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PEACEFUL USES OF EARTH-OBSERVATION SPACECRAFT

VOLUME I: INTRODUCTION AND SUMMARY

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PREFACE

A major objective of programs of the National Aeronautics and Space Administration is to investigate and implement the adaptation of space technology for peaceful uses. As a part of one program, the Federal Systems Division of the International Business Machines Corporation has conducted a comprehensive study of the requirements for conducting an integrated set of experiments in a series of manned earth-orbiting laboratories which would lead to the realization of such peaceful uses of space. The Willow Run Laboratories of The University of Michigan's Institute of Science and Technology was asked to assist in this work and, as a subcontractor to IBM, has conducted a three-month study to survey potential applications of observation spacecraft in a number of important scientific and economic activities and to consider the program of ground-based and orbital experimentation required to develop this capability.

The results of the first phase of this investigation conducted by the Willow Run Laboratories are reported in this three-volume report. Volume I is an introduction and summary of the work performed. Volume II contains a comprehensive survey of potential applications of earth-observation spacecraft and the anticipated benefits. Volume III describes some of the requirements to be met by the orbital sensing devices and the manned earth-orbiting experiments proposed for developing the orbital sensing capability.

This investigation was conducted by the Infrared and Optical Sensor Laboratory under the supervision of Mr. M R. Holter, Head of the Laboratory, and Mr. D. S. Lowe, Principal Investigator. Staff members with major responsibility for the project were I. J. Sattinger, Research Engineer and Project Leader, and F. C. Polcyn, Associate Research Engineer and Project Leader for Experiment Definition Studies.

Since the material in this report was produced through the efforts of people in many disciplines with only a limited time available, the statements made herein are based on their judgments and do not necessarily reflect the endorsement of NASA, IBM, or The University of Michigan. Acknowledgment of the work of the many individuals who participated in or contributed to this study are included in the appendix.

ABSTRACT

Earth-observation spacecraft have many potential applications in the fields of geography, agriculture, forestry, hydrology, wildlife management, oceanography, geology, air pollution, and archaeology. Substantial scientific and economic benefits could result from the use of sensors carried aboard earth-orbiting spacecraft for earth mapping, collection of agricultural census data, forest inventory, wildlife habitat assessment, detection of sea ice, measurement of sea surface temperatures, and many other uses.

Types of sensors to be considered for these purposes include photographic cameras with focal lengths ranging from 0.5 to 20 ft, infrared scanners, multispectral sensing systems, noncoherent and synthetic-aperture radar, microwave radiometers, and laser altimeters. The development of operational systems of observation spacecraft would require a research and development program which included preliminary ground-based and airborne experiments followed by a series of manned earth-orbiting experiments. The preliminary experiments would provide information on sensor characteristics and capabilities for observing natural and cultural phenomena on the earth's surface which would be necessary for design of experimental orbiting sensors and planning of orbital experiments. The objective of the manned earth-orbiting experiments would be to ascertain the optimum conditions for sensor operation and to demonstrate the feasibility of future operational systems. In the manned earth-orbiting experiments, predicted characteristics of the atmosphere would be checked, individual sensors calibrated, sensor performance measured, and imagery and other data collected over both land and water, which would be analyzed to determine the feasibility of detection and identification of earth-based objects and the best methods for employing future operational earth-observation spacecraft.

CONTENTS

TABLES

1
PROJECT OBJECTIVES

One of the most important results of the nation's space program is the development of many useful applications of space technology for civilian purposes. A large class of useful applications can be based on the unique advantages of earth-orbiting spacecraft for observing the land and water surfaces of the earth. The National Aeronautics and Space Administration is now actively engaged in investigating the potentialities of these applications and in planning a comprehensive program for their full development.

As a part of the National Aeronautics and Space Administration (NASA) program, the Willow Run Laboratories of The University of Michigan's Institute of Science and Technology has conducted a study to survey potential applications of observation spacecraft in a number of important scientific and economic activities. Major emphasis of this study is placed on the uses of spacecraft to aid in the survey and management of our important natural resources, such as agricultural land, forests, water, and minerals, a matter of vital importance in meeting the expanding needs of the world's rapidly growing population.

This study has identified a large number of potentially valuable uses for observation spacecraft techniques. Applications studied in considerable detail include those in the areas of geography, agriculture, forestry, hydrology, wildlife and fisheries management, oceanography, geology, air pollution, and archaeology.

Because of limitations of time and effort devoted to this study, the applications discussed in this report do not constitute an exhaustive list of the capabilities of remote sensing. They represent those uses which most obviously meet the requirements of technical feasibility and significant benefit to the nation. It is anticipated that future studies by other members of the scientific community will uncover many additional ways in which observation spacecraft could be usefully employed.

Each of the uses discussed appears to have substantial scientific or economic significance. In some cases, benefits of major economic value are involved. The significance is pointed out in each case, and for some cases quantitative estimates of benefits are cited in as much detail as available data permit.

A preliminary assessment has been made of the technical and operational feasibility of each of the applications. It is recognized, however, that feasibility can be fully established and the techniques fully developed only after more detailed analytical and experimental investigation. A major task of this project has been to plan a program of further investigation which would lead to the full realization of the required orbital-sensing capabilities. The experimental program would include a series of preorbital experiments, conducted in ground-based laboratories and test sites and using preliminary versions of sensing equipment flown in conventional aircraft. This phase of the program is discussed briefly and the results to be obtained from preorbital experimentation are defined. Most of the study effort, however, has been devoted to defining the experiments which must be conducted in manned earth-orbiting research laboratories to complete the development of the techniques and to demonstrate their adaptability to operational use. These orbital experiments would be concerned both with checking the technical performance of equipment and with using the equipment to obtain imagery of selected ground sites which could be studied by scientists in each specialized discipline. The orbital experiments would be performed in a series of manned earth-orbiting research laboratories to be made available as a part of the Apollo Experiments Support Program.

The experimental program described herein should lead to the implementation of a series of observation spacecraft becoming operational in the post-1975 time period.

2
TYPES AND CAPABILITIES OF SENSORS

Remote sensing is the acquisition of information about specific objects of phenomena by an information-gathering device not in intimate contact with the subject under investigation. The data supplied by remote-sensing devices are of two distinct types: basic scientific data providing knowledge relevant to the earth and its environment, and applied scientific data relevant to the exploitation or conservation of natural resources, the solution of engineering problems, and the promotion of national defense.

The acquisition of such data by remote sensors represents, in many cases, a logical extension of the existing capability for research and problem solving. In other cases, it presents a completely new and unexplored approach with many latent applications available to the imaginative scientist or engineer. With remote-sensing devices, it is possible to map large areas, obtain information about the physical characteristics of objects or phenomena, and monitor conditions that change with time. Regardless of the application, when used in aircraft or spacecraft these devices provide a means of acquiring data on environments otherwise inaccessible because of physical limitations or political restraint. In some instances, remote sensors may be the only means of acquiring a certain type of data; in others, they may be the more economical.

Present electromagnetic sensing technology and the ability to operate from orbiting platforms will permit the development of systems providing a substantial increase in ability to sense the meaningful characteristics of the earth and its environment. Recently developed techniques permit observation of the earth using a very wide range of the electromagnetic spectrum extending from the ultraviolet to the microwave region. The information obtained photographically in the visible portion of the spectrum can be supplemented by imagery obtained by these multispectral sensing methods.

2.1. PHOTOGRAPHY IN THE VISIBLE SPECTRUM

Since World War I, aerial photography using the visible portion of the spectrum has been applied to a steadily increasing variety of tasks. At the close of World War II, with the release of many trained and experienced interpreters as well as a great quantity of applicable equipment, the use of aerial photography suddenly accelerated in quantity and scope. In addition to its classic military uses, it has been found virtually indispensable in political, economic, and scientific applications. In reference 1 extensive application is indicated in geology, soils mapping, wildlife, range and watershed management, agriculture, urban analysis and planning, archaeology, geography, etc.

In spite of extensive and increasing utilization of aerial photography, many of its techniques remain relatively modest extensions of the capabilities of the human eye. Numerous methods of analysis and inference have been developed and the use of high-speed aircraft has become common, yet the range of practical usefulness for aerial photography remains more restricted than is desirable. The principal restrictions of such systems are (1) the inability to sense some very important parameters, such as temperature, (2) the relative slowness of interpretation as compared to the rate at which information is desired and can be obtained, (3) the costs of acquiring imagery over large areas, and (4) limitations on the altitudes attainable in aircraft and balloons.

2.2. ADVANTAGES OF MULTISPECTRAL SENSING TECHNIQUES

The development of integrated systems making use of recently developed techniques will remove or alleviate these restrictions. Techniques now available are capable of producing imagery over a very wide spectral range which includes ultraviolet, visible, long- and short-infrared, and microwave wavelengths. Imagery made in spectral bands heretofore little used and comparison of simultaneous imagery made in a variety of spectral bands promise to increase the utility and applicability of pictorial sensing in two ways. First, new types of information not obtainable with conventional photography can be provided. For instance, the use of infrared can furnish indications of the operation of man-made power sources and can produce thermal maps. Furthermore, the ability to sense data in the ultraviolet, visible, infrared, and microwave bands may make it possible to find a spectral region in which discrimination may be accomplished between objects which exhibit no discernible differences in the "photographic" region. Second, a comparison of imagery from a wide variety of spectral regions may permit increased use of pictorial tone differences and lessen the need for strong reliance on the use of the fine details of shape information, one of the principal reasons for the slowness of the normal interpretive processes.

For a number of years the Willow Run Laboratories, under military sponsorship, has been engaged in experimental and theoretical sensing studies in the ultraviolet, visible, infrared, and microwave regions. It has been demonstrated that useful new information can be obtained in spectral bands other than the visible. It has also been demonstrated that simultaneous examination of imagery in more than one spectral band can produce information not deducible from a single band. An account of the conclusions and recommendations of some of the recent work of this nature carried on at the Willow Run Laboratories is contained in reference 2. Additional discussions and examples of multiband sensing are given in references 3 through 6. The physical reasons that tonal differences may be expected to occur in the infrared are discussed in reference 7.

2.3. TYPES OF INFORMATION AVAILABLE FROM REMOTE-SENSING TECHNIQUES

A comprehensive remote-sensing system for acquisition of pictorial data over a broad spectral range must include three basic imaging techniques: photography, for the region from the ultraviolet at 300 mμ to the near infrared at 1 μ; optical-mechanical scanning for the infrared region between 1 and 40 μ (and, for some of the work, between 0.3 and 1 μ); and passive microwave or radar for discrete regions between 1 mm and several centimeters or meters in wavelength. The state of the art is such that all three regions can be adequately instrumented.

Photographic imagery will yield data concerning the amount of solar energy reflected from selected objects on the earth and its cloud cover as a function of wavelength, in selected narrow spectral regions. Further study, based on work currently in progress at the Willow Run Laboratories, may prove that electro-optical or optical-mechanical scanning techniques should be employed in this spectral region in order to acquire data of optimum usefulness. These methods, since they produce data in the form of an electrical video output, permit special processing before final recording on photographic film or magnetic tape; thus, the information from one spectral region may be combined additively with that from another region, for example, and a single picture produced which may represent an optimum image for certain studies.

