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AN OPERATIONAL EARTH RESOURCES SATELLITE SYSTEM: THE LANDSAT FOLLOW-ON PROGRAM

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ABSTRACT

The Landsats 1 and 2 have demonstrated the role of remote sensing from satellite in research, development, and operational activities essential to the better management of our resources. Hundreds of agricultural, geological, hydrological, urban land use, and other investigations have raised the question of the development of an operational system providing continuous, timely data.

The Landsat Follow-on Study addressed the economics, technological performance, and design of a system in transition from R&D to operations. Economic benefits were identified; and a complete system from sensors to the utilization in forecasting crop production, oil and mineral exploration, water resources management was designed.

Benefits to costs ratio in present worth dollars is at least 4:1.

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INTRODUCTION

Growth in the world's population and in the affluency of the developed and the developing nations are placing increasing stresses on the food, mineral, air and water resources of the planet. The meteorological and earth resource satellites have, in recent years, demonstrated the ability to observe and monitor a host of agricultural, geological, atmospheric, and human phenomena and activities and thus provide information by which governments and resource managers can substantially improve their economic and political decisions.

This paper describes the technical, resource, and managerial requirements and plans by which a global observational system called Landsat Follow-on, can be developed and then operated during the period 1981 to 1985. The benefits, through more effective decision-making, to the U.S. economy and to the nation's humanitarian purposes are substantial and far exceed the costs of the system proposed.

THE NEED FOR LANDSAT FOLLOW-ON

Objectives

During the year-long Outlook for Space Study conducted by NASA at the direction of the Administrator, the Study Group examined in some depth the implications of increasing world population and spreading affluency and their interactions with the food, mineral and environmental resources of this finite planet on which mankind lives. The Study's objective was to document the potential roles that observations from space could play in the detection, monitoring and management of these global resources.

The Study Group concluded, in part:

(a) Among humanity's needs which are particularly amenable to the use of space derived data are monitoring and prediction of climate and severe weather, prediction of crop production and water availability, and monitoring of changes to the environment;

(b) The multiple use of operational remote sensing spacecraft will be necessary to economically exploit the utility of the nation's Earth oriented space program. The development and management of these spacecraft will require broadened and innovative cooperative arrangements between government agencies at the federal, state and local levels as well as between government and the private sector.

Some of the background issues that led the Study Group to these conclusions are outlined in the following paragraphs.

Population Growth—With only a few reversals due to famine or disease, the world's population has grown steadily since the agricultural revolution; the rate of growth has become exponential in the last 200 years. Estimates place the world population at the time of Christ at 200 million; by 1750 the number had grown to 800 million; by 1975, to 4 billion; and the year 2000 estimate is between 6 and 7 billion (based on constant fertility and no global disasters).

The population growth is, by and large, a regional or national issue (see Table 1). Although the world average rate of increase is 2.0%, the rates vary from 0.6% for the U.S. and Europe to 2.5 to 3.0% for the underdeveloped areas - Africa, Latin America, and Southern Asia. Many nations perceive their population growth not as a problem, but as a means to ensure economic growth. But massive starvation is an ever-present threat in India, Bangladesh, sections of Africa, and other areas where food reserves and the margins between supply and demand are such that poor crops lead to severe food shortages.

For the U.S., the primary issues associated with population are the changing age distribution and the changing demography as urbanization increases. Growth in total numbers is expected to be modest, from 210 million in 1975 to between 280 and 300 million in 2000. But because of the reduced birth rate and improved health care, the U.S. population is aging; it is projected that the age group over 45 will rise from about 24% in 1975 to 33% in 2000, and the age group 25 to 44 will increase from 22% to almost 30%. The implications are largely economic: shifts in demands for goods, services, and government expenditures for health care and social security. Society's values and priorities may be expected to shift also, because of the different values among these age groups as they mature.

The growth of cities has been concomitant with population growth and reduced dependence on the land; people live in close urban proximity to take advantage of the economic opportunities and the exciting life styles made possible by the city. In developed nations, urbanization has taken the form of suburbanization, an effort of the more affluent to have the advantages of both country living and city life. By the year 2000, based on current projections, over 80% of the U.S. population will live in urban areas (compared to 70% in 1975) with current trends toward congestion, pollution, crime, and alienation of the individual expected to continue.

Table 1

Trends in Population Growth

	1973 POP. (BILLIONS)	ANNUAL RATE OF NATURAL INCREASE (PERCENT)	2000 POP. (BILLIONS)	? ZERO POPULATION GROWTH LEVEL AFTER 2050 (BILLIONS)
U.S.	0.21	0.6	0.3	0.4
DEVELOPED COUNTRIES	1.12	0.8	1.4	1.5-2
UNDERDEVELOPED COUNTRIES	2.74	2.5	5.3	6.5-13
WORLD	3.86	2.0	6-7	8-15

In spite of these trends, there appears to be no world consensus of solutions to the problems. Developed societies, which could accept some growth, tend to curb their growth, while many underdeveloped societies express the view that curbing their growth would deprive them of the opportunity to achieve affluence.

