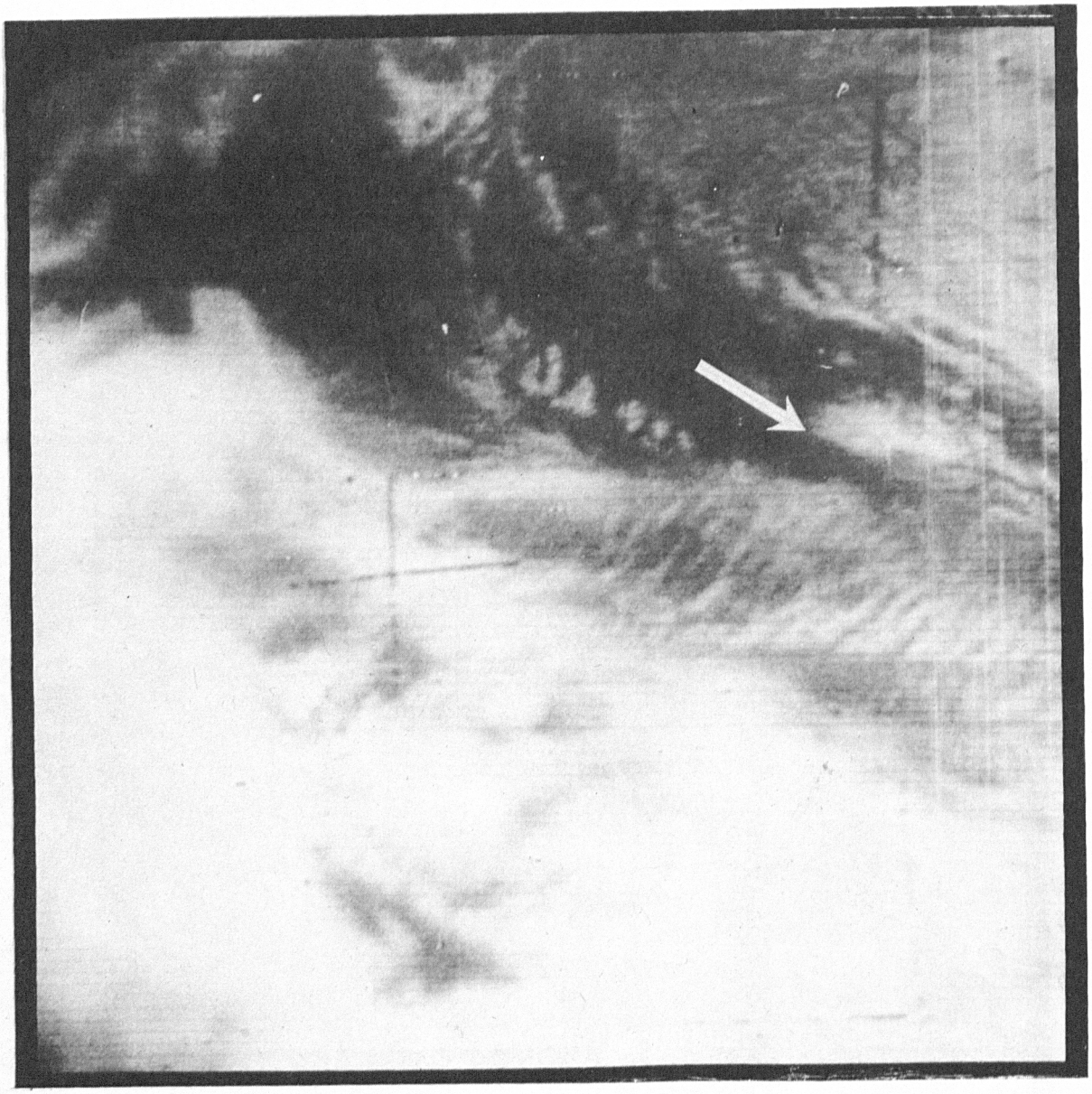

Figure 2.14. Jet Stream Clouds Associated With Extratropical Cyclone over North Pacific near 0000Z, 19 May 1960. The Jet Core Passed North of the Low Center, Which Deepened Rapidly During the Ensuing 12 Hours. Axis of the Jet Is Shown by the Arrow.

located with the aid of upper-air radiosonde observations. Figure 2.14 shows how a jet stream, located by TIROS, could be useful in analysis and forecasting.

2.3.5 Square Tornado Cloud

Figure 2.15 shows the first square tornado cloud ever observed. It was located 50 miles northwest of Wichita Falls, Texas at the time the picture was taken and later moved northeastward, raking Oklahoma with four tornados. Clouds to the north appear to be dense cirrus; those to the south and east largely cumulus and cumulonimbus.

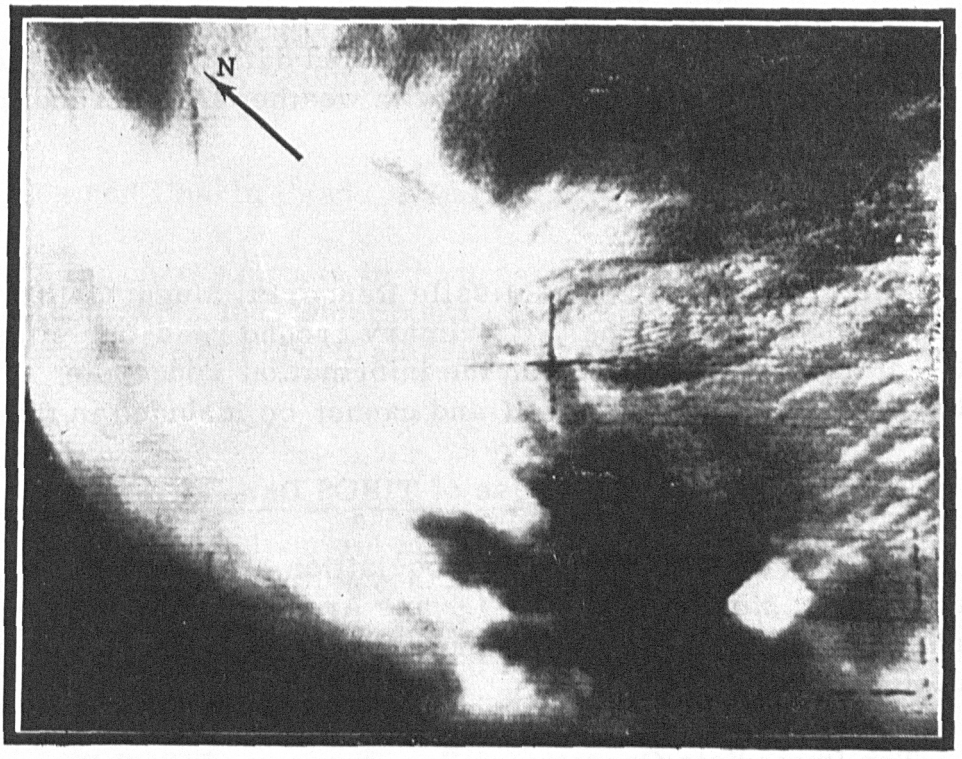

Figure 2.15. Square Tornado Cloud (lower right) Seen by TIROS I. The Square Appearance of the Tornado Cloud May Be Due to Extremely High Reflectivity.

3. NAVAL PARTICIPATION IN PROJECT TIROS

Realizing the potentialities of satellite observations as an operational tool in weather analysis and forecasting, the Navy has been interested in Project TIROS since its inception and is now participating in the NASA TIROS experiments in the following interrelated areas:

1) Data Read-out
2) Immediate Operational Use of TIROS Data
3) Processing, Copying, and Gridding of TIROS Photography
4) Analysis and study of TIROS and related data to develop techniques for the utilization of satellite data in weather analysis and forecasting.

3.1 Data Read-out

The U. S. Navy Pacific Missile Range, Pt. Mugu, California, has been designated one of the two primary ground read-out sites for the TIROS II experiment. Much of the information concerning this phase of the experiment is classified and cannot be included in this report.

3.2 Immediate Operational Use of TIROS Data

Primary command and data acquisition stations for TIROS II are located at Ft. Monmouth, N. J. (Evans Area) and the Pacific Missile Range, Pt. Mugu, California. Information on TIROS II will be included in a later report.

3.3 The Immediate Operational Use Program (TIROS I)

3.3.1 Personnel

Primary command and data acquisition stations were located at Ft. Monouth, N. J., (Evans Area) and at Kaena Pt., Hawaii. Meteorological teams composed of meteorologists from the Weather Bureau and Department of Defense agencies were assigned to each of the read-out sites. The number of men assigned to each site varied from one to seven. A Navy meteorologist was stationed at Ft. Monmouth during the entire operational period of TIROS I. At Kaena Pt. two officers were assigned but neither served for the full period.

