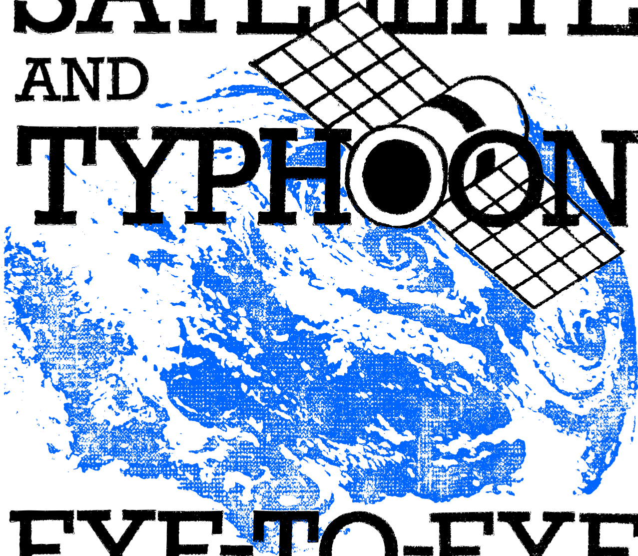
SCIENCE FOR EVERYONE

S. BAIBAKOV
A. MARTYNOV

# SATELLITE AND TYPHOON EYE-TO-EYE



MIR

Science
for Everyone

С. Н. Байбаков, А. И. Мартынов

# С орбиты спутника — в глаз тайфуна

Издательство «Наука» Москва

S. N. Baibakov and A. I. Martynov

# Satellite and Typhoon Eye-to-Eye

Mir
Publishers
Moscow

Translated from the Russian by
Anatoli Rosenzweig

First published 1987
Revised from the 1986 Russian edition

*Printed in the Union of Soviet Socialist Republics*

*На английском языке*

# Preface

A variety of technologies are being used to study atmospheric and oceanic processes, including weather stations and rockets and observational ships and aircraft. They are not always effective enough, however, to permit a detailed investigation into nonstationary (dynamic) phenomena in the atmosphere and ocean, whose time of origin is impossible to predict. Key examples of these unpredictable occurrences are tropical and extra-tropical cyclones, pollution of the ocean and atmosphere caused by man's activities, volcanic discharges into the atmosphere, dust storms, and unusual (nonstandard) cloud formations.

This book instances the study of tropical cyclones to give a popular account of one of possible methods for contact sounding of atmospheric and ocean parameters. Based on unmanned probes descending from the satellite orbit, this method allows one to widen essentially the possibilities for the study of the Earth's atmosphere and ocean. Furthermore, it can conceivably be utilized to explore nonstationary processes in the atmospheres of other planets of the Solar System—Mars, Venus, Jupiter, and Saturn.

The great effort that scientists have accomplished toward unveiling the secrets of tropical cyclones with their awesome destructive power has not led as yet to a complete understanding of the causes for the birth of typhoons and hurricanes, the physics of their development and the patterns of their travel. For this very reason—and despite the wide-ranging network of coastal warning services—tropical cyclones continue to claim human lives and cause a colossal damage to many nations' economies.

The major difficulties involved in the study of tropical cyclones arise from the necessity to tackle on an *operational basis* problems of their detection and deployment of measuring instrumentation in any desired area around the world. A further crucial need is for gathering and processing scientific information and locating the spatial position of balloons and ocean buoys.

The method discussed in the book, which relies on state-of-the-art space technologies for operational sounding of atmospheric and ocean parameters, can be remarkably successful in addressing these tasks.

The book consists of four chapters.

Chapter 1 gives an account of the atmospheric and ocean phenomena which are major research concerns today and reviews existing remote and contact sounding capabilities for their investigation. In parallel, it supplies important background information about environmental state, anthropogenic environmental impacts, and environmental protection measures.

Chapter 2 describes model parameters of tropical cyclones with emphasis on their most probable breeding grounds, seasonal patterns, lifetime at different development stages, key physical characteristics (traveling speed, vertical and horizontal dimensions, wind velocity and direction, temperature and pressure) and laws of their atmospheric motion against time (trajectories). Designers of satellites and unmanned satellite probes need these data directly during scientific experiments in order to engineer the designs and perform ballistic computations for the trajectories of motion of these satellites.

In Chapter 3 there is a discussion on the operational detection and location of tropical cyclones from the satellite orbit. It highlights the guiding principles for the selection of orbit parameters capable of providing the best possible vantage for sensing regions of interest on the Earth's surface and location of typhoons and hurricanes. Monitoring and sounding instruments, and data acquisition and processing by ground-based data facilities are briefly described.

Chapter 4 focuses on a method for prompt operational deployment of research equipment packages into tropical cyclones using descenders—the vehicles descended from orbit. Problems faced by designers of the orbital probes are discussed. The specific features of their descent through the extra-atmospheric and atmospheric segments are also dealt with.

Within the limits of one book the authors have been unable to address a few important issues in the development and operation of contact sounding systems to monitor behavior of the atmosphere and ocean by deployment of balloons from orbit into the desired area of the globe. An all-important related concern is with the collection and processing of the scientific information developed by the instruments in the balloon gondola and determining the coordinates and speed of the balloon in space. But since these issues are adequately covered elsewhere, an inquisitive reader can turn to other sources of the information of interest (see References appended to the book).

The authors hope the book will be useful for meteorologists, climatologists and oceanographers, on the one hand, and space technology specialists, on the other, as well as for all those interested in current developments in astronautics, meteorology, and environmental control.

The authors of this book wish to express their appreciation and gratitude to S.N. Aleksashkin, V.A. Korsakov, and K.M. Pichkhadze for their help in obtaining the results of digital computer simulations and other materials used in Chapter 4.

# Contents

# Introduction

Soviet cosmonautics today is a major sector of the national economy and a tangible presence in this country's daily life. Born of the merger between scientific and technological accomplishments, it has since grown to become itself a powerful stimulator of progress in science and technology. In a somewhat broader context, astronautics* has a vast influence on world politics, economy, scientific development and technological improvement.

The three decades of the space era have seen spectacular progress from the early artificial earth satellites to sophisticated unmanned space stations, from one-man spaceships to multipurpose manned orbital missions with several relief crews, from the simplest experiments in space to fundamental scientific research and practical application of space programme results in various national economy sectors.

The establishment of orbital stations is considered by Soviet scientists to be the major path for man's further development and conquest of space. The reliable and adequate logistic support provided by manned and unmanned transport spacecraft along with the cosmonauts' improved competence in assembly, maintenance and repair work (including extravehicular) have rendered today's orbital stations capable of extended service in space. Examples of this are the *Salyut 6* space

---

* "Astronautics" is an American equivalent of "cosmonautics" used in this country.—*Tr.*

station, which orbited for almost five years, and *Salyut 7*, now orbiting for almost four years. The ever expanding duration of Soviet missions in space is evidence of the high standard of our space technologies and the effectiveness of measures developed to counter the effect of weightlessness on the human organism. All these factors combined give us greater confidence in opening up outer space.

The early Soviet stations of the *Salyut* series had only one docking unit to receive the space vehicles bringing relief crews. The second-generation design differed by the addition of second docking unit (*Salyut 6* and *Salyut 7* belonged to this group). Effective solutions to a host of other technical difficulties further developed the potential to support long-term manned missions in terrestrial orbits.

The duration of manned missions vitally depends on the availability of life-support resources and the capacity for their long-term storage. Ten kg per person per day of resources need to be available. In addition the fuel for the station's orientation and orbit control and spare equipment that will replace worn-out equipment in the course of the mission must be included. If we sum all of this up it becomes clear that a *Salyut* type station, in order to remain serviceable for two years with a crew on board, would require hoarding in orbit a depot of life-support resources, spare equipment, and fuel, having a total weight of 20 tons, roughly equivalent to the weight of the station itself.

The problem of maintaining a long-term manned station found its workable economic solution in the *Progress* cargo transport craft designed to deliver to the station, via the second docking unit, all necessary equipment, food, water, air, and fuel. Also, the station added a new unified engine capable of being refuelled in orbit from supply spaceships. The second docking unit enabled two spaceship crews to operate in the station side-by-side, thus increasing the possibilities for conducting various investigations and experiments.

The experience with extended service of orbital scientific stations which were constructed based on *Salyut 6* and *Salyut 7* designs, has demonstrated the validity of the design solutions and proved more efficient performance of the cosmonauts in orbit.

A further stage in the evolution of space platforms has been the development of a station of a new generation, appropriately named *Mir* (in Russian "Mir" means peace). Provided with a new docking system of six units, the station represents in effect the base on which a multipurpose manned system operating on a sustained basis can be built. Its other capabilities include specialized modules for scientific and economic applications, maximum automation of control of motion, on-board systems and scientific instrumentation, increased capacity of the power supply system, and greater comfort provided for the cosmonauts' work and relaxation.

The Soviet orbital stations have opened up the way into space for international crews. The

Soviet Union's firm commitment to peaceful cooperation in space with all countries, regardless of their political system, has been strikingly confirmed by the missions jointly accomplished with fellow-cosmonauts from Czechoslovakia, Poland, the German Democratic Republic, Bulgaria, Hungary, Vietnam, Cuba, Mongolia, Romania, France, and India on Soviet space vehicles and orbital stations.

At the end of July Soviet-Syrian crew was in space and there now are plans for a French cosmonaut to join a long-term mission on a Soviet orbital station.

Konstantin Tsiolkovsky, the founder of theoretical cosmonautics, alleged that the settlement of space was as inevitable a stage in the development of life as was the conquest of land by aquatic creatures millions of years ago. In his book, *Dreams on the Earth and Sky*, first published in 1895, he described the life of imaginary asteroidal inhabitants and attempted to predict the future life on the Earth, "...only a part of the planet's population actually lives on it; most, chasing after light and space, organize around it—together with their machines, vehicles and buildings—a moving swarm in the shape of a ring, similar to Saturn's, but somewhat larger in comparison." This life, freed from attachment to the planet, results in the formation of "a chain of populous space cities" that rotate around the Sun.

Tsiolkovsky pursued the idea of human settlement in space in his later writings and a most elaborated version of this concept appeared in

1926 in his book. *Space Exploration by Rocket Devices*. There he suggested that the development of space should begin with human settlements located near the Earth.

The first experimental near-earth settlement was the Soviet orbital *Salyut* station and the *Mir* station has been a further practical step towards the establishment of permanently crewed station clusters—the first permanently populated extra-terrestrial settlements.

In sum, the manned and unmanned transport spacecraft developed to resupply orbital stations, the modules specialized for investigations to pursue scientific interests and those relating to the national economy, the longer duration of basic expeditions, crew rotation in the course of the mission, and the ever increasing international cooperation in orbit provide incontrovertible evidence of our advancement from the stage of periodically visiting space to that of making it a permanent operating station.

The long and versatile effort of the orbital station crews has added much to the cost-effectiveness of Soviet cosmonautics. The latter's objectives are now closely intertwined with this country's plans for economic development.

In recent years, because of the orbital stations, rapid advances have been made in fields related to space engineering and the science of space materials, which holds great promise for the development of fundamentally new materials that are extremely difficult if not impossible to obtain on the Earth.

The role of space vehicles is second to none in the overall survey of the Earth's natural resources and in the protection of its natural environment. The space imagery obtained from orbital stations and unmanned satellites has shown sufficient utility to warrant its wide application in the Soviet national economy. For example, space images have to date revealed the existence of several hundred areas holding promise as oil and gas reserves, permitted far more accurate determination of many geological formations, and supported important advances in forestry, fishery and agriculture. For this latter application, they have provided the capability for prediction of crop yields, monitoring the progress of phased crop growth, determination of soil condition, and assessment of ground water availability.

Cosmonauts render great aid to the fishing industry. Ice-field mapping based on satellite image data permits the extension of navigable seasons in the Northern Sea Route. Orbital observation data provide a new foundation for the protection of forests from fires, diseases, and pests, and for the objective assessment of forest resources. Currently, a permanently operated system of environmental control, borne by *Meteor* and *Meteor-Priroda* satellites, is nearing completion of its final experimental testing stage.

Another satellite-borne system, *Cicada*, including *Cosmos 1000* type vehicles, determines with high accuracy aircraft and ship location in any region on the globe, regardless of weather conditions.

Owing to a system of communications satellites, the Soviet Union's television broadcasting system can reach 90 percent of the population.

The Soviet Union has always considered advances in cosmonautics a common goal for the whole of mankind, a contribution to lasting world peace in the name of progress, prosperity, and a better life for all people. Back in 1961, in a message to the nation on the occasion of man's first launch into space, the Soviet leadership emphatically stated the following: "We hold victories in harnessing space to be those of all mankind, and not just an achievement by our people alone. We shall gladly put these advances to the service of all nations to further progress, happiness, and the well-being of all people on the Earth."

An example of such cooperation in space studies is the collaboration of socialist countries in the INTERCOSMOS programme. Using Soviet launchers and space vehicles, this programme of conducting intensive space research has brought together Soviet space scientists and specialists from Bulgaria, Hungary, Vietnam, the German Democratic Republic, Cuba, Mongolia, Poland, Romania, and Czechoslovakia. Space research has also been pursued with the collaboration of India, France, the USA, Sweden, and Austria.

Through their joint efforts, specialists from the USSR, USA, Canada, and France have created *COSPAS-SARSAT*—a space-based system for the search and rescue of downed aircraft and ships in distress. The Soviet *Nadezhda* satellites, the first to be integrated into the system, have quickly gained recognition among the world public.

The Soviet space program addresses principal human activities in the region of the Universe within our immediate reach. Being a peaceful program, it seeks to expand our knowledge about the world around us and to maximize the usefulness of space exploration and the achievements of cosmonautics for all of mankind.

The two unmanned Soviet *Vega* crafts made a great impression on the world public. During one flyby the probes, *Vega 1* and *Vega 2*, explored Venus and Halley's comet. For the first time the spacecraft deployed two weather balloons into the atmosphere of Venus which determined the circulation and meteorological parameters of the planet's atmosphere. They also planted the descent modules for investigating the planet's surface. The *Vega* craft then proceeded to an encounter with Halley's comet, entered its gas and dust coma on the 6th and 9th of March 1986, and passed within 9000 kilometers of its nucleus. The program reported back the first large-scale measurements of temperature and other physicochemical characteristics, examined the chemical composition of the comet's gas and dust components, and surveyed its electromagnetic fields and physical processes. Such a composite study of the cometary matter has fundamental significance.

The scientific equipment on *Vega* was a product of the collaboration between scientists from the Soviet Union, Austria, Bulgaria, Hungary, the German Democratic Republic, Poland, France, West Germany, and Czechoslovakia.

The international space projects will have significant scientific and practical implications. The design and technological options will be developed and utilized in future space technologies for scientific and economic applications.

For investigations into deep space, Soviet scientists are presently considering the possibility of having an unmanned space station fly by several asteroids in a project called *Vesta.* In the late 1980s the launch is planned of project *Phobos* which will include investigations of interplanetary and near-Martian space and comprehensive study of Mars's moon Phobos.

The USSR was the pioneer in cosmonautics. The first artificial earth satellite was Soviet-made, the first man in outer space was a Soviet citizen, and the first international crew was sent into space from a Soviet cosmodrome.

Konstantin Tsiolkovsky wrote that mankind acquired the ocean of the Universe as if it were purposely bestowed upon it in order to unite people as one entity, one family. He justly believed in the joint effort of all of mankind as the most efficient and rational way of harnessing outer space. Soviet people are strongly opposed to the militarization of space and to the deployment of any weapons in space. The further development of cosmonautics urgently requires that the countries of the world unite their efforts and talent around tremendous endeavors that have great constructive potential for the population of our planet.

One of these is the exploration of the Earth's disastrous phenomena such as typhoons, dust storms, and volcanic eruptions which bring incalculable destruction on various countries. This book discusses a possible method for studying these phenomena by using the latest achievements in space technology.

Chapter 1

# Atmospheric and Ocean Research from Satellite Orbit

## Sec. 1. Remote Sensing of the Atmosphere and Ocean

Man's economic activities still depend in many respects on Nature's elements. The sectors particularly sensitive to them are agriculture, aviation and fishery, to name only a few. Already many countries experience a stifling deficit of food protein and shortages of mineral resources, fossil fuels, and other raw materials. Hence the need for greater scope to exploring the World Ocean and, by extension, for more profound investigation of the processes that go on in its interior and on the surface; determination of its mineral, food, and feed resource potential; and assessment of its efficacy for shipping and transportation. Many countries are paying special attention to such hazardous phenomena as tropical and extra-tropical cyclones, dust storms, and volcanic eruptions—all those natural disasters responsible in some cases for heavy environmental pollution, in which man's economic activities are also a contributing factor.

Thus the magnitude and variety of problems faced by mankind in supporting its life and activity give added and compelling urgency to the study of the atmosphere and ocean. This is needed primarily to be able to accurately forecast weather, avoid hazardous effects of pollution, and prevent the damage from natural disasters. Rapidly obtainable "sea state" and atmospheric data are vital for sea transportation, marine fishery, shelf exploration and development, and pollution control in the ocean. Scientists studying atmospheric and oceanic processes require both diverse and maximum amount of information.

Therefore the atmospheric and ocean parameters being mapped and measured in the course of scientific experiments are of great variety. The range of parameters to address is uncertain, partly because of the complexity of particular atmospheric and oceanic processes approached within the atmosphere-oceans-continents system and partly because current theories fail to describe them with sufficient completeness. At the present time, nevertheless, there is a clear idea as to the set of parameters to be first monitored and observed along these lines. For the atmosphere, these are temperature, wind velocity and direction, relative humidity, pressure at the earth's surface, cloudiness, and atmospheric composition. The ocean is characterized by surface temperature, heat content of the top water layer, shear wind stress, surface level, surface currents, subsurface circulation, oceanic eddies, and precipitation over the ocean.

Scientists can now use a great variety of technologies to secure information on the state of the atmosphere and oceans, including weather stations, radiosondes, balloons, radars, rockets, and research ships. For all their diversity, the data they provide about the atmospheric condition over the vast expanses of seas, oceans, and highland regions and about the oceanic processes lacks the needed detail to meet today's scientific needs. Nor are the ten thousand weather stations, 800 sounding stations and hundreds of research vessels, which are currently operated around the world, an adequate answer to crucial problems in the analysis of atmospheric and ocean behavior. Because of that, almost 80 percent of the global surface is remaining, now as before, a "blank spot" for meteorologists, oceanographers and climatologists.

Several years ago the need was recognized to have basically innovative global information about the atmosphere and ocean unobtainable with conventional methods. The solution came with the development of spaceborne remote sensing observational capabilities whose main advantages were large surface area coverage and high information capacity. A man-made satellite, even flying in a low-circular orbit, can take in at a glance a surface area of several thousand square kilometers. Surface coverage increases with altitude, and orbiting at an altitude of 30 to 40 thousand kilometers a satellite can cover an area of the ground representing half the global surface. Furthermore, the volume of measurement data on some parameters of the atmosphere and ocean, e.g. sea surface temperature, available with only one satellite is equivalent to the synchronous measurements from 20 thousand research vessels. It is for this reason that remote sensing programs studying the Earth from satellite orbits gain increasing acceptance for astronautics in the USSR and abroad.

The on-board sensors and sounders flown by Soviet, American, West European, Japanese and Indian satellites of the *Cosmos*, *Meteor*, *Tiros*, *GOES*, *Seasat*, *Landsat*, *Meteosat*, *Himowari*, and *Bhaskara* series, the Soviet and American *Soyuz*, *Gemini* and *Apollo* crewed spacecraft, and the orbital stations of *Mir, Salyut* and *Skylab* systems gave important information about the planet's atmosphere, solid surface and aquatic shell. Various spaceborne instruments have been developed for environmental remote sensing applications.

The most effective global system deployed to date has been a constellation of several satellites in different orbits—low-circular, highly elliptical, and geostationary. The satellites remotely sound the atmosphere and ocean to provide the necessary data for meteorological and oceanographic applications, collect information from drifting buoys and balloons and transmit it to data acquisition and processing stations on the ground.

The requirements to observational atmospheric and ocean data include an optimal set of parameters to be measured and an appropriate spatial-temporal resolution and accuracy of measurement. Once the requirements have been finalized, available space technologies come under scrutiny to analyze their current and future potential for atmospheric and ocean remote sounding applications.

To achieve convenient optimization of the satellite sensor system, a frequently used suite of remote sounding parameters involves [10] imaging resolution, the solar angle, viewing altitude, imaging repeats, and area coverage.

*Table 1*

| Space imaging parameters | User sectors of remote sensing services | | | |
|---|---|---|---|---|
| | Oceanography | Hydrology | Geology | Forestry and agriculture |
| Imaging detail resolution, m | 50-300 | 0-9 | 0-30 | 10-30 |
| Large-scale image resolution, m | 70-100 | 15-100 | 70-100 | 70-100 |
| Sun's angle, deg | 60 | 54-60 | 15-30 | 15-30 |
| Viewing altitude, deg | 20-60 | 10 | 10-60 | — |
| Imaging repeats | 1 day to 4 months | 6 months to 5 years | 6 months to 5 years | 6 months to 5* years 1-20 days** |
| Area coverage, km | 400-1000 | 200-1000 | 200-1000 | 200 |

* For forestry.
** For agriculture.

Table 1 lists key requirements on these parameters for different classes of remote sensing problems [10]. As seen, the requirements imposed by different problem classes are similar for some parameters of the measurement system but distinctly and broadly dissimilar for other parameters. As regards spatial resolution, for example, oceanography is less demanding on imaging detail than hydrology, geology, forestry or agriculture and, conversely, all problem classes equally need a good resolution at large-scale image. For the Sun's angle, more stringent demands are made by remote sensing for oceanography and hydrology than for geology, forestry, and agriculture. All problem classes have similar viewing altitude requirements. As is evident from Table 1, different aspects call for distinct imaging repeats even in the same application area. To address problems in oceanography, the nominal imaging repeats are varied from one day to four months, its variation being greater still in hydrology—from six months to five years. Finally, area coverage requirements appear to be moderate for all these remote sensing applications.

Oceanographic remote observations provide a singularly important source of data on the detection and investigation of typhoons. A suggested cumulative set of principal ocean parameters which should be practically measured from orbit with the instruments on-board the satellite is presented in Table 2. It indicates the requirements for the instrument measuring accuracy and defines the permissible variation ranges for each one of the sensed parameters.

*Radiometer*, the instrument to measure electromagnetic radiation energy, yields radiation budget of the surface-air system, sea surface temperature, distribution of cloud cover, temperature at the upper edge of cloudiness (cloud top temperature). It operates in the visible, infrared and microwave wavelength regions. A *spectrometer* provides chemical composition of the surface layers in the atmosphere and ocean (and therefore an opportunity to look into the physicochemical processes there) and measures atmospheric concentrations of water vapor. A *radioaltimeter* is an instrument which gauges spacecraft flight altitudes in order to recognize variations of ocean surface level and wave height. More detail about these instruments is given below; their key characteristics and necessary imaging repeats in the ocean region of interest are shown in Table 2.

Generally, the instruments carried by weather satellites are operated on the principle of mechano-optical scanning [12], whereby the ocean surface within the instrument's field of view is scanned by successive recognition elements. The unit (elementary) area on the ground that a given instrument is able to scan is called its *spatial resolution* (or simply *resolution*), having a corresponding *unit* (*elementary*) *angle of view*, or *field-of-view*, of the scanner. With a facility on-board the satellite drifting (scanning) the elementary field of view in the plane normal to the orbital plane, it can continuously scan a rather wide band on the ground (scanning swath). With the help of a mirror maintaining oscillatory or rotary motion one can accomplish a shift of the ele-

*Table 2*

| Measured ocean parameter | Parameter variation range | Instrument accuracy | Sensor | Resolution | Spatial resolution, m | Spatial measuring step, km | Scanning swath, km | Imaging frequency |
|---|---|---|---|---|---|---|---|---|
| Sea surface temperature | $-2 \div +35$ °C | 0.01 °C | Infrared and microwave radiometers | 0.1-0.5°<br>1-2° | 100-5000<br>25-100 | 5 | 200-500<br>500-3000 | Twice daily<br>Once daily |
| Color | A scale of 23 gradations | 1 gradation | Spectrometer, radiometer in the visible | 0.01-0.05 mWt/cm² | 25-100<br>500-3000 | 10 | 200-500<br>500-1500 | Once dailly<br>Twice daily |
| Transparency | 0-70 m | 0.1 m | Spectrometer, radiometer in the visible | 0.01-0.05 mWt/cm² | 25-100<br>500-3000 | 10 | 200-500<br>500-1500 | Once daily<br>Once in 5 days |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tides | 0-17 m | 0.1 m | Radioaltimeter, radiometer in the visible | 0.3-1 m | 25-100<br>500-2000 | 5 | 200-500<br>2000-5000 | Hourly<br>Once daily |
| Areas of upwelling, width | 5-100 km | | Radiometer in the visible, IR radiometer | 50-200 m<br>200-1000 m | 50-200<br>200-1000 | 5 | 200-500<br>500-1500 | Once daily<br>Once in 5 days |
| Wind waves:<br>height<br>length<br>direction | <br>0-20 m<br>0-1000 m<br>0-360° | <br>0.1 m<br>10 m<br>1° | Radiometer in the visible, radioaltimeter; microwave radiometer; | <br>0.5-1.0 m<br>25-50 m<br>±15° | 50-200 | 50 | 200-500 | Once daily |
| Absolute sea surface level | 0-200 m | 0.1 m | Radioaltimeter | 0.3-1.0 m | 10-1000 | 5 | | |

*Table 2 (cont.)*

| Measured ocean parameter | Parameter variation range | Instrument accuracy | Sensor | Resolution | Spatial resolution, m | Spatial measuring step, km | Scanning swath, km | Imaging frequency |
|---|---|---|---|---|---|---|---|---|
| Sea ice:<br>quantity<br>age<br>closeness<br>extent of disruption<br>leads | 1-10(5) points | 1 point | Spectrometer, radiometer in the visible | 1 point | 25-100 | | 200-500 | Once daily |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| tion of wind speed at surface | | | | | | | | |
| Cloudiness | Shape and amount | | Visible and infrared radiometers | | 100-500<br>500-3000 | | 200-500<br>500-3000 | Once daily |
| Tropical showers | | 1 mm/h | Microwave radiometer | | 1-5 km | | 200-500 | Once daily |
| Salinity | 0-40‰ | 0.002‰ | To be developed | 0.1-1‰ | 50-100 | 5 | 200-500 | Once daily |
| Currents: velocity and direction | 1-150 cm/s<br>0-360° | 1 cm/s<br>1° | Infrared radiometer, radioaltimeter, radiometer in the visible | 1-10 cm/s<br>±15° | 25-100<br>200-1000 | 5 | 200-500<br>500-1500 | Once daily |

mentary field of view on the Earth's surface.

A multispectral television scanning system is schematized in Figure 1 [12]. It is composed of swinging mirror 1, mirror lens 2, light filters 3 and radiation receivers 4a, 4b, and 4c. In

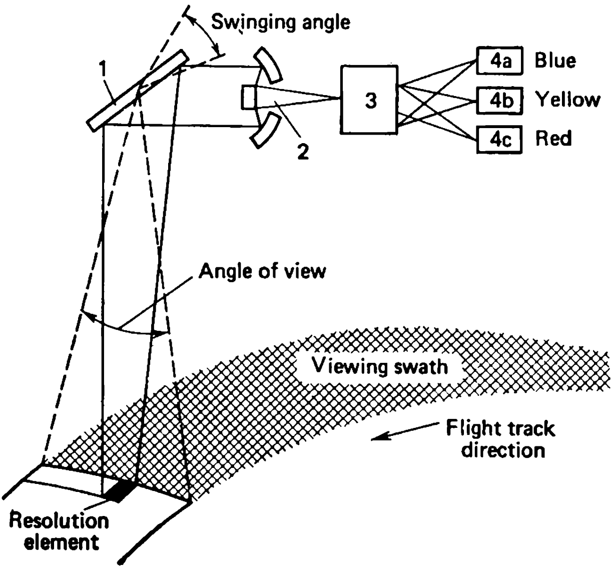



**Fig. 1. Operation of the multispectral scanning system**

the system, the Earth's surface image scan along a track is driven by progress of the satellite itself, and across the track by the swinging of the mirror. Some of the scanning systems provide across-track image scanning capability by swinging the receiving picture tube, with a fixed mirror. The scanning swath width is controlled by satellite altitude and the swinging angle of the rotating mirror (or the receiving picture tube).

Thus, the principal source of information in observing the atmosphere and ocean from space are the images generated on-board the satellite by remote sounding instruments over the electromagnetic spectrum from the UV to the radio band. In this sense they are said to be images of "underlying surface". Accordingly, the methods which take soundings of the ocean and atmosphere from a satellite orbit basically rely on satellite instrument measurements of their emitted (intrinsic) and reflected energies and the latter's estimated intensity to derive certain parameters of the atmosphere and ocean. Remote sensing data generally require sophisticated mathematics and high-speed computers for its processing and direct measurements of atmospheric and ocean parameters for its calibration.

The Earth's atmosphere is known to variously transmit electromagnetic waves through different wavebands. This raises the attended, and challenging problem of how best to choose optimal spectral regions for imaging. There are three distinct wavelength regions—visible and near-infrared, 0.4-1.2 μm; thermal infrared, 3-5, 8-13 μm; and radio, 1 mm-10 m; from these more narrow spectral bands are selected to deal with specific problems in remote sensing studies of the atmosphere and ocean. By analysing the electromagnetic radiation, different types of information can be obtained in each of these wavebands while the measurement techniques and the sensing instruments need to be varied accordingly to match these data types.

There are manifold requirements for the localization and number of spectral intervals. As an example, oceanography applications demand about 100 spectral bands for meaningful research. However a closer analysis of scientific-experiments suggests that nearly 70 percent of the information output comes from sensing in four spectral regions, two in the visible and two in the infrared. The spectral range from 0.85 to 1.1 μm offers maximum information for applications in oceanography. Research has found that, generally, for effective management of environmental remote sensing problems, a dedicated satellite needs a sensor system engineered for imaging in at least five spectral bands, three in the visible and two in the infrared.

It is also important to consider the atmospheric impact on imaged scenes heavily felt in the wavelength intervals, from 0.57 to 0.62, 0.69 to 0.75, 0.79 to 0.82, 1.1 to 1.2, and 1.26 to 1.28 μm. In these ranges reflected radiation is absorbed by the ever-changing atmospheric components: oxygen, water vapor and ozone. No imaging can be done in the 0.3 to 0.4 μm band either as the atmospheric haze overwhelms the reflected signal there. Image recognition employs comparison of radiances between the reflected radiation signals received on-board the satellite and the available *a priori* information on the radiances of natural formations. This breeds, in its turn, a degree of error in the received imagery, due to intermittence or discreteness.

Sensing of the atmosphere and ocean in the visible and infrared is solely feasible on the sunlit side of the Earth as the electromagnetic radiation in these spectra represents the reflected radiation of the Sun.

Few methods of studying atmospheric and ocean parameters from space in the visible range are as simple and straightforward as visual observation from a manned orbital station. The human eye gazing at the Earth from a satellite orbit can confidently recognize the boundaries of cloud cover, types of clouds, and outlines of turbid river water discharges projecting into the sea; it can see through shallow water the bottom topography of an ocean region, define the properties of ocean eddies and dust storms a few hundred kilometers in size, and discriminate the type of plankton present. The integrated perception of observed phenomena in the atmosphere and ocean, selectivity of human vision and logical analysis of observed scenes are the unique properties of the visual observation method that no sensor configuration can match.

The visual observation method has a significantly enhanced potential when supported with instruments extending the limits of human vision such as binoculars, telescopes and night viewing devices with opto-electronic amplification of light. Accurate colorimetric assessments of the ocean surface areas observable from the manned orbital station enable cosmonauts to develop seawater chromaticity tables and provide valuable inputs for design of opto-electronic colorimeters.

Although visual observations of the atmosphere and ocean from space are credited for many useful and interesting discoveries, human vision is less efficient than the information potential of the methods for remote sounding of the atmosphere and ocean based on appropriate technologies. Imaging is perhaps the most widely used technique to study the ocean from a satellite orbit. Space imaging of the ocean captures a great deal of what the cosmonaut's eye can see and, if aided by special sensing techniques, captures many other things out of reach for the unaided eye. Satellite-borne imaging systems can cover in one frame a large underlying surface area—up to several million square kilometers—at a reasonably good image resolution.

Spectral-selective and multispectral imaging methods have wide currency for applications in remote sensing from a satellite orbit. The former method makes use of the photographic materials having several layers, each with a different spectral sensitivity. It provides clues to problems that neither visual methods nor conventional photography can resolve (such as oil slick detection or bioproductivity assessment in the ocean). Multispectral photo imagery expands further the potential for discrimination of fine spectral shading on the ocean surface.

However, the photo-imaging methods lack

in operational efficiency, because the images must be delivered to Earth for processing. TV systems designed for remote sensing from space can aid in this through their ability to transmit information to the Earth in two modes, real time and by recording on the on-board video and subsequent playback to ground data acquisition stations, i.e. on- and off-line.

Multichannel satellite TV systems have been developed which generate atmosphere and sea-surface information which is comparable in quality and other characteristics with photo images. As one relevant example, the *Landsat* TV images of the Earth's surface have a resolution of about 70 m. The satellite acquires images in four visible and near-infrared spectral bands—0.5-0.6, 0.6-0.7; 0.7-0.8; and 0.8-1.1 μm. Using the system, researchers have been able to address a wide range of problems in the identification of ocean surfaces contaminated by oil products and industrial wastes, recognition of new areas above average bioproductivity, spotting relative position of river and sea waters, determining traces of internal waves, and studying the bottom topography.

Still, both photography and TV imaging seem powerless in the face of problems in meteorology and oceanography which demand a very high spectral resolution as for example the global mapping of chlorophyll distribution in the ocean.

Other than the passive optical methods just discussed for remotely observing the ocean from a satellite orbit, the goal is well-served by active methods based on ocean irradiation from the orbit. They provide an improved accuracy in sensing elevation of the bottom topography and permit the deep sounding of suface ocean layers.

Sensing of the atmosphere and ocean in the thermal (infrared) region makes use of two wavelength intervals, 3-5 and 8-15 μm. With the former interval, ocean temperature can solely be measured on the orbit's dark side since on the sunlit side of the Earth the emitted thermal radiation of the ocean will be of comparable intensity with the reflected radiation of the Sun. In the second wavelength interval the solar reflected radiation is so low that the measurements are practically independent of the ocean surface illuminated by the Sun. Temperature soundings in that latter interval are of value for oceanographers by allowing them to monitor the boundaries of ocean currents and locate the position of frontal areas, trajectories of ocean eddies and areas of maximum bioproductivity. Usually, sea surface temperature data in the thermal infrared is acquired by use of scanning radiometers. This is a quick and convenient method that results in clearly visible sea surface temperature maps accurate to 1-3 °C. Here a note is in order that sea surface sounding in the visible and infrared is not feasible if the surface is screened—covered with clouds or fog.

The greater the wavelengths the more freely the ocean radiation signal is known to pass through the atmosphere into space. In such cases it is necessary to move to another spectral region, the microwave, or superhigh-frequency bands. These wavelengths typically range from a few millimeters to several decimeters. In this region the atmosphere has less drastic radiation impact than either in the visible or infrared. This has the effect of providing a great deal more information about hydrophysical ocean parameters than is obtainable with the methods of ocean remote sensing in the optical spectral range.

In the RF-band, ocean remote sensing from space relies on active and passive techniques, using radar sensors in the former case and sensitive microwave radiometers for recording the emitted microwave radiation of the atmosphere and ocean, in the latter. Ocean remote sensing in the microwave range can confidently identify the borders of storm areas and ice fields, and determine thickness, closeness and age of ice and direction of its motion. Over and above these, it has been possible to gauge water salinity, an all-important input for detecting the fresh-saline water interface in the areas of large rivers' issue into the ocean, along with other major variations of salinity. Lastly, the microwave methods of remote sensing earth studies have been effective in locating areas of oil spills in the ocean.

Over the recent years extensive experience has been gained in the operation of active radiometers for remote sensing of the ocean from space. Their operational principle is based on the radar effect: first the source on-board the satellite sends a powerful radio beam directed toward the ocean surface, then the on-board devices receive the reflected radio signal and the arriving echo is analysed.

