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1. INTRODUCTION

This report documents the results of an 18-month contract (NAS5-21927 Trade-Off Analysis of Modes of Data Handling for Earth Resources (ERS)) undertaken by TRW for NASA/GSFC. The purpose of this effort was to review data handling requirements for earth observation missions over a 10 year period commencing in the late 1970's, review likely technology advances over the same period and develop parametric techniques for synthesizing potential systems. A key study output was to be the identification of technology advances which will pace program evolution and hence whose acceleration would be beneficial.

Clearly, prognostication in any form can be the subject of criticism and the work here will be no exception. We have recommended missions and suggested that technological developments be accelerated, which may not come to pass for many reasons. Any recommendation may be bypassed along the way by a better approach which we have overlooked; funding limitations or lack of user demand may delay implementation or the supporting technology may be slower in arriving than we have anticipated. In any event we believe that most of the requirements we began with are real and must be eventually satisfied by one means or another, and our approach to their satisfaction will be at least stimulating to other if not truly prophetic.

Our report has been organized to reflect the tasks that were undertaken in the study. We first reviewed the sensors that were under development and extensions of or improvements in these sensors that might be expected over the interval being considered (Section 2). We then used these as drivers for developing mission models for nine missions spanning land, ocean, and atmosphere observations. Our models included instrument groupings, orbit selection, approximate launch date and identification of disciplines which would be served (Section 3). We next summarized our work in the form of data handling requirements which were used to drive the remainder of the study (Section 4). These requirements included the frequency of coverage and timeliness of dissemination as well as the geographic relationships between points of collection and points of dissemination. It also included user needs versus sensor capbilities as far as output product formats and geometric and radiometric quality were concerned.

Using this summary we reviewed data routing to establish ways of getting data from the point of collection through the center for processing to the eventual user or users (Section 5). We looked at the impact on data load, timeliness of dissemination, quality of data products, of employing on-board tape recorders, using TDRSS, relaying data from point-to-point via landlines and communication satellite, and using on-board versus central versus dispersed data processing. Next we looked at the technologies associated with on-board data processing (Section 6), communications (Section 7), and ground data processing (Section 8).

In our final phase (Section 9) we applied the previous results to the more detailed synthesis of three specific missions selected from the original set of nine. The basis for selection of the specific three was an attempt to span the 10 year interval being studied; cut across several disciplines; include both R&D and operational requirements and exercise the range of data rates, source-destination geometries, and data quality and timeliness requirements. Also included in this section are some recommendations for SRT and ART effort.

Although the effort presented here had the approval of NASA representatives at various review points along the way, all conclusions and recommendations are those of TRW and in no way imply that the government intends to evolve missions or data handling systems for earth resource missions as presented in this report.

2. SENSOR CHARACTERISTICS

Task 2 consists of the identification and description of a set of candidate sensors for use in the selected missions. The set of sensors chosen in this task come from instruments identified by the EOSMRG, ASIWG, and other government and TRW studies. It was selected with the cooperation and approval of NASA to provide a group of sensors capable of meeting the measurement requirements of the study missions. The characterization of these sensors has been carried through in sufficient detail to allow their allocation to the missions and to permit the determination, in the context of these missions, of the requirements they place on data handling functions and techniques.

2.1 Sensor Selection

A preliminary list of sensors was prepared by TRW during the preparation of the proposal for this study. Leading candidates were suggested to represent all the types of instruments believed to be useful for Earth Resources missions. These instruments consited of 16 sensors within the classes of:

- Imaging Sensors
- Spectrometers
- Visible and Infrared Radiometers
- Passive Microwave Radiometers
- Synthetic Aperture Radar.

In a meeting with NASA held on 17 August 1973, a final set of candidate sensors was established, based on a selection from the initial TRW list but expanded to include some additional pertinent sensors at the direction of NASA. This set of sensors is given in Table 2-1.

Table 2-1. Revised Candidate Sensor List

High Resolution Multispectral Point Scanner
Pointable Imager
Imaging Radar (Synthetic Aperture Radar)
Passive Multichannel Microwave Radiometer
Oceanic Scanning Spectrophotometer
Sea Surface Temperature Imaging Radiometer
Advanced Atmospheric Sounder and Imaging Radiometer
Constant Resolution Meteorological Scanner
Data Collection and Location System
Dual Mode Imaging Spectroradiometer
Film Recovery Systems

The list of instruments is not exhaustive of all sensors that might be used in earth resource observations, but it does provide representatives of all the major types, and sensors can be found within the group to satisfy almost all user needs. Representative instruments cover all the regions of the electromagnetic spectrum which are useful for earth observations; the visible and near (reflected sunlight) infrared, the thermal infrared to about 15 micrometers, and the microwave regions. Most of the ultraviolet and long wavelength infrared regions are excluded because of severe atmospheric absorption. All the classes of sensors previously listed are represented by at least one instrument. The distinctions among these classes are not always well defined, and some instruments could be considered as representative of more than one category; for example, the Dual Mode Imaging Spectroradiometer, as its name implies, is both a radiometer and an imager.

The specified instruments also cover a wide range of data handling requirements. The high resolution imagers produce very high data rates, but with low to moderate data analysis requirements. At the other extreme, atmospheric sounders have very low data rates (more than six orders of magnitude smaller than some imagers) but require very complex data inversion techniques.

Data perishability, and the corresponding repetitive coverage requirements, as a consequence of the diverse nature of the measurements and the uses to which they are to be put, vary tremendously. The meteorological and similar types of data begin to degrade in their usefulness after one to a few hours, and hence daily or even more frequent repetition of the coverage is desirable. On the other hand, some of the mapping functions need to be completed only in a matter of months after the data are gathered, and these data may need to be obtained only once during the lifetime of a satellite.

The sensors descriptions given in Section 2.3 detail the specific cases of the ranges in instrument characteristics suggested in the foregoing.

2.2 Cost Estimations

Cost estimation is always a very difficult task, even with very firm instrument specifications. Estimates become progressively less reliable as projections are made farther into the future, where judgments must be made as to the probable state of the supporting technology base as well as the projected specific current state of the art. Even in the short term, many of the conventional relationships used in estimating costs are no longer particularly useful. Most CER's (Cost Estimating Relations) which have been used or proposed in the past have been based on statistically derived weightings of the influence of weight, power requirements, and parts counts of one kind or another. The increasing introduction of more and more sophisticated integrated circuitry has gone far toward invalidating projections based on any of these criteria. Moreover, the increased payload capabilities of spacecraft, particularly those involving the use of Shuttle directly or as a launch vehicle, may be expected to change many design criteria. For example, the cost of an instrument designed for use on Spacelab may actually be reduced by the design implications made possible by an increased weight allowance, whereas traditionally an increase in weight could be fairly reliably correlated with an increase in cost.

One factor which may be expected to remain important in cost estimation is the complexity of the instrument, but of course complexity must be estimated in some way. The most reliable correlation, within sensor classes, is probably the number of data channels involved. Therefore, the cost estimates given in the sensor characteristics tables are based on current instrument costs, with often subjective estimates of the effects of complexity and performance increases leading to higher future costs, modified somewhat by allowances for the advancement of the supporting technology base.

The availability of cost estimates for some of the sensors intended for EOS, as well as some other current or near-term projects, has provided a fairly good baseline for estimating the costs of 1978 sensors. However, it has been somewhat disconcerting to find that even during the period of this study the best estimates of the costs of the Scanning Spectroradiometer and the High Resolution Pointable Imager for EOS have had to be revised upwards by about 70 percent. Extrapolation to 1983 and 1988 costs is evidently still more risky. Therefore the costs can be said to represent only indications of estimated relative costs.

Moreover, there is no way properly to evaluate the effects of specific difficulties in the advancement of the state of the art which is inherent in the development of any particular sensor. The projected costs may be considered as predicting the regular achievement of major technical breakthroughs on a prearranged schedule. Inevitably, some of the sensors will cost much more than indicated, but it is not possible to say which ones.

2.3 Sensor Descriptions

The approved set of sensors described in this section are those from which allocation to the various missions is made. The data products associated with these sensors, together with the specific user/destination requirements, comprise the baseline requirements for the data handling problem. There are already indications that some of the sensor descriptions depart from the most recently planned configurations for the 1978 period. For example, the AASIR (Advanced Atmospheric Sounder and Imaging Radiometer) which is currently in a Phase 0 study and is planned for use on a 3-axis stabilized geosynchronous satellite, may be expected to have a different set of spectral bands than we had originally believed, the most significant change being the elimination of the microwave channels. In the case of the Oceanic Scanning Spectrophotometer, current thinking is tending toward the use of somewhat less than the 20 channels specified, perhaps only five at carefully selected positions in the spectrum. This may be partly balanced in terms of data output by somewhat higher spatial resolution. Overall, the baseline requirements imposed on the data handling system are not materially changed by these variations. It is, in fact, probably safe to say that the effects of these and other changes which will inevitably occur, will not invalidate the usefulness of the conclusions of the data handling study.

It should be noted that a sensor called the Combined Scanning Spectroradiometer and Pointable Imager is included in Missions 3 and 6, but this combination is not included in the sensor descriptions. The reason for this is that, on the one hand, the design studies have not advanced to the point where the physical characteristics are well defined, while on the other, the data output characteristics are by specification the equivalent of the combination of the two separate instruments.

Therefore, for the purposes of this study, the baseline for the data handling analysis is fully defined by the descriptions of the two individual sensors.

The high resolution imaging sensors, including the High Resolution Multispectral Point Scanners, the Pointable Imagers (and the combination of these two) and the Synthetic Aperture Radar produce data rates two to three orders of magnitude greater than those of any other sensors. They will consequently dominate the data handling problem, in spite of the more complicated data reduction required by some of the other sensors. The data rates projected for 1988 exceed current and near term capabilities for handling them, and these capabilities may still be limiting in 1988. However, the factors governing the data rates are interrelated, and tradeoffs different from those implicit in the 1983 and 1988 estimates are possible. A convenient way to look at the data rates of visible and infrared imagers, from the standpoint of user oriented requirements, is given by the equation:

$$DR = \frac{V_g W}{R_g^2} n_c n_b k \qquad (2-1)$$

where

V_g = ground speed

W = swath width

R_g = ground resolution

n_c = number of channels

n_b = number of bits per resolution element

k = number of samples per resolution element

Thus, $V_g W$ give the area covered in unit time, while R_g^2 gives the area of a single picture element, so the quotient is the number of picture elements per unit time, and this, multiplied by the number of channels and the number of bits per picture element, gives the data rate. The relationships among data rate, IFOV (in ground resolution), and encoding level are shown in Figure 2-1.

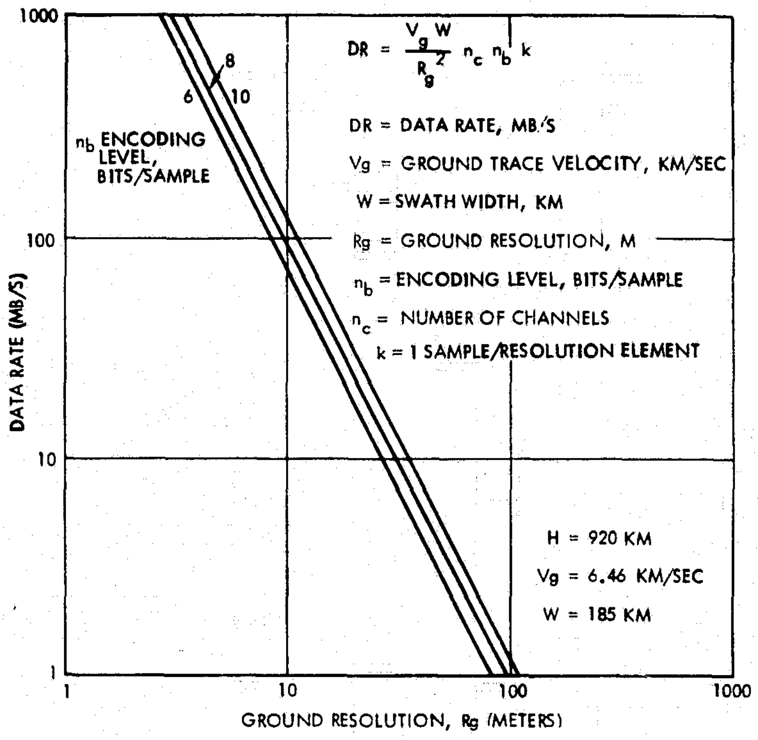

Figure 2-1. Data Rate versus Ground Resolution (Imaging Sensors-One Spectral Band)

In the application of Equation 2-1, it must be remembered that the feasible variation of any of the parameters is dependent on a number of technology factors, which may be interrelated among the parameters. The equation may be used with confidence to choose among the tradeoffs for reducing the data rate by reducing one or more of the parameters, but a tradeoff reducing one while increasing another may violate limitations not explicit in the expression.

Synthetic aperture radar data rates prior to processing the raw data to produce image type data are greater than would be deduced from Equation 2-1 by a factor of 2 or more (it is 6.5 in the 1978 example given). The appropriate equation is:

$$DR = \frac{2 V_g W}{R_g L} n_b \qquad (2-2)$$

where L is the antenna length. The relationships of some of the pertinent parameters in this equation are shown in Figure 2-2, along with estimates

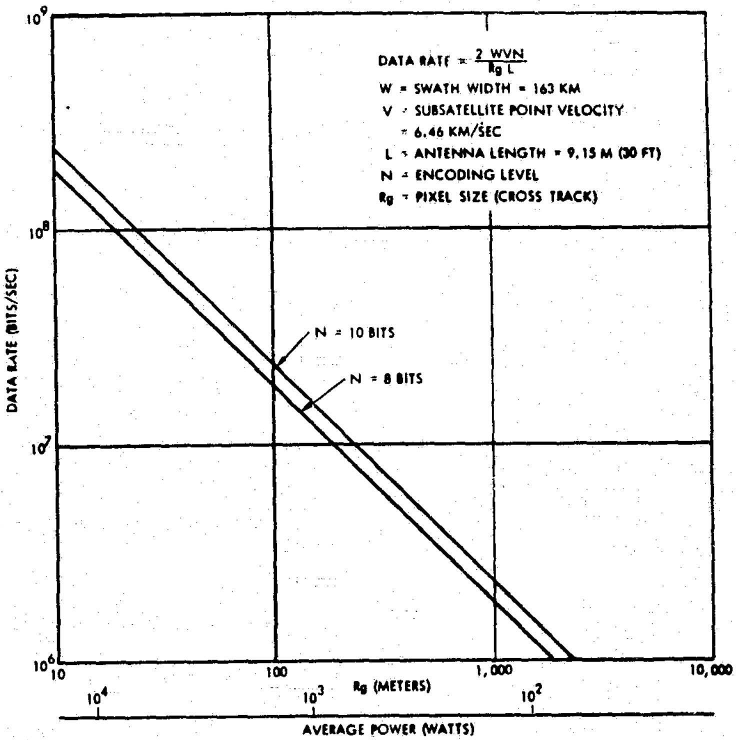

Figure 2-2. Data Rate versus Resolution and Power in Synthetic Aperture Radar

of corresponding power requirements. As with Equation 2-1, tradeoffs must be applied only within limits permitted by the state of the art.

Film camera systems are also high resolution imagers, and the amount of data they can record is typically greater than that of any other sensor. However, they provide their own storage medium (the film) which is easily processed for film recovery systems. The amount of data manipulation required in the applications envisaged for the various missions is very small, since inherently very high geometric fidelity can be obtained and the radiometric accuracy, while only modest, is not subject to any significant correction.

2.3.1 Individual Sensors

This section gives brief verbal descriptions of each of the candidate sensors, while Section 2.3.2 consists of a set of tables summarizing the pertinent design and performance characteristics of each.

2.3.1.1 High Resolution Multispectral Point Scanner

The high resolution multispectral point scanner provides mapping data in several spectral bands from the visible into the thermal infrared from which information can be derived for use in a number of earth resources disciplines such as geology, hydrology, agronomy, forestry and coastal zone studies. Specific uses generally require different combinations of the available spectral bands.

The sensor is in concept a mechanical cross-track scan device with a single detector for each spectral band, the image being built up from a succession of scan lines displaced successively along-track as the result of the vehicle motion. For high resolution scanners, however, it is necessary to provide an array of several detectors oriented perpendicular to the scan direction for each spectral band, so that each mechanical sweep covers that many individual scan lines, in order to keep the scan frequency down to an achievable value. Spectral separation of the bands can be achieved by having the detector arrays for the different bands sufficiently physically separated along the scan direction to permit the use of bandpass filters to define the spectral bandwidths, by the use of dichroic mirrors, or by using a dispersive element (prism or grating), or some combination of these techniques.

The 1978 technology in these sensors is well defined by the results of current design studies. The cycle involving the choice of the most promising of these, the subsequent development period, and the production of one or more flight articles, can be expected to be completed just about in time to fly in 1978. The principal area of divergence in design philosophy among potential producers of these scanners is in the scan mechanism itself. Concepts currently being considered are:

1) Object plane scanning using an oscillating mirror
2) Image surface scanning along an arc centered on the optical axis of the system, resulting in a conical scan on the ground
3) Image surface scanning through the optical axis of the system, resulting in a linear scan on the ground.

Of these approaches, only object plane scanning can be said to be a well established and proven technique. On this account, it is picked as the most likely choice for 1978.

In estimating the sensor characteristics to be expected in 1983 and 1988, it is assumed that better spatial and amplitude resolution, wider swath widths, and more channels will be desired. This has been the traditional pattern in sensor development, and it will probably continue in the next 15 years, even though there is evidence that at least some users can derive more useful information from imagery of modest resolution than they had thought possible prior to experience with data such as that obtained by ERTS. The projections are made on this basis, in accordance with the progress that can be expected in this period. For 1983, it is estimated that object plane scanning will still be the best approach, but by 1988 it is believed that linear image surface scanning will be developed to operational status.

Coverage should be primarily for the U.S. and adjacent areas. However, it is anticipated that friendly nations will want coverage, e.g., Mexico, Brazil, India, Australia. This information must be stored for dumping in the U.S., relay via TDRS, or direct readout into a special-purpose ground station.

2.3.1.2 Pointable Imager

The pointable imager sensor, as described herein, uses linear arrays of solid state detectors oriented across track. The swath width is defined by the angle subtended by the length of these arrays; along-track coverage arises from the orbital motion of the spacecraft. There is an array for each spectral channel used. Cross track sampling is implemented by sequential electronic interrogation of the sensors of the array. Thus, a sensor of this type is sometimes referred to as an electronically scanned device. It is also often called a "push-broom" scanner.

The preamplifiers and switching circuits associated with the arrays inescapably take up considerable image plane space adjacent to the detectors themselves; thus, it is currently necessary to separate the spectral channels by dichroic mirrors, and this limits the number of channels to about four in the current state of the art. The 1978 technology is defined by the performance specified by NASA/GSFC for design studies now under way; the development of a flyable model meeting these specifications can be expected for about that time.

Future performance, in 1983 and 1988, for this sensor class, can be estimated by assuming a desire for greater resolution and more spectral bands, but probably no greater swath width, since the expected use is for high resolution observation of relatively limited areas. The ultimate resolution which can be obtained by a push-broom sensor is limited by the radiation gathering capability of each detector, and this, in turn, is a function of the available integration time and the speed (f-number) of the optical system. These considerations lead to an expectation of no better than about 5 meters ground resolution by 1988. The number of spectral channels, and the wavelength regions covered, are currently limited by both optical design problems and the range of sensitivity of the detectors. Arrays of thousands of elements can be obtained currently with silicon photodiodes or phototransistors, which are sensitive only in the visible and very near infrared. Some research now under way indicates that longer wavelengths, even into the thermal infrared, may be detectable with long linear arrays in the next 10 to 15 years. The most serious problem currently appears to be that of cooling long multi-detector arrays of this kind. Charge coupled device technology, now in a very early stage of development, may relieve some of the optical problems of observing a larger number of channels, since they can be fabricated in two-dimensional matrices. The projections for 1983 and 1988 are based on the developments which can be expected in the areas mentioned with a fair degree of confidence.

The data from this sensor will be received by direct readout for the U.S. and adjacent areas, including Alaska and Hawaii. Stored readout data or relay via TDRS, is a likely requirement for surveys of cooperative countries (e.g., Brazil, India, Australia) and of remote areas such as Antarctica and the Arctic. It is possible that the cooperative countries might setup their own ground stations for direct-readout reception, using less-sophisticated equipment.

2.3.1.3 Synthetic Aperture Radar

The potential use of synthetic aperture radar (SAR) in the observation of the resources of the earth offers promising opportunities as a valuable adjunct to high resolution imaging in the visual and infrared spectral ranges. As a SAR provides its own illumination, and has the capability of penetration of cloud cover, observations can be obtained on the dark side of the orbit and in regions with extensive cloud cover. With increasing payload weight and power capabilities, the use of SAR becomes feasible. Applications of SAR are in the study of geologic features, crop discrimination, mapping of vegetation, regional land classification, and determination of the areal extent of sea ice.

Synthetic aperture radars have been operational in military aircraft for several years. Although configuration studies have been completed for earth observation satellite applications, development for this application has not been initiated. A 30-meter ground resolution SAR is believed to be feasible for 1978, with improvement to 10 meters in 1988. The main impact of the improvement of the resolution is on the data rate, both of the raw data (given by Equation 2-2) and of the data processed to give image information (for which Equation 2-1 applies). The data rates given in the SAR characteristics table in Section 2.3.2 are for the raw data. To achieve the resolutions listed, the ground processing will be required to focus the synthetic aperture to compensate for the spherical wavefront of the reflected energy along the length of the synthetic aperture, as well as Doppler filtering to compress the data in the azimuth direction. Although optical processing has been the only practical technique until very recently, development of digital processing techniques may well make digital processing more practical and economical by the late 1970s.

Storage devices or a TDRS will be needed for such areas as the Antarctic and cooperative countries. In some cases for the cooperative countries, it might be that these countries will set up their own ground stations, probably less-sophisticated than U.S. ground stations. For purposes of this study, however, the storage mode is recommended.

2.3.1.4 Passive Multifrequency Microwave Radiometer

The PMMR postulated for the 1978 period is similar to the GSFC instrument proposed for EOS, measuring apparent or brightness temperature at 4.99, 10.69, 18.0, 21.5, and 37 GHz, for both H and V polarizations. By application of suitable algorithms the ensemble of data from the various frequencies and polarizations will be processed, on the ground, to derive maps of surface temperature, surface roughness, water vapor, and liquid water content of the atmosphere, water-ice boundaries, snow cover and state, and soil moisture. The spatial resolution achieved in the maps will be related to the resolutions at each frequency, which are inherently determined by the antenna beamwidth.

Since the antenna beamwidth is determined by the ratio of the wavelength to the aperture size, the resolution element size varies inversely with frequency, on the assumption that the same aperture size is used at all frequencies. The resolutions will range from 11 km at 37 GHz to 77 km at 4.99 GHz, assuming that the antenna aperture size is two meters, and the orbit altitude is 914 km. Those resolutions would be suitable for meteorological purposes but even the 37 GHz value is much worse than the resolution desired for other purposes, such as coastal oceanography, hydrology, etc., where most users desire a value of 300 meters or better.

In postulating the 1983 PMMR an order of magnitude improvement of resolution is achieved by increasing the aperture by a factor of five, and by reducing the orbit altitude by approximately a factor of two. In addition, a second conical scan angle is added at the 10.69 and 18.0 GHz frequencies to improve the surface temperature accuracy.

The resolution of the 1988 PMMR begins to approach the value desired by the users. The aperture size would become impossibly large if the smallest desired resolution of 30 meters were attempted, but by reducing the altitude still further by another factor of two and again doubling the aperture to 20 meters, a resolution of 300 meters would be possible at 37 GHz. A deployable antenna of that size would be feasible for Shuttle. If a larger antenna could be stowed in parts for launch, and assembled and deployed in orbit, the resolution could be improved further. In any case, realization of the resolutions desired depends on the development of lightweight deployable, scanning antennas with diameters of 20 meters or greater.

Although antenna development is the major problem associated with improved resolution, the reduced dwell time per resolution element will require improvement in the RF bandwidth and noise figure of the radiometer receiver, in order to avoid degradation of temperature sensitivity.

Primary use of the PMMR will be for the U.S. and adjacent waters (including Alaska and Hawaii). However, data from the open seas, Antarctica, and for coastal waters off friendly nations will be useful and must be considered. Accordingly, a means is needed to bring this information to the ground, either via a storage device for dumping over the U.S., or by a TDRS (direct readout), or by direct readout to a smaller ground station in a friendly country or aboard ship.

The costs shown in the table in Section 2.3.2 are based on extrapolation of current single frequency radiometers from the Nimbus series, and the development programs necessary to improve the spatial resolution without degrading the temperature sensitivity. The major development areas are identified above.

2.3.1.5 Oceanic Scanning Spectrophotometer

Specifications for two spectrometers for the measurement of ocean color are presented as anticipated for the late 1970s and 1980s. The mechanical scanning spectrometer, for the late 1970s, is similar to that proposed by NASA/GSFC for EOS A, using a maximum of 20 silicon detectors to obtain a spectral resolution of 150 Angstroms over the 0.4 to 0.7 micron spectral range. There are indications that the use of a smaller number of channels, maybe as few as five covering the spectral regions most sensitive to changes caused by substances of interest in the water (e.g., chlorophyll and particulates), may be sufficient. Cross track scanning will be accomplished by using a rotating mirror. Offset pointing will be provided by a tiltable mirror ahead of the rotating mirror.

The electronic scanning spectrometer, for the late 1970s, similar to the Multichannel Ocean Color Sensor (MOCS), developed by TRW Systems for NASA/LRC under the AAFE program, uses an image dissector tube with a grating spectrometer to obtain the same spectral resolution and spectral range.

These instruments are representative of the current state of the art. Data requirements are moderate. The main improvement in performance postulated for the late 1980s is a 50 percent increase in the spatial resolution and a 50 percent reduction in spectral bandwidth. These, together with a 50 percent extension of the spectral range, results in an order of magnitude increase in the data rate. However, even with that increase, the data rate is still moderate.

Cost estimates are based on extrapolations of the cost of similar current instruments; i.e., MOCS for the electronic scanning spectrometer and the Bendix M^2S.

2.3.1.6 Sea Surface Temperature Imaging Radiometer

A knowledge of water surface temperature and its distribution is of significance to a number of scientific communities. Such information is particularly useful in locating fishing grounds, in charting oceans and lake surface currents, and in monitoring heat budget and thermal exchange between water and the atmosphere. To establish meaningful relationships as to surface currents and successful fishing probabilities, accurate surface temperature measurements are needed. For currents, surface temperature gradients are most important whereas for fishing operations absolute temperatures are also required.

Anding, Kauth, and Turner* have theoretically demonstrated the feasibility of accurate sea-surface temperature measurements from space utilizing multispectral techniques to correct for the effects of the atmosphere and clouds. The surface composition mapping radiometer (SCMR) which flew on Nimbus E in 1972 approaches the problem in a different way, with another set of three spectral bands, providing data on the usefulness of bands at 0.8 - 1.1, 8.3 - 9.3, and 10.2 - 11.2 micrometers.

In the late 1970s, a sensor specifically designed to measure sea surface temperature is proposed to fly on EOS. This sensor, yet to be developed, will make measurements in five spectral bands. Its characteristics are presented in a table in Section 2.3.2. As data from this sensor is compared with theory, it is anticipated that an additional band may be added or substituted in the mid-1980s in order to refine the correction for atmospheric effects. The characteristics of such a sensor are presented in the table.

By the late 1980s, the spectral bands and measurement techniques are expected to be established and the primary interest will be to obtain better spatial resolution. Since sea surface temperature measurements in the IR cannot be made through cloud cover, the continuity and coverage

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* Anding, D., R. Kauth, and Turner, R., 1970 "Atmospheric Effects on IR Multispectral Sensing of Sea Surface Temperature from Space," Willow Run Laboratory, U. of Michigan, Contract NAS 12-2117.

of these measurements are reduced on a global basis. With higher resolution the sensor will be better able to look through holes in the clouds or between clouds and thus improve the continuity and total coverage. It is also anticipated that global coverage will be required in the late 1980s. The characteristics of a higher resolution sensor for the late 1980s are presented in the table. The improved resolution and NEΔT are expected without an excessive increase in size and weight. These will result primarily from improved detector/shield/filter cooling techniques developed in the next 15 years.

2.3.1.7 Advanced Atmospheric Sounder and Imaging Radiometer

The Advanced Atmospheric Sounder and Imaging Radiometer (AASIR) is an instrument intended to provide time- and space-correlated data on atmospheric profiles, cloud distributions, and surface temperatures (including those of cloud tops). The data can be used for monitoring both global and mesoscale weather and to provide inputs for numerical and local area weather forecasting. In many of the missions defined in this study, the data will be used primarily as ancillary information for applying corrections to the output products of other sensors.

A number of current or in-development sensors contribute to the basis for the configurations suggested in the characteristics table in Section 2.3.2. Among these are the Vertical Temperature Profiling Radiometer (VTPR), now operational; the TIROS-N Operational Vertical Sounder (TOVS), and the Advanced Very High Resolution Radiometer (AVHRR) being built for flight on TIROS-N; and the Visible Imaging Spin-Scan Radiometer (VISSR) on SMS. One instrument called AASIR is currently being studied as a modification of VISSR to include temperature and humidity profiling capabilities. This instrument is designed for use on a geosynchronous satellite, while we have postulated a sensor intended for a sun-synchronous orbit.

The 1978 sensor is proposed to have two microwave channels as well as those in the infrared. After about 1985 the emphasis on microwave measurements will increase in order to obtain data below cloud cover. Therefore, several channels near the 0.5 cm oxygen absorption band are suggested, to be used for temperature profiling.

The data rates for this type of instrument are very low, but if the information is to be used operationally for weather forecasting it must be delivered within one to three hours, probably to NOAA at Suitland, Maryland.

2.3.1.8 Constant Resolution Meteorological Scanner

The specific name for this sensor is the Operational Linear Scanner (OLS). This sensor is part of the Data Acquisition and Processing Program (DAPP). The release of this information is in keeping with Executive Order 1165, regarding new security and classification procedures. While certain aspects of the system remain classified, it can be stated that meteorological data gathered by the system, and all specifications necessary to make full use of the meteorological data, are now unclassified.

The OLS is one of several meteorological sensors that will be on a spacecraft to be launched late in 1974 or early 1975. It represents a marked improvement over the present sensor now employed on a similar spacecraft. The spacecraft orbits at a nominal 450 nmi altitude, in a sun-synchronous orbit. The various features of this system combine to form possibly the most responsive operational system of its kind. The meteorological aspects of DAPP were designed under a total systems concept in which not only sensors but communications and ground processing facilities were developed with the primary objective of providing maximum responsiveness to the operational decision-maker, whether supported by a localized tactical field weather unit, or from a centralized weather facility (e.g., the USAF Global Weather Central).

The significant characteristics of the sensor and its associated data processing are intended to facilitate rapid interpretation of the output product by the following features:

- Data appear as if the orbit were perfectly circular
- Foreshortening at the edges is removed
- The nominal scale is switch selectable between 1:7.5 million and 1:1.5 million
- For visual data, along-track variations in solar illumination are compensated for (onboard).

Responsiveness is provided by the sensor characteristics and the associated data stream. Visual and IR information contain both a high resolution capability for limited areas and medium resolution for global coverage. The spectral bandwidth of the visual sensor was selected to optimize distinction among clouds, ground, and water. Circuitry onboard the spacecraft converts the sensed IR energy directly into equivalent blackbody temperature, making temperature the directly displayed parameter.

The sensitivity of the visual channel covers several orders of magnitude, providing useful information from full daylight over highly reflective scenes to an illumination level roughly equivalent to one-half full moonlight.

Cost for the next few years is projected at $2 million per total sensor system. This per unit cost reflects costs associated with earlier SRT, preflight models, and most importantly the fact that a number of similar sensors have been built under the program.

2.3.1.9 Data Collection and Location System

A Data Collection and Location System (DCLS) is assumed to be a universal component among all missions. This system will function in the collection of data from both fixed and moving platforms. Examples of the kinds of data that will be routed through the system are listed in Table 2-2. The DLCS data handling problems are generally unrelated to the volume of data because even the maximum projected volume (for SMS) is on the order of 2,000,000 bits per 6 hour; this volume is based on an anticipated maximum of 10,000 remote platforms. Rather, the DCLS problems are related to such factors as the following:

- Override of signals from other DCLS platforms when critical levels of intensity are reached by seismic, tsunami, water level, or pollution sensors, for example.
- Sensitivity of DCLS components to be compatible with accuracy requirements for locating constant-level balloons, buoys, or other moving platforms.
- Interrogation of selected remote platforms, a problem which is complicated by power requirements for operating receivers on the platforms.

In view of the absence of sensor equipment on the satellite, no characteristics are listed in Section 2.3.2.

Table 2-2. Representative Parameters for DLCS

Parameters	Types of Sensors
Water (Qualitative)	● Acidity/alkalinity (PH)
	● Pollutant identification (organic, chem, biolog.)
	● Pollution level
	● Physical debris count
	● Sedimentation (siltation)
	● Dissolved oxygen
Water (Quantitative)	● Water depth (level)
	● Flow rate (incl. min and peak)
	● Sluice gate status
	● Flow duration
	● Flood frequency
	● Temperature
	● Wave height
Soil Data	● Moisture level
	● Soil temperature
	● Acidity and alkalinity (PH)
Meterological	● Precipitation
	● Lightning strike count
	● Snow depth
	● Humidity/dew point
	● Air temperature
	● Air pollution
	● Wind direction
	● Seismic
	● Atmospheric pressure
	● Atmospheric electricity
Buoys	● Salinity
	● Wave elevation
	● Current direction
	● Current velocity
	● Ambient noise
	● Depth
	● Tidal variation
	● Position (location data)
	● Oxygen
	● Radiological components
	● Sediment level
	● Temperature
Human/Animal Platforms	● Blood pressure
	● Body temperature
	● Skin resistance (galv and basal)
	● EKG
	● EEG
	● EMG
	● Imp. pneumograph
	● Shock (3 planes)
	● Accel. (3 planes)

2.3.1.10 Dual Mode Imaging Spectroradiometer

This sensor is expected to provide high resolution radiometric data in a number of spectral bands over a restricted area in one mode, and similar moderate resolution data over the entire visible earth in the other. It is intended for installation on a geosynchronous satellite. The characteristics of the sensor are based on the GSFC SEOS Study. The oceanographic/meteorological resolution requirements will be driven by requirements related to understanding tornados, hurricanes, and other severe-weather-phenomena. The timelines requirements for both ERS and O/M will become increasingly stringent as the resolutions (spatial, temporal, and spectral) increase, since the phenomena being observed are highly dynamic. It is not anticipated that any significant increase in number of spectral channels will occur, based on ERTS, Skylab, and Nimbus experience. The 1978 data shown in the table in Section 2.3.2 are essentially those developed by NASA/GSFC in their preliminary study of a sensor for SEOS. The 1988 spatial and spectral resolutions appear beyond current technology. The technology for this later sensor is unknown at this time, e.g., we do not know what kind of detectors will replace HgCdTe.

2.3.1.11 Film Recovery Systems

Film recovery systems have been included in four of the missions for which Shuttle launch/revisit is anticipated. Of the several types of film cameras used in aerial reconnaissance, framing, panoramic, or continuous strip, only the first is of importance for use in observations of the earth. The two types of film camera systems considered for use in future observation systems are;

a) a single black and white camera, using 5-inch film (115 x 115 mm format), and

b) a three-camera system for multispectral recording using three boresighted lenses with three images being recorded on a single roll of 5-inch film.

Film cameras of this size have been used for a number of years by the military in satellite applications in conjunction with a recoverable film capsule.

The advantage of this type of sensor is the enormous information capacity of film in comparison to other types of sensors, with the film providing the functions of both sensing and storing of imagery. With a realizable resolution (including the optical system) of 100 lines/mm, the 115 mm format has the capacity of storing information from 1.3×10^8 picture elements on a single frame.

Although shielding of the film is required to prevent fogging due to low energy cosmic radiation from the sun and radiation from the Van Allen belts of the earth, the weight of the shielding required is within the payload capability of future earth observation spacecraft. Although shielding from high energy galactic cosmic readiation is not practical, the density of this radiation is not sufficient to seriously affect performance during a one-year mission lifetime.

One particular advantage in the use of film is the extremely high geometric fidelity of the film record. Wide-angle mapping lenses have been developed for aerial photography, with a half-field angle of 46.7 degrees, using a 9 x 9 inch film format, with both radial and tangential distortion being less than 8 microns at the extreme half-field angle. (Kollsman Geocon IV Mapping Camera Lens). In the orbital application, the required field angle is much smaller and the problem of optical distortion less severe. In the three-camera system to obtain multispectral data; however, the requirement for precisely the same scale factor in all three bands, requiring identical focal lengths in the three optical systems, can represent an element of cost in system development.

The use of image motion compensation will be required in both camera systems to prevent loss of spatial resolution, and particularly in the three-camera system where narrowband optical filters used to obtain spectral separation will result in an increase in exposure time.

The assumption is made for purposes of this study that film camera systems will involve film recovery and refurbishment, with no on-board processing or telemetry of data. Moreover, recovery assumes the use of the Shuttle system, rather than an ejectable capsule. These systems will not significantly impact the data handling system; accordingly, they will not be considered further in the study.

2.3.2 Sensor Characteristics Tables

This section consists of Tables 2-3 through 2-12 which gives the sensor characteristics postulated for 1978, 1983, and 1988 deployment. Characteristics are given for all sensors except the DCLS and the Film Recovery Systems, for the reasons previously stated. Two tables are provided for the Oceanic Scanning Spectrometer, detailing the electronic and mechanical scan versions separately.

Table 2-3. High Resolution Multispectral Point Scanners

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Earth Resources	Earth Resources	Earth Resources
2. APPLICATION	Terrestrial thematic mapping (geology, hydrology, agronomy, forestry, etc.)	Same	Same
3. TEMPORAL COVERAGE	Approximately 20 day repeat cycle	Approximately 20 day repeat cycle	Approximately 20 day repeat cycle
4. USER LOCATION	Central U.S. distribution point such as GSFC; other central processing/distribution points may be available		
5. ORBIT (KM)	Sun synchronous 386 to 1100 km circular 9 AM or 3 PM local time ascending node; assume 920 km for definiteness		
6. TYPE OF SCAN	Bidirectional object plane scanning using oscillating mirror; duty cycle 0.8	Same	Image space scanning giving a linear scan reference to ground
7. IFOV (DEG)	30 µrad = 1.72×10^{-3}	25 µrad = 1.43×10^{-3}	20 µrad = 1.15×10^{-3}
8. OFFSET POINTING (DEG)	±21	±30	±30
9. SWATH WIDTH (KM)	185	280	370
10. SPATIAL RESOLUTION (KM)	0.03 (30 m)	0.025	0.02
11. SPECTRUM/BW (µ)	7 channels: 1 0.5 to 0.6 2 0.6 to 0.7 3 0.7 to 0.8 4 0.8 to 1.1 5 1.55 to 1.75 6 2.08 to 2.35 7 10.4 to 12.6	9 channels: 6 in visible from 0.43 to 0.8	11 to 12 channels: Finer division in visible and maybe one more IR in CA 3 to 5µ region
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	Bands 1 to 6: $\Delta p = 0.003$ Band 7: $\Delta T = 0.4^{\circ}K$	Visible and near IR: $\Delta p = 0.002$ Thermal IR: $\Delta T = 0.3^{\circ}K$	Visible and near IR: 0.002 Thermal IR: 0.3°K
13. ENCODING LEVEL (BITS)	6	7	8
14. DATA RATE (MBITS/SEC)			
a) VIDEO	a) 72	a) 243	a) 700
b) HOUSEKEEPING AND CALIBRATION	b) 0.1	b) 0.2	b) 0.3
c) TOTAL	c) 72.1	c) 243.2	c) 700.3

12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	Bands 1 to 6: Δp = 0.005 Band 7: ΔT = 0.4°K	Visible and near IR: Δp = 0.002 Thermal IR: ΔT = 0.3°K	[illegible] Thermal IR: 0.3°K
13. ENCODING LEVEL (BITS)	6	7	8
14. DATA RATE (MBITS/SEC) a) VIDEO b) HOUSEKEEPING AND CALIBRATION c) TOTAL	 a) 72 b) 0.1 c) 72.1	 a) 243 b) 0.2 c) 243.2	 a) 700 b) 0.3 c) 700.3
15. ORBIT DUTY CYCLE (%)	3 (U.S. only) to 15 (global)	Same	Same
16. DATA LOAD (MBITS/YR)	1×10^8 to 5×10^8	3×10^8 to 1.5×10^9	1×10^9 to 5×10^9
17. COMMANDS	50 to 100	50 to 100	50 to 100
18. CALIBRATION REQUIREMENTS	Inflight calibration once/scan; internal calibration pattern, look at space, look at sunlit surface	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	IR detectors cooled to CA 100°K (passive radiator) thermally isolated from spacecraft, internal active temperature control (heaters) to 20°C ± 0.2 deg	Same	Same
20. SIZE	2.1m cross-track; 0.63m along track, 1.11m nadir axis	2.2m x 1m x 1.5m	2.3m x 1.2m x 1.6m
21. WEIGHT (KG)	230	400	500
22. POWER (WATTS)	55 exclusive of data handling	100	200
23. COST ($'S)	24M development; 7 M/flight article	15M/7M	20M/8M
24. ERROR SOURCES			
(a) GEOMETRIC	a) • Scan variations • Spacecraft attitude and ephemeris errors • Local surface altitude variations	Same	Same
(b) RADIOMETRIC)	b) • Calibration • Atmospheric effects	Same	Same
25. UNIQUE DATA PROCESSING REQUIREMENTS	Account for 14 scan lines/mirror scan; alternate scan directions; varying scan lengths; effects of earth rotation	Same	Account for multiple scan lines per scanner sweep (CA 20) effects of earth rotation

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Table 2-4. Pointable Imagers

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Earth Resources	Same	Same
2. APPLICATION	Geology, Agronomy, Forestry, Coastal	Same	Same
3. TEMPORAL COVERAGE	Every orbit for forest fires, floods, earthquakes within scope of off-track pointing capability	Same	Same
4. USER LOCATION	Central U.S. distribution point, such as GSFC; other central processing/distribution points may become available		
5. ORBIT (KM)	Sun synchronous, circular, 9 AM or 3 PM local time ascending node; 386 to 1100 km altitude; assume 715 km for definiteness		
6. TYPE OF SCAN	Push broom solid state array	Same	Same
7. IFOV (DEG)	$14\ \mu\text{rad} = 8 \times 10^{-4}$	$10.5\ \mu\text{rad} = 6 \times 10^{-4}$	$7\ \mu\text{rad} = 4 \times 10^{-4}$
8. OFFSET POINTING (DEG)	±30 deg in roll	Same	Same
9. SWATH WIDTH (KM)	48	48	48
10. SPATIAL RESOLUTION (KM)	0.01 km (10m)	0.0075 km (7.5 m)	0.005 km (5 m)
11. SPECTRUM/BW (μ)	Four channels: 1 0.5 to 0.6 2 0.6 to 0.7 3 0.7 to 0.8 4 0.8 to 1.1	Five channels: Add 1.55 – 1.75	Six channels: Either add one thermal IR or one in visible blue
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	$\Delta p = 0.003$	$\Delta p = 0.002$	$\Delta p = 0.002$ $\Delta T = 0.4^{\circ}K$ in thermal IR
13. ENCODING LEVEL (BITS)	7	8	9
14. DATA RATE (MBITS/SEC)			
a) VIDEO	a) 85.5	a) 125	a) 500
b) HOUSEKEEPING AND CALIBRATION	b) 0.01	b) 0.01	b) 0.02
c) TOTAL	c) 85.5	c) 125	c) 500

12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	$\Delta p = 0.003$	$\Delta p = 0.002$	$\Delta p = 0.002$ $\Delta T = 0.4°K$ in thermal IR
13. ENCODING LEVEL (BITS)	7	8	9
14. DATA RATE (MBITS/SEC)			
a) VIDEO	a) 85.5	a) 125	a) 500
b) HOUSEKEEPING AND CALIBRATION	b) 0.01	b) 0.01	b) 0.02
c) TOTAL	c) 85.5	c) 125	c) 500
15. ORBIT DUTY CYCLE (%)	3 (U.S. only) to 15 global	Same	Same
16. DATA LOAD (MBITS/YR)	8.2×10^7 to 4.2×10^8	1.2×10^8 to 6×10^8	4.7×10^8 to 2.4×10^9
17. COMMANDS	~50	~50	~50
18. CALIBRATION REQUIREMENTS	Two or three level calibration in orbit once/week	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	80W heat exchange from baseplate to spacecraft at 90 ± 5°C; rest of sensor internally controlled	Same	Same but also thermal IR detector must be cooled to ca. 100°K
20. SIZE (cm)	100 x 30 x 40	120 x 35 x 50	120 x 50 x 60
21. WEIGHT (KG)	39	65	115
22. POWER (WATTS)	110	160	350
23. COST ($'S)	17M development; 5M recurring	10M; 5M	8M; 6M
24. ERROR SOURCES			
(a) GEOMETRIC	a) • Spacecraft attitude and ephemeris errors • Local surface altitude variations	a) Same	a) Same
(b) RADIOMETRIC	b) • Calibration • Dark current • Nonuniformity in response of detectors (photodiodes or phototransistors) • Atmospheric effects	b) Same	b) Same
25. UNIQUE DATA PROCESSING REQUIREMENTS	• Radiometric correction for dark current and nonuniformity of detector responsivities; this might be done onboard	Same	Same
	• Correction for effects of earth rotation	Same	Same

FOLDOUT FRAME 2

Table 2-5. Synthetic Aperture Radar

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Earth Resources	Earth Resources	Earth Resources
2. APPLICATION	Geological survey, land use monitoring, water, ice monitoring	Same	Same
3. TEMPORAL COVERAGE	1/14 day	Same	Same
4. USER LOCATION	U.S., foreign countries, Antarctica		
5. ORBIT (KM)	914	Same	Same
6. TYPE OF SCAN	Along track - spacecraft motion Across track - range discrimination	Same	Same
7. IFOV (DEG)	0.25 x 1.5	Same	Same
8. OFFSET POINTING (DEG)	60 to 75	Same	Same
9. SWATH WIDTH (KM)	40	Same	Same
10. SPATIAL RESOLUTION (KM)	30 m	20 m	10 m
11. SPECTRUM/BW ( )	X-band/10 MHz, dual polarization L-band/10 MHz single polarization	X-band/15 MHz, dual polarization L-band/15 MHz, dual polarization	X-band/30 MHz, dual polarization L-band 30 MHz, dual polarization
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	σ_o = -20 dB	Same	Same
13. ENCODING LEVEL (BITS)	4 plus sign	Same	Same
14. DATA RATE (MBITS/SEC)			
a) VIDEO	240	360	720
b) HOUSEKEEPING AND CALIBRATION	5 bit encoding	5 bit encoding	5 bit encoding
c) TOTAL			

12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	σ_o = -20 dB	Same	Same
13. ENCODING LEVEL (BITS)	4 plus sign	Same	Same
14. DATA RATE (MBITS/SEC) a) VIDEO b) HOUSEKEEPING AND CALIBRATION c) TOTAL	 240 5 bit encoding	 360 5 bit encoding	 720 5 bit encoding
15. ORBIT DUTY CYCLE (%)	10	Same	Same
16. DATA LOAD (MBITS/YR)	3 x 10^{12}	4.5 x 10^{12}	9 x 10^{12}
17. COMMANDS			
18. CALIBRATION REQUIREMENTS	Receiver sensitivity Transmitter power -- Ground control area checks	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	Usual spacecraft temperature specs on electronics	Same	Same
20. SIZE	Antenna - 2 1/2 x 1 x 27 ft Electronics - 4 cubic ft	Antenna Same Electronics 4.5 cubic ft	Antenna Same Electronics 5 cubic ft
21. WEIGHT (KG)	400	500	600
22. POWER (WATTS)	1.5 kw operating 100W standby	2.1 kw operating, 100W standby	3.7 kw operating 100W standby
23. COST ($'S)	16M	12M	15M
24. ERROR SOURCES			
(a) GEOMETRIC	Spacecraft attitude Earth rotation effects Slant range distortion	Spacecraft attitude	Spacecraft attitude
(b) RADIOMETRIC	N/A	N/A	N/A
25. UNIQUE DATA PROCESSING REQUIREMENTS	Azimuth data processing required to achieve azimuth resolution. Compensation for earth rotation and geometric effects.	Same	Same

2

Table 2-6. Passive Multichannel Microwave Radiometer

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Oceanography/Meteorology	Coastal Oceanography, Met.	Coastal Oceanography, Met.
2. APPLICATION	Sea Surface Temp. & Roughness, Sea Ice Water Vapor & Liquid Water in Tropsphere	Same	Same
3. TEMPORAL COVERAGE	Every Orbit	Same	Same
4. USER LOCATION	U.S. & Foreign User, possibly ships at Sea	Same	Same
5. ORBIT (KM)	914	480	235
6. TYPE OF SCAN	Conical ≃ 40° from Nadir, All Freq.	Conical ≃40° from Nadir, All Freq. ≃60° from Nadir, 2 freq. (10.7GHz 18 GHz)	Conical ≃40° from Nadir, All Freq. ≃60° from Nadir, All Freq.
7. IFOV (DEG)	2m Antenna	10 m Antenna	20 m Antenna
8. OFFSET POINTING (DEG)			
9. SWATH WIDTH (KM)	1350		
10. SPATIAL RESOLUTION (KM)			
11. SPECTRUM/BW ( )	4.99 GHz / 0.3 GHz ↓ 2.40 77 10.7 1.12 36 19.0 0.67 22 21.5 0.56 18 37.0 0.32 11 All Frequency Dual Polarization	4.99 GHz / 0.6 GHz ↓ 0.5 8.5 10.7 0.22 4.0 18.0 0.14 2.4 21.5 0.11 2.0 37.0 0.07 1.2 All Frequency Dual Polarization	4.99 GHz / 0.6 GHz ↓ 0.25 2.1 10.7 0.11 0.98 18.0 0.07 0.59 21.5 0.055 0.49 37.0 0.035 0.28 All Frequency Dual Polarization
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δρ, ΔT)	ΔI-N/A, Δρ-N/A, ΔT = 0.5°K	ΔI-N/A, Δρ-N/A, ΔT <0.5°K	ΔI-N/A, Δρ-N/A, ΔT <0.5°K
13. ENCODING LEVEL (BITS)	9	9	9
14. DATA RATE (MBITS/SEC) a) VIDEO b) HOUSEKEEPING AND CALIBRATION c) TOTAL	0.0070 at 37 GHz 0.0023 at 21.5 GHz 0.0002 at 18.0 GHz - 10.7 GHz Negligible - 4.99 GHz Total 0.0095	0.70 at 37 GHz 0.23 at 21.5 GHz 0.17 at 18.0 GHz 0.09 at 10.7 GHz - 4.99 GHz (Negligible) Total 1.19	10.8 at 37 GHz 3.5 at 21.5 GHz 2.7 at 18.0 GHz 0.9 at 10.7 GHz 0.2 at 4.99 GHz Total 18.1

12. AMPLITUDE RESOLUTION ( ) (ΔI, $\Delta \rho$, ΔT)	ΔI-N/A, $\Delta \rho$-N/A, $\Delta T = 0.5^\circ K$	ΔI-N/A, $\Delta \rho$-N/A, $\Delta T < 0.5^\circ K$	ΔI-N/A, $\Delta \rho$-N/A, $\Delta T < 0.5^\circ K$
13. ENCODING LEVEL (BITS)	9	9	9
14. DATA RATE (MBITS/SEC) a) VIDEO b) HOUSEKEEPING AND CALIBRATION	0.0070 at 37 GHz 0.0023 at 21.5 GHz 0.0002 at 18.0 GHz - 10.7 GHz Negligible - 4.99 GHz	0.70 at 37 GHz 0.23 at 21.5 GHz 0.17 at 18.0 GHz 0.09 at 10.7 GHz - 4.99 GHz (Negligible)	10.8 at 37 GHz 3.5 at 21.5 GHz 2.7 at 18.0 GHz 0.9 at 10.7 GHz 0.2 at 4.99 GHz
c) TOTAL	Total 0.0095	Total 1.19	Total 18.1
15. ORBIT DUTY CYCLE (%)	65	65	65
16. DATA LOAD (MBITS/YR)	1.44×10^4	4.3×10^5	7×10^6
17. COMMANDS	On-Off, Data On-Off	Same	Same
18. CALIBRATION REQUIREMENTS	5 Reference Loads - High Temp ≈ 400°K 5 Reference Loads - Cold Temp = 3°K	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	High Temp. Loads Controlled ±0.1°K Cold Loads must View Deep Space Only	Same	Same
20. SIZE	Antenna 6 x 8 ft. - Offset Parabola Electronics 1 x 1.5 x 1.5 ft.	Antenna 30 x 60 ft. - Phased Array Electronics 1.5 x 1.5 x 1.5	Antenna 60 x 120 ft. - Phased Array Electronics 2 x 1.5 x 1.5
21. WEIGHT (KG)	Antenna 9.1 Electronics 22.7	Antenna 227 Electronics 27.2	Antenna 910 Electronics 45.4
22. POWER (WATTS)	150	1.6 KW	3.1 KW
23. COST ($'S)	5M	15M	20M
24. ERROR SOURCES			
(a) GEOMETRIC	Spacecraft Attitude Variations Scanning Variations	Same	Same
(b) RADIOMETRIC	Calibration Atmospheric Side Lobes	Same	Same
25. UNIQUE DATA PROCESSING REQUIREMENTS	Inversion of Data to Separate effects of Temperature, Roughness, Emissivity, Liquid Water and Water Vapor in Atmosphere, and Sea Ice Coverage. Conversion of Conical Scan to Rectangular Grid, or Desired Projection.	Same	Same

2

Table 2-7. Oceanic Scanning Spectrophotometer (Electronic Scan)

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Oceanography	Oceanography	Oceanography
2. APPLICATION	Chloropyll content: pollution Upwelling: ocean currents	Same	Same
3. TEMPORAL COVERAGE	Variable: 1 to 20 days	Same	Same
4. USER LOCATION	Local coastal and intercontinental water, ocean survey, ships at sea	Same	Same
5. ORBIT (KM)	914	Same	Same
6. TYPE OF SCAN	Cross track: electronic scan	Same	Same
7. IFOV (DEG)	0.1	Same	0.05
8. OFFSET POINTING (DEG)	45	Same	Same
9. SWATH WIDTH (KM)	900	Same	Same
10. SPATIAL RESOLUTION (KM)	2	Same	1
11. SPECTRUM/BW ( )	0.4 to 0.7μ/150 Angstrom 20 bands		0.4 to 0.85μ/75 Angstrom 60 bands
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)			
13. ENCODING LEVEL (BITS)	8		10
14. DATA RATE (MBITS/SEC)			
a) VIDEO	0.8		9.6
b) HOUSEKEEPING AND CALIBRATION	0.3		3.6
c) TOTAL	1.1		13.2

12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)			
13. ENCODING LEVEL (BITS)	8		10
14. DATA RATE (MBITS/SEC)			
a) VIDEO	0.8		9.6
b) HOUSEKEEPING AND CALIBRATION	0.3		3.6
c) TOTAL	1.1		13.2
15. ORBIT DUTY CYCLE (%)	65		65
16. DATA LOAD (MBITS/YR)	2.6×10^9		3.2×10^{10}
17. COMMANDS			
18. CALIBRATION REQUIREMENTS	Calibration source in sensor and/or solar input		Same
19. TEMPERATURE CONTROL REQUIREMENTS	±20°C readout photocathode temperature		Same
20. SIZE	20 x 20 x 8		Same
21. WEIGHT (KG)	15		25
22. POWER (WATTS)	15		25
23. COST ($'S)	2M	1M	5M
24. ERROR SOURCES			
(a) GEOMETRIC	Spacecraft attitude Earth rotation Scan distortion		Same
(b) RADIOMETRIC	Calibration Sun angle Atmospheric scattering		Same
25. UNIQUE DATA PROCESSING REQUIREMENTS	Radiometric corrections for shading, sun angle, scan angle Geometric corrections for spacecraft attitude, scan angle, offset angle		Same

FOLDOUT FRAME 2

Table 2-8. Oceanic Scanning Spectrophotometer (Mechanical Scan)

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Oceanography	Oceanography	Oceanography
2. APPLICATION	Chloropyll content - pollution upwelling - ocean currents	Same	Same
3. TEMPORAL COVERAGE			
4. USER LOCATION			
5. ORBIT (KM)	914		
6. TYPE OF SCAN	Cross track line scan (mechanical)		
7. IFOV (KM)	0.1		0.05
8. OFFSET POINTING (DEG)	45		45
9. SWATH WIDTH (KM)	900		900
10. SPATIAL RESOLUTION (KM)	2		1
11. SPECTRUM/BW ( )	0.4 to 0.7μ/150 Angstrom 20 bands		0.4 to 0.85μ/75 Angstrom 60 bands
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)			
13. ENCODING LEVEL (BITS)	8		10
14. DATA RATE (MBITS/SEC)			
a) VIDEO	0.8		9.6
b) HOUSEKEEPING AND CALIBRATION	0.3 (buffered)		3.6 (buffered)
c) TOTAL			

$(\Delta I, \Delta p, \Delta T)$			
13. ENCODING LEVEL (BITS)	8		10
14. DATA RATE (MBITS/SEC)			
a) VIDEO	0.8		9.6
b) HOUSEKEEPING AND CALIBRATION	0.3 (buffered)		3.6 (buffered)
c) TOTAL			
15. ORBIT DUTY CYCLE (%)	65		65
16. DATA LOAD (MBITS/YR)	2.6×10^9		3.2×10^{10}
17. COMMANDS			
18. CALIBRATION REQUIREMENTS			
19. TEMPERATURE CONTROL REQUIREMENTS	Detector cooling		Same
20. SIZE (Inches)	26 x 17 x 9		30 x 24 x 12
21. WEIGHT (KG)	27		75
22. POWER (WATTS)	25		75
23. COST ($'S)	3M	1M	8M
24. ERROR SOURCES			
(a) GEOMETRIC	Spacecraft attitude Earth rotation Scan distortion		Same
(b) RADIOMETRIC	Calibration Sun angle Atmospheric scattering Polarization		
25. UNIQUE DATA PROCESSING REQUIREMENTS	Radiometric corrections for shading, polarization, sun angle, scan angle Geometric corrections for scan angle, spacecraft attitude, offset angle		Same

Note: One or more IR channels may be incorporated.

FOLDOUT FRAME 2

Table 2-9. Sea Surface Temperature Imaging Radiometer

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Oceanography and Meteorology	Same	Same
2. APPLICATION	Sea surface temperature, cloud cover survey, radiation budget over ocean	Same	Same
3. TEMPORAL COVERAGE	Daily	Same	Same
4. USER LOCATION	Coastal; ships at sea	Same	Same
5. ORBIT (KM)	1000	Same	Same
6. TYPE OF SCAN	Cross track line scan ± 51 deg from Nadir	Same	Same
7. IFOV (DEG)	0.11 x 0.11 (2×10^{-3} rad)	Same	0.028 x 0.028
8. OFFSET POINTING (DEG)	-----	----	----
9. SWATH WIDTH (KM)	2870	Same	Same
10. SPATIAL RESOLUTION (KM)	2 x 2	Same	0.5 x 0.5
11. SPECTRUM/BW (μm)	0.2 to 4.0 cloud tag (day); Rad. budget 3.6 to 4.1 cloud tag (night) 6.5 to 7.0 H_2O absorption 8.9 to 9.4 H_2O continuum 10.5 to 11.5 sea surface temperature	Add one spectial band (4.7 to 5.2μ)	Same
12. AMPLITUDE RESOLUTION ($^{\circ}K$) (ΔI, Δp, ΔT)	0.15	0.1	<0.1
13. ENCODING LEVEL (BITS)	10	Same	Same
14. DATA RATE (MBITS/SEC)			
a) VIDEO	0.3 (buffered)	0.36 (buffered)	5.5 (buffered)
b) HOUSEKEEPING AND CALIBRATION	Negligible	Same	Same
c) TOTAL	0.3 (buffered)	0.36 (buffered)	5.5 (buffered)

12. AMPLITUDE RESOLUTION ($^{\circ}K$) (ΔI, Δp, ΔT)	0.15	0.1	<0.1
13. ENCODING LEVEL (BITS)	10	Same	Same
14. DATA RATE (MBITS/SEC)			
a) VIDEO	0.3 (buffered)	0.36 (buffered)	5.5 (buffered)
b) HOUSEKEEPING AND CALIBRATION	Negligible	Same	Same
c) TOTAL	0.3 (buffered)	0.36 (buffered)	5.5 (buffered)
15. ORBIT DUTY CYCLE (%)	60 (oceans and U.S.)	Same	90 (global)
16. DATA LOAD (MBITS/YR)	6.25×10^6	7.5×10^6	1.9×10^8
17. COMMANDS	Cooler on/off Calibration source on/off Sensor on/off	Same	Same
18. CALIBRATION REQUIREMENTS	Calibration source located in housing of sensor; look at space for 0°K reference	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	Radiative or VM cooling of IR detectors (HgCdTe) to ~90°K	Same	Same
20. SIZE (Inches)	8 x 8 x 30	8 x 8 x 32	11 x 11 x 32
21. WEIGHT (KG)	25	30	45
22. POWER (WATTS)	33	35	45
23. COST ($'S)	2.5M	1.0M	4M
24. ERROR SOURCES			
(a) GEOMETRIC	Spacecraft attitude Variable resolution	Same	Same
(b) RADIOMETRIC	Calibration Cloud interference Atmospheric turbidity		
25. UNIQUE DATA PROCESSING REQUIREMENTS	Correlation of data from five channels to determine temperature Calibration data	Same	Same

Note: 20 to 23 assume radiative cooler

Table 2-10. Advanced Atmospheric Sounder and Imaging Radiometer

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Meteorology	Meteorology	Meteorology
2. APPLICATION	Temperature profiles and radiation maps for numerical models and for local area forecasts.		
3. TEMPORAL COVERAGE	Observe continuously along orbit. Day and night coverage	Observe continuously along orbit. Day and night coverage	Observe continuously along orbit. Day and night coverage
4. USER LOCATION	Worldwide, stored data to NOAA, Suitland, Maryland. Direct readouts to local users worldwide	Same	Same
5. ORBIT (KM)	1440, sun synchronous; 0900 equator crossing	Same	Same
6. TYPE OF SCAN	±40 deg, cross-track, samples 400 km apart	Same	Same
7. IFOV (DEG)	0.05 to 0.5	Same	Same
8. OFFSET POINTING (DEG)	None	None	None
9. SWATH WIDTH (KM)	N/A	N/A	N/A
10. SPATIAL RESOLUTION (KM)	50 to 400 Km between soundings	Same	Same
11. SPECTRUM/BW (μ)	21 bands: 8 channels in 15 band 4 channels in 4.3 1 channel at 9.6 1 channel at 11.1 2 channels in 3.8 3 channels in 18 to 30 2 channels in microwave	Same	Same except microwave 10 channels near 60 Ghz
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	$\pm 1^{\circ}K$		
13. ENCODING LEVEL (BITS)	8 to 10	8 to 10	10
14. DATA RATE (MBITS/SEC)			
a) VIDEO			
b) HOUSEKEEPING AND CALIBRATION			
c) TOTAL	20 bits/sec	20 bits/sec	100 bits/sec

	4 channels in microwave		
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	± 1°K		
13. ENCODING LEVEL (BITS)	8 to 10	8 to 10	10
14. DATA RATE (MBITS/SEC)			
a) VIDEO			
b) HOUSEKEEPING AND CALIBRATION			
c) TOTAL	20 bits/sec	20 bits/sec	100 bits/sec
15. ORBIT DUTY CYCLE (%)	100	100	100
16. DATA LOAD (MBITS/YR)	620	620	620
17. COMMANDS			
18. CALIBRATION REQUIREMENTS	1/scan	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	Detectors maintained at 80 to 100°K	Same	N/A
20. SIZE (ft^3)	1.3	Same	Same
21. WEIGHT (KG)	44	Same	Same
22. POWER (WATTS)	63	63	63
23. COST ($'S)	25M	5M	20M
24. ERROR SOURCES			
(a) GEOMETRIC	No significant errors		
(b) RADIOMETRIC	Calibration, detector NEP, atmospheric absorption coefficients		
25. UNIQUE DATA PROCESSING REQUIREMENTS	Inversion of radiometric data; detection to account for effects of clouds		

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Table 2-11. Constant Resolution Meteorological Scanner

CHARACTERISTICS	1978	1983	1988
1. DISCIPLINE	Meteorology	Meteorology and Earth Resources	Earth Observations
2. APPLICATION	Global Cloud Cover Imagery(Day/Nite, Constant Resolution, Real Time & Near Real Time Input to Computer Analysis)	Expansion of 1978 to Include Other Disciplines. Real Time Input to Computer Models and Data Base Via TDRS	
3. TEMPORAL COVERAGE	2/Day; Global	No Change for Meteorology; Temporal Coverage Dependent on Orbital Characteristics	Same as 1983
4. USER LOCATION	Local Area + Regional Direct Readout Stations; Central Station in U.S. For Receipt of Stored Data for Direct Input to Computer	Same; Expansion of Direct User Locations	Same as 1983
5. ORBIT (KM)	8351 KM (Sun-Synchronous)	Same	Same
6. TYPE OF SCAN	Continuous Cross-Track ±27.5°	Same	Same
7. IFOV (DEG)	Nadir = 0.038°	Same	Same
8. OFFSET POINTING (DEG)	Nadir Pointing	Same	Same
9. SWATH WIDTH (KM)	3060	Same	Same
10. SPATIAL RESOLUTION (KM)	0.6 KM High Resolution Mode 3 KM Low Resolution Mode	No Change for Meteorology Earth Resources May require 10x Better	Same for Meteorology; Some Earth Observations May Require 10-20x Better
11. SPECTRUM/BW ( )	Visible 0.4-1.1μm IR 8 - 13 μm 2 Channels	Same	Same
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	Visible Δρ=0.02 IR ΔT=0.4°	Same	Same
13. ENCODING LEVEL (BITS)	6	Same	Same
14. DATA RATE (MBITS/SEC)			
a) VIDEO	-		
b) HOUSEKEEPING AND CALIBRATION	-		
c) TOTAL	~1 MB/Sec in High Resolution Mode	No Change for Meteorology; Higher Data Rate for Earth Resources W/Higher Resol.	Same as 1983
15. ORBIT DUTY CYCLE (%)	100% (IR & Visible) High Resolution	Same for Meteorology; Very Much Less	Same as 1983

12. AMPLITUDE RESOLUTION ( ) (ΔI, Δρ, ΔT)	Visible $\Delta\rho = 0.02$ IR $\Delta T = 0.4^{\circ}$	Same	Same
13. ENCODING LEVEL (BITS)	6	Same	Same
14. DATA RATE (MBITS/SEC)			
a) VIDEO	-		
b) HOUSEKEEPING AND CALIBRATION	-		
c) TOTAL	~1 MB/Sec in High Resolution Mode	No Change for Meteorology; Higher Data Rate for Earth Resources W/Higher Resol.	Same as 1983
15. ORBIT DUTY CYCLE (%)	100% (IR & Visible) High Resolution	Same for Meteorology; Very Much Less (TBD) for Earth Resources	Same as 1983
16. DATA LOAD (MBITS/YR)	$\sim 3.15 \times 10^{7}$	Same for Meteorology. TBD for Earth Resources Applications	Same as 1983
17. COMMANDS	>200 Possible, Including Change of Illumination Models Used Onboard	TBD	TBD
18. CALIBRATION REQUIREMENTS	None OnBoard	Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	±1C°	Same	Same
20. SIZE	No Information Available	TBD	TBD
21. WEIGHT (KG)	91 KG; Includes All Electronics, 3 Tape Recorders, etc. (Total System)	TBD	TBD
22. POWER (WATTS)	~70 Watts (Total System Operating)	TBD	TBD
23. COST ($'S)	~$2 Million	TBD	TBD
24. ERROR SOURCES			
(a) GEOMETRIC	<1 Resolution Element	<< 1 Resolution Element for Meteorology	Same as 1983
(b) RADIOMETRIC	<5% RSS	Same as 1978	Same as 1978
25. UNIQUE DATA PROCESSING REQUIREMENTS	Achievement of High Resolution Data Base for Operational Decision Making; High Res. Data Provided In Terms of Scene Radiance; Data Processed Onboard for Direct Real-Time Readout to Local Ground Stations; Stored Data Readout to CDA Stations for MW Relay to Central Data Processing Facility Where it is Automatically Incorporated Directly into Computer Programs, Data Highly Perishable, Used for Operational Very Short-Term (<6-Hours) Forecasts, On Board Processing Incorporates Stored Ephemeris Data, Models of Scene Radiance As (f) of Angle From Nadir, Allowing Gain To Be Automatically Adjusted in 1/8dB steps	Solution to Most of Ambiguities Arising From Differentiating Real Cloud Data From Ice, Snow Cover, Low-Clouds, Fog, Freshly Fallen Snow, etc.	Same as 1983

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Table 2-12. Dual-Mode Imaging Spectrometer

CHARACTERISTICS	1978	1983	1988	
1. DISCIPLINE	Meteorology and Earth Resources	Meteorology and Earth Resources	Meteorology	Earth Resources
2. APPLICATION	Hurricanes, severe storms, floods, oil spills	Same	Tornado watch	Oil spills, floods, earthquakes, fires
3. TEMPORAL COVERAGE	1 observation/10 minutes (Mode 1)	Same	1 observation/ minute	1 observation/ 30 minutes
4. USER LOCATION	U. S., South America, adjacent oceans (Goddard CDAS)	Same	Kansas City	Sioux Falls
5. ORBIT (KM)	Geostationary, 100° W longitude	Same	Same	Same
6. TYPE OF SCAN	In/from the image plane			
7. IFOV (DEG)	Variable by channel			
8. OFFSET POINTING (DEG)	Probably by spacecraft slewing	± 8	± 8	± 8
9. SWATH WIDTH (KM)	200 x 1000 (high-resolution mode)	Meteorology: 1000 km^2 Earth Resources: 100 km^2	1000 km^2/100 km^2	1000 km^2/50 km^2
10. SPATIAL RESOLUTION (KM)	Mode 1 = 200 m; Mode 2 = 0.5 to 1.5 km	Meteorology: 100 m Earth Resources: 50 m	300m/100m	100m/5m
11. SPECTRUM/BW (μ)	0.4 to 12.5 in 7 bands: 0.5 to 0.7; 0.1 Km IFOV; 2000 element 0.8 to 1.2; 0.1 Km IFOV; 2000 element 10.5 to 12.5; 1.5 Km IFOV, 3 detectors 6.3 to 6.7; 4.5 Km IFOV, 1 detector 3.4 to 4.1; 1.5 Km IFOV, 3 detectors 0.8 to 1.2; 0.5 Km IFOV, 9 detectors 0.4 to 0.8; 1.5 Km IFOV, 12 detectors	Same	10 to 12μ 4 to 5μ 6 to 7μ 0.5 to 0.7μ	0.5 to 0.6μ 0.6 to 0.7μ 0.7 to 0.8μ 0.9 to 1.0μ 10.5 to 12.5μ
12. AMPLITUDE RESOLUTION ( ) (Δi, Δp, ΔT)	0.4 to 1.24μ: $\Delta p = 0.01$; 3.4 to 12.5μ: $\Delta T = 0.4^\circ K$	Same	Same	Same
13. ENCODING LEVEL (BITS)	8			
14. DATA RATE (MBITS/SEC) a) VIDEO	0.5 (high-resolution mode)		5.93 highest rate	2.22 average rate if picture exposure and data rate are continuous over the 30 minute period
b) HOUSEKEEPING AND	0.1			

	0.4 to 0.8; 1.5 Km IFOV, 12 detectors			
12. AMPLITUDE RESOLUTION ( ) (ΔI, Δp, ΔT)	0.4 to 1.24μ: Δp=0.01; 3.4 to 12.5μ: ΔT=0.4°K	Same	Same	Same
13. ENCODING LEVEL (BITS)	8			
14. DATA RATE (MBITS/SEC) a) VIDEO	0.5 (high-resolution mode)		5.93 highest rate	2.22 average rate if picture exposure and data rate are continuous over the 30 minute period
b) HOUSEKEEPING AND CALIBRATION	0.1			
c) TOTAL				
15. ORBIT DUTY CYCLE (%)	25 (day only and only 50% of the daylight = 25%/year)		100 except for visible	
16. DATA LOAD (MBITS/YR)	4.2×10^6		1.87×10^8	7×10^7
17. COMMANDS	Minimal: no constraints	Same	Same	
18. CALIBRATION REQUIREMENTS	1/10 minutes		Same	Same
19. TEMPERATURE CONTROL REQUIREMENTS	Detectors must be cooled to 80°K	Same	Unknown	Unknown
20. SIZE (M)	1.5 aperture	1.5m	Unknown	Unknown
21. WEIGHT (KG)	1000	Same	Unknown	Unknown
22. POWER (WATTS)	100 to 125	Same	Unknown	Unknown
23. COST ($'S)				
24. ERROR SOURCES				
(a) GEOMETRIC	Slant range distortions Parallax Spacecraft attitude and rates Ephemeris	Same	Same	
(b) RADIOMETRIC	Sun angle Atmospheric transmission Detector variation Digital quantization Gamma of output reproducer Cooler variations (scene-to-scene)			
25. UNIQUE DATA PROCESSING REQUIREMENTS	Frame-to-frame location determination is critical. Also, registration of the various spectral-band FOV's must be very precise. For tornado watch, minimum time delay is required for issuance of warnings to the general public.			

