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Establishing an operational weather satellite system.

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Establishing an Operational Weather Satellite System

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I. Introduction

Weather is a global phenomenon—global in extent, in movement, and in effect. If it is to be comprehended and accurately forecast, it must be observed on a worldwide basis. Meteorologists have long understood this and attempted to achieve such observation by extending their observing and reporting networks as widely and completely as possible. Despite their

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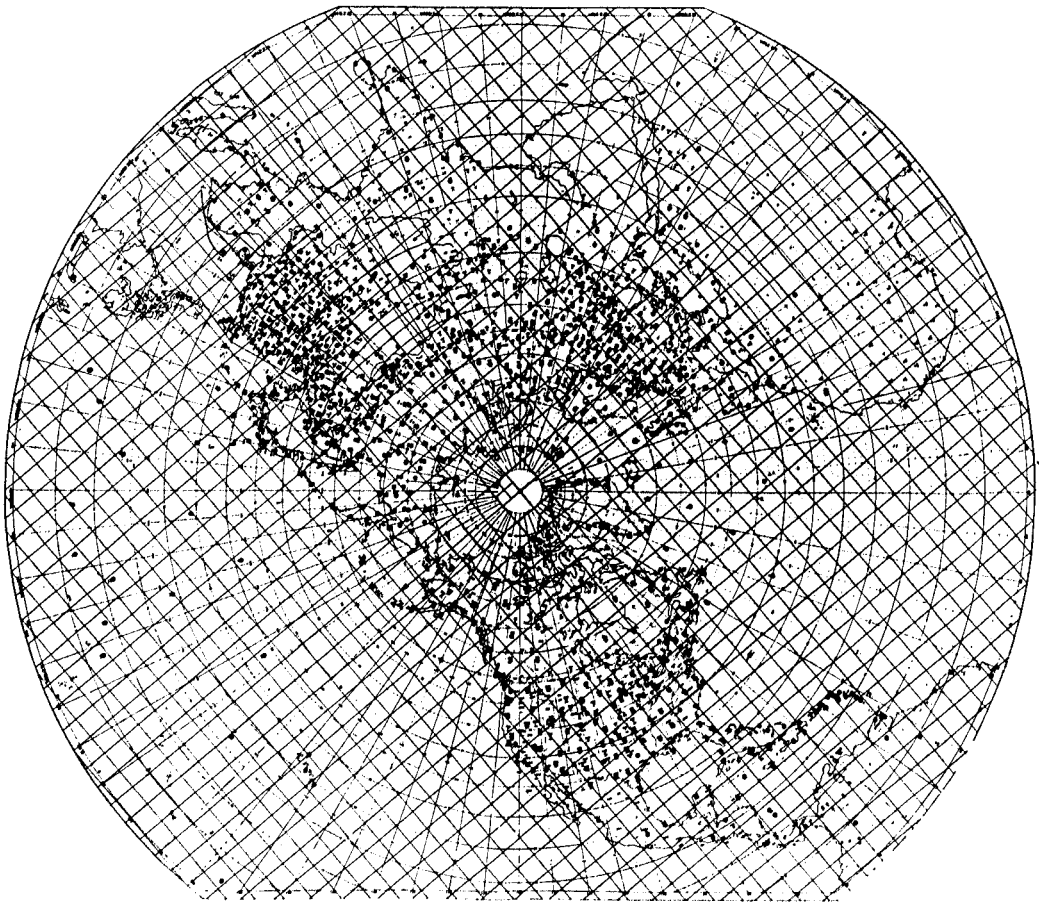

FIG. 1. Major weather observing stations of the Northern Hemisphere. To fill the gaps represented here in oceanic and undeveloped continental areas is a prime objective of the national operational meteorological satellite system (U. S. Weather Bureau).

best efforts, however, only 20 per cent of the Earth's atmosphere is adequately or near-adequately observed by conventional meteorological means. The ocean areas, polar zones, and interiors of lesser developed land masses are typical of the data-sparse areas that dominate the globe, particularly in the Southern Hemisphere (Fig. 1).

In the early and mid-1950's some meteorologists began looking to the artificial satellite as the answer to the problem of how to obtain global weather observation and reporting [1]. As the technology of orbital flight drew closer to realization, these weathermen pressed harder for the appli-

cation of satellites to their requirements. Their theoretical analyses were supported by the hard evidence of the meteorologically useful information contained in the very high-altitude pictures taken by camera-equipped V-2, Aerobee, and Viking sounding rockets fired from White Sands, New Mexico [2]. When, on 5 October 1954, a Naval Research Laboratory Aerobee brought back films showing the presence of an unsuspected tropical storm near Del Rio, Texas, the worth of taking pictures of the Earth's cloud cover from rocket or satellite heights had been positively established [3].

Atmospheric scientists foresaw satellites as carrying out two basic types of meteorological experiments: (1) mapping of the Earth's cloud cover and (2) measuring the Earth's heat budget. From the former, weathermen would be able to plot major weather systems and follow their development and movement. From the latter, they would learn (a) how much of the energy input from the Sun is reflected by the Earth and its atmosphere and (b) how much is absorbed and reemitted. Knowledge of this would assist greatly their understanding of weather processes because it is the energy received from the Sun—and its variations and unequal distribution—which "drives" the atmosphere like a giant heat engine. Weather is to a large extent the result of the shifts and changes undergone by the atmosphere in trying to adjust to the nonuniform heat energy which it contains.

Satellite technology was eventually brought to reality in America in the form of the Vanguard program. Intended to support the research goals of the International Geophysical Year, it is not surprising that meteorological experiments were among those selected to be included. An attempt to orbit a Vanguard satellite containing photocells, for the mapping of cloud cover, failed due to carrier (SLV-3) malfunction on 26 September 1958. Vanguard 2, successfully orbited on 17 February 1959, similarly carried two photocells to sense solar radiation reflected from clouds, using the satellite's spin as its scanning technique. Unfortunately Vanguard 2's spin proved erratic, and useful information was not obtained. The next cloud cover experiment was carried out on Explorer 6, successfully launched on 7 August 1959. This amounted to a television system adapted from the Pioneer 2 lunar probe. Some pictures were obtained of the Earth and its clouds, but quality was unsatisfactory. Explorer 7, which followed on 13 October, took aloft a radiation balance experiment to obtain data for calculating the Earth's heat budget along the satellite's track [4].

These early experiments paved the way for Tiros—the Television Infrared Observational Satellite—which was begun in the spring of 1958 as a development program of the Advanced Research Projects Agency of

the Department of Defense.[1] Later, on 13 April 1959, it was transferred to National Aeronautics and Space Administration (NASA) jurisdiction. Still later, on 1 April 1960, the first Tiros was orbited from Cape Kennedy. Immediately its two television cameras began transmitting cloud cover pictures of remarkable clarity and meteorological value. The weather satellite had come of age.

II. Tiros Satellite and Operations

It is the purpose of this chapter to describe progress made toward the establishment of a national operational weather satellite system. Details of individual spacecraft or spacecraft types are, accordingly, not included except where such details are pertinent basic characteristics or reflect meteorological observation capabilities.

Except for variations in the camera systems and radiation experiments which they carried, the first eight Tiros satellites were virtually identical. Their weight ranged between 270 and about 300 lb. The aluminum alloy/stainless steel shell measured 42 in. in diameter, 22 in. in height. Constructed in the form of an 18-sided polygon, its top and sides were covered with 9200 1 cm by 2 cm silicon solar cells. Current derived from these cells was stored in 63 nickel-cadmium batteries which powered the observing, recording, and communication subsystems aboard.

Telemetry information on the functioning of these systems and on "housekeeping" aspects of the satellite was impressed upon two tracking beacons (50 mw output), operating at 108 and later at 136 Mc.

To observe cloud cover, three basic television camera systems were used involving a narrow-angle lens (12 deg), medium-angle lens (80 deg), and wide-angle lens (104 deg). Viewing the Earth straight down (0 deg nadir angle) from Tiros altitudes of about 450 statute mi, these systems provided pictures 75 mi square, 450 mi square, and 750 mi square, respectively. Pictures were taken with a ruggedized half-inch vidicon, using a solenoid-operated focal plane shutter, and a shutter speed of 1.5 msec. Television lines per frame: 500; frames per second: ½. Straight-down resolution for the narrow-angle cameras: 0.2–0.6 mi; for the medium angle, 1.2 mi; and for the wide angle, 1.5–2 mi.

