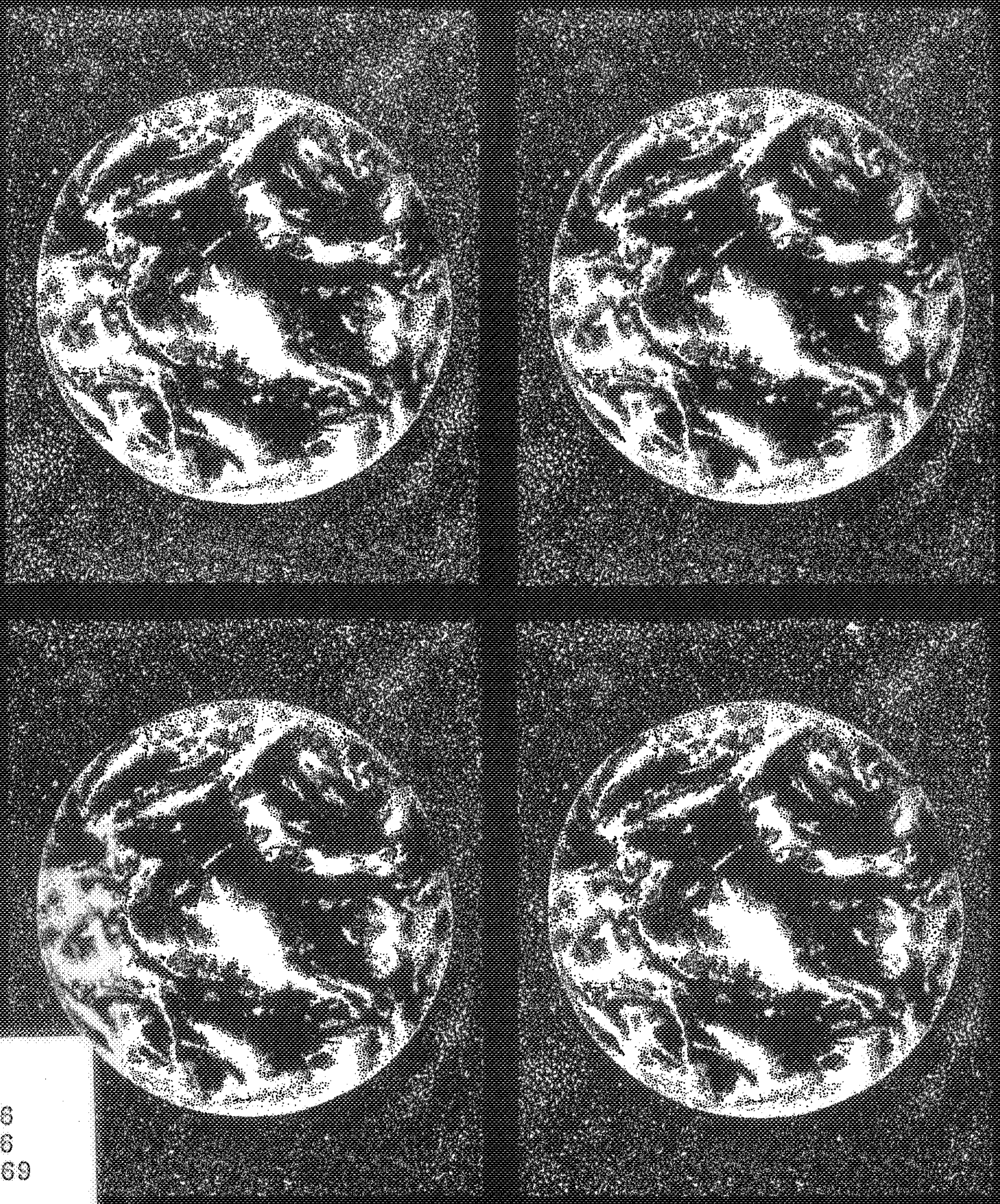
America In Space | The First Decade

PUTTING SATELLITES TO WORK



National Aeronautics and Space Administration

America
In
Space:
The
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This is one of a series of booklets published on the occasion of the 10th Anniversary of the National Aeronautics and Space Administration.
These publications are not intended to be comprehensive history, nor do they deal with all the facets of NASA's aeronautical and space activities. Rather they are overviews of some important activities, programs and events written for the layman in terms of the several science disciplines.

Each of these subjects is treated in more depth in other NASA publications and in scientific journals.

October 1, 1968

Titles in this series include:

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PUTTING SATELLITES TO WORK

by William R. Corliss

National Aeronautics and Space Administration, Washington, D.C., 20546

Introduction

Ten years ago NASA was brought into being to explore space. As stated in the National Aeronautics and Space Act of 1958: ". . . it is the policy of the United States that activities in space should be devoted to peaceful purposes for the benefit of all mankind." One of the major avenues of intellectual and program effort that has guided us at NASA has been the concept, at first unproved but now clearly valid, that space systems can provide unique, direct benefits to man, benefits not before possible or economically feasible.

We do not yet know the full range and scope of the possibilities that spacecraft open for the service of man. Those few particular applications upon which we have concentrated in the past and which are described in "Putting Satellites to Work" have borne out that promise. Communications, navigation, geodetic, and meteorological space systems are operational today, and their existence, once the subject of science fiction, is now a practical fact. It is clear that many potential applications exist: the one most clearly on the horizon is the possibility of surveying the Earth's resources from space. We are really just beginning to develop the possibilities in this area of research, but we can clearly foresee that during the next decade NASA can, in building on its past accomplishments, provide tools which may significantly affect the efficiency and thus the quality of our life here on Earth.

Leonard Jaffe
Director, Space Applications Program

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The Weather Watchers

A Better View of the Weather

Good weather forecasting is worth money. An accurate five-day forecast would probably save between $2.5 and $5.5 billion yearly in the U.S. alone; perhaps $15 billion for the entire world. Most of the savings would be in agriculture, the construction industry, and government operations, such as flood control. The capital investment for a good global weather forecasting system should cost less than a half billion dollars; the potential payoff is impressive.

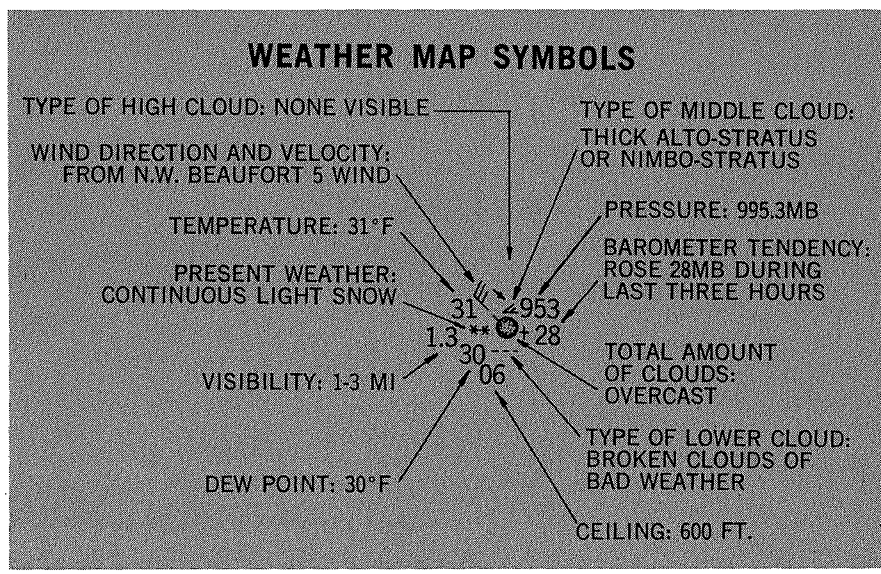
Besides the time-honored approach of watching the skies for weather signs, what can we do to improve weather forecasting? Four possibilities come to mind, and we have been trying all four for over a century:

1. Rather than looking for red sunsets or mackerel skies, we can record more objective data. Examples are: temperature, wind direction and velocity, humidity, and so on. These are all classical measurements that have been recorded regularly at weather stations since the early 1800s.
2. A weather station operator can expand his fund of basic information further by lofting instruments on balloons, or, as was popular in the last century, by flying them on large kites. Better knowledge of the air aloft leads to a better understanding of what is happening to air close to the ground.
3. As meteorologists realized that weather patterns were actually continent-sized rather than local in nature, they began to link individual weather stations into networks. Just before the Civil War, Joseph Henry, of the Smithsonian Institution, began to collect weather observations taken concurrently over a broad area. This *synoptic* information was relayed to Henry by telegraph from stations all over the eastern U.S. Now, many countries have well-integrated networks of stations and there is considerable international exchange of weather data.
4. Another improvement in weather forecasting has come as meteorologists have learned more about the natural forces that actually make weather. Representing these forces mathematically, they have constructed equations that describe the movements of weather fronts and the mechanism of the hurricane. By feeding these equations into a high speed computer and adding the data taken by weather stations and weather satellites, meteorologists believe they can eventually generate accurate two-week forecasts.

Long before the National Aeronautics and Space Administration was conceived, sounding rockets were contributing to our knowledge of the upper atmosphere. NASA, of course, has continued this line of attack, but the Earth satellite is the most valuable meteorological tool contributed by the space program. Like

1 *A surface weather station usually records only highly localized information. Station networks extend coverage geographically. Satellites produce cloud cover and infrared information over the entire globe.*

2 *TIROS III before launch. Cameras are centered in the bottom. Solar cells cover the top and all sides. Weight of TIROS III was about 280 pounds.*