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3. MISSION MODEL DEVELOPMENT

The purpose of this task is to develop a set of mission models and schedules by discipline and by operational or research assignment in accord with NASA Program Plan. For each defined mission, data uses/requirements, sensor use profiles, and mission descriptions (including compatibility with spacecraft weight, size and power) are given.

3.1 Candidate Data Uses/Requirements

As an aid to establishing the use profiles for each sensor and to assist in identifying data handling requirements and constraints, a list of specific data uses are presented here. For each candidate use, the specific measurements and their required frequency and measurement accuracy are identified. In addition, geographic regions for which such measurements are applicable and the perishability of the resulting data are established. Finally, likely destination(s) of data for each use are identified and a summary of this information presented.

3.1.1 User Community Requirements

The data available from ocean survey, meteorology, and other types of sensor measurements can be employed by the user community to describe essential features of the earth's ground, ocean, and atmospheric characteristics. The relationship of these data types to data uses is shown in Table 3-1. In order to best determine user community requirements, it was necessary to survey the field in each of the earth resources categories and evaluate the parameters required by each. These parameters are described below and summarized in the tables which follow. The information was extracted largely from recently completed or current studies addressing existing and projected needs of the earth resources data user community. Most useful in this regard were the following documents:

1) "Coastal Zone Requirements for EOS A/B, Final Report," prepared under Contract No. NASl-10280 by TRW Systems Group, for NASA Langley Research Center, 4 February 1971.

2) "Advanced Study of Global Oceanographic Requirements for EOS A/B, Final Report," prepared under Contract No. NASW-2163 by TRW Systems Group for NASA/Headquarters, January 1972.

3) "A Study of Mission Requirements for an Earth Observation Satellite Emphasizing Meteorology, Final Report," prepared by TRW Systems Group for NASA/Headquarters, January 1972.

4) "Design Requirements for Operational Earth Resources Ground Data Processing," Mid-Term and Final Reports, prepared by TRW Earth Resources Technology Office, Houston Operations, for NASA Manned Spacecraft Center, 15 September 1972.

5) "Study to Evaluate the Economic, Environmental, and Social Costs and Benefits of Future Earth Resources Survey Satellite Systems," study in progress by Earth Satellite Corporation for U.S. Department of Interior Office of Economic Analysis. First and Second Quarterly Progress Reports, February-April 1973 and May-July 1973.

Table 3-1. ERS Data Use Categories

DATA USE	OCEAN SURVEY	METEOROLOGY	AGRICULTURE & FORESTRY	GEOLOGY & MINERAL RESOURCES	GEOGRAPHY, CARTOGRAPHY & CULTURAL RESOURCES	HYDROLOGY & WATER RESOURCES	ENVIRONMENTAL QUALITY	DISASTER WARNING & MONITORING
SHOAL & COASTAL MAPPING	X			X	X			
SEA SURFACE CURRENTS	X							
SEA SURFACE COMPOSITION	X							
SEA SURFACE TEMPERATURES	X	X						
SEA SURFACE ROUGHNESS	X	X						
SEA SURFACE PHASE (SOLID VS LIQUID)	X	X						
CLOUD COVER	X	X						
PRECIPITATION	X	X	X			X		X
OCEANIC RADIATION BUDGET	X	X						
EARTH RADIATION BUDGET		X						
CLOUD PHYSICS	X	X						
UPPER ATMOSPHERIC TEMPERATURE		X						
UPPER ATMOSPHERIC COMPOSITION		X						
SNOW/ICE SURVEY		X	X		X	X		X
SOIL MOISTURE		X	X		X	X		X
TERRAIN MAPPING			X	X	X			
EARTH SURFACE COMPOSITION				X	X			
SEA SURFACE POLLUTION	X						X	
ATMOSPHERIC POLLUTION		X	X				X	X
WATER QUALITY						X	X	
SURFACE WATER MAPPING			X			X		X
SEVERE STORM WARNING	X	X	X					X

In order to summarize the data requirements of the users, the information is presented in tabular form (Table 3-2). The parametric requirements of these data are depicted in Tables 3-3 to 3-11. An explanation of the various terms and data that are used are given below.

Data Use. These categories, taken collectively, are intended to comprehensively cover the range of uses anticipated for remotely-sensed earth resources data for the 1978-88 time frame.

Specific Measurements/Observables. Measurements and/or observables are listed which characterize each category of data use and indicate critical parameters which are amenable to orbital remote sensing.

Data Destination. Listed in this column are the probable primary destinations for earth resources data deriving from satellites operating during the period from 1978 to 1988. These agencies are primary destinations in that they are likely to receive data directly either from

1) the spacecraft (via telemetry link), or from
2) a central ERS data handling system (via telephone link, telemetry, hard copy mail, facsimile transmission, etc.).

No attempt was made to list all ultimate data destinations such as university scientists and private users: the assumption was made that this community of users would receive fully--or partially--processed data secondarily from the government agencies serving as primary receivers.

The status of these agencies as potential primary ERS data receivers was deduced through analysis of their charters as enumerated in the Federal Government Organization Manual (1973-1974) and through consideration of government agency objectives with respect to participation in the experimental Earth Resources Survey Program as enumerated in the NASA Office of Applications Earth Resources Program Plan draft (June? 1973).

Agencies corresponding to the abbreviations used in Table 3-12, in alphabetical order, follow. An organizational breakdown is provided in Table 3-13.

It was not deemed to be within the scope of the present study to examine possible data destinations represented by foreign governments. The focus throughout the study shall be maintained upon remote sensing of domestic terrestrial resources (United States and territories) and global phenomena insofar as they impact the national interest. It is likely that several foreign governments may seek involvement in NASA's earth resources remote sensing programs in the near future. Data management implications for foreign interests might be estimated in much the same manner as is done in the present study--through consideration of data requirements and examination of data processing and transfer alternatives.

Table 3-2. Data Use Requirements Summary

DATA USE	SPECIFIC MEASUREMENTS; OBSERVABLES	DATA DESTINATIONS	REQUIRED FREQUENCY OF OBSERVATION (DAYS)	RANGE OF MAGNITUDES	REQUIRED MEASUREMENT SENSITIVITY & RESOLUTION	FIRST PRIORITY GEOGRAPHIC COVERAGE	DATA PERISHABILITY	ADDITIONAL DATA DESIRED TO AID ACCURATE INTERPRETATION	BASIC FORMAT REQMTS.
SHOAL & COASTAL MAPPING	VISIBLE REFLECTANCE FROM BOTTOM (FOR DEPTH AND COMPOSITION); SHORELINE MORPHOLOGY; ARTIFICIAL STRUCTURES	DOC. NOAA(NOS, NESC, EDS) DOT, USCG DOI. USGS,BLM,BR EPA	30-180	PERMANENT DIMENSIONAL CHANGES OF UP TO HUNDREDS OF METERS PER YEAR. 3000 "DOUBTFUL SHOALS"	±1m (DEPTH) 10-50' GR.RES. Δρ= 0.001	COASTAL U.S. & TERRITORIES	1 YEAR	WATER CLARITY; ACTUAL DEPTH; OTHERS, SAME AS FOR SEA SURFACE COMPOSITION (BELOW)	OL ACR SM GRSM PM TM
OCEAN SURFACE CURRENTS	VISIBLE TONAL CONTRASTS, THERMAL PATTERNS	DOD. NAVOCEANO (NWSC) DOC/NOAA (NOS, NWS, NMFS, NESC, EDS) EPA DOI/USGS (EROS)	COASTAL: OBSERVATIONS COVERING TIDAL CYCLE UNDER A RANGE OF RIVER OUTFLOW & NEARSHORE CURRENT CONDITIONS (TOTAL NO. OBS. MORE CRITICAL THAN FREQ. OF OBS.) GLOBAL: 2-5 DAYS	0 – 5 + KNOTS	0.2-2 NMI, COASTAL 2-20 NMI, OPEN OCEAN	GLOBAL OCEAN	2-5 DAYS	SUN GLITTER IMAGING OF ROUGHNESS; OTHERS, SAME AS FOR SEA SURFACE COMPOSITION (BELOW)	OL TM ACR GRSM
SEA SURFACE TEMPERATURE	SEA SURFACE TEMPERATURE	DOD. NAVOCEANO (NWSC) DOC/NOAA (NWS, EDS, NOS, NMFS, NESC) DOI, USGS (EROS) EPA	1-5 DAYS, OPEN OCEAN 1 DAY, COASTAL	Δ4°C/12 HOURS (OPEN OCEAN)	±0.2°C DESIRABLE ±0.5°C NOMINAL	GLOBAL OCEAN, ESPECIALLY NEAR WATER MASS BOUNDARIES	ANALYSES AND FORECASTS EVERY 12 HOURS. 72-84 HRS.MAX	LOWER ATMOSPHERE TEMPERATURE/HUMIDITY, IN-SITU DATA	OL TM GRSM IMM
SEA SURFACE COMPOSITION	VISIBLE: CHLOROPHYLL CONCENTRATION, WATER TURBIDITY; AQUATIC VEGETATION	DOC, NOAA (NOS, NMFS, EDS, NESC) DOI/USGS (EROS)	4-7 DAYS 5-10 NMI, OPEN OCEAN 0.1-1 NMI NEARSHORE & NEAR WATER MASS BOUNDARIES	0-100 + MG/M^3 CHLOROPHYLL A, 0-50 M DEPTH PENETRATION	±5%	GLOBAL OCEAN, ESPECIALLY IN FISHING GROUNDS & NEAR LAND MASSES	1 WEEK	SURFACE ROUGHNESS (INCL. FOAM) SUN ANGLE CLOUD COVER & ATMOSPHERE CONDITIONS BOTTOM TYPE (IN SHALLOW WATER) SEDIMENT LOAD (FOR PLANKTON ESTIMATION) PHYTOPLANKTON CONCENTRATION (FOR SEDIMENT LOAD ESTIMATION)	TM SS ACR GRSM
SEA SURFACE ROUGHNESS	SEA STATE & SWELL; WIND FETCH AREAS; SLICK PATTERNS	DOD/NAVOCEANO (NWSC) DOC/NOAA (NOS, EDS, NWS, NMFS, NESC) DOI/USGS (EROS)	6-24 HOURS	SEA STATE: 0-13 ON BEAUFORT WIND SCALE. SWELL: 0-20' +	±10% 0.2-2 NMI RES. FOR SLICK PATTERNS	GLOBAL OCEAN	< 1 DAY	GROUND VERIFICATION OF SEA/SWELL DIRECTION AND HEIGHT	OL TM
SEA SURFACE PHASE	ICE EXTENT & CHARACTER, SHIPS	DOC/NOAA (NOS, NWS, EDS, NESC) DOT USCG DOI/USGS (EROS)	3-14 DAYS	0-100% ICE COVER	100-1000' GR. RES.	GLOBAL OCEAN, ESPECIALLY N. HEMISPHERE & HIGH LATITUDES	1-2 WEEKS	GROUND MEASUREMENTS OF ICE THICKNESS, AGE, STRUCTURE, TEXTURE	OL ACR PM TM AI SM SS

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Table 3-2. Data Use Requirements Summary (Continued)

DATA USE	SPECIFIC MEASUREMENTS/ OBSERVABLES	DATA DESTINATIONS	REQUIRED FREQUENCY OF OBSERVATION (DAYS)	RANGE OF MAGNITUDES	REQUIRED MEASUREMENT SENSITIVITY & RESOLUTION	FIRST PRIORITY GEOGRAPHIC COVERAGE	DATA PERISHABILITY	ADDITIONAL DATA DESIRED TO AID ACCURATE INTERPRETATION	BASIC FORMAT REQMTS.
CLOUD COVER	CLOUDS	DOC. NOAA (NWS, EDS, NESC) DOD. NAVOCEANO (NWSC) DOI/USGS (EROS)	CONTINUOUS (2 PER DAY, NOMINAL)	0-100%	1° NEΔT @ 200°K; 1 KM RES.	GLOBAL	DATA REQUIRED ~ 4 HRS. AFTER OBS.	CLOUD TYPE, HEIGHT	OL SS BRIGHTNESS AVERAGING
PRECIPITATION	LOCATION/EXTENT OF RAIN CLOUDS AND PRECIPITATION	DOC/NOAA (NESC, NWS, EDS) DOD/NAVOCEANO (NWSC) DOI. USGS (EROS)			1)	GLOBAL, ESPECIALLY OVER U.S.	DATA REQUIRED <4 HRS. AFTER OBS.		OL TM SS ACR AI IMM
OCEANIC RADIATION BUDGET	SURFACE TEMPERATURE	DOC/NOAA (NWS, EDS, NESC) DOD/NAVOCEANO (NWSC) DOI/USGS (EROS)			2)	GLOBAL OCEAN	NA		TM SS ACR
EARTH RADIATION BUDGET	SURFACE TEMPERATURE	DOC NOAA (NWS, EDS, NESC) DOI/USGS (EROS)			2)	GLOBAL (TERRESTRIAL)	NA		OL TM ACR GRSM
CLOUD PHYSICS (ADDITIONAL TO DATA FROM MICROMETEOROLOGICAL EXPERIMENTS)	CLOUD AMOUNT, TYPE, HEIGHT	DOC/NOAA (NWS EDS, NESC) DOD. NAVOCEANO (NWSC) DOI/USGS (EROS)			1)	GLOBAL	NA	CONVENTIONAL RADIOSONDE PROFILES	PM OL TM IMM SS ACR
UPPER ATMOSPHERIC TEMPERATURE	TEMPERATURE	DOC/NOAA (NWS, EDS, NESC) DOD/NAVOCEANO (NWSC) DOI/USGS (EROS)			3)	GLOBAL	1 DAY	CONVENTIONAL RADIOSONDE PROFILES	TM IMM SS OL
UPPER ATMOSPHERIC COMPOSITION	TABLE A-3	DOC/NOAA (NWS, EDS, NESC) DOI/USGS (EROS)			3)	GLOBAL	1 DAY	CONVENTIONAL RADIOSONDE PROFILES, IN-SITU DATA	TM IMM SS ACR OL GRSM
SNOW/ ICE SURVEY	SNOW & ICE DISTRIBUTION, CHARACTER	DOC/NOAA (NWS, EDS, NESC) DOI/USGS (EROS)			4)	GLOBAL, ESPECIALLY IN LATITUDES GREATER THAN 45° N & S	1 WEEK OR GREATER		OL ACR AI SM IMM MINIMUM BRIGHTNESS COMPOSITES

1) See Table 3-3

2) See Table 3-9

3) See Table 3-5

4) See Table 3-6

Table 3-2. Data Use Requirements Summary (Continued)

DATA USE	SPECIFIC MEASUREMENTS, OBSERVABLES	DATA DESTINATIONS	REQUIRED FREQUENCY OF OBSERVATION (DAYS)	RANGE OF MAGNITUDES	REQUIRED MEASUREMENT SENSITIVITY & RESOLUTION	FIRST PRIORITY GEOGRAPHIC COVERAGE	DATA PERISHABILITY	ADDITIONAL DATA DESIRED TO AID ACCURATE INTERPRETATION	BASIC FORMAT REQMTS
SOIL MOISTURE	SOIL BRIGHTNESS (VISIBLE, IR, OR MICROWAVE)	USDA ASCS, SCS DOI USGS (EROS) DOC/NOAA(NESC)			4)	U.S. & TERRITORIES	2 WEEKS OR GREATER		TM SS GRSM IMM OL SM PM
TERRAIN MAPPING	LOCATION, CHARACTER (IDENTITY & CONDITION) AND EXTENT OF VEGETATION; FOREST FIRES; STORM DAMAGES, MINING ACTIVITIES, GEOTHERMAL SURVEY	USDA/SRS, ASCS, SCS, FS DOI/USGS, BLM, EPA DOC/NOAA (NESC)			5)	U.S. & TERRITORIES	1 DAY (STORM DAMAGES, FIRES); 1 MONTH (OTHERS)		OL TM SS ACR AI SM GRSM IMM PM
EARTH SURFACE COMPOSITION	SURFACE TEMPERATURE & COMPOSITION; GEOLOGICAL STRUCTURAL RELATIONSHIPS; ARTIFICIAL STRUCTURES & URBAN EXTENT	DOI/USGS, BLM USDA/SCS, SRS, ASCS DOC/NOAA (NESC)			6)	U.S. & TERRITORIES	1 YEAR		OL SM PM TM AI GRSM SS ACR IMM
SEA SURFACE POLLUTION	LOCATION, IDENTITY, EXTENT, & MOVEMENTS OF UNNATURAL MATERIALS	DOC/NOAA (NOS, NMFS, EDS, NESC) EPA DOT/USCG DOI/USGS (EROS)			7)	GLOBAL OCEAN ESPECIALLY U.S. COASTAL ZONE	1 DAY -2 WEEKS		OL SM TM GRSM IMM SS ACR AI
ATMOSPHERIC POLLUTION	GASEOUS AND PARTICULATE CONSTITUENCY, ATMOSPHERIC TURBIDITY	EPA DOI/USGS (EROS) DOC/NOAA (NESC)			8)	GLOBAL, ESPECIALLY OVER U.S. CITIES	1 DAY		OL SS IMM TM ACR GRSM
WATER QUALITY	TURBIDITY; OCCURRENCE OF UNNATURAL MATERIALS IN LAKES & RIVERS	DOI/USGS, BR, BSFW EPA DOC/NOAA (NESC)			4)	U.S. & TERRITORIES	1 MONTH		ACR OL AI GRSM TM IMM
SURFACE WATER MAPPING	LOCATION, EXTENT OF WATER (TABLE A-4)	DOI/USGS, BR USDA/ERS, SCS, FS DOC/NOAA (NESC)			4)	U.S. & TERRITORIES	1 MONTH		AI SM IMM PM OL ACR
SEVERE STORM WARNING	LOCATION & MOVEMENTS OF STORM CLOUDS	DOC/NOAA (NWS, NESC) DOD/NAVOCEANO (NWSC)			9)	GLOBAL, ESPECIALLY IN TROPICS	NWS; DATA REQUIRED IN 4 HRS AFTER OBS	SURFACE REFERENCE WEATHER DATA	OL TM GRSM ACR

4) See Table 3-6
5) See Tables 3-7, 3-8
6) See Tables 3-8, 3-9
7) See Table 3-10
8) See Table 3-4
9) See Table 3-11

Table 3-3. Parametric Data Requirements — Air-Sea-Land Interactions

Parameter	Spatial Resolution	Spectral Resolution	Accuracy Required	Geographic Area	Grid Spacing	Time of Day	Time of Year	Frequency of Observations	Remarks
Boundary layer atmosphere temperature profile	Horizontal 1 km Vertical 50 m		0.5 deg	All	10 km	Same local time	All	2 days	
Boundary layer wind profile	Horizontal 1 km Vertical 50 m		1 msec^{-1} 10 deg	All	10 km	"	All	2 days	
Boundary layer humidity profile	Horizontal 1 km Vertical 50 m		10 deg ref. humidity	All	10 km	"	All	2 days	
Atmosphere temperature profile	Horizontal 50 km 100 mb		1 deg	All	200 km	"	All	2 days	
Atmosphere wind profile	Horizontal 50 km 100 mb		2 msec^{-1}	All	200 km	"	All	2 days	
Atmosphere humidity profile	Horizontal 50 km 100 mb		<5 deg	All	200 km	"	All	2 days	
Sea surface temperature	1 km		0.25 deg	All	50 km	"	All	1 day	
Sea state	5 km		5 states	All	50 km	"	All	2 days	
Precipitation	2 km		5 levels of intensity	All	2 km(1)	"	All		(1) When precipitation occurring
Surface pressure	1 km		0.5 ms	All	50 km	"	All	2 days	
Sea temperature profile	5 km horizontal verticle variable(2)			All	200 km	"	All	1 day	(2) Depth to 100 m
Sea surface salinity	2 km(3), 50 km		1 part 10^3	All	2 km(3) 200 km	"	All	1 day(3) 1 week	(3) In vicinity of fresh water, ice melt, precipitation
Cloud patterns	1-6 km 4-6 km	Visible Infrared	1°NEΔT 200°K	All	50% scan line *	"	All	2 days	
Topography of low-level tops	1-6 km 4-6 km	Visible Infrared	100 m 1°NEΔT 250°K	All	50% scan line *	"	All	2 days	
Albedo surface	1-6 km		10% of value	All	50% scan line *	"	All	1 day(4)	(4) Daytime
Surface ice characteristics	1-6 km 4-6 km	Visible Infrared	1°NEΔT 200°K	All	50% scan line *	"	All	1 day(5)	(5) Daytime
Surface soil wetness	50 km		10%	All	50% scan line *	"	All	1 day	
Surface characteristics (bare, vesetative cover) and roughness	1-6 km		Boundaries of classes of land SFC features	All	50% scan line *	"	All	1 week to 1 year(6)	(6) Depending on static or dynamically chaning surface condition

*overlap

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Table 3-4. Parametric Data Requirements — Air Pollution

PARAMETER	SPATIAL RESOLUTION	ACCURACY REQUIRED	SENSITIVITY REQUIRED	GEOGRAPHIC AREA	GRID SPACING	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	LIFETIME OF OBSERVABLES	REMARKS
	URBAN/ GLOBAL	ACCURACY	RANGE	GLOBAL	10-50 KM	10 AM-12 AM	ALL	OBSERVATIONS/ TIME PERIOD	(2)	(1) PREFERABLY THE AVERAGE IN THE LOWEST KILOMETER; ALTERNATELY THE TOTAL CONTENT IN THE PATH
ATMOSPHERIC CONSTITUENTS	(KM)	(1)						(DAYS)		
GASEOUS										
• CO_2	2/200	1 PPM	280-700 PPM					1/5	I III	(2) I SPORADIC II SEASONAL III CONTINUOUS
• CO	2/200	0.3-0.2 PPM	0-100 PPM					1/5	I III	
• N_2O	2/200	TBD	TBD					1/1	I III	
• NO_2	2/200	.02-.1 PPM	0-5 PPM					1/1	I III	
• NO	2/200	.02-.1 PPM	0-5 PPM					1/1	I III	
• O_3	2/200	.01-.05 PPM	0-2 PPM					1/5	I III	
• SO_2	2/200	.01 PPM	0-5 PPM					1/1	I III	
• CH_4	2/200	TBD	TBD					1/1	I III	
• NH_3	2/200	TBD	TBD					1/1	I III	
AEROSOLS										
	2/200	$2\ \mu g/m^3$	$0\text{-}100\ \mu g/m^3$			2 PM-4 PM		1/1	II* III	
ATM. TEMP. PROFILES	AV. OVER 1° LAT SQUARE EVERY .1-1 KM/2-5 KM	1° C	220°-280°K			2 PM-4 PM		1/1	II III	
WIND	100-1 KM HORIZ 1 KM VERT	1 MPS	0-150 KNOTS			2 PM-4 PM		1/1	II	
CLOUDS										
AREA	20/200	10 KM^2	- - -			10 AM-12 PM		1/1	I II	
HEIGHT (BASE/TOP)	200 M	100 M	0-20 KM					1/1	I II	
PHASE	- - -	- - -	LIQ/ICE ABILITY TO DETECT PHASE CHANGE					1/1	I II	
LIQUID CONTENT	AV. OVER CLOUDY AREA	$\frac{10\%}{.1\ GM/M^3}$	.1-30 G/KG					1/1	I II	
DROP SIZE	TBD	.1 MM DIAMETER	02 MM					1/1	I II	
PRECIPITATION										
AREA	20/200	10 KM^2	- -					1 1	I II	
RATE	2/200	*	.25-40 MM/HR	GLOBAL	10-50 KM	'0 AM-12 AM	ALL	1 1	I II	*DIFFERENTIATE LIGHT, MODERATE, HEAVY
PHASE	HORIZ. * VERT. $\frac{5}{200}$ $\frac{5}{5}$		LIQ ICE SNOW ABILITY TO DETECT PHASE CHANGE					1 1	I II	
PLANETARY RADIATION BUDGET										
INCOMING SOLAR RAD.	20/200	0.1%	0-1322 W/M^2					1 1	III	
ALBEDO (VISIBLE)	20/200	0.1%	1-85%					1 1	III	
OUTGOING IR	20/200	0.1%	100-200 W/ST-M^2					1 1	III	
LOW LEVEL TURBULENCE		$\frac{\overline{u'^2}}{\bar{u}^2}$ .05	$\frac{\overline{u'^2}}{\bar{u}^2}$ 70					1 1	III	

Differentiate light, mod, heavy

Table 3-5. Parametric Data Requirements — Upper Atmosphere

PARAMETER	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	ACCURACY REQUIRED	GEOGRAPHIC AREA	GRID SPACING	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	REMARKS
OZONE	200 KM HORIZ AND 1 - 2 VERT FOR ALTITUDES 10 - 35 KM	(2)	1%	PRIMARILY MID LATITUDES	200 KM	SEE REMARKS (1)	ALL	1-2/DAY	(1) MIDMORN TO MIDAFTERNOON FOR UV BACKSCATTER ALONG THE TERMINATOR, OCCULTATION OF SUN STELLAR AND SOURCES. NOT TIME DEPENDENT WHEN USING IR EMISSION TECHNIQUE
	200 KM HORIZ AND 5 KM FOR ALTITUDES 35 KM	(2)	5%	PRIMARILY POLES, TROPICS	200 KM	SAME LOCAL TIME	ALL	1 DAY	(2) DEPENDS ON MEASUREMENT TECHNIQUE
H_2O	VERT 5 KM ≥ 20 - 30 KM ALTITUDES		MIXING RATIO TO A FACTOR OF 2 ≥ 20 - 30 KM, ORDER OF MAGNITUDE FOR TOTAL AMT >30 KM	GLOBAL	200 KM	(1) SAME LOCAL TIME SAME LOCAL TIME	ALL	1/DAY	
PARTICULATE MATTER (METEORIC) (VOLCANIC)	5 KM VERT; 200 KM HORIZ		20%	GLOBAL	400 KM	SAME LOCAL TIME	ALL	1/10 DAYS	
CO, NO_x, SO_2 HYDROCARBONS, ETC.	200 KM		SEE REMARKS (3)	GLOBAL	400 KM	REMARKS (4) SAME LOCAL TIME	ALL	1/30 DAYS	(3) DETECTION ONLY REQUIRED HT ACCURACY TO 10 KM
NO	60 - 120 NMI ≥ - 90 KM ALT		5 - 10% ≥ - 90 KM ALT	GLOBAL*	400 KM	SAME LOCAL TIME; DAY NIGHT (7)	ALL	1-2 DAY	(4) DEPENDS ON DETECTION METHOD *POLAR OBSERVATIONS MOST IMPORTANT
NOCTILUCENT CLOUDS	2 - 3 NMI		(5)	PRIMARILY HIGH LATITUDES	CONTINUOUS	(6)	(7)		(5) DETECTION REQUIRED (6) SATELLITE VIEWING IN TWILIGHT ZONE AND IN SUNLIT ATMOSPHERE (7) SUMMER SOLSTICE 2 MONTHS
TEMPERATURE	50 KM HORIZ, 2 KM VERT <35 KM; 2 KM VERT ≥ 35 - 50 KM		2°	GLOBAL	400 KM	SAME LOCAL TIME	ALL	1/DAY	
	5 KM VERT >50 KM		5°	GLOBAL	400 KM	SAME LOCAL TIME	ALL	1 DAY	
O_2, O	50 KM HORIZ 5 KM VERT		10%	PRIMARILY HIGH LATITUDES	400 KM	SAME LOCAL TIME	ALL	1/DAY	
WIND	5 - 10 KM NEAR 100 KM ALT		10 $MSEC^{-1}$	GLOBAL	400 KM	SAME LOCAL TIME	ALL	1 DAY (8)	(8) 5/DAY TO ACCOUNT FOR TIDAL EFFECTS ON THE MESOSCALE
DENSITY/PRESSURE	100 KM HORIZ 5 KM VERT		10%	GLOBAL	400 KM	SAME LOCAL TIME	ALL	1 DAY	
CLOUD AMOUNT TYPE HEIGHT	500 M			GLOBAL					
PLANETARY RADIATION BUDGET INCOMING SOLAR RADIATION ALBEDO (VISIBLE) OUTGOING IR	200 KM		0.1%	GLOBAL	400 KM	SAME LOCAL TIME	ALL	1/DAY	

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Table 3-6. Data Requirements — Hydrological Resources Inventory and Dynamics

REMOTE SPACE OBSERVABLE PHENOMENA	PARAMETER	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	ACCURACY REQUIRED	SENSITIVITY REQUIRED	ILLUMINATION (SUN ANGLE)	GEOGRAPHIC AREA	SWATH WIDTH N MI	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	LIFETIME OF OBSERVABLES	REMARKS
LAKE AND RESERVOIR INVENTORY													
AREAL EXTENT AND LOCATION OF SURFACE WATER BODIES	COLOR BOUNDARIES	50' TO 600'	0.1μ	ρ_M TBD	TBD	30° TO 90°	GLOBAL	40 TO 100	0900 TO 1500	N/C	3 MONTHS		
	THERMAL IR BOUNDARIES	50' TO 600'	1°K	0.2°K	TBD	N/C	GLOBAL	40 TO 100	N/C	N/C	3 MONTHS		
	RADAR REFLECTANCE CHANGES	50' TO 600'	N/A	N/C	TBD	N/C	GLOBAL	40 TO 100	N/C	N/C	3 MONTHS		
EVAPORATION AND EVAPOTRANSPIRATION LOSSES	COLOR BOUNDARIES	50' TO 600'	0.1μ	ρ_M TBD	TBD	30° TO 90°	GLOBAL	40 TO 100	0900 TO 1500	LATE SPRING THROUGH LATE FALL	3 MONTHS		
	THERMAL IR BOUNDARIES	50' TO 600'	1°K	0.2°K	TBD	N/C	GLOBAL	40 TO 100	N/C		3 MONTHS		
	TOPOGRAPHIC CONTOURS & BOUNDARIES	50' TO 600	0.1μ	TBD	TBD	N/C	GLOBAL	40 TO 100	N/C		3 MONTHS		
SNOW ICE INVENTORY													
AREAL EXTENT AND CHANGE OF GLACIAL AND POLAR ICE AND SNOW	ALBEDO	100' TO 600'	N/A	0.1%	N/C	TBD	POLAR REGIONS N & S AMERICA	40 TO 100	0900 TO 1500	NOT SUMMER	1 WK TO 3 MO		
	THERMAL IR BOUNDARIES	100' TO 600'	1°K	0.2°K	NEΔT TBD	N/A		40 TO 100	PREDAWN	NOT SUMMER	1 WK TO 3 MO		
	BRIGHTNESS TEMP BOUNDARIES	2 TO 4 N MI	1°K	0.2°K	TBD	N/C		40 TO 100	N/C	NOT SUMMER	1 WK TO 3 MO		
AREAL EXTENT OF REGIONAL SNOW COVER AND SEASONAL CHANGES	ALBEDO	100' TO 600'	N/A	0.1%	N/C	TBD	N & S AMERICA	40 TO 100	0900 TO 1500	NOT SUMMER	1 WK TO 3 MO		
	THERMAL IR BOUNDARIES	100' TO 600'	1°K	0.2°K	NEΔT TBD	N/C		40 TO 100	PREDAWN	NOT SUMMER	1 WK TO 3 MO		
	BRIGHTNESS TEMP BOUNDARIES	2 TO 4 N MI	1°K	0.2°K	TBD	N/C		40 TO 100	N/C	NOT SUMMER	1 WK TO 3 MO		
SOIL MOISTURE													
AREAL DISTRIBUTION IN LIQUID AND FROZEN STATES	THERMAL IR BOUNDARIES	50' TO 600'	1°K	0.2°K	TBD	N/C	N AMERICA	100	N/C	ALL	2 WK TO 3 MO		
	BRIGHTNESS TEMP BOUNDARIES	2 TO 4 N MI	1°K	0.2°K	TBD	N/C	N AMERICA	100	N/C	ALL	2 WK TO 3 MO		
SEASONAL VARIATIONS IN DISTRIBUTION	NEAR IR REFLECTANCE	50' TO 600'	0.1μ	$\rho_M = 0.2$	TBD	30° TO 90°	N AMERICA	100	0900 TO 1500	ALL	2 WK TO 3 MO		
	THERMAL IR BOUNDARIES	50' TO 600'	1°K	0.2°K	TBD	N/C	N AMERICA	100	N/C	ALL	2 WK TO 3 MO	I	
	BRIGHTNESS TEMP BOUNDARIES	2 TO 4 N MI	1°K	0.2°K	TBD	N/C	N AMERICA	100	N/C	ALL	2 WK TO 3 MO	I	
MAJOR RIVER BASINS													
TOPOGRAPHY AND DRAINAGE PATTERNS	TOPOGRAPHIC LENGTHS AND CONTOURS	50' TO 300'	0.1μ	N/A	N/A	30° TO 90°	GLOBAL	40 TO 100	0900 TO 1500	LATE SPRING SUMMER FALL	3 MONTHS		
EROSION CHARACTERISTICS	SURFICIAL COLOR BOUNDARIES	50'	0.1μ	N/A	N/A	30° TO 90°	GLOBAL	40 TO 100	0900 TO 1500	SUMMER, WINTER	1 YEAR	III	
TURBIDITY (TOPOGRAPHY)	COLOR/NEAR IR BOUNDARIES	50'	0.1μ	N/A	N/A	30° TO 90°	GLOBAL	40 TO 100	0900 TO 1500	LATE SPRING	1 WK TO 1 MO	I	
	SPECTRAL SIGNATURE BOUNDARIES AND PATTERNS	50'	0.1μ	N/A	N/A	30° TO 90°	GLOBAL	40 TO 100	0900 TO 1500		1 WK TO 1 MO	I	
STREAM AND IMPOUND LEVEL	COLOR/NEAR IR BOUNDARIES	50'	0.1μ	N/A	N/A	15° TO 90°	GLOBAL	40 TO 100	0700 1200 1900	ALL	6 HR TO 1 DAY	III	DETERMINATION OF STREAM & IMPOUND LEVEL DEPENDS ON INFERENTIAL CALCULATIONS & AREA OF WATER
	TOPOGRAPHIC CONTOURS	50'	0.1μ	N/A	N/A	15° TO 90°	GLOBAL	40 TO 100		ALL	6 HR TO 1 DAY	II	
UNDERGROUND WATER													
GROUND WATER DISCHARGE AT RIVERS, LAKES AND COASTLINES	COLOR BOUNDARIES	50' TO 100'	0.1μ	N/C	TBD	30° TO 90°	GLOBAL	100	0900 TO 1500 AM PREF	LATE SPRING & FALL	6 MONTHS		LAND & COASTLINE DATA IS REQUIRED WITH <u>NO WIND</u>
	THERMAL IR PATTERNS & GRADIENTS	50' TO 100	1°K	0.2°K	TBD	N/C	GLOBAL	100		SAME	6 MONTHS		
THERMAL ANOMALIES ASSOCIATED WITH NEAR-SURFACE GROUND WATER	THERMAL IR PATTERNS & GRADIENTS	50' TO 600'	1°K	0.2°K	TBD	N/C	GLOBAL	100	PREDAWN	LATE SPRING	1 YEAR		
VEGETATIVE ANOMALIES ABOVE AQUIFERS	ANOMALOUS COLOR BOUNDARIES	50	0.1μ	N/A	TBD	30° TO 90°	ARID REGIONS	100	0900 TO 1500	LATE SPRING SUMMER, FALL	3 MONTHS		
FRESH WATER POLLUTION													
THERMAL ANOMALIES AND STREAMLINES	THERMAL GRADIENTS & BOUNDARIES	100' TO 300	1°K	0.2°K	TBD	N/C	GLOBAL	100	N/C	ALL	1 MONTH		
CONCENTRATIONS OF LOW FORMS OF AQUATIC LIFE (ALGAE)	SPECTRAL SIGNATURE BOUNDARIES (CHLOROPHYLL)	100	0.05μ	TBD	TBD	30° TO 90°	GLOBAL	100	0900 TO 1500	ALL	1 MONTH		
TURBIDITY AND DISCOLORATION	COLOR BOUNDARIES & CHANGES	100'	0.1μ	TBD	TBD	30° TO 90°	GLOBAL	100	0900 TO 1500	ALL	1 MONTH		

NOTES 1. N/C — NOT CRITICAL

2. LIFETIME OF OBSERVABLES

I - SEASONAL

II - SPORADIC

III - CONTINUOUS

Table 3-7. Data Requirements — Agricultural, Forest, and Rangeland Inventory and Dynamics

REMOTE SPACE OBSERVABLE PHENOMENA	PARAMETER	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	ACCURACY REQUIRED	SENSITIVITY REQUIRED	ILLUMINATION (SUN ANGLE)	GEOGRAPHIC AREA	SWATH WIDTH	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	LIFETIME OF OBSERVABLES	REMARKS
LOCATION AND ACREAGE													
SHAPE, SIZE, AND SPATIAL FREQUENCY OF FIELDS AND FORESTS	COLOR NEAR IR BOUNDARIES, PATTERNS & TEMPORAL VARIATIONS	50' - 300'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	2 WEEKS TO 3 MONTHS	I	
	RADAR BOUNDARIES	50' - 300'	N/A	N/A	N/A	N/C	GLOBAL	100 N MI	N/C	ALL	2 WEEKS TO 3 MONTHS	I	RADAR MAY BE OF VALUE OVER CLOUDY AREAS IN CENTRAL & SOUTH AMERICA AFRICA & PARTS OF ASIA
POTENTIAL ARABLE AND RANGELAND	COLOR NEAR IR AREAL COVERAGE & TEMPORAL VARIATIONS	50' - 300'	0.1μ	N/A	N/A	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	2 WEEKS TO 3 MONTHS	I	
VIGOR, STRESS AND YIELD PREDICTION													
DISEASE, INSECT AND WATER/AIR POLLUTION DAMAGE	COLOR/NEAR IR BOUNDARIES	10' - 100'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	NORTH & SOUTH AMERICA	100 N MI	0900 TO 1500	SPRING SUMMER FALL (LOCAL)	1 WEEK TO 3 MONTHS	I	
	SPECTRAL SIGNATURE BOUNDARIES	10' - 100'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	NORTH & SOUTH AMERICA	100 N MI	0900 TO 1500				
LARGE STORM AND FIRE DAMAGE	COLOR BOUNDARIES	50' - 300'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	NORTH & SOUTH AMERICA	100 N MI	0900 TO 1500	ALL	1 DAY TO 1 WEEK	II	
	THERMAL IR BOUNDARIES	50' - 300'	1°K	0.2°K	$N_e\Delta T$/TBD	N/A	NORTH & SOUTH AMERICA	100 N MI	0200 TO 0400				
EFFECT OF NATURAL AND ARTIFICIAL NUTRIENTS	COLOR/NEAR IR REFLECTANCE CHANGES	50' - 300'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	NORTH & SOUTH AMERICA	100 N MI	0900 TO 1500	SPRING SUMMER (LOCAL)	1 WEEK TO 3 MONTHS	I	
SPECIES RECOGNITION													
REFLECTANCE OF LEAF CANOPY	COLOR NEAR IR REFLECTANCE BOUNDARIES	50' - 200'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	1 WEEK TO 3 MONTHS	I	50' RESOLUTION OR LESS IS REQUIRED FOR FOREST RESOURCES. 200' IS ADEQUATE FOR CROPS & RANGELANDS.
	SPECTRAL SIGNATURE BOUNDARIES	50' - 200'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	1 WEEK TO 3 MONTHS		
INDUCED SCATTERING AND POLARIZATION EFFECTS	DIRECTIONAL SCATTERING & POLARIZATION OF RADAR SIGNALS	50' - 200'	N/A	N/A	N/A	N/C	GLOBAL	40 TO 100 N MI	N/C	ALL	1 MONTH	I	
CULTIVATION PRACTICES MATURITY AND ARTIFACTS	COLOR/NEAR IR BOUNDARIES & PATTERNS	50' - 200'	0.1μ	N/A	ρMIN = 0.1 AT 0.7μ	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	1 WEEK TO 3 MONTHS	I	

NOTES 1. N/C — NOT CRITICAL

2. LIFETIME OF OBSERVABLES

I - SEASONAL
II - SPORADIC
III - CONTINUOUS

Table 3-8. Data Requirements - Environmental Impact of Natural and Man-Induced Modifications to Earth Resources

REMOTE SPACE OBSERVABLE PHENOMENA	PARAMETER	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	ACCURACY REQUIRED	SENSITIVITY REQUIRED	ILLUMINATION (SUN ANGLE)	GEOGRAPHIC AREA	SWATH WIDTH	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	LIFETIME OF OBSERVABLES	REMARKS
LAND USE MAPPING													
VEGETATION AND WATER INTERFACES	COLOR/NEAR IR BOUNDARIES	50'	0.1μ	METRIC	TBD	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	3 MONTHS	III	PHOTOGRAPHIC MAPPING RESOLUTION REQUIREMENTS: 1 1,000,000 MAP SCALE 50' TO 300' 1 250,000 20' TO 60' 1 62,500 5' TO 15'
	RADAR BOUNDARIES	50'	N/A	METRIC	TBD	N/C			N/C			III	
URBAN AND TRANSPORTATION DEVELOPMENT PATTERNS	COLOR/NEAR IR BOUNDARIES & PATTERN	50'	0.1μ	METRIC	TBD	30° TO 90°			0900 TO 1500			III	
	GEOMETRIC PATTERNS	50'	0.1μ	METRIC	TBD	30° TO 90°			0900 TO 1500		3 MONTHS	III	
WASTE STORAGE SITES													
TOPOGRAPHY AND DRAINAGE PATTERNA	TOPOGRAPHIC BOUNDARIES	50' TO 400'	0.1μ	TBD	TBD	30° TO 90°			0900 TO 1500		1 WK TO 1 MO	I	
	THERMAL IR BOUNDERIES	50' TO 600'	1°K	0.2°K	TBD	N/C			N/C			I	
	RADAR/MICROWAVE BOUNDARIES	50' TO 600'	N/A	TBD	TBD	N/A			0900 TO 1500			I	
SOIL TYPES AND PERMEABLE STRATA	COLOR BOUNDARIES	50' TO 600'	0.1μ	TBD	TBD	30° TO 90°			0900 TO 1500			I	
	SPECTRAL SIGNATURE BOUNDARIES	50' TO 600'	0.1μ	TBD	TBD	30° TO 90°	GLOBAL		0900 TO 1500	ALL	1 WK TO 1 MO	I	
FIRE HAZARD FORCASTING													
HISTORICAL AND CURRENT METEOROLOGICAL STRESS	SFERICS ACTIVITY	TBD (1 N MI?)	N/A	N/A	TBD	> 30°	N & S AMERICA		DAY	LATE SPRING SUMMER FALL	1 DAY	I	
	HUMIDITY											I	
	AIR TEMPERATURE											I	
	SURFACE WINDS		N/A	N/A	TBD	> 30°	N & S AMERICA		DAY		1 DAY	I	
VEGETATION STRESS	NEAR IR REFLECTANCE	50' TO 300'	0.1μ	TBD	TBD	30° TO 90°	N & S AMERICA		0900 TO 1500	SUMMER FALL	1 WEEK	I	
	COLOR/NEAR IR BOUNDARIES	50' TO 300'	0.1μ	TBD	TBD	30° TO 90°	N & S AMERICA		0900 TO 1500		1 WEEK	I	
FLOOD WARNING AND DAMAGE													
TONAL AND THERMAL CONTRASTS	COLOR BOUNDARIES/ CONTOURS	50' TO 300'	0.1μ	TBD	$P_{MIN} = 0.1$ AT 0.7μ	30° TO 90°	GLOBAL		0900 TO 1500	EARLY SPRING & FALL	1 DAY TO 1 WK	II	FALL OBSERVATIONS ARE NEEDED TO EVALUATE TROPICAL STORM DAMAGE
	THERMAL IR BOUNDARIES/CONTOURS		1°K	0.2°K	TBD	N/C			PREDAWN	EARLY SPRING & FALL	1 DAY TO 1 WK	II	
VEGETATIVE PATTERN DIFFERENCES	SPECTRAL SIGNATURE BOUNDARIES		0.1μ	TBD	TBD	30° TO 90°			0900 TO 1500	EARLY SPRING & FALL	1 WEEK	I	
	RADAR BOUNDARIES		N/A	TBD	N/A	N/A			N/A			I	
REGIONAL PHYSIOGRAPHICAL CHANGES	TOPOGRAPHIC BOUNDARIES		0.1μ	TBD	TBD	30° TO 90°			0900 TO 1500			II	
	COLOR CHANGES		0.1μ	TBD	TBD	30° TO 90°			0900 TO 1500			II	
STANDING WATER VARIATIONS	THERMAL IR BOUNDARIES	50' TO 300'	1°K	0.2°K	TBD	N/A			PREDAWN			I	PASSIVE MICROWAVE MEASUREMENTS MAY REQUIRE HIGHER RESOLUTION
	BRIGHTNESS TEMPERATURE BOUNDARIES	2 TO 4 N MI	1°K	0.2°K	N/A	N/C			?			I	
	RADAR REFLECTANCE BOUNDARIES	50' TO 300'	N/A	TBD	N/A	N/A			?	EARLY SPRING & FALL	1 WEEK	I	
GEOLOGIC DISASTER													
SPATIAL DISTRIBUTION OF MAJOR FAULTS	SURFACE TOPOGRAPHY AND DISCONTINUITIES	100'	0.1μ	TBD	$P_{MIN} = 0.1$ AT 0.7μ	15° TO 30°			0700 TO 1000	ALL	1 YEAR	III	
	COLOR BOUNDARIES	100'	0.1μ	TBD		15° TO 30°			1400 TO 1700			III	
RECENT EROSION	COLOR/NEAR IR BOUNDARIES & CHANGES	50' TO 300'	0.1μ	TBD		30° TO 90°			0900 TO 1500			III	
AREAS OF POSSIBLE MASS EARTH MOVEMENT	TOPOGRAPHIC BOUNDARIES & CONTOURS	50' TO 300'	0.1μ	TBD		30° TO 90°			0900 TO 1500			III	
	COLOR BOUNDARIES	50' TO 300'	0.1μ	TBD	$P_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500		1 YEAR	III	
	THERMAL IR BOUNDARIES	50' TO 300'	1°K	0.2°K	TBD	N/C			N/C			III	
VOLCANIC ACTIVITY CHARACTERIZED BY UNIQUE GEOMORPHOLOGY THERMAL ANOMALIES, GASEOUS EFFLUENTS, ETC.	SURFACE TOPOGRAPHY & PATTERNS	50'	0.1μ	TBD	$P_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500		1 MONTH	II	
	THERMAL IR GRADIENTS & PATTERNS	50'	1°K	0.2°K	TBD	N/A			PREDAWN			II	
	SPECTRA OF SO_2 H_2S	TBD	0.003μ	N/A	TBD	30° TO 90°			0900 TO 1500			II	
CHANGE OF CULTURAL FEATURES RELATIVE TO GEOLOGICAL HAZARDS	COLOR/NEAR IR BOUNDARIES	50' TO 300'	0.1μ	TBD	$P_{MIN} = 0.1$ AT 0.7μ	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	1 MONTH	II	

NOTES
1. N/C — NOT CRITICAL
2. LIFETIME OF OBSERVABLES
   I - SEASONAL
   II - SPORADIC
   III - CONTINUOUS

Table 3-9. Data Requirements - Geological Resources Inventory and Dynamics

REMOTE SPACE OBSERVABLE PHENOMENA	PARAMETER	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	ACCURACY REQUIRED	SENSITIVITY REQUIRED	ILLUMINATION (SUN ANGLE)	GEOGRAPHIC AREA	SWATH WIDTH	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	LIFETIME OF OBSERVABLES	REMARKS
ROCKS, SOILS, LANDFORMS AND STRUCTURES													
LINEAMENTS, FAULTS, FOLDS, OUTCROPS, ALLUVIAL DEPOSITS	COLOR BOUNDARIES CONTOURS	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	15° TO 30°	GLOBAL	100 N MI	0800 TO 1000 1400 TO 1600	ALL	3 MONTHS	I & III	
	SPECTRAL SIGNATURE CONTOURS	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	15° TO 30°			0800 TO 1000 1400 TO 1600			I & III	
	TOPOGRAPHIC CONTOURS	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	15° TO 30°			0800 TO 1000 1400 TO 1600		3 MONTHS	III	
SOIL TYPE BOUNDARIES	COLOR/SPECTRAL SIGNATURES	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500		1 MONTH		
	BRIGHTNESS TEMPERATURE BOUNDARIES	1 TO 2 N MI	1°K	0.2°K	N/A	N/C			N/C			I & III	PASSIVE MICROWAVE RESOLUTION NOT REALLY ADEQUATE
SURFACE TEXTURE AND ROUGHNESS	SCATTERING												
	• VISIBLE NEAR IR	50' - 600'	0.1μ	N/A	N/A	30° TO 90°			0900 TO 1500			III	
	• IR	50' - 600'	0.1μ	N/A	N/A	30° TO 90°			0900 TO 1500			III	
	• MICROWAVE	1 TO 2 N MI	N/A	N/A	N/A	N/C			N/C			III	
SURFACE MOISTURE CONTENT	THERMAL IR BOUNDARIES	50' - 600'	1°K	0.2°K	$N_e\Delta T$/TBD	N/C			PREDAWN			I	
	BRIGHTNESS TEMPERATURE BOUNDARIES	1 TO 2 N MI	1°K	0.2°K	N/A	N/C			N/C			I	
VEGETATIVE PATTERNS	COLOR BOUNDARIES	50' - 600'	0.1μ	N/A	TBD	30° TO 90°			0900 TO 1500			I	
	SPECTRAL SIGNATURE BOUNDARIES	50' - 600'									1 MONTH		
SOIL TYPE/QUALITY													
SURFACE WATER DISTRIBUTION	THERMAL IR BOUNDARIES	50' - 300'	1°K	0.2°K	$N_e\Delta T$/TBD	60° TO 90°			PREDAWN TO MID-AFT		1 WK TO 1 MO	I	
	BRIGHTNESS TEMPERATURE BOUNDARIES	1 TO 2 N MI	1°K	0.2K	N/A	60° TO 90°				ALL	1 WK TO 1 MO	I	
COLOR/SPECTRAL VARIATIONS	COLOR/NEAR IR REFLECTANCE CHANGES	50' - 300'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500	WINTER TO EARLY SPRING		III	
TEXTURE AND ROUGHNESS VARIATIONS	COLOR/NEAR IR REFLECTANCE	50' - 300'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500	WINTER TO EARLY SPRING		I	
	MICROWAVE REFLECT. & POLARIZATION	1 TO 2 N MI	1°K	0.2°K	N/A	60° TO 90°			0900 TO 1500	WINTER TO EARLY SPRING	1 WK TO 1 MO	I	
GROSS VEGETATIVE CLAFFICIATIONS	COLOR/NEAR IR BOUNDARIES	50' - 300'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500	SPRING SUMMER/FALL	3 MONTHS	I	
MINERAL AND OIL EXPLORATION													
DISTRIBUTION OF FAVORABLE LITHOLOGICAL AND OTHER GEOLOGICAL FORMATIONS AND STRUCTURES	COLOR BOUNDARIES	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	15° TO 60°			0800 TO 1600	ALL	3 MONTHS	I	
	SPECTRAL SIGNATURE BOUNDARIES												
	TOPOGRAPHIC CONTOURS & BOUNDARIES	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	15° TO 60°			0800 TO 1600			I	
OFFSHORE PLACERS IN SHALLOW WATERS	ONSHORE/OFFSHORE COLOR BOUNDARIES	50' - 600'	0.1μ	N/A	$\rho_{MIN} = 0.1$ AT 0.7μ	30° TO 90°			0900 TO 1500			II	
GEOTHERMAL SOURCES													
FAULTS AND FISSURES	TOPOGRAPHIC CONTOURS/PATTERNS	50' TO 600'	0.1μ	N/A	TBD	15° TO 30°			EARLY MORN/ LATE AFT		3 MONTHS	II	
LOCAL HYDROLOGICAL THERMAL ANOMALIES	TEMPERATURE GRADIENTS/PATTERNS	50' TO 600'	1°K	0.2°K	$N_e\Delta T$/TBD	N/C			PREDAWN/ EARLY AFT		6 MONTHS	III	
LOCAL SURFICAL THERMAL ANOMALIES	TEMPERATURE GRADIENTS/PATTERNS	50' TO 600'	1°K	0.2°K	$N_e\Delta T$/TBD	N/C			NOT EARLY AFT		3 MONTHS	II	
GASEOUS EFFLUENTS	SPECTRA OF SO_2, H_2S, ETC.	2 TO 4 N MI	0.001μ	N/A	TBD	30° TO 90°	GLOBAL	100 N MI	0900 TO 1500	ALL	3 MONTHS	II	

NOTES: 1. N/C — NOT CRITICAL

2. LIFETIME OF OBSERVABLES

I - SEASONAL

II - SPORADIC

III - CONTINUOUS

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Table 3-10. Data Requirements – Ocean Pollution

PARAMETER	COASTAL (CO) OR GLOBAL (GL) COVERAGE	SPATIAL RESOLUTION	SPECTRAL RESOLUTION	ACCURACY REQUIRED	SENSITIVITY REQUIRED	ILLUMINATION (SUN ANGLE)	GEOGRAPHIC AREA	GRID SPACING	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	LIFETIME OF OBSERVABLES	REMARKS
SURFACE TEMPERATURE	CO	50' - 10^3'	IR MICRO	.5 - 1° K	.2 - 2° K		1 - 10 NM	-			1/4 - 14	I, II, III	THERMAL PLUMES 100 - 200' WIDE HIGH OBSERVE FREQ FOR TOTAL EFFECTS 2° SENSITIVITY NEAR LARGE POWER PLANT
	GL	.2 - 20 NMI			.1 - 1° K		-	10 - 100 NM			14 - 30	I, II	
SURFACE SALINITY	CO	50' - 10^3'	MICRO		.1 - 5‰		1 - 10 NM	-			1/4 - 14	I, II, III	
	GL	.2 - 20 NM			.1 - 2‰		-	10 - 100 NM			14 - 30	I, II	
CHEMICAL COMPOSITION UPWELLINGS, EDDIES	CO	50' - 100'	VISIBLE .01 - .03μ		$\Delta\rho$ · .001		1 - 10 NM	-			1/4 - 14	I, II, III	NOT APPLICABLE GLOBAL SCALE DUE TO DILUTION
CHLOROPHYLL (PHYTOPLANKTON)	CO	1000'	VISIBLE .01 - .03μ		$\Delta\rho$ - .001		1 - 10 NM	-			14 - 60	I, II, III	
TURBIDITY	CO	50' - 100'	VISIBLE .01 - .05μ		$\Delta\rho$ · .001		10 NM	-			1/4 - 30	I, II, III	INDICATES RIVER PLUMES, SEWAGE OUTFALLS
AQUATIC VEGETATION	CO	50' - 300'	VISIBLE .03 - 0.5μ (BD)		-		2 NM	-			30 - 90	III	COLOR (FAR RED) CHANGES DUE TO POLLUTANTS
CURRENTS	CO	50' - 10^3'	VISIBLE .01 - .03μ		-		1 - 200 NM				1/4 - 14	I, III	CURRENT BOUNDARIES MAINLY CURRENT SPEED NOT APPLICABLE
	GL	.2 - 20 NM	IR MICRO				-	10 - 100 NM			14 - 30	I, III	
SEA LEVEL	GL	2 NM (FOOT (FOOTPRINT)	P. RANGE RADAR	10 CM	SLOPES 10^{-4} - 10^{-7}		-	5 - 20 NM			14	I, III	SLOPES MAY REACH 10^{-3} IN VICINITY OF A HURRICANE
SEA STATE	CO	.2 - 2 NM	VISIBLE (BD) RADAR	NBN	NBN		1 - 10 NM		DAY		1 - 7	III	APPLICABLE TO DISPERSION AFTERNOON HAS HIGHEST SEA STATE, MORNING, CALM WORST CONDITION
SLICKS (SURFACE ROUGHNESS)	CO	50' - 10^3'	VISIBLE .01 - .03μ IR MICRO		-		1 - 50 NM				1 - 30	II, III	SLICKS DUE TO NATURAL SEEPS AND SEWAGE OUTFALLS
SURFACE WIND	CO	.2 - 2 NM	VISIBLE IR MICRO RADAR		-		25 - 100 NM		DAY		1 - 7	III	DISPERSION OF ATMOSPHERIC IMPURITIES OUT TO 100 NM
WIND PROFILE	CO	.2 - 2 NM	VISIBLE MICRO RADAR		-		25 - 100 NM	10 - 50 NM	DAY				
BOTTOM COMPOSITION	CO	50' - 300'	VISIBLE .03 - .03μ	-	-		1 - 10 NM				360	II, III	INDICATIVE OF POLLUTANT BUILDUP
SHORELINE PATTERNS	CO	10' - 50'	VISIBLE .03μ	-	-		1 NM				30 - 360	II, III	BEACH DEBRIS AND SHORELINE/SURF CHANGES DUE TO POLLUTANTS BUILDUP EROSION
ATMOSPHERIC IMPURITIES	CO	5 - 10 NM	VISIBLE .05μ				100 NM				3 - 7	II, III	PLUMES OVER COASTAL WATERS

KEY
I SEASONAL
II SPORADIC
III CONTINUOUS
REFLECTANCE (SENSITIVITY)
NBN NEAREST BEAUFORT NUMBER

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Table 3-11. Parametric Data Requirements – Mesoscale Meteorological Phenomena

PARAMETER	SPATIAL RESOLUTION	ACCURACY REQUIRED	GEOGRAPHIC AREA	GRID SPACING	TIME OF DAY	TIME OF YEAR	FREQUENCY OF OBSERVATIONS	REMARKS
	KM						PER DAY	
CLOUD PATTERNS	4-6	1° NEΔT @ 200°K	SELECTED AREAS CHOSEN ON DAY BY DAY BASIS	50% SCAN LINE OVERLAP	ASCENDING OR DESCENDING NODE: 10 AM* & 10 PM (LOCAL TIMES)	ALL	2	.5 MI VISIBLE RESOLUTION WILL PERMIT CLOUD HEIGHT DETERMINATION
CLOUD-TOP TOPOGRAPHY	4-6	1° NEΔT @ 200°K		50% SCAN LINE OVERLAP			2	
ATMOSPHERIC TEMPERATURE PROFILE	50MB VERT 10-30 HORIZ	0.50 RMS		5-15			2	
PRESSURE	3-30KM HORIZ 50MB VERT	.5-1 MB		2-15			2	
WIND $^{(u,v,w)}$	20 HORIZ 100MB VERT	1 M/S, 10°		20-30			2	SOME VERTICAL ESTIMATES FROM CLOUD TOP TOPOGRAPHY
HUMIDITY PROFILES	10-30	20% REL. HUMID.		5-15			2	OUTSIDE CLOUDS
PRECIPITATION	4-6	5 SCALES		2-3			2	
CLOUD LIQUID WATER CONTENT	4-6	5 SCALES		2-3			2	
SFERICS	20-40	YES OR NO		10-20			2	
SFC ICE CHARACTERISTICS	4-6 1-6	1° NEΔT		50% SCAN LINE OVERLAP			1 (10 AM)	
OZONE	20-40	10% OF TOTAL		10-20			2	TRACER FOR SUBSIDENCE
ALBEDO	1-6	2%		50% SCAN LINE OVERLAP			1 (10 AM)	
COLOR (GROUND)	1-6	2%		50% SCAN LINE OVERLAP			1 (10AM)	
SURFACE TEMPERATURE	4-6	1° NEΔT @ 250°K		50% SCAN LINE OVERLAP			2	
SURFACE CONDITION (TREES, MOISTURE)	1-6	N/A						PRECIPITATION HISTORY ON GROUND IMPORTANCE

* 10 AM LOCAL TIME BECAUSE LOW SUN ANGLE ALLOWS USE OF SHADOWS.
CONVECTIVE ACTIVITIES OVER LAND & OCEAN ARE RELATIVELY LOW, MOVING DETERMINATION OF HOT & COLD SPOTS ON SURFACE.
10AM SURFACE CONDITIONS TOGETHER WITH EARLY MORNING CLOUD ACTIVITY WILL BE USEFUL FOR MESOSCALE PREDICTION FOR REMAINDER OF THE DAY.

Table 3-12. U.S. Governmental Organizations Considered as Primary Destinations for Remotely-Sensed Earth Resources Data

ASCS	Agricultural Stabilization and Conservation Service
BLM	Bureau of Land Management (Washington, D.C.)
BR	Bureau of Reclamation (Washington, D.C.)
BSFW	Bureau of Sport Fisheries and Wildlife (Washington, D.C.)
FS	Forest Service (Washington, D.C.)
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
EDS	Environmental Data Service (Washington, D.C.)
EPA	Environmental Protection Agency (Washington, D.C.)
EROS	Earth Resources Observation Satellite Center (Sioux Falls, South Dakota)
NAVOCEANO (NWSC)	Naval Oceanographic Office, Naval Weather Service Command (Fleet Numerical Weather Control, Monterey, California)
NESC	National Environmental Satellite Center (Suitland, Md.)
NMFS	National Marine Fisheries Service (Washington, D.C.)
NOAA	National Oceanographic and Atmospheric Agency (Washington, D.C.)
NOS	National Ocean Survey (Washington, D.C.)
NWS	National Weather Service (Silver Springs, Md.)
SCS	Soil Conservation Service
SRS	Statistical Reporting Service
USCG	U.S. Coast Guard
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Table 3-13. Organizational Breakdown, U.S. Governmental Agencies

DOC			U.S. Department of Commerce
	NOAA:		National Oceanic and Atmospheric Administration
		NOS:	National Ocean Survey
		NMFS:	National Marine Fisheries Service
		NWS:	National Weather Service
		NESC:	National Environmental Satellite Center
		EDS:	Environmental Data Service
EPA			Environmental Protection Agency
DOI			U.S. Department of Interior
	USGS:		U.S. Geological Survey
	BLM:		Bureau of Land Management
	BR:		Bureau of Reclamation
	BSFW:		Bureau of Sport Fisheries and Wildlife
DOT			U.S. Department of Transportation
	USCG:		U.S. Coast Guard
DOD			U.S. Department of Defense
	NAVOCEANO:		U.S. Naval Oceanographic Office
		NWSC:	Naval Weather Service Command
USDA			U.S. Department of Agriculture
	ASCS:		Agricultural Stabilization and Conservation Service
	SRS:		Statistical Reporting Service
	SCS:		Soil Conservation Service
	FS:		Forest Service

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Required Frequency of Observation. Periods specified indicate appropriate observational intervals for orbital remote sensing. Observation of intervals substantially in excess of those specified would lead to uncertainties in tracing the sequence of dynamic changes in the time-variant phenomena of concern.

