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The Moderate Resolution Imaging Spectrometer-Tilt (MODIS-T)

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ABSTRACT

There will be several state of the art spectrometers in operation on the NASA Polar Orbiting Platform (NPOP-1) as part of the Earth Observing System (Eos). The Moderate Resolution Imaging Spectrometer (MODIS) will consist of two imaging spectroradiometric instruments, one nadir viewing (MODIS-N) and the other tiltable (MODIS-T) for ocean observation and land bidirectional reflectance studies.

The Earth System Science Report by the NASA Advisory Council's Earth System Sciences Committee and the MODIS Science Team shaped the current MODIS-T science performance requirements. The MODIS-T instrument is required to cover the wavelength range of 400 to 880 nanometers in approximately 15 nanometer steps, have less than 2.3% instrument induced polarization, be calibrated to an absolute radiometric accuracy of at least 5% over the full dynamic range of the instrument, have a 1.1 kilometer square instantaneous field of view at nadir, and be capable of ±50 degree along track tilt. The MODIS-T instrument is currently being developed under a Phase B conceptual design study at NASA's Goddard Space Flight Center.

1. INTRODUCTION

Important global-scale research in oceanography, geology, limnology, glaciology, and terrestrial ecology is just beginning to be addressed with the most advanced kinds of sensors now available on satellites. A new generation of optical sensors, called imaging spectrometers, are flying on aircraft and are slated to fly aboard the polar orbiting space platform as part of the Earth Observing System (Eos) Facility. The Eos concept envisions the synergistic use of a number of remote sensing instruments, along with an advanced data management system, to provide global data sets for a fifteen year period. In the spring of 1983, the Eos Science and Mission Requirements Working Group was formed by NASA with representatives from the various disciplines for Earth science to define major questions for the 1990's and to delineate low Earth orbit observables that would materially address these questions. Eos has since become the payload for the polar platform portion of the Space Station. The results of this group's deliberations included requirements for a multispectral radiometer capable of frequent global surveys at a 1 km spatial resolution. This system was designated the Moderate Resolution Imaging Spectrometer (MODIS). The MODIS Instrument Panel formed in mid-1984 further defined the scientific goals and observational requirements. Due to the diversity of these requirements, it was necessary to divide MODIS into two sensor packages, designated MODIS-N (nadir) and MODIS-T (tilt).

The Earth System Science Report by the NASA Advisory Council's Earth System Sciences Committee and the MODIS Science Team shaped the current MODIS-T science performance requirements. The MODIS-T instrument is required to cover the wavelength range of 400 to 880 nanometers in approximately 15 nanometer steps, have less than 2.3% instrument induced polarization, be calibrated to an absolute radiometric accuracy of at least 5% over the full dynamic range of the instrument, have a 1.1 kilometer square instantaneous field of view at nadir, and be capable of ±50 degree along track tilt. The MODIS-T instrument is currently being developed under a Phase B conceptual design study at NASA's Goddard Space Flight Center.

2. THE MODERATE RESOLUTION IMAGING SPECTROMETER-TILT

The Moderate Resolution Imaging Spectrometer-Tilt (MODIS-T) is one of the facility instruments selected to fly on the Eos facility. The baseline instrument concept is a grating-type reflecting Schmidt imaging spectrometer. It provides nearly complete coverage of the spectrum between 400 and 880 nm in 32 bands each with a full width half maximum bandwidth of approximately 14 nm using a photodiode interline CCD area array detector. Table 1 summarizes some of the MODIS-T sensor parameters.

The MODIS-T uses a whiskbroom scan to cover a 1500 km swath (see Fig. 1). This swath width provides nearly complete earth coverage in two days from a 705 km orbital altitude. The 30 (spatial) by 34 (spectral) pixel detector array covers 33 km along track each scan, with a total of 1.13 ms available for integration and readout of the array. Radiometric analysis has been performed to arrive at a design that achieves the signal-to-noise requirements for ocean color observations and still retain the dynamic range required for observations over land. To achieve these ends, the instrument uses two modes of operation: an ocean mode and a land mode. In the ocean mode, the instrument uses the 1.13 ms for integration, whereas only 0.30 ms are used in the land mode for integration. The instrument weighs 148.8 kg and uses an average of 90 watts of power.

