TECHNICAL NOTE No. 189

THE CONTRIBUTION
OF SATELLITE DATA AND SERVICES
TO WMO PROGRAMMES
IN THE NEXT DECADE

WMO - No. 679

Secretariat of the World Meteorological Organization - Geneva - Switzerland
The World Meteorological Organization (WMO), of which 153 States and Territories are Members, is a specialized agency of the United Nations.

It was created:
- To facilitate world-wide co-operation in the establishment of networks of stations for making meteorological observations as well as hydrological and other physical observations related to meteorology, and to promote the establishment and maintenance of centres charged with the provision of meteorological and related services;
- To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;
- To promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics;
- To further the application of meteorology to aviation, shipping, water problems, agriculture and other human activities;
- To promote activities in operational hydrology and to further close co-operation between Meteorological and Hydrological Services;
- To encourage research and training in meteorology and, as appropriate, in related fields, and to assist in co-ordinating the international aspects of such research and training.

The machinery of the Organization consists of the following bodies:

The World Meteorological Congress, the supreme body of the Organization, brings together the delegates of all Members once every four years to determine general policies for the fulfilment of the purposes of the Organization, to adopt Technical Regulations relating to international meteorological practice and to determine the WMO programme.

The Executive Council is composed of 29 directors of national Meteorological or Hydrometeorological Services. It meets at least once a year to conduct the activities of the Organization, to implement the decisions taken by its Members in Congress and to study and make recommendations on any matter affecting international meteorology and related activities of the Organization.

The six regional associations (Africa, Asia, South America, North and Central America, South-West Pacific and Europe), which are composed of Member Governments, co-ordinate meteorological and related activities within their respective Regions and examine from the regional point of view all questions referred to them.

The eight technical commissions, consisting of experts designated by Members, are responsible for studying any subject within the purpose of the Organization. Technical commissions have been established for basic systems, instruments and methods of observation, atmospheric sciences, aeronautical meteorology, agricultural meteorology, marine meteorology, hydrology, and climatology.

The Secretariat, located at 41 Avenue Giuseppe-Motta, Geneva, Switzerland, is composed of a Secretary-General and such technical and clerical staff as may be required for the work of the Organization. It undertakes to serve as the administrative, documentation and information centre of the Organization, to make technical studies as directed, to support all the bodies of the Organization, to prepare, edit or arrange for the publication and distribution of the approved publications of the Organization, and to carry out duties allocated in the Convention and the regulations and such other work as Congress, the Executive Council and the President may decide. The Secretariat works in close collaboration with the United Nations and its specialized agencies.
WORLD METEOROLOGICAL ORGANIZATION

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1987
False colour composite image of Europe derived from special processing of remotely sensed image data obtained by the NOAA-7 polar-orbiting satellite. The composite image consists of data from the near infra-red and two thermal infra-red sensors (Channels 2, 3, 4) of the Advanced Very High Resolution Radiometer (AVHRR). Special processing was done at the Remote Sensing Data Centre of DFVLR in the Federal Republic of Germany.

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NOTE

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FOREWORD

The operational meteorological and hydrological services of WMO Members have derived great benefit from the data and services provided by the global network of meteorological satellites. The WMO Congress has affirmed that the polar-orbiting and geostationary meteorological satellites, in their observation, data-collection and dissemination roles, are of fundamental importance to the operation of the World Weather Watch and indeed to all WMO Programmes.

Since the 1977 publication The Role of Satellites in WMO Programmes in the 1980s (WMO-No. 494), there have been many significant developments in meteorological and other environmental satellites. It is therefore important to keep in mind the possible future role of satellites when considering the overall co-ordination of the long-term plans of WMO Programmes. The present publication, prepared by Dr A. Karpov (USSR) and Dr D. Miller (USA), summarizes the current status of satellite technology and its application to various fields and projects the future of satellite systems in the next decade.

Member countries of WMO are invited to take this report into account in making their contributions to the WMO Programmes and harmonizing national plans with them.

I should like to take this opportunity to express the sincere thanks of the World Meteorological Organization to Drs Karpov and Miller and their colleagues for the vast amount of work they have done to update the information on the applications of satellite data and services. This report will doubtless be of great interest and use to all the countries of the world.

G.O.P. Obasi
Secretary-General
SUMMARY

This publication contains an analysis of the present state of the global network of meteorological satellites. It describes the applications of satellite technology in meteorology and operational hydrology and assesses the future role of meteorological satellites in WMO Programmes in the next decade.

The present global network of geostationary and polar-orbiting meteorological satellites is described in Chapter 2. The types of remotely sensed data available from these satellites and the processing steps needed to produce useful information from these data are also described in this chapter.

Chapter 3 is devoted to a description of the contribution of satellite data and services in the meteorology and operational hydrology programmes of WMO.

Projections for the future global network of meteorological satellites are given in Chapter 4 along with the developments in data-processing systems which will enhance the ability to obtain useful information from meteorological satellite data.

RESUME

La présente publication analyse la situation actuelle du réseau mondial de satellites météorologiques. Elle décrit les applications des techniques satellites dans les domaines de la météorologie et de l'hydrologie opérationnelle et évalue le rôle que joueront les satellites météorologiques dans les programmes de l'OMM au cours de la prochaine décennie.

Le chapitre 2 contient une description du réseau mondial actuel de satellites météorologiques géostationnaires et de satellites météorologiques à défilement. Il donne également le détail des types de données de télémesure transmises par ces satellites ainsi que des différentes phases de traitement nécessaires pour produire des renseignements utiles à partir de ces données.

Le Chapitre 3 expose la contribution apportée par les données et services satellitaires aux programmes de météorologie et d'hydrologie opérationnelle de l'OMM.

Le chapitre 4 contient des projections relatives au futur réseau mondial de satellites météorologiques et traite de l'évolution des systèmes de traitement des données qui permettra de renforcer les moyens dont on dispose pour obtenir des renseignements utiles à partir des données des satellites météorologiques.
РЕЗЮМЕ

В настоящей публикации содержится анализ существующего состояния глобальной сети метеорологических спутников. В ней описываются вопросы применения спутниковой техники в метеорологии и оперативной гидрологии и оценки будущей роли метеорологических спутников в программах ВМО на следующее десятилетие.

Существующая глобальная сеть геостационарных метеорологических спутников и спутников на полярной орбите описывается в главе 2. В этой же главе описываются также имеющиеся от этих спутников типы данных, получаемые способами дистанционного зондирования, и методы обработки, необходимые для получения полезной информации из этих данных.

Глava 3 посвящена описанию предназначения спутниковых данных и обслуживания для программ ВМО по метеорологии и оперативной гидрологии.

В главе 4, наряду с развитием систем обработки данных, которые увеличивают возможности получения полезной информации из данных метеорологических спутников, приводятся данные по будущей глобальной сети метеорологических спутников.

RESUMEN

La presente publicación contiene un análisis del estado actual de la red mundial de satélites meteorológicos. En ella se describen las aplicaciones de la tecnología satelital a la meteorología y a la hidrología operativa y se evalúa la función futura de los satélites meteorológicos en los programas de la OMM para el próximo decenio.

En el Capítulo 2 se hace una descripción de la red mundial de satélites meteorológicos geostacionarios y de órbita polar actualmente en servicio. También se describen en este capítulo los tipos de datos que obtienen estos satélites mediante teledetección, así como los procedimientos necesarios para procesarlos con objeto de obtener de ellos una información útil.

El Capítulo 3 se consagra a la descripción de la contribución de los datos y servicios satelitales a los programas que dedica la OMM a la meteorología y a la hidrología operativa.

En el Capítulo 4 se presentan proyecciones sobre la futura red mundial de satélites meteorológicos, y se exponen los progresos realizados en los sistemas de proceso de datos, que aumentarán las posibilidades de obtener una información útil gracias a los datos que proporcionan los satélites meteorológicos.
CHAPTER 1

INTRODUCTION

Meteorologists all over the world are now able to take advantage of a wealth of observational data and communications-related services flowing from specially equipped and highly sophisticated satellites.

Operational satellite capability has been evolving since the first launch of a meteorological satellite in 1960. By the end of the 1960s the meteorological satellite had grown to a highly sophisticated platform which could provide global coverage of cloud observations and was beginning to provide quantitative measurements of pertinent meteorological parameters. During the 1970s there evolved a co-operative international network of meteorological satellites culminating in a nearly complete global network of meteorological satellites to contribute to the Global Weather Experiment (FGGE).

In the present decade of the 1980s we are witnessing a stabilization of the global network of meteorological satellites in terms of sensor data and services. In anticipating the 1990s, we expect that the next generation of satellites will provide us with many kinds, and vast amounts, of data for meteorology and operational hydrology.

To many readers, the words "satellite data" evoke a mental picture of weather maps, or perhaps of data input to numerical-forecasting computers. While these two uses are certainly the best-known uses of satellite reports, many others are worth considering by weather services which may not undertake multi-day forecasts. Processors for satellite reports with considerable capability can be assembled using today's desk-top computers. By using a man-and-computer combination for satellite-data interpretation, data products can be obtained similar to those produced by automated means in several of the world's largest meteorological processing centres. Data products include sea-surface temperature, estimates of land-surface temperatures and moisture, cloud motion, winds and estimates of local air-mass stability. These data products, as noted in the sections that follow, are in turn useful for short-term forecasts of storm severity, of flash-flood potentials and even of multi-hour weather outlooks. Images mapped as sea-surface temperature are useful for estimates of optimum areas for deployment of fishing fleets. Archives of images will allow estimates of snow accumulation in snowfall regions and hence of spring thaw rates, and perhaps of subsequent river-valley flooding. Changes in the "vegetation index", a numerical estimate of "greenness", can be used for rough estimates of probable crop yields or of the onset of regional droughts.
CHAPTER 2

GLOBAL ENVIRONMENTAL SATELLITE SYSTEMS

The current network of meteorological satellites evolved from the planning for World Weather Watch (WWW) operations and the Global Atmospheric Research Programme (GARP) experiments during the late 1960s and early 1970s. As a result of international co-operation among the satellite operators and their contribution of satellite data and services to the global exchange of meteorological information, the network of satellites forms at present a space-based sub-system in the Global Observing System of the World Weather Watch (see Figure 2.1).

