Itek

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System Overview
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Conceptual Design of an Automated Mapping Satellite System (MAPSAT)

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The Automated Mapping Satellite (MAPSAT) System Conceptual Design Study reported herein is a product of the joint efforts of Itek Optical Systems, a Division of Itek Corporation and the Space and Defense Systems Group of TRW, Inc. TRW provided the analyses and design of the spacecraft, its control and transmission system, and the ground data handling system. Itek performed the epi-polar feasibility analysis, the epi-polar correlation analysis, and the trade-off of optical systems, focal planes, and data compression techniques.

We have been aided in carrying out this study by contacts with personnel at NASA, GSFC, DMA, NOAA and USGS, who graciously made their time and knowledge available at various points during the study period.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Mapsat conceptual design - system overview

By Alden P. Colvocoresses

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February 23, 1981

Memorandum for the Record (EC-78-Landsat/Mapsat)

By: EROS Coordinator, National Mapping Division

Subject: Mapsat conceptual design - system overview

Enclosed is a System Overview of the "Conceptual Design of an Automated Mapping Satellite System (Mapsat)." The full report (ITEK Corp., 1981, 285 p.) to the U.S. Geological Survey is only available in limited quantities and upon specific request.

Mapsat represents a new concept for mapping and monitoring the Earth's surface from space. ITEK's report verifies the technical feasibility of Mapsat and estimates the cost to develop, launch, and operate the system for 7 years at $215,000,000. It also indicates that the system is highly cost effective and could be launched as early as 1986. Multicolored image maps at 1:50,000 scale with 20-m contours are indicative of the products which are within the capability of the Mapsat system.

Elevation data are obtained from the use of the epipolar-plane condition in space. This greatly simplifies the mapping problem by permitting the automated processing of stereo data into digital elevation data, which is an increasingly important mode for expressing the Earth's topography. The Mapsat concept will be presented by the U.S. Geological Survey to appropriate government agencies as a candidate for an operational Earth-sensing system.

Since Mapsat has been developed from Landsat, this memo series has been expanded to Landsat/Mapsat as indicated.

Alden P Colvocoresses
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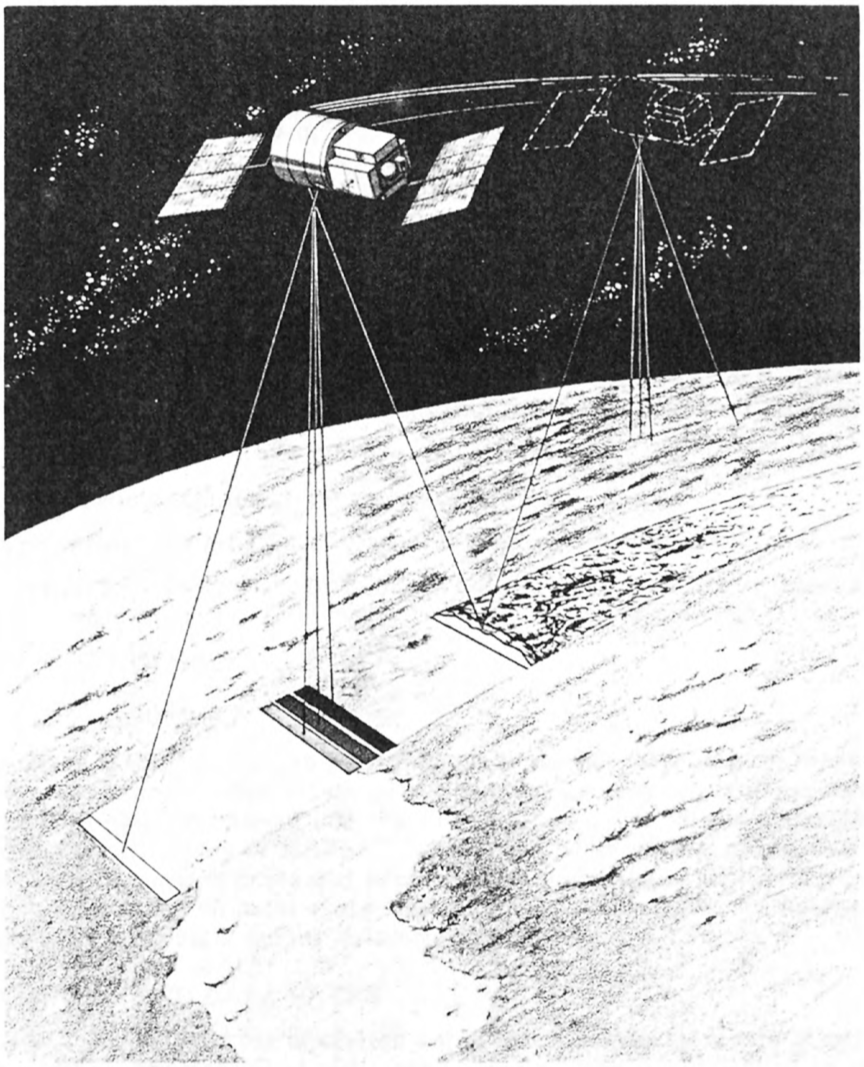
Enclosures: As stated

USGS Open File Report #81-26



MAPSAT

1. INTRODUCTION

After more than 10 years of study and applications of Earth imaging satellite systems, the U. S. Geological Survey has conceptually defined a candidate Operational Land Remote Sensing Satellite. A conceptual design study of this system, known as MAPSAT, has been completed by Itek Optical Systems, a division of Itek Corporation, and the TRW Defense Systems and Space Group. The concept of MAPSAT is based on LANDSAT mission, sensing, and data communication characteristics, but reflects the evolution of technological and application responsiveness. The concept includes the following:

- Global coverage on a continuous basis.
- Open data dissemination in reasonable time and at reasonable cost.
- Variable resolution and swath-width coverage.
- Stereoscopic and multispectral capabilities.
- Compatibility with 1:50,000 scale topographic mapping with a 20-m contour interval.
- Continuity with respect to LANDSAT-1, 2, and 3, including the same basic data transmission system.
- Cost effectiveness.

1.1 MAPPING GEOMETRY

The name MAPSAT implies a mapping system, but this does not mean its primary function is to serve the mapmaker. Disciplines such as geology, hydrology, agriculture, geography, and engineering, to name a few, require multispectral data in accurate mapable form. The high geometric fidelity of MAPSAT is achieved by defining a spacecraft and sensor system having virtually no moving parts and very precise position and attitude determination. The sensor system is based on solid-state linear arrays. Moreover, the antennas and solar panels are defined to remain rigid during data acquisition.

1.2 RESOLUTION AND DATA RATES

MAPSAT is designed for operation using various spectral bands at various resolutions and swath widths. Spectral band and stereo combinations would depend on the type of area to be covered. However, a limitation on the data transmission rate is essential.

1.3 SPECTRAL BANDS

In order to optimize data acquisition against demonstrated practical use, the two near-infrared (NIR) bands of LANDSAT have been consolidated for MAPSAT. The three bands selected are a blue-green (0.47 to 0.57 μm), a green-red (0.57 to 0.70 μm), and a near-infrared (0.76 to 1.05 μm).

1.4 STEREOSCOPIC CAPABILITY

The delineation of the Earth's surface in three dimensions is essential for many uses. MAPSAT will do this with two separate base-height ratios, depending on the type of topography involved. The value of stereoscopic sensing does not end with the production of topographic maps. The stereo mode provides for the automated production of digital terrain data and for depicting and analyzing the Earth's terrain. With it, the computer depiction of topography based on any simulated conditions of illumination is feasible, which is of high importance for geologic interpretation and related applications. Moreover, derivative products such as slope maps and critical-elevation displays can be generated by the computer. Digital elevation data also provides an essential tool for neutralizing the undesirable effects of terrain aspect (slope and its direction) in facilitating land use classification.

1.5 ONE-DIMENSIONAL DATA PROCESSING

MAPSAT is designed to acquire a one-dimensional flow of data from each detector in the linear array. The data from each of the several thousand detectors can be processed by relatively simple computer programs in a one-dimensional mode. Two arrays of detectors are involved during stereo imaging, but by controlling spacecraft rotational rates, corresponding detectors from the two arrays follow the same ground path. This is known as the epi-polar plane condition by which the data from the two arrays are correlated and result in providing elevation data as well as planimetric position. Some ground control is needed, but with the stability and positional accuracy expected of MAPSAT such control need be but a very small fraction of that required for conventional photogrammetry. The correlated data can be processed by automated means and thus provide the basis for an automated mapping system. The proper implementation of this concept would greatly reduce data processing time and costs.

2. SYSTEM OVERVIEW

MAPSAT is a satellite-based remote sensing system that fulfills the requirements for operational data acquisition that have emerged during the experimental LANDSAT era. These requirements have been derived from users of the current LANDSAT materials and in answer to the needs of potential new users whose applications require the higher resolution and stereoscopic viewing that are not available with LANDSAT. Ten meter instantaneous field of view (IFOV) in either stereoscopic or monoscopic mode is available on demand with MAPSAT in any of the three spectral regions of interest.

A high degree of automation in the extraction of topographic information is achieved by control of the spacecraft to satisfy the epi-polar condition in which a ground point images at the same relative field location in both of the stereo sensors, and by exploitation of the resulting uni-dimensional aspect of the data in the identification of conjugate imagery and calculation of point elevations.

These advances are possible because of the burgeoning technologies of solid-state sensing and the very large scale integration (VLSI) of digital electronic circuitry. The advent of the charge coupled device (CCD) has given the system designer a technique for object space imaging that enjoys great stability in both the geometric and radiometric senses, and that makes it possible to achieve high accuracy in geometric line-of-sight recovery. To fully utilize this capability in photogrammetric data reductions requires highly precise ephemeris and attitude information that is provided by auxiliary devices. The digital form of this data makes it appropriate for incorporation into sophisticated computerized least squares estimation techniques, that with ground control produce cartographically accurate output products. Relative topographic products at a scale of 1:50, 000 with 20-m contours and meeting national map accuracy standards should be achievable with the system. To adjust these to the user's local datum, he need only provide a sparse control network.

Solid-state line arrays are uniquely suited to satellite imaging of the Earth. This is achieved by optically projecting the array to the ground, as shown in Fig. 2-1, so that the vehicle velocity causes it to scan the Earth's surface, and by repeated sampling to obtain a two-dimensional record of the terrain radiance. The advantages of this technique over mechanical scanning of one or a few elements through the image format are striking:

1. Because there are no mechanical devices needed for the imaging process there is opportunity for eliminating all mechanical disturbances, the ideal situation for high resolution imaging.

2. The precision geometry of the photoarrays, inherent in the photolithographic process by which they are made, as well as the stability of the silicon structure, provide the basis for registration from one spectral band to another and for the accurate location or mapping of terrain features.