Table 1
MODIS-T Design Parameters

Required:	
Spacecraft	NPOP-1
Platform altitude	705±30 km
Orbit	98.7° inclination
Equatorial crossing	13:30 ascending
Lifetime in orbit	5 years
IFOV	1.56 mr (1.1 km)
Image quality	MTF≥0.3 at Nyquist freq.
Radiometric accuracy	±5% required, ±2% goal ±2% to Sun
Instrument polarization	≤2.3%
Spectral range	400 to 880 nm
Bandwidth	10-15 nm (FWHM)
Swath width	90°
Fore/aft tilting	±50°
Derived:	
Entrance aperture	34 mm diameter
Along track FOV	46.8 mr (33 km)
Detector pixel	161.7 by 220.5 μm
Detector size	30 by 34 pixels
Scan efficiency	25%
Integration time	1.13 ms ocean 0.30 ms land
Quantization	12 bits
Weight	148.8 kg
Average power	90 watts

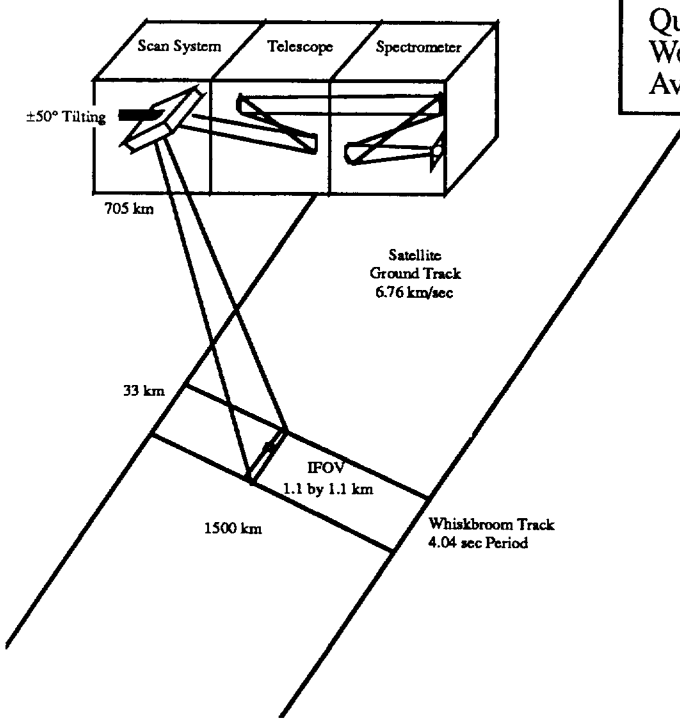

Figure 1. Whiskbroom Scan.

2.1 Scan System

The scan system design is driven by five requirements: 1) a ±45° cross track swath; 2) a maximum of 2.3% linear polarization sensitivity over the ±45° cross track swath and ±20° along track tilt; 3) 25% or greater scan efficiency; 4) on board calibration requirements; 5) instrument volume and weight constraints. Several scan techniques were considered during the design

Table 2
Scan Techniques Considered

Scan Technique	Advantages	Disadvantages	Reason For Choice
Oscillating Scan Mirror	High scan efficiency. Lower detector array readout rate.	Complex mechanism due to large cross track scan. Difficulties in viewing calibration system.	***Two Sided Rotating Mirror***
Two Sided Rotating Mirror	*Simple mechanism. View of calibration system on each scan.*	*Low scan efficiency of 25%. Reduced integration time and faster array readout time.*	*Simple mechanism. View of calibration system on each scan.. Reasonable array readout rates. Lifetime.*
Three Sided Rotating Mirror	Simple mechanism. Higher scan efficiency than two sided.	Scan effiency still fairly low. Difficult to align. Difficult to view calibration sources.	
Two Sided Variable Speed Rotating Mirror	Relatively simple mechanism. 50% scan efficiency. View of calibration system on each scan.	Possible uncompensated momentum. Larger motor. More complex control electronics.	

studies of MODIS-T. The whiskbroom scan technique was found to be the most suitable due to the required wide cross track swath. A two mirror compensating/active scan configuration with a near