Tiros 1 through 7 (Fig. 2) each carried two cameras, the combination of lenses differing from satellite to satellite. (Tiros 8 was equipped with a conventional wide-angle camera and a new automatic picture transmission system described later in Section V.) Each narrow-, medium-, or wide-

[1] NASA did not come into being until 1 October 1958. Pending its establishment, Public Law 85-325 had authorized the Secretary of Defense to engage for one year in advanced nonmilitary space projects as designated by the President.

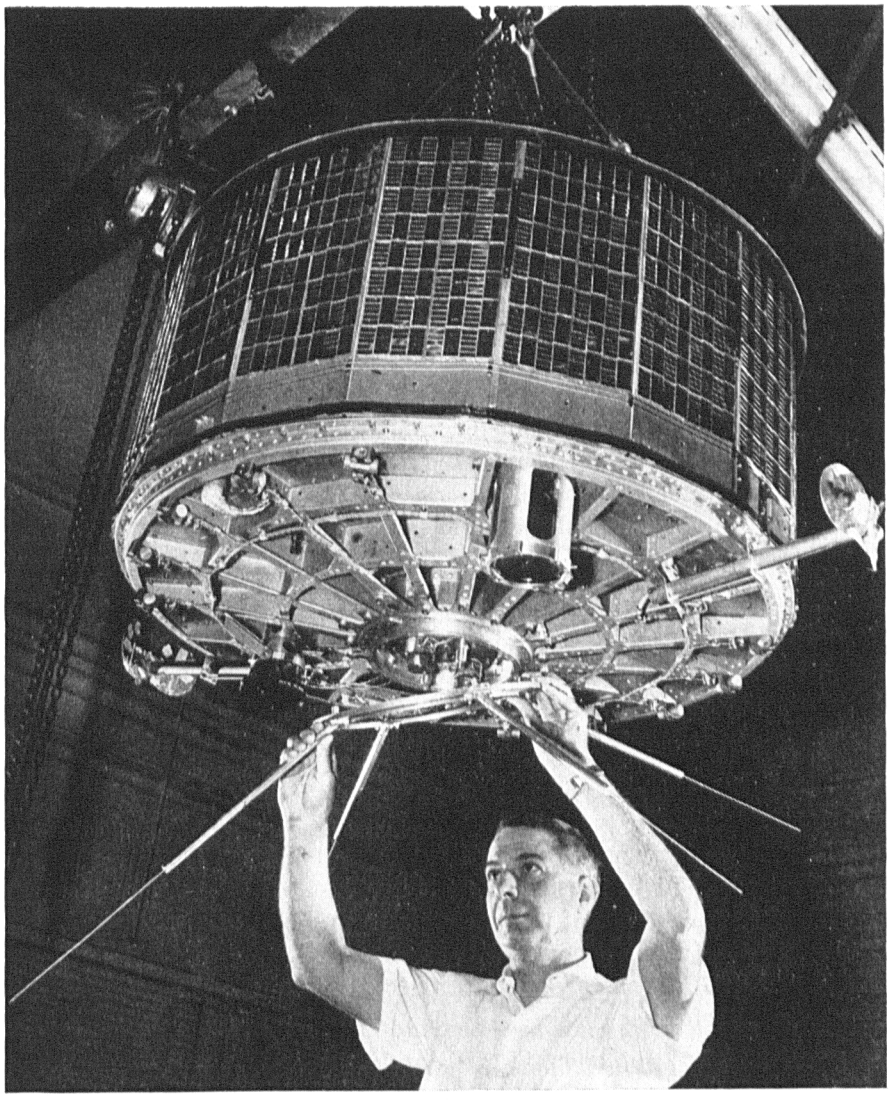

FIG. 2. Tiros, the Television Infrared Observational Satellite, showing its two television cameras protruding like giant eyes from its baseplate. To the far right is one of the telescoping arms carrying the Suomi radiation experiment (National Aeronautics and Space Administration photograph).

angle lens camera had an associated magnetic tape recorder, capable of storing 32 pictures on 400 ft of ⅜-in. wide Mylar-base tape. Camera actuation over remote areas was programmed in advance based upon observational requirements of the U. S. Weather Bureau. This programing

was communicated by NASA to the Tiros Command and Data Acquisition (CDA) stations which would command the satellite accordingly.[2] Readout of these taped pictures, taken at 30-sec intervals, was carried out upon subsequent interrogation by a CDA station. Readout took place over 2-watt FM transmitters operating at 235 Mc and required about 2 sec per frame. The ground station could additionally direct the satellite to take and transmit direct (untaped) pictures at 10- or 30-sec intervals while within CDA range.

Tiros 2, 3, 4, and 7 satellites carried radiation experiments in addition to TV camera systems. These radiation experiments were of three types:

(1) A five-channel medium-resolution radiometer operating at selected wavelengths in the visible and infrared spectrum.
(2) A low-resolution radiometer, consisting of two elements, one sensitive to both the visible and infrared radiation, and the other sensitive only to the latter.
(3) An omnidirectional radiation experiment similar to that flown aboard Explorer 7.

The five-channel radiometer was positioned in the satellite so that it looked out of the bottom and side of Tiros, 45 deg to its spin axis. Scanning the Earth by making use of the Tiros spinning action and of its orbital travel, this instrument was designed to make measurements in the following approximate ranges:

(1) 0.2–5.0 μ (solar radiation *reflected* by the Earth and its atmosphere);
(2) 7–30 μ (an approximation of the total radiation emitted by the Earth and its atmosphere);
(3) 5.5–6.5 μ (region of water vapor absorption);
(4) 8–12 μ (water vapor window);
(5) 0.55–0.75 μ (narrow band of reflected solar radiation—for use as a gross reference check).

The low-resolution radiometer was comprised of two cones, one containing a white detector, the other a black detector. The white element reflected visible radiation and absorbed only the longer-wave infrared radiation emitted from the Earth. The black detector was sensitive to both types of radiation. Both looked down from the Tiros baseplate, their optical axes parallel to the satellite spin axis. Thus, they viewed the same

[2] Primary CDA stations for Tiros 1 were located at Fort Monmouth, New Jersey, and Kaena Point, Hawaii; for Tiros 2, Fort Monmouth and P. Mugu, California; for Tiros 3 to 8, Wallops Island, Virginia, P. Mugu, and (beginning 15 September 1963) Fairbanks, Alaska.

area as did the vidicon cameras, facilitating thereby the comparison and correlation of cloud and radiation data.

The omnidirectional experiment, intended to study the heat balance of the Earth, was designed by V. E. Suomi of the University of Wisconsin. It consisted of two detection devices placed 180 deg apart on telescoping arms projecting from either side of the satellite. Each detector amounted to a black and white bolometer mounted on a mirror surface. The black and white elements performed like the black and white detectors used in the experiment described in the preceding paragraph. Effectively omnidirectional in their viewing of the Earth and space from aboard the spinning satellite, the sensors assumed the characteristics of a sphere isolated at the satellite's altitude and geographical position above the Earth. The readings which they provided made possible computation of (1) the solar radiation reflected by the Earth (its albedo), and (2) the amount of radiation being emitted by the Earth itself.

Data from these radiation experiments were tape recorded and read out to CDA stations at 237 Mc. Up to now, however, they have been used primarily for research applications [5].

III. Operational Use of Tiros Pictures

It has been upon the Tiros pictures and upon extracting the maximum useful weather information from them that the meteorological community has centered its energies and attention.

A picture processing time objective was set—the period between two successive passes and readouts, which amounted to about 100 min. Upon readout of the pictures to the interrogating CDA station, it was planned to record them on tape, from which they could be played back and photographed on a kinescope. The resulting pictures would then be examined by U. S. Weather Bureau (USWB) meteorologists assigned to the station. Interpreting the picture content, they would prepare a nephanalysis—literally, a cloud analysis—showing the type and distribution of cloud cover along the orbital path just photographed (see Fig. 3).