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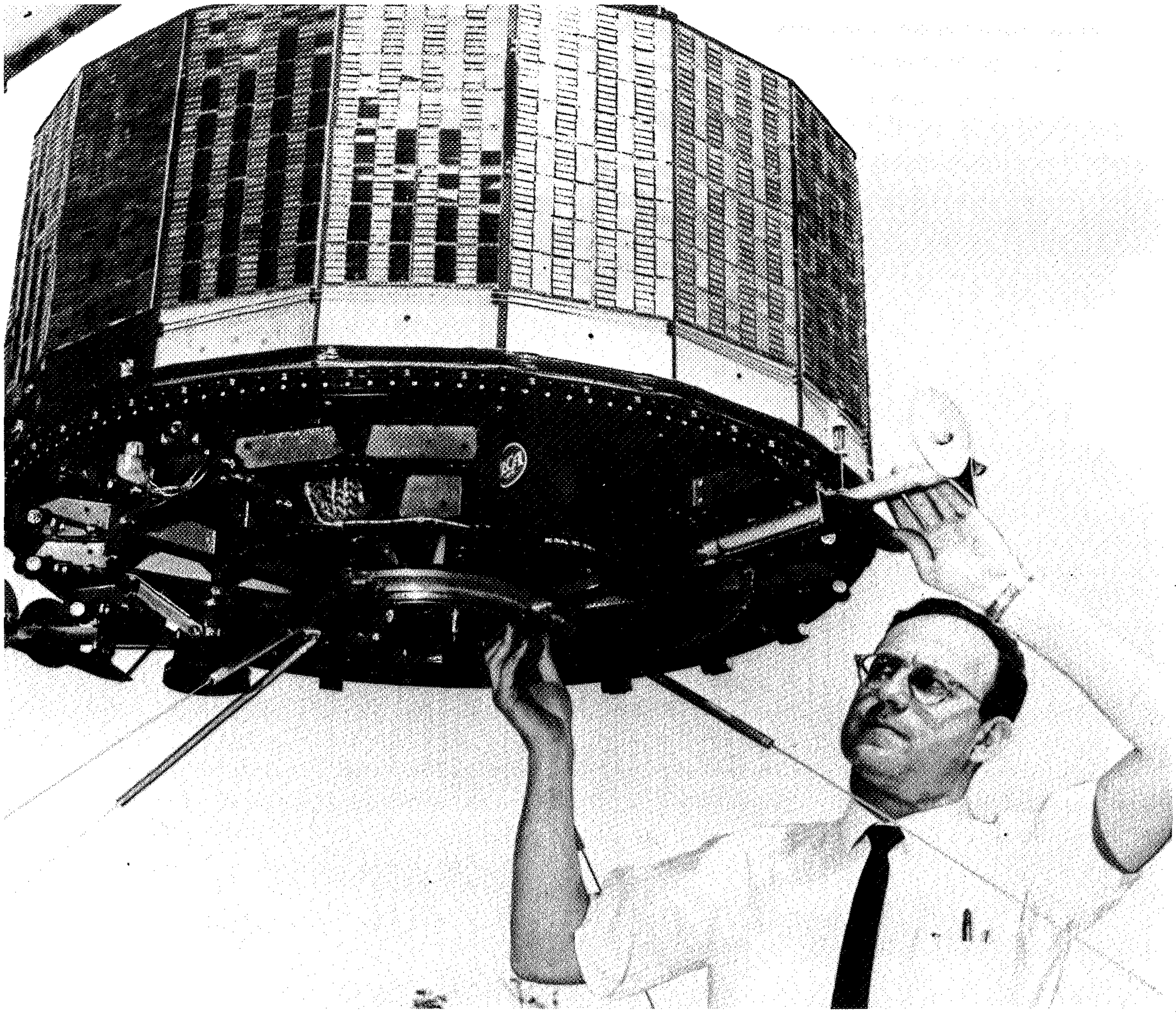
rockets and balloons, satellites carry instruments far above the layer of air hugging the ground; like big networks of stations, they afford a wide geographical perspective of world weather. In fact, no combination of surface station networks can match the panorama of world weather radioed back from satellite cameras.

The meteorological satellites presently operating do have limitations. They orbit so high up that they cannot make direct measurements of temperature and pressure with ordinary thermometers and barometers. They can only "see" what is going on far below. Seeing alone, however, is of great value to meteorologists. Cloud pictures—the stock-in-trade of the weather satellite—show the great weather systems forming, swirling, and dissolving against the backdrop of the oceans and continents. By taking pictures of the Earth in the infrared portion of the electromagnetic spectrum, weather satellites give the meteorologist information about the heat added to and lost from the Earth and its atmosphere. Since the vast cyclones and anticyclones that roll across the globe are really monstrous heat engines, this heat budget information helps forecast weather. Weather satellites by themselves cannot provide all the information needed for good forecasts, but they can help significantly.



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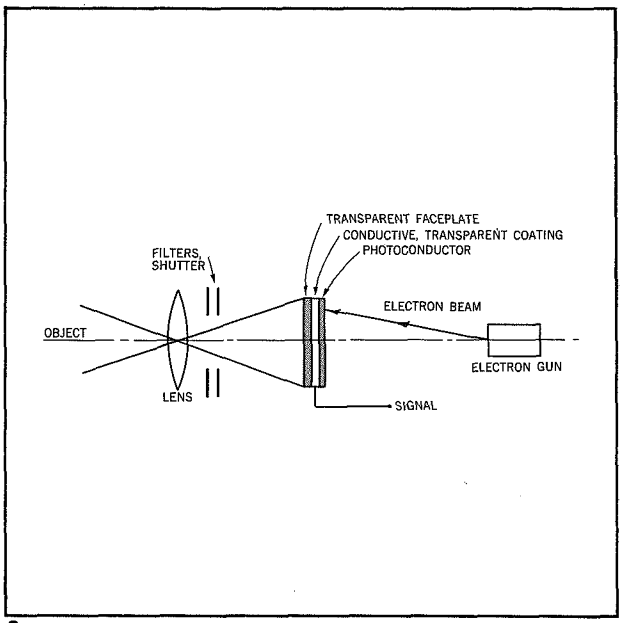
Pictures by the Thousand

Anyone who has flown in an airplane and looked down on the great white cloud banks marching across the landscape has seen only a small fraction of what a satellite sees. An airplane does not fly high enough to see the big picture. Meteorologists did not see truly large-scale pictures of cloud patterns until cameras were flown on high altitude rockets in the late 1940s and early 1950s. What they saw whetted their appetites for more.

The Army, Navy, and industry began studying weather satellites in the early 1950s. In particular, the Radio Corporation of America (RCA) applied to meteorology the experience it had gained studying television-equipped satellites for the Air Force. After it was created in 1958, NASA supported the RCA work. The RCA weather satellite concept eventually became known as TIROS (*T*elevision *I*nfrared *O*bservation *S*atellites).

The first TIROS satellites had the proportions of a hatbox, although they were considerably larger: 42 inches in diameter and 22.5 inches high. They weighed about 270 pounds. The top of the hatbox and each of the 18 facets around the circumference were



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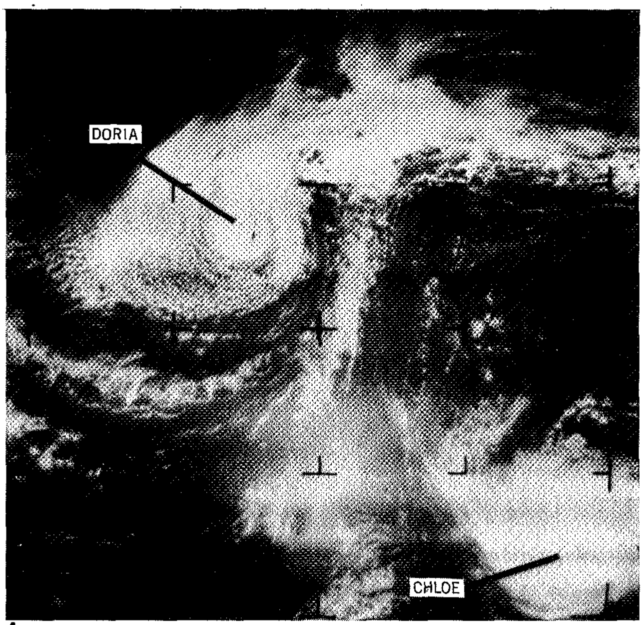

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covered with solar cells, which generated electrical power for the TV camera and the radio transmitter that relayed pictures to antennas waiting on Earth below. The TIROS satellites were spin-stabilized; they spun at about ten revolutions per minute. The satellite's angular momentum kept it from tumbling in space, just as the spin of a rifle bullet stabilizes its flight. On TIROS I, the axis of the hatbox remained approximately fixed in space. As the satellite circled the Earth, its cameras, which were mounted on the bottom of the spacecraft, pointed wherever the satellite axis pointed, which more often than not was toward empty space. Later TIROS satellites carried a coil of wire to improve the cameras' view of the Earth. When electric current was sent through the coil, the satellite became a weak electromagnet and turned in the Earth's magnetic field like the armature of an electric motor. Nevertheless, the early TIROS satellites saw and photographed the Earth only part of the time. A rather frustrating situation, but a complete solution to the problem of camera pointing had to be deferred to the second-generation Nimbus weather satellites.

The heart of a TIROS satellite is its complement of television cameras. Ordinary television cameras, which take many frames a second to give the illusion of smooth motion, cannot be used because TIROS could not possibly transmit that much information to the ground.* A special television tube called a vidicon is used on most U.S. picture-taking spacecraft whether they photograph the Earth's clouds, the lunar surface, or Mars. Replacing conventional film, the vidicon has a sheet of photo-conductive material, which becomes a good conductor of electricity wherever light hits it. Before the shutter of the vidicon is opened to take a picture, the photoconductive sheet is sprayed uniformly with electrons. Then, the shutter is opened and the scene is focused on the sheet. Bright areas in the picture activate the photoconductive material, causing the deposited electrons to be drained away. Electrons remain in the dark areas of the picture. Now an electron gun sweeps across the photoconductive sheet in a pattern or raster consisting of several hundred lines. The electrons from the electron gun will be repelled from dark areas but not from bright areas. The current of electrons flowing out of the electron gun onto the photoconductive surface is thus a

** The transmission of information requires power; double the number of television frames per minute and the power must be doubled.*

3 *Schematic of a vidicon camera.*

4 *Nimbus II APT photo of two 1967 hurricanes, taken September 13. Hurricane Doria is about 300 miles southeast of Cape Cod and Chloe is roughly 1000 miles southeast of New England. The storms are about 700 miles apart.*

measure of the brightness of the image being scanned. This fluctuating current is turned into a signal that can be converted into a television picture back on the Earth.

Between 1960 and 1965, ten TIROS satellites were launched without a failure. All ten radioed back pictures of the Earth's cloud cover—hundreds of thousands in all. The TIROS pictures presented a grand global panorama of the Earth, grander by far than the sights seen by the first balloonists and aeronauts.

The most striking and exciting features of the TIROS pictures have been the large-scale cloud patterns, which show a degree of organization never realized from terrestrial and aircraft observations. In particular, huge vortices—some 1000 miles across—wheel across the oceans and the continents, making weather as they go.

TIROS photos clearly show weather fronts and other patterns that coincide closely to the maps drawn for the newspapers from accumulated surface station readings. This proven correspondence gives meteorologists confidence that they can employ satellite cloud-cover pictures to draw weather maps in portions of the world where ground weather stations are sparse or nonexistent. The correspondence between the satellite panorama and ground-level direct measurements is not perfect. These discrepancies, though small, have led to modification of cyclone theory.

In the pre-TIROS days, hurricanes used to sweep in from the unpatrolled oceans and slam into land areas with little warning. Destruction and loss of life have frequently been high; much higher than they would have been with ample warning time. TIROS has changed all that by constantly monitoring cloud cover over the desolate reaches of the oceans. Anyone who watches TV news programs during the hurricane season has seen TIROS pictures of these intense storms and followed their progress along the U.S. Atlantic coast. Satellite pictures often catch these storms in their formative stages, showing the prehurricane squall lines that ring the growing nucleus. Sometimes, a hurricane interacts with a jet stream, giving meteorologists a ringside seat for the battle between these two powerful weathermakers. Without the high vantage point of the weather satellite this drama would go unseen.