Significantly, all features on the underlying surface are classified into *concentrated* or *distributed* by the pattern of reflected radiowaves they produce. The concentrated features include free-standing single objects; their dimensions are too small to permit independent surveillance by on-board active radiometers. The distributed features immediately apply to studying typhoons from orbit. They consist of sea surface and atmospheric inhomogeneities like clouds or rain. The pattern of radiowave reflection is strongly influenced by the irradiated surface properties. A calm ocean surface in which the dimensions of waves (roughness) represent a minor fraction of the irradiating wavelength is capable of practically specular reflection of radiowaves, with a well-established correlation between the characteristics of the irradiating versus reflected wave. When the radio-frequency wave is of commensurable or smaller length than the ocean surface roughness the echo is bound to be distorted by the interference of the radiowaves reflected from different surface features.

Distinction is made among three types of radio signal reflection patterns by features on the underlying surface—optical, when the feature size is many times the radiowave length; resonant, when the feature size and the wavelength are similar; and Rayleigh, when the wavelength far exceeds the feature size. All these types of the reflected signal differ in reflection intensity and in other characteristics—shape, phase shift, etc.—from the sounding signal.

These distinctive signal reflection patterns have been integrated into instrument designs specialized for radar sensing of the Earth's surface from a satellite orbit. The most common instrument types in today's space research applications are scatterometers, altimeters, and side-looking radars.

*Scatterometers.* The instrument's operational principle exploits the phenomenon of resonant radiowave reflection from sea surface. This is the case whenever the sounding wavelength is about two times the length of the sea wave. As a result, the amplitude of the sea surface echo signal received by the satellite scatterometer varies with mean square wave height, enabling the scatterometers to be used for seawave height measurement. And because the height of sea waves will be generally related with wind-induced waves, the scatterometers can usefully be applied to measure another staple parameter, wind speed in the near-surface atmospheric layer. Practical experience with the scatterometers in various satellite missions [21, 30] has shown their ability to scan across a very wide swath (nearly equal to the orbit altitude). This is because the best scatterometer performance comes with sea surface irradiation by slanted radiowave beams.

*Radioaltimeters.* The instrument concept is fairly simple: by measuring accurately the traveling time of radiowaves between the moments when they are radiated from the satellite and received there again as a surface-reflected echo, and knowing the wave propagation velocity, one should have no problem in estimating the distance from the orbit to the ocean surface. Since an orbiting satellite can now be located to a sufficiently high accuracy the satellite trajectory can provide the baseline for relative measurements of the ocean surface profile. A radioaltimeter on-board the satellite is capable of yielding the variation of ocean surface level caused by storm surges, tsunamis, currents and other ocean phenomena. Finally, the radioaltimeter provides the sea wave height at the satellite sub-point* by the pattern of the radio pulse reflected from the ocean surface.

*Side-looking radar* is an instrument "looking" to one side of the moving platform in order to eliminate right-left ambiguities. It is perhaps the most promising instrument concept for ocean remote sensing from orbit. It relies on short sounding pulses of the transmitting antenna in the horizontal plane to produce radio images of the ocean surface over large spaces with an adequately high spatial resolution. The side-looking radar can build rather rapidly a picture of ocean waves, measure the extent of water surface contamination, and identify ice-field boundaries.

---

* To be more specific, let us say that in remote sounding of the ocean surface with short rectangular pulses that are emitted by an in-orbit radioaltimeter the leading edge of the reflected pulse is modified by an angle determined by sea wave height along the satellite track.

**Atmospheric studies from orbit.** Space-based atmospheric observation goes back to the date of launching the third man-made satellite. To date there have been many special-purpose satellites at work in outer space, for example the Soviet *Cosmos* and *Meteor*, American *Tiros*, *Nimbus*, *ESSA* and *NOAA*, and spacecrafts from other countries.

A satellite can image approximately 20 percent of the Earth's surface in one working day. While the photos of televised scenes from weather satellites show a strip a few thousand kilometers wide, they also provide enough discrimination to distinguish details 1 to 2 km in size. Satellite-based operational weather systems now exist in many countries. The Soviet and US systems have the support, respectively, of the *Meteor* and *NOAA* series. Beyond them, the systems incorporate ground stations in order to receive, process and disseminate satellite information and a service which monitors the condition of and exercises command and control of the satellite on-board systems.

Besides direct television and infrared image broadcasting to the Earth in the direct radio-visibility range of satellite signals, another method is to record them on magnetic tape on-board the satellite and relay them to ground data acquisition stations the moment the satellite appears within their line-of-sight range. The contact may last from several minutes to half an hour.

The ground data acquisition stations perform the recording of satellite information first on magnetic tape and then on photo film. After obtaining television and infrared images they are converted to a format convenient for use by weather analysts. This is a complex process which involves terrain referencing and interpretation of the images by recognition of surface features and identification of various image characteristics. Because data handling at the ground stations requires much time and effort it is usually aided by sophisticated hardware including computers.

In order to judge synoptic processes over large spaces, the accepted practice combines sequential satellite imagery taken along its flight path, even from several adjacent orbits. The result is the so-called *mosaics*.

The operational information obtained from weather satellites about the atmospheric condition, cloudiness, and the surface of land and ocean materially enhances the hydrometeorological information furnished by the traditional techniques for measuring atmospheric and ocean parameters. The method demonstrates the potential for improved weather analysis and forecasting over the oceans and in inaccessible territories on land and for improved accuracy of weather mapping in the regions having a dense network of ground weather stations. The visible and infrared satellite images of land and ocean surface effectively support a variety of applications in hydrology as well as hydrometeorology, and also in oceanography, climatology, forestry, water management, and agriculture.

These and other satellite data applications keep multiplying with each year. Their greatest utility for remote sounding has been in the short-term, 1-3-day weather forecasting. Satellite information has large practical value for civil aviation and is made frequently a part of crew briefings and weather hazard messages for long-distance airways.

Navigation and fishery are major users of satellite meteorological information. Remote sensing data on ocean weather are essential for judging the factors that affect shipping.

The recent years have seen a major growth of maritime operations in the Arctic region. The navigation season is expanded, new ice-breaking and carrying ships enter service, and yet-untried high-latitude navigation routes become operational. These new developments dramatically upgrade requirements on the operational efficiency, accuracy, and contents of current satellite information about ice conditions, and on the quality of their forecast. Satellite data-based assessments of atmospheric dynamics provide agrometeorologists with a needed input in order to forecast overwintering conditions and water availability to crops and to aid the prediction of unexpected cold spells in fall and spring. Television space imagery identifies the cloudiness with promise for seeding to induce artificial precipitation.

The atmospheric and ocean research programs relying on weather satellites allocate much importance to multispectral imaging in the visible and near-infrared through the use of TV-scanners. To study and monitor the state of large natural features and to evaluate short-term and seasonal developments in the atmosphere and ocean encompassing large areas on the ground, wide-area multispectral imagery is desirable.

Multispectral photos show a distinct information advantage over single-band images, permitting simultaneous recognition of large terrain features, assessment of their condition and monitoring of their developmental dynamics. This is made possible by higher image resolution and the possibility to exploit the differences between spectral regions brought about by wavelength-controlled reflectivity variations of natural objects. The multispectral images reveal clearly defined turbid river water discharges into seas and oceans, contaminated shallow waters as a result of perturbing storm-wave influences on water surface, blooming phytoplankton in the coastal sea waters, distinctive morphology and structure of ice cover, pools of water on the surface of ice and the extent of its contamination, etc.

Spectrophotometric information technologies are used to retrieve atmospheric temperature against elevation above sea surface, estimate total atmospheric water vapor and ozone, and to evaluate cloud effects. The radiometric analysis of microwave radiation can identify precipitation zones, quantify cloud moisture content and intensity of precipitation, estimate total atmospheric water vapor, and trace the extent and pattern of ice.

**Studies of cloud cover.** The cloud cover represents a leading factor of climate formation on our planet. It is the most powerful and changeable control of the radiation balance between the atmosphere and the underlying Earth's surface. Multiannual satellite observation data indicate that, while there is a constant amount of cloudiness, on the whole, in the terrestrial atmosphere, the cloud-cover distribution considerably varies over the year. Naturally, the amount of clouds over the ocean is greater than above the land and usually increasing in the warm season and decreasing in the cold season.

The satellite observation data available to date defines mainly the spatial extent and amount of cloudiness. Information on other cloud parameters, such as temperature and the base height of top cloud, moisture content and precipitation is extremely sparse. Increasingly, observations from satellites, especially the geostationary ones, become a principal source of information about clouds. Ground-based and aircraft measurements are necessary support for analysis and verification of the satellite information. On the other hand, dedicated ground and aerial surveys are needed to measure microphysical and radiational cloud characteristics.

The main disadvantage of cloud remote sensing from space stems from the difficulty of providing data on a multilevel cloud structure and the base height of low cloud. To this end the satellites, both existing and planned for future launches, which have atmospheric remote sounding missions, are assigned the main objectives of establishing the base height of top cloud, developing data on cloud patterns over the oceans, and evaluating the daily run of cloudiness [10].

Today's methodologies for climate research based on satellite-derived data recommend cloud cover imaging at a spatial resolution of 250 km and temporal resolution of 3 hours. Ground-based cloud observations and airborne facilities determine the base height of low cloud to an accuracy of 50 m and separate cloud types into cirrus, cirrus-cumulus, altostratus, high stratocumulus, stratus, stratocumulus, cumulus, nimbostratus, and cumulonimbus.

Top cloud temperature is the key to assessing the base height of top cloud. The temperature is derived from measurements of upwel ling (outgoing) radiation in the atmospheric transparency window. Observational satellite data enable the base height of top cloud and temperature to be known with the respective accuracies of 1 km and 1 °C, respectively. The retrieval of cloud-cover characteristics draws on high-resolution scanning radiometer data in the visible and infrared.

To achieve quality measurements of the cloud cover, intercalibrations of instruments between different satellite missions in their simultaneous operation and inputs from ground weather stations are required. But even so the remote sensing technologies occasionally fail to provide desired characteristics with respect to cloud types such as thin cirrus, ceiling clouds above snow, ice or the bright desert, and ceiling clouds at night time.

The determination of wind field by cloud drift [10] is an important goal of meteorology and climatology. This requires a series of high-quality repetitive satellite images of cloud cover, their accurate geographic referencing, and an ability to recognize trackable cloud types known as *tracers*.

The key sources of errors in the wind field reconstruction by cloud drift originate from incorrect altitude referencing, measurement errors, and inaccuracies in the construction of tracer trajectories.

At the present time, the wind speed and direction estimations relying on satellite data are in error by 10 percent and 10° respectively. The errors can be considerably reduced with drifting balloon sounders used to measure the wind field. For such applications, the satellite is coupled with central processing facilities on the ground to detect and locate the balloons and collect data from the balloon-borne sensors. Under this method, the balloons can be located to within a few kilometers (indeed 1 km for state-of-the-art systems) and their velocity vector can be appreciated with an error of several meters per second (down to one m/s for state-of-the-art systems). Temperature measurements by the sensors carried on the balloons can be accurate within $\pm 0.5°$.

In France a programme is being pursued in which operational satellites locate and collect weather data from sea buoys and balloons (*Argos*). The program is a cooperative project with US scientists who turned over their *Tiros-N* third-generation weather satellites to serve as instrument-mounting platforms.

**Studies of the ocean from orbit.** A global ocean-monitoring system requires much of its information input to be developed by remote sensing of ocean parameters from satellites. More conventional means such as buoys, ships, and aircraft are primarily useful for verification. Among the satellites specially injected into orbit to explore the World Ocean are *Cosmos-1076*, *Cosmos-1151*, and *Cosmos-1500*; *Intercosmos-20*, *Seasat*, and *Geos*.

Satellite information must possess adequate accuracy, spatial-temporal resolution* and prompt delivery (Table 3) to suit a more advanced procedure for measuring a series of essential characteristics of oceanic processes [10]. This degree of knowledge of ocean parameters will provide an improved assessment of sea surface temperature fields and other characteristics of water masses needed for fishery. Observations on currents and eddies can be of immediate utility to plotting optimal shipping routes and to improved accuracy of predicting the dynamics of oil slicks on the ocean surface. Wave forecasts are important for the optimization of shipping routes and operations in the shelf zone. The ice-cover boundaries will thus be better delineated to aid the fishing vessels near the ice edge while a clear understanding of sea ice strength will make it possible to appraise the possibilities for navigation at high latitudes.

The pattern of chlorophyll distribution provides a good indicator for the circulation of

* The term is understood to mean minimum recordable dimensions of image elements and time intervals.

*Table 3*

| Parameter | Accuracy | Spatial resolution, km | Temporal resolution | Delivery of information |
|---|---|---|---|---|
| Wind speed | 2 m/s | | 12 h | 3 h |
| Wind direction | 10° | | 12 h | 3 h |
| Global sea surface temperature | 1° | | 3 days | 18 h |
| Local sea surface temperature | | 10 | 1 day | 12 h |
| Wave height | 0.3 m | 25 | 12 h | 3 h |
| Wave direction | 10° | 25 | 12 h | 3 h |
| Extent of ice cover | 15% | 20 | 3 days | 12 h |
| Thickness of ice cover | 2 m | 50 | 3 days | 12 h |
| Age of ice | new<br>annual<br>perennial | | 3 days | 30 days |
| Glacier height | 0.5 m | 10 | 1 year | 30 day. |
| Water turbidity | low<br>medium<br>high | | 1 day | 10 h |
| Velocity of horizontal surface current | 5 m/s | 20 | 1 day | 1 day |
| Direction of horizontal surface current | 10° | 20 | 1 day | 1 day |

ocean water masses, and a knowledge of chlorophyll locations can make fishing more productive. Storm forecasts are of course vital, and so on and so forth.

The oceanographic satellites can carry different payloads of ocean remote sensing instru ments, their composition assorted case-by-case to suit the objectives of the experiment as a whole. As an example, the payload choice for *Seasat*, a US ocean-observing satellite, included a suite of five instruments—a radioaltimeter, scatterometer, side-looking radar, scanning radiometer in the visible and thermal infrared, and multichannel scanning microwave radiometer.

Traveling in an almost circular orbit 800-km high and inclined at 108° to the equatorial plane, *Seasat-1* provided information coverage for 95 percent of the Earth's surface every 36 hours. The *Seasat* radiometer had a surface viewing spot diameter of 1.5 to 12 km—it is enough to measure wave height at satellite sub-point with an accuracy of 0.5 m in the 0 to 20-meter range. The *Seasat* scatterometer irradiated two surface swaths from 500 to 700 km wide and 200 km away from the flight path at a spatial resolution of 50 km. The instrument estimated the wind speed at sea surface to within 2 m/s in the range of 4 to 26 m/s, and wind direction to within 20°. The side-looking radar accomplished ocean surface imaging across a 100-km swath 250-km distant from the satellite track. The spatial resolution was 25 m. The visible and infrared radiometers operated in the wavelength ranges of 0.45 to 0.94 and 10.5 to 12.5 μm, returning images of the ocean surface and cloudiness and reporting back their temperature for a 1100-km wide strip along the satellite track. The temperature measurements were accurate to better than 1 °C.

Determinations of sea surface temperature accurate to 2 °C and of wind speed at sea surface accurate to 2 m/s (in the near-surface air layer) were possible with a multichannel centimetric-band microwave scanner. In addition to these, moisture content and water vapor concentrations were also measured. The measurements were taken in a 600-km swath along the spacecraft track at the spatial resolution of 20 to 100 km.

Many specialists have been working hard seeking to improve the accuracy of ocean remote sensing imagery.

## Sec. 2. Studies of Nonstationary Processes in the Atmosphere and Ocean

Nonstationary processes in the atmosphere and ocean, whose location and time of origin cannot be known beforehand, attract the researchers' special attention. These processes are tropical cyclones, volcanic discharges into the atmosphere, and dust storms. Human history abounds in episodes of these natural calamities which have taken their dreadful toll on human lives and damaged the economies of entire nations. Nonstationary processes affect the planetary climate, act on the soil cover, and change surface topography.

### 2.1. Tropical Cyclones

The tropical cyclone is a large atmospheric vortex with a low-pressure center. The air streams in it move generally toward the cyclone center along near-circular spiral paths. Thus the air streams will be observed from aircraft and satellite to spin counterclockwise in the tropical cyclones of the Northern Hemisphere and clockwise in the Southern-Hemisphere counterparts. Known under a variety of local names, they are familiar to most as "typhoons" or "hurricanes" The word *typhoon* has Chinese origin (from *taai* great and *fung* wind) and designates the intensive storms of the western North Pacific (up to 170°E). The French word *hurakan* is a Caribbean Indian borrowing to denote the tropical cyclones that occur in the Atlantic, the Gulf of Mexico, and the eastern North Pacific. (For the purpose of this book, all the three terms are equivalent and have the same meaning. The more frequent use of the word "typhoon" reflects little else than the authors' personal preference).

Tropical cyclones release immense energy. Scientists estimated that only about 3 percent of a typhoon's heat energy passes into the mechanical energy of wind and waves. But even this small fraction of the energy potential of a medium-sized typhoon would be enough to supply with electrical power a population of 200 to 300 million for half a year.

The tropical cyclone can be likened to a heat engine. The air inside forms a core near the central part, its temperature is a few degrees above ambient. A part of the warm air from the core goes up into the upper layers of the atmosphere, to be replaced by new streams coming from below. The conversion of thermal energy into the mechanical energy of wind in the tropical cyclone is due to a pressure drop—the different air pressures developing in the warm air column at the center and in the cool air environment on the periphery. This pattern of the energetic processes is very tentative and applies primarily to mature typhoons. Although information is still lacking, we do know that the pattern of energetic processes will be different for the typhoons in the stage of development or abatement.

The distress caused by tropical typhoons is hard to predict. But the available statistics over many years of observing tropical hurricanes have been sufficient to develop at least some impact evaluation criteria for them. The first and foremost impact is the number of human casualties. Cases are known when a typhoon has claimed the thousands of human lives, as for example, Typhoon Vera in September of 1959, which caused the death of 5500 persons. A significant upward revision of their number is needed if one considers those who died later from starvation and diseases.

The property damage from tropical cyclones is conventionally represented as direct and indirect. Direct damage is dealt during and immediately after the storm as collapsed buildings, ignited fires, ruined crops, etc. Indirect damage becomes evident in a longer term after the typhoon or hurricane has passed over islands and continents. Examples include several years of crop failure in the fields stripped of topsoil, or reduced production at storm-stricken plants and factories. The dollar amount of indirect damage from a tropical cyclone may be several times the amount of the direct damage. Drawing on many years' observational statistics on tropical cyclones, a few correlations have been discovered to link the damage to some of their physical characteristics and thereby to offer a rough prediction of the magnitude of the oncoming disaster.

Below we shall discuss some of these correlations. Generally, one particular parameter indicative of a typhoon's strength will be segregated and its magnitude compared with the damage caused by the typhoon. The parameter may pertain to the maximum wind speed in the typhoon or the daily amount of precipitation. It has been found that the scope of damage, e.g. the number of fatalities, varies approximately with the cubed maximum wind speed or cubed daily precipitation quantity. The strength of a tropical typhoon is sometimes assessed by a value proportional to the product of the square typhoon radius and the difference between the pressure in the typhoon center and the average pressure on its margin. Normally, the value falls within the range $1 \times 10^{20}$ to $100 \times 10^{20}$ erg/s. In some instances tropical cyclones are classified into wind and rain varieties. For the typhoons of equal intensity, more human lives will be claimed by the rain type and more property damage done by the wind type.

There is also a certain relation between the damage from a tropical cyclone and its distinctive trajectory features. The deadliest trajectory is the one by which a typhoon makes its landfall at the right angle. The typhoon traveling speed plays also an important role and even with a well-organised warning service it is difficult to escape or protect oneself from a typhoon that speeds along at a crushing rate.

Other than causing damage to humans and all their creations, tropical cyclones can change coastal topography and outline by making new straits, digging sand spits and submerging smaller islands.

**The origin and development of tropical cyclones.** The most common breeding grounds for typhoons occur in the tropical zone bounded off by the northern and southern tropics (23°27′N and 23°27′S, respectively). At these latitudes once a year the Sun is exactly at the zenith on 22 June for the Northern Hemisphere and 21 December for the Southern. Meteorologists often extend the zone to 30° latitude.

The tropics are distinct for having essentially similar weather types dominating at different seasons. Subtropical anticyclones take up a position near their border, at 30 to 35° latitude. Inside the zone, there is a stable wind current flowing in different directions; towards the west-southwest in the northern latitudes and west-northwest in the southern latitudes. In marine weather science the current is termed the *trade wind*, or simply trade, its average speed being 5 to 6 m/s at most.

The breeding grounds of typhoons are scattered non-uniformly about the tropical region. It should be noted that the tropical cyclones originate only in the open ocean in the first place. The Pacific typhoons would most typically appear in the western part of the Northern Hemisphere, ranging up to 50 annually.

For the Atlantic ocean, the principal region where most hurricanes are born (at the rate of 8-10 a year) is in the western North Atlantic, with other similar regions in the Caribbean Sea and the Gulf of Mexico. The tropical cyclones of the Indian Ocean originate mainly at Australia's west coast, in the Bay of Bengal, Arabian Sea, and near Madagascar.

There are several viewpoints concerning the origin of tropical cyclones. Many researchers see the focal point of their birth in the *convergence zone* of the trade flows from both hemispheres. Here, the wind looses strength, the air floats upwards and clouds and rains appear. This intratropical convergence zone, approximately 200-km wide, can shift relative to the equator with drifting trade flows to 12-15°N during the Northern Hemisphere summer and 5°S during the Southern Hemisphere summer. The size and force of incipient tropical cyclones are heavily dependent on the position of the convergence zone. With the zone near the equator, the Coriolis force which spins the currents is too low to produce a sufficiently strong closed circulation; however with the zone far enough from the equator, sufficient Coriolis force is generated to impart an adequate spinning moment to the air currents. These perturbations, or seedlings, may develop into violent typhoons where the conditions favor it.

One other possible cause of tropical cyclones resides in the so-called "easterly waves"—

an alternating succession of highs and lows sometimes observed in the easterly trade winds. The "easterly waves" can travel without change to distances as large as 3-5 thousand kilometers. On occasion, an "easterly wave" loses stability with the attended increase of wind speed and precipitation; these can also trigger the formation of tropical cyclones.

Invasion of the tropics by cool air flows from high and temperate latitudes is another reason for the emergence of tropical cyclones.

While the average tropical cyclone has a lifetime of about six days, some of the actual typhoons may be short- (up to a few hours) or long-lived (up to a few weeks). However in the general case, the tropical cyclone experiences a series of stages in its life cycle—those of young cyclone, mature cyclone, and abatement. The first formative stage involves the emergence of a closed vortex with a slightly modified pressure at the center and light wind. In a young cyclone the low-pressure center is deepening continuously, the hurricane-force winds are gaining momentum and enveloping the center, and spiral strips begin to take form. The young cyclone spans a modest area 60 to 100 km across.

A mature tropical cyclone engulfs great spaces up to 2000 kilometers across; the pressure decline at its center comes to a halt and the wind no longer grows in strength. The mature stage lasts about five days on average.

The final stage, abatement, occurs for a variety of reasons. A large proportion of typhoons dissipate upon crossing into the cooler temperate latitudes. Without the heat to fuel it, the typhoon shrinks to an appreciably smaller size and then completely disappears. Some typhoons die in the tropics after reaching the continent.

The intensity of wind is the feature of tropical cyclones frequently adopted for their classification by development stages. If a wind velocity is under 17 m/s the closed vortex is defined as *tropical depression*; if 17 to 33 m/s, it is called *tropical storm*. *Hurricane* or *typhoon* designate a tropical cyclone with the wind velocity above 34 m/s. Finally, the cyclones exceeding a wind velocity of 60 m/s form the group of *strong*, or *violent* hurricanes or typhoons.

**General description of the tropical cyclone.** Although the typical cyclone has a diameter of 200 to 500 km sometimes it may be as large as 1000 km. The pressure in tropical cyclones at sea level averages 930 to 950 mb, thus producing a steep pressure gradient, around 60 mbar per 100 km, and consequently strong winds. The wind velocity is especially high near the cyclone center where it may reach 60 to 100 m/s.

The tropical cyclone usually holds at its center an area of relatively benign weather called the *eye*. A well-developed cyclone exhibits clear-cut boundaries of the "eye", its average diameter is 20 to 25 km, but as large as 60 or 70 km in very strong typhoons. The atmospheric parameters within the "eye" differ markedly from those in the body of the cyclone: the wind speed is down to 4-5 m/s, with lower pressure and higher temperature.

The wind perturbations of tropical cyclones spread up far above the ocean surface and not only through the entire troposphere (to the altitude of 15-16 km), but also into the lower stratosphere. An anticyclone often develops above the cyclone at high altitudes, the pressure in its center higher than on the periphery. Because of that the air stream in the anticyclone looks as if it were spiralling down and out, to form a continuous inflow into the typhoon's lower portion and an outflow from its central part.

The precipitation in tropical cyclones is concentrated on the clearly distinct bands converging towards the center on a spiral path. As they approach the center, their width and the spacing between them decrease on the average from 5 to 13 km. The length of each of the bands extends to a few tens of kilometers and their number does not exceed seven. The amount of rain in most tropical cyclones is enormous, averaging 150 to 200 mm per cyclone. The rainfall is often paralleled by thunderstorms and local atmospheric vortexes of smaller diameter (up to a few hundred meters) called *tornados*. The vortexes most frequently appear in the slow-moving tropical cyclones. The tornado winds develop a very high speed of 300 m/s or so.

The passage of tropical cyclones produces high and rough surface waves in the ocean. In the Atlantic hurricanes, the average wave height varies within 10 to 12 meters and the

Pacific typhoons are reputed to have sometimes stirred up waves up to 30 m high. The waves travel generally at two to three times lower speed than the wind that generated them. But because the wind speed in the typhoon is high the waves formed often run ahead of the typhoon which progresses at a much lower speed than the wind, and travel outside its limits; the wave height becomes progressively lower with a greater distance from the tropical cyclone center.

This description of tropical cyclones clearly suggests their distinguishing characteristics that set them apart from other atmospheric phenomena. They are: origination at low latitudes, near-circular isobars, large pressure gradients, high wind speeds, spiral-shaped lines of the air current, availability of the "eye" at the center, storms and heavy precipitation, and the active season in the summer.

For comparison, the extra-tropical cyclones are characterized by medium-to-high origination latitudes, elongated isobars, moderate pressure gradients, wind velocities, and precipitation; they lack the "eye" and are active in the winter season.

**Problems in the study of tropical cyclones.** Now as before, many aspects of tropical cyclones remain a mystery which has puzzled more than one generation of scientists. There is, to date, no certainty about the necessary and sufficient conditions for the origin and development of typhoons. The workings of the initial impetus that sets the whole system in motion are unclear and the physics of typhoon development through its various stages is poorly understood. A few rather important if yet unsolved queries concern the trajectory of tropical cyclones, namely: which laws govern their movement? what makes typhoon trajectories different from one region to another? what is their seasonal pattern of change? and how accurately can they be predicted?

Most of the existing theories provide answers to these questions. But, for instance a theory on the origin and development of such an intriguing phenomenon as the typhoon "eye", is not adequately developed. In general there are numerous unsolved questions in this field of science. Theoretical advances are visibly impeded by scarce observational evidence, notably for the tropics and the atmosphere over the ocean. The most difficult to monitor are the conditions surrounding the genesis of tropical vortexes and whether there are perturbations at that time and of what particular type.

To be able to work out predictive methodologies for the origin and rise of tropical cyclones it is necessary first to study ways in which synoptic conditions affect the interaction of typhoons and hurricanes with their atmospheric environment and the ocean surface. In some cases their influence can be strong enough to cause a cyclone to change its trajectory. The methods for observing and studying tropical cyclones depend on the range and capabilities of the vehicles used to deliver scientific instrumentation to the effective area of a typhoon. Accordingly, distinction is made between observations from coastal and ship-based stations, aerial reconnaissance, and from satellites.

Perhaps typhoons can most conveniently be researched from land-based weather stations permanently located on minor ocean islands. These islands are too small to break the flow of a tropical cyclone; the stations can report back unique meteorological data when the cyclone passes above the island. A typical example of such facilities are the weather stations on the Marshall Islands.

In addition to the weather stations on small islands, typhoon investigation and monitoring are maintained by the now widespread stations strategically located along the ocean shore on large islands and continents. They are the most advanced and numerous in the countries prone to repeated devastating impacts of tropical cyclones. Such services operate in the USA, Japan, India, Pakistan, Vietnam, China, 'Australia, Hong Kong, Philippines, Madagascar, and in some Central American countries.

Fewer typhoons appear in this country and only occasionally do tropical cyclones appear in the Primorie Territory, Island of Sakhalin, Kuril Islands, and Kamchatka of the Far East. All through the typhoon season operational information about their motion is analyzed at the Regional Meteorological Center in Khabarovsk and relayed if necessary to the areas at risk.

The coastal services for monitoring tropical cyclones are responsible for the acquisition and processing of pertinent meteorological information, preparation of storm forecasts and warnings, and rapid broadcast of the storm alert to the general population.

The most widely ramified information service of typhoon tracking stations is in the United States, comprising 77 stations, each 40 kilometers apart, all along the Gulf of Mexico and Atlantic coast and including another hurricane tracking station in Puerto-Rico.

In their routine work, the coastal stations utilize near-earth surface and aerologic observation data from an extensive network of stations in many countries. Quite a few of them derive valuable information from on-shore radars, however 300 to 500 km is, currently, the maximum range in which radar tracking of tropical cyclones is still possible. The radars can predict an approaching typhoon or hurricane within 10 to 15 hours of its arrival. The radar detects the typhoon "eye" by the shape of the spiral bands from a distance of 280 to 320 km with an accuracy of better than 15 km.

Radars are strategically placed on the coastline to overlap the effective ranges of the neighboring facilities. An experienced weather analyst can by radar readings extract a lot of useful information about the tropical cyclone—its speed, direction, and area coverage.

Radar applications nonetheless have their own limitations. All too often the image on the radar screen is hard to interpret for the assessment of both the overall situation in a tropical cyclone and its particulars. Proper interpretation of radar images may be impossible for a variety of reasons, such as spurious noise circulation, radar beam attenuation in the zones of heavy precipitation, distortion of the picture with the radar's changing position relative to the tropical cyclone, variation of transmitter wavelength and other technicalities, as well as the ill-defined shape of the "eye" and spiral bands. Worse still, the radars are unable to pick up the clouds containing small cloud species not exceeding 0.5 mm in size. In other words, all that the radar can clearly note in the typhoon are the zones of intensive precipitation, squalls, thunderstorms and eye-wall clouds.

Ships are effectively used in the investigation of atmospheric and ocean parameters in the space surrounding the tropical cyclone. For this application, it is important to measure water temperature variations in the typhoon trail on the ocean surface. Ship observations can be supplemented with the information about atmospheric and ocean parameters obtained from automatic buoy stations. These stations, as a rule, are provided with a complete set of meteorological instruments. A device for measuring water temperature in the subsurface ocean layers (to a depth of 200 m) is sometimes installed as an adjunct to these instruments. If such a station is in the path of a tropical cyclone, it becomes possible to obtain unique data on atmosphere-ocean interaction in the effective range of the typhoon or hurricane.

In order to study the effect of tropical cyclones on the structure of the active ocean layer, it is well to concurrently utilize inputs from several vessels making a triangle or rhombus around the tropical cyclone. Without changing their inter-distance, the ships keep moving with the typhoon along its trajectory. Most typically, the shipborne set of instruments includes capabilities to measure weather parameters—pressure, temperature, and humidity—and roll-induced instrument displacements. They carry also recording apparatus, usually a multichannel digital tape recording system and a fast-response (low-inertia) recorder for the visual monitoring of measuring equipment performance.

The best results in tropical cyclone studies and prediction of their behavior can be achieved by continuously observing their evolution in the open ocean. For this application, the radars are ineffective because of their limited range and the ships because of the serious risk to their crews. Planes however can materially assist meteorologists on this task, being able to detect a hurricane or typhoon, penetrate it, define the location of its "eye", perform a physical analysis on its atmospheric parameters, and track its progress. The heavy planes and reconnaissance aircraft are commonly used on such missions. They have flying instruments on board which provide measurements of wind speed with an accuracy of 1.5 m/s, wind direction to an accuracy of 3°, the height of isobaric surfaces accurate to 15 m, temperature with an accuracy of 1°, and humidity to an accuracy of 5 percent. In addition, they can photograph clouds with an imaging radar and cine camera.

Sometimes, the planes headed into a cyclone jettison a dropsonde, which as it descends through the atmosphere, relays to the aircraft information about temperature, pressure and relative humidity at specific altitudes. Through direct airborne penetration into the typhoon "eye" its position can be located to an accuracy better than 15-20 km.

Ocean observing satellites contribute widely to tropical cyclone studies. Remote sounding from a satellite in orbit offers a means of imaging typhoons, tracking their motion, following the evolution of their shape and size, and examining the weather processes that develop in conventional systems and on underlying surface. Although the satellite methods for determining the position of tropical cyclones are not as accurate as the aircraft techniques, they are better at gauging wind speed from observed cloud types.

The maps which analyse cloudiness and are therefore known as *maps of nephanalysis* (Gk. *nephos* cloud) are extremely useful in monitoring typhoons from a satellite orbit. The use of satellite imagery allows the maps to plot out the shape, structure and size of cloud formations and the gaps between them; convergence centers of cloud spirals; the extent of cloudiness and density of the clouds in it. Even though some features of cloudiness have to be sacrificed by replacing the maps of nephanalysis for photo images, these maps are still a very convenient data format to transmit via communication lines for operational use.

Weather satellites can rapidly detect tropical cyclones where they remain unnoticed by other osbervation technologies. The rate of success in identifying the origin of tropical cyclones has greatly improved after satellites were adopted for regular weather monitoring service. They made it possible to more accurately locate the breeding grounds of typhoons and to discover new places of their origin.

Continuous monitoring of tropical cyclones from orbiting satellites provides an opportunity for mapping trajectories of their centers. These maps will be very helpful to warning services in their operational duties and also will be very useful for research on tropical cyclones.

The image characteristics noted above give clues to the development stage of a tropical cyclone. A mature cyclone appears in the image as a bright white disc with sharply outlined margins. The disc exhibits the "eye" in its center with bands spiralled out from it. Sometimes one or several bands of cumulonimbus clouds may be recognizable in the frontal portion of a tropical cyclone.

In this and other ways satellite imagery offers a means of assessing important typhoon parameters and even a peculiar diagnostic tool of their state (strength, duration and further advance).

Other than general qualitative typhoon parameters, satellite imagery can aid in quantitative estimation of at least some of their characteristics. Continuous observation of tropical cyclones over large spaces turns out to be far more convenient with the use of *geostationary* *satellites*; they are injected into a circular orbit 36 000 km in height in the equatorial plane to match their revolution around the Earth with the planet's rotation, thus rendering them fixed relative to its surface. Such a satellite can keep in its field-of-view almost an entire hemisphere making it possible to film sequences unfolding the staged development of the tropical cyclone.

### 2.2. Dust Storms

Dust storms, a widely occurring atmospheric phenomenon, vary in time and space. For centuries, the damage from them has been considerable. Transport of large masses of dust promotes droughts and fosters the expansion of desert; dust buries agricultural lands, orchards and population centers.

Strong dust storms foul the atmosphere to change the optical properties of air, and this affects climate [6]. A change occurs also in the heating of the terrestrial surface and the near-surface air layers. Another impact on climate comes with the altered reflectivity of the Earth's surface or *albedo*. Thus enhanced air dustiness above snow and ice leads to a climatic warming while the opposite is true of a dust-laden atmosphere over the ocean in the regions with large solar angle above the horizon. Dust storms have a substantial influence on a soil cover where it is not stabilized by vegetation: they blow out the topsoil, the most fertile soil layer, as they sweep along. Dust storms cripple vegetation by damaging plants, uprooting them and exposing to chemical salts via soil or directly at the flowering season.