But the derivation of this cloud cover information soon proved not to be a simple task. Tiros, being spin-stabilized (8–12 rpm), sought to maintain a fixed orientation in space. This meant that as it traveled its orbit, its cameras sometimes looked directly at the Earth, sometimes glancingly at it, and sometimes completely away from it. This fixed orientation, which caused Tiros to view our planet from various angles, plus its spinning motion, presented a severe picture identification and rectification problem.

During Tiros 1 and through part of Tiros 2 programs, rectification of

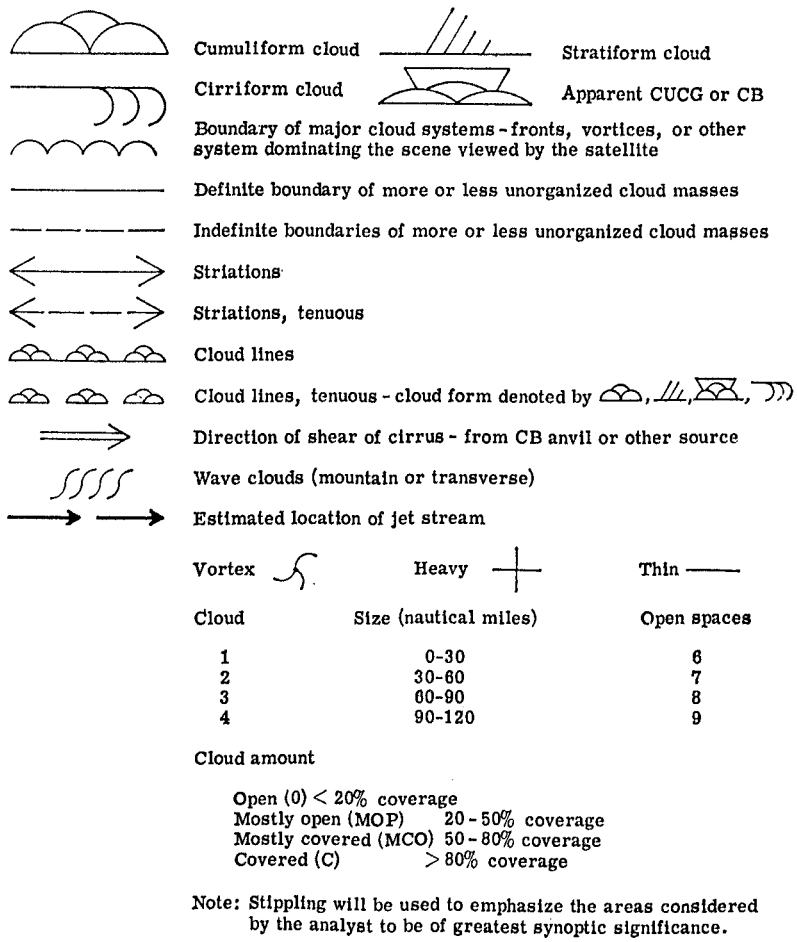

FIG. 3. Using pictures transmitted by Tiros, Weather Bureau personnel prepare special maps called nephanalyses employing symbols to represent cloud types and distribution (U. S. Weather Bureau).

the television pictures by CDA station meteorological teams was carried out by a laborious, hand-conducted process. Using this technique, the picture, recorded via kinescope on 35-mm film, was first projected on a focus sheet and enlarged to a working size. Next, this enlarged image was projected on a perspective grid (depicting the curved horizon and distorted latitude and longitude lines). There then followed a series of steps by which the picture was successively drawn by hand until it was finally translated to a conventional weather map projection. Beginning late in

the Tiros 2 program, a computer technique was introduced making use of predicted satellite orientation, position, and picture times and generating precomputed geographic grids according to these anticipated orbital parameters. With this technique, a capability was developed to produce a nephanalysis within the 100-min time interval between successive readouts. Upon completion, the "neph" was transmitted by facsimile to the Weather Bureau's National Weather Satellite Center at Suitland, Maryland. There, the data it contained were refined and communicated to the Bureau's National Meteorological Center, also at Suitland, where they were added to the other weather information being received through more conventional meteorological reporting sources.

According to the operating procedure established jointly by NASA and the Weather Bureau, responsibility for deciding which portions of an up-coming Tiros orbit should be photographed was largely that of the Bureau, or more specifically, its National Weather Satellite Center (NWSC). Having decided which portions held the greatest meteorological interest, NWSC would request NASA's Tiros Technical Control Center (TTCC) at Goddard Space Flight Center to program the satellite's picture-taking accordingly. The TTCC would then compute the necessary commands and transmit them to the CDA stations for relay to the satellite. To NWSC, the areas of greatest meteorological interest were (1) regions of probable storm development; (2) regions of unusual weather situations, as revealed by examination of available analyses and prognostic charts; and (3) regions concerning which requests had been received for Tiros coverage support.[3]

Scheduling Tiros picture-taking, however, was neither simple nor straightforward. Several factors had to be taken into account: (1) satellite attitude; (2) solar illumination; (3) power availability; and (4) the track of the satellite in relationship to the CDA stations.

To photograph an area of meteorological interest, a Tiros first had to be so oriented that its cameras would be facing that area as it passed overhead. The gyroscopic-like, fixed-attitude-in-space which characterized Tiros did not assure a favorable orientation of the cameras at the desired time. Using a magnetic coil, which interacted with the Earth's magnetic field to produce a torque, it was possible to change this orientation by up to 15 deg per day. Even so, Tiros orientation remained a major problem in picture-taking programing. For this reason and for reason of the satellite's orbital inclination—48 deg for Tiros 1 through 4, 58 deg for 5

[3] Typical of such support provided in 1963 was that given the International Indian Ocean Expedition, Antarctic resupply, solar eclipse studies, Project Mercury, and University of California sea swell studies.

through 8—a Tiros satellite could not be expected to view effectively more than 10–25 per cent of the Earth's surface in any one day.[4]

Because picture-taking requires adequate light, it was essential that the area of meteorological interest be sufficiently illuminated. In terms of solar elevation, this meant that useful Tiros picture-taking was limited to when the Sun was higher than 15 deg or higher in the sky.

To Tiros, sunlight's importance was more than the illumination it provided for photography; it represented electrical power as well. Picture-taking had to take this into account. It was essential that the silicon cells covering the satellite's "hat" receive sufficient solar energy to power the subsystems involved.

Picture programing had to take into account, too, the ability of the CDA stations (1) to set and start the satellite "clock" for remote camera operation, and (2) to command the data readout. Tiros made an average of 14.7 orbits per day. With three ground stations in operation—Wallops Island, Pt. Mugu, and Fairbanks—a total of 9 orbits could be acquired.

By the end of 1963, more than a quarter million Tiros television pictures had been taken, taped, read out, taped on the ground, rectified, analyzed, and their informational content mapped in the form of nephanalyses. During that particular year, nephanalyses based upon 3052 usable picture sequences and 82,687 individual pictures were prepared by CDA stations and sent to Suitland. These satellite-derived data resulted in: (1) 179 adjustments made to USWB National Meteorological Center analyses; (2) 325 *Satellite Storm Advisories* issued to U. S. Navy Weather Centrals and U. S. Air Force Weather Detachments overseas; (3) 129 *Satellite Storm Advisories* transmitted to Weather Bureau activities in the continental United States; and (4) 79 similar advisories provided to foreign countries. It was a year, too, which saw Tiros cameras locate or position 17 out of 41 named tropical storms (see Fig. 4).

IV. Origin of the National Operational Meteorological Satellite System (NOMSS)

The application of Tiros television picture information to operational meteorology was not slow in coming. The cloud cover information provided by Tiros 1 cameras started being entered into nephanalysis form distributed to meteorological forecasters beginning with the 43rd orbit (4 April 1960).

Impressed by the speed with which this new satellite application had

[4] Tiros cameras could view 10–15 deg beyond the subsatellite point. Thus coverage was effected as far as about 70 deg North to 70 deg South.