Infrared imaging devices will produce recordings of the thermal structure and behavior of the terrestrial and meteorological environment. Since experience has shown that terrestrial data in at least two spectral regions (e.g., 4.5-5.5 μ and 8.5-13.5 μ) are often much more useful than either one alone, several infrared channels should be provided. In particular, at the longer wavelengths the contrast of objects seems to be dependent on emissivity differences in the objects; at shorter wavelengths contrast seems more dependent on temperature differences of the objects. The surface condition of the object often affects the relative emittance of the object. Since measurement is of radiation emitted from the objects, the sensing system can be used day and night. Other wavelengths should be used for studies of clouds, wind, ozone distribution as it affects ultraviolet absorption, and air pollution (wavelengths corresponding to absorption regions in the atmosphere).

Radar imagery provides a comparative measure of the reflection from various components of the earth or of clouds. Reflected intensity (radar return) is affected by the aspect of the terrain relative to the beam direction, by the dielectric properties (at the radar frequency) of the material, and, for elements smaller than the resolution limit, by element size. Scanning at small angles (near grazing incidence) yields intensity variations which are a sensitive function of the local slope of complex landforms; it is therefore a singularly powerful technique for topographic mapping. Extensive research may be required to determine optimum frequencies, scan angles, and power requirements.

Passive microwave scanning radiometers have not been developed as extensively as the other sensors under consideration here, but new techniques for improving thermal sensitivity and speed of operation are available. Although comparatively few informative pictures have been produced, polarization effects and the fact that radiation in the passive microwave region originates from beneath the surface of certain terrestrial materials (e.g., ice and snow) offer promising possibilities for geologic and arctic exploration. Passive microwave signals can also provide information about the roughness or other characteristics of land or water surfaces, which would supplement data obtained from other spectral regions.

At present, passive microwave techniques do not have sufficient sensitivity to produce continuous imagery of the earth's surface from an orbiting satellite. Passive microwaves could, however, produce a usable record of the characteristics of the terrain along a transect below the satellite's path. A number of transects, obtained on succeeding satellite passes, could be combined to give an integrated coverage of the earth's surface. Finer resolution data from other spectral regions might also be used to interpolate between transects.

Both radar and passive-microwave data-collection techniques have the advantage that they can be used both day and night and in the presence of cloud cover. This greatly extends their capability for obtaining continuous information concerning the earth's surface, regardless of time of day or weather conditions. It may also supply data on meteorological conditions in areas of cloud cover that are not obtainable in other spectral regions.

2.4. SUMMARY OF FUTURE OPERATING CAPABILITIES

Table I summarizes the detection capabilities of sensors operating in various spectral bands for given parameters. The values in this table include estimates of capabilities in 1970 with technological improvements which can realistically be expected. It is possible to improve performance of the sensor systems in terms of one parameter at the expense of performance in terms of another parameter. This is illustrated in the relationship between ground resolution and thermal sensitivity shown in table I for the infrared and passive microwave spectral bands. It must be understood that apparent temperature differences are not necessarily real tempera-

TABLE I. SUMMARY OF SENSOR CAPABILITIES

Spectral Band	Type of Sensor	Estimated Attainable Ground Resolution	Estimated Minimum Apparent* Temperature Differences Detectable
Ultraviolet, Visible, and Photographic-Infrared (0.3-1.0 μ)	Camera or Scanner	In 1965 18 to 90 ft [8] In 1970 2 to 10 ft	
Infrared (2.0-14.0 μ)	Scanner	In 1965 6000 ft	$0.0003^{o}K$**
		600 ft	$0.06^{o}K$
		240 ft	$0.4^{o}K$
		In 1970 est. 60 ft	$< 1^{o}K$†
Passive Microwave (1000 μ-10 cm)	Scanner	In 1965 12,000 ft	$0.43^{o}K$
		1,200 ft	$4.3^{o}K$
		In 1970 est. 1200 ft‡	$4.3^{o}K$

*See text for distinction between apparent and real temperature difference.

** |Apparent Object Temperature—Apparent Background Temperature| < $1^{o}K$; Signal/Noise = 1.

† Expected improvements in detectors may produce a thermal detection capability of better than $1^{o}K$ with the indicated ground resolution.

‡Significant improvements can come about with further improvements in resolution and temperature sensitivity due to development of submillimeter-wavelength solid-state detectors.

ture differences but are influenced by emissivity of the objects, wind velocity, heat capacity, sky reflections, and atmospheric effects. However, the knowledge of minimum detectable apparent temperature is a guide for determining what phenomena might be measurable. These estimates of capability are typical of a high-quality operating system, but performance could be improved if benefits from applications justified greater size, weight, power, and cost. Therefore, it would be unwise to eliminate an application simply because it requires detection of a ground resolution or apparent temperature difference better than the capability stated in table I.

2.5. DATA-LINK AND FILM REQUIREMENTS

Tables II and III show the requirements for transmitting data from a spacecraft to earth by data link and film, respectively. It is not clear without further detailed investigation whether complete coverage of areas of continental size would be justified at the photographic scale of 1:60,000 or ground resolution of 2 ft; instead, coverage would probably be restricted to sample areas representing a small percentage of the total. At the smaller scales, corresponding to resolutions of 25 ft and 100 ft, the requirements for data transmission are moderate and complete coverage of continental areas could be justified. If higher data-transmission bandwidths were to become available, the data-link transmission times would become shorter, and comprehensive coverage could be seriously considered. Table II shows transmission time requirements for a bandwidth of 1,000 Mc.

For multispectral sensing systems of a given resolution, the data-transmission problem will be more severe than for a single spectral band, increasing in proportion to the total number of bands included in the sensing system. It may also be desirable to use as many as 7 bits to cover the dynamic range of the signal in order to retain all useful information. However, for applications where onboard data processing can be used, the total amount of data transmission can be drastically reduced and the data-transmission requirements would be as the same order of magnitude as shown in tables II and III.

2.6. COLLECTION OF EARTH-BASED DATA BY SPACECRAFT

The use of spacecraft for collecting data from a system of buoys or ground-based data-gathering stations and transmitting the data to centralized receiving points provides a capability which nicely complements that of orbital-sensing systems. By standardizing on data storage and transmission format, a single system of data-collection spacecraft could service ground stations or buoys collecting a wide variety of data, including, for example, meteorologic, oceanographic, and hydrologic data. Such systems would rapidly collect and transmit many types of

TABLE II. DATA-LINK REQUIREMENTS FOR LARGE-AREA COVERAGE*

Resolution**	2 ft		25 ft		100 ft	
Bandwidth	10 Mc	1,000 Mc	10 Mc	1,000 Mc	10 Mc	1,000 Mc
Square Miles/Second	0.29	29	45.3	4,530	725	72,500
Time for Area Coverage						
Continental U. S. (3,022,000 sq mi)	121 days	1.21 days	18.5 hr	0.185 hr	1.16 hr	41.7 sec
Earth's Surface (197,000,000 sq mi)	7,860 days	78.6 days	50.4 days	12.1 hr	3.14 days	0.75 hr
Oceans and Seas (139,000,000 sq mi)	5,550 days	55.5 days	35.5 days	8.5 hr	2.22 days	0.53 hr
Land Areas (58,000,000 sq mi)	2,310 days	23.1 days	14.9 days	1.6 hr	0.92 days	0.22 hr
Swath Width for Real-Time Transmission	0.062 mi	6.2 mi	9.8 mi	980 mi	156 mi	1,000 mi

*Continuous time required to transmit imagery by data link, assuming 5 bits per picture element, 1 bit transmitted per cps of bandwidth.

**Dimension of barely distinguishable picture element. Corresponds to one-half the distance between center lines of two resolvable lines.

TABLE III. FILM REQUIREMENTS FOR LARGE-AREA COVERAGE

Photographic Scale	1:60,000	1:800,000	1:2,400,000
Area covered by 9- × 9-in. film	73 sq mi	13,000 sq mi	116,000 sq mi
Number of 9- × 9-in. frames (assuming no overlap)			
Continental U. S. (3,022,000 sq mi)	41,500	232	26
Earth's Surface (197,000,000 sq mi)	2,700,000	15,200	1,700
Oceans and Seas (139,000,000 sq mi)	1,900,000	10,700	1,200
Land Areas (58,000,000 sq mi)	800,000	4,500	500
Weight of Film (lb)* (assuming no overlap)			
Continental U. S.	2,560	14	1.6
Earth's Surface	167,000	940	105
Oceans and Seas	117,000	660	74
Land Areas	50,000	280	31

*Does not include weight of film packaging.

physical data from extended geographical areas, including many inaccessible locations. The data would provide for widespread sampling of large areas and could also furnish necessary calibration data for the orbital sensors. Although the use of spacecraft for this purpose was considered in this project, major emphasis in this report is placed on the analysis of orbital-sensing devices.

3
ADVANTAGES OF ORBITAL SENSING

There are many reasons which make it desirable to obtain imagery of the entire earth or major parts of it by means of orbital-sensing systems. Such wide coverage cannot be obtained reasonably from aircraft or balloons but could be obtained from an orbiting spacecraft. In some large areas balloon and aircraft access is not permitted by the local governments; spacecraft are not subject to these prohibitions. For some purposes nearly simultaneous (synoptic) imagery of the entire earth is desirable; this is not possible with airborne sensors. Global coverage can be generated in times as short as 26 hours by spacecraft. Such synoptic coverage would be extemely useful for providing data on certain types of events in times which are short compared to the intervals during which large changes can occur.

With observation spacecraft it is possible to obtain coverage of most or all of the earth's surface within a matter of days, the exact length of time depending on the type of sensor, the resolution desired, and the amount of interference from cloud cover. For sizable areas within the field of view of the sensor, the coverage is truly synoptic. This would be of great advantage to research work in the earth sciences and in natural resources, which has been hampered by the time and space scales that arise in the measurement of the variables under investigation. Remote sensing from high-altitude vehicles would permit synoptic time and space sampling that would yield good averages of the variables. The research scientist, moreover, would be enabled to better detect environmental anomalies and to interpret their significance in relation to normals, averages, and trends. The powers of the research worker in the prediction, surveillance, and control of the supply, use, and contamination of natural resources would be enhanced with remote-sensing methods.

It is true that placing a sensing system at satellite altitudes prevents obtaining the finest ground resolutions, but many of the reasons for mapping very large portions of the earth do not require fine ground resolution. In fact, for the recognition of major crop distributions, the mapping of ocean temperature, and the detection of geologic lineaments, the desired information tends to be obscured by a wealth of detailed structure if the resolution is too fine. Because of problems involved in matching the edges of mosaic elements, it is desirable to obtain as wide a coverage as possible in each image. Therefore, in a number of important applications it is desirable to exchange fine resolution for width of coverage. Obviously, at too high an altitude, ground resolution becomes too coarse; at too low an altitude, the usable width of coverage is severely restricted. Calculations based on methods shown in references 9 and 10 indicate that for optical collecting apertures between 6 and 30 inches in diameter and desired ground resolution of a few tens or hundreds of feet, the optimum altitude to maximize the width of coverage is approximately 200 miles.