There is good evidence that dust storms immediately affect animals and humans, not least through the propagation of dust-borne pathogenic microorganisms stimulating outbreaks of diseases. Finally, such storms cover roads with a dust blanket making traffic more difficult.

Their initial outbreak is stirred up by several causes which, singly or in combination, act to produce dust storms of particular intensity in terms of strength and duration. Now we shall review these factors in more detail.

A wind blowing at over 6-10 m/s starts up and sustains the development of sand storms. Although their occurrence probability is the highest in areas with continental or arid climate—the desert, the semidesert, and the steppe—dust storms are not unknown for other types of terrain, for example the drained peat bogs or the Arctic Ocean coast, where a dust cloud can travel through the atmosphere at different altitudes ranging up to 1.5-5 km.

Readily windswept surface sediments, like sand and texturally finer loess-like rocks, contribute to the genesis of dust storms. Soil structure and texture also influence the way in which a dust storm appears and develops: the heavier and coarser the soil, the higher, naturally, is the wind speed. An initial wind speed of 3 m/s is sufficient to get a dust storm started in sandy loam, but in clay soil initial speed of approximately 9 m/s is required.

The larger the soil's particle size, the less it is prone to wind erosion. Soil blowout is more difficult where plant residues occur in the topsoil. There is evidence that soil particles, in order to be airborne and carried off as suspended solids, must have a diameter from 0.01 to 0.05 mm although in stronger storms the wind can transport larger particles.

The color of the dust cloud is determined by the type of weathering rocks. Thus it turns out black if composed of chernozem; yellow, brown or red if carrying suspended loams and sandy loams, and white if swept up from a solonchak. Many dust storms have their origin in human activities (forest cutting, over-exploitation of soils, or reduction of river flows) although the workings of the process are not as yet fully understood. In the late 1960s-early 70s a harsh drought descended upon Sahel—a vast region in the south of the Sahara desert. The desiccated soil was falling prey to a blowout forming dust storms which devastated crop fields, leading to famine and even forced migration of the population from the areas ravaged by crop failures.

Although there is no general agreement on the proximate causes of the disaster some believe it to have arisen out of soil erosion by wind, following harsh range abuse and trampling-out by livestock. The desiccation of soil and the rise of dust into the atmosphere could be the factor behind the change of climate, more frequent droughts, and the advance of desert on the savannah.

The initial locations of dust storms vary in size, morphology, character of deposits, and position on the globe—they may be beach areas, steppes and prairies, or semi-closed intermontane depressions. The features of climate in the initial development areas of dust storms can do much to explain their seasonal patterns. As an example, dust storm development in the West Sahara peaks in January and July while for the Aral Sea region in the southernmost Soviet Union the dust storm seasons are April to June and August to September.

Dust storms can last anything from a few minutes to several days. The strongest of them appear in Africa over the West Sahara and transport dust to many hundreds and even thousands of kilometers.

In areal extent dust clouds can range up to millions of square kilometers. While major dust formations typically develop in dry and hot climate, the dust storm as such has a global extent as the swept-up dust is able to travel to almost any area around the world. A dust stream of several kilometers may not be a single whole. Often it consists of several bands, their number is determined by surface topography and soil structure.

The dynamic characteristics of dust streams have a lot to do with the weather setting. For example, the transport of dust clouds from the Sahara to America rides on large-scale vortexes in the trade-wind strip, taking six to eight days.

It is obvious that the study of dust storms is of great importance to economic activities.

What is of immediate and specific interest to specialists? It is important to know how far the storms can carry the cloud of airborne dust and how much dust can be actually removed therein. The data are required by geologists to guess possible locations for the deposition and accumulation of sediment material, by botanists and agronomists to define areas exposed to the impact of atmospheric salts, and by weather analysts to meet their vested interest in being able to judge the extent of air pollution. Thus many economic sectors can benefit by the timely, short- and long-term forecast of dust storms. However, much remains unclear because of insufficient investigation of dust storm dynamics—speed, frequency, and patterns of dust transport—and vertical profiles of dust concentration, humidity, temperature, and wind velocity through the dust cloud layers.

Dust clouds are difficult to investigate from the Earth's surface. Their real extent is even impossible to appreciate in most cases, chiefly because weather stations are few and far between in some type regions on the Earth—the deserts, the mountains, and the oceans.

Dust transport routes also defy analysis. Indeed, with nothing to help but conventional meteorological ground observation data, one has problems reconstructing the true picture of a large air stream traveling to long distances. Far from easy, too, is a comparative composition analysis—textural, mineralogical and chemical—of dust samples from the dust cloud and soil samples from the area of anticipated lift-off of dust, unless there is at least an approximate notion about possible location of the dust storm's area of origin.

Ground measurements of the mass of dust clouds can only be very approximate, relying as they do on measurements made at separate points. A rough estimate of dust content by ground-based observations is possible by analysing samples of dust-cloud aerosol, measuring atmospheric transparency and gauging dust depositions after the storm has passed. Any credible extrapolation of point ground measurements over large distances to estimate the mass of dust injected into the atmosphere by a dust storm presents a difficult problem.

A global-scale study of dust storms became feasible with the development of space remote sensing observation methods. They provide extensive information about the distribution, dynamics and places of origin of dust formations. Dust storm dynamics is best followed from geostationary satellites "hanging" motionless above certain equatorial Earth regions.

Space surveys provide the most reliable and accurate source of data about trajectories of dust storm particles. The surveys made clear [6], among other things, that cyclones carry dust from North Africa's deserts across the Mediterranean into Europe, and from East Africa across the Red Sea into Asia. The longest atmospheric transport of dust is an over 5000-km route from the Sahara to the American coast.

Only with the advent of spaceborne observation capabilities has it become possible to judge real dimensions of the dust clouds. Thus it has been found [6] that the dust clouds born in the Aral Sea region attain 200 to 400 km in length and those originating in and around the Mesopotamian Lowland range from 500 to 800 km. The greatest extent of dust cloudiness—over Africa and the Atlantic Ocean—runs up to a few thousand kilometers. Correspondingly, the extent of dust clouds also varies widely, from thousands to millions of square kilometers. In 1974 orbital sensing detected over the Atlantic and West Africa a dust cloud nearly seven million square kilometers in area.

Space facilities have been able to discover a fascinating pattern to the origin of Saharan dust storms [6]. In effect, dust is carried out from the Sahara into the Atlantic Ocean in a series of pulses so that for each cloud on its way over the Atlantic Ocean there is a new dust cloud nascent over Sahara. Images received from orbit often captured at one time two or even three dust clouds traveling one after another. The traveling speed of dust clouds can be determined by observing them from space. Because the spatial distribution of dust clouds is clearly visible in space images their mass can be measured with good accuracy when point ground measurements of atmospheric visibility and transparency are available.

Relying on daily all-year-round remote observations of the Earth's surface from space, researchers have been able to estimate the mass of dust transport in the atmosphere. It thus transpired that from 60 to 220 million tons of dust was raised each summer into the atmosphere from the Sahara desert, the worlds' largest breeding ground for dust storms. The total atmospheric input of dust from the areas adjacent to the Aral Sea amounts to 75 million tons per year. Large dust storms are capable of taking aloft from 7 to 10 million tons of dust within 10 to 15 hours.

In remote sensing studies of dust storms from satellite orbit, one can look to the radiance of the ocean surface and atmosphere for an indication of optical depth of the dust-laden atmospheric layer; a 1.5 percent variation of aerosol content causes the radiance to alter by one percent. On closer inspection, the density of negative images of underlying surface was found proportional to aerosol dispersion. This makes it possible to monitor from on-board the satellite the dynamics of particular jet streams in a dust cloud, study airborne dust settlement rates, and even to measure diameters of suspended dust particles.

## Sec. 3. Contact Sounding of Atmospheric and Ocean Parameters Using Unmanned Probes

Remote sounding of the atmosphere and ocean from a satellite orbit was shown in the previous chapters to be able to secure in a short time large quantities of meteorological and oceanographic data. The quality of the satellite information is never too high, however, chiefly because we are unable to appreciate with a sufficient accuracy the impact of the terrestrial atmosphere on the measurement results. This makes contact measurements as important as remote sounding for understanding key characteristics of the atmosphere and ocean such as precipitation, clouds, and sea currents.

Direct *in situ* measurements have an enhanced usefulness for research on nonstationary phenomena in the atmosphere and ocean because a detailed structure of the elemental phenomena like the tropical cyclone or dust storm is practically impervious to observation with conventional technologies. Viewing it requires an imaging capability on-board the satellite, but also a capability for continuous direct measurement of atmospheric and ocean parameters in the study regions over a lengthy period, preferably from the birth of an elemental phenomenon to its abatement.

The management of programs which study *in situ* nonstationary atmospheric and ocean phenomena from the Earth's surface appears to be difficult, chiefly because the time and location of the origin of these phenomena is unpredictable and because the breeding grounds of typhoons, hurricanes and dust storms are typically found in inaccessible areas. Furthermore, none of the conventional vehicles used to take an instrument payload into the area afflicted by the phenomenon being studied, has both the sufficient effective range and the appropriate operational speed. Hence the present bias to pass up in research the more intriguing and essential natural phenomena for the sake of those which seldom appear in the operational range of existing instrument carriers.

Space technologies can be very helpful in these applications. Orbital automatic probes can promptly detect an elemental phenomenon, whisk research instrumentation into the desired area, acquire and process scientific information, and locate balloons and oceanic buoys.

Below, we suggest a feasible program flow for contact sounding of atmospheric and ocean parameters based on unmanned space technologies.

**Operational detection of a nonstationary phenomenon.** A multiprobe orbital vehicle is injected into a satellite orbit. Its instrument module holds observational and recording equipment to be used in conjunction with ground information processing facilities for prompt operational detection of nonstationary phenomena in the regions of our current interest.

Notably, the coupling in one vehicle (probe) of an instrument module with observational and recording instruments and several descenders imposes disparate requirements on orbital parameters, thereby more or less limiting the areas on the Earth's surface open to observation from the satellite orbit. With a mind on observing the atmosphere and ocean over a wider range of zones, one should go for a higher, best of all geostationary orbit;

for the lander to make a fairly accurate descent into the specified area on the land or in the ocean, low-circular orbits are desirable. The only way, then, is to seek a compromise.

Many of the ongoing Soviet space programs geared for global remote sensing studies of the atmosphere and ocean go beyond the use of dedicated meteorological and oceanographic satellites to involve any others that might be orbiting at a given moment.

Broad new opportunities come with international cooperation in this area. As known, national space programs in many countries give increasing recognition and status to space-based environmental monitoring efforts. Collaborative international systems, now being put together, use satellite applications based on the Soviet *Meteor*, US *Landsat*, French *Spot*, and Japanese *MOS-1*.

**Operational delivery of research equipment into target regions.** Several in-orbit descenders containing each one or several balloons and buoys are coupled with an instrument module. The idea is to have the descenders deliver safely the balloons and buoys to a pre-assigned area of atmospheric and ocean studies, varying the array of the measuring and recording instruments to suit the research objectives. The balloons and buoys, along with the measurement and imaging apparatus, are designed to match their operational life with the average time available to study a process of interest. As an example, the operational lives of ten and thirty days are adopted, respectively, for the balloon and buoy to explore *in situ* tropical cyclones and dust storms.

**Collection and processing of scientific information.** The measured values of atmospheric and ocean parameters are stored in digital form on the balloon or buoy in special memory devices. In the periods while the satellite remains in the mutual radiovisibility range with the balloon or buoy the stored information is transmitted to on-board the satellite and relayed to the Earth—to data acquisition and processing stations. Good performance for this application is now expected of the *COSPAS-SARSAT* and *Argos* international satellite systems.

**Location of balloons and oceanic buoys.** Radio equipment installed on-board the satellite's orbital instrument module and on the balloons and buoys is capable of measuring distances between them and the rate at which these distances change. The results are transmitted to a ground computing center and it is there that the required location is determined.

The method just described for the contact sounding of atmospheric and ocean parameters through the use of spaceborne capabilities has important advantages over the conventional investigation methods based on ground weather stations, ships, aircraft or weather rockets. The method ensures prompt operational delivery of measuring instruments into a specific study area. The study may well be global in scope. Lastly, the method is universal and therefore capable of being used for multiple scientific applications.

In fact, it seems possible to investigate the phenomena needing synchronous measurements in several regions of the globe, each 5 to 10 thousand kilometers apart. A further possibility is to create a regular network of atmospheric balloons and buoy stations with global coverage.

The method can effectively support research on stationary phenomena that require sufficiently long schedules of simultaneously sensing different atmospheric and ocean layers at any desired location around the world, as for example in sounding of atmospheric and ocean parameters for regions of intensive heat-and-mass exchange (currents, coastal strips, areas of deep-water uplift, and other similar sites).

This is an all-weather method since the delivery of scientific equipment from orbit into a desired area of research is independent of weather conditions.

The experience to date with remote sensing studies from space indicates that the method of contact atmospheric and ocean sounding is implementable with the current level of technological development. One of the sections that follow will instance the research on tropical cyclones to present key problems in design of satellite-borne systems for contact sounding of the atmosphere and ocean and outline possible ways of their technological solution.

## Sec. 4. Global Environmental Monitoring System

The United Nations Conference on the Human Environment, held in Stockholm, June 1972 was the first forum to assemble a single body of evidence concerning the state, direction of changes, and ways of protecting the environment.

The Conference called for international cooperation on environmental problems and reminded that humankind was not only a triumph of nature, but also—and primarily—a part thereof, and that its very existence, let alone prosperity, crucially depends on how the nearest neighbors feel, that is, man and his environmental surroundings.

The Conference adopted 29 principles, among them the following all-important for our subject: science and technology, as part of their contribution to economic and social development, must be applied to the identification, establishment and control of environmental risks and in the solution of economic problems for the common good of mankind.

Here we wish to make the United Nations Environment Programme (UNEP) an example to illustrate the role and posture of ecological environmental monitoring in the overall complex of ecological concerns. One of these—a shared activity of several UN specialized agencies—applies to solving the mystery of tropical cyclones and typhoons by observing them via a monitoring system. The system, called GEMS, or the Global Environmental

Monitoring System, constitutes an important UNEP segment with functions analogous to those of a technical library. And as in a library, GEMS data are rigorously organized, annotated and cross-referenced.

Because the volume of information is extremely great the traditional ordinary methods of data recording and storage give place increasingly to computers with their staggering data handling capabilities. All data files are stored in computer memory, on magnetic discs or tapes. In the not-so-distant future a satellite-borne sensing system will quite probably have the capacity to provide information on several parameters with respect to every hundred square meters on the Earth's surface, this output alone demanding of the system to be able to store something like ten to the power twelve bits of information.

Instant availability of most information upon request precisely when and as needed is a critical requirement for such a system. To be able to respond to the need, "data banks" are created within the system. Based on state-of-the-art computer technology, they will permit the recording and, most importantly, very fast retrieval and readout of necessary information blocks. The readout, of course, will use the most convenient user format, for example, visual display or communication as calculation inputs (according to the program already stored in the computer memory) using an alfanumeric device on paper, or in any number of ways. Instead of rummaging in books on library shelves specialists will turn to visual displays or computer terminals linked with the central processing unit and in future perhaps via these with any satellite as it passes over the surface area of interest.

The principal purpose assigned to the GEMS system keeps it permanently observing the environmental state in order to develop information about the critical points at which nature calls for man's salutary intervention. The underlying GEMS concept is rather simple: no effective control is possible without knowing the design and workings of the controlled plant or system. This equally applies to a combustion engine and aircraft or to the environment. But whereas the engine or aircraft are fully understood, if only because both are man's creations, the environment and nature in general provide us with no such knowledge in any direct way and therefore no opportunities to control them.

The GEMS is called upon to monitor continuously the environmental state and keep track of ecological trends to forestall undesired consequences of intervention into the natural course of environmental phenomena and arm decision-makers with sufficient environmental inputs to draw up realistic plans of action.

Another important aspect of GEMS activity, known as "assessment", implies the following. Millions of bits of information digested and feedbacked by the environmental monitoring system are only meaningful if systematically arranged. This is done on many different levels. The top level is about making decisions with respect to a particular natural phenomenon. Thus the "assessment" is the aspect of the environmental monitoring system that determines its utility.

"Assessment" starts with a preliminary examination of the problem in hand, notably the attempt to formalize its very understanding. This modeling effort may yield results by which the required action can be effected and followed up by redirection of the monitoring system to keep track already of the latter's results and prompt to experts and operative organisations ways of formulating a further action plan.

Both "assessment" and monitoring became such important aspects of the science of environmental management that specialized agencies were instituted to satisfy the need for independent expertise. One of these is MARC—the Monitoring and Assessment Research Center attached to London University.

The GEMS-related activities would be impossible, of course, without broad international links. Nor could the program be effective without the support of many countries' governments and cooperation of several specialized UN agencies—the Food and Agriculture Organisation (FAO), the World Health Organisation (WHO), the World Meteorological Organisation (WMO), and the UN Educational, Scientific and Cultural Organisation (UNESCO).

With GEMS as the test case, let us see which environmental aspects can be addressed within the scope of the global environmental monitoring system.

**Environmental pollution and human health.** The literature refers now and then to the medieval habit of ingesting small amounts of arsenic in the belief that it improves complexion and makes the person more attractive. There might have been another reason: wary of arsenic poisoning, people rendered their organism immune to the poison. Alas, both these rationales are questionable: it has been ascertained that 6.7 ppm in the human brain can cause congenital mental debility and even death. On the other hand, a few ppm in water, fish and even in human body make up such a low concentration as to remain undetectable with current methods to any degree of assurance.

One GEMS activity studies the environmental impacts of "selected", or "priority" pollutants, among them DDT, cadmium and lead, whose effects on man, generally speaking, are not fully understood to date. This uncertainty prevents appropriate legislative action from being taken now although lead is generally accepted as dangerous to the central nervous system and especially threatening to the brain of the newborns and small children. However we are only just beginning to find out those maximum concentrations which shall not be exceeded in any event. Fifty nursing mothers from several countries have been subjects in an experimental research, as part of a programme of monitoring the quality of breast milk, its other concerns being lead and cadmium concentrations in human blood.

The global environmental monitoring system as it relates to human health has the aim to gather data on environmental concentrations of pollutants and their pathways from source to man. The World Health Organisation (WHO) is running in fifty countries 200 air quality monitoring stations with 180 of them strategically located in 60 cities widely differing in climate, predominant lifestyle and air pollution profile. The feedbacks from these stations provide the information support for a future project which aims to define methods for assessing the effect of atmospheric pollutants on the environment.

Food contamination is a major health risk. The DDT problem is now familiar to everyone. Probably less familiar to the reader are risks from the mycotoxins—the products of fungal organisms growing on wheat, rye, nuts, etc. if improperly stored. They claimed hundreds of thousands of human lives, and presently the FAO and UNEP are co-sponsoring a special project on mycotoxins, with some of the project work undertaken in the USSR as well.

Acid rain is another kind of environmental exposure leaving in its trail leafless trees, dead fish in rivers and lakes, and rusting skeletons of formerly operational structures. This is a result of man's activities, for as a result of burning vast quantities of fuel, sulfur, which is a valuable and useful chemical, is released into the atmosphere where it becomes extremely noxious and hazardous. A simple chemical reaction converts it into sulfuric acid, which dissolves in the rain and falls.

Control of this adversity begins necessarily with an understanding of the process in dynamics, above all the long-range transport of pollutants in air masses, heedless of national boundaries. Sources of pollution may be thousands of kilometers away from the area where its ill-effects are experienced. Canada and Scandinavia seem to be strongly afflicted by acid rain; one-fifth of Sweden's 100 thousand lakes have already lost all their fish.

Besides monitoring as such, the UNEP has a special project of this topic, the Global Biogeochemical Cycle of Sulfur, which the USSR is participating in. Combined with the information from the centers monitoring air-mass transport, this provides additional possibilities to observe processes that bear on the circulation of sulfur in nature.

Much of the stratosphere is taken up by the so-called ozone layer. Ozone is an oxygen form with three atoms in its molecule instead of the usual two. Neither plants nor animals can live in an ozone-rich atmosphere, but without an ozone layer at between ten and fifty kilometers above sea level no life on earth is possible at all. This is because of all atmospheric components ozone is the one to absorb the hard ultraviolet radiation of the Sun. In large doses, the hard UV radiation is deadly for most of the terrestrial and marine fauna. In 1974 the ability of carbon chlorofluorides, more habitually known to us as freons from their use in refrigerator equipment, to be accumulated in the atmosphere at high altitudes was proved. There, solar radiation contributes to their degradation releasing chlorine atoms that destroy the ozone layer by a complex chemical reaction.

The UNEP's Coordinating Committee on the Ozone Layer declared that unless the use of freons subsided there was bound to be soon a 5 to 10 percent reduction of the ozone layer triggering a chain of dire consequences. There was good evidence that no significant results of the ozone layer depletion would be felt or detectable by monitoring in the next 30 to 50 years, by which time the process might become absolutely irreversible. Here, too, the global environmental monitoring system makes its contribution by supplying the relevant information to the organisations and agencies concerned.

Atmospheric carbon dioxide ($CO_2$) presents a contentious problem in that different experts predict different consequences from increasing carbon dioxide concentration in the atmosphere. But all agree that the first outcome of burning large quantities of fuel will be the so-called greenhouse effect that will increase the average temperature of near-surface air and then of topsoil; this in turn will cause a climatic warming with not altogether predictable consequences. One of these, as currently projected, will be glacier- and ice-melting in the Arctic and Antarctic, attended by partial inundation of the continents. Estimates indicate that an average annual temperature rise of 5 °C would in 20 years raise sea level by five meters—enough to plunge under water Leningrad, New York, Washington, London, Stockholm, Calcutta, Singapore, Jakarta and of course all lower-lying areas on land.

High precision measurement of the $CO_2$ atmospheric concentrations began in 1958 as part of the International Geophysical Year. The measurement methods are now so well developed that need only two measurement stations on the Earth's surface for the $CO_2$ content of the atmosphere to be monitored.

A note on renewable resources seems relevant here. While we know a great deal about forests, rangelands, grasslands and fields in which wheat, rye, corn and other staple crops grow, our knowledge of the oceans covering 70 percent of the Earth's surface remains scanty. Three hundred years ago 10 percent of the global land surface was converted to agriculture. Now this figure is 35 percent.

It is now well understood how potential productivity of agriculture varies with geographic location. We realize, for example, that 22 percent of that productivity is controlled by soil composition in North America, 44 percent by the amount of rainfall in Africa, and thus for each major region or continent. But we also realize that agricultural production is assured only on 11 percent of the land area, most of which is in Europe, and Central and North America.

Some futurologists predict that the Earth's population will have nearly doubled by the turn of the next century. This will demand at least a twofold growth in food production. We put the qualifier "at least" because the current situation worldwide clearly fails to provide an adequate quantity and quality of food for the entire global population. This deficit is more painfully obvious in developing countries which possess the most unused land resources. We need to maximize the output from already existing cultivated areas and extend their scope where possible. Whether we do it extensively or intensively, both exert at least some adverse effects but principally soil degradation, wind erosion, salinization, etc., all of which reduce affluent cropping areas, ultimately, to deserts and semideserts.

The Stockholm Conference pointed to the need for utmost urgency in the implementation of measures to stem the expansion of deserts and control soil degradation and in accomplishing programs to sustain renewable resources in the regions at risk. In 1972 the monitoring capabilities under this set of goals were still in their infancy but more than ten years of work in this field, first, have made it a science of substance and, second, established a certain GEMS priority there so that relevant FAO and UNESCO programs are coordinated precisely by UNEP via the GEMS system.

The year of 1979 saw the start of a four-year project, costing more than one million dollars, to investigate the physical, chemical and biological properties of soils in the middle East and North Africa (north of the equator) by means of laboratory research, field surveys, and satellite imagery. Data on wind and water erosion of soils were extrapolated and published in 1 : 5 000 000 scale showing regions at various risk of erosion. These maps in conjunction with supportive data provide an excellent source of reference in the formulation of land-use policies. As one important realization, current cost-effectiveness figures are not the only basis in planning for the routing of railways and motor-roads and there must be proper consideration of the ecological factors and trends appropriate to the regions served by them, as part of the overall concern to preserve nature for future generations.

The monitoring of soil degradation and expansion of deserts is a priority task and must be coupled with other concerns in the management of renewable and other resources to put them into a perspective for solution.

We shall now attempt to introduce a definition: ecological monitoring is measuring the parameters of state and current variations of climate, soils, plant and animal resources, and the impact of contemporary anthropogenic activities on them.

The GEMS program draws from three distinct sources of information in monitoring renewable resources: earth resources satellites, aviation systems providing finer detail but at staggered intervals, and ground-based observation programs that offer the finest detail. All the three sources are mutually complementary.

This book describes the very methods reliedupon for the attempted coordination of the first and third sources so as to span the information gap between the satellite orbit and the earth's surface.

The whole body of information occurring from the various sources is apportioned on a geographic and timely basis according to physical, climatic and other characteristics; after being calculated on computer it is presented as a model of numerous blocks from which any necessary fragments can be recalled if and when needed. Having the ability to quickly perceive particular short-term or seasonal changes, the available global environmental monitoring system provides a means to organize similar but long-term systems to avoid adverse results from predicted events.

The GEMS is also concerned with the future of tropical forests. The reasons are, first, that the broad tropical forest belt which girdles the globe contains a substantial proportion of the world's biomass; it provides a habitat for many unique forms of life; it influences world climate and makes an integral, essential part of the global environment. Second, there is a nagging concern for the condition of tropical forests, spurred by constant media reports about apparent "catastrophic situations" which all too often are not founded on real quantitative information. Third, there has been for some time a compelling need for a realistic and comprehensive review of the situation to make an order of "campaigns" and plans of action.

We shall highlight some of the statistics that was developed, not least with GEMS support, in the course of a four-year study of global tropical forest resources initiated in 1977. The results to date, although giving no cause for complacency, indicate nonetheless that the situation is not as tragic as usually depicted.

The tropical forests are being cut at a rate of 15 hectares per minute, or, to put it differently, an area the size of New York is lost to cutting every four days. On the other hand, if the present rate of destruction should persist, still 88 percent of the global total of 30 million $km^2$ will be standing by the end of this century. Furthermore, the forests of the Amazon basin, Zaire and Indonesia, which together comprise 48 percent of the world's total tropical forest, will have decreased on the average by six percent.

This trend notwithstanding, tropical forests will be wiped out altogether by the year of 2000 in nine countries and halved in another eleven if the existing pace of forest cutting is allowed to continue. Together, these twenty countries add up to a low 1.5 percent of the world's total but even these relatively minor percentages represent an integral part of the local environment.

Experience gained from satellite observations of arid regions—deserts and semideserts—is effectively applied to the monitoring of tropical forests. The project conducted by the FAO (UN Food and Agriculture Organisation) was accomplished by the use of satellite imagery. During fourteen months in 1977-78 a total area of 500 000 sq km was mapped across three countries—Togo, Benin, and Cameroon. Its key finding has been that satellite information can furnish a large portion of needed forest vegetation data and do it at moderate cost, as the entire project comes to less than one million US dollars. If the satellite information was integrated for the project it was not because it is superior to, but because it costs less than conventional data. Moreover, ground measurements also, although on a limited scale, had to be applied if only to calibrate the information received from orbit and for subsatellite "referencing" of the images. However for most problems of a qualitative nature, for example, observing forest vegetation processes, a satellite-based data acquisition system is unquestionably the most cost-effective option.

In the project geared to the three African countries 25 *Landsat* images were used. They provided full coverage of their surface and enough discrimination to separate out 15 specific zones varied in elevation above sea level, extent of precipitation and type of vegetation.

Even though this research involved manual processing and interpretation of the satellite images, more recent experiments have shown these processes to be amenable for automation and computerization. The ways to do it will be discussed later.

The output from monitoring tropical forests can be presented at different levels of which we shall review only three: (1) global, suited for the assessment of trends in the changes of the global tropical forest resources; (2) regional, which helps the countries concerned to evaluate the impact of these trends on their own and neighboring economies; and (3) national, which allows a baseline status evaluation of tropical forests to be included directly into economic development planning.

*Atmospheric pollution* constitutes another important area of concern for GEMS. The related studies extend in two directions. The first deals with *background monitoring*, i.e. with determining concentrations of atmospheric pollutants in the world's "cleanest" regions. It appears that in evaluation of atmospheric pollution, as in geodetic surveying, there is the need for datum points of sorts—those measured concentrations of pollutants which characterize the overall extent of pollution in regions farthest removed from the sources of pollution. Their averaged values over a network of special-purpose "datum" measuring stations should give near-ideal values for the concentrations of specific pollutants in the entire terrestrial atmosphere.

Each datum station comprising the atmospheric pollution monitoring network is in a region with air clean enough to meet the standards of the World Meteorological Organisation. There is a GEMS datum station at the South Pole, a few others on islands in the open ocean or on high mountain tops. As of now, there are twelve baseline stations fully in operation and four at the design stage. True, their cost is high, as exemplified by the one-million-dollar station to be installed on Mount Kenya. In addition to routine monitoring of weather parameters, they measure chemical composition of precipitation, solar radiation, concentration of $CO_2$, $N_2O$ and CO; total and surface ozone, condensation nuclei and the amount of airborne solids. Procedures for this kind of analysis are rather complex— they require, other things apart, a high degree of standardization to permit the comparisons of findings between stations. Also, special measurement laboratories are needed for instrument calibration throughout the network.

The second activity creates a *network of "regional" stations* for atmospheric pollution monitoring. As with the stations just discussed, their location must be far enough from principal sources of pollution and yet remain within regions for which they provide service. This enables them to avoid the influence of local short-term fluctuations of air pollution on the results of their measurements while still keeping them sensitive to integral concentration levels of pollutants in the region concerned. Determining the global trends of atmospheric pollution calls ideally for one station in a region about 500 000 sq km in area, or 1000 stations for global surface coverage. So far, 110 such stations have been established. The basic similarity of the measurement programs and the identity of the methods and instruments used with the baseline counterparts enables a direct comparison of the results between them.

A quantitative analysis into the present state of atmospheric pollution gives cause for concern. While the content of aerosol particles in the air at the Mauna Loa baseline station in Hawaii remained constant at the level of 0.03 throughout 1972-76, the regional station in Baltimore, USA, reported seven times higher concentrations in 1972 but eighteen times higher in 1976.

The World Glacier Inventory goes back to 1975 when the International Commission on Snow and Ice published its research results on the motion of tongues in some glaciers. Following reorganisation of the Commission in 1976, this effort re-emerged under the auspices of the UNESCO and the Swiss Federal Institute of Technology as a World Glacier Inventory, which is now a GEMS activity. Over 750 glàcier stations in twenty-one countries supply information about heat, ice and water balance which is fed into a computer data bank. Plans for the near term are to complete the processing effort on this data file and proceed with the formulation of laws to relate glacier behavior with climate.

Great hopes are being placed on a space-borne monitoring system for routine remote sensing measurements but in addition for identifying perhaps previously unknown glaciers in inaccessible regions.

The aspects of atmospheric pollution and glacier behavior form parts of the large GEMS Climate-Related Monitoring Programme. As distinct from the concept of "weather" that defines short-term effects on time scales of weeks, days and even hours, "climate" reflects the interactions taking place amongst the ocean, the atmosphere, the land, and ice over decades and longer.

Understanding the climate is fundamental to understanding the environment and it is not surprising that in trying to comprehend both scientists are confronted with the necessity to define the laws of functioning of an enormously complex system. Climatic models—even the most simple ones—incorporate hundreds of interacting factors while only two elements, the ocean and the atmosphere, suffice to require consideration of at least thirty variables, many of them interacting with one another and none especially easy to define and formalize—from tides and ebbs to shortwave radiation.

This is further complicated by the need to allow for the continuous variation of past climate year to year and millennium to millennium, with a few recognizable cycles that are multiples to millions of years. Even though it is 300 years now since the invention of the thermometer, regular observations of air temperature did not begin until 100 years ago. If it is considered further that our knowledge about the planet is estimated by a period going back a few hundred million years, it becomes clear that, compared with the historic timeframe of climate formation, hundred years of documented climatic awareness are, to use the jargon of electronic engineers, but "a low noise against the main process in the background".

Most of the time in the past the Earth has been free of polar ice. Consequently, the time we live in is rather an exception than the rule. The last ice age was probably between 250 and 300 million years B. P. and over that entire period until the date of about five million years ago the Earth had been ice-free.

Evidence from the Greenland ice sheet reveals that between 8 and 16 thousand years ago the mean annual global temperature increased by several degrees in one thousand years. Whereas the warming rendered the Northern Hemisphere more habitable for various forms of life, it concurrently changed the Sahara from savannah to desert. If such temperature leaps were to occur in the future too, they would be virtually bound to cause similarly profound effects.

Chapter 2

# Models of Tropical Cyclones

The development of a spaceborne system for contact sounding of the atmosphere and ocean begins with an understanding of tropical cyclone characteristics that affect the choice of parameters for both the whole sounding system and its individual components. The set of these typhoon characteristics with the indication of a numeric variation range for each of them will be defined in the following discussion as *model parameters.* In addition to physical characteristics such as vertical and horizontal dimensions, wind velocity, temperature and pressure in the typhoon, and the latter's lifetime, the model parameters should include the location of typhoon breeding grounds, rate of occurrence and trajectories of motion.

Although some of these model parameters were earlier referred to in Chapter 1 this was descriptively done to clarify the type and features of a nonstationary atmospheric phenomenon of current interest to meteorologists. The parameters will be further concretized below by attributing to each a quantified range of its possible variations.

## Sec. 5. Physical Model of Typhoons and Hurricanes

**Horizontal and vertical dimensions.** Tropical cyclones have rounded or elongated oval shape, their horizontal dimensions controlled generally by the least diameter of the ultimate

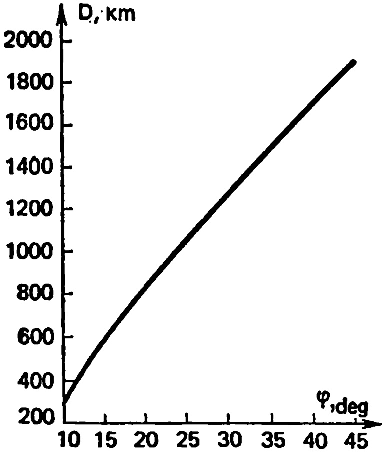



Fig. 2. Mean diameter of the Pacific typhoons against latitude

closed isobar. The diameter varies with the latitudinal position of the cyclone center so that at higher latitudes the cyclone grows across.

As an example, the graph in Fig. 2 shows the mean diameter of the Pacific typhoons against their latitude. It will be seen to be magnified by about 500 km every time the latitude of the typhoon center moves up by another 10 degrees. In the tropics, the Pacific typhoons have a minimum size of 80 km and a maximum size of 1600 km; outside the tropics, the typhoons may grow to be 3000 km across.

The Atlantic hurricanes are not as large as the Pacific typhoons, their average dimensions in the tropics seldom exceeding 150 to 200 km although the largest of them can reach 600 km. The strongest hurricanes of those born in the Atlantic in 1959 possessed the following dimensions: Hurricane Edith, 300 km; Hurricane Flora, 400 km; and Hurricane Grace, 450 km.

The active propagation height of tropical cyclones approaches 15 km. Thus, to a first approximation sufficient for ballistic design, the cyclone can be depicted as a 15-km high cylinder, its diameter varying with the cyclone's latitude. The cylinder incorporates a "funnel" known as the eye of the typhoon, which on average is 20 to 25 km across. While there are practically no winds inside the funnel its walls, nevertheless, constitute the zone of maximum rotation and correspondingly of the strongest winds. The wind velocity beyond these limits slows up dramatically. The funnel walls vary in thickness from a few tens to rarely one hundred kilometers. With the present level of knowledge, the elements in the physical model of cyclones can conceivably be depicted as follows.

As noted earlier, the wind velocity near the cyclone center is moderate, 5 m/s or less but increases with the distance from the center and attains a maximum (80 to 100 m/s) at the eye-of-the-storm boundary. Beyond the boundary, the wind velocity recedes with the expanding diameter.

It also recedes with altitude but its variation gradient is dissimilar at different heights. Up to 6.0 km, equivalent to the pressure of 500 mb, the wind speed varies slightly only to fall off rapidly above that altitude. At the height equivalent to 200 mb the wind velocity is halved. In mild typhoons the rapid decline of the wind speed begins already from the 3- to 4-km altitude.