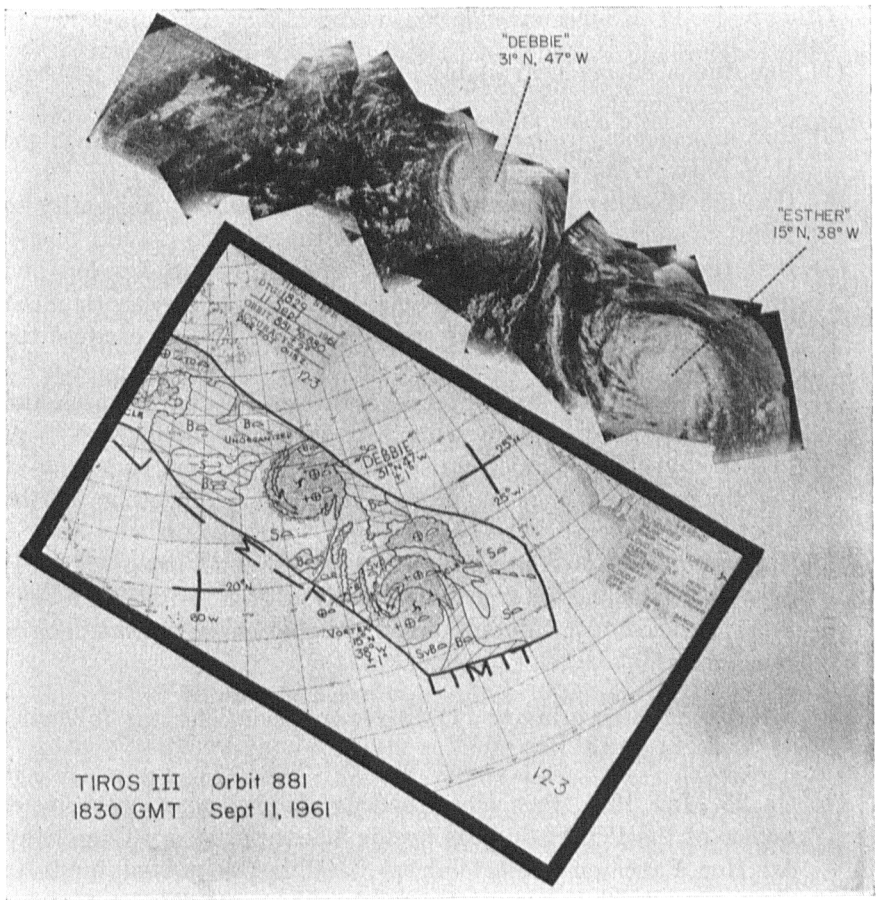

FIG. 4. Two hurricanes, Debbie and Esther, shown by a mosaic of satellite photos and by the corresponding nephanalysis. Tiros 3, which took these pictures, discovered Esther about two days before she would have been detected by other means (U. S. Weather Bureau photograph).

demonstrated its value, representatives of NASA, the Weather Bureau, the Federal Aviation Agency, and the Department of Defense began discussions in late 1960 relative to the establishment of an operational weather satellite system. This group, formalized as the Panel on Operational Meteorological Satellites (POMS) of the National Coordinating Committee for Aviation Meteorology, recommended in April 1961 that the development of such a system be undertaken "at the earliest possible date" [6].

Other major POMS recommendations were:

(1) that funds be made available early in fiscal year 1962 to begin implementing the system;
(2) that management responsibility for the system be assigned to the U. S. Weather Bureau (Department of Commerce);
(3) that the Weather Bureau institute a new organizational entity to fulfill its management responsibility for the system;
(4) that the Weather Bureau contract with NASA to develop and procure for the Bureau the required spacecraft, carrier (launch) vehicles, and ground support equipment, and also to conduct the launches;
(5) that the operational system be derived from NASA's research and development programs—drawing initially upon Nimbus;
(6) that the synchronous meteorological satellite, known popularly at the time as Aeros, be supported for eventual inclusion in the operational system;
(7) that use of Tiros be continued to provide a preliminary operational capability, pending the flight availability of Nimbus; and
(8) that provisions for international participation be initiated on a timely basis.

As a result of these primary POMS recommendations, the following resulted:

(1) On 25 May 1961, President Kennedy, following an enthusiastic review of the POMS findings by his Science Advisory Committee Ad Hoc Panel on Meteorological Satellites, requested funds to "help give us at the earliest possible time a satellite system for worldwide weather observation."
(2) Four months later, funds in the amount of $48 million were appropriated to the Weather Bureau by Public Law 87-332 "to establish and operate" such a system.
(3) To manage its new responsibilities, the Weather Bureau created a new organizational segment, the Meteorological Satellite Activities (later, redesignated the National Weather Satellite Center) located in Federal Office Building No. 4, Suitland, Maryland.[5]
(4) In January 1962, NASA and the Department of Commerce (repre-

[5] The Meteorological Satellite Activities was based upon the Meteorological Satellite Laboratory that had formed a part of the Weather Bureau since 1958. Funding for the Laboratory had been provided in its early days by NASA; its role had been to provide meteorological inputs to the NASA weather satellite research and development programs.

senting the Weather Bureau) entered into an interagency agreement covering the first phase of NOMSS—a phase based upon use of the Nimbus spacecraft, then under development by NASA.

(5) The NASA Tiros research and development program was extended to ensure a continued preliminary operational capability; the use of the narrow-angle lens (Tiros 1 and 2) was at least temporarily abandoned in favor of wider-angle coverage more suited to meteorological observations.

(6) International participation was actively encouraged by (a) USWB/NASA-conducted International Workshop on Meteorological Satellites; (b) transmission of nephanalysis information overseas by teletype code; (c) transmission of the nephanalyses themselves and significant individual pictures overseas by radio facsimile "beamed" toward Europe, Latin America, the Philippines, and Australia; and (d) preparation for foreign nationality use of the direct readout Automatic Picture Transmission (APT) system.

The first steps toward the creation of a National Operational Meteorological Satellite System—the first operational system to emerge from civilian space technology—had been taken.

V. Nimbus—Second-Generation Weather Satellite

The selection of Nimbus as the satellite with which to initiate NOMSS was the result of three factors: (1) Tiros, with its space-orientation and consequent inability to provide truly global coverage, was inadequate; (2) Nimbus, being Earth-stabilized and oriented, offered the promise of providing such coverage; and (3) other than Tiros, Nimbus was the only weather satellite type in being or under active hardware development at the time. Placed in a "high noon" 80 deg Sun-synchronous polar orbit, using its orbital movement to obtain latitudinal coverage and the Earth's rotation to obtain longitudinal coverage, and employing television and infrared sensors, Nimbus appeared extremely attractive as the spacecraft upon which to build an operational weather satellite system (see Fig. 5). Pertinent details of Nimbus "A"—initial flight prototype—have been reported by NASA as follows:

A. Physical Characteristics

Height, in: 114
Width, in: 134
Weight, 700 lb (exclusive of adapter section mating spacecraft to carrier).