The World Food Situation—The availability of foods and the status of agriculture throughout the world are closely tied to the population trends. This is also a regional problem, but on a global scale the most striking fact has been the decrease in world grain reserves, which has fallen from 60 days in 1961 to about 20 days in 1974. The import-export distribution reveals that only North America is a major surplus-producing region; however, in the U.S. and elsewhere, reserves of idle cropland have been reduced in the period of 1961 to 1974, until they are essentially zero in the U.S. The "green revolution" of new strains of grain has stretched the reserves a few years, and now has been slowed by the limited availability of petroleum-based fertilizers. The margins are so small, and the inelasticity in demand so strong, that small changes in weather and other factors, including distribution, produce large fluctuations in the availability of food and, in time, great potential for massive starvation and disease in many regions.

Food production throughout the world has basically kept pace with population growth; available calories per person have risen in the developed nations and remained essentially constant in developing countries. Yet every year there are 75 million more mouths to feed. At this rate, food production will have to double by the year 2000 to maintain the same sub-marginal world levels as exist at present. Related problems focus on the need to improve and protect the world's grain supplies and distribution so that the impact of regional variations in production can be minimized, particularly in the developing nations.

Table 2 shows the population and cultivated land on each continent compared to the amount of potentially arable land outside the humid tropics. It appears that the principal population increases between 1965 and 1985 will occur in Asia, Africa, and South America. In Asia a small fraction of the land now cultivated lies in the humid tropics; hence, the total present cultivated area (470 million hectares) actually exceeds the area that is potentially cultivatable outside the humid tropics. In both Africa and South America, however, the potentially arable area can be increased several times. For all continents, the estimated population increase for the period 1965 to 1985 amounts to about 43%, whereas the potential increase in arable land outside the humid tropics is about 80%. Consequently, the world's food needs might be met until 1985 by significant increases in cultivatable land, with additional means probably being required thereafter. However, large amounts of investment capital, fertilizer, and agricultural knowledge would be required. All are in relatively short supply. In addition, within the definition of "cultivatable land," the most productive land, requiring least capital and effort, is already in use, with the remainder costing more and requiring more effort to achieve a worthwhile output. It would appear, therefore, that the need must be met from a combination of increased yield in presently cultivated areas and an increase in cultivated lands. The criticality of the situation also indicates the need for greater efficiency in managing the

Table 2

Comparison of Population and Arable Land, by Continents*

AREA	1965 POPULATION (BILLIONS)	1965 ARABLE LAND* (HECTARES) CULTIVATED	1965 ARABLE LAND* (HECTARES) POTENTIAL	1965 ARABLE LAND PER PERSON (HECTARES/PERSON)	1985 POPULATION (BILLIONS)	1985 ARABLE LAND PER PERSON (HECTARES/PERSON)
ASIA	1.86	470**	465	0.3	2.70	0.2
AFRICA	0.31	160	500	0.5	0.52	1.0
EUROPE	0.45	150	170	0.3	0.49	0.3
SOUTH AMERICA	0.20	80	370	0.4	0.39	0.9
NORTH AMERICA	0.26	240	450	0.9	0.33	1.4
U.S.S.R.	0.24	230	350	1.0	0.30	1.2
AUSTRALIA AND NEW ZEALAND	0.01	20	120	1.4	0.03	4.8

*Not counting humid tropics

**Some humid tropic area is already under cultivation in Asia.

world's foods, including more accurate forecasting of production and factors such as water, weather, and climate.

The Environment—Increases in population, industrialization, and energy consumption have contaminated the physical environment to an extent that a strong environmental counter-movement has developed, with legislative bodies and other organizations trying to alleviate the problem. Local air pollution has been estimated to cause health damage affecting more than 50 million people at an annual cost of $6 billion in the U.S. alone. Some water supplies are contaminated with carcinogenic compounds. Toxic substances of all kinds, ranging from mercury to the polychlorinated hydrocarbons, have been found in the human food chain. Persistent pesticides such as DDT, which played a major role in health improvement by the control of insect-borne diseases, have been removed from the U.S. market. Solid wastes were produced in the U.S. at the rate of 50 million tons in 1920, and 170 million tons in 1970, and it is estimated that the figure will reach 350 million tons in 1990.

Population increase and the growth of society's aspirations and mobility have led to major incursions upon natural and wilderness areas, wildlife habitats, and agricultural lands. It has been estimated that an additional 20 million acres will be similarly utilized in the U.S. by the year 2000 - an area equal to New Hampshire, Vermont, Massachusetts and Rhode Island. Strip mining, the most economical means of mineral acquisition, is another potential major encroachment. Coal strip mining alone may consume up to 90,000 acres by 1990 and 200,000 by the year 2000. A major problem in the western coal lands, where strip mining is most effective, is the lack of water necessary for reclamation; there is a notable geographic "mismatch" between coal resources and water resources in the U.S.

Globally, waterways have been contaminated by untreated domestic sewage, industrial effluents, and chemical fertilizer from agricultural lands - all of which will increase in proportion to population and the growing affluence of that population.

