GEOLOGY

2

Useful Applications of Earth-Oriented Satellites

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SUMMER STUDY ON SPACE APPLICATIONS

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GEOLOGY

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PREFACE

In the fall of 1966, the National Aeronautics and Space Administration (NASA) asked the National Academy of Sciences to conduct a study of "the probable future usefulness of satellites in practical Earth-oriented applications." The study would obtain the recommendations of highly qualified scientists and engineers on the nature and scope of the research-and-development program needed to provide the technology required to exploit these applications. NASA subsequently asked that the study include a consideration of economic factors.

Designated the "Summer Study on Space Applications," work began in January 1967, guided by a Central Review Committee (CRC) appointed by the Academy. The Study's Chairman was Dr. W. Deming Lewis, President of Lehigh University.

Technical panels were convened to study practical space applications and worked intensively for periods of two to three weeks during the summers of 1967 and 1968 at Little Harbor Farm in Woods Hole, Massachusetts. The work of each panel was then reported to the Central Review Committee, which produced an overall report. Panels were convened in the following fields:

Panel 1: Forestry-Agriculture-Geography
Panel 2: Geology
Panel 3: Hydrology
Panel 4: Meteorology
Panel 5: Oceanography
Panel 6: Sensors and Data Systems
Panel 7: Points-to-Point Communications
Panel 8: Systems for Remote-Sensing Information and Distribution
Panel 9: Point-to-Point Communications
Panel 10: Broadcasting
Panel 11: Navigation and Traffic Control
Panel 12: Economic Analysis
Panel 13: Geodesy and Cartography

The Panel on Geology met and compiled an Interim Report during the summer of 1967. It was revised and made current during the summer of 1968 under the guidance of Ron J. P. Lyon, the Chairman, and William W. Rubey, a Panel member.

The major part of the Study was accomplished by the panels; the function of CRC was to review their work, to evaluate their findings, and, in the context of the total national picture, to derive certain conclusions and recommendations. The Committee was impressed by the quality of the panels' work and has asked that the panel reports be made available to specialized audiences. While the Committee is in general accord with the final panel reports, it does not necessarily endorse them in every detail. It chose to emphasize the major recommendations in its overall conclusions and recommendations, which have been presented in Useful Applications of Earth-Oriented Satellites: Report of the Central Review Committee.

In concluding this preface, it is emphasized that the conclusions and recommendations of this panel report should be considered within the context of the overall report of the Central Review Committee.

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1.0 SUMMARY

1.1 Fields

The principal fields of applied geology are exploration for minerals, oil, and gas and in engineering construction. Although all airborne sensors sample to only limited depths, the sum total of the information they provide is of major assistance in the geological analysis of many types of areas.

1.2 State of the Art

Even today the use of satellites can result in broad synoptic surveys with distortion-free multispectral photography. Side-looking radar from aircraft is another operational tool. Collectively, these permit the trained observer to locate geologic structure and areal features not so evident on the scale of ground observations. But much still remains to be done in relating remote sensing to classical geologic practice. Geology has many remote sensing requirements in common with cartography, agriculture, and hydrology; but the need for viewing with low-angle illumination to reveal geologic features in relief may require a special launch characteristic. Such low-angle illuminations probably require double coverage to view both sides of mountain ranges.

1.3 Goals of the Field

The field has two primary goals.

1. To provide, by means of color photography from spacecraft and radar imagery from aircraft, regional geologic photomaps of North and South America that will serve immediately as an aid to the exploration geologist in the search for new deposits of minerals and petroleum

2. To learn the spectral properties of minerals and rocks at various wavelengths, and to understand more completely how remotely sensed surface information may be used to determine rock identity and geologic structure and recognize lithologic and structural conditions favorable for the occurrence of economic deposits of minerals and petroleum

1.4 Systems Postulated to Achieve These Goals

The panel proposes a two-phase program that meshes with that for Forestry, Agriculture, and Geography, and one that agrees with those for Hydrology and Oceanography in many aspects:

Phase I

As an example of the applications of earth-oriented satellites, a geological resource study of North and South America is proposed, to be called GEROS-I. The initial simple system, to be put into operation in two to three years, would consist of a combined satellite-aircraft approach designed to provide useful geologic photomaps of North and South America. Color photography at a sun-angle of 30 degrees or less is to be obtained from a sun-synchronous satellite, using either capsule-dropped film or TV (return-beam vidicon) if the resolution requirements can be met, and side-looking radar imagery (from two aspects) will be provided by use of aircraft. The aircraft radar is recommended because (a) it is an already-established practice, and (b) it is believed that radar imagery of high resolution is obtainable at much lower cost from aircraft than from satellites (Appendix D).

The proposed data output would be in the form of photographs (and radar-image), hard copy of which would be distributed directly to the many ultimate users in the exploration sector of both industry and government. Since these users are already trained and competent in analyzing such photographs, the processing required is minimal.

Geology per se does not need frequent, repeated sensing, although a good secondary argument can be made for repeat viewing because of seasonal soil-vegetation relationships. Once good imagery has been obtained (which requires several passes to allow for cloud-cover, and perhaps viewing in two directions), further repetition may be unnecessary for years.

Phase II

Between Phases I and II an extensive 10- to 12-year program of software R&D is essential. The ultimate system entails the use of as-yet-untried sensing techniques that are more sophisticated than photography and radar to determine detailed geological structure and rock identity. This system would be closely compatible with the System for Earth-Resources Information (SERI) recommended as the later phase of the Forestry-Agriculture-Geography program.

By far the most significant long-range research-and-development needs are for the interpretational process--the software of the advanced system--and include:

a. Understanding the physics of the coupling between geology and the sensing process. Parameters, such as sun-angle, polarization, spectral properties of minerals, vegetation, and soil structure in the surface layer, are involved.

b. Development of the theory of "interfacial geology," that is, to understand more completely how the remotely sensed air-rock interface information relates to geological-exploration practices in actual mineral provinces.

c. Initial compilation of the available information for rock and mineral identification, under various environments at various wavelengths.

d. Additional effort devoted to narrowing the list of significant ground-truth parameters which operate at the ground-air interface.

The problems are dominantly interpretational and not in hardware development.

1.5 Program Costs

The total cost ($38 or $57 million) of the Phase I system to cover North and South America, is estimated at about $23 or $42 million for spacecraft photography and $15 million additional for airborne-radar imagery. Essential research and development over 10 to 12 years to prepare for Phase II system (the geological part of SERI) is estimated at $15 million for sensor development and testing in aircraft, $25 million to develop software interpretation for the sensor data in terms of geologic features and rock signatures, and about $20 million for aircraft operation and data processing.

1.6 Possible Benefits

Information obtainable from Phase I is expected to assist in the discovery of oil, gas, and minerals through more rapidly delineating promising areas for prospecting and to aid markedly in the planning of large engineering operations.

Several methods were used to evaluate the benefits that might accrue from a GEROS aerospace system, but none were especially successful.

One approach attempted was to examine to what extent present exploration and regional mapping costs might be affected, were GEROS data available. Present annual exploration costs for oil in the U. S. are estimated at $2.05 billion, of which approximately $345 million is directly attributable to geology and geophysics in exploration. A comparable figure for Canada is $35 million. Although mining-industry exploration costs are difficult to obtain, these run at about $200 million for United States and Canada metal exploration, of which about 25 percent, i. e., $50 million, relates to geology and geophysics. United States and Canadian national, state, and provincial regional geologic mapping and geophysical studies probably total about $65 million. Thus a total geology, geophysical, and mapping expenditure in the United States and Canada of about $500 million annually is estimated.

Assuming the collected data have at least a 10-year useful life, it need but contribute a 1-percent saving or efficiency increase toward present exploration and mapping costs to warrant its operation. (The USGS has estimated that the EROS system data would contribute a 7-percent efficiency increase to its geologic and geophysical operations.)

Another approach attempted to estimate the possible benefits from an acceleration of oil and metals production. No increase in total reserves was predicted, but even a small acceleration could yield significant revenue increments. The quantitative results are difficult to defend because they assume an inevitable relationship between the GEROS system data and the realization of discovery. The qualitative aspects of the argument, however, appear justified in that the availability and follow-up of the GEROS data would lead to stimulation of exploration and, therewith, to new discoveries.

A third possible approach is that the entire range of geological activities carried on by national and provincial geological surveys and other agencies of government are generally recognized as useful public services and that these services would probably be improved in effectiveness by data from the GEROS system. These geological activities include not only help in recognizing areas suitable for detailed petroleum and mineral exploration, but also practical aids in selecting sites for engineering projects and sources for construction materials, and in understanding the origin of mineral deposits. They also include the broad cultural benefits that accrue to science, education, and recreation from a better knowledge of the history of the earth and its inhabitants. It is difficult, however, if not impossible, to assess the benefits that the GEROS data would contribute to these activities.

1.7 Recommendations

The Panel recommends an immediate program, using sensors and equipment now available, of low sun-angle color photography from a sun-synchronous satellite and of side-looking radar from aircraft, to give synoptic coverage of North and South America. Restriction of the coverage to these two continents is recommended, because the quantity of data that can be assimilated by exploration geologists in a reasonable time is limited and, also, because of the need to cover geologically well-known areas, such as the United States and Canada, for ground truth and also lesser-known areas, such as parts of South America, where the prospects of discovering new mineral deposits seem promising.

The Panel also recommends an immediate ground-based and field-oriented project, estimated at 5 years' duration, devoted to spectral-signature research on minerals, rocks, and soils at various wavelengths; and a longer term, 10- to 12-year program, progressing logically from laboratory and field research on spectral signatures to controlled experimentation and testing from low-flying, then high-altitude, aircraft, and eventually spacecraft, in order to ascertain the usefulness and dependability of remotely sensed data in the recognition of lithologic, structural, and geomorphic features which may serve as guides in the search for new deposits of minerals and oil.

2.0 GENERAL STATEMENT

2.1 Definition

Geology as used in this report is that portion of the science which deals with the solid earth. It excludes physical geography, hydrology, and oceanography, and hence does not cover submarine, coastal, lacustrine, or riverine features.

Due to the specific ground rules of this study, only the applied aspects of geology have been considered--those of exploration for minerals (including mineral fuels, metallic minerals, and metals) and of engineering practice. Purely scientific applications are identified in Section 5 but are not considered at length.

2.2 Study of Applications of Space Technology to Geology

Of the various disciplines, geology has been among those most closely associated with the space program since its beginning. The lunar space program is heavily influenced by geological thinking, both in rationale and execution. The program for color photography from the 12 Gemini missions was directed by geologists. This Panel, therefore, turned its attention to applications of space activities, specifying those that, in the opinion of the Panel, show promise of immediate application in geology and of economic return. Those areas of research and development that should be emphasized in order to widen the selection of sensors are identified in several tables.

A program is proposed which uses sensors and equipment now available, and which could be implemented at once. This system is called GEROS-I (Geological Resources).

An appraisal of the economic benefits that might be obtained if GEROS-I were applied to all of North and South America is exceedingly difficult. Data on which assumptions could be based were sparse; and, in the time available, only a rough estimate could be made. While the magnitude of such benefits may be argued, the Panel is convinced that the application of remote sensors to those aspects of geology involving exploration for minerals and engineering practice will pay appreciable dividends and should be pursued vigorously.

2.2.1 Further Research Needs

It is already clear that the longer wavelengths beyond the visible should be investigated more fully for future applications. The Panel has given consideration to the basic physics of remote sensing, as it might apply to geological analysis and mapping; and those sensors and techniques that seem promising have been evaluated and ranked (Table 2.4.4). Recommendations for further significant research are tabulated (Table 2.4.5). This approach to sensor evaluation and to sensor development by logical progression from laboratory and ground measurements, through aircraft studies, to the spacecraft testing and operation seems eminently desirable. We strongly emphasize the necessity of such orderly process and recommend strongly against too early a concentration on the spacecraft stage before basic software R&D has advanced sufficiently. Without understanding, too much data only swamp the user.