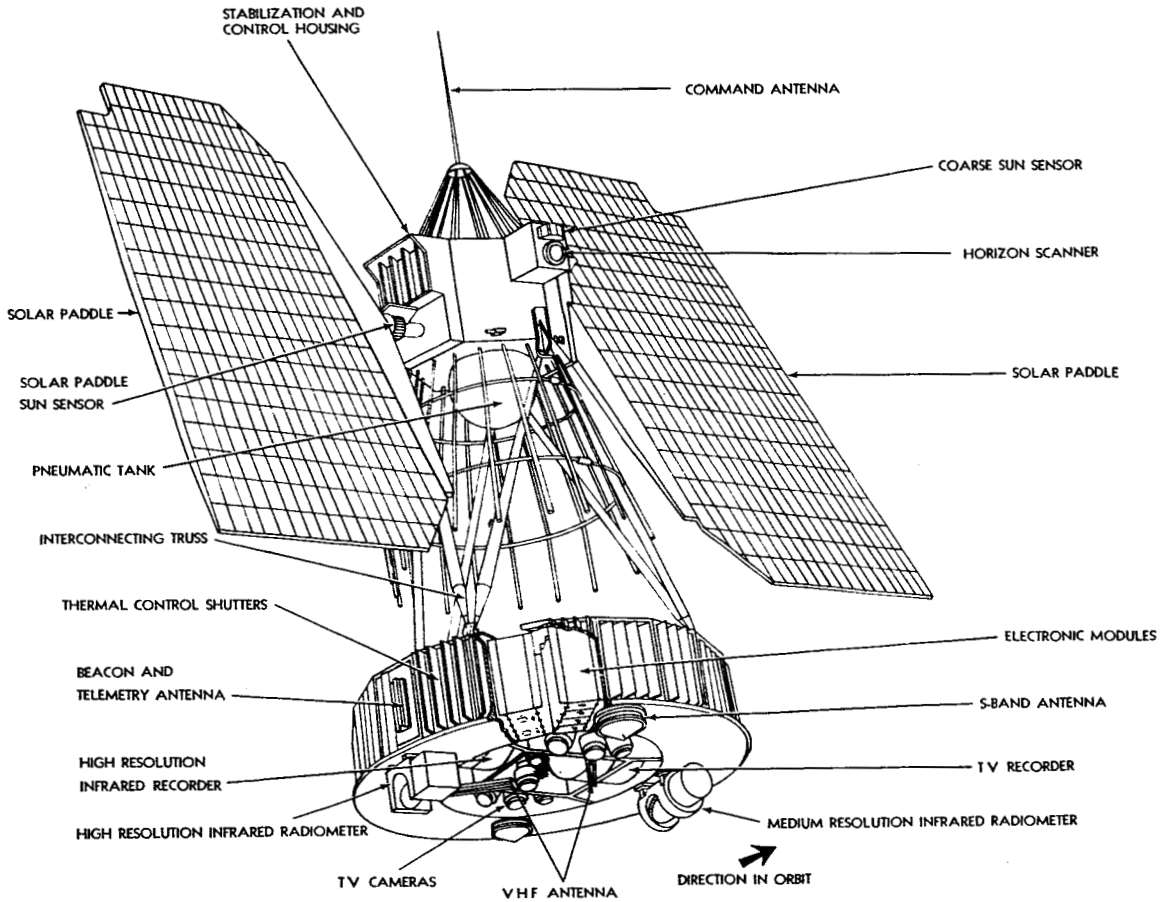

FIG. 5. Nimbus—second-generation weather satellite (National Aeronautics and Space Administration).

B. Carrier Vehicle

Thor-Agena B (launch from Western Test Range).

C. Power Supply

Uses an array of 2 × 2 cm solar cells (10,500 total), arranged on one side of two Sun-oriented paddles. Energy is stored by seven or eight 23-cell nickel-cadmium batteries. System delivers −24.5 volts D C and a nominal power of 250 watts average, 400 watts maximum.

D. Stabilization System

Senses errors in roll and pitch by horizon scanners, errors in yaw initially by a coarse Sun sensor and then by a rate gyro. Corrects and compensates for attitude errors by use of fly wheels and pneumatic jets. Stabilization accuracy is expected to be ±2 per cent.

E. Telemetry System

Samples and stores 544 channels of information; samples and transmits direct 128 additional channels. Uses PCM system which receives data in analog form, converts them into digital, and transmits them to the CDA station over 136 Mc.

F. Television Sensory System

The Nimbus television system is known as the Advanced Vidicon Camera System (AVCS). It consists of three 1-in. vidicons, mounted together in the spacecraft sensory ring so that the center one looks directly down while the camera on either side is canted at an angle of 35 degrees to it. Each camera has a 37 deg field of view. They are mounted at right angles to the path of orbital travel. The pictures which they simultaneously produce—shutter pulses are synchronized—at about 90-sec intervals comprise a triad, a group of three. Taken from an orbital altitude of about 500 mi, this triad will show an area measuring roughly 450 by 1450 n. mi. Optimum resolution will be about ½ mi. The vidicon will contain 800 television lines. Pictures from the three cameras plus a timing signal will be stored on a 4-track magnetic tape—capacity 64 frames (two orbits)—for readout via a 1700 Mc transmitter. Each picture will have superimposed at its edge a 16-increment gray scale for reference checking of

cloud photo characteristics. To accommodate varying degrees of illumination, the cameras are equipped with an adjustable iris which controls the lens opening on the basis of the orientation of the solar cell paddles with respect to the Sun.

G. Infrared Sensory System

The First Nimbus carries a High-Resolution Infrared Radiometer (HRIR) to map cloud cover at night. Observation by television is expected to be limited to daylight. HRIR resolution is about 5 mi. The cloud map produced by this radiometer is actually a reconstitution of the energy sensed. The radiometer is not an imaging device. With a mirror, the instrument scans the night-time Earth, operating in the 3.4- to 4.2-μ region and protected by a filter which minimizes absorption of radiation in that spectral region by carbon dioxide and water vapor. In general, clouds are colder than the surface of the Earth (except, possibly, when the surface is covered with snow or ice). The radiometer senses these variations in radiant energy—variations caused by surface and cloud temperature differences—and stores them on magnetic tape together with a reference time signal. Upon command, the tape is played back and its contents transmitted to the ground over 1700 Mc. After being recorded at the CDA station, the information will be communicated to a processing facility where the data will be played back and the "picture" of varying radiant energies reconstituted using a facsimile recorder. It is expected that Nimbus HRIR data can be put to near real-time usage.

H. NASA Nimbus CDA Station Locations

Gilmore Creek, Fairbanks, Alaska, with backup at Rosman, North Carolina (85-ft parabolic antennas at each location).

I. Communications

Telemetry, television, and infrared data read out from Nimbus at the CDA station, Fairbanks, are communicated to the Nimbus Technical Control Center at NASA's Goddard Space Flight Center over two 48-kc bandwidth data links. In planning for the Nimbus-based phase of the operational system, it was expected that these links would be extended to the Weather Bureau's National Weather Satellite Center for processing, analysis, and distribution of the meteorological content of the data thus obtained.

J. Flight Scheduling

The orbiting of Nimbus I occurred on 28 August 1964.

VI. Reevaluation of NOMSS Planning

The original recommendations made for the National Operational Meteorological Satellite System by POMS (Panel on Operational Meteorological Satellites) were dated 1961. Just as the technology to implement these recommendations has since undergone substantial development and change, so have evolved and become more clearly defined the observational and cost-effectiveness requirements of an operational satellite system the purpose of which is to support the National Weather Service—since 1891 the basic mission of the United States Weather Bureau.

Taking such progress and change into account, the Bureau in late 1963 undertook an operations analysis intended (1) to reevaluate some of its planning for NOMSS and (2) to define, in terms of the latest developments and choices of trade-offs, an optimum such system.

Among the many factors considered, the following were of prime importance: (1) observational requirements, (2) command and data acquisition facilities, (3) data processing analysis, and distribution, and (4) spacecraft lifetime. The satellite is a global vehicle and meteorologists will not be satisfied until it provides them with global coverage—complete viewing of the Earth. To meet their needs, however, global coverage amounts to more than picture contiguity or overlap everywhere about the globe. Viewing angle is also important.

Tiros experience has shown that the meteorological usefulness of cloud cover pictures degrades, the greater is the zenith angle.[6] For macroscale analysis, involving weather systems a hundred miles or more in extent, a zenith angle of up to 65 deg can be tolerated. For smaller or mesoscale systems, the zenith angle should be kept to 45 deg or less. Zenith angle is important because the flatter the camera's view of the cloud deck, the more the features of that deck are distorted and their apparent position shifted. Specifically, it has been shown that a hole in the cloud cover with a diameter equal to the thickness of the cover will not be seen by the camera after the zenith angle reaches 45 deg [7].

Effective meteorological coverage can be expanded, within these zenith angle constraints, by increasing satellite altitude. This immediately

[6] The zenith angle is that angle at a particular Earth point formed by the local zenith and a ray to the focal point of the satellite camera.

sets into motion, however, a chain of interrelated functions and trade-offs, involving orbital periods and the distance between successive equatorial crossings (assuming a polar orbit). It is here, at these equatorial crossings, that the pictures must be contiguous. With higher and higher latitudes, they will overlap increasingly. With increases in orbital height, of course, picture resolution suffers degradation. At the same time, however, such resolution becomes more uniform.

Weathermen would like to use the satellite's global coverage capability to observe every point on the Earth's surface four or more times a day. Desired resolution would be better than 1 n. mi. with a maximum of uniformity over the viewed area and a zenith angle of 65 deg or less. Ability to vary spectral response in flight, to discriminate between eight shades of gray, and to identify low (below 10,000 ft), medium (10,000 to 20,000 ft), and high (above 20,000 ft) altitude cloud tops are additional objectives.

In addition to these broadscale requirements, meteorologists have a need for fine scale coverage as well. For detailed examination of selected areas of meteorological interest, including examination of surface ice conditions, they hope for picture resolution on the order of 0.1 mi (see Fig. 6).