3. Instrument sensitivity is dramatically improved because of the longer dwell time on the area of the focal plane from which the signal is continuously gathered. For the same telescope parameters, the signal is increased directly as the ratio of the number of detectors used. This greater signal gathering power can be used to increase radiometric accuracy, to improve geometric resolution, or to provide narrower spectral bands, thus increasing the precision of the information gathered.

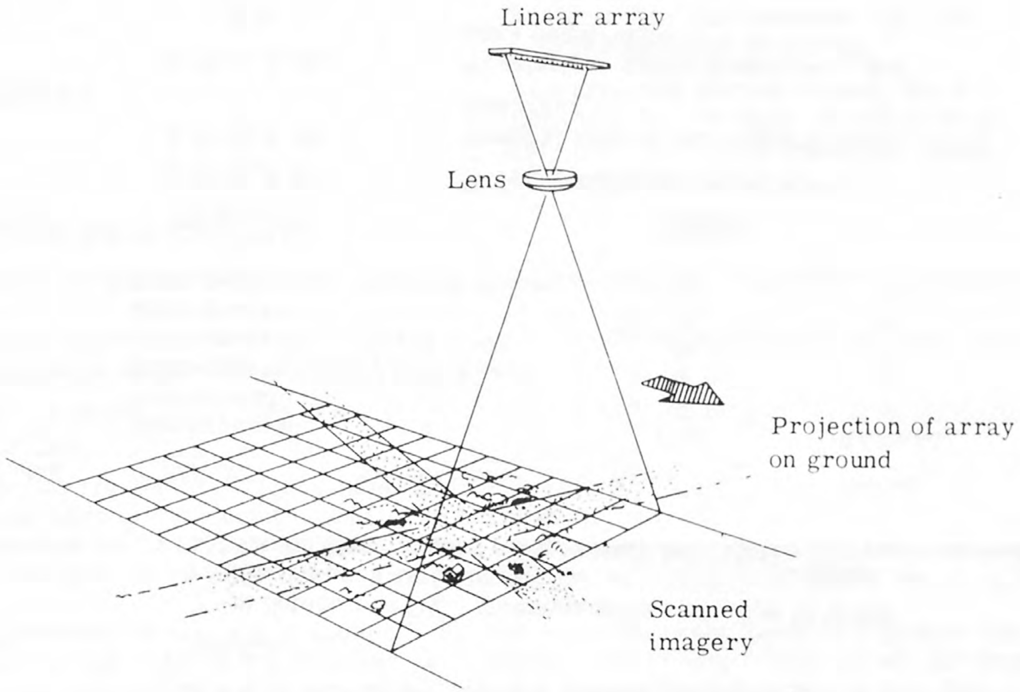


Fig. 2-1 – Pushbroom scan for one-dimensional array

2.1 BASIC SYSTEM PARAMETERS

The parameters of the MAPSAT system design are summarized as follows:

Parameter	Value(s)
Orbit	919 Km, 9:30 A.M. Nodal crossing, descending
Swath width	180 Km
Resolution	10-m detector IFOV. Commandable reduction to lower resolution such as 50 to 100 m. 1.55 x 10^{-3} sec ground sample time (nominal)

Acquisition Modes	Pan/MS	Stereo/Mono	Resolution	Swath
a	Panchromatic	S	Full	Reduced
b	Panchromatic	S	R	F
c	Multispectral	S	F	R
d	Multispectral	S	R	F
e	Multispectral	M	F	F
f	Multispectral	M	F	R

Spectral Bands	Range, μm	Utility
(1)	0.47 to 0.57	Water quality and penetration.
(2)	0.57 to 0.70	General natural and cultural land features.
(3)	0.76 to 1.05	Vegetation, water boundaries, and haze penetration.

Mode	Base/Height Ratios	Utility
(1)	1.0	Fore-aft tilted sensors (±23° tilt) low relief situations.
(2)	0.5	Vertical-fore (aft) sensors [0°, +23° (-23°)] high relief situations.
Optical System		Apochromatic Petzval lenses, focal lengths 1.315-m tilted, 1.119-m vertical, f/no. 5.0, field angle 9.9° tilted, 10.9° vertical.

2.2 RETENTION FROM LANDSAT

The MAPSAT system retains the following characteristics of its LANDSAT predecessors:

1. Similar swathing pattern and framing sizes; i.e., the frame is 180 x 160 Km, thus facilitating access to the existing LANDSAT data base.

2. Spectral bands – coverage of the visible from 0.5 to 1.1 μm with slight modification of band definitions.

3. Data link transmission frequencies and bandwidths are retained. However, more efficient use is made of the channel capacity by a change of modulation technique. The S band center frequencies are at 2229.5 and 2225.5 MHz. The minimum shift keying (MSK) technique permits transmission of 24 Mbits/sec in each channel, giving a total of 48 Mbits/sec.

The constraints on data transmission (i.e., the retention of the LANDSAT ground link) permits transmission of 48 Mbits/sec. We have defined a set of acquisition modes and designed into the sensors swath width and resolution control that permit the fullest use of this data link capacity.

As a result of the MAPSAT feasibility study, we can affirm the availability of wide spectral band optical systems and of silicon solid-state arrays that, in combination with the appropriate spacecraft components, can be configured into an operational pushbroom line array image to replace the capabilities of LANDSAT 1, 2, and 3.

The remainder of this overview demonstrates the performance that can be made available, the schedule to which it can be developed, and the cost of acquisition, launch, and 7-year operation of the system.

2.3 MAPSAT STUDY GOALS

Table 2-1 presents the issues that form the body of the MAPSAT conceptual design study. The content of these tasks and the significant results of the study are summarized.

2.4 EPI-POLAR ACQUISITION

The requirement that the system provide stereo coverage on a demand basis is accommodated by multiple imaging systems, one looking vertically that provides the basic multispectral capability and two looking forward and aft of vertical by 23°. The fore-aft pairs provide a base height ratio of 1.0 that gives strong heighting capability. For moderate to rough terrain, where obstruction effects would occur, a base height ratio of 0.5 is available through use of the vertical with either the fore or aft sensors.

The reduction of stereo data is essentially the determination of conjugate image points within the fore and aft data sets that is traditionally done via the human stereoscopic facility. In existing instruments that replace the human observer by an automated correlation process, the search for image conjugates takes place in both the in-track and cross-track dimensions.

Table 2-1 – Project Goals

Feasibility issues
- Epi-polar acquisitions
    - Control low
    - Spacecraft implementation
- Uni-dimensional correlation
    - Algorithm
    - Hardware implementation
- Performance
    - Radiometric
    - Geometric

Sensor issues
- Transmission limitations
- Optical system
- Focal planes
- On-board processing
- On-board storage

Spacecraft issues
- Orbit selection
- Communications
- Control
- Power, weight, and volume
- Structure
- Launch vehicle

Ground processing
- Topographic products
- Planimetric products
- Multispectral products
- Management system

System acquisition plan
- Schedule
- Costs

Pushbroom imaging offers the potential for reducing this search to a single dimension, thereby improving the computational efficiency of the process. The single dimension is the time of imagery if, for any given pixel in the data stream from one of the arrays, we know which of the elements of the second array also imaged at that point. Control of the spacecraft to ensure that a ground point imaged at some array location in the fore array is also imaged at the same location in the aft array, is a means of satisfying this so-called "epi-polar condition." Fig. 2-2 illustrates the three-dimensional geometry and the dynamics involved. Although the epi-polar condition is shown for clarity to be satisfied for a single point, it must actually be satisfied for all points along the array and for every position of the satellite during image acquisition.

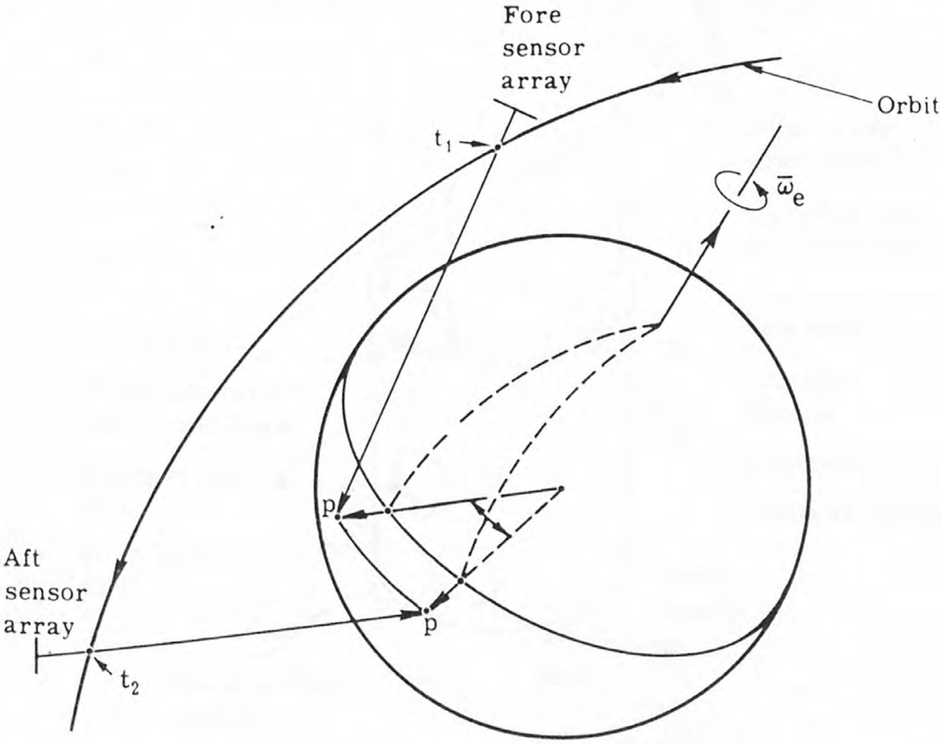


Fig. 2-2 – Epi-polar acquisition geometry

Dynamically, the condition requires control of spacecraft absolute pitch, yaw, and roll to within 10 arc-sec to maintain fractional IFOV errors in epi-polarity. Spacecraft flexibility and uncontrollable dynamics of solar arrays and antenna pointing would preclude achieving this level of control. Thus, spacecraft and solar array rigidity are design requirements, and antenna pointing during acquisition is not permitted. This latter precludes the direct use of the tracking and data relay satellite system (TDRSS) for sensor data transmission.

For moderate to rough terrain, a base height ratio of 0.5 is available through the use of the fore or aft sensors with the vertical.

The ability of current spacecraft control technology to meet the stringent levels required to achieve epi-polarity has been assessed using the Multi-Mission Modular Spacecraft configured as the MAPSAT baseline. An artist's concept of the MAPSAT spacecraft is given in Fig. 2-3, shown with a single solar array. However, there are dynamic advantages to using dual solar panels, as shown in the frontispiece.