Range of Magnitudes. Values in this column indicate the spectrum of variability or dynamic range associated with major phenomena of interest.

Required Measurement Sensitivity and Resolution. These values reflect user needs for contrast and detail as translated into sensor parameters.

Approximate Geographic Coverage. Entries in this column indicate critical geographical regions requiring observation to meet the bulk of user coverage requirements.

Data Perishability. These values indicate the length of time after observation during which a given observation would be of high utility as input to the data base of principal users.

Additional Data Required to Facilitate Accurate Interpretation. Listed are categories of in-situ observables which would provide point calibration data for the associated data use categories.

Basic Format Requirements. A portion of the effort of the study was devoted to an examination of requirements of the user community for data formatting in the various categories of data use. The study recently completed by TRW Houston Operations (cited above) was useful in this regard. Abbreviations used in the column entitled "Basic Format Requirements" correspond to the following data products (definitions excerpted from TRW Houston Operations Study):

PM: Photomap. In its simplest form this product is merely a photograph, but it may include superimposed gridding and annotation. Typical uses of photomaps would include:

- Aid in planning construction
- Assignment of work crews in remote areas (USGS studies have shown marked improvement in the ability to determine exact location with photographic aids instead of traditional maps.)
- The basic information source for visual detection of plant stresses, fault lines, etc.

OL: Overlay. This is a general description of a technique in which more than one image is adjusted in scale and orientation. Thus, an overlay could consist of simultaneous CRT images, prints, or transparencies. This is the primary information source for visual change discrimination. Typical applications of overlays would include:

- Studies of changes in land use
- Monitoring movement of insect infestation
- Changes in mine waste disposal activities.

TM: Thematic Map. Thematic maps are maps upon which geographically distributed attributes are described by visual aids such as contours and color differentiation. The plotting base may either be photographs or maps and plots are often made on transparent material. The information sources could simultaneously include conventional data sources and remotely sensed data. Typical applications of thematic maps would include:

- Contours of concentrations of various minerals displayed on a photograph of a region
- Known wind shears displayed on photograph of estuary to study wind/water relationships.

GRSM: Geometrically Referenced Spatial Measurements. Measurements of spatial relationships within imagery are obviously important for locating objects geographically through photogrammetric processes. Additionally, certain applications require rate of movement information. Typical applications include:

- Mapping of tectonic features
- Detection of surface thermal anomalies.

IMM: Input to Mathematical Models. This category of data products is generated using spectral and spatial measurements discussed above. However, it is introduced as a separate type to account for the facts that conversion to model parameter units and generation of computable input media and format may be required. Typical applications include:

- Calculation of ground slope for input to hydrological models
- Determination of coefficient describing porosity of soil.

SS: Statistical Summaries. This data product is useful for determining trends and characteristics for use in automated processes. Typical applications include:

- Averaging of pixels to dampen high frequency effects
- Calculation of mean and covariance within an homogenous region for use in maximum likelihood classification schemes.

AI: Automated Inventory. This process involves recognition of signatures of certain ground objects and the compilation of the associated areal extent. Various schemes are currently under study including maximum likelihood techniques and clustering techniques. Typical applications include:

- Calculation of the acreage of blighted corn based upon multispectral data
- Acreage of selected crops for forecasting purposes.

ACR: Automated Change Discrimination. For situations in which either the subtlety of changes in spectral responses from a region at different times or the volume of such data preclude manual interpretation, automated change discrimination techniques may be employed. Many of the functions required to generate this product are similar to those used in automated inventorying; however, the requirement of the availability of, and comparison with, additional images and the inherent registration problem intorduces a considerable additional processing burden. Typical applications include:

- Detection of spreading of agricultural blight
- Detection of changes in land use.

3.1.2 Data Products

The earth sciences are largely non-mathematical and to some extent empirical in nature. Considerable emphasis is placed upon the intuitive and subjective processes of a trained analyst or interpreter. The classical discipline of photogrammetry, which borders on being an art form, provides the basis for much of the interpretive work in earth resources. Table 3-14 describes some of the more frequent analytical modes employed by imagery interpreters. The various aids or presentation types most commonly used are shown for the various modes. There are undoubtedly unlimited variations on these analytical modes due to the inherently subjective nature of the analysis processes; however, it is believed that the number of useful aids to interpretation, as well as the media of presentation, are relatively limited.

The remainder of the section describes a set of these interpretive aids or data products. An attempt was made to define the smallest set of products commensurate with satisfying a majority of the projected analytical needs. The following is a list of these data products grouped according to output media:

- Photographic
  - Photomaps
  - Prints
  - Transparencies (including overlays)
- Plotted
  - Thematic Maps
  - Statistical

Table 3-14. Analytical Modes

Analytical Mode	Interpretive Aid
Imagery is used repeatedly for planning construction, assigning work crew, etc.	Photomap
Imagery is used to support visual change discrimination. Comparison base may be maps or other imagery.	Overlays (transparencies or adjusted scale prints)
Imagery is used in photogrammetric processes for mapping or to monitor rate of movement.	Geometrically referenced spacial measurements
Application is concerned primarily with instantaneous spectral or tonal qualities.	Geometrically referenced spatial measurements
Imagery provides source of data to support prediction of future states. Transformation of data to compatible units and calibration/correlation with other data may be required.	Input for mathematical models
Application requires visual association of metric data derived from imagery with other data types.	Thematic maps
Information content is contained in overall trends and properties of the ensemble of metric data of the imagery.	Statistical summaries
Information content is in changes from a given base. Sublety of changes or data volume dictates automated procedures	Automatic report of changes
Application requires assessment of area/extent of imaged region of specific properties	Automated inventory

- Recorded
  - Spectral Measurements of Photographic Imagery
  - X-Y Locations of Features in Imagery
  - High Density Digital Tapes
  - Computer Compatible Tapes (including possible inputs to mathematical models)
  - Specialized Program Tapes
- Tabulated
  - Inventory Summaries (includes change discrimination as a special case)
  - Statistical Data Summaries
  - Production Summaries.

These products are discussed in more detail below; the primary emphasis in the following material is in describing the attributes of the various products which determine the specifications for processing for specific users:

Recorded Products. Some agencies will have capabilities for computer analysis of imagery data. The ground data handling system would provide computer tapes to be used by these facilities.

Precision spectral measurement of products could result from the use of standard densitometric and colorimetric techniques using either electronic of photographic film as the basic data. Such a data product might be required if applications are developed which determine physiological/physical parameters as directly functional to emulsion response.

Attributes would include:

- Spectral range of interest
- Grid distribution of measurements
- User computer tape requirements.

X-Y locations of features in imagery are included to account for support to applications requiring photogrammetric processes. These measurements could be used to monitor the movement of features (e.g., ice flows) or in mapping.

Attributes include:

- Features of interest
- Desired precision
- Desired reference frame.

High density tapes may be required for either raw data or data processed for certain corrections.

Attributes include:

- Level of radiometric and geometric fidelity
- User equipment requirements
- Requirement for supporting data.

Computer compatible tapes would have these same attributes.

Special program tapes are included as a product based upon an assumption of the capabilities of the processing facility(ies). It would appear to be safe to assume that a facility would have available a multiplicity of digital computer algorithms which can be linked together in a flexible fashion. Furthermore, it may be assumed that there will be user agencies with computer capabilities to be used in the analysis of data. Conceivably, a service facility could develop a computer program tape which has the necessary algorithms properly sequenced to serve the needs of the user agency. The information required to specify this product includes:

- The specific requirements for processing
- The raw data
- The user agency equipment.

Tabulated Products. User agencies may require computer printouts of analysis results and possibly some form of transaction summary. Inventory summaries would result from the use of classification schemes, but additional information might be required. This information could include total area for each category or individual areas described by center location, areal extent and classification. Requirements for specification would include:

- Categories to be identified
- Location accuracy
- Accuracy of areal calculations
- Specific form of output.

Statistical data summaries would utilize standard statistical algorithms. Specification requirements would include:

- Parameters to be summarized
- Statistics to be used
- Output format.

Production summaries or catalogs would include description of data received, quality of data, corrections effected on data, products generated, and disposition of raw data.

Figure 3-1 illustrates the above family of data products and the respective media options.

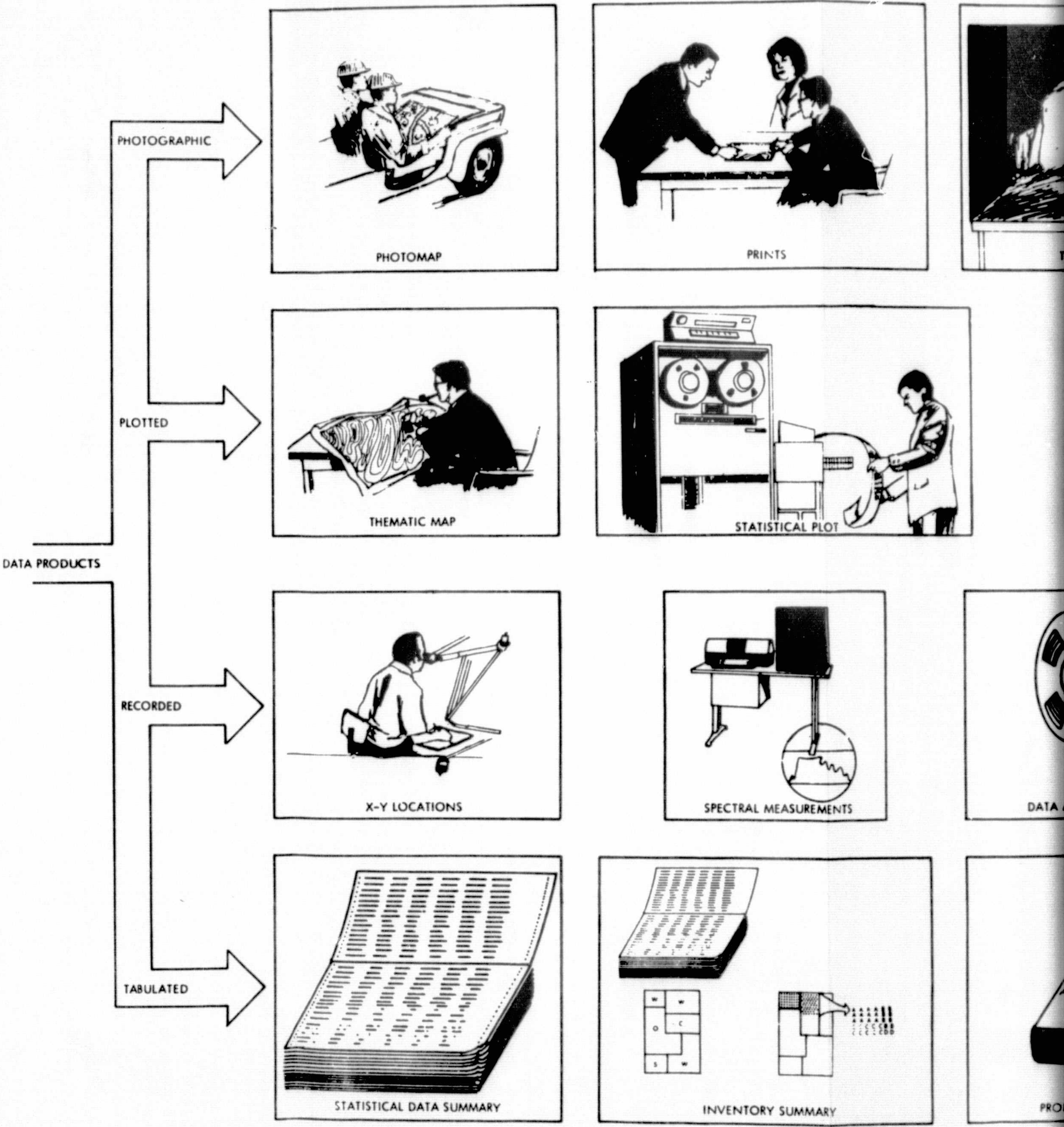
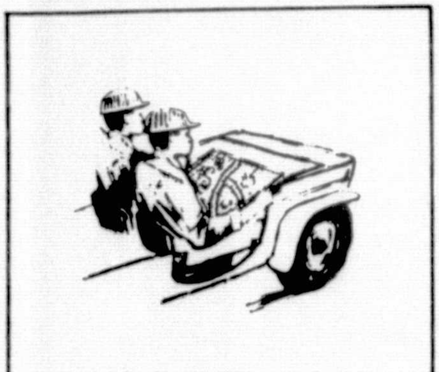
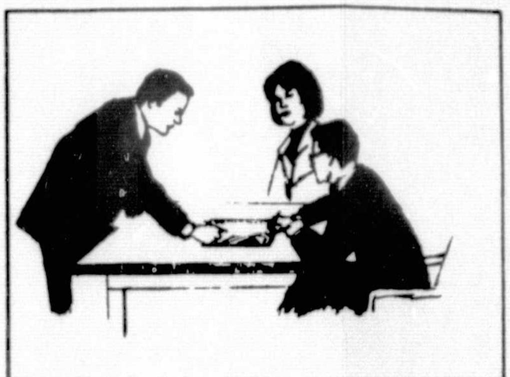
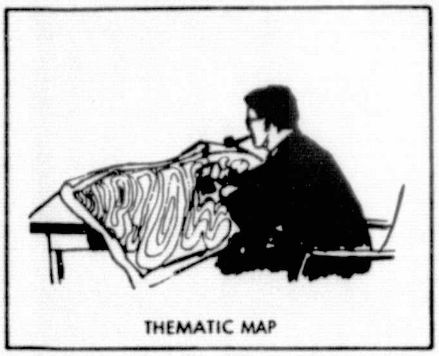

DATA PRODUCTS
PHOTOGRAPHIC
PLOTTED
RECORDED
TABULATED
PHOTOMAP
PRINTS
THEMATIC MAP
STATISTICAL PLOT
X-Y LOCATIONS
SPECTRAL MEASUREMENTS
DATA
STATISTICAL DATA SUMMARY
INVENTORY SUMMARY
PRO

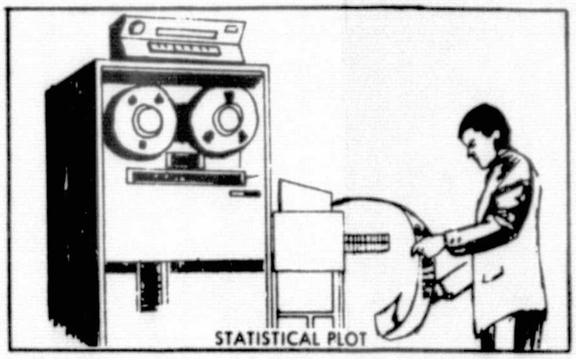
Figure 3-1. Da

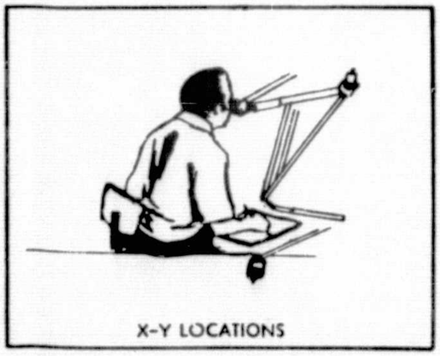

PHOTOMAP

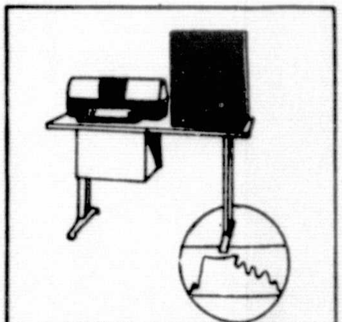

PRINTS

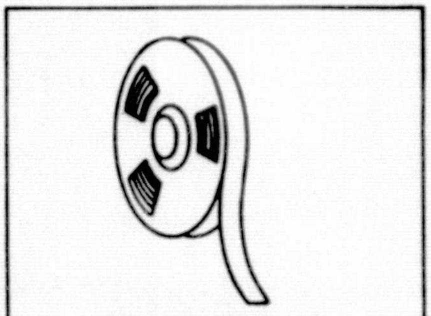

TRANSPARENCIES

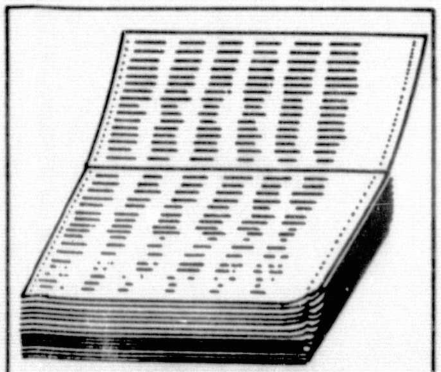

THEMATIC MAP

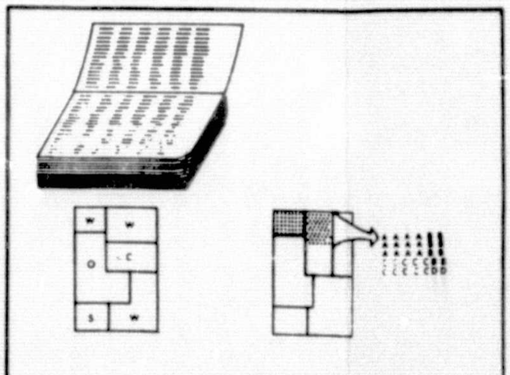

STATISTICAL PLOT

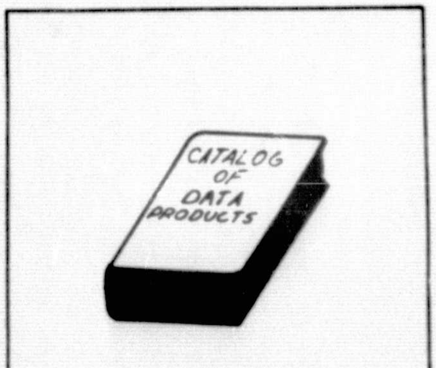

X-Y LOCATIONS


SPECTRAL MEASUREMENTS


DATA AND PROGRAM TAPE


STATISTICAL DATA SUMMARY


INVENTORY SUMMARY



PRODUCTION SUMMARY

Figure 3-1. Data Products Family

3.2 Sensor Use Profiles

Based on the candidate data uses/requirements and mission constraints (e.g., booster and orbital specifications) a set of sensors for each mission has been selected from the list in Task 2. These mission/sensor groupings were presented for approval at the first contract performance review in September-1973 and are summarized in Table 3-15.

Table 3-15. Mission/Sensor Grouping

MISSION ↓ / SENSORS →	SCANNING SPECTRO-RADIOMETER	POINTABLE IMAGER	IMAGING RADAR	PASSIVE MICROWAVE RADIOMETER	OCEANIC SCANNING SPECTROPHOTOMETER	SEA SURFACE TEMP. IMAGING RADIOMETER	ADV. ATM. SOUNDER	IMAGING RADIOMETER	CONSTANT RESOLUTION MET. SCANNER	DATA COLLECTION & LOCATION SYSTEM	DUAL MODE IMAGING SPECTRORADIOMETER	FILM RECOVERY SYSTEMS	COMB. SCANNING S.R. / POINTABLE IMAGER
1. TERRESTRIAL SURVEY ENVIRONMENTAL QUALITY (R)	X	X					X			X			
2. OCEAN SURVEY METEOROLOGICAL (R)		X			X	X	X			X			
3. TERRESTRIAL SURVEY/ ENVIRONMENTAL QUALITY (R)			X				X			X		X	X
4. OCEAN SURVEY/ METEOROLOGICAL (R)				X	X	X	X		X	X		X	
5. TRANSIENT ENVIRONMENTAL PHENOMENA MONITORING (R)							X			X	X		
6. TERRESTRIAL SURVEY ENVIRONMENTAL QUALITY (O)			X				X			X			X
7. OCEAN SURVEY/ METEOROLOGICAL (O)				X	X		X		X	X			
8. METEOROLOGICAL (R)							X	X	X	X		X	
9. METEOROLOGICAL (R)			X	X			X	X	X	X		X	

The groupings were structured for optimal satisfaction of stated mission objectives with the proviso that payload power, volume, and weight requirements must be held within constraints imposed by launch vehicle and spacecraft payload capabilities.

User requirements for areal coverage and frequency of observation dictate the amount of time that a given sensor is operated during a particular mission. Operating time, in turn, determines the data load requiring management for a sensor operating at a given data rate. Sensor use profiles, then, are highly dependent upon the objectives of the various missions as will be illustrated in the following subsections.

3.2.1 Mission 1 (Terrestrial Survey/Environmental Quality, Research)

Mission sensors would be operated only while over CONUS and territories. The profiles below (Figure 3-2) represent sensor operation

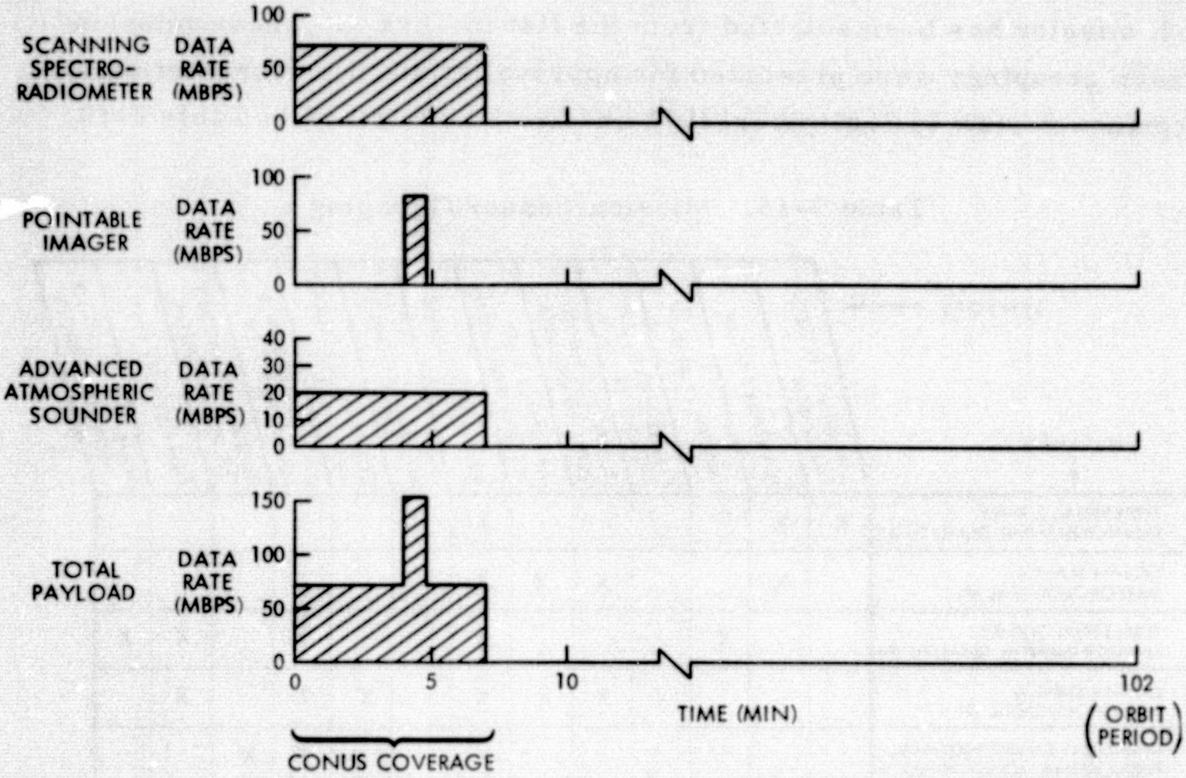


Figure 3-2. Mission 1 - Terrestrial Survey/Environmental Quality

during an orbit which carries the spacecraft directly over CONUS during daylight hours. The profiles illustrate the high data rate density generated in a short time, contrasted to zero data rates which are the mode for this mission. The assumption has been made that the pointable imager, which provides high-resolution data, is operated only 10 percent of the time while over CONUS.

3.2.2 Mission 2 (Ocean Survey/Meteorology, Research)

This mission shall constitute the first in a series of three to culminate in an operational system adequately addressing global oceanological and meteorological user data needs. The first mission will be different from the rest, however, in that it shall be optimized for routine surveillance of dynamic oceanic and meteorological phenomena with emphasis on the North American continental margin. As such, the

Mission 2 sensors would be operated only over the U.S. coastal area. The profiles which appear below (Figure 3-3) represent sensor duty cycles for an average orbit.

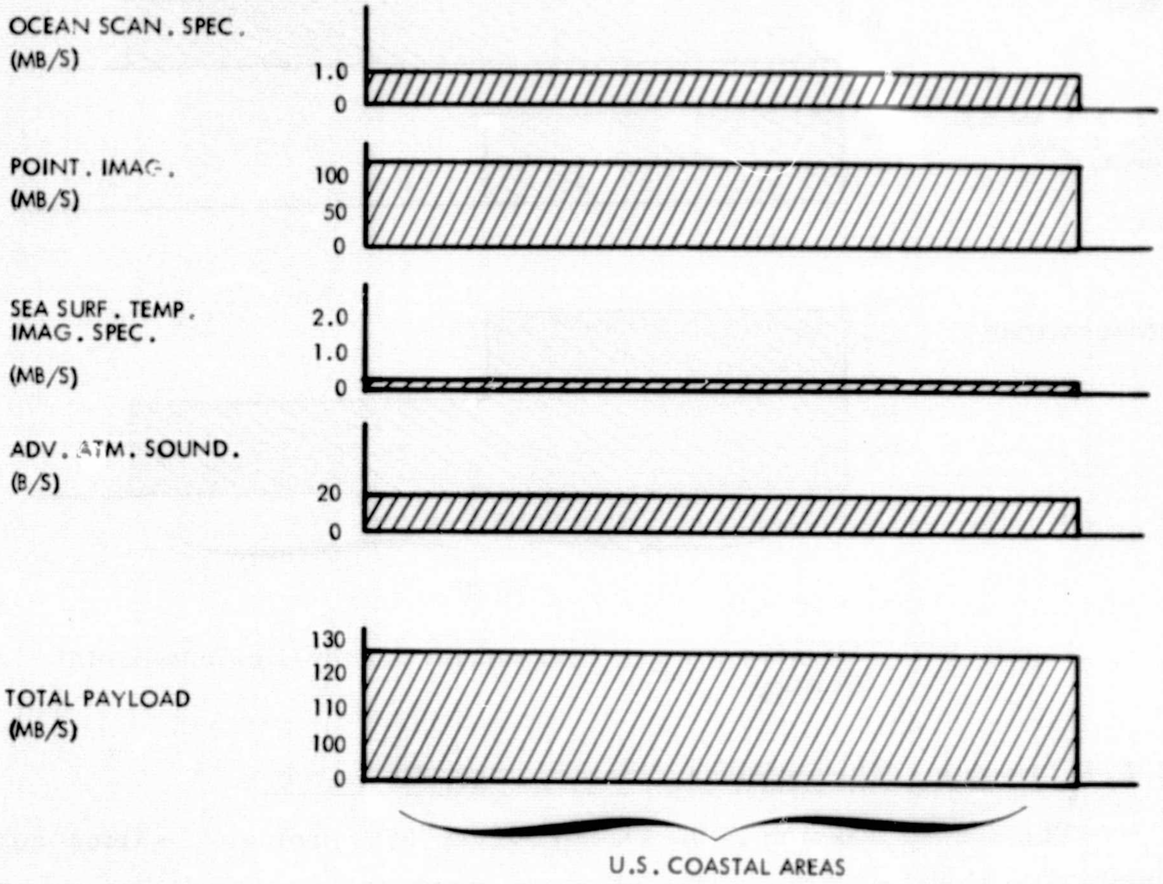


Figure 3-3. Mission 2 - Ocean Survey/Meteorology

3.2.3 Missions 3 and 6 (Terrestrial Survey/Environmental Quality)

Mission 3 is the second research satellite in the Terrestrial Survey/ Environmental Quality series and shall address substantially the same major application areas as Mission 1. The major difference between the two missions will be the increased data rates and data loads generated by the second mission due to a higher orbital altitude and improvements in sensor optics. Mission 6 represents the final and operational system in this series, and as such will have slightly larger data loads. The profiles illustrated in Figure 3-4 represent sensor operation during an orbit which carries the spacecraft directly over CONUS during daylight hours.

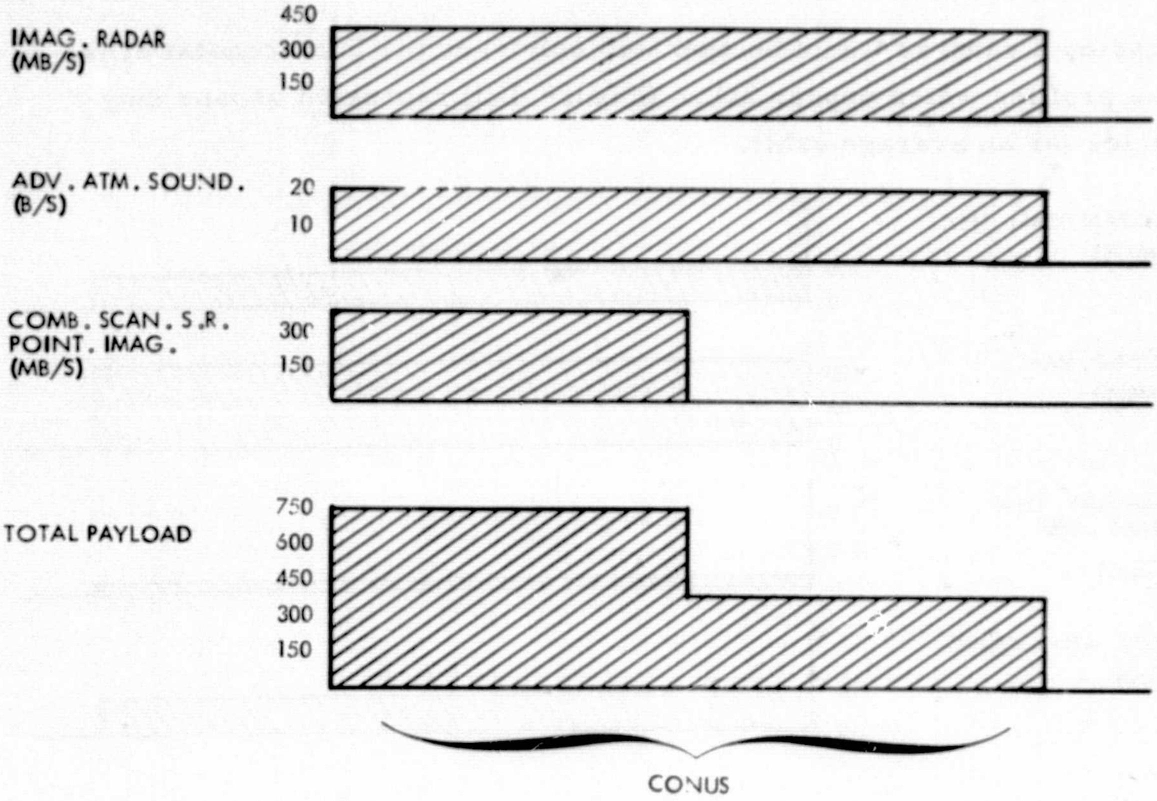


Figure 3-4. Mission 3 + 6 - Terrestrial Survey/Environmental Quality

3.2.4 Mission 4 (Ocean Survey/Meteorology, Research)

The second mission in the Ocean Survey/Meteorological series will emphasize global synoptic surveillance of large-scale oceanic-atmospheric phenomena. The sensors in Mission 4 would be operated most of the time as can be seen by the use profiles in Figure 3-5. These profiles illustrate moderate data rates coupled with extended sensor operating periods, which results in the generation of significantly heavy data loads during each orbit.

3.2.5 Mission 5 (Transient Environmental Phenomena Monitoring, Research

This mission is designed to permit real-time monitoring of natural disasters and other large-scale phenomena. It will constitute an important element in a system structured to enable prediction, dissemination of warnings, assessment of damages, and enforcement of controls. In generating the sensor use profiles (Figure 3-6) for Mission 5, the assumption has been made that the Dual-Mode Imaging Spectroradiometer

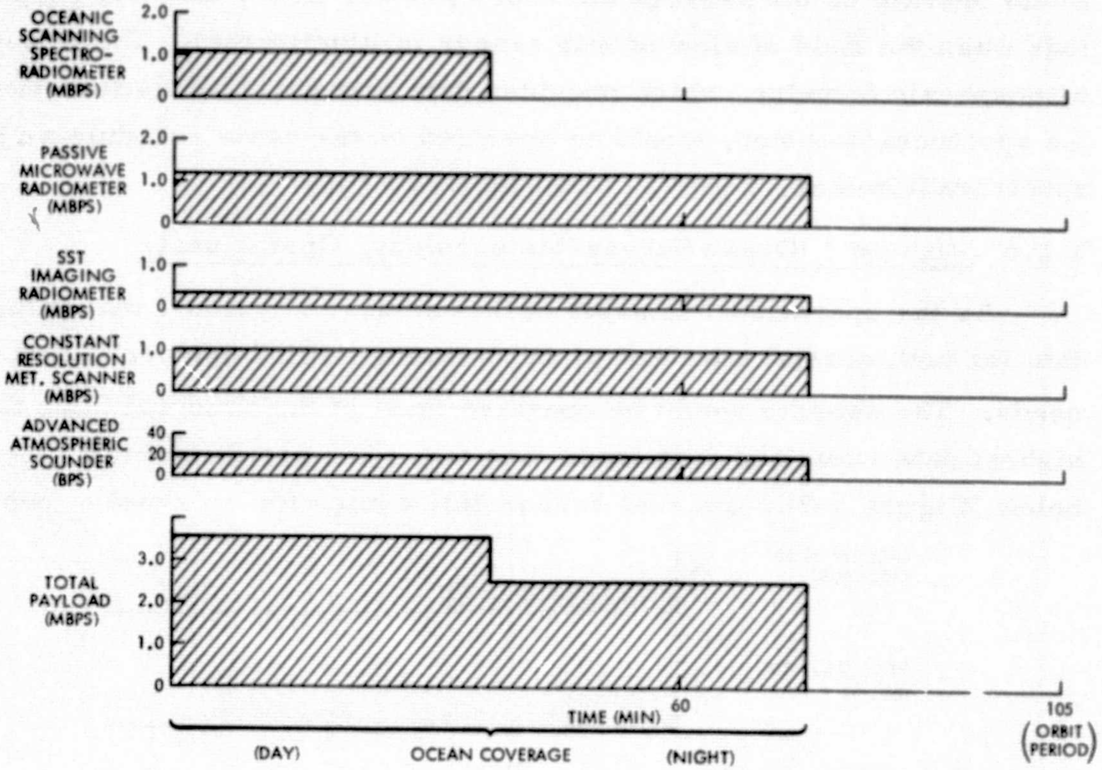


Figure 3-5. Mission 4 - Ocean Survey/Meteorology

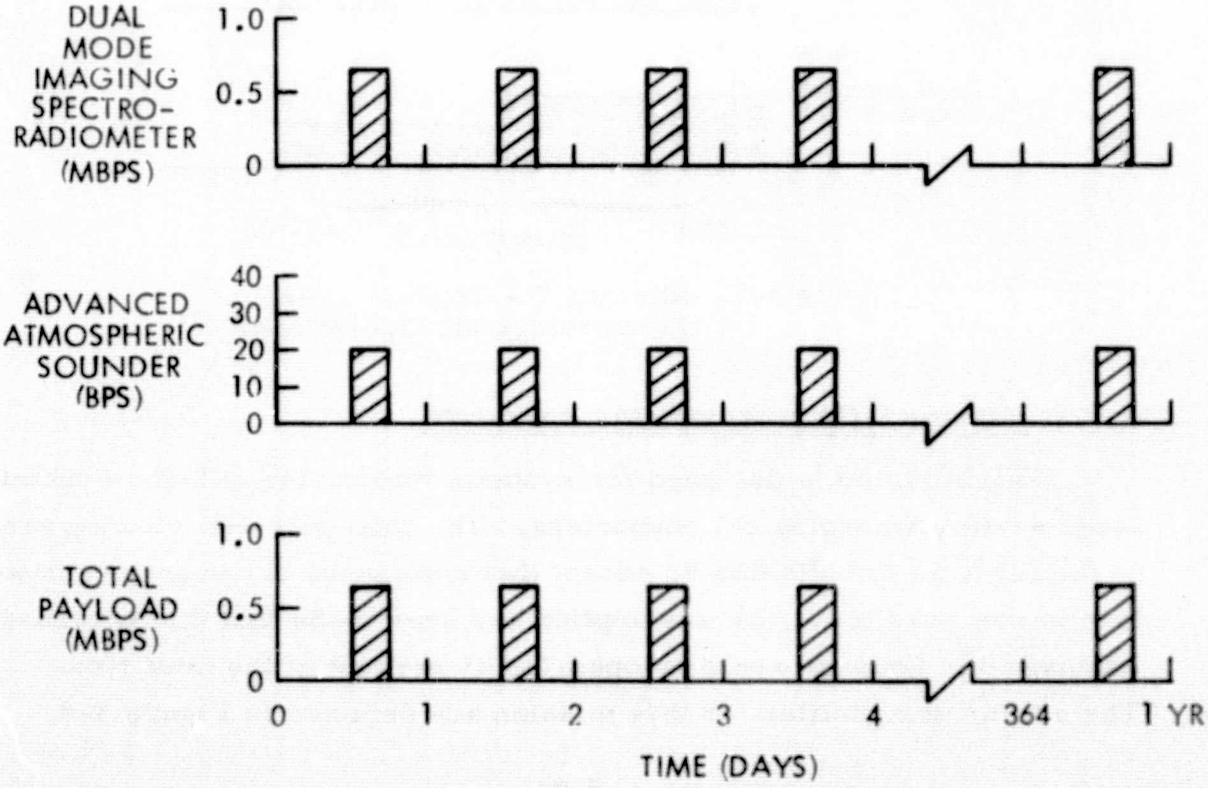


Figure 3-6. Mission 5 - Transient Environmental Phenomena Monitoring

would operate on the average six hours per day (i.e., only during periods when the field of view of this sensor is illuminated). The Advanced Atmospheric Sounder, which provides data primarily for calibration of the spectroradiometer, would be operated on the same schedule as the spectroradiometer.

3.2.6 Mission 7 (Ocean Survey/Meteorology, Operational)

As the operational mission of this series, Mission 7 will gather data for both coastal zone and global oceanographic/meteorological user needs. The sensors would be operated most of the time and have the highest data rates and data loads thus far. The profiles which appear below (Figure 3-7) represent sensor duty cycles for an average orbit.

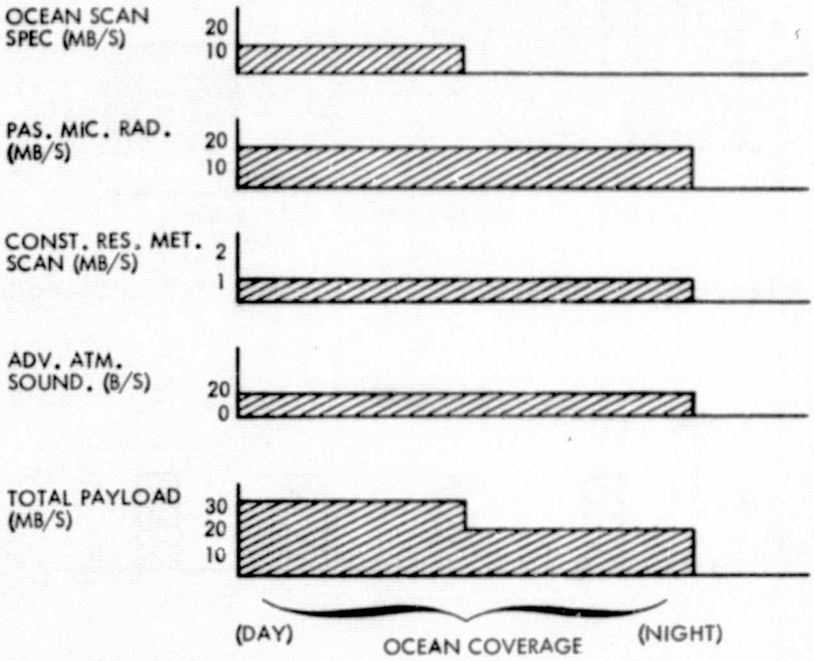


Figure 3-7. Mission 7 - Ocean Survey/ Meteorological, Operational

3.2.7 Mission 8 (Meteorological, Research)

This mission is designed for synoptic monitoring of highy dynamic large scale meteorological phenomena. The total potential viewing area is the same as for Mission 5, except that continuous day/night observation is now possible. The assumption has been made that the Advanced Atmospheric Sounder would be operated 25 percent of the total time. The sensor use profiles for this mission are depicted in Figure 3-8.

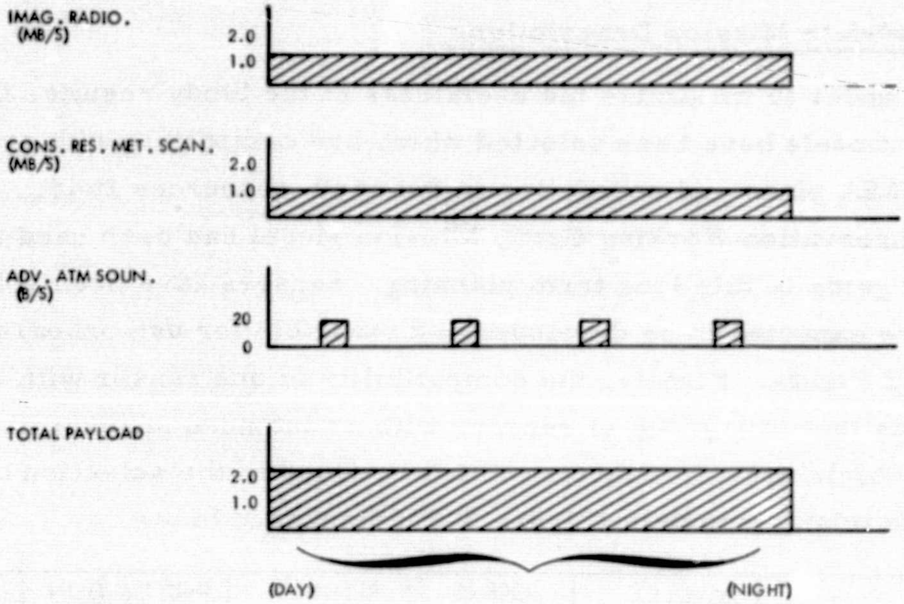


Figure 3-8. Mission 8 - Meteorological, Research

3.2.8 Mission 9 (Meteorological, Research)

This mission is designed to provide high resolution, high frequency data to aid meteorologists in the detection, monitoring, and prediction of dynamic weather systems in the tropical latitudes. Intermittent operation of the sensors is assumed for basic areal coverage during day and night. The sensor use profiles for Mission 9 are depicted in Figure 3-9.

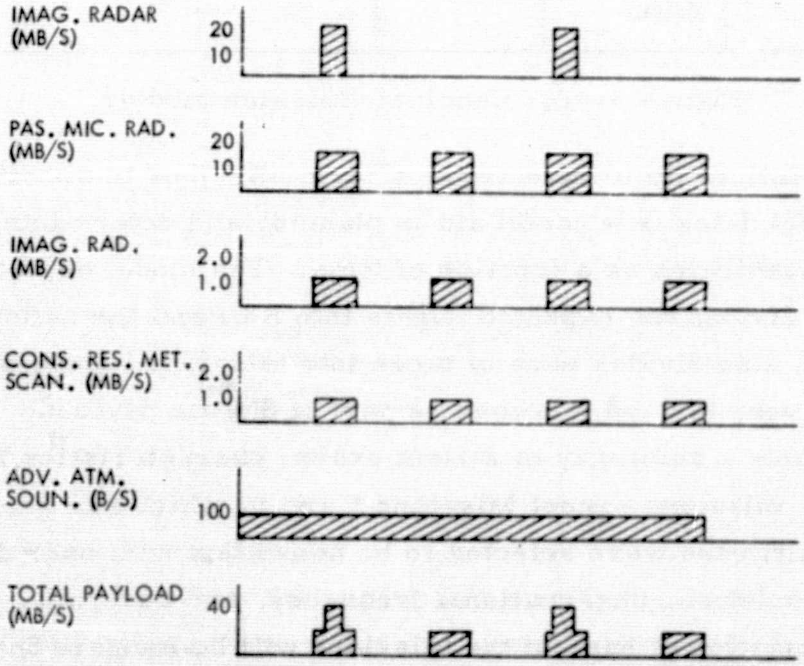


Figure 3-9. Mission 9 - Meteorological, Research

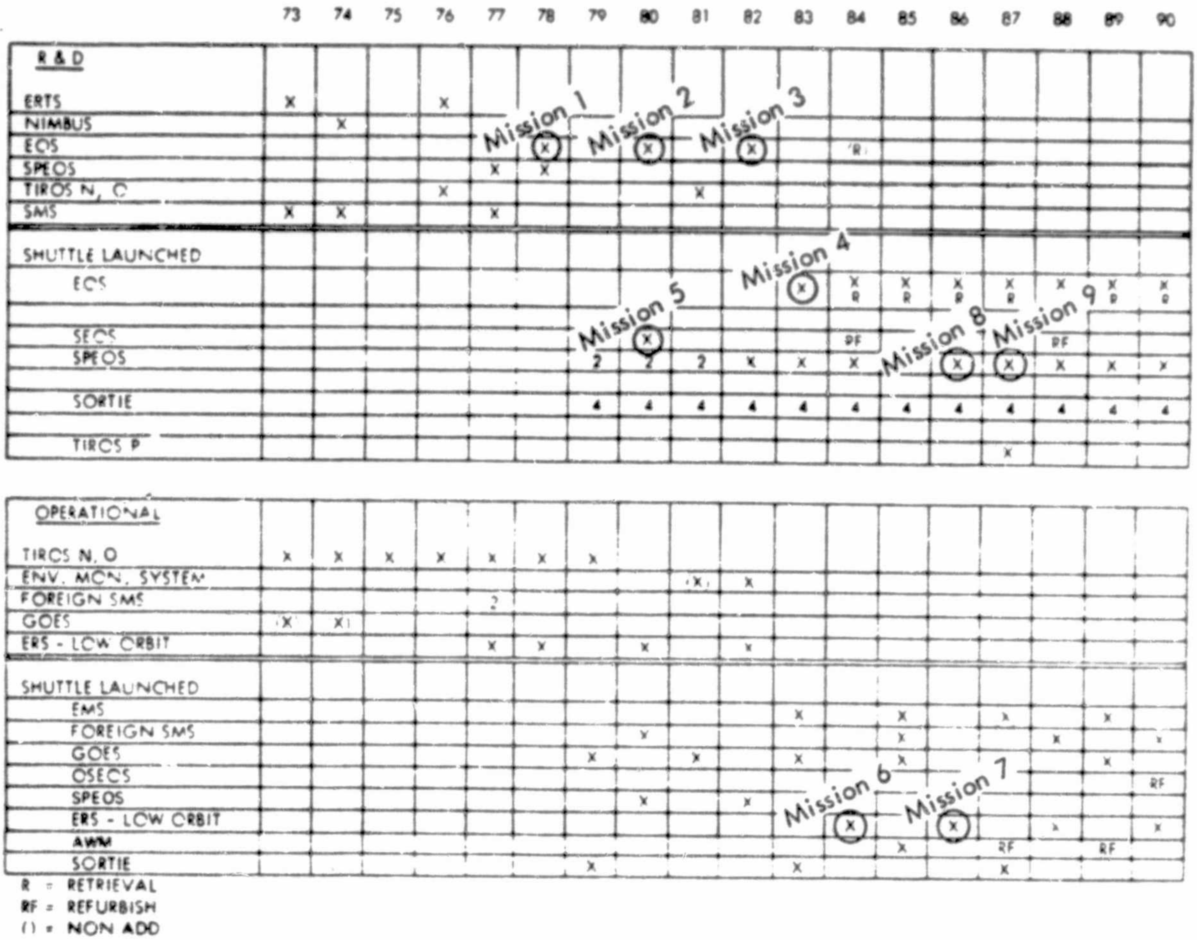
3.3 Candidate Mission Descriptions

In order to maximize the usefulness of the Study results, candidate mission models have been selected which are compatible with presently known NASA plans and scheduling in the earth resources field. The Earth Observation Working Group Mission Model has been used as a primary guide to this long term planning. Sensors have been selected which are expected to be developed and available for use onboard the projected flights. Finally, the compatibility of one sensor with another as well as that of a group of sensors with an intended spacecraft and launch vehicle are other factors which have led to the selection of the candidate mission models (Figure 3-10) discussed below.

MISSIONS		CYCLIC FREQ.	ORBITS / DAY	ALTITUDE KM (NMI)	INCLINATION (DEGREES)	PERIOD (MIN.)
TERRESTRIAL	(1)	17 (DAYS)	14-2/17	852(460)	98° 49'	101.97
	(3)	14 (DAYS)	14-3/14	707(382)	98° 12'	98.93
	(6)	10 (DAYS)	13-3/10	1146(619)	100° 09'	108.26
OCEANO-GRAPHIC	(2)	1 (DAYS)	14	895(483)	99° 00'	102.87
	(4)	7 (DAYS)	13-5/7	995(537)	99° 27'	105.00
	(7)	3 (DAYS)	13-1/3	1133(612)	100° 05'	107.99
METEOR-OLOGY	(9)	123.85 (MIN.)		1852(1000)	0	123.85

Figure 3-10. Candidate Mission Models

The relationship of selected candidate missions to specific EOWG Mission Model dates is a useful aid in planning and determining payload needs and capabilities as a function of time. The model depicted in Figure 3-11 divides the expected flights into R&D and Operational missions and also divides each of these into missions launched directly from launch vehicles and launched as part of Shuttle payload. Figure 3-12 represents a summary of salient orbital characteristics for each of the candidate missions except Missions 5 and 8, which are geosynchronous. The orbital altitudes were selected to be consistent with user data requirements for resolution, observational frequency, and coverage. A more detailed description of each of the missions will be found in Subsections 3.3.1 through 3.3.9.



	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
R & D																		
ERTS	X			X														
NIMBUS		X																
EOS						⊗		⊗		⊗		(R)						
SPEOS					X	X												
TIROS N, C				X					X									
SMS	X	X			X													
SHUTTLE LAUNCHED																		
EOS											⊗	X R	X R	X R	X R	X	X R	X R
SEOS								⊗				RF				RF		
SPEOS							2	2	2	X	X	X		⊗	⊗	X	X	X
SORTIE							4	4	4	4	4	4	4	4	4	4	4	4
TIROS P															X			

	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
OPERATIONAL																		
TIROS N, O	X	X	X	X	X	X	X											
ENV. MON. SYSTEM									(X)	X								
FOREIGN SMS					?													
GOES	(X)	(X)																
ERS - LOW ORBIT					X	X		X		X								
SHUTTLE LAUNCHED																		
EMS											X		X		X		X	
FOREIGN SMS								X					X			X		X
GOES							X		X		X		X				X	
OSECS																		RF
SPEOS								X		X								
ERS - LOW ORBIT												⊗		⊗		X		X
AWM													X		RF		RF	
SORTIE							X				X				X			

R = RETRIEVAL
RF = REFURBISH
( ) = NON ADD

Figure 3-11. Earth Observations Working Group Mission Model

Model No.	Function	Purpose	Orbit	Launch Vehicle
1	Terrestrial survey/ environmental quality	Research	Low altitude sun-synchronous	Improved Delta
2	Ocean survey/ meteorological	Research	Low altitude sun-synchronous	Improved Delta
3	Terrestrial survey/ environmental quality	Research	Low altitude sun-synchronous	Titan/Shuttle
4	Ocean survey/ meteorological	Research	Low altitude sun synchronous	Titan/Shuttle
5	Transient environmental phenomena monitoring	Research	24-hour equatorial	Titan-Centaur
6	Terrestrial survey/ environmental quality	Operational	Low altitude sun-synchronous	Improved Delta
7	Ocean survey/ meteorological	Operational	Low altitude sun-synchronous	Improved Delta
8	Meteorological	Research	24-hour equatorial	Titan/Shuttle
9	Meteorological	Research	Low altitude equatorial	To be determined

Figure 3-12. Mission Orbital Parameters Summary

3.3.1 Mission Model No. 1

3.3.1.1 General Mission Requirements

Function: Terrestrial Survey/Environmental Quality

Purpose: Research

Orbit: Approx. 852 km (460 nmi), sun synchronous

Expected Life: Approx. one year

Suggested EOWGMM* Counterpart: EOS A

Launch Date (FY): Late 1978

Launch Vehicle: Improved Delta

Sensor Complement:

- Scanning Spectroradiometer
- Pointable Imager
- Advanced Atmospheric Sounder
- Data Collection and Location System

3.3.1.2 Mission Description

This mission shall constitute the first in a series of three missions addressing user needs for Terrestrial Survey and management of environmental quality. The first and second missions in the series are to be research missions--precursors to the third mission, which shall be operational in purpose.

The research nature of the first two missions applies not only to the use of an orbital platform as a testbed for the development of sensors and as a means for accomplishing environmental research: emphasis shall also be placed upon development of data handling technology consistent with the overall goals and objectives of the NASA Earth Resources Program Plan. The goal of the developmental program for data handling technology should be the evolution of a system fully adequate to deal effectively with data generated by the operational missions. Accordingly, the first research mission shall involve dissemination of raw and near-raw (calibration factors applied) data to all potential users capable of handling such data, in near-real time. The intent of this approach is to permit

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*Earth Observations Working Group Mission Model

C-2

independent data processing and analysis (additional to research conducted by NASA) by user agencies in order that they may converge on optimal data handling approaches tailored to their specific needs.

The output of this research should drive specifications for data handling technology for the second in the series of research missions, which would involve special processing at the GDHC (ground data handling center) and dissemination of partially processed data, combined in some cases with data from other sources, such as the National Data Buoy System.

By the time the operational system is implemented, all user agencies will have delineated their requirements for special processing and formatting such that the GDHC may provide final form data directly to user agencies for analysis and interpretation.

According to the above scenario, a central data handling facility for earth resources data would evolve from a dissemination center for raw data, to a dissemination center for processed data, and finally to a dissemination center for specially formatted data or information suitable for direct use by agencies served. Table 3-16 summarizes the development of data handling technology in the earth resources disciplines.

The basic objectives of the first mission are those established for the ERTS satellites; however, emphasis will be placed upon application of environmental remote sensing technology developed during and subsequent to the periods of useful operation of the ERTS platforms. Emphasis shall be placed upon interpretation of remotely-sensed data and development of data handling systems with the ultimate goal of capability for accommodating the data produced by an operational system. Major application areas shall include:

- Development of rapid, large area inventory techniques for major crop, timber, and range species
- Development of techniques for stress detection, identification, and monitoring of productivity for the major vegetation species
- Development of mapping and cartographic technology for analysis of land use and mineral resource exploration
- Acquisition of data to advance understanding of Earth science and for assessment of potential geological hazard

- Mapping water on the surface of the Earth
- Detection, location and identification, assessment, monitoring, and prediction of effect of environmental pollution
- Geothermal exploration.

Table 3-16. Special Data Handling Considerations

1.	Terrestrial Survey/ Environmental Quality (R)	Near-raw data* dissemination in near-real time to users and GDHF (independent processing and analysis)
2.	Ocean Survey/ Meteorological (R)	ditto
3.	Terrestrial Survey/ Environmental Quality (R)	Processed data dissemination (data in appropriate eng. units for all users). Some data in special format per user request.
4.	Ocean Survey/ Meteorological (R)	ditto
5.	Transient Environmental Phenomena Monitoring (R)	Mode of data processing and dissemination to be determined on ad hoc basis.
6.	Terrestrial Survey/ Environmental Quality (O)	Formatted data dissemination. (Selective data dissemination tailored to users' requirements re: annotation, screening, data form and quantity, format, etc.). All data formatted according to established user demands (might include raw data).
7.	Ocean Survey/ Meteorological (O)	
8.	Meteorological (R)	
9.	Meteorological (R)	

* data corrected at GDHC only for:
1. Geometric error
2. Photometric/radiometric error.

Orbital Considerations

The orbital altitude selected for Mission I represents a compromise between ground resolution and frequency of coverage requirements. The assumption is made that it would be better for purposes of overall system development, including data handling, to retain optimal frequencies of coverage at the expense of optimal ground resolution.

Working at optimal coverage frequencies is likely to carry more critical implications for data handling during this first research mission than is working at higher ground resolutions: the latter impacts only the data rates and total load, whereas the former impacts data rates and loads and affects the data routing schedule.

3.3.2 Mission Model No. 2

3.3.2.1 General Mission Requirements

Function: Ocean Survey/Meteorological
Purpose: Research
Orbit: Approximately 895 km (483 nmi), syn synchronous
Expected Life: Approximately one year
Suggested EOWGMM counterpart: EOS-B
Launch Date (FY): 1980
Launch Vehicle: Improved Delta
Sensor Complement:

- Pointable Imager
- Oceanic Scanning Spectrophotometer
- SST Imaging Radiometer
- Imaging Radiometer
- Advanced Atmospheric Sounder
- Data Collection and Location System

3.3.2.2 Mission Description

This mission shall constitute the first in a series of three missions to culminate in an operational system adequately addressing user needs for synoptic oceanological and meteorological data. As with the Terrestrial Survey/Environmental Quality series, the first two missions are to be R&D precursors to the third, operational, mission.

Also, as in the case with the Terrestrial/Environmental series, a progression in refinement of data handling techniques as well as in sensor technology is anticipated to develop through the series.

Unlike the Terrestrial/Environmental series, however, the first Ocean Survey/Meteorological mission will address user needs substantially different from those addressed by the second mission in the series. The first shall be optimized for routine surveillance of dynamic oceanic and meteorlogical phenomena with emphasis on the North American continental margin. It will provide an abundance of accurate, timely data on coastal and polar processes. This will in turn permit all potential users of maritime data to converge on data handling techniques which are optimal for their specific individual program objectives. Major application areas shall include:

- Coastal nearshore and estuarine circulation dynamics
- Monitoring of phenomena affecting the status and distribution of populations of living marine resources in the coastal zone (pollutants, natural environmental variation)
- Status and dynamics of physiographic features subject to marine erosional-depositional forces and to human engineering activities
- Causes and effects of dynamic processes in polar regions
- Effectiveness of remedial measures initiated to counter adverse environmental conditions (e.g., storms, pollution episodes); surveillance of damage incurred by natural hazards
- Sources and fates of unnatural materials (especially ocean and atmospheric pollutants)
- Monitoring of air/sea/land interactive phenomena as they impact upon coastal meteorology
- Monitoring of shipping activities.

Orbital Considerations

The orbit selected for the first mission in the Ocean Survey/ Meteorological series is syn-synchronous at 728 km. Tradeoffs associated with specification or orbits compatible with coastal zone data uses information requirements have been examined in a previous study (Reference: "Coastal Zone Requirements for EOS A/B, Final Report, prepared by TRW Systems for NASA Langley Research Center, 4 February 1971). The 728 km altitude chosen is reasonable in view of the conflicting requirements for high resolution and frequent coverage at the launch data assumed, which presses the projected sensor resolution capabilities somewhat (large optics impose serious volume/weight constraints on the launch vehicle). A near-daily repeat cycle is deemed more valuable for this early Ocean Survey/Meteorology mission than is very high ground resolution.

3.3.3 Mission Model No. 3

3.3.3.1 General Mission Requirements

Function: Terrestrial Survey/Environmental Quality
Purpose: Research
Orbit: Approximately 707 km (382 nmi), sun synchronous
Expected Life: Approximately one year
Suggested EOWGMM Counterpart: EOSC
Launch Date (FY): 1982
Launch Vehicle: Titan/Shuttle
Sensor Complement:

- Imaging Radar
- Combined Scanning Spectroradiometer/Pointable Imager
- Advanced Atmospheric Sounder
- Data Collection and Location System
- Film Recovery System

3.3.2.2 Mission Description

The second research satellite in the Terrestrial Survey/Environmental Quality series shall address substantially the same major application areas as specified for Mission No. 1. The orbital altitude will be increased to enhance coverage frequency. Presumably, high resolution can be maintained with improvements in optics. The major difference between the first and second missions will be the higher data rates and data loads generated by the second mission.

Orbital Considerations

The orbit selected for the second research mission in the Terrestrial Survey/Environmental Quality series is the lowest of all missions considered in the present study. The low orbit coupled with advances in sensor resolution capabilities, will provide data at resolutions adequate for satisfaction of the majority of user requirements for orbital remotely-sensed data. Although frequency of coverage will be increased somewhat over that for the first mission (14 day cycle over a given ground reference point, as opposed to a 17 day cycle over the same point for the first Terrestrial Survey/Environmental Quality mission).

- It is expected that the data flow from this mission will impose more severe overall on the data handling system than will be the case for any of the other missions except Mission 6 (Operational Terrestrial Survey/Environmental Quality).
- Data processive and routing requirements.

3.3.4 Mission Model No. 4

3.3.4.1 General Mission Requirements

Function: Ocean Survey/Meteorological

Purpose: Research

Orbit: Approximately 995 km (537 nmi), sun synchronous

Expected Life: Approximately one year

Suggested EOWGMM Counterpart: EOS D

Launch Date (FY): 1983

Launch Vehicle: Titan/Shuttle

Sensor Complement:

- Passive Microwave Radiometer
- Oceanic Scanning Spectroradiometer
- Constant Resolution Meteorological Scanner
- Imaging Radiometer
- Advanced Atmospheric Sounder
- Data Collection and Location System
- Film Recovery System

3.3.4.2 Mission Description

The second mission in the Ocean Survey/Meteorological series shall emphasize global synoptic surveillance of large-scale oceanic-atmospheric phenomena, at time intervals appropriate for gaining better understanding of the dynamics of these phenomena. Primary emphasis will be on ocean survey; secondary emphasis will be on meteorology. In contrast to the first mission in the series, small-scale oceanic features shall not receive emphasis; rather, the second mission will be designed to be a critically valuable element in a system for monitoring phenomena of broad area and global significance.

Major areas of application include:

- Dynamics of ocean surface circulation and associated atmospheric coupling effects
- Distribution and variability in factors affecting population dynamics and migrations of living marine resources (especially phytoplankton and temperature)
- Analysis and prediction of sea state and swell
- Monitoring of large-scale polar processes
- Synoptic analysis of the global heat budget
- Monitoring the benesis, progress, and dissipation of major weather systems
- Charting of navigational hazards
- Assessment of potential for forest fires; detection and monitoring of forest fires
- Monitoring of potential for frost hazard
- Detection of incipient pollution episodes (especially oil spills)
- Measurement of highly time-variant changes in water quality parameters (effluence patterns, saline intrusion, etc.)
- Snow cover survey.

Orbital Considerations

The 1019 km (550 nmi), sun synchronous orbit was selected for the fourth mission to provide synoptic global coverage of the dynamic phenomena listed above at moderately short observational intervals (seven day cyclic frequency). There is no requirement for the high resolution, high frequency data that was the case for the coastal research mission (Mission No. 2).

3.3.5 Mission Model No. 5

3.3.5.1 General Mission Characteristics

Function: Transient Environmental Phenomena Monitoring

Purpose: Research

Orbit: 35,870 km (22,674 nmi), geostationary

Expected Life: Approximately one year

Suggested EOWGMM Counterpart: SEOS

Launch Date (FY): 1980

Launch Vehicle: Titan-Transtage

Sensor Complement:

- Dual Mode Imaging Spectroradiometer
- Advanced Atmospheric Sounder
- Data Collection and Location System

3.3.5.2 Mission Description

This mission is designed to permit real-time monitoring of natural disasters (first priority) and other large-scale phenomena which:

1) Are ephemeral,
2) Undergo rapid changes (significant changes in a matter of hours or a day),
3) Require detection in incipient stages for complete understanding of their dynamics, or
4) Require near-continuous monitoring to compensate for periods of cloud obscuration or undesirable illumination conditions.

Data generated during this mission will contribute to satisfaction of potential user requirements for continuous or near-continuous observations. The mission will constitute an important element in a system structured to enable prediction, dissemination of warnings, assessment of damages, and enforcement of controls.

Major application areas shall include:

- Observation, detection, and tracking of the development of severe local storms; storm damage survey
- Monitoring of river basin flow rates and water levels to improve prediction of flooding; monitoring of flood extent
- Assessment of potential for forest fires; detection and monitoring of forest fires
- Monitoring of potential for frost hazard

- Detection of incipient pollution episodes (especially oil spills)
- Measurement of highly time-variant changes in water quality parameters (effluence patterns, saline intrusion, etc.)
- Snow cover survey.

Orbital Considerations

Requirements for continuous ground data station visibility and continuous sensor viewing capability for a mission dedicated to detection and monitoring of transient environmental phenomena argue strongly for a geosynchronous orbit. Advantages lost in ground resolution ease are more than offset by advantages gained in uninterrupted viewing and data transmission.

3.3.6 Mission Model No. 6

3.3.6.1 General Mission Characteristics

Function: Terrestrial Survey/Environmental Quality
Purpose: Operational
Orbit: Approximately 1146 km (619 nmi), sun synchronous
Expected Life: Two years
Suggested EOWGMM Counterpart: ERS A
Launch Date (FY): 1984
Launch Vehicle: Shuttle
Sensor Complement:

- Imaging Radar
- Combined Scanning Spectroradiometer/Pointable Imager
- Advanced Atmospheric Sounder
- Data Collection and Location System

3.3.6.2 Mission Description

This mission represents the final and operational system in the mission series dedicated to Terrestrial Survey/Environmental Quality. As such, it will generate a data load larger than any of the other missions. Accordingly, data handling considerations will be most critical for this mission. Substantially the same application areas will be addressed as for the first two (research) Terrestrial/Environmental missions. The orbit will be optimized for coverage, repeatability, and ground resolution.

Orbital Considerations

For the operational Terrestrial Survey/Environmental Quality mission, a 11,112 km (600 nmi) orbit was chosen. Although substantially the same phenomena are observed as for the research satellites in this series, improved optics, larger antennas, and refinements in sensor technology are expected to permit an increase in orbital altitude without sacrificing ground resolution.

Increased coverage frequency and higher resolution will be reflected in commensurately increased data rates and data loads, representing the maximum mission data volume to dealt with by the data handling system.