There are two major components in the global satellite system. The first of these is comprised of the various geostationary meteorological satellites which operate in an equatorial belt and provide a continuous view of the weather from roughly 70°N to 70°S. In fulfilling international commitments, WMO Members or international agencies launch and operate geostationary satellites occupying the following positions over the Equator: at 0° longitude – a system operated by the European Space Agency (ESA) called METEOSAT; at 74°E – INSAT, operated by India*; at 140°E – GMS, operated by Japan; at 135°W and 75°W – two spacecraft called GOES, operated by the USA. The USSR also is delivering a series of Geostationary Operational Meteorological Satellites (GOMS) to be located at 76°E. The second major component of the global satellite system comprises the polar-orbiting satellites operated by the USA (NOAA-series spacecraft) and by the USSR (METEOR-series spacecraft). These satellites provide coverage of the polar regions beyond the view of the geostationary satellites, giving complementary data and services to meet global, regional and national observational requirements. Publication WMO-No. 411, entitled Information on Meteorological Satellite Programmes Operated by Members and Organizations, provides details of the satellites used by each operator; a short summary of their performance characteristics is given in the Annex.

2.1 Meteorological satellites in polar orbit

In the more than 25-year history of meteorological observations from space, the polar-orbiting satellites were the first spacecraft to provide data and services for weather analysis and forecasting. The present polar-orbiting meteorological satellites (see Annex), flying at relatively low altitudes (850–900 km) with inclinations from the equatorial plane of 80°–100°, provide two significant capabilities. First, due to its near-polar orbit, the spacecraft is able to acquire data from all parts of the globe in the course of a series of successive revolutions. With its low altitude, on-board instruments of the polar orbiter can acquire data of higher spatial resolution than can the high-altitude satellites in geostationary orbit.

* The Indian satellite is a multi-purpose satellite with combined communication/imagery capabilities.
The polar-orbiting satellites are principally used to obtain:

(a) Daily global cloud cover (satellite pictures taken in visible (VIS) and infra-red (IR) portions of the spectrum);

(b) Daily global sea-surface temperature (SST), vertical temperature and water-vapour distributions in the atmosphere (quantitative satellite soundings).

Another capability recently added to some spacecraft of the polar-orbiting meteorological satellite system is that of data collection and platform location. This data collection system (DCS) allows the spacecraft to receive data from stationary or moving platforms anywhere on the surface of the Earth or floating in the atmosphere. In addition, the position of moving platforms (e.g. drifting buoys in the oceans or balloons in the atmosphere) can be determined on the basis of a Doppler shift in the radio frequency received at the satellite. This data-collection capability provides, from in situ sensors, data which are not recoverable by satellite remote sensing such as surface wind and pressure, rainfall amount, river levels, sea salinity, sub-surface oceanic temperatures and many others. Changing the platform location over time permits the determination of fluid motion such as ocean currents or atmospheric winds.

Remotely sensed and other data acquired by the various sensors are handled in two ways by the on-board processors of the polar-orbiting satellites. Since the spacecraft is in view of a given ground station no more than once per orbit (and sometimes not at all for several orbits), it is necessary to record the data on tape for later playback when the spacecraft enters a "visibility" zone of a specially equipped receiving station. At the same time that the data are being recorded, the spacecraft is directly broadcasting these data which can be received by any station that is properly equipped and within range of the satellite.

The data received from polar-orbiting satellites are forwarded to a central processing facility where a variety of products are produced. Most of these products are then made available to the world meteorological community via the Global Telecommunication System (GTS). The data acquired by the polar-orbiting satellites are also entered into one of the archives associated with the world centres of the World Weather Watch. More information about satellite data management is given elsewhere in this report and in the Annex.

2.2 Meteorological satellites in geostationary orbit

If a satellite is put into orbit at an altitude of about 36 000 km and its orbital plane coincides with the equatorial plane of the Earth, then its orbital position remains unchanged over the given longitude on the Equator. The unique feature of this orbit, called "geostationary" or "geosynchronous", provides a valuable means of continuous surveillance of a large part of the Earth's surface. From its geostationary altitude the spacecraft has communication capability over a circular area of the Earth's surface with a radius of about 7 000 km; the best imaging capability is, however, limited to a radius of less than 5 000 km (see Figure 2.2).

The geostationary satellites are being used primarily for a "continuous weather watch", to produce wind estimates by measuring the motions
of clouds or moisture patterns viewed over a period of one to two hours, and for communication/relay functions. The principal instrument of the geostationary meteorological satellite is a scanning radiometer which uses a large astronomical mirror to collect outgoing radiation in visible and infra-red portions of the spectrum. Spatial resolution varies among the different spacecraft, ranging from 1 km to 2.5 km (VIS) and from 5 km to 8 km (IR). Unlike the polar-orbiting satellites, the geostationary data-collection system (DCS) does not provide a platform-location capability so it is restricted to fixed platforms or to moving platforms which can report their location, such as ships or aircraft. In addition to the imagery and data-collection capabilities, geostationary satellites remain unique platforms for measuring solar protons, alpha particles and electrons, solar X-rays and magnetic fields. Such data are being used in real-time space environment monitoring and warning services.

Since geostationary spacecraft are always in view of their ground station, acquired data need not be recorded on tape recorders and are transmitted immediately to the ground station. There are two types of direct-broadcast services available from geostationary satellites. The first is a full-resolution transmission from which the user can obtain all the image data together with Earth-location and data-calibration information. The second direct-broadcast service is a low-resolution transmission which is commonly referred to as weather facsimile (WEFAX).

The form, signal characteristics and other information on direct broadcasts from polar-orbiting and geostationary satellites are available in Publication WMO-No. 411.

2.3 Other environmental satellites

The need to improve the services which are provided in support of aviation, hydrology, agriculture, marine activities, climate studies, etc. is an important stimulus for the continued development of the other environmental satellite observing systems. During the late 1970s and 1980s there has been significant progress in obtaining new types of information by means of these "non-meteorological" satellites regarding the planet Earth, its oceans, land masses and atmosphere. The advent of so-called "Earth-resources" satellites (the LANDSAT system operated by the USA, METEOR-Priroda spacecraft operated by the USSR and SPOT, operated by France) has demonstrated the ability to use higher-resolution, multi-spectral images of the Earth's surface in a wide variety of agricultural and other land-use applications. With the launch of oceanographic satellites (SEASAT-1, launched by the USA and Kosmos-1500, Kosmos-1602 and Kosmos-1766, launched by the USSR), the technology to monitor a number of ocean parameters by active and passive microwave techniques, regardless of cloud cover, has been demonstrated. The performance characteristics of current Earth-resources and oceanographic satellites are summarized in the Annex. As may be seen from the characteristics, these types of satellites offer very high spectral and spatial resolution up to several metres with relatively small ground-swath width (100 km maximum), which consequently result in a very long period between observations (several days). In contrast to the operational meteorological satellite systems which provide real-time data globally on a continuous and permanent basis, no ocean-observation satellites are in routine operation today. A large amount of high-resolution data from land remote-sensing systems (e.g. LANDSAT, SPOT, Priroda) are increasingly used in conjunction with more frequent data from meteorological satellites in support of various WMO programmes and
international projects (see Chapter 3). The results of these programmes will also be important in determining the future evolution of operational space-based observing systems.

2.4 Satellite data management

Satellite data management, with its sophisticated technology and specific information flow, has become a big element in any satellite system. It requires a large number of steps to turn satellite sensor reports into useful data products and subsequently to archive products for later use. Many data-processing steps can be seen as analogues to the reception of television images. While television is a system with a continuous data flow for display as images, the television data user need not be concerned with each and every pixel (picture element). By contrast, satellite images require data-flow rates often markedly greater than those required for sequential television pictures. Further, each image element must be processed through one or many steps and, for the most part, must be processed in essentially real time, that is, at the rate at which data are flowing from a spacecraft. These requirements place heavy demands on Earth-based processing stations. In some instances, pre-processing is carried out on board the spacecraft to minimize the data processing required of data users.

In the case of the polar-orbiting spacecraft, two data streams are broadcast, one in full resolution (e.g. 1 km field of view (FOV) for visible channels, 4 km for infra-red channels), and a second with reduced resolution and in a format suitable for direct feed to weather facsimile equipment. On-board pre-processing supports this latter direct broadcast to users worldwide. Since full-resolution images from an entire orbit would still exceed the memory capacity of a meteorological or Earth-resources satellite, the resolution of the image data is reduced prior to recording. Only selected scenes in the high-resolution mode are recorded for later playback to the satellite ground station.

Geostationary satellites in general also offer dual data streams, providing high- and low-resolution images. The pre-processing from high- to low-resolution images may or may not be carried out on board the spacecraft, however. Since geostationary satellites never leave radio range of their ground stations during normal operations, various processing steps can be carried out at ground level and facsimile-quality data images can then be relayed through an environmental (or other) satellite to the entire service area.

The direct readout services programme enables government agencies, academic and scientific institutions, commercial firms and individuals all over the world to obtain and use data from environmental satellites without going through a national or regional central data acquisition and processing facility. These services include the automatic picture transmission (APT), high-resolution picture transmission (HRPT) and direct sounder broadcast (DSB) services from polar-orbiting satellites, and the WEFA and imager and sounder data transmissions and data-collection services from geostationary satellites.

The direct readout services are used for operational local, regional, aviation, maritime and agricultural weather forecasting and public services; sea- and lake-ice reconnaissance; snowcover and snowmelt observations; ocean current and temperature studies and many other purposes. They support, among other activities, locust control efforts in Africa; petroleum exploration in the Arctic; and river, lake, and ocean fishing
activities around the world. In some developing countries, direct readout of environmental satellites provides the only opportunity for involvement in space activities. Often, a single readout station in such countries is the major source of environmental data.

2.4.1 Automatic picture transmission (APT)

Automatic picture transmission services (Figure 2.3) are provided by the polar-orbiting satellites and are copied by more than 1 000 users worldwide. Data from two spectral channels are transmitted in a VHF band as the satellite orbits the Earth. The resolution of both visible and infra-red APT data is 4 km. The signals can be received on very low-cost equipment and displayed as an image or converted into digital products showing cloud, ocean or land temperature values. Primary users are government meteorological agencies and ships or land stations in polar latitudes.