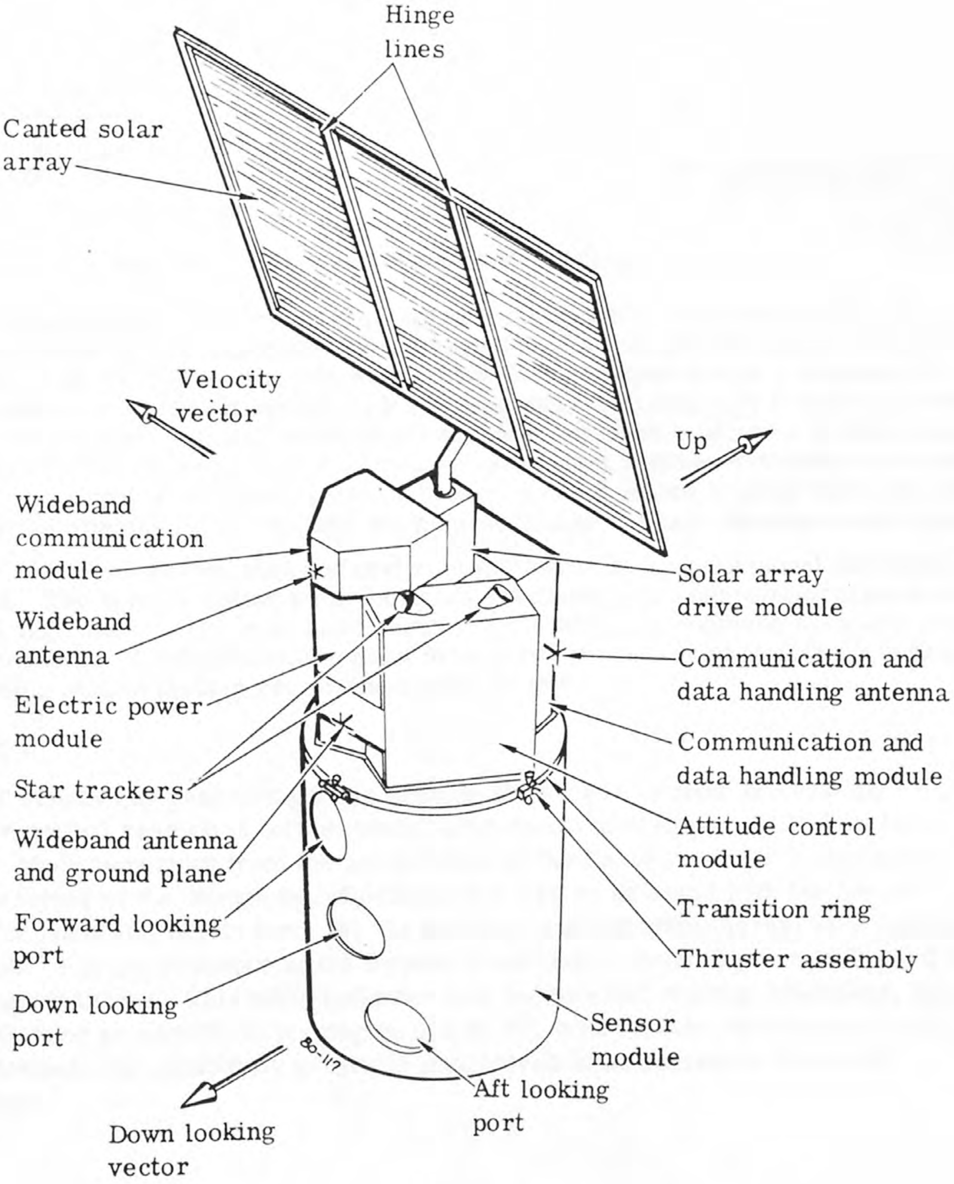


Fig. 2-3 – Artist's concept of the MAPSAT spacecraft

It has been determined that the short term (2 minute) attitude stability will be 0.5 arc-sec/axis, while the long term (20 minutes) pointing accuracy will be 4 arc-sec/axis. This is sufficient to ensure epi-polarity to within 2 m on the ground.

Uni-dimensional correlation is the process of determining the relative time phasing of conjugate image points in the data streams from paired sensors. It consists of two phases: acquisition and centroiding. The acquisition phase refers to the search that is required to initiate the process, while centroiding is the name given to the determination to subpixel accuracy of the time phase. Fig. 2-4 illustrates the effect of terrain height on the output data streams that forms the basis of height determination. The time phase values, once determined, are used in a triangulation procedure to calculate terrain heights.

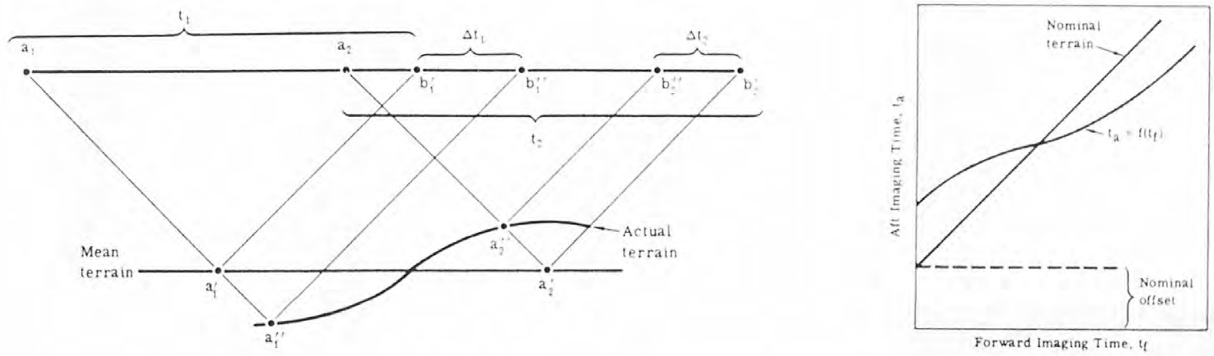


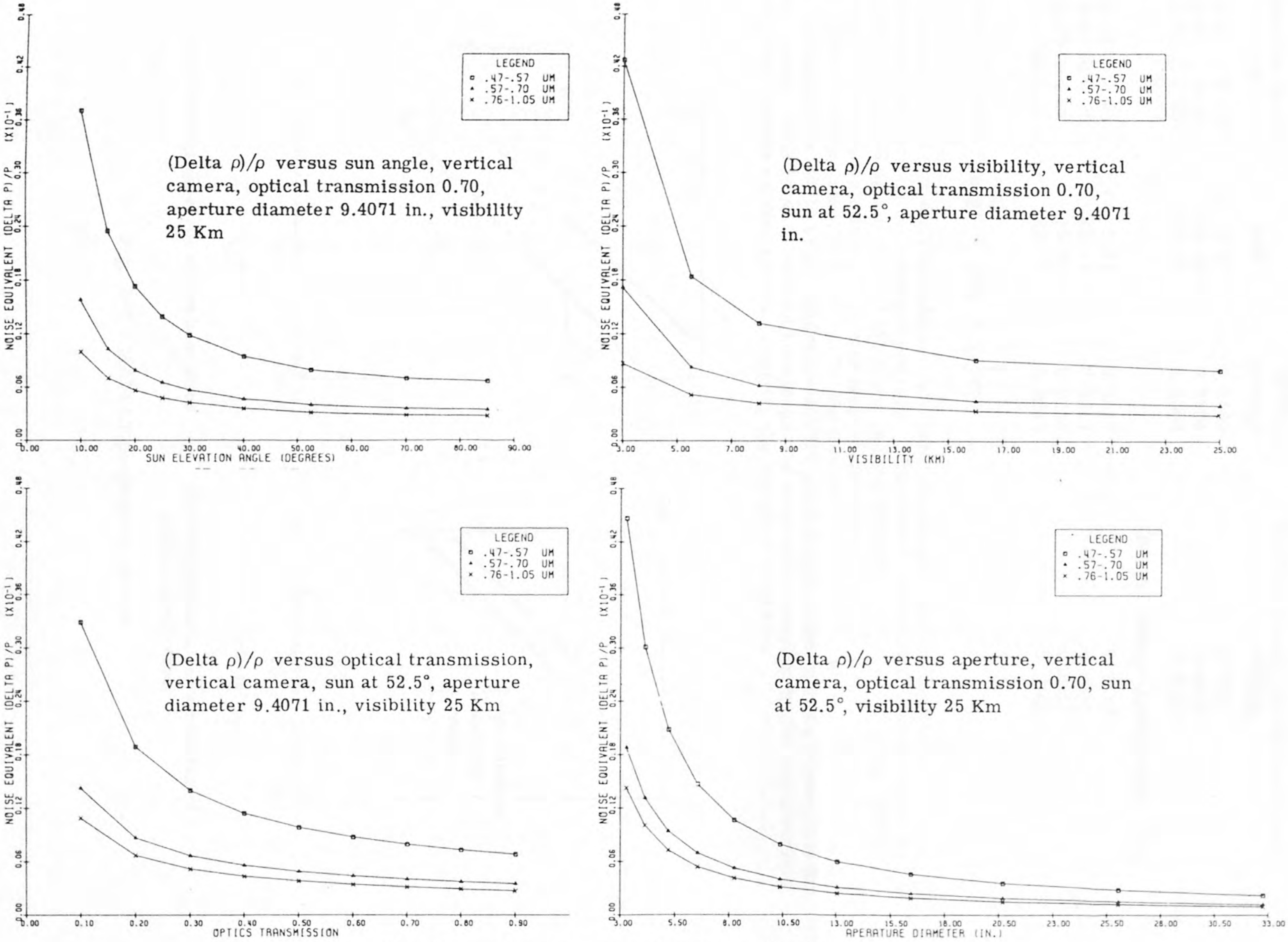
Fig. 2-4 – Epi-polar correlation problem

Since we are assured by the epi-polar acquisition condition that, with certain few exceptions, the conjugate points lie in a restricted time interval in the data from the paired detector, the search process can be limited to that interval. Brute force comparison of a segment of data from the fore sensor with the aft sensor data stream, and computation of a matching index quickly lead to one or, at most, a small number of candidate best match points. At this point, the fine match or centroiding process that is formulated as a least squares estimation process is attempted. The rms error after convergence indicates the true match point if there are several candidates. If the process fails, the data segment is flagged for later manual compilation.

This process has been implemented and tested in software, and a hard wired dedicated processor designed. The software simulation indicates fractional pixel correlation (centroiding) on LANDSAT image data. This level is required if 1:50,000 scale mapping accuracy is to be achieved with MAPSAT. Timing calculations of hard wired processor performance indicates that ground processing station thruput requirements can be met.