As the atmosphere swirls across the surface of the Earth, it encounters land formations that deflect the

5 *In a Sun-synchronous orbit, the orbital plane rotates (precesses) about a degree per day to keep the plane of the orbit (shown edgewise) pointed at the Sun. With no perturbing forces, the plane of the orbit would remain fixed in inertial space. Irregularities of the Earth cause the precession.*

6 *TIROS IX, showing the wheel configuration. Satellite spins like a wheel around the Earth, pointing its two cameras (180° apart) at the Earth one after the other.*

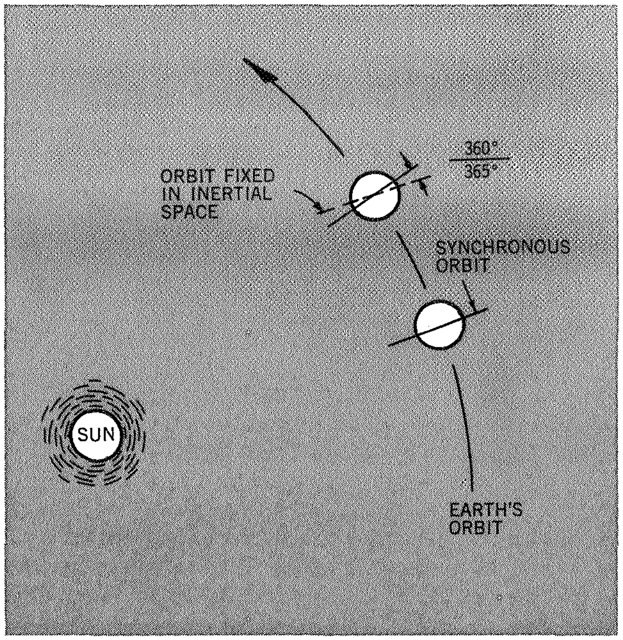
air currents and cause turbulence. The patterns created are intriguing as well as instructive. The Sierra wave, for example, manifests itself as a long linear cloud created as air is pushed up as it tries to slide over the Sierra range. The Andes form similar cloud patterns. In a similar vein, ocean islands with high mountains create strange eddies of clouds that reveal large-scale turbulence, which except for size resembles the turbulence formed behind rocks in a brook.

The first eight TIROS satellites were very much alike. Although they were very successful, NASA and RCA engineers wanted to try some new ideas. TIROS IX introduced the so-called "wheel" configuration in 1965. Instead of mounting the cameras so that they pointed down from the bottom of the hatbox, two were placed on the satellite rim facing outward, 180° apart. After TIROS IX was launched, its axis was twisted so that as it spun it essentially rolled around the Earth, pointing one camera and then the other at the Earth. In the wheel configuration, the TIROS cameras can take more pictures of the Earth.

TIROS X solved another problem: the fact that the angle with which sunlight hits the Earth below the satellite is often poor for picture taking. We cannot control the Sun or the orbit of the Earth, but we can place the satellite in a Sun-synchronous orbit. In this kind of orbit, the satellite is injected into a near-polar orbit. The plane of the satellite orbit contains both the Earth and the Sun. If this configuration could be maintained, the satellite would cross the equator at just about local noon on the sunlit side of the Earth and local midnight on the dark side. The Earth would rotate under the satellite orbit, which is fixed in space, at the rate of 15° per hour. In this way, the equatorial and temperate zones of the Earth could be photographed with the Sun high in the sky all of the time. However, as the Earth rotates around the Sun, it disturbs this ideal situation. The satellite orbital plane remains fixed in space so that a quarter of a year later, it will be perpendicular to the plane containing the Earth and Sun. To maintain the Sun-synchronous condition, the plane of the satellite orbit has to be rotated 360/365 degrees per day. If the satellite is in just the right orbit, the Earth's equatorial bulge will deflect the satellite orbit just this amount. TIROS X demonstrated the practicality of this type of orbit.

While the TIROS program was proving the value of the weather satellite, NASA also worked on the Nimbus weather satellite program. Basically, the Nimbus program is aimed at improving the instruments and spacecraft components used on operational weather satellites.

The Nimbus satellites are large automated spacecraft. For example, Nimbus I weighed 912 pounds, over three times the weight of the early TIROS satellites. Nimbus is fully stabilized; that is, the satellite is oriented so that its instruments always point toward



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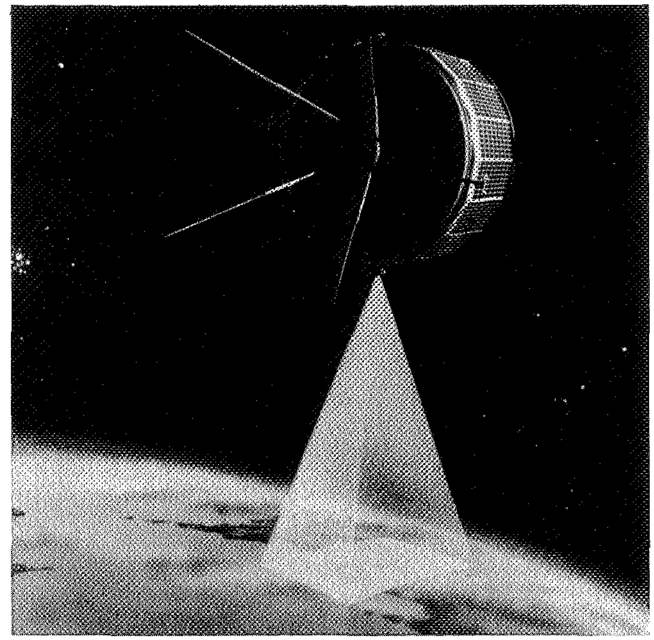
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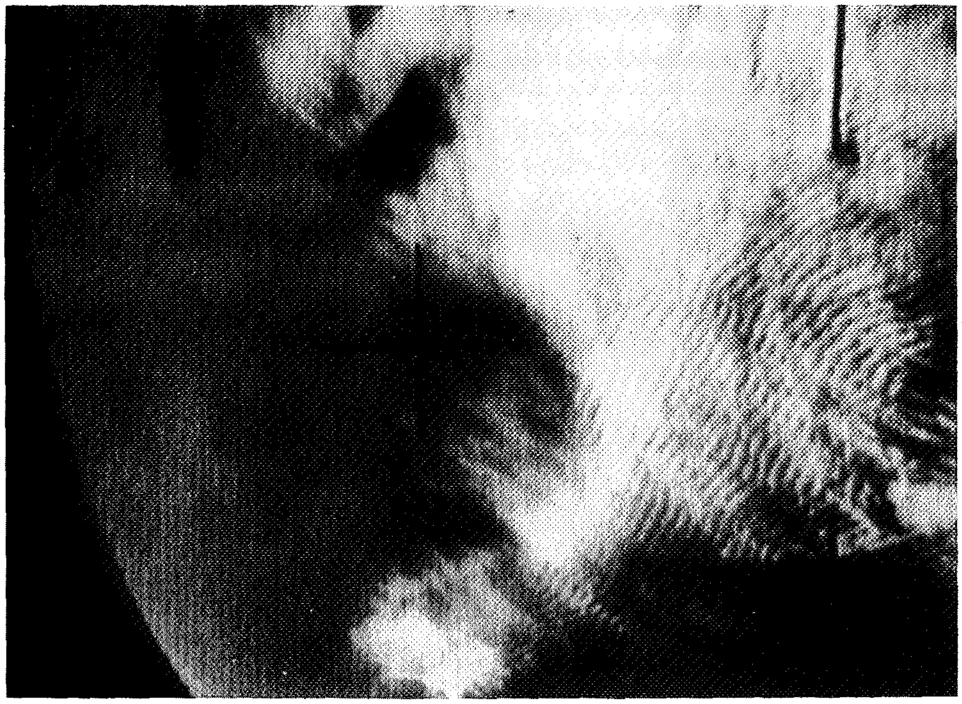
the Earth. The Nimbus attitude control scheme employs three flywheels plus nozzles that squirt Freon gas into space to obtain thrust. Between the flywheels and the jets, the satellite can be kept pointed to within 1° of the center of the Earth's disk.

Nimbus I, launched August 28, 1964, proved the basic spacecraft design, especially the oriented solar panels and the attitude control system. Nimbus I carried three important experiments as well: (1) A new high resolution TV cloud mapping system (the Advanced Vidicon Camera System, or AVCS); (2) An Automatic Picture Transmission (APT) system that allowed local stations to receive weather pictures directly; and (3) A high resolution infrared instrument that allowed nighttime cloud mapping on a global scale. Nimbus II, launched May 15, 1966, carried the same instruments as Nimbus I plus a medium resolution infrared instrument. Future Nimbus satellites will prove out a great variety of optical equipment as well as a nuclear power supply for augmenting the solar panels.

The wheel configuration of TIROS IX, the Sun-synchronized orbit of TIROS X, and the Nimbus camera technology were adopted by the U.S. Weather Bureau for its TIROS Operational Satellites (TOS). The Weather Bureau is now part of the Environmental Science Services Administration. Its satellites are called ESSAs, for Environmental Survey Satellites. Three ESSAs were launched by NASA for the Weather Bureau in 1966 and two more in 1967. The successes of the TIROS and Nimbus programs can be gaged by the adoption of their technologies for operational, routine weather satellites.

Hot Spots Below

Each hurricane is created and sustained by a colossal heat engine that we are just beginning to understand. Somehow, energy from the Sun starts these atmospheric machines turning over. The same is true for the much bigger, but less intense cyclones and anticyclones that make most of our weather. Since weather is really atmospheric turbulence created by too much solar heat at the equator and too little at the poles, measurements of the Earth's heat inflow and outflow should be useful to meteorologists. For this reason, most NASA weather satellites have carried infrared radiometers to record the thermal radiation emitted from the cloud tops and the visible land surface below the satellite. The thermal radiation emitted by the Earth falls mainly in the



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7 Wave clouds over the Appalachian Mountains, photographed by TIROS VII.

