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THE METEOROLOGICAL INSTRUMENTATION OF SATELLITES

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

THE METEOROLOGICAL INSTRUMENTATION

OF SATELLITES

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Goddard Space Flight Center

and

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Environmental Science Services Administration

September 1965

Presented at the Commission for Instruments and Methods
of Observation of the World Meteorological Organization

Tokyo, Japan
October 1965

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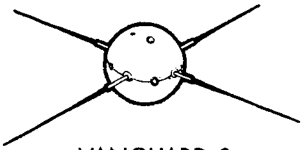

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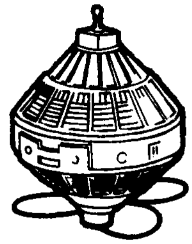

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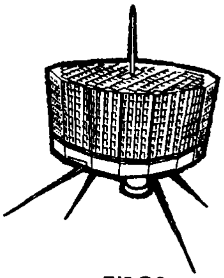

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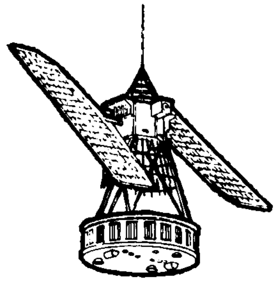

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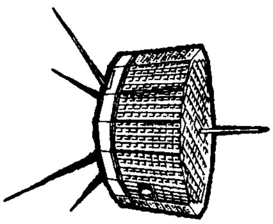

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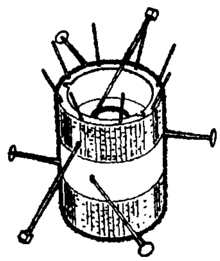

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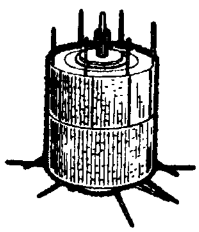

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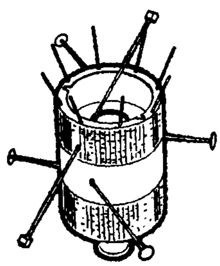


ATS - D

NASA Satellites Carrying Meteorological Experiments

THE METEOROLOGICAL INSTRUMENTATION OF SATELLITES

INTRODUCTION

An understanding of many meteorological problems requires observation of weather parameters on a world-wide basis. In this regard, satellites have made a significant impact in the weather services of the world. For example, the World Meteorological Organization's third report on the advancement of atmospheric sciences states:

> "The meteorological information from satellites has proved useful in many parts of the world in day-to-day forecasting. This is particularly true in those areas in which no meteorological information is available such as large ocean areas. In addition to the general distribution of satellite data, the United States of America continued to inform national meteorological services immediately when observations obtained by meteorological satellites revealed important and dangerous phenomena such as storms, hurricanes, typhoons, etc., especially in those cases where such information could not be detected by conventional methods."

These accomplishments, however, are only a beginning. Although our research and development satellites, TIROS and Nimbus, have provided us with a good deal of meteorological information, their coverage has been sporadic and insufficient for full operational use. With the upcoming launch of operational meteorological satellites (TOS) in early 1966, plus the continued development of more sophisticated and versatile satellites, we believe we are on the threshold of a completely new concept of meteorological observations.

A prime example of what the future holds is the mosaic (Figure 1) constructed from TIROS 9 pictures showing the global cloudcover during a single 24-hour period (0520 GMT, February 13, 1965, on the eastern side and 0540 GMT, February 14, 1965, on the western side).

The mosaic vividly demonstrates the possibilities of satellite vehicles as meteorological sensor platforms. Their ability to survey all of the earth's surface over relatively short time spans, plus their usefulness as a simplified data-collection system, are their principal advantages over conventional meteorological sensor platforms. This report will tell what our meteorological satellites have done, what they are doing for us now, and what we plan for them in the future.

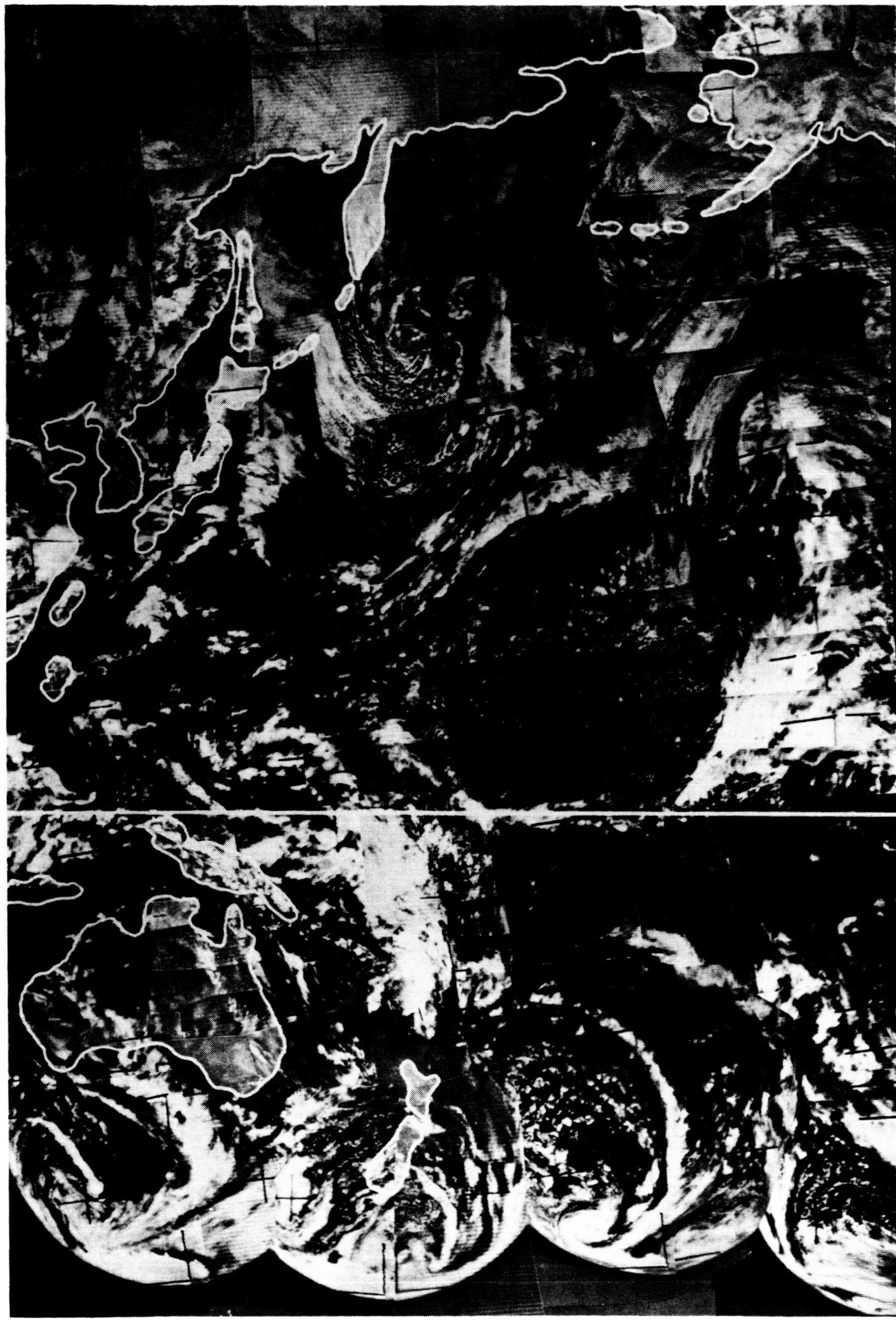
BACKGROUND

Table 1 lists the satellites now capable of carrying meteorological sensors, and summarizes their characteristics.

Table 2 summarizes the measurements needed to define the state of the atmosphere, the techniques for obtaining those measurements, and the status of the instruments we have designed to employ those techniques. Understandably, the status of many of the required sensors is indefinite; for instance, in measuring the velocity and direction of winds, we have no feasible technique which does not require in situ sensors. The sensors we now have will be described in detail later on. The satellite as a platform presents a number of problems not directly concerned with meteorological sensors, but extremely important in making the best use of them.

Table 1
Satellites Capable of Carrying Meteorological Sensors

Vehicle	Size (Inches)	Weight (lb.)	Power Supply (watts)	Payload Capacity (lb)	Stabilization	Comments
TIROS	42 Dia. 22.5 H	300	30	100	Spin-stabilized + magnetic torquing, also wheel mode	Suitable for experimental use; wheel used in TOS
Nimbus	Sensor Ring Only 57 O.D. 40 I.D. 13 H	726	450	200	3-axis, gas jet, reaction wheel	Intended mainly for experiment test bed
OSO	37 H 92 Dia.	450-550	400	250	3-axis, cold gas, 3 inertia wheels	Measure solar radiation
OGO	68 L 33 W 33 H	1000	500	150-220	3-axis, gas jet + flywheel	Intended primarily for experiment test bed
ATS	66 H 59 Dia.	700	N.A.	200	Spin and gravity-gradient	Test bed for gravity-gradient and other experiments



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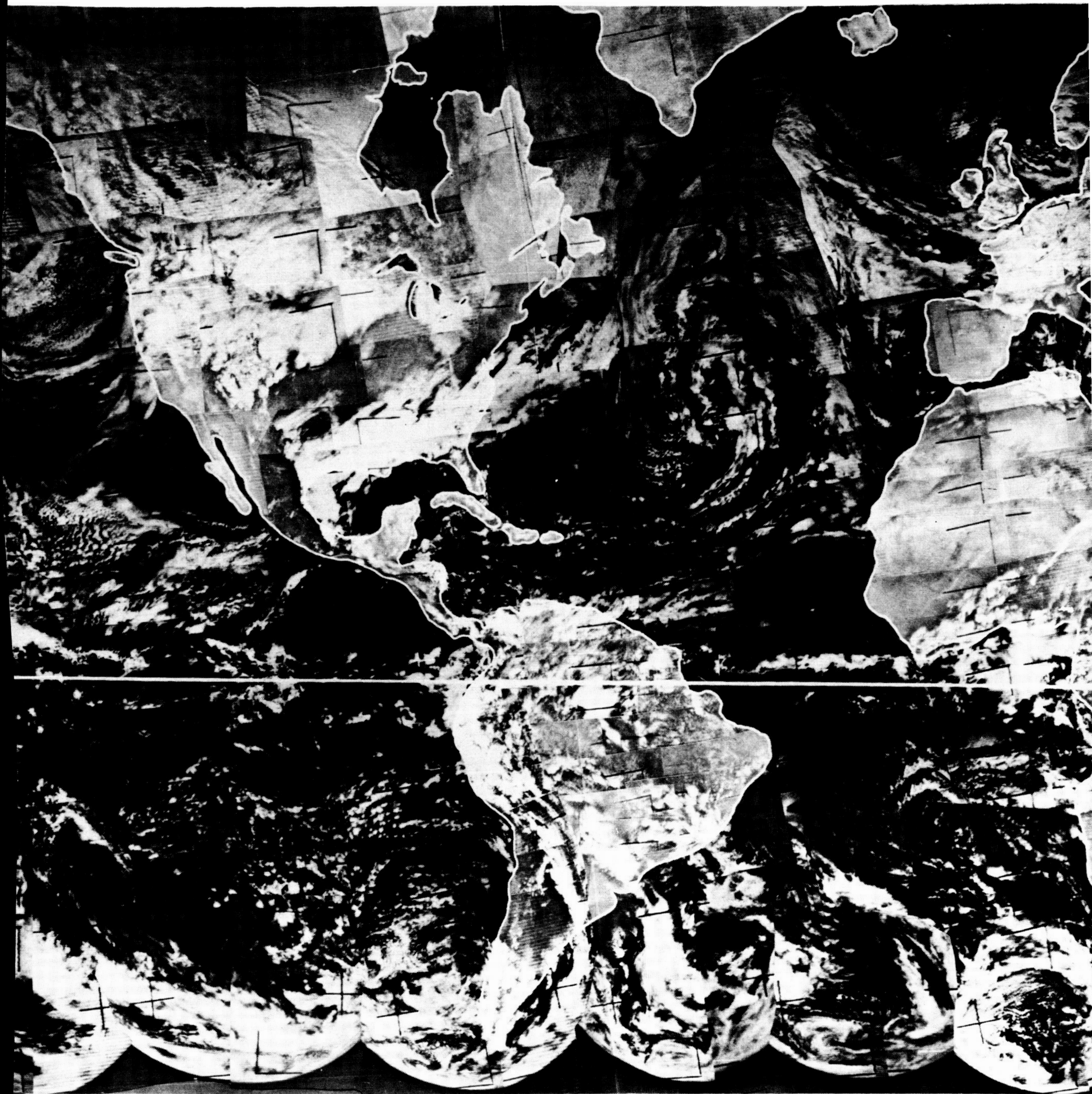

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Figure 1—TIROS 9 Global Photomosaic

Table 2
Parameters Defining State of the Atmosphere

Quantity	Measurement Required	Measurement Technique	Specific Sensors	Status
Cloudcover	Night and day coverage	Television, IR, UV	AVCS television	Flown on Nimbus; will fly on TOS
			APT television	Flown on Nimbus; will fly on TOS
			APT with tape recorder (1)	Under development
			Photomultiplier Cloud camera (2)	Under development
			Dielectric-tape Camera	Under study
			Image-dissector Camera	Under study
			HRIR	Has flown on Nimbus
			Cameras on Manned Spacecraft	Have flown
Temperature	Complete vertical profile, surface to 100,000 feet	IR, microwave	Infrared spectrometer (3)	Under development; will fly on Nimbus
			Infrared interferometer	Under development; will fly on Nimbus
Pressure/ Density	Complete vertical profile	IR, microwave lasers	None	Not developed Ground laser experiments in progress
Humidity	Vertical profile integrated total in column	IR, microwave	None	Not developed
Winds	Speed, Direction; several layers, 750 mb to 10 mb	In situ devices	IRLS GHOST EOLE	Under development
Precipitation	Distribution rate	TV, passive and active microwave	Radar	(See cloudcover) Active, developed for ground use
Heat balance	Solar input, earth radiative output	IR, Visible spectrum	TIROS radiometer	Flown on TIROS
			TOS radiometer	(Developed) will fly on TOS
Ozone	Vertical Profile integrated total in column	UV	UV spectrometer	Not developed
Snow and ice cover, sea state	Horizontal distribution, magnitude	TV, IR, microwave	TV (See cloudcover) (4)	IR, microwave not developed
Sferics	Location, quantity, magnitude	r.f.	Sferics detector	Under development

Footnotes:
(1) Will replace AVCS and APT
(2) Will fly on ATS
(3) Balloon flight has been made.
(4) Correlation with sun glitter has not been quantitatively established.

Orbit Determination

First of all, we must select a satellite orbit that will satisfy requirements for a meteorological program. The factors considered in selecting the orbit include cost, reliability, time and area required for proper data coverage, power requirements, equipment parameters, operating parameters, spacecraft weight, and location of data-readout stations (Butler, 1964).

The objective of a meteorological satellite system is to make observations over the entire globe on a daily basis and collect reports of the observations. The reports lose their value unless they are collected from the satellite and relayed to a central processing point with no more than a 2- or 3-hour delay. For this reason, only two types of orbits are being seriously considered for future operational meteorological satellites: These are sun-synchronous polar orbits, and earth-synchronous stationary orbits. The sun-synchronous polar orbit selected for the Nimbus spacecraft (Figure 2) has an inclination of approximately 80 degrees to the equator (retrograde). The plane of the orbit precesses at a rate equivalent to that of the rotation of the earth around its axis, and is synchronized with the sun, so that the satellite orbital plane maintains its relationship with the earth-sun line.

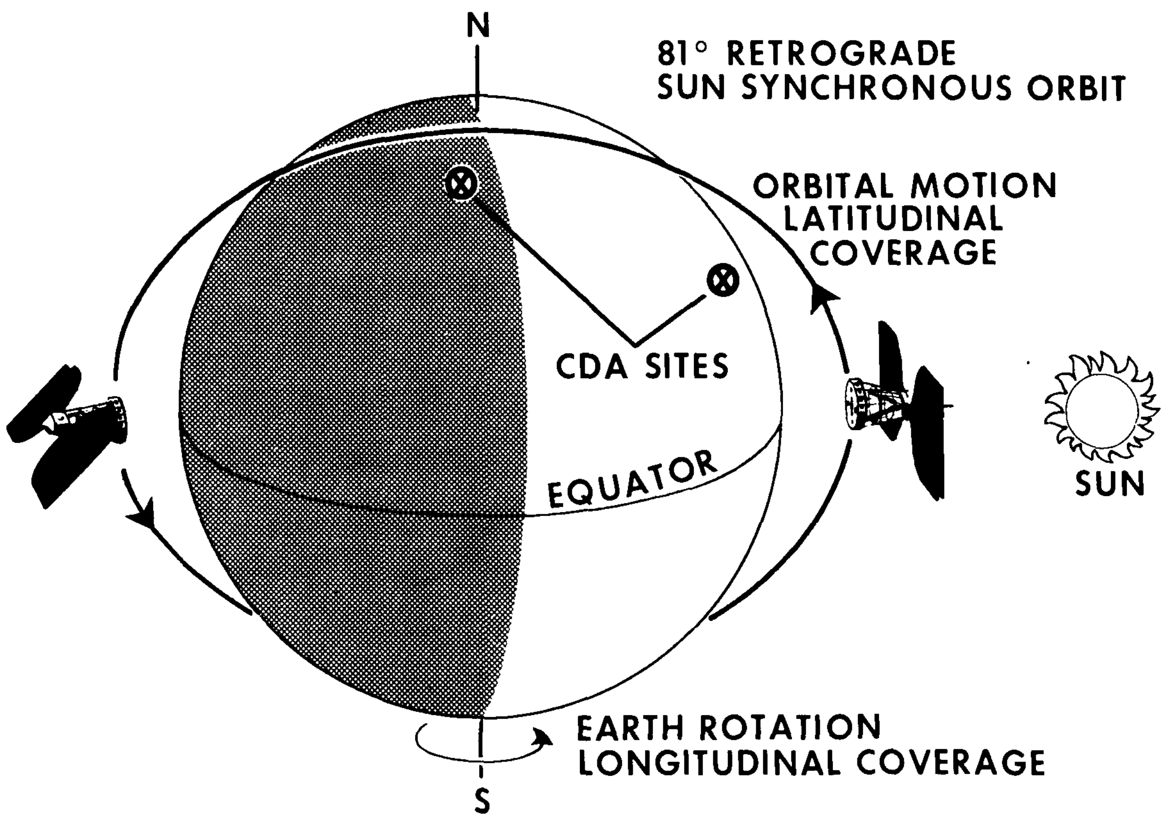


Figure 2–Nimbus Sun-Synchronous Polar Orbit

The earth-synchronous, or stationary, orbit (Figure 3) requires positioning the satellite, like Syncom, at an altitude of approximately 22,300 miles. At this altitude the satellite will circle the earth at the same angular velocity as the earth, and its position will not change relative to the earth. The satellite can be made to hover above any given point on the equator and can observe the same area continuously for hours, days, or months. Full global coverage excluding the polar areas would require a minimum of three satellites.

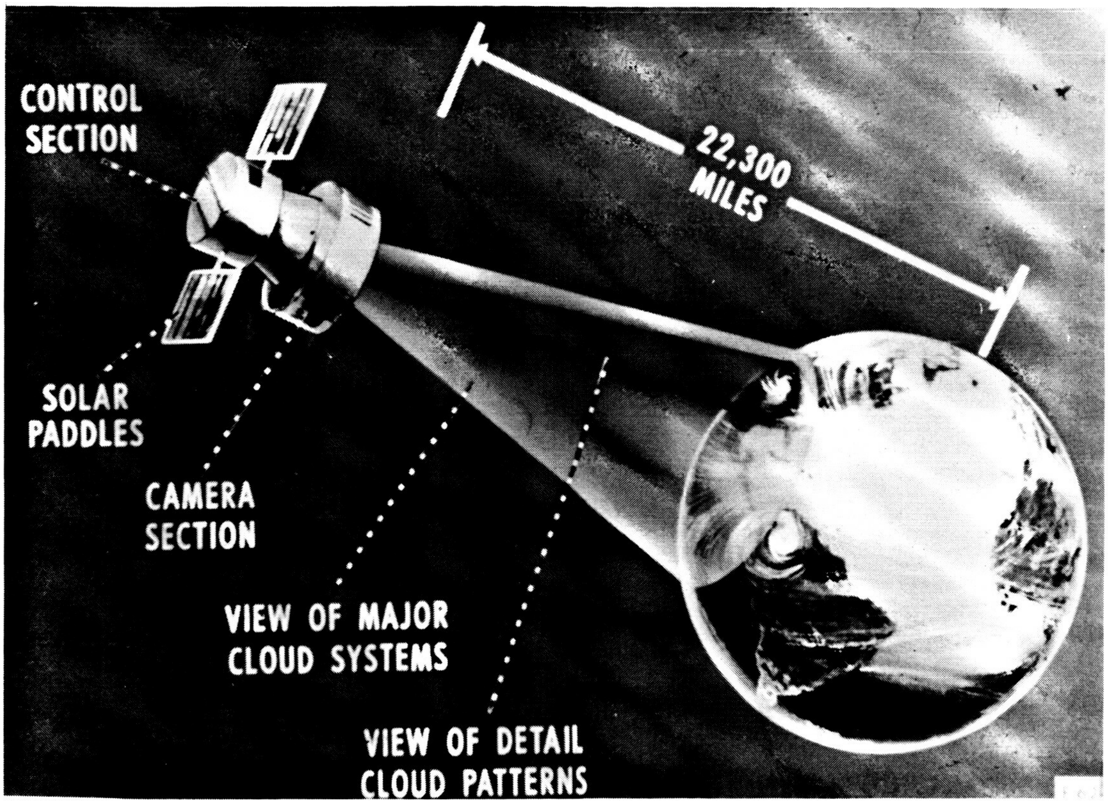


Figure 3—Earth-Synchronous Stationary Orbit

Stabilization and Attitude Control

The choice of the best system for stabilization and attitude control depends upon the accuracy needed for the best performance of the meteorological sensors to be carried on the satellites. Other factors to be considered are altitude, accuracy, cost, complexity, reliability, control lifetime, redundancy, weight and power requirements. Each system has several advantages and several disadvantages. Some of the major systems are:

(a) Three-axis stabilization

Nimbus has successfully used this control system (Figure 4), which includes two infrared horizon scanners, two coarse sun sensors, and a rate gyro acting as a yaw sensor. Three motor-driven flywheels and eight gas nozzles generate a torque which provides attitude control. A pneumatic tank contains the gas supply.