2.5 PERFORMANCE

The MAPSAT sensor has been designed to provide IFOV of 10 m from the 919-Km LANDSAT orbit. In optical resolution terms, this ground resolved distance (GRD) will be in the order of 20 m. More important from the perspective of the Earth resource investigator is the performance in terms of the change in reflectivity that can be detected with the sensor. Fig. 2-5 provides this data in graphic form for the vertical (multispectral array) as a function of solar zenith angle. The performance at the Nyquist frequency (cutoff) is given in Table 2-2 for nominal viewing conditions. This table indicates that for nominal viewing conditions, the system will have limiting sensitivity in the region of 1 to 3%, with terrain reflectance of 0.2. This combination exceeds the sensitivity generally considered to be desirable for Earth resource applications.



(Delta ρ)/ρ versus sun angle, vertical camera, optical transmission 0.70, aperture diameter 9.4071 in., visibility 25 Km

(Delta ρ)/ρ versus visibility, vertical camera, optical transmission 0.70, sun at 52.5°, aperture diameter 9.4071 in.

(Delta ρ)/ρ versus optical transmission, vertical camera, sun at 52.5°, aperture diameter 9.4071 in., visibility 25 Km

(Delta ρ)/ρ versus aperture, vertical camera, optical transmission 0.70, sun at 52.5°, visibility 25 Km

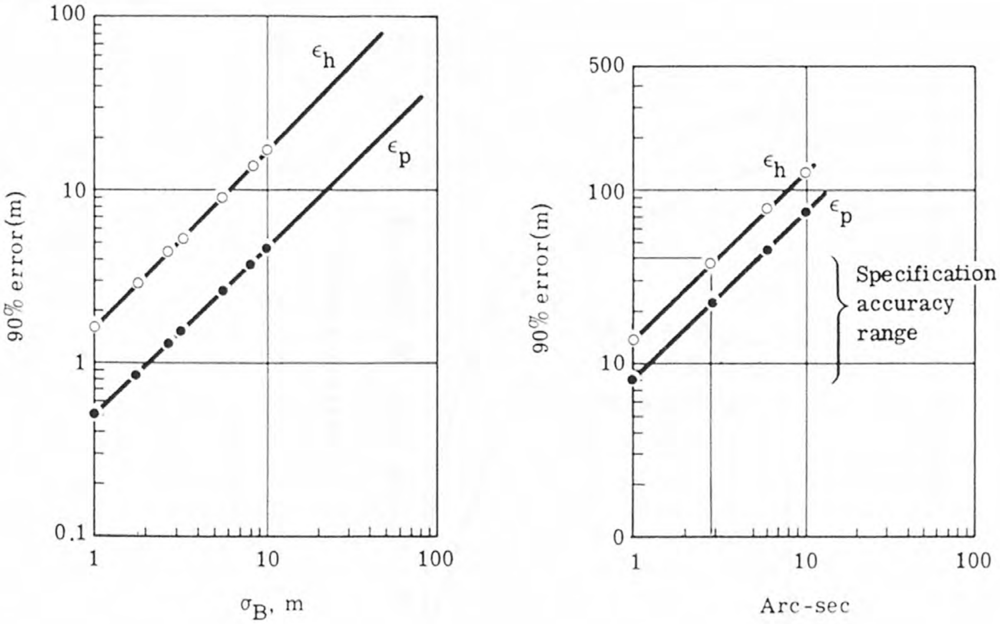
Fig. 2-5 – Illumination performance of MAPSAT sensor

Table 2-2 – NE$\Delta\rho/\rho$ at Nyquist

Spectral Band, µm	SNR	MTF, average	Vertical Sensor-Apochromat Lens NE$\Delta\rho/\rho$
0. 47 to 0. 57	6. 30	0. 2449	0. 0341
0. 57 to 0. 70	12. 42	0. 3104	0. 0136
0. 76 to 1. 05	15. 81	0. 2052	0. 0162
			Oblique Sensor-Apochromat Lens
0. 47 to 0. 57	6. 11	0. 2547	0. 0332
0. 57 to 0. 70	12. 16	0. 3227	0. 0131
0. 76 to 1. 05	15. 64	0. 2134	0. 0155
0. 47 to 1. 05	22. 75	0. 2247	0. 0101

Note: $\text{NE}\Delta\rho/\rho = \frac{0.01}{0.20} \times \frac{1}{\text{SNR}} \times \frac{1}{\text{MTF}}$

Geometric performance calculations are based on the propagation of position and line-of-sight recovery errors into terrain point errors. Planimetric (horizontal) and elevation (height) are given in Fig. 2-6 as functions of the error in base separation and line-of-sight recovery accuracy. These indicate that in order to meet the relative accuracy specifications for MAPSAT of 7 to 25 m (rms) in X, Y and Z, the line-of-sight recovery accuracy must be better than 3 arc-sec for a single height determination (relative height difference is $\sqrt{2}$ times that for a single point). This level of attitude knowledge will be greatly exceeded by the requirements placed on the attitude control system to satisfy the epi-polar condition.



(a) Triangulation error versus base error

(b) Triangulation error versus line of sight recovery error

Fig. 2-6 – MAPSAT propagated errors

2.6 SENSOR ISSUES

Despite the availability of detector arrays and optical technology that permit the development of a solid-state Earth resource sensor, the need for proper balance among considerations of optics, detector arrays, and spacecraft parameters requires careful trades among design options. Considerations include physical compatibility of the sensor with spacecraft; imaging, geometric and radiometric performance; availability of detector materials or devices; and fabrication of optical elements and large focal plane structures. In order to appreciate the importance of the design trades, we must recall the scope of the data acquisition assigned to the sensor; i. e., it must scan in the visible (VIS) and near-infrared bands across a swath 180,000-m wide, providing up to 10-m resolution (IFOV). This demands up to 18,000 detectors for every color band where this requirement holds. When scaled to the altitude of MAPSAT, the focal length is approximately 1 m (using the resolution of demonstrated silicon technology), and the field of view is 11°. The following discussion will touch on several of the critical design issues within the context of this system requirement.

2.7 OPTICAL DESIGN

The first order goals for the optical design derived from the IFOV, swath width, attitude detector pitch, and sensitivity are given in Section 2.1.

The practical issues of optical system complexity, fabrication difficulty, alignment sensitivity, and ultimately cost, were determined for candidate optical designs so that an informed selection could be made. Two basic design forms have been extensively investigated for application to MAPSAT: a catadioptic system (classical Schmidt) and an all-refractive Apochromatic Petzval. Although the Schmidt system has better performance at the extremes of the spectral region, the increased weight and fabrication complexity have driven us to recommend the Apochromat for MAPSAT. Fig. 2-7 presents encircled energy curves for each spectral region for this design.

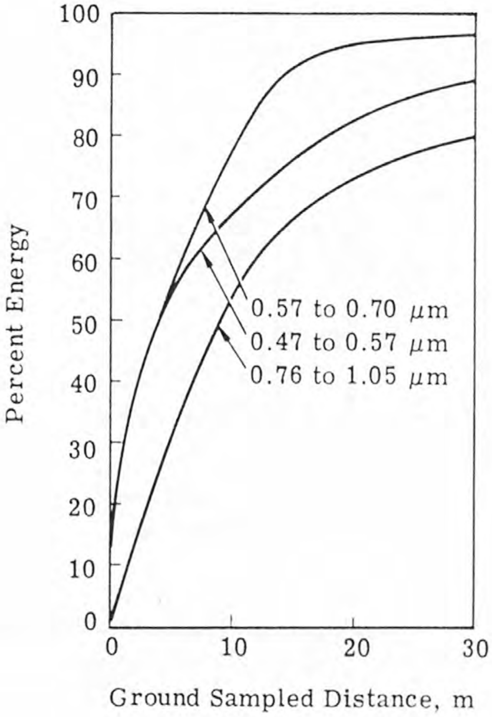


Fig. 2-7 – Encircled energy

Fig. 2-8 presents this optical system with its dimensions, while Fig. 2-9 gives an artist's concept of the three sensors packaged as the MAPSAT payload.