The wind velocity in the traveling tropical cyclone takes on an asymmetric horizontal distribution, with the strongest wind in the typhoon's right quarters relative to its direction of progress. The wind current lines inside tropical cyclones show a spiral pattern. The spiral is characterized by angle $\alpha$ between the wind direction and the current radius of the storm boundary (Fig. 3). Angle $\alpha$ depends on the location of the tropical cyclone center and its intensity. Importantly, the angle between wind direction and current radius tapers off with the higher latitude and greater magnitude of the typhoon. With the latter's progress, angle $\alpha$ becomes larger in the frontal portion and smaller in the rear portion; it decreases with tropical cyclone development, to be greater in young than in mature cyclones.

For the physical model of the tropical cyclone, the angle between wind direction and current radius provides a very important characteristic which affects the dynamics of balloons, parachutes and other scientific payload carriers. Thus the engineering design

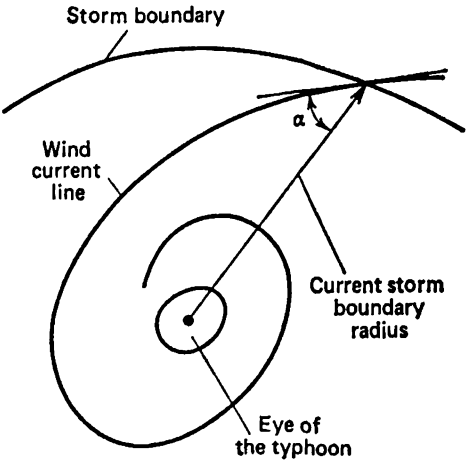



Fig. 3. Arbitrary scheme of the wind current line in the tropical cyclone

and development of such carriers can be directed to averaged values of angles $\alpha$ which vary with the point of entry of wind current lines in the various sectors of the storm's horizontal cross section. We shall divide the horizontal cross section of the tropical cyclone into 16 sectors reckoning them clockwise from tropical cyclone direction. Then the average angle $\alpha$ values in each sector are equal to those given in Table 4.

*Table 4*

| Sector No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\alpha$, deg | 56 | 51 | 52 | 51 | 45 | 41 | 44 | 43 | 49 | 54 | 55 | 54 | 52 | 57 | 62 | 52 |

*Table 5*

| | | | | | | |
|---|---|---|---|---|---|---|
| Pressure drop, $\Delta p$, mb | 10 | 20 | 30 | 40 | 50 | 60 |
| Wind velocity, $V$, m/s | 25.9 | 36.7 | 44.9 | 51.9 | 58.0 | 63.5 |
| Pressure drop, $\Delta p$, mb | 70 | 80 | 90 | 100 | 110 | 120 |
| Wind velocity, $V$, m/s | 68.6 | 73.3 | 77.8 | 82.0 | 86.0 | 89.8 |

The air pressure mean in the tropical cyclone center amounts to 950-1000 mb. A feature of tropical cyclones is a large pressure drop with relatively minor changes of the distance from the center. The largest horizontal pressure gradients in the typhoons may be 1 to 2 mb per every kilometer of the distance. Furthermore, a pressure drop between the low-pressure center and the high-pressure storm periphery shows a consistent relationship with the maximum wind speed in the tropical cyclone, as shown in Table 5 and Fig. 4. The relationship is of a kind making wind speed $V$ in the typhoon increase with a deepening pressure drop $\Delta p$. For example, a 10 mb pressure drop between the center and periphery

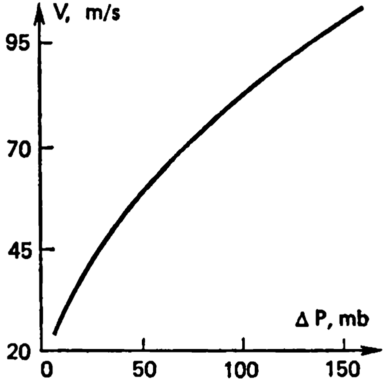



Fig. 4. Variation of wind velocity $V$ in the tropical cyclone with $\Delta p$, the pressure drop between the storm center and periphery

matches the wind speed of 26 m/s, which increases to 73 m/s should $\Delta p$ build up to 80 mb.

## Sec. 6. Areas and Rate of Origin of Tropical Cyclones

The probable breeding grounds for tropical cyclones are essential to know for proper selection of the satellite orbit for observing the atmosphere and ocean and homing descenders with a payload of scientific measurement instruments in the effective range of a typhoon or hurricane. As discussed earlier in Chapter 1, there are several regions on the

Earth where tropical cyclones originate the most frequently. Multiannual statistics suggest that on average the ocean nurture typhoons at the rate of about 60 a year; on the regional basis, the mean annual rate of tropical cyclones stands at 7.9 for the northern Atlantic Ocean including the Caribbean Sea, 28.0 for the northern Pacific Ocean (from Asia to longitude 180°), 8.3 for the northern Pacific Ocean (from North America to longitude 180°), 1.2 for the northern Indian Ocean, 6.8 for the southern Pacific (between 140°E and 140°W), and 5.3 for the southern Indian Ocean.

There are distinctly identifiable geographic zones of possible origin of typhoons bounded by the following coordinates: Zone 1, 5 to 35°N and 100 to 160°E; Zone 2, 10 to 45°N and 100 to 40°W; Zone 3, 5 to 25°N and 75 to 95°E. These zones can provide orientation in the choice of suitable satellite orbits.

One essential model consideration bearing on the appointment of the satellite launching date and the operational life of its instrument package relates to the most probable season for tropical cyclones and the length of their life cycle.

We shall summarize in Table 6 the results of multiannual observational statistics on tropical cyclones with an indication of their monthly average rate. This table can be used to select the best timing of typhoon research for each region. It is only practical to opt for the month in which tropical cyclones are expected with the highest probability of oc-

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northern Atlantic** | 0 | 0 | 0 | 0 | 0.1 | 0.1 | 0.5 | 1.6 | 2.9 | 1.6 | 0.5 | 0 |
| **Northern Pacific (from Asia to 180° longitude)** | 0.5 | 0.4 | 0.3 | 0.8 | 0.9 | 1.9 | 4.3 | 6.5 | 4.9 | 3.8 | 2.2 | 1.6 |
| **Northern Pacific (from America to 180° longitude)** | 0 | 0 | 0 | 0 | 0.2 | 1.3 | 1.4 | 1.6 | 2.4 | 1.2 | 0.1 | 0 |
| **Northern Indian Ocean** | 0 | 0 | 0.1 | 0.2 | 0.2 | 0.1 | 0 | 0.1 | 0.2 | 0.3 | 0 | 0 |
| **Southern Pacific Ocean between 140°E and 140°W** | 2.0 | 1.5 | 1.7 | 0.4 | 0.1 | 0.1 | 0 | 0 | 0 | 0 | 0.2 | 0.7 |
| **Southern Indian Ocean** | 1.6 | 1.5 | 1.0 | 0.4 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0.5 |

currence. As is evident from Table 6, September should be the month of choice for the northern Atlantic Ocean, August for the northern Pacific from Asia to 180° longitude, September for the northern Pacific from America to 180° longitude, October for the northern Indian Ocean, and January for the southern Pacific and Indian Ocean. The statistics in Table 6 make it plain that a tropical cyclone is most likely to be detected in the Northern Pacific region from Asia to 180° longitude, where they are born at the rate of 6.5 every August—the highest average rate of emergence of the tropical cyclones in similar regions. Satellite orbit selection is widely influenced by the average length of typhoon life cycles whose run over 70 years for the northwest Pacific is given in Table 7.

*Table 7*

| Characteristics | June | July | August | September | October | November |
|---|---|---|---|---|---|---|
| Total life of typhoons over 70 years, days | 406 | 1227 | 1351 | 1368 | 1073 | 795 |
| Average life per month, days | 6 | 18 | 19 | 20 | 15 | 11 |
| Total number of typhoons over 70 years | 108 | 263 | 350 | 310 | 213 | 148 |
| Average life cycle, days | 4 | 5 | 4 | 4 | 5 | 5 |

## Sec. 7. Trajectories of Tropical Cyclones

The type of trajectory suggested for the motion of a tropical cyclone is the latter's essential characteristic with a great deal of influence on many parameters of the space system designed for contact sounding of the atmosphere and ocean. With respect to typhoon trajectories, it is important to know the location and traveling speed of typhoons, the way in which their breeding grounds determine the trajectory, and the predictive accuracy of the typhoon's trajectory of motion versus its expected traveling time.

The trajectory characteristics, coupled with the other model parameters listed above govern in a number of ways the selection of suitable satellite orbits, demands on the onboard steering and attitude control capabilities of the satellite and descenders, and requirements for processing the information output.

From observational evidence, tropical cyclones seem to move on trajectories typically parallel to isobars. In other words, the prevailing wind current importantly defines the typhoon traveling path. And, since the trade winds dominate in the tropics, the tropical cyclone speed and direction in the early development phase practically coincide with those of the general wind stream in the area where the typhoons take a start. As a result, the nascent tropical cyclones travel normally due west in the equatorial margin of subtropical anticyclones.

Tropical cyclones, nevertheless, harbor internal forces working to curve their trajectory northeast or east in the Northern Hemisphere and south or southeast in the Southern Hemisphere. Indeed, in the general case, the air within the tropical cyclone is driven by the action of baric gradient—the force created by the pressure drop, centrifugal force and the Coriolis force. Because the Coriolis force increases with latitude, for mature tropical cyclones with a sufficiently large diameter the difference of the Coriolis force between the extreme north and south points is quite appreciable. The resultant Coriolis force acts in the northward direction for a Northern Hemisphere typhoon and in the southward direction for a Southern Hemisphere typhoon.

In the general case, therefore, the Coriolis force bends tropical cyclones poleward in both hemispheres and the so-called Rossby effect sets in. The effect is the stronger and the poleward displacement the more dramatic, the greater the dimensions of the typhoon in question are. In mature typhoons the trajectories may be bent by 1 or 2° latitude per day. Many trajectories exhibit a well-defined turning point, or critical point. As a typhoon approaches the critical point it abruptly slows its speed to a minimum value, practically to zero, and almost stands still for a while, sometimes for a few successive days, only to resume progress after a drastic change of direction.

The tropical typhoon travel from then on depends on many factors. A small perturbing pulse can "tip the balance" and send the tropical cyclone further on one of many possible trajectories. But again, its direction of motion is likely to change time and again near the critical point, and even pitch off a loop, for example. It is not unusual for either tropical cyclones to follow altogether disparate trajectories beyond the critical point in two apparently similar situations.

To accurately predict a typhoon trajectory, especially after reaching the turning point, a thorough analysis of many factors is needed, first and foremost of the system of air streams in the troposphere and within the tropical cyclone itself—something that is rarely achieved.

Heterogeneity of the underlying surface and temperature of the surface water layer have a pronounced influence on the tropical cyclone trajectory. For typhoons and hurricanes, the trajectories resemble sometimes regular geometric shapes—straight lines, parabolas or hyperbolas, not infrequently distorted by convexities, concavities, loops and southwestward or southeastward shifts.

In modeling, tropical cyclone trajectories can be classified by type according to their direction and pattern. On this principle, the trajectories of tropical cyclones can be identified with one of the following six types, based on many years' statistical observations:

(1) an eastern type, for the tropical cyclones which move east to west;

(2) a southeastern type, for the tropical cyclones moving southeast to northwest;

(3) a southern type, for the cyclones moving south to north;

(4) a southwestern type, for the cyclones moving southwest to northeast;

(5) a parabolic type, for the cyclones on the parabolic trajectory with its bulge pointed westward;

(6) an irregular type, for the tropical cyclones having other trajectories than the above five types.

The largest proportion of tropical cyclone trajectories, about 47 percent, is the parabolic type in which one branch of the parabola corresponds to their westward path, another to the eastward path, and the vertex to the turning point. To be sure, this pattern for the motion of tropical cyclones is a mere approximation and their actual path cannot be thus simple.

The southeastern type, representing 21 percent, is second-largest and the irregular type, third-ranking in frequency terms, makes up 14 percent. The southwestern and eastern types account for 7 percent each, and the last and most infrequent, southern type claims 4 percent.

Although tropical cyclones progress on average at 20 to 25 km/h their speed generally increases with the geographic latitude of the cyclone center: it is 8-10 km/h near the Equator but boosting to 40-50 km/h in temperate latitudes.

## Sec. 8. Prediction of Tropical Cyclone Trajectories

To reliably predict the trajectories of typhoons and hurricanes is extremely difficult. It requires knowing exactly the laws of general atmospheric circulation and the whole set of air streams over the Earth, on the one hand, and numerous particulars of atmospheric behavior in the breeding grounds of the tropical cyclone in the few hours following its birth, on the other. A particular value is set on the ability to anticipate unexpected turns of the trajectory with sufficient lead time.

Suggested trajectories for the motion of typhoons can be computed by a variety of methods which fall, according to their basic characteristics, into climatological, synoptic, statistical, and hydrodynamic.

Of these, the *climatological predictions* basically assume that a tropical cyclone in the region of interest will develop in future a speed and direction identical with the averaged typhoons' speed and direction in a certain region over the last few decades. Usually, the regions in the tropics and oceans where tropical cyclones occur are broken down into smaller areas a few degrees on a side. The climatological predictions show a moderate accuracy making them practical only in the absence of current operational information about a tropical cyclone.

The *synoptic predictions* exploit two types of inputs: averaged data on past behavior of tropical cyclones and current reports from weather stations, aircrafts, and satellites. This current information enables forecasters to come up with improved accuracy of the climatological forecasts.

The *statistical type of prediction* involves the use of mathematical methods, specifically the systems of equations which describe a future motion of a typhoon taking into account the position of and the pressure in the typhoon center, and variation of these and other factors over the previous hours or days. Equation coefficients for these systems are selected on the strength of available past statistics with respect to tropical cyclone trajectories. Although similar in appearance to the climatological forecasts, the statistical predictions involve calculations in such a great quantity as to require computers to handle them.

Of the multiple procedures that exist for statistical forecast making, some predict future behavior of the tropical cyclone to an acceptable accuracy. However the statistical methods in general are inadequate to study the impacts of tropical cyclone parameters on their trajectory under new and nonstandard conditions without the backing of documented previous history.

At present, forecasters adopt increasingly for practical predictive applications the *hydrodynamic methods* based on the physical laws of motion of liquids and gases. If one knows an initial state of some atmospheric parameters and has available a set of complex differential equations from hydro-aerodynamics, the predicted atmospheric parameter values in the effective range of typhoons can be computer-estimated with good accuracy in space and time. The method has in fact been used to predict a tropical cyclone trajectory to within 250 km for one day ahead and 550 km for two days. Yet, the synoptic forecasts remain more accurate for the time being, to within 220 km or so for one day and 480 km for two days.

The hydrodynamic methods seem deficient chiefly in that many tropical cyclone parameters, e.g. size and strength, are not known in advance and likely to change considerably over a period of their evolution. Some characteristics of typhoons and hurricanes, e.g. frontal resistance factor, are altogether unobtainable by direct meteorological observations.

This has led some specialists to suggest methods combining the advantages of the statistical and hydrodynamic techniques. One of these, reviewed by Rostkova and Ordanovich in [18], is a method of learning model. It provides a finer resolution on the tropical cyclone parameters that are not known in advance by learning from the trajectory length familiar up to a point in time. Beyond that point, the prediction of the trajectory relies on the hydrodynamic method.

Chapter 3

# Operational Detection of Tropical Cyclones from Satellite Orbit

## Sec. 9. Main Objectives of Satellite-borne Detection System

The investigation of typhoons by contact sounding of atmospheric and ocean parameters performed by instruments delivered from orbit will be the more effective, the earlier they are detected in the open ocean. The needed operational capability for rapid detection of tropical cyclones is provided by enormous area coverage of the Earth's surface from orbit. Pertinent statistics reveal a notable growth of annually detected tropical cyclones since the start of regular satellite observations. Interestingly, most of them were spotted in the earliest development phase and forecasters have been able to make an accurate prediction of the typhoon's further progress and development.

As discussed in Chapter 2, tropical cyclones are contrasted from their environment by the characteristic shape of clouds, the higher temperature and lower pressure in the center, strong wind, and large wave height. To detect any of them from orbit requires continuous monitoring of one or several parameters of the atmosphere and ocean.

Analysis and processing of optical, infrared and radar images of cloud systems provide critically important information on tropical cyclones. Thus enhanced convective cloudiness pinpoints the nascent typhoon. As it develops, the cloudiness becomes more and more like a comma with the center of the depression at its apex. Further on, the cloud cover over the central part expands up to 100 and 300 km across and there are spiral cloud bands converging toward the center. Following an analysis of the cloud cover over the tropical cyclone, both its development stage and the maximum wind speed in it can be determined with sufficient accuracy. Satellite surveillance of the cloud cover can give a clue to a problem second in importance only to typhoon detection—the problem of locating the storm center.

By visually observing cloud formations and by use of their TV and photo imagery one locates the typhoon's eye and works from its position to pinpoint the tropical cyclone center. This method is most accurate unless the eye is ill-defined—then the tropical cyclone center can be identified as the point of convergence of the spiralled cloud formations or, lacking other clues, as the center of the cloud system over the tropical cyclone although this approach demonstrates low accuracy.

Presently, satellite data inputs allow the tropical cyclone center to be rather accurately determined to within 30 to 50 km. The errors depend primarily on geographic referencing of cloud cover imagery, image quality and, naturally, the interpreter's competence. The accuracy of locating a typhoon is noticeably affected by its degree of development so that the center of a full-blown typhoon is definable with a greater precision. The striving for improved timeliness in monitoring for and detection of typhoons makes it important to try to locate in advance their suspected breeding grounds.

A discussion in Chapter 1 has already pointed to atmospheric perturbations as the trigger starting the development of typhoons. There have been reports of sighting such perturbations from a satellite and of being able, in these cases, to predict the appearance of a tropical cyclone. Below we shall provide a list of characteristic signs in the state of the atmosphere and ocean, which most probably accompany the origin of typhoons;

—an area of lower pressure than ambient;
—perturbations of any kind in the tropics;
—a rise of sea surface temperature to 27 °C or more;
—a decrease of wind with altitude;
—a slow motion of the trigger perturbation, or seedling, at 20 to 30 km/h;
—a closed air circulation at low altitude;
—a cloud convection build up to above normal;
—a heated air layer, its thickness greater than the average air layer thickness in the tropics within the pressure ranges

$2 \times 10^4$-$5 \times 10^4$ Pa or $3 \times 10^4$-$7 \times 10^4$ Pa;

—perturbations over the warm center or the crest of the air layer with the pressure of $2 \times 10^4$-$5 \times 10^4$ Pa.

To sum up the foregoing, the basic goals of the satellite system designed for operational detection of tropical cyclones are:

(1) to identify regions likely to generate typhoons in the near future, from observations on cloudiness and by measuring other telltale parameters of the atmosphere and ocean;

(2) to detect typhoons;

(3) to locate the areas where typhoons first appear;

(4) to determine the trajectory of tropical cyclones and predict it for the next few days;

(5) to analyse atmospheric and oceanic processes in the effective range of typhoons;

(6) to measure principal storm characteristics—wind speed, temperature, pressure, vertical and horizontal dimensions, etc.;

(7) to forecast the rate of progress in typhoon development.

Even though the satellite systems on tropical cyclone detection missions may differ in their selected orbit parameters, remote sensing instrument designs and so forth, they must always be assigned the basic duties of observing the underlying surface; recording the acquired information and, if necessary, relaying it to earth for verification and analysis; information processing on board or on the ground into a format convenient for analysis; performing the analysis and sending a tropical cyclone detection message complete with the indication of its position. Obviously, all these tasks must be accomplished with maximum speed and efficiency.

The time of search for a burgeoning tropical cyclone depends on the satellite orbit—low-circular, highly elliptical, etc. and type—manned or unmanned. They are the points we shall discuss next.

## Sec. 10. Satellite Orbit

**Satellite movement.** First, let us offer some basic theory on the orbital motion of satellites which we feel is necessary to understand the following discussion.

The Earth's satellites travel by the fundamental laws of gravitation. Their movement is given by a system of three ordinary second-order differential equations. This means defining six independent parameters to fully understand satellite behavior in orbit. The parameters may be either the initial conditions of motion (three components of the vector satellite center-of-mass position and three components of its velocity vector corresponding to a certain initial moment of time), or a set of six integration constants for the differential equations of motion or, simply put, six independent orbit parameters.

Usually, the former method is applied for sufficiently accurate numerical calculations of orbit parameters, evaluation of their behavior in time, and prediction of the spacecraft center-of-mass position and speed at any specified moment of time in future. The second way of giving orbit characteristics offers greater latitude for visible presentation of the spacecraft trajectory of motion in space relative to the rotating Earth. Needless to say, there is a relationship between the system of the initial conditions of the spacecraft center-of-mass movement and the system of orbit parameters.

At a first approximation, our planet can be seen as a sphere of homogeneous spherical layers. A celestial body of that kind should be capable of attraction as if its entire mass were concentrated in the center. In mind of this its gravitational field is dubbed *central*. Free motion of a material point in the central field follows an ellipse, parabola, or hyperbola. All these orbits lie in planes passing through the Earth's center. Accordingly, the satellite moves on an *elliptical* or, in the particular case, a *circular orbit*.

The parameters controlling the satellite orbit are generally referred to as orbit elements. The most widely used system of orbit elements is as follows: semi-major axis of elliptical orbit, $a$; eccentricity $e$, inclination $i$, pericenter argument $\omega$, longitude of the ascending node, $\Omega$; and the time of passage through the pericenter, $\tau$ (Fig. 5).

Figure 5 illustrates the position of an elliptical orbit trajectory in space. The satellite orbital plane cuts the equatorial plane on the *nodal lines*, the *nodes* being points of intersection of the equatorial plane by the satellite orbit. As the satellite crosses from the Southern into the Northern Hemisphere its orbit cuts the equatorial plane at the *ascending node*; if it passes from the Northern Hemisphere into the Southern the orbit cuts it at the *descending node*. Letters *P* and *A* in Fig. 5

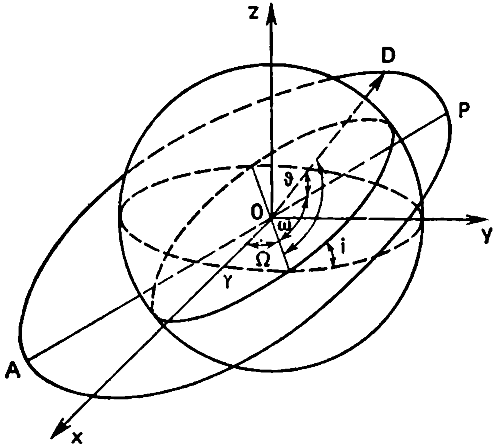



Fig. 5. Spatial position of the trajectory of the elliptical satellite orbit

identify respectively the *perigee* and *apogee* of the satellite orbit—the points corresponding respectively to the minimum and maximum satellite distances from the Earth's center.

The spatial position of the orbital plane is controlled by three of the above six satellite orbit elements; they are the three angles: inclination $i$, longitude of the ascending node $\Omega$ and pericenter argument $\omega$.

*Orbital inclination* $i$ defines the angle between the equatorial and orbital planes having its vertex in the ascending node. The positive values of $i$ correspond to the angle as reckoned counterclockwise from the eastern direction at the Equator. The satellite moves due east if the inclination lies in the range of angles $0 < i < \pi/2$ but its movement occurs due west if in the range $\pi/2 < i < \pi$.

*Equatorial orbit*—the orbit keeping the satellite on permanent station above the Equator—has two corresponding values of orbital inclination, $i = 0$ and $i = 180°$. In the former case, the direction of satellite travel matches that of the Earth's rotation; in the latter, it goes opposite to the Earth's rotation. Finally, inclination $i = 90°$ corresponds to *polar orbit*—the orbit running over both the North and the South poles.

*Longitude* of the ascending node is the angle between the nodal lines and a fixed line in space directed from the Earth's center into the vernal equinox point. Together with inclination, this orbit element defines its position in space.

*Perigee argument* $\omega$ is the angular distance of perigee $P$ from the ascending node reckoned in the orbital plane in the track direction.

The remaining three orbit elements apply to defining its shape and size and the satellite's position in near-Earth space at any moment of time; they are semi-major axis of the orbital ellipse $a$, eccentricity $e$ and the time of passage through the pericenter $\tau$.

*Semi-major axis* $a$ is the orbit semi-diameter.

*Eccentricity* $e$ is the ratio of the distance between the orbital center and focus to the semi-major axis which characterizes orbital extension.

Satellite motion in its orbit may be given by one of the following parameters (Fig. 6):

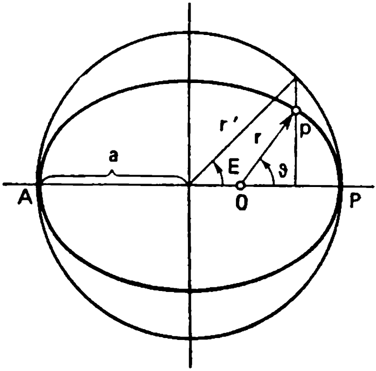



Fig. 6. Orbit elements in a plane

$\vartheta$—*true anomaly*—the angle between current radius vector **r** and the line of apsides (i.e. the line connecting the orbital apogee and perigee points);

$E$—*eccentric anomaly*—the angle between the line of apsides and the radius of auxiliary circle $r' = a$, drawn into the circle's point of intersection with the perpendicular to the line of apsides passing through an orbiting point (the satellite center of mass) (Fig. 6);

$u$—*argument of latitude*—the angle measured in the satellite traveling plane in the direction of movement from the ascending node to current radius vector **r**. Numerically, the argument of latitude equals the sum of angles $\omega$ and $\vartheta$, i.e. $u = \omega + \vartheta$.

While making ballistic calculations for the trajectories of motion one sometimes can conveniently operate a system of equations having true or eccentric anomaly as their argument with no other orbit element affected but the time of passage through pericenter $\tau$.

For a more precise examination of satellite motion it should be considered that the Earth is not a homogeneous sphere but rather—though just as approximately—an ellipsoid with nonuniformly distributed density of matter. Thus satellite motion comes up against air drag, gravitational anomalies, solar and lunar attraction. In reality these perturbations have the combined effect of continuously changing the orbit elements—the fact to be considered in the design and development of the satellite system for operational detection of tropical cyclones from orbit.

**Specific choice of orbital parameters for operational detection of tropical cyclones.** Among the factors to be considered for the selection of orbital parameters, the major ones include the laws of satellite orbital motion that have just been discussed; the mode of surveying specified regions on the Earth's surface; the specifics of data inputs that need to be reviewed (these will be detailed further); the launcher capabilities to place the spacecraft on orbit; broad compatibility of selected orbit parameters to permit growth for possible other applications, e.g. delivery of research instruments from the satellite into a desired target area and localization of balloons and buoys in space; on-board observing and recording instruments capabilities such as Earth-observing swath width, resolution of the instruments used, and so forth.

Keeping a constant gaze on the required Earth's surface area to spot tropical cyclones and track their development is feasible with satellites in the so-called *geostationary orbit*, an equatorial circular orbit 36 000 km high to allow one satellite revolution around the Earth within the sidereal day. A satellite traveling with the Earth's rotation in a geostationary orbit would appear motionless to an earthbound observer. In that case, using the on-board equipment package one should find it relatively easy to arrange for monitoring the same region on the Earth.

The Earth's surface coverage from a geostationary orbit, which provides an 18 000 km spherical diameter of the surface visibility range, should be sufficient for tracking tropical cyclones practically all along their path from the birth to abatement. The geostationary orbit thus appears to be the most convenient vantage for operational detection of a typhoon and monitoring of its progress.

It may be less of a vantage for other tasks such as descending from orbit probes with a payload of research instruments into a tropical cyclone and locating the balloons and buoys situated in and traveling with a tropical cyclone. Circular or near-circular orbits seem better suited for these applications, flying the satellite at lower altitudes, from 500 to 1000 km, over the Earth's surface.

Let us examine several low-circular orbits that can accommodate both the operational detection and tracking of typhoons and the delivery of balloons and buoys into their effective range. But first we shall explain why it is the circular orbits that are the best for typhoon-monitoring applications and not the elliptical albeit low orbits. The point is that circular orbital missions provide the same scale of television and infrared images; this facilitates image data processing on computers and speeds up the compilation of photomosaics, thus affording ultimately a greater ease and efficiency of tropical cyclone detection.

A regular overpass of the same regions is achieved by *circular geosynchronous orbits.* To be considered geosynchronous, and orbit's period of revolution must be a multiple of the sidereal day and this is why a satellite pass over the region of interest takes an integer-valued temporal cycle (one-, two-, or three-day observational cycle). The highest rate of data acquisition on circular geosynchronous orbits is once in 24 hours. Going to a higher rate will solely be achievable with more geosynchronous satellites simultaneously in orbit. The low-circular geosynchronous orbit is deficient in that satellite sensing instruments flown in repeated passes over the same regions on the Earth will be viewing a comparatively narrow band of underlying surface, whereas the target typhoon trajectories can sometimes be as long as ten thousand kilometers or more. The net result is occasional inability of a single geosynchronous satellite to track the tropical cyclone throughout. Parameters of a low-circular satellite orbit—inclination $i$ and height $h$—can be selected to ensure systematic global surface coverage through a series of repetitive scans. However this will significantly increase the time interval between two successive scans of the same underlying surface site which is an undesirable alternative for obvious reasons. The only way out then is to put up more satellites into the same orbit. In effect, a constellation of three satellites in one orbit seems sufficient to afford operational detection of tropical cyclones and monitoring of their progress with a good repeat timing.

To make any region on the Earth amenable to satellite observation, orbits of large inclination are desirable. Usually two orbit types are used to satisfy the need, polar and sun-synchronous.

*Polar* (or near-polar) *orbits* have inclination $i = 80\text{-}85°$. Given the swath width of existing on-board observing instrument technologies, this should be able to offer practically global surface coverage. Indeed, the orbit's projection on the Earth's surface varies over the range of latitudes that equals the inclination of the orbital plane to the Equator. For example, with an 85° orbital inclination the Earth's surface projection of a point on the satellite trajectory circling the polar orbit will be moving from 85°N to 85°S. And, because of the Earth's daily rotation the satellite sub-point on the Earth's surface, rather than re-traversing its former path at each revolution, will be shifting westward relative to its position at the previous revolution. Numerically this westward displacement is equal to the angle by which the Earth rotates on its axis during the time of the satellite's period of revolution around the Earth.

*Sun-synchronous orbits* are uniquely suitable for situations in which constancy of the temporal conditions for observing the underlying surface is required. These orbits possess inclinations in the 95 to 100° range. The satellite flying on a sun-synchronous orbit remains sunlit for several successive months and passes over the same locations at identical local times. This offers a number of data acquisition advantages over the polar orbit.

Firstly, the Earth's surface imaging can be scheduled for the most convenient time of the convective cloudiness over the target areas to be imaged and the Sun's sufficiently high elevation above the horizon. This greatly simplifies interpretation of satellite TV images and enhances operational efficiency of typhoon detection. As a rule, the "most convenient local time" occurs between 8:30 a.m. and 0:30 p.m.

A further advantage of sun-synchronous orbits arises from identity of the physical conditions for observing the Earth's surface through a long time interval, offering improved quality of the satellite imagery.

A third, and last, advantage of sun-synchronous orbits is the ability to image the Earth's surface on a daily basis—at any moment while the satellite's imaging instruments are on and running.

A satellite launch into the sun-synchronous orbit, as opposed to the polar orbit, is directed northwest or southwest, thus imposing special requirements for the cosmodrome location: it dictates that it should be more usefully located in higher latitudes to save on the launch-vehicle energy expenditure for injection into the sun-synchronous orbit.

Sun-synchronous orbits are mostly circular because, as pointed out already, this provides for constancy of the image scale and ready applicability of more simple image processing algorithms. The choice of orbital altitudes is usually in the 600 to 1500-km range. But, where the lowest possible satellite pass over the Earth is desirable the choice of the altitude for a sun-synchronous orbit should meet the constraint of its required active operational life; the choice of a higher orbital altitude is restricted by the demand on the spatial resolution of the acquired image data on the underlying earth surface. Generally, in order to accommodate the daily track displacement, it is common to strive for a higher mission altitude in an attempt to widen the viewing swath on the underlying surface—at the sacrifice of imaging detail. Therefore the choice of altitude for the circular sun-synchronous orbit should be decided on a case-by-case basis and preceded by the research to find ways to meet the conflicting demands that arise out of the attempts at total surface coverage with acceptable image resolution by on-board instruments having a limited field of view.

Many ongoing space research programmes in this country and abroad provide for global remote sensing of the Earth's surface from space based on weather, oceanographic and earth resources study satellites. Should the experiment in contact sounding of atmospheric and ocean parameters in the effective range of tropical cyclones coincide in time with the operational schedules of any satellites engaged in remote sensing applications for other programs, the latter can and should aid in the operational detection of typhoons and tracking of their development.

Let us briefly describe some of these satellites. The Soviet space system *Meteor* has been operated continuously since 1969. The system maintains on a permanent basis two to three active orbiting weather satellites. These can be of two types [19], operational and experimental. The operational spacecraft support continuous hydrometeorologic surveillance and regular global weather data acquisition. The operational *Meteors* are placed on 900-km near-circular near-polar orbits with an inclination of 81.2°. The experimental satellites are designed for new instrument testing and development missions to expand their suite of observational capabilities.

Using TV and infrared imaging facilities, the operational satellites can provide a substantial part of global surface coverage even from one revolution around the Earth. The satellite circles a 900-km orbit in 102.5 minutes. The surface projection of the satellite's trajectory of motion is displaced during one revolution by 2800 km on the Equator and about 1500 km in the midlatitudes. TV and infrared sensors provide a swath width of 2100 km and 2600 km, respectively [19]. The respective resolutions are one kilometer for the TV scanners and eight kilometers for the infrared devices. Clearly, one *Meteor* satellite is incapable of solid global coverage without lapses in the equatorial zone. It is with total global coverage in mind that two or three satellites of the *Meteor* system are simultaneously injected into orbit. They are launched in such a way as to have their orbital planes displaced along the longitudes of the ascending nodes. For a system of two satellites, their orbital ascending nodes will differ by almost 90° in longitude, and for three satellites committed to an observation program the difference will be 60°.

Satellites observing the Earth significantly enhance their output if more of them are in orbit. Thus two orbiting *Meteor* satellites have been able to acquire data from 80 percent of the Earth's surface and provide repetitive coverage of each surface region every six hours.

The experimental *Meteor* vehicles are injected into sun-synchronous orbits with inclination $i \approx 98°$. On these orbits their flying altitude is 650 km, down from 900 km for the operational *Meteors*. The lower orbital altitude of the experimental satellites leads to a proportional reduction of the swath width sensed by the on-board instruments, from 1300 to 1900 km, and correspondingly to an improved ground resolution, to 0.3-1.0 km.

## Sec. 11. Detection from Manned Orbital Stations

Operational detection of tropical cyclones at their earliest possible development stage by using spaceborne capabilities belongs to the class of problems best solved by a specially trained cosmonaut. This is confirmed by the experience of multiple long-duration missions on the *Salyut* manned orbital stations [12]. Many cosmonauts take a preflight course in meteorology studying features of atmospheric phenomena and sampling images of tropical cyclones to be able to recognize typhoons by the characteristic spiral cloud bands, photograph them and locate their storm centers. The training course equips them with the knowledge necessary to cope effectively with the comprehensive mission programme that includes visual observation of the ocean surface to detect tropical cyclones, investigation of their genesis and subsequent development, and prompt communication to earth of the information about the location of typhoons.

The missions accomplished by Soviet cosmonauts on the *Salyut* orbital stations launched into near-circular, 350-km, 52-degree orbits have demonstrated the efficacy of visual Earth's surface surveillance for operational detection of tropical cyclones. In some instances, reports from space came ahead of the observational results from special-purpose weather satellites, contributing to improved accuracy in locating typhoons and hurricanes in the ocean and computation of their trajectories further on. The results could have been more impressive, had it not been for the on-and-off character of sounding the atmosphere and ocean from the manned orbital station. However the much greater duration of the *Salyut* crew missions over the last few years gives promise of a more regular future basis for the observation by cosmonauts of typhoons and hurricanes.