The atmospheric ozone layer, which protects terrestrial life from solar ultraviolet radiation, may be adversely influenced by highflying aircraft, aerosols, and organic chemicals inherent to industrial processes. Small particles are injected into the atmosphere from the burning of fossil fuels, the incidence of carbon dioxide has increased by about 2% since 1910, and carbon monoxide now is increasing by about 2% each year. The effects are not well understood, but the climate seems to be changing in ways that could accelerate the food problem.

Summary of Objectives—The basic objective of the Landsat Follow-on is to provide global information to scientists and planners that will permit them to evaluate the role of remote sensing from space in the management of the Earth's resources and human activities. It is becoming more and more apparent that such observations when provided by an operational system could produce information on resources that the nations' resource managers and decision makers could use in establishing policies for food production and distribution, control of environmental quality, urban growth management, and land use management.

The Landsat Follow-on mission can be best characterized as an advanced R&D test (Thematic Mapper) and an operational test (Multispectral Scanner). Its specific objectives are:

(a) Global Food Production Forecasting

(1) Using the Multispectral Scanner to provide a continuous flow of global data from which measurements of the acreage yields and hence the production of wheat and other major crops such as corn can be made.

(2) Using the Thematic Mapper with its superior observing capabilities as a research tool to extend to the small field agricultural areas of the world and to other crops such as soybeans, oats, and rice, the measurement of areas, yields and hence production.

(3) To supply these observational data to the U.S. Department of Agriculture and other users in an orderly and timely fashion to facilitate their application of the information to their needs.

(b) Hydrological Land Use

(1) Using the MSS to provide a continuous flow of data from over the United States from which hydrological land use, water resource management, water runoff, flood monitoring and other measurements can be made and the information can be applied by the Corps of Engineers, and other federal, state and local planners and managers to their uses.

(2) Using the TM to extend the observing capabilities of remote sensing of hydrological land use and related phenomena to smaller scale and more accurate mapping through a selection of research tasks.

(3) To supply these observational data to the Corps of Engineers in an orderly and timely fashion.

(c) Petroleum and Mineral Exploration

(1) Using the TM to map the geologically significant areas of Earth.

(2) Supply the mapping data in an orderly and timely fashion to the EROS Data Center so that the USGS and other users such as the petroleum exploration industry can prepare geological maps and other information to assist in the exploration for minerals and petroleum.

(d) Land Use Planning and Monitoring

(1) Using the TM to map the United States urban areas on a periodic basis for the purpose of producing land use maps for federal, state, and local planners utilization.

(e) Forestry

(1) Using the MSS to provide the data on acreage, type of tree, growth of large U.S. forested areas for the use of forest resource managers.

(2) Using the TM to extend the remote sensing capabilities on a research basis to smaller forests, a greater number of species and to demonstrate the more accurate yield measure capabilities.

(f) Coastal Zone Mapping/Bathemetry

(1) Using the TM to map the coastal zones of the U.S. and particularly the shallow water surface features to demonstrate the utility of the data in the management of wetlands and shallow water resources, the control of coastal erosion.

(g) Soil Management

(1) Use the TM to map the U.S. and develop soil classification maps for use in agriculture land use management, erosion control, etc.

(h) New Applications

(1) Explore, in a research and development program, new applications of the global remote sensing data of the vegetative cover and surface features. Develop faster, more efficient data processing and information extraction methodologies and techniques.

SYSTEM OBJECTIVES AND CAPABILITIES

The objectives of the Landsat Follow-on program are as follows:

(a) To exploit the demonstrated capabilities of Landsats 1 and 2, and those expected of Landsat C over a three to five year period in the early 1980's by providing a reliability source of information on global vegetative and land cover. This capability would be based on the remote-sensing attributes of the multispectral scanner (MSS) now planned for Landsat C.

(b) To provide an improved, and ultimately operationally needed, research and development capability for remote sensing as represented by the Thematic Mapper (TM).

(c) To provide a complete data processing and information extraction system of sufficient reliability and speed to permit the demonstration of the operational utility of the MSS and the operational potential of the TM, and to yield the economic benefits which our studies have shown are realizable.

(d) To demonstrate and evaluate the role and effectiveness of the space shuttle in-orbit refurbishment of the spaceborne segment of the system, thus providing confidence that the operation of the basic system can be extended throughout the decade without major new systems acquisitions.

(e) Explore, develop and as necessary establish institutional arrangements at federal, state, local, private sector and international arenas required for the establishment and operation of the follow-on operational system.

(f) Provide continuing program of technological research and development to upgrade and make more economic the capabilities of the follow-on operational system.