Observation of the earth with finer resolutions is possible with photographic cameras especially designed for the purpose. Such camera equipment could conceivably be used to map the entire earth at relatively large scales approaching those used in conventional aerial photography. However, the increased resolution introduces major problems in returning the large mass of data to the ground either as photographic film or by data link. It is likely that large-scale photography would be limited to looking at relatively limited portions of the earth's surface, such as individual metropolitan areas, sample areas randomly selected, or sample areas preselected to be representative of certain types of land use. Alternatively, methods of automatic data reduction within the spacecraft might be employed to alleviate the data-transmission problem.

A further advantage of acquiring data by orbiting spacecraft is the fact that all data will be collected by uniform types of equipment and methods of calibration and measurements. This will ensure that all data collected, regardless of time or location on the earth's surface, will be directly comparable and not subject to uncertainty caused by equipment or technique.

Another attractive feature of an orbiting platform for the earth-mapping function is that the cost appears to be considerably less than even a single synoptic global coverage with airborne platforms. Comparative cost figures are discussed in section 5. The economic advantage of obtaining data by means of an orbiting spacecraft is most pronounced for small-scale imagery, for coverage of inaccessible locations, or for sampling over large areas. It is not clear that there is any economic advantage over conventional aerial photography in obtaining large-scale imagery over large contiguous areas in the United States.

Observation spacecraft are subject to some limitations. Because of the relatively small angular filed of view likely to be used with orbital cameras, contiguous photographs will not show substantial stereoscopic effect and will therefore be of limited value for depth perception. If stereoscopic effect is important for certain applications, it might be achieved by special camera design, but this possibility has not been given detailed study here. A single orbiting platform is limited in its ability to observe a specific area at a predetermined time or on short notice by such conditions as cloud cover, lack of daylight (for visible photography), and orbital flight path.

The problem of cloud cover is not troublesome for those applications in which data are not needed on short notice. If data are required on short notice, however, cloud cover must be taken into account and special effort to minimize the effects may be justified. Cloud shadows may also be a problem, especially at low sun angles.

It has been estimated that between one-half and two-thirds of the earth's surface is obscured by clouds at any one time. The fraction is variable, depending on the season of the year and the region of the earth being observed. Cloud cover is greatest over the North Atlantic and North Pacific Oceans, on the eastern coasts of continents, and wherever air moves regularly onto higher land or off water onto land. A pronounced diurnal variation in amount and class of cloud cover exists all over the United States, and presumably over most of the earth's land area. The morning sky, shortly after sunrise, has a strong probability of being clear. This condition is surprisingly stable and normally persists until after midmorning or almost until noon.

If the spacecraft orbit can be selected to pass over areas to be photographed shortly after sunrise, the probability of obtaining a clear view of the photographed area can be maximized. Another approach is to look around or under the clouds by taking photographs at an appreciable angle from the vertical. Several photographs of the same area taken from different points of view have a good probability of filling in coverage gaps, if the total cloud cover in the area does not exceed about 60%. The cameras proposed in section 8 to obtain 1:800,000 and 1:2,400,000 scale photography would have fields of view sufficient to obtain appreciable improvement in coverage by this method.

4
APPLICATION SURVEY

During this project comprehensive survey was made of potential applications for remote sensing from spacecraft of interest to scientists in many disciplines and dealing with many important domestic and world problems. The applications studied did not exhaust the possibilites in the areas covered, and additional scientific and technical areas were not considered because of time limitations. Nevertheless, the applications considered represent a cross section of the uses of space observation systems and indicate the extensive possibilities for important advances in this field of space research.

This section summarizes the survey of applications; tables IV and V condense these uses to outline form. Table IV lists a number of scientific studies which could benefit from the use of space observation methods, and table V lists the uses of these methods for social, political, and economic purposes.

4.1. GEOGRAPHY

Observation of the earth's surface is of special interest to the study of geography because of its concern with the spatial relations of human activity and natural processes. The interests of the geographers are identical with those of scientists in many other disciplines, but the emphasis in geographic studies is on the interrelationships of the individual disciplines. The summary of applications to geography is therefore limited to the interdisciplinary studies; applications primarily related to individual disciplines are discussed in subsequent sections.

Studies of spatial structures of human activities include geographic problems concerned with man-to-man relationships as manifested in the spatial distribution of man's activities, rural and urban settlement patterns and land use, transportation networks, and dynamic analysis in terms of flows and spatial processes. These studies are important for planning and policy making. Observation of land-use patterns, both rural and urban, and transportation networks would indicate trends in urbanization and permit improved estimates of population. Repeated observations separated in time would indicate dynamic patterns depending on seasonal changes or growth trends in industrial, urban, and agricultural development. Proxy measurements might be possible to indicate levels of activity and degrees of economic organization. For example, if man-induced energy could be measured, it might be used to indicate the level of economic activity. Such indexes would form the basis for improved strategies of development in foreign areas and more rational long-range planning relating to world demographic problems.

TABLE IV. TYPICAL SCIENTIFIC STUDIES

Improved topographic base maps
Geographic studies of changing patterns of urban and rural areas, transportation networks, etc.
Vegetation map of the world
Oceanographic studies of ocean currents, air-sea interaction, and wave propagation
Energy budget calculations
Hydrologic processes
Effects of land use, vegetative cover, and distribution of snow, ice, and water on weather and long-range climatic trends
Dispersion of air and water pollutants
Ecology of animal and plant life
Migration habits of birds, fish, and animals
Interpretation of large-scale geologic features and the tectonic processes causing them
Hydrothermal and volcanic activity
Detection of unknown archaeological sites

TABLE V. PROJECTED USES FOR OBSERVATION SPACECRAFT

Cartography
- Map preparation
- Map revision

Geographic Studies
- Land use studies (current distribution, trends, optimum use)
  - Urban areas
  - Rural settlement patterns
  - Forests
- Transportation networks
- Proxy measurements of levels of economic activity
- Population estimates

Food Resources
- Fisheries
  - Location of fishing grounds
  - Monitoring of fishing vessels
- Agricultural resources
  - Soil treatment material surveys (limestone, fertilizer, etc.)
  - Agricultural land use studies
  - Soil classification and mapping
  - Soil conservation studies
  - Studies of site productivity, growth processes
  - Range management (evaluation of vegetative cover)

Aids to Agricultural Operations
- Agricultural census
- Crop prediction and control
  - Agricultural statistics
  - Crop-control compliance checks
- Detection of disease or insect damage
- Drought prediction

Forest Resources
- Forest inventory
- Protection against forest fires
  - Danger assessment
  - Early detection
  - Surveillance

Oil and Mineral Resources
- Reconnaissance for new sources

Wildlife and Recreation-Area Management
- Wildlife and waterfowl habitat assessment
- Beach-area surveillance (water pollution, wind and wave action)
- Tracking wildlife (caribou, fur seals, African and Australian herd animals)

TABLE V. (Continued) PROJECTED USES FOR OBSERVATION SPACECRAFT

Water Supply Prediction
- Water yield estimates
- Streamflow estimates
- Soil moisture conditions
- Basin geomorphology
- Flood prediction, assessment and control
  - Prediction of runoff
  - Delineation of flooded areas
- Distribution of water pollutants

Weather Forecasting and Studies of Climatic Trends
- Sea surface temperatures
- Ocean currents
- Forest influences
- Vegetative map
- Measurement of biomass
- Energy budget
- Snow, ice, glacier reconnaissance

Air Pollution
- Monitoring ozone concentrations

Aids to Shipping
- Ship routing
  - Sea-state measurement
  - Sea-ice reconnaissance
- Ship tracking
- Sea rescue

Aids to Engineering Projects
- Dam-site reconnaissance
- Highway routing

Detection of Unknown Archaeological Sites

Studies of patterns of resource use are concerned with problems arising from man-environment interaction, including both the effects of environment and available resources on man's activities and his effects on the natural environment. The preparation of accurate inventories, which are of fundamental importance for adequate production and control of our natural resources, is discussed in later sections. Evaluation of disasters precipitated by natural causes such as floods and droughts is also a function which requires rapid and accurate data collection.

Physical geography is concerned with the spatial and temporal interaction of natural processes, particularly as they focus on the earth's surface as the home of man. Studies of energy exchange and water balance will add to our fundamental knowledge of climatology and hydrology. These studies use data derived also for studies related to meteorology, oceanography, hydrology, forestry, and agriculture. Studies of plant cover and soils are needed for a better understanding of long-term developmental trends in the ecosystem of the earth, as well as for more immediate problems relating to agricultural development. Studies in geomorphology and glaciology might benefit from measurements of the physical characteristics of glaciers and their effect on climate, the observation of large-scale geologic patterns, and the identification and mapping of soil types.

To aid all of the activities of geography and other disciplines, complete, accurate, and up-to-date maps of all areas of the world are necessary. It is estimated that less than 50% of the land area of the earth has been adequately mapped. Mapping of all types is urgently needed in many of the underdeveloped and remote regions of the earth. The most easily identified cartographic benefits to accrue from orbiting sensors are topographic base maps and coverage of photographic, infrared, radar, or other imagery. With spacecraft, large areas of the earth can be covered in a short time. Many underdeveloped areas of the world might be mapped for the first time. Assuming that the spacecraft imagery can be related to a geodetic control network on the ground, the actual position of any item will be accurately known with respect to all other items. The ability to obtain topographic information from spacecraft is limited, but planimetric information would suffice for many of the needs of map revision and reconnaissance of poorly mapped areas. Revision of maps would benefit from the ability to obtain small-scale imagery for a large region on one photograph. Coverage is required at all scales, ranging from very small to the largest obtainable. The effective use of this new capability calls for the simultaneous development of a comprehensive storage, retrieval, and analysis system.

4.2. AGRICULTURE

Projections of United States population range from 215 to 240 million for the year 1975 and from 270 to 380 million for the year 2000. World population by 2000 is expected to rise to about

6.3 billion people, unless methods of population control can be effectively applied. In 1955 the arable land per person was about 1.25 acres; by 2000, arable land per person will decrease to a little more than one-half acre. It is clear that performing agricultural research and obtaining agricultural information on a world-wide basis must be vigorously pursued.

If multispectral sensing methods can be developed to provide accurate and reliable methods of identifying various types of crops and estimating their health and state of maturity, these methods can be used in conjunction with observation spacecraft for many valuable applications in agriculture.

A number of applications for domestic agriculture appear to be useful. Remote sensing from spacecraft could materially assist in obtaining agricultural census information. To assist the present five-year schedule, summary totals compiled by area measurement and crop identification would provide a more positive and direct check on information collected from farm operators and land owners than is presently available. It would also be possible to provide more up-to-date information by collecting certain types of census data more often than once every 5 years.