3.3.2 Scope and Objectives of the Immediate Operational Use Program.

The immediate objective was to abstract useful meteorological information in such a fashion that it could be used for practical meteorological purposes. Such use depended upon the promptness with which processed satellite data could be placed in the hands of the operational forecaster. Hence, precision and scientific objectiveness were somewhat subordinated to the requirements of speed and productivity.

The ultimate objectives were to develop effective techniques for handling pictorial material contained in the telemetered pictures, and provide a rational evaluation of the potentialities of the meteorological satellite as a tool for increasing the scope of observation and improving forecasting.

3.3.3 Grids and Charts Used for Data Analysis

Grids and charts for use in the program were developed by Allied Research Associates, Inc. under contract with the Geophysics Research Directorate of the Air Force Cambridge Research Command.

3.3.3.1 Perspective Grids

Perspective grids were prepared for all expected altitudes from 325 statute miles to 600 statute miles at 25-mile increments and for nadir angles ranging from 0 degrees to 90 degrees at 2 1/2 degree increments. The purpose of these grids was to allow for the height of the satellite, the various nadir angles and lens distortions. Each point on the perspective grid has a one-to-one correspondence with the transfer grid. A sample is shown by figure 3.1A.

3.3.3.2 Transfer Grid

The transfer grid, figure 3.1B, is the plane counterpart of the perspective grid drawn to the scale of the transverse mercator charts. There is a one-to-one correspondence between points projected on the perspective grid and map points identified by the transfer grid.

3.3.3.3 Transverse Mercator Chart

The transverse mercator chart, figure 3.1C, is a special chart used to facilitate data abstraction. It is similar to the conventional

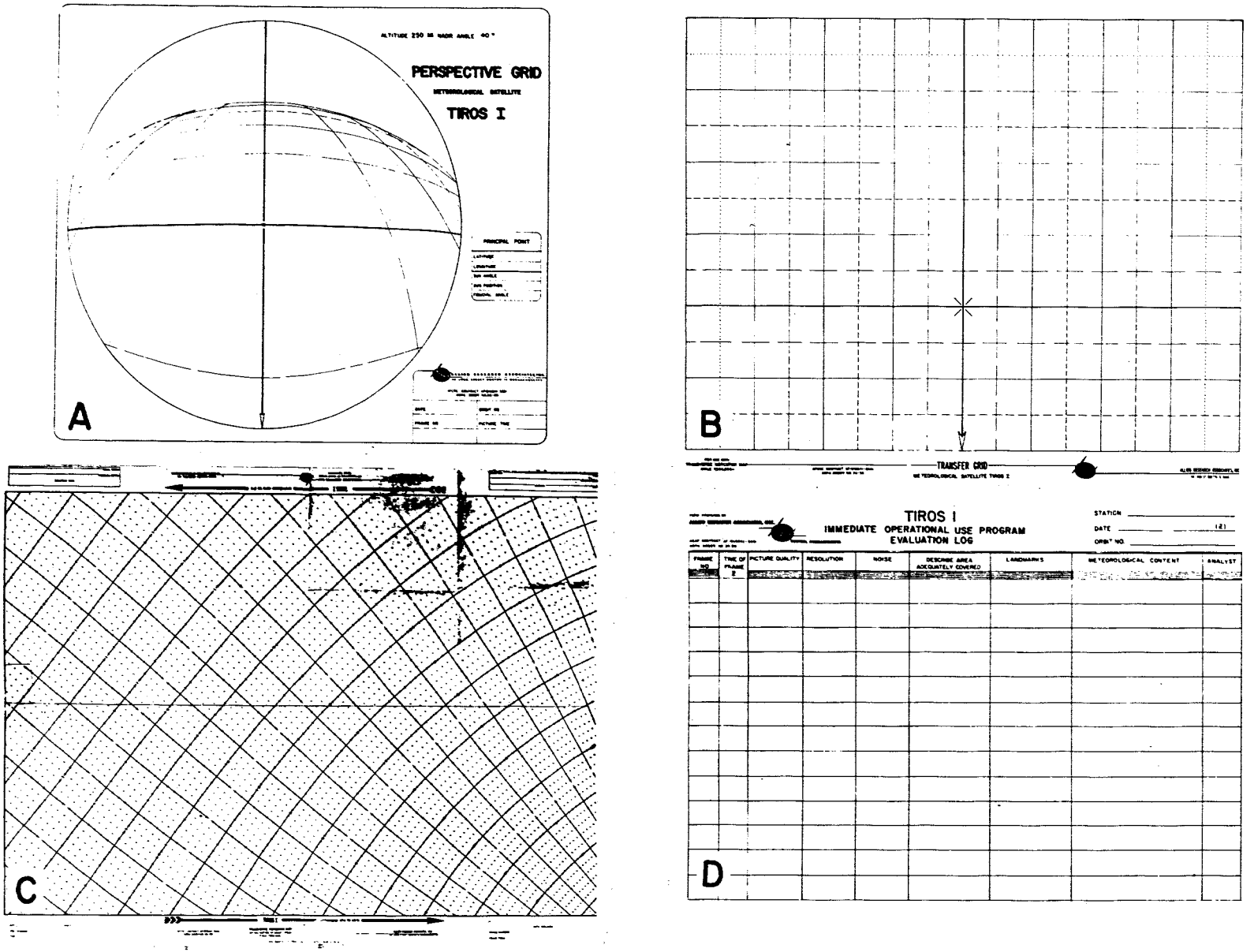

Figure 3.1. Forms Used in TIROS I Immediate Operational Use (IOU) Program.

mercator chart except that the generating cylinder is rotated so that the great circle of contact between the cylinder and the earth's sphere is inclined at approximately the inclination of the satellite orbit. Because of symmetries present, and for convenience, it is possible to break the chart up into three smaller charts which cover a substantial fraction of the satellite orbit.

3.3.4 Data Analysis Procedures*

(1) Upon receipt of program information prepare all required charts and grids. This includes selecting the proper transverse mercator charts, and labelling them with longitude lines to insure that the satellite path is as close to the center as possible in order to reduce distortion factors. Plot satellite subpoints and principal points for the portion of the orbit concerned. Locate the actual subpoint for each programmed picture in accordance with the pre-selected information. Sketch pertinent geographical features on the chart to facilitate picture orientation once rectification is accomplished.

(2) Upon receipt of telemetered information from the satellite in the form of 35 mm film strips, check film strips for picture continuity, number of pictures taken, and picture quality. If the total number of pictures per camera is less than the programmed number, check the events recorder trace in order to discover the discrepancy, if possible.

(3) Once the film strip has been checked for continuity the film is placed in a photo enlarger and the picture enlarged, by the use of a focus sheet, to a size that will permit use of the prepared grids and charts. After focusing, the proper perspective grid is selected by measuring the distance on the enlarged image from the picture center to the horizon, and entering a table to determine the proper grid. This grid, taken from the library and placed over the enlarged image, is oriented to obtain the best fit. Next, a transfer grid is placed over a light box and permanently secured. Nadir angles are marked off on the

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*This section was prepared from the report, submitted by LCDR R. E. Frank, USN, describing activities at the Ft. Monmouth read-out site. The report from Kaena Pt. indicates that there were no significant differences in procedures or in difficulties encountered. Some further refinements in techniques are expected during TIROS II but basic procedures will remain the same.

principal line in the direction of the subpoint in such a way that each nadir angle represents a subpoint. It is then possible to superimpose a transverse mercator chart with plotted subpoints over the transfer grid, center the subpoint on this chart over the appropriate nadir angle marked on the transfer grid and then rotate the chart so that the principal line represented on the transfer grid makes the desired angle with the satellite subpoints plotted on the transverse mercator chart. The picture can be rectified by sketching the desired features directly on the transverse mercator chart from the perspective grid placed over the enlarged photograph. The remainder of the pictures on the film strip can be rectified in a similar manner.

(4) When rectification has been made for a complete orbit the data is transferred from the transverse mercator chart to a conventional mercator chart, primarily to furnish analyzed data to the user in a form with which he is familiar. For TIROS I this chart, properly labeled, was transmitted via a special facsimile circuit direct to the U. S. Weather Bureau Meteorological Center, Suitland, Md. for further dissemination. In addition, a brief word description of the completed analysis was prepared and transmitted via teletype to Suitland for similar distribution. Copies of both messages were broadcast to selected Fleet users by the Fleet Weather Central, Suitland, mostly on a non-scheduled basis.

3.3.5 Analysis Difficulties

Due to failure or malfunctioning of some of the satellite components sun-sensing information, necessary for orienting the picture once rectification had been completed, was missing. Subpoint and principal point data was either received too late or not received at all. Nadir angles received from the Control Center were in error, thus making the principal points almost useless.

Emergency precedures were necessary, in most cases, in order to extract useful information. To offset the lack of sun-sensing data the following procedures were followed:

> Three successive photographs having visible horizons with identifiable landmarks and/or prominent cloud features were rectified together on a blank sheet of paper in order to obtain the best fit. The principal points and subpoints, for each picture, were located in relation to each

other by use of the relationship between nadir angles measured from the photograph and computed distance along the earth between the principal point and the subpoint. Once the best fit was determined, the angle between the line connecting the various subpoints and the principal line for each picture was measured. These angles were then averaged in order to determine the orientation of the principal line in relation to the satellite track. This average angle was laid off on the subpoint plot for the corresponding picture and rectification of the orbit was carried out in both directions from this point either to completion or until photographic features could no longer be identified on successive pictures.

