DESIGN TRADEOFFS FOR A MULTISPECTRAL LINEAR ARRAY (MLA) INSTRUMENT

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Abstract

The heart of the MLA design problem is to develop an instrument concept which concurrently provides a wide field-of-view with high resolution, spectral separation with precise band-to band registration, and excellent radiometric accuracy. Often, these requirements have conflicting design implications which can only be resolved by careful tradeoffs that consider performance, cost, fabrication feasibility and development risk. The key design tradeoffs for an MLA instrument are addressed in this paper, and elements of a baseline instrument concept are presented.

Background

The NASA Landsat program has been thoroughly successful to date, based on the imagery produced by the Multispectral Scanner. Currently, with spacecraft integration underway for the Thematic Mapper protoflight instrument, the second generation of Landsat is approaching fruition. In light of these developments, the design challenge for a third-generation MLA sensor is to conceive an instrument that will provide extraordinary benefits that are well worth the development cost.

The strength of the MLA concept emanates from the pushbroom image-formation approach, which offers some fundamental improvements over opto-mechanically scanned instruments. A dramatic advantage of the MLA sensor is the increased dwell time that can be used to improve signal-to-noise, spectral resolution and spatial resolution simultaneously. The design latitude in all three parameters is such that only the optical blur circle need constrain the spatial resolution. Thus, an outstanding optical design is required to exploit the pushbroom approach. However, higher resolution by itself is a modest justification for a new development program. To fully realize the potential benefits of the MLA concept, the instrument design must be mechanically simple, with a minimal number of moving parts. Otherwise, the promised reliability advantage of the pushbroom approach may not be achieved.

Moreover, the instrument must provide excellent spatial (band-to-band) registration and radiometric accuracy, as well as minimum geometric distortion. Spectral registration and geometric fidelity are essential for accurate color-composite imagery. Object-space registration is also extremely important for successful crop assessment and classification, since the precise radiometric accuracy required for this task is significantly degraded by misregistration. That is, radiometric performance and band-to-band registration are cross-coupled. With inherent band-to-band registration at the instrument, a large segment of the user community might be served by data that come directly from the spacecraft, or with a minimal amount of expensive and time-consuming ground processing that delays delivery of data to the customer. This capability is pivotal for many applications, such as crop-yield assessment or evaluation of transient-pollution phenomena, where the utility of Landsat data declines sharply with time.

Quantitative performance goals have been established for MLA by the NASA Goddard Space Flight Center, which has been guiding MLA design studies at several companies, including SBRC.[1] These design objectives, summarized in Table 1, serve as a point of departure for the tradeoffs discussed in the following section.

Table 1. MLA Design Objectives

Spectral Bands (μm)	IFOV[A] (m)	SNR (min)	MTF[B]
1. 0.45 - 0.52	10-15	73	>0.30
2. 0.52 - 0.60	10-15	149	>0.30
3. 0.63 - 0.69	10-15	126	>0.30
4. 0.76 - 0.90	10-15	168	>0.30
5. 1.55 - 1.75	20-30	54	>0.30
6. 2.08 - 2.35	20-30	77	>0.30

Notes: A. Detector IFOV at 705 km Altitude
B. At Nyquist Frequency

Field-of-View	15° Cross-Track 1→20 IFOV In-Track
Spectral-Band Registration	<20 IFOV In-Track Separation (Bands 1 → 6) ±0.1 IFOV Pixel Position ±0.2 IFOV Parallelism Within Bands (1-4) and (5, 6) ±0.5 IFOV Parallelism Bands (5, 6) W.R.T. (1 → 4)
Pointing Modes:	±30° Cross-Track 0, ±26° In-Track (Stereo)

Table 1. MLA Design Objectives (Continued)

RADIOMETRIC ACCURACY	± 5% ABSOLUTE W.R.T. NBS STANDARDS ± 1% RELATIVE INTERBAND ± 0.5% RELATIVE INTRABAND
DATA COMMUNICATION	2 × 150 MBPS VIA TDRSS 1 × 100 MBPS DIRECT DOWNLINK
SPACECRAFT INTERFACE	COMPATIBLE WITH MUTIMISSION SPACECRAFT (MMS), STS LAUNCH

Design tradeoffs

The system-level tradeoffs, which translate mission requirements into a baseline instrument configuration, establish the basic design parameters and design philosophy for the MLA instrument. The heart of the MLA design problem is to develop a design approach that embodies the following features:

1. Wide field-of-view with high resolution
2. Spectral separation and precise band-to-band registration
3. Stereo and cross-track pointing modes
4. Radiometric accuracy
5. On-board signal/data processing
6. High reliability - minimum number of moving parts.

