Significant Achievements in

Space Applications 1966

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Foreword

This volume is one of a series which summarizes the achievements made in the scientific and technical disciplines involved in the Space Science and Applications Program of the United States. The contribution made by the National Aeronautics and Space Administration is highlighted against the background of the overall progress in these disciplines. Succeeding issues will document the results from later years.

The achievements during the period 1958 to 1964 in the following areas were reported in NASA Special Publications 91 to 100: Astronomy, Bioscience, Communications and Navigation, Geodesy, Ionospheres and Radio Physics, Meteorology, Particles and Fields, Planetary Atmospheres, Planetology, and Solar Physics.

The achievements in 1965 in space science and applications were printed in two volumes, SP–136 and SP–135, respectively. The first summarized the significant progress made in Astronomy, Ionospheres and Radio Physics, Particles and Fields, Planetary Atmospheres, Planetology, and Solar Physics; the second summarized the significant progress made in Communications, Geodesy, and Meteorology.

This volume describes the significant achievements during 1966 in the following areas: Applications Technology Satellites, Communications Satellites, Satellite Geodesy, the Meteorological Program, and the Navigation and Traffic Control Satellite Program. A companion volume (SP–155) summarizes the progress in space science in 1966 in the following areas: Astronomy, Bioscience, Ionospheres and Radio Physics,

Particles and Fields, Planetary Atmospheres, Planetology, and Solar Physics.

Although we do not here attempt to name all those who have contributed to the NASA program during 1966, both in the experimental and theoretical research, and in the analysis, compilation, and reporting of these results, nevertheless we wish to acknowledge all the contributions to a very fruitful program in which this country may take justifiable pride.

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Preface

In 1966 the world, and the United States in particular, witnessed the establishment of the satellite as a useful tool for the benefit of humanity. During the year, satellites were employed operationally to support global programs in communications, meteorology, and geodesy. Other technological developments indicated that satellites could soon provide important benefits in navigation, traffic control, agriculture, forestry, transportation, geology, hydrology, oceanography, and geography. This document summarizes the year's achievements in satellite space applications and supplements the publication, *Significant Achievements in Space Applications 1965* (NASA SP-137). These advances mark the progress in developing space technology that will provide practical and economic benefits to all mankind. Activities include the development of space technology common to Earth-oriented applications generally and the development and flight testing of experiments and systems aimed at specific applications.

The Communications Satellite Corporation (COMSAT) completed its first year of commercial operation in 1966. Early Bird, the first satellite launched for COMSAT, operated successfully during the year and provided reliable and economical transoceanic communications between Europe and North America. Based on the Early Bird experience, COMSAT designed and developed improved communication satellites and ground equipment to provide communications links between North America and Europe and between North America and Asia.

NASA designed, developed, and launched three weather satellites for the Environmental Science Services Administration (ESSA) initiating the first operational weather satellite system. The Tiros Operational Satellite system provides daily observation of global weather during daylight hours. For the first time man can routinely detect and track hurricanes, typhoons, and severe extratropical storms on a worldwide basis. The U.S.S.R. also initiated a weather satellite program and began the exchange of satellite meteorological

data with the United States via conventional communications channels.

The successful launch of the first Applications Technology Satellite (ATS–I) significantly increased experimental capability at geostationary altitude. ATS–I experiments demonstrated the feasibility of two-way voice communications with aircraft, multiple-access communications techniques, trans-Pacific color television transmissions, nearly continuous observation of the Earth's cloud cover during daylight, and dissemination of weather data to simple, inexpensive ground readout stations. Nimbus II demonstrated observatory spacecraft capability for global observations of the vertical structure of the atmosphere and provided extensive data for meteorological research on atmospheric structure and circulation. Nimbus II operated successfully from the May 1966 launch until the end of the year and provided the best global data to date on the structure of the atmosphere.

In the area of geodesy, GEOS–I and PAGEOS contributed data required to establish a worldwide geometric reference system and to define the Earth's gravity field. The year's data were used to establish 12 of the desired 75 geometric reference datum control points and approximately 40 percent of the gravitational constants necessary to define the Earth's gravity field.

Gemini, Nimbus, and Tiros visual and infrared data revealed information on the natural and cultural features of the Earth that will have potential use in geology, geography, agriculture, hydrology, and oceanography. The requirements of the user organizations are considered in planning and executing the space applications programs. Cooperative programs are being conducted by the Departments of Defense, Commerce, Interior, and Agriculture, and the Federal Aviation Administration.

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Applications Technology Satellites

INTRODUCTION

The potential of geostationary satellites for space applications was demonstrated by the Syncom and Intelsat satellites before 1966. The Applications Technology Satellite (ATS) program, established in 1964, is extending geostationary orbit technology with systematic improvements in stabilization, pointing accuracy, and spacecraft power, volume, and weight capabilities. The ATS series will extend the range of scientific and technological experiments that can be conducted in geostationary orbit and will provide the basis for operational satellite development in the 1970's. This section describes 1966 geostationary satellite achievements that will lead to attainment of the program's objectives.

The overall objective of the ATS program is to develop space technology that is common and unique to general satellite applications. The program is directed toward space applications in the higher altitude and geostationary orbits. The specific objectives of the program are discussed below.

Development of Satellite Applications Technology

A number of mission characteristics apply to practically all space applications disciplines; all require Earth orientation and some degree of pointing accuracy. Required orbits are circular and either polar or equatorial. Orbital altitudes are either stationary or intermediate with one exception. Economic considerations dictate an operating life of a few years, in most instances, with generally high satellite electrical power requirements.

Development of Geostationary Orbit Technology

A satellite in geostationary orbit is advantageous for applications that require continuous, wide-area coverage and a closely-spaced sequence of observations of a specific area. The present ATS flight program is directed toward developing a station-keeping capability

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and a modest pointing accuracy, adequate for coverage of the Earth's disk. A satellite in geostationary orbit is exposed to two principal perturbing forces: one causes the satellite to drift east or west in the equatorial plane (except at two stable points), due to the elliptical equatorial section of the Earth; the other causes the satellite to drift north or south of the equatorial plane, due to gravitational force on the satellite by the Moon and Sun. The use of thrust on a satellite to counter the effects of these forces is called station-keeping. East-west station-keeping has been demonstrated by Syncoms II and III and Intelsat I; however, north-south station-keeping requires approximately 20 times more energy than east-west station-keeping. ATS-I and ATS-C will demonstrate north-south station-keeping.

Multiple-Discipline Experimentation Capability

The ATS provides an order of magnitude increase in weight capability at the geostationary altitude. Each satellite can accommodate a number of sensors and radiating devices, which can be positioned for Earth viewing. Data storage and transmission systems are being developed to provide a data storage capability on the satellite and subsequent transmission to the ground readout stations, or for continuous data transmission between the satellite and the ground control stations. The increased ATS capabilities permit flight testing several experiments from one or more application disciplines on each satellite, which results in cost reduction and permits the comparison and correlation of data collected by complementary and mutually supporting instrumentation.

ATS FLIGHTS

Background

Development of second-generation geostationary satellites was continued during 1966. These satellites will have improved, lighter weight structures; increased power supplies; and improved stabilization, pointing, and station-keeping techniques. These technological improvements provide the basis for conducting advanced experiments in such disciplines as communications, navigation, and meteorology.

ATS Flight Objectives

During 1966, the first ATS was successfully flown with improvements in performance and increases in the capability of geostationary

satellites as a test platform for conducting space applications experimentation. The satellite is providing data that will be useful in operational evaluation and research in communications, navigation, meteorology, and the space environment at equatorial synchronous altitude. The ATS program includes five flights—four at geostationary altitude and one at an intermediate altitude. The objectives of the five flights are as follows:

(1) Investigation and flight testing of technology common to a number of space applications

(2) Investigation and flight testing of technology for the stationary orbit

(3) Development and flight testing of a gravity-gradient stabilization system

(4) Development and flight testing of experiments for several satellite applications.

ATS–I, launched on December 6, 1966, is a spin-stabilized satellite, weighing 352 kilograms in orbit, and is in an equatorial synchronous orbit at 151° W. longitude. From this position the satellite can communicate with and/or view 42 percent of the Earth's surface. An Atlas Agena launch vehicle placed the satellite into a highly elliptical transfer orbit, and the firing of the apogee kick motor (an integral part of the spacecraft) resulted in a nearly circular synchronous orbit.

Results

Achievements In Spacecraft Technology

ATS–I is similar in shape to the Syncom satellites. However, it is much larger and carries a broad range of scientific and technological experiments.

Structure

The spacecraft is generally cylindrical with a 147-cm diameter and 135-cm length. The primary structure is a central thrust tube with adapter attachment provisions at the aft end. The spin axis coincides with the cylinder axis. The cylindrical surface is covered with solar cells except for openings for the experiments. The microwave antenna protrudes from one end of the cylinder; and the nozzle of the apogee kick motor, from the opposite end. Eight whip antennas are spaced equally around the periphery at each end of the structure.

Electrical Power Supply

The power supply consists of solar cells, storage batteries, and voltage regulators. Solar energy is converted to electrical energy by 22 000 N-on-P silicon solar cells, initially supplying 185 watts of power. The power is expected to drop no lower than 125 watts after 3 years in orbit. The storage system consists of two nickel-cadmium batteries that provide a total storage capability of 12 ampere-hours. The batteries power the satellite when it is out of the sunlight or when transient peak loads are required.

Reaction Control System

The reaction control system consists of a nitrogen spin-up unit for spacecraft stabilization and two redundant hydrogen peroxide units for orienting the spacecraft and placing it on station in a circular synchronous orbit directly over the equator. The nitrogen spin-up unit operated successfully, achieving a spin rate of 97 rpm versus a nominal spin rate of 100 rpm. One thruster jet in each hydrogen-peroxide system fires parallel to the spacecraft spin axis, while the other fires perpendicular to the axis.

All thrusters can be operated in a pulsed or a continuous mode. Operation of an axial thruster in the pulsed mode provides a method to change the orientation of the spacecraft spin axis. If one or both axial thrusters are operated in the continuous mode, they will impart a velocity increment to the spacecraft along the direction of the spin axis. The spacecraft has been oriented successfully and placed at the desired station location.

Technology Experiments

Communications

The spacecraft communications system consists of microwave communications transponders with traveling-wave-tube, final-power amplifiers, providing multiple-access and frequency translation modes of operation and employing directive antennas for reception and transmission. A VHF communications transponder with a directive antenna array for reception and transmission is also included. The microwave communications frequencies are in the 6000-MHz band for ground-to-spacecraft transmissions and in the 4000-MHz band for spacecraft-to-ground transmissions. An electronically despun antenna produces a highly directional radio beam pointed continuously toward the Earth. The beam is elliptical, diverging about 18° north

and south and 23° east and west. The net gain of this beam is approximately 14 decibels, an order of magnitude greater than a system without a despun antenna. Successful tests have been conducted in all three modes of operation—wide band, multiple-access, and frequency translation.

Good quality television signals have been received at all ATS ground stations and in Japan.

Experimentation has consisted mainly of back-to-back transmission of test patterns and frequency response measurements. Good-quality spin-scan camera transmissions, in the wideband mode, have also been demonstrated.

A number of tests have been conducted in the multiple access mode with all ATS ground stations. Ground equipment problems, however, have resulted in limited test success. The ground equipment is being modified to correct the problems, and additional tests are planned.

The VHF communications transponder is an active frequency translation repeater that receives in the 149-MHz range and transmits in the 135-MHz range without a modulation change. An eight-element phased-array antenna system is phased on both the receiving and transmitting frequencies. Two-way voice communications between aircraft in flight and the ATS ground control station and between two aircraft have been conducted successfully, using off-the-shelf aircraft hardware. Improved communications hardware for aircraft is under development and formal VHF communications experiments will start during the first half of 1967.

Weather Data Relay Experiment

The ATS–I VHF transponder is also used to relay, in facsimile format, processed weather data and spin-scan camera pictures from the ATS Mojave ground station to the local APT ground stations within the satellite's communications range. The data format is compatible with the APT picture data rates and signal strengths; and with minor modifications, any ground station equipped to record APT cloud cover pictures can receive these transmissions. Forty-eight APT ground stations have participated in the test transmissions, and most have received good quality weather facsimile pictures.

Spin-Scan Camera Experiment

The Suomi spin-scan camera experiment first provided pictures on December 9, 1966, and continues to operate successfully. The ex-

periment is described in more detail in the Meteorological Satellite Program section.

Nutation Experiment

The ATS–I nutation sensor consists of two ultrasensitive, low-frequency piezo-electric accelerometers mounted near the spacecraft periphery with the sensing axes parallel to the spin axis. The accelerometers are mounted approximately 90° apart around the circumference of the spacecraft to detect any ellipticity in the nutation (wobble about the spin axis) cone that could result from slight differences in pitch and yaw moments of inertia. This sensor is capable of measuring nutation angles from 0.001° to 5°. Spacecraft nutation has been below the sensor threshold limit. The hydrogen-peroxide axial jets were operated to induce nutation, and the sensor data indicated that the nutation angle dropped from 0.20° to 0.09° within 3 minutes.

Scientific Experiments

ATS–I carries six scientific experiments that will provide data on the orbital environment and the effect of this environment on the satellite. These experiments will also provide data to study magnetic storm disturbances at one longitude.

The environmental measurement experiments are performing as planned and data are being collected on a continuing basis. NASA collects and records the data; scientific investigators analyze and interpret them. Evaluation of environmental effects on satellite performance and lifetime requires measurements over an extended period. Thus, additional data are required to define the space environment of the geostationary orbit and to determine its effects on satellite components.

Suprathermal Ion Detector

The suprathermal ion detector experiment measures positive ions from 0.25 to 50 eV per unit charge in 20 different energy channels. The experiment's primary objective is to determine particle flux as a function of the ion direction of arrival. The principal investigator is J. W. Freeman, Jr., of Rice University.

Omnidirectional Electron-Proton Detector

This sensor detects electrons in the 0.1- to 1.4-MeV energy range and protons in the 5- to 40-MeV range to determine the omnidirec-

tional fluxes and particle spectra. The principal investigator is G. A. Paulikas of Aerospace Corp.

Electron Magnetic Deflection Spectrometer

The electron magnetic deflection spectrometer measures the electron flux in the energy intervals 45 to 150 keV, 150 to 500 keV, and 500 keV to 1.0 MeV. The principal investigator is J. R. Winckler of the University of Minnesota.

Multiple-Element Particle Telescope

A silicon junction particle telescope detector measures electrons, protons, and alpha particle spectra in the following energy ranges:

Particle	Energy, MeV	Number of ranges
Electrons................................	0.4 to 1.2	2
Protons..................................	0.7 to 100	6
Alpha....................................	1.8 to 85	5

The principal investigator is W. L. Brown of Bell Telephone Laboratories.

Magnetometer

The magnetometer experiment provides measurements of the magnetic field environment that can be used for resolving the field into two orthogonal components—one parallel to spacecraft spin axis and one perpendicular to the spin axis. The principal investigator is P. J. Coleman, Jr., of the University of California, Los Angeles.

Ionospheric Beacon

The ionospheric beacon experiment provides data to determine the magnetospheric electron density by measuring the variation in received signal polarization from two phase-coherent beacon signals in the satellite (one at 135. 6 MHz and the other at 406. 8 MHz). The principal investigators are O. K. Garriott and O. G. Villard of Stanford University.

SUMMARY AND CONCLUSIONS

ATS–I has demonstrated that a large, multipurpose satellite can be placed in geostationary orbit. In addition, improvements in propulsion and station-keeping systems have provided the capability to place

and maintain a large spacecraft at a planned location. The nutation damper has provided a method for reducing the spin-axis angular perturbations to less than $0.001°$.

Available spacecraft electrical power, weight capacity, and volume have made it possible to carry an increased number of experiments. Two-way voice communications with aircraft, multiple-access experiments, and color television transmission have been accomplished. The spin-scan camera experiment has provided pictures of the Earth's disk every 20 minutes. The satellite's VHF transponder has transmitted weather data to the APT ground stations. Six scientific experiments are providing environmental data at synchronous altitude. Additional ATS launches will continue to improve spacecraft and applications technology.

ATS–I is important to several areas of space applications. For this reason, additional references to the ATS–I satellite are made throughout this report.

COMMUNICATIONS SATELLITES

Communications Satellites

INTRODUCTION

Space communications activities during 1966 included the first Applications Technology Satellite (ATS–I) communications experiments, additional launches for the Communications Satellite Corporation (COMSAT), continued supporting research and technology effort to advance the satellite communications capability, and a reduced experimentation level with orbiting communications satellites. These efforts contribute to attaining the program objectives.

The overall objective of the communications satellite program is to ensure the technological development required for establishing future communications satellite systems and to fulfill NASA's responsibilities under the 1962 Communications Satellite Act. To accomplish the first part of the overall objective, four specific objectives have been established.

Multiple-Access Techniques

Spacecraft-to-aircraft voice communications are necessary in the radio spectrum VHF range. Multiple- access techniques are needed for a large number of aircraft or small ground terminals to communicate simultaneously via the satellite. The first experimental tests in these areas were conducted on ATS–I.

Deep-Space Communications

Communications with interplanetary probes operating deeper into space and enhanced communications with spacecraft operating around the Moon and on other relatively nearby missions will become a frequent requirement. Wideband real-time color television coverage would be desirable for some missions and perhaps mandatory for others. Millimeter and submillimeter wavelength techniques are being investigated because these wavelengths can support the required bandwidths and provide highly directive beams. Com-

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munications are required between explorers on the lunar surface and the lunar orbiting spacecraft, including those times when the spacecraft or the surface explorers are on the backside of the Moon.

Frequency Utilization

For all our space missions, there are distinct limitations on our present and potential capability for space applications: uncertainties in the noise environment and in propagation effects and anomalies, difficulties in obtaining frequency assignments except on a shared or noninterference basis, and problems in the efficient use of existing frequency assignments. Earth-space communications are currently limited to the range between 0.1 and 10 GHz; use of frequencies above 10 GHz could alleviate sharing and interference problems and provide space communications to meet future needs.

Radio and Television Broadcast Satellites

The use of satellites for direct voice transmission to home receivers offers many advantages over conventional broadcasting methods. Voice broadcasting of high frequency or VHF modulation programs via satellites offers a technique for overcoming range limitations and for providing strong signals in fringe, rural, and mountainous areas. Use of satellites for distribution of video programs to community television systems is another application that could be developed. The ultimate or long-term goal in the satellite communications area is direct television broadcasting to standard home receivers. This capability requires significant advances in space technology, such as the deployment of large antennas in space, precise attitude-control and station-keeping techniques, and very large power sources for use on satellites.

COMMUNICATIONS SATELLITE MISSIONS

Background

As the year 1966 opened, the United States had in orbit five working active communications satellites and two passive communications satellites: Echos I and II, Telstar II, Relays I and II, and Syncoms II and III. During 1966, in addition to ATS–I, a partially successful commercial satellite, the Intelsat II F–1 (Lani Bird) was also launched. At the end of 1966, five out of the six experimental and two commercial communications satellites were still working.

NASA Research and Development (R&D) Communications
Satellites

Echos I and II

Echos I and II remained in orbit through 1966. Although communications experiments were minimal, occasional observations were made to study the satellites' orbital perturbations.

Telstar II

Telstar II functioned satisfactorily throughout 1966, but it was seldom observed after the conversion of the American Telephone and Telegraph Company ground station at Andover, Maine, to Early Bird commercial operations.

Relays I and II

Relay I ceased operating on February 11, 1965, after 26 months of useful life. Relay II continues to function satisfactorily, although its experimental uses are minimal.