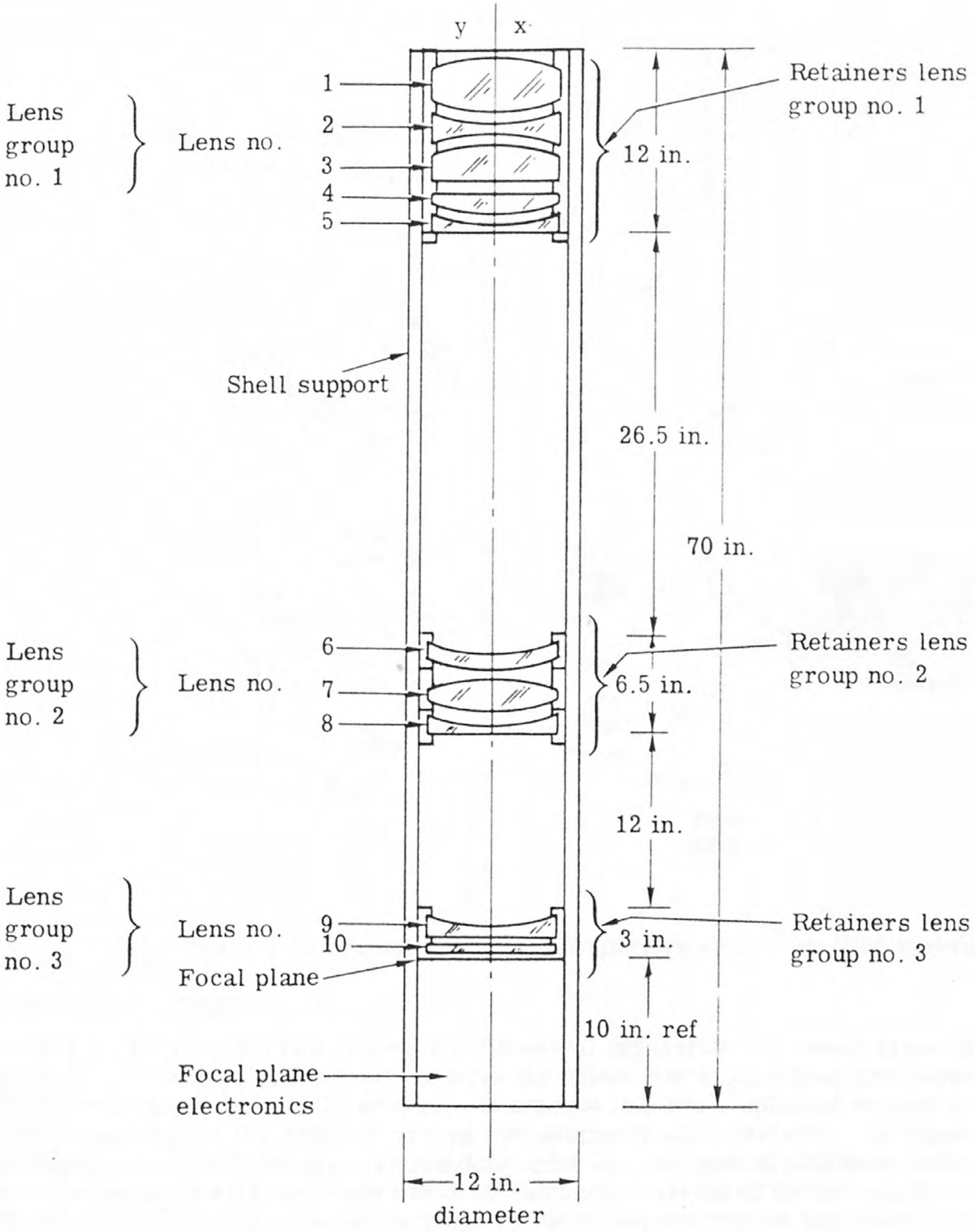


Fig. 2-8 – MAPSAT Apochromat

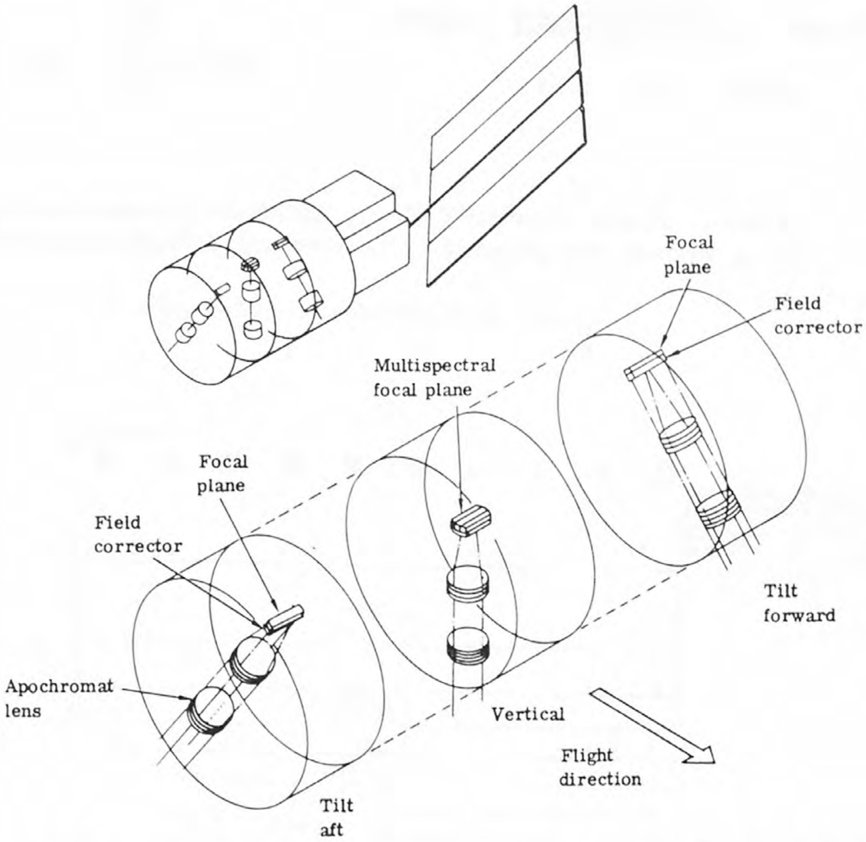
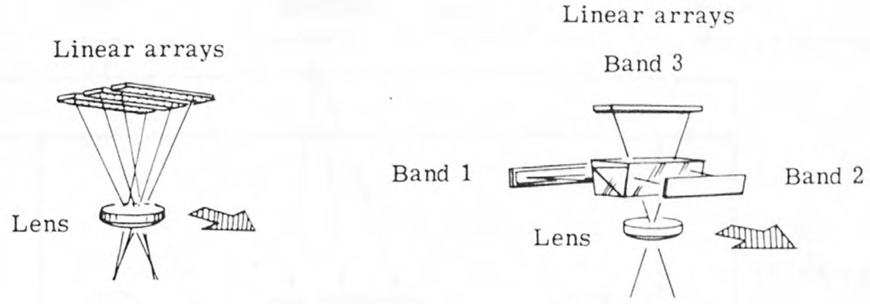


Fig. 2-9 – Apochromat system – perspective view of stacked systems

2.8 FOCAL PLANES

Fig. 2-10 presents two concepts for spectral separation for linear array imagers. In concept (a), the arrays sequentially sample the object space since they are physically separated in the focal plane of the optical system. In concept (b), beam splitting is used to separate the spectral regions, but the detector arrays are geometrically overlayed. In either case, the requirements on interband registration determine the mechanical characteristics of the system. The beam splitter approach has disadvantages in terms of optical quality and total light level since introduction of the beam splitters increases aberration and absorption. The sequential sampling concept requires close spacing of the arrays that is most advantageously achieved if fabricated on the same substrate. This is, in fact, the suggested configuration. Fig. 2-11 is a plan view and Fig. 2-12 is a cross section of the proposed focal plane architecture.

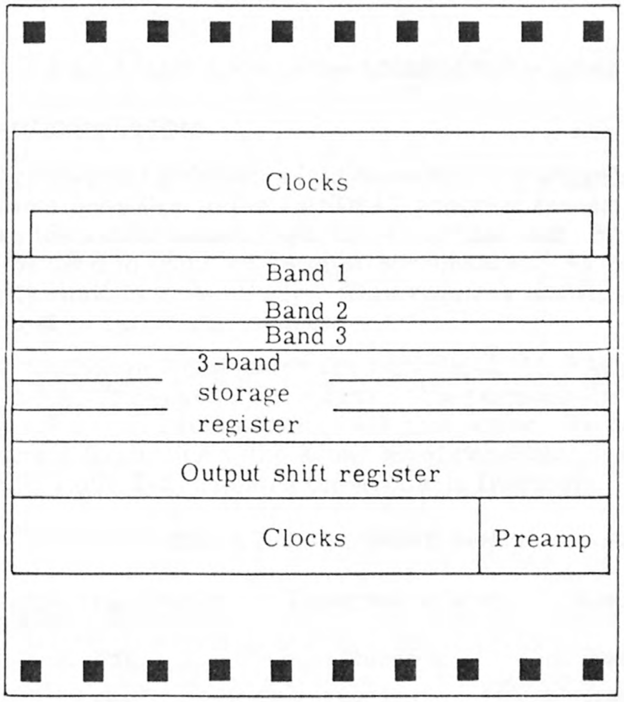
The spatial displacement of sensor bands in this design has been specified at a level that introduces no more than 0.1-pixel misregistration.



(a) Pushbroom scan for sequential sampling multispectral arrays

(b) Pushbroom scan for simultaneous sampling multispectral arrays

Fig. 2-10 – Pushbroom scan concepts



Multiband/buttable
Bands on 0.05-mm centers
2 pixel gap chip to chip

Fig. 2-11 – Focal plane architecture – plan view

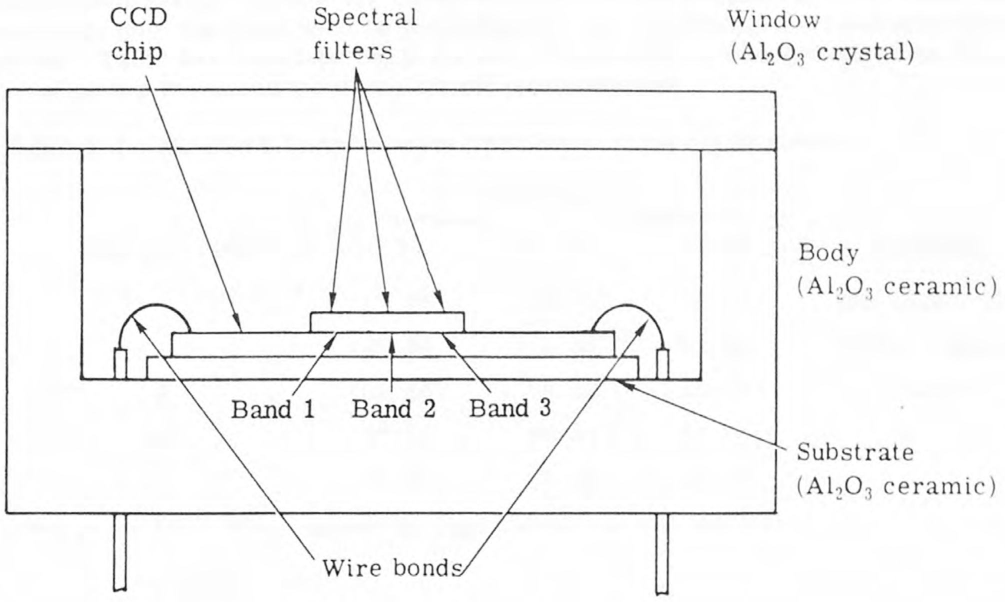


Fig. 2-12 – Focal plane architecture – cross section

2.9 TRANSMISSION LIMITATIONS

The MAPSAT conceptual guidelines laid down by USGS suggest the utilization of the existing ground communications links that in the LANDSAT program transmit 15-Mbit/sec digital data. Our design study has identified unused capacity of this link that, by a variation of the link modulation technique, can be used to transmit 24 Mbit/sec/channel. As two channels are available, the transmission capacity limit is 48 Mbit/sec. This requires modification of the ground receiving equipment, but the cost is extremely modest.

At the highest resolution the sensors are capable of, 11.6 M pixel/sec are generated from each array so that at 6-bit/pixel quantization even this extended link cannot handle the data from a single channel. Therefore, to remain within this restriction, the MAPSAT sensor system has been provided with great flexibility in the selection of resolution levels and portions of the swath that are transmitted. Table 2-3 indicates the available freedoms.

Table 2-3 – MAPSAT Acquisition Modes

Defined Mode	Spectral Region	Topographic Mode	Resolution	Field of View
a	Pan	Stereo	Full	Reduced
b	Pan	Stereo	Reduced	Full
c	MS	Stereo	Full	Reduced
d	MS	Stereo	Reduced	Full
e	MS	Mono	Full	Full
f	MS	Mono	Full	Reduced

In addition, Earth resources data are correlated in the information-theoretic sense across spectral bands so that only one band need be recorded at high resolution, the remaining bands at reduced resolution. Table 2-4 indicates the pixel and bit rates at various quantization levels for this condition, and shows the cases the data link will accommodate.

Table 2-4 – MAPSAT Instantaneous Data Rates at Mixed Resolutions

Quantity	Bits per Pixel	IFOV, m			Condition
		10/20	10/40	20/40	
Pixel rate		17.44	13.08	4.36	Multispectral
Bit rate	8	139.54	104.65	34.88	Three channels
Bit rate	6	104.65	78.49	26.16	Full swath
Bit rate	5	87.21	65.41	21.80	
Bit rate	3	52.33	39.24	13.08	

Note: All rates are x 10^6. (One channel at high and two at low resolution.)