Any one of these objectives might be straightforward to attain, but it is challenging to provide all these features in a single instrument, because these requirements have conflicting and interdependent design implications. For example, the optical design strongly influences the spectral separation-registration technique, the stereo/cross-track pointing method and the design of the on-board calibration source. Before delving into the details of these hardware tradeoffs, we shall begin by presenting the first-order sizing parameters for the instrument.

Instrument sizing

Detector pitch, optical focal length, aperture size and integration time are the basic parameters that determine the physical size and radiometric performance of the instrument. These numbers follow directly from the IFOV, MTF and SNR specifications. Since detector technology is the dominant feasibility driver for the MLA instrument, detector size and density constraints are a good place to begin the sizing analysis. For a given ground-sampling interval and IFOV, the focal length (and instrument size and cost) is reduced in direct proportion with detector pitch and size. Although SNR is degraded as detector size is decreased, this is not a driving constraint on MLA where ample dwell time is available to build SNR. Therefore, the smallest detector size and pitch, consistent with acceptable processing yield and cost, are desirable for MLA.

Once the optimal detector pitch is selected, the focal length is immediately determined from IFOV and sampling interval requirements. Then, the optical aperture size (and hence f-number) is chosen to meet MTF and SNR requirements. This instrument-sizing procedure is illustrated in Figure 1. These sizing tradeoffs lead to an instrument with 12 μm square detectors on 15 μm centers (bands 1 to 4), 705 mm focal length, a 190.5 mm aperture diameter, and other parameters as shown in Table 2. Additionally, the 705 mm focal length yields a fortuitous relationship between dimensions on the ground and on the focal plane: 1m on the ground corresponds to 1 μm on the focal plane (for the 705 km orbit).

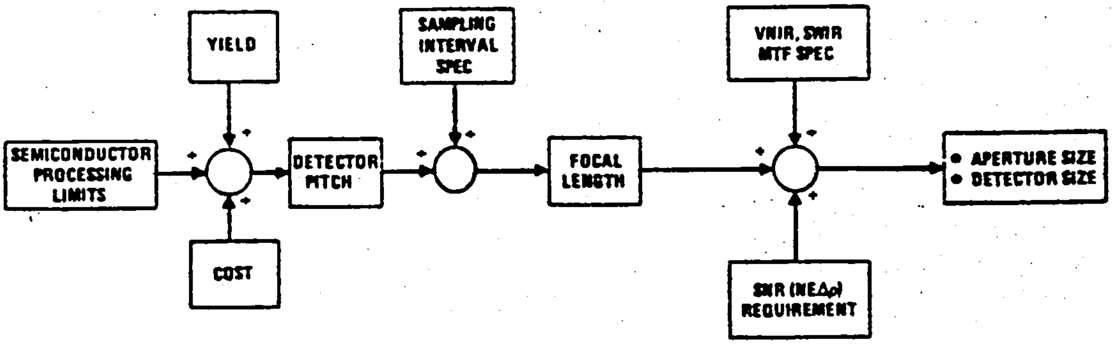


Figure 1. Instrument sizing procedure

Table 2. System Parameter Summary

Aperture Diameter	190.5 mm
Focal Length	705 mm
f/No.	3.7
IFOV at 705 km	12m (17.0 µrad) Bands 1 → 4 25m (35.5 µrad) Bands 5, 6
Sampling Interval	15m (21.3 µrad) Bands 1 → 4 30m (42.6 µrad) Bands 5, 6
Number of Detectors	61,440
Data Rate (Uncompressed)	208-570 MBPS

Configuration tradeoffs

The sizing parameters established above set the stage for configuration tradeoffs. This section summarizes the principal packaging considerations, identifies the most promising candidate, and presents the rationale for that selection.

The overall instrument configuration appears to be most strongly influenced by the following factors, listed in the order of their importance to the selection process:

1. Stereo mode implementation
2. Cross-track mode implementation
3. Radiative cooler field-of-view
4. Spacecraft structural integration

Three generic configurations are possible, with optical systems whose principal axes are oriented along the orbital track, cross track, and nadir directions. Figure 2 illustrates these alternatives, and the relative merits and flaws of each approach are also noted in the figure.