In order to offset the lack of subpoint information, the satellite section of the Weather Bureau prepared subpoint plots based upon previous orbital information received from tracking stations and related to equator crossings of the satellite ascending nodes. From this plotted information and program times it was possible to locate the actual latitude and longitude of the subpoint for each picture with a reasonable degree of accuracy. Ascending node data was furnished by Control Center in Washington several days in advance.

Since the nadir angles received from Control Center were in error, it was necessary to measure the distance from the principal point to the horizon of each picture in order to determine the correct nadir angle. When no horizon was visible this angle could not be determined. Furthermore, the principal line could not be oriented and those pictures with low nadir angles were frequently not rectified. To offset this difficulty a plot of nadir angles measured against latitude was maintained. This plot was extrapolated into the low nadir angle area, thus allowing for rectification of additional pictures. A plot was maintained for each orbit showing the angular shift of the horizon due to the rotation of the satellite about the spin axis for each picture having a visible horizon. An average was taken and used to orient the principal line in areas of low nadir angles.

3.3.6 Communications

No serious difficulties were encountered at either of the read-out sites. Some delays occurred in the delivery of processed data to the Weather Bureau, Suitland, on some occasions because of faulty two-way

communications. Some of these delays could have been avoided by installation of a direct line between the read-out site and the Weather Bureau at Suitland. Other delays could have been avoided by more strict circuit discipline.

A survey was made of 75 satellite messages transmitted by Fleet Weather Central, Suitland to determine the average elapsed time between the mean time of the satellite observation and its receipt in the hands of the operational user. Average time was 20.3 hours, varying from a high of 45.5 hours to a low of 4.1. Normally, only one satellite message was transmitted daily by Fleet Weather Central, usually near the close of the working day. This may account for some of the apparent excessive elapsed times. Others were due to the fact that, in many cases, data acquired during one orbit was not read out until three or more orbits later. Analysis difficulties at the read-out sites delayed transmission in many cases, particularly during the early part of the operating period. Improved analysis techniques during TIROS II should enable the meteorological teams to process the data within one and one-half hours to two hours after receipt. Improved communications could put this information in the hands of possible users within time to be of immediate operational use.

3.4 Processing, Copying, and Gridding of TIROS Photography

The Naval Photographic Interpretation Center, Suitland, Md. expanded its organization to include a TIROS section, which is working closely with the Meteorological Satellite Section of the Weather Bureau to perform detailed photogrammetric analyses of selected films in order to obtain accurate positional information. These data will be used to refine orbital computations and to superimpose latitude-longitude grids on the developed cloud photographs.

3.5 Satellite Data Analysis Techniques - NWRF Task 33

The Navy Weather Research Facility, Norfolk, under Task 33 is making detailed analyses of TIROS data. See figure 3.2.

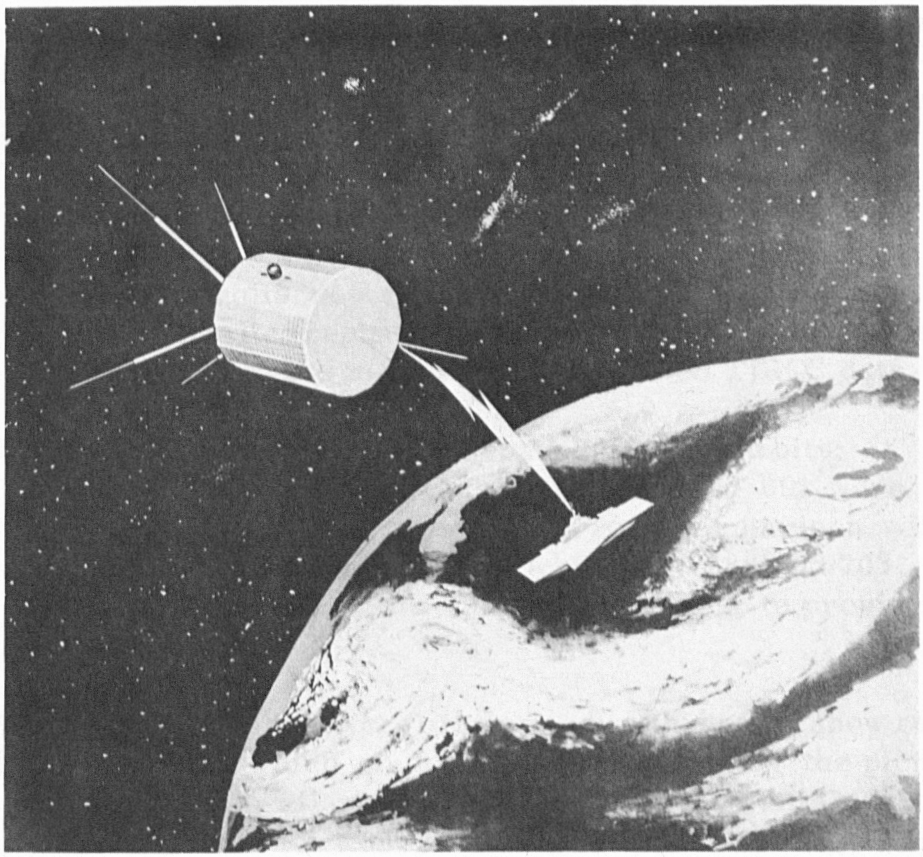
3.5.1 Objectives

(1) Determination of the relationships existing between large-scale cloud masses and synoptic weather features.

Task 33

(Assigned by BuAer ltr Aer AY-30, Ser. 07081 of 7 July, 1959)

METEOROLOGICAL SATELLITE DATA ANALYSIS TECHNIQUES



PURPOSE:

A. Develop techniques for tactical use of available meteorological satellite data in meteorological analysis and forecasting for the U.S. Navy.

B. Investigate:

1) The relationships existing between large-scale cloud masses and synoptic weather features.

2) Application of satellite data to the weather analysis and forecasting in "silent" areas where conventional data are scarce.

3) Development of improved techniques for single station analysis and forecasting through the utilization of satellite data.

4) The kinds of observational data desired from future weather satellites.

Figure 3.2. Analysis and Study of TIROS Data at the Navy Weather Research Facility, Norfolk.

(2) Application of satellite data to the weather analysis and forecasting problem in "silent" areas and areas where conventional data are scarce.

(3) Development of improved techniques for single station analysis and forecasting through the utilization of satellite data.

(4) Determination of the kinds of observational data desired from future weather satellites.

4. WEATHER ANALYSIS FROM TIROS DATA - NORTH PACIFIC, 19 MAY, 1960

4.1 Procedure

At first, sufficient data appeared to be available for a detailed study of North Pacific weather over a ten-day period, based primarily on TIROS photography. A survey of operational messages and nephanalyses transmitted by facsimile indicated that the period from 14 May to 26 May might provide a fruitful field for research. However, the areas covered by successive orbits were not sufficiently large, did not reveal significant weather changes, or were not near enough to synoptic observation times to be operationally useful.

Data from all orbits during the selected period were plotted on mercator charts. Detailed nephanalyses, based on surface observations were then compared with the nephanalyses based on TIROS data.

Photographic mosaics were prepared for six orbits; 687, 688, 689, 690, 691 and 703. Three of these, 689, 690 and 691 were close enough to synoptic observation time to warrant comparison with the 0000Z surface chart of 19 May, 1960. Orbits 687, 688 and 703, which covered only a limited area of the Pacific, were used to provide supplementary information.

Selected frames in the three orbits used in this study show readily identifiable landmarks which could be used in orienting the pictures. Frames showing the Hawaiian Islands and the U. S. West Coast were used, along with information contained in operational messages transmitted by Fleet Weather Central, Suitland, to position the other frames and to determine the area covered. As an aid in analysis, the orbital paths were traced on a global blackboard and nephanalyses based on the photographs were sketched in chalk. (Attempts to photograph these nephanalyses in order to show the distortion induced by the earth's curvature were not successful.) Accurate positioning of individual frames, by plotting subpoints and field of view computed from program data, was not attempted.