2.4.2 High-resolution picture transmission (HRPT)

Like APT services, high-resolution picture transmission services are provided continuously from polar-orbiting satellites. Nevertheless, there are several differences between the services: HRPT provides five rather than two spectral channels with a resolution of visible images of 1.1 km instead of 4 km. The HRPT data must be sent on a broader bandwidth frequency, and consequently much more expensive equipment is needed to receive and process the signals.

There are at least 75 HRPT stations in operation around the world, 23 operated by US agencies and 52 by other countries. Their primary application is to provide more sophisticated observations of meteorological, oceanographic and geophysical phenomena than can be obtained with APT readout. Some specific HRPT applications include the monitoring of pastoral areas for plant growth and development in Africa, the observation of surface currents in the world’s oceans and the study of desert locust breeding grounds in the Mediterranean. Applications of the full-resolution image data are described in more detail in subsequent chapters.

2.4.3 Direct broadcast of sounding data

Along with other types of observation, both the polar and some geostationary satellites broadcast digital radiance data in real time that can be converted into vertical atmospheric temperature and humidity profiles or soundings. Only the sounding data from the polar satellites are used operationally at this time; however, geostationary soundings are still being acquired experimentally and operational transmissions from US geostationary spacecraft are expected to begin in 1987. Sounding data from polar-orbiting satellites are processed by at least 17 countries: Australia, Canada, China, Denmark, Federal Republic of Germany, France, Islamic Republic of Iran, Israel, Japan, New Zealand, Norway, Poland, USSR, Sweden, Taiwan, United Kingdom and the USA.

In terms of hardware, it is relatively easy to receive signals from the instruments that provide the sounding data but retrieval and processing of the data require sophisticated software and a comprehensive understanding of the physical processes that affect data reduction. A university in the US has developed a software package for sounding data processing and is making this package available to interested users around the
world. The exchange of results in applying and modifying the sounding retrieval algorithms benefits all international users in improving understanding of sounding data.

2.4.4 Communication and processing data from satellites

The costs of spacecraft construction, launch and applications development are amortized only through successful processing and distribution of the data it provides. The essential parts of processing and distribution are uninterrupted delivery, timeliness and repeatability of data content; adjuncts to these elements are utility of data presentation and retention of a data record. Satellite data, by virtue of their intent to provide wide-ranging coverage of the Earth, are voluminous and distorted by viewing geometry and atmospheric contamination. These inherent properties are compounded by irregularities in instrument response and signal-to-noise limits in the electronics. As a result, large data-processing resources are necessary to handle the large volume of data and to normalize the known irregularities before presenting the data for product-generation steps.

Figures 2.4 and 2.5 show typical data and communications flow paths to and from satellites and ground stations for the geostationary and polar-orbiting satellites respectively. Since geostationary spacecraft are always in view of their ground station, acquired raw data need not be recorded on tape recorders but are transmitted immediately to the ground station. The geostationary spacecraft also provide two direct-broadcast services. The first of these is a full-resolution transmission from which the user can obtain all the image data available from the spacecraft, both Earth-located and calibrated. Receiving equipment required for this service is more complex and expensive than that required for the second direct-broadcast service, weather facsimile (WEFAX) (Figure 2.6). Raw data acquired by the polar-orbiting satellites are handled in one of two ways. Since the spacecraft are in view of their ground stations no more than once per orbit, it is necessary to record the data on tape for later playback when the spacecraft comes into view of a ground station. At the same time that the data are being recorded, the polar-orbiting spacecraft is providing a direct broadcast of the data for the use of any properly equipped receiving station within range.

The geostationary and polar-orbiting spacecraft each carry a data collection system which enables the spacecraft to receive messages from surface-based or airborne platforms. These systems are depicted in Figure 2.7. The data collection systems provide a capability to obtain from in situ sensors data not recoverable by remote sensing such as surface wind and pressure, rainfall amount, river level, sea salinity, sub-surface oceanic temperature and many others. The system on the polar-orbiting spacecraft can acquire data from free-floating oceanic or atmospheric platforms, which enables their positions to be determined; this permits the determination of fluid motion, i.e. ocean currents or atmospheric winds.

More details on the major steps in the processing of satellite data are included in the Annex.
Polar and geostationary orbital characteristics (Fig. 2.1)

Coverage of currently operating geostationary satellites (Fig. 2.2)

Automatic Picture Transmission (APT) image (Fig. 2.3)
Geostationary satellite data-processing system (Fig. 2.4)

Polar-orbiting satellite data-processing system (Fig. 2.5)
WEFAX transmission and receipt
with application of direct readout capability in Australia
(courtesy Australian Bureau of Meteorology) (Fig. 2.6)
Data collection and distribution system (Fig. 2.7)
CHAPTER 3

THE USE OF SATELLITE DATA IN WMO PROGRAMMES

3.1 Current products and services from satellites

The past decade has shown significant progress in using data from satellites to obtain a wide variety of information concerning the state of the atmosphere and the Earth's surface. A quick comparison of data and pictures obtained in the 1960s with modern satellite products demonstrates these developments very dramatically. Most notable is the improvement in the quality and amount of imaging and sounding data and the speed and accuracy with which satellite-derived data can now be provided to the user. Today, a different payload of environmental satellites (see Annex) enables the accomplishment of imagery, sounding, direct readout, data collection and dissemination/relay missions.

The first satellite "products" of interest to meteorologists were cloud pictures (Figure 3.1A and B). Soon afterward, products derived from data took the form of analyses of significant weather. Before long, cloud analyses for limited areas were being produced routinely. Global cloud analyses became routinely available in October 1966. These were used primarily to assist weather forecasters locate storms and jet streams over data-sparse ocean regions. Corrected weather analyses that described the current state of the atmosphere more accurately became input data for numerical weather predictions. Of considerable value to forecasters was the introduction in 1970 of infra-red imagery which provided nighttime storm surveillance and information about the three-dimensional structure of weather systems (Figure 3.2). In the late 1970s, one numerical data product surpassed all others in importance: vertical profiles of temperature and moisture, called soundings, derived worldwide from satellite multi-spectral radiation measurements (see Figure 3.9B).

Less attention has been given to the increased importance of other products, of which sea-surface temperatures (SST) may be the best known. SST values are obviously of great interest to forecasters and to the world in general (Figure 3.3). Hardly a citizen of the modern world is unaware of the El Niño warming of the tropical waters west of Central and South America, and of the possible links between the El Niño and other climate anomalies seen in many other parts of the Earth. Fewer are aware that the same SST analyses can be of direct economic interest to fishermen, commercial ship operators seeking to follow or avoid major ocean current systems, and even persons charged with responsibility for the ecological health of shore areas and river estuaries.

Data products are mapped values generated by ground-station processing of satellite data, derived for the most part from such multi-spectral imagers as the advanced very-high-resolution radiometer (see Annex). For some products, mapped values from a single channel may be sufficient. In other instances, values from two or more channels are combined through some formula to yield a quantity that best serves the user.
A number of quantitative data currently derived by operators from satellite observations are exchanged internationally via the WWW Global Telecommunication System (GTS). Included are temperature and humidity soundings transmitted using the WMO code SATEM and upper-air winds and sea-surface temperatures transmitted using the WMO code SATOB. Detailed characteristics of transmissions over the GTS are contained in the Manual on the Global Telecommunication System (WMO-No. 386).

Still, some of the cloud images, or nephanalysis, receive limited distribution over the GTS. They continue to be disseminated primarily by direct broadcasts from satellites using automatic picture transmission (APT) service, weather facsimile (WEFAX) broadcasts and high-resolution picture transmission (HRPT) service. Many other products are derived from satellite data for specialized users. Examples are charts of ice and snow coverage, sea-surface temperature gradients, clear land-surface images analysed in terms of vegetation index and various averages of different satellite-derived parameters.

3.2 The contribution of satellites to WMO Programmes

Environmental satellites, through the data which they collect and relay, increasingly play a key role in the Programmes of WMO. As remote sensing from space improves and as new sensors are developed to broaden the scope of knowledge obtainable from space, satellite data can be seen as the core data for weather analysis and prediction to which conventional data are added. Surface data, however, remain essential as "ground truth" against which space reports are judged. WMO is currently planning for upgraded systems for surface observations to support remote-sensing programmes more effectively. Nevertheless, data from space and most WMO Programmes are increasingly interlinked and this trend appears likely to continue.

3.2.1 World Weather Watch Programme

The World Weather Watch Programme (WWW) is the international co-operative effort to ensure that meteorological and related geophysical information is available for use by all Members.

3.2.1.1 Global Observing System

Due to its ability to observe all parts of the Earth, the satellite system is becoming the dominant element in the Global Observing System (GOS) of the WWW. Sensor development may extend this capability into the depths of the oceans, while instruments for the Earth's radiation budget and a planned solar x-ray imager will permit inferences as to the physical processes on the surface of the Sun and within its flaming subsurface. Of more immediate concern, the same data will permit estimates of factors which may have an impact on short- and long-term weather and on the climate of the Earth. Improvement to the GOS will also promote continuity of operational satellite programmes and availability of improved and compatible quantitative satellite data with the required frequency, resolution and accuracy.

3.2.1.2 Global Telecommunication System

Although the Global Telecommunication System (GTS) of the WWW now consists primarily of land communications lines, there is an accelerating trend toward relay through spacecraft of both satellite data and forecast
products. Relay services, either through the capability of meteorological satellites or using commercial communications spacecraft, are often found to be both more reliable and less expensive than land lines. Competition from emerging technology such as fiber-optics cables may reduce communications costs. Nevertheless, space relay services remain attractive since they allow data to move to and from a few or many additional locations with little or no change at the spacecraft and with a minimum of delay (Figure 3.4).

3.2.1.3 Global Data-processing System

The WMO plan for a Global Data-processing System (GDPS) of the WMO envisions data-processing centres to be distributed as needed around the Earth for the computation of mesoscale, regional and local forecasts. Processing of satellite data, given the vast bulk of multi-spectral image data, will obviously demand a large part of the resources of these processing centres. Prompted by the need to cut costs, regional processing centres are already coming into being. A co-operative forecasting centre located in the UK specializes in medium-range numerical weather prediction using conventional and satellite data available over the GTS.