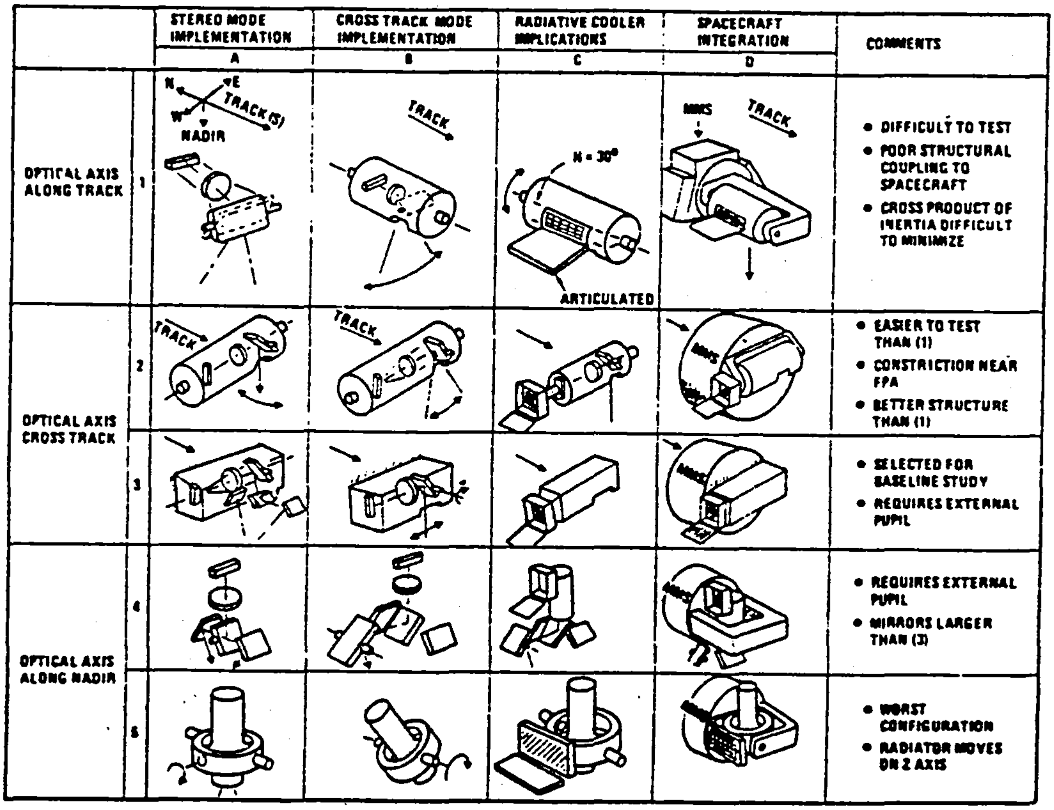


Figure 2. Configuration tradeoffs

Configuration number three (with the optical axis in the cross-track direction), when coupled with an optical design having a convenient entrance-pupil location, was selected. This configuration provides an excellent combination of simplicity and compactness; articulated radiators, rotating sensors, oversized mirrors and other undesirable features are absent.

Optital design tradeoffs

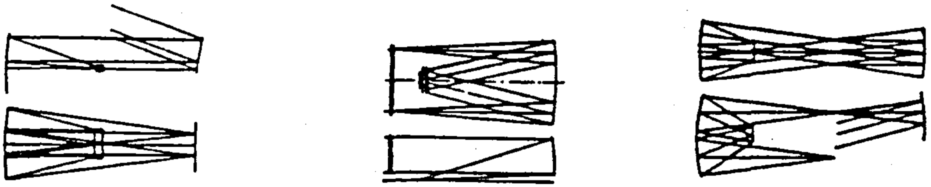
Performance requirements in the areas of pointing capability, field of view (FOV), resolution, spectral coverage, radiometric accuracy and spectral registration are highly coupled and contain important implications for the MLA optical form. As presented in Table 3, a variety of additional optical system characteristics strongly affect the design of other MLA subsystems. For example, a flat focal plane will greatly facilitate detector-array assembly and alignment. The use of a relayed optical form will improve stray light rejection and simplify on-orbit detector calibration. The optical form should permit compact system packaging consistent with MMS payload capabilities, and fabrication and alignment tolerances must be realistic in order to guarantee satisfactory on-orbit optical-system resolution. An unobscured system with adequate performance margin will simplify scaling to sensors with improved resolution, and an all-reflective telescope will permit future inclusion of LWIR spectral bands. Minimal geometric distortion will reduce post-processing requirements for some applications. Finally, telecentricity (normal incidence for all chief rays in the field of view) is an extremely important feature, since it eliminates angular variations in coating performance (for dichroic and spectral-bandpass filters).