Important to meteorological coverage, of course, is location accuracy. From orbital-type altitudes it is easy to misplace or erroneously locate a weather phenomenon by many miles. Reduction of such error to a minimum largely depends upon accurate knowledge of (a) orbital track, (b) position along the orbit (subsatellite point), and (c) spacecraft attitude. It is considered that uncorrected location error should be kept to within 60 n. mi over most of the viewed area and corrected error to less than 5 mi.

Meteorological observation requirements must, of course, take into account the Automatic Picture Transmission (APT) system. This direct readout technique bypasses the usual "take," "tape-record," and "play back" process of the Tiros and Nimbus vidicon cameras.

The heart of the APT system is a "'sticky" one-inch 800-raster-line vidicon. This tube captures the image and retains it for 200 sec. During this time, the picture is slowly read out, thereby conserving bandwidth, and is transmitted to special ground stations over a nominal frequency of 136 Mc. The entire picture-taking and readout sequence requires 208 sec. Any ground station, equipped with appropriate antenna, receiver, and facsimile machine (on which the image is reconstituted) can obtain the picture, provided, of course, the station is located within line-of-sight range. No interrogation of the APT is required. It automatically transmits to anyone equipped to receive it [8].

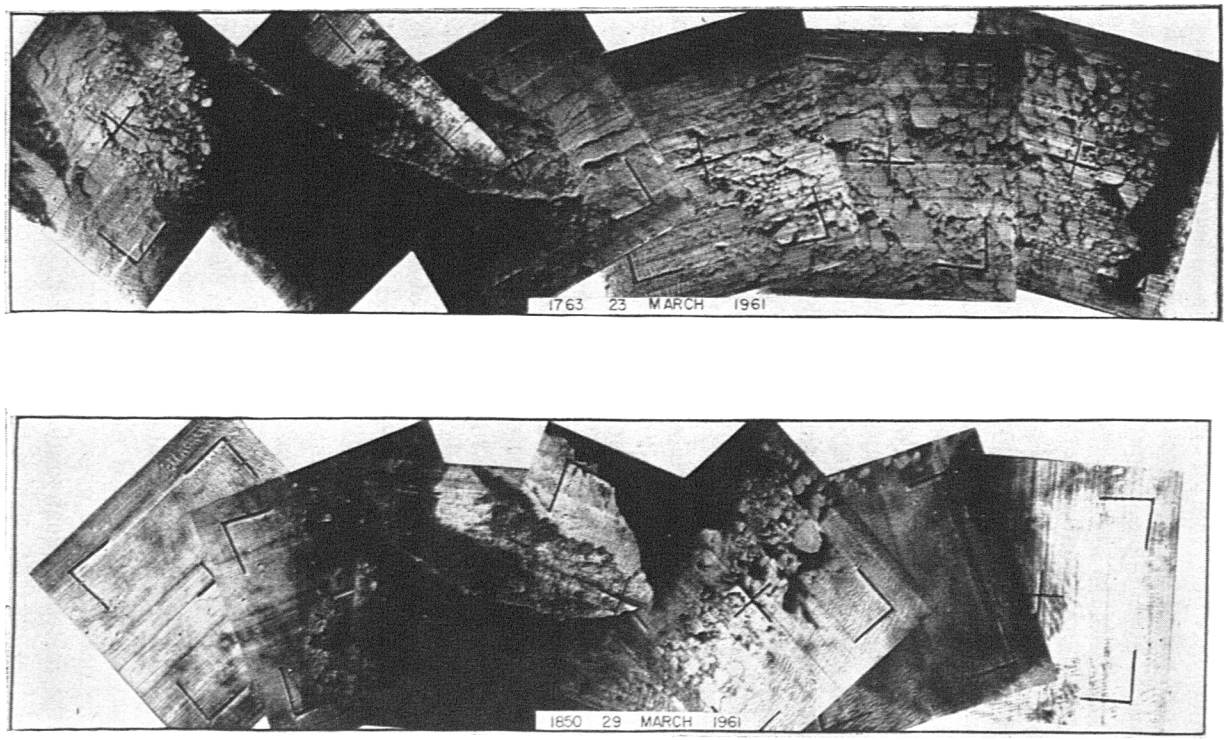

FIG. 6. A major by-product of meteorological satellites is the information which they can provide on ice conditions as they affect shipping and navigation. These pictures, taken by Tiros 2's narrow-angle (12-deg) camera, clearly show major leads and floes in the Gulf of St. Lawrence. Note how the ice has broken away from Anticosti Island (center) and moved down and away to the right (U. S. Weather Bureau photograph).

The advantages of APT are several. It reduces virtually to zero the time lag between picture-taking and receipt in the field of the meteorological information which the picture contains. Where remote and inaccessible geographical areas are concerned, this delay can be considerable. Such areas, furthermore, frequently do not possess adequate communications facilities to receive meteorological information normally transmitted via international networks. Thus APT provides a capability for "instant weather observing." To enable its maximum international use, APT station cost has been held down to about $30,000 and to "do it yourself" plans and information made available to interested countries and national meteorological services.

The first APT experiment was orbited by Tiros 8 on 21 December 1963. The success of this experiment plus the unique capability of APT for taking and transmitting cloud cover pictures in real time make extension of this capability to include nighttime as well as daylight operations a high-priority meteorological objective—as is giving a day/night capability to television camera/recorder/playback systems.

That portion of the Weather Bureau's operations analysis dealing with command and data acquisition concluded that, if possible, a single station site should be used to avoid duplication of facilities, communications, and manpower staffing. The Weather Bureau's existing facility with 85-ft antenna at Gilmore Creek, Fairbanks, Alaska, appeared the most likely to be selected as "the single station" at such time as spacecraft altitudes and orbital characteristics would permit use of only one readout site.

Plans for the processing and distribution of the satellite-derived meteorological products were generally affirmed.

Following readout at the CDA station, the observations made by the operational satellites constituting NOMSS would be communicated to the National Weather Satellite Center. There the meteorologically significant information would be extracted, put into a useful format, and passed to the National Meteorological Center (NMC) for further transmission to meteorological users, domestic and foreign. Because weather information is among the most perishable of all forms of data, the handling and processing of this meteorological information would have to be carried out in as close to real time as possible.

The format of the data thus distributed would be determined, of course, by the nature of the observing systems aboard the spacecraft. In general, the meteorological products would take the form of one or more of the following: (a) gridded television cloud pictures, (b) mosaics of cloud cover derived by infrared techniques (if ir techniques are used), (c) digitized printouts of the world's cloud cover, rectified to standard weather map projections, and (d) interpretive overlays prepared by

NWSC analysts and transmitted with (a), (b), and (c) to assist in the use of the information portrayed.

Distribution of these graphic materials, mainly computer produced, would probably be via facsimile process. Use of NOMSS spacecraft to disseminate or broadcast processed gridpoint data was additionally proposed by Hall of NWSC [10]. According to this concept, satellite acquisition by the CDA station would data-wise achieve two purposes: (a) transmission "down" of raw weather data observed or collected in the orbit just completed, and (b) transmission "up" of refined information for automatic broadcast during the orbit to come.

The final output of NOMSS data processing would be the archival product which, in the form of pictures, maps, tapes, and the like, would be stored at the Weather Bureau's National Weather Records Center (Asheville, North Carolina) for research and climatological use.

Finally, operational satellite lifetime was examined. For maximum amortization of costs, a life of 3–5 yr is desired. Spacecraft reliability of this duration is currently not available for the type of sub-systems envisioned. The achievement of this type of lifetime will probably require power sources other than solar cells and stabilization systems based upon passive or semipassive techniques.

VII. Reorientation of NOMSS and Institution of TOS

As a result of its operations analysis, described in part in Section VI, the Weather Bureau decided upon a reorientation of the National Operational Meteorological Satellite System.

Recognizing that the objectives established by the analysis were not all immediately achievable, the Bureau decided to reorient NOMSS in two phases: (1) using established, proven, and readily available technology, and (2) using future technology yet to be evolved, developed, and demonstrated as sufficiently reliable for incorporation into an operational program. To the system comprising the first phase was given the name TOS—Tiros Operational Satellite. The follow-on phase would be known as the AOMS (Advanced Operational Meteorological Satellite).