Syncoms II and III

Syncoms II and III continued to operate satisfactorily during 1966, although Syncom II exhausted its propellant in February 1965.

ATS–I

The ATS–I was launched in December 1966. It is in a stationary orbit at 151° W. longitude, with a viewing area shown in figure 1. The spacecraft is producing the designed prime power of 185 watts from its 22 000 solar cells. The VHF–FM repeater translator permits voice communications between a ground station and aircraft in flight. Experiments are also planned to use the 600-channel duplex repeater capability which receives single sideband (SSB) signals in the 6-GHz frequency range and converts the SSB into phase modulation in the 4-GHz frequency band for the downlink. This configuration will permit experiments to demonstrate a multiple-access capability. The unique electronically-despun phased-array antenna system keeps the antenna beam pointed toward the Earth even though the spacecraft body is spinning.

Communications Satellite Corporation Activities

NASA launched the first commercial communications satellite, Intelsat I (Early Bird), for COMSAT on April 6, 1965. This satellite continues to provide commercial communications services across the Atlantic.
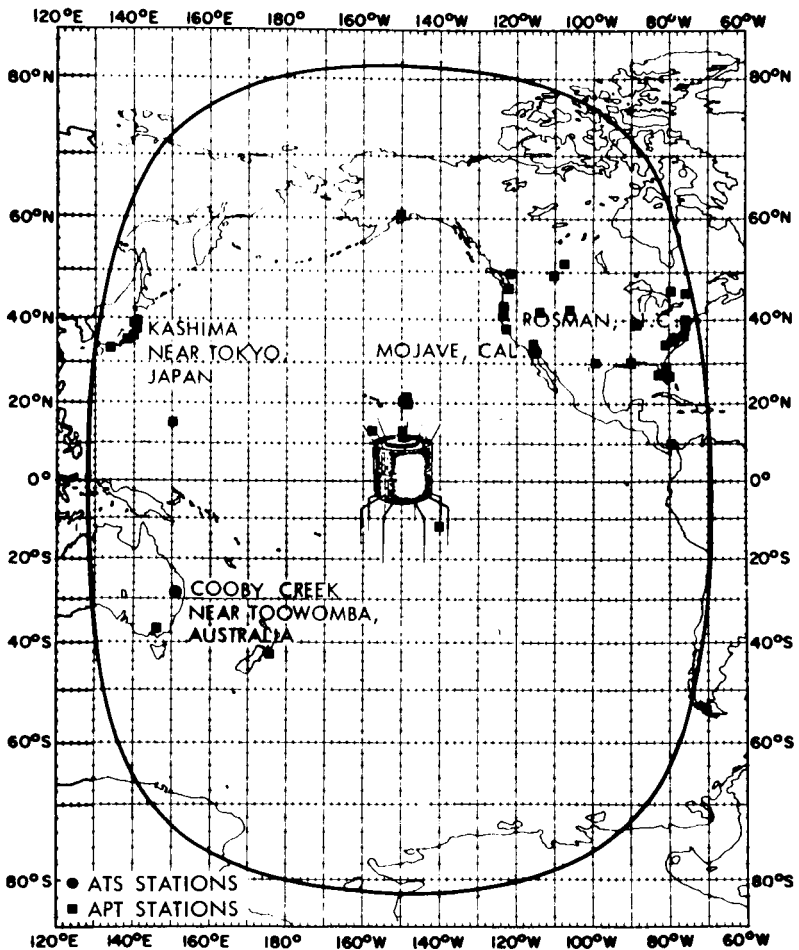
Figure 1.—ATS–I global reception area.

On October 26, 1966, NASA launched Intelsat II–1 for COMSAT. This satellite is the first in a series of second-generation commercial communications satellites. Although Intelsat II–1 failed to achieve a synchronous orbit, it was used several hours each day for commercial communications services between the U.S. mainland and Hawaii. Two additional Intelsat launches are planned early in 1967: one to be positioned over the Atlantic Ocean and the other over the Pacific Ocean. Both satellites will be placed in equatorial synchronous orbit and will provide commercial services and support for the Apollo program.

Foreign Communications Satellites

During 1966 the U.S.S.R. launched two more first-generation experimental communications satellites, Molniya–I–3 in April and Molniya–I–4 in October. Like their two predecessors, these satellites were placed in highly elliptical orbits with apogees of almost 40 000 km. Apogee occurs at, or near, northern culmination of the orbit, which is inclined approximately 65°. Each of these satellites is visible throughout the U.S.S.R. during the 12-hour daily orbit period. With these satellites, communications and television experiments were continued within the U.S.S.R., as were television demonstrations with the French ground station at Pleumeur-Bodou. Molniya–I–3 also carried experimental cameras, reported to be similar to those in the Cosmos meteorological satellites, which took pictures of the Earth's cloud cover from altitudes of 30 000 to 40 000 km.

During 1966 several proposals were advanced for other regional or domestic communications satellite systems; for example, the French proposed a satellite serving Europe and Africa and possibly South America, and the Japanese proposed satellites for domestic service and for coverage of Southeast Asia. None of these proposals, however, had advanced beyond the discussion stage in 1966.

SUMMARY AND OUTLOOK

The capability for providing high-quality satellite communications links for voice, television, and data traffic transmission between sophisticated and expensive ground stations has been developed, demonstrated, and reduced to commercial operational practice. Refinement and use of that capability is being carried out by COMSAT. The NASA communications satellites program is progressing in the development of techniques for satellite communication using simpler and cheaper ground stations with several links in simultaneous use. The use of different frequency bands, such as the VHF for voice communications with aircraft, is being investigated, as are the possibilities for satellite communications offered by frequencies above 10 GHz. ATS–I provided a test bed to conduct two-way voice communications with aircraft, multiple-access experiments, transoceanic color-television transmissions, and dissemination of picture, record, and digital data to simple, inexpensive ground readout stations.

SATELLITE GEODESY

Satellite Geodesy

INTRODUCTION

This section describes significant advances that were made in satellite geodesy during 1966 and highlights the contributions that satellites have made toward attaining the major objectives of the program. The aim of modern geodesy is to determine the size, shape, and gravitational field of the Earth and their variations in time. This implies the establishment of a unified Earth reference system, in which any point on the Earth's surface can be located accurately. Within the overall objective of the geodetic satellite program are three specific goals.

Geometric Geodesy

Satellite geodesy provides an opportunity to interrelate all geodetic datums on a worldwide basis. Preliminary results have reduced the uncertainty in the connections between several major datums. One of the first goals in this area is to determine geodetic station locations, within an accuracy of ± 10 meters, in a worldwide datum referenced to the Earth's center of mass and mean rotational axis. Islands and other places of interest that are difficult to position with ground-based techniques will also be geodetically tied to the world datum. The improvements planned will permit control point positioning in the world system with an accuracy of 1 meter. The ultimate goal is to generate a multitude of fiducial points in the world system for 1:25 000-scale mapping.

Gravimetric Geodesy

The gravimetric objective of the program is to define the Earth's gravity field (in spherical-harmonic representation to the 15th degree) and to pinpoint accurately the magnitude and location of significant gravity anomalies. Data obtained from satellites will provide the broad regional parts of the gravity field with wavelengths of the order of 1000 km or more; surface gravity data will provide local detail. The geodetic satellite program is directed toward determin-

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ing the values of coefficients of higher order and degree in the spherical-harmonic representation of the Earth's gravity potential. At the same time the values of known coefficients will be refined.

Earth-Science and Applications Support

The knowledge of the highly accurate position in space and time of geodetic satellites and the use of geodetic data gathering and processing techniques can provide investigative support in such areas as solid Earth geophysics and geology, meteorology and aeronomy, space dynamics and astronomy, and oceanography. These data would help to determine accurately continental drift, ice motion in Antarctica and Greenland, worldwide snow and ice accumulation and melting, time variability of ocean surface geometry, and locations of deep-space probe tracking stations.

GEODETIC SATELLITES

Background

At the beginning of 1966 the first three active spacecraft of the National Geodetic Satellites Program were in orbit. Explorers XXII and XXVII continued to provide useful Doppler and laser tracking data throughout the year. GEOS–I, launched in November 1965, was just beginning its anticipated 1-year active lifetime. In addition, many satellites whose prime objectives were other than geodetic studies continued to be used for geodetic purposes: for example, Echos I and II were used for geometric satellite geodesy and numerous others were used for gravimetric analyses.

Geodetic Satellites

GEOS–I

All GEOS–I systems remained fully operational from January 1, 1966, until December 1, 1966, thereby meeting and exceeding the original operational goals. On December 1, 1966, the main command unit malfunctioned, destroying a part of the geodetic observation capability (Doppler, range and range rate, and the flashing light). At the end of 1966, data continued to be gathered from the remaining tracking systems (SECOR electronic ranging and laser ranging). From November 1965 to November 1966, tracking data were obtained from 110 worldwide tracking stations, including several foreign participants.

PAGEOS-I

The large passive balloon satellite, PAGEOS, was successfully launched into a nearly circular, approximately 4250-km altitude orbit in June 1966, primarily in support of the planned Earth-centered worldwide geodetic network. At the end of 1966, NASA, the Smithsonian Astrophysical Observatory, and Coast and Geodetic Survey cameras were actively observing PAGEOS from a worldwide network of camera stations.

Results

The original objectives of the NASA Geodetic Satellites Program were threefold: geometric analysis, gravimetric analysis, and systems intercomparison. In 1966 the geometric geodesy program was concerned primarily with gathering the data required to establish a worldwide geodetic network. During the satellite's active lifetime, the flashing lights on GEOS–I were photographed in excess of 20 000 times. Optical and electronic data, reduced and processed, are now archived in the Geodetic Satellites Data Center at Goddard Space Flight Center, where they are made available to scientific investigators on request. At the same time that the data were being obtained, analytical techniques and programs for data analyses were being developed and were largely operational by the end of 1966. As a result of geodetic satellite observations, all Smithsonian Astrophysical Observatory camera stations have been positioned with respect to each other (ref. 1). U.S. Air Force cameras operating in the United States accurately established the positions of isolated islands with respect to the mainland, and Army SECOR stations completed trilateration networks to define local datums in the Pacific area.

During 1966 considerable improvement and refinement of the gravimetric field, obtained through satellite observations, resulted in a gravimetric field definition that is now in essential agreement with available surface data for gravity field components having wavelengths of approximately 2000 km or greater (ref. 1). Certain of the more detailed gravitational field components that have significant effects on the motions of close Earth satellites have also been defined. For example, orbital motions of GEOS-I have allowed definition of the 12,12 spherical harmonic, one of the gravitational field components having a wavelength of approximately 1500 km.

In 1966 a concerted effort was begun by the University of Hawaii, using surface geophysical methods, to examine in detail one of the

anomalous gravity areas revealed by the satellites. This study demonstrates the importance of satellite geodesy to surface geophysical work.

The improved definition of the gravitational field has permitted, during 1966, the beginning of a study of time-varying phenomena causing small variations in orbital motion of satellites. First results have been obtained from the study of the solid Earth deformation—the Earth tides—due to the attraction of the Sun and Moon (refs. 2 and 3). Correct definition of these tides will have an important bearing on understanding the strength of the Earth's interior. More complete information concerning gravitational effects on the orbits of satellites has allowed the determination of short-period variations in the air drag acting on satellites and, thus, the identification of short-period changes in the atmosphere (ref. 4).

One of the GEOS-I mission objectives was to conduct systematic intercomparisons of the operational and experimental tracking systems. Large scale, systematic, side-by-side intercomparisons involving the majority of geodetic tracking systems were obtained for the first time in 1966 (ref. 5). Comparisons have been made among various types of camera data, the Department of Defense SECOR electronic ranging system, and NASA's range and range-rate tracking system. These initial comparisons indicated no serious discrepancies among the various tracking systems. The agreement found among these diverse tracking systems gives added confidence in the overall systems accuracy. As analysis of the 1966 data continues, improved calibrations and detection of small systematic errors should allow even greater improvement in the accuracy of each tracking system. As a byproduct of these intercomparison studies, improved calibrations have been obtained for the NASA range and range rate and the minitrack optical tracking system (MOTS) (ref. 6). This should improve tracking to support the entire space program.

Using GEOS-I and Explorers XXII and XXVII, laser tracking systems were perfected during 1966 and are ready for operational use. The laser can possibly improve tracking accuracy by one or two orders of magnitude. Comparisons between camera and laser data support the expected camera inaccuracies, and the laser data obtained on single passes show random errors of, at most, a few meters. These facts indicate that the accuracies will, in fact, be achieved (ref. 7). Such increased accuracies are important for the future support of Earth sciences investigations.

During 1966, the first full year of operational observations, considerable progress was made toward meeting the primary gravimetric and geometric objectives of the NASA geodetic satellites program. Twelve of the 75 stations of the worldwide geometric network had been located with respect to one another, and approximately 40 percent of the constants required to define the gravity field had been determined. Large amounts of data had been taken which would, on analysis, further the primary objectives.

Future

Much of the data gathered in 1966 will be analyzed in 1967. Plans are underway for a vigorous observational plan using PAGEOS to allow sufficient data acquisition by the end of 1967 to establish an interim geometric reference network. GEOS–B is planned for launch in late 1967 or early 1968.

As the primary objectives of the geodetic satellites program are met, an increasingly important program application will be to provide support for the Earth sciences investigations. The establishment in 1966 of the possibility of achieving ranging accuracies of ± 1 meter provides important opportunities in determining glacier formation and dissipation, height of ocean surfaces, and precise tracking of deep-space probes. Indepth studies of these possibilities are planned to determine which are most promising and to establish mission requirements.

SUMMARY AND CONCLUSIONS

Systematic, side-by-side intercomparison of the various tracking systems used in the Geodetic Satellites Program were obtained for the first time in 1966. Comparisons have been made among various types of camera data, the Department of Defense SECOR electronic ranging system, and NASA's range and range-rate tracking system. These comparisons showed that the measurements obtained by the various systems were essentially in agreement. Tracking system calibration should improve tracking accuracy that will support the entire space program.

In the geometric geodetic area, the satellite observations have been used to tie together all the Smithsonian Astrophysical Observatory camera stations, to tie isolated islands off the southern coast of the United States to the mainland, and to define local datums in the Pacific area. Twelve of the 75 stations of the worldwide geometric network have been located with respect to each other.

The improved definition of the gravitational field has provided data for studying the deformation of the solid Earth—the Earth tides—due to the attraction of the Sun and Moon. Additional information concerning gravitational effects on satellite orbits has allowed the determination of short-period variations in the air drag on satellites and, thus, the identification of short-period changes in the atmosphere. The gravimetric field, as determined from satellite measurements, has been improved and defined and is essentially in agreement with available surface data for gravitational field components having wavelengths of 2000 km or greater. Approximately 40 percent of the spherical harmonic terms required to define the Earth's gravity field have been determined.

The development of the laser tracking system for geodetic purposes was a most significant achievement. The use of laser techniques seems to promise improvements of one or possibly two orders of magnitude in tracking accuracy. The achievement of ranging accuracies of ± 1 meter would permit the extension of geodetic satellite applications into geology, hydrology, geography, and oceanography.

REFERENCES

1. Smithsonian Astrophysical Observatory: Geodetic Parameters for a Standard Earth. Preprint of papers presented at 7th International Space Science Symposium (Vienna), May 14, 1966.
2. Kozai, Y.: Determination of Love's Number by Satellite Observations. Presented at the Discussion Meeting on Orbital Analysis (Royal Society, London), Oct. 1966.
3. Newton, R. R.: An Observation of the Satellite Perturbation Produced by the Solar Tide. J. Geophys. Res., vol. 70, no. 24, Dec. 15, 1965.
4. Jacchia, L. G.; and Slowley, J.: The Shape and Location of the Diurnal Bulge in the Upper Atmosphere. Smithsonian Astrophysical Observatory Special Report no. 207, Apr. 1966.
5. Berbert, J.: GEOS-A Tracking Systems Intercomparisons Experiment. Presented at 47th Annual Meeting, AGU, Apr. 1966.
6. Anon.: Evaluation of Range Accuracy for the Goddard Range and Range-Rate System at Rosman. NASA X–514–66–513, Oct. 1966.
7. Lundquist, C. A.: Results from Photographic and Laser Tracking Systems. Presented at XVIIth International Astronautical Federation Congress (Madrid, Spain), Oct. 15, 1966.

METEOROLOGICAL PROGRAM

Meteorological Program

INTRODUCTION

This section describes the space technological advances made during 1966 that are applicable to meteorology and summarizes the scientific results published during 1966 that were based on satellite and sounding rocket meteorological data. Accomplishments in previous years were described in references 1 and 2.

The general objectives of the meteorological satellite and sounding rocket program are to provide space technology which, with more conventional observational techniques, will increase knowledge and understanding of the Earth's atmosphere, improve weather forecasting ability over extended time periods, and provide a basis for appropriate weather modification and control experiments. Program expansion will provide the necessary technology for meteorological exploration of other planets in a manner similar to the systematic investigation of the Earth's atmosphere. The overall objectives include a number of specific objectives, which are discussed in detail in the following paragraphs.

Technology for Operational Meteorological Systems

The Tiros, Tiros Operational Satellites (TOS), and Nimbus satellites have demonstrated that meteorological satellites can provide periodic global observational coverage of the Earth. The objective of the research and development program is to develop the sensors and techniques to provide the quantitative three-dimensional data on the state of the atmosphere required by the meteorological community. Two methods to accomplish this objective are under development: remote satellite sensing of atmospheric parameters and the data collection from sensors immersed in the atmosphere and/or the surface and subsequent relay by the satellite to the ground readout stations. Furthermore, satellites operating in synchronous orbit (demonstrated by the first Application Technology Satellite (ATS–I)) can provide the required frequency of observations for detecting and tracking violent short-lived storms and other weather phenomena

that demand close monitoring. These observational data, combined with the development of atmospheric prediction models and the increased data-handling capabilities of electronic computers, place the meteorological community on the threshold of obtaining significantly increased accuracies in the areas discussed below.

Day-to-Day Forecasts

The first application of the satellite observing system has been the identification and tracking of meteorological phenomena such as hurricanes, typhoons, extratropical cyclones, and frontal systems. Such identification and tracking of storms is based on the observation of characteristic cloud signatures. The capability is needed for world-wide day and night observations. The satellite obtaining the data must be capable of delivering both stored data to appropriate ground readout stations for global analyses and direct readout data to simple, inexpensive ground equipment at local weather stations within the satellite's line of sight. The National Operational Meteorological Satellite System, initiated in 1966, provides daylight cloud observations to global and local users. The Nimbus High Resolution Infrared Radiometer (HRIR), in conjunction with the Automatic Picture Transmission (APT) system, has demonstrated the feasibility of local and global readout of nighttime cloud picture data, and this capability is being developed for incorporation into the TOS system.

Short-Period Forecasts

A short-period forecast requires nearly continuous viewing of short-duration weather systems. The size and lifetime of storms are related, the larger storms having durations measured in days and weeks and the smaller storms, such as thunderstorms and tornadoes, having durations of 2 hours or less. Also, the longer-lived storms may undergo changes in intensity over a short time. From an equatorial synchronous altitude, the ATS–I spin-scan camera experiment has demonstrated the feasibility of nearly continuous daylight observation of cloud formations. Additional developments are required to extend the capability to nighttime cloud viewing and to other meteorological parameters such as temperature, moisture, and radiative heat flux. A satellite at synchronous altitude can also be used to collect and relay weather observations and to disseminate weather information to the APT ground stations.