The ability to meet these objectives and, thus, to supply accurate, reliable and timely information derives from many years of experience, both civilian and military, with remote-sensing systems such as film cameras, vidicons and scanning radiometers. The present state-of-the-art for civilian spaceflight observations of the surface of the earth is the multispectral scanner (MSS) on the Landsats 1 and 2 and the data processing system in the NASA Data Processing Facility (NDPF) at Goddard Space Flight Center, and the EROS Data Center (EDC) of the Department of Interior/U.S. Geological Survey at Sioux Falls, SD. These flight and ground facilities provide photograph and computer-compatible multispectral imagery data for thousands of R&D applications in crop surveys, water resources, land use, forestry and rangeland, and others![1]

The largest, single, and probably the focal application of the Landsats 1 and 2 data is the Large Area Crop Inventory Experiment (LACIE), a joint project of NASA, USDA and NOAA. This is a three-phase program covering three growing seasons directed to quantitatively determining the ability of the multispectral scanner (MSS) to produce data from which forecasts of wheat production in the U.S. and certain foreign countries can be determined. LACIE has completed Phase II, very successfully, for winter wheat and is starting on Phase III which will be complete by October 1978.

ECONOMIC BENEFIT ANALYSIS

A number of the participating agencies have undertaken economic benefit analyses [2,3,4] which conclude that there are real economic and cost-effective benefits derivable from the use of Landsat (MSS) data. NASA has conducted the most extensive of these studies, with ECON, Inc. and has used the analyses of the benefit mechanisms for two purposes:

(a) To determine the dollar benefits to be derived from both the MSS and the TM instruments, as requested by the Office of Management and Budget.

(b) To define the technological requirements of the observing and the data processing system which then permitted the design of both the space systems and the ground systems, including the mission unique (agricultural, hydrological land use, etc.) information extraction systems. From these designs it was possible to determine the total costs of the program that would be required to produce the economic benefits identified in the analyses.

It is important to recognize that these objectives now size the space and the ground systems when inserted into the perception of information flow in a cost-benefit study as it evolved in this Landsat Follow-on program, shown in Figure 1.

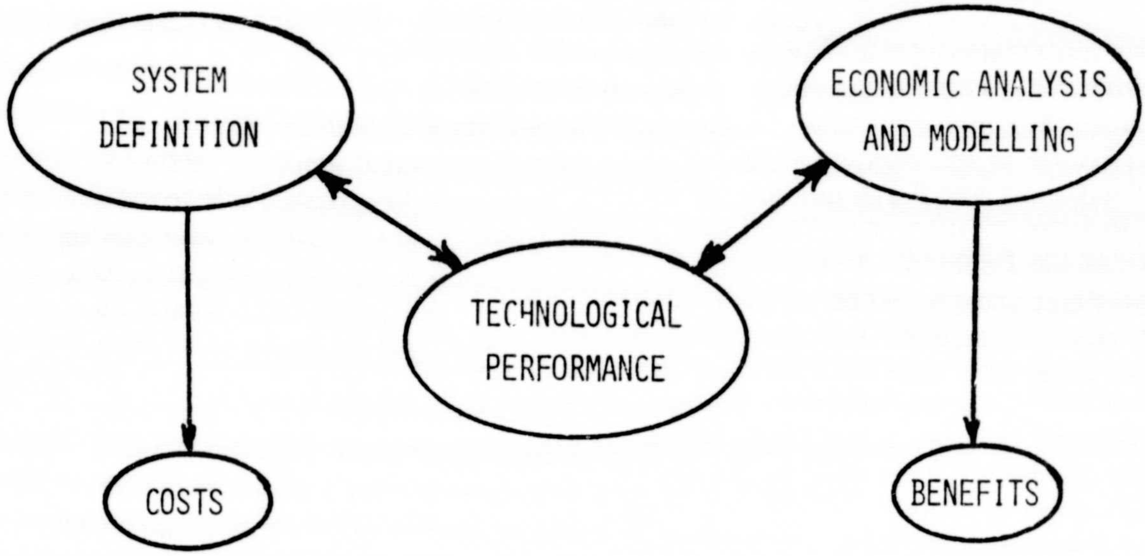

Figure 1. A Perception of Information Flow in a Cost-Benefit Study

Thus, the Study consisted of three major activities:

(a) Economic Analysis and Modelling from which dollar benefits were derived.

(b) Determination of Technological Performance; how accurately can crop production be forecast using MSS and TM data, for example.

(c) Definition of the System, space flight and ground, required to sustain the performance and meet the objectives. Once the System was defined it was possible to determine its costs.

Brief descriptions of each of these activities and their results follow.

The Economic Analyses

There are two mechanisms through which benefits are obtained from the Landsat data; both require that the data be operationally available, i.e., reliably and timely over a long period of time. One mechanism, readily understood, is that of cost-effectiveness; use of the information reduces the costs of a particular operation. An example is the reduction of oil and mineral exploration costs by those industries using the maps of remote areas derived from the Landsat images and using the geological features visible in the images to identify the most likely areas for more intensive exploration. The annual benefits shown in Table 3 were obtained from surveys of involved industrial associations; the range of values arises from the degree of conservatism from the different sources.