The completed mosaic and the surface chart used for comparison are shown in figure 4.1. Figure 4.2 shows a combined surface and nephanalysis with 500 mb and 300 mb analysis for 0000Z. Figure 4.3

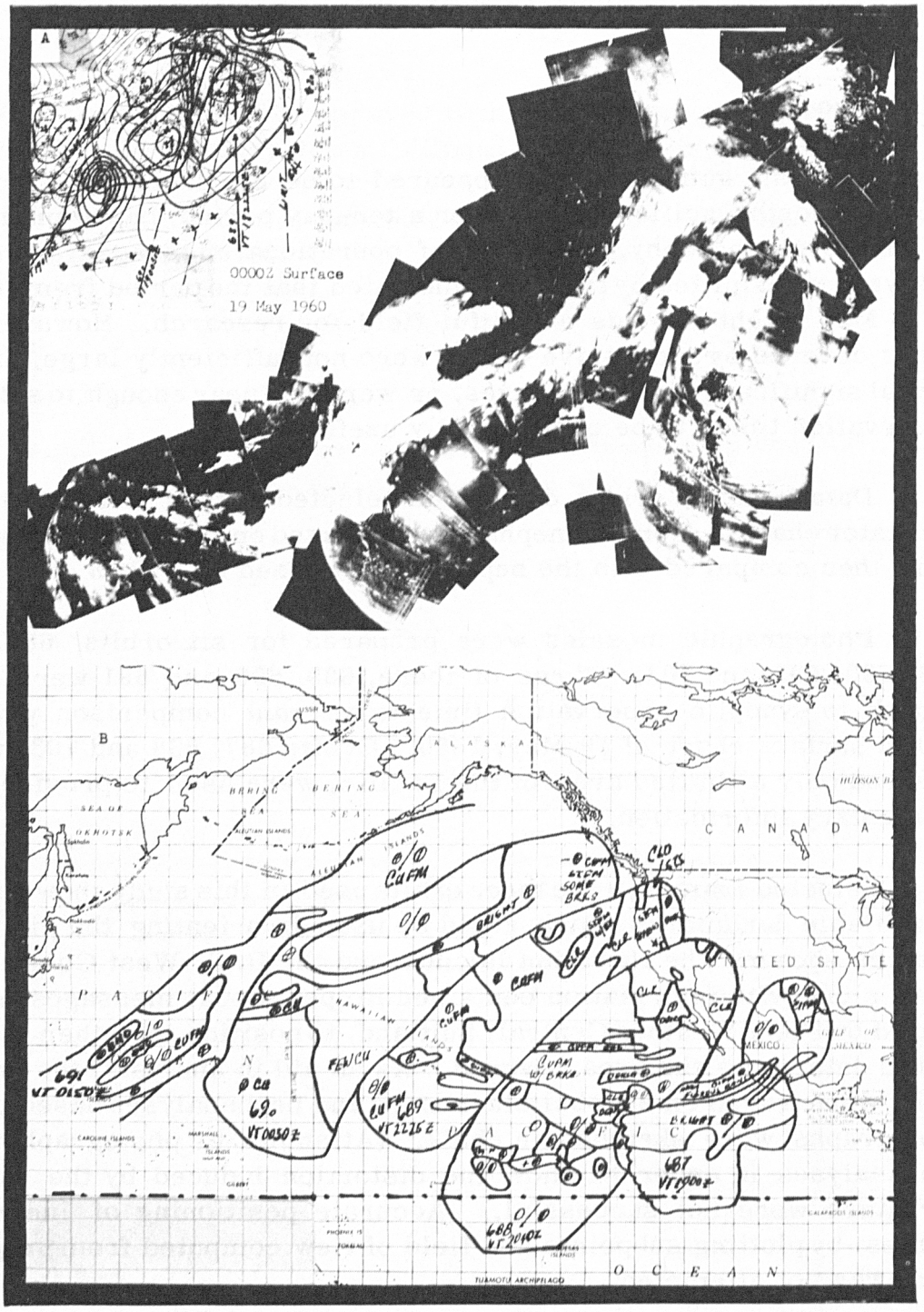


Figure 4.1. Mosaic Constructed of Photographs from Orbits 689, 690 and 691 Compared with (A) 0000Z Surface Chart for North Pacific, 19 May 1960 and (B) Nephanalysis for Same Area Prepared from Facsimile and Teletype Messages.

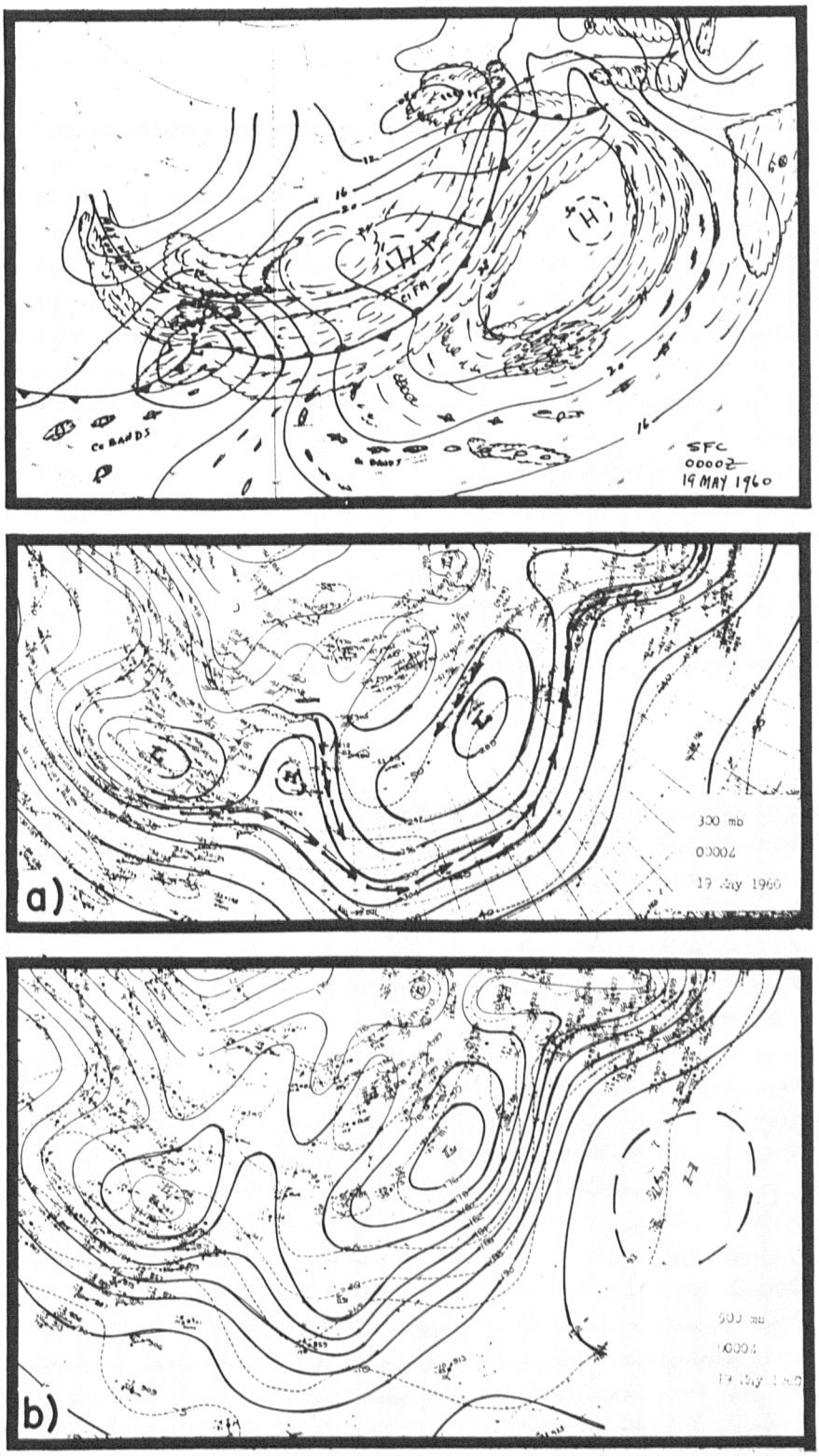


Figure 4.2. Cloud Schematic and Surface Analysis for 0000Z, 19 May 1960 Shown with Analyses for (a) 500 mb, (b) 300 mb.