Extended Forecasts

The atmosphere is a single, unified system in which disturbances

can propagate around the world in as little as 3 or 4 days. To under-
stand and predict the future state and behavior of the atmosphere
beyond 1 or 2 days, it is necessary to know the present state or initial
condition of the atmosphere over the entire globe. This includes both
the thermodynamic structure and the heat budget of the atmosphere.

General mathematical and physical relationships governing
weather predictions have been known for some time and electronic
computers capable of handling large quantities of data could be made
available; however, the meteorologist has been restricted by the lack
of adequate, properly distributed, observational coverage. The
meteorological satellite provides a means of obtaining global three-
dimensional measurements of atmospheric parameters. When com-
bined with conventional observations, satellite-acquired data will pro-
vide a basis for weather predictions as much as 2 weeks in advance.

Participation in Weather Modification and Control

The meteorological program is providing information that will
improve understanding of atmospheric processes. Thus, the program
is helping to establish a scientific basis for atmospheric modification.
It is expected that during the next decade, newly obtained informa-
tion will lead to an increased understanding of atmospheric behavior.
When this occurs, it will be reasonable to consider the study and
design of experiments and the flight of systems in space to attempt the
local or regional modification and control of weather. Conducting
large-scale experiments will require major advances in technology and
in the understanding of the consequence of such experiments.
Whether these experiments are conducted by NASA or by other agen-
cies and nations, it will be necessary to observe in detail the initial
state of the atmosphere and to monitor the effects of the experiment.
The spacecraft systems and technology being developed for opera-
tional satellites are essential for obtaining such detailed observations.

Planetary Meteorology

Data on the planetary atmospheres are important in their own
right and as guides to the history of planetary bodies. However, suffi-
cient meteorological information must be available to permit safe,
effective manned exploration and operation on the planet.

Before a manned landing, the first measurements will be obtained
from flyby and individual probes. Later, the atmospheric circula-
tion and meteorological element variation will be investigated to in-
crease our knowledge of the planet and to provide information for

planning a future manned landing on the planet. Techniques and experiments for measuring the state and structure of the Earth's atmosphere will provide a basis for investigating the atmosphere of other planets, for example, the Martian atmosphere.

Exploration and Study of the Atmospheric Region Between 30 and 100 km

Studies and investigations based on past rocket measurements have confirmed that dynamic and thermal conditions in this region may play an important role in the meteorology of the lower atmospheric regions. The conventional balloon-radiosonde technique is limited in altitude to about 30 km. The minimum altitude for satellites is about 160 km. Rocket-borne techniques must be considered for the systematic sounding of the atmosphere above 30 km. Additional rocket-borne measurements are required to explore and study temporal and spatial variations of the circulation, the sudden stratospheric warmings, the influence of tidal forces, and the effects of solar variations in the region. From an applications point of view, a knowledge of the variations in this region is required for space vehicle design constraints, not only during launch, but also for the return of the spacecraft and its reentry into the Earth's atmosphere.

To permit the extension of observational stations to locations other than those existing at the national rocket ranges, economical, safe, and simplified rocket sounding systems must be developed. Cooperative meteorological sounding rocket programs with other nations will be continued. Thus, data useful to NASA and the scientific community are obtained over various parts of the world through the sharing of effort and resources.

METEOROLOGICAL SATELLITES

Background and Objectives

During 1966 the effort, initiated in previous years, continued to determine which meteorological parameters are best measured using satellites to develop the sensors to make the measurements, to test the systems and sensors in space, to develop the analyses and interpretative techniques for satellite data, and to develop methods of integrating these data into the diagnostic and predictive routines of the weather services. During the year, three TOS satellites were launched successfully for the Environmental Science Services Administration (ESSA), initiating the National Operational Meteoro-

logical Satellite activity. Nimbus II, the world's most sophisticated R&D satellite was launched, achieving or exceeding all its design specifications. Its performance gives every assurance that the Nimbus program will provide the capability for regular and dependable sounding of the global atmosphere.

In addition, the successful performance of the ATS–I spin-scan camera established the feasibility for the nearly continuous observation of the Earth's weather from synchronous altitude satellites. The meteorological data obtained by satellites is still used extensively by meteorologists for operations and research.

The Meteorological Satellite Program consists of the Tiros, TOS, and Nimbus satellites, and meteorological experiments on the ATS. The immediate objectives of these experiments continue to be:

(1) Development of satellite systems, equipment, and techniques and satellite launchings directed toward additional and improved methods of observing atmospheric meteorological parameters and increasing understanding of the atmosphere.

(2) Cooperation with ESSA in establishing and supporting an operational meteorological satellite system.

(3) Participation in conjunction with ESSA, other government agencies, and the World Meteorological Organization in developing and establishing the World Weather Program, including the Global Meteorological Experiment and the World Weather Watch.

Meteorological Satellite Program

Tiros

During 1966 Tiros VII, VIII, IX, and X continued to operate successfully in orbit and were capable of providing a limited amount of meteorologically useful information.

Tiros Operational Satellite (TOS)

The world's first operational weather satellite system was initiated in February 1966 with the launch of two TOS satellites (ESSA I and ESSA II) for the ESSA. ESSA I is a cartwheel-configured satellite similar to Tiros IX and provides stored global pictures to the two TOS Command and Data Acquisition (CDA) stations. The remote data received at the CDA stations are transmitted over wideband communication links to Suitland, Maryland, where they are processed and used by ESSA in conjunction with conventional data for preparing daily weather analyses and forecasts.

ESSA II is a cartwheel-configured spacecraft which furnishes

users with APT pictures of their local area. With the addition of the local readout capability, the TOS system met the total requirement for full daytime operation.

One of the cameras on ESSA I failed in July 1966, and ESSA requested NASA to launch TOS–A (ESSA–II) in September 1966, if possible. ESSA III, launched successfully on October 2, 1966, provides excellent quality pictures from the redundant advanced vidicon camera systems (AVCS). (The AVCS and APT cameras were developed and tested in the Nimbus R&D program.) The additional spacecraft in the TOS system are being developed and qualified to maintain full-time operations. Future TOS launches will be scheduled to ensure continuous operation of one spacecraft with picture-storage capability and one with APT capability.

Nimbus

Nimbus II, launched into a nearly perfect circular orbit on May 15, 1966, is similar to Nimbus I (launched in 1964), but carries more advanced experiments. Nimbus I and II have clearly demonstrated that meteorological satellites have a unique capability to provide global atmospheric observations and measurements.

The Nimbus program flight objectives are as follows:

(1) To flight test sensors and technology basic to the study of the atmosphere.

(2) To provide global quantitative measurements of the structure of the atmosphere.

(3) To provide global collection and distribution of meteorological data.

Each successive Nimbus satellite incorporates basic spacecraft advances resulting from flight experience and supporting research and technology, and carries a payload of significant experiments for atmospheric research and development toward operational use. These meteorological experiments cover the electromagnetic spectrum from the ultraviolet through the visible, infrared, and radio regions.

ATS-1

The spin-scan camera on ATS-I is capable of providing pictures of the Earth's visible disk every 20 minutes. The west-east scan is provided by the spinning motion of the satellite and the north-south scan by a mechanical stepping motor. The camera can be programed to scan limited areas every few minutes. Pictures obtained during the first month of operation indicate that the camera is performing as planned. Numerous picture sequences are being provided during the

time the satellite is in daylight. As many as 50 pictures are provided during an 18-hour period, showing the changing cloud patterns over the visible disk of the Earth.

Results

Achievements in Spacecraft Technology

The TOS system is a joint effort of NASA and ESSA. NASA is responsible for the design and development of the spacecraft, vehicle, and ground systems; launch operations; initial spacecraft checkout in orbit; spacecraft evaluation; and interferometer tracking. ESSA is responsible for the operational phase of each spacecraft, including determining the need for replacement, for operation of the CDA stations and ESSA communications lines, and for acquiring, handling, and processing the data. ESSA also funds and manages the overall system.

The TOS satellites are spin-stabilized wheel-configured spacecraft (fig. 1). The spacecraft structure and subsystems are almost identical to those developed and flight tested on Tiros IX. The basic differences between TOS and Tiros IX are the orbital altitude and the sensors. To meet ESSA's requirement for obtaining global meteorological data on a daily basis, TOS will have two operational spacecraft in a circular, Sun-synchronous orbit at an altitude of approximately 1400 km. The orbits are 78.84° retrograde with an orbital period of 113.5 minutes. The spacecraft are spin-stabilized and magnetically torqued to a wheel attitude so that the spin axis will be normal to the orbital plane and the two radially mounted cameras will view the Earth once each spacecraft revolution. The orbital plane
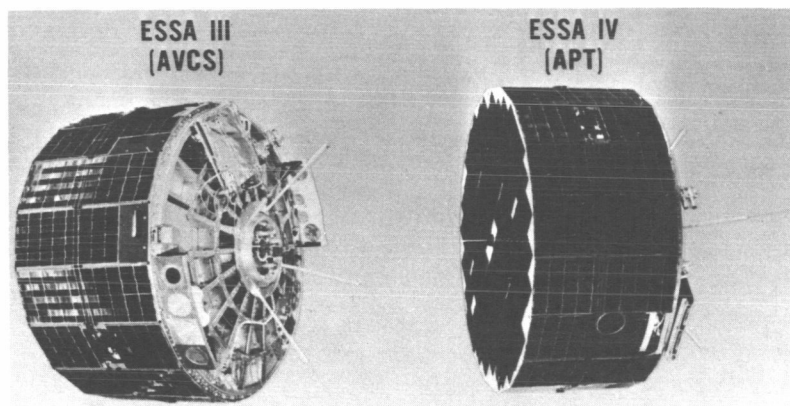

Figure 1.—TOS spacecraft.

precesses easterly about 1° per day, at the same rate as the Earth-Sun line. The 1400-km altitude allows full global coverage with one camera; therefore, two cameras provide full system redundancy.

ESSA Series of APT Spacecraft

The ESSA APT spacecraft weighs approximately 130 kilograms and carries two APT cameras. The satellites are launched into an 0900 local sun time (descending node) orbit. The nominal power available from the solar array is 53 watts, with an average of 28 watts per orbit required for eight pictures. The APT subsystem consists of a camera and transmitter combination designed to transmit slow-scan television pictures of the cloud cover below the satellite. Transmission is automatic and in real time. A Tegea Kinoptic, 108°, wide-angle lens is used with an electromagnetically controlled focal plane type shutter. The camera housing is magnetically shielded to protect against adverse effects of the magnetic fields of the Earth and the spacecraft. The 2.5-cm-diameter vidicon operates on the basis of a long-term image retention by the photoconductor. The resolution is approximately 3.5 km per TV line at the picture center and approximately 8 km at a zenith angle of 65°. Four or eight APT pictures may be programmed per orbit.

ESSA Series of AVCS Spacecraft

The ESSA AVCS spacecraft weighs 150 kilograms and carries two advanced vidicon camera systems. These satellites are launched into a 1500 local sun time (ascending node) orbit. The nominal power available from the solar array is 53 watts, with an average of 20 watts required per orbit for 12 pictures and the heat budget sensor. The camera assembly includes lens, shutter, gray-scale calibrator, 2.5-cm-diameter vidicon, yoke assembly, and preamplifier. The lens and shutter are similar to the ones in the APT camera. The 2.5-cm-diameter vidicon has an inherent storage capability that permits a nominal 6.5-second frame-scan time. Concurrent with shutter actuation, a flash tube of known intensity exposes a 16-increment gray scale on each frame for picture calibration. The tape recorder has four tracks, runs at 75 cm per minute, and can record 36 AVCS pictures on one track. The spacecraft carries two cross-strapped tape recorders that will provide complete redundancy. Track 1 records camera 1 video data and track 2 records camera 2 video data. The remaining two tracks record flutter and wow and telemetry data. The video data are transmitted by the satellite over the 235.00-MHz
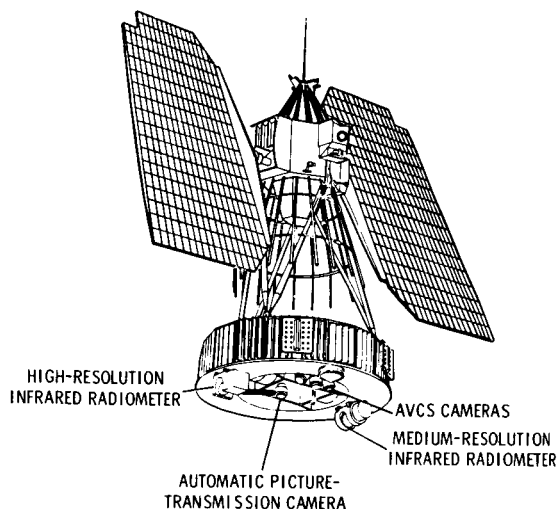
communications link to the major ground readout stations. Six or 12 pictures per orbit may be programmed at 260-second intervals. The 833-line pictures at the 1400-km altitude covers an area of 3150 km on a side. There is a 50-percent picture overlap along the track, and the pictures will be contiguous at the equator with a growing overlap as the latitude increases and the orbit tracks converge.

Nimbus

Nimbus II, launched on May 15, 1966, is a three-axis Earth-stabilized satellite. The basic spacecraft is similar to Nimbus I, launched in 1964, but incorporates a substantially improved solar-paddle control mechanism. By the end of 1966, Nimbus II completed $7\frac{1}{2}$ months of successful operation, with the control system, solar paddles, power supply, telemetry transmitters, and APT subsystem still operating satisfactorily in the space environment.

Spacecraft Configuration

The Nimbus spacecraft, shown in figure 2, consists of three major elements: a 1.4-meter-diameter torus ring that forms the base of the spacecraft and houses the major spacecraft electronics; a smaller hexagon-shaped housing, connected to the ring by a truss, that houses the attitude stabilization and control system; and the two large solar paddles. The basic structural material is magnesium because of its favorable strength-to-weight ratio. The sensory ring consists of 18 uniformly sized bays with active thermal controllers on each bay.

HIGH-RESOLUTION
INFRARED RADIOMETER

AVCS CAMERAS

MEDIUM-RESOLUTION
INFRARED RADIOMETER

AUTOMATIC PICTURE-
TRANSMISSION CAMERA

Figure 2.—Nimbus series spacecraft.

Stabilization and Control

Nimbus II satisfactorily achieved attitude stability about its three axes. The attitude-control system has performed perfectly, exhibiting no perturbations or signs of degradation. Spacecraft attitude has generally been maintained within $\pm 1°$ in three axes. Cold gas disturbances occur infrequently. Reduction in the size of the pitch gas nozzle successfully eliminated the pitch oscillation that was experienced with Nimbus I. Freon gas consumption for attitude control has been very low, using 0.7 kg out of a 7.4-kg supply in $7\frac{1}{2}$ months of operation. Improvements in the solar array drive mechanism on Nimbus II have been very successful. The solar array has tracked the Sun with no observed signs of degradation in the electronic or mechanical systems.

Power Supply

The Nimbus II power system derives its electrical energy from solar energy incident upon 10 500 silicon solar cells located on the two 1- by 3-meter paddles. Initial power output during periods of full solar illumination is 450 watts. The solar array also provides recharge for eight nickel-cadmium storage batteries, which provide power for nighttime operations. An adequate solar array output has been available and voltage regulation has been maintained. The initial 13.7-ampere array output has dropped to 12.3 amperes; the failure of a short string of solar cells caused a 0.6-ampere drop and ultraviolet and high energy particle degradation resulted in the remaining 0.8-ampere loss. Degradation due to ultraviolet and high-energy particle radiation has been less than anticipated; and, as of December 1966, the power output is sufficient to maintain full spacecraft operations. The electronic components show no measurable degradation due to high-energy particle radiation.

Sensor Subsystems

The Nimbus II meteorological sensors have provided significant advances in the volume and range of global atmospheric observations and measurements that can be obtained from a large R&D spacecraft. Improved techniques for data handling and presentation were also demonstrated. Specifically, the major advances over Nimbus I were the addition of the medium solution infrared radiometer (MRIR) and the provision for the direct readout of the nighttime high resolution infrared radiometer (HRIR) cloud cover data. The cameras (APT and AVCS) and the radiometers (MRIR and HRIR) pro-

vided global observations of meteorological features on four scale sizes and in seven spectral bands.

The addition of the real-time transmission of the nighttime HRIR data to worldwide APT users has doubled the cloud data frequency to these locations. Initially, only seven APT ground stations were modified; however, by early November 1966, a total of 35 were known to have been modified, including 12 in foreign countries. The success of this experiment and its implication to international weather data utilization have provided increased justification for developing this capability for the operational weather satellite systems.

The Nimbus II sensors and important modifications are discussed below.

Medium Resolution Infrared Radiometer.—The MRIR is a scanning five-channel radiometer that provides measurements of the emitted and reflected radiation of the Earth and its atmosphere in five spectral bands:

Channel 1—water-vapor absorption band, 6.4 to 6.9 microns

Channel 2—atmospheric window, 10 to 11 microns

Channel 3—stratospheric temperature, 14 to 16 microns

Channel 4—terrestrial radiation, 5 to 30 microns

Channel 5—albedo, 0.2 to 4 microns

Basically, the types of measurements are the same as those obtained on four previous Tiros satellites. The spatial resolution is approximately 55 km at the subsatellite point. Accuracy, data coverage, and data reduction, however, have been vastly improved in the Nimbus experiment. Improvements include two calibration checkpoints, the onboard conversion of the data into a digital format, and the use of a rotating mirror for Earth surface scanning. The use of this rotating mirror results in a considerably simplified scanning geometry, permitting the data for all five channels to be displayed automatically, immediately after spacecraft transmission, on a photographic time strip-map with appropriate geographic referencing. A tape recorder failure caused the MRIR system to cease transmission on July 29, 1966, after 2½ months of operation.

High Resolution Infrared Radiometer.—The HRIR measures radiation in the atmospheric window between 3.4 and 4.2 microns. The ground resolution is approximately 8 km. When the APT was operating, improved shielding reduced the radio frequency interference on the HRIR data and provided clearer pictures. A tape re-

corder failure on November 15, 1966, caused the loss of all information from the HRIR after 6 months.

Advanced Vidicon Camera Systems.—Spatial resolution of the AVCS is 1 km at the subsatellite point on the Earth's surface. The camera iris can be automatically and continuously varied from f/4 to f/16; this technique reduced the picture variation due to solar elevation. The tape recorder associated with this system failed after 3½ months with the loss of the stored-picture capability; however, direct pictures can be transmitted to the major Nimbus ground stations.

Automatic Picture Transmission.—The special high-storage vidicon showed no sign of degradation after more than 7½ months of operation. The Nimbus II APT was used during late 1966 as the primary satellite for providing cloud pictures to the local APT ground stations around the world.

Since launch, the Nimbus II satellite has fulfilled its primary objectives. The basic spacecraft subsystems continued to perform successfully at the end of 1966. The only failures since launch have been the four tape recorders; these failures have been under intensive engineering evaluation since September 1966. An improved data handling and storage system is being developed for subsequent Nimbus satellites. This improved system consists of two redundant five-track tape recorder units and is currently undergoing lifetime tests as part of a program to improve tape recorder reliability.

The Nimbus II HRIR and MRIR data can be obtained from the NASA Space Science Data Center, and the TV pictures are archived with the National Weather Records Center. Monthly catalogs are published containing information about the quantity, type, classification and Earth coverage of all Nimbus II data. The data acquired during 1966 are shown in table I.