Table 3

Summary of Annual Quantified Benefits
(Millions of FY '76 Dollars)

APPLICATIONS	COST SAVINGS	INCREASED PERFORMANCE OR INCREASED SERVICE
AGRICULTURE	-	\$290 - \$580
OIL AND MINERALS	\$64 - \$260	-
LAND USE	\$15	\$33
HYDROLOGIC LAND USE	\$22	-
WATER RESOURCES	-	\$13 - \$42
FORESTRY	-	\$7
SOIL MANAGEMENT	\$5 - \$9	-
TOTALS	\$106 - \$306	\$343 - \$662

The other mechanism is based on the economic theory relating the value of information to net social benefit. The model [4] was used to determine the annual benefits that would accrue to the U.S. economy because of better decisions by crop producers and consumers resulting from their better knowledge (forecasts) of foreign crop production. Thus, in a simplistic example, wheat inventory holders will make better decisions about buying or selling (how much, at what spot or future prices) if they have more accurate information about future foreign wheat production. Tests of the model show that this better information on production does stabilize or reduce the fluctuations in grain prices and stocks. The dollar benefits shown in Table 3 are for wheat, corn and soybean foreign forecasts.

The Technological Performance

Since the largest economic benefits identified in the studies arise from the value of improved information in crop forecasting, the Landsat Follow-on Study concentrated much of its efforts on the determination of the accuracy with which the MSS and TM would permit measurements of acreage of certain crops. This required a rather sophisticated analysis and simulation of their technical performance, based on the LACIE methodology, which is diagrammed in Figure 2. Basically, the production of, say wheat, is determined by measuring acreage

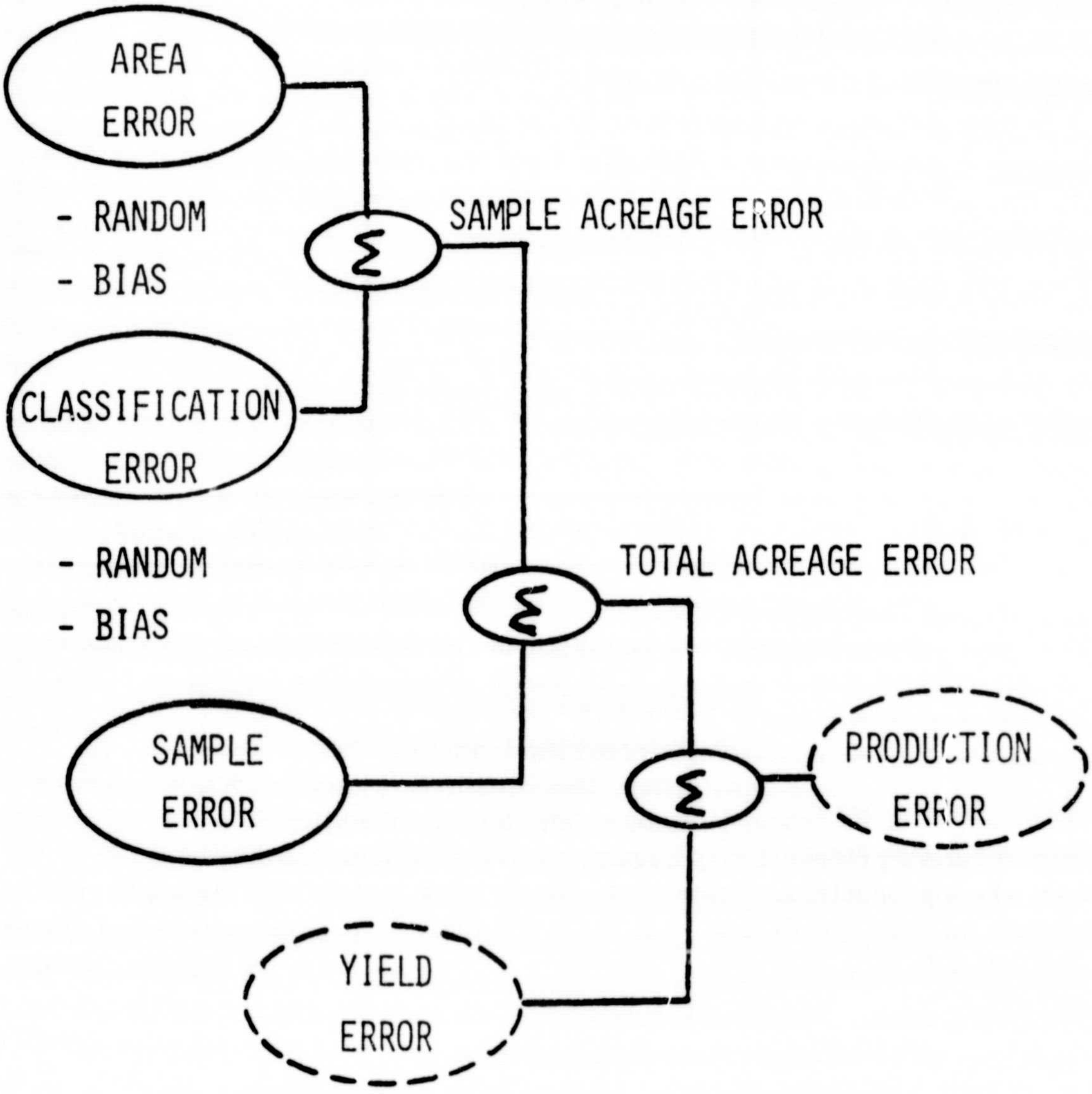

Figure 2. System Error Propagation

from the Landsat imagery, computing yield from linear regression equations relating yield to temperature and precipitation data. The product, acreage times yield, is production. The simulation addressed the random errors in area, classification and sampling to produce a total acreage area. The yield errors were roughly modelled from the a priori and at harvest data.