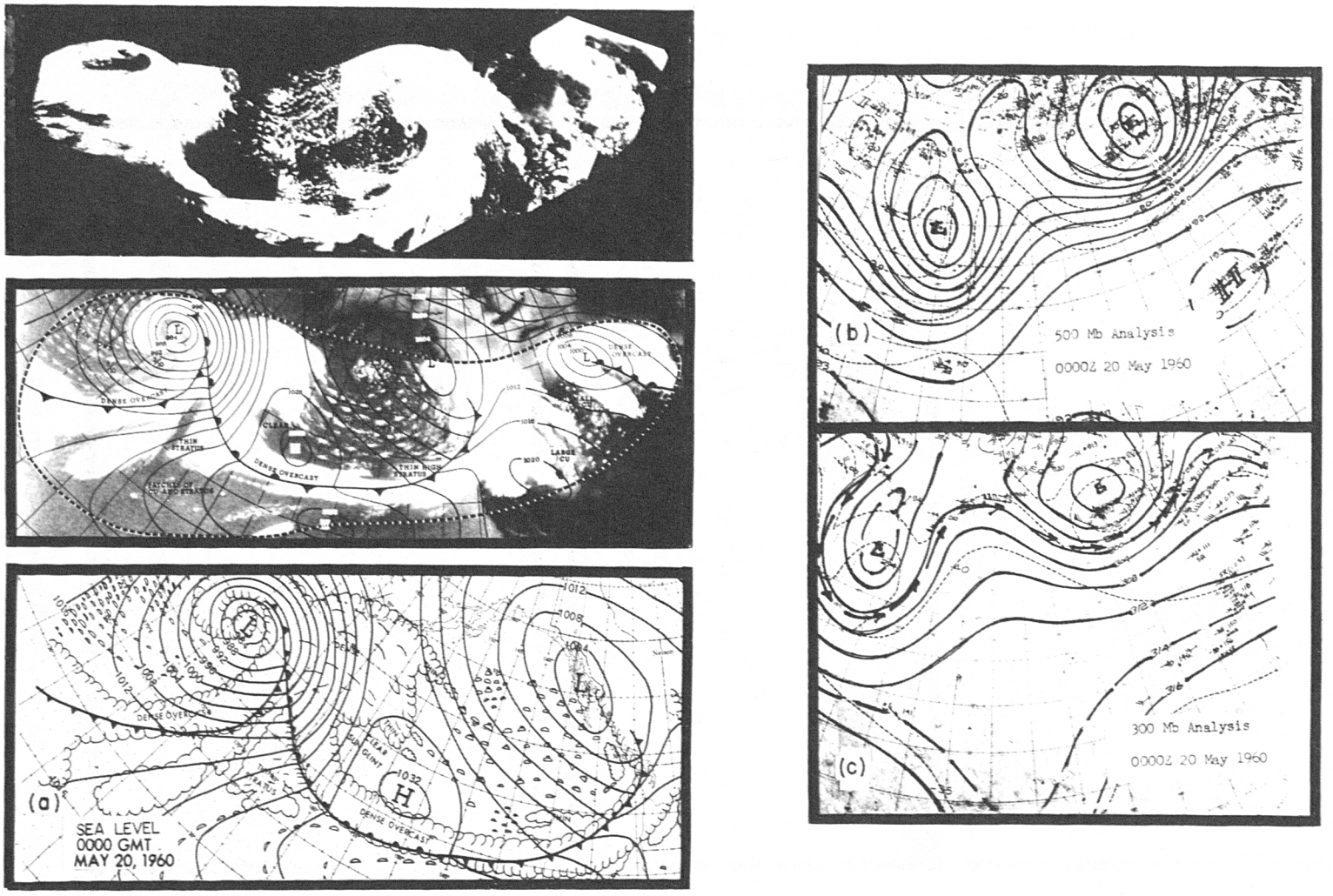


Figure 4.3. Mosaic of TIROS Photographs Superimposed upon Surface Analysis for 20 May 1960 Compared with Conventional Analyses at (A) sea level, (B) 500 mb, (C) 300 mb.

is a similar analysis for the following day, prepared by V. J. Oliver, of the Weather Bureau Office of Forecast Development. Both maps were plotted on the polar stereographic projection normally used in weather analysis and forecasting.

4.2 Analysis of the Data

One of the most striking features of the mosaic is the characteristic feathery appearance of the cirrus clouds associated with the jet stream in orbit 691. It was this feature which first suggested that the orbit might be operationally significant. A check of the 300 mb. chart shows the confluence of two "jet fingers" [26] in this area.

The largest and most active of a cyclone family usually lies somewhere inside an upper air trough. Subsequent members of the same family lie to the west of the trough line and south of the jet stream, and, as they develop, move northeastward into the trough position. The jet stream can usually be found in the rear zone of dissipating clouds behind the major member of the cyclone family. It should cross the occluded front near the point of the occlusion and continue across the cold air ahead of the cyclone. See figure 4.4.

Following Riehl's rule [26] that intense cyclogenesis ensues when a jet stream becomes superimposed on a pronounced frontal zone, one would expect rapid deepening of both cyclones in the series shown in the photographs. And the region of most active surface development should lie along the frontal zone just south of the jet axis. A check of succeeding maps shows that this is exactly what did happen.

The mass of clouds surrounding the westernmost cyclone center in figure 4.1 (near 40N., 175E.) shows the greatest concentration north of the low center and south of the jet axis. The predominant type appears to be nimbostratus, with dense cirrus or cirrostratus fanning out along the edges. The band of frontal clouds breaks up along the western edge of the subtropical anticyclone but thickens into nimbostratus along the northward extension of the cold front and again shows a cyclonic pattern near the center of the low just off the west coast of North America. The band of thin clouds partially shown in orbits 690 and 691 just off the coast is probably stratus associated with the cold Aleutian current, along the northern shores of British Columbia.

Southward, the circulation around the subtropical Pacific anti-

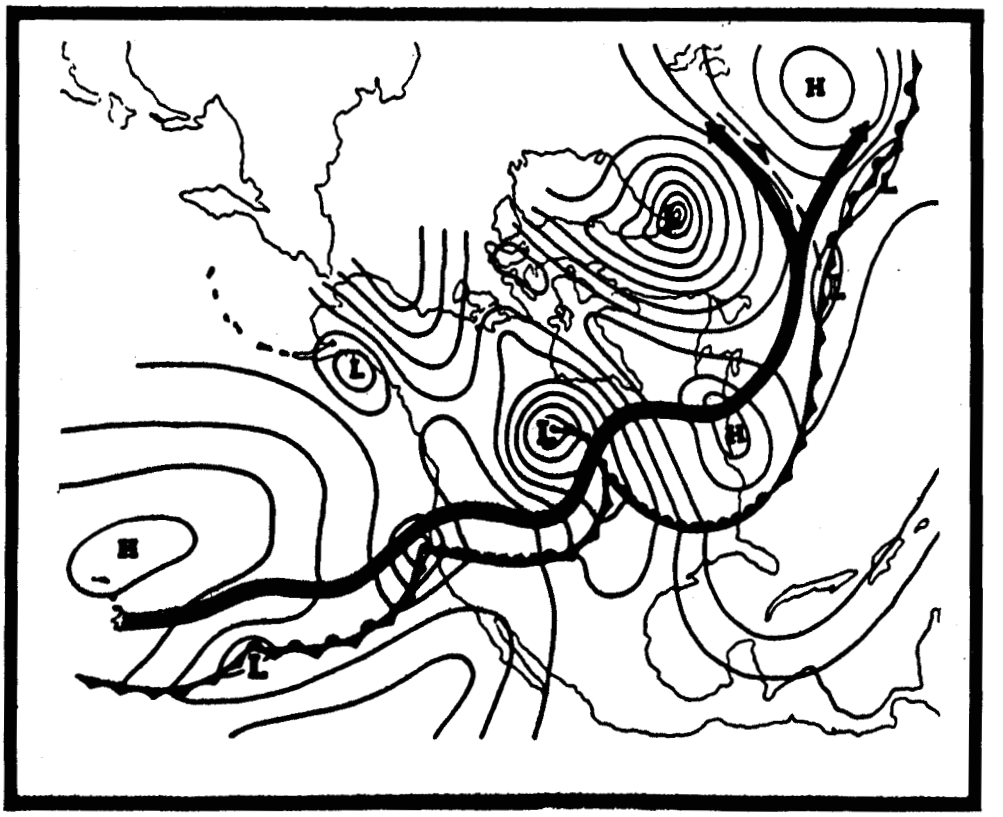


Figure 4.4. Schematic Representation of the Relation of the Jet Stream to the Members of a Cyclone Family. The Thin Lines are Sea Level Isobars, the Wide Line the Jet Stream. From Vederman (1954).

cyclone can be traced by the cloud pattern. The center of the high is clear, with scattered to broken stratocumulus along the southeastern and southern edges. Some altocumulus and altostratus are evident along the southwestern edge near the center, with cumulus rotating around the western edges. Cirriform clouds around the northern fringe merge with the nimbostratus of the frontal zone.

Banner clouds cap the peaks of the Sierras over California and parallel streaks show the billow clouds associated with the "Sierra Wave." Farther east low and middle clouds of a cumuliform type shroud the windward slopes of the Rockies.