SATELLITE CLOUD PICTURES

Introduction

During 1966, the National Meteorological Operational Satellite System provided local and global cloud picture coverage on a routine daily basis. This system, initiated in February 1966 by the launch of ESSA I and ESSA II, requires two operational satellites in orbit to provide local and global daytime cloud picture coverage. Additional spacecraft are launched, as required, to maintain a fully operational system. ESSA III was launched in October 1966 to continue

Table I.—*Nimbus II Data Acquired in 1966*

Subsystem	Operation	Accumulated through 1966
AVCS.....................	Photographs................	112 200
APT.......................	⎰Frames.....................	42 000
	⎱Hours.....................	2 417
HRIR....................	⎰Nighttime swaths...........	2 000
	⎱Daytime swaths.............	200
DRIR •...................	Hours......................	1 370
MRIR....................	Swath......................	780

• Direct readout infrared radiometer.

the global cloud coverage capability after the July 1966 loss of one of the ESSA I cameras.

Nimbus II carries an APT camera, the AVCS, and the HRIR designed to provide local and global cloud picture coverage both day and night. The primary objective of these systems is to provide data for conducting meteorological research and development. However, ESSA used the AVCS and HRIR as the primary source of operational cloud cover data from August to October 1966, the period between ESSA I camera failure and ESSA III launch. Many of the APT ground stations use the Nimbus II APT pictures in addition to the ESSA II pictures. During December 1966 and January 1967, ESSA II was in a twilight orbit and Nimbus II became the primary satellite for providing APT pictures to the local ground stations around the world. The operational use of Nimbus II demonstrates the versatility of Nimbus R&D satellites to meet the needs of research meteorologists and operational weather forecasters.

Cloud Observation

In February 1966, ESSA I, the first operational weather satellite, was launched into a nearly polar, Sun-synchronous orbit at an altitude of approximately 720 km. With the 450 pictures provided each day, ESSA has routinely prepared global cloud maps for use in operational weather analysis and forecasting. The failure of one camera in July 1966 resulted in the loss of complete global coverage by this satellite, and ESSA requested the launch of the next operational weather satellite (ESSA III) in September 1966, if possible.

ESSA II, the first operational satellite to carry APT cameras, was launched during February 1966 into a nearly polar, Sun-synchronous

orbit at an altitude of approximately 1400 km. This satellite provides from four to nine APT pictures of the local area each day to more than 162 worldwide ground stations.

ESSA III, launched in October 1966, carries an AVCS similar to the ones developed and flight tested on Nimbus I and II. The quality of the pictures provided by the AVCS on ESSA III is excellent. Figure 3 shows a montage of the global cloud cover on October 31, 1966, prepared from the ESSA III pictures.

Nimbus II was launched on May 15, 1966, into a nearly polar, Sun-synchronous orbit at an altitude of approximately 1150 km. The satellite is northbound over the daylight portion of the Earth and southbound during the night. The orbital path is inclined so that the orbit precession is synchronous with the Earth's revolution around the Sun. This permits an almost constant relationship between the orbit and the Sun during the picture-taking life of the satellite. The satellite passes over most areas of the world twice every 24 hours, approximately at local noon and local midnight. The stored data are read out to the Nimbus ground stations at Rosman, North Carolina; and Gilmore Creek, Fairbanks, Alaska. The AVCS and stored HRIR data are relayed from the ground stations to Goddard Space Flight Center where the data are automatically decoded, recorded, and displayed with appropriate latitude-longitude and time references. The Nimbus II AVCS, as well as HRIR and MRIR data, are being published in
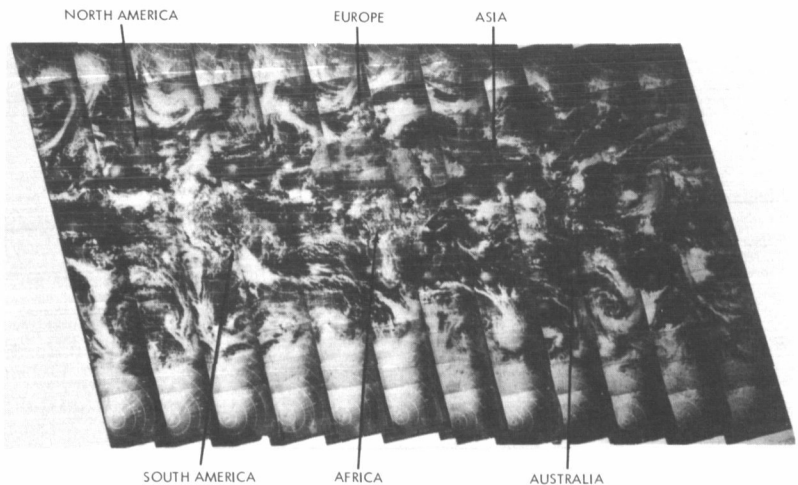
*Figure 3.*—ESSA III 24-hour world cloud cover, October 31, 1966.

pictorial catalogs. The AVCS and HRIR 70-millimeter strips are presented in world montage format.

Simultaneous pictures from each of the three AVCS cameras form a contiguous picture triplet across the orbital path. Successive triplets are contiguous along the orbital path. The entire Earth is viewed by the AVCS each day; however, data for about 10 percent of the viewed area cannot be retrieved because the satellite is outside the communications range of the Nimbus ground stations for two or three orbits. The gray scale resolution of the Nimbus II AVCS pictures favors the white end of the scale, resulting in better cloud resolution but poorer landmark detection.

The APT camera uses a long-storage high-dielectric vidicon. The slowly scanned image is immediately broadcast from the satellite and can be acquired in real time by APT ground stations within the satellite line of sight. A data code experiment (ref. 3) has been integrated with the transmitted TV pictures. This is a communications experiment to provide automatically a coded message on each picture, indicating the time the picture was taken and updating orbital information necessary for orienting the antenna and geographically gridding subsequent picture transmission. Figure 4 is an APT frame depicting the remnants of Hurricane Alma (left edge of the picture) centered near the North Carolina-Virginia coast. A cyclone is located in the North Atlantic centered at 48° N, 49° W (right edge of the picture). A frontal band connects the two systems. Nova Scotia and Prince Edward Island are visible in the upper central part of the picture.

Scientific Results from Meteorological Satellite Data

ESSA routinely uses weather satellite pictures in conjunction with conventional observations for preparing weather analyses and forecasts. Cloud analyses (nephanalyses) based on the weather satellite pictures are prepared and disseminated by international communications channels for use by the weather services of the world. Satellite storm bulletins are also prepared and disseminated internationally; over 1100 storm bulletins were prepared and disseminated during 1966. Research with weather satellite pictures includes the development of methods for the operational applications of cloud data obtained by satellites, development of means for deriving quantitative values from the satellite cloud cover photographs for direct input to mathematical models for numerical weather prediction, and the study and interpretation of the synoptic and mesoscale cloud patterns
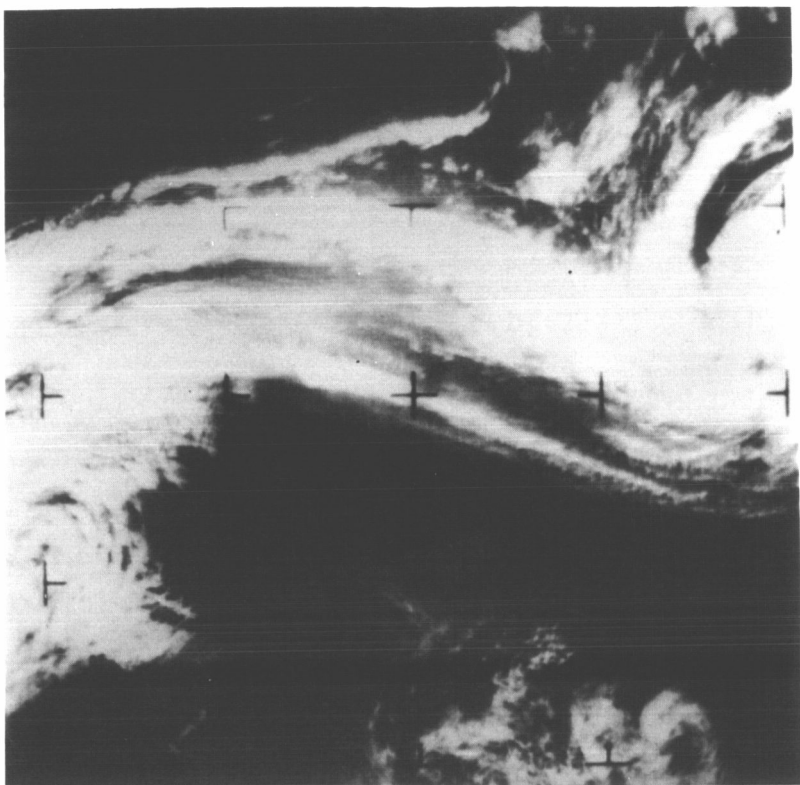
Figure 4.—Single frame of APT picture from Nimbus II showing remnants of Hurricane Alma, June 12, 1966.

depicted in the satellite cloud pictures. The areas of investigation are diverse, including supplementary conventional data for studying jet streams, cyclone formations, mesoscale clouds, and hurricane and typhoon formations.

Use of Satellite Cloud Pictures in Operational Synoptic Analysis

The cloud picture data received from the ESSA and Nimbus satellites show the amount of cloud distribution, cloud pattern and formation, and daily changes. Routine operational meteorological analysis deals primarily with such parameters as wind, pressure, and temperature. To apply satellite data to routine analysis, it is necessary to make reliable inferences from the clouds concerning the cloud-producing wind and temperature fields. For maximum application in operational meteorological analysis, satellite data must be used to

infer the wind and temperature in data-sparse areas where no direct measurements of these parameters are available. To apply this technique, it is also necessary to develop models that relate certain recognizable patterns of cloud organization to familiar synoptic scale flow, patterns, and processes.

Studies by Weigman et al., based on satellite cloud pictures from Tiros I to VIII, identified the cloud formations produced by large-scale cyclone storms, fronts, the jet stream, and upper tropospheric pressure troughs (ref. 4). It was also shown that cloud forms such as cumulonimbus, cumulus congestus, stratocumulus, stratified middle clouds, and several forms of cirrus can be reliably identified in the satellite cloud photographs. Further, it was demonstrated that inferences concerning the relative stability, thermal shear, and the low-level wind speed and direction can be made from the variations in the mesoscale cellular and banded patterns of the clouds.

The Tiros IX global coverage made possible the first daily observation of the cloud formation development and evolution associated with synoptic scale circulation systems. By combining these new data with the results of the previous studies, Anderson et al. have shown that it is possible to formulate, with some confidence, synoptic-scale models showing relationships between cloud patterns and the wind field both in the lower and upper troposphere (ref. 5). Figure 5 is a model of the cloud forms, as seen in the satellite pictures, that accompany an occluded frontal system with its associated upper level trough and jet streams. The model also depicts the comma-shaped cloud formation produced by concentrations of cyclonic vorticity in the upper troposphere and the relationship of these vorticity maxima to a frontal wave (B, fig. 5). The interaction of such upper-level vorticity maxima with frontal baroclinic zones is a major cause of cyclogenesis. Over the oceans, where conventional data are sparse, it is often difficult to identify and locate such vorticity maxima. The distinctive comma-shaped cloud formations are easily identified in satellite pictures. The use of the cloud model shown in figure 6 assists in interpreting cloud forms and distribution in terms of surface and upper air circulations.

Cloud Conditions and Vertically Integrated Moisture Fields

Satellite cloud pictures have been used to infer vertical motions as a means of improving numerical forecasts. Knowledge of the horizontal and vertical distribution of atmospheric water vapor, or of
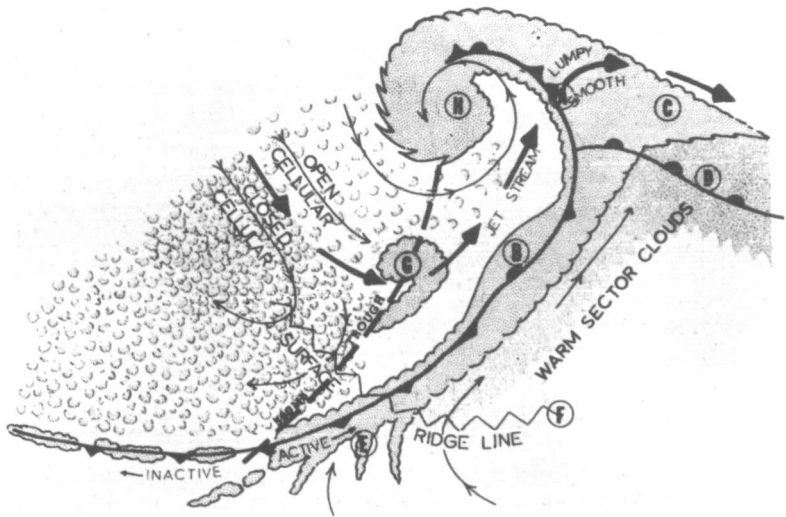
Figure 5.—Model showing typical cloud forms associated with an occluded storm and a developing frontal wave (from Anderson, Ferguson, and Oliver, ref. 5).

the horizontal distribution of the vertically integrated vapor content of the air, is needed for quantitative precipitation forecasting and for including the diabatic effects of latent heat release in numerical forecasting models (ref. 6). Establishment of the relationship between cloud cover given in satellite nephanalyses and some measure of the vertically integrated relative humidity was the first step. The "saturation deficit," a moisture parameter that may be taken as a measure of the mean relative humidity between 1000 and 500 millibars, was selected to determine this relationship. A mean relative humidity of 70 percent corresponds to a zero deficit; large deficits are associated with low humidities. The test data were based on satellite cloud cover pictures from 3 months of Tiros nephanalyses and saturation deficits computed by the National Meteorological Center. As shown in table II, there is a positive correlation between cloud amounts and mean relative humidity; that is, the greater the cloud cover, the higher generally is the humidity value. The principal weakness of this test was that no distinction is made between shallow and deep-cloud conditions.

The 1018 cases in the "covered" category on the nephanalyses were selected for picture interpretation by an experienced analyst.
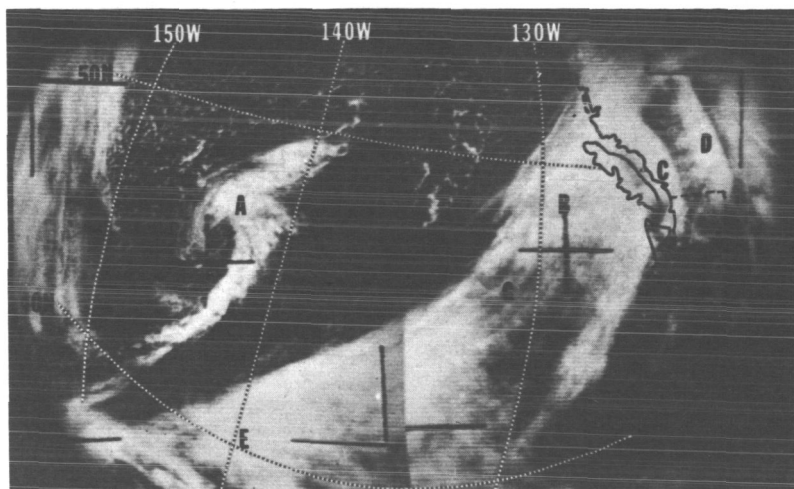
Figure 6.—Clouds produced by secondary center of cyclonic vorticity and frontal band, February 25, 1965 (from Anderson, Ferguson, and Oliver, ref. 5).

The clouds were categorized, using satellite cloud pictures only, into four classes: very deep, moderately deep, predominantly low and shallow stratiform, and predominantly high cirriform or middle-level stratiform clouds. In this analysis, the "covered" cases in table II associated with low relative humidities are, in large part, found in the low shallow or high cirriform cloud categories. Interpretating satellite photographs as to type of cloud conditions results in a considerable sharpening of the relationship between covered cloud conditions and mean relative humidity in the layer 1000 to 500 millibars. This technique is being refined by using information from the ESSA satellites to achieve moisture data output in suitable form for further numerical weather analysis and prediction.

Locating Jet Streams from Satellite Cloud Photographs

Several studies have indicated that cirriform clouds associated with the jet stream may sometimes be detected in satellite photographs. A 1964 study by Oliver et al. pointed out that a shadow cast on the underlying clouds or the Earth may enhance cirrus cloud edge definition. Furthermore, the study suggested that pictures showing these cloud characteristics might be used to identify and position the jet stream. These studies were used as a basis to evaluate the reliability of locating jet streams by means of certain cloud patterns in satellite

Table II.—*Relation of Satellite Nephanalysis Cloud Cover to Saturation Deficit*

Relative humidity (U.S. standard atmosphere), percent	Saturation deficit, unit: 10 m.	Cloud cover from satellite nephanalysis								Total
		Covered (>80%)		Mostly covered (50–80%)		Mostly open (20–50%)		Open (<20%)		
		No.	Percent	No.	Percent	No.	Percent	No.	Percent	
84–70	–6–0	193	19.0	19	7.8	7	2.5	5	0.8	224
69–58	1–6	250	24.5	36	14.7	25	9.0	38	6.3	349
57–48	7–12	220	21.6	47	19.2	62	22.2	98	16.4	427
47–40	13–18	177	17.4	49	20.0	51	18.4	109	18.2	386
39–33	19–24	129	12.7	66	26.9	55	19.8	157	26.2	407
32–21	25–36	49	4.8	28	11.4	78	28.1	192	32.1	347
Total		1018	100.0	245	100.0	278	100.0	599	100.0	2140

pictures and to determine the most definitive characteristics of those patterns (ref. 7).

The primary characteristics for identifying and accurately locating the jet stream are an extensive cloud shield or a "mostly covered" cloud layer that ends abruptly along the edge. This rather smooth cloud layer extends over a long distance and shows no rapid curvature as suggested by Kadlec, Oliver, et al. in 1964. The cloud layer should be within the anticyclonic wind shear area (the tropical side of the jet stream) so that the jet stream is defined by the abrupt polar edge of the cloud layer.

Usually the cloud layer has a decidedly different texture and brightness than the lower clouds. Identification of the cloud edge is materially aided by the appearance of transverse banding and/or when a shadow band is cast on lower layers. A shadow band not only outlines the cloud edge but also indicates a high cloud level that is more likely to be related to the jet stream. Indications are that these characteristics will correctly locate jet streams more than 80 percent of the time. Two provisions are that the jet stream be defined as the axis of the isotach maximum, which does not necessarily conform strictly to contour channels, and that the jet stream clouds be distinguished from frontal clouds.

The cloud pictures supplement conventional observations, not only in sparse data areas, but even in areas with dense network. Jet stream characteristics in satellite photographs may sometimes lead to the analysis of a single primary jet stream where multiple jets adhering to contour channels might otherwise have been analyzed. Further, a position obtained from satellite data is quite useful in stronger jet stream situations. Under these conditions, at least one and often several stations in the jet stream vicinity usually experience incomplete upper level observations due to strong winds that terminate the measurement before the balloon reaches the level of maximum wind speed.

It is necessary to distinguish the frontal from jet stream clouds; however, frontal clouds often help to identify jet-streams associated clouds. Figure 7 is a model picture of jet stream cloud positions relative to spiral patterns, cold fronts, and occluded fronts. The jet clouds define a sharp line approximately one-third down from the top of the mosaic. The cloud spiral of a vortex is shown at the top and a frontal band is located below center of the mosaic.