3.2.1.4 Tropical Cyclone Programme

In the mind of the public, satellite images and tropical cyclones go hand in hand. In the northern hemisphere, from May through September, hardly an evening news broadcast lacks a geostationary view of a nascent storm and its projected path toward islands or mainland. The Tropical Cyclone Programme assists some 50 countries subject to damage from hurricanes and typhoons to plan for coastal-plain evacuation and other steps to remove persons and property from the ravages of a storm's winds and crashing surf. In the future, the Programme's emphasis will be on improving storm-track prediction and estimates both of storm strength (from details of the storm size and appearance) and of the probable storm surge as the threatening vortex reaches coastal areas.

The location of nascent tropical cyclones and the monitoring of their growth and movement have been among the earliest successes of satellite meteorology. Hurricanes and typhoons were easily identified and located in the earliest cloud-image photographs (Figure 3.5). Storm wind speeds were estimated by empirical techniques involving storm diameters and their geographic locations.

Cyclone winds are now routinely calculated by satellite image-processing software using sequential-image movement analysis. Wind heights are assigned on the basis of brightness temperatures of clouds. Storm movement is determined by analytic techniques which treat the whole cyclone as one cloud element for the purposes of time-lapse movement calculation. Storm position forecasts are made with reference to surface and tropospheric wind and pressure patterns and predicted for hours or days in advance.

While satellite temperature and moisture profiles now permit effective forecasts of regions of atmospheric instability, and indeed sea-surface temperature patterns alone delineate low-latitude regions of probable cyclone generation, remote-sensing data do not yet permit us to pinpoint a site of future cyclone genesis nor to say with certainty that an incipient storm will mature into a tropical cyclone.
3.2.2 World Climate Programme

The objective of the World Climate Programme (WCP) is both to aid countries in the application of climatic knowledge to benefit their planning and management activities and to develop the capability to predict future variations and changes in climate which may significantly affect mankind. Climate observations gathered by improved satellite instruments will be of special importance in implementing such major components of WCP as the World Climate Data Programme (WCDP) and the World Climate Research Programme (WCRP). In particular, the continuity of operation of the basic system of two polar-orbiting and five geostationary meteorological satellites is fundamental to providing consistent long time-series of global data needed by the WCP. The Programme would also benefit from any specific improvements in \[\text{WWW}\] systems such as additional satellite cloud drift winds, surface observations and information-retrieval algorithms. Based on the results of the Global Weather Experiment (FGER), the aim is to achieve a daily wind retrieval density at a minimum of two distinct atmospheric levels in each 500 x 500 km² column at least once per 24 hours in the whole field of view of each geostationary satellite and within latitudes 20°N to 20°S.

3.2.2.1 Earth Radiation Budget Experiments (ERBE)

The VIS and IR channels of the AVHRR on NOAA satellites have been processed to estimate the amount of long-wave radiation leaving the top of the atmosphere over a number of years. These data, along with estimates of reflected radiation from clouds, are used to estimate some of the major components of the incoming and outgoing heat flow to the earth-atmosphere system (Figure 3.6).

Long-term monitoring of the Earth's total radiation budget (inflow and outflow of radiation) began with the flight of the Earth Radiation Budget Instruments (ERBI) on the Earth Radiation Budget Experiment (ERBE) satellite in 1983, followed by subsequent flights of the ERBI on NOAA-9 (1984) and NOAA-10 (1986).

The ERBE is important to climate research as it measures the "input", the magnitude of the solar "constant" or Sun's output, and the "output" or return flow of reflected sunlight and thermal energies emitted by the Earth and atmosphere. These flows or "fluxes" are fundamental climate parameters since they determine the sources and sinks of energy that drive the climate system.

3.2.2.2 International Satellite Cloud Climatology Project (ISCCP)

The goal of the ISCCP of WCRP is to collect and analyse satellite-observed radiances to infer the global distribution of radiative properties of clouds, needed to improve the modelling of cloud effects on climate. Started in 1983, the project is based on the collection of data from five geostationary satellites (GOES-E, GOES-W, GMS, INSAT, METEOSAT) and from polar orbiters of the NOAA/TIROS-N type. The feasibility of the ISCCP will depend upon the support and involvement of many national and international agencies and research institutions for the management and processing of satellite data.

3.2.2.3 Other WCRP data projects

While ISCCP is already collecting and archiving global data sets, some projects still in various stages of planning will require a considerable
increase in terms of special satellite measurements. These include the radiation budget climatology project, the global SST data project, the atmosphere-ocean fluxes data project and the global precipitation climatology projects. The implementation options for these projects will be based on the following satellite-borne systems: altimeter for sea-surface dynamic height, scatterometers for wind stress, visible radiometers for surface short-wave flux, microwave sounders for total water-vapour content.

3.2.3 Research and Development Programme

The purpose of the Research and Development Programme is to contribute to the advancement of atmospheric science and to assist Members to provide better meteorological services by fostering research in meteorology and related fields. The use of satellite data in this Programme has always been recognized as a very important activity in the areas of weather prediction, tropical meteorology and environmental-pollution monitoring. Developments in satellite soundings (vertical temperature profiles and sea-surface temperatures) will provide the opportunity for widespread improvements in short-, medium- and long-range weather prediction. Further development of satellite observing techniques for the tropics will promote tropical weather prediction. Some measures of atmospheric constituents (e.g. ozone) are already being done by remote sensing from satellites and this area is expected to increase in importance as the technical capability is developed.

3.2.4 Applications of Meteorology Programme

The Hydrology and Water Resources Programme, the World Weather Watch and the World Climate Programme cover some applications of meteorological and hydrological knowledge. There are three vital areas, namely agricultural meteorology, aeronautical meteorology and marine meteorology, which comprise this Applications of Meteorology Programme. Satellites have offered perhaps their greatest contribution to these areas.

3.2.4.1 Agricultural Meteorology Programme

The purpose of this programme is to help Members provide the practical information to the agricultural community which will assist them to increase production, reduce losses, decrease costs and conserve natural resources.

Meteorological quantities useful for agricultural assessment, and potentially derivable from environmental satellite data, include daily precipitation, maximum and minimum temperature, insolation and weekly snowcover. These quantities are used in soil-moisture and crop-yield models, crop calendars and, in the case of snowcover, winter crop kill. These observations are also used to provide early warning of damaging environmental situations such as drought and freeze events. In addition, satellite data provide a measure of "greenness" directly related to the health and vigour of the observed vegetation. As derived from data from US land-observing and meteorological satellites, the product is called "vegetation index" and has found several important applications, including the following:

3.2.4.1.1 Frost line

In areas subject to frost damage such as the citrus-growing regions of the world, the positions of the frostline can be indicated and
monitored by mapping surface temperatures from IR measurements. The colours or grey-scale of the mapped images can focus attention on the 0°C surface temperature. Soil moisture, a product estimated from rates of surface heating by sunshine compared with nocturnal cooling, can also assist in estimates of both crop yields and the danger of frost resulting from unusual cooling rates at night. Soil moisture is better measured by the use of passive microwave sensors in conjunction with infra-red imagery. A microwave imager is now being module for use on future US polar-orbiting environmental spacecraft. Recent rainfall estimates, based upon satellite cloud imagery, are also useful for estimates of soil moisture.

3.2.4.1.2 Precipitation

Mathematical models used to predict crop yields require the best available meteorological information throughout the crops' growing season. Precipitation is one of the most important crop-yield determinants, and the distribution of precipitation within the growing season may be even more influential than the total amount of moisture.

Methods are being developed and tested which use both geostationary and polar-orbiter data to estimate precipitation on a 24-hour basis (Figure 3.7A). Geostationary spacecraft, making observations at 30-minute intervals throughout each day, provide imagery useful in "life cycle" precipitation-estimation techniques which monitor the evolution of convective cloud systems. However, for those areas of the Earth where geostationary satellite data are not available, cloud-indexing techniques using polar-orbiter data alone can be used. Visible and infra-red observations are the principal data sources.

3.2.4.1.3 Maximum/minimum temperature

Daily maximum and minimum temperatures are important in crop-yield models, soil-moisture models and crop-stress detection. Crop-canopy temperature is the quantity most closely correlated with crop development, but since this value is not routinely available shelter temperature (air temperature near the ground) is used in current crop models. Shelter temperature has a high spatial variability which contributes to crop forecasting errors where observations are sparse and not representative of a whole region. By contrast, quantities derived from satellite data are by their nature area-averaged. For large crop districts, a single satellite temperature estimate may be more representative than one or two conventional shelter observations within the area.

3.2.4.1.4 Insolation

Insolation, the quantity of solar radiation striking the Earth's surface per unit area, is of interest to agricultural monitoring because solar radiation is the primary energy source for growing plants. It is used in numerical models for estimating crop yields, potential evapotranspiration and soil moisture. Satellite data permit insolation estimates to be made quickly over wide areas (Figure 3.7B). Many more sunshine estimates over large geographic areas can be produced from satellite data than are practical or affordable with conventional ground-based methods. Insolation at a site is estimated using satellite measurements of the quantity of solar radiation reflected from the Earth's surface and atmosphere. Absorption of solar radiation is inferred from the reflected amount of solar energy, with clouds
as the major reflectors. For areas not viewed by geostationary spacecraft, the diurnal pattern of reflective clouds is estimated from available polar-orbiter viewings at 0730, 1430 and 1930 local times. These estimates, when verified within geostationary fields of view, show errors of 15–20 per cent.

3.2.4.1.5 Vegetation index

The response of a green leaf (chlorophyll) in various wavelengths of light is shown in Figure 3.7D. Green-leaf reflectance is low in the visible wavelengths, reaching a minimum near 0.65 μm. Reflectivity increases rapidly in the near infra-red portion of the spectrum. Various mathematical combinations of data from visible and IR channels have been found to be sensitive indicators of the presence of green vegetation and are referred to as vegetation indices.