The Statistical Reporting Service of the U. S. Department of Agriculture prepares and issues agricultural statistics on more than 50 major crops. Accurate and timely forecasts and estimates of agricultural production are of importance to government, industry, and individual farmers in planning the harvesting, transportation, processing, and marketing of agricultural products. Orbital sensing could assist in the collection of some types of data used in statistical reporting. With sufficient development of methods of crop identification and early detection of damage caused by insects, diseases, or other agents, it is possible that orbital sensing could lead to more accurate or more rapid forecasting of crop yields.

In order to administer crop-control programs, the Agricultural Stabilization and Control Service must check on contract compliance by individual farmers. The annual cost of field work for compliance checking presently is about $40 million. A capability for crop identification and area measurement by remote sensing from spacecraft could substantially reduce the amount of field work required for compliance checking.

Damage to agricultural production may be caused by flood, drought, windstorm, fire, insects, and disease. In the cases of flood and fire, information is needed on short notice so that relief needs for farmers and livestock can be met promptly. To provide such information, an all-weather day and night sensing capability would be required such as is provided by radar. Such a system could be justified, however, only if it could serve other purposes as well. Additional knowledge of the situation is required on a more extended time scale to determine the magnitude and extent of crop loss as a basis for developing the full disaster relief program. Multispectral techniques would be capable of sensing many of the effects caused by the types of damage listed.

Data acquired by orbital sensors for the above applications could also be used for other agricultural purposes, such as special surveys of resources and land use or economic studies. These additional uses are not of sufficient magnitude to justify separate operational systems.

If observation spacecraft were applied to those applications for which they appear to be most adaptable, they could result in gross benefits of $20 to $50 million annually to cover the cost of preliminary research and development, spacecraft construction and launch, and data transmission and processing. Applications in other developed countries would be similar to those in the United States, and could produce benefits to those countries at least comparable in magnitude to those for the United States.

Remote sensing from orbital platforms can play a very important role in the task of increasing world agricultural production to keep pace with the rapidly expanding world population. The United States must be concerned not only with the humanitarian aspects of the problem but also with the serious political consequences which may ensue if the problem cannot be met.

The food-production problem can be solved if the underdeveloped countries themselves cooperate; the necessary scientific knowledge is already available. A prime need for each country is a current agricultural census of reasonable accuracy to enable the country to monitor current production and predict crop yield. In addition to this primary need, extensive surveys are required which will result in making optimum use of the limited land resources available and in protecting and improving these land resources through appropriate conservation programs. There is also a great need for improved methods of damage assessment. Early warning of the extent of crop damage due to floods and droughts is particularly important, since it can result in famine conditions in a country which has poor food transportation and distribution facilities.

In terms of the direct interests of the United States, a gross benefit of $15 million per year would not be out of proportion to the $1 or $2 billion of U. S. funds devoted to foreign aid. A much larger figure could be justified by considering the cost of obtaining the same types of data by conventional aircraft. Finally, in terms of the extremely critical food situation faced by the world's population and the potential social and political consequences, the advantages of rapid and comprehensive data collection by observation spacecraft could outweigh any cost considerations.

4.3. FOREST RESOURCES

Approximately 10,885 million acres of the earth are covered by forests; 760 million acres of forest land are in the United States. Based on gross revenue, forest products industries constitute one of the four largest U. S. industrial complexes, and, on a world-wide scale, the forest resource may prove to be the largest untapped chemical storehouse available to man. Moreover, forests exert a major influence on climate, available water, and animal populations, and often affect land areas considerably removed from the forest itself. Thus changes in size or character of the forest in one area may exert profound pressures on other areas.

To permit the implementation of intelligent management practices concerning the proper use of forest lands and to gain an understanding of the influences of forests on other natural processes, a comprehensive world inventory of the forest resources is needed. Existing inventory methods do not yield an adequate picture of the total resource because of the time required to gather and analyze data. The first data collected may be obsolete and useless by the time a survey is finished. Rapid data collection from orbiting platforms could substantially facilitate forest management and resource planning.

One of the most promising applications of orbiting spacecraft to forest inventory lies in determining forest location and distribution. Despite the intensity of forest uses, even the United States has no reliable map of this distribution of its forest resources. A second promising application arises from the need to determine tree size. If spacecraft sensors can provide imagery of sufficient resolution to permit determination of only average crown diameter or average height of stands, the resulting stratification of gross forest area would greatly improve statistical sampling procedures and should permit significant reductions in the number of ground plots required to obtain a given confidence level in the final inventory figures.

In the United States, costs of forest inventories during the 1960's averaged 2.1 cents per acre in the North Central and Central States regions. If the 2.1-cent average cost for the central United States is applied to the 508.8 million acres of commercial forest land in the 50 states, the the cost of collecting data for a national forest inventory is at least $10.7 million. An exact determination of cost savings resulting from a reliable map of vegetational resources is not possible, but 20% seems reasonable for the United States. Based on a total data-collection cost of $15.0 million ($10.7 million in federal funds plus $4.3 million in state contributions), the savings would amount to $3.0 million per inventory. For underdeveloped regions of the world, on which little data are available, cost savings could easily amount to 30% to 40% of the cost of conventional surveys. A reasonable estimate of the total value of a world map of forest vegetation is $50 to $75 million. If, in addition to forest location and distribution, tree height and/or crown diameter can be determined from the imagery, the total value of using a spaceborne sensor in forest inventory could easily double in the United States, and triple in less developed areas.

In addition to the collection of inventory data, spaceborne sensors may be employed for the early detection of forest fires and the gathering of data on insect and disease infestation. The use of spaceborne sensors for early forest-fire detection would result in an estimated 2% or 3% reduction of total forest area burned in the United States, resulting in an average annual saving of $1.4 to $2.1 million. For underdeveloped areas of the world, the usefulness of the method will depend on the development of adequate fire-suppression forces. By about 1980, a spacecraft fire-detection system would permit a reduction of 8% of the total forest area burned (a reduction of 16 million acres per year) for a saving attributable to the system of $32 million per year.

A logical next step to the applications discussed so far is the use of spaceborne sensors for the determination of energy-balance relationships and total terrestrial biomass.

Energy-balance relationships in vegetation directly influence evapo-transpiration and therefore water yield and stream flow. The same energy balance also influences the amount of energy available to the plants for utilization in photosynthesis and other metabolic processes, and thereby influences plant growth. Orbital platforms would allow the collection of data on energy-balance relationships leading to a better understanding and prediction of energy-balance changes, and permitting optimization of land-management practices with attendant cost savings.

Biomass, the gross weight of living material of plant and animal origin, can be expressed as total dry weight or as quantity of fixed carbon. Since biomass is a changing quantity, data need to be collected as nearly instantaneously as possible to arrive at a figure for total biomass at any specific time. Orbiting spacecraft would permit rapid data collection over the entire earth, and allow an estimation of total biological productivity (essentially carbon dioxide turnover rate). This information would be useful on a local scale for determination of the distribution of biomass for planning future food and fiber production for a growing population. On a world-wide scale, it would aid in the study of long-range climatic trends.

4.4. WATER RESOURCES

The wide variety of uses to which water is put make an adequate supply of fresh water a major determinant of economic growth and development. Water is used for domestic consumption, industrial processing, production of food and fiber, hydroelectric power, navigation, waste disposal, and recreation. As population increases, the demand for water will also increase, becoming critical in many areas. The principal tasks of world-wide water-resources management are to find adequate amounts of water of high quality at low cost, to forecast future supply, and to control the location, quantity, quality, and timing of that supply.

The accomplishment of these tasks requires the continuing collection of hydrologic data for large areas of the earth's surface. The required data fall into two broad categories: inventory and description of world wide or regional conditions which change relatively slowly, and evaluation of those rapidly fluctuating processes that govern the short-term water balance of the earth or one of its major segments.

The total existing capital investment in water-resources facilities of all types in the United States is about $235 billion. To service this capital investment, some $40 million is spent each year, almost entirely by federal agencies, for routine collection of basic hydrologic data. The data made available by this expenditure are far from adequate; many important areas of investigation have been almost wholly neglected. Furthermore, the deficiency of data is substantially greater in most other parts of the world than in the highly developed United States.

Because of the large areas and extended periods of time which must be covered in collecting adequate hydrologic data, orbiting platforms offer an attractive method for collecting certain types of data. In general, data collected by spacecraft should supplement rather than replace data collected by ground-based methods.

Certain types of information which can be collected by spacecraft describe the relatively permanent characteristics of a region and form the basis for all types of water-resource planning and short-term predictions. Information of interest includes snow and ice cover, vegetative cover, land use, and river-basin geomorphology. Such data will assist in locating untapped water sources, particularly in remote regions, and in defining areas such as snow accumulation zones that are potentially manageable for increased water yields. Further research based on adequate data of this type can lead to methods of classifying areas similar in their water regimes, and hence in their adaptability to water management. This capability for classification can be particularly useful in underdeveloped regions, where hydrologic data are almost completely lacking.

Forecasts of probable future conditions are among the most profitable uses of hydrologic data. Such forecasts are needed by farmers, businessmen, power companies, municipal water supply and treatment plants, and other water users. Prediction of runoff and stream flow would be aided by information gathered on snow volume and snow cover, river and lake ice, and soil moisture and frozen soil, used in conjunction with information on relatively permanent regional conditions previously mentioned.

Valuable assistance can also be furnished for purposes of flood prediction, assessment, and control. A knowledge of snow depth and cover, river and lake ice, soil moisture and frozen soil, along with a knowledge of the vegetation and geomorphology of the region, would aid in predicting flood conditions and planning emergency action. Direct observation of areas of flooding would also aid emergency planning and damage assessment. Long-range flood-control planning could also benefit from such data.

Pollution of water by domestic and industrial wastes is becoming an increasingly serious problem. It may be possible to detect and track polluted water by means of its temperature differential. This type of observation might be used for short-term prediction of pollutant distribution.

Observation of river and lake ice could also be of assistance in planning ice-breaking schedules and predicting navigation conditions.

Scientific uses of hydrologic data obtained by spacecraft are fully as important as the applications more directly related to economic activities. Scientific data are needed to better understand the operation of the hydrologic cycle. This improved understanding is fundamental to fully effective prediction and control of water resources. Many types of hydrologic data which can be collected (e.g., information on vegetation, snow cover, evaporation, transpiration, and energy balance) will contribute not only to an understanding of hydrologic processes but to study of meteorology and climatology as well. Scientific studies by limnologists can use surface temperatures of lakes to observe water circulation and lake dynamics. Surface temperature of lakes also is of interest in studies of biological productivity.