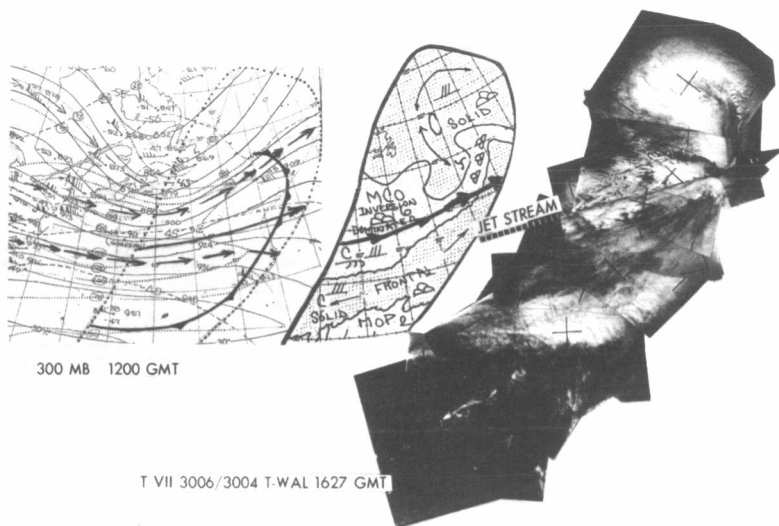The jet stream cloud shield is on the tropical side of the jet stream,

Figure 7.—Mosaic of Tiros VII pictures, pass 3006 tape mode, January 8, 1964, 1627 GMT (from Whitney et al., ref. 6).

which is the favored entrance area of the cloudiness. Extension of the cloud shield into the exit area on the tropical side of the jet stream does occur. These clouds may be slow in dissipating, even if descent is occurring, due to heat required to sublimate the ice particles. Neither conventional data nor satellite cloud pictures alone are sufficient for jet stream locations, but the combination increases the accuracy of jet stream analyses.

Mesoscale Cloud Studies

The satellite photographs provide numerous indications of the organization of cloud systems on a small scale, including lee-waves, lee-eddies, cellular convection, squall lines, and terrain effects. Cellular convection has been of particular interest because of the frequency with which these cloud patterns appear over very large areas of the ocean. The scale of atmospheric motion associated with the clouds is probably a significant link in interaction between the sea and the atmosphere. Reference 8 presents a study of satellite data and associated meteorological data concerning cellular convection. There is evidence that mesoscale cellular patterns develop when convective cloudiness is maintained over a uniform surface for several hours. Every outbreak of cold continental air over a warmer ocean contains such cells, presumably as soon as the water trajectory is sufficiently

long to develop an adequately thick layer and to permit the heat flux to achieve a quasi-steady state. Certain portions of oceanic anticyclones are also favored regions for cellular occurrence. Consequently, millions of square kilometers of the ocean surface are covered at all times with mesoscale cellular convection in various stages of development.

Two types of cellular organizations occur: the "open cell" and the "closed cell" (fig. 8). Open cells are cloudless in their centers because of downward motion in the cell center and upward motion in the walls. Closed cells have upward motion in the center and downward motion in the walls. These mesoscale cells form in cumuli or stratocumuli fields when the air is heated by the underlying surface. Characteristic cell diameters range from 10 to 100 km with the median size approximately 50 km. The diameter-to-depth ratios range from approximately 10:1 to 100:1, with a median ratio of approximately
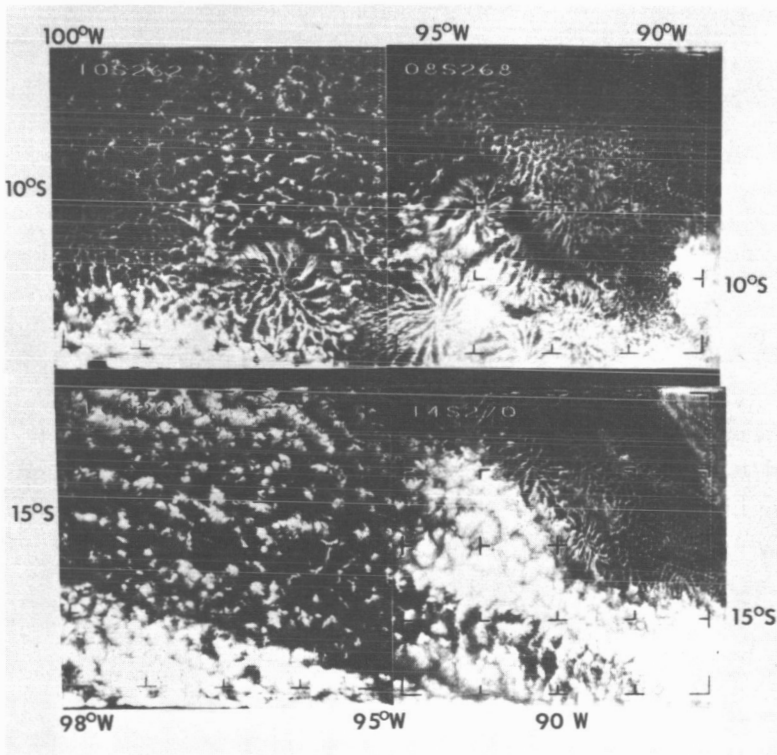

Figure 8.—Nimbus picture of open cells (top), closed cells (bottom), and radial pattern that may be a transitional form (from Hubert, ref. 8).

30:1. The mesoscale cells are frequently confined to a shallow surface layer by a strong inversion. Where the cell exists in a layer with no inversion, there is some evidence that the convective layer is limited by dry-air entrainment. The open cells usually form in conditions of moderate-to-intense surface heating, while closed cells (cloud-filled centers) form in conditions of weak-to-moderate surface heating. Diabatic heating at the Earth's surface and radiation cooling from the cloud tops drive the mesoscale cell circulation against static stability and friction. Less important, secondary effects are the evaporation of cloud tops, release of latent instability, and the enhancement of instability by differential advection or convergence.

The author infers that mesoscale cells develop for the same reason, and in response to the same mechanism, as Bénard cells in the laboratory; i.e., eddy heat conduction is insufficient to prevent the upper or lower (or both) portions of a stratum from becoming excessively unstable, eddy viscocus forces are overcome, and cellular circulation begins. The direction of cell circulation, which produces the open or closed cell type, is determined by the vertical increase or decrease of eddy viscosity. The diameter-to-depth ratio of the atmospheric cells is controlled by the degree of the anisotropy of the eddy viscosity and eddy heat conductor. Mesoscale convection appears important in air-sea interaction because it may represent a scale that makes a significant contribution to eddy exchange processes.

Snowfall in the western portion of Northern Japan has been related to the travel of monsoon winds over the Sea of Japan (ref. 9). Using satellite data, it was found that cloud-free path widths are in the order of 10 to 50 km when there is a fresh outbreak of cold, polar air from the Siberian coast, and that the cloud-free paths increase to a 400-km width with a weakening monsoon. The cloud patterns associated with the flow of the monsoon winds over the Sea of Japan are the cellular type that form over ocean or land with small and uniform albedo.

Large-Scale Vertical Motions

After the first Tiros I observations, it was apparent that large-scale cloud patterns reflected the field of motion in which they were imbedded and provided qualitative flow information. Studies have investigated the relationship of horizontal fields of motion to the satellite cloud pictures. The study of reference 10 examined the relationships between calculated fields of large-scale vertical motion and cloud patterns observed by satellites for two selected cases in middle

latitude. The vertical motions were calculated by combining hydro-dynamic and thermodynamic equations for large-scale quasi-geostrophic flow. The results indicate that horizontal and vertical motions are important factors in determining the configuration of large-scale vertical cloud systems. In the early stages of storm evolution the cloud formations coincide with ascending motion. After closed cyclonic circulations have developed, dry clear air streaming into the eastern quadrants of a storm encroaches upon ascent, while moist cloud-bearing air circulates around the top of the storm and intrudes upon descent in the western quadrants. Generally, in middle latitudes the large-scale vertical motion cannot be directly inferred with confidence from the cloud pictures without reference to the horizontal motions. Cloud vortices occur in a variety of large-scale motion environments and seem to depend on fine-scale variations of motion and moisture structure that escape detection in conventional sounding networks. Further study of satellite cloud photographs will be necessary to derive estimates of vertical motions.

SATELLITE RADIOMETRIC MEASUREMENTS

Introduction

One of the significant achievements of Nimbus II is the wealth of radiation data provided by the MRIR and HRIR. Four Tiros satellites have provided radiation measurements in five spectral bands similar to the Nimbus II MRIR measurements. The unique contributions of the Nimbus II MRIR are the improved quality of the radiation measurements and the extension of the coverage over the polar regions. The Nimbus II HRIR operated successfully for 6 months and will require full-scale computer processing to obtain quantitative data interpretation.

Tiros MRIR Analyses

Because of MRIR degradation on Tiros VII, usable data have not been obtained since mid-1964. However, data from the four previous Tiros MRIR experiments continue to be used for meteorological research. Monthly mean charts of outgoing long-wave radiation using Tiros VII data have been constructed for July 1963 to May 1964, the longest series of such data on this scale ever available. The charts for February to May 1964 were compared with those for the same months in 1962, previously constructed from Tiros IV data. Although there are many similarities in the outgoing long-wave

radiation for the same months in the 2 years, the differences between them average approximately 10 percent, with maximum differences ranging up to 35 percent of the mean radiation values. The patterns of differences are dominated by some broad-scale features that, over the Northern Hemisphere, can be related to differences in the mid-tropospheric flow. Some broad zonal belts of alternating sign differences extend from temperate zones of one hemisphere to the other, indicating substantial north-south displacements of the radiation pattern and the flow field from one year to another. These zonal belts extended over some 60 to 90° longitude. In other longitudinal zones, changes of the same sign extended over broad latitudinal ranges. Further observation and study of these planetary scale variations in radiation from one year to another should lead to new knowledge of the control that heat source and circulation variations in one hemisphere exert on the heat sources and circulation of the other hemisphere.

Long-wave radiation data and cloud cover information from satellite pictures over 15-day periods have been combined for comparison of variations in the Intertropical Convergence Zone (ITC) during February and March of a 3-year period. This study showed that the ITC has the greatest persistency of location in these months over the Atlantic and eastern Pacific Oceans, and the most pronounced variations south of the equator over the Indian and western Pacific Oceans.

An intensive investigation of latitudinal averages for the North Pacific regions of the 5-day mean long-wave radiation data for February through June 1962 shows that the radiation gradient between the subtropics and middle latitudes is directly related to the strength of the westerlies and the anticyclonic shear of the wind. The available albedo data indicate that the gradient of long-wave radiation and albedo interact; that is, the northward albedo increase from the subtropics is strong when the long-wave radiation decreases rapidly northward from the subtropics. This occurs when the westerlies are strongest. These relationships are essentially an expression of the rapidity of the breakoff of cloudiness between the westerlies and the subtropics, essentially reflecting the control by the westerly circulation of the vertical motion field over relatively wide ranges of latitude.

A statistical study of long-wave (8 to 12 microns) radiation data in relation to the height field was conducted using Tiros IV data for March to June 1962 (ref. 11). The 500-millibar heights at selected grid points were specified with some accuracy as a function

of radiation values within a grid whose boundaries may be located several thousand miles away from the point at which heights were to be specified. Although the absolute 500-millibar height values contain rather large discrepancies, the derived contours compare favorably with the observed contours. This suggests that satellite long-wave radiation data may be more useful for the location of upper-level troughs and ridges than for deriving absolute heights. Based on the assumption that these relationships apply to other regions of similar synoptic climatology, this procedure would be useful for improving the height analyses in sparse data areas.

Applying MRIR data to synoptic analysis is reported in reference 12. The Tiros III radiation data from July 16, 1961, and the conventional weather observations on that date were used in the analysis. The radiation field computed from the channel 2 measurements (8 to 12 microns) agreed well with the television picture of a cloud system (later identified as the early stage of Hurricane Anna) (fig. 9). Radiation data and the closest radiosonde data indicated the height of the highest cloud top at 10 600 meters.

Based on the radiation data and synoptic weather information, the surface weather map for 1200 G.m.t. on July 16, 1961, was revised over the United States. The additional evidence derived from the MRIR data provided the basis for the relocation of a cold front from Ohio to Arkansas and the addition of a prefrontal squall line from Virginia to Texas. The addition of these important synoptic weather features helped explain the extensive cloudiness and thunderstorms reported in a zone extending from West Virginia to Texas. The satellite-derived moisture charts using channel 1 (6.0 to 6.5 microns) and the conventional upper tropospheric moisture charts showed good agreement in their outlines of large dry regions over central and western United States (figs. 10 and 11). The moist regions associated with the cold front and the prefrontal squall line, discussed above, were confirmed with minor variations by the conventional and satellite-derived moisture patterns. The global synoptic analyses and the worldwide radiation data were compared. The radiation data outlined the cloudiness associated with the frontal systems in both hemispheres, the four tropical storms in progress, the Intertropical Convergence Zone, and the southwest monsoon in Southeast Asia. The infrared radiation data were particularly useful for revising the surface analysis in the zone from 35° S. to 65° S. latitudes. The results of this study indicate that weather analysts can derive a significant
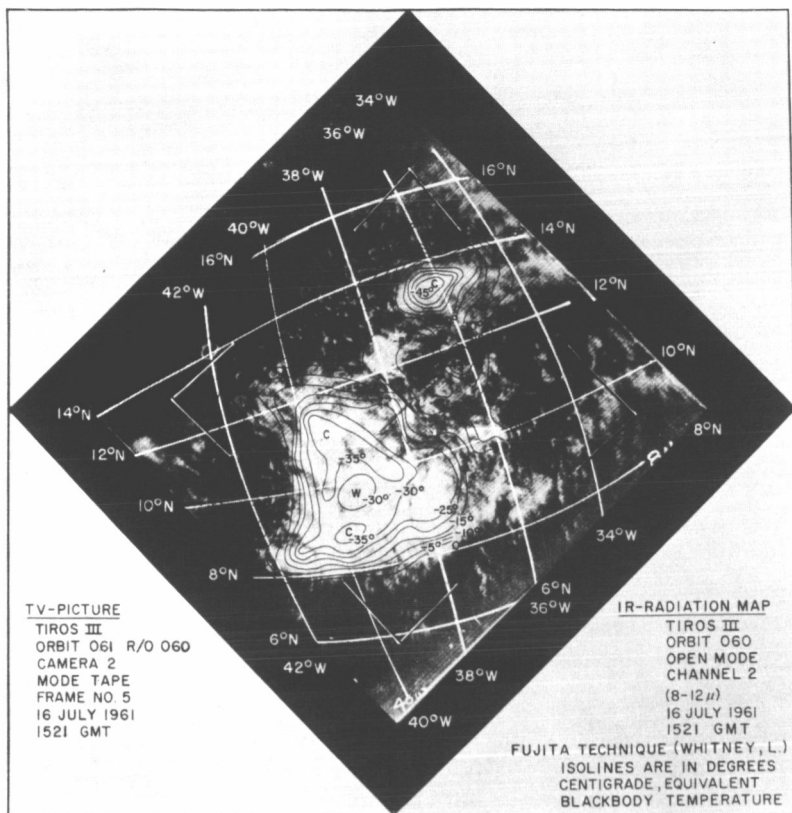
Figure 9.—Composite analysis of channel 2 radiation data and a gridded television picture of the early stage of Hurricane Anna, using the Fujita technique (by L. F. Whitney, ESSA).

amount of synoptic weather information from the satellite radiation data.

Nimbus II HRIR and MRIR Measurements

The Nimbus II HRIR experiment is essentially the same as that flown on Nimbus I. Radiation is measured in the atmospheric window between 3.4 and 4.2 microns. The major change is the provision for using the APT system to transmit directly each HRIR scan on all nighttime passes to the APT ground stations within the satellite line of sight. Nimbus I demonstrated that the HRIR observations have a variety of uses, such as nighttime cloud observations, cloud-height and sea-surface temperature determinations, ice and snow surveillance, terrain feature recognition, and soil moisture determinations.
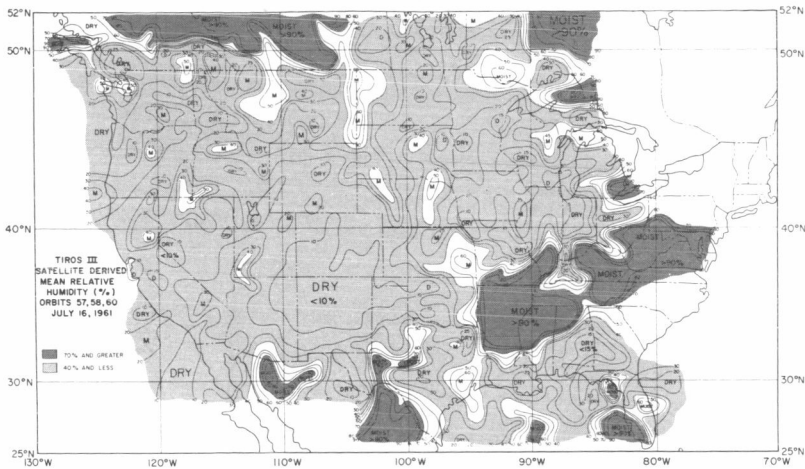
Figure 10.—Analysis of satellite-derived mean relative humidity for orbits 57, 58, and 60 on July 15, 1961 (from Allison and Warnecke, ref. 12).
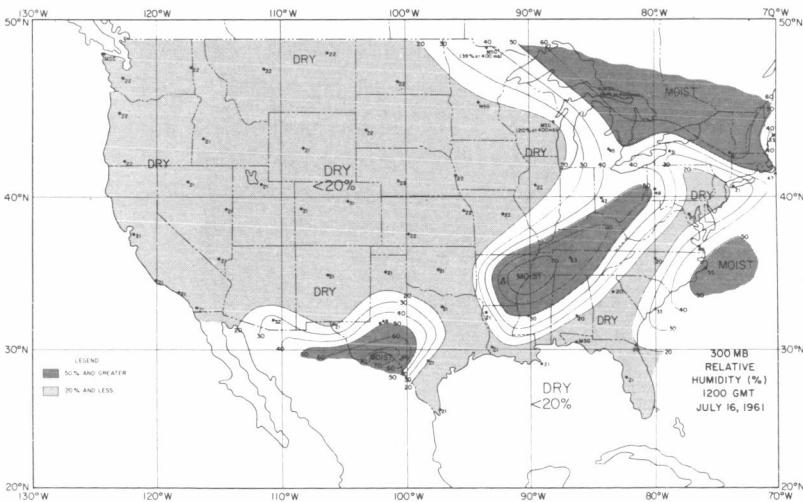
Figure 11.—Analysis of conventional 300-mB relative humidity at 1200 G.m.t., July 16, 1961, over the United States (from Allison and Warnecke, ref. 12).

Reference 13 presents a detailed treatment of the meteorological interpretation of the Nimbus I HRIR data.

Figure 12 shows the equatorial zone cloud band on July 10, 1966 (ref. 14). The upper portion is a montage prepared from Nimbus II AVCS pictures, and the lower section is a pictorial display of the
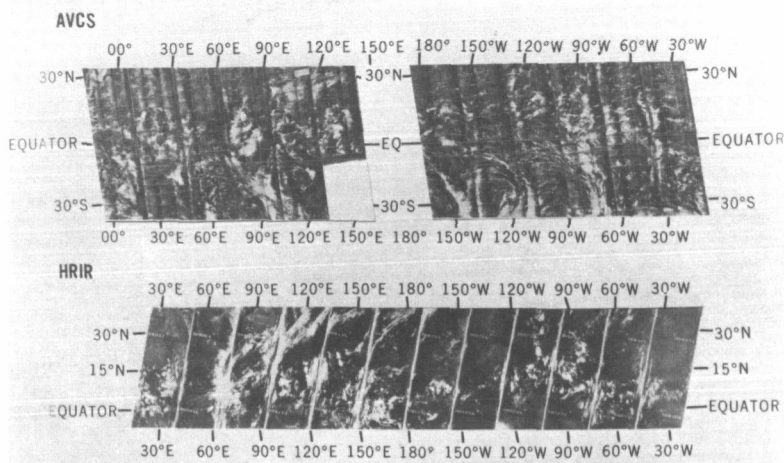
Figure 12.—Observations of tropical cloud formations on July 10, 1966, from Nimbus II HRIR near local midnight and from the AVCS near local noon (from Nordberg et al., ref 14).