Orbit 703, figure 4.5, which covers very nearly the same area as that of orbit 689 almost twenty-four hours later, shows the dense layer of middle and high cloud around the southwestern edge of the sub-

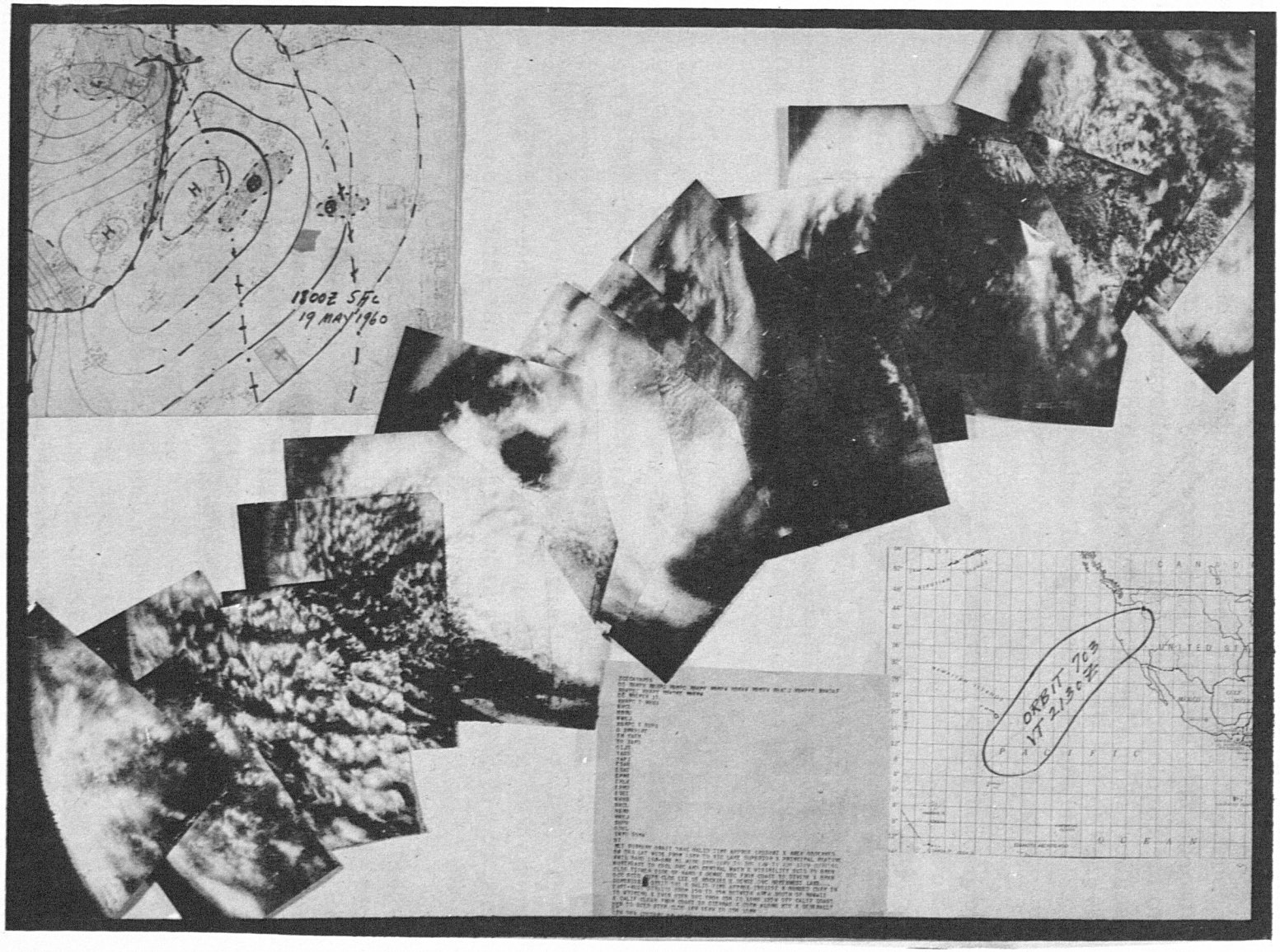


Figure 4.5. Mosaic Constructed of Photographs from Orbit 703 Compared with Operational Summary Transmitted by Fleet Weather Central, Suitland and 1800Z Surface Analysis. Chart at Lower Right Shows Area Covered by TIROS Photographs.

tropical High and the lower part of the clear area near the center. The swirling pattern and the two holes near the center of the picture are probably due to wind shear. They appear to be more pronounced than in orbit 689, but this appearance may be due more to perspective than to meteorological influences. The altocumulus and cirrus around the southwestern edge of the High appear to be a permanent feature of this area.

5. OPERATIONAL USE OF SATELLITE OBSERVATIONS

5.1 Introduction

In a preliminary progress report, issued before TIROS I was launched [32], operational use of the data was predicated upon the assumption that the ship or station using the data could read out the information direct from the satellite.

Read-out stations for the TIROS experiments require elaborate ground installations which would not be practicable aboard ship. However, it is to be hoped that operational weather satellites of the future will contain improvements which will permit their signals to be picked up on standard radio and radar antennae. Until this becomes possible it will still be necessary to station meteorological teams at the read-out sites to analyze the photographic data and prepare it for transmission.

During the TIROS I experiment detailed nephanalyses were prepared from film strips, usually for one orbit, sometimes for several, as shown in figure 4.1. These nephanalyses were transmitted to operational units either in the form of facsimile charts or standard word messages. Various delays in preparation of the data and transmission and handling of the messages detracted from their value for immediate operational use. Some improvement is expected in TIROS II, but the same procedures used for TIROS I will be followed.

Experiments with transmission of TIROS photographs by land-line facsimile circuits have been reasonably successful, but it is not likely that useable pictures could be transmitted by radio-fax at the present time. It appears, therefore, that for the immediate future, at least, operational use of the data will have to be based upon either nephanalysis charts transmitted by facsimile or detailed analyses transmitted by radio in plain language.

TIROS II will have essentially the same orbit as TIROS I and is expected to provide the same photographic data, with some modifications. In addition, TIROS II will have Infra-Red radiation sensors which are expected to give information on the earth's albedo, thermal radiation and water vapor content. This is not expected to be in a form that will be operationally usable.

Future space plans of the National Aeronautics and Space Administration call for meteorological satellites in both polar and fixed (22,000 mile equatorial) orbits within the next five to six years. They are expected to give data on the following meteorological parameters:

a. Cloud cover - type, layer thickness, heights.
b. Wind direction.
c. Distribution of water vapor, carbon dioxide, and ozone.
d. Temperature.
e. Radiation balance.
f. Spectra of solar, atmospheric and terrestrial radiation.
g, Electrical disturbances.

Instrumentation will include television cameras, radar, bolometers, and other radiation detectors. With communications satellites, establishment of a "real time" data link and a fully operational satellite "real time" data input to weather centrals, is planned.

The first polar-orbit meteorological satellite is currently planned for early 1962. This will be followed by one in a 22,300-mile equatorial orbit, and, when it becomes feasible, by radar satellites and a "real time" data link in connection with planned communications satellites.

The first communications satellites are expected to be of the "passive" type, with no instrumentation, similar to ECHO I. Plans are to put 12 to 24 of these balloons in equally spaced orbits of 1,000 to 3,000 miles.

Later plans call for three active communications satellites in fixed equatorial orbits (i.e., at an altitude of 22,300 miles), with a useful life of 2-3 years.

5.2 Use of Satellite Observations in Naval Operations

Only a few areas on the earth's surface (Europe, parts of the U. S., Japan) have close networks of weather stations. Under conditions of war or threat of war most of these may be missing. Meteorological observations would not be available from most of the oceanic areas over which the Navy is required to operate; satellites may be able to provide detailed cloud information over these areas.

Even clouds which have no apparent meteorological significance

may hamper naval operations, such as photographic or bombing missions. Cloud patterns often give some indication of atmospheric processes and the extent of cloud cover can give some information about the size and intensity of oceanic storms. When sufficient cloud photographs become available it may be possible to estimate sea conditions and wind velocities from cloud photographs, just as wind velocities are estimated from photographs of sea conditions at present.

5.2.1 Carrier Raids on Tokyo - 1942

To emphasize the importance of weather observations in modern warfare one can easily cite two outstanding instances where lack of such information seriously affected the success of the mission. The first of these, the bombing of Tokyo, in 1942, by Army Air Force bombers launched from the aircraft carrier Hornet, has been described often enough in books and movies to prove that weather was an important factor in the operation and that cloud photographs of the area west of the carrier's position would have contributed immeasurably to the success of the undertaking and may have prevented some of the tragic crashes which occurred later.

5.2.2 Normandy Landings - 1944

On the other hand, despite an abundance of weather information from conventional means, the Allied invasion of Normandy almost met with disaster because of severe weather during the days following the landings. The Allied forces received weather information from the United States, Canada, Greenland, Iceland, and ships at sea. And yet, Allied meteorologists were unable to forecast accurately the severity of the storm which caused the loss of numerous invasion ships and millions of dollars worth of supplies. A better idea of the severity of the storm might have been obtained from cloud photographs similar to the one shown in figure 5.1, depicting the storm which appears in figure 1.8.