4.5. WILDLIFE AND FISHERIES MANAGEMENT

Uses of spacecraft for wildlife and fisheries studies are particularly compatible with other uses in respect to an integrated data-acquisition program. Since wildlife and fish occupy specific ecological niches of varied natural environments, the major requirement for analyzing game populations is knowledge of that environment. Thus, the major value to wildlife and fisheries to spacecraft research and operation will be derived from use of the same types of data collected for agriculture, forestry, hydrology, geography, and oceanography. The sensors designed for study in these disciplines will be sensing animal environments. In the long run, the greatest total use of game for food and/or recreation can be assured if abundance is balanced with physical and biological factors and man's activities. Agricultural sensing will be very important because 72% of this country's hunting is for farm game. Data collected for forestry purposes also provides similar types of habitat analysis. Multispectral sensing, identifying crop and vegetation types and indicating seasonal condition, as well as visible photography providing information on distribution and juxtaposition, will enable a big step to be made in the direction of more scientific game management. Recurrent information on crops and vegetation when coupled with meteorological data, such as number of days of cloud cover, will permit more valid forecasting of game population levels and condition at a later season.

Oceanographic sensing systems will be studying the sea environment and the knowledge and understanding gained will help in furnishing better marine angling. Direct detection of fish, their effects, their predators (including man), their food, and their movements in coastal waters will be a boon to commerical and sport fisherman alike. The same oceanographic sensing systems will also provide temperature and plankton data for lakes and other inland waters sufficient in size for detection. Use of geographic data will help to better understand the present and required situation in terms of distribution of game and the people using game.

Besides data collected for other purposes, the spacecraft could analyze conditions of water and vegetation on the waterfowl breeding and wintering grounds, including agricultural damage in the latter, national wildlife refuges, and range lands.

A spacecraft may be able to detect migrations of caribou to aid the people who hunt them in northern Canada. Nocturnal locations of other herd animals, wild or domestic, throughout the world, might also be detected. A spacecraft and transponder system could provide a means of detecting the presently unknown home range of the fur seal. Oil pollution on the sea or large lakes, which is a serious hazard to waterfowl, could also be recurrently assessed with a spacecraft.

Most of the benefits of spacecraft will come from increased knowledge of the world environment, its changes, and energy flux. Because wildlife and fish depend directly on that environment and its dynamics, the management of these resources will benefit from knowledge gained through spacecraft activities. A conservative analysis of benefits from spacecraft activity shows that the value of recreation maintained due to our increased ability to maintain usable game populations would be at least $18 million a year.

4.6. OCEANOGRAPHY

The possibilities of oceanographic research by means of orbital-sensing systems were thoroughly explored in the NASA-sponsored Conference on the Feasibility of Making Oceanographic Observations from Manned Orbiting Laboratories convened at Woods Hole Oceanographic Institution in August 1964 [11].

Overall scientific knowledge of the oceans as physical and biological environments can be enhanced by observations from space of sea surface temperatures, ocean currents and waves, sea ice, and coastal geography. These observations will in most cases supplement rather than replace methods of data acquisition by surface instrumentation. Spacecraft can also provide rapid recovery of more detailed measurements of ocean parameters obtained by methods of buoy and ship interrogation and data relay. The data obtained by spacecraft can be used to answer many scientific questions concerning the dynamic processes of the ocean, its relation to the atmosphere, near-shore processes, and distribution of fish.

Improvements in long-range weather forecasting are a goal of much current research in oceanography and meteorology. The major economic effects of weather on government, business, and agricultural activity give this type of research a large potential payoff. Synoptic measurements of sea surface temperature, sea ice, and ocean currents will provide additional inputs useful for long-range weather forecasting. Information on sea state and sea ice as well as weather forecasting will further the recently developed technique of ship routing.

The spacecraft has a potential for aiding the harvesters of sea resources. Aids to locating and exploiting additional fish would benefit the domestic fishing industry and would increase the availability of fish for the world's protein-starved population. The location of commercially usable concentrations of fish can be aided not only by research on fish migration habits but by operational methods of transmitting existing oceanic conditions. Schools of herring-like or tuna-like fishes might be detected directly by their surface indications, or by location of upwellings of cold water, oceanographic fronts, and biomaterial such as phytoplankton. These methods would also aid any international efforts toward conservation of fish resources, as would methods of locating and tracking fishing vessels.

Observation of coastal geography and near-shore processes would be of interest in connection with matters of water pollution and recreational use of ocean beaches. Information is needed on the ability of the oceans to absorb disposal of sewage and radioactive and industrial wastes and to identify those areas most feasible or least dangerous for disposal purposes. Recreational use of ocean beaches is adversely affected by water pollution and by the action of wind and waves on the beaches. Spacecraft could obtain some of the information desired through color and high-resolution visible photography, but, except in special cases, aircraft reconnaissance of coastal geography may be the more economical method of data acquisition.

4.7. GEOLOGY

Remote sensors are a very important aid in rapidly exploring the earth's crust and will no doubt be instrumental in further exploring presently productive regions for minerals and petroleum and locating new wealth in unmapped portions of the world. Remote-sensing techniques can be used to locate areas favorable to mineral and petroleum accumulations by the identification of geologic features peculiar to such areas. This preliminary reconnaissance makes it possible to concentrate field investigations in relatively limited areas.

Sensors used in petroleum exploration would delineate faults, lineaments, folds, domes, basins, haloes, diagnostic minerals or elements, and presence of hydrocarbons in an area. Remote-sensing devices showing real promise are photographic, microwave, and infrared (near and far).

Sensors may prove valuable in mineral exploration in locating faults, lineaments, fold systems, and gossans. Depending on their geologic size, large metasomatic replacement deposits, supergene enrichment areas, and large veins may be detected from space. Photographic, infrared, and microwave devices have already proved successful and show promise for further development. Perhaps some of the more sophisticated sensors (i.e., geochemical, ultraviolet, fluorescent) will also prove to be valuable after current research is completed, but their worth would best be determined from tests with airborne sensors.

Moreover, imagery acquired with electromagnetic sensing equipment could be used in compiling maps showing the world-wide distribution of geomorphological features and, in particular, tectonic landforms such as folds, faults, and eroded or exhumed igneous masses.

A spacecraft in polar orbit would be the ideal platform for performing the task of acquiring data to be used in the compilation of a global tectonic map because the entire land masses of the earth would be surveyed on successive orbits.

The benefits that would accrue from this proposed use of orbiting sensors are manifold. First is the acquisition of new knowledge relating to tectonic processes. The ability to preserve continuity of surface tectonic features over entire continental masses and an anticipated ability to more accurately project these manifestations from one continent to another will provide geologists with data which could lead to a better understanding of the nature of terrestrial deformation mechanism. Aside from the purely basic scientific merit of this data-acquisition program there is an attendant capability that has economic and social aspects of immediate interest to persons occupying the geologically unstable areas of the world. Through a combination of thermal, radar, and photographic data acquired over areas of active faulting and volcanism, it may be possible to derive criteria for predicting crustal movements or valcanic eruptions. If such criteria can be established, human life and property could be saved by adequate alerting.

4.8. AIR POLLUTION

Explosive cultural developments and ever-increasing industrialization are causing rapid and severe alterations in the earth's biosphere. This alteration results from the pollution of the air by reactive chemicals in the gaseous and particulate form. In terms of pure economics, air pollution is costing the United States billions of dollars a year. Polluted air may contain strongly reducing and oxidizing compounds which act as severe irritants and actually attack organic material causing chemical and physical changes.

There is presently no wide-scale monitoring of air pollution throughout the world or even over sizable urbanized regions of the United States. Little or no information seems to be available concerning the influences of weather patterns, diurnal cycles, and seasonal cycles on large-scale patterns of pollutants and particularly on local saturations and subsequent atmospheric dispersion of the contaminants.

The various molecular species present in polluted air show absorption characteristics in the near-infrared regions. However, many of the absorption bands of these contaminants occur at or very near the absorption due to water vapor and carbon dioxide. Ozone shows some promise as a tool for monitoring air pollution because it is associated with pollution and because its spectrum is not completely masked by the normal atmospheric constituents. At low altitude, that is, from the earth's surface to about 3 km, ozone results from the photochemical reduction or organic material in the atmosphere, and much of this material arises from air pollution sources such as hydrocarbons released from exhaust fumes. There is also an ozone layer in the upper atmosphere, between 20 and 30 km, which is produced from the photochemical diassociation of diatomic oxygen by ultraviolet radiation. This high-altitude concentration of ozone varies with seasons of the year and with latitude and longitude; however, the lateral variations are gradual and small and the equilibrium at high altitudes changes slowly. There is no apparent exchange of the high-altitude ozone with the ground layer.

At the earth's surface, the concentration of ozone is approximately one-tenth that in the 20- to 30-km region, and, at first sight, one would assume that the greater concentration of ozone at the higher altitudes would mask the radiation from the lower ones. However, the lower concentration is at a higher temperature and its variations are more rapid and fluctuate over a wider range. Thus the changes might be detectable.

A computer program was designed to calculate the radiation from a polluted area through the higher-altitude ozone distribution and, in fact, through the entire atmosphere. The results of this calculation are neither forbidding nor extremely encouraging. Collecting optics of about 1 ft in diameter can be used with thermistor detectors to get the required sensitivity for ozone concentration of twice the normal amount.

4.9. ARCHAEOLOGY

Observation spacecraft have two possible types of applications to archaeological studies. First, the reconnaissance of large areas to observe sizable archaeological remains would aid in locating presently unknown sites. Remote sensing from orbit would avoid the problems of interpretation created by the use of mosaics and would take advantage of multispectral sensing to detect large sites or narrow linear sites (such as roads, canals, and walls). Second, the use of orbiting sensors for the detection of small features to aid in the detailed direction of excavations would have an advantage over conventional methods of aerial photography only where such photography was difficult or impossible to obtain for political or other reasons.

5
EVALUATION OF OBSERVATION SPACECRAFT

5.1. ANTICIPATED BENEFITS

Scientific understanding and adequate information are basic to the success of most scientific and economic endeavors. The basic data required for achieving these objectives may be difficult or impossible to obtain by conventional means of data acquisition because of fundamental limitations in spatial and temporal coverage. Observation from spacecraft derives its justification from its ability to provide many types of data rapidly and economically for a great variety of uses.

Benefits expected from these applications fall into three basic categories, which are not mutually exclusive: (1) Scientific, (2) sociological and political, and (3) economic.

5.1.1. SCIENTIFIC BENEFITS. The national space program has already made possible extremely significant advances in our understanding of the space environment, the sun, the moon, the planets of the solar system. Observation of the earth from space promises to add further to our understanding of natural phenomena. The suggested experiments would provide an overall picture of the dynamic characteristics of the oceans and their influence on weather and climate, large-scale geologic features of interest in understanding the forces which are constantly modifying the earth's crust, world-wide energy and water budgets and their relation to vegetation distribution and climate, and many other natural phenomena which are at present only imperfectly understood.

Not all scientific advances can be anticipated. Much of the significance of research programs comes from unexpected and unpredictable findings. A number of examples of this have already occurred in connection with earlier observation spacecraft. Imagery obtained from the Tiros meteorological spacecraft, for example, has revealed consistent regional patterns of weather which were previously unsuspected.