HRIR data taken on the nighttime portion of the orbits. The Intertropical Convergence Zone is less pronounced in the television pictures than in the infrared window. The much lower temperatures of the tropical tropopause provide a much better contrast between tropical and extratropical high altitude clouds in the emitted radiation than in the reflected light. The HRIR shows a distinctly sinusoidal course of the cloud bands. Day and night observations will provide information to study the diurnal oscillations of the Intertropical Zone of Convergence. Reflectances between 3.4 and 4.2 microns measured by the Nimbus II HRIR were 0.25 over the Sahara Desert and less than 0.10 over the oceans and the Great Lakes. The HRIR also measured ocean temperatures off the North Carolina coast. Temperatures ranged from $287^\circ K$ to $294^\circ K$ over the open Atlantic. A sharp temperature gradient marks a warm band extending from Cape Hatteras in a northeasterly direction across the Atlantic. This warm band obviously traces the course of the Gulf Stream.

The Nimbus II MRIR experiment employs a five-channel scanning radiometer. The water-vapor channel (6.4 to 6.9 microns) encompasses a strong water-vapor absorption band. Radiation measurements in this wavelength region permit inferences of the

total water-vapor content in the upper troposphere. The atmospheric depth of the received radiation, and therefore the inferred temperature, increase with decreasing water vapor content. In a dry and cloudless standard atmosphere, radiation in this channel would be received from the surface at a blackbody temperature of 288°K. If this atmosphere contains 2 cm of precipitable water vapor according to a typical height profile, the major portion of the received radiation originates at 400 millibars or above, with only about 14 percent coming from below 500 millibars. In this case the equivalent blackbody temperature measured in this channel is about 230°K.

The window channel (10 to 11 microns) comprises a spectral band where atmospheric gases are practically transparent. Measurements permit inferences of surface or cloud top temperatures (ref. 15). From these, cloud top heights may be deduced. This channel is most useful for day and nighttime mapping of cloud systems associated with storms and fronts.

The carbon-dioxide channel (14 to 16 microns) is centered at the strong 15-micron band of CO_2. Maximum radiation is received from near the 16-km level, and approximately 75 percent of the radiation emanates from above 10 km. This permits inferences of the average temperatures in the upper troposphere and lower stratosphere. The spectral interval is somewhat wider than that of the previous experiment on Tiros VII and results in considerably more accurate measurements; however, this depresses the infrared-temperature height range to lower altitudes.

In the 5- to 30-micron channel about 85 percent of the total radiation emitted by the Earth and its atmosphere is measured. These measurements will be used primarily for heat-budget computations. The reflected radiation channel (0.2 to 4.0 microns) covers about 99 percent of the total solar spectrum. Large-scale reflectances of Earth surfaces and clouds are measured in this channel.

Orbital strip charts provide a method to use the MRIR data for immediate interpretation of cloud patterns and cloud heights. Inferences of vertical motions and dynamic activity associated with these cloud patterns can be made from simultaneous evaluation of the water vapor and window channels, and stratospheric events can be deduced from the temperature patterns displayed in the CO_2 channel. The spatial resolution is adequate for planetary and synoptic scale analyses and, in some cases, will permit mesoscale interpretations. Figure 13 shows a time-strip chart of MRIR data taken by Nimbus
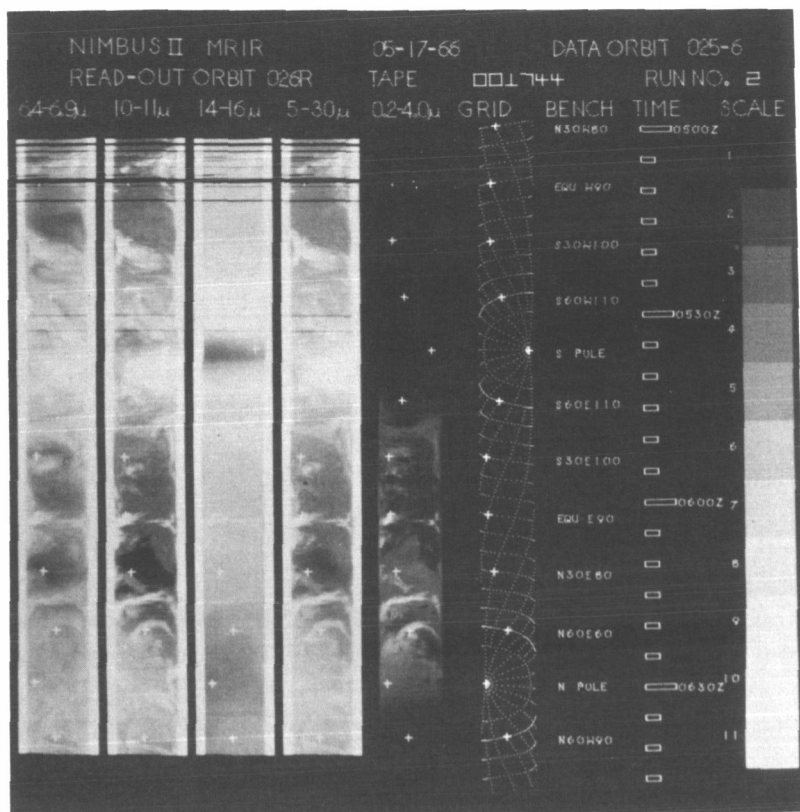
Figure 13.—Time-strip chart presentation of MRIR data for Nimbus II orbits 25 and 26, May 17, 1966. Light shades correspond to cold temperature or high reflectance values; dark shades correspond to warm temperatures or low reflectance values (from Nordberg et al., ref. 14).

II on May 17, 1966. Reference 14 gives a detailed description of the synoptic information provided by the five spectral-band strip maps. Simultaneous measurements in the five spectral bands provide data for determining cloud heights, delineating moist and dry regions aloft, and locating strong subsidence areas. In the absence of major high cloud systems, the CO_2-channel observations can be interpreted on a planetary scale in terms of the stratospheric temperature fields that can, in turn, be related to stratospheric circulations. Similar measurements from Tiros VII have already resulted in satellite mapping of stratospheric warming, the Aleutian anticyclone, and similar phenomena below 65° N. latitude. For the first time, these observations

include the polar regions. Also, because of the improved coverage and sensitivity and because of the instantaneous photographic display, day-to-day variations in these phenomena were detected by Nimbus II, while Tiros data provided only weekly or longer time averages. Preliminary analyses of the equivalent blackbody temperature inferred from the CO_2-channel measurements indicate that the lower-stratosphere temperature patterns around the South Pole in the height of winter (June and July) are far from symmetrical. Over the Arctic, however, warm air is distributed around the North Pole in nearly perfect symmetry during the entire summer period.

Some preliminary quantitative measurements from the 0.2- to 4.0-micron channel show reflectances of 0.60 to 0.70 micron over thick (bright) clouds. Over low-level stratus clouds off the California coast, reflectances were 0.40 to 0.53 micron; over the Sahara Desert these clouds averaged 0.30 to 0.34 micron. Total reflected solar and emitted terrestrial radiation measured by Nimbus II on a global scale during the first 2 weeks in July 1966 confirms the same latitudinal variation predicted by theory and measured by four Tiros satellites. Minimum total outgoing radiation is less than 0.2 langley (ly) per minute at the South Pole, and the maximum is about 0.37 ly per minute near 15° S. latitude. The global average inferred from Nimbus II data for total outgoing radiation for this time period is 0.32 ly per minute. Inferred global albedos, however, are much less than required by theory. The global average inferred from Nimbus II for the first 2 weeks in July 1966 is 23 percent; the maximum of 45 percent occurs at the North Pole and the minimum occurs at 20° S. The theoretical value of the global albedo is closer to 35 percent.

Operational Applications

Introduction

Twice daily during 1966, the National Operational Meteorological Satellite System provided the meteorologist with satellite cloud pictures. The global cloud pictures are used by the National Meteorological Center and the Department of Defense weather services for routine support for their analyses and forecast efforts. Direct local pictures are made available through the APT system to local ground stations around the world. ESSA prepares nephanalyses from the gridded cloud pictures and mosaics, and distributes these cloud analyses to international users. In addition, miscellaneous satellite bulletins are prepared and transmitted to interested weather services

when significant weather features are identified that do not appear in conventional weather analyses.

Day-to-day analysis of satellite cloud pictures has made it possible to identify cloud systems ranging in scale from the largest storms to cloud elements a few kilometers in diameter, to relate them to atmospheric motions and temperature structure, and to apply the data to daily conventional meteorological analyses and prognoses. Based on their brightness, pattern, structure, texture, shape, and size, clouds in satellite photographs can be identified as to type and, to some extent, height above the Earth's surface. From the satellite data, inferences concerning wind and temperature and stability fields can be made, and particular synoptic situations can be identified. Fronts are readily identified and can be classified as active or passive depending upon the appearance of the frontal band clouds. Frontal waves, which appear as a broadening of the frontal band, can be traced from the formative period to final dissolution. Cyclonic disturbances of all scales appear in the cloud pictures as vortical cloud patterns that can be used to diagnose stages of storm development. Concentrations of midtropospheric cyclonic vorticity in the westerlies produce distinct cloud formations that can be recognized and tracked. These formations have proven useful in predicting wave developments along fronts.

Midtropospheric troughs and ridges can often be positioned precisely by abrupt changes in cloud amounts along the trough and ridge lines. Large-scale upward vertical motion causes a maximum of clouds from the 500-millibar trough to the 500-millibar ridge downstream, and subsiding air from the ridge to the next downstream trough favors a minimum of clouds. A cold front or stationary front in advance of the upper trough appears in the satellite cloud photographs as a wide, multilayered band. To the rear of the trough the frontal band abruptly narrows and appears ragged, often splitting into two narrow bands.

The organization of clouds into rows, lines and bands, observed directly in satellite pictures, is used to infer wind and temperature fields. Studies indicate that when convective clouds form into bands, the bands are alined parallel to the wind shear through the convection layer. Cellular cloud patterns, both open and closed, are associated with several varieties of large-scale regimes exhibiting characteristic stability patterns in the lower troposphere.

A major contribution of satellite data is in the detection, classification, and tracking of tropical storms. Table III lists the tropical storms, including hurricanes and typhoons, observed by meteorological satellites in 1966; two hurricanes and three typhoons were first discovered by satellite observation. Studying thousands of satellite cloud photographs has made it possible to recognize signs of formation, intensification, and decay of tropical cyclones, ranging from very weak disturbances to mature hurricanes and typhoons. Photographs are used to estimate the maximum wind speed in tropical storms through analysis of their organization with respect to size and

Table III.—*Tropical Storms Observed by Meteorological Satellites, January 1966 Through December 1966*

Atlantic Ocean	Eastern Pacific Ocean	Western Pacific Ocean
Hurricane Alma, 6/66	Tropical Depression Adele, 6/66	Typhoon Irma, 5/66
Tropical Storm Becky, 7/66	Tropical Storm Blanca, 8/66	Typhoon Judy, 5/66
Hurricane Celia, 7/66	Tropical Storm Connie, 8/66	Typhoon Kit, 6/66
Hurricane Dorothy, 7/66	Hurricane Delores, * 8/66	Tropical Storm Lola, 7/66
Tropical Storm Ella, 7/66	Tropical Storm Eileen, 8/66	Typhoon Mamie, 7/66
Hurricane Faith, 8/66	Hurricane Francesca, 9/66	Typhoon Ora, 7/66
Tropical Storm Greta, 9/66	Tropical Storm Gretchen, 9/66	Typhoon Rita,* 8/66
Tropical Storm Hallie, 9/66	Hurricane Helga, 9/66	Typhoon Susan, 8/66
Hurricane Inez,* 9/66	Tropical Storm Ione, 9/66	Typhoon Tess,* 8/66
Tropical Storm Judith, 9/66	Tropical Storm Joyce, 9/66	Typhoon Viola,* 8/66
Hurricane Lois, 11/66	Tropical Storm Lorraine, 10/66	Tropical Storm Winnie, 8/66
	Tropical Storm Maggie, 10/66	Typhoon Alice, 8/66
		Typhoon Cora, 9/66
		Tropical Storm Doris, 9/66
		Typhoon Elsie, 9/66
		Typhoon Flossie, 9/66
		Tropical Storm Grace, 9/66
		Tropical Storm Helen, 9/66
		Typhoon Ida, 9/66
		Typhoon Kathy, 10/66
		Tropical Storm Lorna, 10/66
		Typhoon Marie, 10/66
		Tropical Storm Nancy, 11/66
		Tropical Storm Olga, 11/66
		Typhoon Pamela, 12/66

* Indicates storm discovered by satellite observation.

pattern. This procedure has been tested with independent data and shows an accuracy of $\pm$ 10 m/sec. Satellite pictures also provide valuable information on the storm's eye, annular clear zone, outer convective bands, and cirrus outflow from the top of the storm. As a result, the distinct stages of storm development are better understood and more easily identified (ref. 16).

Many of the mesoscale cloud patterns observed in satellite pictures result from terrain irregularities and surface-heating variations. Effects of mountain barirers on cloud distribution are discernible in satellite photographs as lee waves, upslope cloudiness, and clearing in areas of strong downslope motions on leeward sides of orographic barriers. The lee-wave pattern, frequently seen in the pictures, provides information on wind direction, speed, and turbulence (ref. 2).

Islands and island chains markedly affect the distribution of low-level clouds and fog. Satellite photographs reveal the areal extent of clearing on the leeward side of the island and often show mesoscale eddy patterns forming downstream from island barriers. These eddies develop on the lee side of steepsided islands in the low clouds that extend above strong temperature inversions. At times an entire family of mesoscale vortices develops downstream from the island obstacle (ref. 17).

Satellite cloud photographs reveal the delineation of fog and stratus. Fog-filled valleys stand out sharply, and contours of foothills and mountains are readily identifiable in the edges of encroaching fog and stratus. In satellite pictures, fog has a flat, smooth appearance; the uniform height characteristic of the layer's upper surface accounts for its sharp definition of terrain contours. Nearly every day, satellite pictures reveal extensive fog or low stratus along and off the west coast of continents where upwelling brings cold water to the surface from great depths, and cold currents carry polar water toward the equator. Large areas of sea fog and stratus are quite common during the summer months at high latitudes over oceanic regions, as warm air from lower latitudes is convected poleward across the cooler waters.

Non-Meteorological Satellite Applications

Meteorological satellite pictures have been used for studies and investigations in geophysical areas in addition to meteorology. The broad range of scientific and operational applications of these data was described in references 1 and 2.

Ice

Satellite pictures are used routinely to identify ice-covered areas ranging from small frozen lakes to the huge Antarctic ice pack. A concerted effort, using American and Canadian aircraft, ground observers, icebreakers, and other ships in coordination with the satellite, has demonstrated the feasibility of satellite ice reconnaissance and has delineated the extent and evolution of ice fields in such areas as the Gulf of St. Lawrence and the Davis Straits. Satellites provide detection of the early winter ice formation and the spring breakup, over vast areas where observation by other methods is impossible. Leads in the ice on lakes and along coastlines are clearly discernible as dark lines cutting across the bright ice surface. Large-scale ice boundaries change very slowly, and daily determinations of these boundaries over oceans, gulfs, and large lakes reduce the possibility of confusing ice with clouds. ESSA initiated ice boundary mapping over the Great Lakes on an operational basis during the 1965–1966 winter season.

Snow

Despite similarities in appearance, snow can be distinguished from clouds in satellite photography. Land form and vegetative cover are two important factors for determining snow-covered terrain. Tops of mountain ranges form a white dendritic pattern; snow-covered grassland appears much whiter than forestland covered with an equal amount of snow. Deciduous forests are generally whiter in appearance than evergreen stands, particularly if the snow has disappeared from the upper part of the conifers. Because of such differences, each snow-covered region has its own unique appearance, which varies insignificantly from day to day. Snow-covered ground shows landmark patterns that form a background to the everchanging cloud cover. Recognition of these landmark patterns permits detection of clouds over snow since clouds obscure these patterns. Areas of snow and ice-cover for the entire Northern Hemisphere are being mapped routinely by ESSA.

METEOROLOGICAL SOUNDING ROCKETS

The objectives of the meteorological sounding rockets portion of the Space Applications Programs are to provide and improve the capabilities required to obtain meteorological data and to foster international cooperative efforts that contribute to obtaining mutually

useful data. That is, this portion of the program is directed toward the providing of capabilities and techniques for the exploration and understanding of the structure of the region from 30 to 100 km as it relates to meteorology, the temporal and spatial variations, and the dynamic processes involved in the interaction of this region with atmospheric regions below 30 km. In addition, the technological capability to obtain reliable and economical routine measurements required for aerospace operations and research is being improved.

The meteorological sounding rocket effort consists of three parts:

(1) The research meteorological sounding rocket program for the exploration of the upper atmosphere, requiring the use of Nike-Cajun class and, occasionally, the Aerobee class of rockets.

(2) The development of an operational meteorological sounding rocket system for the improvement of the overall capabilities of systems currently using the Arcas and Loki class small rocket vehicles and their associated payloads and ground equipment.

(3) The sounding rocket field experiment support that provides for the launch of meteorological sounding rockets from other countries.

Research Meteorological Sounding Rockets

Objectives

The measurements obtained and the research conducted under this portion of the program are directed toward exploring various characteristics and phenomena in the atmosphere above 30 km, such as:

(1) The seasonal and temporal variations of the large-scale circulation.

(2) The polar stratospheric and mesospheric structure.

(3) The temperature and wind structure associated with noctilucent clouds.

(4) The synoptic-scale circulation, including stratospheric warmings and horizontal eddies.

(5) The solar influences (long-term, seasonal, diurnal, and short-term).

During the last several years, the program has developed considerable information on these aspects, but an adequate understanding requires long-term analysis. Therefore, the program is continuing efforts in these areas and, because of their relevancy, the following aspects have been included for examination in the program:

(1) Gravity waves and tidal effects.

(2) Turbulent energy exchange between the mesosphere and thermosphere.

(3) External energy inputs (solar ultraviolet and aurorae).

(4) Relationship of composition to heat budget.

(5) Interactions between the neutral and charged media.

In addition, the program capabilities have been used to flight test the solar-ultraviolet energy sensor to be flown on the Nimbus satellites.

1966 Meteorological Research Sounding Rocket Program

Three different measurement techniques were used in conducting the research: the light reflecting or luminous vapor, the pitot-static tube, and the acoustic grenade. Each of these techniques requires the use of Nike-Cajun class rockets.

Two series, of five experiments each, using both sodium and trimethyl aluminum vapor, were launched from Wallops Island, Virginia—one series on January 17 and 18 and one on July 17, 1966. In each series the five launches were made during a 24-hour period to obtain diurnal data for analyses of three postulated modes of motion in the upper atmosphere in this geographical region: internal gravity waves with a period of about 2 hours, atmospheric tidal motions, and the longer term prevailing flow. The two series would permit delineation of some of the seasonal aspects of these phenomena. Both series were entirely successful in obtaining the required data, and analyses are underway.

Upper atmosphere density profiles were measured with five pitot-static tube experiments in 1966. The first two flights were from Ascension Island on February 27, 1966. The purpose was to provide reentry atmospheric density data for the Apollo flights and, by launching a second experiment 12 hours later, to evaluate diurnal changes in the structure of the tropical atmosphere. The density profile for the Apollo reentry was obtained; but, during the second launch operation, the rocket's second stage failed and no data were obtained.