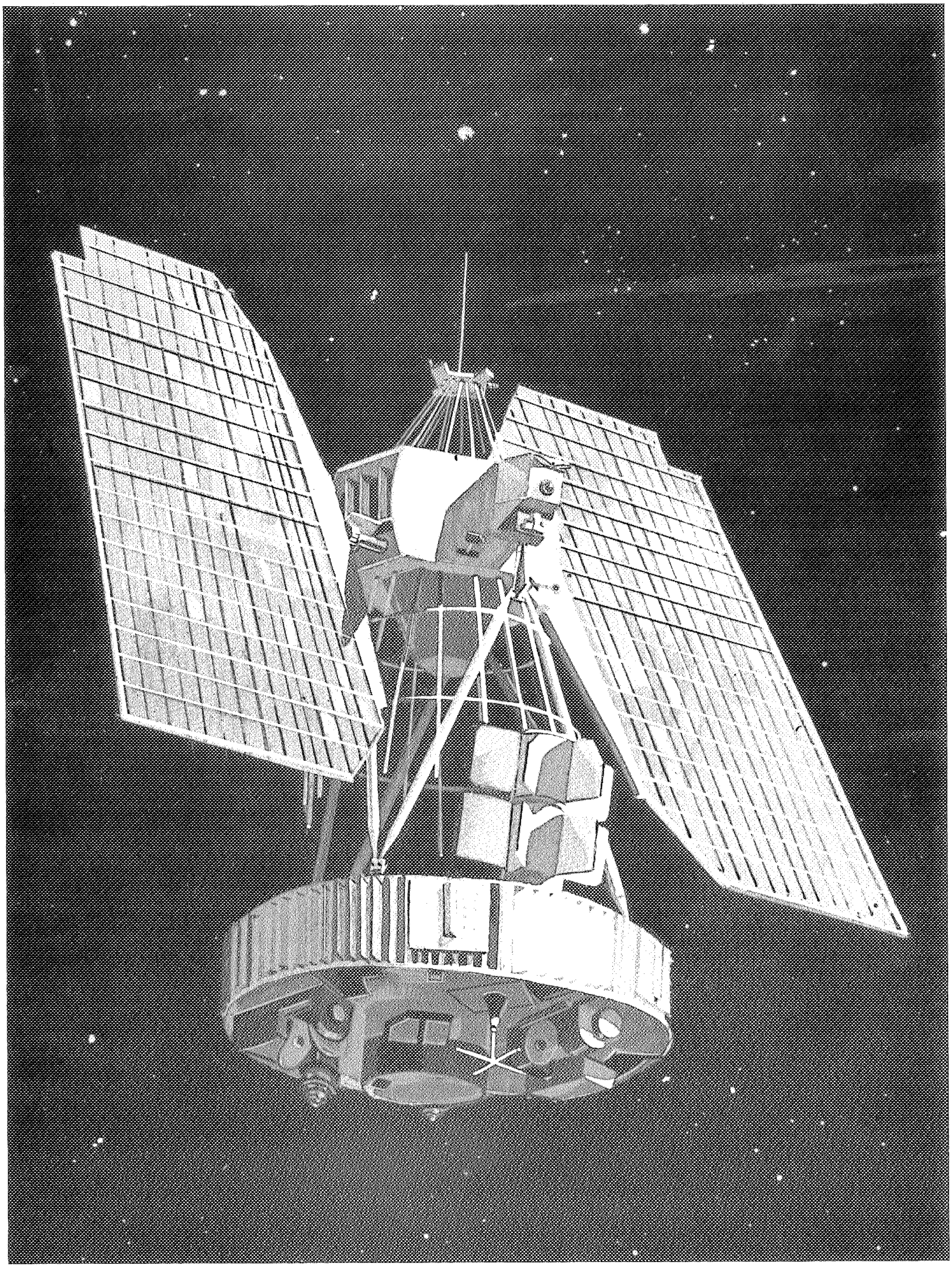
8 The Nimbus weather satellite carries attitude control devices (gyros and gas nozzles) that keep its cameras in the base pointed at the Earth. The solar cell paddles are driven by a motor that keeps them perpendicular to the Sun's rays.

range from 5 to 50 microns.* These wavelengths are far longer than the long wavelength limit of the eye at about 0.7 micron. Unlike the vidicons which operate with visible light, the infrared radiometers are useful both day and night in determining cloud cover and the speed with which the Earth cools once the Sun has set.

In infrared radiometers, lenses focus the infrared radiation on a detector made from a photoconducting material, such as lead selenide, which becomes a good electrical conductor when illuminated by infrared light. The amount of current passed by the detector is proportional to the intensity of the infrared light and therefore the amount of heat being radiated from Earth to outer space.

Infrared radiometers can be made sensitive to various wavelength ranges or channels through the use of filters. For example, the high resolution infrared radiometer on Nimbus I was sensitive to only that radiation between 3.4 and 4.2 microns. Radiation of this wavelength is emitted from cloud tops and gave Nimbus I a way of mapping cloud cover at night. An infrared channel between 6 and 7 microns helps determine the amount of absorption caused by water vapor in the air. Data from such a channel aid in constructing worldwide. humidity charts of the upper atmosphere. Analysis of the radiation emitted by the

** A micron is one-millionth of a meter.*

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9 *ESSA I took this picture of North America on February 5, 1966. It shows a heavy rain producing storm along the west coast, ice in Lake Erie, snow cover over Northeastern United States, clouds in cold air flow off the east coast.*

10 *The High Resolution Infrared Radiometer on Nimbus II was able to distinguish the Gulf Stream along the U.S. east coast by virtue of its warmer temperature.*

warm Earth by radiometers, spectrometers, and other optical equipment can provide the following kinds of meteorologically useful data:

Atmospheric temperature and humidity profiles
Vertical water vapor distribution
Vertical ozone distribution
Surface temperature

When added to photos taken in visible light by weather satellite cameras, meteorologists see the world's weather from a superb vantage point at wavelengths they have never been able to use before.

Pictures on Request

Will the Boy Scout hike be rained out tomorrow? Do the smudge pots have to be lit in the orange groves tonight? This is the kind of weather information that most people want to know; that is the local forecast, the local situation. The local weather forecaster would like very much to see what is going on in his area as he prepares his predictions. The APT (Automatic Picture Transmission) system gives him local cloud pictures with a minimum investment in equipment.

The basic idea is to have special cameras on the weather satellites (TIROS, Nimbus, ESSA) that continually transmit cloud cover pictures as they are taken. Anyone on the Earth below within 1500 miles of an APT-equipped satellite can receive these pictures with modest equipment that he can purchase or build himself. Every time an APT satellite passes overhead, the owner of an APT ground station can collect up to three overlapping pictures of weather systems within about 1000 miles of his station.

The APT concept is particularly helpful to foreign weather forecasters who cannot get the maps and cloud cover photos that the U.S. Weather Bureau transmits to many U.S. locations. Hundreds of APT ground stations have been set up all over the world, not only by professional weathermen but also by radio amateurs and high school science classes.

Extraterrestrial Relays

The Advantages of Height

More and more TV programs come to us from the far corners of the world *via satellite,* as the subtitles sometimes say. What is not

10

so obvious is the immense commercial and military communication traffic carried between continents by satellite. Not only do people talk to people, but computers and data handling equipment talk among themselves in their own languages.

The possibility for this global conviviality was first described back in 1945, when the British writer Arthur C. Clarke, better known for his science fiction, published an article entitled "Extraterrestrial Relays" in the magazine *Wireless World.* Clarke pointed out that small artificial satellites in orbit high above the Earth could relay messages between continents and greatly improve long distance communication. As befits a writer of science fiction, Clarke was ahead of his time, but only by about fifteen years.

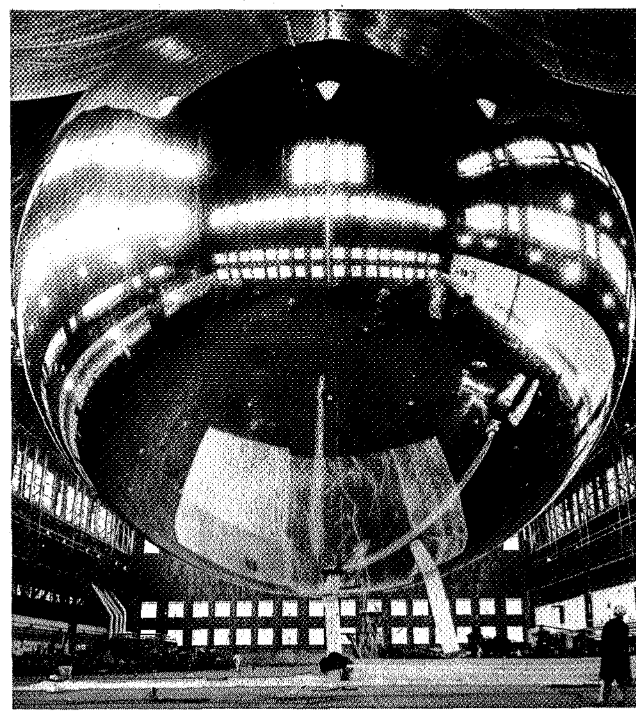
Radio waves travel away from their transmitting antennas in straight lines at the speed of light. Unless something changes their direction of travel, radio communication beyond line of sight is impossible. The Earth's ionosphere some fifty miles above the surface reflects some radio waves back to Earth, making long distance communication possible. But the ionosphere is fickle, moving up and down and disappearing when we don't want it to. Further, it reflects only those wavelengths longer than roughly 100 feet.* Dependable, long range radio communication requires an artificial radio wave reflector high in the sky.

Covering the whole sky with radio wave reflectors is out of the question; but, as Clarke suggested, satellites can do the job. The most primitive kind of communication satellite is passive in character; that is, it only reflects the signals hitting it, like a mirror. In contrast, active communication satellites rebroadcast signals with greater strength. Signal amplification takes electrical power, of course, but the relayed signals are easier to detect.

** Equivalently, frequencies below 10 MHz (10,000,000 cycles per second) are reflected.*

11 *Echo I, a 100-ft diameter balloon satellite. Echo I was a passive communication satellite.*

12 *NASA has experimented with passive and active communication satellites at various altitudes. The active synchronous satellite was ultimately selected for commerical use.*



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Height above the Earth's surface makes communication satellites useful. Antennas well over the horizon at ground level can see a satellite in a 100-mile orbit. A communication satellite in a synchronous orbit 22,300 miles high can be seen by nearly half the radio antennas on Earth. A system of three or more evenly spaced synchronous communication satellites can relay messages between any two points on the inhabited parts of the globe.

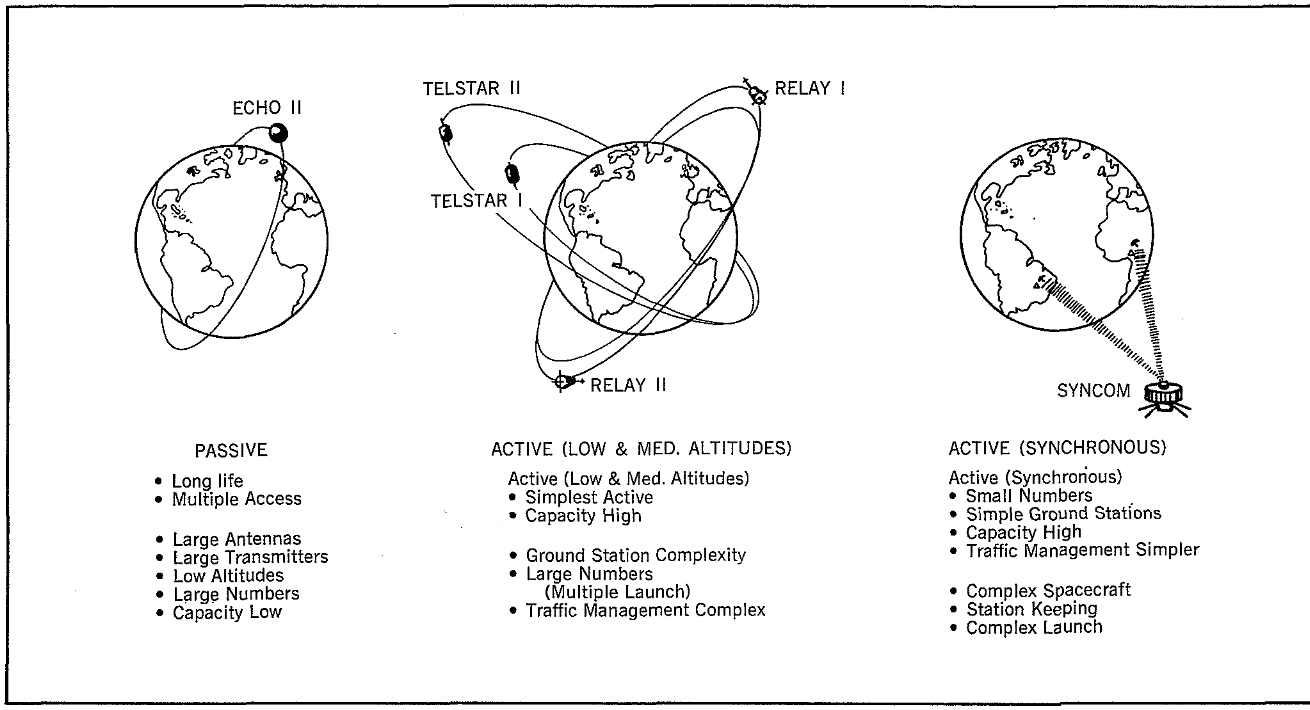
Balloons in Orbit

One prominent communication satellite is rarely mentioned: our natural satellite, the Moon. During the 1950s, the U.S. Army bounced radio signals off the Moon in long range communication experiments. And while artificial satellites were getting all the glory, the Moon gave the Army an operating communication link between Washington and Hawaii. This was the world's first operational space communication system; it was called CMR, for Communication by Moon Relay.