We wish to commend NASA for its airborne multisensor testing program and again urge that it be continued and expanded. The cooperative in-house studies of NASA and the U.S. Geological Survey, together with the NASA-sponsored research projects at several universities (Kansas, Stanford, University of Michigan, Northwestern, Nevada, and the Jet Propulsion Laboratories of California Institute of Technology) have contributed much to the existing level of understanding of geologic remote sensing. These efforts must be doubled at least, for without the soft R&D--the basic understanding of the fundamental physics of the interaction of electromagnetic radiations at the air-rock interface--the wealth of information in the data cannot be uncovered. Unless this aspect is boldly undertaken, the value of photographs and other data will be unduly limited.

2.3 Advantages of Synoptic Coverage from Satellite or Aircraft

Several advantages for the use of aerospace systems in geology may be listed.

1. A synoptic coverage (or overview) enables the observer to have a grasp of regional features, free from distortions and artifacts introduced by reduction from large-scale to small-scale photos or maps. A comparable effect is achieved by side-looking radar.

2. The resulting uniformity of lighting conditions over broad areas markedly enhances the photographic quality, a feature also achieved by the constant-beam geometry of side-looking radar.

3. As a bonus, small-scale coverage (photos or equivalent) is available immediately after a flight, with attendant benefits in the accelerated selection of areas for further, more intensive investigation, in mineral exploration or in engineering planning. However, synthesis of synoptic coverage from conventional air photos is not currently feasible.

4. In case of geophysical force-field methods--gravity and magnetic--"noise" due to local anomalies may be eliminated, and emphasis can be placed on large continental-scale variations related to major features in the crust and upper mantle.

2.4 Needs and Required Developments in Exploration by Remote Sensing

Geology is an intensely analytical, deductive, three-dimensional science, and remote sensing has been applied to its study only in recent years. To relate the two, to define their needs more clearly, and to identify where developments are required, the Panel analyzed a typical exploration effort, thereby hoping to identify, step by step, the subsystems involved in this new relationship. A typical flow diagram of geological analysis for such an economic application is shown in Figure 2.2.1. This is expanded in Figure 2.2.2 to show how the existing level of basic geologic understanding and training can be tapped by a simple satellite system--like GEROS-I. By providing synoptic photography and radar data for geologic analysis, a specific redirection and impetus to mineral exploration could follow. As in the past, significant benefits could be achieved.

2.4.1 Geological Exploration—Typical Sequence

1. Study and interpretation of aerial photographs, preparation of lineament* maps, structural and synoptic geological maps
2. Selection of specific areas for more detailed examination by standard field (and laboratory) methods
3. Field and laboratory geochemical studies (in some cases)
4. Investigations of localized structures by geophysical methods, followed by drilling

The end product is a geological map and report, interpreting the surface geology, and, where possible, the subsurface. This is a continuing process, as there is no such thing as a finished geological map or a completed interpretation. Areas are reworked as data increase and new theories develop, which may pinpoint the localization of minerals missed in earlier studies.

2.4.2 Geological Exploration—Present State of the Art

Exploration for minerals requires interpretation by trained geologists of data derived from many techniques. Today, in many regions, economic mineral deposits are no longer exposed in such a manner that direct discovery is possible. Exploration theory is the key, then, which leads to recognition and delineation of structural and/or lithologic conditions favorable for hidden mineral occurrence. Intensive geological, geophysical, and geochemical examination and drilling of these smaller areas then are undertaken. The costs increase by an order of magnitude between these two stages, but the probability of success is magnified.

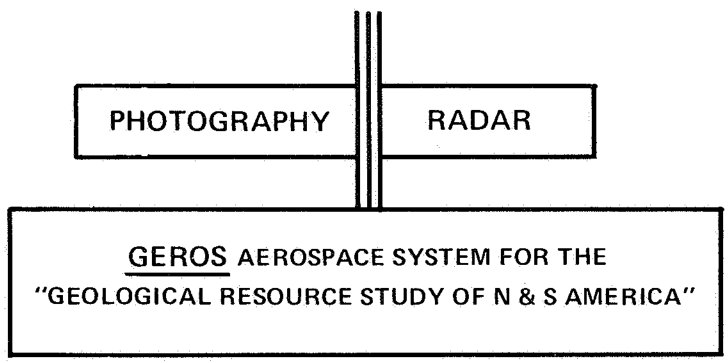
One should not neglect some of the presently unevaluated sensors (infrared, microwave, etc.), nor underestimate the potential of the synoptic space view by those already in use. It is our opinion, however, that the future development of new, expanded, and more comprehensive exploration theories for the formation and localization of mineral deposits in depth below the surface is the most probable payoff from continuing basic geological investigations, that could lead to increased detection of deposits now covered

*Linear features are further defined in Appendix A.

EXPLORATION FOR MINERALS

IS BASED UPON GEOLOGICAL MAPPING,
WHICH IS A SPATIAL DESCRIPTION OF ROCK
UNITS, LINEAMENTS, FOLDS, FAULTS,
AND COLOR PATTERNS.

SPATIAL DATA ARE BEST REVEALED BY SHADOWING.*



DATA OUTPUT FORMAT: COLOR PHOTOS, RADAR IMAGES

TOTAL 5500 SQ FEET OF DATA, 9x9 INCH FORMAT; SCALE 1:700,000.

INTERPRETATION IS RELATIVELY SIMPLE AND RESTS UPON THE
TRAINING ALREADY POSSESSED BY A GOOD EXPLORATION GEOLOGIST.

*See Appendix A for definitions.

FIGURE 2.2.1 Rationale for first simple system–GEROS-I.

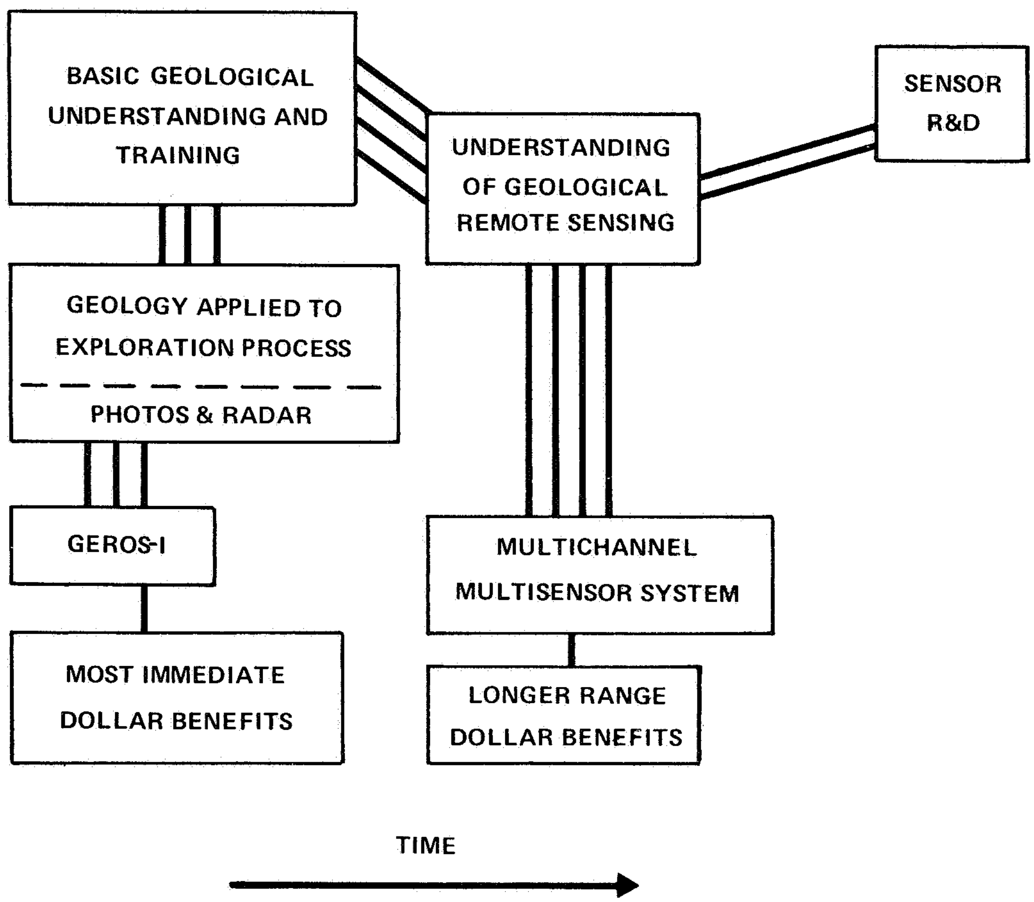


FIGURE 2.2.2 Flow diagram showing the fundamental routing of geological analysis for an economic problem (and how this would be assisted by GEROS-I and later aerospace systems).

or in depth. Our specific problem here, though, is to ascertain the contribution of remote-sensing systems to this established pattern.

2.5 Fundamental Problem

The basic problem in applying remote-sensing data lies in relating the electromagnetic and force-field data to rocks and soils and, in turn, to the analytical process, as used by exploration geologists. How can these data assist the field geologist in his search for new mineral wealth? Just what use does he make of the data?

In addition, a basic physical concept is involved, which limits the depth to which remote-sensing techniques may be applied. Electromagnetic radiation is attenuated to varying amounts by all media through which it passes. In some media this loss is very slight, but in others it is quite large, and concepts of "optical depth," "depth to opacity," or "skin depth" have been developed* to describe this attenuation. These depths are always wavelength dependent and hence one may "see" through a piece of normally opaque metal if the rays are short (or long) enough. In a comparable way, one cannot see far into the water except in some of the visible wavelengths, and into rocks and soils except in the longer wavelengths. A geologist who wishes to use remote sensing must recognize that his observational data too are dependent upon wavelength. The human eye cannot perceive visible light from beneath the surface. Radar skin depths are similarly measured in low multiples of wavelengths, or about 1 to 10 centimeters. Yet we expect to be able to infer geological features that occur far beneath the surface.

An extensive research-and-development (R&D) effort in the interpretation of these new types of data is proposed, which is deemed more essential for the geologist than R&D effort on the sensors themselves. Without this increase in the understanding of the interrelationships in geologic remote sensing, the flying of more refined sensors than those in the simple GEROS-I will be of limited value. A correct mix of R&D in all aspects of the geological problem must be developed. A quantum jump in understanding sensor data must be achieved, and a distribution of effort, as shown in Table 2.2.1, and stressing the rock-air interface, will materially advance the usefulness of the data.

*See Appendix A.

TABLE 2.2.1

RESEARCH-AND-DEVELOPMENT EFFORT RECOMMENDED FOR REMOTE SENSING IN GEOLOGY

Type of Data	Effort in Lab	Effort in Field	Data from Aerospace
Classical geology*	C	C	C
Interfacial geology	B	A_1	A_2
Interrelating remote-sensing data to surficial geology	A_1	A_1	A_2
Remote-sensing technology and hardware	C	A_1	B_2

A, Dominant effort. A_1, A_2 implies a time-step sequence.

B, Moderate effort

C, Minor effort

Interfacial geology (based on optical depth, depth to opacity, skin depth) generally $\frac{\lambda}{10}$ to 10λ, (where λ = wavelength). These terms are further defined in Appendix A.

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*The broad questions of mineral occurrences and their relationships to structure, lithology, tectonics, and crustal mantle features, together with the association of minerals with their host rocks, are contained here but not so closely related to remotely sensed data as is interfacial geology.

3.0 SYSTEMS OF SPACE APPLICATIONS IN GEOLOGY

3.1 Initial Simple System--GEROS-I Summary

3.1.1 Objectives

The objectives are to conduct a geologic resource study of North and South America, with a system to be operating in 3 to 5 years, and to obtain at least one cloud-free photograph coverage.

We anticipate that detailed study of color photos and radar imagery by trained, competent exploration geologists would suggest new areas, or entire geologic provinces, for more detailed exploration for minerals. If this is in any way relatable to the discovery of a single new productive area, the entire program cost of GEROS-I would be justified. Other advantages can be expected in the initial planning stages of large engineering and construction projects such as reservoir studies, pipe lines, and road construction from the ready availability of good geological base maps (particularly in Alaska).

3.1.2 Method

The method will be by analysis of the gross geologic patterns, structural, lithologic, and geomorphic features as revealed by low sun-angle,* synoptic, space, color photography and airborne-radar imagery of the two continents. Such a complete coverage of any large area has never before been available and permits broad interrelationships to be recognized.