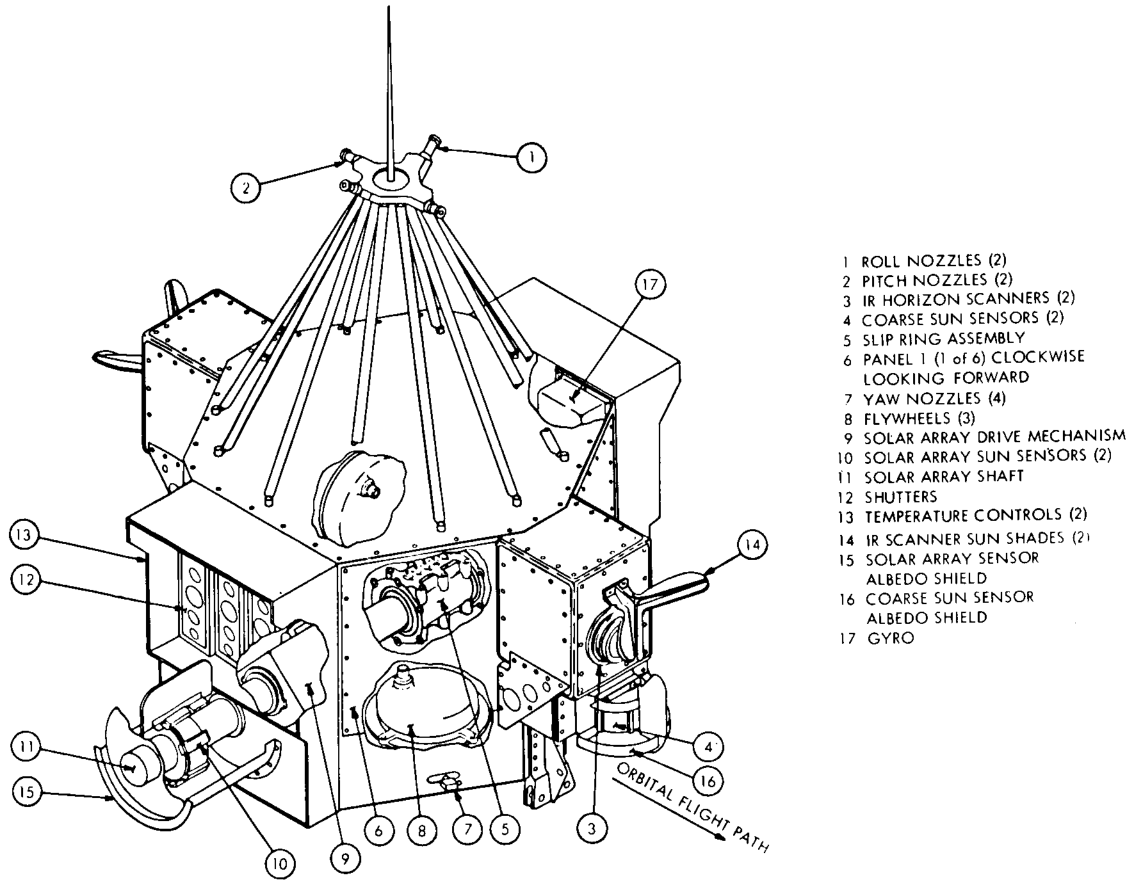


Figure 4—Nimbus Control System

Figure 5 shows the spacecraft coordinate system, which is defined by the location of the optical scanners and the inertial devices used to orient the axes. The yaw axis points toward the center of the earth; the roll axis, perpendicular to the yaw axis, is parallel to the orbital plane; the pitch axis is perpendicular to both the yaw and roll axes.

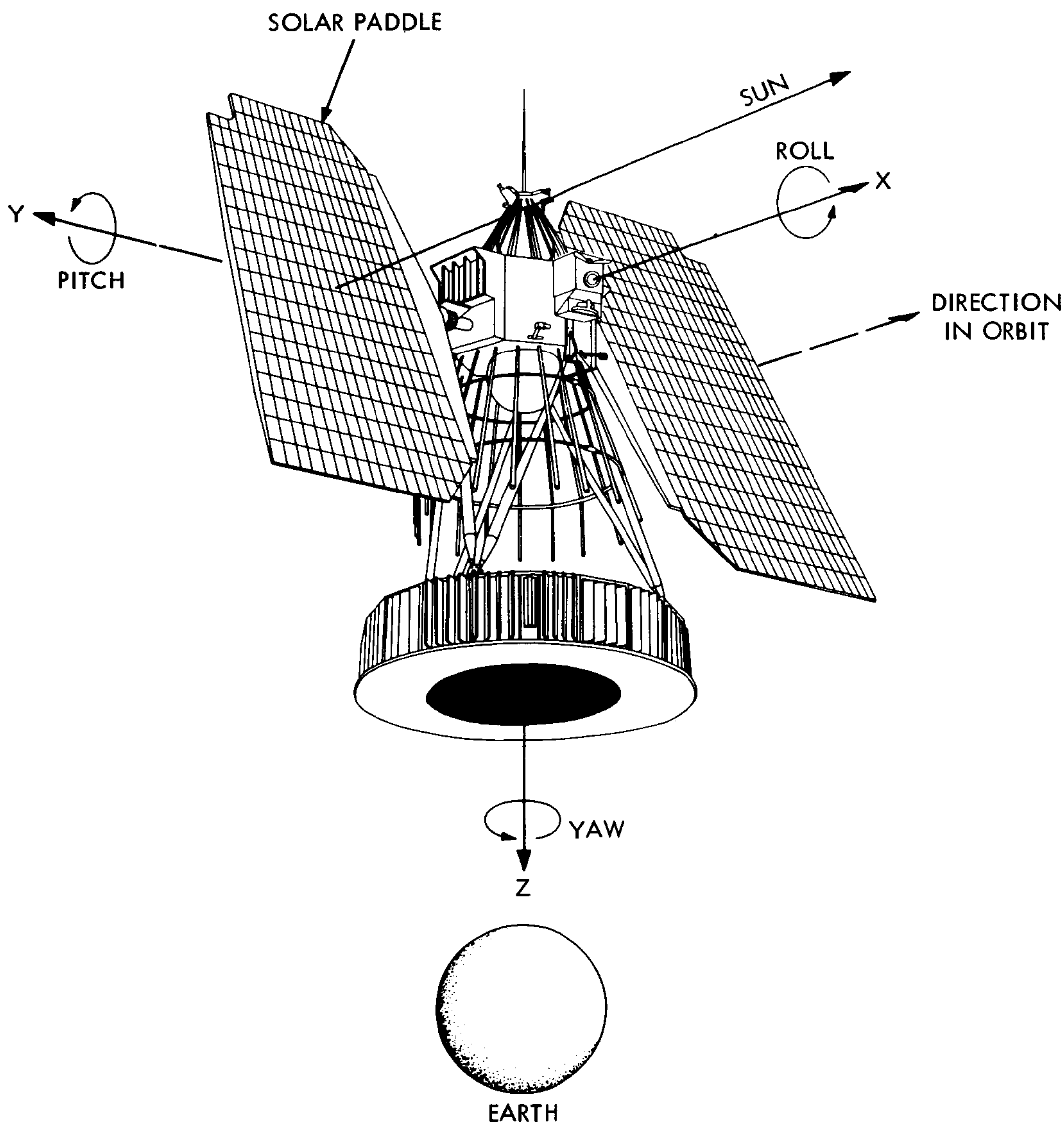


Figure 5–Nimbus Coordinate System

By using signals from the horizon scanners, rate gyro, and sun sensors to control the gas jets and flywheels, we can point the spacecraft with accuracies in the range of 1 to 2 degrees.

(b) Spin Stabilization

A satellite spinning in space ordinarily will not stay oriented with respect to the earth, because its spin axis is fixed with respect to space. For instance, in the standard TIROS configuration (Figure 6a), the spin and camera axes were parallel and space-stabilized in the orbit plane. As a result, the cameras viewed the earth during only a small portion of each orbit.

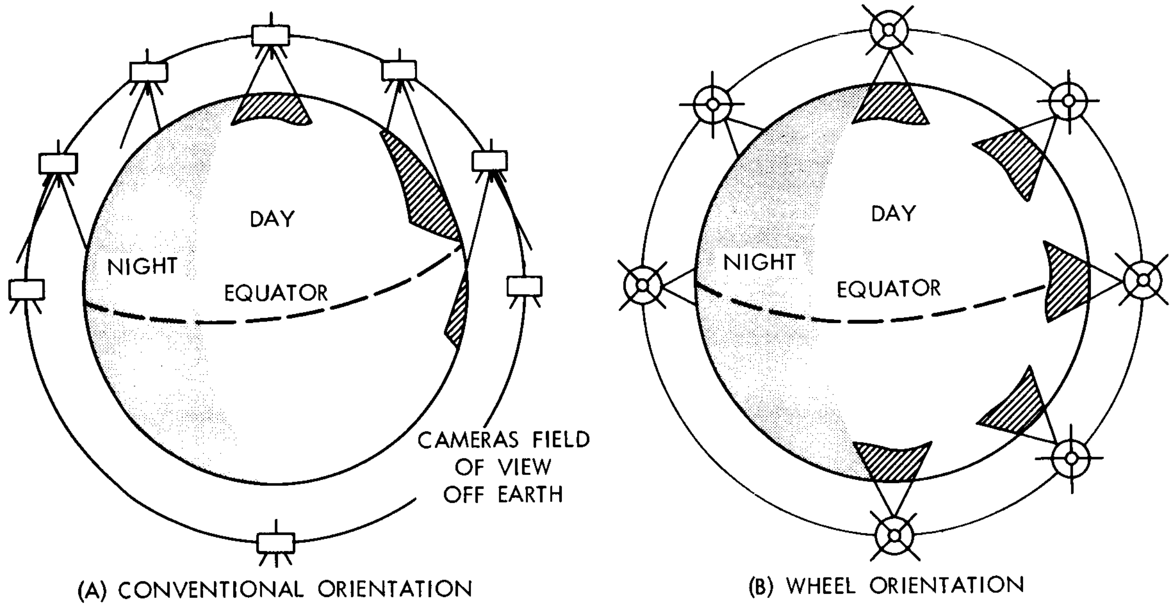


Figure 6–TIROS Picture Coverage in Conventional and Wheel Orientations

A more efficient configuration is the TIROS wheel (Figure 6b) which carries an earth-oriented camera system in a spin-stabilized spacecraft so that the camera can look down at the earth from any point in the orbit, greatly increasing data coverage.

In the wheel configuration, the spacecraft after final separation is despun from a nominal rate of 120 rpm to approximately 10 rpm by the release of two weighted cords called yo-yo's. At separation, the position of the spin axis may be unsatisfactory in relation to the photographic coverage desired. In order to adjust this position, a magnetic attitude control system is used. This system consists of a coil of wire wound around the periphery of the spacecraft and connected to a stepping switch, commanded from the ground to vary the magnitude and direction of the current in the coil. The current in the coil creates a magnetic field which, interacting with the earth's magnetic field, provides the force for attitude control.

A second coil of wire positioned at right angles to the attitude-control coil, acting as the armature of a dc motor, provides a means of controlling the spin rate of the satellite.

We can control the attitude of the TIROS spacecraft within a few degrees, and by analyzing the data can determine the attitude after the fact to approximately 1 degree.

(c) Gyromagnetic Stabilization

Gyromagnetic stabilization (Figure 7) is a three-axis attitude-control system which uses magnetic torquing to control either spinning or nonspinning earth-orbiting satellites. This type of satellite is constructed in two sections, a spinning flywheel and a stabilized platform. The flywheel has a controllable spin rate which, through coupling to the stabilized platform, can make the stabilized platform rotate through exactly one revolution per orbit. In this way, we can keep one portion of the payload structure facing the earth at all times.

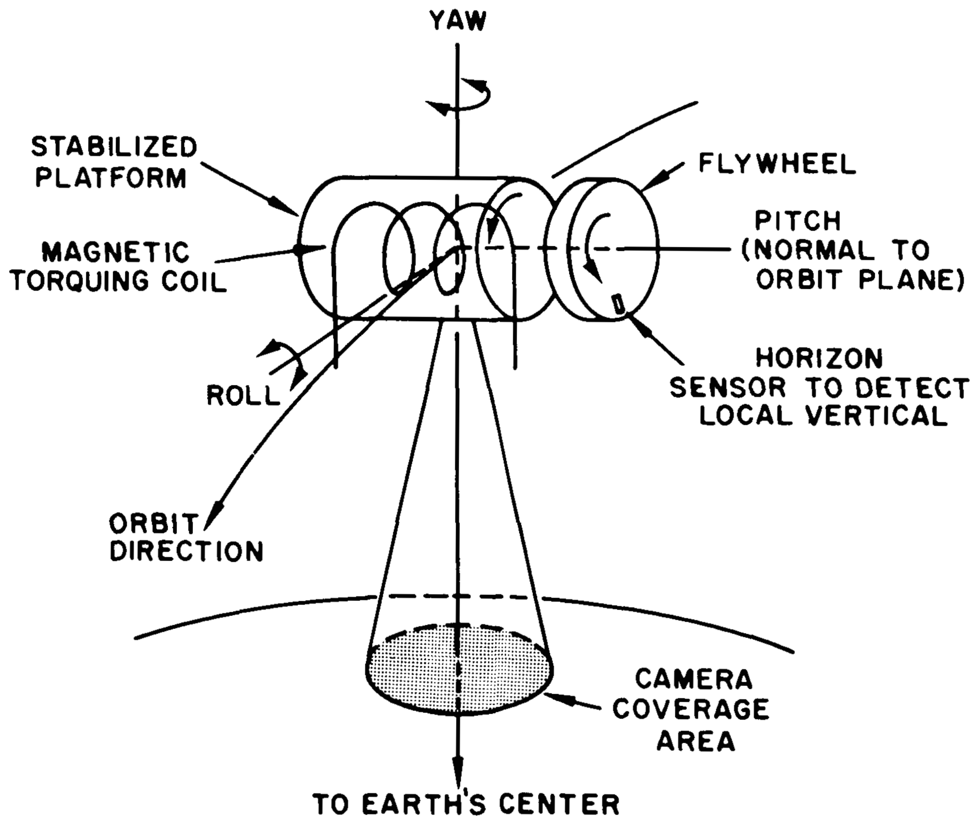


Figure 7—Gyromagnetic Stabilization

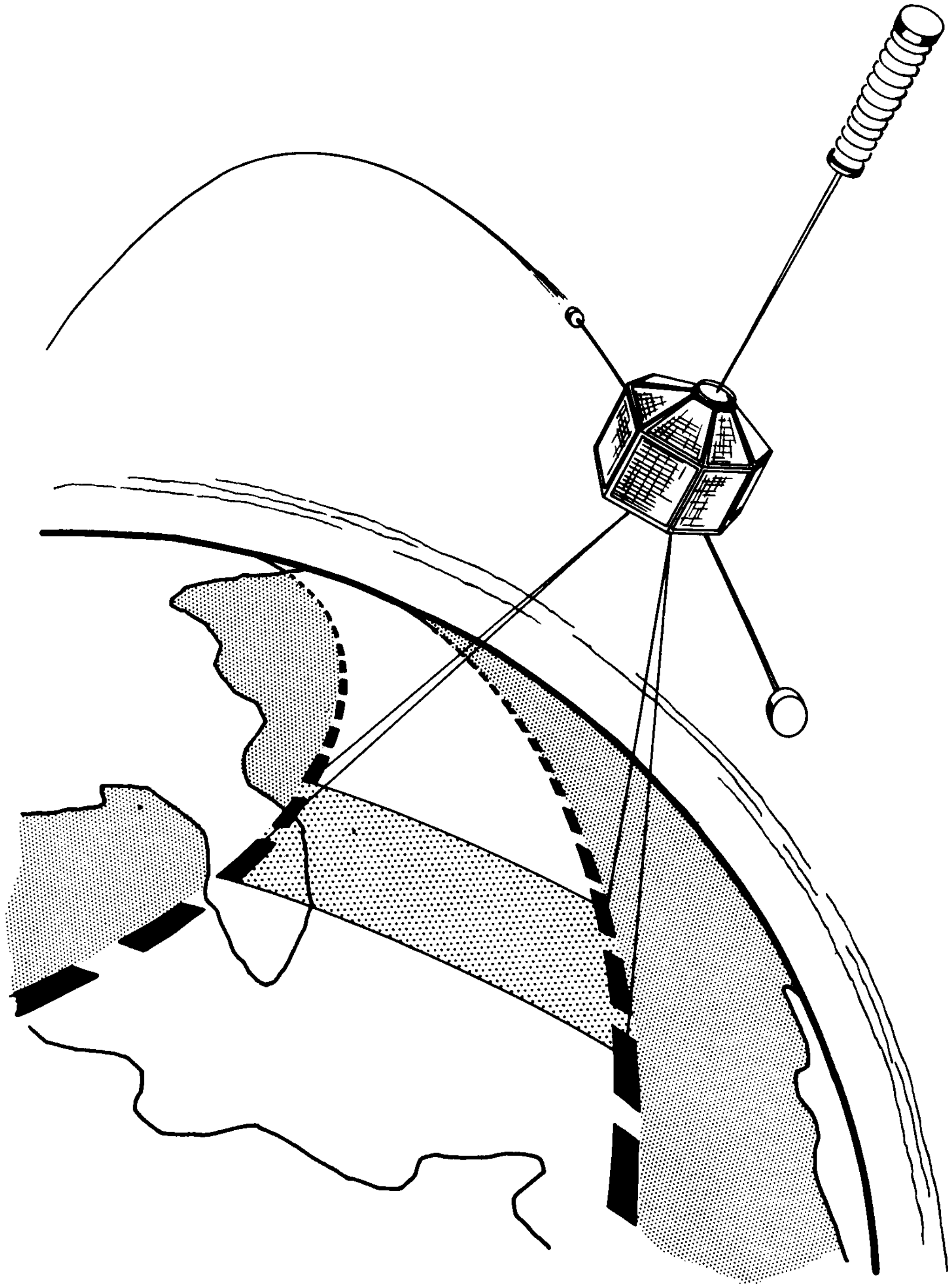


Figure 8–Gravity-Gradient Configuration

(d) Gravity-Gradient Stabilization

The gravity-gradient torquing system (Figure 8) consists of extendable rods that are deployed either automatically or by ground command after the spacecraft is in orbit.

The gravity-gradient system causes a satellite to orient itself with the axis of minimum moments-of-inertia along the vertical and the axis of maximum moments-of-inertia perpendicular to the orbit plane.

Some type of damping control is required to reduce perturbing forces caused by solar radiation pressure, atmospheric drag, interactions with the geomagnetic field, mechanical displacement, and the movement of satellite parts, such as tape recorders and shutters.

Although the best pointing accuracy achieved to date by the gravity-gradient system is marginal for meteorological uses, considerable effort is being expended to improve the system's stability because of its inherent long life and reliability.

Satellite Power

All meteorological satellites flown until now have been powered by solar cells, which have the important advantages of relatively low cost, low weight, and no need for on-board fuel. We have been constantly improving solar cells to make them more efficient and more resistant to radiation. The cells to be used on the TOS satellites will be an n-on-p configuration with about 10-percent efficiency. A major drawback in using solar cells to supply power is that they require direct solar radiation on the cells for maximum power output. We can overcome this problem either by putting excess cells on the satellite, as we did on the TIROS series, or by designing "sun-seeking" solar paddles such as those used on Nimbus.

The other serious contender for supplying satellite power is the radioisotope thermal generator (RTG). A 30-watt RTG will be flown as an auxiliary power supply on a future Nimbus satellite. However, because of the high cost of nuclear fuel, most operational satellites will continue to use solar-cell power supplies for some time to come.

The concept of using satellites for weather observation was discussed as early as 1951 by S. M. Greenfield and W. W. Kellog. In 1954, H. Wexler presented the idea of a satellite weather observatory equipped with infrared detectors, radars, and television cameras, and S. F. Singer specified the requirements for meteórological measurements from a minimum satellite vehicle. However, the first real attempt at image sensing from an earth satellite was made in the cloud-cover experiment on Vanguard 2.

Vanguard 2

Vanguard 2 (Figure 9) was the first satellite put into orbit with equipment especially designed to obtain meteorological information. It has been discussed in some detail by Hanel (1961). The equipment consisted of two photocells mounted at 45 degrees to the proposed spin axis of the satellite. During each spin, one of the photocells would sweep across the earth. Signals received by the photocells were stored on magnetic tape and transmitted to the ground when the satellite passed near a readout station. After these signals were received on the ground, they were to be recombined to form a cloud picture. This experiment was unsuccessful meteorologically because the satellite wobbled erratically in orbit, and it was not practical to reconstitute the photoelectric scan signals when they were received on the ground.

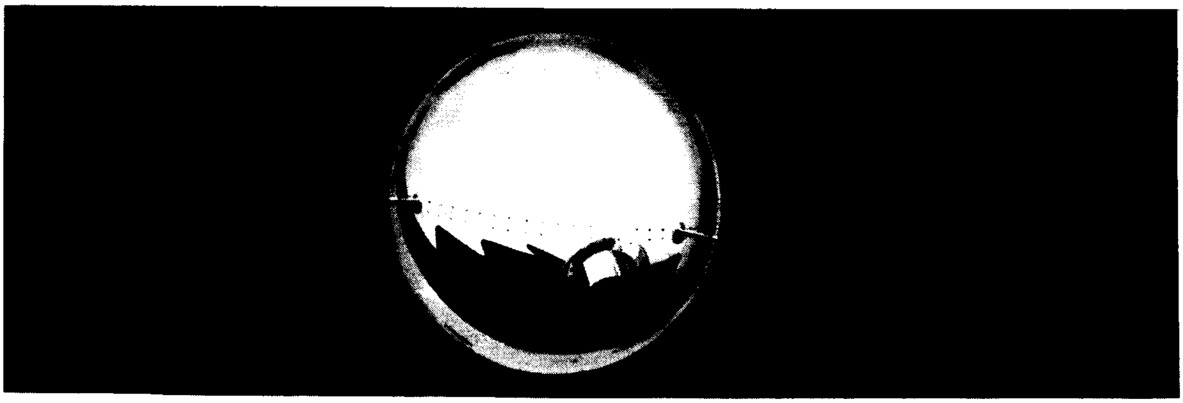


Figure 9—Vanguard 2

Figure 10—Explorer 7

Explorer 7

After the Vanguard experiment failed, a second experiment, devised by Professor V. Suomi (1961) for measuring the planetary heat budget, was successfully flown on The Explorer 7 satellite (Figure 10).

This experiment was also flown on the TIROS 3 and TIROS 4 satellites, and an updated version will be flown on the TOS A and TOS C spacecraft.

TIROS 1-10 and Nimbus 1

Since early 1960, we have successfully launched one Nimbus (Figure 11) and ten TIROS spacecraft, which have provided us with practically continuous weather-satellite data. The program includes substantial research and development in sensor and spacecraft technology. For the past year and a half, we have been developing and constructing an operational system based generally on the TIROS spacecraft, but using the latest technology developed for both TIROS and Nimbus.