Human vision is far more effective than existing technical means [12]. It has the advantages of high sensitivity to contrast, high resolving power with a large visual field, adequate discrimination of colors, low threshold of visual sensation, capacity for work despite major variations of brightness and illumination and, finally, fast responsiveness. With our current methods it is impossible to design all these advantages into a single optical system however perfect.

These strengths of human vision prove themselves in cloud cover observation from orbit. Many cosmonauts reported [12] that it was a high degree of contrast making all the difference between the visually observed picture of a cloud system and its optical instrument representation. Under the normal conditions of illumination the human eye can discriminate contrasts up to 1-2 percent, imaging sensors up to 10-15 percent, and TV equipment up to 20-25 percent [12]. The greater contrast recognition potential of human eyesight allows the cosmonauts (with normal visual acuity) to scan clearly from a 250-350-km orbital altitude details of the cloud system around tropical cyclones ranging in size from 100 to 1200 m. In so doing, a better resolution is achieved for the more contrasting cloud formations.

Flying the low-circular 250-350-km orbit, a cosmonaut has a good view of a 300- to 400-km swath on the underlying surface. A wider swath is out of view because of the atmospheric haze. The limited viewing range would not let cosmonauts simultaneously watch the whole cloud system connected with a major tropical cyclone, but does not prevent their tracking from orbit the typhoons' origin and movement. Cosmonauts watched on numerous occasions the cloud cover changes that were early signs of the birth of a tropical cyclone, indeed sometimes of a whole family of cyclonic perturbations. Regular observations on cloud cover and ocean surface resulted, among other things, in new concepts about a relationship between the cyclonic cloud formations and surface water layers. Thus during the 1978 *Salyut* mission cosmonaut Vladimir Kovalyonok perceived a relation between drops of ocean water levels and the cyclonic type cloudiness [12].

Visual observations from orbit are distinct for their significant and close dependence on the physiological parameters of the cosmonauts' vision, giving them a strictly individual character. The human eye is subjective in its perception of the colors and brightnesses of objects even in normal terrestrial conditions. Determined by individual optical characteristics of the eye and the physiological features of eyesight, the parameters of human vision, moreover, are changed under the effect of weightlessness, the change being the more dramatic, the longer lasts the state of weightlessness. This needs to be considered for assessing the degree of subjectivity and accuracy in visually observing tropical cyclones from on-board the manned orbital stations.

As part of preparing cosmonauts for missions on orbital spacecraft and stations, each cosmonaut has his or her visual abilities (acuity, operational working capacity, contrast and spectral sensitivity) carefully measured under a methodology based on the application of special test tables. Similar testing tables are present on-board the manned stations. Using these tables and data from the preliminary ground examination of the cosmonauts' vision, its parameters can be verified by comparing similar indicators for the degree of variation due to weightlessness in a real mission.

Apart from the physiological characteristics of cosmonauts' vision, the quality of visual observations of tropical cyclones is susceptible to such other parameters as the time and speed of the orbital station's pass over typhoons, inclination of the viewing axis, and distorted visible dimensions of the cloud formations in tropical cyclones. Most notably, the recognition of incipient (small-scale) typhoons, as also details of mature tropical cyclones, depends on the time of observing them from orbit and their speed of motion in the cosmonaut's field of vision. When the angular speed of displacement of an orbital station relative to an observed tropical cyclone is greater than 20 degrees per second and the observation time shorter than 10 to 12 seconds, cloud formation details would be unrecognizable.

Thus, regular visual observations of cloud formations from orbit provide, though with some constraints, a means for operational detection of nascent tropical cyclones and open good prospects for their further investigation.

## Sec. 12. Detection from Low-orbit Unmanned Satellites

Tropical cyclone detection by the cosmonauts who observe them visually, in the course of long-term missions on crewed orbital stations achieves good efficiency and prompt delivery of data. Yet such stations, permanently orbiting on a yearly basis, are not part of current remote-sensing practices while the cosmonauts usually have tight mission schedules of widely diverse tasks and experiments, leaving them little time to systematically observe the ocean surface.

So for now most tropical cyclone detection is accomplished by low-orbiting automated satellites carrying payloads of sensing and measuring instruments and, in some cases, also data processing and analysis capabilities. This method of monitoring typhoons must be necessarily computerized in full or in part. With full computerization, the data handling facilities on-board the satellite record, process and analyse all of the information acquired or only a part of it—then the on-board data acquisition and processing facilities are coordinated with ground-based systems of information processing and analysis. Under the second alternative, the information obtained in orbit by remote sensing instruments is relayed from the satellite via a telemetry link to ground stations and processed only there. The post-processing output is examined by a weather analyst who determines by characteristic features whether tropical cyclones are present in the geographical area of interest.

While each system has its advantages and disadvantages and its distinctive ways of technical implementation, there is one common element which equally needs to be used in all candidate systems for operational detection of tropical cyclones. The element comprises a package of sensors and sounders designed for remotely observing the Earth's surface from orbit. We shall therefore discuss at some length specific applications for the various observing instrument types.

## 12.1. Tropical Cyclone Observing Instruments

The on-board remote sensing capabilities are set the goals of global Earth's surface coverage and coordinate referencing of detected typhoons. These broad goals determine a wide range of payload requirements. Indeed, on the one hand, it is necessary to ensure global monitoring of the Earth's surface to be able to detect tropical cyclones as quickly as possible and to track their movement as far as possible. It is just as necessary, on the other hand, to provide for adequate detail in studying individual components of observed objects and typhoon centers above all, or else no accurate location of the centers and their trajectories is possible.

These requirements are best satisfied by a complement to the payload including instrument capabilities for remote sounding of the Earth's surface over extremely diverse regions of the electromagnetic spectrum, from the optical frequencies to the microwave band. Earth's surface imaging from space is distinguished into the following broad categories [5]: photo and TV, both made in the wavelength interval $\lambda = 0.45$-$0.75$ μm; multispectral, $\lambda = 0.4$-$1.3$ μm; infrared, $\lambda = 3.5$-$5.6$ and 8-12 μm; and microwave, $\lambda = 0.5$; 0.8; 1.35; 1.55; 3.5; and 8.5 cm.

The first three categories map and measure the reflected radiation of the Sun and the infrared imaging captures the emitted heat radiation of the Earth's surface; also, the infrared range is suited for sensor operation, at any time of the day or night. As opposed to the first four categories sensing in the microwave range exploits an active radar principle. This range permits all-weather sounding instrument to acquire data on the underlying surface and on the characteristics of subsurface layers of cloud cover over tropical cyclones at any time during the 24-hour period.

We shall now review the parameters of each one of the imaging types enumerated above.

**Photographic equipment.** Photographic cameras are the most straightforward by design and operational principle and the most potentially informative of all imaging technologies. Tropical cyclones in the photo images made on-board the unmanned satellite look natural to the human eye and are readily interpreted by their shape, size, tone, and contrast from the background image. Typhoon photo imaging achieves the highest resolution of all spectral intervals. Yet, at the stage of searching in ocean expanses and having to observe large earth surface areas the excessive photographic detail can considerably slow down the process by unduly complicating image interpretation, thus extending the overall processing time.

Also, detailed photography, if it chooses to apply the conventional method of recording imaged scenes on photo film, will require prohibitively large quantities of it. For example, detailed global coverage using the 230-mm × 230-mm frame will need 75 tons of film for the imaging scale 1:60 000 and 400 kg for the scale 1:800 000; an acceptable weight of about 50 kg would require an enhanced photographic scale to 1:2 400 000. Yet one-time photography of the entire Earth's surface or some particular portion of it is usually inadequate to detect atmospheric anomalies. The need to repeat photography on a regular basis would excessively magnify the film weight.

The second impediment to the use of photographic equipment in these applications is the long time required for data communication to the Earth, specifically by physical delivery of the film strips from orbit on landers.

Thus, detailed photography is only practical upon detection of tropical cyclones—as a means of selecting the most interesting of them for a closer study by contact sounding.

In the general case, three types of photography are practicable in underlying surface sensing from orbit: *plan*, when the camera's optical axis coincides with the vertical; *oblique*, when the camera's optical axis deflects from the vertical by some angle; and *panoramic-oblique* with the capacity to photograph a wide surface swath.

Spaceborne photography can image single areas or objects that fit into one image, and this is *point photography*. Or it records a strip of terrain in or out of the satellite track, whose images are interconnected by the necessary forward overlap. The method is called *strip photography*. A third, and last type is *areal photography* which images bands on the ground held together by side overlap. Basing on the experience of space imaging application, to locate single objects and features it is best to use 60 percent longitudinal and 25 to 40 percent lateral overlap. When needing the photos to recognize Earth's surface features the forward overlap of 30 percent and side overlap of 50 percent are required.

A designer of orbital photo-imaging techniques should set the requirements to its main parameters—focal length, relative lens aperture, exposure, speed, and film resolution. Their optimal selection critically depends on a properly defined evaluation criterion of photo-image quality. It is not an easy problem as there exists, to date, no precise understanding of how these parameters relate to earth-observing program goals. Nevertheless available evidence points to there being at least some correlation between the goals of tropical cyclone monitoring by cloud cover and the ground resolution of the photo images; this correlation is given by the formula [14]:

$$A \quad H/(2fN)$$

Here $A$ is ground resolution; $f$ is the focal distance of the lens; $N$ is photo-image resolution; and $H$ is orbital altitude. More often than not, designers of photographic cameras adopt as the key figure of merit precisely the ability to photograph the Earth's surface to a desired resolution. However the only way to get a good resolution is with heavy-weight and large-size systems.

In order to define the usefulness of spaceborne photographic equipment for research on tropical cyclones, it is necessary to know imaging requirements such as desired image resolution, degree of allowance for the Earth's sphericity, necessary combination of photographic material and light filters, applicability of multispectral and multiscaled imagery. Much depends also on natural conditions—the atmospheric spectral transfer function, radiance and spatial-frequency variability of surface features, imaging season and time of day—and the accepted interpretation procedure. Space imaging of the Earth can be accomplished over a broad range of altitudes, between 100 km and to 6 to 90 thousand kilometers. Photography holds a leading position in the Earth remote sensing from space using the range of altitudes from 600 to 900 km.

Photo-image-based studies of the Earth's surface employ two methods differing in the way surface photo images are delivered to the Earth (Figs. 7 and 8). In the first method the photographic film is processed on board and the pictures transmitted via a radiochannel (Fig. 7). The second method relies on descenders to take special containers with photographic film from orbit to ground data handling facilities (Fig. 8).

Although the second technique provides much better images in terms of improved resolution it has low efficacy for typhoon studies, taking too much time to deliver the images to the Earth. There is more promise in the way photographic equipment is put to use under the first method. In the general case, the on-board photographic package consists of one or several cameras, a converter to transform negative pictures into electrical signals, a developing machine, telemetry image communication equipment, and control block (see Fig. 7).

The developing instrument should be able to provide high-speed tape transport, good

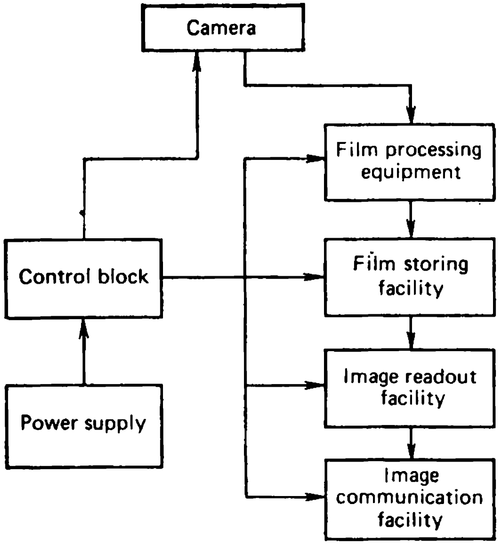



Fig. 7. A photographic system flow with on-board film processing

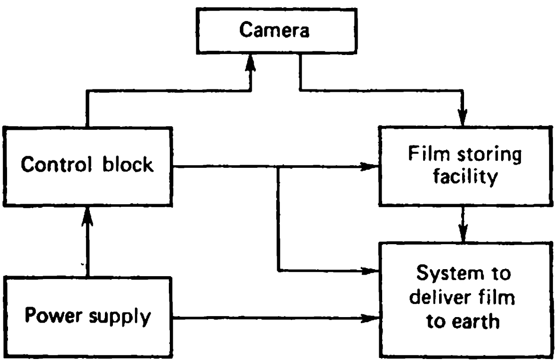



Fig. 8. A photographic system flow with film delivery to earth

solution temperature stability, automated selection of suitable solution formulations and developing modes. Moreover, exposure time—a function of photo equipment parameters, imaging conditions, and optical characteristics of surface objects—also needs to be considered for developing quality images.

It is far from simple to speed up the processing and interpretation by ground stations of the image received from the satellite down the telemetry channels. As an adjunct to powerful computer complexes, the instruments now under development such as a display support for digital image processing, opto-electronic analyzer, etc. will provide a much faster photo-image processing capability. Its key stages [16] will be searching for the video image fragment of interest by the latter's specified coordinates; terrain referencing of photo images; classification of photo images by resolution elements; a man-readable output format.

This image processing sequence presupposes computer-aided interpretation of the images into the digital format. The great incoming data rate from the satellite orbit—a strip of several thousand images from each session—precludes the required operational efficiency of the above image processing sequence from being reached even by the use of powerful, high-speed and large-memory computers. Furthermore, a part of the images will require an expert analyst for their interpretation.

To achieve increased photo-image processing efficiency, optical and electronic image conversion methods will be called for. An image analyzer now in the design stage will integrate TV conversion of photo images into electrical signals with analog methods of their processing. The analyzer will enable image processing to be accomplished practically in real time. This data processing mode can also be built around a digital computer supported by a videomonitor which displays the resultant images to permit the operator a rapid change of the image processing algorithms to suit the incoming data flow. Physically, the sheme is implementable as follows [16]. The space image film is located on the analyzer flat illuminator in front of a television camera. Once out of the camera, a video signal proceeds to the analog processing block and onwards to the videomonitor which displays the resultant image.

The photo-image processing scheme so organized offers the advantages of high speed and ease of control by the operators who analyze the scenes of the underlying surface. But it also shows a few disadvantages. Chief among them is the comparatively low resolution of television camera tubes rendering the system ineffective for interpreting surface features. Also, because of signal distortions there are disturbances of the resultant image parameters and image interpretation accuracy degraded by relatively high intrinsic noise of TV tubes.

**TV sensing equipment.** The on-board TV earth-observing system is usually configured of two major elements, the radiation receiver and the photomultiplier tube. Ways of implementing the TV system vary widely but in the general approach TV systems are classified [5] by the type of scan, into mechanical or electronic; by type of storage, into system with electrical filter, electronic storage, and TV photography; by the time of video-image conversion into those with on-line data transmission for analysis with simultaneous storage and readout and off-line data transmission with delayed readout after storage and recording.

Television imagery has numerous advantages over space photography. It obviates the need to keep on board a large film stock with its subsequent return back to the Earth; it has little difficulty acquiring, storing and automatically processing image data; the on-board TV sensors have a long life, serve multiple applications and make TV image reception rather simple.

At present, unmanned satellites successfully obtain global TV imagery, with sun-synchronous orbits best-suited for TV sensing of cloud cover at a moderately high resolution of 1 to 3 km. The joint operation of two satellites with orbital altitudes of 1000 to 1400 km and near-90-degree inclinations provides TV coverage of a certain region on the Earth every six hours [5].

The TV systems needed for more efficient and speedy detection of the cloud formations indicative of tropical cyclones should display maximum sensitivity to their spectral responses in the longwave portion of the visible spectrum while offering sufficiently large ground resolution, adequate coverage, and high imaging frequency.

**Multispectral imaging technologies.** Simultaneous orbital imaging in different spectral intervals yields Earth's surface data which is second to none in diversity and reliability. Multispectral imagery gives a higher probability of identifying a tropical cyclone. At first, the probability grows with an increasing number of spectral intervals up to a certain value, usually five or six, but then it remains practically unaltered or even reduced because of complexities and errors in data processing.

Presently in development are multispectral sounders [14] applicable for a wide variety of scientific and economic uses and adaptable to computerized image processing. The sounders will have potential for rapid detection of tropical cyclones. Soviet scientists collaborated with counterparts from the German Democratic Republic in the design and practical transfer of a multispectral photographic camera, MKF-6, capable of simultaneous imaging in six spectral ranges.

The designers assumed as the figure of merit for the MKF-6 camera a 20-30-meter resolution on the ground from 200 to 400-km imaging altitude with the minimum focal distance of the lens. The MKF-6 multispectral camera was tested on the *Soyuz* spacecraft and *Salyut-6* orbital station. The tests validated the previous calculations as the Earth's surface imaging from an altitude of 260-270 km has attained the actual resolution of about 20 m [14].

**Infrared equipment.** Observing instruments that operate in the infrared range exploit two wavelength bands, $\lambda = 0.6$ to 2.5 μm and $\lambda > 3$ μm. The former band is used to measure the reflected radiation of the Sun and the latter to sense the thermal radiation of the Earth.

In the former IR-measurement range good performance in studying the Earth's cloud cover is achieved with $\lambda$ 0.6 to 0.8 μm. The spatial resolution in that application is between 10 and 20 km. The clouds imaged in this range show a lighter shade than seas and oceans.

The instruments operating in the thermal radiation range at $\lambda > 3$ μm locate a tropical cyclone by the rather abrupt leap of surface radiation temperature between the effective range of the cyclone (typhoon) and its environment, because the emissivities of different surface features are varied in this range. The surface radiation temperature controlling the infrared image signal is linked with physical surface temperature. It depends on numerous factors, the principal ones being air humidity and temperature, wind force and direction, time of day, season, cloudiness, fog and precipitation, and weather over the previous days.

Figure 9 shows a flowchart of an infrared radiometer consisting of prism *1*, modulating disc *2*, filter *3*, lens *4*, amplifier *5*, recorder *6*, and transmitter *7*. Not infrequently, such radiometers are made multichannel, with different filters set in each of the channels to be able to emphasize certain spectral bands over the others, if necessary. As an example, a five-channel scanning radiometer flown on

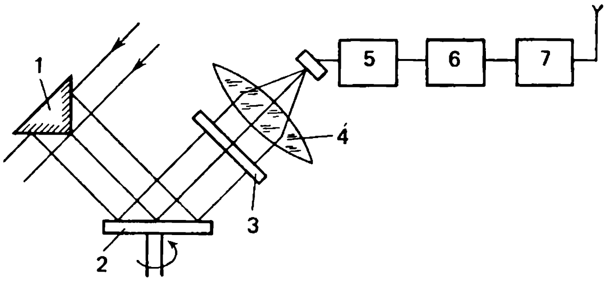



Fig. 9. A flowchart of an infrared radiometer

one of the American weather satellites mapped and measured:

—thermal radiation in and around the intensive absorption band for water vapor, λ = 5.7-6.9 μm, giving the opportunity to sense the water-vapor layer temperature;

—cloud-cover distribution over the Earth's surface, top cloud temperature and elevation, and the Earth's surface temperature in the absence of significant cloudiness (λ = 7.5-12 μm);

—shortwave radiation and albedo of the atmosphere-Earth's surface system (λ 0.2-5.5 μm);

—longwave radiation of the Earth (λ 7.5-30 μm);

—radiance distribution on underlying surface (λ = 0.55-0.75).

The five-channel radiometer has inputs in the opposite sides of the satellite main body, enabling the oriented satellites to measure the difference between radiation fluxes from the Earth and space.

The infrared radiation of sea surface would not pass through clouds. Although it thus becomes useless as a means of sea surface temperature measurement it nonetheless has no difficulty sensing the cloud cover structure over the ocean at any time of the day and identifying typhoons in this manner.

There is evidence that the local thermal inhomogeneities that accompany tropical cyclones seem well recognizable in the first atmospheric window of the Earth's heat radiation at $\lambda = 3\text{-}5$ μm. The hot spot so detected has a minimum size from 10 to 15 km. The second window, in the wavelength interval $\lambda = 8\text{-}14$ μm, is extremely effective in surveying cloudiness which is sharply contrasted against the background of land and ocean. Imaging in this range has a temperature resolution of 1 to 3° for positive temperatures and a spatial resolution of one km.

Thus, the now operational on-board instruments remotely observing the Earth's surface in the infrared supply adequate image detail of cloud cover and ocean heat maps. These instruments recognize the contours of a cloud system over tropical cyclones during the day or night, and typhoons can be spotted in clear weather on the ocean heat map by the contrast they make with their environment.

**Radar equipment.** Radars are capable of remotely sensing the Earth throughout the day or night independently of weather conditions. Some basic radar designs—scatterometer, altimeter, and side-looking radar—were discussed in Chapter 1. There too, each type was characterized in terms of advantages and possible applications. The limitations of the satellite radar sensors grow out of the necessity to fly an extra-payload including a powerful source of electricity, wide-band capability for data communication to Earth, and large antenna systems, and the complexity of processing acquired information. Because of these limitations the radar equipment has, currently, limited utility for tropical cyclone detection.

## 12.2. Operational Detection of Tropical Cyclones by the Ground-based Operator

**General diagram of information flow from satellite on-board instruments to the ground operator.** Remote sensing of the Earth's surface from space based on conventional methods dictates that the payload incorporate devices to record instrument readings. Once the satellite has entered the visibility zone of ground observation facilities, this information is transmitted to the Earth via the telemetry link by the on-board programmable timer controlling the operation of remote sounders and the operating modes of the on-board facilities transmitting data to the ground receiving stations. There, the arriving data are processed and analyzed by the data analyst in order to reveal the signs which are characteristic of the sought-for atmospheric anomalies. The information, before it can be communicated to the earth-bound receivers, must be reformatted on board and reinstated in an easy-to-read format after being received by the ground stations. They first perform its reduction to make sure that the telemetry link is going well. Overall, the flowchart of recording, transmission, reduction and processing of telemetry data comprises its recording on magnetic tape, feeding from magnetic carriers to computers, reduction and verification, presentation in man-readable format, and analysis by the ground-based operator.

Because of the prodigious flow from the satellite data, high-rate transmission links are an absolute necessity if data processing is to be done with minimum delay.

The computer-based telemetry handling system incorporates an input subsystem to interface the computer and the tapes. The subsystem is typically built around a minicomputer that has a flexible I/O capability. The mini [16] organizes the source data stream to adapt it to the host, routes control signals from the host to the source and, if necessary, passes scientific and housekeeping data in the opposite direction. It also supplies universal coordinated time reference signals to the host.

Computer input data are pre-processed using special algorithms to restore the remote-sensing data format degraded in the downlink. Not until this has been accomplished can the data be converted to man-readable form that readily lends itself to operator analysis.

**Processing of satellite-derived data to user-oriented form.** Processing of remote sensing data [19] to accomplish for conversion of incoming radio signals to video- and IR-images, time and terrain referencing of the atmospheric and ocean images and their subsequent interpretation and analysis is time-consuming.

One generally adopted technique is *neph-analysis* of cloud cover that has been said to require special symbols for schematic representation of cloud cover on a map or a mosaic made up of IR-images. A nephelometric map helps identify cloud formation boundaries, cloud types and amount, typhoon centers and other relevant features. It is compiled by the weather analyst visually interpreting IR-images.

Underlying surface data sensed in the infrared are also handled by computer-aided data processing stations on the ground. They yield radiation temperature fields represented as digital maps with the Earth's graticule. Digital data processing is delegated to general-purpose computers with appropriate software support; a dedicated processing and display facility then converts the computer output into video images. The facility's software enables the user to process video data interactively, correct it as required, accomplish its geographical referencing and convertion to a desired projection and scale. The output data formats conducive to the search for tropical cyclones include maps of nephanalysis, digital maps of radiation temperature fields and the base height of top clouds as well as video and infrared imagery.

The dedicated facility should be adjusted to cope with large and frequently updated video inputs in close-to-real time and in a way well-adapted to the video data parameters and the algorithms used [16]. The processing speed is essentially controlled by the time taken to retrieve the required image frame from the tapes and by software efficiency.

Video data can be accessed in a variety of ways. To reduce the access time, all spectral bands of an image are often combined in the backing store into a feature known as the *multispectral video file*. The software should provide for sequential access to each video file item, random access using a key feature, and algorithm-controlled access to the file items. The system must also have a display capability and incorporate a VDU or a printer.

Processing time can be drastically cut back if the relevant software is adapted to exploit the inherent properties and characteristics of video data [16]. Thus, one-by-one search through numerically represented gray levels of each recognition element may often be abandoned in favor of more practical reliance on a goal-oriented algorithm to identify the required gray level. The approach sometimes reduces the time costs by as much as 90 percent.

As an example we list below the procedures of a problem-oriented system used by the Space Research Institute of the USSR Academy of

Sciences to handle multispectral images [16]. These are:

—multispectral video file procedures;
—generation of a work file using the desired fragment angle coordinates and spectral bands;
—geographic referencing of an image and its conversion to a desired projection;
—presentation of a given spectral channel on a display peripheral;
—calculation of a gray-level histogram, an average gray-level vector or other image characteristics of interest;
—generation of a linear combination of multispectral images;
—representation of classification data in a desired projection.

The user is free to invoke any or all of the above procedures to accomplish his goal.

**Multispectral image processing with minimum delay.** Because spaceborne multispectral imaging sensors deliver a huge amount of the Earth's surface data, the conventional computer techniques cannot satisfy the time constraints of operational tropical cyclone detection, taking too long to process each image of the target area.

Data handling efficiency can be speeded up by using optoelectronics to analyze the spatial spectrum [14]. This method is most effective when applied to detect the incipient tropical cyclone of a moderate size close to the image resolution. The transparency of a multispectral image taken from orbit can accommodate the radiance, spectral, and geometric characteristics of ground features. When the transparency is illuminated, the image data modulate the amplitude and phase of the light wave. One can then derive the spatial distribution of light intensity, or the *Wiener spectrum*, to retrieve the spatial frequency spectrum and thereby explore sea and ocean surface. The end result of such structural analysis appears as the output of the opto-electronic image analyzer.

The analyzer generally comprises a light source, a transparency in the form of a photo-plate or film, optics to focus the light beam to illuminate the transparency, an image converter, and a receiver. The receiver output is accepted either by a video display or a computer—the very features identifying tell-tale characteristics of the tropical cyclone and enabling the multispectral image analyzer to investigate the sea roughness structure using radiation intensity.

**Coordinate image referencing.** Coordinate referencing and transformation to a desired cartographic projection are important image processing activities enabling the analyst to follow the behavior of the atmospheric and ocean parameters of interest and thereby to progress faster towards the detection of a tropical cyclone. As video images are often digitized prior to being transferred to magnetic media, there is much advantage attached to computerized image referencing and conversion to a given projection, not least by saving on the time costs. For example, with a magnetic tape unit employed as a direct access store it takes only 10 minutes to transform a 500 × t00 pixel array; for a disc the time is cut back 8urther to 4 minutes [16].

**Operational data analysis.** The prime objective in undertaking the operational analysis of remote sensing instrument data is the evaluation of state of the ocean-atmosphere system. Besides appraising the remote-sensing data inputs, the analyst (habitually a meteorologist) monitors on-board and on-earth equipment performance, checks the data for rate and integrity and times the subsequent processing steps.

Fast access to any desired data record is essential to success and speed of the operational analysis. It should be recalled that the ground-based weather analyst has to go through an enormous amount of satellite-derived data to detect a burgeoning tropical cyclone. The data typically reside in magnetic storage (tapes or discs). Even if customized software were to be used to print them out in the best and most compact man-readable form the analyst would have to go through an enormous pile of paper.

The procedure is very tedious and much delaying the analysis. Besides, a repeated reference to the same record would require of the analyst yet another laborious search through the information of no further use to him. One way to expedite things at this stage is by use of a facility that locates a record using various keys (the time reference, the frame number in the session, etc.) and displays it on the VDU screen in an easy-to-read form or else prints it out.

Under one plausible flowchart of satellite-derived data analysis [16] the operator interacts with the computer from his keyboard; the system allows him to set the data format for the display, he can also decide on the time to keep the frame in the refresh store and the way to replace the display. The contents of the VDU screen can be moved by scrolling or page turning. Scrolling implies that the contents of the screen move up or down, a line at a time, so that each "image" differs from the previous one by two lines, the first and the last. This looks like a live overhead news bulletin where any two successive "images" differ by two letters. With page turning the entire display changes to a new one. The operator is free to alter any time the data format and the presentation procedure, and it is he who controls the analysis rate by setting the pace at which the frames are scanned.

### 12.3. Recognition of Tropical Cyclones on-Board the Unmanned Satellites

Unattended data processing and analysis on-board the satellite significantly slash the delay in detecting tropical cyclones. To this end, the satellite must carry one or several digital computers providing a sufficient data-processing capability for the recognition of target features and objects. The on-board computers, remote sensors and storage units make up a data acquisition system. The latter serves to

—switch the sensors on and off as commanded by the timer or by parameter settings;
—poll the sensors at various rates;
—calculate atmospheric and ocean parameter characteristics;
—check the sensors for error-free operation;
—format the measurements as required;
—load the data into a long-term storage;
—average the measurements over a given period;
—compare instantaneous parameter values with those averaged over some preceding period;
—use the comparison results to generate a signal if a tropical cyclone has been detected;
—send a command to the relevant on-board systems to locate the typhoon;
—transfer to the downlink the data of interest to ground-based weather analysts;
—pass the cyclone's location data to the cyclone path predictor, attitude control system, descender deployment controller, etc.

Software development for the spaceborne data-handling system must take into consideration the complexity of the hardware used as well as the memory, speed, and accuracy requirements. Each cyclone-detection algorithm is individualized, that is, tailored to the phenomenon to be observed and keyed down to its physics. Other application for the system comes in the analysis as performed by the ground-based operator. Indeed, the limited capacities of the downlinks and on-board data storage do not allow the operator to poll the sensors frequently enough or analyze atmosphere parameters during tight schedules. One can get around the limitation if the satellite software can itself accomplish a large effort in scanning and analysis of physical parameters of the ocean and atmosphere in order to recognize their changes pointing to a tropical cyclone such as pressure and temperature leaps in the near-surface layers or variations in wave height and wind speed.

The on-board software must naturally be debugged and tested in conjunction with the hardware to make sure both perform up to standard. With this goal in mind the on-board facility is emulated by a ground-based general-purpose computer. The emulator enables the programmer to debug the satellite software, notably the data processing and tropical cyclone detection algorithms; verify its reliability, and eliminate errors using the language of the on-board computer. At the design stage the emulator and the relevant environmental models serve as a benchmark package to choose the best data-processing algorithm. Simulated data inputs are provided either by appropriate analytic atmosphere and ocean models or by models derived from the real-world telemetry acquired in previous missions [16]. The latter type model would typically describe nonstationary processes and the data-processing system's responses to them provide essential inputs for the instrument package designers.

Jointly simulated data-handling algorithms and sensor outputs help evaluate the algorithm's performance on the two-fold criterion of the algorithm response and the computational capabilities needed to support the processing function on-board the satellite. The latter are inferred from the speed and memory requirements.

Simulation experiments have demonstrated that the designer has a variety of on-board computer system alternatives to choose from [16]. With a single on-board computer, data acquisition and processing are controlled centrally. Thus one can easily vary the polling rate, the effective instrument range or the sensors' mode of operation. The centrally-controlled configuration simplifies data transfer to ground stations and communication with the ground-to-satellite link that transmits control commands. The configuration also improves hardware utilization efficiency. Unfortunately, this scheme involves stringent computer speed and memory requirements and moreover the supporting software is much too complex.

Another possible scheme operates several equal-status computers, each being less powerful in terms of speed and memory and with simpler hardware. Each computer serves one or several sensors, reducing the net time costs and power supply requirements. While focused on the Earth from orbit, the sensors do not need to operate concurrently, and at any given instant several of the computers will be off. One structural advantage of this configuration is that the array of scientific instruments may be wired fast to a computer. The problems of the system stem from its somewhat "extravagant" use of hardware resources and lack of centralized control of data processing.

The best trade-off is to employ a hybrid system [16] with a host computer and several front-end processors. The host computer controls the front-end computers, polls them, and communicates with other spacecraft systems. The front-end processors have the status of subscribers and are accessed as such while their functions are independent and their software need not meet any stringent speed requirements. The host is capable of simultaneously processing data inputs from several sensors.

In summary, a spaceborne data-handling system offers several advantages over an earthbound one as it drastically reduces processing time and helps detect a tropical cyclone much faster. It can do with an unsophisticated I/O interface as the sensor outputs are directly applied to the computers and passed on to other spacecraft systems. Finally, the system's computer works on a smaller number of tasks, so making its software more manageable.

### 12.4. Ocean and Atmosphere Observing Satellites

Much consideration is being given to the design and development of low-orbiting satellites to monitor the ocean and atmosphere. These are *Meteor* (USSR), *Tiros-N* (USA), *Topex* (USA), *MOS* (Japan), and *ERS* (the

European Space Agency, ESA). Their specifications are given below.

*Meteor*. Figure 10 presents the *Meteor* configuration [19]. The payload comprises an instrument bay with sensors selected as required [19].

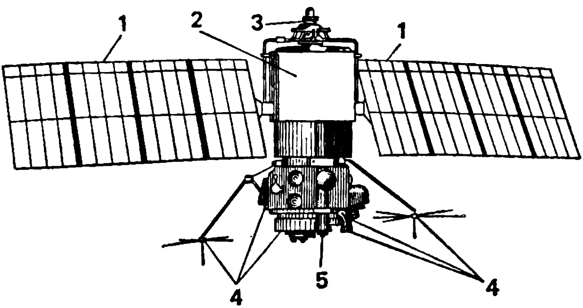



Fig. 10. The *Meteor* weather satellite:
*1*—solar battery panels; *2*—thermal control screen; *3*—solar panel orientation sensors; *4*—antennas; *5*—payload module

A scanning telephotometer is used to derive the local cloud pattern during daylight hours. The sensor operates in the 0.5-0.7 μm band and images over a 2100-km wide swath with a resolution of 2 km. It transmits the images to ground on-line with no on-board recording.

The global cloud pattern is mapped during daylight hours by a scanning sensor similar to a TV camera and operated in the same 0.5-0.7 μm band. The sensor scans in swaths 2200 km wide with a resolution of 1 km, records the image obtained and relays it to a ground station when the satellite enters the latter's area of radiovisibility.

Another on-board instrument with image-storing capability is a scanning infrared radiometer. It detects and tracks cloud cover in the dark hemisphere and measures the radiation temperature of the underlying surface on a global scale. The sensor scans across a 2600-km swath. It has a resolution of 8 km and uses the 8-12 μm band.

The global atmospheric temperature measurement is done by a multichannel scanning infrared radiometer sensing at seven wavelengths: 11.1, 13.33, 13.7, 14.24, 14.43, 15.02, and 18.7 μm. The radiometer scans in swaths 1000 km wide with an angular resolution of 2°. *Meteor* may also carry other instrumentation. For example, it can perform multispectral cloud and surface imaging using multispectral scanning sensors with a low resolution of about 1 km or a medium resolution of several hundred meters. A microwave radiometer that operates in the Ka- (0.8 cm), the K- (1.35 cm), and the S-band (8.50 cm) secures information about the atmospheric moisture content, precipitation pattern and rain intensity.

*Tiros-N/NOAA*. The US National Oceanic and Atmospheric Administration (NOAA) regularly launches the *NOAA* series of weather satellites. Their orbit has an altitude of 830 to 870 km. The first *Tiros-N/NOAA* satellite was placed on orbit in 1979 [35]. *NOAA* has replaced the *Tiros* series as the second generation weather satellite series. Eleven spacecraft of this series are to be built by 1990 [32].