In order to make the system more flexible, on-board tape recording is employed. The recommended tape recorder can handle all of the data of the nominal mission (200 frames/day) at high data rates approaching those of the most demanding modes and play it back at a rate matching the link capacity.

This solution is clearly of limited value since in the long run the tape recorder must fail and the flexibility will be lost.

In order to extend the life of the recorders, a cloud sensing precursor imager and data processor are included in the design to prohibit the recording of excessive cloud covered areas. This device will also be used for dynamic range determination for the main sensors. Looking 32-deg ahead of the forward sensor, it will process visible scene information at low resolution (1.0 Km) and produce a go/no-go signal based on decisions made by a hard wired processor whose decision threshold can be commanded from the ground.

The technology for the precursor rests on available solid-state linear arrays and off-the-shelf optics for the visible region. Because a short wave infrared detector is not included, the process will not be able to distinguish between clouds and snow. The cloud-snow decision can, however, be based on a priori information given by existing weather satellites.

2.10 ON-BOARD PROCESSING

The MAPSAT conceptual design guideline argues for the restriction of quantization to 6 or 7 bits. Eight bits or more must be considered since cases can be contrived wherein the scene content covers this range. Fig. 2-13 summarizes the range of values that potentially exist in some scenes of interest to Earth resources data users. This chart indicates that a scene dynamic range of 10 bits may be available. Rather than eliminating these scenes from consideration for full quantization by a priori limiting the quantization to 6 bits, we have investigated the use of data compression to reduce the 10 bits to a smaller number. Data compression must be information-preserving if radiometry is not to be lost. We have found that a combination of differential pulse code modulation (DPCM), followed by optimal selection of digital code word (Huffman coding), can provide nondestructive encoding of Earth resource scenes to about 5 bits/pixel.

Fig. 2-14 indicates the data flow in this concept, beginning with the radiometric calibrator. This precedes the DPCM module since radiometric variations from pixel-to-pixel and from chip-to-chip would, if not eliminated, destroy the correlation of scene pixel differences that is the basis for DPCM compression.

We have estimated the physical characteristics of this form of data compression and have found that the compressor portion of the hardware (Fig. 2-14) will occupy 2 ft^3, weigh 80 lb, and consume 700 W.

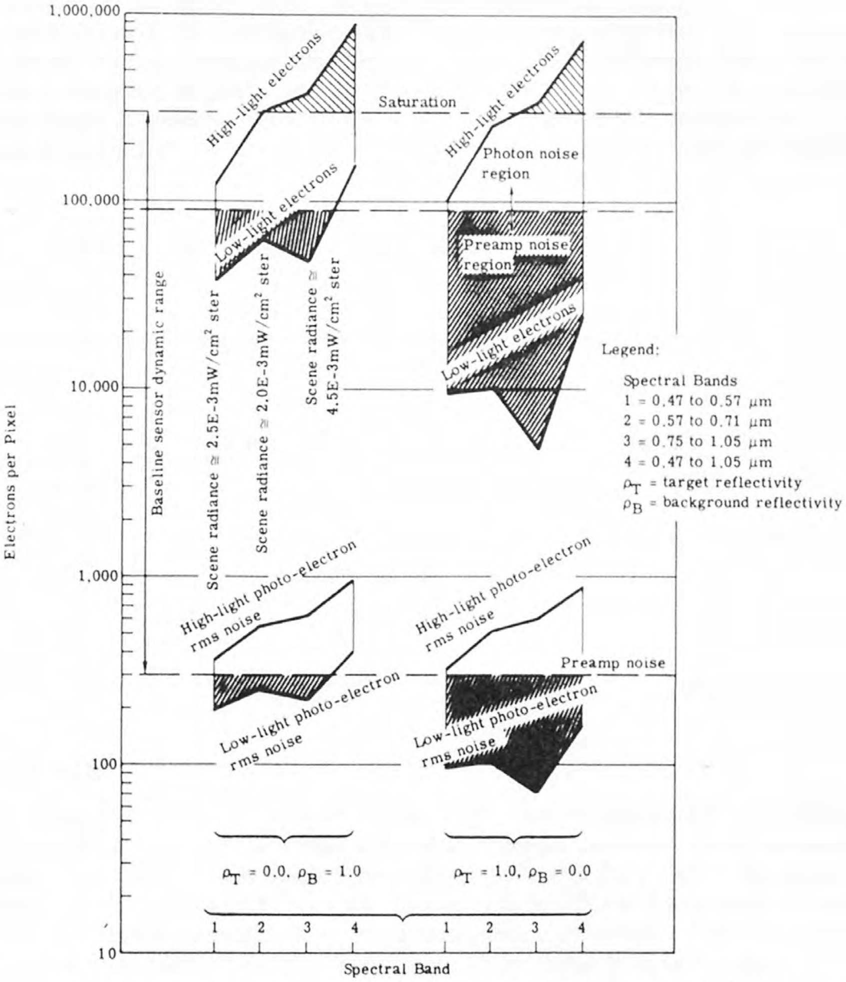


Fig. 2-13 – Baseline performance for 25-Km atmosphere

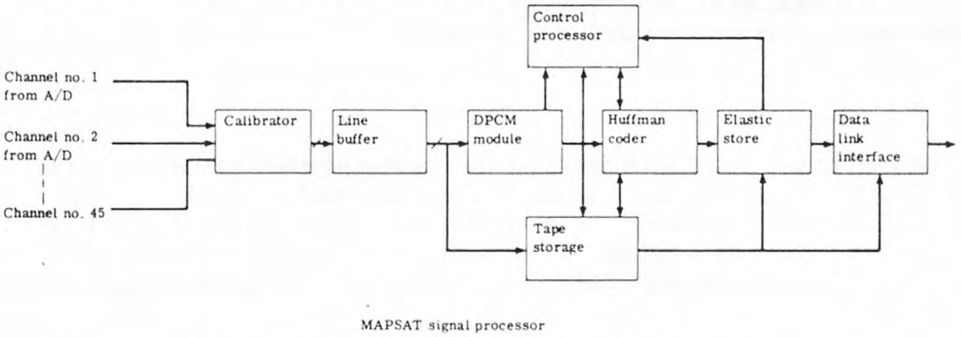


Fig. 2-14 – Compression processor data flow

This roughly doubles the power required to be generated by the solar array and increases its area by the same factor. For this reason, and because level slicing based on the precursor sensor can be used to limit the transmission to the required 6 to 8 bits/pixel, thereby eliminating the complexity of the compression processor, we are not recommending its inclusion in the baseline MAPSAT system.

The remainder of the on-board processing required for MAPSAT is shown functionally in Fig. 2-15. Also shown is the hierarchy of control functions that must be performed by the on-board controller. It controls all of the main instrument data acquisition and transmission, as well as that of the cloud detection precursor. It monitors the health and states of all sensor related subsystems, particularly the thermal control system, and indicates all instrument calibration sequence, whether radiometric or geometric. The preferred radiometry calibration source is the sun, with a suitable diffuser in the sensor entrance aperture. For geometric calibration, a ground test range provides initial correction to the preflight calibration. A technique that scans a given star across a given detector element will give the ultimate geometric calibration.

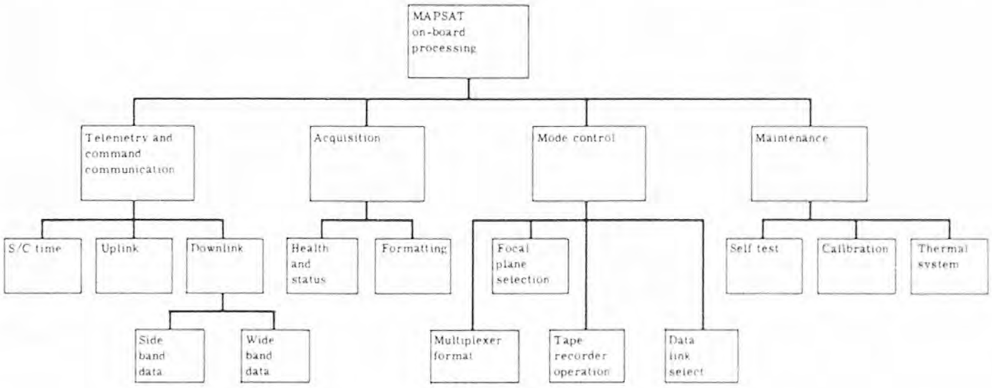


Fig. 2-15 – MAPSAT on-board processor functional requirements tree

2. 11 ON-BOARD STORAGE

The need for on-board storage is dictated by the high instantaneous bit rates that exceed the capacity of the data link and by the fact that access to ground stations is not available at all times. An intermediate data buffer is needed that will smooth the data flow into longer, slower, and more timely transmissions. Table 2-5 gives storage capacity as a function of resolution and quantization for the minimum conditions of the conceptual guideline. These capacities are far in excess of the realistic capabilities of any medium other than magnetic tape.

Tape recorder capacity for space missions has been constantly growing until today, when there are instruments under development that can store the equivalent of 45 MAPSAT scenes at 8 bits/pixel and high resolution (10 m) in three channels, and that have the desired acceptance rates.

2. 12 SPACECRAFT ISSUES

Because the major spacecraft-related issue is to establish feasibility and to generate credible cost estimates, the Multi-Mission Spacecraft (MMS) has been selected as the MAPSAT design approach. Should the MAPSAT concept advance to the preliminary design phase, it will be totally appropriate to reopen the issue of vehicle design to ensure the optimum has been selected. Table 2-6 presents the equipment list that makes up the MAPSAT spacecraft.

2. 13 ORBIT SELECTION

Orbit selection means primarily the choice of spacecraft altitude, inclination, and time of nodal crossing to satisfy some objective criteria. In MAPSAT, one major criterion is compatibility with the previously obtained LANDSAT data base that is most readily obtained through use of the same orbital characteristics. Since no compelling rationale exists for choosing any other orbit, the baseline system orbit has been retained from LANDSAT. This has a 919-Km altitude, 99. 092° inclination, and crosses the node at 9:30 AM local time in its descending leg and features a contiguous swathing pattern. It is also possible from this orbit, but not from the lower LANDSAT D orbit, to achieve full data transmission over the co-terminous U. S. to a ground station we suggest be set up at Sioux Falls should one or more of the LANDSAT (STDN) ground stations be closed down.