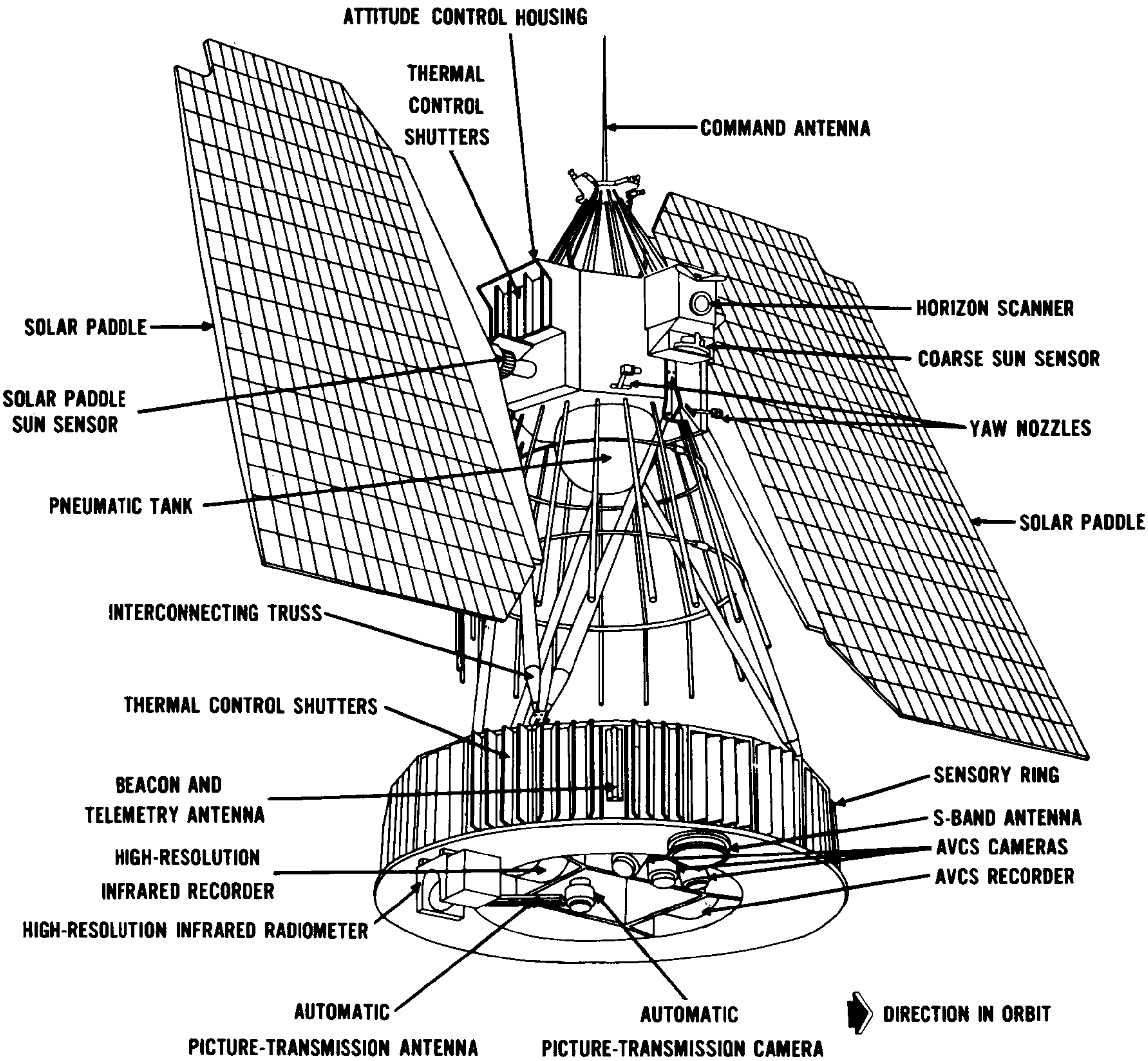


Figure 11–Nimbus 1 Spacecraft

The operational system will use the advanced vidicon camera system (AVCS) and the automatic picture-transmission (APT) system which were developed for the Nimbus program.

Several highlights of the program should be mentioned:

- The exceptionally long life of TIROS 7 and 8 which are still producing excellent photographs after more than 2 years in orbit for 7 and more than eighteen months for 8.

- TIROS the first "wheel" spacecraft in a polar sun-synchronous orbit. The cameras, mounted radially, are giving us full coverage of the sunlit portion of the earth on a daily basis.

- TIROS 10 is an experiment in spacecraft technology in which an early version of TIROS (Camera axis parallel to spin axis) was injected into a sun-synchronous polar orbit and its spin-axis steered magnetically to a position vertical to the earth at 20 degrees north latitude (Figure 12), thus providing hurricane and typhoon coverage from approximately 5 degrees south latitude to 45 degrees north around the earth.

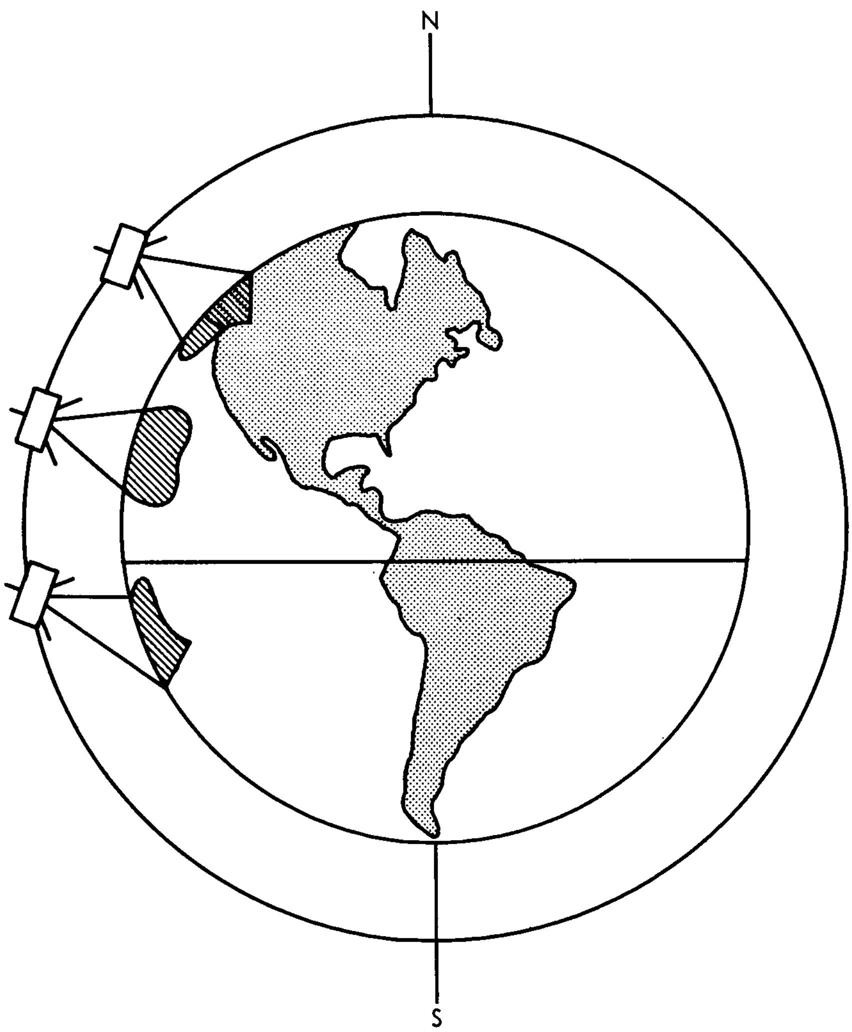
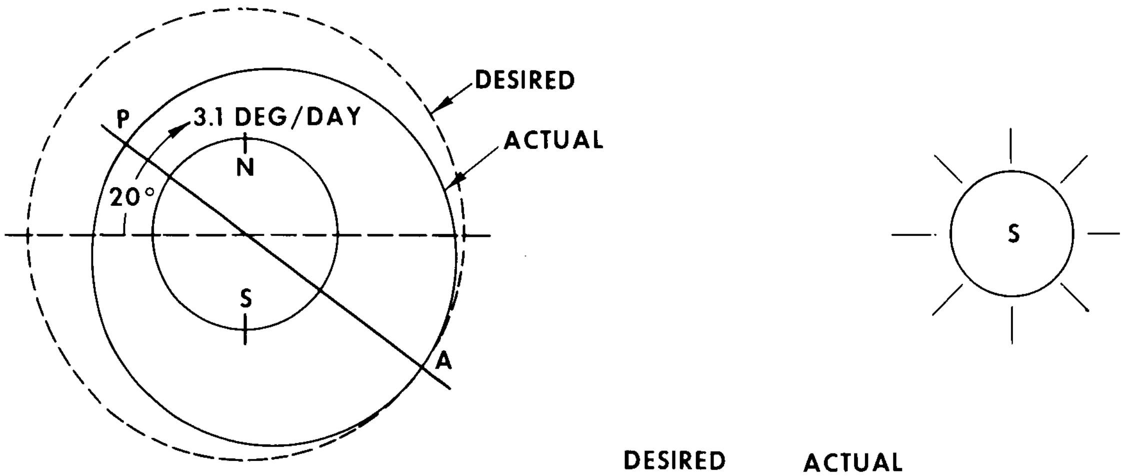


Figure 12–TIROS 10

It is worthwhile to look at some of the above highlights from the point of view of their instrumentation. Nimbus 1 was designed to operate at a nominal orbit altitude of 600 nautical miles, taking into consideration a number of factors such as the capabilities of the launch vehicle, sensor resolution, and data-transmission requirements. Details of the Nimbus program have been described by Press (1965). The attitude-control system, which will be essentially the same for the next two Nimbus flights, is a full three-axis active system: that is, it uses infrared horizon scanners for pitch and roll attitude determination and a rate gyro as a yaw sensor. Three motor-driven flywheels and four pairs of gas nozzles (2 pitch, 2 roll, 4 yaw) will generate torques to provide attitude control at 600 nautical miles. The system was designed to achieve pointing accuracy in all three axes to within ±1 degree and to hold rates of motion to less then .05 degree to prevent smear and consequent loss of sensor resolution.

Because of a short second burn of the Agena vehicle, Nimbus 1 achieved an elliptical orbit with a 579-nautical-mile apogee and a 263-nautical-mile perigee instead of the nominal 600 nautical miles planned (Figure 13). These lower altitudes increased the sensitivity of the horizon scanners to cold clouds and, in combination with the highly elliptical orbit, placed a severe burden on the control



	DESIRED	ACTUAL
ORBIT (MI)	576	579-263
(KM)	929	932-423
PERIOD (MIN)	103.5	98.7
HIGH NOON	±8°	-8.1°
SUN SYNC. (DEG/MO)	±2.3	+3.3
ORBITS/DAY	13.9	14.7
BLIND ORBITS/DAY	2-3	2-7

Figure 13–Nimbus 1 Orbit

system. Nevertheless, the sensors had pitch and roll accuracies to within ±1 degree, and yaw to within ±2 degrees, for as much as 50 percent of the data (as estimated from checks made against known geographical references located in about 10 percent of the pictures). On an average basis, ±2 degrees pitch, ±3 degrees roll, and ±8 to 10 degrees yaw, and rates up to 1/4 degree per second, would be a fair estimate of the actual performance.

The variation in altitude caused by the elliptical orbit did produce a valuable by-product; it provided sensor data with approximately 2:1 variation in resolution, which should help to resolve some of the questions about resolution requirements for various meteorological applications.

Nimbus 1 also successfully demonstrated the advanced vidicon camera system, (Figure 14), which employed three vidicon cameras in a trimetrogon array with slightly overlapping fields-of-view. Resolution at the subsatellite point was approximately 1 nautical mile at apogee and improved to approximately one-half

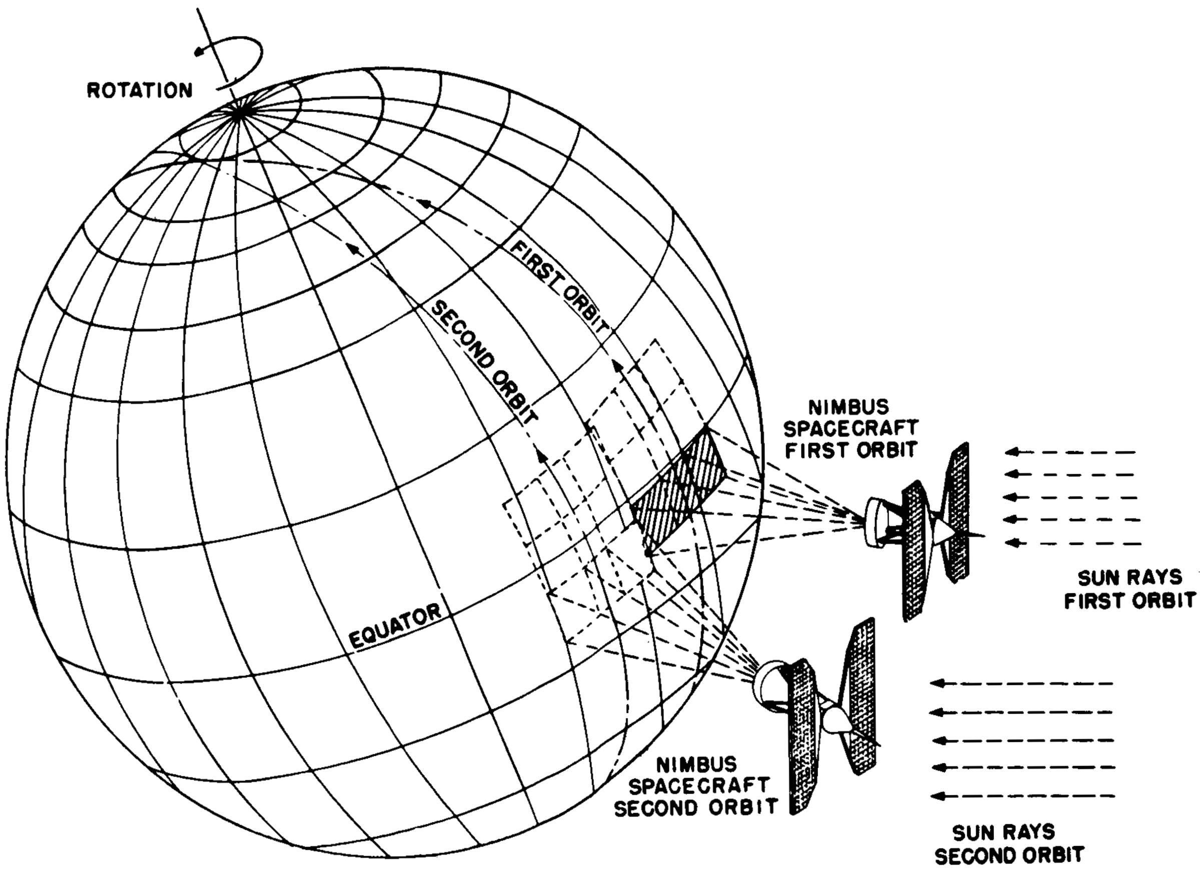


Figure 14–Nimbus Television Coverage

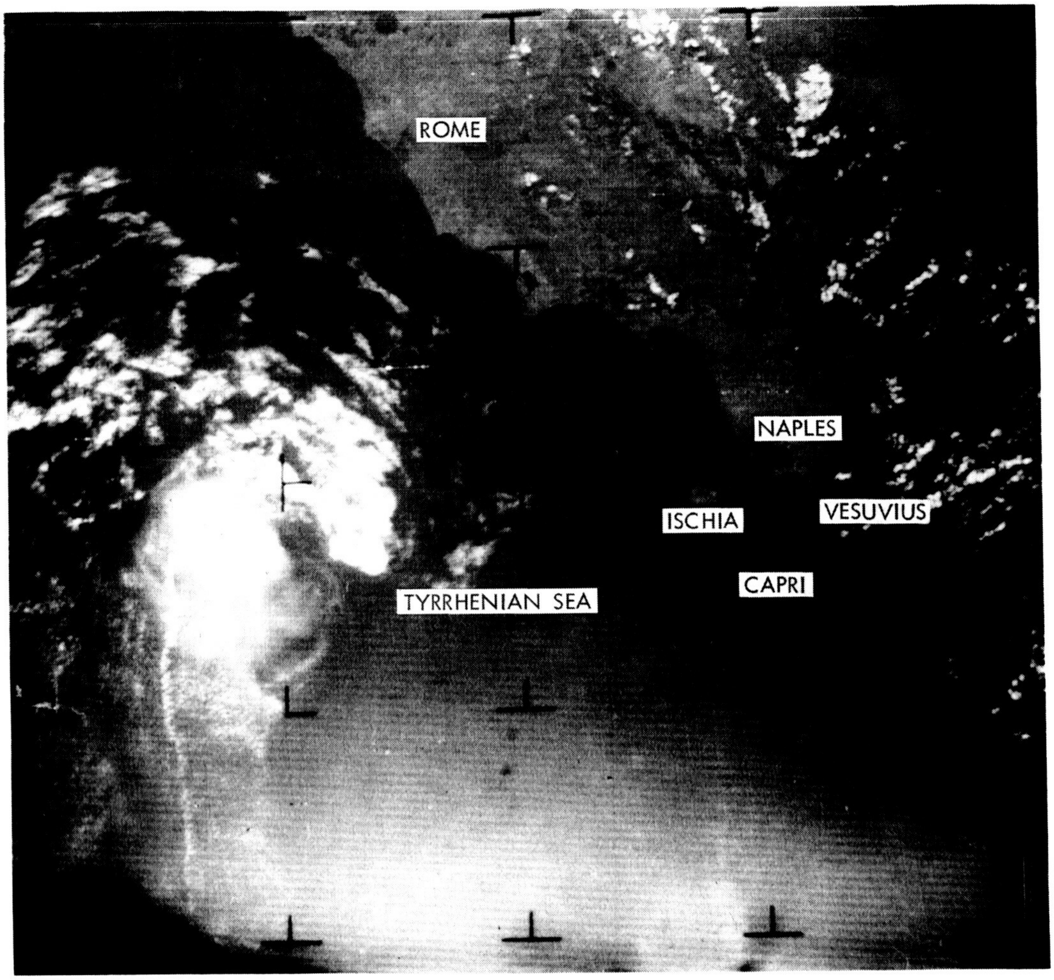


Figure 15–Nimbus 1 AVCS Photograph of Central Italy (Orbit 265, September 15, 1964)

nautical mile at perigee with some very striking results. Figure 15 is an AVCS photo taken September 15, 1964 by Nimbus 1 during orbit 265. Central Italy can be seen extending from about 42 degrees north just north of Rome to 40 degrees north south of Naples. The picture clearly shows the rough mountainous terrain of the Appennines with clouds above the higher elevations. Mount Vesuvius, the active volcano on the Bay of Naples, is also cloud-capped. The islands of Ischia and Capri are discernible in the Bay of Naples. A huge cumulonimbus cloud is located over the Tyrrhenian Sea. The smaller cumulus clouds seem to have a vortical circulation around them. Nothing else on the surface of the weather map for the same day shows or even suggests the presence of this small-scale disturbance; instead, the map indicates that all the Mediterranean is under the influence of a high-pressure system.

The AVCS is designed to provide 800-line resolution and a gray scale of 10 which represents an improvement of about 2:1 over the cameras flown on TIROS. The system also has self-contained facilities for in-flight calibration of the gray scale and sweep linearity. The TIROS operational satellite (TOS) system will carry two of these cameras on one spacecraft, using them as redundant single cameras and not in the triplet or trimetrogon array.

The high-resolution infrared radiometer (HRIR) (Figure 16) has also produced striking results. This instrument, designed to scan the earth in the 3.4- to 4.2-micron region, represents the first major breakthrough in the problem of obtaining data on the nighttime cloudcover of the earth (Figure 17). The HRIR uses a lead selenide detector radiation-cooled to -76°C, in conjunction with a narrow precise filter, to sense the earth's radiation in one of the atmospheric window regions, and to measure the temperature of the radiating surfaces. The HRIR can measure temperatures over the range 210°K to 300°K with an accuracy of ±1°K.