The first five *Tiros-N/NOAA* satellites belong to the *Tiros-N* series proper. The others feature a modified design and incorporate additional instruments; they are known as *Advanced*

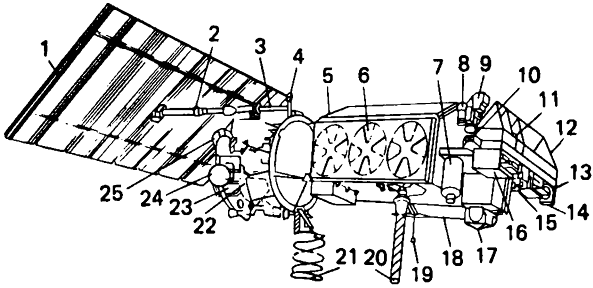



Fig. 11. *NOAA* spacecraft:
*1*—solar array; *2*—solar array drive motor; *3*—array drive electronics; *4*, *19*—omnidirectional antennas; *5*—equipment support module; *6*—thermal control pinwheel louvers; *7*—Earth sensor assembly; *8*—high energy proton and alpha particle detector; *9*—medium energy proton and electron detector; *10*—solar sensor detector; *11*—inertial measurement unit; *12*—instrument mounting platform sunshade; *13*—payload; *14-17*—radiometers; *18-21*—antennas; *22*—battery modules; *23-25*—reaction control system

*Tiros-N* (*ATN*) spacecraft. The principal manufacturer of the satellites, RCA Corporation, has developed several versions of *Tiros-N* differing in structural design and observing instrument suite. Figure 11 illustrates the *Tiros-N* configuration [32]. The satellite lift-off weight is 1418 kg and the in-orbit weight is 737 kg. In real *NOAA* launches the weight was somewhat different [38].

The spacecraft carries a 230-kg payload. The satellite, including an injection motor assembly, is approximately 3.71 m in length and 1.88 m in diameter. The power system provides an average load capacity of 420 W in the worst-case operational environment.

In sunlit portions of the orbit, power is supplied by an 11.6-m$^2$ solar array made up

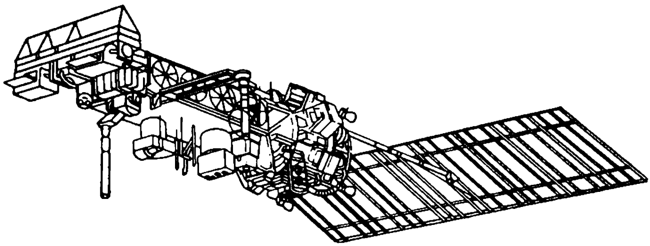


Fig. 12. Advanced *NOAA* series of spacecraft

of eight panels of solar cells, 2.38 × 0.61 m each. During the satellite's flight in orbit, the preset direction of the panel toward the Sun is maintained by a special drive. Two 26.5 A-h Ni-Cd batteries supply spacecraft power during dark portions of the orbit. The *ATN* satellite (Fig. 12) is provided with a payload complement including a search and rescue system, *Sarsat*, complete with repeater and processing units. The spacecraft body thus had to be elongated by 0.5 m and the planned launch weight, plus the apogee motor, increased to 1693 kg. A *NOAA* satellite can operate in circular near-polar, sun-synchronous orbit at a nominal altitude of 850 km.

The *Tiros-N* instrument package can make measurements of ocean and atmospheric parameters on a global scale and observe near-Sun space; it can also support search and rescue operations. Its data collection and location system services automated terrestrial and atmospheric scientific platforms; the facility receives data from the platforms, relays them to ground, and computes the location of a platform when necessary. One or two satellites are always in orbit to provide service. Let us elaborate a little on the key environmental instrumention carried by the *Tiros-N/NOAA* spacecraft [26]. It features primarily three different radiometer types.

Known together as the *Tiros* operational vertical sounder, this three-instrument group consists of: 1) the High Resolution IR Sounder (HIRS/2): 2) the Stratospheric Sounding Unit (SSU); and 3) the Microwave Sounding Unit (MSU).

The HIRS/2 is a 20-channel instrument that measures incident radiation in the IR spectrum between 0.69 and 15 μm. Data from the HIRS/2 yield atmospheric temperature profiles from the planetary surface to the top of the atmosphere (1 mb), water vapor content at three layers from the surface layer to the tropopause, and the total ozone content. The field-of-view of each channel is 1.2°. The scanning time is 0.1 s or less. The HIRS/2 spatial resolution is 17.5 km and its temperature accuracy is approximately 1.5-2°. The channels have various maximum sensitivities that fall in the 240 to 340 K range.

The SSU operates in three channels. The primary objective of the instrument is to obtain the stratospheric (25-50 km) temperature profile. The unit has a resolution of 150 km.

Since clouds interfere with HIRS/2 measurements, the MSU is used to produce atmospheric temperature profiles in a cloudy environment. The MSU is a 4-channel Dicke radiometer with a resolution of 110 km.

A new microwave sounding system is under development in the USA to replace the second and third type radiometers. Out of its twenty spectral channels fifteen will sense the atmosphere below cloud cover, even in stormy weather. The other five channels will measure the moisture content of the troposphere. The system is enhanced with respect to the SSU and MSU, because the spatial resolution at nadir for temperature will be 40 km, compared with the 110 km of the MSU. The instrument provides moisture content, sea ice extent and rain cloud pattern with a resolution of 15 km.

High-resolution day and night cloud mapping and sea surface temperature estimates are essential for rapid typhoon detection on a timely basis. The task is addressed by the Advanced Very High Resolution Radiometer (AVHRR), a 4-channel scanning radiometer sensitive in the visible and infrared window regions. Channel 1, 0.55-0.90 μm is allocated for daytime cloud mapping. Channel 2, 0.725-1.1 μm is reserved for surface water delineation. Channel 3, 3.55-3.93 μm is used for sea surface temperature measurements and day and night cloud mapping. The instrument is being upgraded. A fifth channel will be added on a future AVHRR and the operating wavelength bands will be: 0.58-0.68 μm for channel 1; 0.82-0.87 μm, channel 2; 1.57-1.78 or 3.55-3.93 μm, channel 3; 10.3-11.3 μm, channel 4; and 11.5-12.5 μm for channel 5. Note that only one band of channel 3 will be used at a time: the first is expected to be used for imaging in daytime hours and the second in night-time hours. The resolution is 1.1 km at the satellite sub-point. The fifth channel is used to provide daytime cloud observations which will assist in distinguishing between snow and clouds.

Other instruments may also be incorporated on a future *Tiros-N* mission. An example is a laser instrument to measure atmospheric winds, called Windsat. It will use a Doppler lidar to measure radiation from a laser beam shot toward the Earth from the *Tiros-N* platform and reflected back to the instrument by windborne tracers such as dust. Wind speed and direction will be determined by frequency changes in the reflected radiation; these were earlier said to be crucial parameters for typhoon detection.

*Topex*, a series of oceanographic satellites which are designed to support an ocean-science program, the Ocean Topography Experiment. *Topex* will yield both operational and research data. The operational data, to be available within 10 hours of acquisition, include wave heights, current and wind parameters, and the satellite height above the

Earth's surface. For research purposes *Topex* will provide time-averaged data on ocean behavior and satellite attitude [21, 40].

*Topex* will weigh around 1500 kg at lift-off. The orbit chosen for the satellite is 1300 km high, circular, and inclined at 65°. The satellite will cover the same parts of the globe once in 10 days. The first *Topex* will be launched in 1989 and from either a space shuttle or the Ariane launch vehicle. The instruments to be flown on *Topex* are: a radar altimeter, microwave radiometer, laser retroreflector array, Doppler beacon, and tracking system. The data-handling arrangement adopted is to record observations on board and relay them to ground when convenient. The radar altimeter is expected to measure wave height with an accuracy of about 14 cm. The primary measurement frequency is Ku-band (13.6 GHz), the second auxiliary frequency is C-band (5.3 GHz). The microwave radiometer is used to check the altimeter measurements. The on-board laser retroreflector array makes an independent height measurement from a laser site to calibrate the radar altimeter. The Doppler beacon is a prime instrument for orbit determination.

*ERS*. In the late 1980s the European Space Agency plans to launch *ERS-1* for the exploration of natural resources of the seas and oceans. *ERS-1* observations will facilitate typhoon detection and tracking. Another mission objective is to improve weather forecasting, to promote safer ship-routing and offshore and coastal project planning, and to design for oil rigs, ports, etc. Figure 13 depicts the key features of *ERS-1* [27]. The satellite will be placed on a circular sun-synchronous orbit

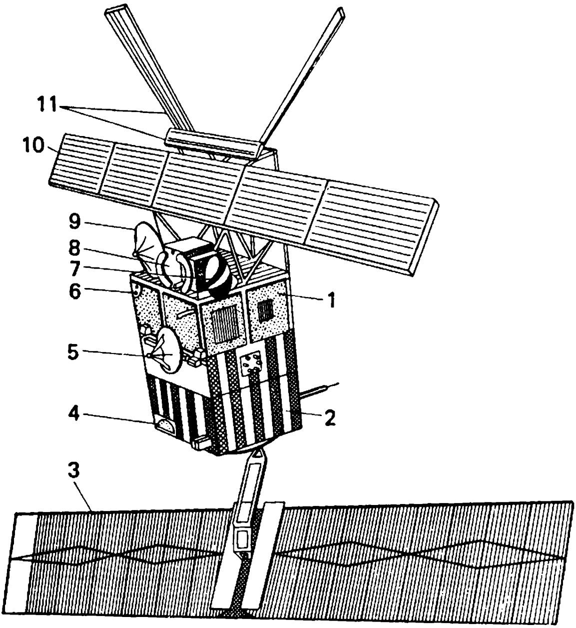



Fig. 13. *ERS-1* in-flight configuration:
*1*—payload module; *2*—service module; *3*—solar array; *4*—precision range and range rating equipment; *5*—instrument data handling and transmission system antenna; *6*—laser retroreflector; *7*—microwave sounder; *8*—infrared along-track scanning radiometer; *9-11*—antennas.

at an altitude of 780 km. Its active lifetime is expected to be 2 to 3 years: the principal constraint is the limited amount of propellant for the thrusters that make orbit corrections and provide attitude control. The life expectancy of the on-board data storage is approximately the same. *ERS-1* will weigh 2160 kg when launched from the Earth. This launch weight includes 900 kg of payload and 300 kg of the thruster propellant hydrazine—enough to permit the satellite to change orbit in order to observe specific parts of the World Ocean. Power supply is provided by a 2.2-kW solar array and four Ni-Cd batteries (96 A-h).

We will now outline the core set of scientific instruments *ERS-1* will carry.

One core sensor is called the Active Microwave Instrumentation (AMI); it can operate as either a radar or a scatterometer using different antennas. Ocean imaging and wave spectrum measurements rely on the Synthetic Aperture Radar (SAR). The SAR antenna is a 10-$m^2$ planar array (*10*, Fig. 13) that allows imaging over an 80-km swath that lies 250 km off the satellite ground track.

The scatterometer employs three smaller planar antennas (*11*, Fig. 13) directed to 45°, 90°, and 135° with respect to the flight direction. The AMI operates in the C-band (5.3 GHz) and measures

—sea-surface wind speed within the range 4 to 24 m/s with an accuracy of $\pm 2$ m/s or better;

—sea-surface wind direction with an accuracy of 20° for any direction;

—wave direction with an accuracy of 15° for any direction;

—wavelength between 50 and 1000 m with an accuracy of 20 percent.

The AMI has a spatial resolution of 100 m or better for the entire image swath.

The other basic sensor is a radar altimeter that operates in the Ku-band (13.7 GHz). It uses an antenna 1.2 m in diameter (*9*, Fig. 13). The altimeter derives the height above the sea surface with an accuracy of 2 m or better. Wave height measurements yield an accuracy of about 0.5 m for the wave heights that fall in the range 1 to 20 m.

*ERS-1* also carries an Infrared Along-Track Scanning Radiometer and Microwave Sounder. The instrument measures sea-surface temperature with an accuracy of $\pm 0.5°$ within a 50-km swath. It also estimates the atmospheric water vapor content with an accuracy of 10 percent within a circle 25 km in diameter, i.e. within the spot scanned by the microwave sounder.

*MOS-1* (Japan) is used for studying natural resources of the oceans and seas. It is currently planned for an active operational life of two years. The total spacecraft weight is expected to be about 750 kg. The planned orbit for *MOS-1* is sun-synchronous with a height of 910 km and an inclination of 99.1° [23]. The satellite will repeat the ground track every 17 days. Figure 14 shows the *MOS-1* configuration. The payload comprises three radiometers with multispectral, microwave and conventional sensing capabilities.

The Multispectral Electronic Self-Scanning Radiometer (MESSR) scans in swaths 100 km wide, using four wavelength bands between 0.51 and 1.1 μm. Based on MESSR measurements, a sea surface color can be worked out. Changes in this color may indicate pollution or plankton-rich regions suitable for fishing. The MESSR has a resolution of 50 km.

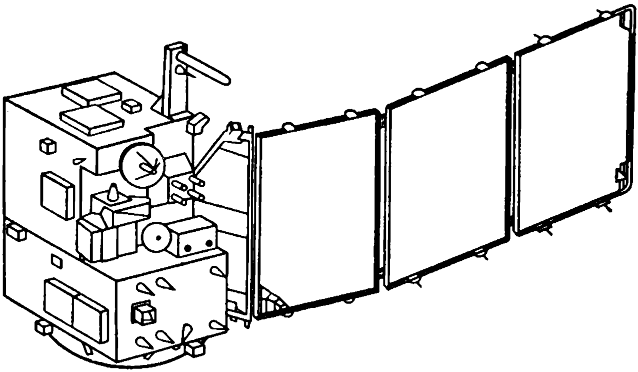


Fig. 14. *MOS-1* spacecraft

The Microwave Scanning Radiometer is used to measure water vapor content of the atmosphere. The instrument consists of two Dicke type radiometers making a conical scan across a 320 km swath beneath the spacecraft. The first radiometer operates in the K-band (23.8 GHz) and has a resolution of 31 km; the second, with a resolution of 21 km, operates in the Ka-band (31.4 GHz) [23].

Sea surface temperatures will be measured by the Visible and Thermal Infrared Radiometer. It can scan across a rather wide swath of about 1500 km with a resolution of 2.7 km using visible and infrared wavelength bands

(0.5-0.7 μm along with 6-7 μm and 10.5-12.5 μm).

Let us note that the instrumentation is being enhanced. For example an upgrading of the VTIR is expected to improve its resolution to 1 km. Besides, new sensors to carry on *MOS-1* are under development [23]. One of them is a radar altimeter that measures wave height with an accuracy of 10 cm; another instrument is a scatterometer that yields wind speed with an accuracy of 2 m/s and wind direction accurate to within 20°.

## Sec. 13. Operational Detection of Tropical Cyclones from High Orbits

Sensing the Earth from satellites in high orbits provides sufficient imaging coverage in the visible for almost the entire sunlit hemisphere and in the infrared and radio infrared for the whole visible hemisphere. But, once the satellite is injected into a stationary orbit and begins imaging from 36 000 km, a visible arc of the hemisphere in one image is 160° [5]. However at the edges of the arc the effect of perspective and the atmospheric density interfere with image interpretation, thus imposing on useful imagery a penalty of 10 to 20° to either side of its field-of-view.

One other current method of full global coverage employs composition of the TV images derived from weather satellites in low-circular orbits. The composition procedure is computerized to permit automatic conversion, composition, and coordination of the images. However local TV image mosaics have several disadvantages compared with the single Earth hemisphere image.

The key advantages of the space imagery returned from high orbits are [5]:

—large area coverage in one image, faster data acquisition and conversion, and capability to obtain synchronous images of two far-flung areas on Earth;

—rapid image transmission to ground-based facilities without prior on-board storage and the absence of distortions associated with composing local images such as excessive mosaic patterns, photometric and geometric incompatibility, etc.;

—capacity for repetitive imaging at short time intervals (every 20 to 30 minutes).

A drawback of the high-orbit Earth imagery is its distortion because the spherical surface projection is much too inaccurate, hemispheric solar illumination nonuniform and atmospheric optical depth different at extreme points in the image [16].

The global imagery taken from the 36 000-km orbit has an effective resolution around 10 km, against the one-km resolution of regional images.

Four geosynchronous satellites orbiting at an altitude of 36 000 km are sufficient for global coverage to incorporate any region on the Earth. They can yield on-line information on the state of the Earth's surface and clouds at any time of the day and in any area around the world; the only poorly observable regions are those farthest-removed from the orbital inclination.

The geostationary satellites of proven usefulness to monitoring for the origin and development of tropical cyclones have been, to date, the *GOES* series, USA; *Meteosat*, ESA; and *Himawari*, Japan. A brief description of each satellite system follows.

*GOES*. A system of two satellites in geostationary orbit is focused on weather in the US territory and those of the neighboring countries and adjacent ocean regions. From its "station" at 75° West longitude the first of these, known as *GOES-East*, encompasses in its field-of-view the eastern United States and nearby Atlantic Coast. The second satellite, *GOES-West*, stationed at 145° West longitude, looks down on the western United States and adjoining areas in the Pacific Ocean. But because the hurricane season on the East Coast is out of phase with the typhoon season on the Pacific Coast full coverage can sometimes be achieved with one of the satellites moved from one station to another on a timely basis.

By 1985 there had been six orbiting *GOES* satellites, with two other systems in the development stage and five more about to be ordered by the US National Oceanic and Atmospheric Administration [30].

The general *GOES* configuration, as shown in Fig. 15 [22], comprises the following principal features and systems: high gain antenna *1*, omni antennas *2* and *3*, radiometer *4*, heat shell *5*, magnetometer bus *6*, attitude control thrusters *7* and *8*, Earth-pointed sensors *9* to locate imagery with respect to the Earth, solar sensors *10*, *11*, and *12*; solar arrays *13*, high-energy particles detector *14* and X-ray detector *15*.

Upon insertion into stationary orbit, *GOES* weighs 400 kg with a height of 3.7 meters

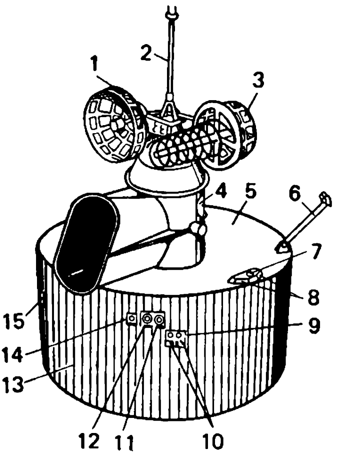



Fig. 15. *GOES* satellite

and a diameter of 2.1 meters. Moving on the orbit, the satellite spin-stabilizes itself at an angular speed of 100 rpm. The power supply system feeding from the solar arrays should maintain a minimum of 320 W.

Radiometer *4*, the key feature of the *GOES* satellite, has one visible and twelve infrared channels which, together, provide essential coverage of the vertical atmospheric profile with respect to temperature and water vapor content at specific altitudes. The information can give important insights into typhoons with their characteristic vertical cloud structure. The radiometer offers imagery at 30-minute intervals and with a 30-km resolution as it sounds the vertical profile of moisture and temperature over cloud-free surfaces and a resolution of 60 to 90 km over cloud-covered regions. The resolution is much improved for Earth surface soundings to 0.9 km in the visible and 6.9 km in the infrared at night.

In ocean-observing applications, the *GOES* imagery comes in on special displays at ground data acquisition and processing stations. When forecasters spot down a region in the ocean with signs of possible typhoon events they command the satellite to take focused temperature and water soundings in the area and utilize them to more accurately forecast weather and the progress of typhoons.

The forward-looking *GOES* models will, as do the now operational satellites, perform cloud imaging and take temperature and moisture soundings in the vertical atmospheric profile. Several alternative designs are now under review for implementing these goals [30]. The first involves two radiometers *4* mounted on a spin-stabilized satellite platform. The second, also spin-stabilized design, is expected to carry one radiometer *4* and one special-purpose instrument capability to measure temperature in areas on the Earth's surface; this feature will be installed on a platform fitted with a spin-off system. The third, and last *GOES* alternative will be a three-axis stabilized one, with one radiometer *4* being installed.

Whatever design is picked up, it is bound to be furnished with two transceivers instead of the previous one to make possible continuous transmission of instrument readings concurrent with relaying meteorological information that will include synoptic charts.

*Meteosat*. A number of West European states collaborated on the *Meteosat* project—Belgium, Great Britain, Denmark, Italy, France, West Germany, Switzerland, and Sweden.

The 700-kg satellite [33, 34, 36] features a three-channel radiometer capable of yielding images of clouds and underlying surface every 25 minutes. The first channel senses in the visible, the second in the near-infrared and the third in the infrared—the region consistent with the absorption band of water vapors. *Meteosat* is placed onto a stationary orbit, the station being right above the Greenwich meridian to enable coverage of Europe, the Middle East, and Africa. The imagery will be transmitted to a ground monitoring station in West Germany to be processed at the *Meteosat* command and control center. After that the information is to be relayed via the same *Meteosat* satellite to many countries. So far the operating experience with *Meteosat* has been rewarding in that its information has in fact lessened errors in weather forecasting. For the European countries involved in the

*Meteosat* project this forecast accuracy gain over the satellite's operational life from 1978 through 1984 had been 4 percent for very short-term weather forecasts (less than 12 hours), 7 percent for short-term forecasts (12 hours to four days), and 7 percent for medium-range forecasts (four to ten days). For the African countries the percent improvements of forecast accuracy were 11, 14 and 16 for the very short-term, short- and medium-term forecasts, respectively.

*Himawari.* The satellite, weighing 300 kg, is injected into its station over 140° East longitude [33]. It is fitted to transmit to the Earth images of cloud cover every 30 minutes and relay the meteorological information collected from the ships and aircraft to the data acquisition center. Its principal capability, a radiometer, takes soundings in the visible, 0.5-0.75 μm, and infrared, 10.5-12.5 μm, bands; their respective resolutions are 1.25 and 5 km.

Chapter 4

# Scientific Instrument Deployment from Orbit into Tropical Cyclone

## Sec. 14. General Scheme of Descent

A thorough investigation into the physics of mass-energy exchange between the atmosphere and ocean is the main purpose to be served by placing scientific instrumentation on-board the satellite into the effective range of a tropical cyclone in the hope to better understand the mechanisms of its origin and development during the life-cycle and to more accurately locate the cyclone center.

Atmospheric and ocean parameters are measured by instruments inside the buoys floating on the ocean surface or submerged to some depth and the gondolas of the balloons wind drifting at specified heights. For an effective study of tropical cyclones it should be practical to have a maximum possible range of balloon drift heights (1-2 km to 15-20 km) and a sufficient depth of buoy measurements (to 500 m below sea surface) of ocean parameters. Balloons and buoys can be rapidly deployed by a probe jettisoned from orbit to any desired location around the world.

Figure 16 illustrates a general flow of balloon and buoy deployment from orbit. Conceptual-

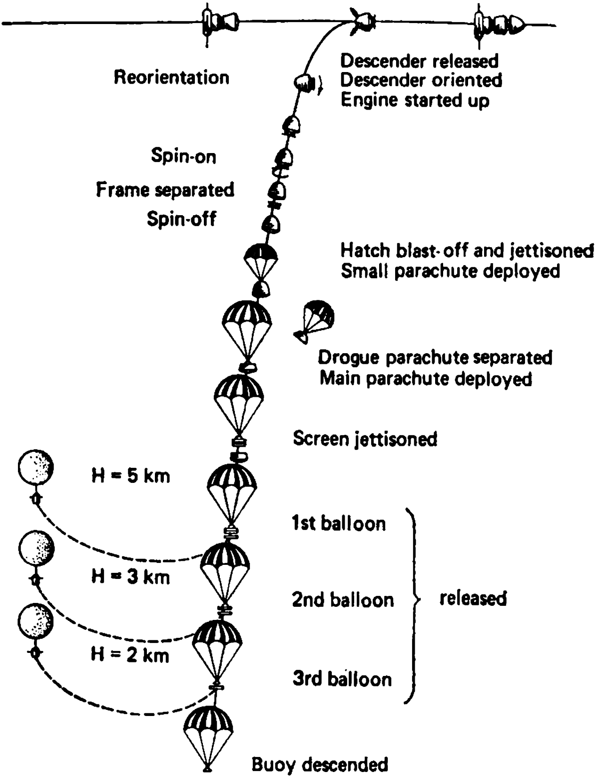



Fig. 16. Deployment flow of balloons and buoys from orbit

ly it is assumed that the multiprobe orbital vehicle carries three descenders, each with three balloons and one buoy.

The central part of a tropical cyclone, i.e. the region in and around the "eye" of the storm, provides the most attractive target for exploration, being the very portion in the typhoon or hurricane to which the measurement instrumentation should be delivered. But because this area is relatively small—a few tens of kilometers across—it is by no means an easy task to target it from an orbit a few hundred kilometers up and away from the cyclone. That is why a thorough-going preparation is needed prior to the launch episode.

Descender deorbiting and progress through the dense atmosphere are simulated on ground-based computers. The quest for required parameters proceeds by dedicated algorithms employing models of atmospheric probe descent and tropical cyclone motion over the Earth's surface. These parameters pertain to the instant the probe comes off the orbit, or its deorbiting point; the operational time required by the on-board motor to release the descender; the thrust and its direction. The more closely the calculated parameters are maintained, the higher will be the accuracy of deploying the balloons and buoys to the tropical cyclone center.

Upon establishing the deorbiting parameters they are coded and transmitted via the command link to the satellite which, generally speaking, may carry more than one descender. Shortly before the thrust braking, the descender and its systems begin to be prepared for deorbiting. First, the orbital module with its descent probes needs to be properly oriented using the thrusters of the attitude control subsystem run by the on-board orbit control system. The probe separation system and its programmable timer are actuated by a command from the mission control, whereafter the timer takes over control of all further preparation, deorbiting and atmospheric descent. Special devices perform separation of the descender from the orbital module, following which it is oriented in space as described earlier. The probe, its brake engine on, deorbits and makes a speedy, 8-9 km/s, entry into the atmosphere, assuming its upper boundary of 80 to 100 km. During the atmospheric descent the air drag to which the probe is exposed damps much of its entry velocity.

Although after the main airbraking stage the probe descent velocity is kept down to 100-200 m/s, it still remains too high for the descender to release safely into surroundings the balloons it carries. Further speed dampening is achieved with a parachute system: by command from the programmable timer the hatch of the parachute bay is blast-off and a small parachute is deployed, drawing away the thermal protection shell and the frontal screen of the descender; both the shell and the screen shield the descender against the impact of intense heat flows developing along the strong airbraking segment but are dropped when the heat protection is no longer needed. Then the main parachute is pulled out, inflated, and deployed. The vehicle's rate of descent slows to several meters per second—a low enough speed for the safe release of the balloons which come into operation one after another at specific heights. This is achieved with another

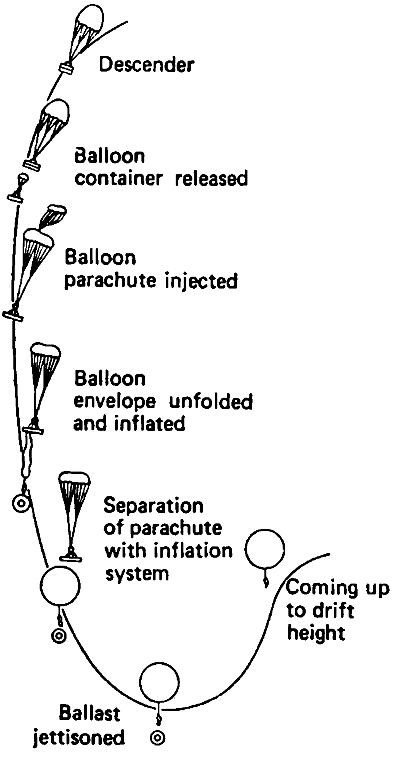



Fig. 17. Balloon deployment flow

system of parachutes performing each of its assigned functions (Fig. 17). One of them is used to control the attitude of the balloon container and partially damp its velocity, to be jettisoned from the system after that. Another parachute attains the main speed reduction to acceptable levels (5 to 10 m/s) for the release and inflation of the balloons.

The balloon begins to function as the container is separated from the parachute-carried probe. The container bottom (ballast) is dropped pulling out the balloon envelope and gondola. Then the programmable timer sends a command to open the blast valve and inflate the balloon envelope with lifting gas from a specially designed gas-balloon system. When the balloon envelope has been inflated the supply pipeline in its top portion is pressurized and the parachute separated from the balloon, integral with the inflation system.

To draw the parachute with the inflation system away from the balloon requires the use of the container bottom, ballast, which is jettisoned only upon reaching a necessary gap between their respective heights. And even though the horizontal wind may change very slowly with height this will make sure that the parachute is pulled away from the balloon far enough to prevent their collision. Only then is the ballast released by a command from the threshold sensor.

Once the ballast has been jettisoned the balloon is braked by the combined action of the drag and aerostatic forces. It reaches the point of maximum sinking at which its descent velocity becomes zero, and then begins ascending to the equilibrium height for which the condition implied by Archimedes' principle is valid:

$$\rho_a \cdot V = m_g + M$$

where $\rho_a$ is the atmosphere density at the equilibrium height; $V$ is the balloon volume; $M$ is the net mass of the balloon and its payload; $m_g$ is the gas mass.

The excess pressure of the gas relative to ambient at the equilibrium height can be found from the ideal gas equation of state

$$(p + \Delta p) \times V = \frac{m_g}{\mu_g} RT_g$$

where $p$ is ambient pressure; $\Delta p$ is excess pressure; $R$ is the universal gas constant; $\mu_g$ is the molecular weight of the gas; $T_g$ is the absolute temperature of the gas.

At the equilibrium height the balloon strikes a heat equilibrium with the environment and is drifting with the air flows relative to the Earth.

The descender minus the first balloon continues its downward motion on the main parachute deploying at specified heights the remaining balloons. All that is left beneath the main parachute is the buoy with the weather instrument unit about to be landed on the ocean surface.

This general flowchart of descent into the eye of the typhoon leaves us with some essential details we have not touched-upon yet but will move on to discuss now.

## Sec. 15. Satellite Orbit Selection

The question of how to select orbital parameters so as to maximize the usefulness of remote sensing instruments for observing tropical cyclones was considered in Chapter 3. As we have seen, the orbit choice made by the flight planner is dictated by characteristics of the launch vehicle; the payload to be launched; constraints attributed to performance characteristics of the on-board orientation and control systems; the satellite's required operational life; radiovisibility from the measuring and tracking stations on the USSR territory; the situation for surveying the birth and migration of a tropical cyclone in a given ocean region; and the physical setting for satellite data transmission to ground-based stations. The conditions pertaining to delivery of balloons and buoys into the effective area of a tropical cyclone have been left out though they can noticeably affect deployment.

The discussion that follows will deal with ways to select two key parameters of a circular satellite orbit, height $h$ and inclination $i$. The requirement to minimize the distance between earth surface projections of two successive orbits so as to heighten the success rate in taking the balloons or buoys into the tropical cyclone can be used as the criterion of optimality.

*Orbit-to-orbit distance* $\Delta l$ measured at the equator as a function of orbital inclination $i$ for several circular orbit heights, $h_c$, is given in Fig. 18. Obviously the orbit-to-orbit distance $\Delta l$ decreases with lower $h_c$. Thus, the change of altitude from 650 to 450 km reduces the $\Delta l$ value from 24.8 to 23.75° for the orbits with $i = 51°$. Going to higher orbital inclinations produces the same effect. With $i$ magnified from 40° to 80°, the orbit-to-orbit

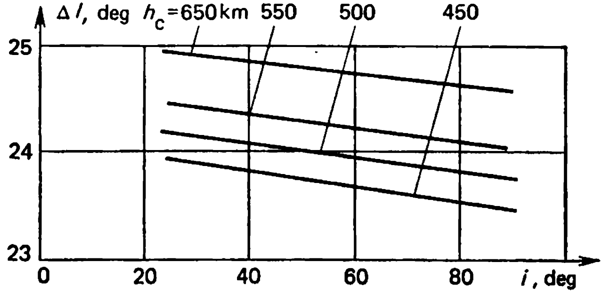



Fig. 18. Orbit-to-orbit distance $\Delta l$ measured at the equator as a function of orbital inclination $i$

distance diminishes from 24.1 to 23.85° for $h_c = 500$ km. Thus the satellite injection into a circular orbit with the least possible height $h_c$ and largest inclination $i$ seems practical from the standpoint of more accurate descender touch-down in the effective range of the tropical cyclone. The daily satellite track deviation at the equator should be minimized to provide good conditions for descender landing in a tropical cyclone and for its subsequent radio communication with the parent orbital module. As suggested by the relationships in Fig. 19, the diurnal shift $\Delta l_d$ is also affected by circular orbit height $h_c$ and inclination $i$, the height being far more influential on $\Delta l_d$ than the inclination. Indeed the variation of $i$ over a fairly wide range changes $\Delta l_d$ but slightly whereas any variation of $h_c$, however small, would considerably alter the

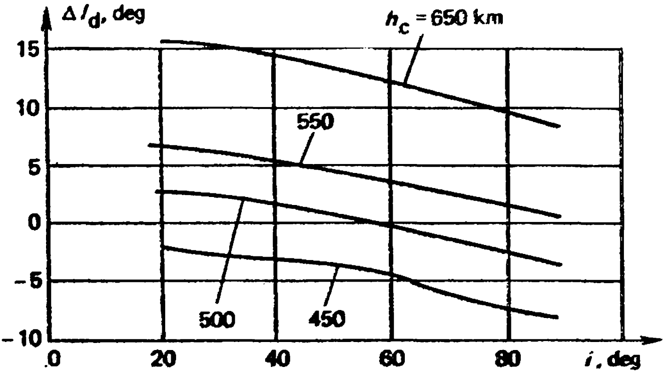



Fig. 19. Diurnal equatorial shift $\Delta l_d$ of satellite swaths (diurnal shift of the orbital node) as a function of orbital inclination. Positive $\Delta l$ identifies westward shift, negative $\Delta l$ identifies eastward shift

diurnal shift of the orbit. For instance, with inclination $i$ varied from 51 to 90°, $\Delta l_d$ falls from 3.8 to 0° (for an orbit whose $h_c$ is 550 km) but is reduced from 12 to 3.8° when $h_c$ is modified from 650 to 550 km.

In the above example the selection of orbital parameters was only directed to the accuracy of deployment into tropical cyclone leaving aside energy considerations, mainly the fuel-costly braking requirements (or the corresponding braking pulse values) for deorbiting. These considerations, nevertheless, sometimes fundamentally determine the orbit choices between low-circular and highly elliptical.

## Sec. 16. Extra-atmospheric Approach

The probe's descent trajectory may be tentatively divided into two portions, extra-atmospheric and atmospheric, differing by the nature of forces acting upon the probe. Gravity is the main influence during the extra-atmospheric descent approach.

The required descent trajectory is chosen by carefully adjusting the magnitude and direction of the thrust and the time of brake engine operation. Usually, design calculations assume an instantaneous thrust but neglect the duration of the jet braking portion of the trajectory, and hence the term *braking pulse*.

For the orbital probe complete with balloons and buoys to make an assured and accurate descent in the effective range of a tropical cyclone, demands compliance with the necessary conditions of the probe's entry into the dense atmosphere (Fig. 20). To be assumed as the latter's boundary is the maximum altitude above the Earth's surface at which the aerodynamic braking force applied to the descender becomes several percent of the Earth gravity. The generally accepted 100-120-km boundary is often referred to as "conventional" in the sense that no consideration of the aerodynamic forces above that boundary is incorporated into the design calculations.