Would an artificial moon be any better than the natural one? It would certainly be much closer, reflected signals would be much stronger, and signal delay times would be negligible compared to the 2½ seconds for Moon bounces. To test the artificial moon idea, NASA launched two metalized plastic balloons that inflated once in orbit. Echo I (100 feet in diameter) was launched in 1960; Echo II (135 feet in diameter) in 1964.

By aiming transmitting and receiving antennas at the balloons, two-way conversations between the U.S. and Europe proved feasible. There was no limit to the number of users. This multiple access feature is one of the big advantages of the passive communication satellite. Other pluses are their long life and high reliability. With no parts to fail or wear out, balloon satellites should last forever. They don't; they get punctured by meteoroids; they get wrinkled and eventually the tiny bit of atmosphere remaining will slow them down and bring them back to Earth. This is just what happened to Echo I on May 23, 1968 when it reentered the atmosphere and burned up over South America.

Despite all their virtues, passive communication satellites were bypassed in favor of active repeaters. One reason is that a great many balloons—perhaps 50—would have to be launched into low orbits to make worldwide communication possible. Orbits had to be low because signals reflected from high altitude



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satellites would be too weak. Because the balloon satellites do not amplify the signals, ground stations have to have big antennas and high power transmitters.

Active Communication Satellites

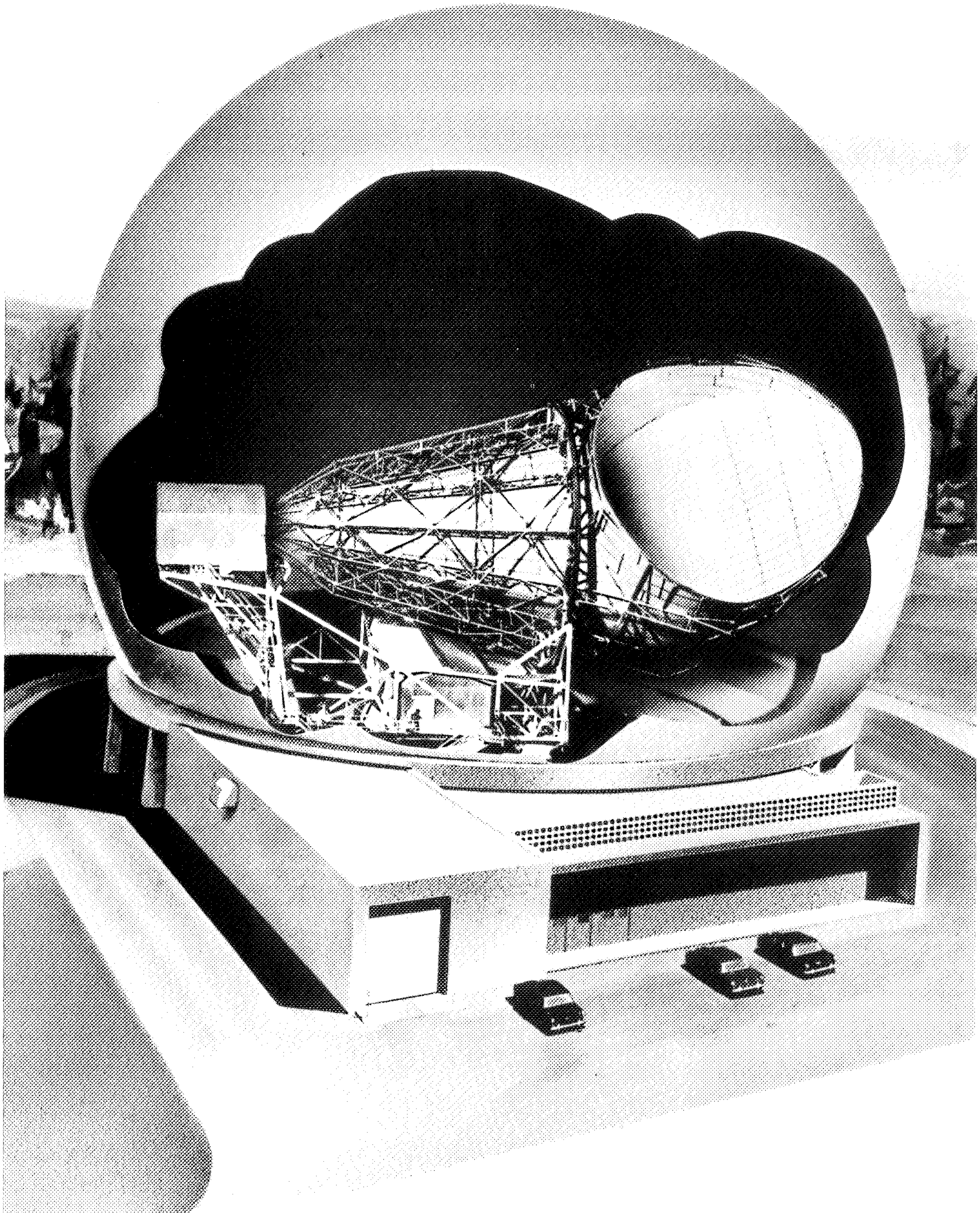
The U.S. Army in its perpetual search for more reliable and more secure long-distance communications built the first active communication satellite. SCORE (an acronym for Signal Communication by Orbiting Relay Equipment) was launched on December 18, 1958. SCORE relayed voice conversations, code, and teletype directly. The satellite also carried a tape recorder that stored messages and repeated them when triggered by a signal from the ground. President Eisenhower's 1958 Christmas message was carried around the world by SCORE in one of its more dramatic performances. Score ceased operation after twelve days.

The Army followed up its success with SCORE by orbiting Courier in 1960. Courier was a large satellite by U.S. standards; it weighed 500 pounds. It was covered with 20,000 solar cells, and carried four receivers, four transmitters, and five tape recorders. During its 18 days of active life, Courier received and retransmitted 118 million words.

Despite these successful demonstrations, the commercial feasibility of the communication satellite was unproven. How long could an active communication satellite operate? Should it be at high, low, or intermediate altitude? How many should there be? Three programs were designed to answer questions like these: the NASA Relay and Syncom programs and the joint NASA-AT&T Telstar program.

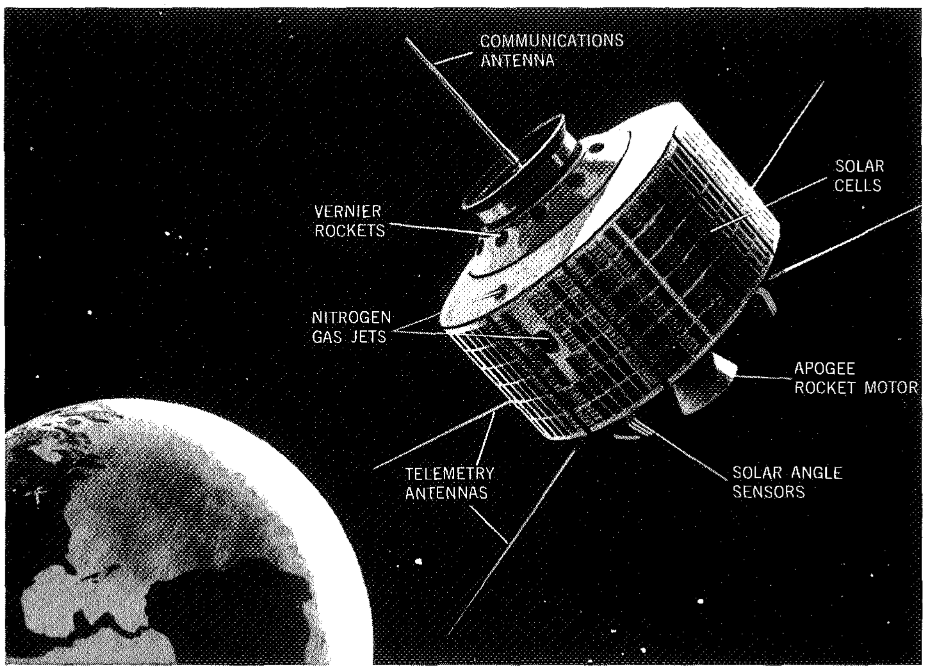
The Relays were medium altitude (about 4600 miles) active repeaters; while the Syncoms were injected into synchronous orbits at about 22,300 miles. The two Telstars were designed by AT&T, with NASA providing the launching rocket and the ground tracking facilities on a reimbursable basis. They were placed in orbits similar to those of the Relays. The Telstars foreshadowed the fact that the success of communication satellites would inevitably bring private industry into the picture.

When an engineer tries to answer a complex question like: What kind of communication satellite is best? he thinks in terms of tradeoffs. He can, for example, put his satellite in a higher orbit to gain a better view of the Earth's surface in trade for a loss in signal strength from the more distant satellite. Or, he can add more solar cells to the satellite to increase transmitter power at the expense of discarding one of the extra transmitters he wanted to make the



13 *A communication satellite ground terminal at Andover, Maine. The antenna consists of a large horn that collects the incoming radio waves. This facility belongs to the Bell Laboratories.*

14 *Artist's concept of the Syncom satellite.*



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satellite more reliable. What the engineer wants to do is optimize the entire communication system from ground station to satellite to ground station. Because communication is a salable commodity, optimization usually means transmitting the most information for the least cost in terms of satellites, ground facilities, and operations.

The question of communication satellite altitude provoked the biggest battles among the engineers. The altitude options were three: low (100 to 500 miles); medium (2000 to 12,000 miles); and synchronous (22,300 miles). Altitude buys visibility. Also, the higher the satellite the more slowly it moves from horizon to horizon and the easier it is to follow with antennas. The visibility of low orbit satellites was so poor that fifty to one hundred would be required for good worldwide coverage. Further, they would fly over so quickly that ground station operators would have to pick up a new satellite every few minutes. For these reasons, low altitude communication satellites were eliminated from the competition early.