5.2.3 Amphibious Assaults

The weather requirements of an amphibious force are extremely complex. Amphibious assaults must be closely coordinated with the weather in order to proceed with maximum efficiency and minimum loss in personnel and material. Among the requirements for both the softening up process preceding the landing of troops and the actual in-

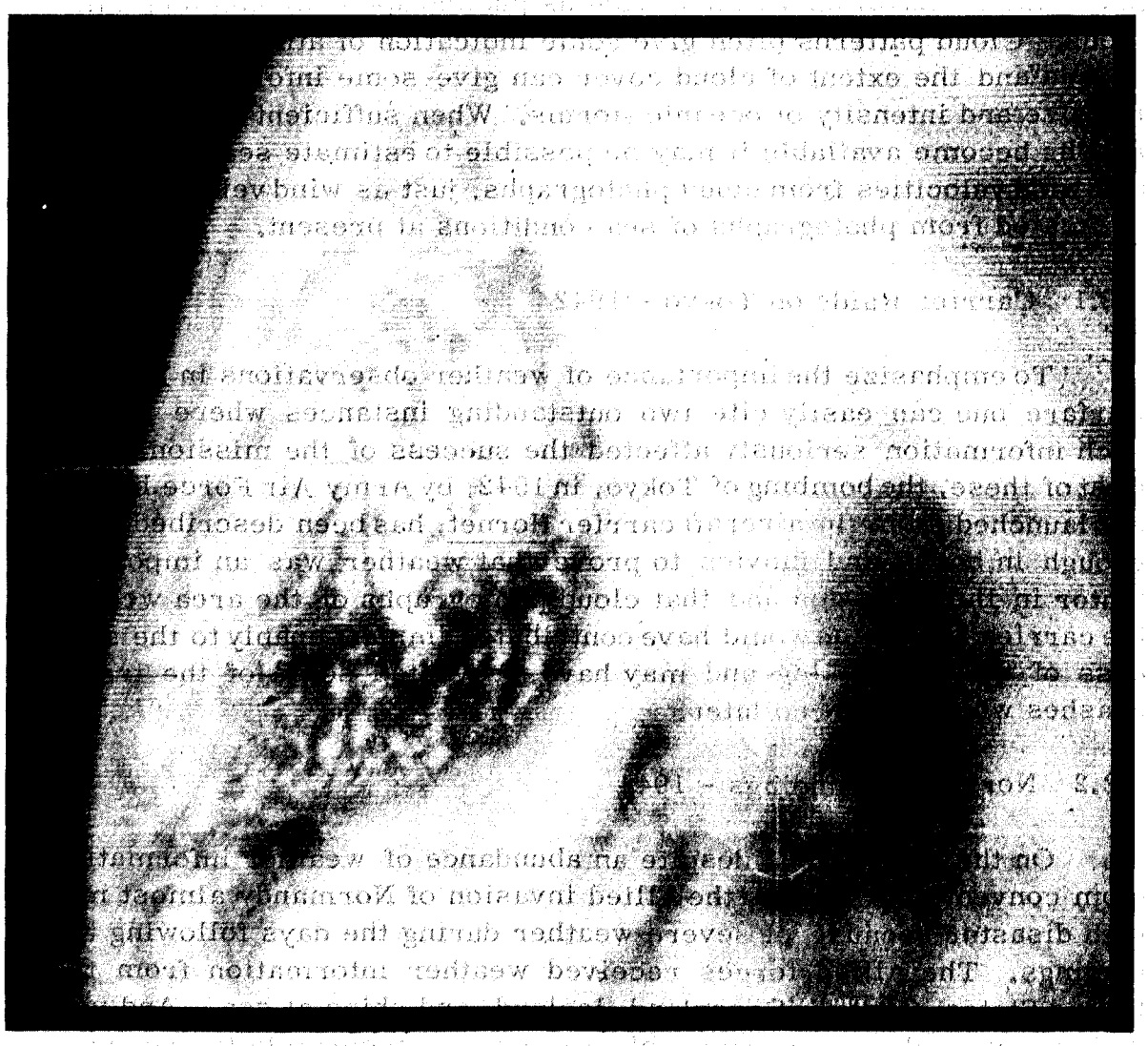


Figure 5.1. TIROS Photographs of North Atlantic Storm Showing Heavy Clouds over British Isles and France.

vasion are clear skies or scattered clouds. These conditions over the landing area cannot always be determined accurately from even a fairly dense network of reporting stations, but are immediately apparent from a satellite photograph.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Navy Operational Requirements

It should be fairly obvious that meteorological satellites can provide observations that are particularly suited to the Navy's operational requirements. What is not so obvious is how these requirements can be fitted into the present national meteorological satellite program.

The meteorological requirements for refueling at sea are not the same as those for refueling in air. The requirements for anti-submarine warfare, for amphibious assaults, for carrier operations at sea, and for Polaris launchings do not coincide with those of the Strategic Air Command. Nor do the requirements of civil aviation fit those of the Navy's Ship Routing Program.

It may well be that the Navy's needs could best be served by meteorological satellites designed for direct read out aboard ship or at Fleet Weather Centrals. This would eliminate the delays caused by present methods of processing data at the ground read out sites.

Operational satellites in circular near-polar orbits, fully earth-oriented, will give vertical photographs, thus eliminating the rectification and orientation procedures needed in the TIROS experiments.

Direct vertical shots of cloud cover within the operating radius of carrier-based aircraft and Polaris submarines would provide sufficient weather information for short-range operational planning.

Two satellites at intermediate altitudes (4-600 nautical miles) would give information on cloud cover over an area about 500 miles in radius every six hours. Three satellites, properly spaced, would furnish observations every four hours. Storage capacity could be sacrificed to reduce weight, but some measures should be taken to prevent enemy jamming or interference.

6.2 Recommendations

The most urgent need is for trained personnel to participate in the national meteorological satellite program and to develop techniques for utilization of the data.

Other services participating in the satellite program have created meteorological sections within their own organizations and are integrating satellite data into their present systems of weather analysis and forecasting.

This does not imply that the Naval Weather Service should establish a section which would merely duplicate the work of other activities.

Most important should be the realization that the number and variety of meteorological satellite observations will continue to increase. An expanded research program will be needed to effect fullest utilization of the data. The workload of some operational units of the Naval Weather Service will be increased as the Navy Weather Service starts to use satellite observations, because all of the more conventional types of analyses must also be carried on in parallel with satellite data analyses until the latter is more fully understood and accepted. Therefore, the present training program should be expanded in order to insure that officers and men are properly trained in the analysis and utilization of data received from this new source of weather information and that the transition into the age of operational meteorological satellites will be as smooth as possible.

BIBLIOGRAPHY

1. BIELINSKI, L. S., "Location of Jet Maxima." Bulletin of the American Meteorological Society. Vol. 41, No. 7, pp. 368-371. 1960.

2. BJERKNES, J. and H. SOLBERG, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation." 1922.

3. BROOKS, C. F., "The Use of Clouds in Forecasting." Compendium of Meteorology. pp. 1167-1178. 1951.

4. BRUNT, D., Weather Study. New York: Ronald Press. p. 135. 1942.

5. CANFIELD, N. L., "Weather and Navigation of the Sea." Weekly Weather and Crop Bulletin - National Summary of Jan 9, 1956. 1956.

6. CONOVER, J. H., "Observations and Photographs of a Cold Front Made from an Aeroplane." Bulletin of the American Meteorological Society. Vol. 29, pp. 313-318. 1948.

7. CONOVER, J. H., "Cloud Patterns and Related Air Motions Derived by Photography." Blue Hill Meteorological Observatory Final Report under Contract No. AF 19(604)-1589. Harvard University. 1959.

8. CONOVER, J. H. and MAJ. JAMES C. SADLER, "Cloud Patterns as Seen from Altitudes of 250 to 850 Miles - Preliminary Results." Bulletin of the American Meteorological Society. Vol. 41, No. 6, pp. 291-297. 1960.

9. CONOVER, J. H. and SARAH H. WOLLASTON, "Cloud Systems of a Winter Cyclone." Journal of Meteorology. Vol. 6, pp. 249-260. 1949.

10. DEPARTMENT OF THE ARMY, NAVY, AND AIR FORCE, "Handbook, Photographic Interpretation." TM 30-245, NAVAER 1Q-35-610, AFM 200-50. 1953.

BIBLIOGRAPHY (Continued)

11. FRITZ, S., "On Observing the Atmosphere from Satellites - I. Cloud Observations." Weatherwise. Vol. 12, No. 4, pp. 139-144. 1959.

12. FRITZ, S. and H. WEXLER, "Cloud Pictures from Satellite Tiros I." Monthly Weather Review, March 1960. Vol. 88, No. 3, pp. 79-87. 1960.

13. GLASER, A. H., "Meteorological Utilization of Images of the Earth's Surface Transmitted from a Satellite Vehicle." Blue Hill Meteorological Observatory, Report under Contract No. AF 19(604)-1589, Phase II. Harvard University. 1957.

14. Hearings before the NASA Authorization Subcommittee on Aeronautical and Space Sciences. U. S. Senate. 86th Congress on S. 1582. April 7-10, 1959.

15. "How the World Looks to a Satellite." U.S. News and World Report. April 18, 1960.

16. JOHNSON, DAVID S., "Image Sensing as Applied to Meteorological Satellites." Journal of the Society of Motion Picture and Television Engineers. Vol. 69, pp. 14-18. 1960.