As a preliminary to manned earth-orbiting experiments, a series of experiments must be conducted in the laboratory or field or by the collection and analysis of data acquired by airborne sensors. These preliminary investigations of the terrestrial environment, while being essential to the earth-orbiting experiments, have great value in themselves. The cost of preliminary experiments can therefore be justified largely by the addition to our basic knowledge concerning these natural phenomena, independently of the value of the experiments as a part of the manned earth-orbiting program.

Basic experiments, although conducted primarily for scientific purposes, will inevitably have long-range economic benefits of great value in improving our ability to harness the forces of nature. But because these are indirect results of the research program, it is difficult to put an accurate price tag on them. In spite of the difficulty of accurately quantifying these ultimate benefits they are nevertheless real ones and in the aggregate may well overshadow more obvious benefits which are anticipated.

5.1.2. SOCIOLOGICAL AND POLITICAL BENEFITS. Remote sensing from space will have an important role in providing information needed for management of the world's resources. As the world's population expands and its living standards improve, there is increasing pressure on all types of resources which support man's economy, whether these be food, land, timber, water, oil, or minerals. The rapidly increasing demand for these resources threatens to outrun the supply, and major efforts to meet the demand will be called for to avoid serious sociological and political repercussions. Effective resource management requires large masses of current information. While information is generally available in this country, in many respects it is far from adequate. In other countries, particularly the developing nations, the available information is inadequate or nonexistent and the job of collecting such information will be time consuming and extremely expensive. The collection of this information is the most significant social, political, and economic benefit to the anticipated from orbital-sensing systems. Although observation spacecraft cannot acquire all types of information needed, they are capable of doing much of the job satisfactorily.

5.1.3. ECONOMIC BENEFITS. Apart from its scientific significance, the program for remote sensing from space offers the possibility of achieving results in many phases of the economy which will have both direct and indirect payoff. This payoff can come about in several ways. The economic benefits which can indirectly result from purely scientific investigation have been discussed previously.

A second major function which can be performed is that of providing accurate and timely information on which to base important economic decisions. The lack of adequate information can lead to the commission of costly errors in economic planning and decision making. Even slight improvements in major allocation and investment decisions can justify sizable expenses for data gathering. Crop predictions based on early indications of weather and available water provide the basis for important decisions concerning planting, harvesting, transportation, and marketing.

Another important function is that of world-wide reconnaissance in detecting and locating additional natural resources or other valuable items, for example, minerals, oil, and likely fishing grounds.

Several applications are aimed at protecting against serious property damage or loss of life. In developing countries, where transportation and distribution facilities are generally inadequate, crop failures may have serious repercussions, even to the extent of creating famine conditions. Early indications of the development of such conditions will permit timely remedial action. The early detection of forest fires, monitoring of water and air pollution as a basis for applying control measures, and the surveillance of flooded areas to assess damage and guide rescue efforts are other examples of such applications.

Under some circumstances, remote sensing from space can produce data needed for operational purposes by government, agriculture, and industry at considerably less expense than current earth-based collection methods. Such data might include photography useful for planning highways, dams, and other engineering projects or for observing cities or other restricted areas of moderate size. Use of space photography for the preparation of accurate and up-to-date world maps would be a major contribution to the role of cartography for scientific and business purposes.

5.1.4. RESOURCE MANAGEMENT. As the world's population expands and its living standards improve, resources are being depleted by increasing use, as well as by natural causes. These resources must be conserved, either by limiting their use, by replacing them, or by finding substitutes. To be effective these steps must be taken well in advance of the time at which the growing demand exceeds the available supply. Thus, collection of accurate data on current inventory and rate of depletion can provide information vitally needed for alerting mankind to forthcoming pressure on resources and for indicating appropriate steps to be taken. The synoptic coverage of orbital-sensing systems promises to be particularly useful for obtaining a world-wide forest inventory and for observing the current status and changes in land use and the distribution of crops. Certain types of infirmation related to water resources can also be obtained.

For wasting assets such as minerals and oil, the problem is to maintain our reserves by locating new resources to replace those being depleted. Aerial photography is being increasingly used to explore for oil or minerals by identifying geologic features associated with their presence. Space photography offers the opportunity to extend this capability throughout many parts of the world which have not yet been adequately surveyed.

The information provided by observation spacecraft can be of major assistance in enabling us to make the most efficient use of available resources. This increased efficiency can be derived from basic research which throws light on the nature of the resource and the method of its formation. In addition, information on the extent and distribution of resources in a given region may be the foundation for planning the optimum exploitation of the limited resource available. Thus, each country needs to make the best possible use of its limited supply of land for agricultural and other purposes. Misuse of land in the past has done irreparable damage to large areas. Forest land has been converted to agricultural land for which it is not suited. The destruction of forests can have serious effects on the hydrology of the region, reducing available water and increasing flood danger. Malpractices in farming have caused deterioration of soil quality and permitted erosive forces to act. Optimum use of the available land requires extensive surveys to establish the amount and character of all land available and its present use. For this purpose, extensive data can be supplied for geographic studies of forest inventory, land use, and regional hydrology.

5.2. METHODS OF BENEFIT ANALYSIS

One of the major objectives of this project was to assess the benefits which would accrue to the nation from a program of research and development leading to the introduction and use of observation spacecraft. To provide such information, a number of the projected uses for the resulting data as outlined in this report were studied as representative examples. These estimates are summarized in section 4 for the examples studied.

All the applications discussed in section 4 have survived a preliminary screening to limit the study to those which are believed to be technically feasible. At this early stage, however, some uncertainties still exist concerning technical feasibility of specific applications and the manner in which sensor outputs would be used in an operational system. Furthermore, many of the benefits will be realized in an indirect or unpredictable manner; this is particularly true of those cases where the application results primarily in improved scientific understanding of the environment. For these reasons, cost-effectiveness studies would be very difficult to make at this time and could produce unreliable and misleading results. We have therefore directed our efforts to the task of estimating only the gross benefits to the user which would result from a successful use of the application.

In some cases, the acquisition and processing of data are only a part of a comprehensive program for achieving important national or international objectives. Initiative is required by other parties if the data are to be profitably employed in making decisions or taking action.

To assure the necessary cooperation, space-observation programs should be conducted in close cooperation with the agencies who will ultimately benefit from the use of the space-acquired data. This cooperation should assure that the necessary complementary actions will be taken by these agencies to make full use of the data.

5.2.1. COMPARISON OF ALTERNATIVE COSTS. One approach to the estimation of benefits from the use of observation spacecraft would be to consider the cost of alternative methods of achieving the same results. This method of estimating benefits is an acceptable one if the type and extent of data collected by spacecraft do not differ radically from the alternative method. The method is useful where spacecraft and alternative methods of measurement seem to be reasonably competitive.

Comparison of costs for different methods of obtaining certain types of oceanographic data is presented in a feasibility study of system concepts for using spacecraft [12]. In this study, spacecraft were considered as a means of performing ice surveillance over the Arctic Ocean, of obtaining extensive sea surface temperature data, and of relaying various types of oceanographic data obtained by a large number of buoys spread out over large areas of the ocean. In each case, the annual cost of obtaining data by spacecraft (including research and development and costs for replacing operational equipment) was much less expensive than accomplishing equivalent results by means of an aircraft. For example, the measurement of sea surface temperatures by aircraft over an area of 17 million square miles (roughly one-half of the ocean area of the northern hemisphere) would have an annual cost of about $42 million. Another alternative would be to take measurements by means of a system of 750 surface buoys, a number several times the quantity presently planned for operational use by the Navy. Assuming a buoy cost of $50,000, a life of 5 years, and servicing once a year, the annual cost for a buoy system would be about $18 million. The equivalent annual cost of performing the same measurements by spacecraft amounts to about $10 million. The spacecraft gives greater density of coverage, except when cloud interference is prohibitive. Furthermore, it can be extended without additional cost to provide full ocean coverage.

Collection of world-wide oceanographic data by surface ships would also be extremely expensive. According to reference 13, the current program in oceanographic research "is carried out chiefly from surface ships that occupy stations in about three latitude-degree squares per day at a cost of the order of $1,000 per square degree. If it were feasible to occupy every degree square of the world ocean, this would require 34 ship years and cost $38 million."

It is apparent that data collected for large areas of the earth and repeated at frequent intervals would lead to exceedingly high figures in terms of the equivalent cost of collecting data by aircraft. This cost is reported [1] to range from $2.50 to $4 per square mile, depending on a number of factors, particularly the accessibility of the observed area. Considering the relative inaccessibility of much of the earth's surface, the cost of obtaining this coverage by air would approach the higher figure of $4 per square mile. Of this total figure, perhaps $1 per square mile is needed for the laboratory and office expenses. Thus each single complete coverage of the 58,000,000 square miles of land area of the earth would cost $174 million. By comparison, a spacecraft could without great difficulty obtain a single coverage of the earth's surface at a small fraction of the cost (exclusive of laboratory and office expenses) of doing it by aircraft, perhaps 4% to 6%. Furthermore, the spacecraft could repeat the coverage a considerable number of times during its lifetime.

If the need for complete coverage of the earth's surface were justified by the circumstances, the figure of $174 million could be an accurate statement of the gross benefit of the observation spacecraft. It is unlikely, however, that the use of this figure for each of many repeated coverages could be justified in terms of the real value of the data. In this case, it is preferable to arrive at an assessment of the benefits of observation spacecraft in terms of their usefulness for the purpose intended.

5.2.2. ESTIMATION OF VALUE OF DATA. In estimating benefits in terms of the value of the resulting data, it is not possible to present precise figures. It is possible, however, to gain some insight into the manner in which this new space capability can contribute to the solution of many current problems and to provide some general estimates of the dollar magnitude of this contribution for specific cases.

In most of the examples studied, figures represent the estimated value of benefits to the ultimate user. The manner in which the application benefits the user will vary from instance to instance, and a fundamental initial step in the analysis process has been to set forth clearly in qualitative terms the exact nature of the contribution made for the user's purposes along the lines discussed in section 5.1.

The value to the user may be considered to be the amount of financial support he could justifiably allocate to the types of data available from space sensing systems. This support would be available for expenditures associated with the tasks of obtaining such data. Specifically, these would include the operational costs of construction and launch of the operational spacecraft, reception of acquired data, whether by data link or return capsule, and processing and distribution of the data. Presumably, the research and development costs leading up to the operational spacecraft system must also be accounted for. It may be noted, however, that much of the research and development program, including the preorbital phase, can be justified by the value of scientific results it achieves, apart from any contribution made to the establishment of operational spacecraft systems.

If estimates are stated in terms of gross benefits, these must necessarily cover not only data-acquisition and data-processing costs, but all other costs associated with accomplishing the intended purpose. These may include costs of exploiting new resources or reclaiming land. It must be apparent that gross benefits stated in this way cannot all be directly credited to the use of observation spacecraft. The statement of such benefits can be only an indication of the total value of the results to which remote-sensing methods are contributing. Nevertheless, this type of information provides some understanding of the magnitude of the ultimate objectives. If we also know the manner and extent to which remote sensing contributes to this objective, we can realistically assess the value of the remote-sensing operations.