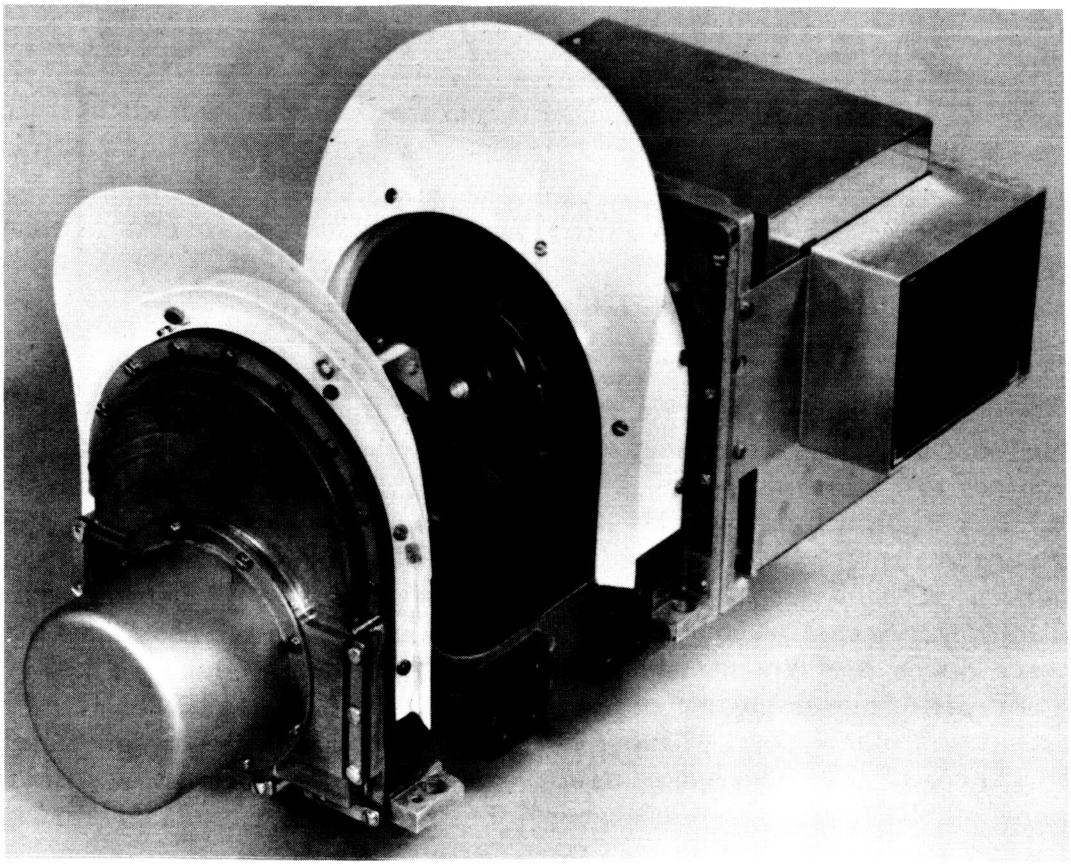


Figure 16–Nimbus High-Resolution Infrared Radiometer

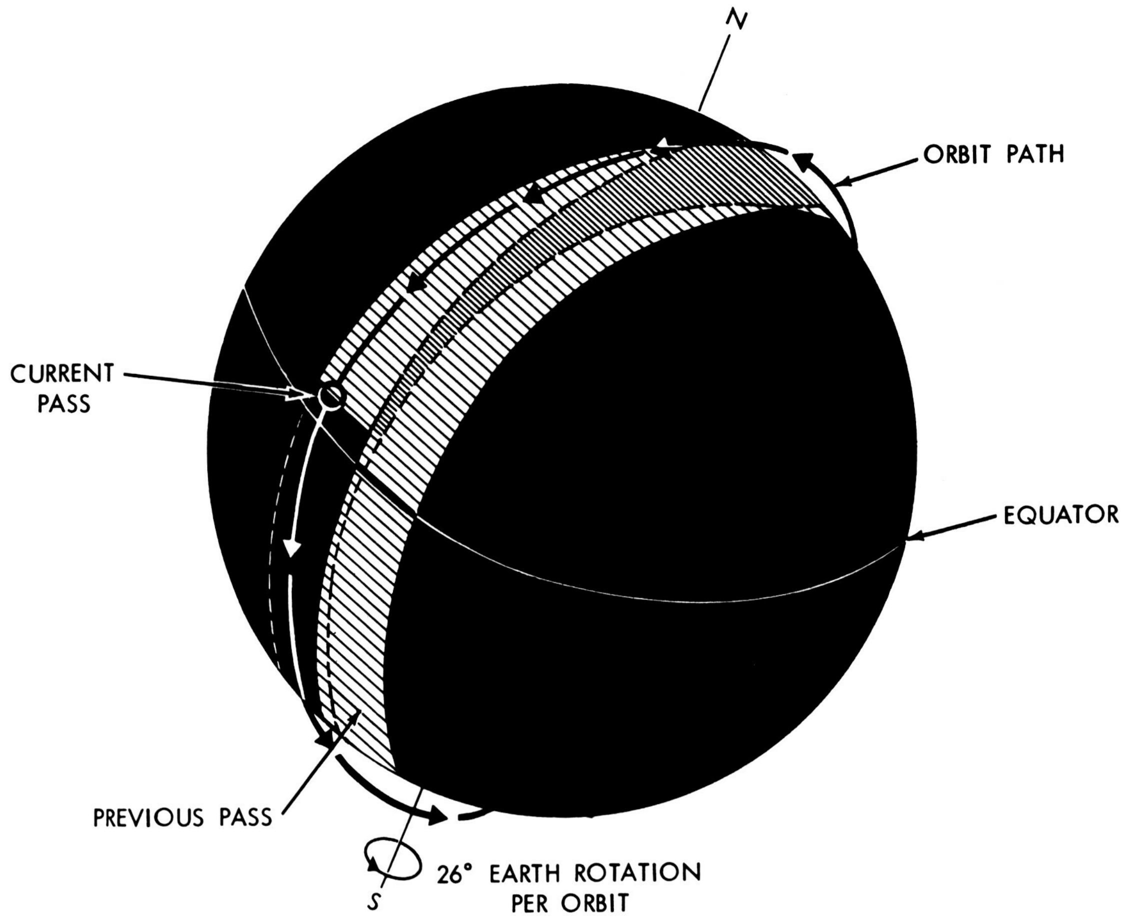


Figure 17–Nimbus HRIR Coverage

Although it was designed for a nominal resolution of 5 nautical miles, the actual resolution in the elliptical orbit of Nimbus 1 ranged from about 2 miles at perigee to 5 miles at apogee. Figure 18 is an HRIR photo taken September 6, 1964 by Nimbus 1 during orbit 136. It covers an area in the Western Pacific from approximately 5 to 50 degrees north and 125 to 140 degrees east. In the lower half of the picture is Typhoon Sally, centered at about 15 degrees north and 140 degrees east. The upper half of the picture shows the coastlines of Siberia, Korea, and Japan bordering the Sea of Japan. The islands of Sado and Okushiri off the eastern coasts of Japan and Hokkaido are discernible. Most of the southern coast of Japan is covered by bands of clouds associated with a stationary front connected with a low-pressure system east of Hokkaido. Plainly visible in the upper left corner is Lake Khanka, north of Vladivostok.

The computer-produced grids are displaced northward and eastward approximately 2 degrees in latitude and 1 degree in longitude from the true latitude and longitude.

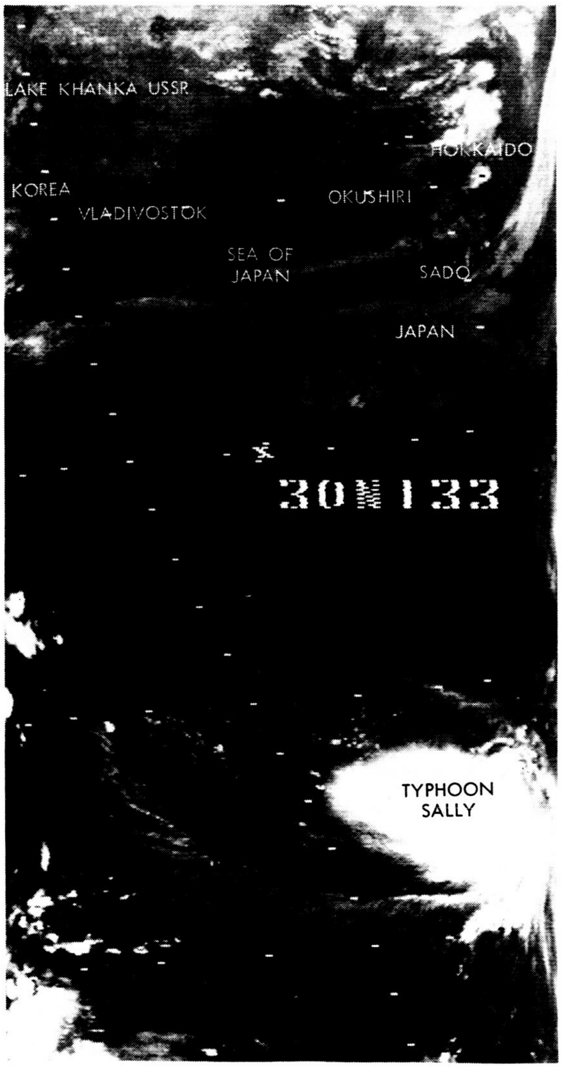


Figure 18–Nimbus 1 HRIR Photograph of the Western Pacific Area (Orbit 136, September 6, 1964)

Figure 19 is a section of an infrared strip map of Hurricane Gladys, taken on September 18, 1964 over the Atlantic near midnight during orbit 305. The dark shades are warm clouds and the white shades are cold. The eye of the hurricane can be clearly seen. The figure also reproduces the original analog record of one single scan from horizon to horizon across the center of the hurricane. Scales are shown for the equivalent temperatures expressed in degrees K, and the corresponding cloud heights expressed in kilometers. The scan has registered temperatures near 290°K in the center of the eye and near 300°K outside the storm. The recorded temperatures of about 300°K inside the storm, corresponding to the sea-surface temperature over the clear skies outside the storm, show that the HRIR was able to detect clouds. The 290°K temperature was taken at a height of 2 kilometers over the eye of the hurricane. The cloudtop temperatures correspond to cloud heights in excess of 12 kilometers, or 37,000 feet.

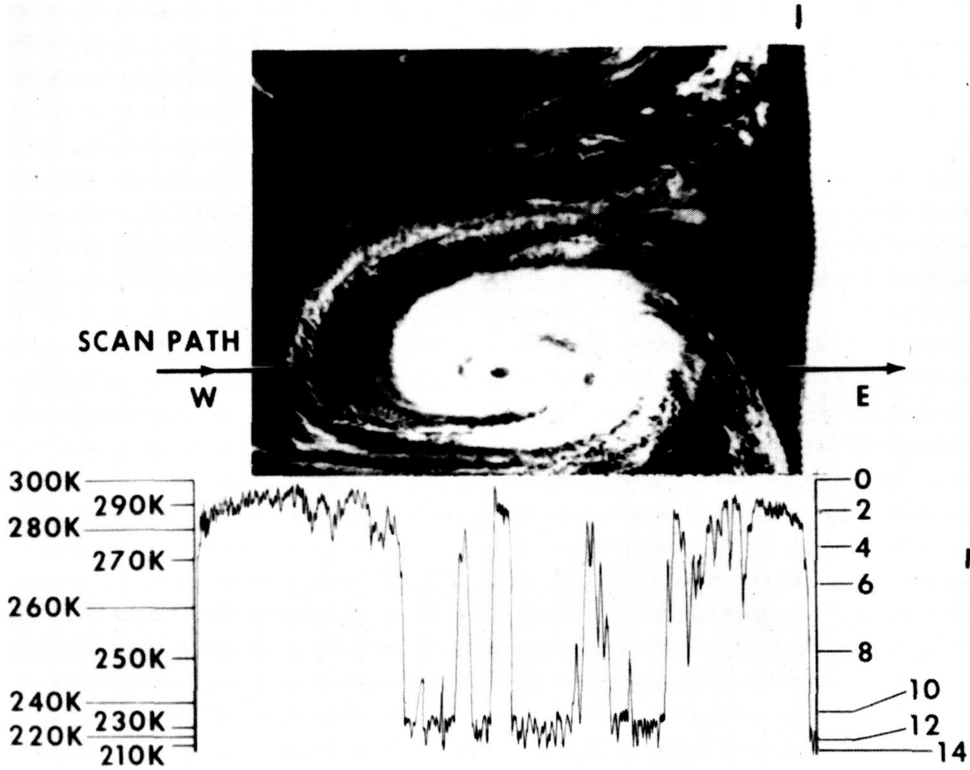


Figure 19–Analog Trace of a Single Nimbus 1 HRIR Scan Through Hurricane Gladys (Orbit 305, September 18, 1964)

The automatic picture-transmission (APT) system (Figure 12) was the third major sensory system flown on Nimbus 1. The basic concept of transmitting daytime cloudcover pictures directly to local users is well known, since it has been widely publicized and was flight-tested in 1963 on TIROS 8. The Nimbus results were clearly superior, mainly because of the stabilized platform which resulted in pictures covering approximately 1000 square nautical miles looking straight down at the subsatellite point; also, because of high-noon sun-synchronous orbit which provided high uniform illumination. Also, the Nimbus APT pictures did not show banding of the scan lines which appeared in the TIROS 8 pictures as a result of the modulation of the camera-tube electron beam by the earth's magnetic field.

Figure 20 is an APT photo taken on September 9, 1964 by Nimbus 1 during orbit 177. It shows southern Italy and Greece, read out by the APT ground station in Lannion, France. Italy and Sicily are nearly cloudfree, while most of southern Greece and the Aegean islands are covered by convective clouds. Even though the resolution of the APT system is not as good as that of the AVCS, it is still possible to distinguish small islands like Capri and Ischia in the Bay of Naples, or mountain wavecloud patterns only a few miles in wavelength over southern Yugoslavia.

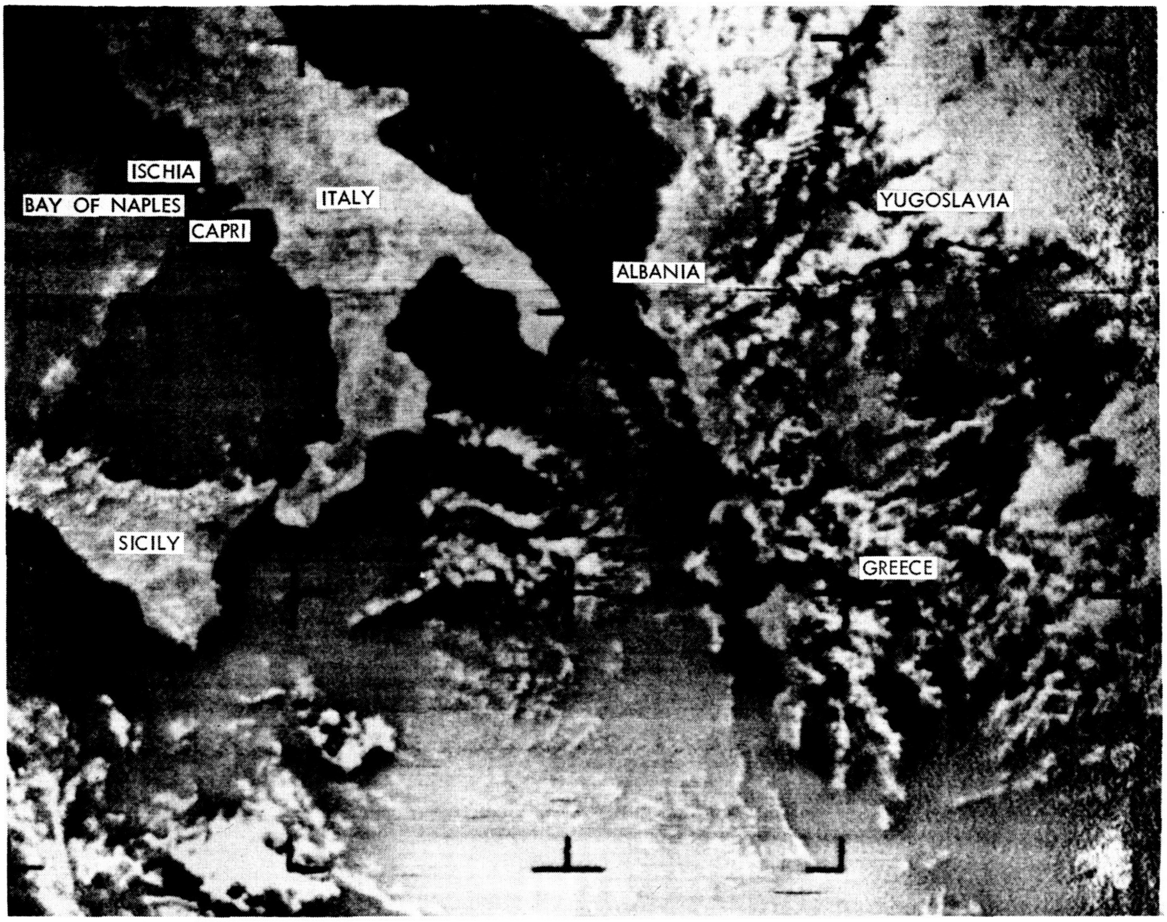


Figure 20—Nimbus 1 APT Photograph of Southern Italy and Greece (Orbit 177, September 9, 1964)

The APT mode of operation aroused great interest, and users around the world participated actively during the test flights on both TIROS and Nimbus.

The APT camera will be used again on the next Nimbus flight early in 1966, and continuous coverage on an operational basis is planned as part of the TOS system, also scheduled to begin early in 1966.

TIROS 9 represented a somewhat radical departure from the eight previous TIROS satellites; it was designed to obtain global picture coverage of the earth's cloudcover, and to provide information which would help in developing an operational satellite system.

Earlier versions of TIROS carried a camera whose optical axis was oriented parallel to the satellite spin axis. Since the spin axis is essentially fixed in free space, the cameras viewed the earth for only a part of the orbit. Furthermore, these earlier spacecraft were designed for equatorial orbits, and the highest inclination used was 58 degrees. These two factors limited the daily coverage to about 20 percent of the earth's surface.

TIROS 9 was designed as a "wheel"; that is, the camera axes were positioned radially, and the spin axis was torqued by magnetic attitude control to be at right angles to the orbit plane so that the satellite rolls or "wheels" around the orbit. Horizon scanners trigger the cameras when they are viewing the subsatellite point. Figure 6 illustrates the difference in coverage obtained.

To satisfy the global coverage requirement, a polar rather than an equatorial orbit was selected, and because of its special advantages a sun-synchronous orbit was selected for meteorology. The advantages are constant illumination of the ground from orbit to orbit, and a relatively constant satellite/sun angle which simplifies the thermal and power-supply designs of the spacecraft. Thermal and power considerations made it impractical to design TIROS 9 for a high-noon orbit like that of Nimbus because the solar-cell-covered top of the satellite must be illuminated as well as the sides. Therefore a 3 p.m. or 9 a.m. orbit was required, with the top of the spacecraft pointing toward the sun.

TIROS 9 did indeed provide full global coverage of the sunlit portion of the earth on a daily basis, as shown in Figure 6. As a fortuitous by-product of a malfunction in the launch vehicle, TIROS 9 was injected into a rather elliptical orbit with a perigee of 400 nautical miles and an apogee of 1600 nautical miles. Figure 21 is a pair of pictures taken near apogee which prove that, even with the reduced effective resolution at that altitude, the basic cloudcover information is still highly useful.

MANNED SPACEFLIGHT EXPERIMENTS

Although the unmanned satellites like TIROS and Nimbus have been the primary source of meteorological photographs from space, a number of significant cloud photographs have been obtained by the Mercury and Gemini manned missions (Figure 22).

The inadequate resolution of some weather-satellite pictures has made it difficult to interpret certain cloud formations. Therefore, it has been desirable to get detailed color views from satellites at lower altitudes. Experiments on the MA-8 and MA-9 Mercury flights have made it possible to examine the spectral-reflectance characteristics of clouds and of land and water areas in photographs taken through wide-bandpass color filters from outside the atmosphere. These photographs confirmed that the spectral sensitivity of a television camera system for daylight use on a meteorological satellite should be restricted to the 5000-7200 Angstrom interval.

Figure 21—TIROS 9 Photograph of a Double Vortex Over the North Atlantic Ocean (Orbit 0101, January 30, 1965)

The Gemini 4 flight carried a hand-held modified 70-mm Hasselblad Model 500C camera, using Eastmancolor film ASA 64. A haze filter was fitted to the standard 80-mm f/2.8 lens to reduce the intensity of the blue light scattered back from the atmosphere. The field-of-view of the camera was 35 degrees.

Just before their flight the astronauts were briefed on interesting meteorological features to watch for. Figure 23 is a dramatic photo taken by the astronauts at a lens setting of one 250th of a second at f/11 during the June 3-7 orbital mission. Cumulus clouds are evident over an ocean near sunset; the specific area is not identified. Note the portion of the spacecraft appearing at the bottom of the photo. Perhaps of greater meteorological interest is Figure 24, a photo taken at a lens setting of one 250th of a second at f/11. Clearly visible are the convective cells in cloud structure taken over an ocean. As in the previous photo, the exact location is not given.

Of the pictures taken by the astronauts, approximately 100 showed clouds or contained information of meteorological interest. Some of the photographs had a resolution of 60 to 80 feet. The Gemini 4 cloud photos, which have been described in some detail by Nagler and Stanley (1965), are now being analyzed and compared with TIROS pictures which were taken during the same period of time.

Figure 22—Gemini and Mercury Manned Satellites, Artist's Conception

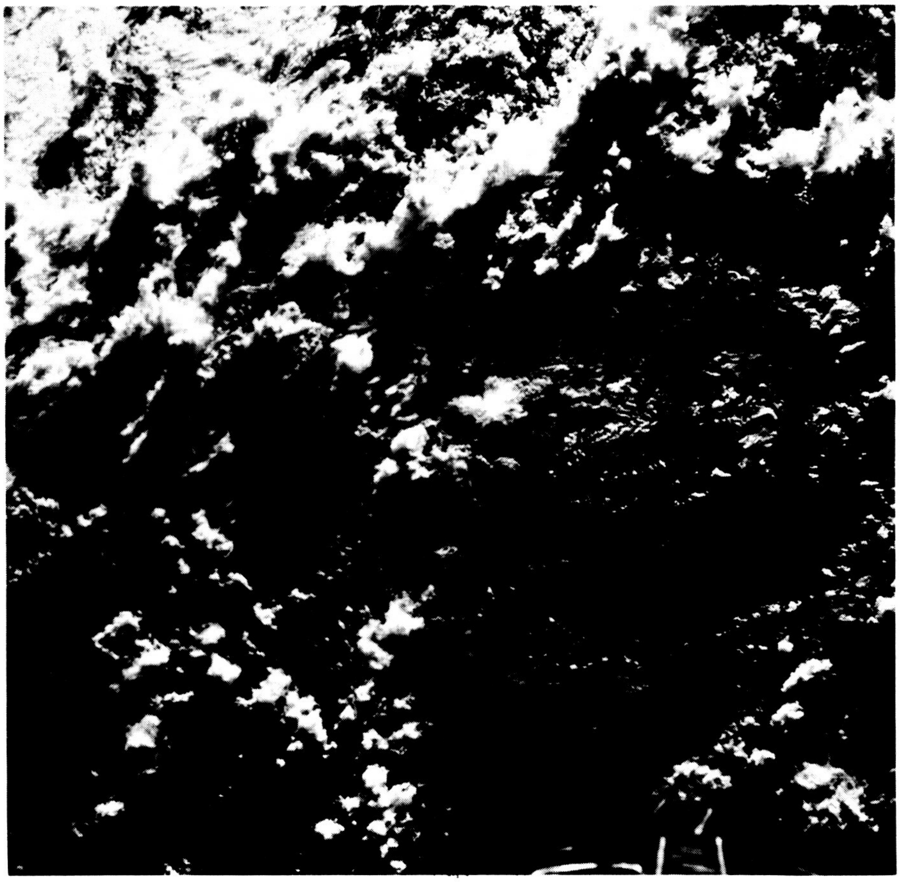


Figure 23–Gemini 4 Photograph of Cumulus Clouds Over an Ocean at Sunset, June 3-7, 1965

CURRENT PROGRAMS

TIROS Operational Satellite (TOS)

The great increase in meteorological information obtained from the TIROS and Nimbus research programs led the U. S. Weather Bureau, with the cooperation of NASA, to embark on an operational satellite program which could meet the meteorologist's need for regular and continuous data from the entire globe on a daily basis. This program is the TIROS Operational Satellite (TOS) system.

The TOS system is intended to provide cloudcover pictures of the entire sunlit portion of the earth, with a zenith angle at point of contiguity between orbits not to exceed 65 degrees, and linear resolution at contiguity not to exceed 4 to 5 nautical miles. The dual satellite system will provide both direct readout (APT) to local

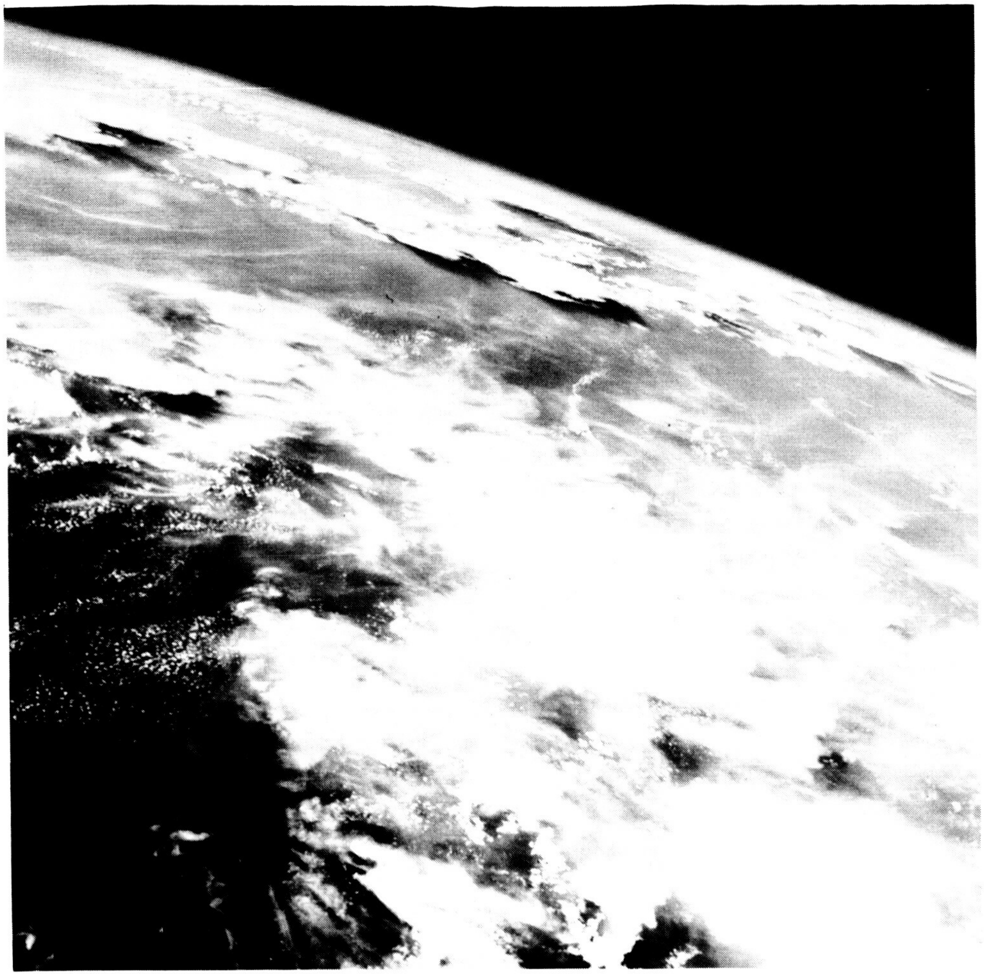


Figure 24—Gemini 4 Photograph of Convective Cells in Cloud Structure Over an Ocean, June 3-7, 1965

stations, and on-board storage of the data for delayed readout at the command and data acquisition (CDA) stations, the delay to be no more than 2 orbital periods. The ground system will then relay the data to a central location, the National Weather Satellite Center (NWSC), for global analysis, forecasting, and distribution.