Operation of the TOS system, based upon Tiros technology, will begin in late 1965. The AOMS system might be expected to become operational in the early 1970's.

The TOS spacecraft will be an outgrowth of the Tiros "cartwheel" configuration. This configuration, embodied in the ninth of the Tiros series of research and development satellites, relocates the television cameras so that they look out from the sides of the spacecraft instead of from its baseplate. Placed into a polar orbit, the satellite can be torqued,

using its magnetic attitude control coils, so that it aligns itself wheel-like in its orbit, its spin axis perpendicular to the orbital plane. Spinning at about 10 rpm, it "rolls along" its orbit, its cameras actuated by horizon sensors which trigger the shutters when the spacecraft is looking straight down. In this manner, Earth-oriented vertically-taken pictures can be achieved.

Two prototype cartwheels will be flown prior to the institution of the TOS system. One of these, scheduled for launch in 1964, will become Tiros 9 upon successful entry into orbit. The second, funded by the Weather Bureau, will be orbited in the second quarter of 1965. Each will carry conventional Tiros one-half inch vidicon cameras.

The Tiros Operational Satellite System, programed to become operational in the fourth quarter of 1965, will maintain two operating cartwheels in 750-n. mi Sun-synchronous near-polar orbits at all times. One will contain two Automatic Picture Transmission (APT) camera systems, each system operating independently and serving as a backup to the other. The one-inch "sticky vidicon" described earlier will be used. From 750-n.-mi altitude, APT pictures will cover 1700 n. mi to a side and will be receivable by ground stations located within a radius of about 1800 n. mi (see Fig. 7).

The second TOS spacecraft will be equipped with two redundant one-

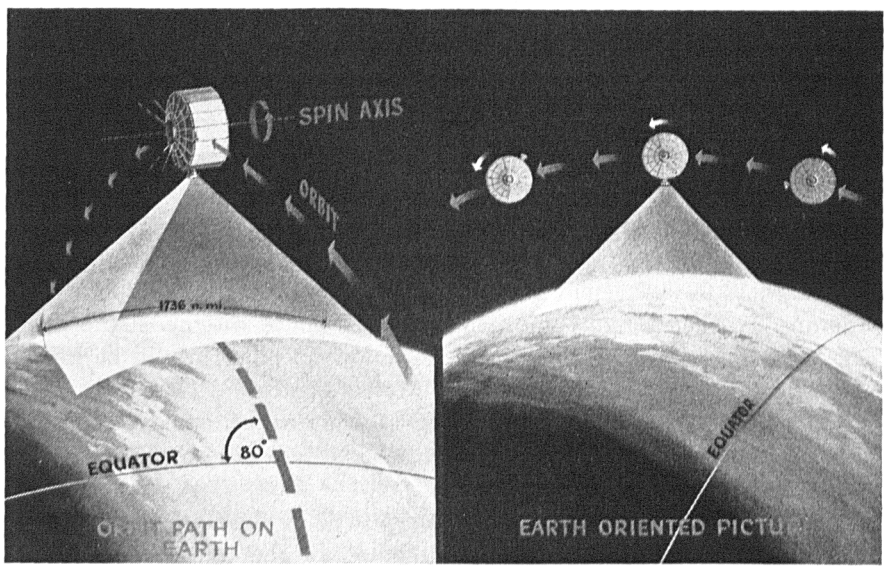

FIG. 7. Artist's concept of the Tiros Operational System (TOS) showing camera coverage and the approximately 80° retrograde orbit (U. S. Weather Bureau photograph).

inch Advanced Vidicon Camera System (AVCS) units, of the type developed by NASA for the Nimbus program. Picture resolution, looking straight down, will be 1.5 n. mi per line. Coverage will amount to about 1700 n. mi to a picture side. Each camera system will store its pictures on magnetic tape for commanded readout to Command and Data Acquisition stations at Fairbanks, Alaska, and Wallops Island, Virginia.

In addition to direct readout APT pictures and tape-recorded AVCS pictures, the TOS system is expected to include infrared measurements as well. At first these will be very low resolution measurements for heat budget studies and gross detection of large cloud systems at night.

Improved technologies and subsystems are anticipated to increase the observing capability, lifetime, and meteorological usefulness of the TOS system as its implementation and operation progress. Advanced infrared equipment ranks high among these future improvements for more detailed cloud cover observation.

VIII. Satellite Interrogation of Constant Level Balloons

Just as the technological details of TOS are not yet fixed, neither are details for the much farther downstream Advanced Operational Meteorological Satellite. Certain concepts have been advanced for the AOMS, however. One of the most technically interesting and challenging of these is that of using satellites to interrogate balloons for obtaining wind information.

The satellite technique does not exist today whereby wind direction and velocity can be directly sensed or measured. From the appearance of cloud forms and other clues, experienced analysts can infer certain wind information. Quantitative data are not available by satellite observation. Yet wind information, particularly upper wind information, is important. It is a keystone of the Numerical Weather Prediction system, the computer-based operation upon which the Weather Bureau depends for hemispheric analyses and forecasts.

To enable upper air wind information to be obtained in meteorologically unreported regions, it has been proposed that long-endurance, constant-level balloons be placed at critical pressure heights within the atmosphere. Drifting with wind currents as they exist at the particular altitudes involved, these plastic helium- or hydrogen-inflated cells would serve as atmospheric "tracers." Electronically equipped, they would respond to satellite interrogation. The characteristics of their return signals—they might be interrogated as many as three times during a single orbital pass—would be recorded by future NOMSS spacecraft, stored, and "dumped" at the CDA station for transmission via data link

to NWSC, Suitland. There these signals would be decoded and the position of each balloon computed for the time of interrogation. By addressing the balloon during each satellite pass and plotting its movement between passes, computation of winds at that altitude would be possible.

Although the concept is simple, its implementation is complicated by these seven considerations:

(1) The number of balloons required to provide adequate coverage of any selected pressure altitude, 500 mb as an example, will run into the hundreds.
(2) A certain number of these—the percentage or number are not yet known—will have to be replaced owing to balloon destruction or to congregation of balloons into stagnant "graveyard" areas.
(3) The 500-mb height, suggested level at which to begin operational implementation of the concept, amounts to about 18,000-ft altitude.
(4) This altitude, plus the probable density of the balloon network and the long endurance of the cells (upward of 30-60 days) would make mandatory the certification of these balloons as nonhazardous to flight; test data must be obtained to prove conclusively that balloons of this type (probably 12-ft diameter) can be safely impacted by high- and low-speed aircraft and ingested by jet engines.
(5) To pass these air safety tests to the satisfaction of the Federal Aviation Agency, the Air Line Pilots Association, and the general public, the mass carried by these balloons in the form of transponders and associated electronic equipment will probably have to be distributed as widely as possible over the balloon vehicle.
(6) Such distribution of mass will mean without much doubt thin-film solar cells, thin-film batteries, and other sophisticated electronics techniques associated with solid state microcircuitry.
(7) This will result in a high cost per balloon.

In addition to these factors, there are others involving: (1) the number and location of launch sites for instituting and maintaining the network to the density desired; (2) the trajectories to be anticipated; and (3) the reaction of other nations to the continuing overflight of their territory and the entering into their airspace of considerable numbers of such balloons.

Of all the considerations that will determine if the concept of balloon position-determination by satellite interrogation is to be implemented, the most decisive is that of cost-effectiveness. How much will such a system cost? Meteorologically, will it be worth the price? The Weather Bureau expects to have the answers to these questions in 1964–1965. Upon these answers will be decided whether or not to incorporate a balloon/satellite system of this type in NOMSS.

IX. Satellite Collection of Meteorological Observations

The preceding section discussed the inability of weather satellites thus far to obtain direct measurements of wind. Similarly they have, to date, been unable to sense precipitation within or below the cloud cover which they photograph. A new infrared spectrometer, under joint development by the Weather Bureau and the NASA, holds promise of direct satellite measurement of the vertical distribution of temperature within the atmosphere beneath it. Weather conditions may be inferred for the Earth's surface, but the clues for so doing (Sun glint on the water, for example) are not always present.

Because weather forecasting continues to take into account surface conditions and because surface conditions are unreported in the data-sparse areas, the combined use of unmanned reporting stations and data-collecting satellites is under consideration. This forms the Satellite Collection of Meteorological Observations (SCOMO) plan.