Table 3. MLA Optical System Desired Characteristics

Desired Feature	Motivation
Flat Focal Plane	Simplified alignment and assembly for FPA detectors
Telecentricity	Low focal plane angles of incidence, simplified spectral separation, uniform filter performance
Relayed Optical Form	Intermediate image: simplified on-orbit calibration and stray light rejection
Real Entrance Pupil	Reduced Stereo mirror size
Unobscured Aperture	Improved optics MTF
Compact Packaging	Maintain compatibility with MMS
Feasible Optical System Tolerances	Simplify sensor integration, reduce risk
All-Reflective Telescope	LWIR growth capability
Performance Margin	Simplify scaling to 10m/20m system
Minimal Geometric Distortion	Reduced post-processing requirements

A variety of telescope design forms have been considered for use in the MLA sensor. These optical designs have been evaluated against the set of performance requirements and desired features listed above. The design form options considered for MLA are depicted in Figure 3. The various Schmidt designs and the four-mirror telecentric system are the principal design candidates. However, the Schmidt approaches have serious flaws ranging from non-telecentricity and curved focal surfaces (for some variants), to unfavorable pupil locations and intractable pointing-mirror sizes. For a complete exposition of the key tradeoff issues, the reader is directed to Reference 2.

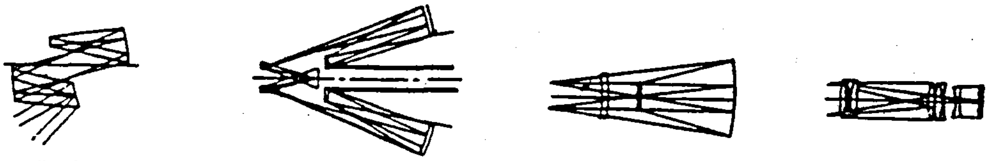
The four-mirror telecentric design (Figure 3.1-5c) has been selected as the MLA optical system baseline because of its excellent combination of optical performance and desirable features. Main advantages of this form are its real entrance pupil, intermediate image, flat focal plane, and telecentricity. The folded version of this telescope provides compact packaging, and image quality (10-12 μrad 80% blur diameter in band 3) is better than MLA specifications. Moreover, this all-reflective design has an unobscured aperture. Although the as-designed optical performance of this system is outstanding, fabrication feasibility, alignment sensitivity and on-orbit alignment stability are also important. Each of these issues has been addressed in depth, as discussed in Reference 2. This work has shown that the four-mirror telecentric system is a thoroughly workable design for MLA. Hughes has demonstrated (with hardware) a similar four-mirror system with off-axis aspheric elements, and the measured performance of this system is as predicted for the design. A key factor in achieving the designed performance for these systems is a Hughes-developed computer-aided optical alignment method which ensures optimal alignment of the mirrors and permits relaxation of figure tolerances.



a) REFLECTING SCHMIDT

b) SHORT, FLAT-FIELD SCHMIDT

c) FOUR-MIRROR TELECENTRIC



d) WALRUS

e) RETROCENTRIC (SCHWARTZCHILD)

f) BOUWERS CONCENTRIC

g) PETZVAL

Figure 3. Telescope design alternatives

Spectral separation and registration

The requirements for spectral separation and band-to-band registration are significant considerations for the MLA instrument. The spectral-separation approach has implications that ripple through the system, in the areas of optical design, detector packaging, cooling, structural design and signal/data processing.

Two fundamental points of departure for selecting a spectral-separation approach hinge on the desirability of maintaining true object-space registration and on the location of the visible-near infrared (VNIR) and short-wave infrared (SWIR) focal planes. The key tradeoff in achieving spectral registration centers on how the detectors are mounted. The mounting of the detectors is affected by the choice between the two different philosophies for registration of the MLA bands; time delay between parallel rows of detectors or spectral beamsplitting of the incoming energy.

The time-delay approach leads to a misregistration of 0.2 IFOV at the edge of the field of view, even with ideal (constant focal length) optics. Thus, object-space registration is not achieved, and extensive corrective data processing would be required to produce the registered imagery needed for many applications. Therefore, a beamsplitter utilizing dichroic filters has been selected, as illustrated in Figure 4. This approach provides coincident images in all six bands.