3.3.7 Mission Model No. 7

3.3.7.1 General Mission Characteristics

7.1 Function: Ocean Survey/Meteorological

7.2 Purpose: Operational

7.3 Orbit: Approx. 1133 km (612 nmi), sun synchronous

7.4 Expected Life: Two years

7.5 Suggested EOWGMM Counterpart: ERS B

7.6 Launch Date (

7.7 Launch Vehicle: Shuttle

7.8 Sensor Complement:

- Passive Microwave Radiometer
- Oceanic Scanning Spectrophotometer
- Constant Resolution Meteorological Scanner
- Advanced Atmospheric Sounder
- Data Collection and Location System

3.3.7.2 Mission Description

As the operational mission of the Ocean Survey/Meteorological series, this mission will focus upon acquisition of data germane to both coastal zone and global oceanographic/meteorological user needs. The orbital specification represents a compromise between global drivers (for synoptic observations of large-scale dynamics) and coastal drivers (for high resolution, high frequency data). All areas of application listed for the research missions in the series shall be addressed by this operational mission.

Orbital Considerations

The operational Ocean Survey/Meteorological satellite shall be placed in a 1133 km sun-synchronous orbit with an observational repeat cycle of three days, consistent with its mission objectives for survey of coastal and global ocean surface phenomena, with meteorology as its secondary objective. It is anticipated that improvements in sensitivity of surface temperature sensors will justify relaxation of spatial resolution to some extent for this class of sensors: visible and microwave sensors are expected to operate at the optimal ground resolutions for coastal phenomena despite the increase in altitude over the 895 km coastal zone research mission (Mission Model No. 2).

3.3.8 Mission Model No. 8

3.3.8.1 General Mission Characteristics

8.1 Function: Meteorological

8.2 Purpose: Research

8.3 Orbit: 35,870 km (19,360 nmi), geostationary (24-hour equatorial)

8.4 Expected Life: One year

8.5 Suggested EOWGMM Counterpart: SPEOS

8.6 Launch Date (FY): 1986

8.7 Launch Vehicle: Shuttle

8.8 Sensor Complement:

- Imaging Radiometer
- Constant Resolution Meteorological Scanner
- Advanced Atmospheric Sounder
- Data Collection and Location System
- Film Recovery System

3.3.8.2 Mission Description

The purpose of this mission is to marshall the most highly sophisticated technology available in the early 1980s and apply it toward the monitoring, analysis, and prediction of atmospheric phenomena. Specific application shall include:

- Monitoring major weather systems from their terminal stages
- Short- and long-term dynamics of air masses containing heavy amounts of atmospheric pollutants
- Analysis of broad-scale (hemispheric) transport of atmospheric constituents (water, gaseous and particulate pollutants) and heat exchange.

Orbital Considerations

This mission is designed for synoptic monitoring of highly dynamic large scale meteorological phenomena: for this application, all but geosynchronous orbits are precluded. It is reasonable to expect that refinements of the sophisticated NOAA/NESC data handling system now in existence for SMS/GOES missions will be adequate to appropriately handle data from Mission 8 and other geosynchronous meteorological satellites. Accordingly, extensive study has not been devoted during subsequent tasks to examination of data handling requirements for this geosynchronous mission.

3.3.9 Mission Model No. 9

3.3.9.1 General Mission Characteristics

9.1 Function: Meteorological
9.2 Purpose: Research
9.3 Orbit: 1852 km (1000 nmi), equatorial
9.4 Expected Life: One year
9.5 Suggested EOWGMM Counterpart: SPEOS
9.6 Launch Date (FY): 1987
9.7 Launch Vehicle: Shuttle
9.8 Sensor Complement:

- Imaging Radar
- Passive Microwave Radiometer
- Imaging Radiometer
- Constant Resolution Meteorological Scanner
- Advanced Atmospheric Sounder
- Data Collection and Location System
- Film Recovery System

3.3.9.2 Mission Description

This mission is designed to provide much-needed high resolution, high frequency data to aid meteorologists in the detection, monitoring, and prediction of dynamic weather systems in tropical latitudes. High-resolution capability, unique among meteorological satellites, is needed to enhance understanding of important air-sea interactive phenomena. The high frequency, high resolution data from the mission will complement low-resolution, broad perspective data from geosynchronous meteorological satellites.

Orbital Considerations

An equatorial orbit at 1852 km (1000 nmi) is consistent with the stated objectives of this mission. At this altitude, it will be possible to cant sensors for oblique viewing of atmospheric/oceanic phenomena up to 20 degrees north and south latitudes.

3.3.10 Payload Compatibility With Launch Vehicle and Spacecraft

The combinations of sensors selected for use on each of the nine candidate missions described have also been analyzed to determine the resulting payload weights, powers, and maximum data rate associated with each mission. This information is depicted in Figure 3-13 and is compared with anticipated launch vehicle payload carrying capabilities. A more detailed discussion of the data requirements (data rates, data loads, etc.) is presented in Section 4 of this report.

MISSION	PAYLOAD				LAUNCH VEHICLE PAYLOAD CAPABILITY
	WEIGHT* (KG)	VOLUME* (M^3)	POWER* (WATTS)	MAX. DATA RATE (MBITS/SEC)	
1	313	1.62	228	154	1050 (DELTA)
2	154(1)	0.33(1)	273(1)	126(1)	750 (DELTA)
3	1009	5.57	2423	728	3400/1400 (TITAN/SHUTTLE-DELTA)
4	434(1)	0.22(1,3)	1783(1)	4.5(1)	3000/10,000 (TITAN/SHUTTLE)
5	1044	?	188	0.6	6200 (TITAN-TRANSTAGE)
6	1009	5.57	2423	728	5300/9000 (TITAN/SHUTTLE-DELTA)
7	1165(2)	0.31(2,3,4)	3308(2)	32(2)	5300/9000 (TITAN/SHUTTLE-DELTA)
8	151	0.08(3)	158	2	6200/2400 (TITAN/SHUTTLE-DELTA)
9	1606	2.22(3,4)	5358	41	7000 (SHUTTLE-AGENA)

* NOT INCLUDING DCLS OR FILM RECOVER SYSTEMS

(1) ASSUMES ELECTRONIC SCAN SPECTROPHOTOMETER
(2) ASSUMES MECHANICAL SCAN SPECTROPHOTOMETER
(3) NOT INCLUDING CONSTANT RESOLUTION METEOROLOGICAL SCANNER
(4) NOT INCLUDING MICROWAVE ANTENNA

Figure 3-13. Payload Compatibility with Launch Vehicle and Spacecraft

4. DATA REQUIREMENTS SUMMARY

The purpose of this task was to provide a quantitative baseline for the performance of Phase B (Tasks 5, 6, 7, and 8). The parameters considered were data rate, profile, total data loads, data perishability, source and destination locations, geometric and photometric quality requirements, and other data handling system driver requirements.

4.1 Data Handling System Requirements--Summary

The data handling requirements were summarized for each mission in a matrix-like format. The items covered were:

	Reference Section
● Payload	3.3
● Operating Data Rate	2.3.2
● Sensor Use Profiles	3.2
● Primary Data Destinations	3.1
● Sensor Data Quality and Preprocessing Requirements	2.3.2
● Maximum Data Rate	2.3.2
● Data Perishability	3.1
● Data Load	

The first seven items were derived for each mission in Tasks 2 and 3 and the remaining item, Data Load, was completed in Task 4. Section 4.1.1 describes the process used to compute data load.

4.1.1 Estimation of Data Volume/Time Profiles for Each Mission

The volume of data generated by a remote sensing instrument is dependent upon the operating data rate and the duty cycle, which is the amount of time that the sensor is operated. The data rate (number of bits generated per second) is a function of:

- Sensor swath width and ground speed (parameters which are optimized for coverage of areas of interest)
- Number of spatial resolution elements required per unit ground area
- Number of levels of sensitivity used
- Spectral resolution required for raw data.

Sensor use profiles were established through consideration of coverage requirements for each mission. Data loads generated per year for each sensor were estimated by applying the following approximate equation:

$$L = \frac{2\,T}{F_C} \; \frac{A_C}{A_G} \; F_C \, R_D$$

where L = sensor data load per year

T = 31,556,736 sec/year

F_C = satellite cyclic frequency

A_C = area (km^2) of globe requiring coverage

A_G = surface area of globe

R_D = operating data rate of the sensor (Mbits/sec)

The equation simplifies to: $L = 2\,T\,R_D\,(A_C/A_G)$

The factor of 2 is deleted for sensors requiring daytime observations (these sensors achieve coverage of A_C only once per cycle: day-night sensors achieve double coverage during the same amount of time). See Section 2.3 for calculation of sensor data rate.

Some simplifying assumptions are associated with application of the equation in calculating data loads for the missions. For example, during the earlier tasks involving sensor characterization, assumption of an orbital altitude figured into determination of sensor data rates. The orbital altitudes assumed for data rate calculation differ somewhat from actual altitudes subsequently specified for each mission; however, the effect of this factor on data load is small relative to the effects of coverage considerations.

For certain missions, utilization of the full swath width capability of a sensor might result in generation of superfluous data. The convention of estimating sensor operating time on the basis of area requiring coverage ignores swath width considerations. One might imagine that, in practice, only a portion of the swath would be completed over certain areas, keeping the same ground resolution, sensitivity, and spectral resolution.

In one sense, the data loads derived in this manner represent maxima for visible sensors requiring clear atmospheric conditions. In reality, these sensors might not be operated over cloudy areas. The data loads calculated here thus assume operation over areas requiring coverage regardless of atmosphere conditions and telemetry of all such data to ground receiving stations. Editing of data for clear observations becomes a ground data handling problem by this convention.

An additional major consideration factored into the postulation of sensor duty cycles: it was assumed that only the United States and adjacent coastal areas, and the global ocean insofar as domestic interests are concerned, would be within the purview of the missions contemplated.

Data acquired for foreign interests would be done on a non-simultaneous basis and the resulting data would be channeled through ground data receiving and data handling located in foreign countries. The data volume estimated herein for domestic purposes may be extrapolated to additional areas of the globe simply by estimating coverage areas, spatial and spectral resolutions, and coverage frequencies.

The data volume/load profiles for each mission are shown in Tables 4-1 to 4-10.

4.1.2 Matrix Summaries

The data handling requirements are summarized for the nine candidate earth resources system missions in Table 4-11.

Table 4-1. Mission No. 1 - Terrestrial Survey/Environmental Quality, Research

1.1 Basic Areal Coverage

Assumption: Total areal coverage for U.S. and all territories

Gross area, land and water (Source: U.S. Dept. of Commerce, Statistical Abstract of the United States--1972)

Total: 9, 396, 691 km^2 (3, 628, 066 mi^2) = 1.84% of globe

1.2 Sensors (assuming 1978 state of art)

1.2.1 Scanning Spectroradiometer

Duty Cycle: Continuous operation over U.S.

Data Rate: 72.1 Mbits/sec

Data Load: (assume operation 1.84% of total time during year):

Load = $C\ R_D\ (A_C/A_G) = 4.186 \times 10^7$ Mbits per year

1.2.2 Pointable Imager

Duty Cycle: Operation 10% of the time while over the U.S.

Data Rate: 82.2 Mbits/sec

Data Load: 58,064 sec/year operation

Load = 4.773×10^6 Mbits/year

1.2.3 Advanced Atmospheric Sounder

Duty Cycle: Continuous operation over U.S.

Data Rate: 20 bits/sec

Data Load: 23.2 Mbits/year

1.2.4 Data Collection and Location System

Duty Cycle: 100 platforms interrogated per day

Data Rate: NA (storage/dump)

Data Load: (assume 200 bits per interrogation)

Load = 7.3 Mbits/year

Table 4-2. Mission No. 2 - Ocean Survey/Meteorological, Research

2.1 Basic Areal Coverage

Coastal Water Area (Excludes Alaska, Hawaii, water areas outside U.S. jurisdiction, inland waters. Includes Great Lakes. Source U.S. Dept. of Commerce, Statistical Abstract of the United States--1972)

Total for States: 192,603 km^2 (74,364 mi^2)

General Coastline (Figure represents length of general outline of seacoast. Measurements were made with a unit measure of 30 minutes of latitude on charts as near the scale of 1:1,200,000 as possible. Coastline of sounds and bays is included to a point where they narrow to a width of unit measure and includes the distance across at such a point. Includes Alaska and Hawaii. Source: U.S. National Oceanic and Atmospheric Administration, Coastline of the United States, April 1, 1961.)

Total for U.S.: 19,924 km (12,383 mi)

Assuming a one mile coastline FOV for the mission:

Total Area = 32,072 km^2 (12,383 mi^2)

Total = 224,675 km^2 (86,747 mi^2)
= 0.044% of globe

2.2 Sensors (assuming 1983 state of art)

2.2.1 Pointable Imager

Duty Cycle: Continuous operation over U.S. coastal areas

Data Rate: 125 Mbits/sec

Data Load: Assume operation 0.044% of total time during year:

13880 sec/year operation

Load = 1.736 x 10^6 Mbits/year

2.2.2 Ocean Scanning Spectrophotometer

Duty Cycle: Continuous over U.S. coastal areas

Data Rate: 1.1 Mbits/sec

Data Load: Assume 900 km swath in straight lines along U.S. coast:

Continued...

Table 4-2. Mission No. 2 - Ocean Survey/Meteorological, Research (Continued)

900 km x 8800 km lineal coastline (approximated from map) =

$7.92 \times 10^6 \text{ km}^2 = 1.553\%$ of globe

Assume operation 1.553% of total time during year =

490,076 sec/year

Load = 5.390×10^5 Mbits/year

2.2.3 Sea Surface Temperature Imaging Radiometer

Duty Cycle: Continuous over U.S. coastal areas

Data Rate: 0.36 Mbits/sec

Data Load: Assume same coverage as in 2.2.2 above, i.e., 1.553% of globe (multiply by 2, as day and night operation is possible), =

979,920 sec operation per year

Load = 3.528×10^5 Mbits/year

2.2.4 Advanced Atmospheric Sounder

Duty Cycle: Continuous day/night operation

Data Rate: 20 bits/sec

Data Load: 1.262×10^3 Mbits/year

2.2.5 Data Collection and Location System

Duty Cycle: 500 platforms interrogated per day

Data Rate: N/A

Data Load: (assume 200 bits per interrogation)

= 36.5 Mbits/year

Table 4-3. Mission No. 3 - Terrestrial Survey/Environmental Quality, Research

3.1 Basic Areal Coverage

Assume same as for Mission No. 1:

Total: 9,396,691 km^2 (3,628,066 mi^2),

$$\frac{A_C}{A_G} = 1.84\% \text{ of globe}$$

3.2 Sensors (assuming 1983 state of art)

3.2.1 Imaging Radar

Duty Cycle: Continuous day/night operation over U.S.

Data Rate: 360 Mbits/sec

Data Load: 4.181×10^8 Mbits/year

3.2.2 Combined Scanning Spectroradiometer/Pointable Imager

Duty Cycle: Continuous daytime operation over U.S.

Data Rate: 125 Mbits/sec (P.I.),
243.2 Mbits/sec (S.S.R.)

Data Load: Assume 1.84% operation during year

$$\begin{array}{rl} \text{Load} = & 7.258 \times 10^7 \text{ Mbits/year (P.I.)} \\ + & 2.824 \times 10^8 \text{ Mbits/year (S.S.R.)} \\ \hline \text{Total} = & 3.550 \times 10^8 \text{ Mbits/year} \end{array}$$

3.2.3 Advanced Atmospheric Sounder

Duty Cycle
Data Rate
Data Load

Same as for Mission No. 1 (Section 1.2.3)
= 23.2 Mbits/year

3.2.4 Data Collection and Location System

Same as for Mission No. 2, i.e., Data Load = 36.5 Mbits/year

Table 4-4. Mission No. 4 - Ocean Survey/Meteorological, Research

4.1 **Basic Areal Coverage**

Global ocean area, including adjacent seas (Source: Sverdrup, H. U., Johnson, M. W., and Fleming, The Oceans, 1943):

Total: 361.059×10^6 km^2 (105.265×10^6 nmi^2)

= 70.78% of globe

Assumption: Total world ocean is surveyed for dynamic features every seven days

4.2 **Sensors** (assuming 1983 state of art)

4.2.1 **Passive Microwave Radiometer**

Duty Cycle: Continuous day/night operation over all ocean areas

Data Rate: 1.19 Mbits/sec

Data Load: 5.316×10^7 Mbits/year

4.2.2 **Ocean Scanning Spectroradiometer**

Duty Cycle: Continuous daytime operation over all ocean areas

Data Rate: 1.1 Mbits/sec

Data Load: 2.457×10^7 Mbits/year

4.2.3 **Sea Surface Temperature Imaging Radiometer**

Duty Cycle: Continuous day/night operation over all ocean areas

Data Rate: 0.36 Mbits/sec

Data Load: 1.608×10^7 Mbits/year

4.2.4 **Constant Resolution Meteorological Scanner**

Duty Cycle: Continuous day/night operation over globe

Data Rate: 1.0 Mbit/sec

Data Load: 6.311×10^7 Mbits/sec

4.2.5 **Advanced Atmospheric Sounder**

Duty Cycle: Continuous day/night operation

Data Rate: 20 bits/sec

Data Load: 1.262×10^3 Mbits/year

4.2.6 **Data Collection and Location System**

Duty Cycle: 1000 platforms interrogated per day

Data Rate: N/A

Data Load: (assume 200 bits per interrogation)

= 73 Mbits/year

Table 4-5. Mission No. 5 - Transient Environmental Phenomena Monitoring, Research

5.1 Basic Areal Coverage

Assuming satellite is stationed at 35,870 km at approximately 100° West Longitude, and assuming the imaging spectroradiometer has a FOV of 12,780 km in diameter (115° longitude at Equator), total potential viewing area is approximately:

128,212,800 km^2 (37,379,823 nmi^2)

Coverage of the total amount of this potential area is realized only once per day for the imaging spectroradiometer (local noon) due to the illumination conditions.

5.2 Sensors (assuming 1978 state of art)

5.2.1 Dual Mode Imaging Spectroradiometer

Duty Cycle:	Daytime operation, continuous during 50% of 12-hour illumination cycle (25% continuous operation during year)
Data Rate:	0.63 Mbits/sec
Data Load:	4.970 x 10^6 Mbits/year

5.2.2 Advanced Atmospheric Sounder

Duty Cycle:	Assume operation 25% of total time
Data Rate:	20 bits/sec
Data Load:	157 Mbits/year

5.2.3 Data Collection and Location System

Duty Cycle:	Simultaneous interrogation of 150 platforms, four times per day
Data Rate:	N/A
Data Load:	(assuming 200 bits per interrogation) 43 Mbits/year

Table 4-6. Mission No. 6 - Terrestrial Survey/Environmental Quality, Operational

6.1 Basic Areal Coverage

Assumption = same coverage as for Missions Nos. 1 and 3 (1.84% of globe)

6.2 Sensors (assuming 1985 state of art)

6.2.1 Imaging Radar

Duty Cycle: Continuous day/night operation over U.S.

Data Rate: 360 Mbits/sec

Data Load: 4.181×10^8 Mbits/year

6.2.2 Combined Scanning Spectroradiometer and Pointable Imager

Duty Cycle: Continuous daytime coverage of U.S.

Data Rate: 125 Mbits/sec (P.I.),
243.2 Mbits/sec (S.S.R.)

Data Load: (assuming operation 1.84% of total time during year):

Load = 7.258×10^7 Mbits/year (P.I.)
$+ 2.824 \times 10^8$ Mbits/year (S.S.R.)
Total = 3.550×10^8 Mbits/year

6.2.3 Advanced Atmospheric Sounder

$$\left.\begin{array}{l}\text{Duty Cycle}\\ \text{Data Rate}\\ \text{Data Load}\end{array}\right\} \begin{array}{l}\text{Same as for Mission No. 4 (Section 4.2.5)}\\ = 1.262 \times 10^3 \text{ Mbits/year}\end{array}$$

6.2.4 Data Collection and Location System

Duty Cycle: 1000 platforms interrogated per day

Data Rate: N/A

Data Load: (assuming 200 bits per interrogation)
73 Mbits/year

Table 4-7. Mission No. 7 - Ocean Survey/Meteorological, Operational

7.1 Basic Areal Coverage

As the operational mission of the Ocean Survey/Meteorology series, this mission will focus upon acquisition of data germane to both coastal zone and global oceanographic/meteorological user needs. The orbital specification represents a compromise between global requirements (for synoptic observations of large-scale dynamics) and coastal requirements (for high-resolution, high-frequency data). All areas of application listed for the research missions in the series (Missions 2 and 4) shall be addressed by this operational mission.

The assumption is made that a scanning spectrophotometer capable of performance associated with 1988 state of the art (Table 2-7, Section 2) would be available for this mission. Coastal zone requirements for spatial resolutions exceeding approximately 1 km would not be satisfied by the mission, however. Accordingly, the assumption is made that the scanning spectrophotometer would operate in a high-resolution mode for coverage of the U.S. coastal zone. The high spatial resolution would be achieved by reducing the swath width and modifying the scan rate for measurements over coastal areas. The same data rate as for the normal mode is assumed.

7.2 Sensors (assuming 1988 state of art)

7.2.1 Oceanic Scanning Spectroradiometer

Duty Cycle: Continuous daytime operation over global ocean

Data Rate: 13.2 Mbits/sec

Data Load: Global (70.78% of globe):
2.948×10^8 Mbits/year

Coastal (0.044% of globe):
1.833×10^5 Mbits/year

Total = 2.950×10^8 Mbits/year

7.2.2 Passive Microwave Radiometer

Duty Cycle: Continuous day/night operation over global ocean

Data Rate: 18.1 Mbits/sec

Data Load: 8.086×10^8 Mbits/year

7.2.3 Constant Resolution Meteorological Scanner

Duty Cycle: Continuous day/night operation over globe

Data Rate: 1 Mbit/sec

Data Load: 6.311×10^7 Mbits/year.

7.2.4 Advanced Atmospheric Sounder

Duty Cycle
Data Rate
Data Load
} Same as for Mission No. 4 (Section 4.25)
= 1.262×10^3 Mbits/year

7.2.5 Data Collection and Location System

Duty Cycle
Data Rate
Data Load
} Same as for Mission No. 4 (Section 4.2.6)
= 73 Mbits/year

Table 4-8. Mission No. 8 - Meteorological, Research

8.1 Basic Areal Coverage

Total potential viewing area same as for Mission No. 5, except continuous day/night observation is possible.

8.2 Sensors (assuming 1983 state of art)

8.2.1 Imaging Radiometer

Duty Cycle: Continuous day/night operation

Data Rate: 1.22 Mbits/sec

Data Load: 7.700×10^7 Mbits/year

8.2.2 Constant Resolution Meteorological Scanner

Duty Cycle: Continuous day/night operation

Data Rate: 1 Mbit/sec

Data Load: 6.311×10^7 Mbits/year

8.2.3 Advanced Atmospheric Sounder

Duty Cycle Data Rate Data Load	Same as for Mission No. 5 (Section 5.2.2) = 157 Mbits/year

8.2.4 Data Collection and Location System

Duty Cycle Data Rate Data Load	Same as for Mission No. 4 = 73 Mbits/year

Table 4-9. Mission No. 9 - Meteorological, Research

9.1 Basic Areal Coverage

Viewing capability from equator (nadir) to approximately 20 degrees north and south latitudes is assumed. Approximate maximum coverage is 1.78 x 10^8 km (4445 km) (40,000 km) every 124 minutes.

9.2 Sensors (assuming 1988 state of art)

9.2.1 Imaging Radar

Duty Cycle: Intermittent operation day or night, assume operating 10% of total time

Data Rate: 21 Mbits/sec
Note: Resolution relaxed to 1 km for coverage of storm clouds

Data Load: 6.627 x 10^7 Mbits/year

9.2.2 Passive Microwave Radiometer

Duty Cycle: Assume operation 33% of time (for basic areal coverage--day and night--every six hours, approximately)

Data Rate: 18.1 Mbits/sec

Data Load: 1.904 x 10^7 Mbits/year

9.2.3 Imaging Radiometer

Duty Cycle: Same as 9.2.2

Data Rate: 1.22 Mbits/sec

Data Load: 1.28 x 10^7 Mbits/year

9.2.4 Constant Resolution Meteorological Scanner

Duty Cycle: Same as 9.2.2

Data Rate: 1.0 Mbits/sec

Data Load: 1.051 x 10^7 Mbits/year

9.2.5 Advanced Atmospheric Sounder

Duty Cycle: Continuous day/night operation

Data Rate: 100 bits/sec

Data Load: 3160 Mbits/year

9.2.6 Data Collection and Location System

Duty Cycle: 500 platforms interrogated per day

Data Rate: N/A

Data Load: (assume 200 bits per interrogation)

Load = 36.5 Mbits/year

Table 4-10. Data Rate/Load Summary for Future Earth Resources Missions

Mission Number	Launch Date	Expected Operating Lifetime (Years)	Max. Data Rate (Assuming All Sensors Operating) (Mbits/sec)*	Data Load (Mbits/year)
1	1978	1	154.3	4.536×10^6
2	1980	1	126.46	2.629×10^6
3	1982	1	728.2	7.731×10^8
4	1983	1	3.6	1.573×10^8
5	1980	1	0.6	4.970×10^6
6	1984	2	728.2	7.731×10^8
7	1986	2	32.3	1.167×10^9
8	1986	1	2.2	1.401×10^8
9	1987	1	41.3	1.086×10^8

*Figures do not include Data Collection and Location System

Mission	Payload	Operating Data Rate (mbps)	Sensor Use Profiles (Appendix C)	Maximum Data Rate (mbps)	Data Load (mbits)		P
					Per Orbit	Per Year	
1. Terrestrial Survey/ Environmental Quality (R), 1978 Launch	• Scanning spectro-radiometer (SSR)	72.1	Continuous (daytime) over CONUS and territories	154.3	741	4.5 x 10^6	USDA, AS DOI/USGS EPA DOC/NOA DOD/NAV
	• Pointable imager (PI)	82.2	Continuous (daytime) 10 percent of time over CONUS and territories				
	• Advanced atmospheric sounder (AAS)	-	Continuous over CONUS and territories				
	• Data collection and location system (DCLS)	-	Intermittent				
2. Ocean Survey/ Meteorology (R), 1980 Launch	• Oceanic scanning spectrophotometer (OSS)	1.1	Continuous (daytime) over U.S. coast (900 km swath)	126.5	426	2.6 x 10^6	DOC/NOA NOS, NWS DOT/USC DOI/USGS EPA DOD/NAV
	• (PI)	125	Continuous (daytime) over U.S. coast (1.6 km swath)				
	• Sea surface temperature imaging radiometer (SSTIR)	0.36	Continuous over U.S. coast (900 km swath)				
	• AAS		Continuous over U.S. coast (900 km swath)				
	• DCLS		Intermittent				
3. Terrestrial Survey/ Environmental Quality (R), 1982 Launch	• Combined SSR/ pointable imager	368.2	Continuous (daytime) over CONUS and territories	728	1.3 x 10^5	7.7 x 10^8	Same as f
	• Imaging radar (IR)	360	Continuous over CONUS and territories				
	• AAS	-					
	• Film recovery system (FRS)	-					
	• DCLS	-	Intermittent				
4. Ocean Survey/ Meteorology (R), 1983 Launch	• OSS	1.1	Continuous (daytime) over global ocean and adjacent seas	3.6	2.5 x 10^4	1.6 x 10^8	Same as f
	• Passive microwave radiometer (PMR)	1.19					
	• SSTIR	0.36					
	• AAS	-					
	• Constant resolution meteorological scanner (CRMS)	1.0	Continuous over global ocean and adjacent seas				
	• FRS						
	• DCLS		Intermittent				
5. Transient Environmental Phenomena Monitoring (R), 1980 Launch	• Dual mode imaging spectro-radiometer (DMIS)	0.63	Continuous (daytime) approximately 25 percent of total time	0.6	----	5.0 x 10^6	DOC/NOA EDS, NM EPA DOI/USGS DOT/USC DOD/NAV USDA/AS
	• AAS	-					
	• DCLS	-	Intermittent				

* Perishability Legend:
High = Near Real-Time to 1 Day
Moderate = 1 Day to 1 Week
Low = >1 Week

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Table 4-11. Data Handling Requirement
for Candidate ERS Mission

Primary Data Destinations (Appendix B)	Data Perishability*	Sensor Geometric and Radiometric Data Quality and Preprocessing Requirements	Data Transfer Considerations
USDA, ASC, SAS, SCS, FS DOI/USGS, BLM, BR, BSFW EPA DOC/NOAA (NESC, NWS, EDS) DOD/NAVOCEANO (NWSC)	Moderate Moderate (high for BSFW) High High High	SSR: Accounting for 14 scan lines; alternate scan directions; varying scan lengths; effects of Earth rotation. Error sources (geometric): scan variations, spacecraft attitude and ephemeris errors, local surface altitude variations; (radiometric): calibration, atmospheric effects. PI: Radiometric correction for dark current and nonuniformity of detector responsivities. Correction for effects of Earth rotation. Error sources (geometric): spacecraft attitude and ephemeris errors, local surface altitude variations; (radiometric); calibration, dark current, nonuniformity in detector response, atmospheric effects. AAS: Inversion of radiometric data; detection and accounting for effects of clouds. Error sources (geometric): none; (radiometric): calibration, detector NEP, atmospheric absorption coefficients.	High data rates and large data loads (preclud storage). Many applications require data in Users not expected to have converged upon o data type, quantity, quality, or format; acce central receiving and preprocessing facility raw data to users (corrected largely for sen and radiometric error, and for satellite-to- mission errors).
DOC/NOAA (NMFS, NESC, NOS, NWS, EDS) DOT/USCG DOI/USGS, BLM, BR EPA DOD/NAVOCEANO (NWSC)	High (NWS, EDS, NESC) Moderate Low High High (NWSC)	OSS: Radiometric corrections for shading, sun angle, scan angle. Geometric corrections for spacecraft attitude, scan angle, offset angle. Error sources (geometric): spacecraft attitude, Earth rotation, scan distortion; (radiometric): calibration, sun angle, atmospheric scattering. PI: Same as for Mission 1. SSTIR: Correction of data from five channels to determine temperature. Calibration data. Error sources (geometric): spacecraft attitude, variable resolution; (radiometric): calibration, cloud interference, atmospheric turbidity. AAS: Same as for Mission 1.	High data rates during U.S. coastal zone o tion and weather data of high perishability. raw (corrected) data to users as for Mission
Same as for Mission 1	Same as for Mission 1	Combined SSR/PI: Same as for Mission 1. IR: Azimuth data processing required to achieve azimuth resolution. Compensation for Earth rotation and geometric effects. Error sources (geometric): spacecraft attitude, Earth rotation effects, slant range distortion; (radiometric). AAS: Same as for Mission 1.	Very high data rates and data loads (precludi on-board storage). Users expected to have c requirements for special processing by this Central Data Handling Facility(s) responsibl nation of processed data (in appropriate engi and a limited amount of specially-formatted
Same as for Mission 1	Same as for Mission 1	OSS: Same as for Mission 2. PMR: Inversion of data to separate effects of temperature, roughness, emissivity, liquid water and vapor in the atmosphere, and sea ice coverage. Conversion of conical scan to rectangular grid, or desired projection. Error sources (geometric): spacecraft attitude, scanning variations; (radiometric): calibration, atmospheric, side lobes.	Low operational data rates, but high data vol because of continuous operational cycle over perishability high for weather synopsis and board data storage and/or relay via ships at necessary due to limited ground station visib expected to have converged upon requiremen processing by this time frame: Central Data Facility(s) responsible for dissemination of (in appropriate engineering units) and a limi specially-formatted data to users.
DOC/NOAA (NESC, NWS, EDS, NMFS, NESC) EPA DOI/USGS, BLM, BR, BSFW DOT/USCG DOD/NAVOCEANO (NWSC) USDA/ASCS, SRS, SCS, FS	High for most users	DMIS: Error sources (geometric): Slant range distortions, parallax, spacecraft attitude and rates, ephemeris; (radiometric): sun angle, atmospheric transmission, detector variation, digital quantization, gamma of output. AAS: Same as for Mission 1.	Data telemetry in real-time from geostation ground station(s) continuously in view. Data be available in near-real time for principal data rates low. Maximum data rates during of dynamic phenomena of interest (real-time will be most critical during these periods).

Table 4-11. Data Handling Requirement Summary for Candidate ERS Missions

	Data Perishability*	Sensor Geometric and Radiometric Data Quality and Preprocessing Requirements	Data Transfer Considerations
FS BSFW S, EDS) SC)	Moderate Moderate (high for BSFW) High High High	SSR: Accounting for 14 scan lines; alternate scan directions; varying scan lengths; effects of Earth rotation. Error sources (geometric): scan variations, spacecraft attitude and ephemeris errors, local surface altitude variations; (radiometric): calibration, atmospheric effects. PI: Radiometric correction for dark current and nonuniformity of detector responsivities. Correction for effects of Earth rotation. Error sources (geometric): spacecraft attitude and ephemeris errors, local surface altitude variations; (radiometric); calibration, dark current, nonuniformity in detector response, atmospheric effects. AAS: Inversion of radiometric data; detection and accounting for effects of clouds. Error sources (geometric): none; (radiometric): calibration, detector NEP, atmospheric absorption coefficients.	High data rates and large data loads (precluding on-board storage). Many applications require data in near-real time. Users not expected to have converged upon optimal (ultimate) data type, quantity, quality, or format; accordingly, a central receiving and preprocessing facility will disseminate raw data to users (corrected largely for sensor geometric and radiometric error, and for satellite-to-ground transmission errors).
SC, SC)	High (NWS, EDS, NESC) Moderate Low High High (NWSC)	OSS: Radiometric corrections for shading, sun angle, scan angle. Geometric corrections for spacecraft attitude, scan angle, offset angle. Error sources (geometric): spacecraft attitude, Earth rotation, scan distortion; (radiometric): calibration, sun angle, atmospheric scattering. PI: Same as for Mission 1. SSTIR: Correction of data from five channels to determine temperature. Calibration data. Error sources (geometric): spacecraft attitude, variable resolution; (radiometric): calibration, cloud interference, atmospheric turbidity. AAS: Same as for Mission 1.	High data rates during U.S. coastal zone overflights. Pollution and weather data of high perishability. Dissemination of raw (corrected) data to users as for Mission 1.
	Same as for Mission 1	Combined SSR/PI: Same as for Mission 1. IR: Azimuth data processing required to achieve azimuth resolution. Compensation for Earth rotation and geometric effects. Error sources (geometric): spacecraft attitude, Earth rotation effects, slant range distortion; (radiometric). AAS: Same as for Mission 1.	Very high data rates and data loads (precluding substantial on-board storage). Users expected to have converged upon requirements for special processing by this time frame: Central Data Handling Facility(s) responsible for dissemination of processed data (in appropriate engineering units) and a limited amount of specially-formatted data to users.
	Same as for Mission 1	OSS: Same as for Mission 2. PMR: Inversion of data to separate effects of temperature, roughness, emissivity, liquid water and vapor in the atmosphere, and sea ice coverage. Conversion of conical scan to rectangular grid, or desired projection. Error sources (geometric): spacecraft attitude, scanning variations; (radiometric): calibration, atmospheric, side lobes.	Low operational data rates, but high data volume per orbit because of continuous operational cycle over oceans. Data perishability high for weather synopsis and prognosis. Onboard data storage and/or relay via ships at sea may be necessary due to limited ground station visibility. Users expected to have converged upon requirements for special processing by this time frame: Central Data Handling Facility(s) responsible for dissemination of processed data (in appropriate engineering units) and a limited amount of specially-formatted data to users.
FW) S	High for most users	DMIS: Error sources (geometric): Slant range distortions, parallax, spacecraft attitude and rates, ephemeris; (radiometric): sun angle, atmospheric transmission, detector variation, digital quantisation, gamma of output. AAS: Same as for Mission 1.	Data telemetry in real-time from geostationary orbit to ground station(s) continuously in view. Data products must be available in near-real time for principal users. Routine data rates low. Maximum data rates during occurrences of dynamic phenomena of interest (real-time data transfer will be most critical during these periods).

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AME 2

Mission	Payload	Operating Data Rate (mbps)	Sensor Use Profiles (Appendix C)	Maximum Data Rate (mbps)	Data Load (mbits)		Primary Da Destination (Appendix
					Per Orbit	Per Year	
6. Terrestrial Survey/ Environmental Quality (O), 1984 Launch	• Combined scanning spectroradiometer (SSR)/ pointable imager (PI)	368.2	Continuous (daytime) over CONUS and territories	728	1.2 x 10^5	7.7 x 10^8	Same as for Missio
	• Imaging radar (IR)	360	Continuous over CONUS and territories				
	• Advanced atmoshperic sounder (AAS)	-	Continuous over CONUS and territories				
	• Data collection and location system (DCLS)		Intermittent				
7. Ocean Survey/ Meteorology (O), 1986 Launch	• Oceanic scanning spectrophometer (OSS)	13.2	Continuous (daytime) over global ocean and CONUS coast (1.6 km swath-high resolution mode)	32.3	1.8 x 10^5	1.2 x 10^9	Same as for Mission
	• Passive microwave radiometer (PMR)	18.1	Continuous over global ocean				
	• Constant resolution meteorological scanner (CRMS)	1.0	Continuous over globe				
	• Film recovery system (FRS)	-	-				
	• DCLS	-	Intermittent				
8. Meteorology (R), 1986 Launch	• CRMS	1.0	Continuous over globe	2.2	----	1.4 x 10^8	DOC/NOAA (NWS, NESC) DOD/NAVOCEANO DOT/CSCG
	• Imaging radiometer (IRAD)	1.22					
	• AAS						
	• FRS	-	-				
	• DCLS	-	Intermittent				
9. Meteorology (R), 1987 Launch	• Imaging radar	21.0	Intermittently, 10 percent of total time	41.3	1.5 x 10^4	1.1 x 10^8	Same as for Missio
	• Passive microwave radiometer	18.1	Intermittently, 10 percent of total time				
	• CRMS	1.0					
	• Imaging radiometer	1.22					
	• AAS	-	Continuous				
	• FRS	-	-				
	• DCLS	-	Intermittent				

Table 4-11. Data Handling Requirement Summary
for Candidate ERS Missions (Continue

rimary Data Destinations (Appendix B)	Data Perishability*	Sensor Geometric and Radiometric Data Quality and Preprocessing Requirements	Data Transfer Considerations
or Missions 1 and 3	Same as for Missions 1 and 3	CSSPI: Same as for Mission 1.	Extreme data rates and data loads per orbit. Same as Mission 3, except final-format data products dissemina to users by one or several data reception and processi centers.
or Missions 2 and 4	Same as for Missions 2 and 4	OSS: Same as for Mission 2, except the mechanical scanning spectrophotometer assumed for this mission requires additional radiometric corrections for polarization. PMR: Same as for Mission 4. CRMS: Same as for Mission 4. AAS: Same as for Mission 1.	Moderate data rates and extreme data loads per orbit because of continuous operational cycle over oceans. D perishability high for weather and coastal phenomena. Final-format data products disseminated to users by on or several data reception and processing centers.
A (NWS, EDS, OCEANO (NWSC) G	High	CRMS: Same as for Mission 4. IRAD: Different spatial resolutions required in direct and stored readout modes: stored is derived at lower spatial resolution, while direct should be at higher resolution. Error sources (geometric): spacecraft attitude, ephemeris; (radiometric): detector calibration. AAS: Same as for Mission 1.	Direct readout stations will not necessarily have sophisticated equipment. Data telemetry in real-time from geostationary orbit to ground station(s) continuou in view.
r Mission 8.	High	IR: Same as for Mission 3. PMR: Same as for Mission 4. CRMS: Same as for Mission 4. IRAD: Same as for Mission 8.	Stored readout mode will probably be deleted as DRS comes into operation. The direct-readout ground stati will become a mix of better-quality (regional, natio stations and smaller stations in underdeveloped countri and aboard ships at sea.

Table 4-11. Data Handling Requirement Summary for Candidate ERS Missions (Continued)

	Data Perishability*	Sensor Geometric and Radiometric Data Quality and Preprocessing Requirements	Data Transfer Considerations
and 3	Same as for Missions 1 and 3	CSSPI: Same as for Mission 1.	Extreme data rates and data loads per orbit. Same as for Mission 3, except final-format data products disseminated to users by one or several data reception and processing centers.
and 4	Same as for Missions 2 and 4	OSS: Same as for Mission 2, except the mechanical scanning spectrophotometer assumed for this mission requires additional radiometric corrections for polarization. PMR: Same as for Mission 4. CRMS: Same as for Mission 4. AAS: Same as for Mission 1.	Moderate data rates and extreme data loads per orbit because of continuous operational cycle over oceans. Data perishability high for weather and coastal phenomena. Final-format data products disseminated to users by one or several data reception and processing centers.
C)	High	CRMS: Same as for Mission 4. IRAD: Different spatial resolutions required in direct and stored readout modes: stored is derived at lower spatial resolution, while direct should be at higher resolution. Error sources (geometric): spacecraft attitude, ephemeris; (radiometric): detector calibration. AAS: Same as for Mission 1.	Direct readout stations will not necessarily have sophisticated equipment. Data telemetry in real-time from geostationary orbit to ground station(s) continuously in view.
	High	IR: Same as for Mission 3. PMR: Same as for Mission 4. CRMS: Same as for Mission 4. IRAD: Same as for Mission 8.	Stored readout mode will probably be deleted as TDRS comes into operation. The direct-readout ground stations will become a mix of better-quality (regional, national) stations and smaller stations in underdeveloped countries and aboard ships at sea.

4.2 Data Handling System Driver Requirements

The implications for data handling on a mission-by-mission basis have been summarized; however, in some cases it is more meaningful to examine critical data handling considerations on a source (mission/sensor) and destination (uses/user) basis. Those source/destination pairs which create unique data handling system problems (driver factors) will be considered here.

The very high data rates and orbital data loads associated with Mission 3 (Table 4-12) strongly favor consideration of real-time telemetry while sensors are operative, because of limited data storage capability. The driver is data volume rather than timeliness of data availability. The fact that receiving stations will be in view during sensor operating periods may eliminate the need for data relay.

A unique feature of Mission 3 with respect to data usage for geological structural/compositional relationships is the utility of film camera systems. By virtue of very low data perishability, recoverable film camera systems offer valuable data that would augment data acquired earlier. An important implication for data handling involves provision for association of data deriving from film analysis with data acquired and telemetered prior to film recovery by other sensors in the mission payload (see Table 4-13).

Mission 4 is characterized by moderate data rates and relatively high orbital data loads, the latter derived from requirements for continuous sensor operation during much of the orbital period (see Table 4-14). In contrast to Mission 1, real-time telemetry direct to ground receiving stations during sensor operation is not possible, and data perishability is a critical factor. Accordingly, some form of data storage (possibly including data compression) or data relay (to satellite or to ships at sea, for example) must be considered.

A unique feature of Mission 5 is the geosynchronous orbit, which permits continuous viewing of a major sector of the globe, and the fact that the satellite is continuously within view of ground data receiving stations. The primary driver in this case is high data perishability associated with dynamics of tropical storms (see Table 4-15).

Table 4-12. Data Handling System Driver Requirement
(Data Use Category: Terrain Mapping)

DESTINATION:	USDA/SRS (AGRICULTURAL CROP INVENTORY)
SENSORS:	• SCANNING SPECTRORADIOMETER/POINTABLE IMAGER • FILM RECOVER SYSTEM
MISSION 3:	TERRESTRIAL SURVEY/ENVIRONMENTAL QUALITY
• COVERAGE	CONUS
• OBSERVATION FREQUENCY	2 WKS - 3 MOS (SEASONAL DEPENDENT)
• GEOMETRIC FIDELITY	≤ 1 KM
• RADIOMETRIC QUALITY	0.1μ SPECTRAL RESOLUTION
• DATA RATE	368 MBPS
• DATA VOLUME	33×10^9 BITS/ORBIT
• PERISHABILITY	1 MONTH
• GEOGRAPHICAL RELATIONSHIPS	• RECEIVING STATION ALWAYS IN VIEW • RELAY TO PROCESSING STATION (WASH.D.C.)
• FORMAT	• ENHANCED IMAGERY WITH GEOGRAPHICAL OVERLAYS • COMPUTER-COMPATIBLE TAPES
• SPECIAL CONSIDERATIONS	SPECIAL PROCESSING REQUIRED FOR CROP IDENTIFICATION

Table 4-13. Data Handling System Driver Requirement
(Data Use Category: Earth Surface Composition)

DESTINATION:	DOI/USGS (ANALYSIS OF GEOLOGICAL STRUCTURAL/COMPOSITIONAL RELATIONSHIPS)
SENSORS:	• COMBINED SCANNING SPECTRORADIOMETER/POINTABLE IMAGER • IMAGING RADAR • FILM RECOVERY SYSTEM
MISSION 3:	TERRESTRIAL SURVEY/ENVIRONMENTAL QUALITY
• COVERAGE	CONUS
• OBSERVATION FREQUENCY	3 MONTHS
• GEOMETRIC FIDELITY	≤ 1 KM
• RADIOMETRIC QUALITY	0.1μ SPECTRAL RESOLUTION
• DATA RATE	368 MBPS (COMB. SCAN. SPECT./POINTABLE IMAGER) 360 MBPS (IMAGING RADAR) -- (FILM RECOVERY SYSTEM)
• DATA VOLUME	7.7×10^8 MBITS/YEAR
• PERISHABILITY	VERY LOW (>1 YEAR)
• GEOGRAPHICAL RELATIONSHIPS	RECEIVING STATION ALWAYS IN VIEW DURING OPERATION OF CSS/PI AND IMAGING RADAR
• FORMAT	ENHANCED IMAGERY, COMPUTER-COMPATIBLE TAPES, FILM
• SPECIAL CONSIDERATIONS	FILM OFFERS HIGH-DENSITY DATA STORAGE MEDIUM FOR USE IN AUGMENTING TELEMETERED DATA. DATA HANDLING SYSTEM SHOULD BE POSTURED TO ACCOMMODATE DATA DERIVING FROM PHOTOGRAPHIC ANALYSIS

Table 4-14. Data Handling System Driver Requirement (Data Use Category: Sea Surface Temperature)

DESTINATION:	NOAA/NMFS (FOR ULTIMATE USE BY VESSEL SKIPPERS FOR TACTICAL FISHING DECISIONS)	
SENSORS:	• SEA SURFACE TEMPERATURE IMAGING RADIOMETER • PASSIVE MULTICHANNEL MICROWAVE RADIOMETER	
MISSION 4:	OCEAN SURVEY/METEOROLOGY	
	• COVERAGE	GLOBAL OCEAN (ESPECIALLY TRADITIONAL FISHING GROUNDS)
	• OBSERVATIONAL FREQUENCY	5 DAYS
	• GEOMETRIC FIDELITY	LOCATION TO 5-10 KM (SPACECRAFT ATTITUDE, SCANNING VARIATIONS)
	• RADIOMETRIC QUALITY	CALIBRATION, CLOUDS, ATM. TURBIDITY
	• DATA LOADS:	LOW RATES (3.6 MBPS), HIGH VOLUME PER ORBIT (25 x 10^9 MBITS)
	• DATA PERISHABILITY	MODERATE (1-3 DAYS)
	• GEOGRAPHICAL RELATIONSHIPS	GROUND STATION/PROCESSING CENTER FAR-REMOVED FROM FISHING GROUNDS (OTHER HEMISPHERE IN SOME CASES)
	• FORMAT FOR DATA PRODUCTS	SURFACE ISOTHERM CHARTS, ANNOTATED WITH CATCH AND EFFORT DATA
	• SPECIAL CONSIDERATIONS	• INCORPORATION OF IN-SITU POINT VERIFICATION DATA FROM VESSELS • CORRECTION OF SSTIR 5-CHANNEL DATA FOR TEMPERATURE • INVERSION OF PMMR DATA TO CONTROL NON-TEMPERATURE VARIABLES • CONVERSION OF PMMR CONSCAN TO DESIRED PROJECTION

Table 4-15. Data Handling System Driver Requirement (Data Use Category: Severe Storm Warning)

DESTINATION:	NATIONAL WEATHER SERVICE (NATIONAL HURRICANE CENTER) MIAMI, FLORIDA	
SENSORS:	DUAL MODE IMAGING SPECTRORADIOMETER ADVANCED ATMOSPHERIC SOUNDER	
MISSION 5:	TRANSIENT ENVIRONMENTAL PHENOMENA MONITORING	
	• COVERAGE	WESTERN TROPICAL ATLANTIC OCEAN
	• OBSERVATION FREQUENCY	1-6 HOURS (STORM SEASON)
	• GEOMETRIC FIDELITY	5 KM
	• RADIOMETRIC QUALITY	LOW
	• DATA RATE	0.63 MBPS
	• DATA VOLUME	5 x 10^6 MBITS/YEAR
	• PERISHABILITY	2 HOURS
	• GEOGRAPHICAL RELATIONSHIPS	• RECEIVING STATION ALWAYS IN VIEW • RELAY TO PROCESSING STATION (WASH.D.C.)
	• FORMAT	• ANNOTATED IMAGERY • COMPUTER-COMPATIBLE TAPES

As shown in Table 4-16, the critical driver in Mission 6 is data perishability. In certain situations, the need may exist for near real-time data monitoring of a catastrophic phenomenon being sensed remotely several hours removed from the nearest receiving stations. Consideration of data relay satellites is warranted in such cases.

In many areas where environmental factors such as surface roughness and water turbidity interfere with the radiometric capability of the Oceanic Scanning Spectroradiometer to accurately discriminate spatial variations in phytoplankton concentration, contemporaneous in situ data would be a routine requirement. A significant data handling problem is the management of data derived from in situ sources such that it may be associated with the corresponding remote data without compromising timeliness of the product information. Mission 7 illustrates this problem (see Table 4-17).

Table 4-16. Data Handling System Driver Requirement (Data Use Category: Surface Water Mapping)

DESTINATION:	NOAA/NESC (FOR IMMEDIATE USE BY SPECIAL DISASTER COMMITTEES OR U.S. DEPARTMENT OF STATE FOR FOREIGN AID DECISIONS)
SENSORS:	• COMBINED SCANNING SPECTRORADIOMETER/POINTABLE IMAGER • IMAGING RADAR
MISSION 6:	TERRESTRIAL SURVEY/ENVIRONMENTAL QUALITY
• COVERAGE	EMERGENCY COVERAGE OF AREAS SUBJECT TO FLOODING
• OBSERVATION FREQUENCY	DAILY
• GEOMETRIC FIDELITY	LOCATE TO WITHIN 1 KM
• RADIOMETRIC QUALITY	ADEQUATE TO DISTINGUISH WATER-LAND BOUNDARY
• DATA RATE	368 MBPS (C.S.S./P.I.) 360 MBPS (IMAGING RADAR)
• DATA VOLUME	LOW
• PERISHABILITY	DATA REQUIRED IN NEAR-REAL-TIME
• GEOGRAPHICAL RELATIONSHIPS	LOCATION OF AFFECTED AREA MAY BE SUCH THAT SEVERAL ORBITS ARE REQUIRED TO ACHIEVE GROUND STATION VISIBILITY
• FORMAT	TIME-SEQUENCE IMAGERY, GEOGRAPHICALLY REFERENCED, WITH TOPOGRAPHIC OVERLAY
• SPECIAL CONSIDERATIONS	DATA DISSEMINATION TO DECISION-MAKERS MUST BE IN NEAR-REAL-TIME

Table 4-17. Data Handling System Driver Requirement (Data Use Category: Sea Surface Composition)

DESTINATION:	NOAA/NMFS (SURFACE CHLOROPHYLL CHARTS FOR DISTRIBUTION TO FISHING FLEET)
SENSORS:	OCEANIC SCANNING SPECTRORADIOMETER
MISSION 7:	OCEAN SURVEY/METEOROLOGY
• COVERAGE	GLOBAL OCEAN AND CONUS COAST, ESPECIALLY OVER FISHING GROUNDS AND NEAR WATER MASS BOUNDARIES
• OBSERVATION FREQUENCY	4-7 DAYS
• GEOMETRIC FIDELITY	10-15 KM
• RADIOMETRIC QUALITY	ADEQUATE FOR ESTIMATION OF CHLOROPHYLL CONCENTRATION TO ±5% OF ACTUAL AMOUNT
• DATA RATE	13 MBPS
• DATA VOLUME	3 MBITS/YEAR
• PERISHABILITY	1 WEEK
• GEOGRAPHICAL RELATIONSHIPS	GROUND STATION/PROCESSING CENTER FAR-REMOVED FROM FISHING GROUNDS
• FORMAT	GEOGRAPHICALLY-REFERENCED ISOPLETH CHARTS OF CHLOROPHYLL CONCENTRATION WITH SURFACE ISOTHERM OVERLAY. ANNOTATED WITH CATCH AND EFFORT DATA FROM THE FLEET
• SPECIAL CONSIDERATIONS	IN-SITU (GROUND TRUTH) MEASUREMENTS REQUIRED FOR CALIBRATION. COORDINATION OF THIS DATA WITH SATELLITE DATA REQUIRED. SPECIAL POST-ACQUISITION DATA PROCESSING TO SEPARATE EFFECTS OF ATMOSPHERE AND WATER TURBIDITY, SURFACE ROUGHNESS, ETC.

5. DATA ROUTING ANALYSIS

Various data routing paths have been examined to transfer data from the Earth Observatory Satellite to a processing center. Selection of a path is dependent upon data volume, data collection rate, data perishability, and cost of data transmission. The interrelationship among these factors has been examined and a procedure developed to establish tradeoffs for comparing the various methods of data routing. The following sections document the results of this task.

5.1 Method of Approach

The procedure that was developed to analyze data routing employs the following steps in the order listed below.

1) Step 1. Determine bounds of data collection rates and data volume per orbit.

2) Step 2. Determine the limitation of on-board storage devices for mass storage of data assuming late 1980 employment.

3) Step 3. Determine limitations of ground-based storage devices for mass storage of data assuming late 1980 employment.

4) Step 4. Determine important characteristics of ground stations for collecting spacecraft data.

5) Step 5. Determine future data transmission techniques and forecast tariffs for these based upon tariffs in existence at present.

6) Step 6. Develop a method for comparing various data paths on the basis of time delay and cost.

This approach is described in detail in the sections that follow and in addition, these sections establish the constraints under which the methodology can be applied.

5.2 Mission Requirements - Step 1

A total of nine missions have been postulated to cover a range of scientific interest believed to be of concern within the time-frame of interest. Each of these missions has been characterized and typical data requirements have been established. The primary mission characteristics, which directly affect data routing, are data collection rate and data volume per orbit (assuming that data storage, if used, can be limited to about one orbit).

The data collection rate is that rate established when the sensor(s) is on and operating and includes the effects of data compression accomplished on-board, prior to transmitting the data to a ground station. In the event no compression or processing exists on-board then, of course, the data rate is the raw data rate delivered by the sensor(s).

Data volume is the total amount of data that may be expected during a single orbit of the spacecraft. This definition assumes that storage devices for use on board the spacecraft may be used and will have about a one-orbit capacity.

With the above definition established, a scatter diagram showing the data volume per orbit and the data collection rates for the nine missions was prepared to establish boundaries for the parameters of the data routing task.

This scatter diagram is shown in Figure 5-1. The points plotted

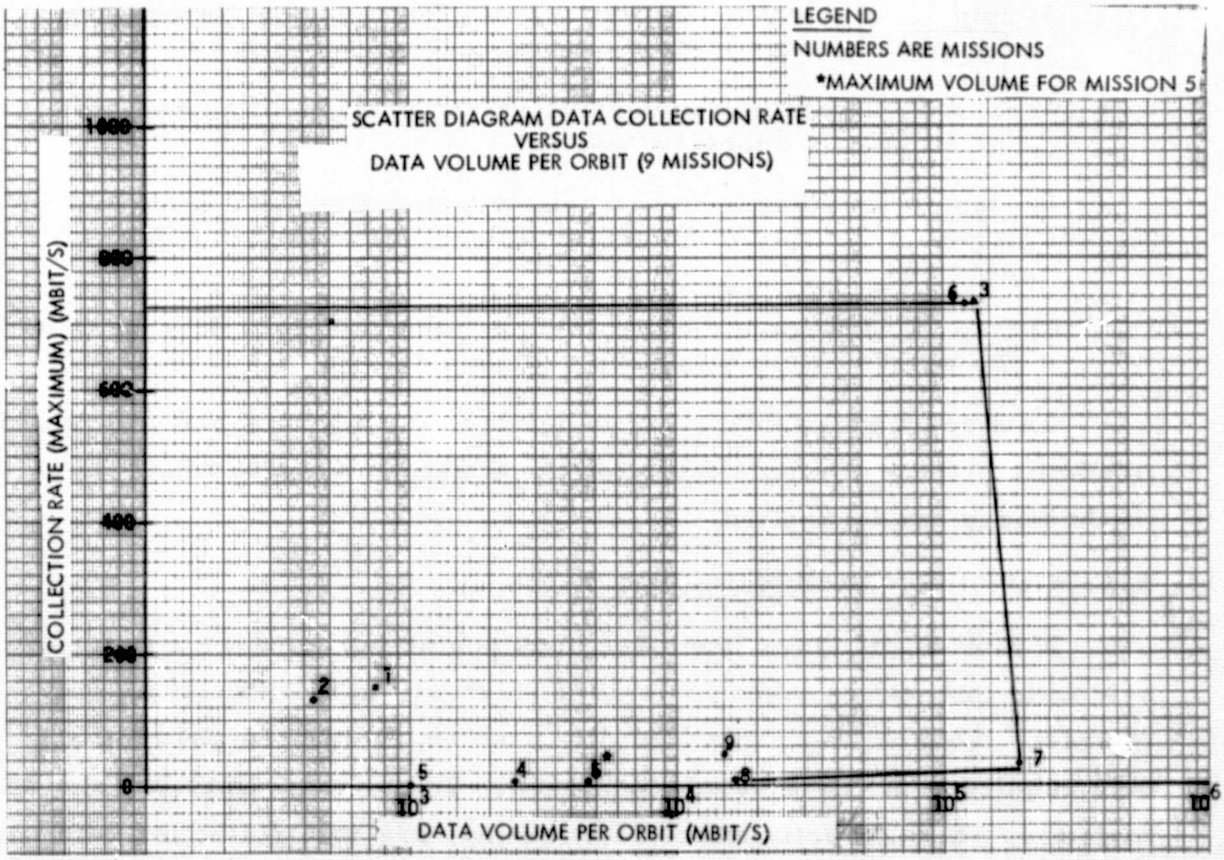

Figure 5-1. Mission Scatter Diagram

on the scatter diagram refer to the mission number. The missions are summarized in Section 4. Not unexpectedly, Mission 3 and 7 establish the upper boundary values of the two data parameters of rate and volume. Mission 3 establishes the rate of 728.2×10^6 bit/s and Mission 7 establishes the volume of 1.8×10^5 Mbit/s.

The lower-bound values are established by Missions 2 and 5. The lower-bound on data volume is 426 M/bits per orbit for Mission 2 and the lower-bound on data rate is set by Mission 5 at 0.63 Mbit/s.

This information provides the ranges over which the data parameters were defined for the other steps in the analysis process. While the defined missions may change in the future, any mission that can be plotted within the defined bounds on the scatter diagram may be analyzed and traded under these conditions. The method is then limited by the bounds of the parameter and not by the missions postulated.

5.3 Data Storage - Steps 2 and 3

A further limit on the data parameters is imposed by the future state of the art in tape recorders. Even though the bounds of mission requirements show a need for data transmission rates exceeding 700 Mbit/s, this rate cannot be handled by a general-purpose ground processor whose input rate is likely to be limited to 50 Mbit/s even for advanced machines. Consequently, data transmission rates to the ground processor were limited to a rate that could be handled by ground-based tape recorders. This rate is estimated at about 300 Mbit/s in the foreseeable future and thus limits the spacecraft data rate to 300 Mbit/s per channel. For Missions 3 and 6, one has the choice of operating a single sensor at a time for a rate not exceeding 300 Mbit/s or of compressing the data from both sensors so that the compressed rate is limited to 300 Mbit/s, or providing multiple communication channels.

In view of these points, the parameter boundaries for the data routing task were established for rates up to 300 Mbit/s per channel and for volumes in excess of 2×10^5 M/bits.

Section 6.7 describes the current and projected technology and performance capabilities for data storage devices. Based upon these data, the following conclusions were reached:

The magnetic tape recorder has been selected for the majority of spacecraft bulk data storage applications where optimum size, weight, power, cost, and reliability tradeoffs have been considered, and a random access memory is not required. Where data storage over 10^7 bits is required in a serial format, no other candidate memory system currently available compares favorably with the tape recorder. Considerable effort and studies are currently in progress to replace the electromechanical nature of a tape recorder with an all solid-state memory. Some of this effort appears promising, but is admittedly many years away from flight operational status. The progress of these studies should be monitored closely as they develop from the laboratory to potential flight operational hardware. However, a review of NASA programs in the 1978 to 1980 time period indicates that where hardware dollars have actually been committed for flight hardware the magnetic tape recorder is still being selected for those applications requiring 10^7 bits (non-random access) or greater data capacity.

Ground-based machines with a rate of 300 Mbit/s appear to be possible during the time-frame of interest and this rate has been selected for use in the data routing task.

5.4 NASA Ground Stations - Step 4

In conducting the data routing analysis, plans which NASA has formulated to upgrade and improve its data collection and routing capability were examined. These plans incorporate the TDRS spacecraft for real-time high-data rate use for low-orbiting spacecraft. They also cover some improvements to STDN and NASCOM. These plans were used for the data routing task to the extent they were directly applicable. The specific characteristics of TDRS and STDN are not drivers in conducting this study but will certainly impact conclusions from the study if these plans are changed. Important characteristics and their impact on conclusions are discussed below.

5.4.1 TDRS

The significant characteristic of TDRS is its ability to provide virtually 100 percent orbit coverage for low-orbiting spacecraft and to provide a 300 Mbit/s data link to the ground station. This rate is consistent with the predicted long-range capability of ground-based tape recorders and with real-time sensor data collection rates.

The impact of lowering the TDRS maximum data transmission rate is to limit the maximum sensor data rate that can be transmitted via the TDRS. This does not necessarily preclude the mission, assuming alternate transmission means are possible, but it does preclude using TDRS as part of the data routing paths for those sensors.

5.4.2 Space Tracking and Data Network

The STDN system is in a state of change and modification. For the purposes of this study, six STDN stations, located in CONUS were used as representative of stations which could be used to read out data. These stations are: Mojave, Rosman, Ft. Meyers, Greenbelt, Hawaii and Corpus Christi.

A group of four representative spacecraft orbits were selected. The orbits are as follows:

Orbit	Period (Min)	Inclination, (Deg)	Altitude (Km)
1	108.3	100.16	1153
2	123.8	0.1	1860
3	98.92	98.2	714
4	101.97	98.82	860

For the above STDN stations and spacecraft orbits, station contact times were calculated and plotted. These plots were used to estimate an average value of contact time to use in calculating the necessary data transmission rate for a value of data volume which is stored on-board the spacecraft. A value of ten (10) minutes is believed to be a conservative number for these stations and orbits as indicated in the same contact plot in Figure 5-2.

The contact plots were also used to verify the need to store at least one-orbit's worth of data on-board the spacecraft for those missions that could use the stored mode of operation. Examination of the contact plots show that for these stations as many as three orbits can occur without seeing one of the above STDN stations but since the concern here is to examine those orbits that primarily cover CONUS, coverage at least once per orbit over CONUS and ajacent sea areas is provided.

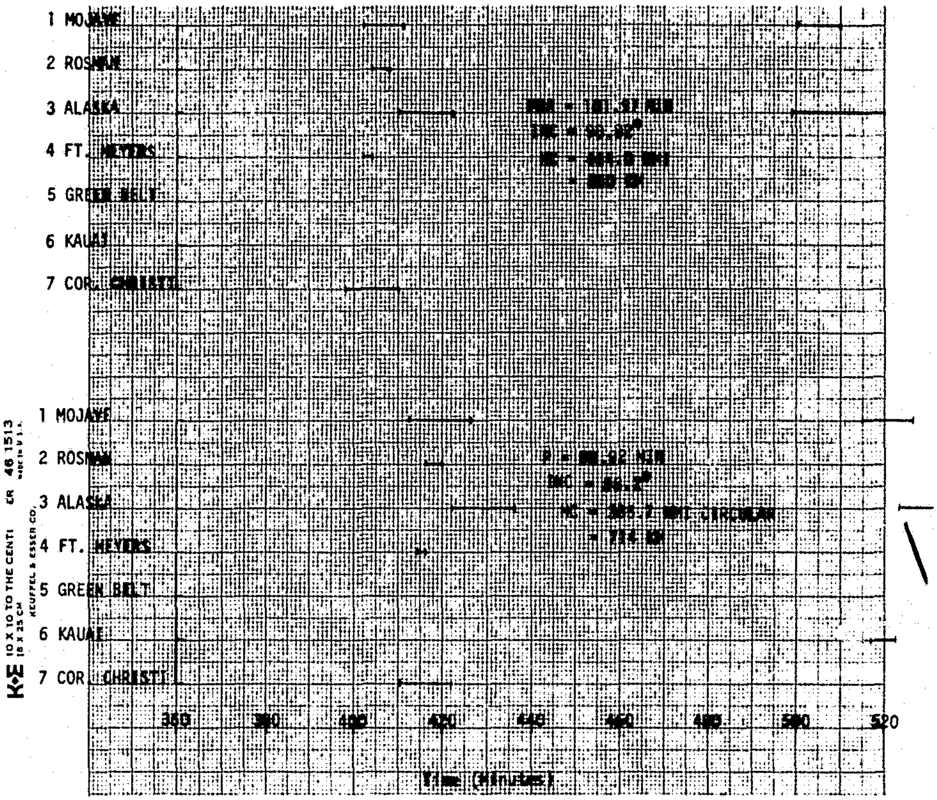

Figure 5-2. Sample Contact Plot

In conclusion, it has been shown that data rates can be established by assuming a STDN pass time of 10 minutes for the on-board data volume to be transmitted and the on-board data volume can be established by the sensor collection rate and schedule over the previous orbit.

5.4.3 Real-Time Data Transmission

It is possible to use TDRS for real-time data transmission in those cases where data perishability or data rate requires this mode of operation. However, it appears that scheduling problems associated with TDRS and users demand for service will necessitate adding high data rate capability to STDN stations. These rates will be subject to the same constraints as those discussed above in Section 5.3. Namely, a real-time rate of 300 Mbit/s limited by ground-based tape recorders and a stored data playback rate of 300 Mbit/s limited by spaceborne tape recorders.

5.4.4 Remote Station Readout

Data transmission directly to a remote read out station is an additional mode of mission operation. Data routing analysis for this mode assumes that the mission and station location have been selected to meet the mission demands. In this sense, the remote station can be treated from a data routing analysis standpoint as if it were a STDN station and the same values of pass time used. For special cases not fitting these assumptions, contact plots must be run separately for the correct spacecraft orbit, phasing, and station location.

5.5 Data Transmission Techniques - Step 5

One of the purposes of data routing analysis is determining costs for alternate data transmission schemes. These costs, together with allowable data delay to meet perishability requirements, provide the tradeoff parameters for comparing various alternative data routing schemes. It is therefore important to examine the trends in costs associated with data transmission over long distances as data rates are pushed higher and higher by future mission demands.

Data rates may vary over a wide range from as low as 4800 bit/s to as high as 300 Mbit/s for the cases under consideration. This range is the one chosen from which costs were extrapolated.

5.5.1 Future Data Transmission

The Bell Telephone Company is presently evaluating data transmission circuits at speeds of 224 Mbit/s. A laboratory demonstration of a 500 Mbit/s link has been conducted. Satellites can provide wideband point-to-point service and will be available in the future. The existing and planned facilities therefore appear to be consistent with our requirements for rates as high as 300 Mbit/s. The problem is to forecast the tariffs associated with these services when they become available.