These results were used for two purposes: one, they were inserted into the econometric model, as an improvement in accuracy over the present U.S. Department of Agriculture foreign crop forecasting data and the benefits previously discussed obtained. The second application was to specify the performance of the MSS and the TM, as shown in Figure 3.

At this point, it was possible to specify the technical performance objectives, Figure 4. Landsat carries the MSS; Landsat Follow-on, both the MSS and the new TM.

In the consideration of technical performance, there was one other key systems parameter - a data systems driver. That was the numbers of images per day, over which areas of the world, that would be required to produce the benefits that had been identified. An image acquisition strategy was devised based on

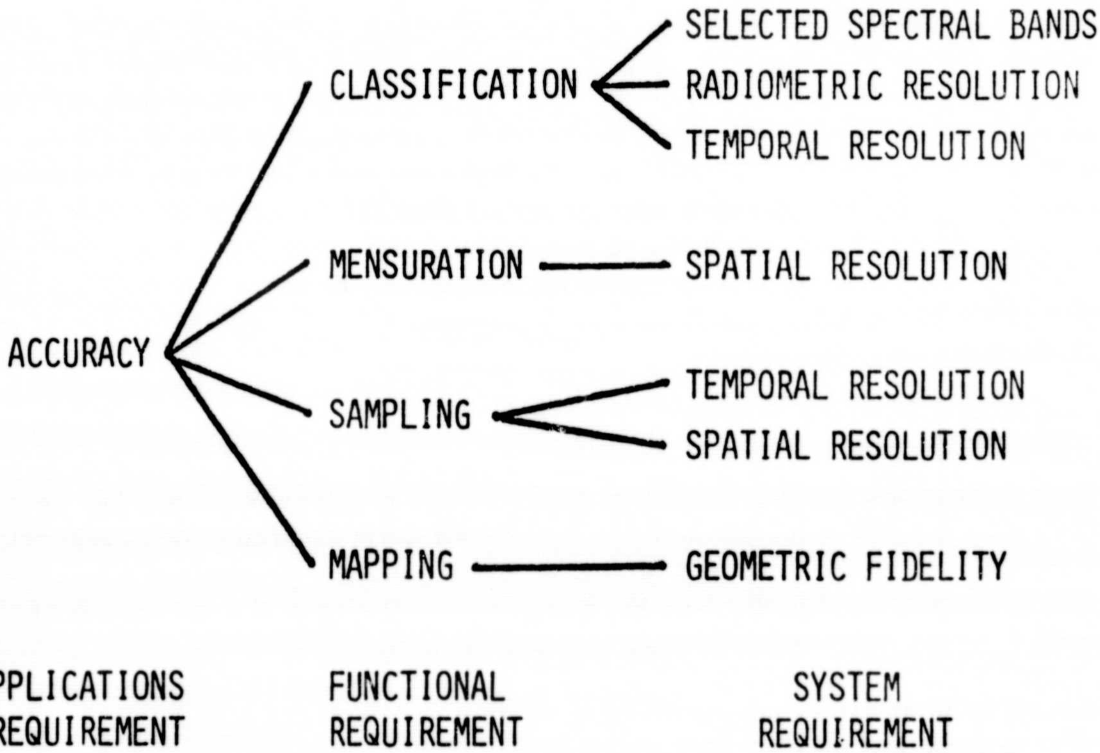

Figure 3. Accuracy and Systems Requirements

	LANDSAT FOLLOW-ON	LANDSAT
SPECTRAL BANDS (NUMBER)	6	5
RADIOMETRIC RESOLUTION (GRAY LEVELS)	256	64
TEMPORAL RESOLUTION (DAYS)	9	18
SPATIAL RESOLUTION (METERS)	30	80
COVERAGE	GLOBAL TO CENTRAL LOCATION	LIMITED BY TAPE RECORDER
REGISTRATION ACCURACY (METERS)	15	100

OPERATIONAL DEMONSTRATION REQUIRES:

CONTINUITY = NO INTERRUPTION IN SERVICE

DATA THROUGHPUT TO MEET REPORTING CYCLES

Figure 4. System Technical Performance Objectives

the fact that the bulk of crops like wheat are grown in a relatively few regions of the world, such as the U.S. Great Plains, the Canadian Great Plains, USSR Central and Kazakh Uplands, etc. Similarly, the geological areas important for future oil and mineral exploration are limited. An important ground rule for the study was to use the TM only when its superior observing capabilities were needed; otherwise use the MSS with its much lower (1/10) data rate. This study revealed that a data system sized to process and distribute 100 TM and 200 MSS scenes per day (a scene is a composite of 5 images, one image for each spectral band) would be capable of producing the data needed for the agricultural, oil and mineral and other applications.