The conditions required for the probe's atmospheric entry at the altitude of its conventional boundary are: velocity $v_0$, angle of trajectory slope with respect to local horizon $\theta_0$

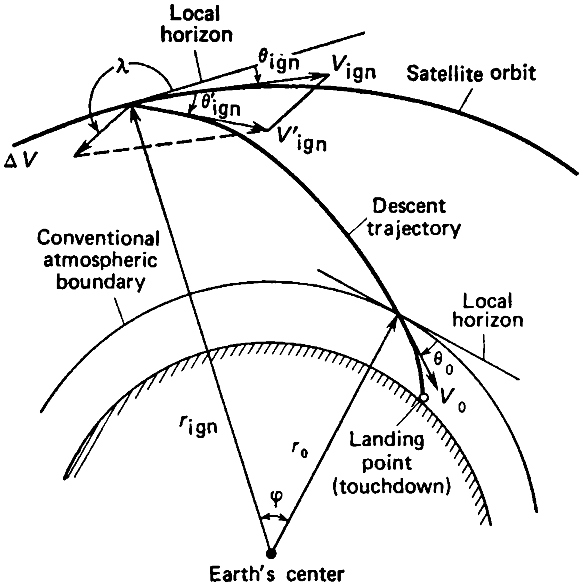



Fig. 20. Scheme of the probe's descent trajectory

(descent angle), radius vector from the Earth's center $r_0$, and argument of latitude $\omega_0$. Where these are familiar they define in effect the parameters of the transfer ellipse down the extra-atmospheric approach and the orientation of its line of apsides. Knowing the satellite orbit parameters (pericenter and apocenter radii, $r_\pi$ and $r_\alpha$, respectively, and pericenter latitude $\omega_\pi$), the orbital point of intersection with the transfer ellipse determines engine

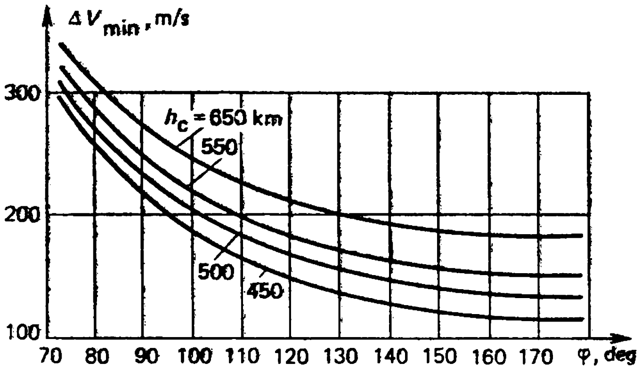



Fig. 21. Variation of the minimum deorbiting impulse $\Delta V_{min}$ versus angular range $\varphi_{h=80}$

ignition instant $\tau_{ign}$, braking pulse $\Delta V$ and the latter's direction $\lambda$ relative to the orbital velocity vector, descent time $t_{desc}$ and length. The formulas to obtain these values are given by the equations of elliptical motion [8, 9] in the central field of gravity.

Below the extra-atmospheric descent segments will be analyzed for: a low-circular orbit with $h_c = 450$ to $650$ km and a highly elliptical orbit with perigee at $h_\pi = 200$ km and apogee at $h_c = 200\,000$ km.

**Descent from a low-circular orbit.** Figure 21 illustrates variation of the minimum deorbiting impulse, $\Delta V_{min}$, with the descender angular range, $\varphi$, for different circular orbit altitudes. The angle $\varphi$ is measured from the instant of engine ignition $t_{ign}$ to $h = 50$ km. (The problem was solved for the thrust impulse with no regard to the atmospheric effects.) It will be seen that the circular orbits with a higher altitude over the Earth's surface require greater impulses and therefore heavier fuel consumption to damp the descent velocity. This is aslo true of the descent into a tropical cyclone along trajectories with a short angular range $\varphi$ which demands high energy costs for braking. For the "short" descent trajectories ($\varphi = 90°$) the impulse value $\Delta V_{min}$ should be 210 m/s for the orbits whose $h_c = 450$ km and 270 m/s for $h_c = 650$ km; for the "long" trajectories ($\varphi = 180°$), $\Delta V_{min} = 120$ m/s ($h_c = 450$ km) and $\Delta V_{min} = 180$ m/s ($h_c = 650$ km).

Figure 22 gives the $\varphi$-dependence of the thrust-vector orientation angle $\lambda_{opt}$ for an orbit with $h_c = 500$ km. As is evident, the optimal value of $\lambda_{opt}$ corresponding to the least value of $\Delta V_{min}$ for each $\varphi$ decreases with the increasing range.

Also shown in Fig. 22 are the $\varphi$-dependences of the initial entry velocity $V_0$ and the trajectory slope angle to local horizon, or descent angle $\theta_0$. They were evaluated for each $\varphi$ by use of normalized equations and found to match optimal $\Delta V_{min}$ and $\lambda_{opt}$. As seen, the initial entry velocity for the "short" descent trajectories, $V_0 = 7880$ m/s, and the initial descent angle, $\theta_0 = -3.1°$ (the atmospheric entry angle). Larger angular ranges produce a higher $V_0$ and a lower $\theta_0$. Thus an increase of

$\varphi$ to 180° increases the entry velocity $V_0$ to 7950 m/s but makes the entry angle $\theta_0$ more shallow at —1.2°.

**Descent from highly elliptical orbits.** We shall now consider the extra-atmospheric segment of the vehicle's descent trajectory from

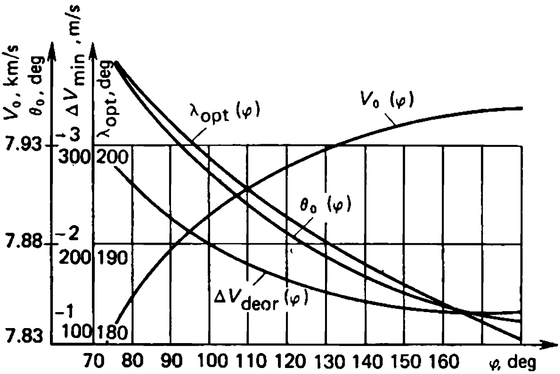



Fig. 22. Minimum deorbiting impulse $\Delta V_{min}$ and its respective thrust vector $\lambda_{opt}$, initial entry velocity $V_0$ and angle $\theta_0$ as a function of the angular range $\varphi$ ($h_c$ = 500 km, $\varphi$ corresponds to $h$ = 50 km)

a highly elliptical orbit. The sought-for value is the minimum deorbiting impulse $\Delta V_{min}$ required to pass from the initial highly elliptical orbit to the transfer orbit with a conventional perigee altitude $h_\pi = 0$. The transfer orbit supports atmospheric entry and touch-down on ocean surface in a specified area. The period of the transfer orbit $T_t$ is always assumed below that of the initial orbit $T_1$. The values of $\Delta V_{min}$ and $T_t$ versus the true anomaly $\vartheta$ are presented in Fig. 23. As would be expected, an increasing true anomaly results in a much smaller $\Delta V_{min}$ and a greater $T_t$ for the transfer orbit: when $\vartheta = 0$, $\Delta V_{min} = 3.18$ km/s and $T_t \approx 1.5$ h; when $\vartheta = 50°$, $\Delta V_{min} = 0.68$ km/s and $T_t \approx 12$ h; when $\vartheta = 100°$, $\Delta V_{min} = 0.18$ km/s and $T_t = 38$ h.

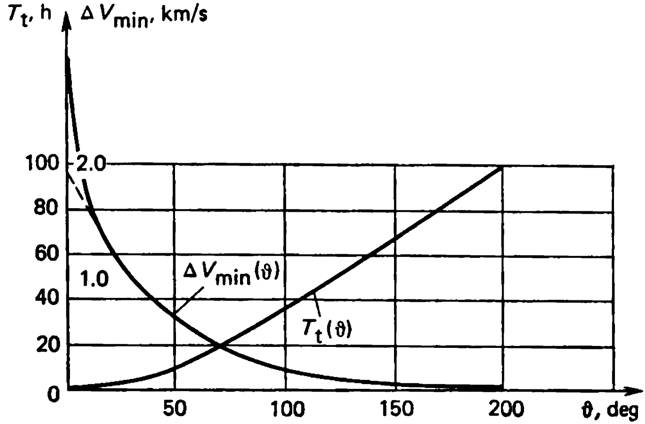



Fig. 23. Minimum required impulse $\Delta V_{min}$ and transfer orbit period $T_t$ as a function of the true anomaly $\vartheta$ (for the initial orbit $T_i = 98.5$ h, $h_\pi = 200$ km, $h_\alpha = 200\,000$ km, and for the transfer orbit $h_\pi = 0$). The dashed line corresponds to violation of the condition $T_i \geqslant T_t$

Thus, to summarize, the analysis of the extra-atmospheric approach yields the impulse value for probe departure from both the low-circular and highly elliptical orbits. Since the fuel requirements for braking the descender are controlled by the deorbiting impulse, a simple comparison among the $\Delta V_{min}$ values helps to pinpoint the best orbit as that which minimizes the fuel costs. As suggested by the above analysis, to hit a tropical cyclone both the impulse and the amount of fuel required to take the descender off a circular orbit far exceed those for the comedown from a highly elliptical orbit.

## Sec. 17. Atmospheric Descent

Probe descent through the atmosphere needs a thorough-going examination as it is critical to a success in delivering the instrument package into the detected tropical cyclone.

Descent in the dense atmosphere is indeed crucial since all along it keeps the probe exposed to powerful physical impacts. The major difficulty is therefore one of having to damp practically all the potential and kinetic energy of the probe as it descends. The energy is enormous; it suffices to say that the specific energy per kilogram of descender mass is measured in tens of millions of joules. During the probe's descent the air drag impedes its progress through the dense atmosphere. As the probe velocity is abated, both the vehicle and its surroundings are heated in the process because the mechanical energy converts into thermal energy to be dissipated in the probe's atmospheric milieu. The descender structure, as it glides down through the atmosphere, must be able to tolerate high g-loads.

**Descender protection from heat loads.** Part of the heat energy picked up by the descender cruising through the atmosphere dissipates via surface emission and ablation of its heat-protective coating material. The residual energy is absorbed by the heat shield and structure of the probe. The latter's heating rate depends on the initial entry velocity, aerodynamic configuration and duration of the atmospheric flight. The higher the entry velocity and the longer the atmospheric descent, the greater reliability of the heat-protection system is required.

The thermal impacts on the probe's basic structural elements are so great that there is a risk of probe body destruction because the high temperatures lower the strength of the structural materials. The payload normally has limitations with respect to maximum environmental temperature and duration of exposure to it, which introduces stringent requirements for an adequately low thermal conductivity of the probe structure.

The most influential parameters in this respect are flight velocity (heat generation grows as the square of the velocity), total or "exposed" area of the probe surface, and its roughness. Heating is greatest at maximum curvatures, forcing the edges and other exposed surfaces to be smoothed or blunted. Other, less significant factors of shell heating will not be discussed here.

The entry velocity of a probe is largely determined by the type of orbit it comes off. In the low-circular-orbit descent the entry velocity is the lowest (about 7.8-8 km/s), the effective heat flows are moderate and the mass of required heat-protective coating represents a low 5-10 percent of the total probe mass. For highly elliptical orbits the entry velocity is up, at 9-9.5 km/s, introducing the need for a more rugged heat-protective shell, its mass increases to 15-20 percent.

The thermal shielding of a probe is typically provided by an advanced heat-protection system and improved aerodynamic shape of the descender.

Heat-protection systems vary by structural design and heat-protective material. In design terms, they fall into ablative and reradiative. The ablative heat protection concept implies that the greater part of the heat flux arriving at the surface spends itself to change the physical state of melted material while the remainder finds its way into the probe interior. In the vehicles with the reradiative system the heat is partly reradiated by the surface and the rest is absorbed. The reradiative system features a radiation screen, an insulation blanket, and an internal cooling unit.

Together, the two systems can use a variety of heat-protective materials, the key distinction being into metals .and nonmetals. The nonmetals capable of intensive energy absorption by sublimation generally come for use in the ablative systems. Highly carbonaceous charring ablators perform equally well there. Other options include phenolic nylon, teflon, refrasil and phenolic fiberglass [8].

Another group of nonmetals can be employed in heat-protection systems with no loss of mass. Where this is the case, the outer thermal insulation layer of fiber or ceramic material covers the structural metal skin to minimize the temperature of the descender body. For the nonablative systems (without the loss of mass) to perform better, their nonmetal materials should have high melting temperatures, high mechanical strength, resistance to oxidation, low thermal conductivity, high heat capacity, and low density.

To select the material for the outer insulation layer of the nonmetal heat-protection system that would best satisfy all the requirements defined above is something of a problem. One frequent choice is a multilayer insulation with each layer made of different material to tailor it to some specific need. Thus the outermost layer should be able to withstand high thermal and mechanical loads which become progressively lower for the subsequent (over) layers. The pattern of temperature distribution within the thermal insulation is the key to optimal selection of the best available materials for the inner layers. In effect, each temperature variation range has an optimal material suited to it.

In terms of weight as well as cost-effectiveness and simple design, ceramics offer the greatest potential for the nonmetal heat-protection systems with no loss of material: they are chemically inert at high temperatures, with low thermal conductivity and small volumetric weight.

In the heat-protection systems employing metal outer shields the choice of metal is also dictated by the mechanical and heat loads to which the probes are likely to be exposed. One indispensable condition requires that the probe structure maintain its mechanical strength while also keeping within the limitations of the temperature range allowed for the descent stage. There are good prospects here for niobium, cobalt, nickel, and titanium alloys.

**Aerodynamic configuration of descenders.** Aerodynamic configurations are generally classified on the basis of the method used to develop required aerodynamic forces. Most of the now operational descender designs incorporate an efficient brake flap which provides the aerodynamic forces needed for deceleration or maneuvering. Their advantages include excellent braking performance, low convection heat transfer, and high volumetric efficiency. Their drawback is a too low aerodynamic lift to provide flexible control of the atmospheric descent trajectory.

For another group of descenders their body shape is the main producer of aerodynamic forces. The aerodynamic lift thus obtained seems high enough, but then the drag is also high while the convection heat flux and volumetric efficiency are unacceptably low.

Lastly, winged descenders produce an even higher aerodynamic lift. They are, however, less practicable since neither the reliable heat protection nor the wing strength required for high-speed atmospheric descent can be provided without major difficulties.

This classification is of course arbitrary and numerous intermediate configurations can be designed to emphasize widely differing performance characteristics.

A well-managed probe descent into a tropical cyclone hinges critically on achieving maximum aerodynamic efficiency. Controlled by the lift-to-drag ratio, it suggests the ability to steer the vehicle during descent. Its maneuverability is evaluated by analyzing descent trajectories. Higher L/D ratios give the probe wider opportunities to make its goal of scientific instrumentation deployment to the cyclone center.

The simplest, *ballistic descenders* are so called for having no lift, that is, zero L/D ratio. Their descent in the atmosphere is uncontrollable.

*Low L/D (0.5 to 0.7) descenders*, or "gliding-type" probes, can execute a controlled maneuver on the descent trajectory to reduce g-loads and heat exposure and to correct the possible errors in the initial entry conditions, atmospheric parameters and aerodynamic characteristics so as to more accurately guide the probe to the cyclone center.

*High L/D (1 to 1.5) descenders* feature a combination of high maneuverability with good tolerance to the g-loads and heat acting on the descender. Such probes can achieve precision landing into a tropical cyclone for a wide range of initial deorbiting conditions. This is as important to selecting a minimum-energy trajectory as it is to control of braking engine performance by ground-based stations.

Technically, however, the enhanced L/D ratio presents a complex problem, more so with respect to descent control. As a result probes with a simpler geometry and moderate L/D ratios provide a more viable alternative for the delivery of balloons and buoys into tropical cyclones.

The selection of optimal descent trajectories is the central task of entry probe design. The principal types of descent trajectories are considered below.

**Trajectories of uncontrollable ballistic descent.** The descent of a ballistic probe with zero aerodynamic lift is the simplest to implement, as no sophisticated systems are needed for the control and stabilization of descenders through their atmospheric flight. The ballistic approach also enhances the reliability of descent (in the final count) and therefore the chances of delivering the probe with the scientific instrument payload to the target area.

On the other hand, the ballistic descent trajectory shows a number of essential disadvantages. Most importantly, it exposes the descender surface to large g-loads, high temperatures, and intense heat fluxes. The g-loads experienced by the descender impose stringent requirements on the strength of its structural elements. The net heat flux determines the required weight of the heat-protective coating, while the thermal resistance of the structural materials to be used is often selected to match the highest possible temperatures that the probe may have to tolerate during atmospheric descent.

In the ballistic descent from a low-circular orbit the maximum g-load significantly depends on the entry angle; it is 8-13 for shallow entry ($\theta_0 = -1$ to $-3°$) and 50-80 for steep entry ($\theta_0 = -15$ to $-20°$). Whatever the ballistic trajectory, the pattern of g-load variation at a time of flight remains essentially

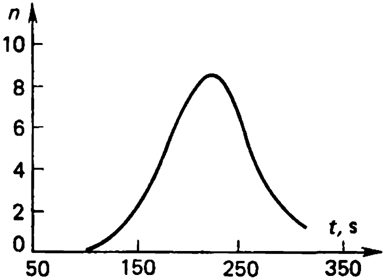



Fig. 24. G-load against ballistic descent time (for the entry angle $\theta_0 = -2°$)

the same. At the probe's atmospheric entry—the first 150-200 seconds—the g-load increases as shown in Fig. 24, reaches maximum and then declines until the end of the descent stage. The ballistic probes descending from low-circular orbits experience very strong heat-flux and high-temperature impacts. Of these, the temperature increases and the heat flux decreases with larger entry angles.

The shallow trajectories ($\theta_0 = -1$ to $-3°$) are associated with the heat-flux intensity close to 100 kcal/m$^2$ and the maximum temperature around 3000 °C. Variation of the probe's surface temperature against the descent time is shown in Fig. 25. Interestingly, the temperature maximum along the descent trajectory is reached somewhat in advance of the maximum g-load. The ballistic probe descending from a highly elliptical orbit develops a higher entry speed than it would coming down from

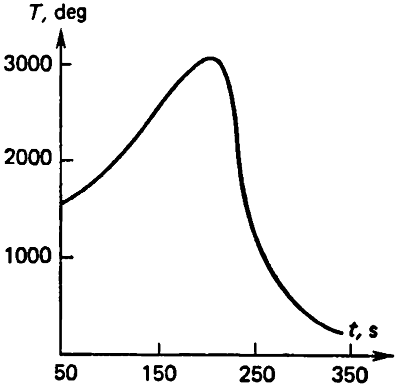



Fig. 25. Temperature against ballistic descent time (for the entry angle $\theta_0 = -2°$)

a low-circular orbit. The result is a substantial increase in maximum g-load, heat fluxes, and temperatures. For example for shallow entries ($\theta_0 = -5$ to $-7°$) the g-load grows to 20, the temperature to 3500 °C, and the net heat flux to 200 kcal/m$^2$.

**Trajectories of controllable descent.** The descent trajectory can be controlled even if the probe has low values of aerodynamic lift. This imparts a good margin of flexibility to the key trajectory parameters of maximum g-load, maximum heat flux, and maximum body surface temperature. Moreover, the probe can be headed for a more accurate hit in a typhoon. This is achieved by programmable control of the aerodynamic lift or L/D ratio during the descent. The probe's control algorithm can be varied on the descent trajectory to match the mission objective. It can be defined analytically, using complex differential equations to describe vehicle motion through the atmosphere, and state-of-the-art methods of optimal control theory. The discussion below reviews a few alternatives of controllable descent in the atmosphere.

A constant maximum L/D ratio minimizes g-loads along the descent trajectory. In this case the use of even a low aerodynamic lift reduces g-loads more substantially than under similar conditions of entry in ballistic descent for the simple reason that on such trajectories probe braking has to be executed in less dense atmospheric layers than in the uncontrollable ballistic descent. (In other words, under the same conditions of entry these trajectories run higher, because of aerodynamic lift, than any ballistic trajectory.) For instance, the entry (from a low-circular orbit) at an angle of $-2$ to $-3°$ involves a maximum g-load of about 2-3 for the probes whose L/D ratio $R \approx 0.2$; as seen, the g-load is three to four times lower than for the ballistic descent and can be lowered further to 1-1.5 by the use of vehicles with the L/D ratios as high as 0.5.

The descent trajectories that make it possible to minimize the heat fluxes can be controlled in a variety of ways depending on the initial entry conditions and the probe's ballistic characteristics. Five types of the controllable trajectories are:

(1) constant maximum aerodynamic lift ($k = k_{max}$);
(2) single reversal of aerodynamic lift from the negative ($k = -k_{max}$) to the positive peak ($k = k_{max}$);
(3) double reversal of aerodynamic lift from the negative ($k = -k_{max}$) to the positive peak ($k = k_{max}$) and back to the highest negative value ($k = -k_{max}$);
(4) single reversal of aerodynamic lift from its positive peak value ($k = k_{max}$) to its highest negative value ($k = -k_{max}$);
(5) constant minimum aerodynamic lift ($k = -k_{max}$).

A controllable descent trajectory designed to minimize the net heat flux may be further constrained in terms of maximum permissible g-loads. Incorporation of the constraint also affects the type of trajectory control applied. If, for example, the descender enters the atmosphere from a highly elliptical orbit at an angle of $\theta_0 = -6°$ and the maximum permissible g-load is $n_{per} = 10$ its control is executed as follows.

The probe enters the atmosphere with the highest negative lift ($k = -k_{max} = -0.2$); at 40-50 s into the flight the aerodynamic lift is reversed to its maximum positive value ($k = k_{max}$); in another 25-35 s with $k = k_{max}$ the descender reaches the maximum permissible g-load $n_{per} = 10$. For the next 50 to 60 s it descends with a variable aerodynamic lift to keep the g-loads constant and equal to their maximum permissible values. Then the constraint is removed and the final portion (20-30 s) of the descent proceeds with the lowest aerodynamic lift ($k = -k_{max}$).

The requirement to minimize the maximum temperature tends to modify descent trajectory control in ways dictated by the surface temperature behavior during the probe's atmospheric descent. Specifically, it causes several temperature maxima ($T$) to appear along the descent trajectory. However, when or where the expected minimized temperature maximum springs up on the descent trajectory is impossible to predict. There are several ways to get around it, in particular through the kind of descender control that will minimize the first temperature maximum as it occurs. Should this prove successful, the flight must be made to proceed at constant temperature $T = T^*$. Research has established that, because of the limitation on the magnitude of aerodynamic lift the constant-temperature descent is solely possible for the $T^*$ values at or above some permissible minimum temperature $T_{per}$.

To sum up, the descent trajectory control ensuring the least maximum temperature includes: entry with the highest aerodynamic lift and descent as far as the first temperature peak; descent after the temperature peak $T_1$ with some constant aerodynamic lift such that the descender should enter the flight regime with a uniformly varying trajectory angle to the local horizon ($\theta = \text{const}$, the *regime of* *steady gliding*); descent along the steady gliding path; discontinuation of steady gliding in view of the constraints on the aerodynamic lift; descent at a zero roll angle.

Under this control algorithm, the maximum descent temperature occurs either as the first peak or as the highest temperature along the steady gliding portion as dictated by the designer's choice of ballistic specification and initial entry conditions.

During deployment of research instrumentation in the effective area of a tropical cyclone it is sometimes necessary to provide favourable conditions for measuring atmospheric parameters across a wide range of heights. This is achieved through descent trajectory control allowing maximum flight altitude to be maintained along the aerobraking path and the specified velocity to be reached at the parachute system deployment. The descender enters the atmosphere with the highest (in magnitude) negative aerodynamic lift ($k = -k_{\max}$). Then, at some point in time the aerodynamic lift is reversed to its positive peak ($k \quad k_{\max}$), whereupon the descent occurs with a constant maximum aerodynamic lift until the touchdown.

Landing the descender in the desired area is a key challenge to typhoon research based on instrument deployment from orbit. The higher the landing accuracy of the descender relative to the "eye" of the typhoon, the more effective is the investigation method. The problem of landing the vehicle in a pre-assigned location can be solved by properly selecting and implementing the suitable conditions of entry. However such an approach to range control may or may not be practicable even with a large tolerance for dispersal of the hitting points. True [8], a careful selection of the braking engine switch-on time and the braking pulse value and direction can provide the desired longitudinal flight range during the probe's descent from its orbit. However atmospheric flight control is the only way to offset the lateral deviation relative to the typhoon center and only in rare cases, when the typhoon has a long lifetime, can one wait for the landing orbit track to run across the designated target site. If the hitting accuracy must be high, as in the case of precision landing in the typhoon "eye", range control solely by manipulation of deorbiting parameters prevents accurate instrument delivery into the target area.

A good knowledge of the probe's maneuverability or, to put it differently, its possible zone of maneuver is critically important when aerodynamic lift is applied for control. The descender *maneuvering zone* is defined as the region of negotiable longitudinal and lateral ranges for a certain descender geometry given the initial conditions of atmospheric entry [8]. With the accurate descender landing to aim at, its maneuvering zone needs to be larger than any possible dispersal of hitting points to accommodate the various perturbing influences due to a misjudged and misdirected braking pulse during deorbiting and errors during atmospheric flight. These "atmospheric" errors arise as the calculated air drag departs from its true value, a function of air density, vehicle air friction coefficient, and ballistic design characteristics of the descender. To estimate the extent of the maneuvering zone requires identification of the descent trajectory control mode sufficiently flexible to support maximum and minimum longitudinal and lateral ranges. In effect, the designer should define four control procedures for the aerodynamic lift of the descender, one for each of the following alternatives:

(1) maximum longitudinal range;
(2) minimum longitudinal range;
(3) maximum lateral range; and
(4) minimum lateral range.

Computer-aided descent trajectory simulation provides a way to evaluate maneuverability for different probe geometry.

We shall consider next control modes applicable to some of the trajectories that determine the maneuvering zone of a descender.

The control mode seeking to minimize the descender flight range is straightforward enough to require merely that the highest negative aerodynamic lift be maintained throughout the descent segment. Simple as it is, the mode is not always feasible on account of high g-loads. Hence the majority of applications adopt a more sophisticated control mode capable of satisfying the constraint on maximum permissible g-load. At the probe's entry into the dense atmosphere all its aerodynamic lift is directed "downwards" getting the probe to adhere to the maximum negative

L/D ratio. After 40 to 50 s the descender "turns upside down" and its aerodynamic lift is reversed to an upward thrust. The reversal timing is chosen so as to generate the required maximum g-load equal to the permissible value. For 20 to 30 s the probe moves with the maximum aerodynamic lift. Once the permissible g-load has been reached, the descender

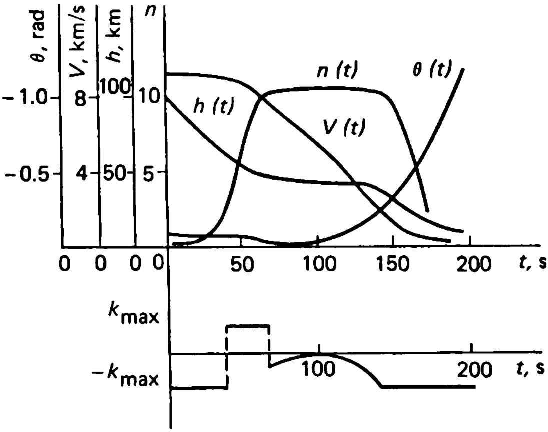



Fig. 26. Variation of minimum-descent-range trajectory parameters

changes to a variable aerodynamic lift which enables it to tolerate for 60 to 80 s the maximum permissible g-load. Then the probe performs a maneuver known as *constraint removal* to let the lift surge up to its maximum value ($k = k_{max}$) which the vehicle maintains through the remaining period of descent (120 to 140 s). By way of illustration Fig. 26 shows how the behavior of some descent trajectory variables (such as height, velocity, trajectory angle to the local horizon, and g-load) and the control parameter (L/D ratio) relates to the atmospheric descent time.

The trajectories yielding the maximum longitudinal flight range are not as steep as the minimum range trajectories. As a result, the g-loads that ensue are typically not too high and the aerodynamic lift control procedures applied need not accommodate the constraint on their magnitude. A probe on the maximum-range trajectory should generally be controlled so as to maintain its maximum positive lift throughout the descent. Sometimes the aerodynamic lift may be switched briefly to its negative peak to prevent the descender leaving the dense atmosphere, whereupon the probe resumes its flight with the positive lift until the descent trajectory runs out.

For lateral maneuvering in the atmosphere the longitudinal flight range becomes substantially smaller for given initial conditions of entry than the maximum longitudinal descent range discussed above. Each particular longitudinal range has only one matching value of the lateral range (Fig. 27) and, conversely, there is one quite definite value of the longitudinal range corresponding to the maximum lateral range.

Some deployments of an orbital probe down into the tropical cyclone center may well demand flying the longest lateral-range trajectory. As a rule, this raises the attended condition of rigorously maintaining the longitudinal range setting as well. One will see from Fig. 27 that these are conflicting requirements since the probes with preset design ballistics can maximize their lateral descent range only for some specific longitudinal range. To obtain the desired lateral descent range requires prop-

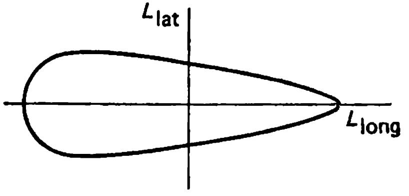



Fig. 27. Descender maneuvering zone

er adjustment of the satellite orbit and meticulous timing of the braking engine switch-on during descent.

The maneuvering zone dimensions depend on initial entry conditions and the L/D ratio. A higher probe entry velocity pushes the zone to expand as do also shallower probe entry angles and greater L/D ratios. The lateral/longitudinal range relationship is identical for aerodynamically dissimilar probe configurations. Note the limited potential for lateral maneuverability in the "gliding probe" with its low aerodynamic lift. Although the maneuvering zone is somewhat diminished to accommodate the constraints on descent trajectory parameters (e.g. permissible g-load) the lateral/longitudinal relationship is not affected.

The longitudinal orbit-to-orbit shift of the low-circular orbit projection for one orbit ranges 2500 to 3000 km at the equator. The analysis of statistics on the motion of typhoon trajectories over the ocean surface suggests that it is not impossible for a tropical cyclone center to appear for a time between two successive orbits, traveling at the diurnal orbit shift rate. The situation has the least promise for an accurate touch-down in the center of a tropical cyclone and, to achieve it, the descender should accomplish some lateral maneuvering. The aerodynamic lift or velocity side thrust at the instant of deorbiting must be sufficient to power the maneuver. In the former case, high L/D ratio descenders (on the order of 2) should be used to cover the orbit-to-orbit gaps. Alternatively, the orbit-to-orbit gaps can be closed by a ballistic probe if it carries enough propellant to apply side thrust. For the lateral ranges about 1300 to 1500 km in magnitude the side velocity pulse of 1500 to 1700 m/s is required for the "short" descent trajectories.

## Sec. 18. Descender

The descender has the aim to deliver a payload (balloons and buoys with a scientific instrument package are the case in point) from the satellite orbit into a tropical cyclone.

Designers of space technologies, scientists and engineers have credit for dramatic successes in the development of descenders for landing on the Earth and other large celestial bodies of the Solar system (Moon, Venus, Mars). Yet neither the available know-how nor the methodologies evolved so far to simulate descender trajectories or their individual parameters have been able to rigorously formalize the design process. Radical design concepts of descent vehicles to serve innovative applications in a new unconventional environment (of which the transport of instrument package into the location of active tropical cyclones is but one) tend to draw heavily on the design features of the earlier models. The design tools used include approximate parametric estimations, full-scale experiments and methods of similarity theory. The rationale for such an approach emerges from a multitude of problems in the design and development of new descenders.

Since descenders are indeed heavy-duty vehicles they must be made robust enough to remain operational against adverse conditions both during the orbital approach (vacuum, zero gravity, solar radiation, and so on) and the atmospheric descent (intense heat fluxes, air drag, elevated temperatures and g-loads).

In other words, the probe intended for return to the Earth from orbit must combine the functions of an orbital spacecraft and a flying vehicle capable of independent control movement in the dense atmosphere. One important probe design consideration assumes the descent trajectory to be predetermined by the braking pulse applied while the probe is still in orbit. For this reason a sufficient reliability margin should be built into the descender design to help it get the better of perturbations on its way to touch-down.

The descender geometry (its outline), weight and layout are defined at the engineering design stage. The forces and torques exerted on the descending probe must be also considered at this stage since they control its linear and angular accelerations and therefore its strength. Chief among these are surface distributed aerodynamic forces, or the pressure at each point of the descender surface flown-over by air, along with the gravity forces and inertia due to thrust-induced accelerations and the air drag.

Their total (cumulative) force is defined in terms of magnitude, direction and point of

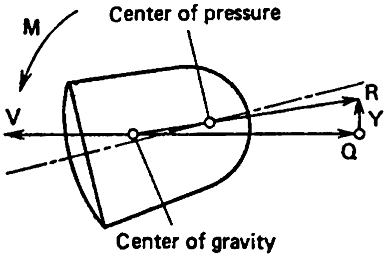



Fig. 28. Aerodynamic forces applied to the descender: *R*—total aerodynamic force; *Q*—drag; *Y*—lift

application which is called the *center of pressure* (Fig. 28). This force times the distance from its line of action to the center of mass gives the probe its torque. The instantaneous angular acceleration of the probe varies proportionally with the torque and inversely with its moment of inertia. The latter is the higher the larger the mass of the probe components and the farther they are removed from its center of mass.

The probe attitude with respect to the flight direction can be reliably controlled only as long as the probe's center of pressure stays behind its center of mass. Their spacing must be kept within very tight limits because if they are too close, random probe vibrations decay slowly and the probe flies tilting all the time.

To choose the final descender configuration and structural design much research is required by a variety of disciplines in science and technology. The main disciplines are ones which establish the descender's ballistic characteristics, select the best-suited heat-protection scheme, find optimal aerodynamic configuration of structural components, develop individual components and the overall structure, configure a system to deploy balloons and buoys in the oncoming air flow, identify the best system to maintain control and stabilization in all descent stages, establish and design other systems—e.g. power supply, automatic control, thermal control, radio communication and telemetry support.

Consideration is needed for the impacts specific to the operation of the descenders, balloons, and buoys in the effective range of typhoons. These are, first, large uncertainties in our understanding of the behavior of the atmospheric and ocean surface layers within the effective area of each specific typhoon targeted for study *in situ*; second, tremendous wind speeds and wave heights, and third, wide cyclone-to-cyclone variations of atmospheric and ocean parameters such as wind speed, temperature and pressure.

Other factors to be considered for the descender design that restrict possible choices include lead time, payload option for delivery to the target area, maximum permissible size and weight, maximum affordable g-loads and angular velocities on the descent path, full-scale testing of the descender and its systems in a relevant (near-operational) environment, current potentials of manufacturing technology, the science of materials and instrument engineering, and, last but not least, projected overall costs.

Finally, a critical feature which sets apart the descender models for tropical cyclone studies from all earlier designs is this: whereas all previous missions sought to land the descenders in areas with known latitude and longitude, the landing site is not known in advance for descents into tropical cyclones. Furthermore, after a cyclone is detected and located, its position keeps changing in ways that are unpredictable.

The overall R and D objective is to provide optimal solutions in each of the guidelines in descender design. Not infrequently, however, the particular optimal solutions are in conflict with inherent descender characteristics or with one another thus requiring that compromises be made.

In designing a descender research usually begins with choosing key ballistics. For the ballistic vehicles with uncontrollable atmospheric descent these include normalized load on the front surface or the ratio of the descender mass to the area of its characteristic cross section and drag coefficient.

For the low lift/drag ratio descenders (on the order of 0.5-0.7), or "gliding" vehicles controlled by varying the bank angle, the critical ballistic parameters are normalized load on the front surface and the L/D ratio.

The main ballistic parameters of a descender importantly define all other R and D guidelines. They govern the choice of the descender trajectory in the atmosphere crucial to setting further design priorities and only upon establishing the key ballistics can one proceed to calculate the g-loads, heat fluxes, and temperatures the descender may have to withstand going through the atmosphere. They also provide a glimpse of the operational environment with respect to radiocommunication, control, thermal control and other systems. Based on the atmospheric descent trajectory, more focused work can be done to select the descender's heat-protection system, configuration, optimal aerodynamics, and controls consistent with the key ballistics chosen.

Aerodynamic research represents a guideline of descender design concerned with theoretical and experimental studies and model and full-scale tests. The aerodynamic design employs computer-aided simulation and wind tunnel tests; the full-scale tests are supported by aircraft, helicopters and carrier-rockets and structured as a two-staged procedure.

The objective of the first stage is examining the aerodynamic behavior for a large number of descender configurations to determine the feasibility of various types of descenders for getting inside the tropical cyclone after being released by a satellite.

The second stage focuses on the selected descender configuration and provides more insight into its aerodynamic behavior. As the second stage involves a variety of full-scale tests and unique experiments, more money and manpower are required than during the first stage. This stage of the aerodynamic research is decisive because its findings, if they disprove the theoretical estimates of the first stage, may urge rejection of the original descender configuration and a search for other acceptable design options.