Table 2-5 — MAPSAT Storage Requirement
(180-Km Swath Width at Different Scan Lengths and Resolution Versus Quantization)

Quantity	Bits per Pixel	Capacity x 10^9 at IFOV				Condition
		20 m	60 m	60 m	Total	
Pixels	N/A	0.45	0.05	0.05	0.55	180 Km x 1,000 Km
Bits	8	3.60	0.40	0.40	4.40	(1) 20-m bands
Bits	6	2.70	0.30	0.30	0.30	(2) 60-m bands
Bits	5	2.25	0.25	0.25	2.75	
Bits	3	1.35	0.15	0.15	1.65	
		10 m	10 m	10 m		
Pixels	N/A	1.80	1.80	1.80	5.4	180 Km x 1000 Km
Bits	8	14.4	14.4	14.4	43.2	(3) 10-m bands
Bits	6	10.8	10.8	10.8	32.4	
Bits	5	9.0	9.0	9.0	27.0	
Bits	3	5.4	5.4	5.4	16.2	
Pixels	N/A	0.33	0.33	0.33	1.0	180 Km x 185 Km
Bits	8	2.66	2.66	2.66	8.0	(3) 10-m bands
Bits	6	2.00	2.00	2.00	6.0	
Bits	5	1.67	1.67	1.67	5.0	
Bits	3	1.0	1.0	1.0	3.0	

Table 2-6 – MAPSAT Equipment List

- Attitude Control Module
  - Inertial reference unit
  - Fixed head star tracker 8° x 8° FOV
  - Three-axis magnetometer
  - Reaction wheels, 20 Newton meter per axis
  - Magnetic torquer, 100,000 pole-cm per axis
  - Attitude control electronics
  - Remote interface units
- Communications and Data Handling Module
  - Power conditioning
  - STACC central unit
  - STACC interface unit
  - On-board computer with memory
  - Remote interface unit
  - Standard tape recorder
  - Pre-mod processor
  - S-band transponder
- Electrical Power Module
  - Power regulator unit
  - Batteries
  - Power control unit
  - Signal conditioning assembly
  - Bus protection assembly
- Solar Array and Drive Assembly
  - Solar array panels
  - Solar array drive
  - Deployment mechanism
  - Control electronics
- Wide Band Communication Module
  - S-band solid-state amplifier
  - Video tape recorder
  - Modulator and preamplifier
  - Remote interface unit
- Sensor Assembly
  - Forward looking sensor
  - Rear looking sensor
  - Planimetric multispectral sensor
  - Electronics and sensor control assembly
- Structure Assembly
  - Structure
  - Thermal blankets
  - Electrical harness
  - Thrusters
  - Antennas
  - Propellant tank and valves

2.14 POSITION AND ATTITUDE DETERMINATION AND CONTROL

For MAPSAT to produce topographic products having accuracies in the order of 7 to 25-m relative and 50 to 100-m absolute, satellite position must be known to a fraction of these values since the error budget must be shared by line-of-sight recovery components. The satellite position can best be determined using the Global Positioning System (GPS) for frequent position updates, and by fitting an orbital model to this data in real time on board the spacecraft. This will permit the computation of Earth-centered position that is required by the attitude control system to achieve epi-polarity. The accuracy of position determination by this means is about 40-m today, and will be at the 10-m level when the full complement of GPS satellites has been deployed. The estimated user cost of this equipment is slightly over one million dollars.

Attitude control for MAPSAT has been investigated by simulation of the modular attitude control subsystem that consists of a stellar-aided inertial reference system and four reaction wheels that provide control torque. The system uses two fixed, head star trackers for low-frequency attitude and gyro bias updates and the DRIRU-II, a three-axis gyro package for high bandwidth attitude data.

The performance of this system in the short term has been estimated to be 0.53 arc-sec/axis. Table 2-7 presents the long term anticipated accuracy. Both of these are within the range necessary to achieve epi-polarity.

Table 2-7 – Estimated Pointing Accuracy, 1σ (10-min Stellar Updates)

	Roll, arc-sec	Pitch, arc-sec	Yaw, arc-sec
Attitude pre-update	2.2	2.55	2.3
Sensor bias	3.0	3.0	3.0
Ephemeris (5 m)	1.122	1.122	1.122
Total rss error	3.9	4.1	3.9

2.15 ELECTRIC POWER

Flying in a sun-synchronous orbit permits MAPSAT to employ a power subsystem that is similar in many ways to that of LANDSAT. The power requirements differ due to the specifics of the sensor and to the restriction that the solar array be stationary during data collection. Two strategies are available for dealing with this restriction. The first is to use an array that is permanently fixed, thus saving the cost of a drive mechanism at the expense of additional array area. The other is merely to stop the array motion during image collection and to drive it normally at other times. In the first case, the increase in size is immediately given through the ratio of the geometric efficiencies. This yields a fixed array size of 11.75 m^2 to deliver the same power as a 6.75 m^2 fully driven array.

For the second case, it is necessary to define the normal motion of the array. Because the orbit is sun-synchronous, motion is required about only one axis and that axis is the normal to the orbit plane. About that axis the array should rotate at a constant rate so that a complete rotation occurs during an orbit period. The deployed array should be held at a constant angle relative to the drive shaft. In this configuration, the worst case efficiency is the same as for a two-degree of freedom array.

When the solar array motion is to be stopped, we assume that immediately before stopping we step the array ahead so that it will be normal to the sun line at the middle of the image collecting interval. The loss in efficiency resulting from this for the LANDSATS 1, 2, and 3 orbit has been calculated as a function of the image collecting duration, and shows that the loss for a 20-min period is essentially negligible and is well within the tolerance of the calculations.

It is the goal of the MAPSAT mission to survive for 7 to 10 years. For this to be possible, several things must transpire:

1. There must be successful launch and deployment.
2. There must be sufficient expendables aboard (propellant).
3. Items that can wear out must survive or complete their usefulness before they wear out (tape recorders, reaction wheels, array drive).
4. Items that can degrade must be adequately oversided (solar cells and batteries).
5. At least one of every type of component needed to perform the mission must not fail.

Recent experience with the Thor-Delta launch system has been excellent and there is every reason to expect this trend to continue into the future. Once on-orbit, it is necessary to deploy the solar array using a straightforward sequence that has been proven with similar spacecraft. Problems are unlikely here.

The propulsion subsystem has been sized to last 10 years, to stabilize the attitude during velocity correction firings, and to permit initial attitude acquisition. Because an appreciable part of the propellant is required to compensate for most unlikely launch vehicle injection errors, a nominal launch will leave a substantial excess of propellant for the balance of the mission.

Potential wear-out items include tape recorders, reaction wheels, and the solar array drive. Tape recorders are notorious for their limited lifetime and this will not change in the MAPSAT era. They are essential to the mission, however, only for regions of the Earth's surface out of range of one of the receiving stations. By care in planning their use, the MAPSAT mission should be a success despite their limited lifetime.

The solar array drive is not likely to cause problems because of its low speed and higher torque. Items that require lubrication, however, always require care in their design when a 10-year lifetime is sought.

The reaction wheels are the most likely source of wear-out type failure in the 10-year mission. For this reason, redundancy is called for. Three wheels are the minimum needed to stabilize the satellite. Four wheels properly oriented permit the elimination of pointing transients caused by wheel speed reversals. Only four wheels are provided in the MMS attitude control module so that failure of one wheel does not cancel the mission but would cause the occasional rejection of collected data during wheel speed reversals. If in a later phase a new spacecraft design is sought, serious consideration should be given to adding a fifth wheel.

Batteries and solar cells are the principal components that have predictable degradation characteristics and are necessary to the continued operation of the spacecraft. In the 919-Km sun-synchronous orbit, experience indicates that a 10% reduction in array efficiency can be expected over the 10-year mission. The solar array size indicated in this design takes that degradation into account.

Battery lifetime is a more serious factor. Repeated charging and discharging of a nickel-cadmium battery, such as will occur in the MAPSAT orbit, decidedly reduces a battery life and may cause complete failure. The design proposed here deals with this problem by using a low depth of discharge (15%), keeping the batteries cold (0 to 5°C), and including three separate units so that failure of any one means greater care must be exercised in turning on sensors and recorders, but does not permanently destroy the mission.

It is never possible to eliminate all single point failures, but a good design will eliminate all single point failures that have a significant probability of occurring. The MMS modules, as they appear in this design, are already provided with redundant critical items. Additional redundance can be supplied in some cases at a dollar cost and a weight penalty if a more detailed analysis justifies the need.

Based on spacecraft of similar complexity, and bounded by similar weight and cost constraints, we would anticipate a calculated mean mission duration for MAPSAT in the range from 3 to 5 years. One must keep in mind that there is a wide dispersion about the mean that accounts for some spacecraft surviving for many years despite a low calculated MMD, and others that fail immediately after launch despite a calculated MMD of several years. The point of these comments is that there is no way to assure a mission lifetime of 7 to 10 years. What one must do instead is conduct a thorough failure modes and effects analysis (FMEA) and design alternative means of surviving the most likely failures. Then, during fabrication, a quality assurance program must impose controls on cleanliness and storage and work procedures that experience has shown increase the likelihood of survival on orbit.

2.16 DATA MANAGEMENT AND PROCESSING

The variety of MAPSAT data collection modes implies that the data storage, retrieval, and processing capabilities of the ground station must be flexible to allow for product demand changes over the mission life cycle, which could be 10 to 20 years. Although MAPSAT creates products similar to the current LANDSAT, the requirement for flexibility means that the conceptual design of MAPSAT must not be biased by existing patterns of LANDSAT data usage. In fact, the MAPSAT conceptual design anticipates greater demand for data in digital form as the number of sophisticated users increases.

In addition to this general requirement, the MAPSAT ground design has been assessed with regard to other key performance measures such as product accuracy, thruput, and turnaround time. Furthermore, the design accommodates the constraints imposed by the data transmission capabilities of the flight segment and the chosen computing technology.

Described at the top most level, the ground segment provides the interface between the MAPSAT space segment and MAPSAT user community. By effectively managing the collection and processing of data, user requests for either or both of these services can be fulfilled in the most timely manner consistent with satellite and sensor operating constraints. Processes included in the ground segment are mission planning, spacecraft monitoring and control, transmission of commands and reception of telemetry, reception and forwarding of sensor data, reformatting and correction of image data, data archiving, user inquiry and ordering, production control, and product generation. To deal with these processes, the ground segment has been organized into the subsystems shown in Fig. 2-16. A ground segment functional specification has been prepared and will be found in the body of this report.