The System

Having defined the systems technical performance requirements, and having decided that the system definition would include all activities from the spacecraft instruments to the delivery of information to the manager or planner whose use of the information would produce the benefits, the design of the spacecraft and ground data systems was relatively straightforward.

Figure 5 is an artist's concept of space system and communications links. The orbital altitude and swath width are such that each area on the earth can be observed every 18 days by one satellite. Two satellites are required for the 9-day

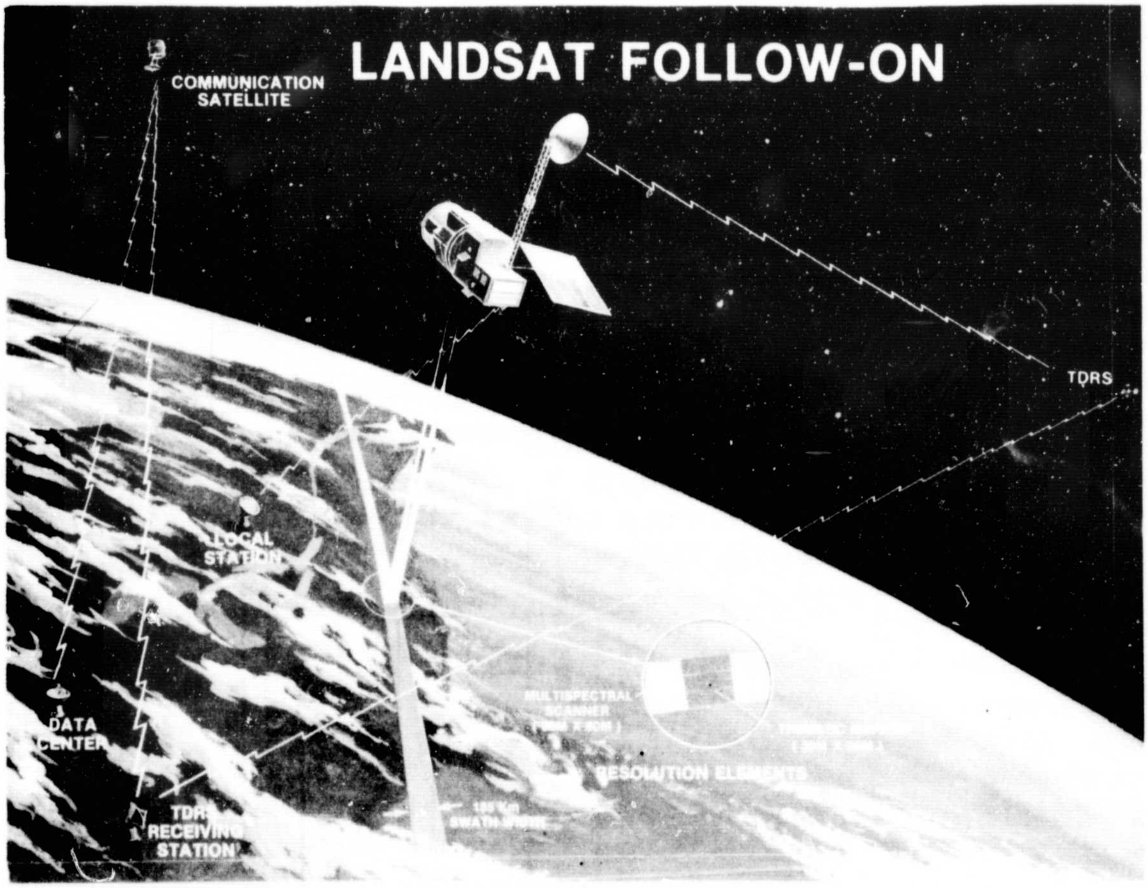

Figure 5. An Artist's Concept of the Landsat Follow-on System

repeat cycle planned. The use of the Tracking and Data Relay Satellite System (TDRSS) permits essentially continuous acquisition of the high data rate (120 MBps) from the TM - there is a small coverage gap over part of the Indian sub-continent.

The data system flow diagram is illustrated in Figure 6. The entire Landsat Follow-on data system is digital; the principal data products are high density digital magnetic tapes, which are also the archival medium. Image products, such as color composites, would be available from the EROS Data Center at Sioux Falls, as they are now for Landsats 1 and 2.

The strategy for providing an operational capability in the space systems was to make the spacecraft compatible with launch and retrieval by the Shuttle. Three spacecraft would be procured; the first two, launched by Delta launch vehicles out of the Western Test Range in early 1981, would provide 9-day repeat coverage. By 1983 the Shuttle would be operating out of the West Coast into polar