These costs have been forecast by using available tariffs in terms of dollar cost per kbit/s per month and extrapolating these to higher data rates. The ultimate cost by the mid 1980's has been estimated at about \$30/circuit/year*. This translates to a tariff of about \$10.00 per kbit/s per month. The available cost information was plotted versus data rate and is shown in Figure 5-3.

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*Classified report

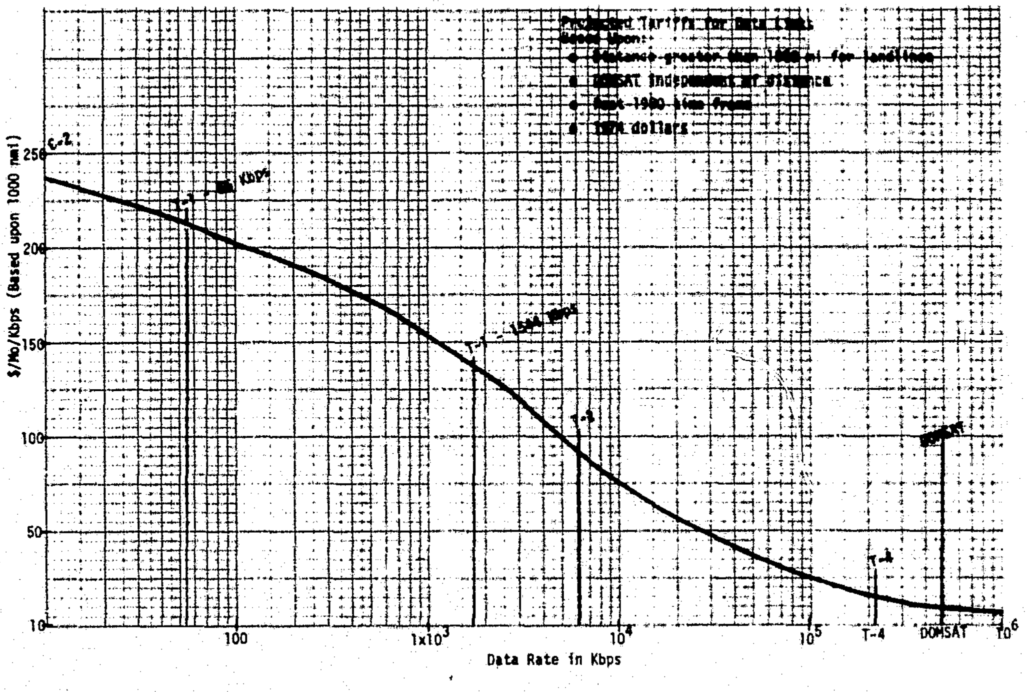


Figure 5-3. Projected Tariffs for Candidate Data Links

5.5.2 Cost Data

The information regarding existing tariffs was obtained from the Bell Telephone Company and is in terms of 1974 dollars. All cost information has been made consistent with these data. The data circuits are described in the order of increasing data rate from a conditioned C-2 line to a domestic satellite link and are shown in Tables 5-1a and 5-1b.

Table 5-1a. Specifications of Conditioned Voice Lines in the U.S.A.

Name of conditioning: Telephone companies: Western Union:	Type C1 conditioning "Class E" lines		Type C2 conditioning "Class F" lines		Type C4 conditioning "Class H" lines	
Former names: Telephone companies:	Line Type 3003 Type 4A conditioning		Line Type 3004 Type 4B conditioning		Line Type 3005 Type 4C conditioning	
Voice lines applicable to:	Two Point or Multipoint Half or Full Duplex Two Wire or Four Wire		Two Point or Multipoint Half or Full Duplex Two Wire Four Wire		Two Point Half or Full Duplex Two Wire or Four Wire	
Specifications for amplitude variation:	Amplitude Variation	Frequency Range	Amplitude Variation	Frequency Range	Amplitude Variation	Frequency Range
	−2 to +6 db	300-999	−2 to +6 db	300-499	−2 to +6 db	300-499
	+1 to +3 db	1000-2400	−1 to +3 db	500-2800	−2 to +3 db	500-3000
	−2 to +6 db	2401-2700	−2 to +6 db	2801-3000	−2 to +6 db	3001-3200
Specifications for envelope delay:	Envelope Delay (Micro-seconds)	Frequency Range	Envelope Delay (Micro-seconds)	Frequency Range	Envelope Delay (Micro-seconds)	Frequency Range
	Less than 1000	1000-2400	Less than 500	1000-2600	Less than 300	1000-2600
			Less than 1500	600-2600	Less than 1500	800-2800
			Less than 3000	500-2800	Less than 1500	600-3000
					Less than 3000	500-3000

Table 5-1b. Technical Characteristics of Candidate Data Links

DESIGNATION	DATE INTRO. OR STATUS	TRANSMISSION RATE (MEGABITS)	PULSEWIDTH (NANOSECS)	CABLE TYPE	REPEATER SPACING (MILES)	SIGNAL CODING	SIGNAL LEVEL	ERROR LEVEL	SIGNAL SHAPE	REPEATER POWER
T-1	1962	1.544	324	TWISTED PAIRS '0' AND 'ON' LINES	1.0	BIPOLAR (REVERSED MARKS	3V PK			1 WATT (BI-DIRECTIONAL
T-2	LATE 1970	6.3		TWISTED PAIRS PULP OR PIC	0.8-3	BIPOLAR (625)	4.2V PK	10^{-7}	RECTANGLE	(160 mA)
T-3										
T-4	EXPERIMENTAL 10 MILE RUN 1965	224		0.27" SOLID OUTER COAXIAL	1.0*	PST	1,37V PK	$<10^{-10}$	COSINE	7.5W (450 mA)
T-5	LABORATORY DEMO	~ 500								
DOMSAT	PLANNED	> 300								

A description of the costs associated with each of these is presented below. The costs for land-lines are reduced to a common set of units and are based upon an airline distance of 1000 n mi. The costs for communication satellite links are independent of distance for a satellite coverage area (CONUS).

Tariff for Type 3002 C-2 Conditioned

Distance (n mi)	Cost \$/Month/n mi	Terminals Cost (2) \$
First 25	3.00	66
Next 75	2.10	
Next 150	1.50	
Next 250	1.05	
Greater than 500	0.75	

Tariff for T-1, 56 kbit/s Data Channel

Distance (n mi)	Cost \$/Month/n mi	Terminals Cost (2) \$
First 250	15	850
Next 250	10.50	
>500	7.50	

Tariff for T-1, 1.544 Mbit/s Channel

Distance (n mi)	Cost \$/Month/n mi	Terminals Cost (2) \$
First 250	375	40,000
Next 250	262.50	
> 500	187.50	

Tariff for T-2, 5.250 Mbit/s Channel (Extrapolated)

Distance (n mi)	Cost \$/Month/n mi	Terminals Cost (2) \$
Any	468	\$1000/mo + installation

Estimated Tariff for T-4, 224 Mbps Channel

Distance (n mi)	Cost \$/Month/n mi	Terminals Cost (2) \$
Any	3000	\$100,000

Estimated Tariff 300 Mbit/s DOMSAT Link

Distance	Cost \$/Month/kbit/s	Terminal (2) \$
Any	10.05	2.5×10^6

This estimate was performed as follows:

Terminal cost = 2.5×10^6 each end

2 ends = $\$5 \times 10^6$

+ 20 percent per year maintenance x 10 years = 20×10^6

amortization and monthly maintenance = $\$166.7 \times 10^3$/month

Link cost at \$30/voice circuit/year for 300 Mbit/s bandwidth

= \$187,000/month

Cost/month = 187,000

Terminal amortization + maintenance = 166,700

Total cost/month = \$353,667/month

$$\text{. Cost per month per kbit/s} = \frac{\$353{,}667}{3 \times 10^5} = \$1.18$$

The tariff is expected to be about 8.5 times the cost or about \$10.00 per month per kbit/s.

The known tariffs were reduced to a common base of dollar cost per month per kbit/s for a distance of 1000 n mi. The COMSAT costs were estimated as a 1000 n mi link as described above and these points were plotted and a smooth curve drawn through them as shown in Figure 5-3 Since tariffs were known for C-2 conditioned lines, for T-1 links and for T-2 links and a reasonable estimate for costs was available for the DOMSAT costs, only the T-4 tariff was unknown. It was extrapolated by selecting the 224 Mbit/s data rate and reading the tariff from the ordinate of Figure 5-2 as $15.00/mo/kbit/s for 1000 n mi distance.

In using these data it must be remembered that land-line tariffs are a function of distance but that communication satellite tariffs are independent of distance for a single satellite coverage area.

The data shown in Figure 5-3 was used to prepare parametric curves to show cost of data transmission as a function of required data volume and acceptable delivery time. These curves are discussed in greater detail in the following section.

5.5.3 Data Link Characteristics

This section provides some useful background information on the data link characteristics that have been considered as candidates for data transmission. The links considered include telephone-type lines with appropriate equalization to improve the error rate for digital data, and various T-carrier links. Specific information regarding DOMSAT data links is not available but it was assumed that 300 Mbit/s point-to-point service will be provided using dedicated terminals at each end. Technical information on the various landlines is given below.

Type 3002 - C-2 Lines. The Type 3002 line is a voice circuit used for data transmission. To increase the signaling rate which is limited to about 600 bit/s on the unconditioned line, the line is conditioned or equalized to improve the performance for higher data rates. Type C-2 conditioning was chosen as representative in this study because it is most widely available. The characteristics of the 3002-C-2 line is shown in Table 5-1a. This table also shows the characteristics of C-1 and C-4 conditioning.

TELPAK Service. TELPAK is a private link "bulk" communication service offered by the telephone companies and Western Union. It is designed for use by large business and government agencies with large point-to-point communications requirements. Since the future of TELPAK is uncertain and because the T-carrier system provides essentially the same service, TELPAK was not considered as a candidate data link.

T-Carrier System. In 1972, AT&T filed an application with the FCC for T-1 digital channel service to interconnect five cities: Boston, New York, Washington, D.C., Chicago, and Philadelphia. This service provides signaling up to 56 kbit/s and by 1976 is expected to embrace a 96-city network.

Additional T-carrier systems are being planned and a T-5 link with 500 Mbit/s speed has been demonstrated in the laboratory. The pertinent characteristics of the T-carrier systems are shown in Table 5-1b.

5.5.4 Parametric Cost Curves, Step 5

The data links considered for relaying digital data from a ground station to a processing center include both Bell System lines and DOMSAT lines. At present, very little is known about the specific characteristics of DOMSAT links regarding service, method of use, and tariffs. Much more is known about the existing and planned services of the Bell System. The characteristics of the existing Bell System that are of interest in the data routing analysis task are presented in this section.

Future data tranmission facilities will be provided to meet industry and government demands for high-speed data service on a dedicated or dial-up basis. Predicting these requirements is a sizable task and one that is continually being conducted by the various common carriers. Thus, to predict the availability of a 300 Mbit/s service from a specific ground station to Washington, D. C. in 1985 is extremely difficult. It is reasonable, however, to predict that major cities will be interconnected via high-speed data circuits and that the relative cost of such service can be predicted. This alone is enough for tradeoff purposes. Once the tradeoffs have been accomplished, final assessment of more accurate cost will require specific information on ground station location with respect to closest data services, analysis of means for connecting the ground station to the link terminal, lease or buy decisions, and other factors necessary to conduct a thorough economic study. Such a task is beyond the scope of this study. Development of cost data adequate for use in tradeoff studies has been accomplished and are described below.

The range of data volume was determined in Step 1 of the procedure described in Section 5.2 and covers the missions of interest for this task. Cost information and tariffs have been extrapolated to cover the range of data transmission rates required as described in Section 5.3 The next step is to prepare parametric curves to relate the data volume that must be transmitted from some ground station to a processing site, and the time within which the data must be transmitted to meet perishability needs, to cost of data transmission. These curves allow determination of cost as a function of time delay due to transmitting a known data volume.

Figures 5-4 through 5-12 show the data transmission time for a given data volume as a function of cost of the data link.

The following notes apply to Figures 5-4 through 5-12 as well.

- Costs are monthly cost for a distance of 1000 n mi except for DOMSAT
- DOMSAT costs are monthly costs independent of distance
- Costs are based upon projected tariffs in 1973 dollars
- Costs include tariffs, terminals, and maintenance assuming 10-year amortization for capital investment.

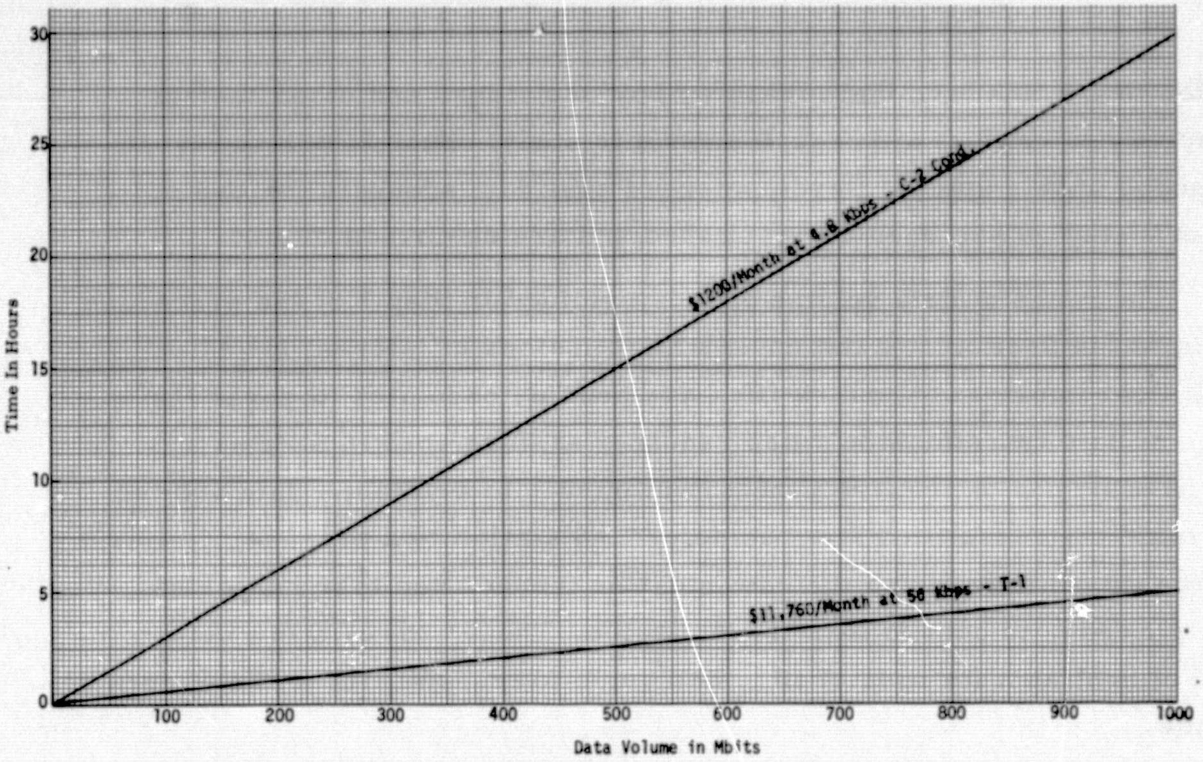


Figure 5-4. Performance and Cost for Various Data Link Configurations

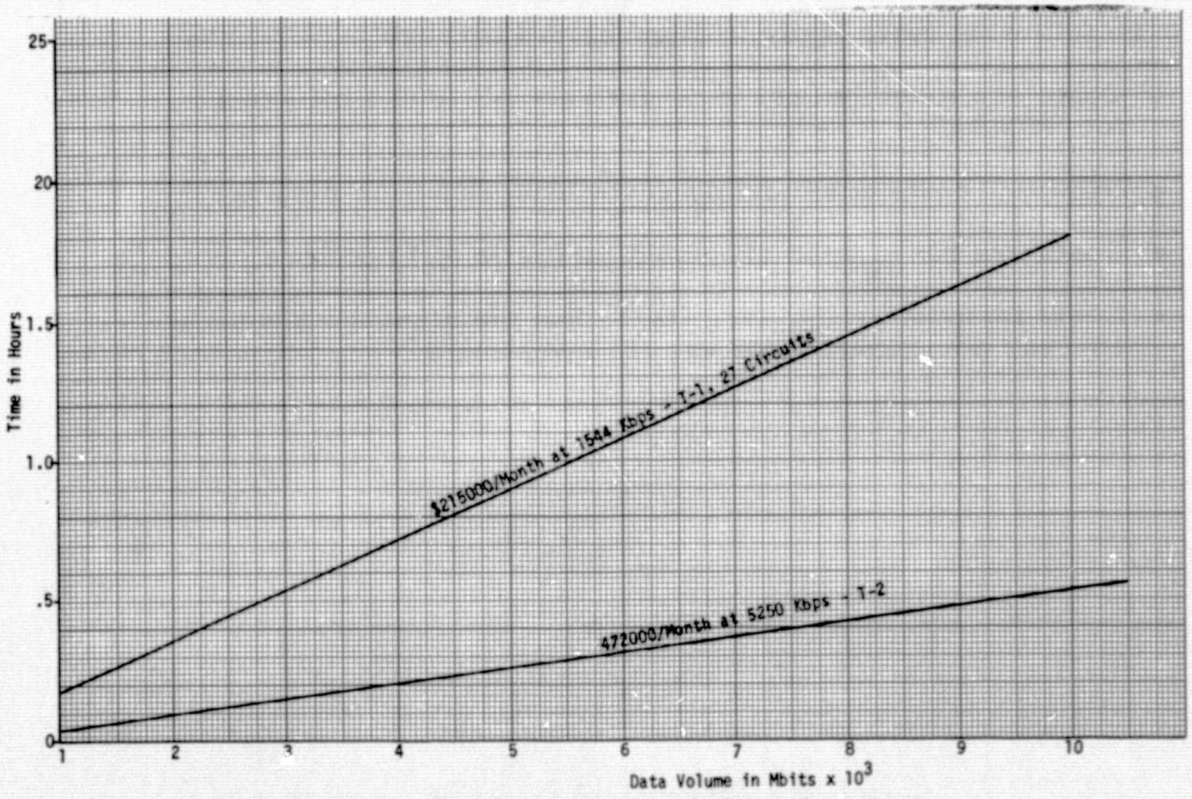


Figure 5-5. Performance and Cost for Various Data Link Configurations

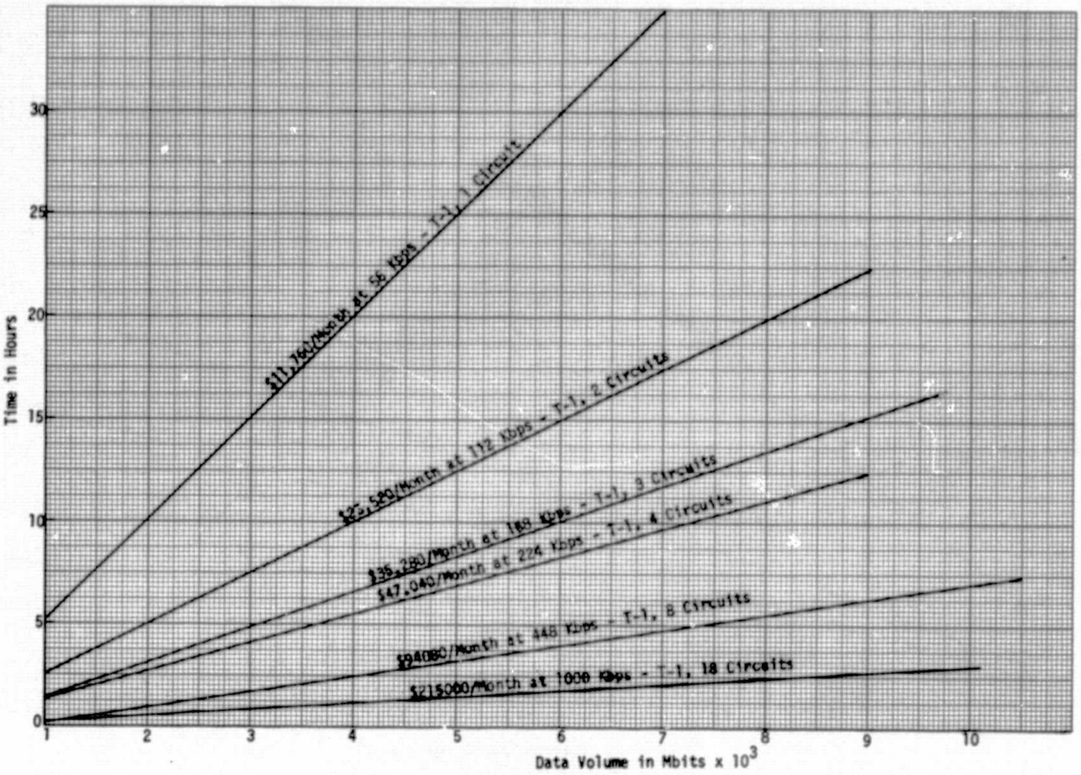


Figure 5-6. Performance and Cost for Various Data Link Configurations

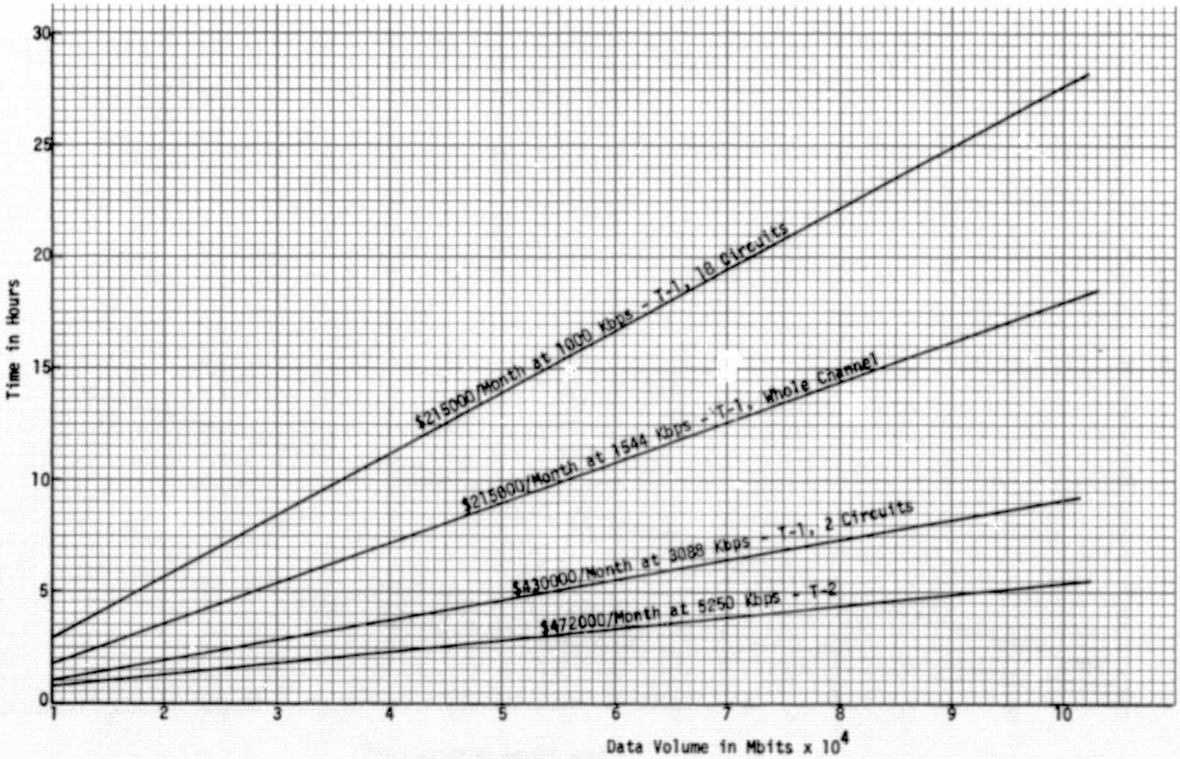


Figure 5-7. Performance and Cost for Various Data Link Configurations

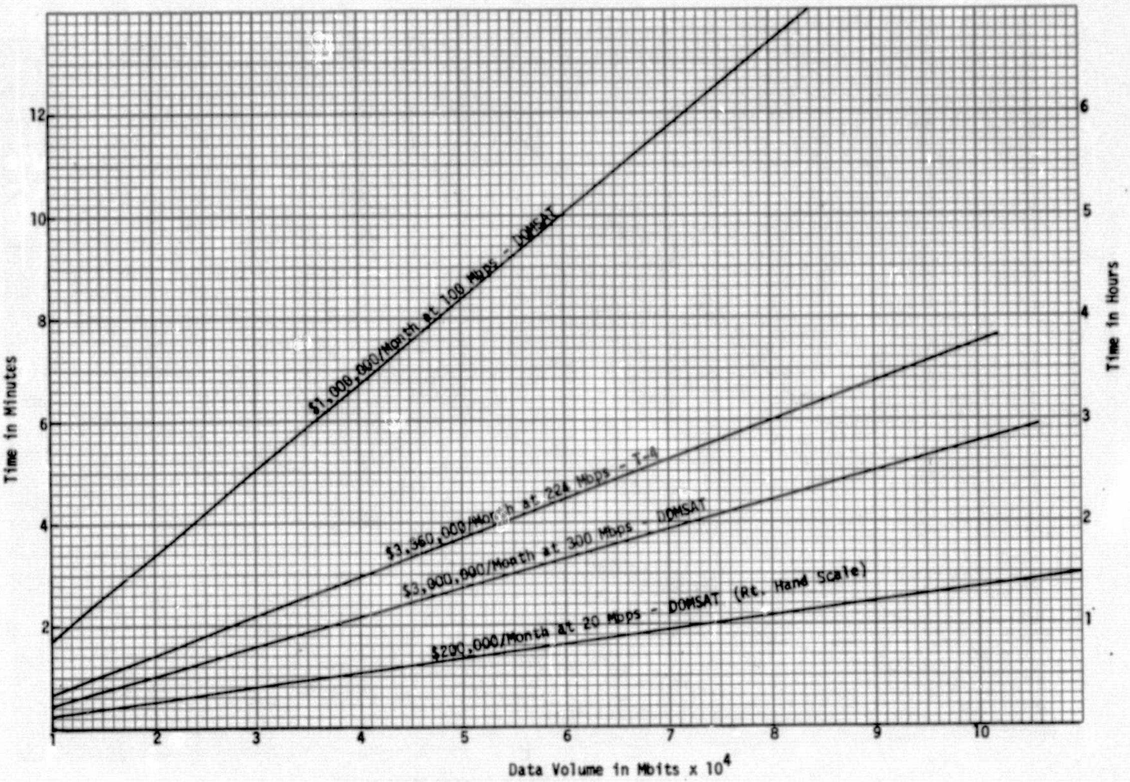


Figure 5-8. Performance and Cost for Various Data Link Configurations

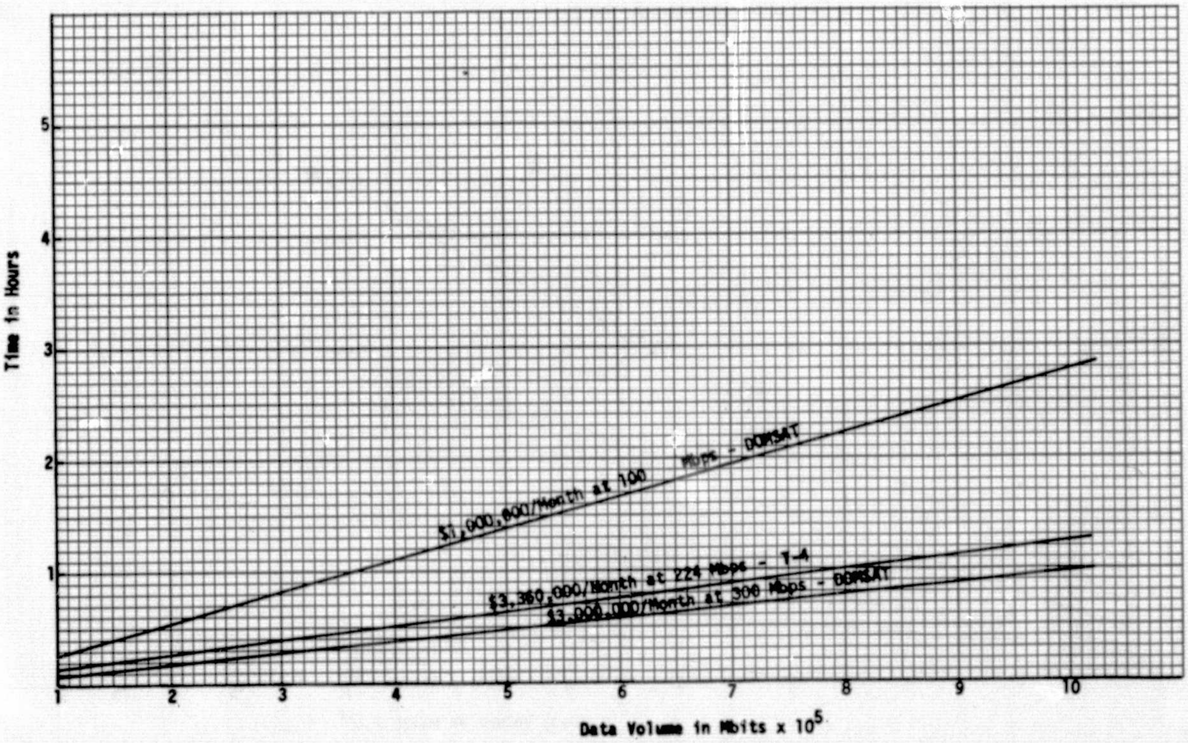


Figure 5-9. Performance and Cost for Various Data Link Configurations

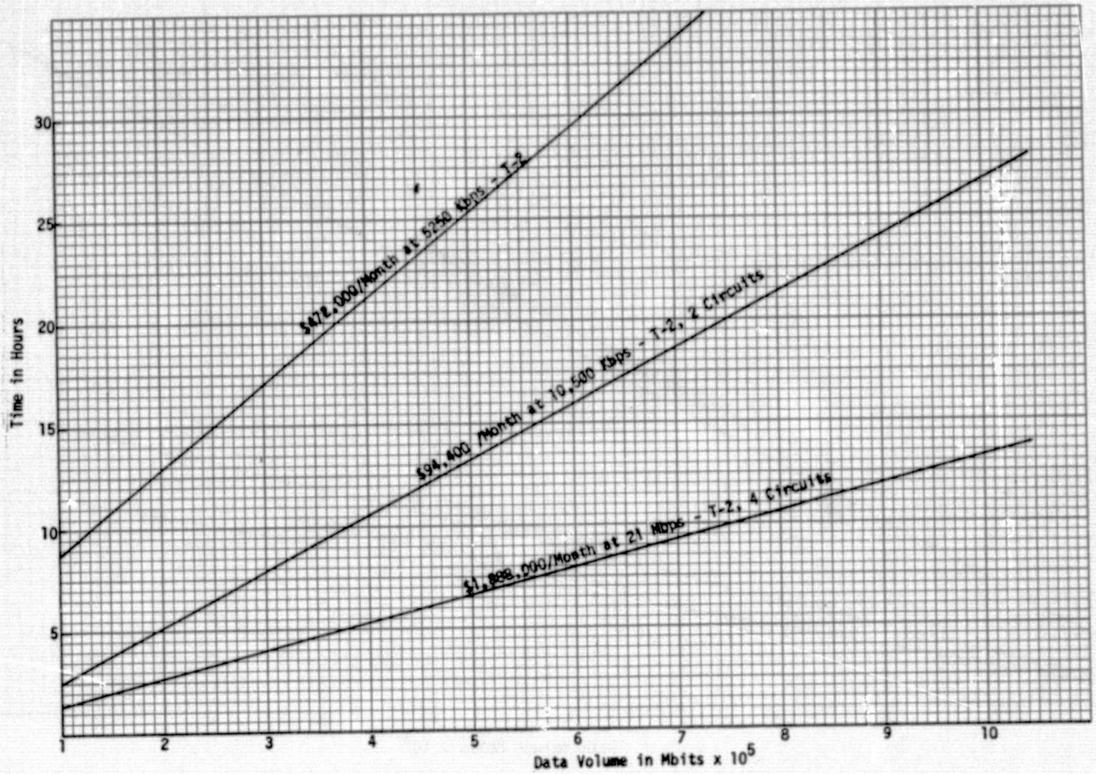


Figure 5-10. Performance and Cost for Various Data Link Configurations

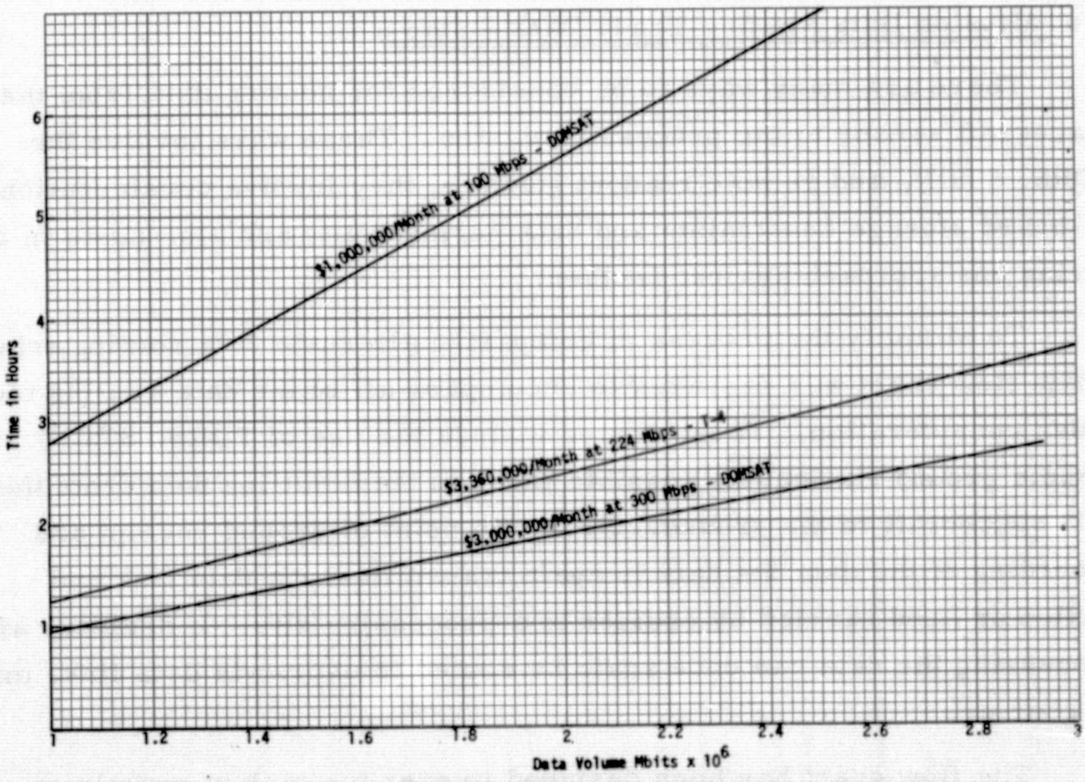


Figure 5-11. Performance and Cost for Various Data Link Configurations

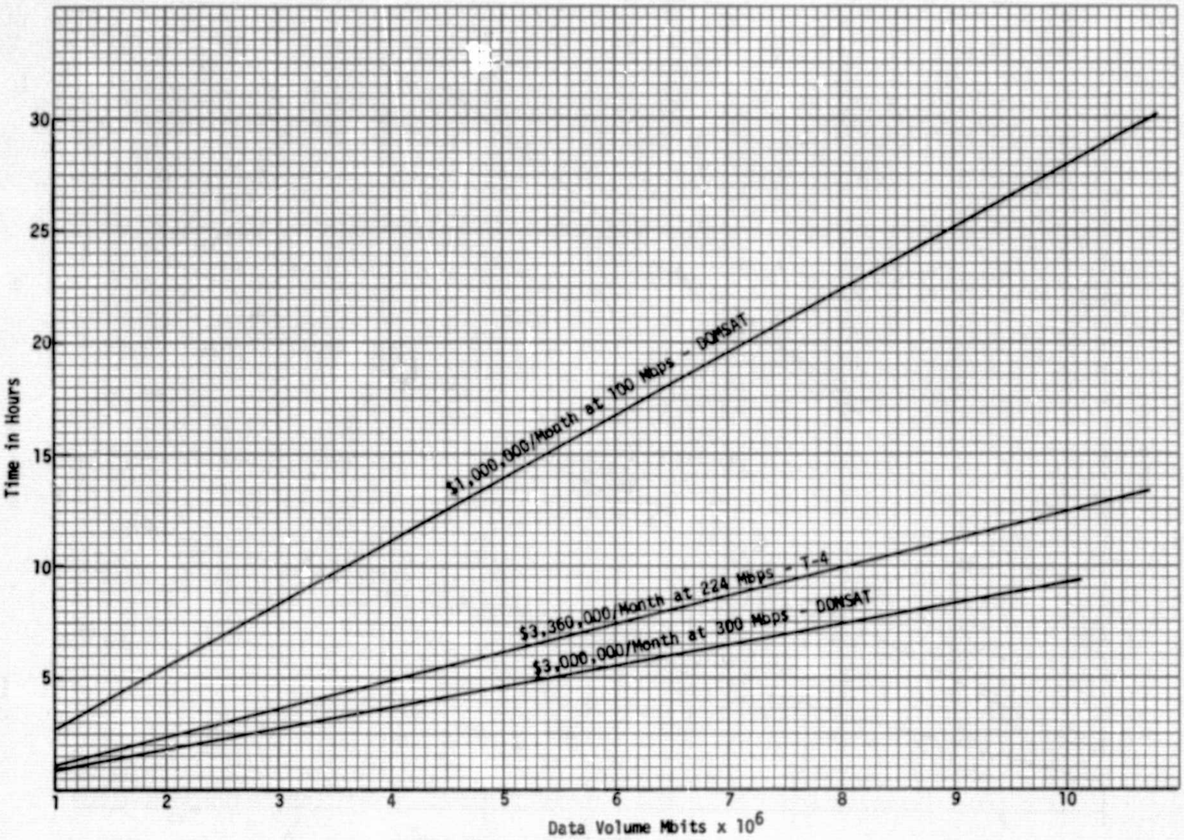


Figure 5-12. Performance and Cost for Various Data Link Configurations

5.6 Mission Data Routing Trade Data - Step 6

There are many ways to be considered for routing data from the spacecraft sensor to the processing center. These ways involve the TDRS, STDN, and remote readout stations; they involve consideration of on-board storage constraints and data perishability and also costs in comparing one approach against another.

To simplify the process of comparing alternate data routing schemes, a data flow chart was prepared to encompass all of the data routing means under consideration. These routes include the use of TDRS, STDN, and remote ground stations as possible paths in transmitting data from the EOS spacecraft to the ground. From the point of ground receipt and recording of the data the data is again transmitted via data link and mailed or hand carried by courier to a processing site. If desired, after processing the data can once again be routed to users via data link, mail, or courier.

The flow chart has been designed to ease the task of examining alternate paths by providing a systematic approach to the problem. The flow chart is supplemented by the use of a mission log sheet that is used to collect pertinent information regarding the selected data routing path, the various time delays which result, and the cost increase for the particular path chosen. Before describing the procedures for using the flow chart, a description of time delay factors is useful.

5.6.1 Data Time Delay Factors

The elements of time which contribute to the total time for data delivery are listed and defined below.

a) Initial Response Time. This is defined as the interval between the time when a decision to conduct a mission is made and the time when the spacecraft is first in position to observe the area of interest in its sensor coverage. For some missions, initial response time may not be of interest, in others it may be extremely important because it can become a very large portion of total data transmission delay.

b) Data Collection Time. This is defined as the cumulative time over which the sensor operates between successive data readout intervals for those cases employing on-board data storage. For real-time operation this interval is defined as the time the sensor is collecting data. The data collection time multiplied by the rate at which data are collected then provides the data volume that must be handled.

c) Time to Next Ground Station. This interval is defined as the time between completion of the data collection period and the beginning of data readout to a ground station. For real-time operation, this time interval is zero.

d) Return Link Transmission Time. This is defined as the length of time required to transmit a given volume of data at a selected rate to a ground station and is computed by

$$\text{Return Link Transmission Time} = \frac{\text{Data Volume from a)}}{\text{Link Data Rate}}$$

e) Station Turnaround Time. This interval includes all the tasks and procedures that must be accomplished prior to the start of relaying data to the next point in the data path. It includes such items as establishing the data link, recording header information, handling tape reels, and other administrative functions or procedures which must be followed.

f) Ground Link Transmission Time. This is the length of time required to transmit a given volume of data at a selected rate to the processing site and is computed by

$$\text{Ground Link Transmission Time} = \frac{\text{Data Volume from a)}}{\text{Link Data Rate}}$$

In the event mail or courier service can be substituted for this link, the time is that required for delivery of the data to the processing site.

g) Processing Time. This is the amount of time to receive the the data at the processing site, input the data to the processor, and prepare the final product (as may be defined for a particular routing path and mission).

h) Ground Link Transmission Time – Product. This interval is the time to deliver the product data to the next point in the network. This point may be another processing site, a user, or a combination. The time is computed the same as for f) above.

This completes the various time delay elements which, when summed, account for the total delay in mission data. Inclusion of item a), initial response time, is an option since it is mostly a function of mission planning factors and not a characteristic of the data routing path.

5.6.2 Mission Data Routing Analysis

The routing analysis flow chart is shown in Figure 5-13. It includes all possible routing paths and constraints that have been discussed in Section 5 and provides an organized procedure for analyzing alternate paths for all missions within the bounds defined in Figure 5-1. The flow chart is used in combination with a mission data log sheet to keep a record of the choice made at each branch in the flow chart and be able to determine total time delay and determine the cost that results from the choices made. A typical log sheet is shown in Figure 5-14.

5.6.3 Example of Mission Data Routing Analysis

To illustrate the method of using the flow chart and other data contained in Section 5, an example mission was chosen and analyzed by use of the flow chart to determine relative costs for data link versus data delivery time to meet perishability requirements. The example mission is to provide waving of several stations within two hours of observation by the spacecraft sensor.

The example log sheet, Log No. 1A, in Figure 5-15 provides the results of following the flow chart. The sequence used in Notes (1), (2),

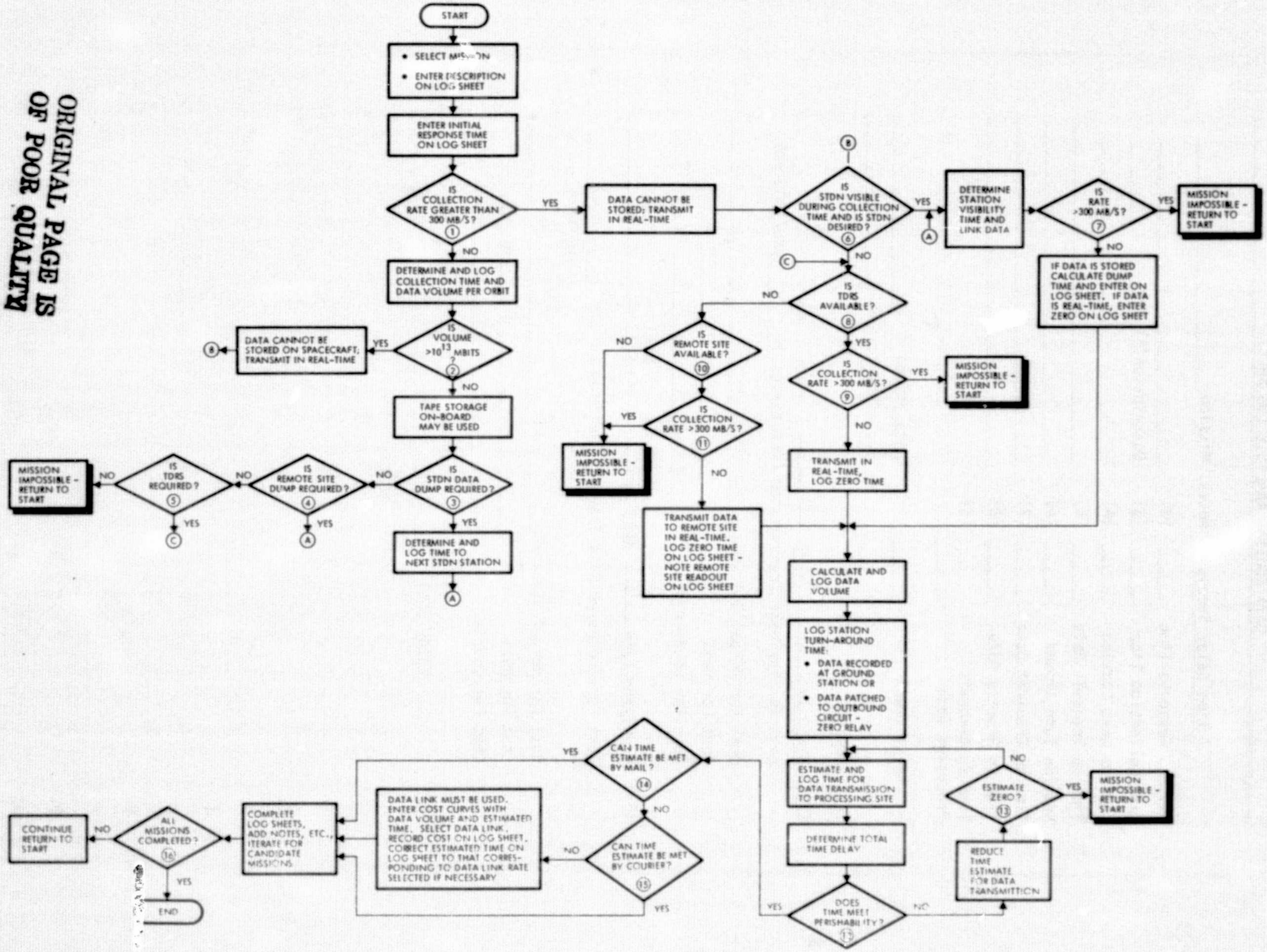


Figure 5-13. Data Routing Analysis Flow Chart

Log Number__________

DATA ROUTING ANALYSIS LOG SHEET

Time Delay Seconds   Notes   Mission ____________________

Initial Response Time ______ (2)   ____________________

Data Collection Time ______ (3)   Description(1) ____________

Time to Next Station ______ (4)   ____________________

Time to Transmit Data ______ (5)   ____________________

Station Turn Around ______ (6)   ____________________

Time to Transmit Data ______ (7)   ____________________

Time to Process Data ______ (8)   ____________________

Time to Transmit Processed Data ______ (9)

______

Total Time ______   Data Volume ______________

Data Rate to Gnd ____________

Cost Summary

(10) Raw Data ______ Rate __________

Cost for Raw Data Transmission From Curves $________/Mo/1000 nmi

Cost For Actual Distance________nmi ____________________

Cost For Mail ____________________

Cost For Courier ____________________

(11) Processed Data ______ Rate __________ Data Volume ____________

Cost For Processed Data Transmission From Curves ____________

________/Mo/1000 nmi

Cost For Actual Distance________nmi ____________________

Cost For Mail ____________________

Cost For Courier ____________________

TOTAL COST ____________________

NOTES

1.

2.

3.

4.

5.

6.

7.

8.

9.

Figure 5-14. Data Routing Analysis Log Sheet

EXAMPLE

Log Number 1A

DATA ROUTING ANALYSIS LOG SHEET

Mission Severe Storm Warning

Description(1) Use dual mode imaging spectroradiometer and advanced atmospheric sounder to monitor transient environmental phenomena. Geosynchronous orbit destination - National Weather Service, Miami, Florida, Perishability: 2 Hrs

		Time Delay Seconds	Notes
	Initial Response Time	0	(2)
	Data Collection Time	600 Sec	(3)
	Time to Next Station	0 (Dump)	(4)
: 1 Mbps)	Time to Transmit Data	360	(5)
	Station Turn Around	60	(6)
	Time to Transmit Data	7200	(7)
	Time to Process Data	3600	(8)
	Time to Transmit Processed Data	643	(9)
	(12) Total Time (hrs)	3.5	

Data Volume 3.6×10^8 bits/10 min sample

Data Rate to Gnd 1×10^6 bit/s

Observation Freq 1-6 Hrs

Cost Summary

(10) Raw Data Rate 56 kbit/s

Cost for Raw Data Transmission From Curves $11,760 /Mo/1000 n mi

Cost For Actual Distance 2000 n mi $23,520/Month

Cost For Mail N/A

Cost For Courier N/A

(11) Processed Data Rate 56 kbit/s Data Volume 3.6×10^7 bits

Cost For Processed Data Transmission From Curves $11,760 /Mo/1000 n mi

Cost For Actual Distance 1000 nmi $11,760/Month

Cost For Mail N/A

Cost For Courier N/A

TOTAL COST $35,280/Month

Figure 5-15. Data Routing Analysis Log Sheet

NOTES

1) Assumed Goldstone acquisition station is only station equipped with required transmission lines (additional cost for added stations).

2) Initial Response Time — No initial response time logged in this example - synchronous orbit.

3) Data Collection Time — Assumed at 10 minutes.

4) Time to Next Station — Assumes Goldstone in view during collection time because orbit is geosynchronous.

5) Time to Transmit Data — Assumes a 1 Mbit/s downlink rate for a tape recorder playback rate of 1×10^6 bit/s during a station access of about 10 minutes. This provides a data transmission time of:

$$\frac{3.6 \times 10^8}{1 \times 10^6} = 360 \text{ seconds}$$

6) Station Turn Around Time — Two minutes are allowed to turn the data around at Goldstone and begin transmission to GSFC.

7) Time to Transmit Data — This time is assumed as 7200 seconds; a line capable of delivering the 3.6×10^8 bits within 7200 seconds is a 56 kbit/s line as shown in Figure 5-9 as cost $11,760/month/1000 n mi.

8) Time to Process Data — This was estimated for the example at one hour. in actual use the processing time would be determined analytically for the mission. This also assumes the resulting data are compressed by a factor of ten.

9) Time to Transmit Processed Data - This was calculated by assuming a 56 kbit/s line from GSFC to NWS Miami, Florida to carry the compressed processed data of 3.6×10^7 bits or 643 seconds.

10) T-1 data line (56 kbit/s) is projected STDN capability.

11) Processed Data Rate — 56 Kbit/s.

12) Observation frequency must be greater than two hours if only one T-1 (56 kbit/s) data line is available at Goldstone.

Figure 5-15. Data Routing Analysis Log Sheet - 1A (Continued)

(3), (7), and (12) where the numbers refer to the specific branches chosen in the flow chart. The time delays were calculated as follows:

Data volume = 3.6×10^8 bits for 10 minutes of data collection at 600 kbit/s.

Initial Response Time. No initial response time logged in this example — synchronous orbit.

Data Collection Time. Assumed at 10 minutes.

Time to Next Station. Assumes Goldstone in view during collection time because orbit is geosynchronous.

Time to Transmit Data. Assumes a 1 mbit/s downlink rate for a tape recorder playback rate of 1×10^6 bit/s during a station access of about 10 minutes. This provides a data transmission time of:

$$\frac{3.6 \times 10^8}{1 \times 10^6} = 360 \text{ seconds.}$$

Station Turnaround Time. Two minutes are allowed to turn the data around at Goldstone and begin transmission to GSFC.

Time to Transmit Data. This time is assumed as 7200 seconds; a line capable of delivering the 3.6×10^8 bits within 7200 seconds is a 56 kbit/s line as shown in Figure 5-9 as cost $11,760/month/1000 n mi.

Time to Process Data. This was estimated for the example at one hour. In actual use the processing time would be determined analytically for the mission. This also assumes the resulting data are compressed by a factor of ten.

Time to Transmit Processed Data. This was calculated by assuming a 56 kbit/s line from GSFC to NWS, Miami, Florida, to carry the compressed processed data of 3.6×10^7 bits or 643 seconds.

Total Time. The sum of the above factors equal about 3.5 hours.

Cost Summary. The total costs for this data routing and for 3.5 hours of data delivery time is $35,280/month as shown in Figure 5-15.

Since the 3.5 hours did not meet perishability requirements of 2.0 hours, the example mission was repeated for routing the data directly from the spacecraft to the Goddard station where it is processed, then routed via a 56 kbit/s line to the NWS at Miami, Florida. The results show a data delivery time of 1.5 hours at a cost of $11,760/month as shown in Figure 5-16.

By repeating the above process, a cost versus delivery time curve may be prepared for this mission. A typical curve for the example mission is shown in Figure 5-17.

EXAMPLE

Log Number 1B

DATA ROUTING ANALYSIS LOG SHEET

Mission Severe Storm Warning

Description(1) Same as Log No. 1A

		Time Delay Seconds	Notes
	Initial Response Time	0	(2)
	Data Collection Time	600	(3)
	Time to Next Station	0	(4)
(at 1 Mbps)	Time to Transmit Data	360	(5)
	Station Turn Around	0	(6)
	Time to Transmit Data	360	(7)
	Time to Process Data	3600	(8)
	Time to Transmit Processed Data	643	(9)
	Total Time (Hrs)	1.5	

Data Volume 3.6×10^8 bits/10 minute sample

Data Rate to Gnd 1×10^6 bit/s

Cost Summary

(10) Raw Data N/A Rate 1×10^6 bit/s

Cost for Raw Data Transmission From Curves $ —— /month/1000 n mi

Cost For Actual Distance ____ nmi

Cost For Mail

Cost For Courier

(11) Processed Data ____ Rate 56 kbit/s Data Volume 3.6×10^7 bits

Cost For Processed Data Transmission From Curves $11,760. /month/1000 nmi

Cost For Actual Distance 1000 n mi $11,760./Month

Cost For Mail N/A

Cost For Courier N/A

TOTAL COST $11,760.

NOTES

1) Assume acquisition station at NTTF; short microwave transmission in real-time to NDPF.

Figure 5-16. Data Routing Analysis Log Sheet

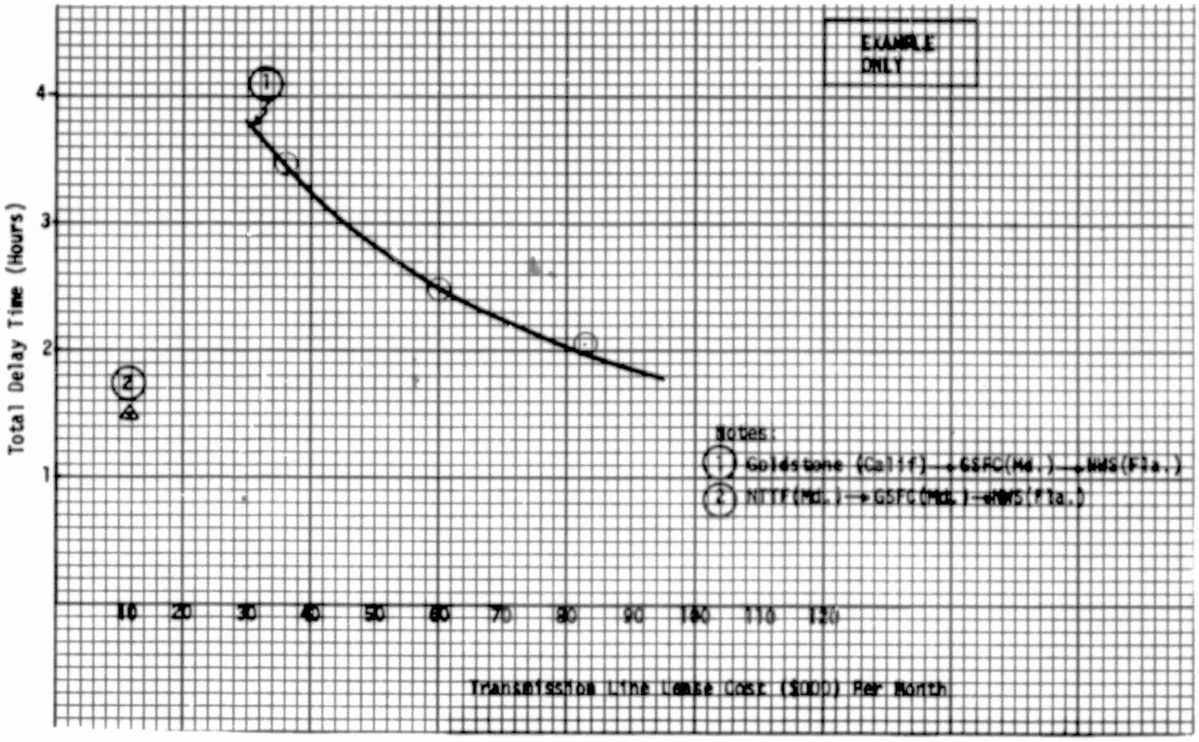


Figure 5-17. Candidate Mission - Comparative Costs of Leased Transmission Lines Versus Delay Time

REFERENCES

1. TRW Memorandum Number 7130.41-6, "IRAD" dated 11 October 1972.

2. Classified report.

6. ONBOARD PROCESSING CONSIDERATIONS

Between phenomena and data user, a variety of information manipulations may take place including sampling, digitizing, compressing, multiplexing, calibrating, storing, and correcting. Some must necessarily be done on the spacecraft to prepare the information for transmission to the ground while others may optionally be done onboard or on the ground. The decision as to which will depend on need, cost, impact on spacecraft weight, power, and other factors. Usually one would prefer to perform at the ground stations all functions not required on board. However, certain functions, if done on board, can ease other onboard functions or substantially ease a ground problem. Examples of the latter include data compression which could substantially ease a communication problem or data calibration and correction for APT (or LCGS) type transmission to minimize such functions at several or even hundreds of small ground reception sites.

The objective of this study is to generate a parametric data base which will be useful in analyzing and synthesizing on-board data handling systems for earth resources spacecraft in the 1978-1988 time frame and demonstrate the application of this data base to the requirements of typical missions. Background material is presented to give the reader a better understanding of the capabilities and limitations of the systems and hardware technologies discussed. Thus, the reader will be better prepared to intelligently apply the parametric data contained herein to actual system planning and design.

This report encompasses the following four general areas of interest in on-board data handling systems for earth resources spacecraft:

- Sensor interfacing (analog-to-digital conversion (ADC), multiplexing, and optical processing techniques)
- Conditioning for downlink transmission (formatting, speed buffering, data compression, and coding)
- Special on-board processing (geometric and radiometric image corrections, and synthetic aperture radard data processing)

- **Status and trends of large-scale integrated circuits, digital hardware, and mass memories.**

Section 6.1 discusses high-speed, low-power analog multiplexing and A/D conversion necessary in processing data from high-resolution images such as those anticipated for Earth Resources Systems missions. It is shown that of these two processes, A/D conversion causes the greatest problem today when it is desired to couple high accuracy with low-power and wideband operation. However, developments in monolithic comparator circuits will ease this problem so that by 1980, the projected maximum multiplexing and encoding rate will be 1.5 G bits/s. This rate exceeds identifiable mission data handling requirements for the types of users planned in the 1978 to 1988 time frame. Optical processing techniques are discussed, and although potential applications to ERS science data are numerous, no practical systems have yet been found.

The concepts of speed buffering, line stretching, and formatting are discussed in Section 6.2. Projections of the speed of operation for these signal conditioning functions indicate that 700 M bits/s image data can be handled by 1980 at reasonable equipment power and weight levels. Digital multiplexing is also considered in this section; rates of up to 1 G bits/s exist today while 10 G bits/s is predicted for 1980.

Sections 6.3 and 6.4 discuss data compression and coding techniques. It is shown that on-board compression (complete information preserving, if desired) and coding are feasible by 1980, the coder being much simpler than the compressor unit. However, at the ground processing station the converse is true, i.e., the decompressor unit is simpler than the decoder. For high-data rate channels a rather expensive decoding process may be necessary, using possibly 8 or 10 units operating in parallel at data rates around 20 to 25 M bits/s, and priced at approximately $20 - 30,000 each. From the results of the design of a 3:1 on-board compression unit, it was determined that operation on input data streams at 120 and 200 M bits/s at power consumption levels of 31 and 108 watts, respectively, is feasible today. By 1980, 200 M bits/s operation should be possible, at about the same power consumption and compression level.

The feasibility of on-board processing of synthetic aperture radar (SAR) data is determined primarily by the memory requirements, as shown in Section 6.5. For the configuration selected in this section and the "vector addition" processing algorithm chosen, around 30 Mbits/s of storage with access times approaching 1.2 nsec would be required. Using parallel and pipelined processor architecture strategies, it appears that on-board processing of SAR data will be feasible in the 1980's even with these difficult specifications.

Section 6.6 discusses image correction and resampling, ground control point, reseau extraction, radiometric correction, and calibration of sensor data. Algorithms for performing each of these functions are discussed and the need for very accurate spacecraft attitude control (around 0.01 degree pointing accuracy and 10^{-6} deg/sec rates) is pointed out so that equipment complexity can be minimized. Onboard performance of all the above functions is shown to be feasible by 1980.

Mass memory technology is considered in Section 6.7; emphasis is placed on tape recorders, charge-coupled device (CCD), bubble, plated-wire, and holographic memories. Currently, the magnetic tape recorder is the leader in this field, but by 1980, CCD and bubble memories are expected to offer lower cost, power, and weight in the 10^9 to 10^{10} bit storage range. For systems with capacities in the 10^{11} to 10^{13} bit range (or even higher), holographic "tape recorder" storage systems may challenge magnetic tape recorders in the archival memory area during the 1980's, even for onboard use. Meanwhile, the 200 Mbit/s tape recorder presently under development should offer 1.6×10^{11} bit capacities (13 minutes at 200 Mbit/s) for missions in the late 1970's.

Digital hardware status and trends are considered in Section 6.8. Important LSI technologies are reviewed and parametric data are given. Dramatic increases are foreseen in the number of transistors per chip (by a factor of up to 40 by 1980) and maximum clock rates (by a factor of 6 by 1980). At the same time, greater efficiency will be possible (power consumption may be held constant or even reduced while clock rates are increased by 6:1). Such gains will be possible because of many factors, notably higher packing densities (with the corresponding decrease in device parasitic capacitances and power consumption) and larger chip sizes (up to 300 or even 500 mils on a side appears feasible by 1980). The impact of these gains will be felt on all of the on-board processing systems discussed in this report.

6.1 Image-To-Data Stream Conversion Techniques

6.1.1 The Multimegabit Operation Multiplexer System (MOMS) Concept

As a result of the increasing use of high-resolution imaging sensors for earth resource missions, a need has been created for effective means of handling wideband data. Typical missions using multispectral scanners (MSS's) may require multiplexing and encoding subsystems capable of operating in the range of 200 Mbit/s or higher. For example, an EOS-A MSS sensor complement consists of a thematic mapper (TM) and a high-resolution pointing imager (HRPI). Since each of these sensors has an output data rate of around 100 Mbits/s, the combined sensor requirement is for approximately 200 Mbits/s multiplexing and encoding rate. The Multimegabit Operation Multiplexer System (MOMS) development program is intended to provide equipment to meet this kind of requirement, yet operate at low power for spaceflight purposes.

The basic MOMS configuration is a tandem combination of analog multiplexer and A/D converter. A typical MOMS requirement is that it will accept 200 parallel analog inputs and each input will be sampled and converted to a 7-bit representation every 6.67 microseconds. In this case, the output data rate would be (200 inputs) (150 x 10^3 samples/sec/input) (7 bits/sample) = 210 Mbit/s. High power and large size are inherent in the techniques conventionally used to multiplex and encode analog data at such a rate. Since these factors are not acceptable for ERS missions, the primary objective of the MOMS program is to develop a system that would accommodate the required data rates while satisfying the constraints imposed by the spacecraft environment.

The MOMS development resulted from a GSFC SRT program for a "high data rate PCM processor that is capable of accepting a wide variety of analog inputs and producing an output bit stream at rates up to 280 Mbits/s." The desire was to achieve the above at a maximum power dissipation of 27 watts. Essentially the goals of the program were met using two MOMS units, each operating at 140 Mbit/s (20 million samples/sec at 7 bit/sample).

However, a basic accuracy problem was uncovered during the development in that it was found difficult to obtain ADC comparators well enough matched to achieve a true 7-bit ADC accuracy. The analog multiplexer portion of MOMS functioned as expected, so that the real stumbling block to 200 plus Mbit/s operation was in the high-speed ADC. Specifically, "to implement such a system, requires use of state-of-the-art small geometry transistor with f_t in excess of 1.0 GHz at 1.0 mA. Because of the extremely shallow base widths of these devices, production yields are relatively low thereby making the selection of high-gain matched pairs economically unfeasible for anything more producible than a laboratory demonstration prototype". The resultant system operated accurately only at 5 bit/sample quantization.

TRW has critiqued the MOMS system; some pertinent comments are:

- Transistor matching problems in the discrete comparator and high-speed analog multiplexer can be eliminated by existing monolithic technology. For example, TRW has developed a single comparator and a 2BQ (two bit quantizer, four comparators and decoding logic) in monolithic form. (See 6.1.2)
- Locating the sample and hold circuit in the A/D rather than in the multiplexer has two advantages: 1) multiplexing and quantizing can be overlapped; 2) ±1/2 least significant bit (LSB) aperture error at 7 bits (±LSB at 8 bits can be eliminated
- The A/D converter uses a two-stage feed forward technique without an analog delay between stages. Hardware and power can be decreased by using the series parallel feedback (SPFB) approach and feeding back, thus, using the first stage twice. (See 6.1.2)

The inherent problem of designing high-accuracy converters is one that has always plagued linear IC designers, that of producing precisely matched components. Although IC processing techniques have for a long time produced well-matched components (which sometimes outperform their discrete counterparts) the need for high precision nevertheless present a great challenge. Sufficient accuracy and matching has been obtained by one scheme through the use of ion-implanted resistors, combined with standard bipolar processing methods. Therefore, the converter can be manufactured on the same process line as high-volume products, with only a small amount of additional handling. Since resulting switching times can be in excess of 200 million samples/s, the future ability to realize ADC's with MOMS-like requirements seems assured.

Further discussion of A/D conversion will be deferred to Section 6.1.2. Suffice it to say here that 1974 to 1975 technology will permit realization of the MOMS goals, probably even at 8-bit quantization accuracy. A projection of MOMS capabilities into the 1980's is given in Figure 6-1.

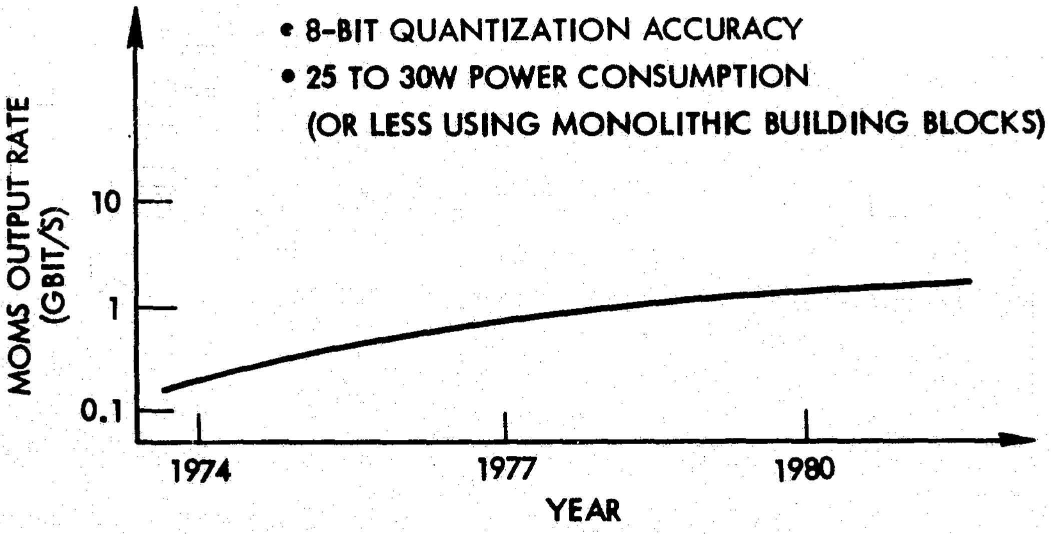


Figure 6-1. Projected Data Rate Capabilities of MOMS-Type Systems

6.1.2 Low-Power A/D Conversion

Recent developments in high-speed A/D converters have resulted in configurations such as:

- 100 Mbit/s conversion at 4 bits quantization
- 20 Mbit/s conversion at 10 bits quantization,

with power dissipations in excess of 30 watts. These converters use modulator packaging and hybrid circuitry and have power consumptions beyond that desirable for ERS applications. The future trend indicates that increased development in the monolithic integration of the major subsystems of the converter and also integration of many discrete component parts will reduce power, ease interconnect requirements and reduce part counts.