3.1.3 Ultimate Users

The users of the data would be any or all geologists involved in the search for new mineral wealth on these two continents. These men need these data and can put them to immediate use. Rapid distribution into the private sector must be an essential goal.

3.1.4 System Description GEROS-I

3.1.4.1 General

The system components and program for the initial simple system are listed on the following pages.

*Low sun-angle (illumination) markedly enhances the vertical dimension of hills and other geological features. It is similarly useful in urban studies to show the shapes of buildings.

Prime Sensor:

Color photography was specified because geologists are accustomed to working with aerial photographs, and the use of color provides many additional data. Very little aerial color photography is available, even in the United States.

Operational Mode:

Satellite photography will provide the synoptic view essential to regional geologic work. (Resolution 100 feet, 100 x 100 miles field of view, linear distortion no greater than 1 percent).

Back-Up Sensor:

Radar coverage will provide additional geologic data and also will provide coverage of areas normally obscured by clouds or dense vegetation. Radar imagery resembles high-altitude photography and can be used immediately by geologists for structural studies. Further interpretational R&D may enable other geologic parameters (e.g., rock types) to be derived from the same data.

Operational Mode:

Aircraft are recommended to provide radar coverage because high-resolution imagery is apparently obtainable at much lower cost than presently estimated for radar in satellites (resolution 100 feet or less, 10- to 40-mile swath width).

Geographic Coverage:

Initial coverage will be limited to North and South America in order to restrict the data to a quantity that can be assimilated by geologists in a reasonable time and to cover both geologically well-known areas (United States/Canada) and lesser-known areas (parts of South America). The choice is also dictated by the fact that existing political frameworks will facilitate the sharing of the data.

The need for a synoptic photographic view with maximum delineation of surface relief defines a sun-synchronous orbiting satellite, with sun-angle lower than 30° above the horizon (see Figure 2.3.2). Such a photo subsystem would cover a 100-mile swath, whereas a space radar covers 50 miles. A review of possible space radar costs and existing aircraft radar systems clearly indicates a cost saving by flying in aircraft. A close parallel was shown in the swath width of space-radar versus aircraft-radar, with a somewhat better resolution achievable from aircraft. (See Appendix D).

A diagrammatic system flow plan is shown in Figure 2.3.1.

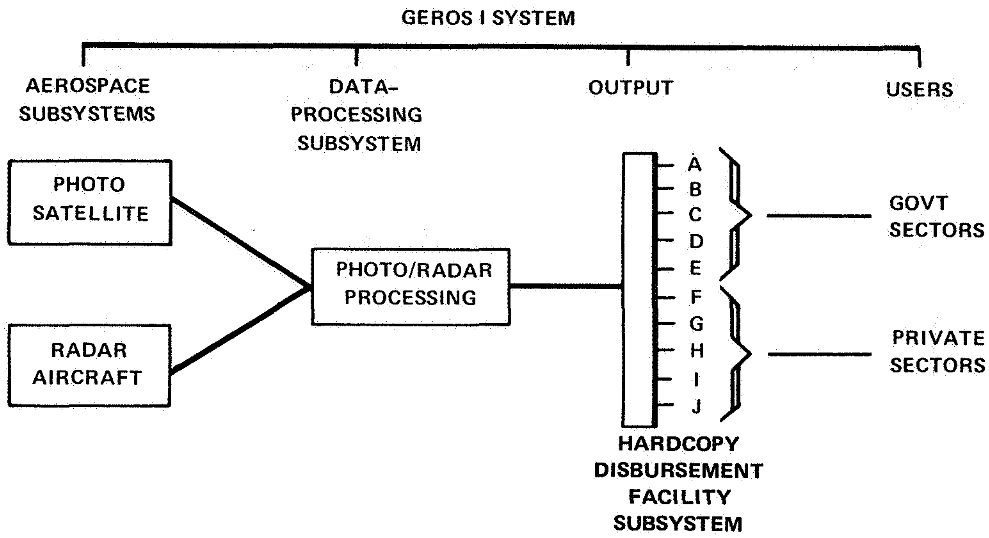


FIGURE 2.3.1 GEROS-I system.

3.1.4.2 Spacecraft Photo Subsystem

Requirements:

Final output of hard copy, regular color photography (of Gemini type), taken with filter selected for maximum contrast

Spatial resolution should provide for discernment of objects (within the range of normal contrast) which are no larger than 100 feet in lineal dimensions

Sun-synchronous circular orbit with 17- to 20-day repeat cycle

Low sun-angle for maximum shadowing, approximately 30° from horizon (A "nominal" 30° sun-angle at Latitude 50° N at the spring equinox. See Figure 2.3.2.)

100 x 100 miles sq coverage, 1:700,000 scale, approximately 15.1 million sq miles, 26% of world's land surface

Data output may also be enhanced* by line-edge techniques to reveal lineaments

10% forward and 10% side overlap necessary. If stereo coverage is flown, this would require 60% forward overlap.

*See Appendix A for definitions.

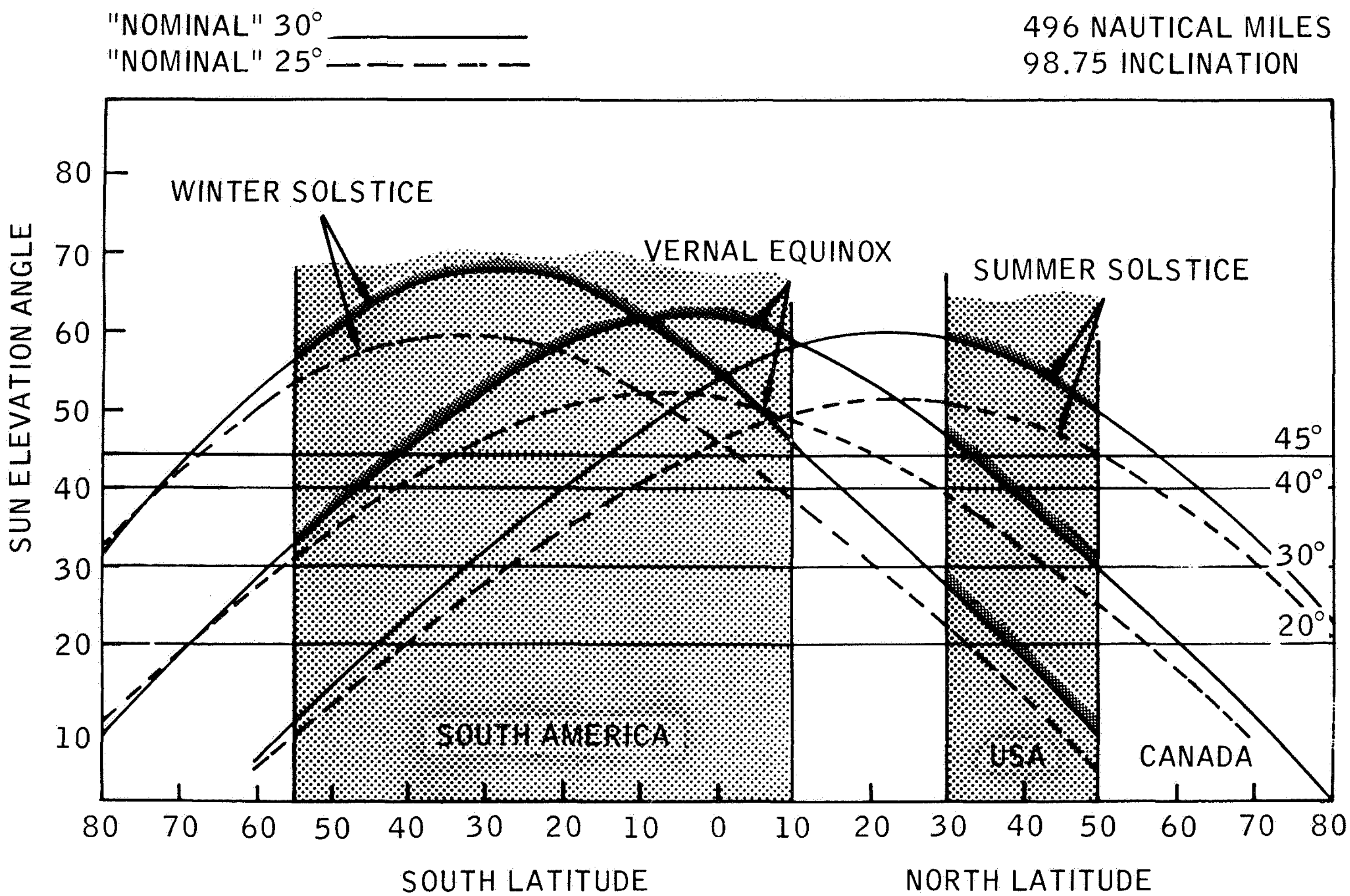


FIGURE 2.3.2 Sun-angles as a function of season for a typical EROS orbital inclination.

Orthographic presentation

At least three coverages to minimize cloud cover, perhaps covering two seasons. Both east and west illuminations would be desirable, but not essential.

Proposed Data Medium:

Not clearly defined, as there is a definite question whether the TV system can meet GEROS resolution and color-reconstitution specifications. For options, see also Table 2.3.1 and Figure 2.3.3.

Option (A) Return Film, regular color (Gemini type); implies capsule-drop Percheron-like system, and probably a 30-day film life in space. (Two cameras should be used for redundancy, and it may be useful to consider infrared color film for the second camera--see TV discussion below.) Initial Film Drop per camera, 1510 frames (no overlap), or 2570 stereo frames (10% sides, and with 60% stereo overlap). Three coverages yields 7700 frames, (see Appendix C). Negative size is not specified, but may be 70 mm if resolution requirements can be met. No allowance made for orbit convergence at poles.

Option (B) TV System, return-beam vidicon, etc. System to produce 2- (or 3-) color-separation negatives, which essentially ensure registry for reconstituted color film to preserve the resolution required. Sensed data should provide the opportunity to distinguish water, soil, and vegetation, and to recognize major condition changes. Three spectral bands appear appropriate for general user requirements. One band in the blue-green part of the spectrum is needed, (a) to meet acceptable haze penetration and produce good penetration of ocean, bog, and lake water for mapping of shallow underwater features, and (b) to represent land forms and the distribution of cultural features. A second band is required in the red and near-infrared parts of the spectrum to provide minimum penetration into water for shoreline mapping and some estimation of moisture distribution and vegetation vigor. The third band lies between the first two with no overlap. It is selected to improve the recognition potential of vegetation and to provide for 3-band reconstitution of infrared color.

One to 2-year life presumed, probably using a TIROS-M satellite system.

TABLE 2.3.1

VISUAL AND NEAR-INFRARED PHOTOGRAPHIC OPTIONS

Option 1:

Full-color, hard-film, capsule drop

either color Ektachrome (S0121 type) and/or color infrared Ektachrome

Option 2 (A or B):

Multiband* filtered B/W color-separation bands which may be reconstituted to form regular color or color ir

2A Hard-film capsule drop from 3 matched cameras

or

2B TV (return-beam vidicon) from 3 matched vidicons

*Multiband, to reform color, may be performed by a red and yellow, plus blue, band in the visible (to make regular color), or an infrared, orange-yellow, plus blue-green, band (to form color infrared).

Initial Data Output:

Telemetry, 2- (or3-) camera data over 15.1×10^6 sq statute miles (see Appendix C). Reconstituted from two B/W separation negatives to form regular-color film master negatives (or to form ir-color if this option is selected by inclusion of the third longer-wavelength band).

Final Print Output:

Regardless of film-drop or TV system, approximately 4350 sq ft of color master negatives will be produced as a hard copy (9 x 9 in.). Prints and/or transparencies are to be provided for users, with some requests for mosaics. Scale 1:700,000 as prints.