Even a short overview of the problems that arise in every design discipline is voluminous enough. We shall now outline in brief two structural design alternatives for the probe to deliver balloons and buoys with a payload of scientific instruments into typhoons and hurricanes.

*Alternative 1.* Figure 29 gives the general view of a descender configured as conical screen *1* with an aperture angle of 120°. The screen being the principal load-bearing component, all other units and systems are attached to it. The frontal screen carries inside cylindrical skin *2* with primary frame *3* with three balloons fitted to it. The primary frame and the skin are made up of four sections connected by bolts of the separation system;

15*

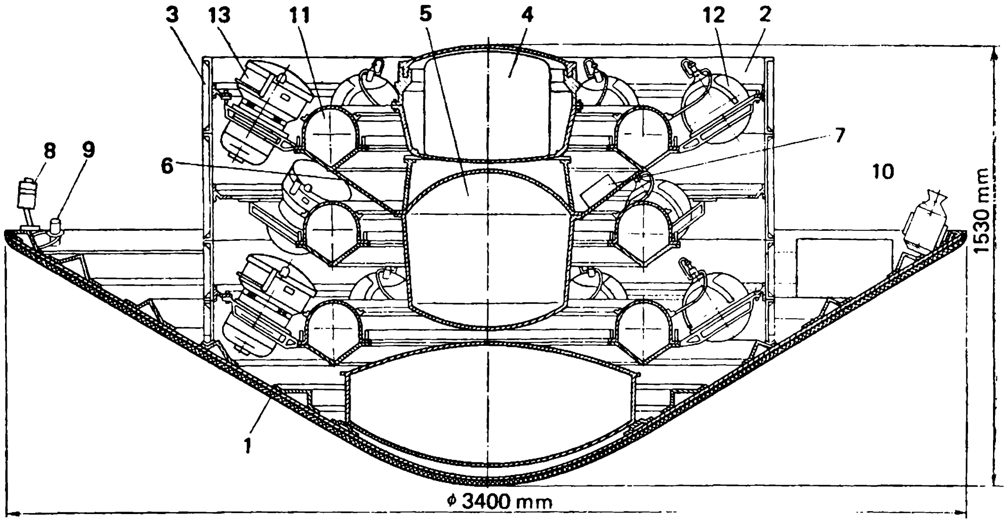



Fig. 29. The first type descender: general view

the bottom section is attached to the frontal screen.

The central part of the descender houses parachute container *4* held together with container *5* for meteorological instruments. Load-bearing cone adapter *6* is used to fasten the containers to the upper balloon. The cone also carries functional unit *7* of the control system and the power supply one. Control system actuators are mounted on the front screen periphery and consist of four gas nozzles *8*, two spin-on and two spin-off engines *9*. The peripheral layout of the engines provides for the highest torque with the same thrust from *8* and *9*. Deorbit engine *10* is another screen periphery feature. The braking screen bow holds the scientific instruments, a transmitter, and a memory unit.

The balloon is an independent system having load-carrying cone *6* as its primary structure. The cone bottom carries torus-shaped container *11* with a drift system whose components are the balloon envelope, its apexes and suspension, and a gondola.

Container *11* is a two-piece structure held together by explosive bolts. After the balloon is deployed and inflated the container bottom serves as the ballast to separate the drift system from the deployment system, which is jettisoned at the lowest point of the balloon descent trajectory.

In the cone top there are six pressurized spherical helium bottles *12* connected via a common manifold to the valves feeding gas to the envelope. In addition the cone top houses container *13* with the packed, stabilizing parachute and balloon deployment parachute.

*Alternative 2.* Another descender configuration, depicted in Fig. 30, features a frontal

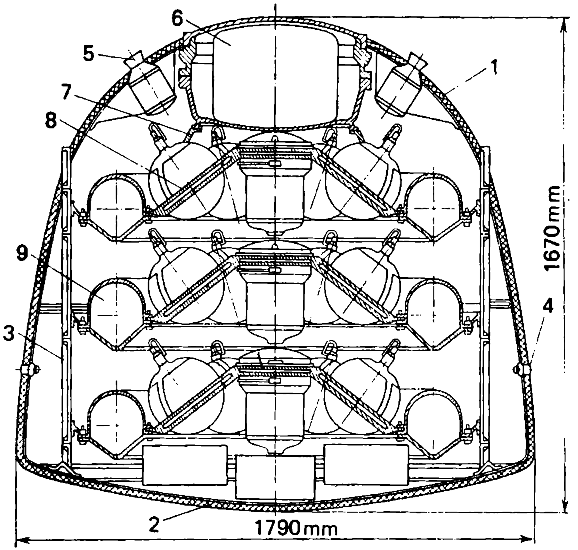



Fig. 30. The second type descender: general view

screen shaped as a spherical segment, a side conical surface, and a spherical rear section.

Inside the descender there are three balloons located beneath one another along the satellite axis and attached to four load-bearing rods *3*. Each rod has five sections connected by explosive bolts of the separation system. The top and bottom sections are fixed, respectively, on the top hemisphere and frontal screen of the descender.

The control system and its actuators (four gas nozzles) are also mounted on the top hemisphere. Spin-on and spin-off engines *4*, both of them components of the control system, are attached to the side surface, and the deorbit unit out of four powder engines *5* with calibrated deorbit pulse is secured to the top hemisphere.

In the aft, the descender holds parachute container *6*, held together with the shell container of the upper balloon by load-bearing cone *7*. The parachute container and cone support the power supply system and the instrument package. Load-bearing cone *8* is the key structural design component.

In the cone margin are found torus-shaped container *9* incorporating the shell of the balloon system with top and bottom caps and suspension, and the gondola, which together make up the float system. Six pressurized bottles are tucked between the shell container and the parachute container atop the load-bearing cone.

## Sec. 19. Balloon

Because of the severe environmental conditions such as high wind speed, excessive humidity, and low pressure, measurements in tropical cyclones require a special-purpose flying vehicle capable of sustained operation.

The development of an efficient vehicle of this kind must rely on a good knowledge of flight aerophysics, in-depth examination of possible aerodynamic and aerostatic configurations, and layout alternatives. When calculating the optimum lifting capacity of a particular version, the designer should also keep in mind the development costs. Once several design options have been established, their travel ranges should be estimated along with the probable impact of the design variables on flight altitude and duration.

The balloon appears to be the most attractive vehicle concept to fly into the effective ranges of tropical cyclones for the reasons that follow.

First, the balloon is very convenient for carrying out a variety of scientific experiments. When applied for meteorological observations in tropical cyclones, it provides the means to monitor globally the processes around typhoons and to follow the migration of tropical cyclones; it can collect data at almost any point over the globe within a wide altitude range, up to about 50 km; it can help calibrate satellite-derived remote sensing data using measurements from contact sounding of the atmosphere.

Second, the balloon can drift with the wind air currents in the tropical cyclone's interior, the property of singular importance to studying the air current pattern in a typhoon or hurricane. Indeed, relying on the radio equipment on-board the balloon and satellite, one can track the balloon with a high accuracy and thus derive the velocity and direction of air currents in the cyclone, the location of its center (the eye of the storm), and the cyclone path over the ocean.

Its further advantages are those of being relatively simple in design, highly robust in service and capable of floating for several months. The balloon is an all-weather craft, consumes no energy to move, combines the highest lifting capacity with a very simple design, and minimizes the time for its manufacture.

An inherent limitation of the balloon arises from the difficulty of controlling its vertical and horizontal motion within the tropical cyclone.

Sounding balloons have been widely used as scientific platforms in the atmosphere. Thousands of unmanned balloons are flown every day all over the globe. In recent years, ballooning has become a major factor in atmospheric studies. Every probe of this kind is an unmanned weather station that carries a package of high-accuracy instruments to support regular operational observations of the atmosphere in a wide altitude range up to 50 km with prompt data delivery to the end-user.

Windborne unmanned balloons have come to be recognized [3] as a vital component of the global atmospheric and ocean research system. The system also incorporates weather satellites, aerological stations, rockets, aircraft-based weather stations and research ships.

It is to be noted that the free-floating balloon-borne measurements of the atmospheric parameters have been employed beyond the Earth as well. It is well known that the Soviet interplanetary probes of the *Vega* project delivered balloons into the atmosphere of Venus in June 1985. Over a fairly long period (about a day) these balloons radioed back to the Earth measurements of the atmospheric parameters at 55 km above the Venus surface.

The balloon design flown into a tropical cyclone from orbit must meet some specific requirements that are seldom, if ever, expected of the counterparts launched from the Earth. First of all, the balloon envelope material must be able to stay folded through a long flight and then deploy intact to be filled with a lifting gas with the aid of a special parachute system. The descender that houses the probe slows down from 8000 m/s to about 200 m/s, but even at this fairly low speed, releasing the balloon and inflating its envelope is a difficult challenge. First and foremost, this is due to the hard dynamic shock produced when the probe is caught up in the counter airstream and which may damage or even destroy the probe and its scientific instrument package. The speed must therefore be further damped by means of another parachute system.

These envelope deployment and inflation problems lead to another constraint to be factored into the design of a balloon intended for delivery from orbit by a descender.

And the final factor to be considered is the severe atmospheric environment the balloon will encounter when floating in the tropical cyclone center. This environment places a premium on balloon stability. The balloon generally has six degrees of freedom: three of them define the motion of its center of mass and the other three define the rotation about the center of mass.

Given the harsh operating conditions in the tropical cyclone's interior and the constraints imposed by the experiment design it is the designer's primary concern to ensure that the balloon's upright position be statically stable. To this end, the center of mass of the entire system (the gas-filled envelope, gondola together with the instrument package, power supply, transmitter, etc.) must lie below the center of static lift which is naturally that of the gas volume. Strong atmospheric disturbances generated by a tropical cyclone put a statically stable balloon off its equilibrium. The balloon tends to regain the original equilibrium, and with a small distance between the balloon's center of mass and the center of pressure of the lifting gas in the envelope, wind disturbances amplified by the balloon's oscillations, may cause the balloon to overturn.

**Basic balloon components.** As shown in Fig. 31, structurally a balloon comprises three components: a gas-filled envelope, suspension system, and payload (e.g. measuring instruments, a transmitter, power batteries, etc.). It is a design component and an autonomous system of the descender. Balloon envelopes may be open, semi-closed or closed.

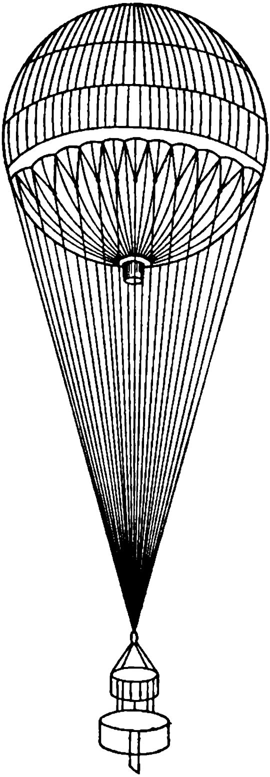


Fig. 31. Balloon

A balloon of the open or the semi-closed type has either an appendix in the envelope or a valve to maintain the internal pressure. The envelope of a closed-type balloon has no valve to control the pressure and is made of a high-strength material. When inflated its lifting gas pressure is higher than ambient at the design float altitude and hence another name for the vehicles of this kind is superpressure balloons.

Note that a more rigorous treatment of the balloon envelope design should, strictly speaking, include the effect of the internal pressure which decreases from the bottom to the top in the same way as the external pressure changes. By magnitude, however, its variation with altitude is lower than of ambient air. Thus, the pressure differential maximum will come at the top envelope and the minimum at the bottom. On the Earth this effect is negligible. Not so in the Venusian atmosphere with its predominantly high pressure levels. The Soviet balloon which in June 1985 was delivered into the Venusian atmosphere under the *Vega* project and sped through it driven by a strong wind, had a shell with a more reinforced construction at the top than at the bottom.

Special attention must be given to the envelope shape responsible for lift variation. The spherical shell gives the balloon the highest possible lifting capacity. Indeed, for a given shell surface area, the balloon volume will then be the largest possible while the weight of the material will be minimized. The volume of a balloon designed to fly a specified payload weight is strongly correlated with the air density at float altitude.

Given a constant static lift, the rated shell volume required to fly at altitude $h$ varies as the reciprocal of atmospheric density and can be approximated as [4]:

$$V_s(h) \approx V_0 \frac{\rho_0}{\rho(h)},$$

where $V_0$ is the rated volume at sea level; $\rho_0$ is the atmospheric density at sea level. The balloon's envelope is assumed to maintain its geometry despite float altitude variation.

Because the float altitude actually determines the air density, the lower-altitude mission calls for the smaller balloon.

The best option for a sounding balloon to be released from orbit is a closed spherical envelope. Such an envelope consists of soft collapsible strips and top and bottom caps (poles). The caps help seal the ends of the strips and provide a mechanical link between the envelope and the gondola. Modern balloon materials are durable and can hold the lifting gas over a long period (for months and even years).

The balloon shell is best inflated with a light inert gas such as helium which is neither flammable nor explosive. A light gas causes the internal pressure to rise above the ambient as the balloon ascends. The overpressure has the effect that the lifting gas serves the dual function of generating the lift and providing a kind of frame to maintain the shape of the envelope.

Given the balloon mass $m_1$, the mass $m_g$ of the lifting gas is related to the gas constant $R_1$ of the ambient air and $R_g$ of the lifting gas as [4]:

$$m_g(h) = m_1 R_1 / R_g.$$

Put another way, the lifting gas to balloon weight ratio is constant. With helium as the lifting gas, the ratio is 0.138; with hydrogen it is 0.07.

The balloon's gondola carries a transceiver and a meteo package, an antenna with a feeder, sensors, and batteries. The gondola is fastened to the bottom cap of the envelope by a suspension rope 10 to 15 m long.

Comparisons between balloon design configurations are made in terms of aerodynamic, aerostatic, and design specifications as well as geometry, lifting capacity, and transportability. The designers apply various criteria to judge their flight performance. One extensively used criterion seeks to maximize the payload weight while abiding by the estimated production costs and desired operational reliability with a specified length of service.

Not infrequently, theory and full-scale experiments help derive the balloon's payload

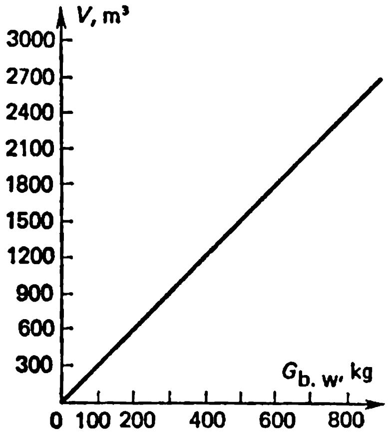



Fig. 32. Shell volume vs balloon payload

weight as a function of its size and geometry. As an example Fig. 32 [4] presents the payload weight against balloon envelope volume. It can be seen that a smaller volume supports a proportionally smaller payload. For instance for the envelope volume of 1200 m$^3$, the payload weight is about 400 kg. For a smaller volume of 300 m$^3$, the payload also drops to 100 kg.

The weight of the various balloon components is selected to match the float altitude.

There is an optimum float altitude capable of yielding the smallest weight for the entire balloon. The optimum altitude increases proportionally with the gondola weight and inversely with the envelope weight [15].

The balloon's maximum operating altitude is a critical design parameter, reaching its highest value when the envelope has been filled to capacity.

The gas in the shell expands as the balloon climbs higher. With the mass of the gas remaining constant, the shell is filled to capacity when the balloon attains a certain altitude (at a lower balloon altitude the envelope is somewhat creased but smooths out as it ascends). With increasing altitudes the internal pressure may generate stresses in excess of the film strength, destroying it. Thus, the film quality and strength control the maximum operating altitude of the sounding balloon. Shell materials typically harden at a lower temperature and the shell strength decreases accordingly, which is why the lowest operational altitudes are achievable in winter and at night-time.

The balloon's float altitude is also related to its dead weight and its payload. The smaller the balloon's net weight, the higher altitude it can reach. For this reason light materials have greater usefulness for both the balloon and its instrument package.

Ideally a superpressure balloon with no vertical motion control must float at the height corresponding to constant density level. In actual fact that is not the case, primarily because of unstable film properties, wind disturbances, and variation of the radiation environment at the float altitude.

Collected readings of the pressure sensors and radar altimeters justify the conclusion [3] that the greatest altitude excursions are brought about by the radiative heating and cooling of the solar cycle. As the lifting gas temperature varies in the course of the day, the internal pressure fluctuates and so does the balloon's float altitude. To give an illustration, for a balloon 2-4 m in diameter, altitude variations due to shell stretching and lifting gas leakage may be 50 to 70 m while the daily altitude excursions caused by the difference in ambient air temperature from daytime to night-time range 200 to 300 m and show a regular 24-hour pattern.

Altitude variations are also strongly affected by cloudiness.

The flight duration of a superpressure balloon is mainly governed by icing, solar radiation, and gas leaks through the shell material. Available operating experience and theoretical investigations confirm [3] that the balloon can float in the upper troposphere or in the stratosphere for several years on end provided helium is the lifting gas and the shell is made of an appropriate material, e.g. polyethyleneterephthalate. In the lower troposphere the balloon's flight duration is much shorter (20-30 days) because of icing.

Large-scale theoretical studies and experiments concentrate on ways to extend the balloon's operational life. A number of approaches have been developed to support long-duration ballooning at different float altitudes [3]. One of these makes use of multilayer films to hold back the gas bleeding through the micropores in the balloon material although they do create an additional weight penalty and require more lifting gas for the same payload.

There are several ways to prevent the balloon from icing [3]. In particular, this is achieved by the addition of carbon black to the balloon material to augment solar heating, or envelope impregnation with a water repellent.

An extensively used technique to combat ice build-up consists of taking the balloon out to another float altitude by vertical maneuvering.

The balloon's envelope usually bursts after some time and the housing together with the instrument package falls to the ground or into the sea, thus terminating its operation in the atmosphere.

It may so happen that the data acquired can be transmitted only after a time delay. In this situation the data are first recorded into a storage device and kept there until the radiosonde comes into the visibility range of a relay satellite—then the scientific data are transmitted by the satellite to ground stations. With this data link arrangement it is desirable that the storage device and transmitter remain operational some time after the balloon hits the ground or the water. To make this possible, the radio package is put into a waterproof container complete with a small parachute whereby the container can stay afloat for a period of time.

Of particular interest in typhoon exploration is the balloon model featuring adjustable static lift. This balloon design can acquire comprehensive data on the atmospheric parameters in the different layers of a tropical cyclone.

The balloon design with a ball-shaped envelope and adjustable static lift has altitude control but lacks flight direction control which can be accomplished by shaping the balloon as an elongated cigar provided with motors and rudders; but again the lightweight motor is far from easy to develop. In the early stages of balloon-supported cyclone exploration uncontrolled balloons or those with unsophisticated vertical motion control appear to be the best alternative.

One of the simplest methods to control the static lift and, consequently, the balloon's vertical motion is to let some of the lifting gas escape into the atmosphere; another approach reduces the balloon's weight by jettisoning the ballast. In the first scheme the static lift is increased taking up the balloon; in the second, a lower lift causes the balloon to descend.

The balloon can rise up to a limit as ambient atmospheric pressure falls with altitude to hold down the static lift and the ascent rate. There comes a point when the static lift is offset by the net weight of the balloon and payload—this altitude is termed balloon ceiling.

This balloon control strategy proves unreliable when the ballast water freezes or the gas relief valves stick, or for other reasons. Besides, gas release impairs the flight range and duration.

The balloon control with no ballast to adjust its vertical motion requires more power to vary the internal gas temperature or pressure by means of a gas burner with a reserve of fuel which may be mounted below the balloon's appendix. Alternatively, the static lift can be controlled by heating the lifting gas [4] with the hot exhaust gases of a piston engine carried in the gondola. In this case the balloon's static lift is produced by the combined buoyant forces of the helium and exhaust gases. By heating or cooling the exhaust gases the static lift can be altered, thereby moving the balloon up or down.

Yet another option involves a balloon with adjustable life, the pressure inside the envelope being the controlled variable. Based on simple calculations [4], one may take it, as a general rule of thumb, that a ballast which accounts for five percent of the balloon's weight is equivalent in terms of lift to an additional gauge pressure of 0.05 $kgf/cm^2$.

**Typhoon studies using the parent balloon.** We will now take a look at another useful design option to explore *in situ* tropical typhoons [15]. From an orbiting satellite a descender can deploy a parent free-floating balloon into a tropical cyclone. This balloon carries on board smaller lightweight balloons or parachute radiosondes to be released into the atmosphere as required by the experi-

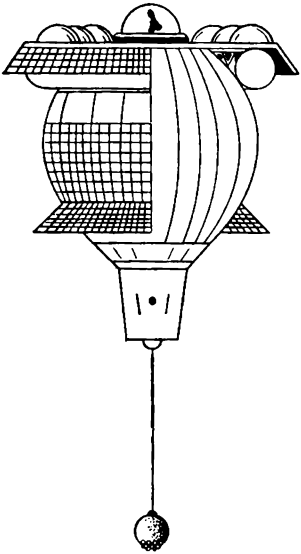


Fig. 33. Parent balloon

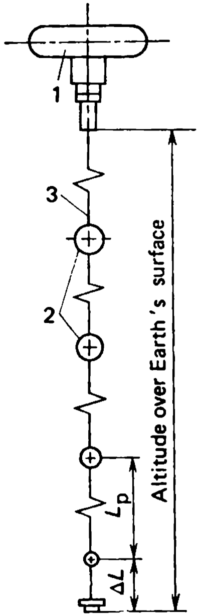



Fig. 34. Lift-type balloon:

*1*—carrier balloon; *2*—intermediate balloons; *3*—rope

ment design. The scheme may well afford an enhanced package of scientific equipment to obtain detailed information. A general view of the parent balloon is depicted in Fig. 33.

**Simultaneous vertical sounding of the atmosphere.** A research project may call for concurrent vertical profiles of atmospheric or ocean parameters. This part of the measurement program may run into difficulties if the parent balloon or the descender deploys single balloons. A "lift" configuration may then be more attractive, still more so if the target is the eye of a typhoon. The arrangement is shown in Fig. 34 [15]. The parent balloon carries smaller intermediate balloons attached to a rope. The intermediate balloons ride on the suspension to offset its weight and that of the scientific instruments mounted next to the balloons. The bulk of the supporting equipment (power supply, programmable timer, transmitter, etc.) and some scientific instruments are borne on-board the parent balloon.

The "lift" arrangement provides a comprehensive simultaneous data acquisition capability with respect to the various atmospheric parameters over a range of altitudes in a tropical cyclone through the altitudinal profile of the balloon's flight path. The parameters include humidity, pressure, density, temperature, and illumination in the atmosphere, wind velocity and direction, atmospheric heat transfer, and several other parameters.

**Variable-geometry balloons.** The typhoon observation balloons are given a fixed or variable shape so they can drift in its effective zone. In a number of applications the variable-geometry balloons are superior to the conven-

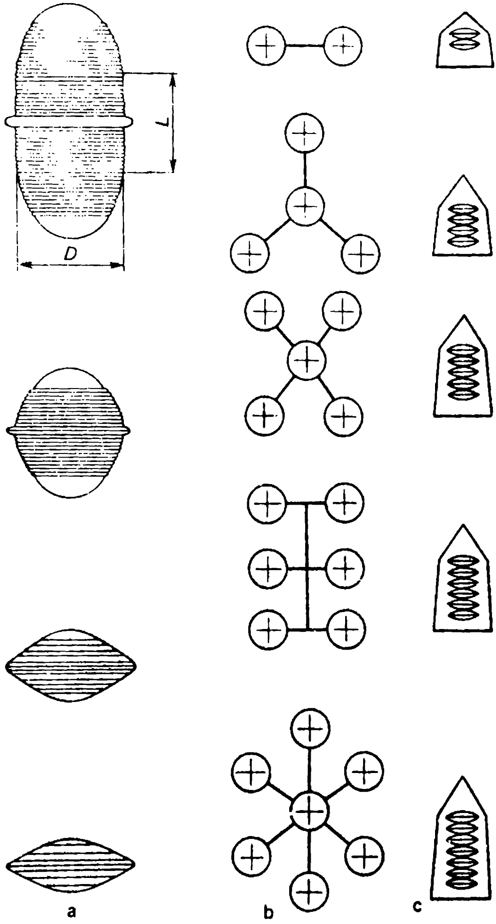



Fig. 35. Variable-geometry balloons:
*a*—envelope shape at various ambient pressures; *b*—arrangements of deployed LTAs; c—arrangements of folded LTAs

tional fixed shape vehicles. Figure 35 shows a possible configuration [15] which employs LTA discs as its components. The shape of a disc can vary with ambient atmospheric pressure from a spheroid to a sphere or cylinder. It can be seen from the figure that disc-shaped components can be conveniently stacked in the descender as a package.

To summarize, it can be said that progress in contact sounding of tropical cyclones depends on advances in long-duration ballooning and the development of progressively smaller, ruggedized components of the instrument package.

## Sec. 20. Acquisition of Vertical Profiles of the Atmosphere and Ocean

Research information on typhoons would be more complete if regular measurements of the vertical profile of the atmosphere and ocean by means of long-duration balloon stations and buoys should augment atmospheric and ocean measurements at one or several designated depths and altitudes. The vertical profile comprises the atmospheric parameters represented as a function of the altitude above sea level and the ocean parameters as a function of sea depth. In addition, these data are of interest to many other relevant concerns in meteorology, oceanography, climatology, and environmental monitoring. Space technology allows the vertical profile of the atmosphere and the ocean to be measured in any region of the globe with minimum delay.

A single launcher can insert in orbit around the Earth a large number of small-size lightweight descenders joined together into an array of 160 to 200 modules. Each vehicle houses a balloon to sense the required parameters of the atmosphere and ocean.

At a specified instant the satellite's attitude is set steady and a command causes a descender to detach from the array; the descender then deploys its balloon over the desired region. When the descender speed is essentially canceled out from 8 km/s to 0.8-0.9 km/s inflatable balloons or parachutes further brake it to a speed rendering the atmospheric parameters possible to measure. The measurement activities are in progress all along the radiosonde descent path to the point of touch-down. The radiosonde can stay afloat for 20 to 30 hours and continuously measure ocean parameters. When the satellite passes over the balloon, all accumulated data about the vertical profile of the atmosphere and ocean are relayed by the satellite to the ground data acquisition center.

The other descenders remain coupled in-orbit until the pre-scheduled deorbiting instant for each of them. To rapidly deploy an instrument package over a desired region, it is useful to place the descender array on a low-circular orbit where the satellite repeats the ground track every 24 hours. Such an orbit must have an altitude of 500 km. When the satellite moves in this orbit it rotates 15 times a day around the Earth and can thus deploy a balloon in the vicinity of any point along its flight trajectory. If needed the satellite orbit can be adjusted to permit deployment of platforms with an array of scientific instruments in the Earth's regions lying off the original trajectory without changing the interval between satellite overpasses.

Thus the orbit parameters uniquely determine whether, where and how rapidly the instrument package can be delivered. The regions where the deployment is feasible are called its "area of coverage". It is worth pointing out that the profile acquisition technique described above makes the "area of coverage" essentially dependent on the required measurement rate and data repeats. A lower rate obviously leads to larger "area of coverage". For example, to measure the vertical profile only once every three days the satellite must have an altitude of 400 km—then the "area of coverage" can be significantly enhanced for the same data rate.

As pointed out above, the measurement of atmospheric parameters begins as soon as the envelopes of the braking balloons have been inflated, at 25 km above the ocean. It takes an atmospheric balloon about 25 minutes to climb down from the 25-km height to the surface of the ocean.

In vertical atmospheric sounding the temporal resolution is a function of the balloon descent rate and meteorological sensor lag. The type and number of the sensors are then dictated by the mission objective and experimental design. The sensor signals are typically converted into d.c. voltage and the electrical signals are applied to a multichannel A/D converter that generates a train of square pulses whose number is related to the input level of the physical variable to be measured. The pulse number total accumulates in a dedicated counter. The binary code thus obtained is loaded into a special register together with the binary address of the interrogated channel.

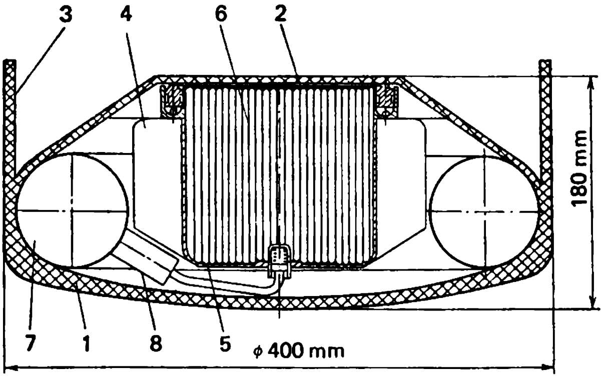



Fig. 36. Descender design

The data word generated by the above procedure is read out into a storage device. While the satellite is within the visibility range, the word is passed to a driver and transmitted via the telemetry link to the satellite on-board receiver. The balloon sensors and transmission facilities must be configured as a multichannel system adjusted for a high transmission rate, high accuracy and reliability and acceptable error-rate coupled with low power consumption, small size and light weight.

The transmitted volume of data is controlled by the measuring time and the sojourn of both the balloon and the receiving stations in the radiovisibility range of the satellite. Significantly, the time of measuring atmospheric and ocean parameters shows a definite relationship to the period while the stored measurement data can be relayed to the receiving stations. The measurement to transmission time ratio is typically 5:1. Given the amount of data collected by the instruments per unit time as well as the data transmission rate and session length, one can readily calculate the net volume of data transmission.

Figure 36 presents a plausible design configuration of the descender. The vehicle comprises heat-insulated body *1*, bottom *2* with a blast-off system, and flaps *3* to maintain descender attitude control in the atmosphere. Housing *4* holds an instrument container with sensors, batteries, a storage device and a radio package. The housing is ball-shaped. It also incorporates cylindrical container *5* that accommodates inflatable balloon *6*. Gas tank *7* is implemented as a doughnut bottle and linked to the balloon envelope container by pressurized system *8*. In another configuration the balloon envelope is replaced by a parachute system.

# References

1. Yu. Zh. Al'tner-Zalik, *Zondirovanie atmosfery s pomoshchyu aerostatov* (Sounding the Atmosphere with Balloons). Leningrad: LPI (1981).
2. V. I. Bazhenov and M. I. Osin. *Posadka kosmicheskikh apparatov na planetu* (Spacecraft Landing on Planets). Moscow: Mashinostroyenie (1978).
3. E. P. Borisenkov, Yu. Zh. Al'tner-Zalik, and A. D. Kuznetsov. *Zondirovaniye atmosfery meteorologicheskimi aerostatami* (Sounding the Atmosphere with Weather Balloons). Leningrad: Gidrometeoizdat (1982).
4. B. G. Broude. *Vozdukhoplavatel'nye letatel'nye apparaty* (Aeronautical Flying Vehicles). Moscow: Mashinostroyeniye (1976).
5. B. V. Vinogradov. *Kosmicheskiye metody izucheniya prirodnoi sredy* (Spaceborne Techniques for Environmental Studies). Moscow: Mysl (1976).
6. A. A. Grigoriev and K. Ya. Kondratiev. *Pylevye buri na Zemle i Marse* (Dust Storms on the Earth and Mars). Moscow: Znaniye (1981).
7. V. I. Ermakov, A. F. Kuzenkov, and V. A. Yurmanov. *Sistemy zondirovaniya atmosfery* (Atmospheric Sounding System), Leningrad: Gidrometeoizdat (1977).
8. N. M. Ivanov and A. I. Martynov. *Dvizheniye kosmicheskikh letatel'nykh apparatov v atmosferakh planet* (Spacecraft Motion in Planetary Atmospheres). Moscow: Nauka, 1985.
9. N. M. Ivanov and A. I. Martynov. *Upravleniye dvizheniyem kosmicheskogo apparata v atmosfere Marsa* (Spacecraft Motion Control in the Martian Atmosphere). Moscow: Nauka (1977).
10. K. Ya. Kondratiev. *Sputnikovaya klimatologiya* (Satellite-borne Climate Studies). Leningrad: Gidrometeoizdat (1983).

11. K. P. Feoktistov, editor. *Kosmicheskiye apparaty* (Spacecraft Designs). Moscow: Voennoye izdatel'stvo (1983).
12. A. I. Lazarev, V. V. Kovalyonok et al., *Atmosfera Zemli s Salyuta-6* (The Earth's Atmosphere: A Perspective from *Salyut-6*). Leningrad: Gidrometeoizdat (1981).
13. V. Mikhnevich and N. Glushchenko. *Tekhnika molodezhi*, 7, (1984).
14. *Mnogozonal'nye aerokosmicheskiye syomki Zemli* (Multispectral Aerial and Space Imaging of the Earth). Moscow: Nauka (1981).
15. G. M. Moskalenko. *Mekhanika polyota v atmosfere Venery* (Flight Mechanics in the Venusian Atmosphere). Moscow: Mashinostroyeniye (1978).
16. *Obrabotka informatsii poluchaemoi po programme Interkosmos* (Processing Information Output of the Intercosmos Programme). Moscow: Nauka (1982).
17. V. I. Rogal'sky and V. A. Bogdanov. *Zarubezhnaya radioelektronika*. (Satellite System *Argos*), 1 (1984).
18. T. B. Rostkova and A. E. Ordanovich. *Meteorologiya i gidrogeologiya*, 6, (1980).
19. P. A. Rumyantsev. *Kosmicheskaya sistema Meteor* (*Meteor* Space System). Moscow: Znaniye (1983).
20. R. Svoren. *Nauka i Zhizn*. 8 (1983).
21. *Astronautics and Aeronautics*. 21, 11:60-2,65 (1983).
22. C. Covault. *Aviation Week and Space Technology*. **113**, 11:24 (1980).
23. J. K. Davies. *Spaceflight*. 25, 7-8:326 (1983).
24. *Flight*. **123**, 3858:1063 (1983).
25. *Aviation Week and Space Technology*. **115**, 10:25 (1981).
26. Report 1. Working Group on Satellite Observing Systems for Climate Research. Joint Scientific Committee/Committee on Climate Changes and the Ocean. *The World Climate Research Programme*, September 1984.
27. P. R. C. Gillett. *Journal of the British Interplanetary Society*. 36, 9:387-393 (1983).
28. *Flight*. **118**, 3719:598 (1980).

29. J. C. Lowndes. *Aviation Week and Space Technology.* **120**, 20:78 (1984).
30. J. C. Lowndes. *Aviation Week and Space Technology.* **120**, 6:28 (1984).
31. *Air et Cosmos.* **18**, 817:38 (1980).
32. *Aėrospace Daily.* **122**, 33:263 (1983).
33. *Air et Cosmos.* **19**, 870:44, 52 (1981).
34. *Flight.* **120**, 3770:429 (1981).
35. *Flight.* **124**, 3888:1288 (1983).
36. *Aviation Week and Space Technology.* **115**, 9:25 (1981).
37. *Air et Cosmos.* **19**, 866:50, 53, 55, 57 (1981).
38. *Journal of Spacecraft and Rockets.* **18**, 2:172-177 (1981).
39. *New Scientist.* **82**, 1219:856 (1980).
40. *Flight.* **125**, 3898:146 (1984).

# To the Reader

Mir Publishers would be grateful for your comments on the content, translation and design of this book. We would also be pleased to receive any other suggestions you may wish to make.

Our address is:
Mir Publishers
2 Pervy Rizhsky Pereulok
I-110, GSP, Moscow, 129820
USSR

УДК 629.783:525=20

# SCIENCE FOR EVERYONE

Studies of typhoons and hurricanes based on conventional tracking technologies ground weather stations, ships aircraft, and weather rockets rarely turn out to be effective enough, since the time and place of typhoon origin are unpredictable. A new avenue of approach to the problem is opening up with advances in space technology. This book presents a detailed method to explore in, typhoons and hurricanes using satellites and satellite probes to deliver balloons with a payload of measuring instruments into their effective range. There is also an extensive discussion of problem areas in meteorology, oceanography, and environmental science capable of being addressed by space-borne technologies. The book is intended for those interested in astronautics, oceanography and in the protection of the environment.

ИЗДАТЕЛЬСТВО • МИР •