6
OPERATIONAL CONCEPTS

It is assumed that the manned earth-orbiting experimentation program would lead to the introduction of operational observation spacecraft and their associated ground-based data-processing systems coming into use for the post-1975 period. Studies of potential uses of these operational systems should therefore be based on conditions expected to prevail at that time.

In general, it may be expected that as the world's population continues to expand and standards of living improve, the pressures on available natural resources will also increase and may reach critical proportions in some cases, such as the requirements for food, water, and certain minerals. Thus, the need for expanded effort to make the most efficient use of available resources will continue to call for improved data collection.

World air photographic coverage at the present time is only partially complete, and much of the photography is more than ten years old. Because of the size and cost of the job of obtaining aerial photography of large areas, it seems likely that the status of air photographic coverage will still be far from adequate in 1975. In addition, many of the most valuable applications of remote sensing require the use of imagery in spectral regions outside the visible region. Much of the world's surface will remain to be observed for the first time in these spectral regions.

6.1. OPERATIONAL SYSTEM CHARACTERISTICS

Operational systems are not necessarily restricted to a particular type of orbit or a small range of orbital altitudes. Depending on the characteristics of the array of applications which eventually prove to be technically and economically feasible, several series of spacecraft may be selected with varying orbital characteristics. The lower altitudes, in the neighborhood of 200 n mi, will be most useful for those applications which require high resolution or which transmit their data to earth in the form of film or tape. At these altitudes, polar orbits will be used for applications in which complete world-wide coverage is required, and surveillance of arctic regions is involved. Applications in which interest is centered on areas of the earth at lower latitudes would use inclined orbits to good advantage, since these would increase the frequency of coverage in these areas.

For those applications which can accept lower resolutions, for example, collection of some types of ocean data, higher altitude orbits can be considered. At higher altitudes, much more of the earth's surface can be observed at a single instant and the continuous observation of any one point can be extended. In the limit, a spacecraft in a synchronous orbit can continuously observe an area of continental size.

Operational systems of satellite remote sensing must be designed to meet the requirements for imagery to be used for many different purposes. In many respects, however, these diverse requirements can be standardized and coordinated so that a relatively few specific equipment designs will meet the variety of requirements.

In particular, it seems likely that all photographic sensing devices may be standardized in terms of three or four focal lengths, for example, including scales at 200 miles altitude of 1:2,400,000, 1:800,000, and 1:60,000. If possible, there should also be standardization among the scales to be produced by the various types of sensors, so that equivalent frames from each sensor in each spectral region will have comparable resolution and will cover identical areas.

During the orbiting experiments, at least one set of pictures should be obtained of the entire earth in the useful spectral ranges. This should be done at small scale in order to keep the total amount of imagery within manageable limits. Photographic coverage could probably be obtained at a scale of 1:800,000. This preliminary coverage of the earth would supply the scientific community with useful data so that members of the various disciplines could make preliminary studies of the earth's surface which are of special interest to them and could select areas to be observed at increased scale by the operational system.

When the operational system becomes available, it should be used to obtain a second coverage of the earth's surface at an increased scale dictated by economic considerations. It seems likely that the use of the finest resolution which could be obtained by equipment of reasonable size, complexity, and cost would produce excessive amounts of imagery, if an attempt were made to cover the entire earth. Consequently, fine-resolution imagery would probably be produced only over limited areas where it has been specially requested.

Thus, the operational system will probably produce imagery on several different schedules:

(1) Synoptic coverage of the entire earth at a small scale, performed only once.

(2) Complete coverage of the entire earth at a larger scale, to maintain up-to-date records. Coverage of the United States, in which we have primary interest, might be performed at the same repetition rate but on a still larger scale.

(3) Coverage of preselected areas at appropriate scales up to the largest available. These areas would be covered at the request of scientific, business, or government personnel or

agencies. Quick reaction or frequently repeated coverage would be provided in special cases (e.g., to observe floods or other natural disasters).

The operational system would provide accurate position determination for all imagery produced. The position of the principal point of each image frame should be provided in terms of a generally accepted set of geographic coordinates. This position-determination information can be computed as a function of ephemeridal data on the satellite orbit, the instant at which the imagery was taken, and the orientation of the camera or scanning system. The computation of image position can be performed and appended to the imagery after its return to the ground.

The imagery obtained should include coverage of the complete spectrum useful for multispectral sensing, with the total number of spectral regions dictated by economic and technical considerations. Imagery obtained with this broad spectral coverage would be of use for many of the purposes anticipated in this report, so that one set of imagery of a given area could be used by many disciplines, even though it may have been requested for a specific purpose.

6.2. OTHER SYSTEM CONSIDERATIONS

The great volume of imagery which would be collected must be managed in such a manner that it is easily and rapidly available to all users. Efficient and economical methods of data processing, storage, retrieval, and distribution must be adopted if this objective is to be achieved. The implementation of this data-management system requires careful consideration and planning well in advance of the time at which it will be needed.

The extensive use of observation spacecraft also implies that a substantial expansion is needed in the capabilities of scientific personnel to interpret the imagery obtained. Photointerpretation requires special training to develop the ability to recognize and interpret satellite imagery.

Of equal importance to the successful functioning of the projected operational systems is an increased capability for automatic data interpretation. Development needs to be concentrated on methods of automatic recognition of objects and of electronic correlation of multispectral signals to identify spectral signatures of vegetation, soils, etc. Such methods greatly reduce the need for human photointerpreters, which might otherwise present a serious bottleneck to the full application of observation-spacecraft capabilities.

If the full potential of orbital-sensing systems is to be realized, the data provided by these systems must be available not only to the federal government of the United States, but to state and local agencies, to domestic industries, and to foreign governments and industries. The collection and dissemination of such information can have important political, legal, and financial consequences. Questions of participation and financial support by other countries are involved. Consequently, the scientific program proposed here must be accompanied by a program for investigating and resolving these problems.

Many scientists have stressed the importance of free, rapid, and easy access to data from observation spacecraft. Data processing should be handled by government agencies, but the information should be distributed to the users in much the same manner that weather maps are distributed. This will be particularly important when the spacecraft detects unusual events. Rapid distribution of the information would permit researchers to direct their efforts quickly to analyzing the event. Although the importance of these matters is recognized, it is outside the scope of this report to consider them in detail.

7
EXPERIMENTAL PROGRAM

7.1. PREORBITAL PROGRAM

As a means of making any program of orbital reconnaissance experimentation fully effective, a preliminary program of preorbital experimentation must be conducted to explore the use of new sensor capabilities from conventional aircraft and to establish the ground test sites, where ground truth has been carefully measured and recorded, against which the orbital reconnaissance data may be checked.

The necessity for preorbital research programs is fully recognized. However, the preorbital phase will be discussed in this report only briefly to present the main outlines of this portion of the program. Emphasis is placed on defining the orbital phase of the experimental program, based on the assumption that the initial phases have been successfully performed.

Each ground site selected by NASA to represent a particular area of technical or scientific interest would contain a series of objects or features typical of that interest, as a means of determining the capabilities of orbiting sensors to detect and identify such objects. Special ground-based systems of meteorological instrumentation and sensor calibration would be installed. To measure sensor resolution, special test patterns could be used. The ground test site would be completely surveyed to provide photogrammetric control for analysis of the pictorial data obtained by airborne sensors.

A major function of the preorbital experimentation is to produce a detailed and accurate record of all conditions at each ground test site pertinent to the recording, analysis, and evaluation of pictorial data. This can be done both by observation from the ground and by overflights of the test site using each type of sensor with suitable combinations of spectral range, sensitivity, and resolution, and under various conditions of temperature, lighting, and weather.

The preorbital testing should furnish practical experience with the types of sensing equipment which would later be used in the orbiting system. It would be possible to select the best operating parameters and modes of the equipment and to make any final adjustment and modifications in system design which appear necessary for the orbiting system. Investigations of proposed methods and equipment for data transmission, data processing, attitude control, or image motion compensation may also be conducted, if necessary.

7.2. ORBITAL EXPERIMENTATION

The preorbital program of experimentation and site preparation just described would provide the necessary foundation for the interpretation of the data acquired during the subsequent program of orbital experimentation.

The data generated by the equipment in the orbiting laboratory would be studied to achieve the following objectives:

(1) Selection of the system design parameters and operating conditions producing the best system performance.
(2) Evaluation of the usefulness of imagery obtained by the various sensors.
(3) Collection of information on which to base the design of future operational systems for specific applications.

7.2.1. TEST PROCEDURES. During the orbiting experimental program, each of the various sensors would be operated to acquire imagery as the spacecraft passed over each of the ground test sites. The sensor operating modes and parameters would be varied to determine the best operating conditions. Auxiliary data on communication, navigation, and image motion compensation equipment would also be recorded simultaneously to assist the analysis of system performance. Data measurement and recording activities would also take place at the ground site concurrently with periods of observation from the orbiting laboratory.

The analysis and interpretation aboard the spacecraft would be confined primarily to quick looks at the data to ensure that the equipment is functioning as expected and to make decisions concerning subsequent experiments. More detailed analyses leading to extrapolations of the test results to other conditions and evaluation of specific configurations would be deferred for investigation by ground-based personnel.

7.2.2. DATA ANALYSIS. Imagery obtained during the orbiting experiments would be studied intensively to provide information of several types. One type of information desired is concerned with the technical performance of the sensing equipment. The imagery returned to the ground would be studied to measure the ground resolution, tone gradations, and temperature sensitivity obtained, and to note the effects of atmospheric interference, system noise, and other disturbing influences. In addition to pictorial data itself, information concerning system performance would be obtained from the recording and examination of auxiliary data on position location, vehicle attitude, data transmission, etc.

Since the performance characteristics of sensing and data-transmission equipment are already generally known, the primary emphasis in space experimentation should be to learn how the environment and operating conditions of space affect these characteristics. The effects of the individual design and operating features on image quality (resolution, dynamic range, sensitivity, etc.) can be assessed by comparisons of imagery obtained under different system conditions and at different points along the data-transmission chain.

In addition to the quantitative measures of system performance, the usefulness of the imagery for photointerpretation of test objects and conditions at each of the ground test sites would be investigated. The image quality can be evaluated by personnel experienced not only in the interpretation of photography in the visible region but in the special problems of interpreting imagery in the infrared and microwave regions.

Once the capabilities of the sensing system for its various uses have been established, the experimental orbital sensing equipment would be used to acquire samples of imagery from other areas of the earth's surface as a means of extending our knowledge of system capabilities for observing unknown environments. In addition, this sample data along with a complete small-scale coverage of the earth's surface would provide the scientific community with a preliminary look at the earth in various spectral regions which would be useful for planning the later acquisition of operational data in areas of special interest.