Vegetation indices computed from NOAA satellite data are being used by several government agencies for both operational and experimental purposes. The US Department of Agriculture uses vegetation indices for assessment of crop conditions in important agricultural regions of the world. The Food and Agriculture Organization of the United Nations uses the data to monitor potential desert locust breeding grounds in North Africa and the Middle East. (Locust numbers increase where moisture permits an increase in plant growth.) Other uses of the index include monitoring rangelands and for numerical models that estimate damage from forest fires (e.g. regrowth periods, runoff and erosion potential, etc.).

3.2.4.1.6 Soil moisture

An important parameter for routine monitoring of all land areas is soil moisture. It is useful in agricultural land management, including irrigation control and crop–yield predictions, and has further utility in water-resource management, including drought assessment and flood predictions, and in climate studies.

Single observations of the land surface in either an infra-red or microwave channel tend to produce a signature not clearly related to ground water. In both IR and microwave bands, the texture of the land surface obscures the signal soil moisture would cause. As a result, multi-channel observations are preferred.

For microwave measurements, long-wave sensors are preferred (e.g. 1.4–4 GHz). Active microwave sensors (which send out signals comparable to radar pulses) are preferred to passive microwave radiometers (which measure thermal radiation as emitted from the terrestrial surface).

Techniques in which day and night observations of a site are compared and patterns of surface cooling mapped are believed to hold considerable promise for future soil–moisture studies.

Another promising technique is the use of active microwave sensors in a mode called synthetic aperture radar (SAR). In the SAR mode, pulses sent over a period of time from a moving spacecraft have the effect of rays sent out from and received back to a very large antenna. SAR data have shown an ability to penetrate the sands of deserts to show the hidden topography beneath. For soil moisture surveys, SAR data tend to "see through" vegetation canopies.
3.2.4.1.7 Forest fires

Imagery missions, provided by LANDSAT and METEOR-Priroda type satellites have been extensively used in monitoring forest fires (Figure 3.7C). More recently, it has been shown that measurements in the 3.8 μm absorption bands AVHRR are useful for identifying sub-resolution-scale high-temperature sources. Because of contamination by reflected solar radiation in the channel, positive identification of such sources is feasible at present only with nighttime data. Employing an algorithm involving data from two channels, it is possible to determine the blackbody temperature of hot sources and the portions of the 1.1-km pixels covered by the "hot" targets. According to this technique, data from the two AVHRR thermal channels on board the current NOAA-series operational satellites have been used to identify forest fires over the western USA and in Alaska, fires associated with "slash and burn" agricultural practices and gas fires from producing oil fields.

3.2.4.2 Aeronautical Meteorology Programme

The purpose of the Aeronautical Meteorology Programme is to provide operational meteorological information required for safe, regular and efficient air navigation. In this connection, it should be mentioned that imagery from the present geostationary operational environmental satellites provides forecasters with the means by which weather systems of all scales can be monitored every half-hour on a 24-hour basis. This observing capability is uniquely suited to the requirements of aviation. The frequency of observation and resolution of geostationary data make such satellites one of the basic data sources for any nowcasting procedures dealing with mesoscale weather events. Animated geostationary satellite images, in particular, in the hands of the aviation forecaster with responsibilities for monitoring the weather in a given area or over fixed routes, are a powerful tool for detecting both the beginning of certain forecast hazardous weather and the extent of the area affected. Perhaps more importantly, they can reveal the onset of unforecast hazards and result in revised forecasts of fog and stratus, intensity of convection, height of convective clouds, location of surface gust fronts, location of the jet stream, location of large temperature gradients in the upper troposphere and areas of potential turbulence.

Moisture-channel imagery (at 6.7 μm available on GOES and METEOSAT) helps to define the large-scale upper-level flow better than IR (at 11.5 μm) in areas devoid of wind reports and Cirrus cloud-motion vectors. It also helps to locate and diagnose more precisely features of upper-level circulation such as wind maxima (jet streams), storm centres and deformation ("stretching") zones. It is possible to infer a great deal about the upper-level flow patterns from the motions of Cirrus and the evolution of large-scale cloud formations as they appear in the IR window channel. The IR moisture channel makes this process easier since it shows the spatial continuity of upper-level moisture and cloud fields which are related to circulation features. Moisture patterns are present even when clouds are absent, thus providing clues to the upper-level flow.

Moisture patterns combined with cloud patterns can be used to locate more precisely the position of the jet-stream axis over the oceans. A strong jet can be located by the sharp, well-defined poleward cloud edge of an associated Cirrus cloud shield. The stronger the jet the better defined the edge and the less ambiguity in interpretation. These jet indicators occur predominantly in south-westerly upper-level flow (see Figure 3.8A).
Ongoing studies comparing turbulence reports and satellite imagery suggest that greater than normal reports of moderate turbulence are observed associated with dark bands in the water–vapour imagery (see Figure 3.8B).

While the optimum routeing for airlines involves almost all elements of modern weather prediction, there are instances in which satellite data are uniquely useful to route planners and airline pilots. Today, winds reported aloft in remote areas are based almost completely on satellite data (Figure 3.9A). Satellite data can disclose potential regions of clear air turbulence (CAT). Airport fog at unmanned alternative airports can be detected and reported to concerned flights. Ash plumes from volcanoes, already shown to be capable of choking jet engines to cutoff, can be seen in satellite data even before knowledge of the source eruption is known to the world at large. Similarly, plumes can be tracked until dispersal renders them harmless.

In recent years, loss of life in airline crashes at modern, fully instrumented airports has shown the need for new rules for airline pilots, new approaches to detection of locally severe storms and new methods of estimating which fronts and storm systems are of potential danger. Although a full answer to this problem may require sophisticated radar and extensive data processing in almost real time, dangers can be reduced by increased caution and more rigorous storm tracking. Satellite data have been shown to be of great value in the latter effort (Figure 3.8C).

3.2.4.3 Marine Meteorology Programme

The major purpose of the Programme is the promotion of marine meteorological and oceanographic services for high seas, coastal and port areas.

3.2.4.3.1 Coastal areas, islands

Experiments with remotely sensed spectral data from near-shore regions have shown that ocean colour may be an even better tool for fish location than temperature alone. Ocean colour varies with biomass and other constituents. Several satellite operators are considering addition of an ocean colour instrument (in which the visible image of the ocean surface is scanned in perhaps a dozen narrow spectral bands) to satellites scheduled for launch in the next decade. Ocean colour is expected to be of great use to studies of estuarine ecology and to successful programmes for reducing river-carried pollutants and soil erosion.

Typhoon (hurricane)-driven storm surges have been studied for more than a quarter of a century. As a result, formulas have been developed that allow coastal residents to be warned as to the extent to which they are threatened by an approaching storm. The formulas are based on satellite reports of the size, intensity and movement of the cyclone.

Tsunami warnings utilize the communications capabilities of environmental satellites rather than their remote sensors. Warning of possible tsunamis (tidal waves) are based on reports of earthquakes from coastal or undersea regions from which tsunami generation is likely. After one coastal area is struck, others throughout the Pacific basin can be alerted with a high degree of probability as to time and severity of coastal inundation. Plans for future satellite sensors include use of radar-like
altimeters capable of determining the sea-level altitude with sufficient accuracies to disclose the presence, in the open ocean, of tsunami-causing waves. This capability should permit discovery at sea of otherwise undetected tsunamis and of seiches, tidal waves caused by abrupt changes at sea of atmospheric pressure and hence not seen in seismic records.

3.2.4.3.2 Ocean areas

Commercial routeing of large ships using satellite data is a fully developed business, as shippers seek to achieve the fastest voyages with the least damage to cargo and vessel. Even Atlantic Ocean racing yachts now listen to radioed reports of gulf-stream positions in planning their next day's headings - though not always with as much success as crews might wish. Routeing is also based on the growth rates and positions of storms affecting shipping which can be estimated from remotely sensed images of cloud movement. Algorithms are used to translate cloud winds to surface-wind and wave-height values (future satellite sensors may include "active" sensors which act like space-borne radar to determine both surface winds and wave heights).

Location of sea-ice boundaries is important to ship operators in polar regions. The edge of the icepack can be closely monitored with satellite data (Figure 3.10C and D, Figure 3.11). Knowledge of the ice edge allows estimates of the maximum likelihood of "calving" of icebergs into the seaway.

3.2.5 Hydrology and Water Resources Programme

The overall objective of the Programme is to ensure the assessment and forecasting of the quality and quantity of water resources both for different uses and for hazard mitigation.

3.2.5.1 River basins

River valleys are complicated ecosystems and the most cost-effective management of a valley region involves careful consideration of all hydrological factors. Impoundments behind storage or hydroelectric dams must be lowered if unusual winter snows or abnormal spring-thaw rates suggest the probability of floods. In several river valleys in which satellite data and ground-truth studies provide estimates of the depth of winter snowfalls and of snow-depletion (i.e. thawing) rates in spring, even more complex analyses and forecasts have proved possible. Hydrological models have evolved to the extent that forecasts of flooding in excess of the capability of control dams can be made. River-management engineers can, with considerable certainty, forecast when, where and how bad a flood will be. What remains uncertain are the varying day-to-day rates of thawing, since thaw rates depend on the amount of sunshine and the temperature and strength of regional winds traversing the snowpack. Thus, there is some certainty as to the timing of flooding but little with respect to its occurrence, until portended by thaw rates.

For drainage systems fed more by upland rainfall than mountain snowmelt, satellite data now permit estimates of rainfall rates and, through the use of soil moisture estimates, calculation of how much rain must fall before flooding begins. For areas served by geostationary meteorological spacecraft, rainfall estimates can be made within minutes and flash-flood warnings broadcast only moments later. In some countries the accelerating
growth of ownership of a simple type of "weather radio" tuned directly to regional forecast offices attests to the public's realization of the value of flash-flood warnings and similar messages in addition to routine forecasts.