To meet these requirements, TOS will use two operational spacecraft, similar in many respects to the TIROS 9 "wheel", in a circular 750-nautical-mile sun-synchronous polar orbit beginning early in 1966 (Figure 25). The first TOS spacecraft, weighing about 290 pounds, will carry two automatic picture-transmission (APT) cameras and will be launched into a 9 a.m. (descending node) orbit. The second spacecraft, weighing about 316 pounds, will carry two AVCS cameras and tape recorders and will be launched into a 3 p.m. (ascending node) orbit.

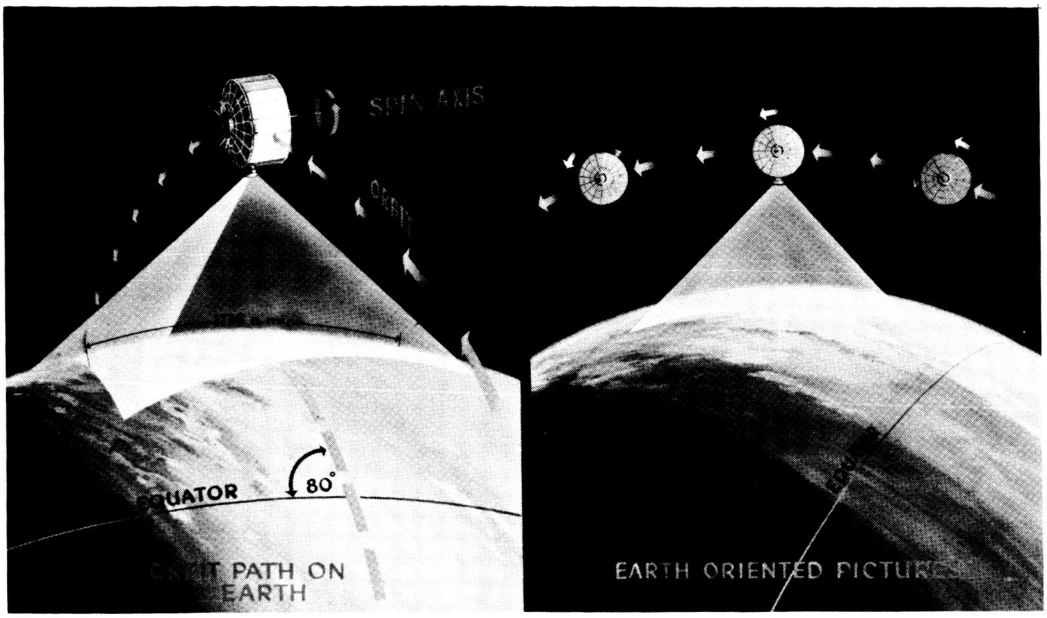


Figure 25–TIROS Operational Satellite (TOS)

The second TOS spacecraft will also carry a system to obtain data on the earth's infrared heat budget system. This system, consisting of a set of sensors for measuring direct and reflected solar energy, an electronic control subsystem, and a digital tape recorder, will continuously scan the earth and sky and record the digitized data on tape for subsequent readout at the CDA station.

The heat sensors are two sets of flat-plate sensors, suspended beneath the edge of the baseplate on opposite sides of the spacecraft and connected in parallel to provide nearly omnidirectional coverage. Two of these sensors respond to energy in both the visible and the infrared spectra: the first, which is nearly omnidirectional, receives energy continuously from both the sun and the earth's albedo. The second, which is shielded from the sun, receives energy only from the albedo. The other two sensors are similar except that they respond to infrared energy only, excluding the visible. Data from these sensors will help to determine the geographic and spectral distribution of energy radiated from the earth and its relationship to energy received from the sun.

Follow-on spacecraft will be alternately APT and AVCS (Figure 26). Eventually we plan to combine these two functions in one spacecraft, and to add nighttime coverage when the high-resolution infrared radiometer (HRIR) has been proven on a spin-stabilized spacecraft.

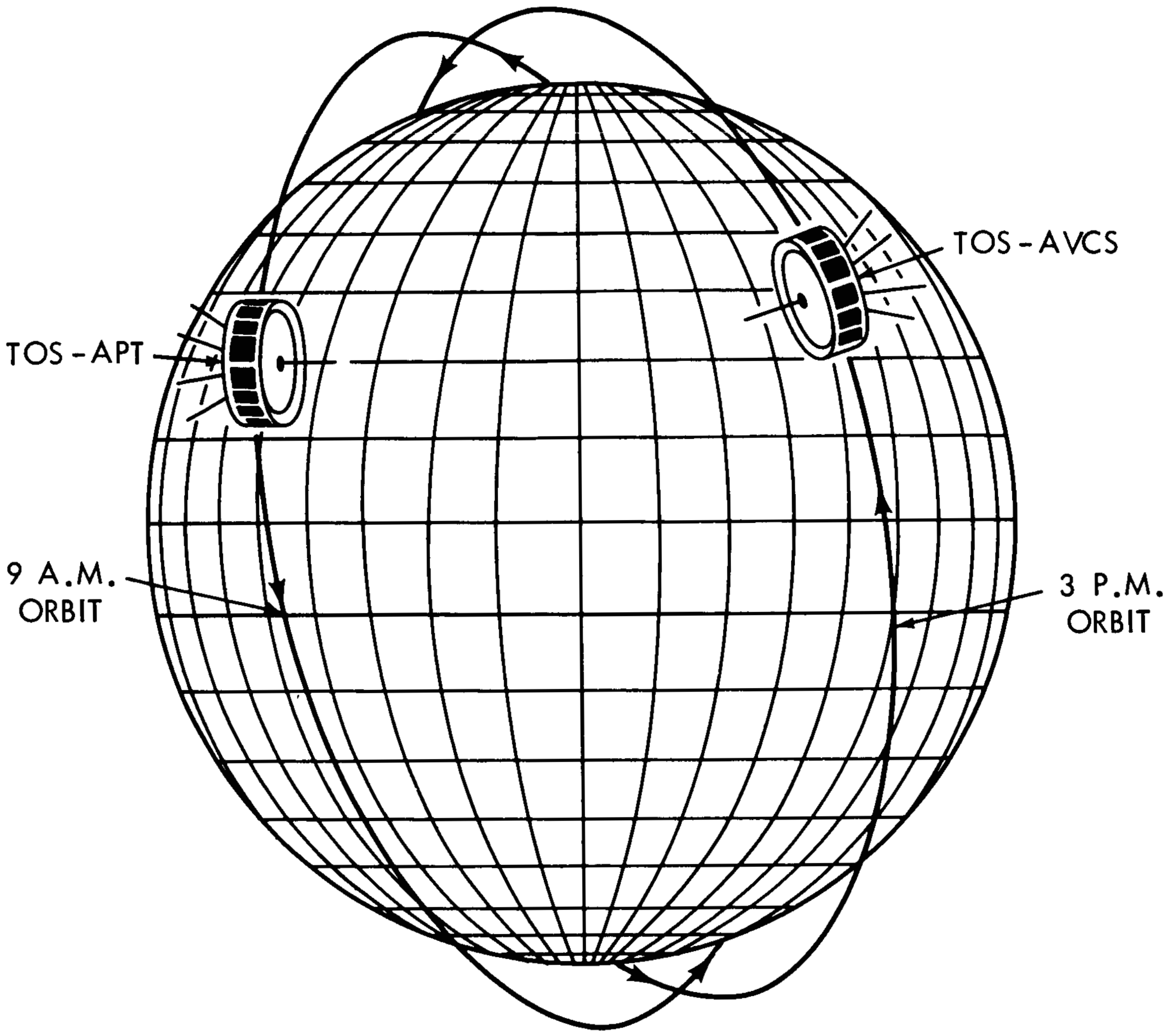


Figure 26–TOS APT-AVCS System

CDA stations at Fairbanks, Alaska, and Wallops Island, Virginia, will command the spacecraft and acquire the meteorological and spacecraft data. Using these two stations with the spacecraft's capability for on-board storage of at least two orbits of AVCS data will give us complete global coverage each day with minimum delay in obtaining the data. All spacecraft data, both meteorological and spacecraft housekeeping, will be sent to the NWSC by wideband (48-kc) land lines for analysis and dissemination to the meteorological community (Figure 27).

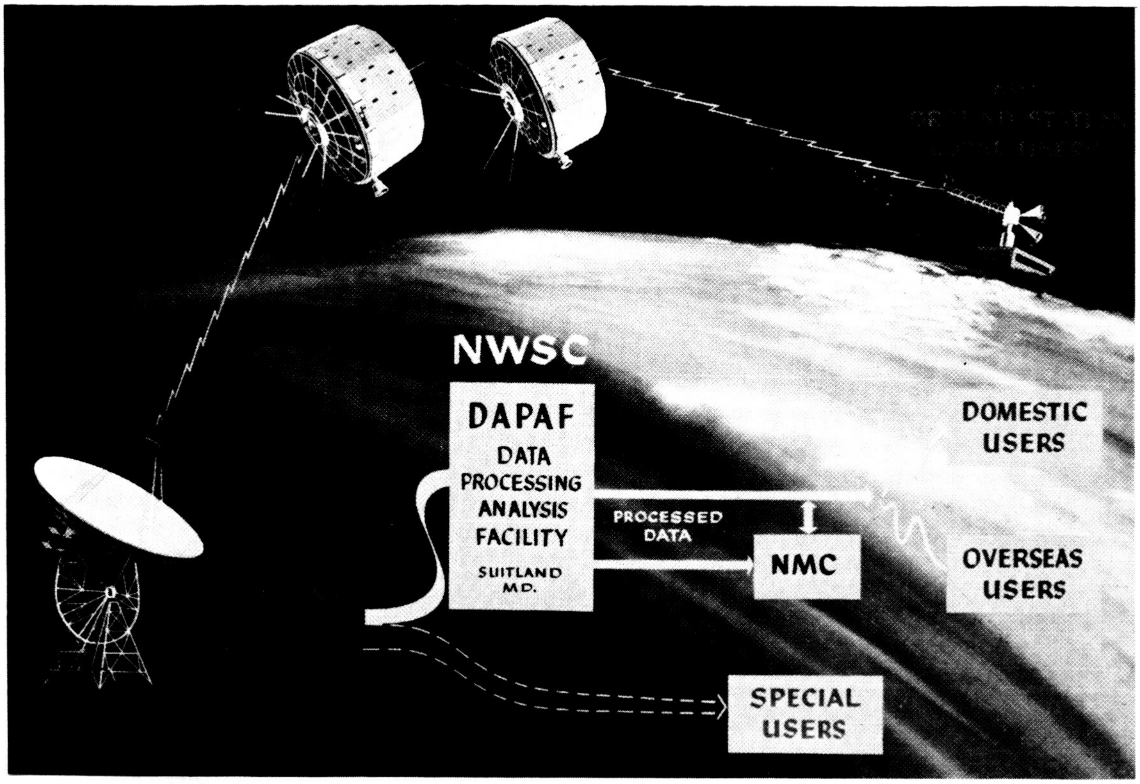


Figure 27—TOS System Data Flow

TIROS J

When the high-resolution infrared radiometer (HRIR) on Nimbus 1 proved successful, we decided to try this instrument on a spin-stabilized spacecraft of the TIROS class. Our idea was to determine whether such a system could provide us with cloudcover and cloudtop measurements over the entire nighttime portion of the earth which were urgently needed on a regular and continuing basis. A secondary requirement was for direct readout of the data to local stations, using techniques similar to the automatic picture-transmission (APT) system.

The most practical solution to the problem was to use the TIROS spacecraft in the wheel mode demonstrated by TIROS 9, and to mount the IR instrument so that its optical axis is radial to the spin axis. The axis of the scanning mirror is positioned at right angles to both the spin axis and the optical axis, and the rotation rate of the mirror is synchronized with the spin of the satellite. Figure 28 is an artist's conception of the system in orbit, and Figure 29 shows how the instrument functions in the spacecraft. If the mirror-rotation rate and spacecraft-rotation rate are the same, and are properly synchronized, the scan path will approximate a straight 45 degree line running through the subsatellite point. The actual trace is somewhat S-shaped, as shown in Figure 28.

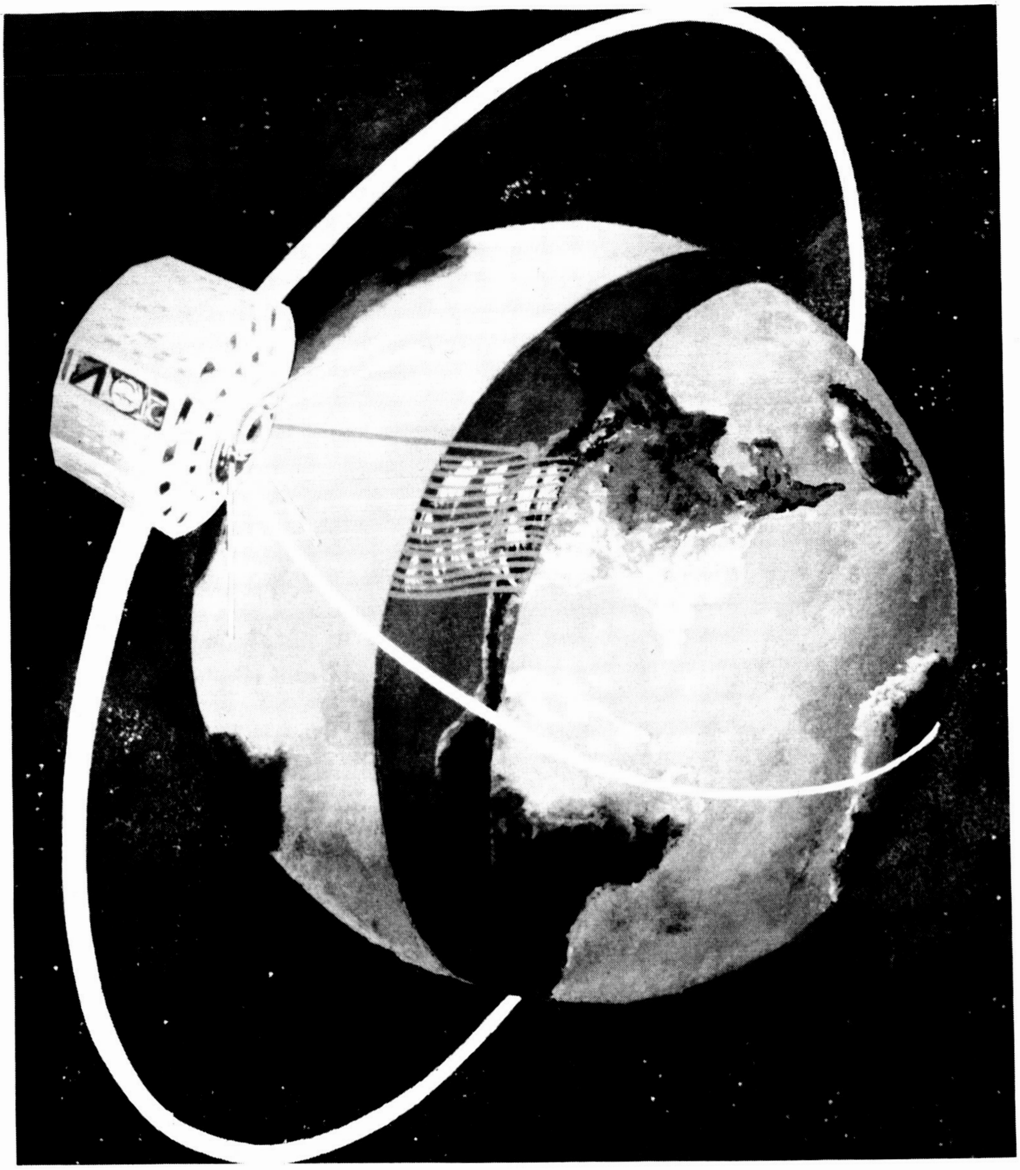


Figure 28–TIROS J HRIR Coverage

Synchronization is established by using two index pulses, one generated by a horizon scanner as it scans through the sky-to-earth transition, and one generated by a magnetic pickoff on the mirror shaft when the optical axis is vertical. These two pulses are fed into a circuit which measures the time difference between the two and generates a single pulse; the output pulsewidth is proportional to the time difference, and the phase (plus or minus) varies according to which input pulse occurred first. The output pulse is then used to adjust the frequency and phase of the voltage applied to the scan-mirror drive motor until the time difference between the horizon pulses and the corresponding scan-mirror pulses is effectively zero.

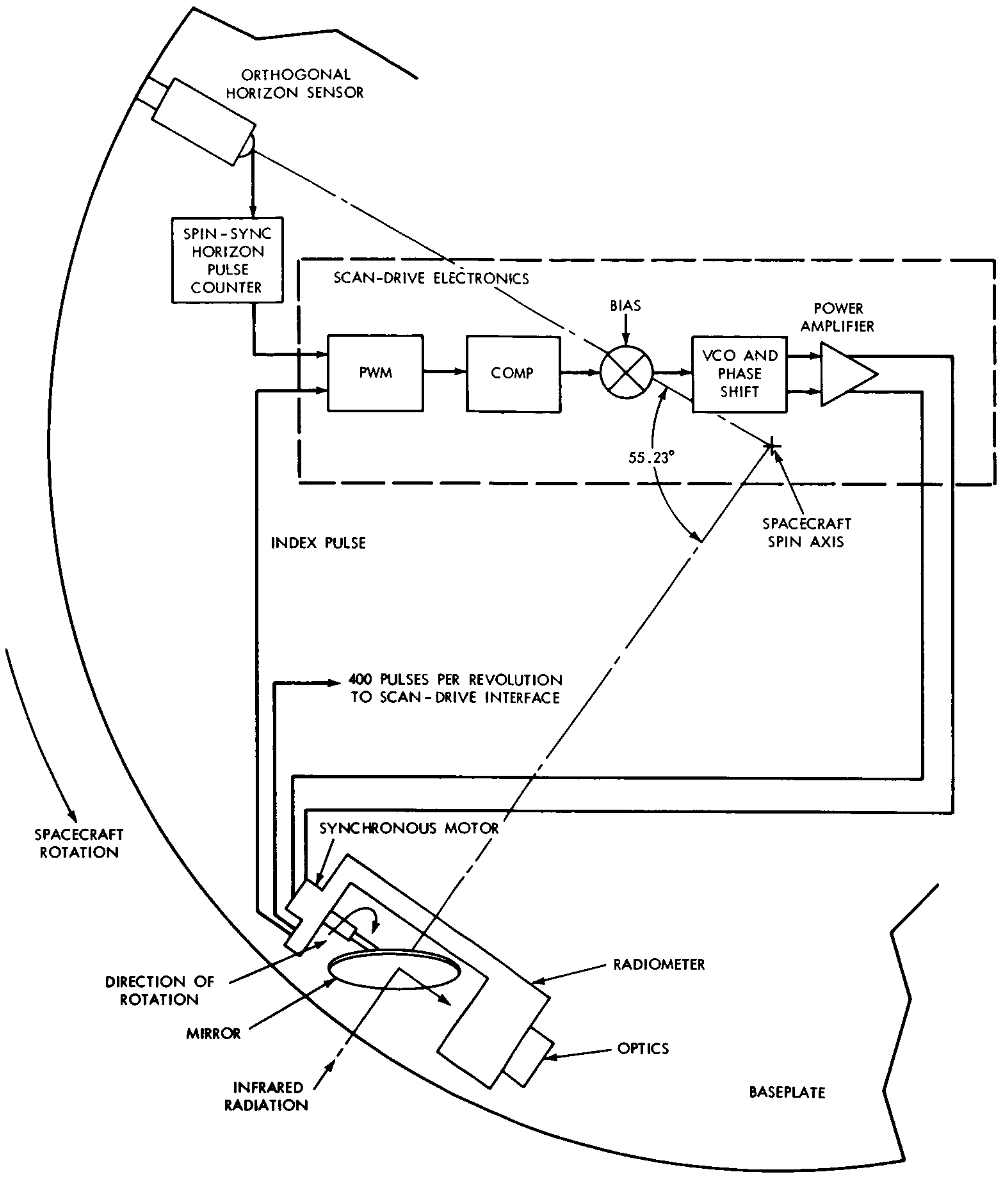


Figure 29—TIROS J HRIR Scan-Mirror Drive System, Functional Diagram

Table 3 lists the characteristics of the instrument as it was carried on Nimbus 1; however, some minor changes are proposed for the new application. A scan rate of 30 rpm will provide an overlap of about 50 percent at the subsatellite point at the orbit altitude of 750 nautical miles. This altitude was selected to keep the zenith angle at the equator at the point of contiguity between orbits, to less than 65 degrees. The orbit will be near-polar and sun-synchronous (approximately 81 degrees retrograde).

Table 3
Nimbus HRIR Radiometer Characteristics

Optics:	4 inch f/1 Cassegranian telescope spectral response 3.4 to 4.2 microns, field-of-view 8.6mr × 8.6mr.
Detector:	Evaporated lead selenide Area 3/4mm × 3/4mm Cell temperature -76°C Time constant less than 700 microsec.
Scan Mirror:	Flat ellipse 5.688" × 4.032" Mounted 45° to axis of rotation Rotation rate 44.715 rpm
Electronics:	Bandwidth 0-280 cps Chopper frequency 1500 cps
Total Power:	4 watts; weight 11-3 lbs.