Numerous A/D converter organization schemes for low-power, high-speed conversion applications have been studied and implemented recently including all-parallel concepts, all-serial concepts, and certain serial-parallel concepts. Several of these architectural techniques will now be introduced, and key features of each will be given.

6.1.2.1 Techniques for High-Speed, Low-Power A/D Conversion

Key features for each of four important ADC architectures are the following:

1) Successive approximation (SA) including present speed limited to 8 million samples/sec, (at 8 bits resolution), lowest power, highest accuracy, and preferred approach below 8 million samples/sec.

2) Successive approximation interleaved (SAI) consisting of two SA A/D's in parallel, speed and power twice that of SA, and accuracy lower because the two channels must track.

3) Successive approximation feed forward (SAFF) consisting of two SA A/D's in series and speed and accuracy comparable to SAI with lower power.

4) Series parallel feedback (SPFB) similar to SA but with several bits determined per cycle, present (1974 to 1975) speed limited to 25 million samples/sec at 8-bit resolution, power and accuracy performance second only to SA method, and preferred approach above 10 million samples/sec.

The first three techniques discussed above are useful primarily at data rates less than 10 Mbit/s. The SPFB architecture appears to be the most effective for high-speed, low-power applications, and a block diagram for such a system (capable of over 100 bit/sec operation for MOMS-like ERS applications) is shown in Figure 6-2. Note that low-power is achieved here by using the same four-bit quantizer for each of two passes. Resultant operation is at 160 Mbit/s with only a 4-watt power consumption level.

6.1.2.2 ADC Performance

Relative performance for each of the four major ADC architectures is given in Figure 6-3.

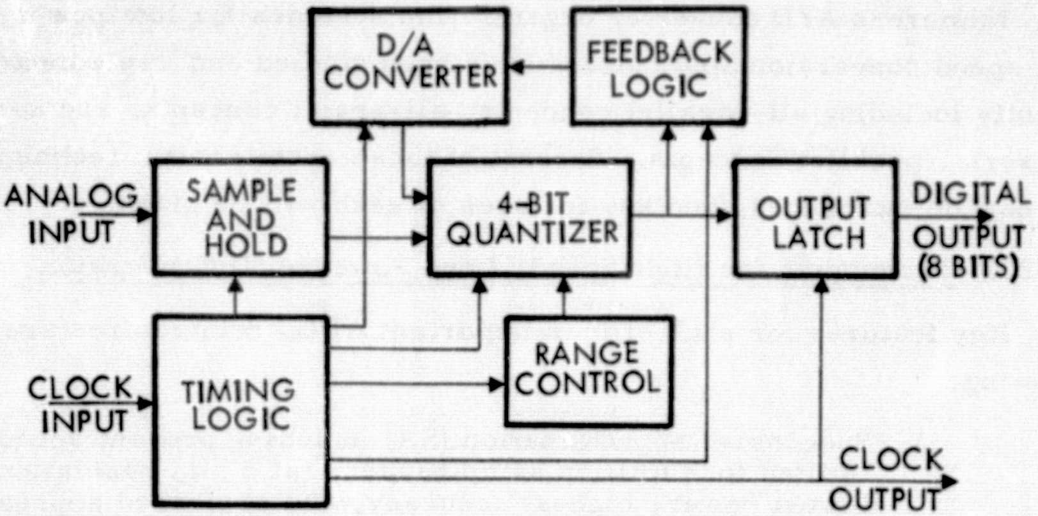


Figure 6-2. Block Diagram for 8-Bit, 20 Million Samples/Sec A/D Converter Using SPFB Technique

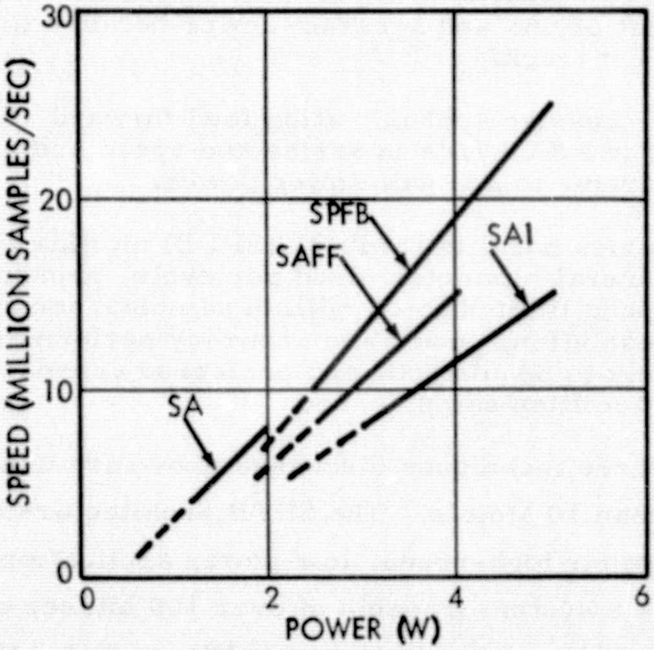


Figure 6-3. Performance for Various Low-Power 8-Bit A/D Converters

Figure 6-3 demonstrates that the SPFB scheme is superior for achieving high-conversion speed while maintaining relatively low-power consumption. It is also of interest to plot conversion rates versus resolution of SPFB techniques in order to see development trends more clearly. This is done in Figure 6-4, which shows present low-power ADC capabilities using SPFB techniques.

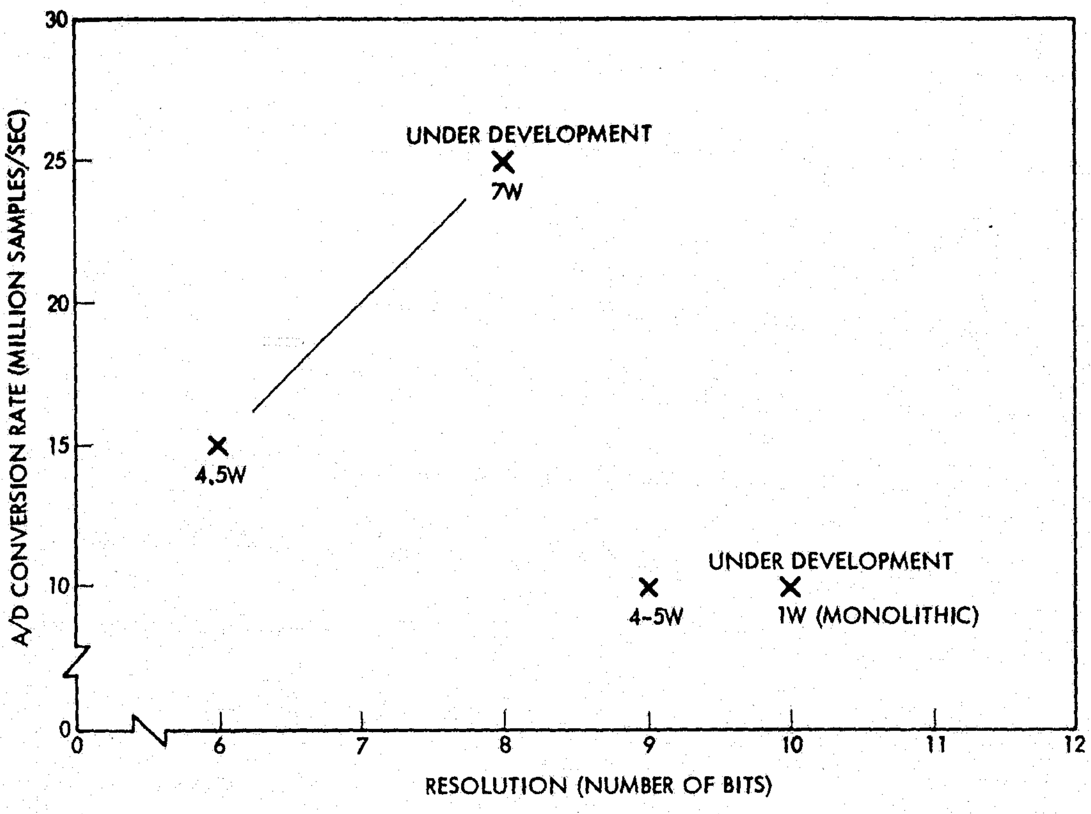


Figure 6-4. Present Low-Power ADC Capabilities

Projection of ADC capabilities to inset future onboard encoding requirements are not shown in this section, in that they are essentially the same as shown in Figure 6-1 (i.e., the MOMS unit includes an ADC so that Figure 6-1 is also a future ADC capability projection).

6.1.3 Optical Processing Techniques

In electrical systems it is possible to separate signals of differing frequencies by a network of reactive components. The unique frequency dependent properties of capacitive and/or inductive reactance furnish the desired discriminatory action.

Optical components such as the prism, diffraction grating, and thin film interference filter, allows analogous separation between light constituents of differing frequencies. In addition, optical components can perform what has become known as spatial filtering.

Although it is a hundred years since Ernst Abbe published his now famous paper on the transform and associated spatial filtering properties of lens systems, it is only in the last 10 years that the results have been applied to any extent.

The principle involved is that a simple convex lens spaced its own focal length from an object will produce in its image plane an intensity distribution that is the Fourier transform of the spatial frequency distribution (intensity) of the object, if the object is illuminated by a coherent light source.

If a second lens is positioned its own focal length from the image plane of the first lens, a second transformation will be affected resulting in an untransformed image of the original object appearing in the image plane of the second lens.

If opaque masks are placed in the image plane of the first lens (called the transform plane), the final image becomes a spatially filtered version of the original object. The general arrangement required to perform these operations is illustrated in Figure 6-5.

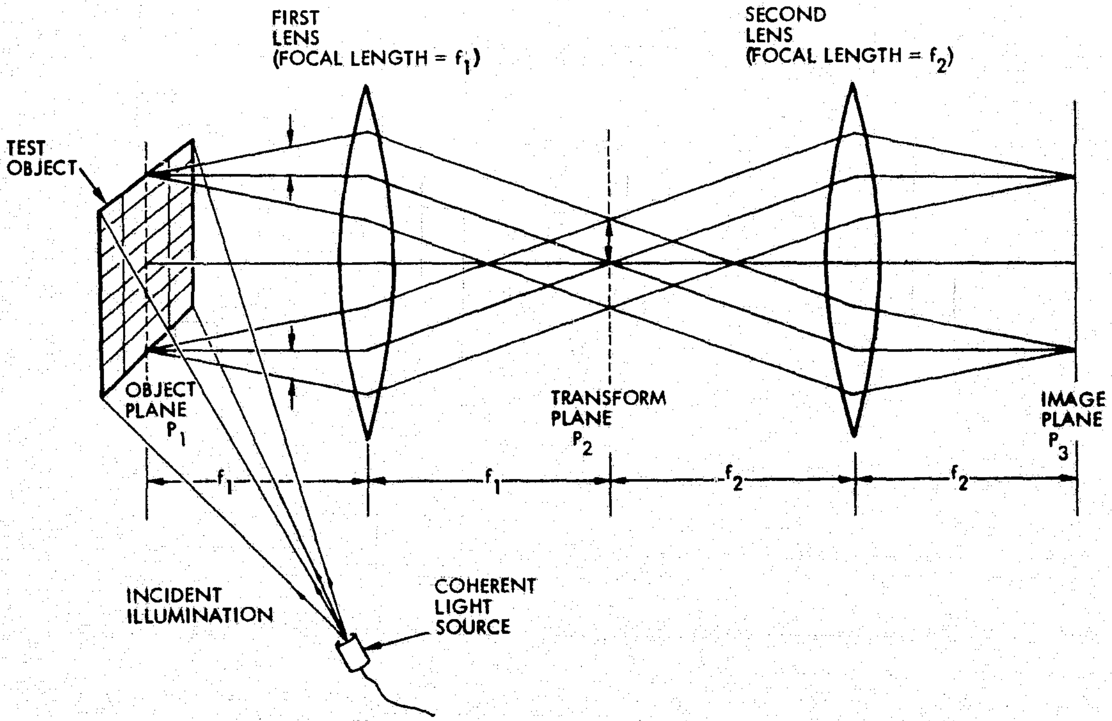


Figure 6-5. Optical System Arrangement for Spatial Fitting

Examples of spacecraft applications of optical processing are the high pass filtering of satellite weather photos in order to sharpen boundaries of the sea, clouds, ice, and shoreline, and the resolution enhancement of the Surveyor VI moon photos.

6.1.3.1 Information Processing

Optical systems can perform a number of processing functions beyond simple spatial filtering, examples are:

- Spectrum analysis
- Signal correlation and cross correlation
- Pulse shaping (compression/expansion)
- Pattern recognition
- Analog simulation
- Matched filtering
- Convolution

Several of these operations can be generalized into the following form:

$$r(x_o, y) = \int_{a(y)}^{b(y)} s(x, y)\, h(x-x_o, y)\, dx \qquad 6\text{-}1$$

where x_o, a, and b may be functions of time.

Operations of the above type are inconvenient if it is necessary to evaluate the integral for a large number of y values. With the aid of an optical processor however, such operations can readily be carried out for a large number of y values — say several thousand — simultaneously. Furthermore, a generalization of the operation to include an integration over y as well as x is also readily accomplished.

It is very easy to become so excited about the capabilities of coherent processors that noncoherent processors are completely neglected.

Assume that light of unit intensity s(x, y) is incident upon a transparency that has a (real) energy transmittance. (For noncoherent systems, light intensity is specified since there is no time-independent phase relationship across the plane of a collimated input beam — i.e., the beam is spatially incoherent.) With the aid of two lenses to form a unit telescope, the transparency is imaged onto a second transparency having an intensity transmittance $h(x, y)$. Planar translation of this transparency forms $h(x-x_o, y-y_o)$; $s(x, y)h(x-x_o, y-y_o)$ then describes the light intensity as it leaves the plane of h. Thus, the integrand in Equation 6-1 has been formed and awaits integration.

Two-dimensional integration merely involves collecting of all the light over a specified region of the plane where the integrand appears. Specification of the region is with the aid of an aperture mask or the transparency itself. After the light has been collected and focused to a point; the intensity is determined with an appropriate energy detector. A photocell or a small region of photographic film would be suitable. Mathematically the operation is

$$r(x_o, y_o) = \int_c^d \int_{a(y)}^{b(y)} s(x, y)\, h(x-x_o, y-y_o)\, dxdy \qquad 6\text{-}2$$

Multichannel one-dimensional integrations are possible with astig matic systems using cylindrical lenses. By this technique, integration with respect to x may be performed, y being used as a parameter. Equation 6-1 then once again defines the precise operation.

Because energy transmittance values are necessarily real and in the interval (0, 1), the above noncoherent operations are constrained. Dual polarity or bipolar functions are admissible only if suitable bias terms are employed. Assuming such a requirement for the function h as an example, the product sh might become $sh' = s(A + Bh)$ where B is used to keep h' from exceeding unit. Additive bias applied to both terms in a product is generally not possible since there will be an overlapping of spatially varying terms with the desired product term. In such cases, processing with a coherent light system is appropriate.

6.1.3.2 Operations with Coherent Light

Operations with spatially and temporally coherent light allow a relaxation in the constraints on filter functions. The constraints are in fact, less stringent than they are for typical electrical filters. Reflect on the manner in which a transparency affects light passing through it. Opacity of the film alters the magnitude of the complex amplitude while thickness variations alter the phase. Independent control of the phase and magnitude is therefore possible and consequently, filter functions which lie anywhere within a unit circle surrounding the origin of the complex plane can be realized.

In a generalized coherent processing system (see Figure 6-5) the illumination leaving the first spatial distance plane (or object plane) P_1 is of complex amplitude $s(x, y)$. The first transforming lens then casts the function $S(\omega_x, \omega_y)$ on to the complex transparency $H(\omega_x, \omega_y)$ placed in the first spatial frequency plane (or transform plane) P_2. Subsequent transformation of the product S H into the image plane P_3 creates the function

$$R(x, y) = \frac{1}{4\pi^2} \iint S(\omega_x, \omega_y) H(\omega_x, \omega_y) e^{j(\omega_x x + \omega_y y)} d\omega_x d\omega_y$$

$$= \iint s(x-\alpha, y-\beta) h(\alpha, \beta) d\alpha d\beta \qquad 6\text{-}3$$

where

$$h(x, y) = {}^{-1} H(\omega_x, \omega_y)$$

The operation is that of two-dimensional convolution. The general name of the method used is "frequency plane processing" since the filter function H is located in a spatial frequency plane. Often in practical applications, the H function turns out to be nothing more than a slit or some other shaped hole in an opaque material. H functions of this type are known as binary spatial frequency filters. Apertures that allow the passage of light in the vicinity of the optical axis only, act as low-pass filters, while slits off axis act as band-pass filters. Purely imaginary functions take the form of phase plates, such as a simple optical wedge, or in more complex situations, variations in the refractive index of a sheet of liquid caused by sound pressure waves.

An alternative to the frequency plane processor is the spatial distance plane processor. This method utilizes a filter function $h(x, y)$ placed in a spatial distance plane. Placing the displaced input function $s(x-x_o, y-y_o)$ in the previous distance plane (or in physical contact with h) and casting it onto h forms the product $s(x-x_o, y-y_o)h(x, y)$ which is then ready for transformation:

$$R(\omega_x,\omega_y,x_o,y_o) = \iint s(x-x_o,y-y_o)h(x,y)e^{-j(\omega_x x+\omega_y y)}dxdy \qquad 6\text{-}4$$

By observing this output only on the optical axis $(\omega_x, \omega_y = 0, 0)$ we obtain,

$$R(0,0,x_o,y_o) = R(x_o,y_o) = \iint s(x-x_o,y-y_o)h(x,y)dxdy \qquad 6\text{-}5$$

which is a cross-correlation.

A slight modification of the method of recording s allows two-dimensional convolution. It is necessary merely to substitute $s(-x,-y)$ for $s(x,y)$ in Equation 6-5.

Frequency plane processing and spatial distance plane processing are thus the two means available for realizing operations with a given filter function. Either $H(\omega_x, \omega_y)$ or $h(x,y)$ is needed for placement in a frequency plane or a distance plane respectively. A very important difference between the two methods is the way in which the output information is obtained. Spatial plane processing yields an output on the optical axis whereas frequency plane processing provides an area output. Observing the output only on the optical axis requires that either s or h be mechanically scanned past an aperture.

By simultaneously applying both types of processing, operations of the type shown in Equation 6-6 are possible.

$$r(x_o,y_o) = {}^{-1}[H_2(\omega_x,\omega_y) \quad \int s(x-x_o,y-y_o)h(x,y)]\,] \qquad 6\text{-}6$$

Such a combined technique would be useful for matching to a signal containing colored Gaussian noise. Filter h might be used to whiten the noise and H_2 to match the then modified signal.

While the potential applications of optical processing to ERS scientific data are numerous, no practical systems are being developed at the present time for specific missions. This is due primarily to a lag in the development of optical processing technology as compared to other information processing technologies.

Although the prospects of on-board optical scientific processing in the circa 1980 time-frame appear dim, several other related programs are under way: 1) a coherent optical star tracking system is under development for attitude control of spin-stabilized spacecraft, (stored Vander Lugt filters of various constellations are used in a two-dimensional correlation scheme), 2) a study of digital, optical and hybrid techniques for parallel processing for the 1985 time period is being made and 3) a system for simultaneous logical operations on two-dimensional images using fiber-optic bundles for input/output is under development, but with application to ground data processing. Operations such as AND and OR on arrays of around 100 x 100 elements should be possible at high-data rates.

6.2 Formatting and Multiplexing Techniques

In many of todays spacecraft, inefficient data communication results from the informationless value of sensor rescan time. To eliminate this time within a single sensor an electronic line stretcher is required. However, if there are multiple sensors whose data phasing can be controlled, time division multiplexing of various sensors could provide a satisfactory solution without line stretching. In the more general case, both multiplexing and line stretching might be used together in assembling data for transmission to the ground.

Another aspect of data formatting which could ease the data rate problem is adaptive multiplexing. By careful consideration of the purposes of a mission and the characteristics of the payload members, one can establish a priority schedule for the assignment of such limited resources as spacecraft power and data bandwidth. This priority schedule should deal with the end utility of each sensor's data, both along and combined with, data from the other sensors. It should also include such factors as terrain being observed, lighting conditions, cloud cover, perishability of data, and the nearness to readout, sensor health, and other factors. Some inputs to the priority decision model could be automatic, while others would have to be entered manually through the command system. In any event, the consequence to the data handling system would be a division of the available bit rate between sensors in a more or less optimum fashion for each measurement interval.

In this section, an example formatting problem encountered in EOS missions is considered which illustrates the utility of line stretching. Then, state-of-the art techniques for digital multiplexing are discussed.

6.2.1 Line Stretching and Formatting

A fundamental problem in the design of on-board processors is efficiently formatting the digitally encoded sensor outputs for the downlink communication system. Line stretching is a part of this; a technique for compensating for less-than-100 percent duty-cycle sensor outputs, typically yielding a smooth, continuous data stream output at a reduced rate. The approach of this section is consideration to a proposed EOS-A wideband data handling system, examine in detail the line stretching and formatting requirements, and then discuss a particular system which meets these requirements and its hardware implementation. From these results we shall generalize 1980-era capability.

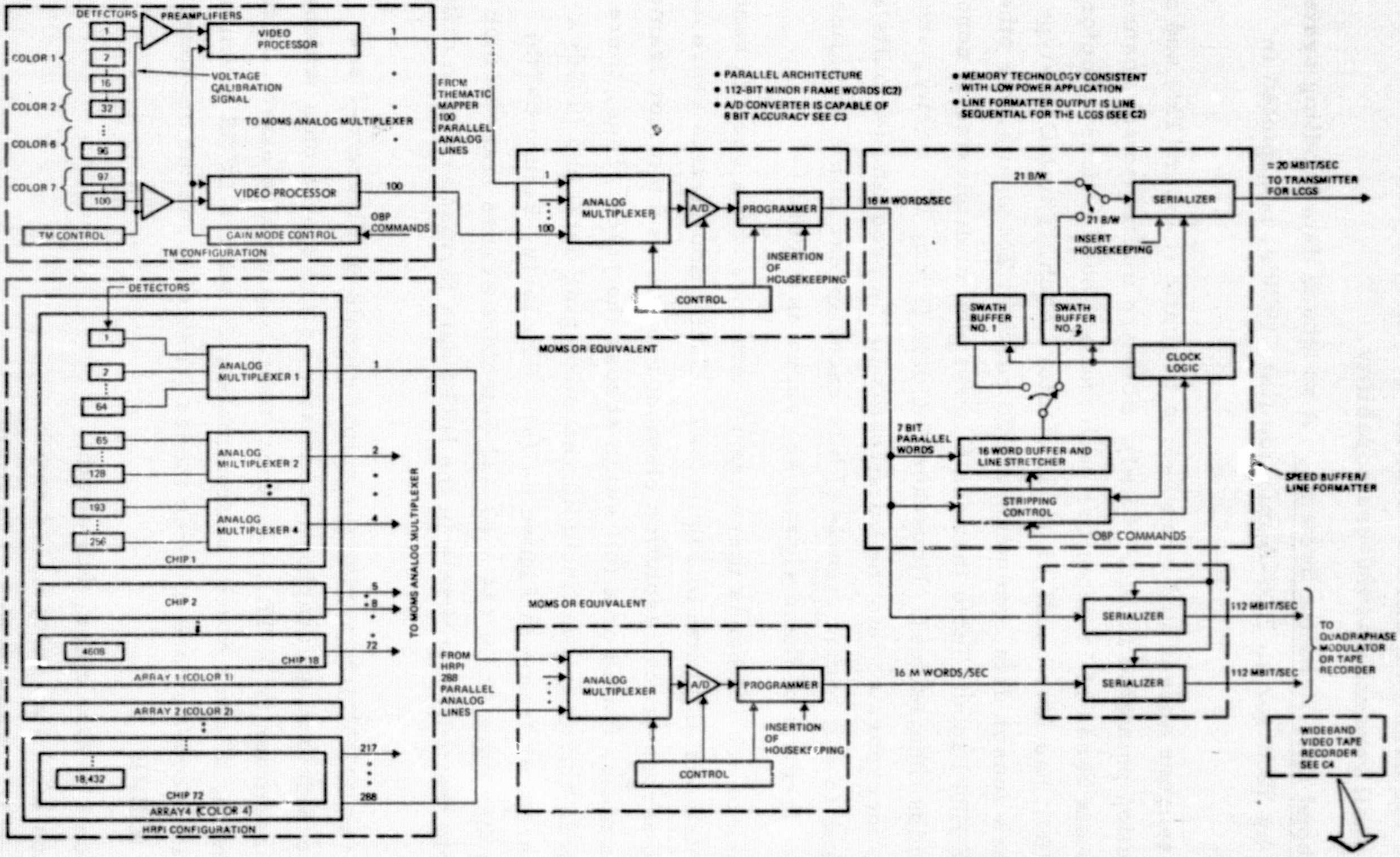
Wideband Data Handling Systems. A wideband data handling system considered by TRW for an EOS-A mission (late 1970's) is depicted in Figure 6-6.

Two sensors appear in Figure 6-6, a thematic mapper (TM) and a high-resolution pointable imager (HRPI). Both are multispectral scanners; the TM has six bands of 16 detectors each and one band of four detectors, while the HRPI has four bands of 4608 detectors each. Two MOMS-type units process sensor data, one accepts 100 parallel TM inputs, the other accepts 288 HRPI inputs (note that some low-speed multiplexing is done on the HRPI chips themselves). Housekeeping data (sycn, ID, parity, and others) are incorporated into the bit streams in the programmer units and two wideband 16 word/μsec signals (7 bits each) appear at the serializer inputs. The formats of these signals are shown in Figure 6-7.

In each of six TM bands there are 16 detectors and a seventh band has four detectors as shown in Figure 6-7. Each minor frame represents a minimum across-track resolution element and 9000 such minor frames constitute a major frame or a full swath across the track. Thus, there are 104 words/minor frame (including housekeeping data) and (9000) x (104) words/major frame in Figure 6-7(a). Similarly, Figure 6-7(b) shows that there are 128 x 144 = 18,432 detectors across track in four bands. Note that adjacent pixels in the HRPI data format are from different bands.

The two 112 Mbit/s serializer output signals in Figure 6-7 are sent on to a wideband quadraphase modulator or are stored on a wideband video tape recorder (WBVTR). A "local user" option also exists, in that upon command, a lower speed, approximately 20 Mbit/s LCGS downlink transmission occurs in one of three modes (control is via the on-board processor (OBP):

Option 1 : One color, full swath
Option 2: Two colors, 1/2 swath
Option 3: Four colors, 1/4 swath



- PARALLEL ARCHITECTURE
- 112-BIT MINOR FRAME WORDS (C2)
- A/D CONVERTER IS CAPABLE OF 8 BIT ACCURACY SEE C3

- MEMORY TECHNOLOGY CONSISTENT WITH LOW POWER APPLICATION
- LINE FORMATTER OUTPUT IS LINE SEQUENTIAL FOR THE LCGS (SEE C2)

Figure 6-6. Wideband Data Handling System

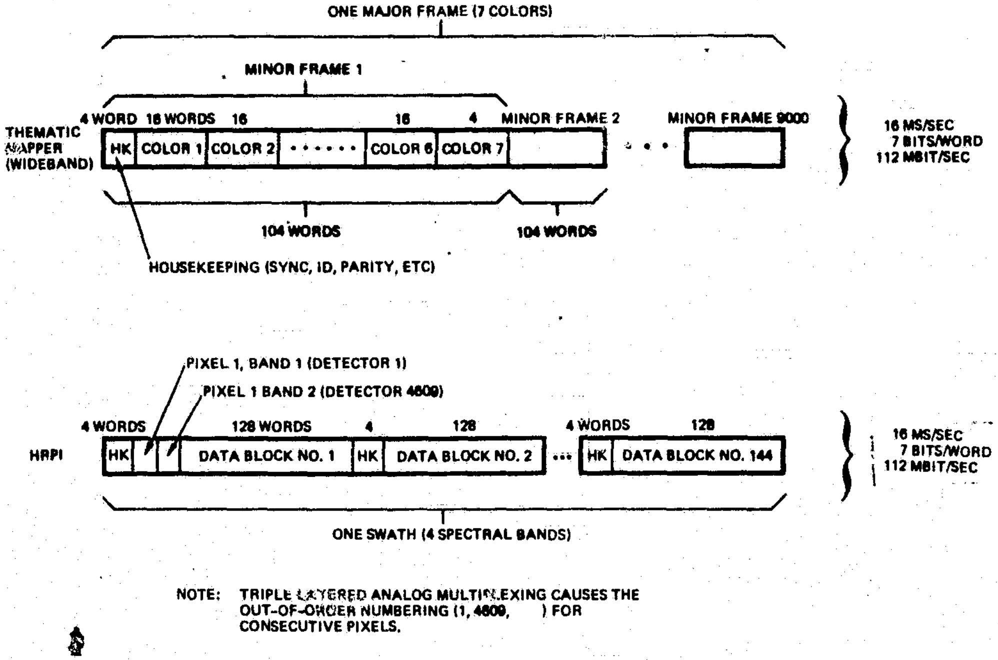


Figure 6-7. Thematic Mapper and HRPI Wideband Formats

Thus, using a relatively inexpensive ground station, it is possible to receive a portion of the total data gathered by the TM. For this convenience, however, we must pay the price of adding a relatively complex substem, viz., the speed buffer/line formatter of Figure 6-6 (expanded in Figure 6-9). This unit operates on the wideband TM data producing the format of Figure 6-8 (Option 1 shown).

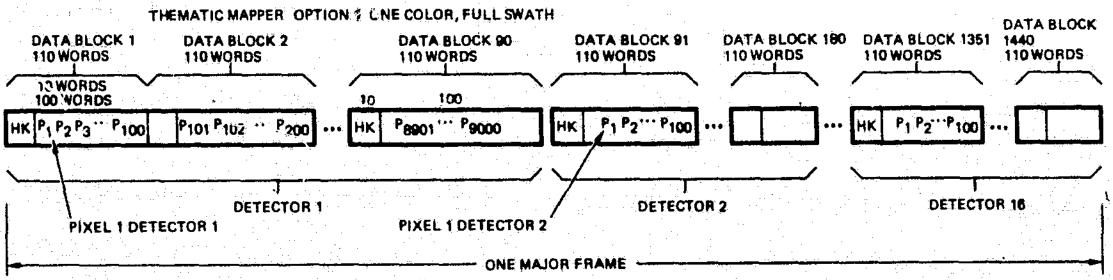


Figure 6-8. LCGS Format

An important consideration in synthesizing the LCGS format in the form of Figure 6-8 is that the data be in line-sequential format, useful for display purposes. The cost of developing such a format on board is minor when considering the cost savings at all of the low-cost ground stations (LCGS) (assuming that there are many such stations).

A double buffering technique is used in Figure 6-9 to achieve a line-sequential format such that data are output to the modulator at an even, synchronous rate. The stripping control unit allows a selected portion of the wideband data to be buffered at a high-data rate. Line stretching is accomplished in that the 16-word buffer outputs a slower, synchronous data stream for storage in the swath buffers. Using the technique shown, a total of 9000 x 32 x 7 bits ≈ 2 Mbit of random access memory (RAM) storage is necessary. Due to this rather large store, however, the line sequential output is possible, thus easing the data processing requirement at each LCGS.

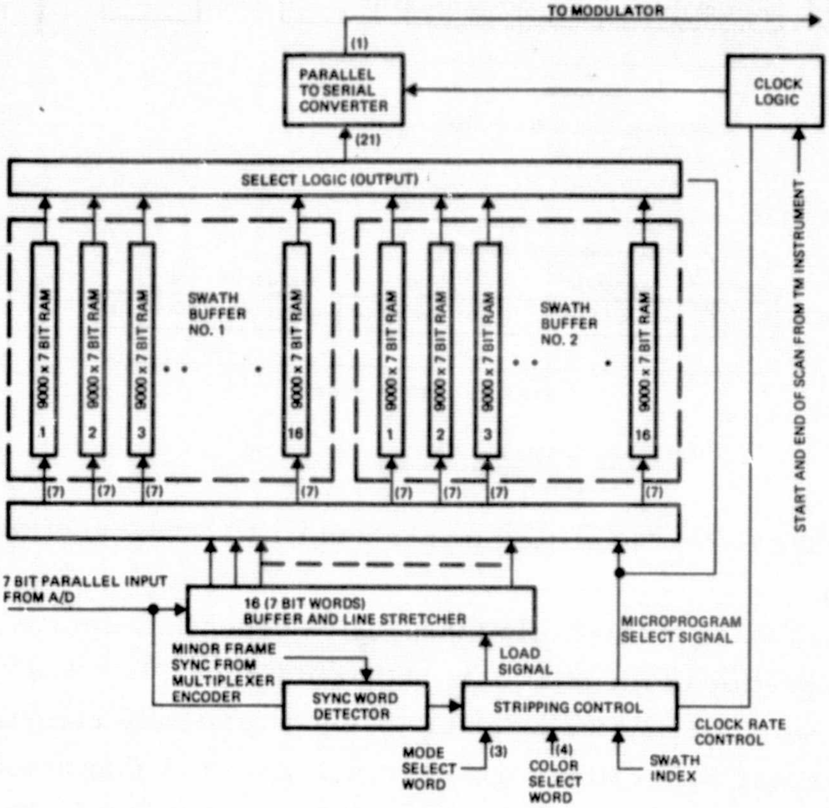


Figure 6-9. Speed Buffer/Line Formatter

Preliminary estimates indicate that implementation of the wideband data handling system discussed is possible at reasonable weight, cost, and power by 1975 to 1976 and that necessary speed and accuracy goals could be reached. The study was not carried out to the extent, however, that power and weight were calculated. Finally, projection of formatter/speed buffer capabilities into the 1980's is made in Figure 6-10.

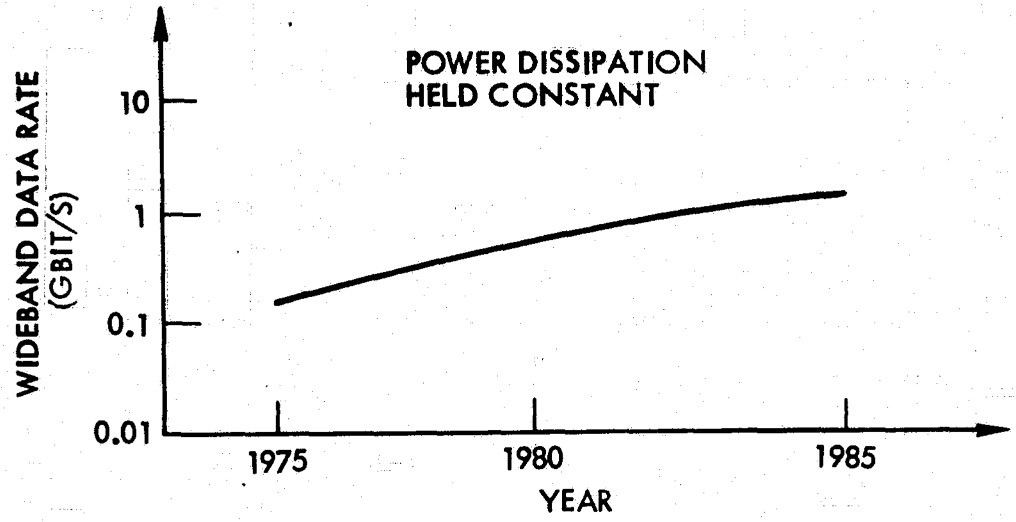


Figure 6-10. Projected Maximum Input Rate to a Typical On-Board Speed Buffer, Formatter, and Line Stretcher

6.2.2 Digital Multiplexing

The use of data multiplexers to gather information from many different sources within a spacecraft for subsequent downlink transmission over a single (or several) communication channel(s), has become a classical design task that must be addressed in virtually every spacecraft design. The design approach taken is highly dependent upon the nature and quantity of the various information sources and the available communication channel bandwidth. Usually there is a mixture of analog and digital signals to be multiplexed. Depending upon the various speed requirements, the spacecraft multiplexer may be required to operate at several speeds, and in many cases the multiplexing task is divided between separate high- and low-speed multiplexer designs.

Techniques for accomplishing the multiplexing at the very high bit rates will require further effort. Read-only memories (ROM) have proven satisfactory for establishing one of several multiplex formats at rates up to 10^9 bit/sec and within the next five to ten years this rate should increase by a factor of almost ten. Where alternate formats are possible, it is, of course, necessary to ensure that the ground demultiplexing is using the same format as the on-board multiplexer. This is accomplished by inserting an appropriate format code in a fixed position in the telemetry frame. In the case of the system in Figure 6-6, the insertion could take place in the programmer boxes.

Low-Speed Time Division Multiplexers (TDM). The advent of large scale integrated circuit technology allowed multiplexers, in general, to become smaller in size, weight, and cost. The most notable advances have been made in low-speed TDM's that use large-scale integrated (LSI) circuits employing metal oxide semiconductor (MOS) technology. The present trend is for incorporation of more of the multiplexer functions on a single LSI chip. For example, several companies are now offering multiple-channel fully decoded multiplexers on a single chip. Siliconix has a 16-input fully decoded analog multiplexer (Siliconix DG506) on a chip. Previously, Siliconix and other manufacturers were merely supplying the multiplexer solid-state switches in one package. There is little doubt that this trend will continue. The number of functions and multiplexer inputs will be limited only by the chip size and the number of I/0 pins available in the package.

Due to the varied processing requirements there has been an increasing tendency on the part of manufacturers to offer more of the LSI circuits in building block (interface compatible) form. This trend is expected to continue and will, of course, affect multiplexers. It is expected that more building block expandable multiplexers and their control functions will be offered in LSI chips. This will decrease multiplexer cost while increasing flexibility. It seems reasonable to assume that more extensive use will be made of LSI (ROM's) to perform the multiplexer switch sequencing and programming. Designs will be such that the multiplexer switching program can be completely revised by mere substitution of a different ROM.

More extensive availability of analog C-MOS multiplexers will drastically reduce multiplexer operating and standby power requirements. The C-MOS analog multiplexer can be readily converted for a digital output by use of an analog to digital converter which will probably be available in a single low-cost ($5) hybrid integrated circuits (IC) (fully space qualified) before 1985.

With the cost of IC ROM's and random access memories steadily decreasing in cost, it is likely that the extent to which multiplexer sequencing arrangements can be changed, while in flight, will increase considerably. The ability to change the multiplexing sequencing, at will, via ground control will allow the spacecraft to easily adapt to the demands of the signal monitoring situation.

High-Speed Multiplexer Development. High speed data multiplexer/ demultiplexer systems using sub-nsec logic techniques that operate at data rates above one Gbit/sec are now available. TRW has designed and breadboarded a unit under an Air Force contract which operates at rates up to 1.4 Gbit/s. The digital system consists of the following features:

- Variable frequency operation from DC to greater than one Gbit/s serial data rate
- Incorporates low-power logic elements exhibiting gate delay-power products of less than 10 picojoules
- Sync code injection and automatic sync acquisition allow preservation of word and frame organization
- 500 picosecond hybrid logic with extremely high noise immunity is used.

The multiplexer unit consumes 16 watts of power, but this could be reduced considerably by using more monolithic circuits in the design. As to the future, we may conclude that by the mid-1980's, integrated circuit spacecraft multiplexer/demultiplexers which can operate at data rates near 10 Gbit/s should be available for on-board applications.

6.3 Data Compression

For any sampling strategy there remains a wide variety of possible means for associating a binary sequence with an image. The usual way is to express each sample magnitude as a binary number of, say, 7 bits and then sequence these numbers according to the sampling plan. Using this sampling strategy the average number of bits required to represent an image can be reduced by taking advantage of the statistical distribution over the class of possible images, e.g., highly likely images can be coded with fewer bits and less likely ones with more bits in accord with Huffman coding practice.

For practical reasons one would prefer to apply this statistical approach over many local regions rather than over an entire image, but compressibility suffers as the unit which is compressed becomes smaller and smaller. This is so because one ignores more and more joint probability between units as they become smaller. Thus, there is a practical limit to how small a unit should be individually compressed. For example, no gains can be made in trying to compress one bit at a time and even with one picture element at a time, round off errors alone (we cannot use 3.4 bit/picture element so we round off upward to 4) can account for an increase in the amount of data by 20 to 50 percent. On the other hand, if a sensor is simultaneously producing four registered spectral bands and 7 bits represent the sample amplitude in each band, the round off penalty would not exceed 5 to 15 percent.

For a 4-spectral band sensor whose amplitues are quantized to 7 bits, 28 bits characterize the "color" at each pixel. If a probability of occurrence is assigned to each of the 2^{28} possible "color" combinations a Huffman code can be created that reduces the average sequence length an amount which depends on the specific probability distribution.

The probability distribution can be assigned absolutely or conditionally. An absolute assignment takes no account of the "color" already observed in adjacent samples, while a conditional assignment can depend on as many of the previously sampled values as one desires and considers practical. TRW's IR&D studies indicate that average compression ratios of 2 to 5 can be expected with practical conditional assignment strategies depending on the terrain type and the quality of the sensor.

The approach to image data compression discussed above is called information preserving because the transmitted (and usually shorter) digital representation of the image can always be expanded to yield the original representation without ambiguity. Another class of data compression techniques produces nonreversible (but subjectively acceptable) representations and with proper caution, can also be used.

Inherent in data compression is the need for buffering. This buffering permits the averaging of data peaks and valleys as compression over local regions varies. As compression techniques become more effective the amount of buffering required to prevent over-or under-flow grows. To be effective the buffer must normally be able to accept variable input rates and yield a constant average output rate. Variable speed tape recorders working with solid-state memories show great promise in this area.

6.3.1 Effectiveness Measures

One of the difficulties in this field is the great diversity of specialized techniques, coupled with the fact that there is at present, no universally applicable measure of the effectiveness of a given technique. As a result, it is difficult to make any tradeoff of effectiveness versus complexity without reference to a particular communication system. Steps in this direction are being taken, but it may be some time before the theoretical analysis of data compression systems is sufficiently well developed to be effective. For a given source and error criterion, the minimum possible transmission rate is found in the rate distortion function of Shannon. Except for simple cases such as the mean square error criterion, the mathematics are formidable. However, the concept of rate distortion is of considerable value, due to the generality of its definition, potential application, and because it offers a yardstick by which the effect of many of the various data handling operations can be measured. Briefly, the rate distortion (RD) function is defined as the minimum information rate required to transmit information from a given source to a receiver with average distortion no greater than D. The concept of distortion can be made to fit any fidelity criterion, and any information processing system. Applications include sampling, quantization, coding, estimation, dimensionality reduction, pattern recognition, data compression, and modulation; in fact, any process that lends iteslf to characterizing information generated by a source with a probability distribution. For example, in signal coding, the rate distortion function is just the capacity of the binary symmetric channel with transition probabilities D and (1-D).

The recent upsurge of interest as evidenced by activity in the literature indicates a concentrated effort to develop bounds and approximations to extend the range of application of the rate distortion function. An entire book devoted to rate distortion theory has appeared in which important new results are collected and presented and classical results are presented tutorially. Andrews has published a bibliography on rate distortion theory and Tasto and Wintz have published their results on a bound on the rate distortion function and its applications to images. O'Neal has recently published results on the bounds on subjective performance measures for source encoding systems. This last work has included results on the application of rate distortion theory with a frequency-weighted mean-square error criterion.

There are three other figures of merit in common use in describing data compression systems, as discussed in detail by Davisson. These are:

- The data compression ratio (DCR)
- The bit compression ratio (BCR)
- The energy compression ratio (ECR)

Their definitions are summarized in Table 6-1.

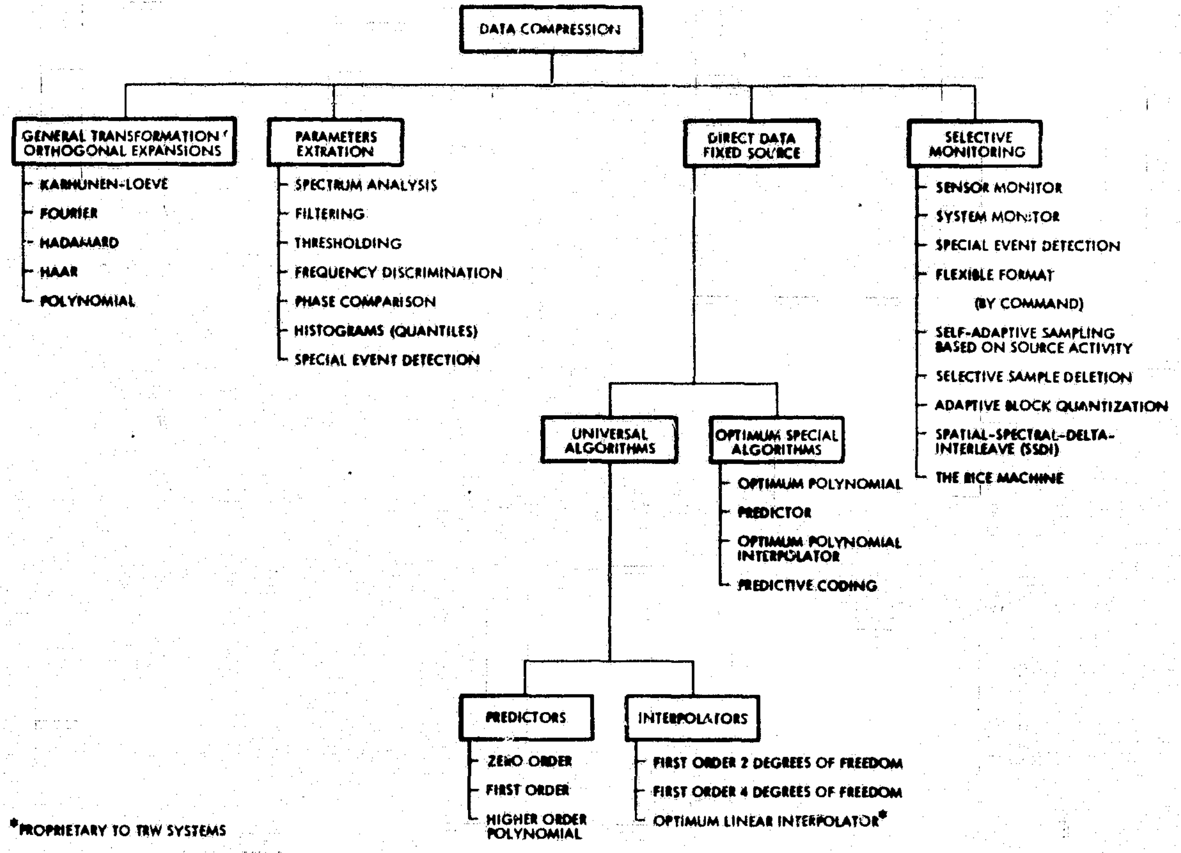
Generally, these measures of effectiveness are less informative than the rate distortion bound, but they can still be useful in the comparison of competing systems.

Table 6-1. Figures of Merit in Common Use for Data Compression Systems

Figure of Merit	Definition
DCR	The ratio of generated sample values to the transmitted values. This figure of merit can most easily be applied to the sampling and zero order or fan prediction and interpolation data compression techniques, with fixed pulse code modulation (PCM) word lengths.
BCR	The ratio of the information bits for transmission of the original sample values to those required in the system with data compression including all reconstruction information in addition to the transmitted sample values. The effect of channel transmission errors is to make the received reconstructed data of generally lower quality than in the straight transmission of the sample values.
ECR	The energy compression ratio is defined as the energy required per sample to transmit the data uncompressed divided by the energy when compressed under the same noise conditions and transmission scheme for the same reconstructed "quality," such as mean square error or probability of error.

6.3.2 Classification of Techniques

A large number of compression schemes have appeared in the literature; some are listed and categorized in Figure 6-11. A discussion



*PROPRIETARY TO TRW SYSTEMS

Figure 6-11. Data Compression Techniques

of all of these techniques is beyond the scope of the present work, however, papers relating to most of the categories can be found in the bibliography. Most recent work in the area of compression of multispectral scanner (MSS) imagery has been with predictor, selective monitoring, and orthogonal transformation techniques. For example, three studies currently underway relating to MSS compression are based upon:

1) Orthogonal expansions (using the Karhunen-Loeve (KL) transformation) (Purdue University)

2) The SSDI algorithm (a DPCM-like predictor method, see 6.3.3) with Rice encoding (TRW Systems)

3) A hybrid technique (transforms and prediction) (NASA/GSFC)

A group of candidate techniques can be selected that at present appear to be the most suitable for on-board MSS compression. These are listed in Table 6-2 along with information about their performance

Table 6-2. Candidate Information Preserving Compaction Algorithms and Their Relative Performance

Coding (Compression) Techniques	Number of Bits/Pixel*	Approximate Compression Ratios**	Implementation Complexity for Near-Real-Time Output
PCM (reference)	6 to 8	1:1	(reference)
Differential PCM (DPCM), predictors, interpolators, etc.	3	2:1 or higher	Simple to moderate
Adaptive DPCM (e.g., Rice Machine)	2 to 5	3:1	Simple
Adaptive 2-dimensional DPCM (e.g., Shell Coding) spectral-spatial delta interleave and their modifications	2 to 2.5	higher than 3:1	Simple to moderate
1-dimensional transform techniques	2.5 to 3	3:1	Moderate
2-dimensional transform	2 to 2.5	higher than 3:1	Moderate to complex
Adaptive 2-dimensional transform	1 to 1.5	5:1 and higher	Complex

*Approximate number of bits/pixel required for same quality picture produced by 6 to 8-bit PCM.

**Compression ratios achievable with non-information preserving techniques are much higher than that achieved with information preserving techniques.

and complexity. It is shown that for information preserving (distortionless) compression, the highest compression ratios are associated with the more complex mechanizations.

If we let C stand for the compression ratio shown in the table and let M stand for a measure of the algorithm's mechanization cost, an efficiency E can be defined: $E = C/M$. E can be considered to be a measure of the overall effectiveness of a technique. It has been shown that DPCM-like techniques have values of E that are significantly higher than those for KL transform methods. One would then expect that for on-board processing difference procedures would be more efficient than KL transform techniques. We thus consider spectral-spatial-delta-interleave (SSDI) algorithms to be the most probable method for realizing practical on-board compression systems in the circa 1980 time period.

6.3.3 Spectral-Spatial-Delta-Interleave (SSDI) Algorithm

The spectral-spatial-delta-interleave (SSDI) algorithm is a method of data compression developed for multispectral data, which removes a maximum amount of redundancy subject to the constraints of minimizing complexity and maximizing operating speed. This compression algorithm first operates on the spatial redundancy in each spectral band and then uses the information obtained to reduce spectral redundancies between adjacent bands.

In order to provide a conceptual description of the basic SSDI algorithm and several of its modifications, a situation in which there are three spectral bands, α, β, γ will be described. Each ground pixel, I, consists of three quantized spectral components, I_α, I_β, and I_γ. The algorithm proceeds in the following fashion. First, within each spectral band, each pixel intensity is subtracted from the intensity preceding it in the scan direction. (This technique is essentially DPCM, treating each spectral band separately.) To each pixel, then, there can be assigned a triple of these differences denoted $(\Delta\alpha, \Delta\beta, \Delta\gamma)$.

Next, these deltas are themselves differenced to obtain second differences in adjacent spectral bands, viz., $d_A = \Delta\beta - \Delta\alpha$ and $d_B = \Delta\gamma - \Delta\beta$. Here too, each pixel may be assigned the triple $(\Delta\alpha, d_A, d_B)$ which provides the same type of information as the triple $(\Delta\alpha, \Delta\beta, \Delta\gamma)$. However, due to spectral band correlation it should be true that on the average, $|d_A| + |d_B| \leq |\Delta\beta| + |\Delta\gamma|$, and the d_A and d_B are clustered closer to the origin than the first differences $\Delta\beta$ and $\Delta\gamma$.

These differences are transmitted in a manner allowing the original PCM sensor data to be recovered exactly from the coded sequence. Corresponding to each pixel, the triple $(\Delta\alpha, d_A, d_B)$ is developed. Given the preceeding pixel intensities, denoted $(I^{i-1}_\alpha, I^{i-1}_\beta, I^{i-1}_\gamma)$ the current intensities may be obtained by the recursion relationships

$$
\begin{aligned}
I^i_\alpha &= I^{i-1}_\alpha + \Delta\alpha \\
I^i_\beta &= I^{i-1}_\beta + \Delta\alpha + d_A \qquad\qquad 6\text{-}7 \\
I^i_\gamma &= I^{i-1}_\gamma + \Delta\alpha + d_A + d_B
\end{aligned}
$$

The SSDI algorithm, which is tailored to the multispectral data compression problem, will be used later in conjunction with an optimal coding scheme called Rice encoding, to yield an efficient overall compression technique.

6.3.4 The Rice Coding Algorithm

The Rice encoding algorithm, developed by R. F. Rice at JPL is a variable length coding system which is basically strictly information preserving. Operating on a sequence of source symbols, the Rice machine adapts by selecting one of three coding schemes with computational capability for optimally switching to that one of three codes which is compatible with the data activity. Code No. 1 performs well with low data activity, Code No. 2 performs well for data of medium activity, and Code No. 3 performs best with very active data. In order to adapt to rapid changes in activity, the basic Rice compressor monitors data activity and selects the appropriate code mode based on small blocks of data symbols.

Rice assumes that the adjacent samples of Δ are statistically independent and that the probability distributions of these symbols decrease monotonically on either side of $\Delta = 0$. For his assumed zero-memory source, Rice seeks to assign the shortest code words to source symbols that have the greatest probability of occurrence and the longest code words to those symbols which have the least probability of occurrence.

For each block of J symbols, the entropy of first order linear differences is given by

$$H(P) = \sum_{i=1}^{q} p_i \log p_i \qquad \text{bits/pixel} \qquad 6\text{-}8$$

where p_i represents the probability of the $i^{\underline{th}}$ source symbol and the log function is base 2. Parameter q can vary from zero to $2^{N+1}-1$, where N is the number of bits used for source quantization. Entropy can be considered as the quantitative measure of the source data activity.

Let L(P) be the number of bits/pixel required to code the sequence of difference samples which have the distribution $P = \{p_i\}_{i=1}^{2^{N+1}-1}$. Under Rice's assumption of a zero memory source, the average code length cannot be less than H(P):

$$E[L(P)] \ge H(P) \qquad 6\text{-}9$$

where E denotes the expectation operator.

The generality of Rice's model assumes that P can change completely from block-to-block and the coding algorithm can change from block-to-block, depending on the distribution, P, within each block. System performance is measured by comparing $E[L(P)]$ with the lower bound $H(P)$. In operation, the Rice algorithm monitors the data activity of each block of symbols and selects one of three codes, dependent on the activity range.

6.3.5 Implementation of the SSDI/Rice Algorithm

A data compressor unit (DCU) using the SSDI/Rice algorithm has been configured recently. The baseline design uses SSI and MSI low-power Schottky TTL (SN54LSXXX) combined with bipolar 1024 x 1 RAM's. Custom LSI (TRW emitter follower logic) was investigated for repeated functions such as ALU latches. The estimated impact was principally in a reduction of total parts and power of 10 percent and 0.8 watts, respectively, as compared to the baseline. Since the development cost of the LSI chip is sizable and the net effect on the DCU was small, LSI was not included in the baseline. Since the development cost of the LSI chip is sizable and the net effect on the DCU was small, LSI was not included in the baseline design.

The baseline DCU without a power converter is summarized below:

- Data clock rate 10 MHz (equivalent data rate 80 Mbits/s
- DCU parts total: 263 IC, 60 discretes or 323 total
- Power: 26.7 watts
- Weight: 3.0 pounds
- Volume: 192 in.^{3} (6 x 8 x 4 in.)

The maximum clock rate capability is 10 MHz for the given (T^2L) design. The rate can be further increased to 15 MHz maximum if selected components are substituted with standard Schottky TTL MSI and speed enhancement IC's are applied, such as look-ahead carry generators for the arithmetic/logic units (ALU's). There is then a penalty in additional parts and power dissipation with a corresponding slight increase in packaging.

Characteristics of the system, for both configurations described above and also for a third, higher-speed configuration, are tabulated in Table 6-3 for: I) for 10 MHz, II) for 15 MHz, and III) for 25 MHz. Type III was sized using (basically) Schottky TTL with emitter coupled logic (ECL) at critical points. The resulting power consumption is relatively very large. An optional power converter is also listed in the same terms as the DCU and would be directly additive to the associated DCU type if used. For example: power (Type I) = 26.7 + 9 = 35.7 watts total.

Table 6-3. DCU Unit Parameters

Type	Input Clock Rate (MHz)	Input Data Rate (Mbit/s)	Parts IC	Discrete	Total	Power (W)	No. of Slices	Weight (lb)	Volume (in.^{3})
I	10	80	263	60	323	26.7	2	3.0	192
II	15	120	290	60	350	30.7	2-1/2	3.7	192
III	25	200	333	160	493	108.0	3	4.5	384
Power Converter									
I			10	240	250	9.0	1	1.5	96
II			10	240	250	10.0	1	1.5	96
III			20	250	270	36.0	1	3.0	128

The implementation discussed here has demonstrated that it is feasible to build a data compressor for MSS scanners with the following characteristics in 1974:

- 120 Mbit/s input data rate (Type II)
- ≈40 Mbit/s output data rate (information preserving, 3:1 compression)
- Power and weight held to reasonable levels.

Projection of these results indicate that by 1980 compressors operating on 200 Mbit/s data streams will be feasible with about the same 3:1 compression ratio yet with even lower power and weight. To achieve even higher data rates it is possible to use parallel compressor units, but of course higher power would result.

It is also worth noting that for more than four spectral bands per sensor, the compression ratio (while maintaining distortionless compaction) increases markedly. Thus, the 3:1 ratio quoted earlier (for a four-band sensor) may be as high as 5:1 or 6:1 for systems with 6 to 10 or more spectral bands. Finally, we note that ground reconstruction of the original data is possible using either a minicomputer, or (for high-data rates), a special purpose decompressor that is very similar in complexity to that of the DCU.

6.4 Data Coding

The application of redundancy-reducing data compression techniques places increased value and importance on each data bit because it represents a distilation of the raw data, and will require a greater reliability in the communications channel. Coding tends to make the channel performance less sensitive to SNR degradation and errors caused by phenomenon such as multipath (especially at low antenna elevation angles) and weather conditions like lightning and rainstorms since each of the digital words are reconstructed at the receiver from the observation of many signal-plus-noise samples rather than just one. A complete analysis of any modern communication system performance, particularly one incorporating data compression, must therefore consider the effect of coding on performance.

6.4.1 Classification of Codes

A coding family tree is given in Figure 6-12. Of the various types of codes shown, the two classes of major interest for use in earth resources channels appear to be the block codes and the tree-type convolutional codes. Several categories of algebraic, or block codes in common use, are described in more detail in Table 6-4. Included are several of the parity check or group codes and one orthogonal code.

In contrast to block codes are the shift-register encoded convolutional codes. These yield information sequences that may be decoded on a continuous basis and have no well-defined code-block boundary. Two types of algorithm, sequential and viterbi, are found to be effective in decoding convolutional codes. Some characteristics are:

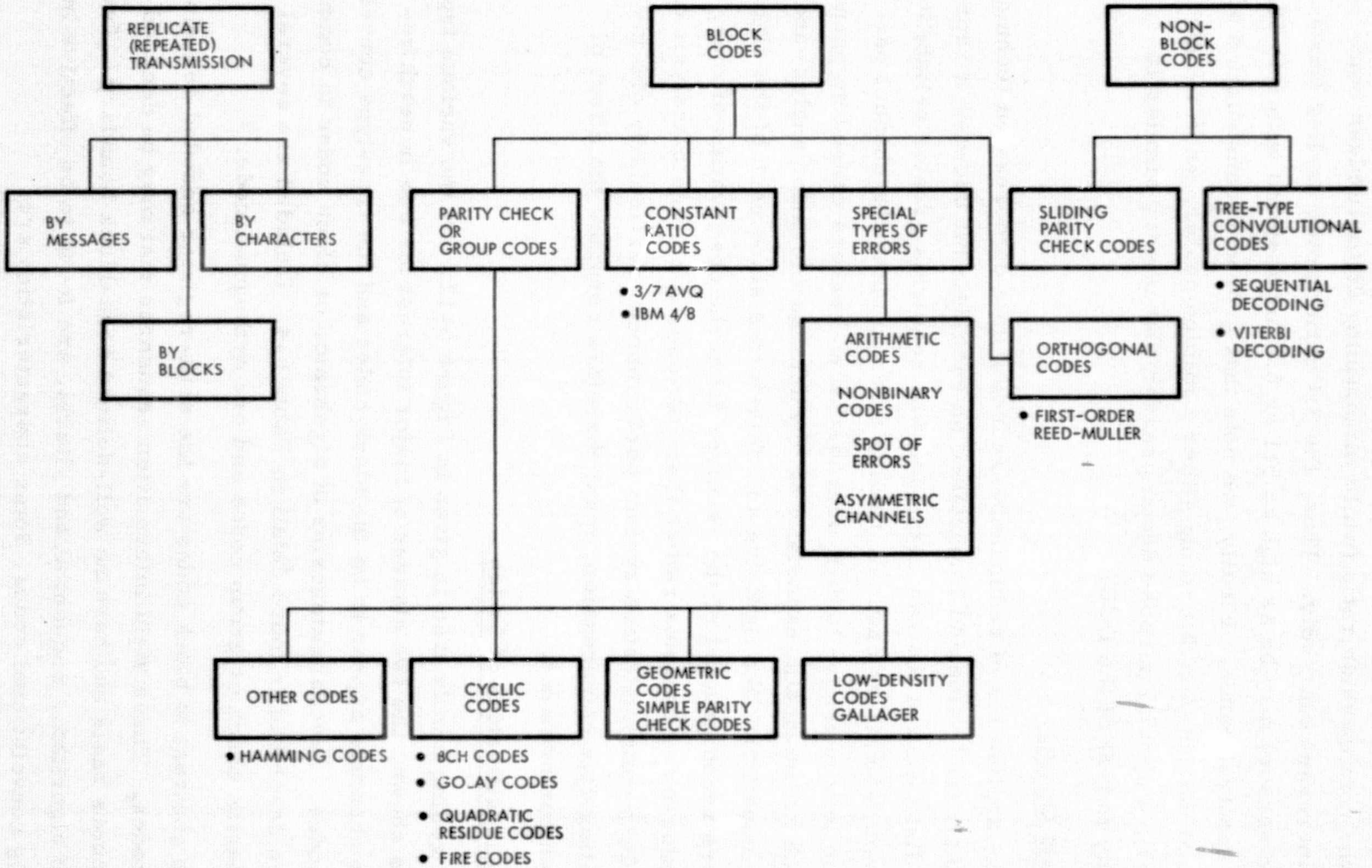


Figure 6-12. Family Tree of Communication and Data Transmission Codes

Table 6-4. Binary Code for Error Correction and Detection

Code	Description
Cyclic	Systematic group codes for coding blocks of k binary information symbols into blocks of n binary symbols by adding n-k parity checks
Fire	A class of cyclic codes that correct or detect errors in a single block. A fire code corrects any single burst of length b or less, and detects errors in any single burst of length $d \leq b$. The length of the code must not exceed the least common multiple of $2^m - 1$ and $b + d - 1$, where m is an arbitrary parameter relating the length of the code (n) and the number of parity bits ($n - k$, which equals $m + b + d - 1$).
Hamming	Based on the theory that, for any m, there is a code of length $2^m - 1$ that has m parity bits and $2^m - 1 - m$ information symbols and can correct any single error. One parity bit can be added to permit double-error detection as well as single-error correction; or alternatively the correction of adjacent double errors as well as of single errors.
Bose-Chaudhuri (BCH)	Based on the theory that for any m and t, there is a code of length $n = 2^m - 1$ that will correct all combinations of t or fewer errors. The number of parity bits never exceeds mt.
Fixed-Count	Error-detecting codes in which all blocks contain the same number of ones. An undetectable error occurs only when the number of erroneous ones is the same as the number of erroneous zeros, which is unlikely.
Golay (24, 12)	A cyclic code that corrects all patterns of three or fewer errors out of 24 symbols.
Simple-Parity Check	A single parity bit is appended to each information block for error detection. Additional error detection and even error correction can be achieved by arranging the information in a rectangular array and adding parity bits to every row, every column, and even every diagonal.
Reed-Muller	Based on the theory that, for any m and r (where m exceeds r), there is a code that can correct any combination of $2^{m - r - 1} - 1$ or fewer errors. For this code: $$n = 2^m,\ k = \sum_{i=0}^{n} \binom{n}{i} \text{ information symbols}$$ where n is the number of coded words. The Digilock telemetry system uses this kind of code. The decoding equipment is quite complex.
Low-Density Parity-Check	Each parity bit checks only a few symbols in each coded block.

1) Viterbi decoding

- Optimal (maximum likelihood) decoding
- Fixed-decoding delay
- No buffer overflow
- Throughput limited

2) Sequential decoding

- Nonoptimal longer constraint length
- Random time to decode
- Buffer overflow consideration
- Complex mechanization.

6.4.2 Coding Candidates. We now compare the two basic classes of error correcting codes, viz., block codes and convolutional codes in order to determine characteristics useful for ERS applications. Against random channel errors, convolutional codes have been shown to perform block codes with coding and decoding equipments of equal complexity. For instance, the results of a recent comparison study of rate 1/2 codes are shown in Figure 6-13. Block codes shown are the best available in terms

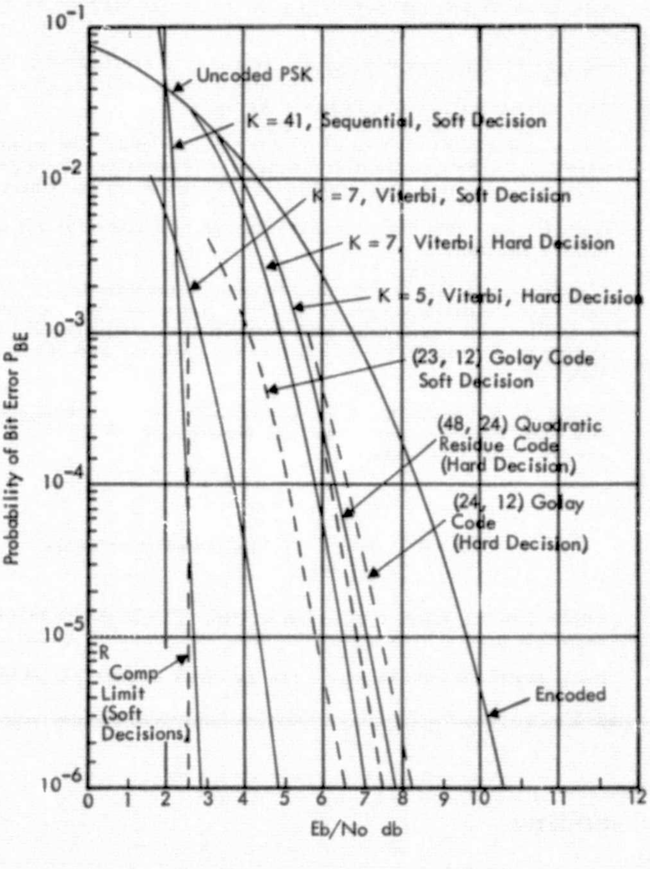


Figure 6-13. Performance Data for Rate 1/2 Codes

of decoding simplicity and coding gain, and still the convolutional codes outperform the block codes. For comparison purposes, the hard decision decoder for the (24, 12) Golay code is about as complex as the K = 5 hard decision Viterbi decoder, while the (48, 24) quadratic residue decoder is about equivalent to the K = 7 hard decision Viterbi. The new (23, 12) soft decision decoder for the Golay code is more complex than the K = 7 soft decision decoder. The most complex mechanization considered for a desired output BER of 10^{-3} is the soft decision sequential decoder. The complexity of this mechanization is due to the large input buffer and fast processor needed to prevent buffer overflow and loss of message.