7.2.3. SUMMARY OF SENSOR APPLICATIONS. The major specifications of the specific sensors proposed for orbital experimentation are summarized in tables VI through XII. This proposed complement of equipment is of a preliminary nature only. It is anticipated that later more detailed studies by instrumentation teams and contractors designated by NASA will modify the list suggested in this report.

TABLE VI. THREE CAMERAS

Diameter of Objective (in.)	f/no.	Focal Length (in.)	Scale	Ground Resolution at 200 n mi (ft)	Approx. Area Covered (sq mi)	Minimum Film Resolution Required (line pairs/mm)
3	f/2	6	1:2,400,000	20-100	$74^{\circ} \sim 296$	33
12	f/1.5	18	1:800,000	5-25	$28^{\circ} \sim 112$	50
36	f/6.6	240	1:60,000	2-10	$2^{\circ} \sim 8$	45

TABLE VII. MULTISPECTRAL SENSORS

	Optical-Mechanical Scanner-Spectrometer	Miltispectral Camera
Wavelength Bands (N selected intervals) (μ)	0.3 μ to 14 μ	0.32 μ to 0.9 μ
Resolution from 200-n mi altitude (ft)	200; 600	25 to 100
Diameter of Collecting Aperture (in.)	12 to 36; 12	2 to 4
Total Field of View	1/25° to 3.6°; 26°	25°
Data Processor	Real-time electronic decision circuitry	Film reader or image interpreter

TABLE VIII. INFRARED SENSORS

	Radiometer	Low-Resolution Scanner	High-Resolution Scanner
Total Field of View (deg)	-	28 × 28	2.3 × 2.3
Angular Resolution (mrad)	1/6	3	1/6
Ground-Patch Dimension (ft)	200	3600	200
Absolute Temperature (^{o}K)	±0.5	±0.5	±0.5
Temperature Sensitivity (^{o}K)	±0.1	±0.1	±0.1
Telemetry Bandwidths (cps)	270	10^6	4×10^6
Pointing Accuracy Req'd (min)	±1	±60	±10
Operational Periods (min/orbit)	30-60	30-60	30-60

TABLE IX. THREE PASSIVE MICROWAVE SENSORS

	Ka Band	X Band	S Band
Antenna Diameter (ft)	17	34	50
Wavelength (cm)	0.8	3	10
Resolution; Scan Angle (mrad)	2; 68	4; 55	8; 51
Figure of Merit	0.09	0.0185	0.024
ΔT (^oK) (one-dimensional)	0.45	0.68	0.05
ΔT (^oK) (two-dimensional)	2.6	2.55	0.13
Weight, Electronics Antenna* (lb)	200 300	200	200
Volume, Electronics Antenna (stored)* (ft^3)	2-4 20		
Power (watts)	400		

*Single antenna usable for all units

TABLE X. CONICAL SCANNING RADIOMETER

Wavelength	X band
Antenna Diameter	1 meter
Elevation Angle	10^{o} to 45^{o}
Component	Radiometer (50 lb, 1 ft^3)
	Tape recorder and data readout (25 lb, 0.5 ft^3)
	Antenna (20 lb, 6 ft^3)

TABLE XI. THREE RADARS

Type	Noncoherent		Coherent
Operating Frequency	35 Gc	1.5 Gc	8-10 Gc
Antenna Parameters			
Azimuth Aperture (beamwidth) (ft)	25 to 50 (0.08^{o} to 0.04^{o})	25 to 50 (0.9^{o} to 1.8^{o})	50 (0.15^{o})
Range Aperture (beamwidth) (ft)	0.5 to 1 (4^{o} to 2^{o})	2 (20^{o})	~5 (1.4^{o})
Elevation Angle	45^{o}	45^{o}	45^{o}
Pulse-Repetition Frequency (pps)	50 to 100	2 to 4	1200
Pulse Width	2 to 4	60 to 120 μsec	35 nsec
System Predetection Bandwidth	0.25 to 0.5 Mc	10 to 20 kc	40 Mc
Nominal Ground Resolution (ft)	1,500-3,000	30,000-100,000	25
Illuminated Ground Swath Width (n mi)	14 to 30	300	10
Required Transmitted Peak Power	30 to 800 kw (η_{min} = -40 db, S/N = 10)	50 to 350 watts (η_{min} = -40 db, S/N = 10)	1.3 to 3.5 mw (η_{min} = -30 db, S/N = 10)
Required Transmitted Average Power	3 to 150 watts (η_{min} = -40 db, S/N = 10)	10 to 70 mw (η_{min} = -40 db, S/N = 10)	45 to 120 watts (η_{min} = -30 db, S/N = 10)
Maximum System Data Rate			
Resolution elements/sec	(1.2 to 10)10^3	30 to 120	~10^9
Bits/sec	(5 to 40)10^3 (for a 16-level gray scale)	120 to 480 (for a 16-level gray scale)	
Approximate System Volume (ft^3)	18 (including antenna)	20	30 (including antenna)
Approximate System Weight (lb)	125	100	<200

TABLE XII. TWO LASER ALTIMETERS

	FM-CW	Pulsed
Operating Wavelength (μ)	1.0610	1.064
Diameter, Optics (transmitter-receiver) (in. and ft)	2 and 3.2	2 and 3.2
Transmitter Beamwidth (arc sec)	10	10
Receiver Bandwidth (Mc)	100	100
Input Prime Power (watts)	1205	285
System Weight (lb)	202	128
System Volume (ft^3)	15.3	9.8

8
CONCLUSIONS

Although this study has been limited to a relatively short-term intensive effort, it has been able to provide an early detailed review of a proposed program in space reconnaissance for peaceful purposes which may well become of major importance to the nation. Furthermore, it provides for an evaluation of many suggested applications in terms of what may realistically be expected in sensor technology over the next ten years.

The study has confirmed the belief that a large number of potentially valuable applications exist for operational spacecraft capable of observing the land and water surfaces of the earth. The anticipated results range from those of purely scientific significance to political, social, and economic benefits which for some applications seem likely to represent a substantial return on the effort, time, and money invested.

There are at present definite limitations on sensor capabilities in relation to user needs. Furthermore, many operational problems need to be resolved in order to achieve the performance demanded by the users. The study appears to eliminate certain types of applications because of sensor limitations or operational constraints, and at the same time to confirm the technical and economic feasibility of a large number of others. However, we have avoided any tendency to summarily rule out sensor types and uses which appear unlikely, because we realize that much more analytical and experimental investigation is required before final statements can be made regarding these matters. Furthermore, sensor technology is advancing rapidly, and new capabilities will broaden the range of feasible applications.

Expanded participation in this field of space research is needed on the part of many researchers in the earth and life sciences as well as specialists in sensor technology to define the exact role which peaceful uses of space reconnaissance will play in the nation's future and to do the job necessary to achieve that role.

Appendix
LIST OF CONTRIBUTORS

Individuals who participated in the survey of applications for various subject areas are listed below. Unless otherwise noted, they are members of the faculty and staff of The University of Michigan.

GEOGRAPHY:	
Melvin G. Marcus	Assistant Professor of Geography
John D. Nystuen	Professor of Geography
Waldo R. Tobler	Associate Professor of Geography
John F. Kolars	Assistant Professor of Geography
Alan Backler	Graduate Student
Lynne Friedrich	Graduate Student
Gary Gnauck	Graduate Student
AGRICULTURE:	
E. H. Jebe	Research Mathematician
Ralph King	Graduate Research Assistant
FOREST RESOURCES:	
Charles E. Olson, Jr.	Lecturer in Forestry and Research Associate, Willow Run Laboratories
WATER RESOURCES:	
Charles Cooper	Hydrologist, U. S. Public Health Service
WILDLIFE AND FISHERIES RESOURCES:	
George Mattfeld	Research Assistant
OCEANOGRAPHY:	
Vincent Noble	Associate Research Physicist
George Mattfeld	Research Assistant
GEOLOGY:	
John S. Dudar	Professor of Geology, Eastern Michigan University
Dana Parker	Associate Geological Research Engineer
ARCHAEOLOGY:	
Robert L. Farrell	Graduate Student
AIR POLLUTION:	
William L. Wolfe	Research Engineer
William C. Levengood	Associate Research Physicist

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Analog Computer Laboratory	
Donald A. Siekmeier	Research Associate
Radar Laboratory	
Gilbert O. Hall	Research Engineer

Optical and Radio Systems Laboratory	
Russell A. Rollin	Research Engineer
Fred Zwas	Graduate Research Assistant
Infrared Physics Laboratory	
Dana C. Parker	Associate Research Geological Engineer
Infrared and Optical Sensor Laboratory	
Max E. Bair	Research Associate
William L. Brown	Graduate Research Assistant
Grover W. Trytten	Research Associate
James L. Alward	Research Associate
Jerry L. Beard	Research Assistant
Alfred W. Krause	Research Associate
Stanley Sternberg	Research Assistant

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SCHOOL OF NATURAL RESOURCES

Conservation Department	
Lyle E. Craine	Professor of Conservation, Chairman of Dept.
Lee R. Martin	Professor of Resource Economics
Richard L. Meier	Associate Professor of Conservation
Fisheries Department	
John E. Bardach	Professor of Fisheries and Zoology
Forestry Department	
Kenneth P. Davis	Professor of Forest Management, Chairman of Department
John Carow	Professor of Forest Management
Samuel A. Graham	Professor Emeritus of Economic Zoology
G. Robinson Gregory	George Willis Pack Professor of Resource Economics
Fred B. Knight	Associate Professor of Forestry
Robert Zahner	Associate Professor of Forestry
Wildlife Management Department	
Warren W. Chase	Professor of Wildlife Management, Chairmen of Department
Archibald B. Cowan	Associate Professor of Wildlife Management

COLLEGE OF LITERATURE, SCIENCE AND THE ARTS

Department of Geology and Mineralogy	
Donald F. Eschman	Professor of Geology, Chairman of Dept.
Edwin N. Goddard	Professor of Geology, Director of Geological Fieldwork
E. William Heinrich	Professor of Mineralogy
Donald R. Peacor	Assistant Professor in Geology and Mineralogy
Department of History of Art	
Oleg Grabar	Professor of History of Art and Near East
Kelsey Museum of Archeology	
George H. Forsyth	Director of Museum, Professor of History of Art

COLLEGE OF ENGINEERING

Department of Meteorology and Oceanography	
E. Wendell Hewson	Professor of Meteorology

INSTITUTE OF SCIENCE AND TECHNOLOGY

Great Lakes Research Division	
Charles F. Powers	Associate Research Oceanographer

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William Fischer	Branch of Theoretical Geophysics U. S. Geological Survey
Thomas Frey	U.S.D.A. Resources Development Economics Division, Land and Water Branch
K. P. Harris	Deputy Directory of the Aerial Photography Division, Agricultural Stabilization and Conservation Service
William R. Hemphill	Branch of Theoretical Geophysics, U. S. Geological Survey

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Woodrow Jacobs	Director of the National Oceanographic Data Center
Joseph King	Director of Marine Research Bureau of Commercial Fisheries and Staff
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NASA-Langley, 1966 CR-586