3.1.4.3 Aircraft Radar Subsystem

Requirements:

Westinghouse-type equipment

100-ft azimuth and range resolution as a minimum

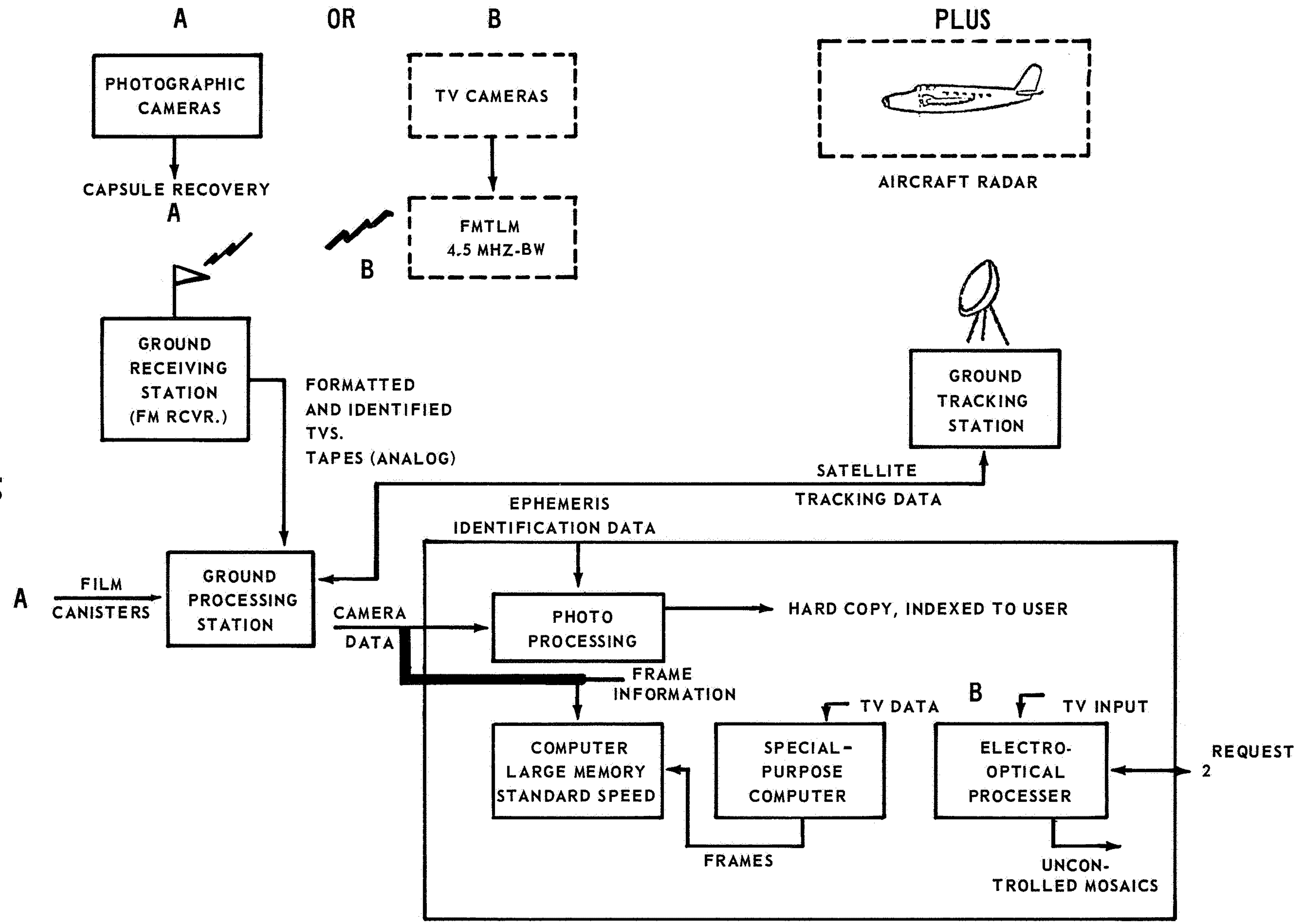


FIGURE 2.3.3 First-generation data link and data processing.

K- or X-band (2 to 8 cm) or longer to achieve "penetration" effect on soils and vegetation

Low shadow-angle

Both sides of hills, requires 2 coverages

50-mile swath width

As close to a true orthographic presentation as possible

Two seasons, for a total of four coverages

Proposed Data Medium:

Initial signal-film output 5-in.-wide film

Processed in aircraft and on ground to yield data film

Data Output:

Westinghouse-type data output

5-in.-wide signal film (equivalent to a photo master-negative), 40,000 ft long

5-in.-wide final data film, 2500 ft long or 1200 sq ft of data

Data Format:

Rectified image, same scale (1:700,000) as photography on 9x9-in. prints to achieve visual comparison

3.1.4.4 Data-Processing Subsystem

The proposed data output would be as hard-copy 9x9-in. photographs and radar images. These are to be sent out immediately to the users in the exploration sector of both industry and government. Release of these data to both groups would have to be made at some previously fixed date.

The whole basis of this initial system is that the data processing is minimal and that a ready, technically qualified and trained user is awaiting the data release. We already possess the competency to analyze the photos and images and can make independent and rapid judgments from them.

3.1.4.5 Research and Development

A possible further data-processing technique of line-edge enhancement* is strongly recommended. The identification of linear features

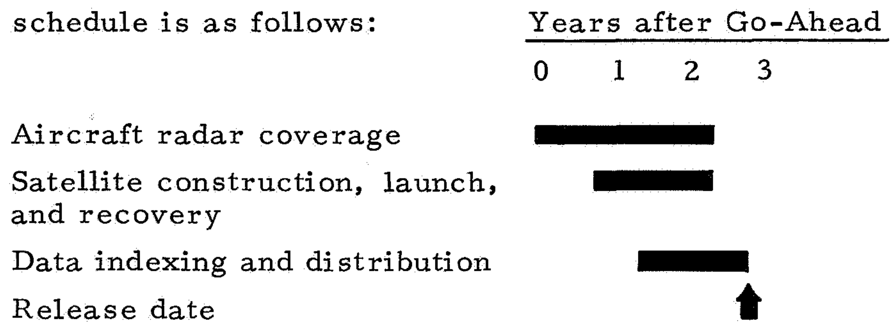
*See Appendix A for definitions.

(lineaments) is basic for structural analysis, and this assists their location. In addition, it is recommended that research on radar-imagery interpretation be accelerated, because we are certain that more information than just topography resides in the imagery.

3.1.4.6 Time Scale for GEROS-I

The proposed system will use existing sensors derived from aircraft programs, existing spacecraft technology, existing aircraft, and existing methods for interpretation of the data; consequently, the following represent the only constraints on completion of the initial program.

The schedule is as follows:



3.2 Ultimate System--SERI

The Forestry, Agriculture, and Geography Panel has proposed an ultimate system culminating in a System for Earth-Resource Information (SERI). Similarly, the Geology Panel has proposed a two-phase program of geologic-resource study for economic benefits: (1) an early aerospace system (GEROS-I) for photographic and radar coverage of North and South America and (2) a more sophisticated 12-year program, essentially of software R&D to involve other wavelengths and other sensors. The latter program is closely comparable with that in the SERI concept, as both emphasize extensive research in interpretation of remotely sensed data.

GEROS-I is only the initial phase in the solution of the basic problems of (1) how rocks may be defined in other than the radar and visible spectral interfacial wavelengths and (2) how the interfacial geology (as detected by remote sensing) may be specifically related to the geological interpretation as it appears on a geological map. The long-range SERI concept in agriculture and forestry is based upon identification of vegetation types, by electromagnetic signature, and the various relative spatial and temporal distributions of these signatures. The geologists require a similar understanding, but need to establish initially if rocks and soils have such signatures and whether these signatures can be used to give compositional information. SERI is a long-term commitment (12 years) to develop a technique that has economic utilization. With such a long-term program in geology, the potential is high to expand beyond the simple structural map of GEROS to a complete compositional geological map, in which, possibly, the depth dimension would be included. Such maps would markedly decrease the field time needed to localize an exploration program for mineral deposits.

3.2.1 SERI Research-and-Development Program

In geological studies, as with forestry, agriculture, and geography (FAG), an extensive research program in signature analysis (of rock and soils) is essential. Two aspects are planned and essential.

1. An immediate short-term, ground-based, and field-oriented research project over 5 years devoted to spectral signature-data acquisition. Field spectrometer equipment must be further developed, digital recording facilities assembled, and test areas evaluated, as rapidly as possible. This is estimated to be about $1 million per year for geological research, and is presumed to be included in the $10 million per year requested in the FAG report for the same type of work (on vegetation).
2. A longer-term, 10- to 12-year R&D, $60-million total program, logically progressing from the field (and the laboratory) to testbed aircraft as the now-defined equipment becomes available.

The integration of this Phase II SERI/Geology program and the GEROS aerospace system is detailed in Table 2.3.2. Ground-based operation with portable, reliable (and rugged) equipment, however, is the keystone of the research and must be directed by discipline-oriented scientists. For years, spectral research has been the regime of the physicist and electronics engineer. Now that the equipment is in sight, the emphasis must be returned to the field and to each scientist who is doing the experiment and defining the significance of the rock and soil signatures.

The year-by-year funding level for this Phase II (SERI) R&D in geology is detailed in Figure 2.3.4. The "soft" R&D--the thrust of the whole research effort--is shown inside the shaded borders. The program includes three test aircraft, one low-level test-bed, one general-purpose aircraft, and an "operational" high-altitude (30,000 ft to 50,000 ft), final-test unit for spacecraft-simulation studies. Equipment is developed, integrated, and moved from test-bed to operations in accordance with Figure 2.3.5. These aircraft are, most likely, in addition to those in FAG/SERI. Clearly, the equipment development costs are for the same hardware (e.g., the multichannel visual/infrared scanner), but duplicate units need to be installed sequentially in the three Geology/SERI aircraft.

TABLE 2.3.2

GEROS-I AND SERI RESEARCH-AND-DEVELOPMENT COSTS FOR GEOLOGY

Year	Hardware R&D	$	Soft R&D	$	Applications	$
1-3	SERI Develop field sensors $0.5 M/yr	1.5M	SERI Soft R&D on lab and field spectral signatures 1.7 M/yr	5.1M	----	
4-6	SERI Build and integrate aircraft hardware into 3 A/C $4 M/yr	12M	SERI Soft R&D on lab and field spectral signatures 1.0 M/yr	3.0	GEROS flights 2-3 years total cost including aircraft radar Film drop - 37M TV - 73M	37.0 or 73.0
			SERI Soft R&D on aircraft signatures 0.6 M/yr	1.8		
7-12	----		SERI Soft R&D on aircraft signatures 1.2 M/yr	7.2	SERI Aircraft operations (3) 1 M/yr	6.0
			SERI Aircraft operational photo interpretation R&D 0.3 M/yr	1.8	SERI Data processing 72K "photos"/yr 2.2 M/yr	13.2
			SERI Agency inhouse R&D on A/C data 1 M/yr	6.0		

Total Costs of GEROS and SERI for Geology

(millions of dollars)

Hardware R&D	13.5		13.5
Soft R&D	24.9		24.9
Applications			
(Film capsule drop)	56.2	(Vidicon)	92.2
	94.6	or	130.6