From Figure 6-13 we may conclude that for rate 1/2, convolutional codes do indeed outperform block codes of equivalent mechanization complexity. There are several reasons. The most basic reason is that Viterbi decoding actually performs maximum likelihood decoding, large buffer sequential decoding very nearly approximates it. This means that no matter what channel response is received, the decoder will find the code word which is the closest match to the received sequence. Practical block decoders, on the other hand, are limited in the sense that the received sequence must be within some minimum distance of the true code word before decoding correctly. This minimum distance decoding is, in general, limited to half the distance between the two closest code words in the code book. So, if the block code is a three-error correcting code and a received sequence occurs which is distance four from the correct code word, the decoder makes an error, even if the correct code word is the closest match to the received sequence.

The second advantage of convolutional over block codes is in the ability to perform simple soft decision decoding. Until very recently, block codes have been constrained to hard decision decoding in which the received sequence is hard quantized and the decoder must work with this binary message stream. On the other hand, convolutional codes, using either Viterbi or sequential decoding, can operate on soft decisions from the channel. For binary channels, this means that a measure of the probability of the transmitted bit being a 1 or 0 is used directly in the decoding. Simulations of the Viterbi algorithm and the sequential algorithm have shown that an incremental 2 db in coding gain may be realized by using soft decisions as opposed to hard decisions. Recent theoretical work on block codes has made possible soft decision decoding of block codes beyond minimum distance, and the result of a TRW design for soft decoding of the (23, 12) Golay code is also shown in Figure 6-13. Note that the use of soft decoding in this case only gains about 1.5 db (not maximum likelihood decoding), and that the resulting decoder is slightly more complex than the full K = 7 soft Viterbi decoder which does 1.5 db better yet.

However, for burst channels, where prohibitively large interleavers are needed to randomize the error patterns enough to allow Viterbi decoding, soft decision block codes are a viable candidate, and must be considered. Furthermore, for channels with rates too high for practical application of convolutional coding, block codes with less complex decoding equipment can be used to provide some error correction capability.

Block decoders have a disadvantage in the area of synchronization in that they must be synchronized to the edge of each code word because the encoding/decoding is always performed on a fixed-length basis. Although this does not affect performance, it does represent additional complexity in the decoder.

Two classes of convolutional decoding algorithms are in general use: the Viterbi algorithm and the Fano sequential algorithm. The Viterbi decoding algorithm, named for the algorithm's discoverer, performs optimem decoding and generates the maximum likelihood code word based on the whole received sequence. Practical Viterbi decoders operate on a moving window of five constraint lengths of data, and perform within 0.05 db of the theoretical optimum limit. The algorithm decodes by postulating, at each clock time, all 2^K possible encoder states for a constraint length K encoder. Each postulated state is examined for all possible ways to reach that state, and the cost (log likelihood) of each way is evaluated. This evaluation consists of summing the incremental log likelihood of the received message conditioned on the old-state to new state hypothesis plus the stored minimum cost (log likelihood) of getting to the hypothesized old state. This total cost is compared for all ways of getting into the postulated state, and the minimum cost entry is determined. This becomes the stored minimum cost of getting into the postulated state, to be used during the next clock period (iteration of the algorithm). Since all possible states must be examined at each time, the decoder complexity grows exponentially in constraint length K. For this reason, practical Viterbi decoders are limited to codes with constraint lengths on the order of 7, corresponding to minimum Hamming distance between code words of 10 for rate 1/2, and 14 for rate 1/3.

Sequential decoders are suboptimum "valley seeking" decoders which attempt to follow along the locally best branches of the code tree as long as good agreement is observed between tree branches and the received sequence. Where poor agreement is noted, back searches are initiated to find paths with better agreement. For fast processors and large input buffers (during back searches the inputs continue), very deep back searches can be tolerated, and the undetected error performance of the suboptimum sequential algorithm approaches optimum. However, the time to decode each bit is still random, depending on the number of back searches needed; and the inputs must be buffered to allow for this delay. If the input buffer capacity is exceeded, then a portion of data is lost, causing a gap in the output stream. For 10^{-3} BER voice, this may be unacceptable, or at least less desirable then sending through a message, even if it is noisy. The problem can be circumvented by using a systematic code in which one of the channel bits is the uncoded data stream, and this stream may be directly output (still noise corrupted) when buffer overflow occurs. However, the fact still remains that the sequential decoder has large complexity in the fast processor and large backup buffer.

Sequential decoding complexity is independent of constraint length, so very long codes (K = 40 or above) are used for extremely good error correcting capability. The source of errors is thereby restricted to the overflow problem mentioned above. For fixed-processor rate and buffer size, the likelihood of buffer overflow can be found by calculating the probability that the number of computations will exceed the product of computation rate times the time to fill the buffer. This quantity has been evaluated, and exhibits a Pareto distribution. For a desired output bit error rate, the sequential decoder speed and buffer is sized so that the probability of overflow, times the number of bits lost due to overflow, meets the BER requirements.

There is a fundamental limitation on the amount of improvement available, however. Above a certain channel bit error rate, the expected number of computations needed to decode goes to infinity. By evaluating the expected number of computations as a function of error rate, the information rate at which the expected value becomes infinite may be determined. This value, known as R_{comp}, is equal to

$$E_o(1) = \log_2 \sum_j \left[\frac{1}{2} \sum_i p \text{ (receive/transmit j) } \frac{1}{2} \right]^2 \qquad 6\text{-}10$$

This expression is also equal to the Gallager random coding bound error exponent. R_{comp} gives a very good approximation to the error correcting capability of a convolution code. For code rate R (number of information bit/channel bit), the Gallager error exponent will give a lower bound on the signal-to-noise ration which any convolutional decoder can tolerate and still give coding gain. Thus, in the PSK rate 1/2 example of Figure 6-13, a signal-to-noise ratio of 2.6 db is needed for $R = R_{comp} = 1/2$, and this represents the R_{comp} lower bound on coded signal-to-noise ratio for rate 1/2 convolutional codes. Note that the full blown complex K = 41 sequential decoder exhibits an exceptionally sharp decrease in BER at E_b/N_o slightly greater than 2.6 db, and actual coding loss (more errors coded than uncoded) below 2.6 db.

6.4.3 Hardware Implementations

An IR&D study was carried out recently at TRW to configure various Viterbi decoders for data rates in the Mbit/s range. A summary of the results are shown in Table 6-5, both for MSI and LSI configuration. It was found that 10 MHz (or 10 Mbit/s) is presently the practical upper data rate limit.

Table 6-5. MSI and LSI Viterbi Decoder Parameters

Operating Rate (MHz)	Off-the-Shelf MSI-IC				TRW Custom LSI			
	TTL		ECL		EFL		ECL	
	Parts (IC's)	Power (W)	Parts (IC's)	Power (W)	Parts (IC's)	Power (W)	Parts (IC's)	Power (W)
2.0	282	102						
2.5	367	132						
5.0	836	300						
7.0					149	73		
10.0	1700	610	760	215			133	138

For the higher rates, custom LSI designs provide mechanizations with reduced power and parts counts, but of course, higher initial development costs would be inevitable. All designs were for rate 1/2 systems and a constraint length of K = 7. For the 10MHz case, note that mechanization with ECL was more efficient than with TTL and the minimum power configuration for all designs used TRW's triple diffused-EFL process (see Section 6.8). In all cases, completely parallel computation was performed in a 64-node tree search, and it was concluded that attaining speeds higher than 10 MHz would be difficult, either from the circuit technology or the architectural viewpoint.

Commercial Viterbi and sequential decoders for decoding convolutional codes at a variety of constraint lengths and data rates are now available; some are shown in Table 6-6.

Table 6-6. Commercially Available Decoder Parameters

Decoder Type	Code Rate	Constraint Length	Maximum Data Speed (Mbit/s)	Quantization	Coding Gain for Bit Error Rate (db)		
					10^{-3}	10^{-5}	10^{-7}
Viterbi	1/2	7	100*	Soft	3.7	5.1	5.5
	3/4	9	100*	Soft	2.8	4.1	4.5
	1/2	7	2	Soft	3.7	5.1	5.5
	1/2	7	10	Soft	3.7	5.1	5.5
	3/4	9	10	Soft	2.8	4.1	4.5
Sequential	1/2	41	40	Hard	1.7	4.3	5.7
			10		2.3	4.8	6.1
			1		2.7	5.3	6.5

*kbit/s

Note that the data rates for Viterbi decoders are limited here to 10 Mbit/s also while those for sequential decoders extend up to 40 Mbit/s. This limitation is due primarily to the architectural constraints imposed upon the decoder by the algorithm in the Viterbi case; such is not the case for sequential decoding.

Convolutional encoders are very simple devices in comparison to the decoders, and constructing one for spaceflight purposes would offer no great challenges. The real difficulty is building an efficient decoder, especially at high-data rates. Projected maximum data rates for rate 1/2 decoders by 1980 are:

- Viterbi (K = 7).....25 Mbit/s
- Sequential (K = 40) ... 100 Mbit/s

Using the above, we now propose a configuration for optimal (Viterbi) ground data processing of coded earth resources data for both a high-rate and a low-rate channel. It is assumed that the data is derived from multispectral scanners and that a data compression ratio of approximately 3 to 1 can be achieved using a SSDI/Rice-like algorithm (See Section 6.3.3).

a) Possible low-data rate configuration (1980):

- 30 Mbit/s information rate
- 10 Mbit/s compressed rate
- 20 Mbit/s channel rate (rate 1/2 code)
- One 20-Mbit/s Viterbi decoder used.

b) Possible high-data rate configuration (1980):

- 300 Mbit/s information rate
- 100 Mbit/s compressed rate
- 200 Mbit/s channel rate (rate 1/2 code)
- Eight 25-Mbit/s Viterbi decoders used (in parallel, with associated multiplexers).

Finally, for systems where compression cannot be used and the maximum channel data rate is, for example, 300 Mbit/s, a higher rate convolutional code could be used. Example configuration without data compression for 1980 is:

- 200 Mbit/s information rate
- 300 Mbit/s channel rate (rate 2/3 code)
- Twelve 25-Mbit/s Viterbi decoders used (in parallel, with associated multiplexers).

6.5 Synthetic Aperture Radar Data Processing

As an advanced sensor for the Earth Observatory Satellite (EOS) program, NASA/GSFC has proposed a synthetic aperture radar (SAR). The use of synthetic aperture radar for sea-state determination, oil slick observation, and soil mosture content is particularly attractive because of radar's all-weather capability compared to cloud-cover-hampered sensors in the visible and infrared (IR) portions of the spectrum.

Unfortunately, for reasonable ground resolution and swathwidth, the pre-processed data rate is extremely high, as illustrated in Figure 6-14.

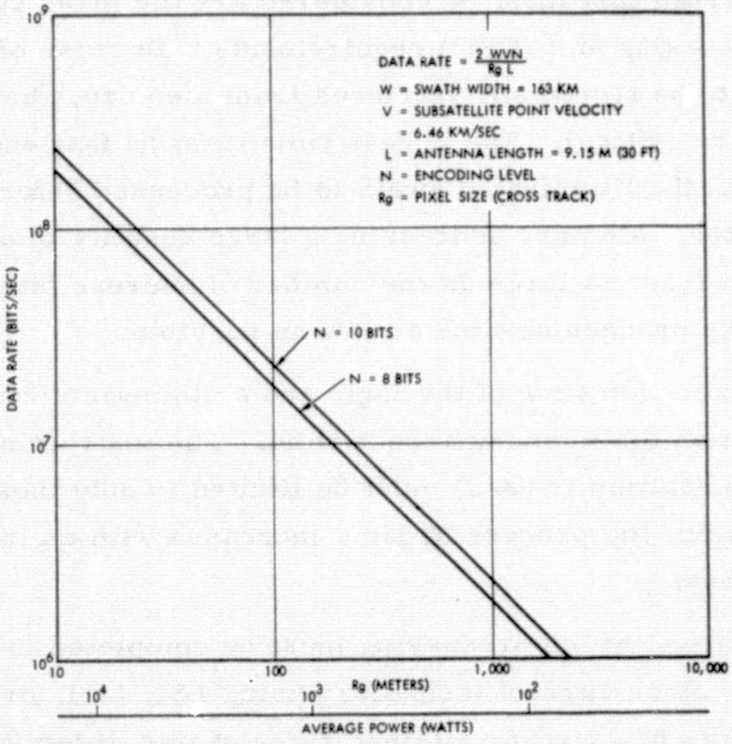


Figure 6-14. SAR Data Rate Versus Resolution and Power

Given the set of parameters shown in the figure, it is seen that data rates on the order of 50 to 100 Mbit/s are necessary in order to achieve ground resolutions significantly below 100 meters. However, if on-board processing were performed to the level of providing a digital number representing the radar reflectivity of each resolution element in the field of view, the data rate could be reduced by a factor of around ten. Thus, on-board processing of synthetic aperture radar data is a fruitful area to pursue for data rate/quantity reduction.

6.5.1 Processing Requirements

In designing an on-board processor for a synthetic array radar, two major areas that must be considered are the mass storage and central processing unit (CPU) requirements. Because of the large quantity of data to be stored and retrieved from memory, the access time and word size are critical. The access time must be fast enough to allow all returns from the illuminated swath to be processed before the next pulse is transmitted. Memory addressing a large quantity of data requires a word size at least as large as the number of address bits required in order to keep processing time as low as possible.

The execution time of the logic and arithmetic circuits must be at least as fast as the memory access time. The instruction set (if general purpose computation is used) must be limited to only those that are necessary since the processing time increases with an increasing number of instructions.

The rate at which processing must be completed is on the order of a few nsec. Since current technology using LSI, MSI, or standard integrated circuits has already attained rates of this order for logic circuitry, the feasibility of an on-board processor is determined by the memory access time requirements.

6.5.1.1 Synthetic Aperture Radar Parameters

The following SAR parameters will be used in establishing requirements for the on-board processor.

Satellite Altitude	1000 km
Swathwidth	164 km
Ground resolution	100 m
Wavelength	3 cm
Antenna depression angle	55 deg.
Satellite velocity	6.36 km/sec
Synthetic Array length	202 m
Array formation time	31.7 m/s
PRF	1595 pps
Number of cross-track range bins	1640
N, number of pulses to form array	50
D_A-along-track aperture size	8 m
D_E-cross-track aperture size	0.43 m
Receiver bandwidth	2.72 MHz
Pulse width	0.38 μsec.
Slant Range R_s	1342 km

Appropriate radar analog signal processing has been shown to consist of quadrature demodulation followed by array focusing, pulse compression, and a square law envelope detector. The radar processor operates on each pulse return sequentially removing any random phase errors present such that the signal presented to the digital processor for a resolution element across the swath is of the form:

$$V = \sum_i \cos\left[\frac{4\pi\chi_i V_s t}{\lambda R_s}\right] \qquad 6\text{-}11$$

where V = return voltage

χ_i = along track position of resolution element within the real beam azimuth pattern

V_s = Satellite velocity

λ = wavelength

R_s = slant range

t = time after pulse transmission.

6.5.1.2 Digital Processor Configuration

Equation 6-11 represents returns from all resolution elements within the real beam azimuth pattern for a single range increment within the 164 km swathwidth. The functions which the digital processor must now perform consists of:

1) Sampling this signal at each of the 1640 range bin elements
2) Quantizing each sample using six bits per sample
3) Storing each sample in some mass storage device
4) Retrieving the returns of 50 pulses at a given range and summing each of these samples to yield the return of the SAR for that resolution element.

6.5.1.3 Pulse Return Sampling

Each time the transmitter pulses the receiver will obtain returns from the composite azimuth resolution elements within the real beam of the antenna for each of the 1640 range bins. The composite signal in each range bin must be sampled and stored until the array time has elapsed and then summed to form the array for the resolution element which lies at the center of the array. Since the radar processing has focused the array, only the resolution element in the center of the array will yield a maximum array factor when each composite signal return is preserved in amplitude and phase and subsequently summed. To determine the required sampling rate for each composite signal, it is necessary to determine the maximum Doppler shift which will exist in any given range bin. The highest Doppler frequency due to return from the azimuthal resolution elements at the edge of the real beam is given by:

$$f_{max} = \frac{2V}{\lambda} \sin \frac{\psi A}{2} \approx \frac{V}{D_A} \qquad 6\text{-}12$$

$$\approx 795 \text{ Hz}$$

where ψ_A = antenna 1/2 power beamwidth

D_A = antenna aperture = 8 m

However, the maximum Doppler shift required to be measured is limited further by the filter bandwidth such that the 100-m resolution is achieved and will be no greater than:

$$f_{max} = \frac{2V}{\lambda} \frac{L}{2 R_s} \qquad 6\text{-}13$$

$$= 31.8 \text{ Hz}$$

Assuming that each composite signal is sampled at 2.5 times its maximum frequency component, the sampling rate is

$$f_s = 80 \text{ samples/sec} \qquad 6\text{-}14$$

Quantizing at six bits per sample yields

$$f_s = 480 \text{ bits/sec/range bit.} \qquad 6\text{-}15$$

Each pulse will provide composite returns in each of 1640 cross-track range bins. These returns must be sampled, stored, and processed before the next pulse returns are received; approximately 627 μs.

6.5.1.4 Processing, Access Time, and Storage Requirements

The processing required consists of storing 80 6-bit samples for each of 1640 range bins for the first pulse and adding each group of 80 samples to the returns obtained for the second pulse. This process is repeated until 50 pulses have been transmitted. The array is formed for the 51st pulse, as described by vector addition in the following relationship:

$$S_i = n_i + S_N - n_{N-1} \qquad 6\text{-}16$$

where S_i = new sum for the new array

n_i = words from the new pulse

S_N = accumulated sum from previous pulses 1 to 50

S_{N-1} = words from pulse N-1.

Thus, the new array is formed by subtracting the words from the N-1 pulse return and adding the words from the new pulse transmission. The number of memory accesses required to supplement Equation 6-16 is given by:

$$A = \frac{4 \text{ accesses}}{\text{sample}} \cdot \frac{80 \text{ samples}}{\text{range bin}} \cdot 1640 \text{ range bins}$$

$$A = 524,800 \text{ accesses} \qquad 6\text{-}17$$

These accesses must be completed within 627 μsec (1/PRF). The access time required is:

$$t_a = \frac{1}{A \cdot \text{PRF}}$$

$$= \frac{627\ \mu\text{sec}}{524,800}$$

$$t_a = 1.2 \text{ nsec.} \qquad 6\text{-}18$$

The storage required would be:

$$50 \text{ pulses} \cdot \frac{1640 \text{ range bins}}{\text{pulse}} \cdot \frac{80 \text{ words}}{\text{range bins}}$$

or 6,560,000 6-bit words. Addressing memory locations would, therefore, require 23 bits. The word length of the processor would have to be at least 32 bits to accommodate memory addressing, sample size, and operational codes (unless a hard-wired processor were used).

6.5.2 Feasibility of Implementation

At the present time, access times for space-qualified hardware are on the order of a microsecond but equipment using 16 bits/word random-access memory with access times of less than 100 nsec will be available shortly.

Thus, the implementation of on-board processing for the SAR does not appear to be feasible at this time assuming:

- Space-qualified hardware
- Radar performance required such as swathwidth PRF and resolution
- The use of vector addition in amplitude and phase to form the array.

However, due to the dramatic projected increase in the capability of various LSI technologies by the 1980's both in logic, arithmetic, and memory circuits*, it appears that on-board processing of SAR data will be feasible in that time-frame. With VLSI packing densities on the order of 200,000 transistors per chip by 1980 (see Section 6.8.2), it is reasonable to conclude that massive paralleling and pipelining will be feasible, aiding in the mechanization of the logic and arithmetic as well as the memory functions at the high rates required.

For systems in which the swathwidth could be reduced from 164 km performance demands would be reduced since this is one of the most difficult parameter to be satisfied. Furthermore, the vector addition technique was used here when summing the returns from 40 azimuthal resolution elements in each range bin. This procedure is only one of three equivalent techniques for forming the array pattern. The two others are cross-correlation of the signal returns with a synthetic array weighting function and the Doppler filtering of the signal spectrum with the Fourier transform of the synthetic array weighting function. Investigation of these two methods might have lead to more elegant approaches requiring less storage and larger access times.

A brief reference will not be made to two other reports which came to similar conclusions. On 1973 report concluded that "satellite-borne SAR systems will require some new design considerations, particularly with regard to data management, but that on-board digital processing is a real possibility" before 1980. This conclusion was reached by studying various possible processing schemes but no figures of exact specifications for a specific design are given.

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* For example, CCD and bubble memories with 10^9 and 10^{10} bit capacities, respectively, are expected before 1980 (see Section 6.7.6).

A more detailed point design was considered by Gerchberg for a relaxed swathwidth requirement of 40 km but with a 30-m resolution requirement. The resulting processor would require an estimated 7.3 Mbit memory, consume 200 watts, weigh 60 pounds, and would be 5 cubic feet in volume using pre-1980 technology. The proposed organization calls for 1334 parallel independent banks of storage and assumes the use of LSI memory chips with access times of 100 nsec and power dissipations of 10 μwatts/bit (which should be available with pre-1980 technology). Figure 6-15 summarizes the storage requirements determined in the two detailed studies just considered.

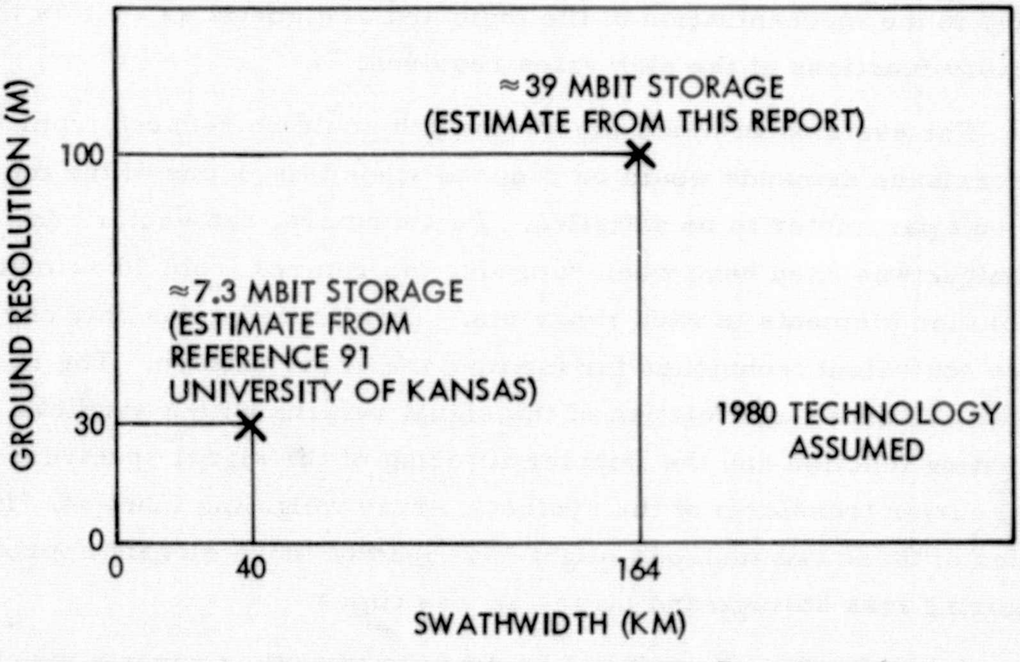

Figure 6-15. SAR Processor Storage Requirements for Two Sample Designs

Finally, it should be mentioned that elegant techniques for optical processing of SAR data have been devised. However, application of these techniques is presently being considered mainly for use at ground processing facilities.

6.6 On-Board Correction and Calibration

Image data obtained from earth observation satellites currently must be processed in a central data processing facility before it is in a form suitable for most users. This procedure is disadvantageous for two principal reasons: (1) delay in delivery of processed images and computer compatible tapes (CCT's) to data users*, and (a) the dependence on a central data processing facility that may not be responsive to all user requirements.

Practical sensors introduce various geometric and photometric distortions into the data produced. The principal contributors to geometric errors are satellite position and attitude, sensor scan irregularities, and the earth's rotation and curvature. While the main causes of photometric errors are detector quantum-efficiency variations and atmospheric conditions. Correction of these errors is often required before the data can become useful and is typically done in ground processors. For small APT type users, however, simplicity and cost savings would result from transmitting fully corrected images. In addition, on-board correction can be designed to minimize noise introduced by the correction process, i.e., corrections can be made before conditioning for optimum communications.

The feasibility of such on-board corrections depends on algorithm and equipment practicality and the availability of information needed to make the corrections. The development of simple algorithms and application of LSI techniques would appear to render on-board processing feasible by 1980 as far as the equipment is concerned. However, obtaining information needed for making corrections may be more difficult.

Four areas important in the data processing problem for multispectral scanner (MSS) and framing camera return beam vidicon (RBV) sensor data are:

- Image correction and resampling
- Ground control point (GCP) extraction
- Reseaux extraction
- Radiometric correction

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* Current experience with ERTS data indicates an average lag of about six weeks; some data is delayed as much as twelve weeks from acquisition.

By far the most significant problem is image correction and resampling, which involves pixel-by-pixel calculations. This processing is based upon a procedure of determining corrected pixel locations and then performing two-dimensional interpolation to obtain the "resampled" values. Corrections are made for spacecraft attitude and ephemeris, scan nonlinearities, scan length, earth rotation, and curvature.

For geodetic control of images, GCP's must be found on the images so that correctional coefficients can be computed. The GCP's lie within an uncertainty region that is dependent upon data available for spacecraft attitude, altitude, ephemeris, and velocity. Algorithms have been developed to circumvent a brute force cross-correlation procedure involving each GCP uncertainty region and the corresponding reference image (residing in a GCP library).

RBV image correction techniques use reseaux markings on the camera faceplates. Again, highly efficient algorithms have been developed to rapidly locate the reseaux with high precision.

Finally, it is to be noted that radiometric correction is necessary for both MSS and RBV sensor data. Thus, each of 24 MSS detectors (six per band for four bands) must be calibrated by means of a table lookup procedure. RBV vidicon tube shading must also be corrected by means of a more complex table lookup.

Each of the four important data processing areas will not be considered separately for applicability to on-board processing using both present technology capabilities and those estimated for 1980.

6.6.1 Image Correction and Resampling

Precision image geometric correction involves first a determination of the corrections required and then implementation of a pixel-by-pixel correction procedure. The first problem involves fitting a piecewise low-order (bilinear) distortion model to the precision calculations for a small number of image locations. Though straightforward, these calculations may be tedious since one must consider effects due to the spacecraft attitude, altitude, velocity, and ephemeris, as well as earth curvature, earth rotation (for line and array scanners) and optical distortions (framing camera). For maximum precision one must also utilize GCP's for geodetic control. Line scanner anomalies (line length and scan nonlinearities in particular) can also be significant and should be included.

Typically, the determination of the required geometric correction transformation for the current ERTS mission requires about 1500 lines of Fortran code for the MSS and 1700 lines for the RBV ERTS sensors. The output of this code is a set of 512 MSS distortion coefficients (10,368 for a complete RBV scene), consistent with a piecewise bilinear distortion model. On a large scale machine such as a CDC-6500, execution requires under 15 seconds of CPU for MSS calculations (around 40 seconds for RBV calculations including reseaux extraction), exclusive of GCP extraction. Extraction of GCP's using a sequential similarity detection algorithm requires from 1 to 6 sec per GCP depending upon the size of the uncertainty region (see Section 6.6.2). It has also been found in the course of current ERTS contract work, that around 160 kbits of core is required for the MSS calculations and 190 kbits for the RBV calculations. Inasmuch as no assembly language coding was employed, these numbers may be regarded as conservative. Furthermore, these codes can be extrapolated to a minicomputer (PDP-11/45 class) with an appreciable (factor of two) increase in speed.

Thus, implementation of the distortion determination calculations onboard a spacecraft dictates a significant on-board computer capability. Using the projected 1980 on-board computer capability (see Section 6.8) with four 64 kbit LSI memories for each band for buffering and special-purpose bipolar hardware for 50 nsec algorithm processing, distortion determination calculations should be technically possible in the late 1970 or early 1980 time-frames for ERTS-type sensors. Further aspects of this problem, such as real-time ephemeris and attitude determination, are discussed later in this report.

Following geometric correction calculations the actual pixel-by-pixel image resampling must be accomplished. Implementation of algorithms to accomplish this are dependent upon the order of interpolation; higher order algorithms, which preserve maximum information content without distortion, process more data and thus consume more CPU time.

The TRW cubic convolution process for image resampling that currently appears to be optimal with respect to speed and precision, requires about 100 μs/pixel when coded efficiently on a CDC-6500. Extrapolations to a minicomputer reduced this figure to around 50 μs/pixel. Using parallel processing architecture, however, it is possible to implement the TRW process in special logical circuitry, making possible still greater speeds (~1 μs/pixel) independent of the order of interpolation, and with minimal demands on a CPU. This immediately suggests that spaceborne image correction is a possibility, assuming the circuitry to be capable of the sensor rates considered (for ERTS MSS, 2.4 Mbit/s; the RBV analog signal has a video bandwidth of 3.2 MHz).

An additional consideration is the number of lines required to be stored simultaneously in a buffer. This factor is dependent upon attitude control (principally yaw) and the order of the interpolation algorithm. Thus, for example, a yaw correction of ≈0.5 degree for the ERTS MSS requires ≈20 lines in a buffer; this requirement is independent of the choice of interpolation algorithm which alone may require as many as 5 lines of buffering. Thus, each MSS spectral band would require ≈0.490 Mbits for precision correction in this case. This buffer requirement is roughly proportional to attitude control processing, though asymptotically approaching ≈0.114 Mbits/band for the convolution process. For one-dimensional image correction (earth curvature, scan line length correction, nonlinearities, and skew) only ≈0.049 Mbits/band, two lines for double buffering would be required, independent of interpolation method. Buffer requirements of the EOS scanning spectral radiometer (SSR), which is projected to have ~2.7 times the resolution of the ERTS MSS, are nearly tripled; however, the anticipated improved attitude control system specifications of EOS (0.01 degree and 10^{-6} degrees/sec) reduce the amount of buffering needed to the one-dimensional image correction minimum of two lines of double buffering (≈0.1 Mbit). These buffer requirements could be met with present LSI technology utilizing a number of chips for implementation.

6.6.2 Ground Control Point Extraction

For precise geodetic control of imagery in the absence of continuous and accurate spacecraft attitude, ephemeris, and altitude data, it is necessary to use data derived from features on the ground for which such control is available. These GCP's must be located on the bulk data, using a search or correlation algorithm within a corresponding uncertainty region. Alternatively, special sensors onboard the spacecraft could be used in conjunction with selected features on the ground, or signal emitters (e.g., lasers) on the ground, to accomplish the same objectives. Attention here, however, will concentrate on completely self-contained spacecraft processing of imagery data.

For ERTS the uncertainty region from which the first GCP (assuming 32 pixels by 32 lines) must be extracted depends upon orbital phasing uncertainties (≈5 km along track) and attitude uncertainties (≈15 km x 15 km), and is ≈250 lines x 250 pixels. Subsequent GCP's can be located within uncertainty regions of ≈50 pixels x 50 lines. For an EOS spacecraft the absolute attitude/ephemeris uncertainty is only ~200 m. Thus, a GCP search region in this case need be only ≈30 lines by 30 pixels (assuming a GCP to be 20 lines x 20 pixels for EOS).

An on-board GCP extraction processor for an EOS mission would require storage for three GCP's obtained prior to each data collection pass. Note that internal consistency accuracy (~1 pixel) is obtained even without GCP's; however, for geodetic control GCP's are required. On the other hand for an ERTS mission, each scene requires between three and eight GCP's for geodetic control which greatly increases storage and processing requirements over that for EOS. Furthermore, it is not possible for GCP's to be extracted simultaneously with image correction processing; for EOS however, GCP processing can be accomplished prior to image data collection and processing, assuming said GCP's are unobscured. Of course, in the event of GCP obscuration, only part (if any) of the data acquired could be precision processed (i.e., with geodetic control) onboard.

6.6.3 Reseau Extraction

For a framing camera such as the ERTS RBV, reseau marks on the faceplate of the vidicon are used to rectify imagery. Algorithms developed for the ground data processing ERTS study contract currently perform a spiral search of each reseau uncertainty region (240 pixels x 240 lines). This is required individually for each band, and is the most time consuming part of the distortion determination software (≈33 sec/band using a Fortran program on a CDC-6500 machine). The principal difficulty with respect to on-board processing is the simultaneous core storage of nine such uncertainty regions/band (57.6 K bytes per region). The storage requirements translate into a 420 Kbit RAM, at least a projected 1980 technology. Real-time image correction is not indicated inasmuch as all reseaux must be processed before image correction can begin.

6.6.4 Radiometric Correction

Radiometric calibration of sensor images, even on the ground, is a difficult task. It requires measurements of each detector for line and array scanners and a number of points for framing camera scanners. Typically, the individual detector measurements are used to update a lookup table used to radiometrically correct the detector output voltages, and the calibration points for the framing camera scanner are used to implement a bilinear correction algorithm to correct for shading and absolute radiance errors. The sensors are initially calibrated on the ground; then in-flight calibration procedures are used to update correction estimates for both short-term (on the order of a day) and long-term (on the order of a week) radiometric error sources.

It is estimated that radiometric correction for line scanners (assuming 20 detectors/band) would require a RAM of about 18 Kbits and a nominal speed for the table lookup processing on the order of 5 MHz clock rate. Because of a larger number of detectors, array scanners (4000 detection band) have much more demanding requirements; one scheme would require a RAM on the order of 26 Kbits with access cycle times on the order of 100 nsec and fast bipolar processing speeds for table lookup on the order of 50 MHz. Therefore, line scanner radiometric correction is within the capability of present technology, but the array scanners will require predicted 1980 technology for on-board processing.

A considerable savings in complexity could be obtained if only a calibration of each chip of detectors would be necessary, i.e., only one detector on each chip would be used to calculate the coefficients for all other detectors on that chip. Furthermore, if the detector output versus radiance value were a straight line relation, as assumed for the ERTS MSS, then only two coefficients per detector would be needed, a savings for both line and array scanners.

Radiometric correction for framing camera scanners definitely requires 1980 technology for on-board processing. It is estimated that a RAM of over 50 Kbits and processing speeds over 50 MHz would be required to radiometrically correct framing camera scanner data in real-time.

6.6.5 Additional Concepts

In lieu of complete on-board image processing, it is still desirable to incorporate data processing features onboard which can help provide useful data to the user community in a more timely manner. One realistic goal is to transmit images from the spacecraft that are internally consistent (and which have residual geodetic errors) and are represented in a standard coordinate system, such as space oblique mercator. Processing of the received image using GCP's would then be necessary for the user to remove the residual errors. This approach would allow low-cost ground stations (on the order of $100K) to be used for receiving earth images in real time.

Only three image processing steps are essential to ensure this type of user product: image correction and resampling, data reformatting, and radiometric correction. (Framing camera scanners are not considered a candidate sensor because of the relatively large digital processing requirements for reseau extraction and radiometric correction.) Also required is a precision attitude control system for the spacecraft (0.01 degree and 10^{-6} degrees/second) and accurate ephemeris estimates (~30 meters) for spacecraft location. The sensor output data would be reformatted, radiometrically corrected, and then single-line resampled to geometrically correct the data to a standard reference system. It is conservatively estimated that these on-board image processing requirements translate into 5 Mbits of buffering, 300 Kbits of RAM, and processing speeds on the order of 50 MHz; specifications that should be met with the projected 1980 technology.

There are other image data processing components that are candidates for on-board implementation. Ephemeris estimates can be calculated using an on-board computer with polynomial fits to predicted orbit parameters determined by standard ground data processing methods. Attitude estimates can also be generated using the on-board computer with the addition of special-purpose hardware to perform the iterative algorithm and fit the attitude sensor measurements to the estimate polynomials. The estimates for ephemeris and attitude then would be available for transmission to users along with the image data, a feature attractive for implementing the local user terminal concept now under consideration for EOS.

The local user terminal concept provides a portion of all sensor data in real time to the user. Obviously, there is great economy gained by decreasing the amount of ground data processing the user must perform. Complete on-board image processing is the best solution, followed by on-board processing of the critical steps required to ensure internal consistency. In order of increasing difficulty, the following tasks might be considered for on-board processing: radiometric correction, image correction and resampling, and GCP extraction. The choice of candidate on-board processing steps should be made consistent with the data processing requirements of the users and possibly in conjunction with the local user terminal concept.

Finally, a number of signal processing functions, such as modulation transfer function (MTF) compensation and noise filtering, should be considered for on-board processing. These signal processing functions are best implemented within the sensor design; present LSI technology could be utilized.

6.6.6 Conclusions

ERTS image data is presently processed on the ground using a hybrid analog/digital image processing facility. All-digital techniques are being evaluated and under consideration for ground data handling systems. Thus, on-board all digital image processing is two generations removed from the present ground data handling system and should be considered in the framework of 1980's technology.

Three sensor types are considered for the visible and IR spectral ranges: line and array scanners, and framing camera scanners. Line and array scanners will probably replace framing camera scanners in future applications because of the comparable performance capabilities within the earth resources requirements, inherent band/band registration and less demanding data processing requirements (no reseaux extraction and simpler radiometric correction procedures). The possibility of on-board image processing is therefore most applicable to line and array scanners.

Based upon predictions of attitude control system performance, ephemeris estimation accuracy, spacecraft computer hardware, and LSI technology available around 1980, on-board image processing of line and array scanner sensor data should be considered feasible. Of course, something less than complete on-board image processing can also be considered a possibility, and estimates of data processing requirements of low-cost local user terminals should be used to determine the amount of on-board processing desirable.

6.7 Storage Techniques

The need for large efficient mass memories of about 10^7 bits, or greater capacity in spacecraft data processing systems is becoming more and more apparent, especially for earth observation satellites (EOS). In the measurement of earth resources and exploration of other planets, the spacecraft of the mide-1970's will require use of magnetic tape recorders to store the mass of data gathered by a variety of multispectral imaging sensors. As an example, for EOS missions, data rates and volume increases exponentially because of the desire for higher resolution and greater spatial coverage. Data storage for EOS missions will therefore require large capacity, durable, long-life mass memories.

In the 1978 to 1988 time period, the use of magnetic recording devices for on-board mass storage will be challenged by large capacity solid-state memories. Application of solid-state mass memory technology is particularly important from the standpoint of improving reliability and reducing weight, size, and power over that obtained with conventional electromechanical devices employed in current spacecraft systems. It remains to be seen whether advances in nonmechanical memories such as magnetic bubble, holographic optical memory, plated wire, and others, will eventually overtake the tape recorder and displace it from its present dominant position.

Figure 6-16 shows the genus of various mass memories; the underlined areas identify those currently experiencing the greatest concentration of research effort by numerous U.S. industries, universities, and government research laboratories. These research activities are expected to result in larger capacity, more rapid access, and more efficient mass storage capabilities for spaceborne applications by the 1978 to 1988 time period.

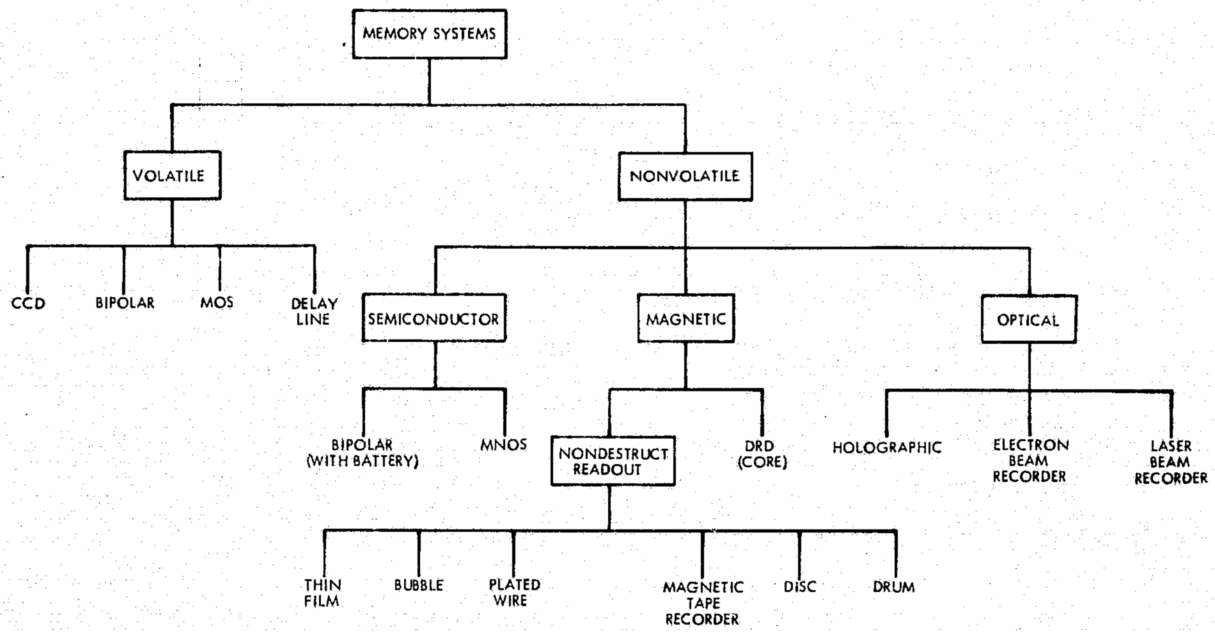

Figure 6-16. Genus of On-board Data Storage Techniques

In general, NASA's requirements for on-board mass storage are different than those for commercial memories. Commercial memories are exemplified by their requirement for more rapid access time. In spacecraft data storage applications, size, weight, power, cost, and reliability tradeoffs need to be considered. Parallel memory organization with an adequate bit packing density and data rate will usually suffice and there is generally no need to have rapid access to individual characters in the memory.

In this section, the current and expected (circa 1980) status of on-board mass memory systems is discussed for magnetic tape recorders, bubble, CCD, optical, and plated-wire memories. Comparative parameters are included that give the expected range of capacity, packing density, data rate, weight, and power consumption for the period under consideration (shown later).

6.7.1 Magnetic Tape Recorders

In the past decade a variety of tape recorders have been built for NASA programs (OGO, OAO, Nimbus, Tiros, ERTS, SESP, and Mariner). Some of these have achieved calendar lives of over five years, and some have operated continuously for over 22,000 hours. At present, the tape recorder seems to be the best suited technique for on-board storage applications despite failures that have occurred due to the mechanical nature of the device.

Anticipated recurring costs for the space-qualified magnetic tape recorders range from 0.5 to 0.005 cents per bit. Magnetic tape recording is a highly-developed technology, and where data storage greater than 10^7 bits is required its performance and capability demonstrated in space applications is very impressive compared to other, still to be developed memories.

Today's packing densities are around 25,000 bit/in. (Manchester code); well below the theoretically attainable resolution of 200,000 bit/in., as estimated from the size and distribution of the magnetic domains. The significant increase in achievable input data rates comes about primarily from newly developed forms of coding especially suited to tape recording. These are known variously as Miller coding, delay modulation, and double-density codes. Similarly, developments in mechanical features such as liquid ferromagnetic bearing seals, new alloys, and new tape materials will contribute to recorder lifetime and performance under the expected environmental conditions.

These factors give a tradeoff strongly favoring the magnetic tape recorder for the mass memory storage applications at least until the 1975 to 1976 time-frame. Recent tape transport configurations are depicted in Table 6-7.

Table 6-7. Recent Tape Transport Configurations

Contractor/ Model	RCA/ERTS	RCA/ERTS	RCA/SH	Ampex/AR 700 (Skylab)	Ampex/AR 500	Leach/MTR 7000	HEAO (Proposed)
Number of tracks	One	100	One	28	One	12	Three
Recorder operation	Helical scan	Longitudinal	Helical scan	Longitudinal	Rotary head	Longitudinal	Longitudinal
Tape speed (ips)	Effectively 1964	40	Effectively 1333	60	Effectively 2000	120	Record 1.54 Playback 28
Tape length (feet)	2000	2000	2400	7200	2200	9200	2100
Tape width (inches)	2	2	1	1	2	1	1/4
Bandwidth (Mb/sec/T)	15-20	1	5	1.0	5.5	2.0	Record 25.6 kbps Playback 512 kbps
Packing density (kb/1/T)	7.5-10	25	Analog	20	Analog	16.7	5.94
Weight (lbs)	74	74	50	48	115	100	15
Size (cu ft)	2.3	2.3	1.0	1.3	2.6	3.7	600 cu in.
Power (watts)	90	90	75	175	?	700	2.5 (Maximum)
Signal/noise (db)	42	30	38	20	22	22	45
Data capacity (bits)	2.4×10^{10}	8×10^{10}	Analog	4.8×10^{9}	Analog	2.2×10^{10}	4.5×10^{8}

For the pre-1980 time frame, longitudinal and transverse tape recorders, with characteristics (expected maximum angle) as shown in Table 6-8 should be available for Earth Observatory Satellite applications.*

Table 6-8. Projected Tape Recorder Specifications (Pre-1980)

Type: Longitudinal direct recording - multiple track	
Number of tracks	Up to 100
Maximum recording to playback ratio:	Limited to maximum playback rate of 100 Mbps
Data capacity:	10^{11} to 10^{13} bits
Flux transitions per inch per track:	50,000 (equivalent to 50K bpi/T double density or 25K bpi/T Manchester)
Weight:	25 to 70 pounds
Power (output rate dependent):	25 to 250 watts (depending on transport construction and playback speed)
Volume:	800 in.^{3} to 3.7 ft.^{3}
Cost/bit:	0.005 to 0.01 cents/bit

Type: Transverse direct recording	
Bandwidth:	40 MHz
Tape speed:	7-1/2 ips
Effective tape to head speed:	Effectively 2,000 ips
Tape length:	3,000 ft
Weight:	70 pounds
Power:	75 watts
Volume:	2 cubic ft.

Typically, the tape recorder has been the device chosen for on-board mass storage; mostly through default of any viable alternatives. Being electromechanical devices they suffer a number of inherent disadvantages; chief among these are the tight mechanical specifications dictated by the needed recording performance and the space environment. High-data-rate inputs are achieved through high packing densities, multiple tracks, and high tape speeds leading to special coding techniques and special synchronization considerations. Unreliability then appears, caused by progressive tape and head wear and high dropout rates due to tape debris and increased flutter contribution. Although very high bit rates and packing densities are obtainable on ground recorders, their size, weight, and power may be excessive for many spacecraft applications. Even if the physical requirements are met, however, a tradeoff is always at work between high performance and the reliability goal. The requirement for total unattended, maintenance-free operation during the mission lifetime causes unmanned spacecraft recorder performance to lag that of ground recorders.

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*The 200 Mbit/s recorder (see 6.7.1.1) is not included because of its large weight (≈190 pounds).

Performance, reliability, and physical requirements dictate the choice of tape recorder type. The longitudinal recorder is better for very high-digital data rate sources while the transverse recorder is better for wide analog bandwidths. The single-track head in the transverse recorder presently limits the bandwidth to about 20 MHz. Wider bandwidth requires higher head rpm, leading to shorter tape lifetimes. In comparison, the complexity of multiple track electronics and data buffering required for the longitudinal recorder is significant. The high tape speed required for the longitudinal recorder makes unattended operating lifetimes difficult to achieve and also sharply limits the record duration.

A significant feature of tape recorders for use as on-board buffer storage is the recording-to-playback speed ratio. In past applications, this ratio has tended to be high due to low sensor-output data rates and short communication periods. For maximum record rates, playback cannot be faster since maximum head-to-tape speeds are already being used. This is true for both types of recorders. Thus, time-compression may be difficult to achieve at the highest recording rate, and a one-minute recording leads to one minute of playback, imposing a fundamental limitation on storage possibilities.

6.7.1.1 200-Megabit per Second Spacecraft Tape Recorder

A program for developing a spacecraft tape recorder capable of recording and reproducing digital data at rates up to 200 Mbit/s is underway at NASA.[126] Specifications for the system, which is to be ready by 1976, are:

1) General

- Data Rate: up to 200 Mbit/s
- Bit Error Rate: $<10^{-6}$
- Capacity: 1.6×10^{11} bits (13 minutes at 200 Mbit/s)
- Size: ≤ 0.16 M^3 (10,000 in.^{3})
- Weight: $\leq$190 pounds (without LSI)
- Power: 205 watts record
  270 watts playback
  <56 watts orbital average.

2) Tape Transport

- Tape: 6500 feet x 2 inches
- Tape Speed: $\leq$100 in/s
- Number of Tracks: ~100
- Longitudinal Packing Density: 20,000 bit/in./track.

Potential use of this instrument is closely coupled at this time with the output of scanning spectroradiometers. These instruments are presenting the highest data rates now. For instance, the thematic mapper (TM) program is anticipating rates significantly in excess of 100 Mbit/s. In one possible high resolution configuration for EOS-A, the thematic mapper and high-resolution pointable imager (HRPI) combine to present a rate of near 200 Mbit/s. Although there is no stated requirement of on-board storage for EOS-A, there is a firm need for a 200 Mbit/s ground recorder. It is felt that completion of the first phase of this program should contribute to the technology needed on the ground. Also, as the data rates of various other sensors continue their inexorable climb, more programs will require the higher rates.

Prior to this time, the highest spacecraft data rate was the 15 Mbit/s from the ERTS multispectral scanner. The ERTS recorder can be extended to perhaps 30 Mbit/s, but anything beyond that will require a multitrack approach. The reason that ERTS is not extendible is primarily because to maintain the ERTS packing density such a single-channel recorder would need to operate at a head-to-tape speed of 26,000 in./s which is not now feasible. In multitrack recording, the data is split up into many low-rate channels thereby facilitating the recording process. This program will not only demonstrate the ability to store 200 Mbit/s, but will provide the specific technology necessary to also implement intermediate data rate requirements.

The implementation of this concept requires no new physics. The approach is, in a large part, scaling up techniques employed for many years. The type of tape, tape transport geometry, tape guidance, tensioning, and the drive motor are familiar and proven. The problem here, then, is to scale up the data rate and capacity without linearly scaling up the size, weight, and power. For example, linearly scaling up the successful OGO recorder would result in a weight of 4000 pounds. Obviously the data density must be increased. This device will exhibit an areal packing density of 10^6 bit/in.^{2} of tape. This is achieved by increasing the longitudinal packing density to 20,000 bit/in. and the lateral density to 100 tracks on a two-inch wide tape. The tape will move at 100 ips for a period of 13 minutes. This requires a tape load of 6500 feet.

This next step of implementation is not trivial and is further expressed by the fact that this device will record at a rate 13 times and with a capacity of 6 times greater than that of the current highest capacity recorder — ERTS WBVTR.

6.7.1.2 Conclusions

The magnetic tape recorder has been selected for the majority of spacecraft bulk data storage applications where optimum size, weight, power, cost, and reliability tradeoffs have been considered and a random access memory is not required. Where data storage over 10^7 bits is required in a serial format, no other candidate memory system currently available compares favorably with the tape recorder. Considerable effort and studies are currently in progress to replace the electromechanical nature of a tape recorder with an all solid-state memory. This effort appears promising, but is admittedly some years away from flight operational status. The progress of these studies should be monitored closely as they develop from the laboratory to potential flight-operational hardware. However, a review of NASA programs in the pre-1980 period indicates that where hardware dollars have actually been committed for flight hardware, the magnetic tape recorder is still being selected for those applications requiring 10^7 bits (nonrandom access) or greater data capacity.

Figures 6-17 and 6-21 show the projected range of capacity, packing density, recurring cost, weight, and power of magnetic tape recorders. These data were based upon a TRW internal research project conducted in 1972. The failure of tape recorder technology to approach the performance and cost goals set for 1975 is one impact of the current state of the economy and illustrates the deficiences of long range technology forecasts. A comparison of tape recorders and other storage devices is presented in

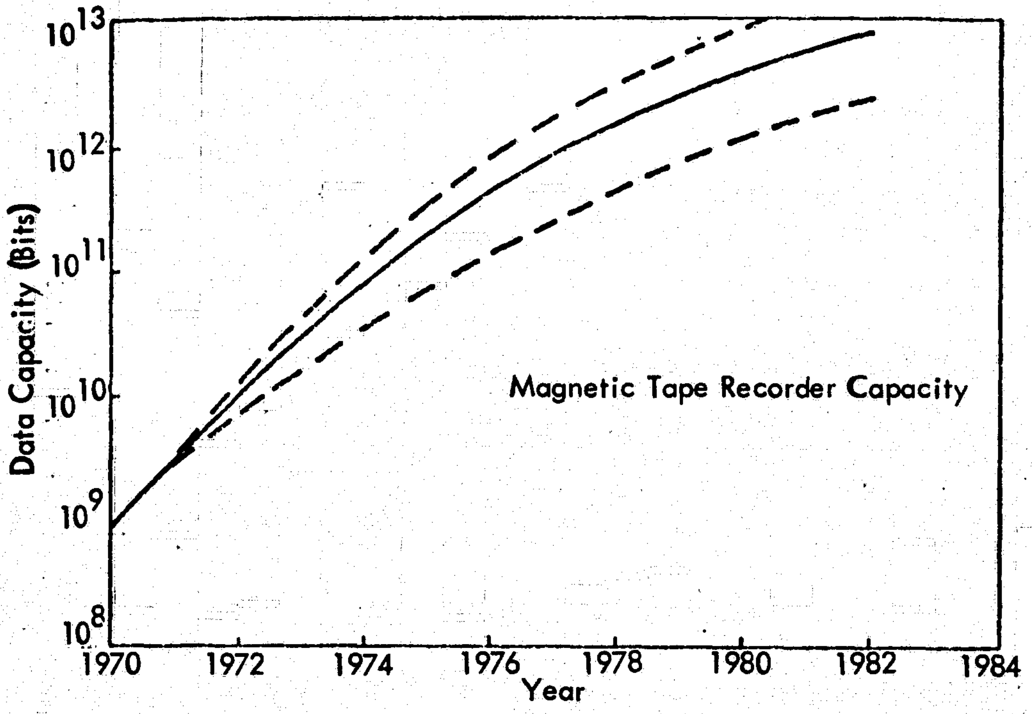

Figure 6-17. Projected Magnetic Tape Recorder Capacity

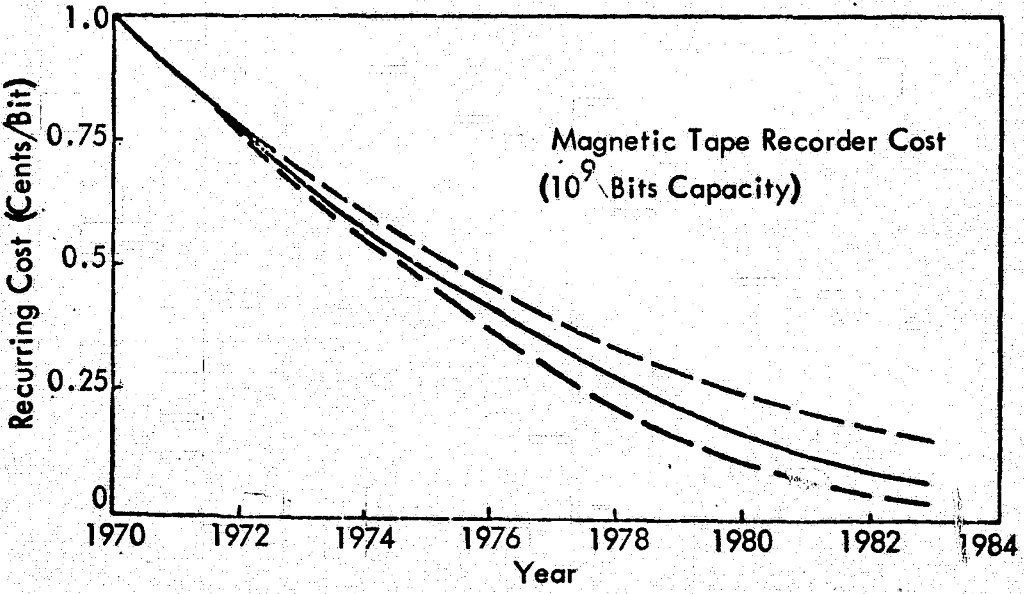

Figure 6-18. Project Magnetic Tape Recorder Cost

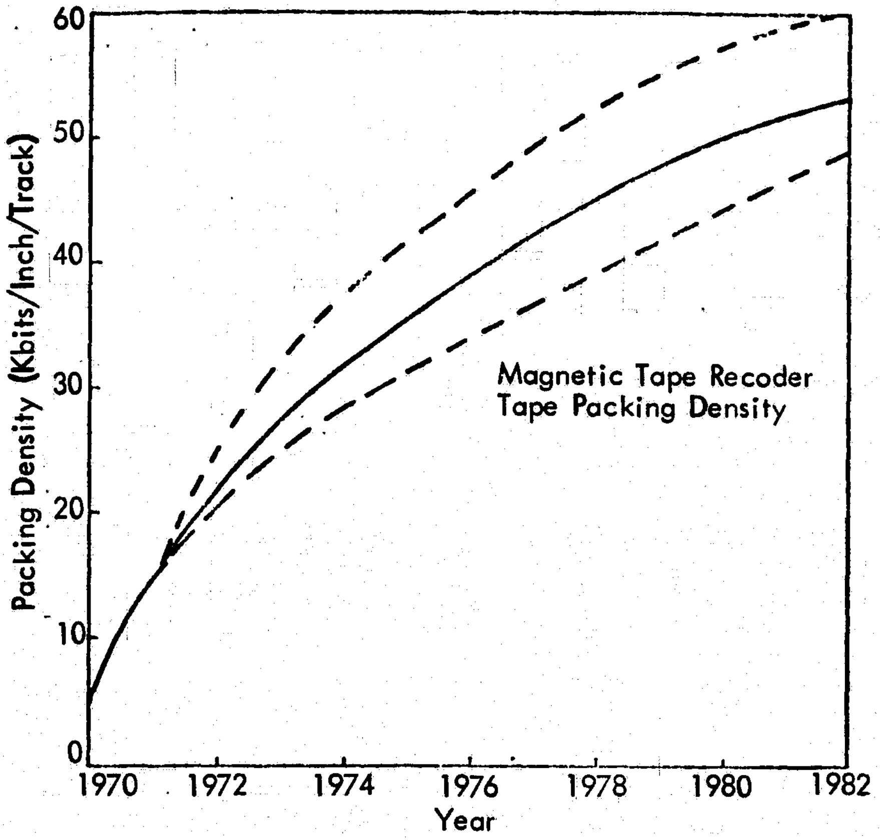

Figure 6-19. Project Magnetic Tape Recorder Packing Density

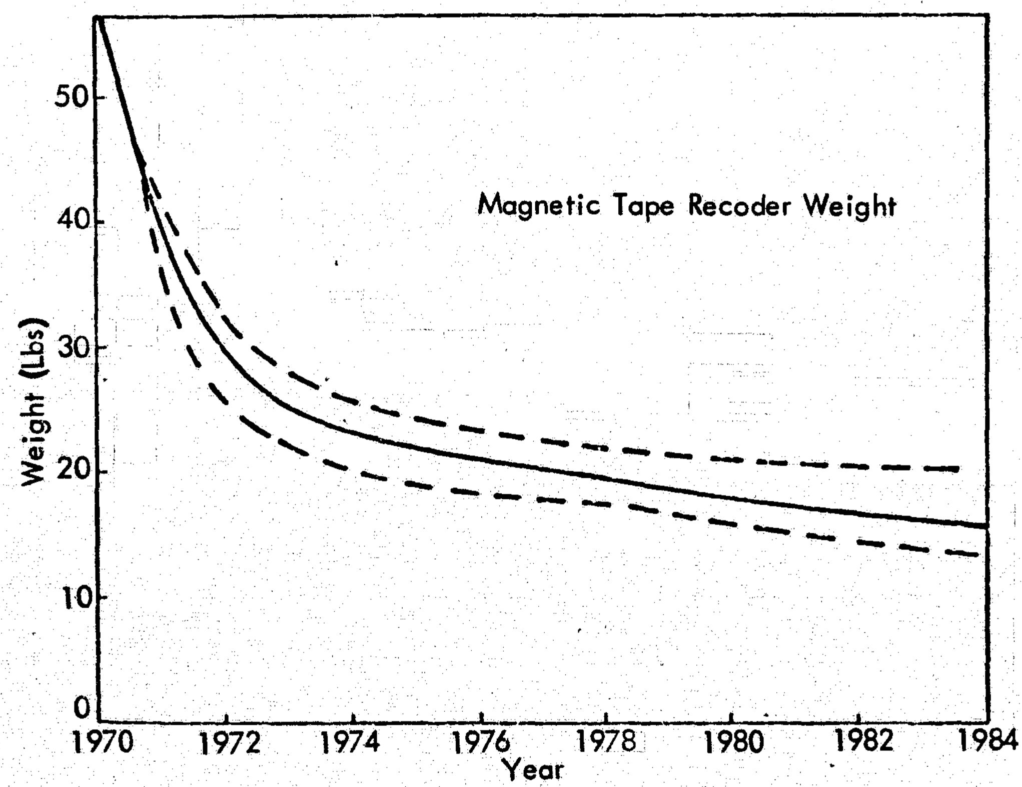

Figure 6-20. Projected Magnetic Tape Recorder Weight

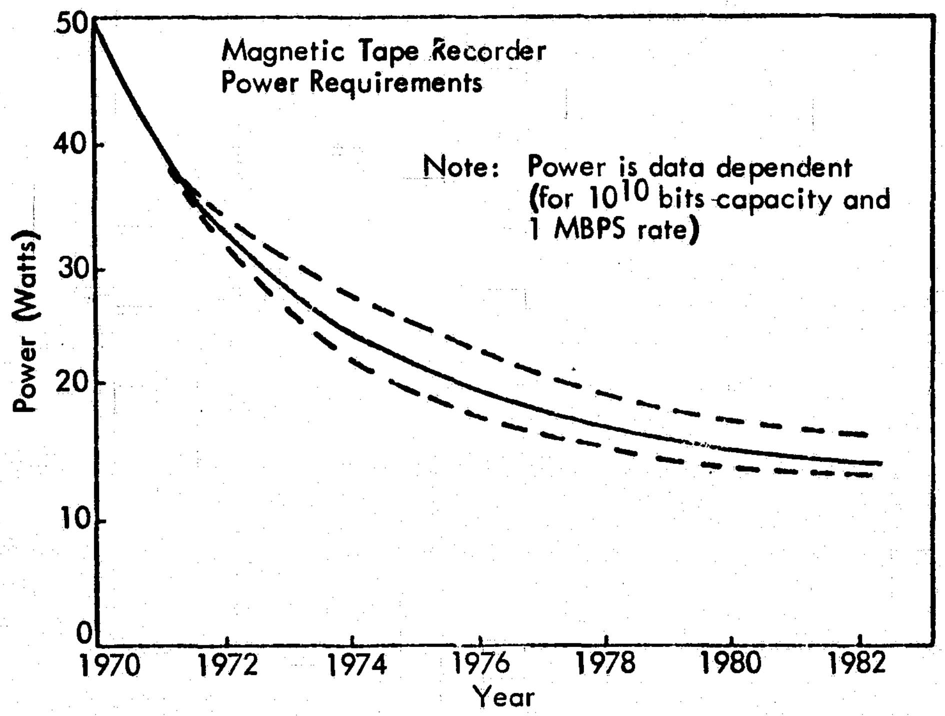

Figure 6-21. Projected Magnetic Tape Recorder Power Requirements

Table 6-9 and shows the present performance value plus the projected capabilities into the early 1980's.

Table 6-9. Projected Characteristics of Data Storage Devices

DATA STORAGE TECHNOLOGY	PARAMETER PRESENT ('74-75)/PROJECTED ('80)									
	CAPACITY (BITS)	PACKING DENSITY	DATA RATE (MBPS)	WEIGHT (KG)	POWER (W)	MTBF (HR)	ENVIRONMENTAL RESPONSE			
							TEMP	SHOCK	VIB	RAD
TAPE RECORDER	$10^9/10^{11}-10^{13}$	25/50	56/300	46	200	4×10^4	A	A	A	G
CCD	$10^7/10^9$	0.9/2 $(\times 10^6$ BITS/IN$^2)$	10/50-100	3/6	3/20	10^6-10^7	G	G	G	A
BUBBLE MEMORY ①	$10^8/10^{10}$	1.5/100 $(\times 10^6$ BITS/IN$^2)$	0.6/10	4.5/7	4/5	10^{10}	A	G	G	G
PLATED WIRE	$10^6/10^7-10^8$	50/1000 $(\times 10^3$ BITS/IN$^3)$	0.5/1	15/70	20/40	②	A	A	A	G

① LABORATORY MODEL — 10^7 BITS

② DEPENDENT ON ELECTRICAL CONNECTION.

LEGEND:

G = GOOD
A = ADEQUATE
P = POOR

6.7.2 Magnetic Bubble Memory

The application of magnetic bubble domain technology to mass memory applications has been under considerable investigation since first publicized by Bobeck of Bell Laboratories.[115] A major goal of this technology has been to provide mass storage devices that have shorter access time, comparable or lower costs, lower power dissipation, and smaller volume than currently used disks, drums, and tape recorders. Present bubble technology appears close to achieving this goal.

The basic storage medium consists of a thin film containing cylindrical regions of magnetic energy called domains or bubbles, which are formed by the application of magnetic fields perpendicular to the film surface. Once these bubbles are formed, they tend to maintain a certain minimum separation since they repel one another. The bubbles are stable over a moderate range of temperature and magnetic field, and can be moved around by the varying of an external field. The cylindrical magnetic bubbles can be treated as digital bits and the storage of information is thus based on the presence or absence of a domain at a given point. The principal development efforts have been aimed at devising the best methods for manipulating these bubbles and formulating magnetic materials that provide optimum performance.

6.7.2.1 Bubble Memory Technology

Magnetic bubble technology has progressed to the point where design and fabrication of practical memory chips is feasible. The so-called LPE[*] film growth process is capable of producing films with sufficiently uniform magnetic properties and low defect densities to be useful for producing bubble devices with an area of up to 1 cm^2.

Bubble devices operate by serial movement of data, and therefore lend themselves to shift register and disk storage kind of applications. A number of methods for organizing mass memories have been investigated by various researchers. A particular system developed at

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[*] Liquid Phase Epitaxial

Bell Laboratories[129] illustrates one way in which a serial mass memory can be organized. The system has a capacity of 2 x 10^7 bits. The chips contain up to 20 kbits organized in filed-accessed, major-minor loop shift registers. Module dissipation is 0.8 watt for the bubble circuitry and 3 watts for the drive coils. The average power is about 3.8 nw/bit for the 10^9 bit system. The fully operational chips have not been temperature cycled to date, but preliminary data, although taken on a different material, indicates the feasibility of sufficient temperature insensitivity for operation over temperature range of 0 to 100°C.