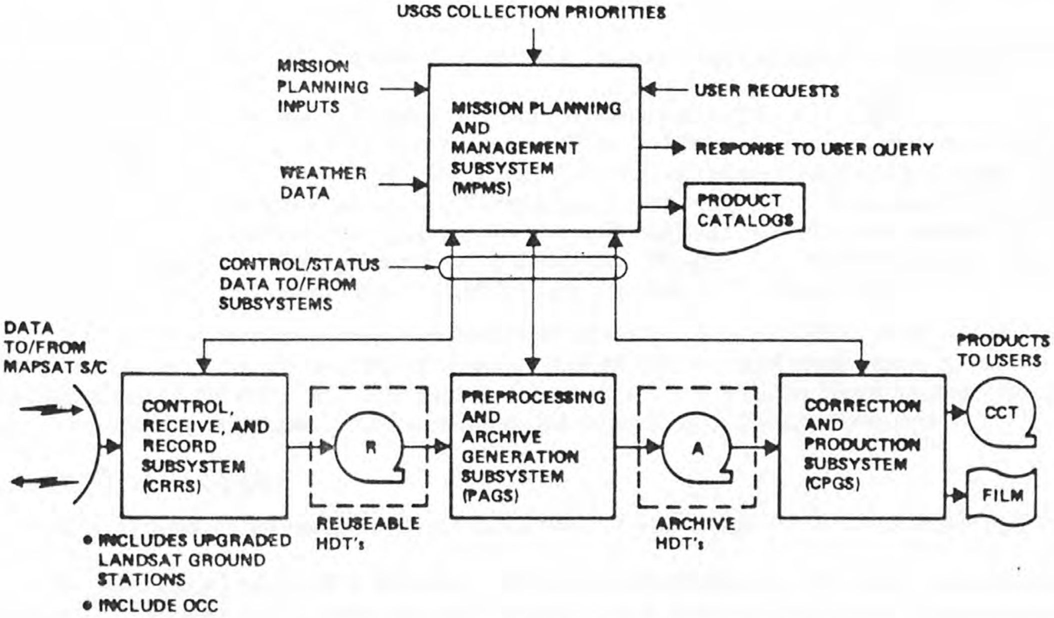
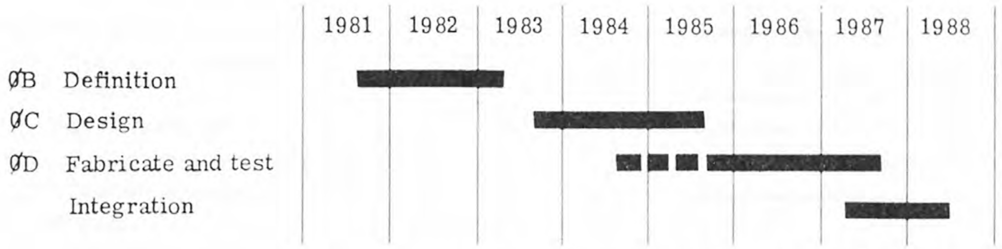


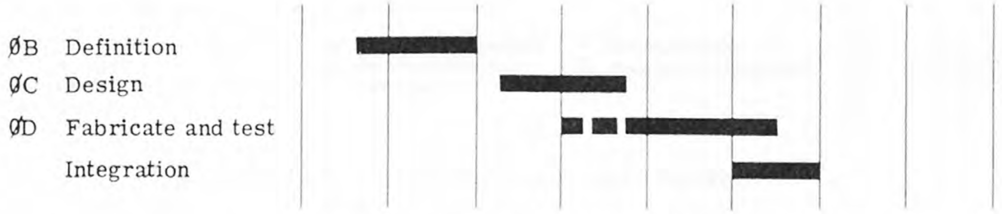
Fig. 2-16 – Overview of MAPSAT ground segment

2.17 SYSTEM ACQUISITION PLAN

Two schedules for phases B through D and final integration have been examined. One extreme, in which for instance no competitive efforts are used to shorten the program, is shown in Fig. 2-17a. It was assumed in this case that phase B would start with FY82 (October 1981) and last 18 months. Six months were allowed to review proposals for phases C/D and to let a contract after the end of phase B. This means that the approval for a new start, and such paperwork as the writing of an RFP, would probably have to coincide with the phase B effort. The combined phases C/D will require about 4 years, and 6 months are needed for final integration of payload to spacecraft and to checkout before the first flight. As a result of this schedule, the first flight could not occur before the 2nd quarter of calendar 1988.



a) A conservative schedule, with a first flight in 1988



b) A tight schedule, with a first flight in 1986

Fig. 2-17 – Conservative and tight schedule for procurement of MAPSAT

We have also looked at a schedule that requires exceptionally tight management and have found that perhaps 15 months could be saved (Fig. 2-17b). The same October 1981 start for phase B was used. It is unlikely that phase B could be reduced below 15 months, and only two months were allowed after phase B before phase C was started. This short time can be achieved in this kind of program by having parallel phase B efforts, with the two contenders writing their phase C/D proposals while phase B is in process. Phases C/D were cut from 48 to 39 months. As a result, the first flight could occur before the end of calendar 1986.

The tight schedule is based on the level of detail shown in Fig. 2-18. The lines represent a best estimate of the times required according to our current understanding of the MAPSAT hardware and performance. The figure shows that there will be requirements for breadboarding, long lead procurement, and a substantial amount of software development.

2.18 COST ANALYSES

The ground rules used in the development of estimated costs for a MAPSAT mission are:

1. All costs are in 1979 dollars. Where actual costs for like items were available, they were used. Where costs could be extrapolated from similar programs, this was done; otherwise, costs were built up from estimates for labor and materials.

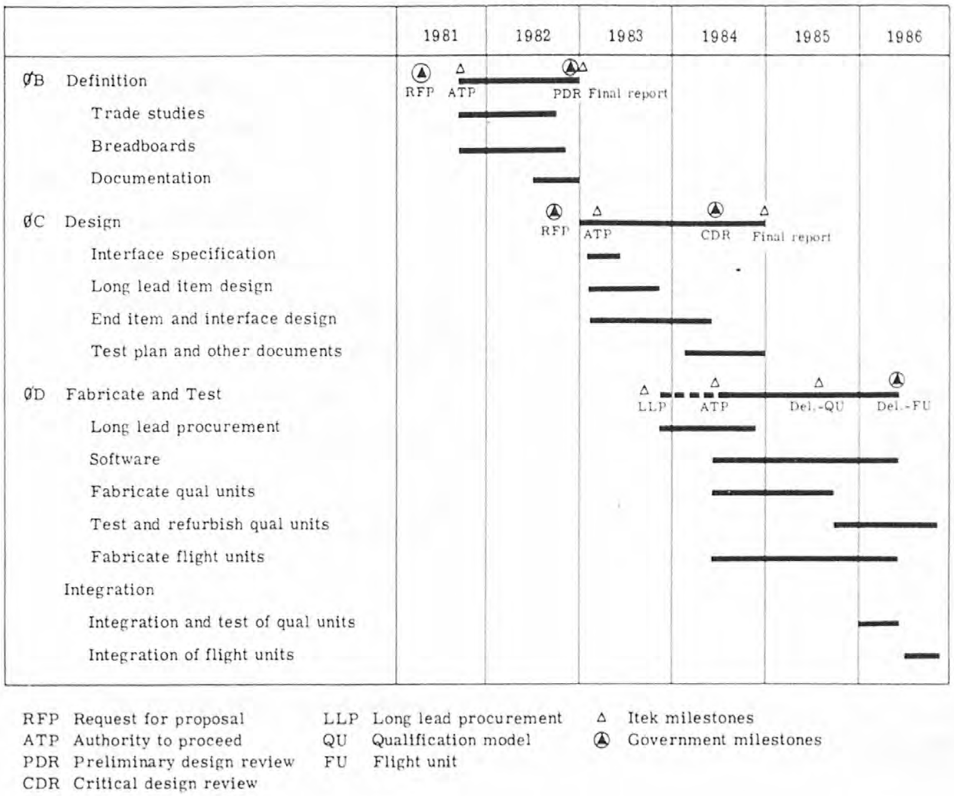


Fig. 2-18 – Detailed tight procurement schedule

2. Costs include everything needed to design, produce, validate, and fly one complete spacecraft and to develop, install, and check out a complete ground segment. Costs for the sensor assembly are based on building one qualification unit, one flight unit, and on refurbishing the qual unit as a potential second flight, according to the development schedule. Estimates have also been developed for the yearly cost to operate the MAPSAT program.

3. Costs are for budgetary and planning purposes only and are not supported by formal pricing exercises. Tables 2-8 through 2-11 summarize the derived costs.

2.19 CONCLUSION

The preceding has presented an overview of a conceptual design of an automated mapping satellite for Earth resource applications. We have found the basic concept to be feasible. In particular, the epi-polar acquisition condition can be satisfied in theory and in a practical satellite vehicle. Epi-polar correlation has been determined to be feasible as a strategy for furthering the automation of the extraction of topographic information, although it is not capable of providing full automation. The system has the potential (using a-posteriori processing) of 1:50,000 scale topographic image mapping with 20m contours as indicated in Section 3.2. Optical design trade-offs have led to a simple optical system that usefully covers the desired spectral range. Current silicon CCD focal plane technology, the basis of the pushbroom concept, will support the fabrication of special buttable multi-dimensional focal planes that provide inherent geometric fidelity and band-to-band registration. Data storage in the form of magnetic tape can hold the equivalent of 45 full multispectral frames at high resolution to reduce transmission data rate requirements.

Finally, we have developed schedules for the design verification, detailed design, and construction phases of a MAPSAT program that can lead to a first flight in 1986 with 7-year mission life at a cost for the full program in the region of $215M.

Table 2-8 – Space Segment Estimated Cost ($000)

ACS module	11,000
Power module	3,000
C&DH module	9,500
Structure thermal	2,000
Solar array/drive	1,500
Wide band communications	6,000
Electrical integration assembly	4,000
Propulsion subsystem	2,000
Subsystem design analysis	3,000
Flight software	1,000
System integration and test	7,500
System engineering	3,500
Quality assurance	3,500
Program management	4,000
Flight segment less sensor	61,500
Sensor	29,000
Total flight segment cost	90,500

Table 2-9 – Estimated Launch Cost ($000)

Launch vehicle	15,000
Spacecraft support	500
Sensor support	200
Total launch cost	15,700

Table 2-10 – Estimated Orbital Operations Cost ($000/yr)

Ground stations (3 only)	3,000
Mission planning/OCC	2,000
Data processing and product generation	1,500
Data processing supplies (undelivered items only)	2,000
Archive cost	800
DOMSAT lease	500
Operating cost per year	9,800
Operating cost for 7 years	68,600

Table 2-11 – Ground Segment Estimated Cost ($000/yr)

System engineering		4,500
Hardware procurement		12,000
MPMS	1,000	
PAGS	5,500	
CPGS	4,000	
CRRS	1,500	
EPCN	2,000	
Software development		15,500
MPMS	1,500	
PAGS	4,000	
CPGS	7,000	
CRRS	1,000	
EPCS	1,000	
Logistics		6,500
Program management		4,000
Total ground segment cost		41,500