The other three pitot-static tube experiments were launched from Ft. Churchill during August 1966, in conjunction with other experiments. The first was conducted within 45 minutes after an acoustic grenade experiment, and each of the other two was launched in parallel with the launch of a thermosphere probe experiment from the Aeronomy Program. These experiments, when combined with

data from radiosondes and the smaller meteorological rocketsondes, will provide a continuous profile of the atmosphere's vertical structure from the surface to approximately 300 km. This information is applicable to the analysis of the turbulent energy exchange between atmospheric regions such as the mesosphere and the thermosphere.

Thirty-eight acoustic grenade experiments, which provide wind and temperature vertical profiles, were distributed among the winter, spring, and fall seasons to study temporal and seasonal variations and especially to observe the atmospheric structure during the presence and absence of certain atmospheric phenomena. During the latter part of January and early February 1966, there was a total of 10 launches from Point Barrow, Alaska; Ft. Churchill, Canada; and Wallops Island, Virginia; to study atmospheric circulation and vertical structure during the presence and absence of auroral activity over Ft. Churchill. Coordinated launches were made from the three sites several days before, during, and within 24 hours after auroral activity. In addition, diurnal variability data were byproducts of the last two series.

A fourth launch site at Natal, Brazil, was added to the launch complex in 1966. This site, 6° south of the equator, will provide excellent information on the tropical atmosphere. Grenade experiments were launched from each of the four launch sites on May 1 and 3, 1966. This period was selected to coincide with the circulation transition over Wallops Island from a westerly flow to an easterly flow.

Atmospheric characteristics during the presence and absence of noctilucent clouds were again the subject of investigation during the summer. Noctilucent clouds are tenuous clouds that appear at irregular intervals during the summer over the Arctic and Antarctic at an altitude of approximately 80 km. These clouds are rendered luminous by the rays of the setting Sun. A total of 11 experiments were conducted from Point Barrow, Ft. Churchill, and Wallops Island during the latter part of June and during August 1966. This series provided measurements of the structure and circulation before conditions favorable for the cloud formations existed and during the period of frequent noctilucent cloud appearance.

The final series of grenade experiments in 1966 obtained data for the study of the thermally driven tides. During a 24-hour period in late September and early October, four experiments were launched from Wallops Island and five from Natal. The launches occurred at local noon, sunset, midnight, and sunrise. These soundings will pro-

vide comparative equatorial and midlatitude diurnal data for application to and evaluation of theories regarding thermally driven tides. Table IV summarizes the monthly and geographical distributions of successful NASA sounding rocket launches to obtain meteorological research data.

Two launches were conducted to further instrument and technique development. An experimental instrument planned for inclusion in the Nimbus satellites to measure solar ultraviolet energy in the spectral range from 1200 to 3000 Angstroms was tested successfully in September. Three other experiments were flown with the Nimbus instrument on the same Aerobee 150 rocket that went to an altitude of 200 km. The other three experiments, not part of the meteorological program, were to measure day airglow in the far ultraviolet, detect molecular nitrogen in the 750- to 1000-Å band, and to test a Langmuir electron temperature probe. A chemiluminescent ozonesonde experiment was launched in December 1966 from White Sands Mis-

Table IV.—*Monthly and Geographical Distribution of Successful NASA Research Meteorological Sounding Rocket Launches in 1966*

[G indicates grenade; N, sodium vapor or TMA release; P, pitot static tube; MUSE, monitor of ultraviolet and solar energy. Number indicates number of launches.]

Month	Types of payloads launched at—					
	Wallops Island, Virginia	Fort Churchill, Canada	Point Barrow, Alaska	Acension Island, British West Indies	Natal, Brazil [a]	White Sands, N. Mex.
January.....	5N	1G	....	....	....	....
February....	3G	3G	3G	1P	....	....
March......	....	....	....	....	....	....
April.......	....	....	....	....	....	....
May........	2G	2G	2G	....	2G	....
June........	....	2G	2G	....	....	....
July........	5N	....	....	....	....	....
August......	2G, 2P	1G, 1P	2G	....	2G	....
September...	2G	....	....	....	....	....
October.....	2G	....	....	....	2G	1MUSE
November...	....	....	....	....	....	....
December....	....	....	....	....	....	....

[a] Added to launch complex in 1966.

sile Range. Ozone measurements are a primary requirement for determining the heat budget of the upper atmosphere. Unfortunately, the parachute failed to deploy properly and the sonde descended too rapidly to obtain ozone measurements. However, the payload signals received indicated that the sensor was functioning. This was the second of the two failures encountered in the 55 launches conducted in 1966.

Data Analyses

In 1964, 30 experiments with rocket grenades and pitot-static tubes were performed at the several launch sites then in use. Reference 18 presents the data obtained in these experiments; however, the material does not include analyses of the meteorological significance of the data. Rather, reference 18 should be considered a record of the basic, unsmoothed measurements that may serve as the bases for further investigations and interpretations of atmospheric structure.

A number of data analyses have been completed in several areas during 1966. Eight pitot-static tube soundings were made from the U.S.S. *Croatan* during March and April of 1965, off the west coast of South America. These experiments were launched along a nearly constant longitude as part of the 1965 Mobile Launch Expedition. Six were spaced between the Tropic of Capricorn and 60° S. latitude and two were launched at the equator. During May 1965, a diurnal pair of soundings, launched at 8° S. latitude (Ascension Island), were included as appropriate to the analysis even though they were longitudinally displaced from the other soundings. Analyzed data from these launches are plotted on figure 14. The analysis shows a uniform stratosphere between 15- and 40-km altitude. Another feature is that the stratopause is warmer in the low and high latitudes than in the midlatitudes. The most spectacular variations in the cross-section appear above 80 km. The mesopause starts near 80-km altitude at the equator but, between 6° S. latitude and 35° S. latitude, it is approximately 100 km higher and more than 20°K colder than at the equator. The lower and warmer mesopause exists again between 38° S. and 48° S. latitude but it becomes higher and colder again south of 48° S. latitude.

During the summer of 1965, a series of grenade soundings at Point Barrow was initiated during a noctilucent cloud display at approximately 84 km. The first launch was during the noctilucent cloud display and was followed by two launchesd uring full daylight hours. No clouds were visible because of the daylight. Two days later, when a
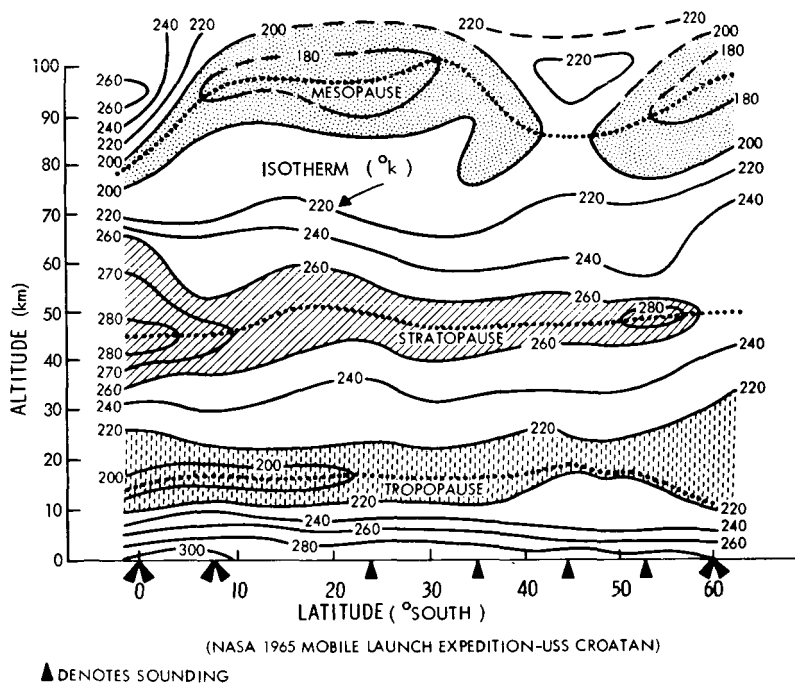
Figure 14.—Temperature cross-section, March–May 1965 (from NASA 1965 Mobile Launch Expedition—USS *Croatan*).

cloud display was definitely not occurring, a fourth experiment was launched as a control measurement. The four vertical temperature profiles, except for minor variations, are the same, with a steep uniform decrease in temperature from the stratopause to the mesopause and a minimum mesopause temperature of 140° K to 132° K at approximately 85 km. The complete absence of diurnal effect in these soundings is a result of the almost continuous August sunlight at Point Barrow, Alaska (refs. 19 and 20).

During noctilucent cloud displays, the temperature soundings at Kronogaard, Sweden (66° N.) in 1963 and at Ft. Churchill in 1964 and 1965, were similar to the soundings at Point Barrow. In each case where the noctilucent clouds were observed, the temperature at the mesopause was less than 140° K. Thus, since such low temperatures occur in both the presence and absence of these clouds, the low temperatures are a necessary, but not sufficient, condition for cloud existence; an increase in atmospheric moisture content may be necessary at these altitudes during the occurrence of low temperatures (refs. 19 and 20).

On the basis of data analyzed from launches in 1966 and in previous years, the following conclusions concerning the temporal variations in the temperature and wind structure of the mesosphere can be drawn (refs. 19 and 20):

(1) The stratospheric warming observed over Barrow in midwinter 1965 can be explained in terms of the circulation features at 50-km altitude. A southward migration of the polar vortex, combined with the building of the Aleutian anticyclone over the Alaskan Peninsula, brought warmer air to Barrow during an 8-day period; and reestablishment of the polar position of the vortex restored the colder flow to Barrow 4 days later.

(2) In the northern hemisphere, the polar vortex and the Aleutian anticyclone pressure systems, as well as the planetary scale waves, dominate the circulation of the lower mesosphere during winter. The wind and temperature fields are subject to gradual major changes that occur over a period of days or weeks. Smaller hourly variations result from the diurnal cycle, but no middle scale, short-term variations were detected, largely because of the sparse data coverage. Above 70-km altitude, tidal forces and, possibly, internal gravity waves exert the major influences on wind and temperature structure.

(3) Wavelike structures in the mesospheric temperature profiles of middle- and high-latitude sites appear to exist only in winter, and their oscillation amplitude increases with increasing latitude. Conversely, these variations appear to be completely suppressed under the typical high-latitude summer regime that is characterized by a steep lapse rate at uniform temperature, easterly circulation, and an inferred upward motion.

OPERATIONAL SOUNDING ROCKET SYSTEM DEVELOPMENT

Objectives

If adequate observational coverage of the upper atmosphere is to be achieved, an inexpensive meteorological rocket sounding system must be developed that is capable of reliable routine launches and amendable to the requirements for range support, research, and network operations. An operational meteorological sounding rocket system with a 100-km altitude capability, including direct readout, may be available by 1975. The falling mass hazard inherent in spent vehicles must be eliminated during the work in order to increase the

number of locations that can use such a system. However, for widespread usage a production model must be developed to reduce cost. Soon after 1975, this system is expected to serve as a basis for a worldwide system, independent of limitations imposed by special launch sites and environment.

The project has consisted of payload development and launch vehicle development. Improvements to existing systems are essentially completed and will be supplemented by development of a new 60-km altitude vehicle and a new payload incorporating necessary changes not possible with existing systems. Extension of the altitude capability to 100 km will, for some parameters, demand new sensors because the reduced density at those altitudes requires a different measurement technique. Supporting research is in progress.

Work in Progress

NASA and the U.S. Army Missile Command are cooperating to develop the new 60-km altitude vehicle. This effort is expected to reduce costs sharply, as well as to eliminate the wind-sensitivity difficulties characteristic of the Arcas class vehicles. NASA and the Army are also cooperating in funding background development of both frangible and self-consuming rocket cases. The feasibility demonstrations have been successful; however, work is continuing to improve the rocket cases that are presently heavy and expensive.

Among program accomplishments in 1966 was the completion of a series of 23 rocketsondes launches, coordinated with launches of 12 radiosondes, over a 60-hour period to provide data on:

(1) Instrumentation errors in rocketsondes caused by the effects of solar radiation.

(2) Differences between simultaneous measurements by radiosondes and rocketsondes.

(3) Diurnal temperature variations above 30 km.

Work is also continuing on further improvements to the payloads and development of a temperature measurement capability extended to 100 km (ref. 21). Development of solid-state power oscillators and transmitters and bolometer circuits with small time constants is included in the payload improvement effort. Development of parachutes suitable for use at altitudes at, or above, 60 km was also reported by Eckstrom (ref. 22). After testing, the improved payload components are included in the operational sounding rocket system.

Approximately 175 operational development sounding rockets were launched in 1966. The meteorological data from these flight tests were also used to support range operations. These data were made available to other agencies and reported by the Army Electronics Research and Development Activity at White Sands (ref. 23).

Data Analyses

Finger and Woolf reported the results of their analyses of data obtained in September 1965 from an experiment designed to determine the diurnal temperature and wind variation and to detect possible errors in rocketsonde temperature measurements in the upper stratosphere. (ref. 24).

Fourteen Hasp and two Arcas rockets, carrying WOX–1A and Arcasonde–1A instrumentation, respectively, were launched at Wallops Island from 1745 e.d.t. on September 8, 1965, to 0838 e.d.t. on September 10, 1965. These rockets obtained measurements at altitudes between 30 and 60 km. Analysis of the observed rocketsonde temperatures indicates a diurnal variation ranging from approximately 276° K at 30 km to 282° K at 48 km. Marked temperature differences measured by rocketsondes launched before and after sunrise and sunset suggest that a portion of the variation may not be real, but may possibly be a function of instrumental error. Support for this inference is provided by computations using the rocketsonde winds as an independent means of determining the diurnal temperature wave. The results, which are consistent with theory, yield an amplitude approximately half that of the observed variation in the 35- to 45-km altitude layer. Temperatures obtained from several rockets launched within a short time disclose that the HASP (WOX–1A) system can reproduce a given temperature profile with a relatively small random error. In addition, Arcas (Arcasonde 1A) measurements appear compatible with those of the HASP. However, a definite discrepancy was found to exist between rocketsonde temperatures and those reported by the supporting rawinsonde observations.

The meteorological program of the NASA Mobile Launch Expedition in the southern hemisphere during the International Quiet Sun Year included shipboard meteorological rocket measurements of wind and temperature to altitudes of 65 km (ref. 2). The unique data from 32 soundings are presented and discussed by Chamberlain and

Manning (ref. 25) as a first look at the circulation of the upper atmosphere in the data-sparse region to 60° S. latitude.

FIELD EXPERIMENT SUPPORT

The NASA field experiment support program, through cooperation with other countries, provides for the launch of sounding rocket experiments from their territories.

The Experimental Inter-American Meteorological Rocket Network (Exametnet) was established as a cooperative program to extend sounding rocket measurements into Latin America on an experimental basis. Memoranda of Understanding were signed with Brazil and Argentina in 1965. During 1966, beginning January 12 from Natal, Brazil, and April 27 from Chamical, Argentina, boosted-dart type sounding rockets were launched to obtain meteorological data. By December 31, 1966, 30 rockets had been launched from these stations. Plans for increasing the number of launch sites and the scope of the program were discussed at the annual Exametnet meeting held at Chamical in September 1966. By expanding the program and using data from other existing sites, a study could be made of the structure and circulation of the atmosphere and the interrelation of the atmospheric behavior in both the northern and southern hemispheres.

Personnel of the other nations have been trained at Wallops Station to operate the launch sites in their countries. The scientists, engineers, and administrators in their own national space programs participate in the planning, operation, and scientific analysis of data from Exametnet.

On January 14, 1966, Memoranda of Understanding were signed with Spain to provide a cooperative program in both research meteorological sounding rockets (using the acoustic grenade experiment) and the smaller Arcas- and boosted-dart class sounding rockets. On August 19, 1966, the Spanish technicians completed their training at NASA's Wallops Station, and in October 1966, launches were initiated from a site at Huelva, Spain.

Cooperative programs are being developed for testing and cross-calibrating meteorological sounding rockets, payloads, and ground equipment developed by the United States and other nations. In this manner, internationally obtained data become directly comparable and of significantly increased validity and utility.

SUMMARY AND CONCLUSIONS

Accomplishments

Meteorological Satellites

In 1966, Nimbus II demonstrated the versatility of large, sophisticated R&D meteorological satellites for providing both research and operational data. Changes incorporated in the Nimbus II spacecraft significantly improved the performance and lifetime of the satellite and the value and total yield of the scientific data. The Nimbus II satellite has provided the most complete set of global meteorological observations to date for studying atmospheric phenomena and behavior.

A major milestone in meteorology occurred with the establishment and operation of the National Operational Meteorological Satellite System in 1966. The system provides cloud pictures of the entire sunlit portions of the Earth twice daily. The TOS spacecraft, carrying the APT camera system, transmits pictures to the local APT ground stations during local midmorning. The TOS spacecraft with the AVCS camera system collects, stores, and relays data globally during the local afternoon hours. Additional TOS spacecraft are under development to maintain a local and global cloud-cover photographic capability for operational weather use.

All Tiros research and development satellites launched since June 18, 1963, continued to operate in orbit. That is, Tiros VII, VIII, IX and X are still capable of providing cloud cover data as of December 31, 1966. However, with the successful operation of ESSA I, II, and III, these satellites are programmed for minimal use.

One of the spectacular and promising events during 1966 was the successful operation of the ATS–I spin-scan camera. This camera is providing the first high-quality cloud-cover pictures taken from an equatorial synchronous satellite. These pictures show the disk of the Earth between 52° latitude N. and S. with a resolution approaching 3 km. The camera system can take the disk pictures once every 20 minutes and smaller areas more frequently, affording a potential continuous watch of global weather patterns. Another meteorological experiment on ATS–I transmits meteorological data (weather maps, cloud analyses, and spin-scan cloud pictures) from the ATS ground station at Mojave, California, via the satellite's VHF transponder, to APT ground readout stations in the United States, Canada, Japan, Australia, and islands in the Pacific.

Some of the scientific results obtained from meteorological research based on satellite TV pictures are listed below:

(1) Additional criteria were developed for relating cloud picture data with surface and upper-air circulation, relative stability, thermal shear, and cyclogeneses.

(2) Satellites pictures were used to infer the vertically integrated moisture content of the air between 1000 and 500 millibars; this experiment showed a positive correlation of the cloud amount and types with the mean humidity.

(3) Satellite pictures provide a reliable method (over 80 percent of the time) for identifying and locating the position of the jet stream.

(4) Satellite cloud pictures have revealed the extent and frequency of cellular cloud cells over the ocean, and a recent study indicates the role of heating, atmospheric stability, and air trajectory in cell formation.

(5) Indications were found that cloud patterns observed in satellite pictures are not directly related to the computed field of vertical motions; horizontal motions were important in the development and pattern of cloud vortices.

(6) The most significant achievement in satellite radiometric measurements was the amount of medium- and high-resolution infrared data collected by Nimbus II. The improved quality and extension of MRIR data coverage over the polar regions are important advances provided by Nimbus II.

(7) Comparisons of the variations in the monthly mean values of the long-wave radiation, based on Tiros IV and VII data, have revealed maximum yearly differences ranging up to 35 percent of the mean value of the radiation.

(8) A statistical study of long-wave radiation data in relation to 500-millibar height field indicated that the radiation data can be useful for locating upper-level troughs and ridges.

(9) The MRIR data from Nimbus II revealed that the winter (June–July) temperature patterns in the lower stratosphere around the South Pole are not symmetrical.