By this reasoning, the synchronous satellites should have been adopted forthwith. With three synchronous satellites spaced equally around the equator, almost every inhabited spot on Earth would be covered. Ground station antennas could be aimed at the satellite and locked into position because synchronous satellites over the equator rotate at the same speed as the Earth and would appear to be fixed in space. Actually, the synchronous solution was not obvious because high altitude is good for some things but bad for others. To illustrate:

1. The launching and positioning of a synchronous satellite is difficult. The altitude has to be just right. To launch an equatorial satellite from Cape Kennedy, the launch rocket trajectory has to take the satellite south and then turn ("dogleg") when over the equator and inject the satellite into orbit.
2. Furthermore, once the tough synchronous equatorial orbit has been achieved, the satellite has to run continually just to stay in one place—

U. S. COMMUNICATION SATELLITES

Satellite	Launch Date	Injected Weight (lbs)	Orbit (miles) Apogee	Perigee	Remarks
SCORE	12-18-58	8750 [1]	914	115	First active comsat. Transmitted for 13 days.
Echo I	8-12-60	166	1052	941	First passive comsat. Relayed voice and TV.
Courier 1B	10- 4-60	500	767	586	Functioned 17 days. Active.
Telstar 1	7-10-62	170	3053	593	Medium altitude active comsat.
Relay I	12-13-62	172	4612	819	Medium altitude active comsat.
Telstar 2	5- 7-63	175	6713	604	Medium altitude active comsat.
Syncom I	2-14-63	86	22953	21195	In near-synchronous orbit. Communications lost at injection.
Syncom II	7-26-63	86	22750	22062	First successful synchronous comsat.
Relay II	1-21-64	172	4606	1298	Medium altitude active comsat.
Echo II	1-25-64	547	816	642	Passive comsat.
Syncom III	8-19-64	86	22312	22164	First Geo-stationary comsat.
LES 1 [2]	2-11-65	545	393	343	Air Force all-solid-state comsat.
INTELSAT I [3] (Early Bird)	4- 6-65	85	22733	21740	Owned by INTELSAT [3] Based on Syncom technology.
LES 2	5- 6-65	82	9384	1757	Air Force comsat.
LES 3	12-21-65	35	18000	100	Air Force comsat.
LES 4	12-21-65	115	20890	124	Air Force comsat.
IDCSP 1-7 [4]	6-16-66	100	all near-synchronous		Seven Air Force comsats launched together.
INTELSAT II F-1	10-26-66	190	23300	2020	Not in planned synchronous orbit.
INTELSAT II F-2 (Pacific 1)	1-11-67	192	22257	22254	For transpacific commercial service.
IDCSP 8-15	1-18-67	100	all near-synchronous		Eight Air Force comsats launched together.
INTELSAT II F-3 (Atlantic 2)	3-22-67	192	22254	22246	
IDCSP 16-18	7- 1-67	100	all near-synchronous		Eight Air Force comsats launched together.
INTELSAT II F-4 (Pacific 2)	9-27-67	192	22245	22220	
IDCSP 19-24	6-13-68	100	all near-synchronous		Eight Air Force comsats launched together.

1 *Includes last stage of launch vehicle.*
2 *LES = Lincoln Experimental Satellite, built by Lincoln Laboratory.*
3 *INTELSAT = International Telecommunications Satellite Consortium, an organization of more than 60 countries; also INTELSAT spacecraft.*
4 *IDCSP = Initial Defense Communication Satellite Program.*

just like Alice in Wonderland. Natural forces, such as the pressure of sunlight and the gravitational attraction of the Sun and the Moon, keep pushing the satellite from its assigned position. Keeping it in the same spot is called station keeping, and it is accomplished by small nozzles that squirt charges of cold gas whenever the orbit needs correcting.

3. Synchronous communication satellites are smaller than medium orbit communication satellites

because rocket payload is sacrificed to reach the higher altitude and perform the dogleg maneuver.

4. Signals relayed from 22,300 miles are some twenty times weaker than those from 4,000 miles, assuming the same transmitter power levels. In addition, there are significant propagation delays resulting from the fact that radio waves do not travel infinitely fast.

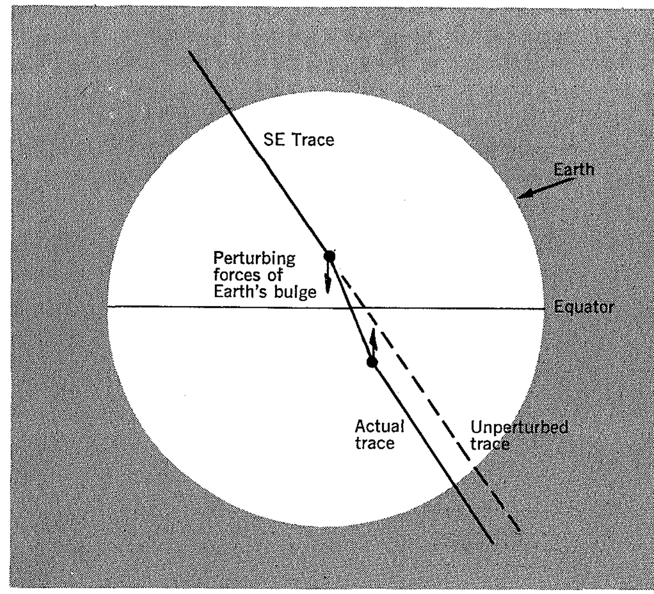
Despite these objections, synchronous communication satellites finally emerged victorious. The last half of the table on page 16 attests to the completeness of this victory. The NASA Syncoms paved the way by proving that synchronous orbits could be attained and maintained on an operational basis. Without this practical proof of feasibility, the debate might still be going on.

Once NASA proved the feasibility of the synchronous communication satellite, the technology was used by a commercial enterprise called the Communications Satellite Corporation—Comsat for short. Comsat was created by an act of Congress on August 31, 1962. It was formally incorporated on February 1, 1963. The large communication companies and the public hold stock in the Corporation, which is closely regulated by the Government.

Comsat's two major tasks were to establish an operational system of communication satellites and enlist the support of foreign governments in setting up international service. The latter was accomplished through organization of the International Telecommunications Consortium (INTELSAT) which now includes more than 60 countries. The Consortium owns the communication satellites, called INTELSATs. (See table, page 16.) Regular transoceanic service commenced in 1967, with synchronous communication satellites stationed over the Atlantic and Pacific oceans.

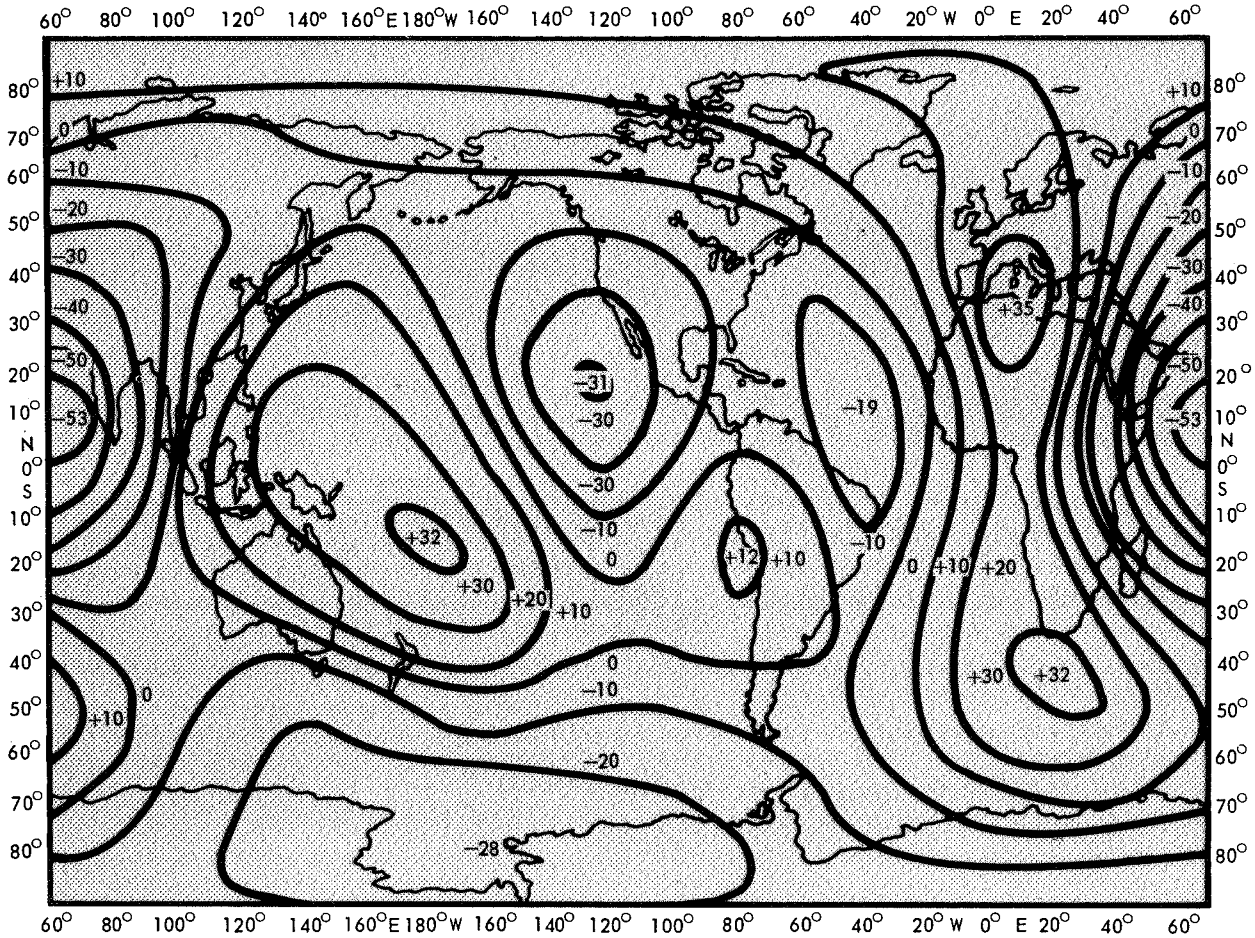
The Figure Of the Earth

Satellites have once more proved that the Earth is round, but how round is it? Answering this question is the first task of *geodesy*, the science that deals with the shape or "figure" of the Earth and the nuances of its gravitational field. The Earth's field is far from uniform. Large sections of the Earth's crust have different densities; heavier sections locally strengthen the Earth's field, lighter sections weaken it. Such differences in the gravitational field are termed "anomalies," and many are detectable by satellites. For decades, small-scale anomalies have guided geologists to local mineral deposits. Eventually satellites may be able to do the same. In addition to describing the shape of the Earth and the structure of its field, geodesy is concerned with accurately locating points on the Earth's surface with respect to one another. The precise whereabouts of points on the Earth is basic to map makers, navigators on ships and planes, and NASA itself, which must know exactly where its spacecraft tracking stations are located.