3.2.5.2 Arid, semi-arid lands

The vegetation index and estimates of soil moisture are efficient tools for analysis of the growth or retreat of drought area boundaries and such associated phenomena as locust migration. For arable areas, repeated analyses can disclose the effects of changing strategies for enhancing groundwater retention and hence increased stands of forage and food crops. The increasing conviction among meteorologists today that "drought is contagious" may very well lead to a dramatic increase in the use of satellite data as an operational tool in efforts to restore many arid areas to useful production. Studies of several areas in the world have shown that, if spring rains are lacking over land that is normally arable, this land will become increasingly dry all summer until the changes associated with autumn finally break the cycle. By contrast, the same area, if moist in spring, will through evaporation and convective lifting cycle its groundwater through local showers and, by retaining a cooler surface temperature, permit the inflow of moist air to become additional rains and so supplement existing surface moisture. This suggests that habitually arid lands may not necessarily require irrigation longer than is necessary to break the cycle of dry surface leading to hot surface leading to clear skies, further surface heating, lowered relative humidity and so on. Satellite-monitored test regions could be designated for varying reclamation strategies without the need for costly in situ soil monitoring.

3.2.5.3 Large lakes

Many factors relating to the ecological health of large lakes are visible in satellite data. Wind-driven regions of upwelling, periods of seasonal overturning of the lake and periods in which deposition of carbonates occurs have been demonstrated in space-gathered data. Satellite surveys of ice conditions in the northern large lakes like the Great Lakes of the USA and Lake Ladoga in the USSR have substantially lengthened the shipping season of these water routes.

3.2.5.4 Snowcover

The near-continuous view of the poles provided by polar-orbiting satellites has served to provide a long-term record of the Earth's snowcover. The southern extent of the winter snow and ice boundary is an indicator of inter-annual and longer periods of climate variability. Figures 3.10A and B are examples of "snow-line" data from years of satellite data.

Until recently, information on snowcover from satellites was limited to simple estimates of the areal coverage of snow. This was a useful product, since the data user could determine, for instance, whether crops needing winter snow for freeze protection were in fact covered. An enhanced snowfall product now utilizes remote-sensing images for snow estimates as input to forecast models for basin drainage during snowmelt periods. Each basin must be calibrated. Satellite image brightness values first are tied to in situ measurements of snow depth. During melt periods, snowcover area reduction is compared with runoff water rates. In subsequent seasons, satellite data alone are sufficient to permit estimates of total stored water,
and forecasts of river heights during melt seasons based on changing brightness (hence varying snow thickness) and areal-cover diminution. Dramatic successes have been achieved by this technique in the many countries with forecast lead times sufficient to allow hydrologists partially to drain downriver impoundments in preparation for new surges of meltwater. Frequent updates of flood forecasts keep the potential flood hazard in the public eye and have led to many timely preparations by downriver communities to minimize local damage.

In preparing melt forecasts, satellite data processors estimate melt rates caused by sunshine, rainfall and warm-air advection. Corrections include estimates of re-evaporation, in the case of melting by warm, dry winds such as "chinooks", and of meltwater retention as groundwater.

3.2.6 Education and Training Programme

The successful implementation of the above-mentioned Programmes of WMO depends to a large extent upon the strengthening of national Meteorological, Hydrometeorological and Hydrological Services, particularly in developing countries. For this reason, the Organization's education and training activities continue to be regarded as a matter of high priority.

The transfer of knowledge in the area of management and applications of satellite data is being covered by this Programme through the organization and implementation of several international training events in all of the WMO Regions. The Education and Training Programme collaborates closely with other agencies of the UN system and with international organizations. The Organization is also engaged in the preparation of syllabuses and corresponding training materials for the education of meteorological personnel in satellite meteorology, the provision of fellowships for training in meteorology and operational hydrology and the organization of regional training events.

3.2.7 Technical Co-operation Programme

The applications of satellite technology in meteorology and operational hydrology form an important element of the technical co-operation activities of WMO. These activities are generally undertaken with assistance either from the Voluntary Co-operation Programme (VCP) or the United Nations Development Programme (UNDP).

Each year, several projects are completed under the VCP for the provision of APT/WEFAX equipment. Supplementary WEFAX equipment is provided to existing APT stations. Support is also given under the VCP for training personnel and for operation and maintenance of APT stations. From 1977 to 1985, a total of 54 APT/WEFAX readout satellite stations were installed with the support of the VCP: eight stations in Asia, 23 in Africa, two in Europe and 21 in Central and South America. Twelve countries already equipped with an APT system were provided with the additional equipment necessary for WEFAX reception.
NOAA-5 high-resolution image of Hurricane Diana, 1984 (Fig. 3.1B)

Early TIROS I view of a tropical storm, 1960 (Fig. 3.1A)
Mapped satellite products. Top, orbit-by-orbit data; opposite page, top and middle, Mercator display of visible and infra-red data; bottom, northern and southern hemisphere displays of satellite data (Fig. 3.2)
SST / GLOBAL
Satellite-observed sea-surface temperature (SST) charts, global 50-km analysis and local 14-km analysis; opposite page, display of climatological observed and anomaly sea-surface temperature charts during the El Niño event. December 1983 (Fig. 3.3)
Global Telecommunication System (Fig. 3.4)

A GMS view of a Pacific typhoon (left), an infra-red and radar view of Hurricane Diana (right) (Fig. 3.5)
Depiction of the Earth-atmosphere radiation balance (Fig. 3.6)
Satellite-derived precipitation (Fig. 3.7A)

Satellite-derived total insolation chart (Fig. 3.7B)
Fire detection from the NOAA polar satellite (Fig. 3.7C)

A vegetative index display (Tucker, NASA/USA) (Fig. 3.7D)
Jet stream cloud pattern in the visible (top), infra-red (middle) and water vapour (bottom) channels (Fig. 3.8A)
Turbulence reports relative to water vapour boundaries (Fig. 3.3B)

Severe thunderstorms in visible (middle) and infra-red imagers (bottom) (Fig. 3.3C)
New and multi-year ice cover (Fig. 3.10C)

Ice chart (Fig. 3.10D)
CHAPTER 4

CONCLUSIONS AND PROJECTIONS FOR THE FUTURE

Planning, purchase, fabrication and preparation for launch of satellites is a lengthy (as well as costly) process. Procurement is now in progress in the USA for polar-orbiting spacecraft, for launch beginning in 1990-1992, that are virtual replicas of satellites now in orbit. A single new sensing system for microwave soundings is now also in procurement. A quite different type of geostationary spacecraft is also being built to begin service at about the same time, planning for which began more than five years ago. At the same time, planning is in progress for sensors to be used in 1995, 2000 and even 2015.

Given these long lead times for satellite and sensor purchase (not to mention the even longer development times for new types of instruments), the future pattern of environmental satellites has been set, barring factors now unforeseen, for the next two decades.

The launch of many innovative types of satellites and sensors is planned for the remaining years of this century, but these are for the most part high-technology sensors (Figure 4.1). Many will require data-processing tasks exceeding the processing capability now in place in Washington, Moscow, Bracknell or Melbourne. One example will illustrate the trend. A prototype synthetic aperture radar (SAR) flown on a NASA SEASAT satellite observed a surface swath only 100 km wide. Objects as small as 10 m could be detected. The pattern of ocean waves that could be calculated could, with sophisticated processing, disclose the sub-surface patterns of the underlying sea bottom (to continental edge depths) and perhaps even the unseen passage of a submerged submarine. But to disclose this information requires the processing of 117 mbps (megabits per second).

Changes planned for the present system of meteorological satellites include the addition of a 20-channel microwave sounder AMSU (advanced microwave sounding unit) to supplement the present IR sounding system. AMSU will permit quality soundings to be made through clouds opaque to IR. Slight changes are envisioned for the IR imagers until perhaps 1995, when present plans call for a new 10-channel imager with a 500 m FOV (versus 1.1 km today). No significant changes are expected in either the direct-to-user broadcast services or the frequencies carrying them. A change from the present analog facsimile to digital facsimile is probable, but not yet scheduled.

The continued development of desk-top "personal" computers could have a significant impact. Since the first hand-held and desk-top computers several years ago, microprocessors have evolved from four-bit operators to 32-bit machines. (A four-bit processor treats a number as large as 16 as a unit to be moved through the calculating system; in a 32-bit machine, the unit number can be 4 billion (US) or 4 million million (European).) With the larger machines, a brightness value for a single pixel could carry with it, throughout the computation, tags for its time and location which would greatly simplify the data-processing steps needed to produce a useful product.
CHAPTER 4

Nor is this the end. In the preceding paragraph, we are still thinking in terms of a "single processor" machine, that is, we see a number-processing factory in which we still have only a single employee, although he is quite fast and can carry a large armload of numbers. Almost certainly, in the years just ahead, computer buyers will be offered "parallel processors" in which a team of processor-employees sit side by side in the number factory, each one with the capacity of the present processor. Three-dimensional problems like forecasting, and certainly two-dimensional tasks such as mapping sea-surface temperature patterns, will be vastly accelerated and processing costs reduced. Even "array processors", in which number-handling employees sit in rows and columns like a schoolroom, are being developed.

The USA (NASA), Europe (ESA), Japan (NASDA) and others have announced plans for large, multi-use satellites called "platforms" on which large groups of Earth-observing sensors are borne (Figure 4.2). Two of these space platforms initially are to be launched into morning and afternoon, sun-synchronous, polar orbits (one operated by the USA and one by ESA). The platforms are to be long-lived and operate for 10 to 15 years without replacement. To achieve this longevity and to provide for replacement/refurbishment of parts of the facilities, the platforms are to be "serviced" at approximately three-year intervals by shuttle-type servicing vehicles. The servicing shuttle will rendezvous with the platform and provide replacement of sensors, power modules, control systems, etc. as needed.

This co-operative, international commitment to long-term Earth observational systems in polar orbit has, as a primary goal, the provision of long-term, near-continuous observations of the Earth. The platforms will bear a large variety of active, passive, multi-spectral sensors for viewing, monitoring and measuring a multitude of the physical characteristics of the Sun-Earth-atmosphere system. The goals of these measurements are to maintain today's "operational" meteorological measurements while adding sensors of advanced technology to perform interdisciplinary scientific study and evaluation of the long-term state of such important features as variabilities of carbon dioxide, ozone, the Earth-atmosphere radiation balance, climate trends, chemical cycles, agricultural and biochemical cycles, hydrological cycles and others.