A typical magnetic bubble shift register memory consists of three major components:

1) A magnetic bubble material that is magnetizable along one axis, has a reasonable domain wall velocity, and a relatively small bubble diameter.

2) A magnetic field generating system consisting of:
   - A permanent magnet field for controlled bubble diameters
   - A Helmholtz coil pair driven in quadrature to accurately provide the drive field in the plane of storage medium
   - An array of conductor loops to provide the magnetic field sequence necessary to move the bubbles.

3) An access system consisting of:
   - A magnetic bubble generator/annihilator
   - An output sensor
   - An address and tuning system for data selection.

6.7.2.2 Radiation Effects of Magnetic Bubble Domain Devices

An important factor in determining the potential of magnetic bubble domain memory devices for use in military and space applications is their tolerance of nuclear and space radiation. Magnetic bubble devices were postulated as being intrinsically radiation hardened since magnetic devices such as ferrite cores and plated wires, which operate on their bulk properties, have historically been able to tolerate much higher levels of radiation than their semiconductor counterparts. However, in bubble-domain devices, a perfect single-crystal material is required since the formation and propagation of a bubble domain is highly sensitive to crystalline structure imperfections. Therefore, defect clusters and vacancy-interstitial pairs caused by high energy neutrons or electrons could be detrimental to bubble memory devices. But experimental results to date demonstrate that magnetic bubble domains have high radiation hardness. A magnetic bubble domain memory would remain operational without noticeable degradation after exposure to at least 10^{15} n/cm^2 (1 Mev equivalent). The bubbles stored in the shift register would be stable under the bombardment of a high-energy electron beam at least up to 10^4 rad in a 30 nsec pulse.

6.7.2.3 Recent On-Board Mass Memory Studies

An extensive and detailed review of on-board mass memory technology was conducted in 1970 for NASA.[111] The report recommended the magnetic bubble technique as a replacement of tape recorders in space applications after 1975. A Sylvania study for the Air Force[112] on solid-state bulk memory storage techniques recommends bubble magnetic shift registers for the 10^9 bit bulk memory system.

IBM has completed the conceptual design of a reliable 10^8 bit bubble domain memory for the NASA space program.[113] The storage unit was designed as a buffer memory for tape recorder replacements in satellites to enhance reliability and increase capacity while minimizing power and weight. The memory has random access to blocks of closed-loop shift registers and uses self-contained bubble comain chips with on-chip decoding. The final design assumed 4-micron diameter bubbles, and 2.5-micron line width photolithographic technology to achieve a memory weighing 27 pounds, and having a maximum data rate of 6.4×10^6 bit/s with 200 μsec access time with average power dissipation less than 25 watts. In addition, the feasibility of the conceptual design approach was shown by fabrication and operation of a 64-bit memory chip. This work is continuing at IBM where the goal now is a 10^8 bit bubble memory, that weighs 10 pounds and occupies 100 in.^{3}.

6.7.2.4 Conclusions and Recommendations

Although magnetic bubble technology is new, developers hold high hopes for its future. This is quite evidenced in the current level of "bubble" interest by U.S. companies and by several recent studies[111-113] recommending magnetic bubble mass memory ($>10^7$ bits storage) for spacecraft applications over other memory technology. The Arthur D. Little study of mass memory applications recommended the bubble technology as "being a potential successor to tape recorders in spaceborne data processing systems after 1975." An analysis of various mass memory technologies shows that magnetic bubbles are most suitable for replacing tape recorders in spaceborne applications. Potentially, they are the smallest, lightest systems with a reasonable power consumption, nondestructive readout is possible, and they are nonvolatile and capable of durability in the space environment. As many as 10^8 bits of memory can be packed into less than 0.5 cubic feet. The estimated pre-1980 bit packing density is 10^8 bit/in.^{2}, with a power dissipation of 0.7 μw/bit and a cost of 10 millicents/bit.

In summary, a considerable potential exists in the application of magnetic bubbles for digital computers and spaceborne mass memories. Bell Telephone Laboratories, Autonetics, Hewlett Packard, Honeywell, IBM, Monsanto, RCA, Texas Instruments, UNIVAC, and numerous universities and government research laboratories are known to be working in the area. Magnetic bubbles hold promise for long-life, low-cost mass memories, and if the present level of effort is maintained over the next few years, one should not rule out the replacement of tape recorders by a totally nonmechanical "bubble" mass memory in spacecraft within the 1978 to 1982 period.

Table 6-10 gives a summary of the bubble memory technology including the projected status (1978 to 1982) of a spaceborne mass memory system. Figures 6-22 and 6-23 give the projected range of capacity and packing density of this technology into the early 1980's.

Table 6-10. Summary of Magnetic Bubble Technology

Present Status	Projected Status (Pre-1980)	More Development Needed In
Under development in research labs (some operational)	Capacity: 10^{10} bits Bit density: 10^8 bits/sq in. Data rate: 1 to 10 Mbps Weight: 20 to 40 pounds Cost: 0.05 to 0.01 cents/bit Volume: less than 0.5 cubic feet	Preparing plates of materials Methods for manipulating the magnetic bubbles Maintaining thermal equilibrium Optimizing signal-to-noise ratio Packaging the memory

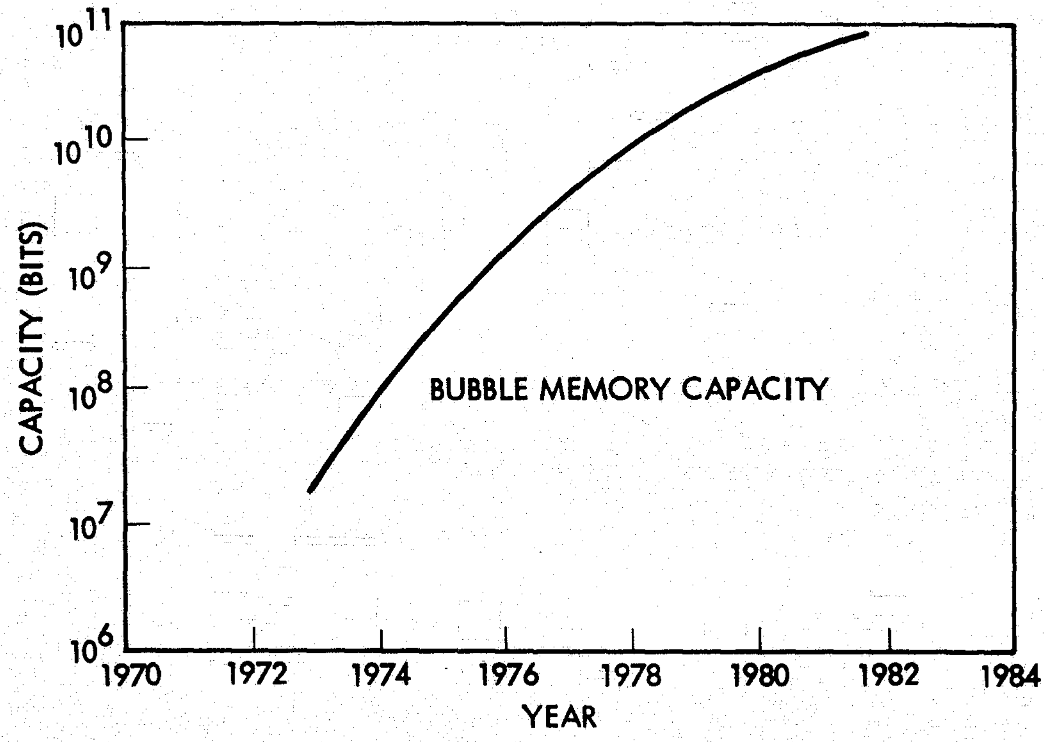


Figure 6-22. Projected Bubble Memory Capacity

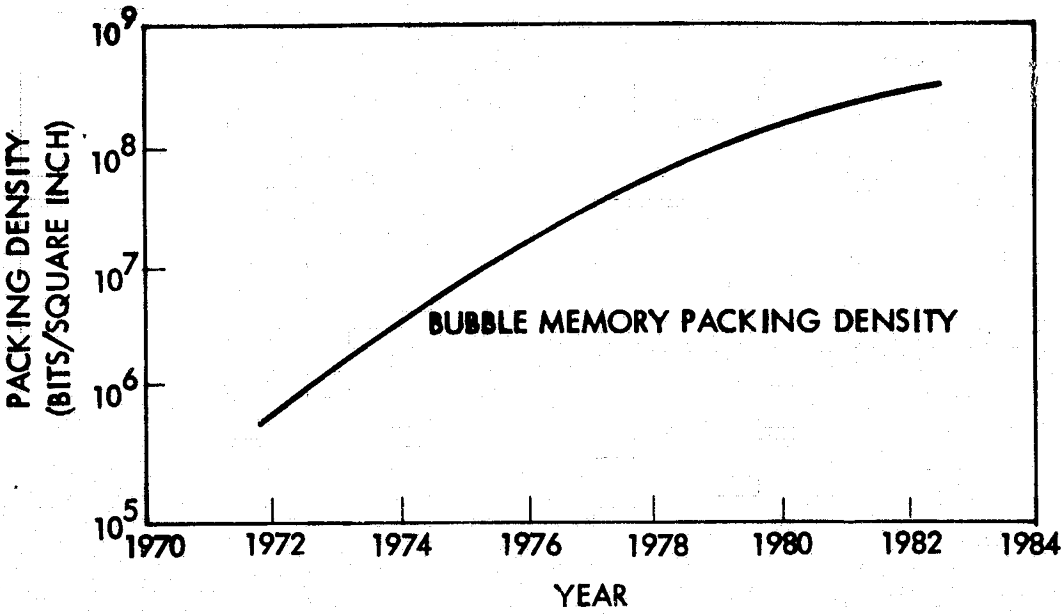


Figure 6-23. Projected Bubble Memory Packing Density

6.7.3 Charge-Coupled Device (CCD) Mass Memory

An emerging very high-density solid-state technology, charge-coupled device (CCD) has many attractive features making it a leading candidate for future mass memory applications. CCD has predicted bit capabilities of 100 thousand to half a million bits per chip or integrated circuit and power dissipation in the range of 5 to 10 nW/bit. Simplicity in device fabrication and projected clock rates of 10 to 50 MHz are other CCD attributes. Although a relatively "young" technology (about four years old), the basic fabrication technology and device physics are all derived from the well-known MOS technology that has been around since the mid-1960's. Many firms are actively pursuing device development in the CCD field, as noted in the literature.[127-136] This implies good availability and many possible second sources.

Desirable as the CCD technology may seem, there are also negative factors. Technological maturity is presently very low, still being a laboratory device. CCD memory is volatile; data loss occurs if the power is turned off or the clock signal (data-shift clock) is removed. Depending upon the system requirements, this could be a disadvantage. Since the clock signal must be applied at all times data is circulating constantly making it more complex from an implementation standpoint to externally synchronize to the beginning of the stored data stream.

6.7.3.1 Mbit Charge-Coupled Device Memory

The CCD mass memory organization of a 2.5 x 10^6 bits is described here to illustrate a CCD data storage application. The organization of the memory is intended to accept 16 bits of either parallel or serial data input depending on speed requirement. Due to the volatile nature of CCD, an internal clock is generated and applied to the CCD chips continuously. Thus, even when the external signals are removed (if the system is in the stop mode) the stored data is still preserved.

The basic memory element of an array is a large scale, 50 x 10^3 to 100 x 10^3 bits CCD shift-register integrated circuit. Due to the extremely high density of this circuit only about 25 chips are needed for the 2.5-Mbit memory.

During the write mode (in the case of serial input data) 16 bits of data shift into the data register. Subsequently, a data transfer is made into the CCD shift registers. Data bit 1 inputs to the first shift register and data bit 16 inputs to the last shift register, respectively. Data stored in this system will be formatted with an identification and synchronization pattern so that identification will be possible. During the read-mode, parallel data are loaded into the output shift register and then shifted out serially. In this approach, the data rate would be 16 times faster than the maximum frequency of a single CCD shift register. If the memory clock were operating at a 100-kbit/s data rate, it would require only 2.5/1.6 Mbit/s $\approx$ 1.6 seconds to write data in or read data out from the 2.5-Mbit memory.

Another advantage of the parallel data organization scheme is an increase in transfer efficiency of the memory. During the data cycling, data are restored, amplified and read back into the shift registers. Hardware used to implement the logic for this system should be CMOS to minimize power consumption. The internal clock typically has two or four phases and the clock input and output buffers and drivers are T^2L compatible. A 10^7-bit CCD mass-memory organization can be realized by combining four of the 2.5-Mbit memory modules described above.

6.7.4 Optical Data Storage Technology

Optical data storage techniques may have space application for large capacity ROM's and are therefore considered in this report.

The virtue of optical storage derives from the high storage densities that are available and the potential low cost per bit. Densities of 3 x 10^9 bits per square inch and 10^{14} bits per cubic inch are theoretically possible with visible light.

Optical storage systems can be divided into two general types according to whether they use point writing or distributed writing. Point writing, most common and easily understood, involves a point-to-point mapping of the data bits on the recording material. The most common distributed writing systems are holographic where each data bit maps into the relatively large area of the hologram. A hierarachy of distributed writing systems depends on the dimensionality of the hologram.

- Slit hologram: data bits map into a line
- Planar hologram: data bits map into a two-dimensional area
- Thick hologram: data bits map into a volume.

The basic unit of storage is the hologram and the data bits which map into the hologram constitute a data block or page. Holographic memories are said to be block oriented since the data contained in a single hologram is handled as a block (in parallel). Holograms are generally small (e.g., 1 mm^2) and storage capacity is increased by arranging them into arrays.

Distributed writing is preferred to point writing since data loss due to dust, scratches, and imperfections in the recording medium are much less likely. Errors in point writing systems tend to be of the burst variety and are difficult to correct with simple codes. Addressing is simpler in distributed writing systems since the block orientation permits compound addressing, increasing with the dimensionality of the hologram. Point writing systems can in effect be considered as the lowest member of the storage hierarchy. Although comparisons may be made to point writing systems, the remainder of the discussion will center on holographic storage.

6.7.4.1 System Configuration and Data Addressing

A large number of configurations are possible, including optical counterparts to magnetic storage systems, e.g., disc, drum, tape, strip, and fiche. The block orientation of holographic storage offers the possibility of precise data addressing without high mechanical tolerances.

Systems are currently under development using both mechanical and nonmechanical addressing. Mechanically addressed systems, although having longer access times, are much simpler and are capable of much larger storage capacity. Holographic tape recorders are being developed with 10^{12} bit storage capacity and high-data transfer rate using simple tape handling equipment.

Nonmechanical addressing requires the use of sophisticated beam deflectors. The larger (fixed) array of holograms that must be accommodated by the optical system, the more difficult it is to store a large data block on each hologram. Phillips has constructed a 1024 x 1024 position deflector system using a 1024 x 1024 cascade of electro-optic Kerr cells for addressing an array of planar holograms. Any hologram can be selected for readout in 2 μsec and the data are projected on a fixed photodetector matrix. If each hologram contains a 30 x 30 bit data block, the total system capacity with no moving parts would approximately 10^9 bits.

Point writing systems can record data at a rate limited by modulator speed and scanning rate. After much development, the state of the art is limited to less than 100 Mbit/s. In principle, the read rate should be equal to, or greater than, the recording rate; however, in practice the read rate is less because of the required tracking precision.

Holographic systems, because of block orientation, have the capability for greatly increased data recording and read rates. Each bit in the data block is recorded or read in parallel, so that the effective rate is equal to the modulator or detector speed multiplied by the block size. Similarly, any mechanical scanning is from block-to-block rather than bit-to-bit so that greatly reduced mechanical speed and complexity results. At present, the problem is the fabrication of modular arrays without undue size and drive requirements. Ferroelectric light modulators appear feasible with 10 Mbit/s in arrays of 1000 elements so that 10 Gbit/s is a future possibility.

Readout rates can easily match the recording rates since the optical power requirements are lower for readout and solid-state detectors are sensitive and have nsec response times. Array fabrication technology is advancing rapidly.

6.7.4.2 Recording Media

Systems currently under study fall into two important categories: archival storage and erasable storage. Archival systems that write only once but can be read many times, commonly use silver halide photographic film for the storage medium because of its low cost and relative high sensitivity although a number of alternate materials are under development which promise substantial improvements in cost, storage density (by virtue of lower noise), and high light efficiency. At present, 10^5 bits per mm^2 of storage area with reasonable error rates (10^{-7}) are feasible. The use of nongrain based, nonabsorbing recording materials may permit another order of magnitude increase in density without any increase in error rates.

Some new materials lend themselves well to low cost, mass replication for micropublishing applications (e.g., video tape recording and credit data distribution).

Erasable materials suitable for holographic recording are in a primitive state of development. Some of those being investigated, along with their principal handicaps are:

- Magneto-optic films: very low efficiency, and high-power exposure threshold
- Ferroelectric crystals: limited retention time, and high-power exposure threshold
- Thermoplastic film: limited resolution, materials fatigue, cumbersome charging and erase
- Photochromics: poor stability, low efficiency.

It is difficult to predict breakthroughs in the erasable material area, but research is vigorous. Like recording, erasure is block oriented so that the block size used depends on the type of application. At present, erasure is thermal or magnetic and is rather slow and cumbersome. Erasable holographic memories are not expected to displace semiconductor memories in the foreseeable future.

6.7.4.3 Lasers

Laser light is necessary for both the recording and readout of holographically stored data. Recording is more demanding of coherence, wavelength, pulse length, and power than is readout. Fortunately laser technology has been advancing rapidly for the past ten years so that a number of useful lasers are available.

The low power C. W. He-Ne laser is most commonly used where readout rate is limited to a few Mbit/s. These are small (12 inches long), low cost ($50), reliable (15,000 hours), and require only a few watts of power. Larger and more expensive versions can be used to increase the readout rate by a factor of ten. He-Cd lasers are under development and, although they have not yet reached refinement in manufacture, promise to provide serious competition to He-Ne.

When very high power is required for extremely high-data rates, solid state Nd-Yg, argon or xenon are candidates, although these require high-input power and special cooling. GaAs diode lasers have been used for readout, but their limited coherence severely restricts their application. Improved versions might find more general application, especially where small size and/or array sources are required.

For hologram recording, a short pulse length with high peak power is desired. C. W. lasers are shuttered or modulated, with a consequent loss of efficiency. Additionally, some recording materials are sensitive only in the blue-UV region of the spectrum so that the laser wavelength is more restricted. For systems using silver halide photographic emulsions at modest data rates, the low-cost He-Ne laser (shuttered) has proven quite satisfactory. The C. W. He-Cd laser with output in the blue-UV region looks quite attractive for recording applications. Some recording materials, such as magneto-optic films and ferroelectrics, have exposure thresholds requiring high-peak power such that small lasers are not yet practical. For thick recording media, lasers with tunable wavelength (e.g., dye lasers) are attractive since one means that the storage medium can be addressed, in depth, is by changing the wavelength.

6.7.4.4 Page Composers

The page composer is an array of optical modulators (light valves) such that light from the recording laser can be spatially modulated in accordance with the block of data to be recorded (simultaneously) on the hologram. The number of modulators in the array is equal to the number of bits contained in the hologram, and increases dramatically with the dimensionality of the hologram. Although less desirable, thick holograms are recorded by a sequence of exposures using a two-dimensional modulator.

Since data recording is in parallel in a block-oriented memory, the recording rate is equal to the modulation rate of an individual modulator multiplied by the number of bits in the block. For this reason the data recording rate can be enormous.

Modulators which have been considered are:

- Liquid crystal arrays: very slow, but quality and low-voltage requirements
- Ferroelectric ceramics: moderate quality at present, but promising. 200-volt switching at MHz rates
- Electromechanical modulators: moderate speed
- Photographic transparency: slow, but excellent quality with large data blocks
- Acousto-optic delay lines: high speed
- TITUS Tube (electron beam addressed KDP array): under development for five years and promising for moderate speed applications with large data blocks.

The page composer is a key component in the recording system and, although progress has been rapid, still further development is needed for a truly satisfactory system. Present systems suffer variously from slow switching speeds, nonuniformity, low contrast (on-off), fatigue, small data block size, or power requirements too large for IC drivers.

An alternative to the generation of holograms by means of an array modulator is to use a digital computer to calculate (fast Fourier transform) the hologram and write by means of a point writing system. Although this has been very effective for generation of slit holograms, limitations in computation speed have limited the approach to about 5 or 10 Mbit/s and the recorder suffers many of the problems of a point writing system (e.g., precision high-speed mechanical scanning).

6.7.4.5 Readout Photodetector Arrays

Although there are a large number of well developed photosensor devices, the silicon detector with broad spectral sensitivity has been adopted as the favorite. They are easily manufactured in large arrays by IC techniques and at present linear arrays up to 1024 elements with integrated self-scan electronics for serial readout are commercially available ($600). Self-scan arrays (64 x 64 element) are also available (approximately $3K) and it is only a matter of time until even larger arrays are fabricated at reasonable cost. Charge-coupled devices, have been built in large rectangular arrays and offer high manufacturing yield.

Although serial readout is most convenient and simple, data rates are limited at present to about 10 Mbit/s. Much higher rates will require parallel or serial-parallel readout of the detectors with increased electronic complexity.

The detector field is moving so fast it is unlikely that it will lag behind the other component technology necessary for mass storage systems with high-transfer rate capability.

6.7.4.6 Conclusions and Recommendations

In making a projection of the future of holographic data storage, one must not ignore the fact that it will not satisfy all requirements. The need for a nsec read-write-erase memory will not be satisfied with an archival storage system, no matter how cheap or large. It appears that in the foreseeable future, read-write-erase holographic memories will not displace semiconductor or magnetic storage systems.

Erasable holographic storage is at a primitive stage and considerable advancement in recording media and lasers is needed to bring about practical systems. It may take ten years for a practical system to emerge and it will then have to compete with the advanced status of other storage technologies.

However, in the archival memory area, great potential exists for holographic storage despite the present limitations of coherent optical components. Holographic storage will quickly outstrip point writing systems and emerge not only with superior performance, but lower cost. Practical systems in the near future will be restricted to archival storage (no erase) and these should find important applications in mass memories. Storage capacities of 10^{12} and 10^{14} bits are reasonable objectives and one could expect data transfer rates eventually to approach 10 Gbit/s. Such systems will probably be limited to mechanical addressing with modest access times. Practical nonmechanical systems may appear in three or four years, although unless marked improvements are attained in bulk storage, their capacity will be limited (10^{10} to 10^{11} bits).

The most fruitful area in the next few years is the development of holographic mass memories, using mechanical addressing (e.g., holographic "tape recorder"), emphasizing transfer rates of 1 to 100 Mbit/s and archival storage. The commercial market (i.e., banking, retailing, law enforcement) may also find a place for modest storage (10^7 to 10^8 bit) capacities with slow access but a cheap price. Only archival nonerasable holographic memory is expected to become competitive in spaceborne mass storage systems because of its superior performance and lower costs.

The status of holographic storage technology as well as a projection to 1980, is summarized in Table 6-11. Further developments, which should prove fruitful to this technology, lie in the following areas:

- Recording media: erasibility, efficiency, no processing
- Lasers: efficiency, lifetime, tunability
- Light beam deflectors: smaller and more reliable, higher speed, more spots
- Page composers: higher speed, higher contrast, lower voltages.

Lower data rate and capacity archival systems are available now. High data rate systems are expected to be available as: archival (1977), and erasable (1981).

Table 6-11. Summary of Projected Characteristics of Various Data Storage Devices (1975 - 1980)

	STATUS (1974 - 1975)					PROJECTED STATUS (1980)				
	CAPACITY (BITS)	PACKING DENSITY	DATA RATE (MBPS)	WEIGHT (LBS)	POWER (WATTS)	CAPACITY (BITS)	PACKING DENSITY	DATA RATE (MBPS)	WEIGHT (LBS)	POWER (WATTS)
TAPE RECORDER	10^9	25 KB/ INCH/ TRACK	56	40	50	10^{11} TO 10^{13} BITS	50 KB/ INCH/ TRACK	100	35	40
BUBBLE MEMORY	10^8	1.5×10^6 BITS/IN^2	0.6	10	4	10^{10}	10^8 BIT/ SQ IN.	10	20	10
ARCHIVAL* HOLOGRAPHIC MEMORY	10^{11} *	2×10^7 BITS/IN^2	10	-	-	10^{13} TO 10^{14}	5×10^7 BITS/IN.^{2}	200	-	-
CCD	10^7	0.9×10^6 BITS/IN^2	10	5	3	10^9	2×10^6 SQ IN.	50 TO 100	12	20
PLATED WIRE MEMORY	10^6	50×10^3 BITS/IN^3	0.5	32	20	10^7 TO 10^8 BITS	10^6 BITS/ CU IN.	1	>150	>40

* POINT-WRITING OPTICAL SYSTEMS WITH CAPACITIES OF 10^{12} BITS ARE PRESENTLY AVAILABLE, BUT ARE NOT INCLUDED HERE DUE TO LARGE SIZE

6.7.5 Plated Wire Technology

Plated-wire memories are used in practically all U.S. Air Force and Navy computer main memories presently built and in some NASA computers and on-board processors. While the 5-mil diameter wire has been successfully used for both ground and space applications, the 2-mil version, presently used by NASA for deep-space applications and by the Air Force on an experimental basis, in addition to increased bit density, appears to have superior qualities in some applications. The 2-mil diameter plated wire memory appears suitable for EOS data processing (buffer) applications in the 10^4 and 10^7 bit capacity range.

Plated wire is a magnetic storage element fabricated by electroplating approximately 8000 Å of nickel-iron alloy (which has a relatively square hysteresis loop) onto a continuous substrate of beryllium-copper wire. Typical wire, about 5-mil diameter, serves as the sense and bit current winding in the memory stack.

If the copper wire is carrying a current during the plating process the magnetic field, due to this current, will cause the atoms being plated to form anisotropic crystals and hence have anisotropic magnetic properties (properties that differ in different directions). The result of this will be the magnetic material "prefers" to be magnetized around the wire rather than along it. The directions around the wire is called the "easy" axis and the direction along the wire, the "hard" axis. This anistropy permits us to read out the stored information nondestructively.

Plated-wire memories seem attractive because they are designed for nondestructive readout. This feature has two advantages:

- Read operation requires less power
- Memory contents can only be altered by a write operation.

For the first point, restoring data in a core memory requires about 12 times the address current, on the average. Although plated wire memories must also be able to write and therefore must be able to supply such currents, writing new data is a less common operation. In a simple operation as moving a word from one memory location to another, only one-fourth of the memory accesses involve writing new information.

The second advantage is less obvious. Read operations are quite sensitive to noise, and in read-restore operations using volatile memories mistakes are perpetuated. In a memory, which does not destroy the data as it is read, read errors can be detected and re-accessed; the data are still there.

The basic parameters to be studied in a wire memory design trade-off include the number of wires per bit, their diameter, a number of word straps per word, bit density, application of keepers, etc. The influence of these decisions on the memory quality and performance is very well understood today and it has been, of course, inspired by the numerous military and space applications.

6.7.5.1 System Comparisons

The standard plated wire element is 5-mil in diameter, although memories using 2-mil plated wire are now being manufactured. The use of 2-mil wire reduces the magnetic path around the wire. This allows smaller word straps to be closer together in a smaller package, which reduces the word and bit current requirements by 50 percent. The smaller currents and faster switching times result in a significant power saving. For a 1970 comparison, 200,000-bit plated wire memory systems using both 2- and 5-mils are shown in Table 6-12.

Table 6-12. Plated Wire Systems Comparisons
(8,192 Words of 24 Bits Each)

Characteristics	1970 (5-Mil)	1970 (2-Mil)	1970 (5-Mil/2-Mil)
Component count (parts)	2,010	1,070	2:1
Speed: Read (μs)	1.0	0.25	2.6:1
Write (μs)	1.0	0.5	
Volume (in.^{3})	560	142	4:1
Power (W)	28	22	1.4:1
Weight (lbs)	15	5.5	2.7:1

6.7.5.2 Performance

Packing densities for plated wire are expected to approach 50,000 bit/in^3 for thinner diameter mini wires such as 2-mil wire. A 5-mil diameter wire compared to a 2-mil wire requires approximately three times the weight and needs twice the power. Thus, future developments in the thinner plated wire technology will open up more uses in a spacecraft system. With a packing density of 50,000 bit/in^3, a 10^8 bit memory will occupy 2000 cubic inches. This is a minimum because of the need for information and address buffers, address decoders, drivers, switches, and a controller. The weight of this memory will be of the order of 300 pounds if a ferrite keeper is used. At a data transfer rate of 10^5 bit/s 100 watts are required.[111]

Switching speeds of less than 15 nsec are presently possible, which allows memories with less than 100 nsec read cycles and 150 nsec write cycles. The NDRO characteristic eliminates data regeneration, simplifies the associated electronics, and permits very short read cycles. Mass memories with storage capacities of 100 million bits can perform a memory cycle within 0.5 μs and main-frame memories with capacities of 0.5 million bit can operate at 100 nsec.

The switching energy of the wire element is extremely small; for example, a random access plated-wire memory operating at 10 MHz can be designed to dissipate less than 1 mW/bit. Table 6-13 gives capacity, size, weight, and power requirements of some existing programs that use plated-wire memory.

Table 6-13. Recent Plated-Wire Memory Configurations

Program	Capacity (k bits)	(cu in.)	Weight (lbs)	Power (W)
Minuteman (Honeywell)	580 (5 mil)	468	15.2	1
Viking (Honeywell)	500 (2 mil)	255	8.5	~ 1
NASA (Motorola)	600 (5 mil)	410	19.0	< 1.2
NASA	600 (2 mil)	232	9.0	< 1.2

6.7.6 Conclusions

During the pre-1980 period, plated wire has a good chance to develop as the best choice for a computer main memory in the 10^5 to 10^7 bit capacity range for spaceborne applications. This is evidenced by its use in a number of programs such as Minuteman, Viking, Poseiden, and others, and the current research activity by the U.S. Government and many industrial organizations. Plated-wire memories in spaceborne systems behave well under conditions of stress, shock, and acceleration because of their rigid construction and the use of zero magnetostrictive wire. They can be operated over a wide range of temperatures and are insensitive to nuclear and particle radiation.

For mass memory application above 10^7 bits, plated-wire memories in their present form are inadequate. The packing density should increase beyond 10^6 bit/in.^{3} without adding too much weight in the form of keeper magnets. The basic limitation on bit density is the interference between adjacent bits; therefore, better techniques must be found to localize the magnetic fields to reduce this.

Plated-wire technology is continuously in the process of improvement, and by 1975 should be suitable for spaceborne 10 million-bit computer mass memory and other applications such as nonvolatile scratchpad memory. Table 6-11 gives a summary of plated-wire technology and Figure 6-24 shows projected capacity and speed of plated-wire memories.

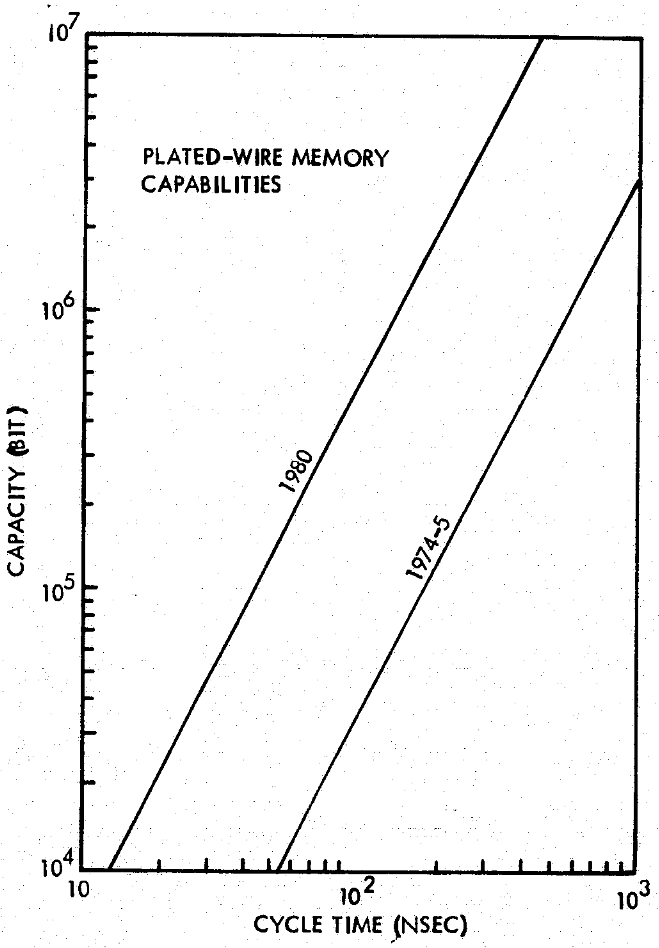
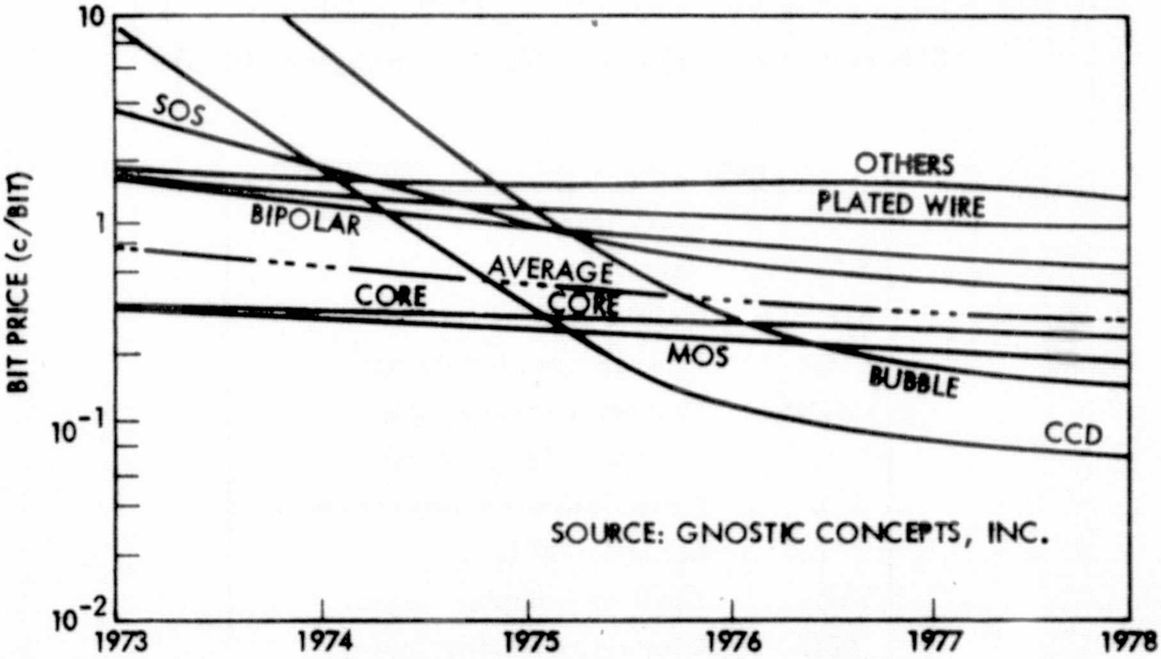


Figure 6-24. Current and Projected Capabilities of Plated Wire Memories

A status summary and a projection to 1980 of parameters for the five types of mass storage considered most suitable for on-board missions is presented in Table 6-11. Generally speaking, most of the parameters listed for a given technology are interdependent, e.g., the data rate can often be increased if one is willing to pay a higher price in terms of power consumption. Thus, it must be kept in mind that many configurations are not shown in the table, e.g., the 200 Mbit/s tape recorder described in 6.7.1 is not included. (Instead, a 100 Mbit/s recorder is listed that is much smaller and hence, may prove to be useful in a wider variety of missions.

Finally, Figure 6-25 shows projected costs of various memory technologies. Note that CCD and bubble memories are predicted to be the least expensive per bit by 1976. However, it should be noted that both are typically used in serial access systems only.



SOURCE: GNOSTIC CONCEPTS, INC.

Figure 6-25. Projected Costs of Various Memory Technologies

6.8 Digital Hardware Status and Trends

Due to the dramatic increase in microelectronic circuit capability in recent years, an explosion of new structures and circuit forms has taken place. In an attempt to better understand the interrelationship of the various forms, a classification of the more important LSI technologies of 1973 are given in Figure 6-26. Table 6-14 contains terminology useful in interpreting the figure. It is noteworthy that at least 50 distinct LSI technologies are present in industry today and many other (not shown in Figure 6-26) secondary device structures exist.

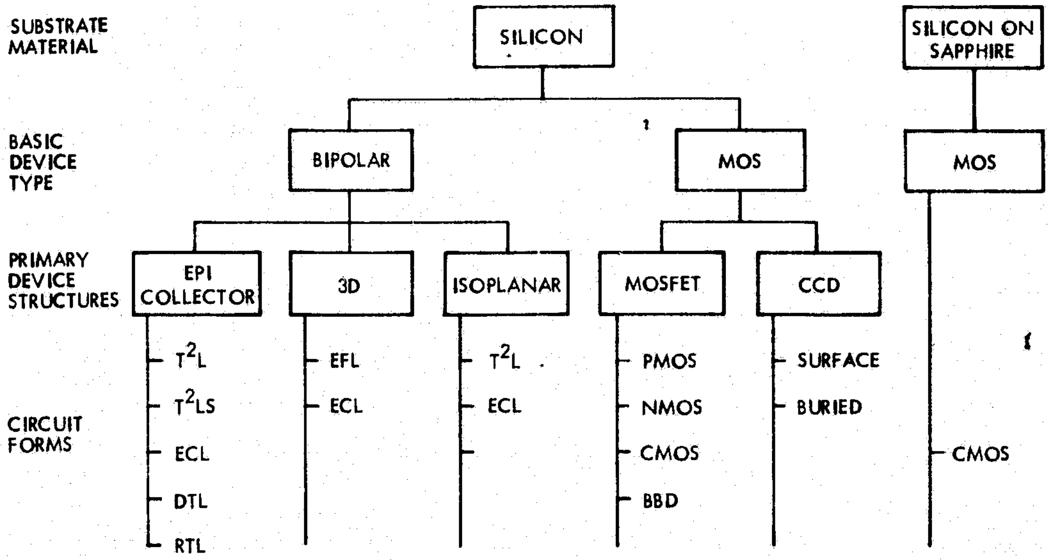


Figure 6-26. Types of LST Technologies (1973)

Table 6-14. LSI Terminology

MOS	Metal oxide semiconductor
EPI	Epitaxial
3D	Triple diffused
CCD	Charge coupled device
CMOS	Complementary MOS
BBD	Bucket brigade device
T^2L	Transistor-transistor logic
T^2LS	Schottky T^2L
ECL	Emitter-coupled logic
DTL	Diode-transistor logic
RTL	Resistor-transistor logic
EFL	Emitter-follower logic

The development of systems using LSI arrays, regardless of the specific technology employed, pose unique challenges in design and fabrication. The system design is often governed by the practical constraints of interconnect density on an array and the number of pins on a package. In general, serial systems are more easily implemented than systems involving many parallel operations. The large clock loads presented by a single array may sometimes create a design constraint for a multichip high rate clock system. This difficulty can sometimes be reduced by including clock buffers "on chip." In system tradeoffs, the components and designs required for clocking systems can be an important consideration.

The power dissipation of MOS arrays is generally low; however, bipolar arrays may require the addition of a thermally related structure.

Interfaces with other devices may require level shifting which reduces system performance in terms of speed and sometimes adds an unexpected number of components. A specific case which clearly presents this problem is that of a large number of parallel data lines that interface with a memory.

The development cycle for an LSI system is generally longer and more costly than one using standard integrated circuits. Close liaison between the system designer and the LSI array manufacturer is essential. Logic simulations with computer simulation programs are necessary to minimize expensive design iterations.

None of these problem areas detract from the desirability of LSI in equipment design. The large number of logical functions that can be incorporated on a single array significantly reduces the number of components in a system. The effect ripples throughout the system design resulting in lower multilayer board count and lower power requirements with attendant reductions in weight and volume. When considering a high reliability, complex system, the increased development cost for an LSI design approach may pay for itself with the fabrication of as few as five sets of equipment.

We now present introductory discussions of various circuit forms and device structures of the LSI and then show tradeoffs and projections for 1980 technology. Digital hardware for high-speed processing is then considered. Finally, a survey of available digital hardware is presented.

6.8.1 LSI Technologies

PMOS Technology. The p-channel MOS device differs from the conventional transistor in that it is a voltage-controlled rather than a current-controlled device. Its principle is exploitation of semiconductor surface effects. There are two variations of PMOS; one is enhancement mode and the other is depletion mode. The one described here is the enhancement mode device. With no bias applied to the gate, the source-substrate junction and the drain-substrate junction are reverse biased, to impede any current flow. With the gate sufficiently negative biased, the n-material under the gate becomes inverted and a thin layer of p-channel is induced. This channel serves to bypass the reverse junctions so that current can flow from source to drain. The gate is usually made of aluminum. The insulating material is made of silicon dioxide. The source region and drain region are p-type diffusions. The PMOS transistor is self-isolating. This property eliminates the need for isolation diffusions and enhances the packing density per chip.

Semiconductor components are sensitive to both the displacement effects created by neutron bombardment and the ionizing effects of gamma radiation. Studies on MOSFETS show them to be relatively immune to displacement effects. However, they are severely degraded by ionizing radiation, which causes changes in surface states. Large threshold voltage shifts result from radiation damage.

Recent advances in the radiation hardening of MOS devices and circuits center around the use of ion implantation techniques for accurately controlled impurity doping of bipolar p and n regions, and for the controlled introduction of traps in oxides leading to a reduced susceptibility to ionizing radiation.

Ion Implantation MOS Technology. In addition to radiation hardness, the ion implantation structure achieves both speed and low threshold. Higher speed is realized through reduced gate-source and gate-drain capacitances as a result of self-aligning gates. A portion of the source and drain regions is diffused and the rest is implanted with boron ions. The gate is used as the mask for the implantation process. Hence, the gate is fully self-aligned. Type <100> crystal orientation is used to achieve a low threshold device. Channel implantation is also used to achieve a low threshold device.

Ion implanted MOS is at an earlier stage of development than silicon gate and has less industry interest. Since both processes provide similar device performance characteristics, it is difficult to predict which process will become a preferred industry standard.

Silicon Gate MOS Technology. The silicon gate structure replaces the metal gate with silicon over a lamination of silicon nitride and silicon dioxide. The end result is a lower gate capacity and high-yield structure with a significant improvement in speed and density. The speed is increased by a factor of four and density by 30 percent over conventional PMOS.

Although silicon gate MOS processing is limited to a few manufacturers, there is strong interest in the industry and heavy commitments have been made to establish the technology.

N-Channel MOS. An important trend in MOS has been the transition from p-channel devices to n-channel. This is due to the better operating characteristics obtainable with NMOS because the mobility of electrons in these devices is higher than holes. That is, NMOS devices use electrons for large conduction while PMOS devices use holes for conduction and at normal electric field intensities, electron mobility is about twice that of hole mobility. This means that the on-resistance of NMOS devices is half that of PMOS devices. To put it another way, for the same value of on-resistance, the size of an NMOS device is about half of that of a PMOS device, and hence twice the packing density over the PMOS.

Other advantages of NMOS over PMOS are speed, compatibility with TTL inputs, and the fact that power can be obtained from a single +5-volt supply. The increase in speed is a direct result of smaller junction areas. Proponents of NMOS also claim that it has the best speed-power performance of all single channel LSI technologies.

NMOS has one major drawback, however, and that is processing difficulty. Since contaminants are mostly positively charged, they can bias a NMOS device on. This difficulty can be overcome by heavily doping the substrate with p-type impurities to offset the effect of the contaminants. However, because of the source bias effect, this technique is very effective only if the source is grounded as in CMOS.

Complementary MOS Technology (CMOS). Still another participant in the MOS race is CMOS, standing for complementary symmetry MOS (also commonly called COSMOS). CMOS devices are fabricated using both p-channel and n-channel devices in a complementary configuration.

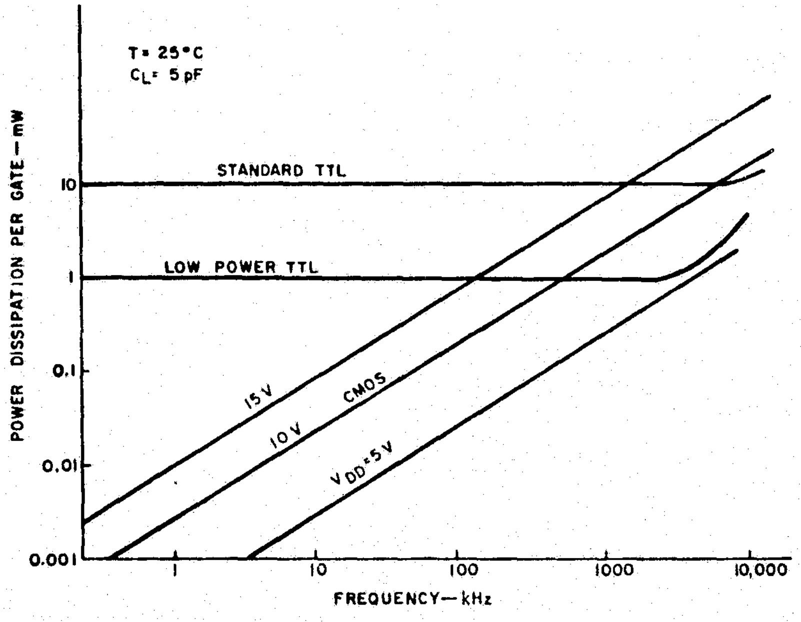
The CMOS structure circumvents the difficulty caused by the source bias effect by grounding the source of the n-channel devices. This type of circuit brings to IC's the advantages of complementary symmetry circuit configurations that originated with discrete devices, which include low power, quiescent operation, fast propagation delay, high noise immunity, large fanout, well defined 1 and 0 levels, and operation from a single power supply. However, to achieve symmetry the circuits must be built with matched p- and n-channel devices, which makes the device designer's job more difficult.

Comparing NMOS and PMOS memory technologies, we find that the biggest advantage of CMOS is low power dissipation. CMOS devices dissipate very little power because there is no direct DC path to ground. The only power dissipated is due to the leakage current of the off transistor. A static CMOS cell requires one percent of the total power of an analagous dynamic NMOS device. CMOS also operates over a wider power supply range, starting at about the n+p threshold voltages and going up to the maximum voltage. However, in logic arrays, a dynamic PMOS or NMOS array can have power dissipation almost as low as dynamic CMOS. But static PMOS or NMOS has much higher dissipation than static CMOS.

NMOS has the edge in lower cost and greater packing density. The CMOS structure requires a p well diffusion for the n-channel device and a guard band or channel stopper which result in large areas for logic functions. In addition, the nature of the complementary drive requires a larger number of devices than single polarity technologies for a given logic function. As a result, packing densities are approximately half those achievable with other MOS technologies.

Conspicuously absent so far in the single-channel field are standard parts that provide logic building blocks. This is an area in which CMOS contrasts favorably with PMOS and NMOS logic. Recent variants of and improvements in basic single-channel MOS processes are compatible with CMOS technology and can be applied equally well to enhance performance. There is every indication that PMOS and NMOS technologies will prosper within selected areas. What is equally clear is that CMOS combines the best of two worlds and takes on the quality of a general-purpose logic form, supplementing rather than replacing single-channel MOS, and extending it with dramatic savings in power.

An interesting aspect of CMOS technology is the type of dependence of power dissipation frequency, illustrated in Figure 6-27*. CMOS power dissipation is negligible at DC and increases linearly with frequency, whereas bipolar dissipation tends to be constant. Thus, at low to intermediate frequencies, CMOS can represent a dramatic reduction in dissipation.



Source: Karstad[160]

Figure 6-27. CMOS Power Dissipation Characteristic

CMOS processing is inherently simple and less critical than bipolar and promises higher yields for circuits of equal complexity. MOS technology ushered in the era of MSI/LSI and provided a lower cost per function than could bipolar. CMOS will do this better than any other branch of the MOS tree, because of its extraordinarily low power consumption. The result is larger chips with greater packing densities without exceeding thermal limitations of the package and without the need for expensive cooling methods.

Silicon-on-Sapphire (SOS). On the basis of transit time considerations, the MOS device is capable of high frequency performance previously thought attainable only by the bipolar transistor, which, at its

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*Similar effects are found in CCD, PMOS and NMOS circuits.

upper performance limits, requires the use of high power, nonsaturating current-mode logic. Comparable performance with only microwatts of dissipation can be obtained from the MOS device. However, it requires combination of the best features of thin film and monolithic silicon technology in an LSI environment.

One technology expected to extend CMOS speed capability into the upper range of TTL is SOS. In this process, CMOS transistors and crossunders are fabricated in a thin film of single-crystal silicon growth on an electrically insulating substrate, such as sapphire. Any unused silicon is removed from the substrate, leaving perfectly isolated islands of silicon for transistor fabrications. Use of thin-film silicon allows virtual elimination of the parasitic capacitance of the drain-to-substrate diodes and of the metal over silicon wiring found in conventional bulk silicon devices that seriously degrade performance of bulk-silicon MOS circuits. The only significant capacitance is due to the active channel of the driven MOS device. The internal array time constant approaches that of bipolar devices, which may be as low as a fraction of a nanosecond.

A silicon-gate, 256-bit dynamic shift register has operated at clock signals of 200 MHz at 10 volts with dynamic power dissipation at 50 MHz and 5 volts of, typically 90 μW/bit. The major problem with SOS is substrate cost — \$20-\$30 compared to \$2-\$4 for conventional MOS.

Some of the 4000A series standard parts are now offered in CMOS/SOS-equivalent versions. Si-gate CMOS/SOS circuits are also reportedly in pilot production. While these gate-level functions have shorter propagation delays than do their CMOS counterparts in bulk silicon, the gain is moderate because the signal going off the chip must drive a capacitance load. The real payoff in speed improvement will be in complex LSI functions. It is the prospect of large subsystems operating at high speed with ultralow power dissipation which is bound to influence future designs in the computer industry. The sapphire substrate is probably not the final word in the evolutionary MOS process; work is also being done with spinel, which is a closer crystallographic match to silicon than sapphire, and is easier to machine.

Bipolar LSI. In bipolar circuits, recent emphasis has been on widening and second-sourcing product lines and on developing smaller devices to improve performance and increase integration levels. Two of the processes being developed to meet these goals are Isoplanar II and OXIM (oxide-isolated monolithic technology). An important objective of these and other processes has been to reduce isolation areas to shrink transistor sizes. Another goal is to minimize collector-to-substrate capacitances for greater speed.

TRW has successfully developed a triple diffused (3-D) high-yield high-speed, technology with a single layer of metallization. Deliveries for high-reliability spacecraft equipment are in progress. The triple diffusion technique will be an important future process since it has yields well in excess of other technologies and in most cases, comparable operating rates. Since standard TTL and ECL are well established, these are not discussed further. A description of Schottky Clamped TTL, OXIM, Isoplanar and 3-D devices is presented below.

Schottky Clamped TTL Technology. The Schottky Clamped transistor is produced utilizing conventional epitaxial processing. The Schottky barrier diode is fabricated in parallel to the base-collector junction of the normal TTL npn transistor. As the Schottky barrier diode has a lower forward voltage than the base-collector junction, it clamps the transistor V_{CE}, diverting most excess base current from the base-collector junction and prevents the transistor from reaching classic saturation. Excess stored charge does not exist in the Schottky barrier diode clamped resistor.

The OXIM Process. The OXIM structure is part of an evolution of bipolar processes that began with the standard buried collector (SBC) structure in which isolation is achieved with a diffused p-type guard ring. The next rung in the evolutionary ladder was the collector diffusion isolation (CDI) structure in which the collector contact diffusion surrounds the active transistor to achieve collector contact and isolation in the same operation. This structure is smaller than the SBC. However, parasitic capacitances are not reduced in the same ratio as the area, because of high capacitance between the collector contact and the extrinsic base diffusion.

In the OXIM process, isolation is achieved by selectively oxidizing the region around the transistor using silicon nitride as an oxidation mask. This technique produces a transistor that is slightly smaller than the CDI transistor and yet has substantially smaller parasitic capacitances. The reduction in capacitances can be as much as a factor of 10 in some cases.

OXIM uses both isoplanar and ion implantation processing steps.

Isoplanar Processes. The original Isoplanar technology eliminated space between the base and the isolation layer. Isoplanar II also eliminates space between emitter ends and the edge of the base. One circuit built with Isoplanar II is a dual ECL gate made by Fairchild Camera and Instruments, which sports a subnanosecond propagation delay. Even more important than its speed is that the inherently reduced parasitics of Isoplanar II structure achieve a propagation delay as low as 650 ps with standard ECL power supply voltages and logic levels.

Triple Diffusion. The triple diffused structure is a four-layer structure wherein the top three layers form an npn device and the bottom three layers a pnp device. The structure is formed by three sequential impurity diffusions. The fabrication sequence is exceptionally simple. The collector is formed by an arsenic diffusion into a p-type substrate. Standard base and emitter diffusions follow and circuit interconnections are made by n plus diffused cross-unders and one level of titanium-aluminum metallization.

The triple diffusion structure is ideally suited for high-density LSI circuits. The device geometries are small, the transistors are self-isolating, and the transistor coalescing is possible. The packing density of the triple diffusion LSI is similar to that of the MOS technology. Substrate pnp transistors are formed as a by-product of the npn triple diffusion process. Rather than attempting to attenuate those parasitic pnp transistors, they are enhanced and used throughout as active logic elements.

Charge Coupled Devices. Charge transfer devices, consisting of charge-coupled devices (CCD's) and bucket brigade devices (BBD's) were announced four and five years ago, respectively, and the first commercial CCD devices were introduced last year. The basic function of these devices is to transfer a quantity of charge from one part of the circuit to a neighboring element. The uses arising out of this mechanism are collecting charge from photosensors, delay lines, filters, and serial memories.

The CCD concept is elegant in its simplicity. A charge-coupled device consists of a series of closely spaced metal electrodes over silicon dioxide grown on silicon. Charge is transferred from plate-to-plate by applying appropriate potentials to the plates. The essential idea is to store information in the form of electric charge in potential wells, which are created at the surface of a semiconductor. These wells are created by means of a dielectric (oxide) interface between the semiconductor and metal electrode to form a string of capacitors. As the voltages applied to these capacitors are properly sequenced, the underlying potential wells and associated charge can be moved from one well to an adjacent one. The device works as a shift register: minority carriers are introduced at some specific point and are then moved around from one electrode to another. In this sense, they are completely analogous to magnetic bubbles where magnetic charges are generated at one point and moved around in a shift register fashion. One difference is that magnetic bubbles are nonvolatile as long as the bias field is present whereas CCD is volatile upon removal of power.

CCD's can be operated in either an analog or digital mode, require little power, and can be packed with very high density onto a chip (one device per square mil is feasible). In 1973, Fairchild Semiconductor introduced the first commercial image sensors: a 500-element, linear, self-scanned device and a 100 x 100 array. The linear sensor can provide a single line of a TV picture at a time, while the area device views an entire picture simultaneously. The array has been built into a miniature TV camera about the size of a package of cigarettes.

CCD image sensors offer the advantages of smaller size and lower power requirements than vacuum tube image sensors. The array operates from a 20-volt power supply, compared to about 2000 volts for typical vacuum tube sensors. Nominal power consumption is 50 mW.

6.8.2 Tradeoffs and Projections

This section contains detailed information relating to the state-of-the-art and projections up to 1980 of various LSI technologies. Table 6-15 resulted from a 1972 study of LSI characteristics including radiation effects on various types of circuits. Note that the bipolar circuit forms have generally less radiation susceptibility than the MOS forms, occupy greater chip area, and operate at higher speeds. Of the faster circuit forms, it is noteworthy that 3-D is the only bipolar challenger to MOS in terms of truly low power operation.

Table 6-15. LSI Tradeoff Comparison (1972)

	Maximum Frequency (MHz)	Power Dissipation per Gate at 1 MHz (mW)	Relative Density	γ = Dose Threshold (rad)	Neutron Irradiation Threshold (N/cm^2)	Nondestructive Transient Failure Threshold [rad(Si)/sec]
PMOS	1	1.5	1.0	1×10^4	$>3 \times 10^{12}$	10^7
CMOS	5	0.8	0.7	1×10^4	$>3 \times 10^{12}$	10^7
Triple diffusion	20	3	0.7	10×10^4	$>5 \times 10^{12}$	$>10^8$
ECL	150	26	0.3	10×10^4	$>5 \times 10^{12}$	$>10^8$
TTL	8	15	0.4	5×10^4	$>3 \times 10^{12}$	$>10^8$
TTLS	30	6	0.4	5×10^4	$>3 \times 10^{12}$	$>10^8$
Ion implantation	3	1	1.3	2×10^4	$>3 \times 10^{12}$	10^7
Silicon gate	3	1	1.3	2×10^4	$>3 \times 10^{12}$	10^7
NMOS	2	1.5	1.5	0.5×10^4	$>3 \times 10^{12}$	10^7

The results of a more recent study are given in Table 6-16. Note the high operating rates of ECL and the small number of masks necessary to produce 3-D.

Table 6-17 is concerned with technology projections into the 1980 time frame. Particularly noteworthy is the phenomenal growth in LSI capabilities (to VLSI) projected for 1980. The number of transistors per chip are predicted to increase dramatically, both due to higher packing densities and larger chip sizes, by a factor of close to 40 for some technologies between 1973 and 1980 while maximum clock rates should increase about six times.

Table 6-16. LSI Parameter Summary 1973 (Source: References 162 and 163)

System Parameter Circuit Technology	Nominal Stage Delay (nsec)	Dissipation at 1 MHz (mW)	Speed-Power Product (PJ)	Area (mil^2)	Clock Rate (MHz)	Number of Masks	Process Steps
Silicon gate CMOS MSI	30 to 45	-	-	30 to 40	8	7 to 9	-
Silicon gate CMOS (with/without ion implant) LSI	9 to 11	0.18 to 0.22	2 to 3	20 to 30	16	7 to 9	-
CMOS isolation (dielectric/SOS) LSI	4 to 7	0.15 to 0.2	-	20 to 30	30	7 to 9	-
TTL low power MSI	25	1.2	30		5	7 to 9	60 to 65
TTL low power Schottky - LSI	10 to 15	1	15	65 to 75	3 to 12	7 to 11	60 to 97
TTL	8	7.5	60	104 to 115	20 to 25	7 to 11	60 to 97
TTL Schottky	3	15	45	126	50 to 70	7 to 9	60 to 74
Standard ECL-MSI	2	25	50	288	100 to 130	7 to 9	60
TTLS LSI	1.5	15	22	98	120 to 160	7 to 9	60 to 65
ECL LSI	1	25	25	150	200 to 250	7 to 11	60 to 94
Triple diffused EFL (TRW) LSI	7	1.5	10 (1 MHz) 15 (20 MHz)	33	30	5	65

Table 6-17. LSI Technology Projections

	1966 (SSI)	1973 (LSI)	1980 (Projected) (VLSI)
LSI Parameter			
Performance			
Clock rate (maximum) (MHz)	25	300	2000
Transistor bandwidth (GHz)	0.3	1	6
Speed-power product (pJoule)	100	3 to 10	0.1 to 1
Complexity			
Chip size (maximum) (mil)	100	250	500
Area per device (mil^2)	20 to 50	2 to 5	0.1 to 0.3
Transistors per chip (maximum)	50	5000	200,000
Typical Monolithic Circuits			
Random access memory	16 bits	2048 bits	64,000 bits
Serial memory	32 bits	30,000 bits (CCD)	5 x 10^6 bits (CCD)
(Random) logic	4 gates	500 gates	10,000 gates
Digital correlator	-	64 bits	2048 bits
RF analog circuits (bipolar)	-	HF PLL	S-band RF circuits
Secure code generator	-	32 bits	1024 bits
Sensor mosaics (CCD)	-	100 x 100 elements	1000 x 1000 elements
Minicomputer CPU (bipolar)	-	10 chips at 5 MHz	1 chip at 50 MHz

Finally, Figure 6-28 illustrates clock rate, transistor density, and cost projections to the year 1980. The 1973 cost figure of $1000 is for a memory subsystem consisting of 20 RAM chips, at $50/chip. In 1980 fewer chips will be necessary in order to mechanize a subsystem of equal complexity while the price of each chip will increase only a small amount. Thus the projected 1980 cost for the same subsystem will be $200 (assuming that large quantities are purchased).*

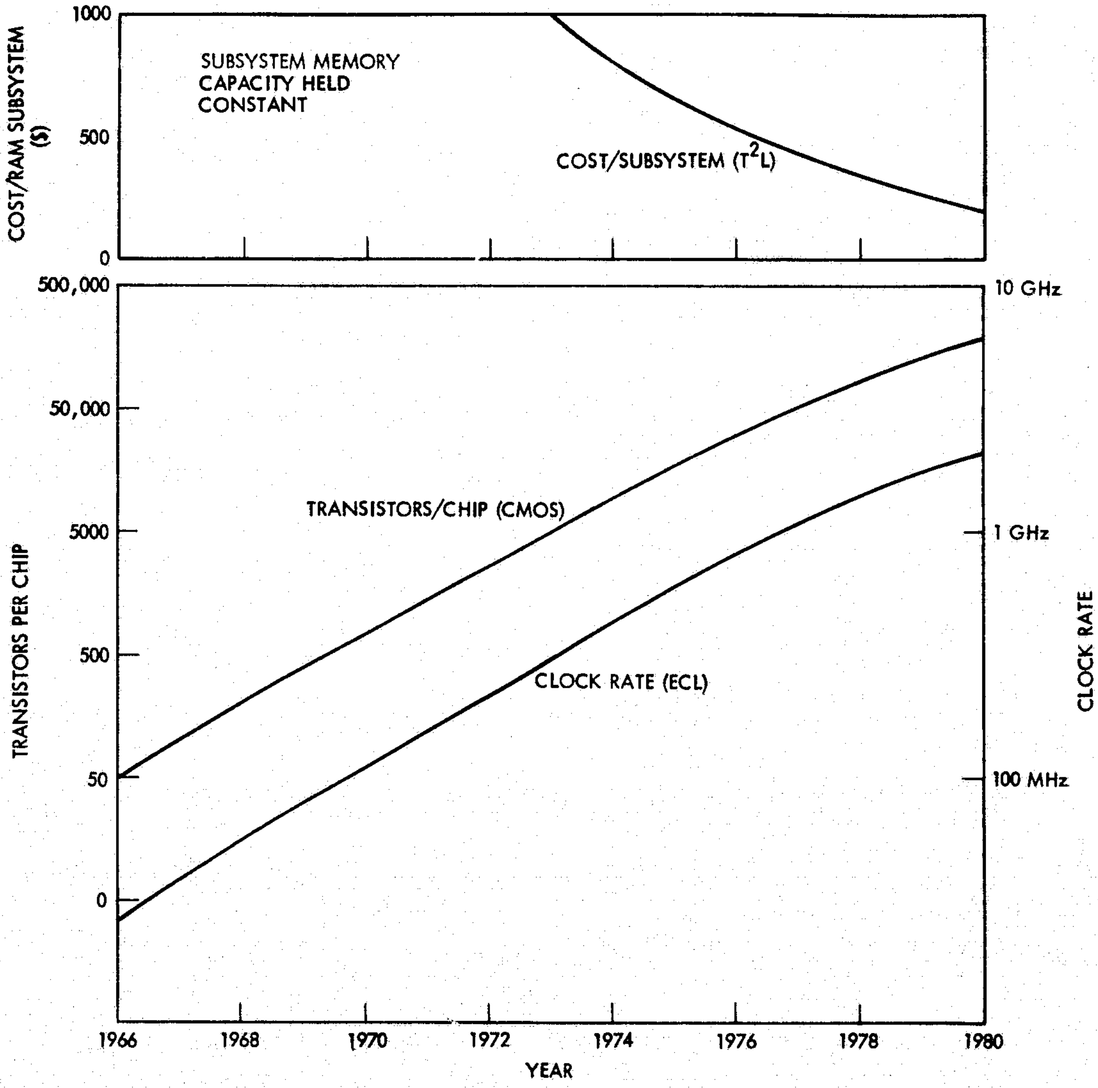

Figure 6-28. Projection of LSI Density, Speed and Cost to 1980

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* It should be noted that the $50/chip price is merely a component cost and is not for flight-qualified hardware.

From the above we may conclude that the definite trend toward smaller, cheaper and faster building blocks for electronic systems will dramatically increase the data handling capabilities of on-board processors in the 1980's.

6.8.3 LSI, Bipolar and Other Techniques

In considering the digital hardware that could be used in various portions of an earth resources spacecraft, many of the processing bandwidths require high-speed logic for proper operation. In the following paragraphs, various commonly available logic families are compared with an eye toward future high-speed operating potential.

The comparison of bipolar versus MOS technologies reveals bipolar to be far ahead in speed/power performance. P-MOS circuits are presently limited to 1 to 5 MHz data rates, with C-MOS extending this capability to 10 to 30 MHz. In contrast, bipolar techniques can be extended to 500 MHz. C-MOS may have lasting appeal in applications requiring minimum power with low-duty cycle data rates, such as found in some memory applications. However, for the high-speed digital processing application, the technology is not attractive due to the high-duty cycle operations of filter functions and the C-MOS speed limitation far below 100 MHz. Even if C-MOS on sapphire grows in capability to the 100 MHz range, bipolar circuits offer yet better performance with limitations closer to 1000 MHz rates.

The real high-speed tradeoffs are among different bipolar technologies. First let us examine standard wafer techniques versus custom-made circuits. A number of companies (e.g., TI and Motorola) offer large arrays of standard logic functions that are interconnected to accomplish a unique function. The advantages of this approach include fast turnaround time and low nonrecurring costs. The disadvantages, however, can be severe in that the system function must be implemented with standard digital building blocks that do not allow for optimization. Also, the presently available circuits offer primarily only standard TTL configurations that operate in the 8 nsec/gate delay range. In contrast, the custom approach allows:

- Faster circuits to be fabricated

- Flexibility of adjusting the speed-power performance on an individual function within the total circuit to optimize overall performance.

Circuit Configurations. Next, let us consider the relative merits of TTL and ECL. TTL received a healthy boost in speed with the advent of the integrated Schottky diode. TI has introduced an IC logic line with 3 nsec, 20 mW gates, and flip-flops that can toggle up to 100 MHz. The Schottky clamp inhibits transistor saturation, thereby eliminating storage time from switching time constants and has reduced the practical speed limit of TTL from 5 to 3 nsec, thereby becoming more competitive with ECL. It remains, however, a technology that is limited to applications with less than 100 MHz system data rates. In contrast, ECL comes into its own for data rates above 50 MHz, and is a viable technique up through 200 to 300 MHz data rates. The tradeoff between TTL and ECL is quite dependent upon the system speed goals. Of even more importance, ECL offers potential speed improvement to 1 nsec delays at power dissipation levels down to 25 mW per gate delay. This cannot be approached by Schottky clamped TTL.

In the past, computer logic elements such as single gate and flip-flops and then, later, adders and shift registers were considered to be basic computer system building blocks. Today with large LSI arrays available, new concepts must be applied to the thinking of what constitutes a computer system block.

Looking toward the future, the availability of these high performance LSI elements can be expected to influence the concept of new systems and suggest new areas for application.

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