15 *The gravitational pull of the Earth's bulge deflects a satellite slightly westward each pass.*

The orbital path of a satellite is not a perfect ellipse. The satellite weaves sideways and up and down as it plies its course around the Earth. These small orbital



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perturbations are measured only in feet, but they can be detected by Earth-based tracking stations and made to reveal new facts about the Earth's structure. The larger the distortion of the globe, the bigger the effect on satellite orbits; for example, the equatorial bulge of the Earth causes the entire plane of the satellite orbit to rotate in space.

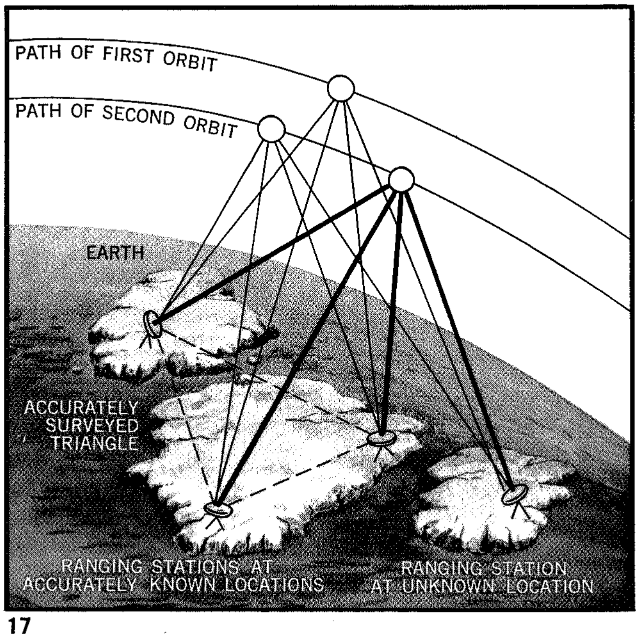
The bulge perturbation can be understood by considering a satellite approaching the equator from the northwest. The extra mass in the bulge gives it an extra southward pull. This deflects the satellite orbit into a more southerly path. After it passes over the equator, the bulge pulls the satellite north and straightens the orbit out. But it is too late, the plane of the orbit has already been shifted westward. To a ground observer the plane of a satellite's orbit seems to shift westward 15° each hour, as the Earth rotates under the orbit. The effect of the Earth's bulge is added to the 15° per hour. Other imperfections of the Earth, such as the inexplicable concentration of continental land mass in the northern hemisphere, cause other orbital perturbations that are superimposed upon the "normal" 15° per hour westward drift.

A geodesist needs extremely accurate ground-based tracking equipment that tells him where a satellite is at every moment. Tracking data will show perturbations from the ideal mathematical ellipse. From the total perturbation, he must subtract those deviations due to the pressure of sunlight on the satellite, the drag of the tiny amount of air remaining at satellite altitudes, and the gravitational attractions of the Sun and Moon. The remaining perturbations should be due to the Earth itself.

For high precision satellite tracking, NASA takes

16 *Map of the Earth's major gravitational anomalies expressed in terms of height above (+) or depression below (—) an ideal Earth shaped like an oblate spheroid. Contours are in meters.*

17 *In the Secor approach to tying geodetic grids together, known and unknown stations observe range of the same satellite simultaneously. The satellite is, in effect, a known landmark.*



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photographs of the satellite against the accurately known background of fixed stars with large Baker-Nunn cameras, operated by the Smithsonian Astrophysical Observatory. Localized perturbations to a satellite's orbit can often be measured better with radar or other radio equipment. For example, NASA has experimented with tracking satellites by laser. Explorers XXII, XXVII, and XXIX carried special reflectors that mirrored laser light flashes, permitting accurate range determinations. Eventually, lasers and high precision microwave equipment may be able to fix a satellite's position to within a foot or so.

Precision in satellite tracking leads to precision in terrestrial map making. On the North American continent, surveyors have laid out a grid enabling them to locate any point with respect to another to within about 30 feet. There are similar grids in other well-developed countries, but they are not tied together. A surveyor cannot see over the ocean with his transit to make the connections. The locations of many islands in the Pacific were not known to better than a few miles before satellites were developed. Again, it is satellite height that makes it a valuable tool. Observers several thousands miles apart can see a high satellite simultaneously. By making simultaneous measurements with optical and radio tracking instruments, they can determine just how far apart they really are. The current goal of satellite geodesy is to tie all geodetic grids together with an accuracy of 30 feet. The U.S. Army is expected to make important progress along this line with its Secor (Sequential Collation of Range) satellites. By island hopping across the oceans, using high satellites as geodetic markers, the world's continents will eventually be tied together to one common reference system.

Almost all satellites are valuable to geodesy. The most useful ones are those that are easy to track. The Echo communication satellites, for example, were very useful because they were so easy to see with optical instruments. Pageos is another balloon satellite orbited by NASA in 1966 specifically to help the geodesists. To help make truly simultaneous observations, flashing lights were installed on several "active" geodetic satellites. The lights flash in coded sequences so that widely separated ground stations can compare time exposure photographs taken against the background of the fixed stars. The Department of Defense satellite Anna 1B* carried the first optical beacon into orbit in 1962. Geos I (Explorer XXIX), launched November 6, 1965 by NASA also included a flashing light in its payload. Radio beacons of various types are placed on many satellites to aid tracking. NASA's two Beacon Explorers (Explorers XXII and XXVII) carried both radio beacons and laser reflectors. GEOS II (Explorer XXXVI), launched on January 11, 1968, is now fully operational. In addition to a full complement of geodetic instrumentation, it has C-band radar transponders to determine if the approximately 65 C-band radar tracking stations can track with geodetic accuracy. The preliminary results are far better than were expected.

The United States has centralized its satellite geodetic activities in the National Geodetic Satellite Program. NASA has overall responsibility, and the Departments of Defense and Commerce participate.

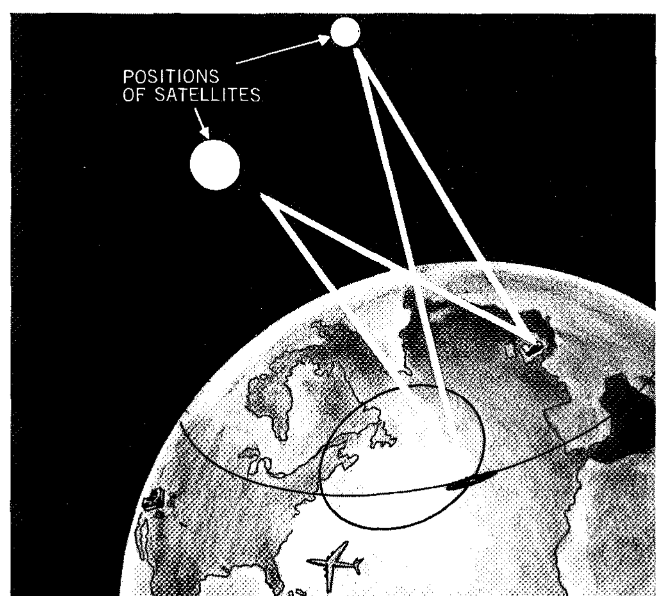
** Anna = Army, Navy, NASA, Air Force; the cooperating Agencies.*

Better Brick Moons

About a century ago, Edward Everett Hale wrote a short story entitled "The Brick Moon." In it, the hero proposed launching four satellites, 200 feet in diameter, into polar orbits passing over Greenwich, England, and New Orleans. The rockets of the 1870s could scarcely lift Hale's brick moons, so he hit upon the idea of flinging them into orbit with huge flywheels. Once the artificial moons were in orbit, navigators at sea could determine their longitudes by measuring the elevation of the moons above the horizon. It was a precocious plan, although Hale overlooked the fact that satellites cannot remain in orbit over a given meridian because of the Earth's rotation.

Today we need better brick moons to help aircraft and ships fix their positions to within a mile or two. Aircraft traffic is congested and safe control of this

18 *Navigators on the Earth's surface can locate themselves by measuring the ranges of two satellites in synchronous equatorial orbits. The navigator must be at one of the two intersections of the circles.*



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traffic depends upon pilots and traffic controllers knowing precisely where aircraft are located.

The U.S. Navy has already launched its system of navigation satellites: the Transit satellites. The Transit system is complex and expensive; too much so for commercial aircraft and ships. Nevertheless, its features are interesting because they offer ideas for economically practical systems.

A ground rule that makes the Transit system expensive is that a ship trying to fix its position should not transmit signals that would reveal its location to others. With this in mind, the satellite does two things for the ship navigator below:
(1) It transmits a radio signal at constant frequency so that the navigator can obtain a Doppler curve* and
(2) It transmits in code the latest information about its own orbit. This information was inserted in the satellite's memory when it last passed over a Transit ground station. From (1), a shipboard computer calculates the satellite's distance of closest approach. Knowing this distance, the orbital data relayed by the satellite, the time, and the ship's speed, the computer gives the navigator his position to within one mile.

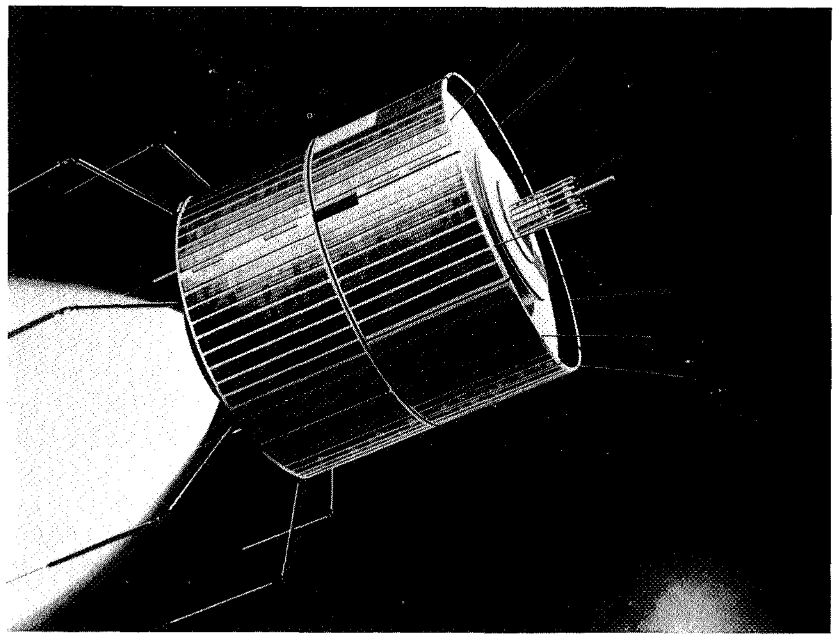
A less expensive plan of possible commercial interest would place satellites in stationary orbits above the equator where their positions would be relatively fixed and where they could be seen by most potential users. A navigator wishing to fix his position addresses satellite #1 by radio in a known code. Satellite #1 responds. By timing the transit of signals, the range of satellite #1 can be determined. Next, satellite #2 is addressed, and its range is found in the same way. If the navigator is on a surface vessel, he can now draw two circles on his map. Each circle is the locus of points at the just-measured range from the satellite. The ship is at one or the other of the two points where the circles intersect. Normally, the navigator can resolve this ambiguity from the knowledge that he is at sea rather than in the cornfields of Iowa. An airplane navigator, of course, needs his altimeter reading before he can draw his circles.