WMO Programmes will benefit from the implementation of these new Earth-observation systems. Operational weather services of the world will continue to receive data comparable to those of today and the world's research communities in many disciplines beyond those represented by WMO will greatly benefit from the long-term commitment to continuous Earth observations. Future improvements in operational sensors will come from these technologies demonstrated in the research instrumentation.

One of the greatest challenges posed by the polar-orbiting platform is the design and implementation of the ground processing systems to handle the tremendous volumes of data to come from the sensor payloads. If operational instruments, comparable to those existing in about 1995 (including improved imaging radiometers (IR and VIS) and microwave sounders), are carried on these vehicles, then an upgraded version of the direct broadcasts of the operational data would be provided. The demand for data from oceanographic sensors might someday be included in the direct broadcasts or, alternatively, establish their own radio frequencies for direct broadcasts. Users may be asked to upgrade their ground systems when changes are requested of satellite
operators by the growing world demand for new data. On-board processing may offer alternative ways of preparing and presenting the direct-broadcast data for the benefit of all users after 1995.

Growing demands to have reliable information about the current and future state of the environment and of the processes that determine weather and climate constitute a basis for the long-term plans of WMO's scientific and technical programmes. At present, perhaps more than in the past, there is a common understanding that it will be possible to meet these needs only within a framework of international co-operation through major technological advances, especially with respect to satellites, computers and telecommunications.

This report has outlined currently available and projected benefits from the installation and operation of satellite receiving stations and appropriate processing systems ranging from simple end-user's hardware to highly sophisticated multinational centres for data processing. The progressive upgrading of satellite systems would make it possible to respond more fully to the problems of national Hydrometeorological Services in both developing and developed countries.

The regional and national aspects of the satellite data-application activities under WMO Programmes will continue, however, to have their own specific importance. A balanced approach, allowing the most developed countries to go ahead and the less developed to be included as they are able, would play a crucial role in achieving these goals. For this, national Meteorological and Hydrological Services will need more resources than they now have, but the required expenditure is modest compared with the potential benefits to be derived.
**rational and research satellite systems (Fig. 4.1)**

**METEOR**  
Operational polar-orbiting satellite (USSR)

**NOAA**  
Operational polar-orbiting satellite (USA)

**GOES**  
Geostationary operational environmental satellite (USA)

**METEOSAT**  
Geostationary operational meteorological satellite (Europe)

**GMS**  
Operational geostationary meteorological satellite (Japan)

**GOMS**  
Geostationary operational meteorological satellite (planned by USSR)

**SPOT**  
Earth remote-sensing satellite (France)

**LANDSAT**  
Earth remote-sensing satellite (USA)

**COSMOS**  
Experimental Earth and ocean observation satellites (USSR)

**MOS**  
Marine observation satellite (Japan)

**IRS**  
Earth resources satellite (India)

**ERS**  
Earth resources satellite (Europe)

**JERS**  
Japan Earth resources satellite (Japan)

**ADEOS**  
Advanced development Earth observation satellite (Japan)

**JPOP**  
Japan polar-orbiting platform (Japan)

**RADARSAT**  
Ice remote-sensing satellite (Canada and UK)

**UARS**  
Upper-air research satellite (USA)

**TOPEX**  
Ocean topography experiment (USA)

**POLAR PLATFORMS**  
Refer to Earth observation systems planned for polar orbit by USA and Europe as part of the international space station programme. It is planned that the operational mission of the NOAA satellites would be flown on these platforms.
Artist’s concepts of ESA (top) and USA (bottom) polar platform systems. (Fig. 4.2)
ANNEX

SUMMARY OF GLOBAL ENVIRONMENTAL SATELLITE SYSTEMS

I. The polar-orbiting meteorological satellites

METEOR-2 Operational Series (USSR)

Orbit:

Near polar (inclination 81°), altitude 900 km, period 102 minutes.

Number of satellites constituting the system:

Two or three in orbit at the same time.

On-board instruments:

- Scanning telephotometer for APT, one channel (0.5 - 0.7 μm), resolution 2 km, swath width 2 100 km;

- TV-type scanner, one channel (0.5 - 0.7 μm), resolution 1 km;*

- Swath width 2 400 km;

- Infra-red scanning radiometer, one channel (8-12 μm), resolution 8 km, swath width 2 600 km;

- Infra-red scanning sounder radiometer, eight channels (11.1, 13.33, 13.70, 14.24, 14.43, 14.75, 15.02, 18.70 μm), resolution (angular) 2°, swath width 1 000 km.

Direct broadcast capability:

APT, one channel: visible (2 km) or infra-red (8 km), standard transmission and format.

NOAA Operational Series (USA)

Orbit:

Sun-synchronous, near-polar (inclination 98.9°), altitude 833 or 870 km, period 101 minutes.

* Resolutions specified here are at satellite subpoint
Number of satellites constituting the system:

One or two in orbit at the same time of the advanced TIROS-N design.

On-board instruments:

- Advanced very-high-resolution radiometer (AVHRR), four or five channels: NOAA-8 (0.55-0.90, 0.72-1.10, 3.55-3.93, 10.3-11.3 μm)
  NOAA-9 (0.58-0.68, 0.72-1.10, 3.55-3.93, 10.3-11.3, 11.5-12.5), resolution 1 km, swath width 2 600 km;

- TIROS operational vertical sounder (TOVS), with three sub-systems:
  - High-resolution infra-red sounder (HIRS), 20 channels, resolution 20 km, swath width 2 250 km;
  - Stratospheric sounding unit (SSU), provided by the UK, 3 channels in 15 μm CO₂ band, resolution 147 km, swath width 1 500 km;
  - Microwave sounding unit (MSU), 4 channels (50.3, 53.7, 55.0, 58.0 GHz), resolution 110 km, swath width 2 250 km;

- ARGOS data-collection and platform-location system (DCPLS), provided by France, locates and collects data from platform (e.g. drifting buoys) and relays the data to central processing facility. Up to 4 000 platforms can be handled per day. Location accuracy is about 1 km;

- Solar backscatter ultra-violet (SBUV) radiometer for determination of total amount and vertical distribution of ozone in the stratosphere (beginning with NOAA-9). Fixed nadir-viewing spectrometer measures radiation at several wavelengths from 160 to 400 nm.

Direct broadcast capability:

- APT, two channels: visible and infra-red (4 km, standard transmission and format;

- HRPT, same channels, resolution and coverage as AVHRR. S-band transmission also includes all other digital sensor data (TOVS, ARGOS, SBUV, etc.);

- Direct sounder broadcast (DSB), TOVS digital data are broadcast on the VHR beacon frequency.

II. The geostationary meteorological satellites

METEOSAT (European Space Agency)

Number of spacecraft in operation and location:

One at 0° longitude.
On-board instruments:

- High-resolution radiometer, 3 channels: 0.4-1.1 μm at 2.5 km resolution, and 5.7-7.1 and 10.5-12.5 μm at 5 km. Full Earth disk coverage possible every 30 min;

- Data collection system (DCS), 62 channels of 3-kHz bandwidth. CGMS standard format and transmission characteristics, to relay data from data collection platforms (DCPs).

Direct broadcast capability:

- WEFAX (weather facsimile) dissemination full time in APT format according to CGMS standards for reception by secondary data user stations (SDUS). Between WEFAX transmissions, DCP data are transmitted to modified SDUS ground receivers;

- High-resolution image dissemination to primary data user stations (PDUS); format and transmission specifications are unique to METEOSAT.

INSAT (India)

Number of spacecraft in operation and location:

One at 74°E.

On-board instruments:

- Very-high-resolution radiometer (VHRR), 2 channels: 0.55-0.75 μm at 2.75 km resolution, and 10.5-12.5 μm at 11.0 km. Coverage over India and adjoining land and sea area possible every 30 min;

- Data collection system (DCS), capable of collecting meteorological data from up to 400 data collection platforms (DCPs) with pseudo-random, burst mode reporting.

Direct broadcast data capability:

- All images and data transmitted to Meteorological Data Utilization Centre (MDUC), New Delhi, for processing and analysis and distribution of processed data to Indian forecasting offices using point-to-point communications. Synoptic inferences and cloud motion vectors are transmitted on the GTS twice and once a day, respectively.

GMS (Japan)

Number of spacecraft in operation and location:

One at 140°E.

On-board instruments:

- Visible and infra-red spin scan radiometer (VISSR), 2 channels 0.5-0.75 μm at 1.25 km resolution and 10.5-12.5 μm at 5 km. Full Earth disk coverage possible every 30 minutes;
- Data collection system (DCS) in accordance with CGMS standard format and transmission characteristics to relay data from data collection platforms (DCPs).

Direct broadcast capability:

- Low-resolution facsimile (LR-FAX) (WEFAX) dissemination part-time in APT format according to CGMS standards for reception by secondary data utilization stations (SDUS);
- High-resolution facsimile (HR-FAX) dissemination to medium-scale data utilization stations (MDUS); format and transmission specifications are unique to GMS.

GOMS (USSR)

Number of spacecraft planned and location:

One at 76°E

On-board instruments:

- Scanning radiometer, 2 channels: visible at 1–2 km resolution and 8–12 μm infra-red at 5–8 km;
- Data collection system (DCS), in accordance with CGMS standard format and transmission characteristics to relay data from data collection platforms (DCPs).

Direct broadcast capability:

- Two full-time weather facsimile (WEFAX) dissemination channels in APT format according to CGMS standards;
- Two digital (alphanumeric) data broadcast channels;
- High-resolution image dissemination.

GOES (USA)

Number of spacecraft operational and locations:

Two at 75° and 135°W; one at 107°W with WEFAX direct broadcast only.

On-board instruments:

- VISSR (visible and infra-red spin scan radiometer) atmospheric sounder (VAS), two imaging channels: 0.55–0.75 μm at 1 km resolution and 10.5–12.6 μm at 7 km. Four-channel multi-spectral imaging mode: above two channels plus any two of the sounding channels at 14 km resolution. Both modes can cover the full Earth disk every 30 minutes, smaller areas more frequently. Sounding mode: 12 channels at 14 km resolution (3.94, 4.44, 4.52, 6.72, 7.2, 11.24, 12.66, 13.3, 14.0, 14.2, 14.4, 14.7 μm); all channels except 3.94, 4.44, 4.52, 14.4 and 14.7 μm can also be used with a resolution of 7 km. Time to acquire soundings for a 20-latitude-wide
(N–S) zone is about one hour. Only one operating mode of VAS can be used at a time;

- Data collection system (DCS), 160 channels of 3-kHz bandwidth. CGMS standard format and transmission characteristics, to relay data from data collection platforms (DCPs).