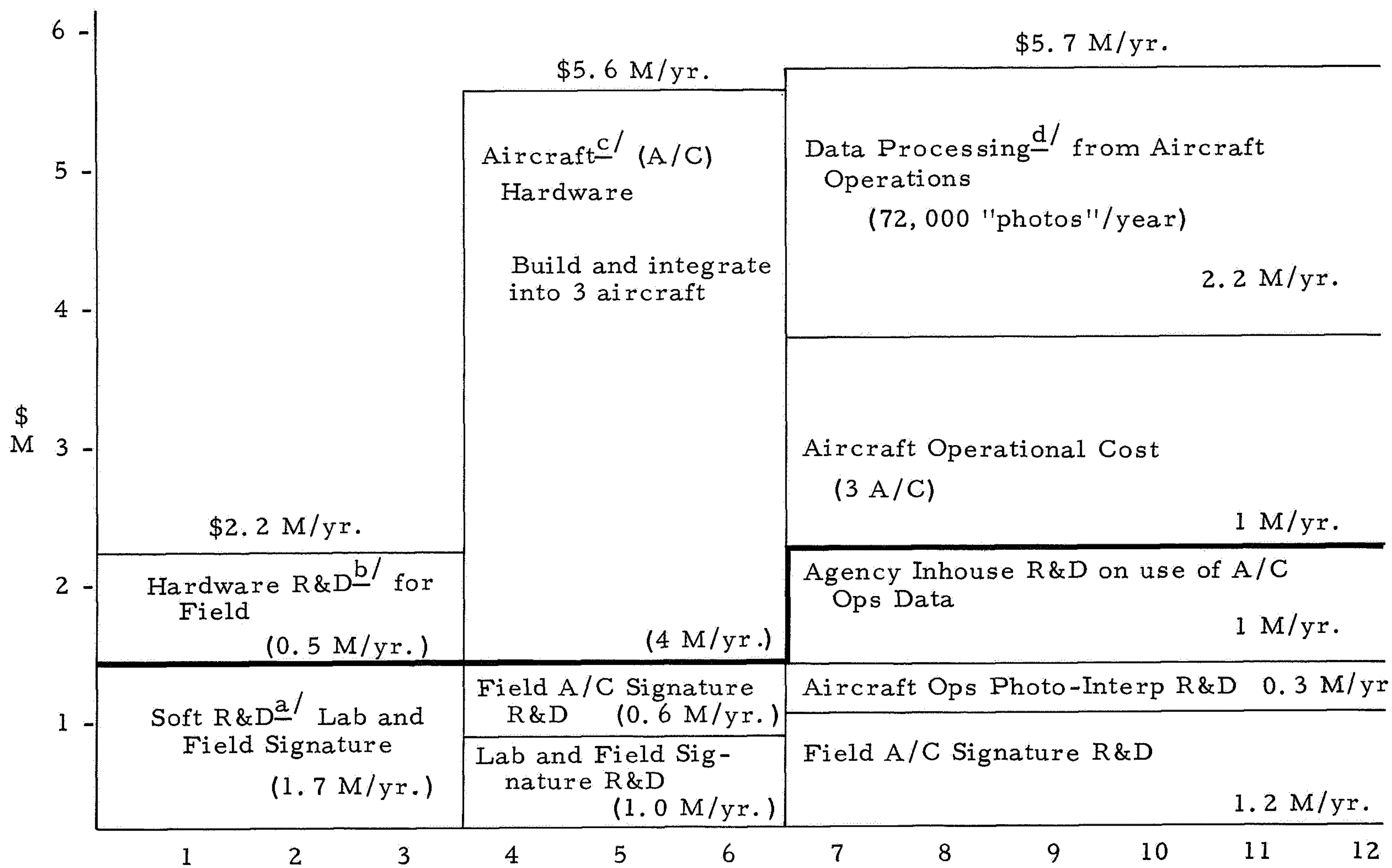


FIGURE 2.3.4 Year-by-year funding level for SERI/Geology R&D. "Soft" (interpretational) R&D is shaded.

a/ See Appendix D.1
b/ See Appendix D.2
c/ See Appendix D.2
d/ See Appendix D.3

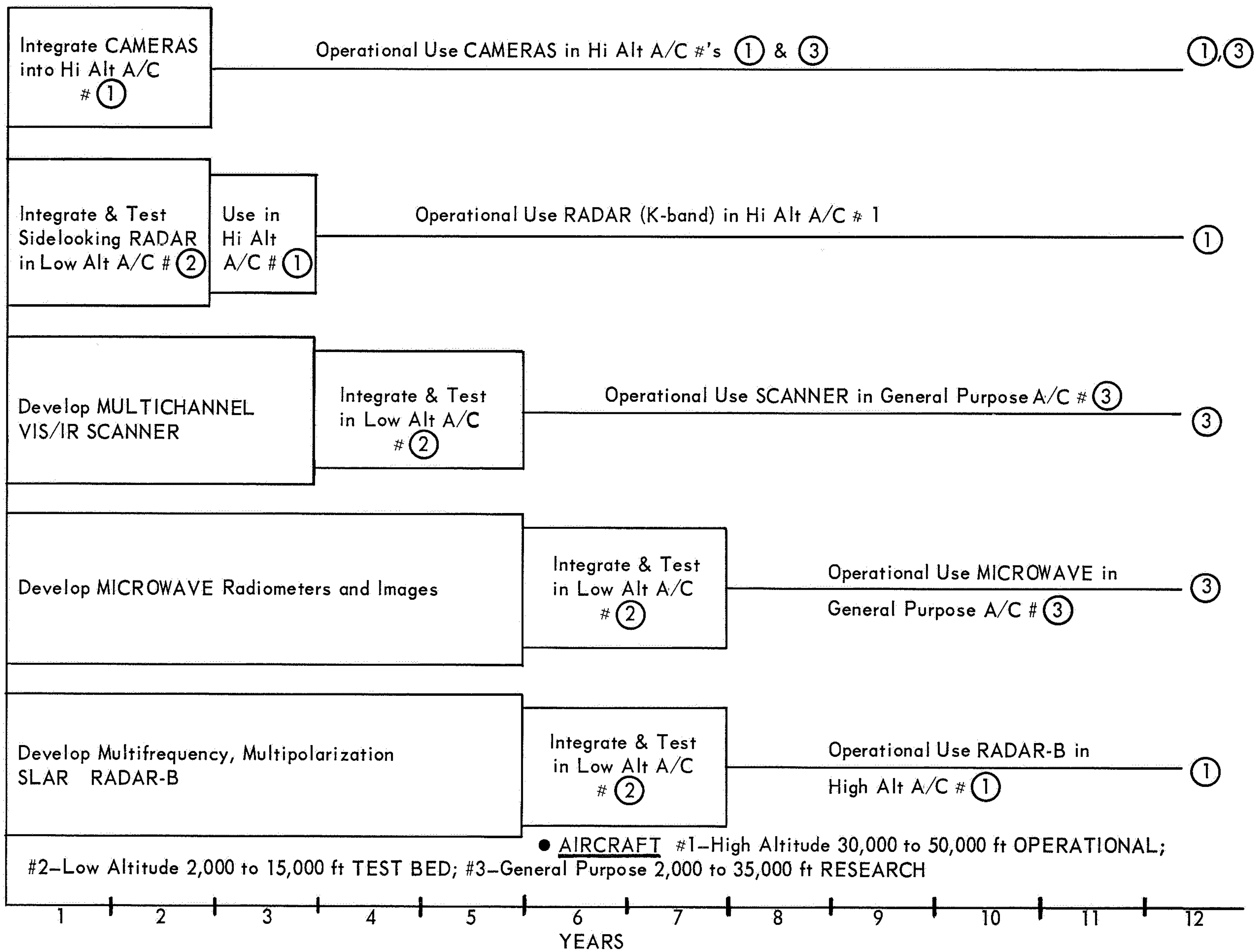


FIGURE 2.3.5 Year-by-year development of R&D and integration for a three-aircraft SERI/Geology equipment test program.

4.0 ECONOMIC ANALYSIS OF GEROS-I AND LATER SYSTEMS

4.1 Ultimate User

GEROS-I is a readily achievable system designed to facilitate a geologic-resource study of North and South America. Modern exploration for all minerals (including oil and gas) is based solidly upon geological mapping, without which these exploration efforts would be impossible. Geological mapping is a complex, time-consuming effort designed to analyze and depict the spatial distribution of rock units, folds, faults, and other structural features. If we could increase the quality and coverage of mapping by the use of the GEROS-I system, then the efforts of the world's geologists could be more effectively utilized.

There are many users in the broad areas listed below, but these early data must be widely spread into the private sector. In this way, they would reach the exploration geologist who is actively seeking new mineral wealth. This is the ultimate user, and he will go into the field better equipped if he has this color photography and radar imagery.

A list of users would include:

Governmental	International	Private
U.S. Geological Survey	Agencies of Canada, Mexico, and other American governments	Petroleum companies
U.S. Bureau of Reclamation	Organization of American States	Mining companies
Corps of Engineers	Agency for International Development/ State Department	Engineering and construction companies
Environmental Science Services Administration		Consultants
U.S. Bureau of Mines		Universities
State agencies		

4.2 Benefits

4.2.1 Description of Benefits

GEROS-I data will be especially useful for mineral exploration (including oil and gas) and preliminary large-scale engineering studies. Benefits of three types are expected.

1. Those benefits related to the extension of a known technique (high-altitude photography) to new areas, and those related to enhancement of this technique (synoptic, distortion-free, orthographic photography). Neither color nor orbital-altitude photography is generally available, and it is estimated that in South America even black-and-white photography coverage is only 70 percent, some of it having been taken more than 20 years ago. The availability of high-quality color photography for this hemisphere, plus the added effect of the synoptic view from space, will certainly stimulate exploration and lead to the discovery of new materials.
2. Those benefits related to the introduction of a new technique (e.g., side-looking radar). This equipment permits the delineation of topography in forested areas and statistically emphasizes the dominant linear patterns, which are controlled by folds, faults, and joint patterns. Radar can operate any time of the day or night, it always operates with a constant and low illumination-angle, and it will penetrate most clouds and haze. It will make available surface information in persistently cloud-covered areas that photography may never fully reveal.
3. Those benefits that result from planning of operations, with attendant cost savings, will be facilitated. An important element is the possibility of early selection and localization of promising sites for more extensive exploration in searching for mineral deposits, but early studies of areas for large-scale engineering construction would be greatly assisted by this synoptic coverage.

4.2.2 Experience from Past Introductions of New Techniques

Though difficult to quantify, past experience in minerals exploration shows that, when either a new technique is introduced, or a known technique is extended to new areas, an increase in both exploration activity and finding rate occurs.

The introduction of refraction- and reflection-seismograph techniques and of the torsion-balance and gravity meter coincided in time (1924 to the present) with a 30- to 40-fold increase in rate of discovery of new oil fields per year.

In exploration for metallic minerals, the introduction of airborne magnetometers in 1945, combined with greater use of other aerial surveys (such as electromagnetic), has resulted in an upsurge of discovery. In Canada alone, more than 100 new discoveries were, in part at least, the result of the use and followup of these new techniques. In 1966 alone, 20 new mines came into production in Canada.

It is recognized that this stimulation due to the seismic, airborne-magnetic, and electromagnetic developments, in part, resulted from their ability to penetrate beneath the surface and indicate local geologic and mineral features, so that comparison with the GEROS results is not wholly justified. Nevertheless, it is felt that, in part, the stimulation resulted from new data parameters and an ability to portray areas that could not be mapped geologically. In the sense that new data and partly mapped areas will be presented, a parallel stimulation can result.

4.3 System Costs

4.3.1 General Considerations

Cost estimates were based on the following considerations:

1. Primary objectives of the cost-benefits methodology were to identify the major cost components of the system hypothesized by each technical panel and to maintain consistent coverage and treatment of these cost components among the several technical panels. Hopefully, the pursuit of this objective served to make more comparable the system costs presented for each panel.
2. Costs were estimated only to the detail deemed necessary to permit program comparisons and evaluations on a consistent basis.
3. This costing process reflects neither the extensive nor intensive tradeoff analyses that might be considered for each system. Furthermore, costs (and quantifiable benefits) were not discounted, nor was the impact of the inflation question specifically addressed, in view of the approximate nature of the estimates. In short, although costing was performed within a relatively consistent framework, the dollar quantities (like the system configured) must be viewed as approximate.
4. Generally, the elements included in the costing procedure were incremental costs only, i.e., those costs that would be incurred by implementing the hypothetical satellite system. It is important to note, however, that the estimates presented do not include the following major cost items that undoubtedly would be incurred because of implementation of a particular system:
   a. Costs incurred by user agencies for education or extensive training and upgrading of personnel and procedures
   b. Costs of analysis and interpretation (e.g., photographic interpretation) of the data received by user agencies
   c. Any costs incurred by individuals or organizations "downstream" from the user agencies, e.g., costs to a farmer to revise his farming methods or to replace machinery due to new information provided by the satellite system

5. The primary functional categories were divided into collecting data from space, and processing and distributing these data to user agencies:
   a. Space-segment costs
      (1) Spacecraft (satellite) and sensors
      (2) Launch (launch vehicle, launching-pad costs)
      (3) Ground system (in general, ground stations, communication links, and tracking used to monitor, track, and control the satellite)
      (4) System management and administration of the space system

b. Processing-and-distribution-segment costs

(1) Spectral-signature analysis and ground truth
(2) Ground system (in general, ground stations, communication links, and tracking needed to read out imagery and other information collected)
(3) Processing (equipment for processing, organizing collected data into a form suitable to the user agencies, and distributing the data)
(4) System management and administration of the processing-and-distribution segment
(5) Platform equipment, such as buoys, balloons, and various types of ground collection-transmitter stations

4.3.2 Specific Considerations

Two GEROS-I systems, as described in Section 3.1.4, are presented. Option A (Table 2.4.1) provides film-capsule return from space. Option B (Table 2.4.2) provides a three-channel TV system, called the vidicon option. Either option also includes an aircraft-radar system using unfocused radar, costs for which are given in Table 2.4.3.