Another change is the synchronizing and phasing signals that have been added to the transmitted carrier so that the information can be received by stations anywhere in the world. In other words, the data will be transmitted from the satellite in real time on a line-by-line basis as acquired by the radiometer. Thus, any interested user equipped with nominal receiving and reproducing equipment can receive the signal (expected to be at 136.95 Mc) and can reproduce the data in his own area of interest. Figure 30 shows the components of a typical APT ground station.

The 45 degree S-shaped scan line produced by the TIROS HRIR will create some problems for the local user who has the electromechanical facsimile reproducers designed for APT photographs. Without modification, the facsimile machines will skew the data by 45 degrees as they scan linearly at right angles to the motion of the paper. Figure 31 is an example of the distorted image and the grid overlay which must be used to correct the distortion.

A solution which eliminates the distortion and provides a superior result uses a cathode-ray oscilloscope, combined with a camera and a rapid film processor, to correct the distortion by reconstructing the 45 degree S-curve on the face of the tube and moving either the film or the trace vertically between scans. Figure 32 shows how the scan curve can be approximated by three straight lines in both directions from the subsatellite point represented by zero on the graph.

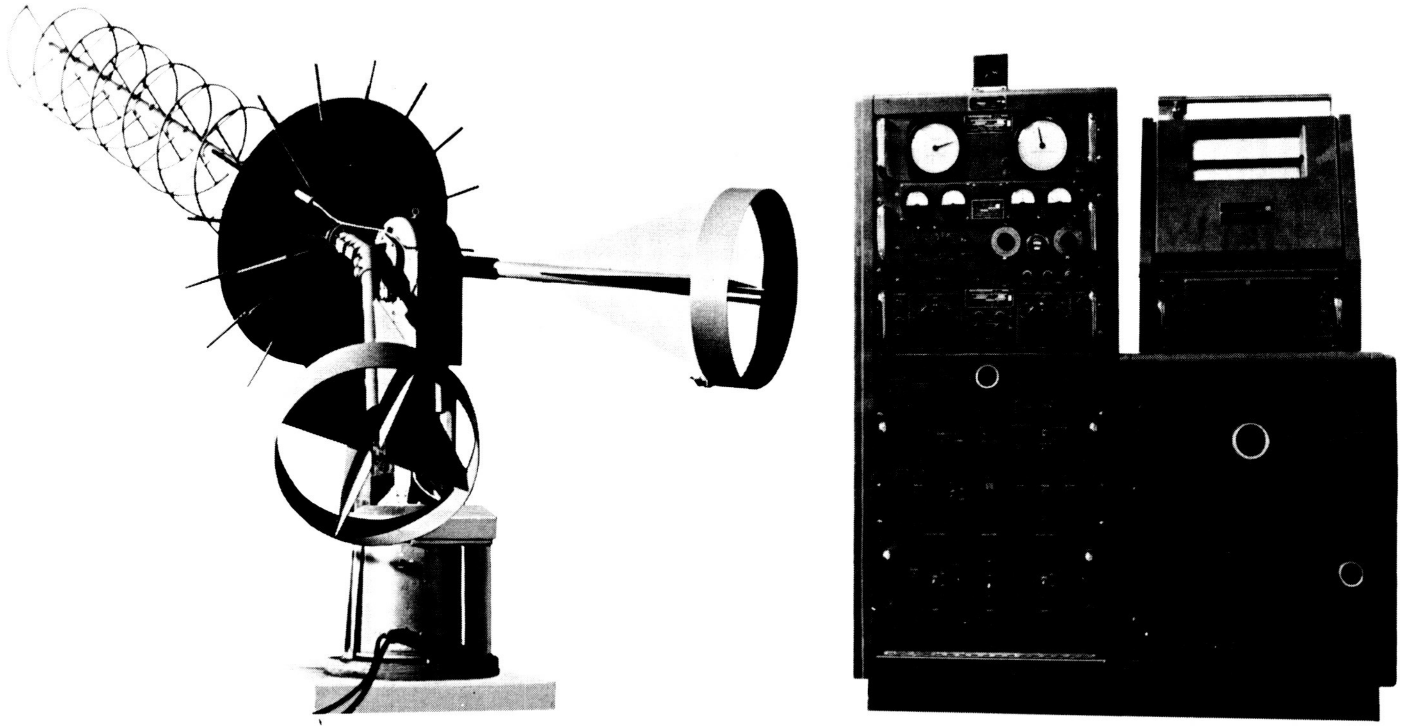


Figure 30–APT Ground Station Components

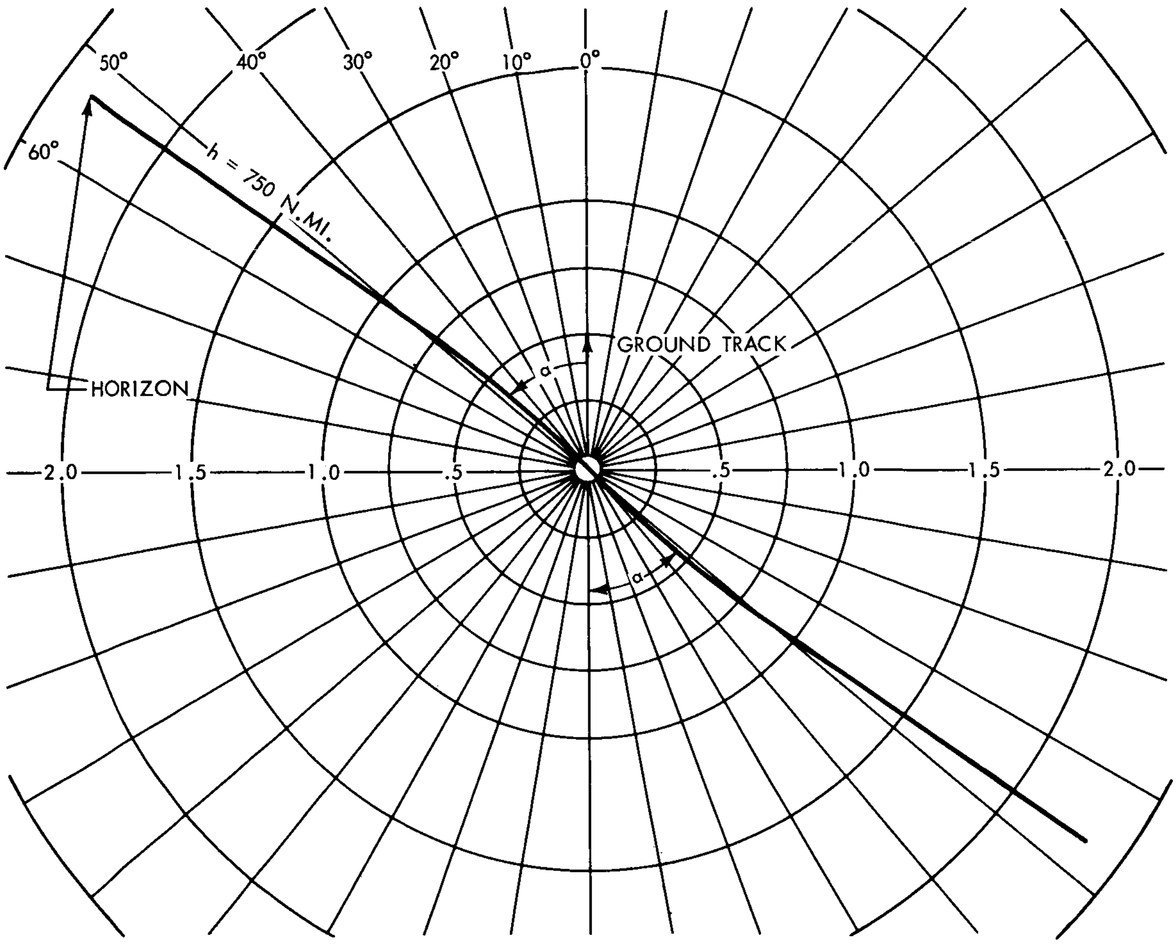


Figure 31—Nimbus HRIR Earth-Scan Path on TIROS Cartwheel Circular Orbit (Scan Mirror Synchronized With Spacecraft)

Although the HRIR was designed essentially as a nighttime instrument, it produced some remarkable results during daylight tests on Nimbus 1. Figure 33 is the result of one of these tests at high noon over Central America, and shows Hurricane Dora located north of Cuba. Comparison with the nighttime picture (Figure 18) shows that the daytime contrast between the clouds and the land is very low. This is because the reflected energy from the clouds combines with their emitted energy, and the result is approximately equal to the energy emitted from the land. The reflection of the sun can be clearly seen over the water in the center of the picture.

To improve the daytime performance of the HRIR, a narrow passband at about 0.5 micron will be put into the optical filter of the instrument to increase the response in the visible part of the spectrum with minimum effect in the 3.4- to 4.2-micron region. A day-night switch programmed by ground control will be added for

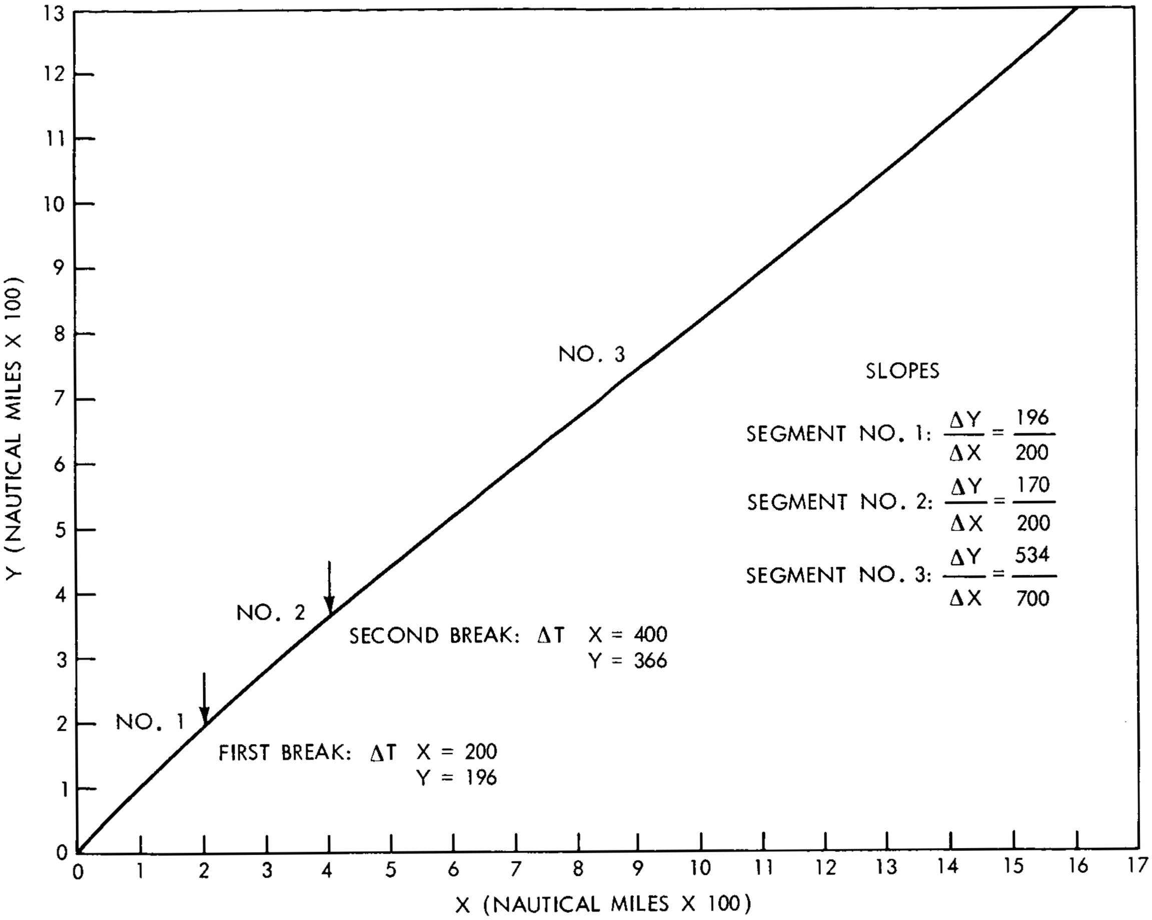


Figure 32–HRIR Scan Curve Approximated by Three Straight Lines

changing the gain of the electronics accordingly. It may be possible to add a neutral-density filter to the visible band of the filter in order to equalize the output with that of the window band and eliminate the need for day-night switching. Although these modifications are expected to improve the daytime cloudcover photographs, we are still unable to provide a calibration for measuring cloudtop temperatures in daylight, so neatly illustrated by the analog trace of Figure 19.

A separate effort is underway to develop a sensor in the 10- to 11-micron range which can measure temperatures both day and night.

Figure 33–Nimbus 1 HRIR Daytime Photo

NIMBUS FOLLOW-ON PROGRAM

The Nimbus program has the primary objective of developing a meteorological satellite system which can meet the research and development needs of atmospheric science and weather service. Nimbus 1 was launched in August 1964. Nimbus C, the back-up for the first mission, is scheduled for launch early in 1966. The third of the series is Nimbus B, scheduled for launch in the latter part of 1967.

Nimbus C

Besides the AVCS, APT and HRIR systems flown on Nimbus 1, Nimbus C (Figure 34) will carry a medium-resolution infrared radiometer (MRIR) experiment.

Medium-Resolution Infrared Radiometer (MRIR)

The MRIR experiment (Figure 35) is similar in many ways to the five-channel radiometer flown on TIROS 2, 4, and 7. It will measure the intensity and distribution of emitted infrared and reflected solar radiation of the earth and atmosphere in five selected spectral intervals.

The MRIR uses a scanning-mirror optic system with detectors at the focal point and mechanical lightbeam choppers. Each detector produces a signal in the spectral band to which it is sensitive. The instantaneous field-of-view is 2.85 degrees, corresponding to about 30 miles on the surface of the earth from the nominal orbit altitude of 600 nautical miles. It scans at 8 cps. For global coverage, the data will be recorded continuously night and day for playback at the CDA stations.

The five spectral intervals and their specific functions are:

- Water vapor band – 6.5 to 7.0 microns – provides information on atmospheric structure and water vapor distribution

- Atmospheric window – 10 to 11 microns – measures the temperature of the earth in a band where the atmosphere is essentially transparent. In addition, MRIR maps showing isolines of radiant emittance can be interpreted like cloudcover maps (such as those prepared from the 8 - 12-micron TIROS data) to provide low-resolution backup to the AVCS and HRIR observations.

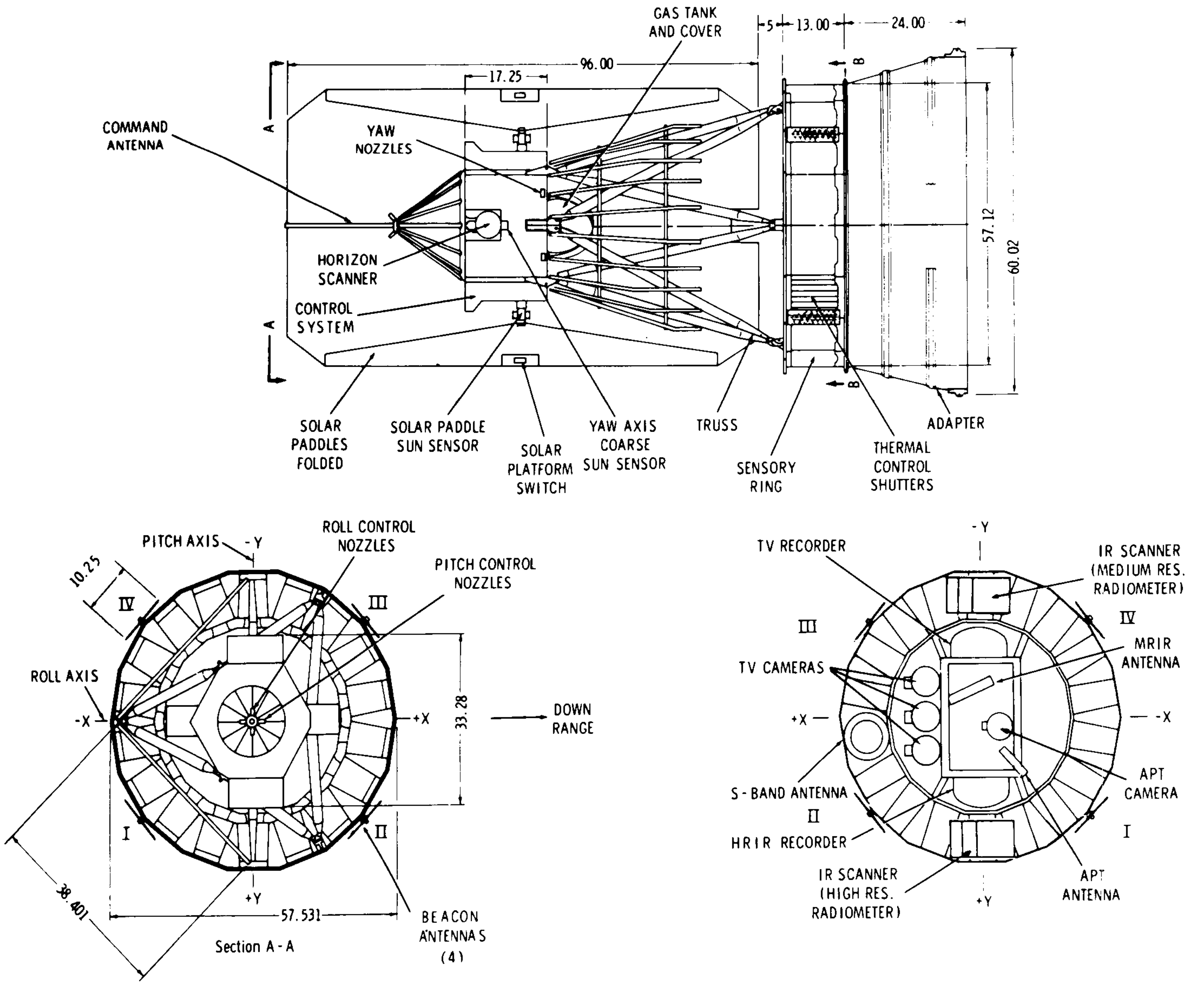


Figure 34–Nimbus C Spacecraft, General Arrangement

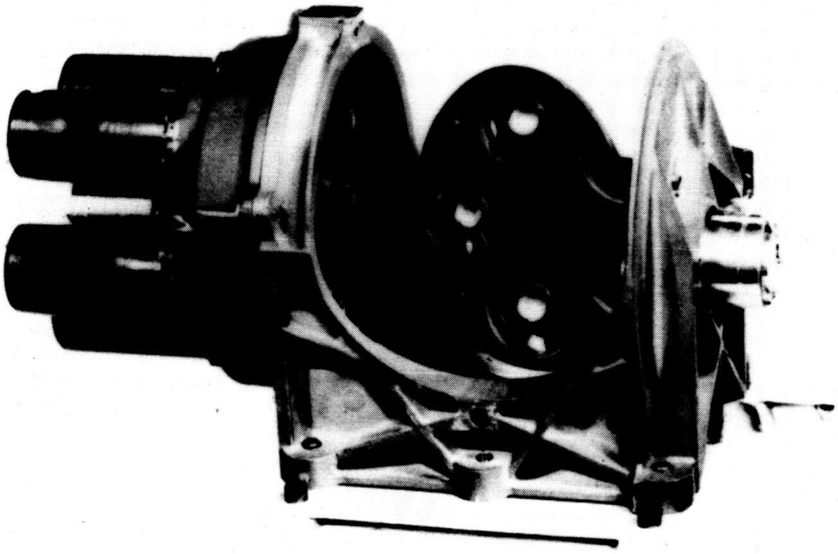


Figure 35–Medium-Resolution Infrared Radiometer (MRIR)

- Stratospheric temperatures – 14 to 16 microns – measures the emission from the CO_2 absorption band.

- Terrestrial radiation – 7 to 30 microns – measures the earth's total longwave infrared emission.

- Albedo – 0.2 to 4 microns – measures the energy reflected from the earth in the near-infrared region.

By using the sun-synchronous orbit and stabilized sensors, we should obtain much more information on the heat budget of the earth from MRIR channels four and five than we obtained with the TIROS radiometers.

Another major change from Nimbus 1 in the sensor systems concerns the HRIR data. Nimbus C will be equipped to transmit HRIR data directly to local users. In this experiment, the HRIR video and the necessary synchronizing signals will be fed into the APT transmitter at night or at any other time when the APT camera is not in use, for reception by APT ground stations. Because of differences in the scanning rates of the APT camera (240 rpm) and the Nimbus HRIR (48 rpm), changes will be required in the ground reproduction equipment. Further information on this experiment will be disseminated before Nimbus C is launched.

Nimbus B

In addition to the MRIR and HRIR, Nimbus B (Figure 36) will carry several new experiments for quantitative measurement of the atmosphere structure.

Infrared Interferometer Spectrometer (IRIS)

The IRIS experiment (Figure 37) is a Michelson-type interferometer designed for use on a stabilized spacecraft of the Nimbus class. It will measure the earth's spectral radiances in the 5- to 20-micron region with a spectral resolution equivalent to 5 reciprocal centimeters. The purpose of IRIS is to measure the parameters such as temperature, humidity, and cloud height which describe the vertical structure of the atmosphere. The interferometer will scan the earth's atmosphere with a nominal field-of-view of 1.57×10^{-2} steradians at discrete positions along the path of the satellite. The instrument will take approximately 11 seconds to scan through the interval and to record the interferogram function.

Satellite Infrared Spectrometer (SIRS)

The SIRS experiment is a Fastie-Ebert grating spectrometer, also designed for use on a stabilized spacecraft of the Nimbus class. It will measure the earth's spectral radiances in the carbon dioxide absorption band for use in calculating the temperature structure of the atmosphere. In this particular instrument, the grating angle is fixed. Exit slits with separate detectors are positioned above the grating to measure (a) the energy in seven spectral channels centered about the 15-micron wavelength, (b) a separate channel in the 11- to 14.5-micron region to aid in the case where partial clouds exist in the field-of-view, and (c) a ninth channel which measures an internal blackbody reference for in-orbit calibration.

Solar Ultraviolet (SUV) Experiment

The SUV experiment will monitor the ultraviolet solar flux at several different wavelengths to provide data on the formation of the ionosphere, the establishment of photochemical equilibrium, and the heating of the upper regions of the stratosphere. The measuring will be done by five photodiodes having peak sensitivities at 1500 Å, 1800 Å, 2100 Å, and 1216 Å. The angle of the solar flux incident on the photodiode surfaces will be measured simultaneously by a digital solar-aspect indicator which measures the aspect angle of the sun using a 64-degree field-of-view with an accuracy of ±0.5 degree.