Direct broadcast capability:

- WEFAIX dissemination part-time in APT format according to CGMS standards (full-time transmission from GOES at 107°W);

- High-resolution image dissemination to primary data user stations; format and transmission characteristics are unique to GOES;

- DCP dissemination on a single DCP channel can be received directly by a user equipped with an appropriate receiver.

III. Other environmental satellites

Land-observation satellites

LANDSAT series (USA)

Orbit:

Sun-synchronous, near-polar (inclination 98.2°), altitude 706 km, period 98.9 min, 16-day repeat cycle of observation.

Number of satellites constituting the system:

One non-operational satellite.

On-board instruments:

- Multi-spectral scanner (MSS), four channels (0.5–0.6, 0.6–0.7, 0.7–0.8, 0.8–1.1 μm), resolution 80 m, swath width 185 km;

- Thematic mapper (TM), seven channels (0.45–0.52, 0.52–0.60, 0.63–0.69, 0.76–0.90, 1.55–1.75, 2.08–2.35, 10.4–12.5 μm), resolution 30 m (except 10.4–12.5 μm is about 120 m), swath width 185 km.

Data transmission:

Direct broadcast of both MSS and TM to specialized local receiving stations and transmission to central facility via tracking and data-relay satellite system (TDRSS).

METEOR-Priroda series (USSR)

Orbit:

Sun-synchronous, near-polar (inclinations 98°), altitude 650 km, period 97.3 min, 14- to 17-day repeat cycle (for high-resolution scanners), four- to five-day repeat cycle (for medium-resolution scanners).
Number of satellites constituting the system:

One or two satellites in orbit at the same time.

On-board instruments:

- Standard sensors (MRTVK): Multi-spectral optical mechanical scanner (MSU-S), two channels (0.5-0.7, 0.7-1.0 μm), resolution 240 m, swath width 1 380 km;

- Multi-spectral optical mechanical scanner (MSU-M), four channels (0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.1 μm), resolution 1 x 1.7 km, swath width 1 930 km;

"Quick look" experimental sub-system sensors:

- MSU-SK, multi-spectral mechanical scanning radiometer of medium resolution (170 m), 4 channels (0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.0 μm), swath width 30 km;

- MSU-E, multi-spectral 600 electronic scanning radiometer of high resolution (30 m), 3 channels (0.5-0.7, 0.7-0.8, 0.8-1.0 μm), swath width 30 km.

Data transmission:

- Analog direct broadcast to simplified receiving stations of one channel from standard MRTVK low-resolution sensor;

- Analog link in 460-470 MHz band to central receivers for all MRTVK output, and MSU-SK and MSU-E.

MSU-K and MSU-E can also be transmitted over a digital link.

Ocean-observation satellites

SEASAT (USA)*

Orbit:

Non-synchronous, near-polar (inclination 108°), altitude 850 km.

Number of satellites constituting the system:

One non-operational satellite.

On-board instruments:

- SEASAT-A scatterometer system (SASS) - a radar operating at 14.6 GHz, resolution 70 km x 50 km, swath width 1 900 km;

- Altimeter (ALT) - a radar operating at 13.5 GHz, resolution 10 km, nadir measurements;

- Synthetic aperture radar (SAR), operating at 1.27 GHz, resolution 25 km, swath width 100 km;

- Scanning multi-channel microwave radiometer (SMMR), five channels (6.6, 10.7, 18, 21 and 37 GHz), resolution 44 km x 29 km, swath width 920 km;

- Visible infra-red radiometer (VIRR), two channels (10.5-12.5 μm, 0.4-1.1 μm), resolution 1 km, swath width 2 246 km;

Data transmission:
- Raw data and housekeeping information transmitted to the ground station using SEASAT telemetry system. No direct data transmission foreseen.

KOSMOS-1500 series (USSR)

Orbit:
Near-polar (inclination 82°6), altitude 660 km, period 97.7 min.

Number of satellites constituting the system:
One or two spacecraft in orbit at the same time.

On-board instruments:
- Side-looking radar (RLSBO), operating at 3.2 cm, resolution 2 km, swath width 450 km;

- Multi-spectral optical mechanical scanner (MSU-M), four channels (0.5-0.6, 0.6-0.7, 0.7-0.8, 0.8-1.1 μm), resolution 1.5 km, swath width 1 930 km;

- Multi-channel microwave radiometer, three channels (0.8, 1.35, 8.5 cm), resolution varies from 20 to 80 km depending on channel, nadir measurements.

Data transmission:
- Analog direct broadcast of RLSBO and MSU-M outputs to simplified receiving stations at 137.4 MHz.

*     *

*     *     *
APPENDIX

Major steps in the processing of satellite data

Data received from a satellite is often difficult to use directly. Different instruments provide data at different times. These are then multiplexed (combined) into a single data stream and recorded or directly transmitted to a receiving station in a compact format. This "raw" data, which is called "1A"-level data, must be pre-processed into a more manageable and useful format with the addition of certain ancillary data, such as calibration and Earth-location parameters. The resulting "conditioned" data is referred to as "1B" data. This transformation from "1A"-level to "1B"-level data is described as "pre-processing".

Satellite data pre-processing includes the following six steps:

1. Data broadcast from the satellites are "ingested" or received into the processing computer.

2. Different types of data are separated (or decommutated) into data sets according to the originating satellite and instrument.

3. Instrument data is "calibrated" or described in a form which can be easily related to a scientific measurement.

4. "Earth location" information is added so that each measurement can be directly related to a location on the Earth.

5. The performance of the instrument and data transmission are measured for evaluation.

6. The final "1B" data are stored in a data base which is conveniently accessible by the product processing programmes.

It is imperative that these six pre-processing steps be executed at a pace at least equal to the rate at which the data are broadcast from the particular satellite or satellites used, and without error. Since the time frame for utility of meteorological data is quite brief, the products for processing systems require these data to be made available as soon as possible and with any errors and irregularities flagged. If pre-processing systems cannot reliably detect errors, then the data product systems must perform their own quality checking. Given the time constraints involved, this is best avoided.

Instrument calibration

The calibration process involves exposing the radiometer to an external source which has been calibrated against a primary or secondary standard of one of the national laboratories and establishing a relation between the electrical output of the radiometer and the amount of radiation (radiance) entering the radiometer.

All the radiometers flown on the polar-orbiting meteorological satellites undergo extensive pre-launch radiometric calibrations at the instrument manufacturer's facilities to establish their stability, linearity of response
and sensitivities. Instruments operating in the visible and near-infra-red regions are calibrated against lamps whose output is viewed through the aperture of an integrating sphere.

Pre-launch infra-red (IR) calibrations are performed in a thermal/vacuum environment to simulate the environment of space. Calibrations are performed at several instrument-operating temperatures to provide a measure of the deviation of the instrument's response as a function of temperature. Visible and near-infra-red calibrations are performed at ambient temperature in air. A typical IR calibration will expose a radiometer to a source whose temperature is varied, in discrete steps, over the entire dynamic range of interest.

Radiometers are subject to performance degradations in orbit. Unless some method is provided to assess these degradations, the pre-launch calibrations may quickly be rendered useless or the instrument may yield questionable results. Therefore, the radiometers flown on polar-orbiting satellites have been designed to perform in-orbit calibrations routinely, at intervals during their scan sequences (these are done in the IR and microwave regions only; no attempt is made to perform in-orbit calibrations in the visible region).

In-orbit calibration is accomplished by programming the radiometer's scan mirror to view scenes of known radiance: (1) space (as a near-zero radiance) and (2) part of the instrument housing, which is designed as a known temperature radiative source.

Calibration of sensors for visible radiation is difficult in orbit or before launch. Light sources such as light bulbs are used as known sources, but light sources deteriorate at unpredictable rates; reflecting surfaces are used to bring sunshine to the sensor's detectors, but reflecting surfaces degrade under the impact of solar ultra-violet radiation. Efforts continue to evolve more satisfactory short-wave (i.e., visible and near-infra-red) calibration techniques.

**Earth location of satellite data**

Once the satellite instrument data have been separated and identified according to their source and calibrated, they must then be directly associated in some way to locations on the Earth or in its atmosphere. This process is called "Earth location" and is usually done in one of the following three ways:

1. Imagery data which will be used in a "qualitative" manner may be "gridded". Certain data samples (in the case of an image these are often called "pixels") are altered to show the locations of latitude or longitude lines or geographic or political boundaries. This is often vital when dense clouds obscure recognizable land features;

2. Data used in a "quantitative" manner may require knowledge of the equivalent Earth location of any or all of the data samples. This is often accomplished by calculating the latitude/longitude position of certain selected samples in the data stream such that the Earth location of the others can be interpolated;

3. A third, more computationally demanding, process is to "map" all satellite data onto a well-defined Earth map projection. Examples of such
projections may be Mercator (for the use of data along the tropics), polar-stereographic (which presents data about both poles), or a nominal satellite projection. METEOSAT data are mapped in this last way onto a well-defined projection so that each picture can be easily registered (aligned) with another.

Direct relay is now in operation or planned for almost all meteorological satellites. Polar satellites may relay signals instantly to anyone within "radiovisibility" of the spacecraft. Generally, messages are also recorded on board for playback to the operators' ground stations. Using the Doppler frequency variations noted in transmissions from surface-based data collection platforms, polar-satellite-relayed messages can be used to locate such platforms as drifting buoys. A special case of data relay is the search and rescue (S&R) system, in which the platform is a ship or aircraft in distress. Geostationary spacecraft cannot locate platforms but, unlike polar-orbiting spacecraft which appear overhead and depart, are always available for relay service.

Direct broadcast services permit individuals and institutions other than satellite operators to benefit from the overflight of satellites. Typical broadcasts include full-resolution images, reduced-resolution images (to permit users to use less costly ground equipment) and still-more-reduced-resolution images in the form of weather facsimile transmissions.
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