The preferred tilted-plate beamsplitter approach leads to the next major tradeoff; to mount all the detectors on a common substrate and cool the entire assembly or to cool only the two SWIR bands. If only the SWIR bands are cooled then they must be registered with an ultra-low hysteresis mount or servoed into a position of registration with the visible detectors. Cross-track registration becomes another issue because the cooled detectors may have a coefficient of expansion that is large enough to misregister detectors along the length of the array relative to the corresponding warm VNIR arrays. For these and other reasons it appears that cooling all the detectors on a common, isothermal substrate minimizes misregistration due to structural compliance and differential thermal effects.

Radiometric accuracy and calibration tradeoffs

Achieving the required radiometric precision for MLA raises several important issues regarding detectors, signal-processing, and calibration approach. Much of the radiometric-accuracy issue hinges on the performance of the detectors, particularly for the SWIR bands, so this is a good place to begin the discussion. The detector material and temperature directly affect radiometric performance because responsivity and 1/f noise (which are material and temperature dependent) influence SNR and calibration frequency. Moreover, the selection of a SWIR detector material is tightly coupled to other aspects of the instrument design, since the operating-temperature requirements influence the cooler size, mechanical layout and spectral-registration approach.

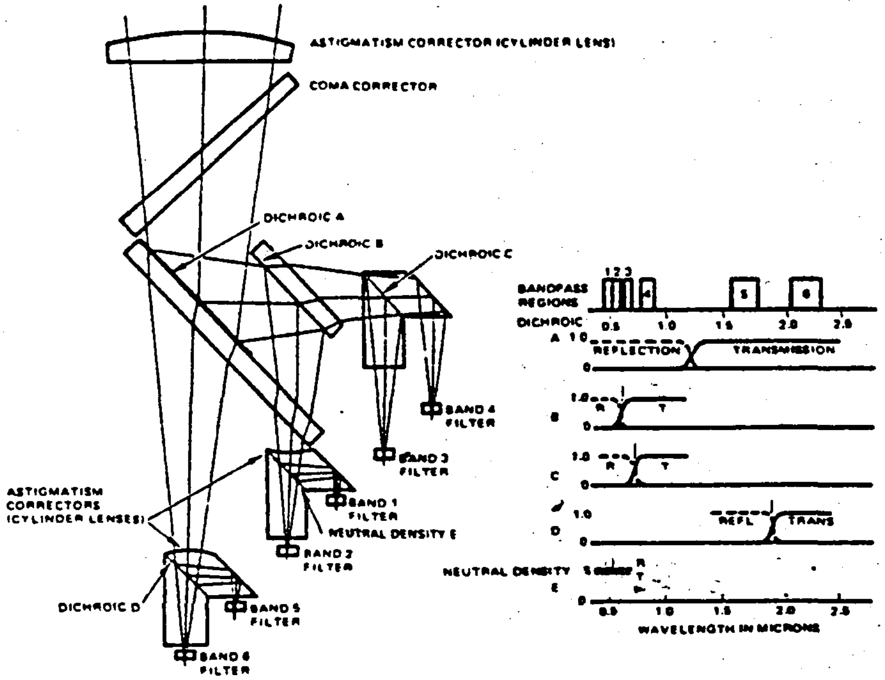


Figure 4. Beamsplitter concept

The preferred spectral-separation/registration approach, with a six-band colocatd, isothermal focal-plane assembly, poses some temperature restrictions, if reasonably-sized radiative coolers are employed. Specifically, a complete six-band focal-plane assembly requires on the order or 5W of cooling capacity, including the parasitic heat loads due to cables, supporting structures, and the like. With a tractably-sized radiator, say with an area of 0.2 m^2, focal-plane temperatures as low as 155K are achievable. In this operating-temperature regime, the detector material of choice is HgCdTe. Palladium silicide, another candidate detector material, requires a much lower temperature (circa 110K) and has poor responsivity. However, if the 1/f noise properties of HgCdTe introduce radiometric-drift errors that must be corrected by frequent recalibration — or even a chopper assembly — then the attractiveness of the isothermal-FPA approach and HgCdTe SWIR detectors comes into question.

The crux of this issue is the potential requirement for an opto-mechanical chopper. Incorporating a chopper would violate the no-moving-parts design philosophy of MLA. While an MLA instrument without a chopper would still have movable pointing mirrors, the fundamental imaging operation of the instrument would not depend on any rotating or oscillating components. Indeed, if a chopper were necessary, the entire issue of a scanned versus pushbroom instrument would merit reexamination, since the perceived reliability advantage of the pushbroom design might be eliminated. In addition to the severe reliability issue inclusion of a chopper would reduce SNR in proportion to the effective transmission loss caused by periodic blanking of the detectors.