Cost estimates are made under the following assumptions:

1. Time frame:
   a. Option A, film-capsule return. One year R&D followed by 1 year operational.
   b. Option B, vidicon photography: One year R&D followed by 2 years operational.
   c. Aircraft unfocused radar: One-quarter year R&D followed by 2-1/4 years operational.
2. Spacecraft (satellite)
   a. Film-capsule return option. Sun-synchronous, near-polar, circular orbiter with several weeks' life presumed, costing $1 million each. Contains three color cameras plus peripheral equipment. Total of two spacecraft required.
   b. Vidicon option. Sun-synchronous, near-polar, circular orbiter with 1-year minimum life, costing $1 million each. Contains a three-color camera plus peripheral equipment. Total of three spacecraft required.
3. Launch vehicles
   a. Thor-Delta type vehicle is used to launch all satellites. The launch vehicle is priced at $3 million. Launching-pad operations costs are $2 million.
4. Contingencies
   a. Film-capsule return option. One cloud-free coverage required. Two launches, including spare.

TABLE 2.4.1

GEROS-I SATELLITE SYSTEM--SEPARATE DISCIPLINES
FILM-CAPSULE RETURN OPTION
COSTING ESTIMATES
(MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft (satellite and sensors)–near-polar	1	2		3
Launch (vehicles, pad costs) near-polar orbit		6	4	10
Ground system (station, network, tracking)		*	1	1
Systems management			1	1
Air-radar sensors and processing		2		2
Air-radar flight and management			12	12
Capsule Recovery			1	1
TOTAL - SPACE SEGMENT	1	10	19	30
PROCESSING-AND-DISTRIBUTION SEGMENT				
Signature analysis and ground truth	2			2
Ground system (station, network)			1	1
Processing (equipment, data handling, film, distribution		*	3	3**
Systems management			1	1
TOTAL - P&D SEGMENT	2		5	7
GRAND TOTAL	3	10	24	37

* Included in O&M.

**Nominal amount due to geologist's desire to work with raw 9 in. x 9 in. color prints.

TABLE 2.4.2

GEROS-I SATELLITE SYSTEM--SEPARATE DISCIPLINES
VIDICON OPTION
COSTING ESTIMATES
(MILLIONS OF DOLLARS)

	Research and Development	Initial Investment in Capital-Like Equipment	Operations and Maintenance	Total
SPACE SEGMENT				
Spacecraft (satellite and sensors)—near-polar	12	3		15
Launch (vehicles, pad costs) near-polar orbit		9	6	15
Ground system (station, network, tracking)		2	4	6
Systems management			2	2
Air-radar sensors and processing		2		2
Air-radar flight and management			12	12
TOTAL - SPACE SEGMENT	12	16	24	52
PROCESSING-AND-DISTRIBUTION SEGMENT				
Signature analysis and ground truth	3			3
Ground system (station, network)		1	2	3
Processing (equipment, data handling, film, distribution)	2	1	8	11
Systems management			3	3
TOTAL - P&D SEGMENT	5	2	13	20
GRAND TOTAL	17	18	37	72

TABLE 2.4.3

COST FOR 707-TYPE AIRCRAFT FLIGHT PROGRAM

	$Millions
Basic aircraft	7.0
Annual cost per aircraft:	
Crew, 7 @ $40,000 per year	0.28
Operate and maintain @ $500 per hour - for 180 flights @ 7 hours per flight	0.63
Staging once each year	0.10
Annual cost, excluding investment	1.01
Investment costs--amortization, interest, profit, and all taxes, 20% of $7,000,000	1.40
Total per year	2.41

Flight time required:

1. 50-mile-wide swath x 3000 miles long: 150,000 sq miles per flight
2. Effectiveness factor, 50%, x 150,000 = 75,000 sq miles imaged per flight
3. Number of flights required for North and South America $\frac{15,000,000}{75,000} = 200$
4. Number of flights required for four-time coverage (two seasons, two sides of elevations) = 800 flights
5. Number of aircraft years required $= \frac{800}{180} = 4.4$ years

Cost of aircraft flight program for North and South America - 4.4 x $2,410,000

Total $10,604,000

Program will use two aircraft for period of 2.2 years.

Summary	$Millions	$Millions
Air-radar flight	10.6	
Management	1.4	
Total	12.0	12.0
Radar-sensor costs (2 aircraft)	1.8	
Information processing	.2	
Total	2.0	2.0
Signature and ground-truth research		1.0
		15.0

b. Vidicon option. One cloud-free coverage required. Twenty-two repeat passes are expected from a satellite. Three satellites are provided, one as a spare, and launching costs for all are assumed in the total.

5. Data interpretation will be performed primarily by photo-interpreters and other trained personnel in agencies now working in their prospective fields.

4.4 Overall Technical Appraisal

GEROS-I is a simple, single-use, aerospace system, using space photography and airborne radar to yield a synoptic structural map of North and South America on a scale of about 1:700,000. Such a map-like photograph and radar image has been estimated to save years of effort on exploration programs. It can be achieved by a reasonable outlay of funds that is minimal when the lead-time return is considered. The technology is at hand for such an operational system, and little or no difficulty is foreseen in reducing the data to a photoformat that is immediately usable by a modern exploration geologist. These photos would form a working base map for his field efforts.

4.5 Recommendations for Research and Development

4.5.1 Research and Development Potential and Requirements in Geology

A clear distinction has not previously been made between the potential and the present status of achievement of remote-sensing techniques. For geological applications, this is extremely significant, as the gap is wide. In Section 2.4 of this report (Needs and Required Developments), an analysis was made of the methodology used by the exploration geologist. A satellite subsystem of low sun-angle photography and airborne side-looking radar is proposed in the GEROS program to aid the exploration geologist in his search for new deposits.

In subsequent sections, the really basic problem is discussed--that of relating the remotely sensed data to the geological features. This is outlined, and its essential R&D software efforts are identified. A concept of interfacial geology is identified which requires a significantly increased level of understanding before any further effort should be devoted to sensor development, and before spacecraft hardware is "frozen." The panel recommends the R&D priorities in Table 2.2.1.

A detailed appraisal of the problem is shown in Table 2.4.5 and summarized in Figure 2.4.1. Based upon an analysis of the data and interpretation resulting from the present-stage (1968) operational systems (Table 2.4.4), we have proposed a priority listing for R&D. This listing in Table 2.4.5 is related in terms of estimated potential for both basic and applied geology, and in the R&D needs ranked for hardware and for interpretational process. The mutual consideration of Table 2.4.5 with Table 2.2.1 would indicate where the R&D effort should be placed for geological applications.

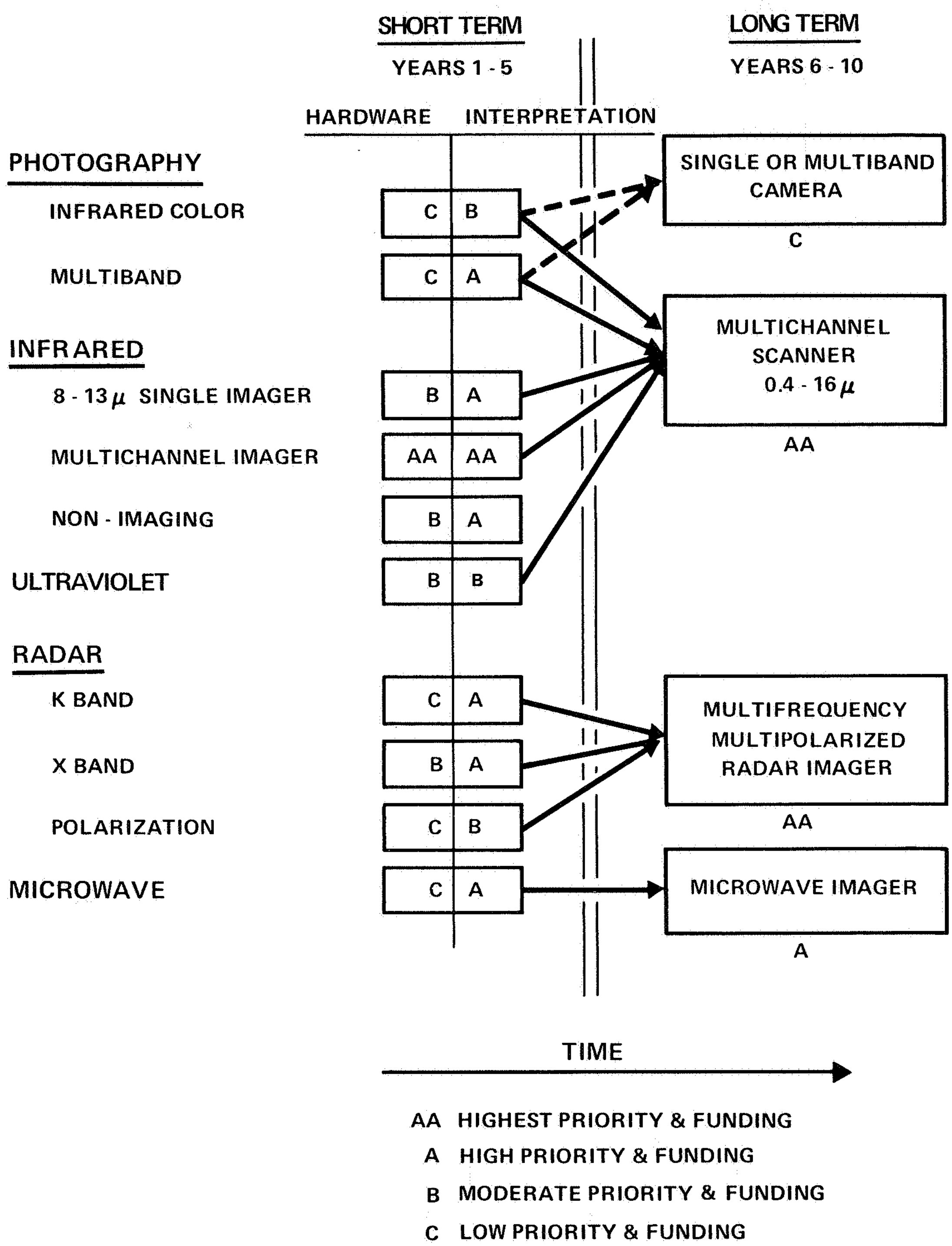


FIGURE 2.4.1 Summary of research and development recommendations for remote sensing in geology.

TABLE 2.4.4

STATUS IN 1968 OF REMOTE SENSORS FROM VIEWPOINT OF ECONOMIC* GEOLOGY

Sensor (in priority)	Application in Economic Geology	Operating Mode		Rationale
		Spacecraft	Aircraft	
I. Photography (0.4-1.0μ)	A. Structural geology (lineaments, faults, folds, etc.)	Best	–	Affords essential synoptic view and orthogonal presentation.
II. Radar	A. Structural geology (lineaments, faults, folds, etc.)	–	Best	It is assumed that resolutions from aircraft will be finer than those from spacecraft. Swath widths for both are comparable.
III. Infrared imaging and/ or spectroradiometric	A. Convective mass transfer at surface (volcanoes, geothermal power)	–	Best	Areas are small, localized, and/or need repeated monitoring.
	B. Conductive heat transfer to surface			
	1. Landslides, oxidizing orebodies	–	Best	Areas are small and localized near lineaments or intersections of lineaments.
	2. Outcrop maps (soil/rock interfaces, physical compositon)	–	Best	Diurnal rate of change of ΔT is essential. Not achievable except from geosynchronous orbit.
Spectroradiometric	Rock and soil composition (chemical – mineralogical)	–	Best	Spectrometer field of view is fixed by available energy, and smallest ground resolution is essential. Spacecraft smear is higher than with aircraft.
IV. Magnetics	A. Regional anomaly mapping structure delineation	–	Best	(1) Ionospheric problems with spacecraft. (2) Wavelength of anomalies of interest to economic geology are better delineated from lower altitudes.
V. Gravity	A. Regional mapping Basin structure delineation	–	Best	Same as (2) above.
VI. Ultraviolet	A. Rock-type discrimination	–	Best	Increasing altitude cuts off useful lower wavelengths.
VII. Microwave	A. Ground penetration ability	?	Best ?	Field of view wider than acceptable except when used in aircraft. Needs R&D.