Meteorological Sounding Rockets

Research meteorological sounding rockets were launched up to 100 km to obtain data pertaining to solar influences, polar stratospheric and mesospheric structure, seasonal and temporal variations of the large-scale circulation, and the temperature and wind struc-

ture associated with noctilucent clouds. Analyses conducted during 1966 disclosed the following:

(1) The stratospheric warming observed over Point Barrow, Alaska, in midwinter 1965 can be explained on the basis of the southward migration of the polar vortex combined with the buildup of the Aleutian anticyclone pressure system over the Alaskan Peninsula.

(2) The polar vortex and the Aleutian anticyclone pressure systems, as well as the planetary scale waves, dominate the circulation of the lower mesosphere during the northern hemisphere's winter season.

(3) In winter, the oscillation amplitude in the mesospheric temperature profiles increased from the middle to high latitudes, while the typical high-latitude summer regime is characterized by a steep, uniform temperature lapse rate and an easterly circulation.

Operational sounding rocket program activities were directed toward developing the payload and launch vehicle for a low-cost, reliable system to meet the requirements for range support, research, and network operations. Data analysis from the operational development sounding rockets provided the following results: The rocketsonde temperatures indicate a diurnal variation ranging from about $276°$ K at 30 km to $282°$ K at 48 km. Analysis of the rocketsonde winds and theory yields an amplitude about half that of the observed variation in the 35- to 45-km layer, which indicates instrumental errors in the temperature measurements.

Significant Questions and Outlook

Advances in the theory pertaining to atmospheric processes and in computer and satellite technology provide a basis for developing a system that will extend the weather forecasting process to higher levels of accuracy and to longer time periods. The World Meteorological Organization recognized the global extent of the system and has established the World Weather Watch (WWW) that will provide the international focus for planning and implementing the program. WWW is a system for observing, collecting, processing, and distributing weather information using the latest developments in communications, data processing, and space technology. The major objectives of the WWW program are to improve worldwide services, increase the accuracy of weather forecasts, and develop the capability for making long-range weather forecasts.

The largest obstacle to implementing the WWW program at this time is the lack of adequate data on the atmosphere over the entire

globe. The meteorological satellite has become a scientific tool that can provide the required observational data regularly and dependably. The WWW system will include meteorological satellites, horizontal sounding balloons, meteorological ocean buoys, automatic and manned weather stations, comunications satellites, and meteorological sounding rockets.

Basically, a satellite uses two modes for obtaining meteorological observations and measurements. The first mode involves sensors which measure the intensity of the electromagnetic radiation of the Earth, its atmosphere, or both. The second mode involves sensing *in situ* and using the satellite as a data collection relay. The satellite is used to interrogate, record, locate, and relay the data from a platform to processing centers. Platforms can include automatic or manned weather stations, moored or floating buoys, and instrumented free-floating balloons.

Work is progressing to improve the present meteorological satellites and their instrumentation. Satellite systems for locating and interrogating surface and airborne platforms are being readied for flight test. Satellite sensors for detecting the vertical distribution of atmospheric temperature and humidity are under development and will be tested soon. Cameras and infrared scanners for nighttime cloud-cover observation are being constructed. The second generation of operational meteorological satellites is being developed to replace the present TOS series.

Data collected by the meteorological sounding rockets have been used to increase knowledge and understanding of the atmosphere. The launching site network has been extended to provide wider geographical distribution of the observations. The long-range goal is to extend the research rocket network to 30 to 50 worldwide sites with several hundred launches per year. During 1966, 55 rockets were launched to collect research data and to further instrument and technique development in the meteorological program.

The smaller operational development sounding rockets are being improved to achieve an economical and reliable system for range-support, research, and network operations. This development is expected to continue until about 1975.

The ultimate goal of the meteorological sounding rocket program is to develop a system for obtaining sufficient data, properly distributed over the world, to provide a detailed description of the atmosphere up to 100 km. This information is required for a com-

plete understanding of the region and for developing reliable meteorological predictions.

The goal of the NASA meteorological program is to develop the space technology required to provide a capability for observing the behavior of the global atmosphere. These observations will provide the basis for improving understanding of atmospheric behavior and ability to predict the weather accurately and for longer periods of time.

REFERENCES

1. ANON.: Significant Achievements in Satellite Meteorology, 1958–1964. NASA SP–96, Jan. 1965.
2. ANON.: Significant Achievements in Space Applications, 1965. NASA SP–137, 1966.
3. GOLDSHLACK, L.; and WIDGER, W.: Nimbus II Data Code Experiment. NASA CR–80162, 1966.
4. WEIGMAN, E. J.; HADFIELD, R. G.; and SEREBRENY, S. M.: Atlas of Cloud Vortex Patterns Observed in Satellite Photographs. Stanford Research Institute, Feb. 1965.
5. ANDERSON, R. K.; FERGUSON, E. W.; and OLIVER, V. J.: The Use of Satellite Pictures in Weather Analysis and Forecasting. TN 75, WMO–90–TP96, World Meteorological Organization, Geneva, Switzerland, Mar. 1966.
6. McCLAIN, E. P.: On the Relationship of Satellite-Viewed Cloud Conditions to Vertically Integrated Moisture Fields. Monthly Weather Rev., vol. 94, no. 8, Aug. 1966, pp. 509–514.
7. WHITNEY, L. F., JR.; TIMCHALK, A.; and GRAY, T. I., JR.: On Locating Jet Streams from Tiros Photographs. Monthly Weather Rev., vol. 94, no. 3, Mar. 1966, pp. 127–138.
8. HUBERT, L. F.: Mesoscale Cellular Convections. Meteorological Satellite Laboratory, rep. no. 37, U.S. Department of Commerce, May 1966.
9. TSUCHIYA, K.; and FUJITA, T.: A Satellite Meteorological Study of the Evaporation and Cloud Formation over the Western Pacific Under the Influence of the Winter Monsoon. Satellite and Mesometeorology Research Project, Department of Geophysical Sciences, Univ. Chi., Sept. 1966.
10. BARR, S.; LAWRENCE, M. B.; and SANDERS, F.: Tiros Vortices and Large-Scale Vertical Motion. Monthly Weather Rev., vol. 94, no. 12, Dec. 1966, pp. 675–696.
11. JENSEN, C. E.; WINSTON, J. S.; and TAYLOR, V. R.: 500-mb Heights as a Linear Function of Satellite Infrared Radiation Data. Monthly Weather Rev., vol. 94, no. 11, Nov. 1966, pp. 641–649.
12. ALLISON, L. V.; and WARNECKE, G.: Synoptic Interpretation of Tiros III Radiation Data Recorded on July 16, 1961. Bull. Am. Meteorol. Soc., vol. 47, no. 5, May 1966, pp. 374–383.
13. WIDGER, W., JR.; BARNES, J. C.; MERRITT, E. S.; and SMITH, R. B.: Meteorological Interpretation of Nimbus High Resolution Infrared Radiometer (HRIR) Data. Allied Research Associates, Inc., Concord, Mass., 1966.
14. NORDBERG, W.; McCULLOCH, A. W.; FOSHEE, L. L.; and BANDEEN, W. R.: Preliminary Results from Nimbus II. Bull. Am. Meteorol. Soc., vol. 47, no. 11, Nov. 1966, pp. 857–872.

15. ALLISON, L. J.; KENNEDY, J. S.; and NICHOLAS, G. W.: Examples of the Meteorological Capabilities of the Nimbus Satellites. J. Appl. Meteorol., vol. 5, 1966, pp. 314–333.

16. FRITZ, S.; HUBERT, L. F.; and TIMCHALK, A.: Some Inferences From Satellite Pictures of Tropical Disturbances. Monthly Weather Rev., vol. 94, no. 4, Apr. 1966, pp. 231–236.

17. ANON.: Nimbus II Users' Guide. NASA Goddard Space Flight Center, July 1966.

18. SMITH, W.; THEON, J.; KATCHEN, L.; and SCHWARTZ, P.: Temperature, Pressure, Density, and Wind Measurements in the Upper Stratosphere and Mesosphere, 1964. NASA TR R–245, Aug. 1966.

19. THEON, J. S.; NORDBERG, W.; KATCHEN, L. B.; and HORVATH, J. J.: Some Observations on the Thermal Behavior of the Mesosphere. NASA TM X–55621, 1966.

20. THEON, J. S.; NORDBERG, W.; and SMITH, W. S.: Measured Temperature Structure in Noctilucent Clouds. NASA TM X–55648, 1966.

21. DREWS, W. A.: A Thermistor Arrangement to Improve Temperature Measurements at High Altitudes. NASA CR–533, Aug. 1966.

22. ECKSTROM, C. V.: Development and Testing of the Disk-Gap-Band Parachute Used for Low Dynamic Pressure Applications at Ejection Altitudes at or Above 200 000 Feet. NASA CR–502, June 1966.

23. INTER-RANGE INSTRUMENTATION GROUP: Meteorological Working Group, Data Reports of the Meteorological Rocket Network Firings. Documents 109–62, vols. LIII to LV, U.S. Army Electronics Research and Development Activity, White Sands Missile Range, N. Mex., 1966.

24. FINGER, F. G.; and WOOLF, H. M.: An Experiment Designed To Determine the Diurnal Temperature and Wind Variation and To Detect Possible Errors in Rocketsonde Temperature Measurements in the Upper Stratosphere. NASA TM X–1298, Nov. 1966.

25. CHAMBERLAIN, L. W.; and MANNING, J. C.: Shipboard Rocket Measurements of Wind and Temperature up to 65 km in the Southern Hemisphere. NASA TN D–5674, Nov. 1966.

NAVIGATION AND TRAFFIC CONTROL SATELLITE PROGRAM

Navigation and Traffic Control Satellite Program

INTRODUCTION

Present position fixing, traffic control, and communications aids are inadequate for both the aircraft and marine industries to cope with the projected growth of transoceanic traffic. This section describes space technology developments applicable to air and marine navigation and traffic control pursued during 1966. These developments mark progress toward the attainment of the program's objectives.

The overall objective of the navigation and traffic control satellite program is to provide the space technology that, together with more conventional methods, will help ships and aircraft operate safely, efficiently, and economically on a global basis. The program will provide the basis for improved methods of traffic control, traffic coordination, and emergency land and sea rescue assistance. The overall objective has been divided into three specific objectives for implementation.

Space Techniques for Position Fixing of Mobile Surface and Airborne Craft

Satellites launched by the Department of Defense have demonstrated the feasibility of using space technology to provide surface ships with precise location determinations. The Navy Transit satellite system, however, is limited by costly shipboard equipment, a position-computation time of 6 to 8 minutes, a position determination only once every 90 minutes, and no capability for providing the ship's position to shore stations for traffic control purposes. The civilian requirements for a navigation satellite system include simple, inexpensive equipment for use on ships and aircraft, communication of the craft's position to traffic control centers and rescue service agen-

cies, and techniques to determine the position of transoceanic aircraft with speeds ranging from subsonic to supersonic. Space techniques for accurate position determination of ships and aircraft are being developed in the supporting research and technology program and will be flight tested on manned and automated spacecraft missions. Experiments are presently under development for flight testing on the ATS.

Traffic Control Techniques Using Space Technology

The Joint Navigation Satellite Committee (JNSC), in its report on a nonmilitary satellite system for air-sea navigation and traffic control, recognized the need for communications between the craft and air traffic control centers as well as accurate position location by the ship or aircraft (ref. 1). The important key to the solution of the transoceanic air traffic problems is the control center's need for accurate position locations of all aircraft operating in the area and a reliable means for the ground control station to communicate with these aircraft. To satisfy this requirement, space technology must be developed that can provide communications to aircraft within a noisy environment using low-gain (0 to 3 dB) antennas. Multiplexing techniques that allow controllers, aircraft, and ships to communicate through the satellite equipment with minimum waiting periods need to be developed. Experiments are being conducted on ATS–I and will be continued on other spacecraft, both manned and automated, to test the needed technology.

Space Technology for Data Collection

Several environmental and geophysical sciences require a method for collecting data from a large number of instrumented remote platforms on the Earth's surface as well as airborne. Real-time position information is also needed for the mobile platforms (balloons and buoys), as is a method to collect the environmental data being generated by the instruments. These platforms will provide *in situ* measurements of various atmospheric, oceanographic, hydrologic, and geologic parameters, such as the wind and water velocity, temperature, pressure, and humidity. Experiments to develop the needed space technology will be conducted at synchronous altitude on the ATS series and at medium altitude by the polar-orbiting Nimbus satellites.

NAVIGATION AND TRAFFIC CONTROL

Background

During 1966, the position determination, data transfer, and data collection efforts, initiated in previous years, were continued. These efforts are directed toward the development of methods, techniques, and spaceborne equipment to provide the bases for developing navigation traffic control satellites in the 1970's. Supporting research and technology work at NASA installations, universities, and industries is being pursued, and experiments for flight on approved spacecraft are being developed.

Joint Navigation Satellite Committee

The six-agency JNSC (Departments of Commerce, Defense, Interior and Treasury, Federal Aviation Agency, and NASA) was established in September 1964 and concluded its work in May 1966. The possibilities were examined for a nonmilitary satellite system for air-sea navigation, traffic control, emergency and rescue operations, and related functions. The results, conclusions, and recommendations of this *ad hoc* study group are presented in reference 1 and summarized below.

The JNSC recognized that satellites should not merely provide the ship location or aircraft position but also should provide information required to ensure safe and efficient transport from one point to another on the Earth's surface. Therefore, communications and relay of pertinent en-route environmental data such as weather and sea-state conditions were also considered.

It became clear during the committee's deliberations that the aviation needs would become critical within a few years, primarily for air traffic control over the North Atlantic region. The JNSC also concluded that the ". . . future air and marine navigation and communications requirements will not be met completely by existing systems or combinations of existing systems," and that "space technology and economic considerations are now sufficiently promising to warrant continued determined investigation of the technical and economic feasibility of utilizing satellites for the purposes considered by the JNSC, ether separately or in combination with non-satellite techniques." The commttee concluded that it is not now possible to make accurate long-term assessments of the aircraft and marine requirements for meeting their navigation and communications needs. The JNSC stated that, "Further detailed study of requirements, tech-

nical developments, experiments and operational demonstrations are necessary to lay an early and proper base for any eventual systems implementation."

The JNSC further recommended that, "A system utilizing satellites combining communications air traffic control surveillance and navigations functions, either separately or in combination with nonsatellite techniques, should be investigated further." Efforts to accomplish this, in part, are under way, using presently planned NASA satellites.

Aviation Interests in Satellites

In July 1966, the Federal Aviation Agency (FAA) asked NASA to provide an experimental capability on a future satellite for communication and independent position determination services between aircraft and ground facilities in the frequency band of 1540 to 1660 MHz. This frequency range is presently allocated to aeronautical radio communications and navigation. Of particular interest to the FAA is the North Atlantic air route system. The Electronics Research Center has been assigned the responsibility to develop the needed technology in this area. Flight tests of the particular technology may be made using existing NASA spacecraft, such as the ATS series, Nimbus, or the Apollo manned spacecraft.

The FAA has also expressed interest in the Omega Position Location Experiment (OPLE), scheduled to be tested with the ATS–C, as it might relate to navigation or independent aircraft position. The OPLE uses the transmissions from a minimum of three Omega ground stations received at an aircraft or ship and then relayed to a ground station via a sattellite. A communications transponder located on the ATS–C will relay the Omega signals to the ground for position computation. The position location would then be sent to the craft or to a traffic control center.

Manned Earth-Orbiting Satellite for Navigation

A study by Westinghouse has been completed that investigated the feasibility and utility of conducting navigation and communications experiments aboard a manned Earth-orbiting spacecraft. In particular, a series of such experiments was defined that would give due consideration to exploiting the advantages of manned craft and the presence of the astronauts to assist in performing the experiments. The results indicate that the development of data collection, and navigation and traffic control technology can be performed more

expeditiously using manned spacecraft than would be possible using a series of smaller automated satellites. The astronaut could assist in angle-measuring tests using interferometer antennas by observing the interferometer boom deployment, photographing boom movement, changing boom length, changing antenna feeds, and monitoring in-flight angle-measuring equipment. The Apollo lunar module or the command-service module could house the angle measuring, distance, or distance-rate position experiments and the data transfer transponder.

Data Collection

In early 1966, approval was granted for an experiment involving the Navy's Omega Navigation System and a transponder in the ATS–C spacecraft. The experiment is designed to demonstrate that the position of a large number of free-moving, automated, and instrumented platforms (balloons, buoys, ships, and aircraft) can be located, and that geophysical or other data being acquired can be collected. Prime interest for this experiment is the collection of meteorological data, such as temperature, pressure, and possibly humidity, and determination of wind speed and direction.

Developments have been initiated on the platform electronics— VLF receiver and VHF transmitter and associated antennas and upconverter—and for a ground station that is capable of receiving the platform Omega signals, computing the location, receiving the geophysical data, and initiating platform interrogation commands via the satellite. Breadboard models of the OPLE platform electronics have been completed and tested. Work on the control center equipment is progressing on schedule to meet a late 1967 launch of ATS–C.

The interrogation, recording, and location experiment (IRLS), selected for flight on the Nimbus B spacecraft, continued to progress satisfactorily during 1966. Models of the platform equipment have been completed and units have been tested for spacecraft compatibility.

A number of government and research organizations have expressed interest in utilizing IRLS platforms for position location and geophysical data transfer purposes. The oceanographic community has expressed the greatest interest in the IRLS experiment to be carried on Nimbus B. Ocean buoys, containing an IRLS receiver and transmitter and suitable instruments to measure water parameters, will be provided by the Naval Oceanographic Office, Bureau of

Commercial Fisheries, National Science Foundation, and the Woods Hole Oceanographic Institution. Meteorological experiments will be conducted by the U.S. Air Force and the National Center for Atmospheric Research. The U.S. Navy has expressed interest in examining the use of IRLS for monitoring ice floe movement and as an aid for air-sea rescue. A University of Florida scientist, with support from the Office of Naval Research, will use IRLS to track a large turtle in an attempt to determine its means for navigation.

SUMMARY AND CONCLUSIONS

During late 1966, ATS–I demonstrated that voice communications can be conducted between aircraft in flight and a ground station. These test demonstrations included transoceanic flights as well as flights over the continental United States. The VHF communications equipment normally available on transoceanic commercial aircraft was used in these tests.

A study completed during 1966 indicated that the presence of the astronaut on manned missions would enhance the conduct of navigation, traffic control, and data collection experiments.

Experiments are being developed for the ATS–C flight scheduled in 1967 for position determination of and communications with aircraft. The position determinations require the use of the U.S. Navy Omega ground stations, the VHF transponder on the spacecraft, and a ground station for position computations. This technique will also be tested to obtain the location of instrumented free-floating balloons and ocean buoys. In addition, environmental data will be collected from these instrumented platforms. A data collection experiment is also under development for flight test on Nimbus B, scheduled for flight in early 1968. A number of government agencies and research groups will use the Nimbus B equipment to collect oceanographic and meteorological data from balloons, buoys, and automatic land stations.

Satellite technology promises to provide the basis for developing a global navigation and traffic control system to meet future air and ocean transportation needs. Establishment of a global system employing satellites requires the development of a multiple-access capability for communicating simultaneously with numerous ships and aircraft. The equipment required for use on ships and aircraft should be inexpensive and easy to operate and maintain. Accuracy of position location for many applications will have to be within 2 km or less. Ground

controllers will require a capability for continuous contact with all ships and aircraft within the system. NASA has initiated supporting research and technology to satisfy many of the requirements of a future global navigation and traffic control satellite system.

REFERENCES

1. JAFFE, L.; ET AL.: Final Report of the *Ad Hoc* Joint Navigation Satellite Committee. May 1966.