17. LANDSBERG, H. E., "Geophysics and Warfare." Research and Development Coordinating Committee on General Sciences, OFFASSTSECDEF R and D. March, 1954.

18. LUDLAM, F. H., "The Forms of Ice-Clouds." Quarterly Journal Royal Meteorological Society. Vol. 74, pp. 39-56. 1959.

19. LUDLAM, F. H. and R. S. SCORER, Cloud Study. New York: Macmillan Co. 1958.

20. Meteorology Branch, GSFC, NASA. Operational Plan Project TIROS. 1959.

21. NAVAER 00-80U-22. "Aerology for Naval Aviators." 1952.

BIBLIOGRAPHY (Continued)

22. NAVAER 50-1P-529. "Single Station Analysis and Forecasting Techniques." 1955.

23. NAVAER 50-1P-541. "Numerical Weather Prediction." 1956.

24. NAVAER 50-1R-35. "Practicable Map Analysis Utilizing a Single Ship's Reports." 1945.

25. NAVAER 50-1R-212. "Aerological Intelligence." 1947.

26. NAVAER 50-1R-246. "Forecasting in Middle Latitudes." 1952.

27. NAVAER 50-50R-2. "Wartime Developments in Applied Climatology."

28. NAVAER 50-1T-2. "Clouds of the Aleutian Islands." 1943.

29. NAVAER 50-30T-1. "The Invasion of Sicily." 1944.

30. NAVAER 50-30T-8. "The Invasion of Southern France." 1945.

31. NAVAER 50-30T-9. "Amphibious Landings in Lingayen Gulf." 1945.

32. NWRF 33-0360-029. "Operational Use of Weather Satellites." 1960.

33. NEGLEY, RICHARD M., "On the Use of High-Altitude Cloud Photographs as a Basis for Inferring the Distribution of Wind, Temperature, and Pressure." Report under Contract AF 19(604)-1754 with CRD, AFCRC, ARDC. 1959.

34. O'CONNOR, J. F., Cloud Significance and Forecasting. 1953.

35. "Operational Plan for Project TIROS. ARA-739." Allied Research Associates, Inc., Boston. November 1959.

36. PANOFSKY, HANS, "Vertical Motion and Changes in Cloudiness." Bulletin of the American Meteorological Society. Vol. 27, pp. 312-313. 1946.

BIBLIOGRAPHY (Continued)

37. PANOFSKY, HANS, "Introduction to Dynamic Meteorology." Pennsylvania State University Press. 1956.

38. PROSSER, NORMAN E. and WM. A. DRYDEN, "Optimum Utilization of Satellite Observations in Weather Analysis and Forecasting." Final Report under Contract AF 19(604)-1754 with GRD, AFCRC, ARDC. 1959.

39. Publication 479 - "Research and Education in Meteorology." Committee on Meteorology, National Academy of Science. 1958.

40. RADIO CORPORATION OF AMERICA, "This is TIROS." Reference Handbook for TIROS I Meteorological System prepared under Contract No. DA-36-039-SC-78902 with NASA under USASRDL.

41. SCHAFER, V. J., "Cloud Forms of the Jet Stream." Tellus. Vol. 5, pp. 27-31. 1953.

42. SCHERESCHEWSKY, P. L., "Clouds and States of Sky." Handbook of Meteorology. pp. 882-920. 1945.

43. "Sea Power 'The Navy in Space'." NAS Norfolk Dope Sheet. Vol. 19, No. 19. 1960.

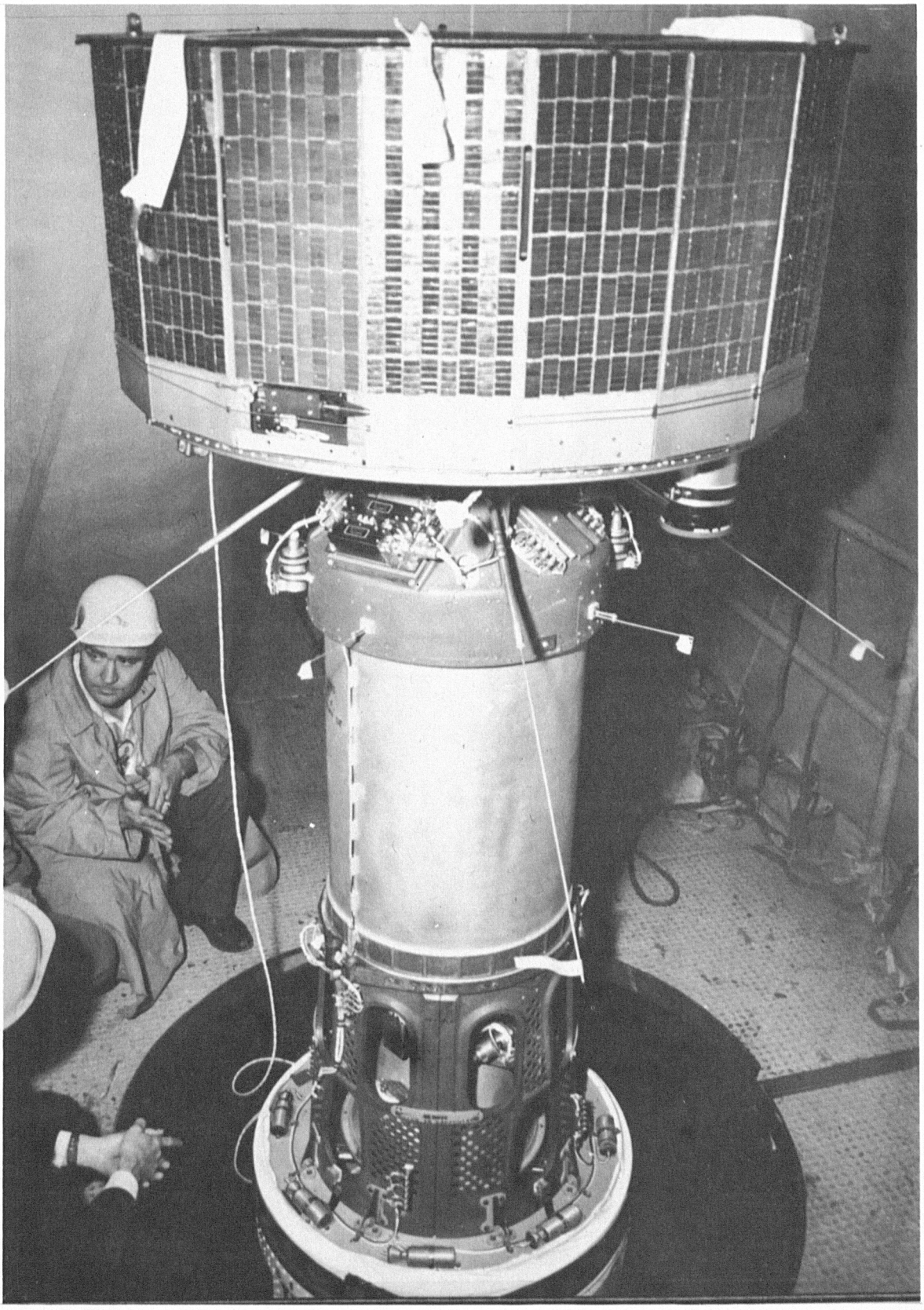
44. SHERMAN, L., "A Mechanism for Producing Cloud Lines." Journal of Meteorology. Vol. 9, pp. 110-117. 1952.

45. "Space Aeronautics." p. 31. May 1960.

46. "Space Handbook: Astronautics and Its Application." Staff Report of the Select Committee on Astronautics and Space Exploration. Washington. 1959.

47. "Space Surge." TIME. pp. 57, June 6, 1960. Copyright Time Inc. 1960.

48. "Space, the New Frontier." NASA Publication. 1960.



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BIBLIOGRAPHY (Continued)

49. STROUD, W. G., "Initial Results of the Tiros I Meteorological Satellite." Journal of Geophysical Research. Vol. 65, No. 5, pp. 1643-1644. May 1960.

50. STROUD, W. G., "Our Earth as a Satellite Sees It." National Geographic Magazine. pp. 293-296. August 1960.

51. STYER, CAPT. CHAS. W. and CAPT. R. F. FREITAG, USN, "The Navy in the Space Age." U. S. Naval Inst. Proc. Vol. 86, No. 3, pp. 86-93. 1960.

52. U. S. NAVY HYDROGRAPHIC OFFICE, American Practical Navigator (Bowditch). pp. 295-297. 1942.

53. VEDERMAN, JOS., "The Life Cycles of Jet Streams and Extratropical Cyclones." Bulletin of the American Meteorological Society. Vol. 35, pp. 239-244. 1954.

54. "Weather from Above." Time. p. 57, August 1, 1960.

55. "Weather Modernization Program." Progress Report of USAF Weather Observing and Forecasting System 433L. 1959.

56. WIDGER, W. K., JR. and C. N. TOUART, "Utilization of Satellite Observations in Weather Analysis and Forecasting." GRD, AFCRC. 1958.