In view of the pivotal nature of this issue, a comprehensive analysis of drift and 1/f noise was undertaken. This analysis was verified by measured data, and the results of this work indicate that drift in the SWIR (as well as the VNIR) bands will be less than 0.05% of full scale during an orbital period when HgCdTe detectors are operated at 175K. This drift level is well within the GSFC radiometric-accuracy specification. The predicted drift is also well below the even more stringent ~ 0.2% uniformity required to avoid cosmetic defects (striping) in the imagery. Thus, a chopper mechanism is unnecessary.

Other tradeoffs affecting radiometric accuracy, including the design and location of calibration sources, the precision of A/D quantization and subsequent on-board calibration correction, have also been addressed.

Instrument concept

The design tradeoffs outlined above have led to the instrument concept illustrated in Figure 5. This figure is a photograph of a full-scale mockup fabricated at SBRC as an aid for visualizing the key elements of the instrument. Figure 6, which is a cutaway drawing corresponding to the mockup photo, reveals the internal details of the sensor. The mockup does not show the instruments' covers or stereo mirror module, and these additional items are depicted in Figure 7.

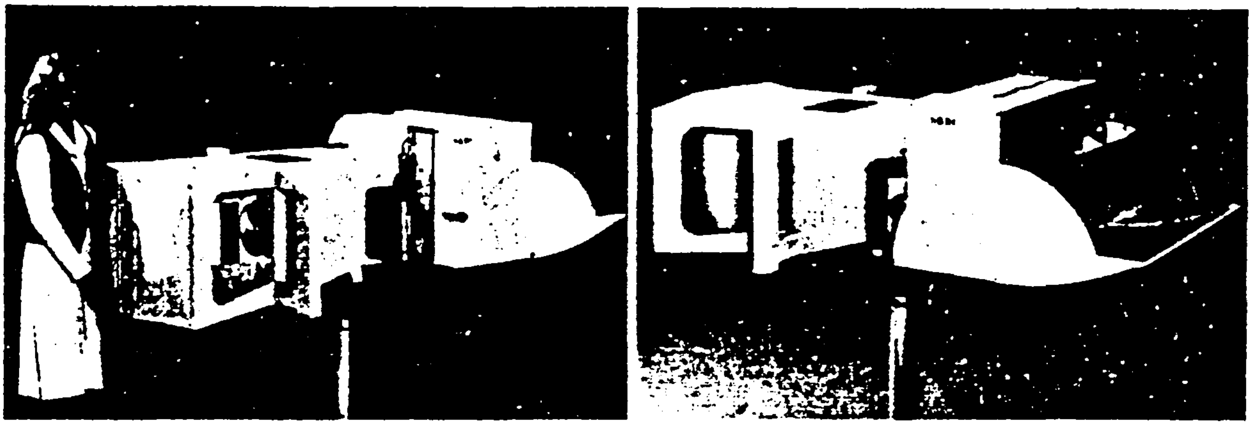


Figure 5. Multi-spectral linear array (MLA) instrument full-scale mock-up

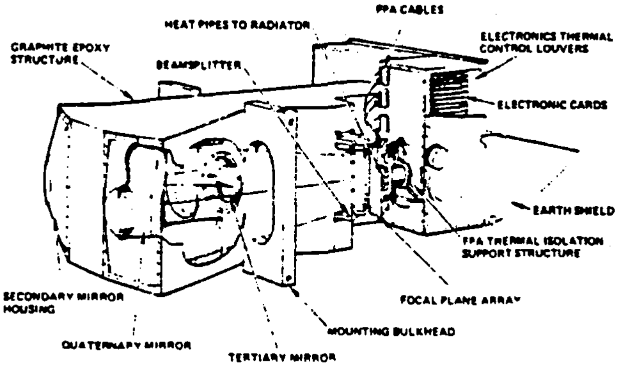


Figure 6. MLA instrument cutaway view

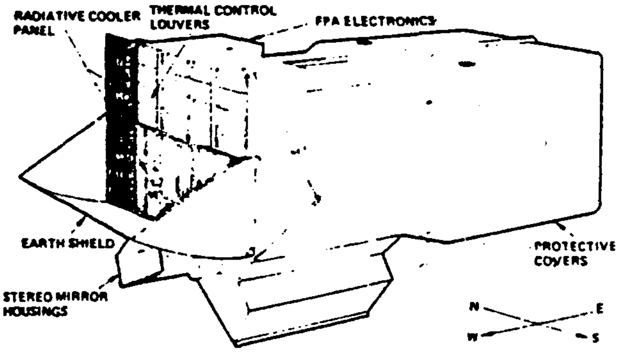


Figure 7. MLA instrument with covers and stereo module

The telescope and beamsplitter have been described in the preceding section; highlights of other subsystems are presented below.