* Herein defined to include engineering geology; but excludes hydrology and oceanography.

TABLE 2.4.5

RESEARCH–AND–DEVELOPMENT POTENTIAL AND REQUIREMENTS IN GEOLOGY

Sensor Priority	Potential: Basic Geol.	Potential: Applied Geol.	R&D Needed: Hardware	R&D Needed: Interpretation
Photography				
Regular color film	A	A	C	C
Ektachrome ir (infared color film)	B	B	C	B
Multiband process	C	C	C	A
0.4-0.6 μ	C_1	C_1	C	A
0.6-0.7 μ	C_3	C_3	C	A
0.7-0.9 μ	C_2	C_2	C	A
TV cameras	–	–	A	–
Radar				
Imaging K band	A	A	C	A
X band	AA	A	B	A
Nonimaging	B	B	B	A
Infrared				
Single channel 1-5 μ	A	B	B	A
8-13 μ	A	A	B	A
Multichannel imaging (0.4-15 μ)	AA	A	AA	AA
Nonimaging	A	B	B	A
Magnetics	B	A	C	C
Gravity	B	A	C	C
Ultraviolet imaging	B	B	B	B
Microwave imaging and nonimaging	C	B	C	A
Telluric currents	C	C	B	B
Absorption spectrometer				
Airborne geochemistry	C	A	B	A

AA = Most important
A = High
B = Moderate
C = Low
Subnumbers indicate time sequence

Figure 2.4.1 is a summary of Table 2.4.5 but also carries a time sequence for short-term (year 1 to year 5) and long-term (year 6 to year 10) commitments.

Additional research effort must be directed to what is loosely termed "ground truth." A brief listing of the active phenomena in geologic remote sensing is most instructive concerning how far we have yet to go in the understanding of these processes:

- Sun-angle effects
- Polarization
- Goniometric effects
- Roughness (as a function of wavelength)
- Spectral signatures in all wavelengths (uv through radar)
- Effect of particle size on signatures as a function of diurnal temperature cycles
- Dust and sand layers covering outcrops
- Vegetation—lichen and trees or grass
- Soil moisture content and gradient
- Effect of wind
- Relative humidity and aerosols in air path to the sensor
- Absorptivity/emissivity ratios
- Soil structures in top meter

In summary, therefore, we recommend:

1. A research-and-development program that heavily weights study of the physics of the coupling between geology and the sensing process

2. A sensor development directed to (a) longer wavelength (and hence deeper penetrations) radar images, and (b) multichannel, single-aperture scanning systems in the infrared, visible, and ultraviolet wavelengths

3. An effort directed to narrowing the list of significant ground-truth parameters, and to developing simpler measurement methods for their determination

4. An effort heavy in the data-processing and data-interpretational aspects of future systems, without which their development is wasted

4.5.2 Commonality between GEROS and Other Satellite Subsystems in This Report

Clearly, many of the satellite photo subsystems proposed in this report are similar, and only their orbital requirements differ. Significant differences occur in the emphasis upon sun-angle and seasonal sequencing.

The similarities with the several other sets of disciplinary requirements are summarized in Table 2.4.6.

TABLE 2.4.6

SUMMARY OF COMMONALITY FOR EARTH—RESOURCE DISCIPLINES FOR FIRST—GENERATION OPERATIONAL SYSTEM (3 to 5 YEARS FROM START) (MINIMUM REQUIREMENTS ONLY)

	Forestry Agriculture Geography (GLU)	Geology (GEROS)	Hydrol-ogy	Ocean-ography	Meteor-ology
Orbit Inclination	Polar	Polar	Polar	Polar	Polar
Photo B/W Color ir Color Resolution	 Color ir Color 35m	 Color ir Color 35m	 Color ir Color 35m	 Color 10Km	 Color 1Km
Thermal ir Resolution	--	--	Yes (Close to 35m as possible)	Yes (NIMBUS HRIR is OK) 5Km	Yes 1Km
Radar	--	Aircraft only	--	--	--
Microwave	--	--	--	--	--
Frequency of essential observation	3 mos	1 cloud-free pass needed (est. 3 passes to achieve this)	17 days (or 2@ 8.5 days)	17 days (or 2@ 8.5 days)	Daily
Sun-Synchronous	Yes	Yes	Yes	Yes	Not defined
Sun-Angle	High	Low 30°	High	High	Not defined

5.0 COMMENTS ON SUGGESTED EXPERIMENTS

5.1 Geophysical Methods Looking at the Deep Crust or Upper Mantle

5.1.1 Delineation of the Earth's Gravity Field from Orbital Heights

Information on the gravity field at orbital heights is being obtained currently from measurements of orbital perturbations of spacecraft. These extremely interesting and significant data reveal the figure of the earth, and hence its inherent strength (McKenzie, 1966, pp. 3996-4000). Possibly, gravity gradiometers in spacecraft may have shorter integration periods, and hence reflect variations in the true field more accurately. Anomalies of the size that would be observable may well reflect density distributions associated with upper-mantle convection currents, if such exist.

5.1.2 Delineation of the Earth's Magnetic Field from Orbital Heights

Broad magnetic anomalies, with wavelengths up to several hundred miles and amplitudes of the order of 1000 gammas, should be readily detectable at orbital heights (up to 200 nautical miles) with existing magnetometers. At this altitude, the magnetic field contains both stable and rapidly fluctuating components from sources external to the earth. If the crustal contribution can be identified (and I. Zietz of the USGS thinks it can), then a survey from an orbiting satellite gives a synoptic view of the earth's magnetic field. It appears that these data may be rather directly related with depths to the Curie point and, hence, to temperature distribution within the earth (Pakiser and Zietz, 1956, pp. 509-510). At present, it does not appear probable that such data will be useful directly in finding mineralized areas, because of the necessarily great breadth of the detectable anomalies.

5.1.3 Study of Telluric Currents at Orbital Heights

One of the consultants to the Panel, Arthur A. Brant, suggests that observation of magneto-telluric currents at orbital heights may be feasible. For periods of about 100 sec, the currents reflect conductivity in the earth's mantle to depths of about 100 km. Conductivity is temperature-dependent, hence these data would also reflect the distribution of subcrustal temperatures. Also, there are the modifications due to energy passage down and up through the ionosphere. This suggestion warrants theoretical analysis to determine whether R&D should be recommended.

5.1.4 Increased Precision in Relative Location of Points on the Earth's Surface

Perhaps the most actively debated issue in geology today is the question of the reality of continental drift. Absolute proof of drift can be established only by measurements which are precise enough to show relative movement, or lack of movement, between selected points on two continents. Indicated rates of oceanic spreading, and hence, presumably, of continental drift, are of the order of 2 to 8 cm per year. If the geodesists are able to attain their goal of relative location of two points on the earth with a precision of about 1 m, then a series of measurements over a few decades will solve the continental-drift question with a high degree of probability. We heartily endorse the efforts of the geodesists in this direction and urge that the appropriate R&D be pursued vigorously.

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APPENDIX A

DEFINITIONS

A. 1 Lineament

By definition, a geological lineament is any obvious linear feature with a length measured in miles. A lineament may consist of a single linear feature, such as the trace of a fault or a long, straight stretch of a river, or it may be a zone containing many shorter linears of similar or diverse character. Experience shows that the component linears, as well as the total lineament, very commonly reflect dominant regional structures such as faults, master joints, shear zones, and the strike of steeply dipping bedding or foliation surfaces. Such linears and lineaments, often the keys to regional and local structure, are strikingly revealed by side-looking radar and by air photographs taken at low sun-angle.

A. 2 Optical Depth, Depth to Opacity, Skin Depth, Penetration Depth

By definition, these are the depths at which the intensity of an electromagnetic wave is attenuated by a factor of e^{-1} after a distance of travel in a material. This depth is the penetration depth and varies with frequency (and wavelength) (E. U. Condon and H. Odishaw, Handbook of Physics, pp. 3-123, McGraw-Hill, New York, 1958.)

A. 3 Shadowing

The method used to emphasize the third (vertical) dimension, by the use of natural (solar) or artificial illuminations, usually operated at a low angle to the horizontal.

A. 4 Line-Edge Enhancement

Electronic (usually analog) processing of the photographic image tapes to emphasize rapid changes in radiance level (1st and 2nd derivatives of the signal are used). Additional linear expressions of similar rapid signal changes appear as enhancements in the subsequent photographs.

APPENDIX B

CALCULATION OF POSSIBLE BENEFITS FROM GEROS-I

In calculating the benefits that might accrue from a GEROS aerospace system, several methods were tried, but none was especially successful. One method (A) tried was to examine what are the present exploration costs to see how these might be modified by GEROS data. Another system (B) was based on the assumption that the rate of discovery and of production would be accelerated by the availability of the GEROS data.

Present exploration costs for oil in the United States are estimated to be about $2.05 billion, of which $345 million is directly attributable to geological and geophysical activities in exploration. A comparable figure for Canada is $35 million. Mining-industry exploration costs are harder to obtain, but they appear to run at about $200 million for U. S. and Canadian metal exploration, of which geology and geophysics cost about 25 percent, or $50 million. United States and Canadian national, state, and provincial regional geologic mapping and geophysical studies probably total about $65 million. Thus, not counting exploration costs in Mexico, Central and South America, a total geology, geophysics, and mapping expenditure of approximately $500 million annually is indicated. If only a 1-percent saving or improvement in effectiveness of present exploration and mapping costs were to result from availability of the GEROS data, and if this saving or improvement continued for 10 years, the resulting $50 million benefits would pay for the GEROS program.

This estimate of possible benefits is thought to be conservative. The USGS has estimated that the somewhat similar EROS system data would contribute a 7-percent efficiency increase to their geologic and geophysical operations.

Method B was based on the assumptions that the total reserves would not be increased by an accelerated discovery rate, but that 5 percent of the ultimate reserves would be brought into accelerated production during a 20-year period following application of Phase I, and that this accelerated production would, in effect, be "borrowed" from the second 20-year period. The net benefit would then be the difference between the present worth of accelerated production and that of the "borrowed" production. This type of analysis shows a benefit amounting to about $16 billion over a 40-year period for petroleum, gas, and minerals. Yearly benefits, therefore, would be about $400 million from this calculation. It may be noted that, if not 5 percent but only 0.5 percent of the ultimate reserves were brought into accelerated production, the net benefits would be at an average rate of $40 million annually.

The quantitative results of this Method B calculation are difficult to defend, however, because they assume an inevitable and rapid acceleration of discovery and production following availability of the GEROS data. Nevertheless, the qualitative aspects of the argument appear justified in that the planning of mineral exploration programs in the lesser-known areas of North and South America by private industry and by national, state, and provincial governments could very probably be accomplished more expeditiously and more intelligently.

Still another basis, also largely qualitative in nature, for estimating benefits from the GEROS data, overlaps somewhat with Method A, yet is distinct from it in emphasis. The various geological and related activities now carried on by geological surveys and other agencies of government in this and other countries are generally recognized as useful public services. Any benefit to these services, either as a saving in cost or an improvement in effectiveness, thus becomes a public benefit.

These various geological services not only include the preparation of regional maps useful for many purposes and especially helpful in recognizing areas suitable for detailed petroleum and mineral exploration, but they also include the making of more detailed geologic maps and geochemical, geophysical, and theoretical studies. These geological activities encompass a number of functions that serve the public interest in other ways, additional to that of help in finding metals and petroleum. Among such other uses are the practical ones of aid in selecting sites for bridges, dams, reservoirs, and other engineering projects; in delineating nearby sources of nonmetallic products such as sand, gravel, and building stone; and in learning the conditions favorable to the accumulation of valuable mineral deposits.