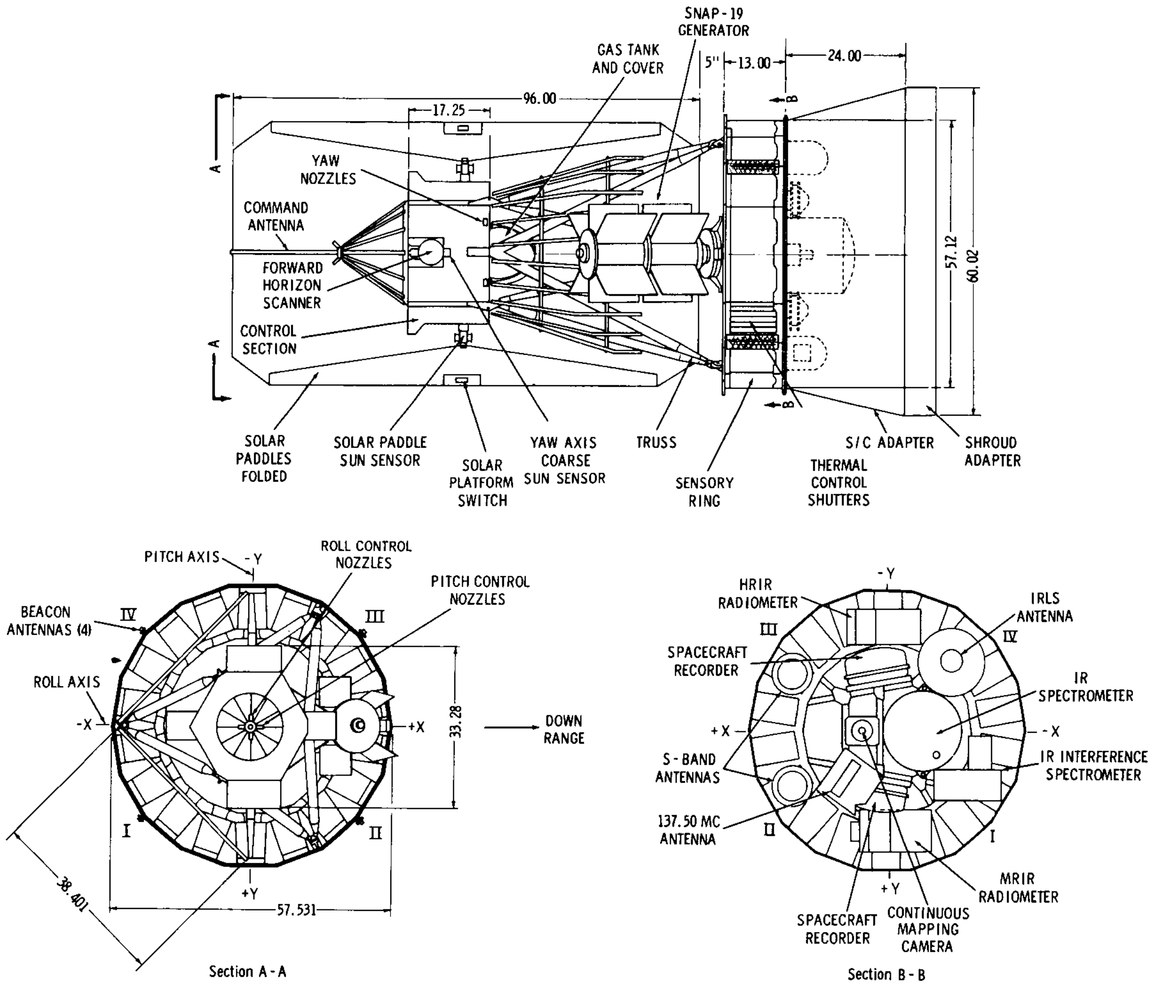
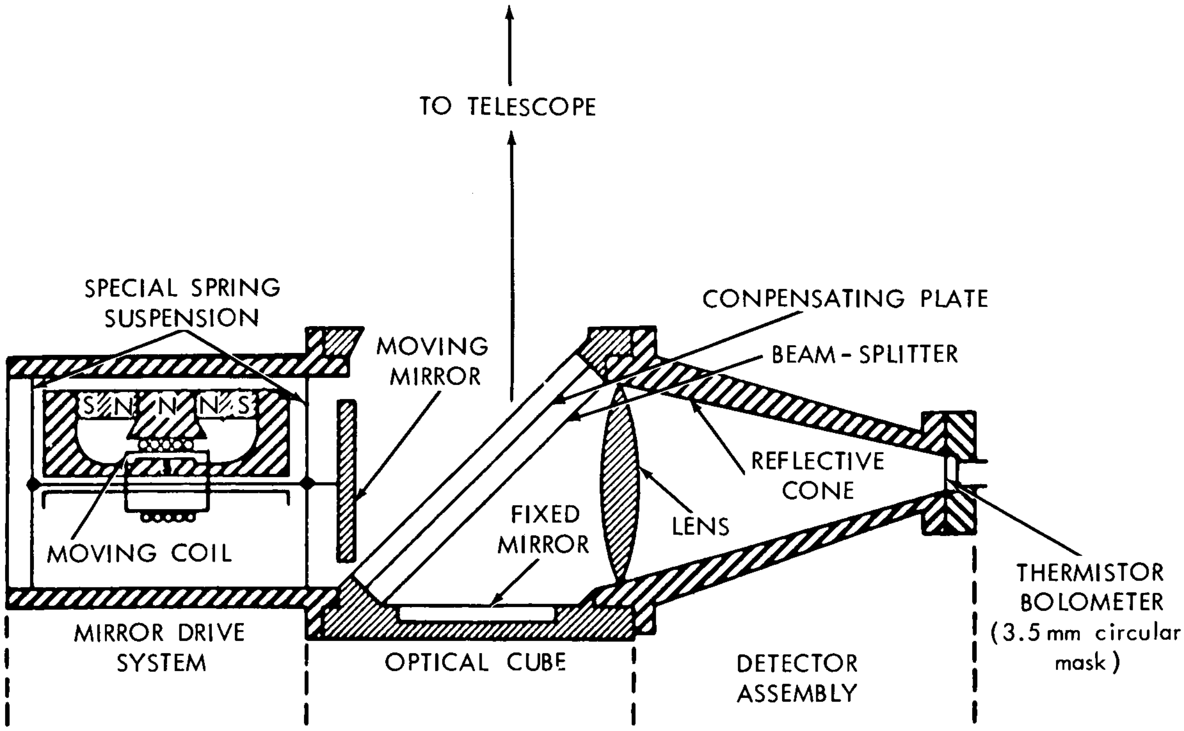


Figure 36–Nimbus B Spacecraft, General Arrangement



Neon Light Source and Auxiliary Detector for 5852 Å Reference Line Not Shown

Figure 37–Interferometer Cube, Mirror Drive Assembly, and Detector Assembly, Schematic Diagram

Interrogation, Recording, and Location System (IRLS)

The IRLS experiment (Figure 38), described by Cressy and Hogan (1964), will perform three basic functions.

The first function, interrogation, allows the satellite to communicate with any specific surface station. An interrogation sequence is read into the satellite at a CDA station. Each of the remote platforms, such as balloons, buoys, and automatic land stations, is assigned a specific "signature" or address consisting of a digitally coded number containing sixteen bits. The interrogation command is stored in the satellite in two parts: the exact time for interrogation, and the specific remote-platform address. When the remote platform receives its unique address, it responds to the satellite by retransmitting this address. When the satellite receives this address from the surface platform, it prepares the satellite storage system to receive the surface platform data.

In the recording function, the satellite receives the digital data from the surface platform and records them on tape for subsequent readout to the ground station. The average storage capability of 1000 bits of data from each platform interrogated is entirely adequate to record the meteorological parameters which the platform will measure, such as temperature, humidity, and pressure.

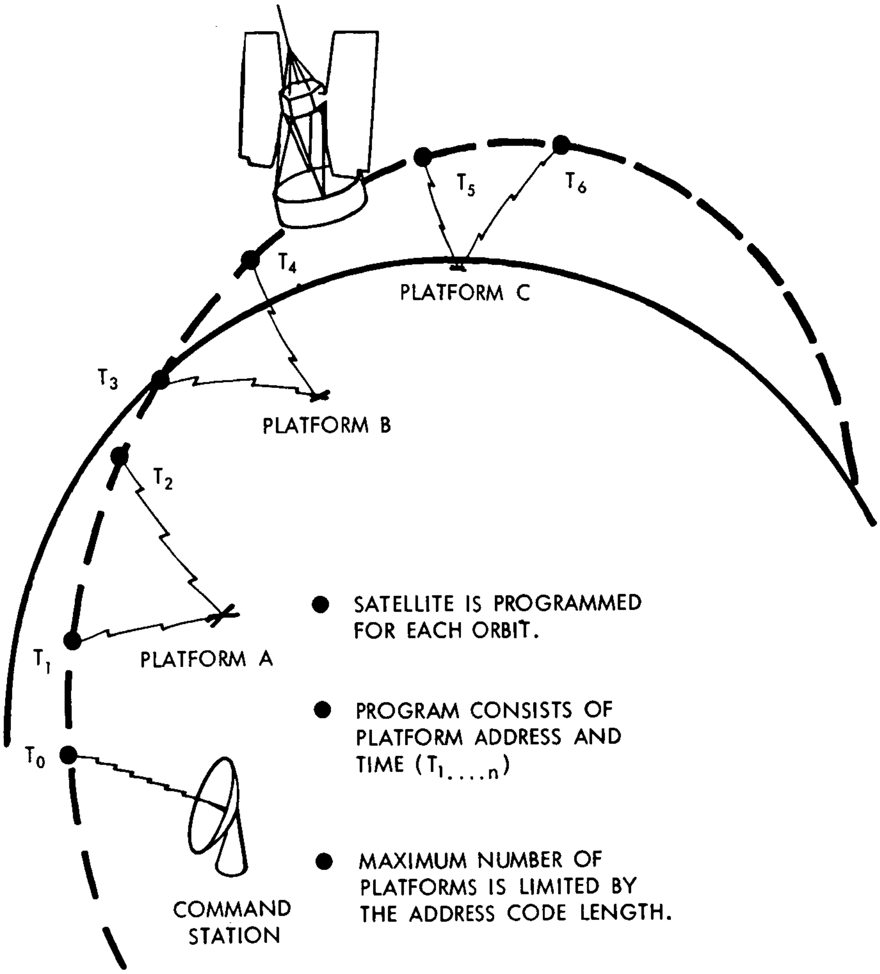


Figure 38—Interrogation, Recording, and Location System (IRLS) Operation

Location, the last and most significant function of the IRLS experiment, provides a means for locating any surface station interrogated to an accuracy of ±2.0 km with 0.95 probability.

The station is located by programming the satellite to interrogate a specific space platform at two different positions along its orbit. The ephemeris data of the satellite thereupon locates two points in a plane triangle. The surface platform, which remains relatively stationary during the time between satellite interrogations, forms the third point of the plane triangle.

The distances between the satellite and the ground station for the two interrogations are determined by measuring the round-trip propagation time of the interrogating signals to determine the position of the surface platform. The fact that the platform could lie on either side of the satellite orbital track is an ambiguity that can normally be resolved in two successive orbits.

Omega Position-Location Experiment (OPLE)

The OPLE is an interesting and quite promising experiment which can be carried out by using the data channel of the IRLS just described. The surface platform position would be determined by the U. S. Navy's ground-based Omega navigation system. This system, when completed, will provide world-wide position fixing with an accuracy of 1 mile by phase comparison of VLF (10-14 kc) continuous-wave radio signals from strategically located ground-based transmitting stations.

If the OPLE experiment is successful, it will enable an earth-synchronous satellite to locate the position and pick up meteorological data on a real-time basis from constant-level balloons, buoys, and automatic land stations.

Continuous Mapping Camera System (CMCS)

The CMCS (Figure 39) is a new camera experiment designed to provide a continuous daylight picture of the earth's cloudcover. The CMCS will use an image-dissector tube (Figure 40) and line-scan techniques in which the camera provides horizontal deflection at 4 scans per second, and the motion of the spacecraft along the orbit path, the vertical displacement. The picture will appear similar to the APT pictures and will be compatible with the APT ground stations. The system will photograph and transmit a continuous daylight picture 800 miles wide with a resolution of 760 TV lines. The camera employs no moving parts or thermionic cathode, and therefore has an expected lifetime of from 1 to 3 years.

APPLICATIONS TECHNOLOGY SATELLITE (ATS) PROGRAM

Medium-Altitude Gravity-Gradient Experiment (MAGGE)

The MAGGE mission (Figure 41) will be flown on ATS-A, a gravity-gradient stabilized satellite in a 6000-nautical-mile orbit with three-axis orientation and an uncluttered downward view. It will carry a meteorological TV camera system designed to:

- Obtain pictures of the full earth disc with approximately 6-nautical-mile TV line resolution
- Obtain high-resolution pictures within the field-of-view of the full earth pictures
- Determine how the TV camera and tape recorder system perturb the stabilization of the spacecraft

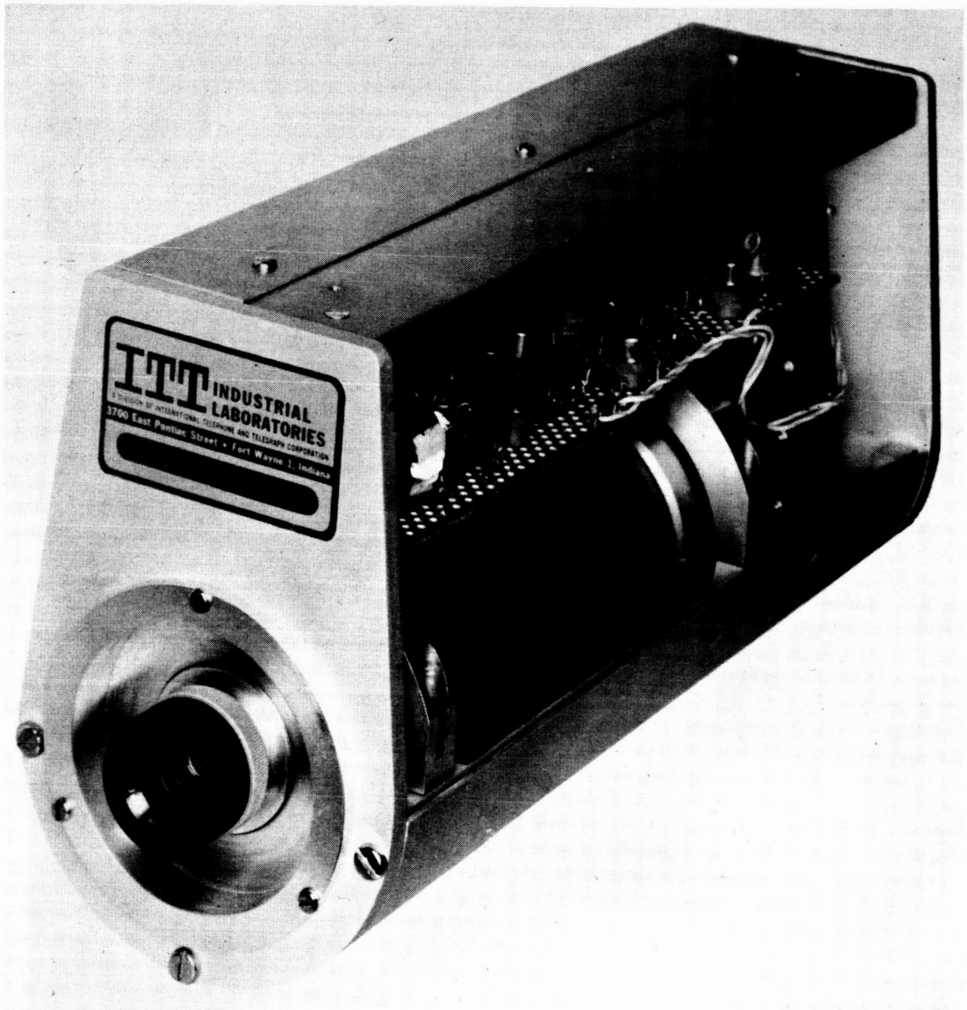


Figure 39–Continuous Mapping Camera System (CMCS)

- Evaluate the effect of gravity-gradient stabilization on the pointing accuracy of the cameras

- Evaluate the effects of the spacecraft attitude-perturbation rates on the allowable shutter speed and image smear

The TV camera system on this satellite will consist of a Nimbus tape recorder and two advanced vidicon camera systems.

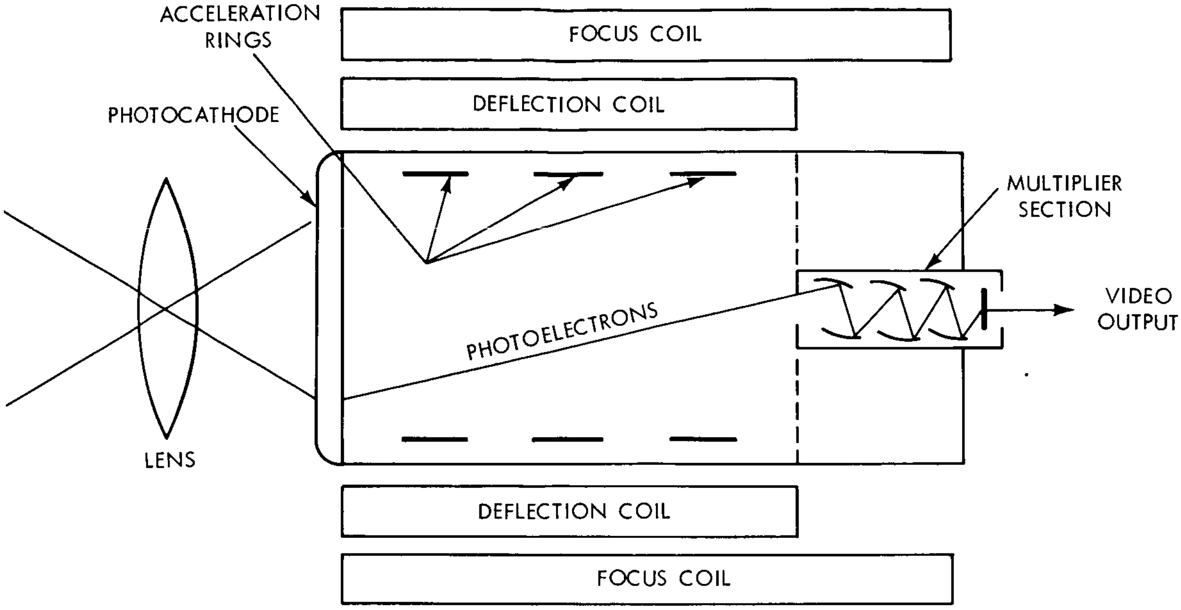


Figure 40—Image-Dissector Tube, Schematic Diagram

- A single-camera AVCS with an f/1.5 - 12.5-mm focal length lens for full disc coverage of the earth will monitor the gross cloudcover and circulation systems of the earth with a resolution of approximately 6 nautical miles per TV line.

- A single-camera AVCS with an f/4 - 200-mm focal length lens that can produce high-resolution TV pictures with a 4.5 degree field-of-view will observe smaller portions of weather systems with a resolution of approximately four-tenths of a nautical mile per TV line.

Each camera housing will contain a lens with an iris that can be commanded to 3 preset positions.

Circuitry in the camera electronics module will amplify the video data from the camera preamplifier, insert the appropriate sync pulses, and set the black-and-white video level. The resultant analog composite video signal will either be available for recording on a tape transport for subsequent remote transmission to a ground station, or will be fed to an FM modulator for direct transmission to a ground station.

Table 4 lists the characteristics of these camera systems, and Table 5 lists the performance specifications.

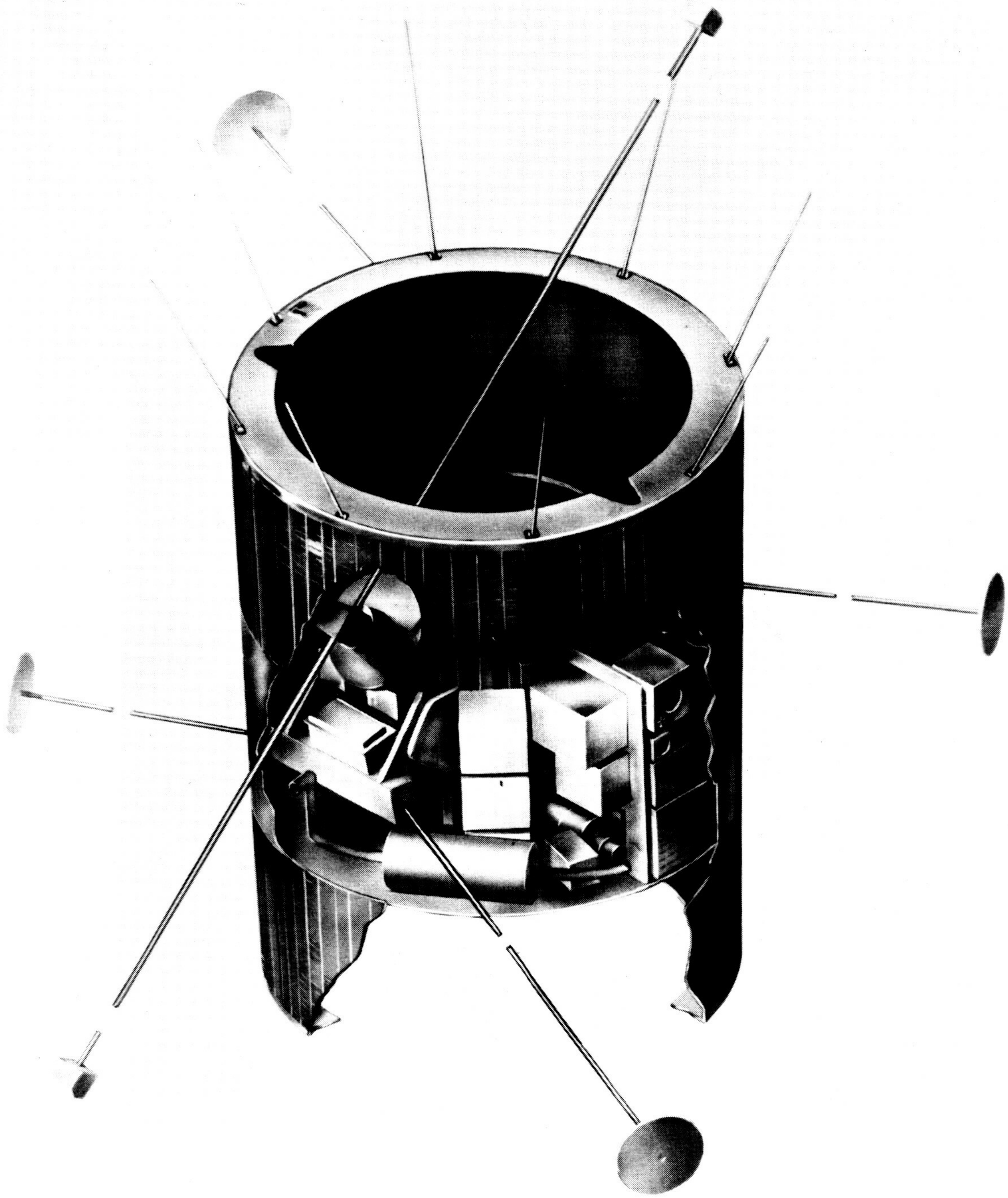


Figure 41—Medium-Altitude Gravity-Gradient Experiment (MAGGE)

Table 4
General Characteristics of MAGGE Cameras

No. of cameras	2
Camera 1	
Lens	12.5-mm TT and H Vidital, f/1.5
Field-of-view	66 degrees
Ground resolution	Approximately 6 nautical miles
Shutter	Double blade, focal plane 40 milliseconds exposure
Camera 2	
Lens	200-mm Kinoptic (Cine), f/4
Field-of-view	4.5 degrees
Ground resolution	Approximately 0.4 nautical mile
Shutter	Double blade, focal plane 40 milliseconds exposure
Picture repetition rate	1 picture each 5 minutes starting on command
Aspect ratio	1×1
Vertical sweep period	6.5 seconds
Vertical retrace time	250 milliseconds
Horizontal rate	133.3 cps
Horizontal blanking	750 microseconds
Readout time	6.25 seconds
No. of active scan lines	833

Table 5
Performance Specifications of MAGGE Cameras

Video Bandwidth	60 kc
Sync level	-6.4 to -6.5 volts
Black level	-7.75 ± 0.1 volts
White level	-11.25 ± 0.25 volts
S/N ratio	32 dm minimum
Horizontal centering and size	±2%
Vertical centering and size	±2%
Percent response @ 800 TV lines	7% minimum
Percent response @ 600 TV lines	15% minimum
Percent response @ 400 TV lines	50% minimum
Percent response @ 200 TV lines	75% minimum
Vertical and horizontal nonlinearity	● 0.5%
Residual image	10% maximum
Dynamic range	50.1 minimum
Vertical shading	20%
Horizontal shading	20%

Synchronous-Altitude Spin-Stabilized Experiment (SASSE)

An earth-synchronous satellite like ATS-B carrying SASSE (Figure 42) can take a "time exposure" of the earth below the subsatellite point. Near-earth satellites like TIROS and Nimbus give such a fleeting view of a specific cloud system that the life history of a typical storm can be deduced only by viewing a number of different storms at different times.