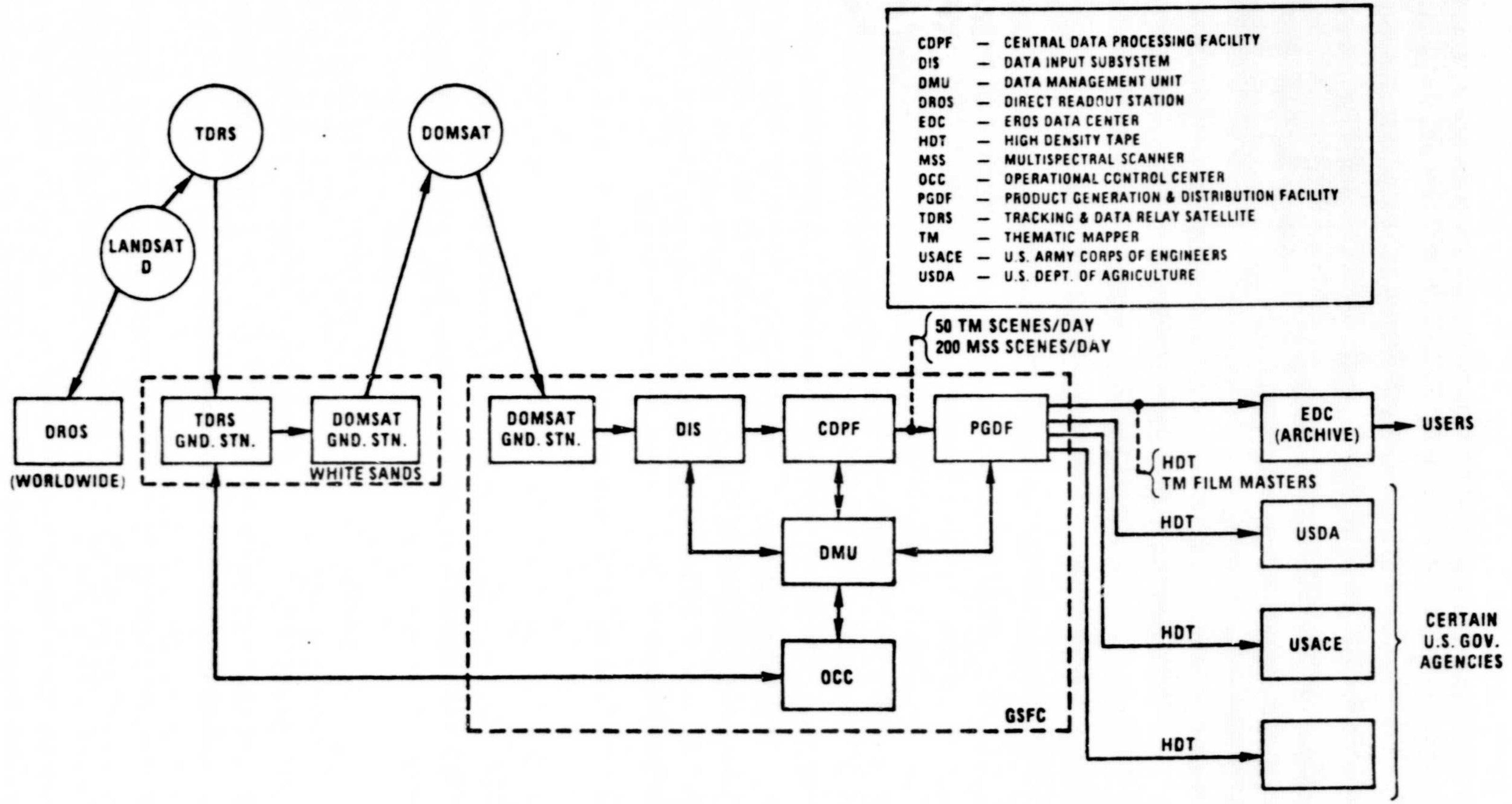

Figure 6. Landsat Follow-on End-to-End Data System

orbit and would be able to maintain the two-spacecraft system over a ten year period using the third unit as a spare.

This design was studied in some depth and the costs of the various components estimated with a modest certainty.

CONCLUSIONS

The results of the benefit and cost determinations for the Landsat Follow-on program are displayed in Table 4. These are present value benefits, FY-76

Table 4

Present Value of the Benefits and Costs of the Landsat Follow-on System
(FY 76 Dollars Discounted at 10%)

SYSTEMS AND USERS	BENEFIT ($ MILLION)	COST ($ MILLION)
SPACE AND DATA MANAGEMENT SYSTEMS	-	342
AGRICULTURAL CROP INFORMATION	1,705-3,370	55
HYDROLOGIC LAND USE	128	10
PETROLEUM-MINERAL EXPLORATION	202-819	
WATER RESOURCES MANAGEMENT	75-237	
FORESTRY	41	122
LAND USE PLANNING-MONITORING	87-278	
SOIL MANAGEMENT	29-52	
TOTAL (ROUNDED)	2,260-4,920	530

BENEFIT COST RATIO = 4.3 - 9.3

dollars discounted at 10% to an eighty year horizon, a way of presenting them that is well known in economic circles. The benefit cost ratio, greater than 4:1, is quite favorable.

From this study it would appear, if the results are at all credible, that an operational Landsat Follow-on Program, based on the two multispectral scanning radiometers, would be a practical investment for the nation. It would produce global information on agricultural, forest, water, land, oil and mineral and human resources that would be of great value in the private and public management of the production, distribution, and conservation of these resources.

ACKNOWLEDGEMENTS

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