Focal plane assembly

The baseline focal-plane design consists of six color bands arranged in stairstep fashion as dictated by the beamsplitter design. The focal plane is modular at the band level, with each assembly electrically independent of the others, as illustrated in Figure 8. thus, the band assemblies can be functionally tested separately and in parallel. With special tooling, the detector modules are precisely located on a substrate, and these completed band assemblies in turn mount to a monolithic staircase structure which has diamond-machined mounting surfaces that provide the required positioning accuracy for the detector arrays. The staircase is thermally coupled to the radiative cooler via two redundant heat pipes. Although the focal-plane temperature is controlled at 175K, the cooler has sufficient design margin to achieve temperatures as low as 155K with the nominal 5W total heat load, as discussed earlier.

On the focal plane, bands 1 through 4 employ silicon photodiodes, while HgCdTe photodiodes are used for bands 5 and 6. The two SWIR detector arrays each consist of 6,144 detectors, and the four VNIR detector arrays each have 12,288 detectors. Each of the six band-level assemblies are composed of precisely-butted modules. To read out all the more than 60,000 detector signals, each module has a corresponding multiplexer (MUX). In the VNIR bands, the MUX and detector array are a monolithic unit. In the SWIR bands, a hybrid structure is used: HgCdTe detectors with a silicon MUX chip.

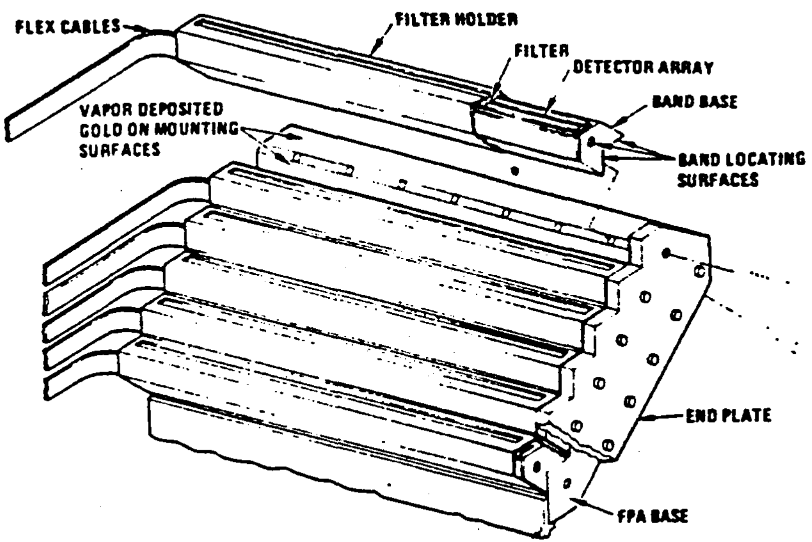


Figure 8. Focal plane assembly

Electronics

The existence of a large array of detectors and simultaneous signal output from many modules pose significant problems in signal processing, such as speed and reliability. An attractive solution is a highly distributed hardware design, involving many replicated electronic systems working in parallel. For the purposes of signal processing, the focal plane was organized into 48 sections, or "slices," each containing its own independent processing chain. Each slice consists of the aforementioned output multiplexing devices, as well as associated analog-to-digital converters, and digital signal processing circuits. This distributed approach is the key to meeting reliability objectives while fulfilling the high-speed signal-processing requirements for MLA. The architecture provides additional benefits in terms of low power dissipation with correspondingly simple thermal control. Moreover, the parallel approach yields thoroughly tractable data rates through the signal-processing chain illustrated in Figure 9.