SASSE can take continuous time exposures over the total earth disc, following a single storm from beginning to end.

Several alternative camera systems are suitable for a spinning earth-synchronous satellite:

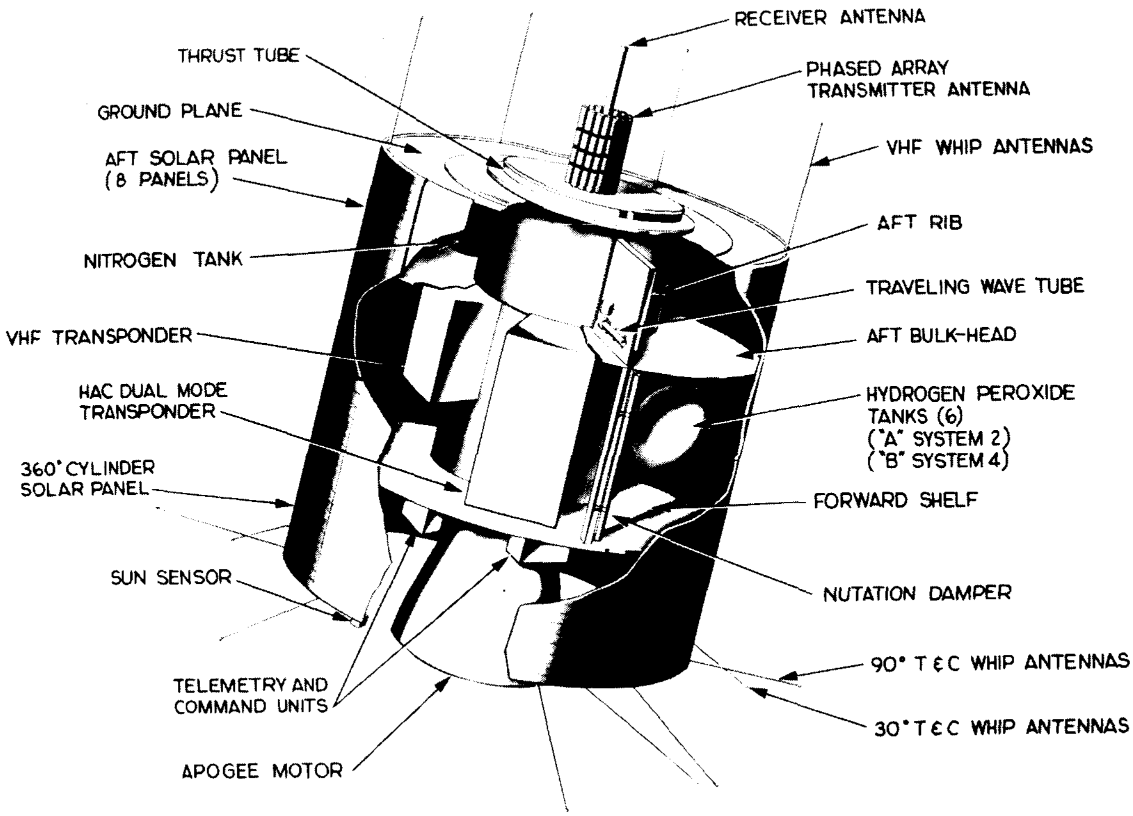


Figure 42–Synchronous-Altitude Spin-Stabilized Experiment (SASSE)

- An image-dissector camera tube, using various combinations of lenses and reflective optics

- A moving pinhole in the image plane of a 7-inch focal length f/2.5 lens. The light passing through the pinhole is measured by a photomultiplier tube after passing through a minus blue filter to improve the contrast.

- A rocking telescope system which employs a 10-inch focal-length Cassegrainian telescope whose primary mirror is 5 inches in diameter. A stationary pinhole aperture is equipped with a minus blue filter and a photomultiplier detector similar to the one used in the above system.

Each of the camera systems would scan from east to west by the rotation of the spacecraft; the north-south scan, however, must be generated by the camera system. This can be done by magnetically deflecting the electron image along the spin axis using an image-dissector tube; or, the aperture can be moved along the spin axis; or, the whole camera can be tilted on an axis normal to the spin axis.

The rocking telescope system, the last-mentioned below, has been selected as the first to be flown. This system is scheduled to fly on the SASSE in 1966. Table 6 is a design summary of this system, and Figures 43 and 44 are schematics of the telescope. This camera will permit a picture of approximately the total disc (50° North and South) with a ground resolution of approximately 2 miles. A breadboard of this system has been built and demonstrated at the Santa Barbara Research Center, a subsidiary of Hughes Aircraft Company.

Table 6
ATS-B Cloud Camera Design Summary

Optical System	
Type:	Two-element reflective
Primary mirror:	5-inch parabolic
Secondary mirror:	2-inch diameter, flat
Instantaneous field-of-view:	0.1 × 0.1 milliradian
Spectral bandpass:	4750 to 6300 Angstroms (defined by optical filters)
Photomultiplier	
Type:	EMR Model 541 A -01-14
Photocathode:	S-11 surface, 1-inch diameter
Scan System	
Line Scan:	Spacecraft rotation, 100 rpm
Latitude or step scan:	Sealed mechanical drive (one step per line)
Lines per frame:	2000 lines
Frame time:	Approximately 20 minutes
Vertical retrace time:	Approximately 10 seconds
Dwell period (time for for instantaneous field to scan a point source):	9.6 microseconds

The application technology satellites C and D are both earth-synchronous. ATS-C the second ATS satellite to be spin-stabilized, will probably carry image-dissector cameras. Image-dissector tubes require no filament and no shutter, nor do they require image-motion compensation (IMC) as vidicon systems do. The vidicon systems must have IMC because of their requirement to integrate light from the scene.

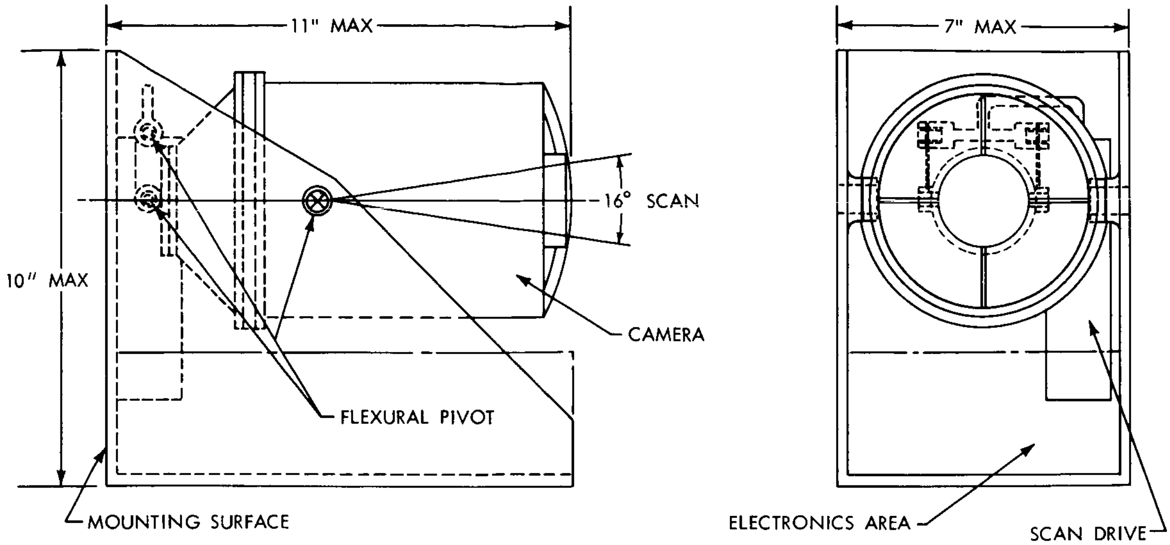


Figure 43–ATS Cloud Camera Outline and Mounting Drawing

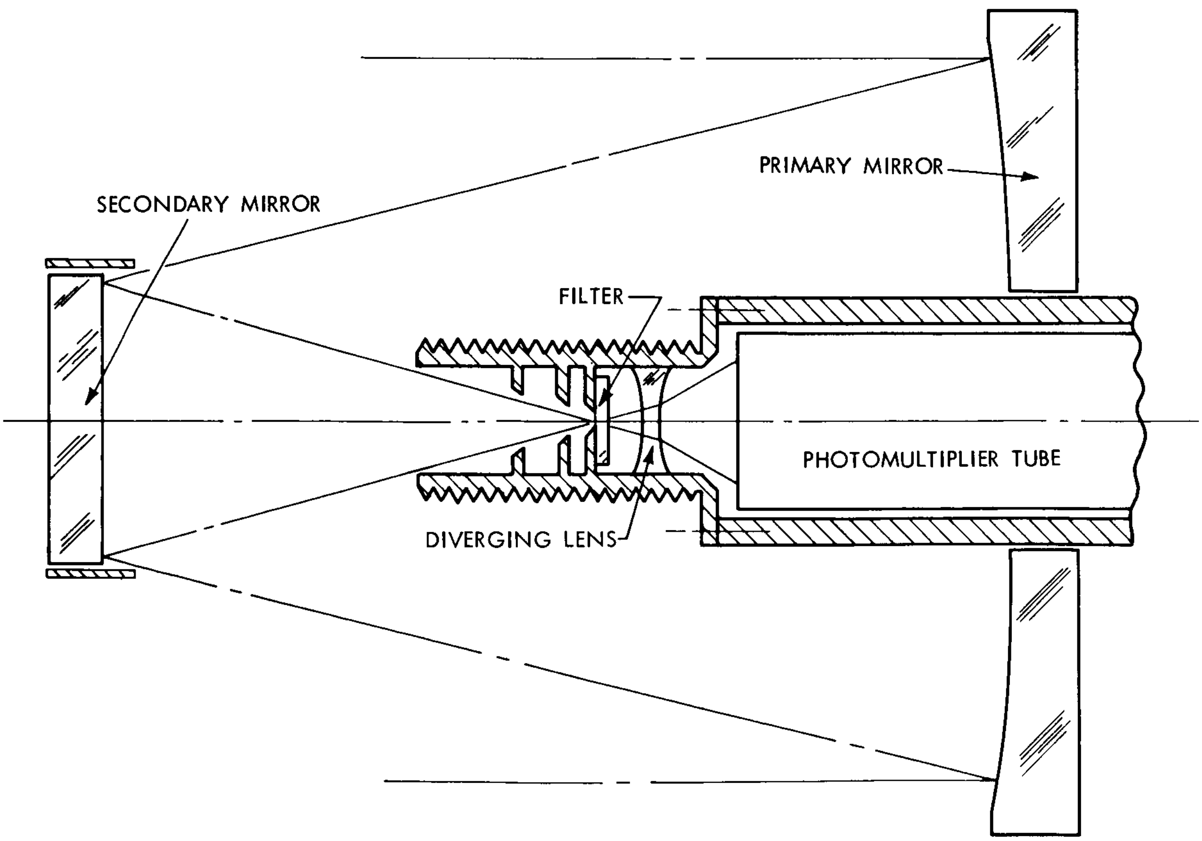


Figure 44–Optical System Diagram

The image-dissector tube is a nonstorage video sensor with a photoemissive cathode upon which the optical image is focused. The photoelectrons from the photocathode are focused upon a plane parallel to the photocathode by an axial magnetic field and an electric field produced by accelerator rings around the periphery of the tube. This focus plane contains an aperture through which the photoelectrons pass into a series of secondary emission multiplier stages. The entire raster is passed across the multiplier aperture by deflecting the axial magnetic field.

The ATS-C camera system will use a 1-1/2-inch-diameter 1000-TV-line image-dissector tube, mounted so that its axis will view the subsatellite point once every revolution.

Synchronous-Altitude Gravity-Gradient Experiment (SAGGE)

ATS-D, also an earth-synchronous satellite, will carry a gravity-gradient experiment (SAGGE) which is still under development. Figure 45 is a picture of the SAGGE prototype.

Table 7 lists characteristics of the camera systems on ATS-C and D.

Table 7
ATS-C and D Camera Systems Characteristics

	SASSE	SAGGE
Satellite spin rate	100 rpm	
Resolution	1000 TV lines	1200 TV lines
Ground resolution at subsatellite point	6.15 n. mi.	5.10 mi.
Bandwidth	16.7 K cps	2.7 K cps
Dynamic range	66.7:1	100:1
Signal-to-noise ratio	30 db	30 db
Shading	Less than 10%	Less than 10%
Shuttering	None required	None required
Sun protection	Required	Required
Iris operation	Fixed	Fixed
Geometric distortion by camera system	1% or less	1% or less
Frame rate	10 minutes	5.0 minutes
Horizontal scan frequency	33.33 cps	4 cps

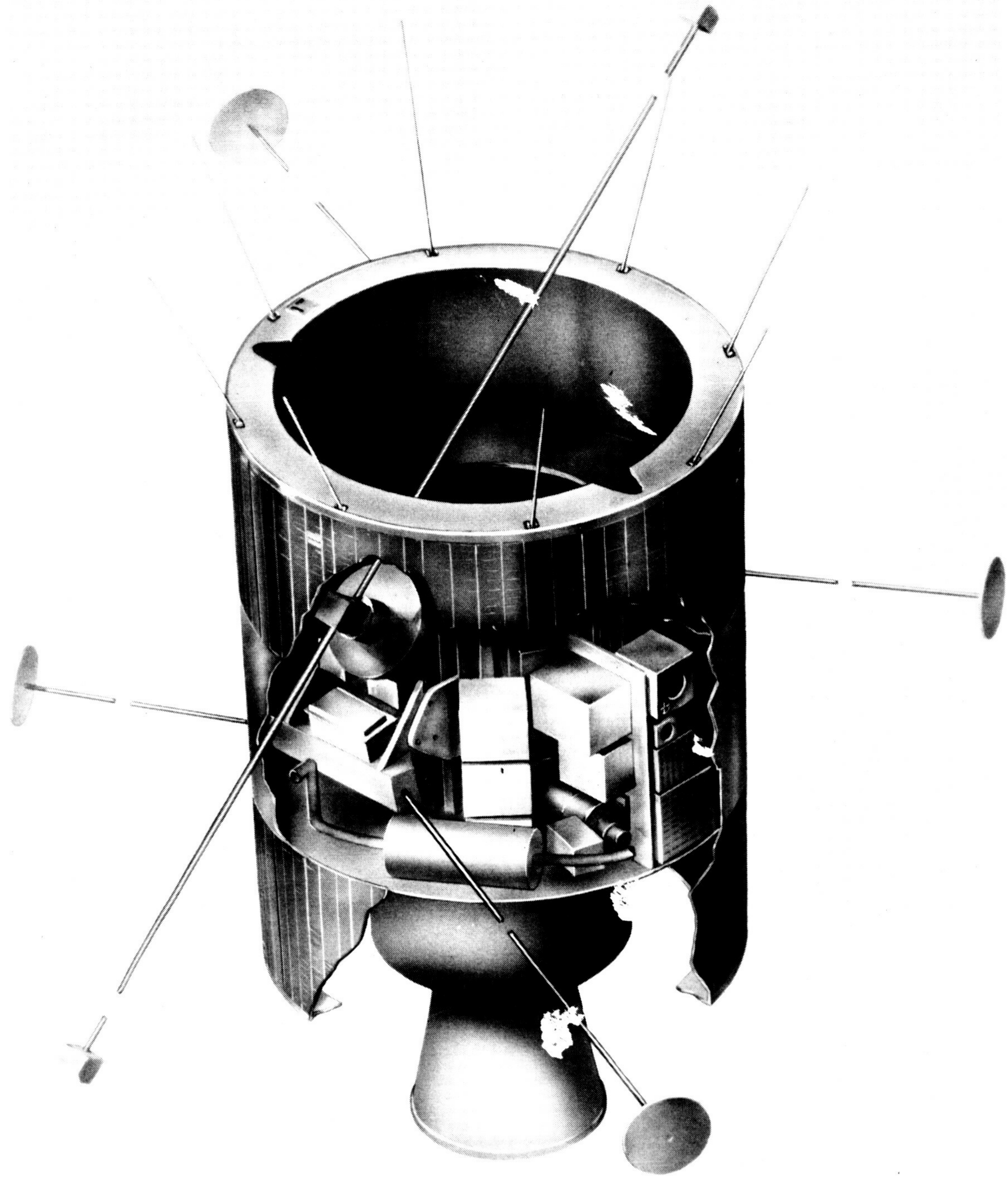


Figure 45–Synchronous-Altitude Gravity-Gradient Experiment (SAGGE)

FUTURE PROGRAMS

Microwave Radiometers

Microwave radiometers have a number of possible applications in meteorology which have been described by Frye (1964), Miller (1964), and Parker (1965). Some of these with their respective frequencies are:

Stratospheric temperature distribution	55-65 Gc/sec
Tropospheric temperature distribution	55-57 Gc/sec
Sea surface temperature	10-35 Gc/sec
Water vapor and precipitation distribution	18-26 Gc/sec
Snow cover	94 Gc/sec
Sea state	10-25 Gc/sec

Measurement of the microwave region has two possible advantages over other meteorological satellite sensor systems. First, microwave radiation has minimal attenuation through most clouds, because of its long wavelength compared to droplet size. Large water drops, hail, or snow are efficient scatterers and therefore may be opaque to microwave frequencies, but the restrictions are less severe than for the infrared spectrum.

The second advantage is the wavelength resolution resulting from the use of a coherent detector. This will permit determination of temperatures to greater heights, and better vertical resolution, than is possible by using infrared radiometers.

Continuing research and measurements of the microwave radiation from sea surfaces, terrain, and the atmosphere by instruments on balloons and aircraft will further define the best frequency requirements for satellite-borne instruments. Considerable development will be required to reduce the weight and power requirements of microwave radiometers to make them compatible with meteorological satellite limitations.

Lasers

Lasers may offer a new tool for indirect probing and sounding of the atmosphere. The technique involved would be to emit extremely intense light pulses (approximately 10^9 watts) in a very narrow beam directed downward, and to analyze the light scattered back to the satellite by the gaseous (Rayleigh-scattering) and aerosol (Mie scattering) components of the atmosphere. Theoretically, the system would make it possible tomeasure density, temperature, water vapor, and aerosol content between cloudtop level and 100,000 feet with a resolution of 3000 to 4000 feet, assuming that the two scattering effects (aerosol and gaseous) could be separated. For gaseous components, advantage could be taken of the Raman effect in which a small percentage of the scattered light is shifted in wavelength from the incident light. These Raman lines adjacent to the main wavelength are sharply defined, and are distinct for each gaseous element. Once the gaseous density is known, the remaining backscatter could be attributed to aerosols.

Since the system would operate as a light radar (lidar), the height of the volume samples would be determined by radar ranging techniques.

Laser systems for use on meteorological satellites are still in the initial study phase. Many problems remain to be overcome, especially the determination of the feasibility plus order-of-magnitude reductions in weight and power requirements.

Global Horizontal Sounding Technique (GHOST)

Remote sensing of winds by satellite is still beyond the state-of-the-art. Many proposals have been made such as that by (Lally, 1960) to combine in situ devices, primarily constant-level balloons (CLB's), with satellites to measure this vital meteorological parameter.

Using CLB's is not an ideal solution, because many engineering problems are associated with them. For example,

- Development of balloon electronic and power systems nonhazardous to aircraft in case of collision. The Federal Aviation Agency, which is investigating this problem expects to define the criteria for nonhazardous packages by 1968.

- Balloon lifetime – Economic factors require a CLB to have a service life of 6 months. Although the material (Mylar) is capable of achieving this, manufacturing techniques must be improved. A joint New Zealand, United States program is under way to ascertain whether carefully constructed balloons can achieve a 6-month operational lifetime. Approximately 100 ground-tracked CLB's will be launched from Christchurch, N. Z., over the next 6 months. These balloons will be flown at 500, 300, and 30 mb and tracked globally from the ground during their entire lifetime.

- Balloon clustering – Computer studies indicate that CLB's may tend to congregate in specific areas. The experiment just described will probably give more insight into the probability of a clustering problem

- Flyover problems – A CLB system would be a global network, requiring approval by all nations before these meteorological sensors could fly over sovereign territories.

The United States is investigating the use of CLB's in several systems:

GHOST (global horizontal sounding technique), Omega (VLF ground-based navigation system), Datacol, STROBE (Satellite Tracking of Balloons and emergencies), and IRLS (interrogation, recording, and locating system).

The Nimbus B IRLS experiment previously described will be the first of these flown. The French are investigating an alternate approach to the use of CLB's which they call EOLE (Beller, 1965).

Most operational CLB programs would require a total deployment of about 5000 balloons. Operational heights will be 750 mb, 500 mb, 300 mb, 30 mb, and 10 mb on a grid structure of approximately 600 nautical miles.

CONCLUSION

This report has described past, present, and future meteorological satellite sensor systems, and the requirements which they place on satellite systems.

Satellites can be put to other meteorological uses besides acting as sensor platforms. In the area of communications, for instance, communications satellites will contribute heavily to the collection and dissemination of meteorological data because of their ability to receive and retransmit meteorological observations from remote areas to central and regional meteorological centers.

Another area under study is the integration of satellite observations (SATOBS) into numerical forecasting programs. The logical evolution now taking place in the digitizing of sensor data, much of it at the source, will speed up this integration process.

As mentioned previously, the first operational meteorological satellite system will begin operation early in 1966. The scope of this one program indicates in itself the need for continued research and development on new and improved satellite sensors and spacecraft systems in order that we may realize the ultimate capabilities of satellite meteorology.

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