According to this plan, unmanned stations consisting of Weather Bureau Marine Automatic Meteorological Observing Station (MAMOS) buoys would be anchored in untraveled ocean areas. There, they would record such conventional parameters as temperature, pressure, wind direction and velocity, sea temperature, and the like; and store these data pending overflight by an operational weather satellite containing a data-collector package or subsystem. Upon interrogation, the buoy would relay its observations to the spacecraft which in turn would store and read them out to its CDA station. Processing of these data by NWSC and their incorporation in National Meteorological Center analyses would follow.

Unmanned land stations would be deployed in the Arctic, Antarctic, and in undeveloped continental interiors and their data acquired by passing Weather Bureau satellites in the same manner. A fascinating thought is the possibility that, with sufficient refinement and development, these unmanned remotely-located stations might be given the capability for the firing of meteorological sounding rockets and the automatic recovery of their data.

In addition to the problem of how to make and report conventional surface weather observations in remote marine areas, there is the question of how most economically and rapidly to communicate such observations where they are made by merchant vessels at sea. As part of a cooperative international program sponsored by the 124-nation World Meteorological Organization, a total of about 1100 merchant ships make surface observations at 6-hr intervals (0000Z, 0600Z, etc.). They then report these observations in coded form to shore stations as rapidly as practicable, which is not always very rapid since the service is provided free and other

radio traffic frequently takes priority. In some areas, relaying the message by ocean station vessels (the fixed weather ships), for instance, causes the CW-transmitted 5-digit numerical code to become garbled owing to operator error. Commercial marine radio stations which receive these messages charge the Weather Bureau for their handling. The communication cost thus incurred amounts to about one-half million dollars annually. The economics involved in the satellite pickup of these merchant vessel reports—the mate on watch would "punch in" the required information, using a single transmitting device that would be actuated upon interrogation—are being investigated.

Also under examination from dollars-and-cents, time-saving, and reliability-increasing standpoints is the possibility of providing similar satellite pickup weather observations from the fixed ocean station vessels in the Atlantic and Pacific and from the 15 ships comprising the mobile ship program in the Atlantic, Pacific, and Caribbean. The observations made by these fixed and mobile ships differ from the surface reports of the merchant ships in that they include radiosonde and rawinsonde operations, increasing the data variously to be stored, collected, and read out.

Finally, the data-collection technique is being considered by the Weather Bureau to expedite collection of reports and to minimize the cost of their communication from the remotely-situated USWB stations on Koror, Yap, Ponape, and Majuro in the Trust Territory of the Pacific Islands.

During 1964–1965, economic and operational analyses being conducted on the various types of SCOMO applications—buoys, automatic land stations, merchant shipping, fixed ocean station vessels, mobile weather reporting ships, and remote manned stations in the Pacific—will have been completed and the most promising of these applications identified. Implementation will require the solution of several problems: (1) how to provide a sufficiently low-cost automatic shipboard device; (2) how to handle the roughly 1100 ship addresses that would be involved; and (3) how to synchronize satellite passage and interrogation with weather observing times to prevent the data from becoming stale and, therefore, useless (operationally speaking).

X. The Future

The techniques and systems applicable to and, in many cases, inevitably destined for use in the National Operational Meteorological Satellite System are almost as numerous and varied as the techniques of science or engineering itself. The role that future developments, particularly in space technology, will play in NOMSS is more accurately the subject of an entire book, rather than of an individual chapter.

If anyone doubts this, let him consider carefully the impact upon an operational system of the availability of:

(1) a synchronous meteorological satellite, in a 24-hr stationary equatorial orbit, for meteorological observation and communication and dissemination of meteorological reports and graphic products;
(2) pattern recognition devices, satellite-borne and ground-based, capable of identifying and discriminating between cloud patterns of known significance;
(3) microwave radiometry to supplement television and infrared as basic sensory techniques;
(4) applicable and practicable radars, sferics detectors, and lasers as satellite-borne sensors or probes;
(5) manned space platforms, with room aboard to accommodate meteorologists and meteorological instrumentation.

XI. Summary and Conclusion

As a result of the spectacular observational achievements of NASA's Tiros program, a National Operational Meteorological Satellite System has been funded and responsibility for its establishment and operation assigned to the U. S. Weather Bureau. Plans, formulated in 1961, to base NOMSS upon NASA's research and development Nimbus satellite have been reoriented to reflect a more complete understanding of the economics, observational requirements, orbital elements, satellite lifetime, and other factors which combine to describe and identify the optimum operational system.

Like the weather it is intended globally to observe, NOMSS is certain to undergo change. To keep informed of such changes, interested parties should contact the Weather Bureau, which is responsible for the system establishment and operation, or NASA, which will provide the space technology required.

References

1. Greenfield, S. M., and Kellogg, W. W. (1951). Inquiry into the feasibility of weather reconnaissance from a satellite vehicle. Classified Rand Corporation Report. Re-issued as unclassified Rand Corporation Rep. R-365 in August 1960 (Santa Monica, California.)
2. Vaeth, J. G. (1951). "200 Miles Up," pp. 67–76. Ronald Press, New York.
3. Hubert, L. F., and Berg, O. (1955). A rocket portrait of a tropical storm. *Monthly Weather Rev.* **83**, 119–124.
4. U. S. Senate Committee on Aeronautical and Space Sciences, Staff Report (1962). Meteorological satellites, pp. 145–148. (Government Printing Office, Washington, D. C.)

131 907

5. Nordberg, W. (1963). Research with TIROS radiation measurements. *Astronautics Aerospace Eng.* **1**, 76–83.
6. U. S. Senate Committee on Aeronautical and Space Sciences, Staff Report (1962). Meteorological Satellites, pp. 153–173. (Government Printing Office, Washington, D. C.).
7. Gray, T. I., Jr., and Singer, S. F. (1963). An investigation of meteorological satellite characteristics for continuous earth coverage. U. S. Weather Bur. Meteorol. Satellite Lab. Manuscript (National Weather Satellite Center, Washington, D. C.).
8. Stampfl, R. A., and Stroud, W. G. (1963). The Automatic Picture Transmission (APT) TV camera system for meteorological satellites. NASA Goddard Space Flight Center Rep. X-650-63-77 (Greenbelt, Maryland).
9. Pyle, R. L., and Singer, S. F. (1963). An analysis of CDA station effectiveness in relation to satellite orbit. U. S. Weather Bur. Meteorol. Satellite Lab. Manuscript (National Weather Satellite Center, Washington, D. C.).
10. Hall, W. F. (1964). Cloud mosaic broadcasts from weather satellites. Unpublished manuscript (National Weather Satellite Center, Washington, D. C.).

Bibliography

The amount of professional literature covering the application of satellites to meteorological problems and observations—975 papers and articles from 1956 through 1962—makes a detailed or meaningful listing impracticable here.

Readers interested in such literature are referred to: (1) "Bibliography on Meteorological Satellites 1952–1962" (available from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20401). Price: $1.25; and (2) "Publications on Meteorological Satellites by Staff Members of the National Weather Satellite Center" which is kept updated and is avaiable at no cost from NWSC, U. S. Weather Bureau, Washington, D. C. 20235.

Readers are particularly referred to several excellent and comprehensive summaries of the meteorological satellite program:

1. American Institute of Aeronautics and Astronautics (April 1963). Special issue on weather satellite systems. *Astronautics Aerospace Eng.* **1**.
2. National Aeronautics and Space Administration (1962). Final report on the Tiros I Meteorological Satellite System. Technical Rep. R-131, Goddard Space Flight Center (Greenbelt, Maryland).
3. National Aeronautics and Space Administration and U. S. Department of Commerce, Weather Bureau (1961). Proc. Intern. Meteorol. Satellite Workshop, November 13–22, 1961. (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20401.) Price: $1.75.
4. U. S. Senate Committee on Aeronautical and Space Sciences, Staff Report (1962). Meteorological satellites. (Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20401.) Price: $0.55.
5. World Meteorological Organization (1963). Reduction and use of data obtained by TIROS meteorological satellites. Tech. Note No. 49. (Secretariat of the World Meteorological Organization, Geneva, Switzerland.) Price: 6 Swiss francs.