Less tangible, but no less real, are the cultural benefits to education, recreation, science, and a heightened appreciation of the world we live in--benefits that follow from a better understanding of the history of the earth and its inhabitants. One cannot estimate in any very convincing way the cost benefits from these kinds of applied and basic geological research. And if the GEROS data were to become available as recommended, it is unlikely that a reduction in the cost of these publicly supported geological activities would follow. However, both the practical and cultural values of these services would almost certainly be enhanced significantly by the new data.

APPENDIX B. 1

METHOD A–PRESENT COST OF EXPLORATION AND POSSIBLE IMPROVEMENT

Over the years 1964 and 1965, the U. S. oil industry expended an average of $2. 05 billion in exploration, or 18. 7 percent of production value. Of that figure, an average of $345 million per year (Appendix B. 4), or 3. 1 percent of production is directly attributable to geological and geophysical activities (G&G) in exploration search.

A comparable figure for Canada is $35 million (Appendix B. 4).

The mining-industry data are much more difficult to obtain. Gross annual mineral production in the United States and Canada was approximately $4. 8 billion in 1966, and exploration costs in these countries have commonly ranged from 4 percent to 5 percent of production. Of the total exploration costs, about 25 percent (or $48 million to $60 million) has been for geological and geophysical work (Appendixes B. 2 and B. 3).

National, state, and provincial geological surveys are involved in regional geological mapping on a variety of scales. This expenditure has been estimated at $59 million ($40 million federal and $19 million state) in the United States and $6 million in Canada.

TABLE 2. B. 1

APPROXIMATE PRODUCTION OF PRINCIPAL METALLIC MINERALS, 1964[a]

(In Millions of Dollars)

	United States and Canada	Mexico, Central and South America	North and South America
Bauxite	17.9	169.8	187.7
Copper	1123.	629.	1752.
Gold	185.	49.5	234.5
Iron ore	1260.	542.	1802.
Lead	134.	117.9	251.9
Mercury	4.4	5.1	9.5
Molybdenum	99.8	15.1	114.9
Silver	86.8	119.3	206.1
Tin	18.1	96.0	114.1
Titanium			
Ilmenite	29.6	0.2	29.8
Rutile	0.8	0.04	0.84
Tungsten	11.3	4.2	15.5
Uranium	186.	—	186.
Vanadium	13.0	0.1	13.1
Zinc	354.	152.2	506.2
Be, Co, Cr, Mn, Ni, Pt, Sb, Zr, rare earths	57.1[b]	33.6[b]	90.7[b]
	3580.7	1934.0	5514.7

a/ Quantities from pages 3 and 38, Minerals Yearbook, 1964, Vol. IV, Area Reports: International, U.S. Bureau of Mines. Unit prices from page 703, U.S. Book of Facts, Statistics, and Information for 1967, Washington Square Press, Inc., New York.

b/ Data for individual minerals not available. Total estimates from ratio of total value of these minerals to total value of all other minerals produced in the United States in 1964.

APPENDIX B. 2

COSTS OF MINERAL AND OIL EXPLORATION

Source: W. D. Carter, USGS, Washington, D. C. (Taken over phone by R. Lyon, 7/10/68.)

A. <u>Minerals</u>

1. <u>Total Value U. S. Production 1966*</u>

Mineral Fuels	$ 15. 1 billion
Non-Metals	5. 2 billion
Metals	2. 6 billion
	$ 22. 9 billion

2. <u>1966 Drilling U. S.</u> — 3. 6 million feet ($40 million@ $11 per foot)

3. <u>Canadian Mineral Production 1967**</u>

Mineral Fuels	$ 1. 3 billion
Non-Metals	0. 9 billion
Metals	2. 2 billion
	$ 4. 4 billion

4. Canadian Exploration Costs***

"of 20 mines which came into production in 1966, the average pre-production costs ranged from $400, 000 to $14. 5 million. Exploration costs ranged from $10, 000 to $2. 75 million (i. e., about 1/6 of pre-production expenses)."

20 x 7. 5 = $150 million

*D'Amico, Kathleen, J., Statistical Summary, pp. 105-145, vol. 1 and 2 Metals, Minerals, and Fuels, Minerals Yearbook, 1966, U. S. Bureau of Mines.

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B. Oil and Mineral Fuels

1. Offshore Drilling Costs*

a. "$4-6 billion (to be) spent to explore, develop, and bring into production Free World acreage leased in 1967-68. This (to) be spent over a 5-year period," and in addition,

b. "$1.5 billion/year (is) now being spent offshore on older leases."

c. "last 12 months Free World spent $2 billion on underwater leases and concessions alone; of that figure petroleum firms paid U.S. Government $1.7 billion."

d. "costs of exploration and development in offshore are 2 to 4 times shore-based costs."

e. "lease costs range from 1/5 to 1/3 of total investment required to make an offshore (well) productive."

f. "offshore drilling costs $11-16 per foot."

g. "Ecuador spent $1 million offshore operations (in 1967)."

h. "Cook Inlet, Alaska, $700 million already invested."

*Huge Spending Boom to Reach New Highs, World Oil, July 1968, pp. 81-84.

APPENDIX B. 3

EXPLORATION COSTS FOR METALLIC MINERALS

A. Canadian Metallic Mineral Exploration/Production Costs Ratios (Derry, 1967, p. 99)

Year	Exploration cost (millions $)	Production* (millions $)	%Exploration/ Production
1950	5.4	660.6	0.82
1951	9.2	795.3	1.13
1952	13.6	781.7	1.74
1953	17.8	746.7	2.38
1954	26.8	833.7	3.21
1955	26.9	992.3	2.40
1956	48.4	1079.9	4.49
1957	54.4	1086.8	5.00
1958	32.5	1091.2	2.98
1959	43.0	1278.2	3.36
1960	43.6	1341.9	3.24
1961	43.5	1313.5	3.31
1962	43.8	1353.9	3.23
1963	43.5	1324.1	3.29
1964	49.5**	1423.1	3.48
1965	66.3**	1622.5	4.09
1966	80.1**	1726.2	4.63

* Excludes iron ore, but includes asbestos.

** 1964-66 exploration data estimated, not yet published.

APPENDIX B. 4

OIL-EXPLORATION COSTS—UNITED STATES 1951-67

Reference: Joint Association,* Survey of Industry Costs
(W. D. Carter, USGS)

Years	Total Cost of Exploration (Million dollar - 10)			Cost Attributable to Geology & Geophysics (Million dollar - 10^6)	% of G&G to Tot. Expl. Cost
	Production***		% Exp/Prod		
1951	5694(1950)	1600	26. 7	824**	-**
1952		-		-	-
1953		1960		987**	-**
1954					
1955	8271	1990	24. 0	306	15. 4
1956		2100		360	17. 2
----		-		-	-
----		-		-	-
1959		2000		320	16. 0
1960	9627	2000	20. 8	277	13. 9
1961		1850		280	15. 2
1962		2300		299	13. 0
1963		1800		300	16. 7
1964	10869	2100	19. 4	336	16. 0
1965	11147	2000	18. 0	355	17. 8
Ave.		$1972	21. 8%	$302(w/o 1951/3)	15. 7%

*Joint Association—Mid-Continent Oil & Gas Association, Independent Petroleum Association, American Petroleum Institute, and National Petroleum Council.

**Includes dry hole costs, as well as geology and geophysics.

***Crude oil, natural gas liquids, natural gas, World Almanac, 1968, p. 593.

APPENDIX B. 5

OIL-EXPLORATION COSTS—CANADA 1947-67

	(millions of dollars)	
1947-57	$1, 018. 7	
1958	160. 2	
1959	148. 9	
1960	151. 6	
1961	145. 5	
1962	143. 0	
1963	148. 5	
1964	161. 3	
1965	165. 3	
1966	212. 9	$219/yr.
1967	224. 2 (est.)	

If geology and geophysics is 16 percent of total exploration, as in the United States, then $219 million x 0. 16 = $35 million per year.

Source: W. D. Carter, 8/2/68.

APPENDIX C

GEROS SYSTEM LOAD

C.1 Photographic Film Frames Required for North and South America

(Presumes capsule drop of film)

Coverage required	=	100 x 100 miles = 10^4 sq miles
Area of N and S America	=	1.51×10^7 sq miles
Frame required	=	$\frac{1.51 \times 10^7}{10^4} = 1.51 \times 10^3$ frames

Note: No allowance is made for orbit convergence at poles.

Add 10% side to overlap	=	0.15×10^3 frames
Add 60% front overlap for stereo coverage	=	0.91×10^3 frames
Total per single coverage	=	2.57×10^3 frames

C.2 System Load--Photographic Processing

Square feet of film = $2.57 \times 10^3 \times (0.75)^2$ prints
(9" x 9" finished prints)

= 1.45×10^3 sq feet per single complete coverage

(North and South America)

or = 4.35×10^3 sq feet for 3 complete coverages

C.3 Reconstituted Color from TV 3-Channel Systems

Problems: Registration of 3 channels

Steps:

1. Satellite telemetry to ground-station tapes

2. 3-channel tapes to 3 B/W master-negatives

3. 3 B/W master-negatives to regular color or infrared color film (70% of operational costs are assumed to lie in step 3)

APPENDIX D.1

COSTS OF "SOFT" R&D—SPECTRAL-SIGNATURE RESEARCH

USGS Budget - EROS

The FY 68 budget of USGS calls for the expenditure of about $6.6 million on remote sensing.

Source	Million dollars	Use
USDI	$4.5[1]	Total expenditures are distributed in the disciplines of geology, hydrology, cartography, and geography. Approximately $1.7 million may be designated as "Geology-Spectral Signature R&D" (see Figure 2.3.4)
NASA	2.1	
	$6.6	

[1] Distributed as follows:

		Thousand dollars
1)	Redirected funds for program management	$300
2)	Research on remote sensing directly related to earth-resources program	1000
3)	Ground truth in NASA test-site studies, serving dual purpose of supporing NASA funded research and contributing to USGS geologic programs	3000
4)	Direct appropriation	200
		$4500

Source: W. A. Fischer, 7/16 and 31/68, plus USGS EROS Program-Issue Paper dated September 1967.

APPENDIX D. 2

HARDWARE COSTS FOR SERI—GEOLOGY R&D (FIGURE 2. 3. 4)

1. Field units

		(thousands of dollars)	
a.	IR emissivity measurement units (spectrometers or radiometers)	7 at $50	$350
b.	Interferometers for 1-mm-wavelength studies	1 at $100	$100
c.	Luminescence detectors	2 at $50	$100
d.	Microwave truck units, several wavelengths	3 at $200	$600
e.	Meteorology stations	5 at $10	$50
f.	Data-recording systems for fixed field operation	4 at $50	$200
	Total for 3 years R&D		$1400

2. Airborne Units

		(millions of dollars)	
a.	Multichannel visual/ir scanners	2 at 1.5	$ 3.0
b.	Microwave scanners, radiometers	2 at 0.75	$ 1.5
c.	Luminescence detectors	2 at 0.5	$ 1.0
d.	Multifrequency multipolarization radars	2 at 2.5	$ 5.0
e.	Interferometer in 1-mm wavelength	1 at 0.5	$ 0.5
f.	Integration into (3) aircraft		$ 1.0
	Total for 3 years R&D and integration		$12.0

APPENDIX D. 3

DATA PROCESSING FROM AIRCRAFT OPERATIONS (FIGURE 2. 3. 4)

Aircraft Operational Use - Film Production

("Data gathering" = actual on-site photography runs)

20 hours/month data gathering/aircraft

60 hours/month data gathering for 3 aircraft

60 x 120 "pictures"/year x 10 sensors

= 72×10^{3} "pictures"/year with 3 aircraft

If rectification to make orthographic prints is needed, this is $60. 00 per print. (USGS-W. A. Fischer-7/18/68)

Operational Filmprint Costs

$$72 \times 10^{3} \times 10.00$ processing cost / picture

= $720, 000 per year

Operational processing costs	= $	720, 000
Other R&D etc., duplicate prints	=	400, 000
Orthographic prints for 25%	=	1, 080, 000
Probable Total		$2, 200, 000 / year

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