Another navigation scheme under study by NASA involves more difficult geometry. Imagine three satellites in stationary orbits over the equator. Satellite #1 (the *master* satellite) emits a radio signal. At two different, precisely known intervals afterwards, satellites #2 and #3 (the *slave* satellites) emit their signals. The signal cycle repeats, and the navigator receives sequences of three signals. Each signal contains information identifying the satellite that originated it. The true time intervals between signals from satellites #1 and #2, #1 and #3, and #2 and #3 are known, but the navigator will receive them at slightly

** A Doppler curve is a graph of the apparent frequency of the satellite transmitter. The frequency is higher when the satellite is approaching, lower when receding (like a train whistle).*

19 *ATS I carried a wide variety of weather, communication, and attitude control experiments.*

20 *THE ATS-I view of the Pacific basin from synchronous orbit (about 22,000 miles altitude.)*



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different intervals because of the different times required for the radio waves to flash from the satellites to the ship. Knowing these time discrepancies, he can calculate the *differences* between the distances of the three possible pairs of satellites from his ship. The locus of points which have a constant difference in distance from a pair of satellites is a hyperboloid. There is a hyperboloid for each of the three satellite-pair combinations. The navigator finds his position from the common intersection of all three hyperboloids. Though this approach sounds complex, it is really only an extension of a two-dimensional system used for ship navigation since World War II. This system is called loran (Long Range Aid to Navigation). There are many land-based loran master-slave transmitters in the better developed parts of the world. The proposed satellite navigation system extends the loran concept to three dimensions and, in the process, the rest of the world.

Testing Laboratory In Space

Once NASA has developed weather and communication satellites, the responsibility for operating them on a regular basis falls to other agencies of the Government or to private industry. However, NASA retains the job of finding better ways to do these tasks. Better cameras, better means for maintaining stationary orbits, better navigation transponders; all are typical of the new technology NASA is developing.

It often happens that the best way to test a new

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camera or any other piece of space hardware is to put it on a satellite and try it out. NASA has built a series of Applications Technology Satellites (ATS) for this purpose. The ATS satellites are multipurpose testbeds.

ATS I, the first in the series, looks like a large version of the Syncom communication satellite. It was launched on December 6, 1966 and successfully maneuvered into a synchronous equatorial (stationary) orbit over Christmas Island in the Pacific. The most dramatic results have been the remarkably sharp pictures of the entire Earth. From 22,300 miles up, the ATS special spin-scan camera has been able to take thousands of pictures of planet-wide circulation patterns in the atmosphere. Because the ATS I is fixed in one spot over the Earth, it has been able to provide long sequences of snapshots of weather showing the time development of convection cells, typhoons, and jet streams. In effect, ATS takes a movie of the weather over nearly 40% of the Earth, a perspective the lower, fast-moving TIROS satellites cannot see.

ATS I is also involved with the Weather Data Relay Experiment, more commonly known as WEFAX. The WEFAX experiment has demonstrated the feasibility of disseminating weather data from a central facility to widely scattered weather stations via a synchronous satellite relay. In other words, ATS I acts like a Syncom to relay weather satellite data.

Many communication experiments have also been conducted using the special radio equipment installed on ATS I. ATS I was the first satellite permitting two-way very high frequency (VHF) communication between aircraft and the ground—an important accomplishment for traffic control over the oceans and sparsely populated areas.

21 The U.S. Geological Survey has used Nimbus pictures to update and correct its maps of Antarctica. More advanced survey satellites will be capable of much greater resolution.

22 Schematic showing how satellites can be used to relay data taken by unmanned instrument platforms to centralized data collection points.

The payload of ATS II, launched April 5, 1967, also contained a wide variety of experiments and equipment. The primary objective was to test a gravity-gradient attitude control device. Also included were two weather cameras, a microwave communication experiment, and eight scientific experiments. Unfortunately, ATS II did not attain the desired circular orbit because the second stage engine failed to restart. Nevertheless, data were obtained from many of the experiments.

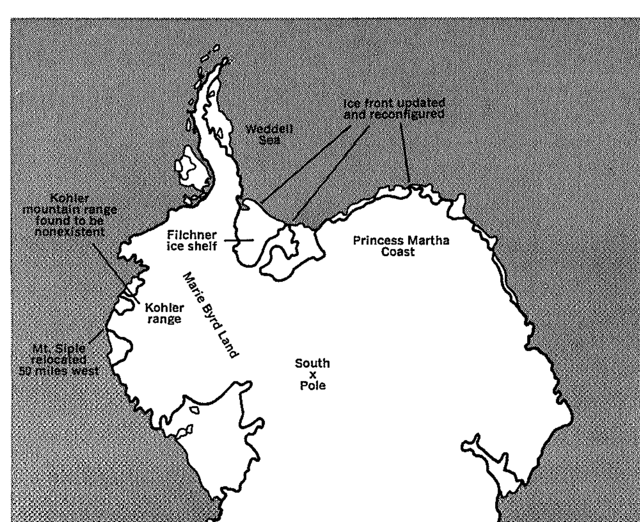
ATS III was launched November 5, 1967. Another spin-scan camera, able to take full color pictures, was carried along this time, plus an Image Dissector Camera System. The ATS role is to test such equipment for possible use on operational weather satellites. A third experiment concerns satellite navigation systems—more specifically the Omega Position Location Experiment (OPLE). The OPLE navigation concept is not directed toward aiding navigators aboard aircraft and ships but rather in the direction of locating unmanned instrument platforms sent out for the purpose of gathering meteorological and oceanographic data. OPLE can interrogate such instrument platforms for data and relay the data to a central facility. Eventually, however, OPLE could also be applied to air traffic control, since an airplane can also be thought of as a moving instrument platform.

The Earth: The Big Picture

From their vantage points 100 miles and more up, satellites can see large-scale patterns and phenomena that Earthbound observers cannot—either because they are too close to them or are actually immersed in the phenomena. Cloud patterns, already mentioned, are obvious examples, but we can add agricultural patterns, ocean currents, geological formulations, buried archeological sites, and many more.

One of our problems in studying the Earth is that we are too close to it; this is certainly the case in mapping large weather systems where high altitude meteorological satellites are unbeatable. Aircraft help some in seeing the Earth in the large, but satellites fly considerably higher and see the big picture much better. The questions are: What can satellites see of importance from so high up, and how can this information be put to practical use?

Besides scrutinizing the Earth below in visible light, satellite infrared and microwave sensors can scan the oceans and continents at longer wavelengths. The infrared and microwave radiation emitted by the Earth depends upon surface temperatures and the composition of surface materials. The use of infrared sensors on weather satellites to monitor atmospheric processes, such as the Earth's heat budget, has already been described, but the same sensors can also be used to study the Gulf Stream, detect forest fires, and locate subterranean heat sources.



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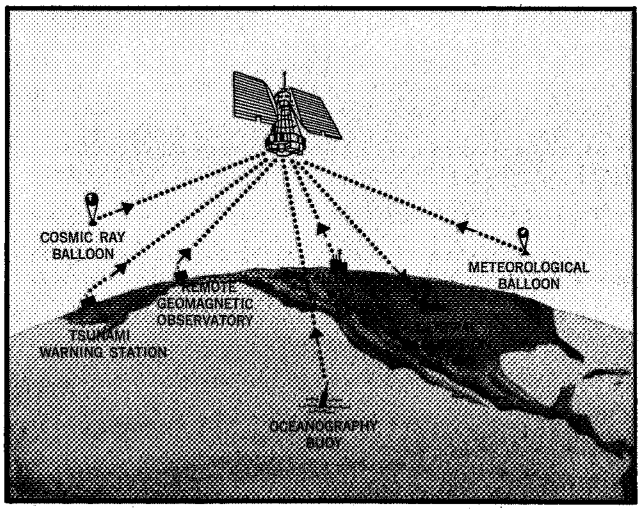

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The key elements in seeing more than weather from satellites are: (1) Look harder; that is, use more magnification; (2) Study the infrared and microwave emissions from the Earth; and (3) Subtract out the effects of the Earth's atmosphere. Once these things are done, some surprising possibilities emerge, although it should be stressed that considerable research and development work lies ahead before these applications can be realized.

Map preparation. Transportation networks and urban/rural settlement patterns, at some future time, may be quickly and economically mapped to facilitate highway and pipeline routing.

Agricultural census and crop prediction. Different crops may be identified by satellite sensors, leading to frequent and economical forecasts of the world's food supply. Furthermore, invasions of insects and disease may be spotted early and countermeasures organized on the basis of satellite data.

Detection of forest fires. Satellite infrared sensors may scan the forests in the U.S.

Water resource surveys. Satellites may help keep accurate inventories of fresh water supplies for the entire country. Droughts may be predicted and, eventually, water flow may be controlled to offset droughts. Satellite surveys may also help plan new dams and artificial watercourses.

Mineral resource surveys. Satellites may survey quickly and cheaply the huge areas of the world that are inadequately explored geologically. Satellites may identify particularly promising areas that it might take ground survey crews many years to find.

Discovery of archeological sites. For the same reason, buried cities, ancient roads, mound sites, and other partially obscured relics of past civilizations may be discovered.

Air pollution surveys. Like forest fires, sources of air pollution may be spotted from a satellite, mainly through the way they absorb light. The spread of pollutants under various wind and terrain conditions could also be studied with an eye to better control.

Location of hydrothermal energy sources. Infrared sensors may spot geothermal anomalies on the Earth, such as those at Yellowstone, where natural heat may be converted into electrical power.

Oceanography. Despite the more than 100 miles between an earth satellite and the sea, the satellite may turn out to be one of the most powerful oceanographic tools devised. Satellite cameras can monitor such factors as pollution patterns, beach erosion, river run off, and sedimentation patterns. Temperature patterns in the sea have already been distinguished by weather satellites, and knowledge of temperatures can improve the fish harvest. Wave heights can be mapped over large areas of the ocean by measuring the "Sun glint" off the sea surface. In a different vein, satellites can receive radio transmissions from large numbers of unmanned oceanographic buoys and relay their data to central land facilities.

The practical value of the satellite as a monitor and explorer of the Earth's surface is just beginning to be appreciated.

On the basis of preliminary conclusions drawn from studies and the results obtained from remote sensor experiments on aircraft, an Earth Resources Technology Satellite (ERTS) Program plan has been drafted by NASA in cooperation with several other interested departments and agencies of the Government. Testing of an early version of such an experimental satellite should be possible in the 1970s.

Additional Reading

For titles of books and teaching aids related to the subjects discussed in this booklet, see NASA's educational publication EP-48, Aerospace Bibliography, Fourth Edition.

Information concerning other educational publications of the National Aeronautics and Space Administration may be obtained from the Educational Programs Division, Code FE, Office of Public Affairs, NASA, Washington, D. C., 20546.

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