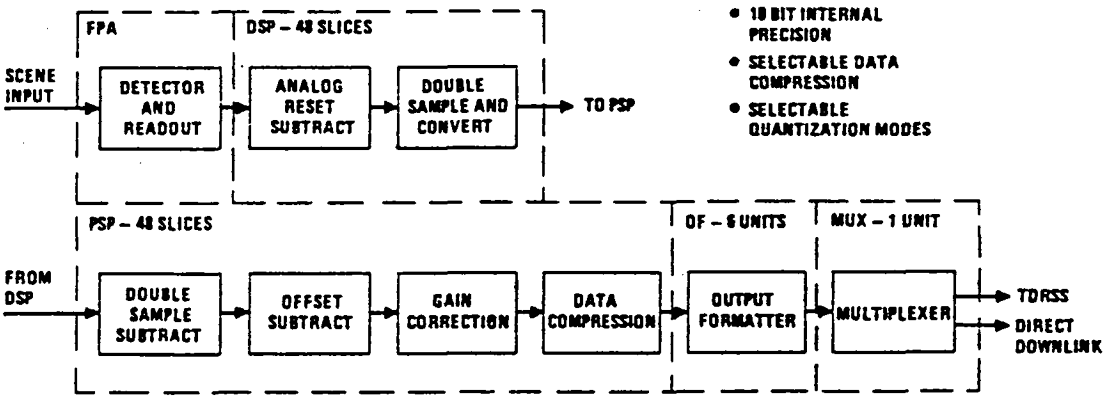


Figure 9. Distributed signal processing from FPA to output

The processing starts at the FPA, with the first-level multiplexing. Under the supervision of ten timing and control (TC) circuits, all 48 FPA slices are processed simultaneously. From the FPA, signals enter the detector signal processor (DSP), where ten-bit A/D conversion is performed in an interleaved fashion that obviates the need for buffer memory. Under microprogram control, the DSP/TC provides the variable-rate timing for different orbits.

The digital signals from the DSP can be transmitted uncompressed at full ten-bit resolution from the 705 km orbit. However, at the lower orbits (283 and 470 km), the short detector sample time leads to data rates that exceed TDRSS capacity. Therefore, in addition to detector gain and offset correction, the programmable signal processor (PSP) provides data compression. Selectable compression modes include standard differential pulse code modulation (DPCM) as well as a Hughes-developed advanced DPCM (ADPCM), which combines DPCM with a predictive coder. ADPCM will provide lossless data compression for many scenes. Various quantization modes are available which take advantage of the ten-bit A/D converter precision. For example, one mode allows increased precision over a reduced dynamic range. From the PSP, the 2.3 to 6.3 MHz parallel data (depending on the orbit) enter the output formatter where they are organized for serial transmission. Additionally, there is a command processor which orchestrates control and telemetry for the entire instrument.

On-board calibration

The on-board calibration concept includes a controlled calibration source at the intermediate image plane between the folding mirror and the secondary mirror, a movable solar diffuser that can be positioned in front of the entrance pupil, and a backup collimator located within the stereo-mirror module. The location of the source allows for system calibration from the secondary mirror to the video output, while the solar diffuser provides an end-to-end calibration reference that also encompasses the mirrors that precede the controlled calibration source. However, the reflectance properties of these mirrors will change slowly, so relatively-infrequent solar calibration will be adequate.

The principal on-board calibrator is a cylindrical integrating source (CIS), which consists of a metal cavity with thirty incandescent lamps distributed along the length of the cylinder. The interior of the cavity, which has a diffuse surface coating, serves to average or "integrate" the lamp illumination, so that nearly uniform radiance appears at the exit slit. During calibration, the folding mirror near the intermediate image plane is rotated so that the CIS illuminates the focal-plane assembly (FPA). A closed-loop silicon-photodiode sensor circuit controls the CIS at six discrete light levels, which are obtained by activating different numbers of lamps.

Summary

The principal design tradeoffs for an MLA instrument encompass the opto-mechanical layout, spectral separation/registration approach, detector selection and signal-processing architecture. These tradeoffs led to an instrument concept employing a four-mirror-telecentric telescope, coupled with a six-way beamsplitter, an isothermal focal-plane assembly and highly distributed signal processing. Key features of the concept include object-space registration of all six spectral bands, stereo and cross-track pointing via compact mirrors, and a small overall envelope compatible with the multimission spacecraft.

Acknowledgements

The MLA instrument study represents the cooperative effort of over forty people at Hughes/SBRC, as listed below, and it is this collective work that has been summarized in the preceding paper. The work reported here was supported in part by NASA Contract No. NAS5-26591, under the technical direction of Mr. H.L. Richard of the Goddard Space Flight Center.

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