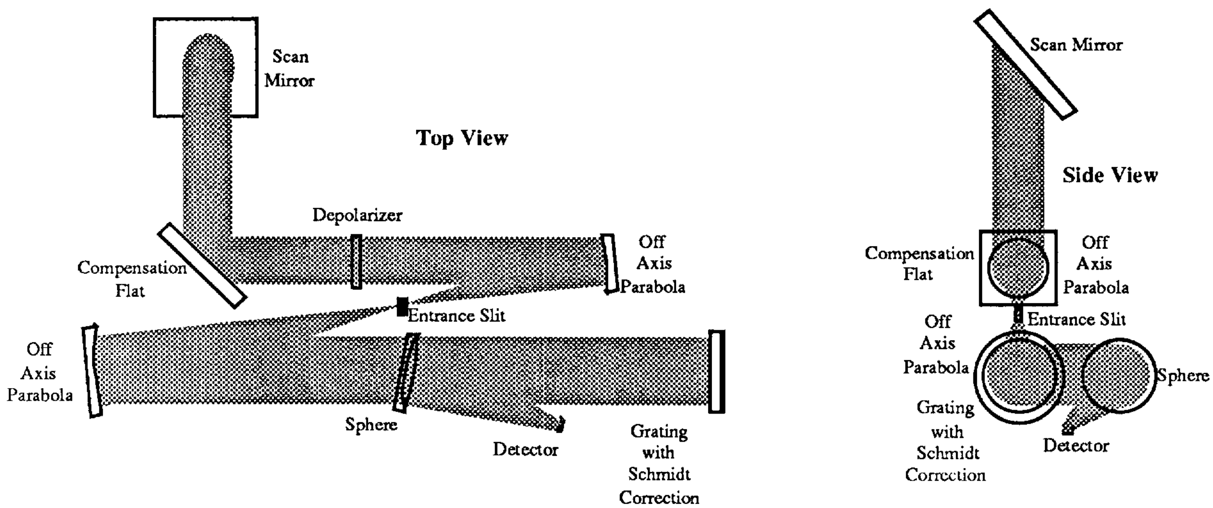

Figure 2. Baseline Optical System.

Table 3
Spectral Separation Techniques Considered

Technique	**Advantages**	**Disadvantages**	**Reason For Choice**
Stripe Filters	Low polarization. Simple optical system.	Difficult fabrication and alignment. Bandcenter shift with along track spatial detectors. History of filter characteristics changing with time. Staggered detector array needed to achieve spatial registration of spectral channels. Difficult on orbit calibration.	
Wedge Filter	Low polarization. Simple optical system. Rugged filter.	Bandcenter shift with along track spatial detectors. History of filter characteristics changing with time. Staggered detector array needed. Difficult on orbit calibration.	
Dispersive Approach (Prism)	All spectral bands of a spatial element sampled simultaneously. Long term spectral stability. Low polarization. Easier on orbit calibration.	More complex optical system than stripe or wedge. Tight optical fabrication and alignment tolerances. High image distortion. Low effective optical throughput.	**Dispersive Approach (Grating)**
Dispersive Approach (Grating)	*All spectral bands of a spatial element sampled simultaneously. Long term spectral stability. Low polarization. Fabrication. Easier on orbit calibration.*	*More complex optical system than stripe or wedge. Moderate polarization. Zero order and second order.*	*All spectral bands of a spatial element sampled simultaneously. Long term spectral stability. Low polarization. Fabrication. Easier on orbit calibration.*

normal incidence spectrometer was found to be the best system especially from a polarization point of view. Table 2 compares some of the scan techniques which were considered.

The cross track scan mechanism selected is a single speed, continuously rotating device utilizing a two sided mirror. The scan time (180° rotation of the mirror) is 4.54 seconds which takes into account orbital and timing variations and insures that the 33 km wide swaths are always slightly overlapped. The scan mirror assembly can be rotated about the center of the scan mirror 90° forward and 50° aft by a fore/aft tilt mechanism (67° forward to view the moon, 90° forward for launch stowing).

2.2 Baseline Optical Design

The baseline MODIS-T optical design is a grating type reflecting Schmidt imaging spectrometer (see Fig. 2). Several techniques were considered for spectral separation in the MODIS-T instrument. Table 3 is a comparison of these techniques. The dispersion approach utilizing a grating was selected. A parallel study is presently underway to further investigate the feasibility of using a prism approach.

The fore optics consist of a decentered parabola which is also the entrance pupil. The instantaneous field of view of the instrument is defined by a physical entrance slit. A decentered parabola serves as the spectrometer primary mirror and recollimates the light. This mirror forms a confocal parabola with the fore optic parabola. The dispersing element is a conventionally ruled plane grating with about 118 lines/mm. The grating also serves as a reflective Schmidt corrector which has a fourth order aspheric term added to the plane grating substrate. A Schmidt spherical mirror is located at the radius of curvature from the grating and centered along the first diffraction order of the central wavelength.

The detector array is curved in one direction (within plane) to reduce spatial distortion. The maximum magnitude of the curve is about 0.1 pixels. An order sorter filter is located over the detector array since the wavelength range is greater than an octave. The baseline optical system linear polarization sensitivity approaches 2.3%. To meet the 2.3% requirement a depolarizer is located in collimated space. This depolarizer degrades the optical system MTF, however it is not an MTF driver.

The entire optical system and detector mounts to a common optical baseplate. Thermal analysis of this system has shown that there is adequate MTF and pointing knowledge margin for the entire optical and support structure system to be fabricated from aluminum, which is the baseline material.

2.3 Detector and Radiometric Analysis

The baseline detector is a 34 (spectral) by 30 (spatial) photodiode interline CCD (see Fig. 3). The pixel size is 220.5 μm (spectral) by 161.7 μm (spatial). There are two output ports with separate analog processing electronics and 12 bit A/D converters. The CCD width of the detectors in each spectral channel is determined by the required charge handling capacity. Anti-blooming and drain structures are implemented on the detector. With the dual operating mode, 1.13 ms are used for the ocean

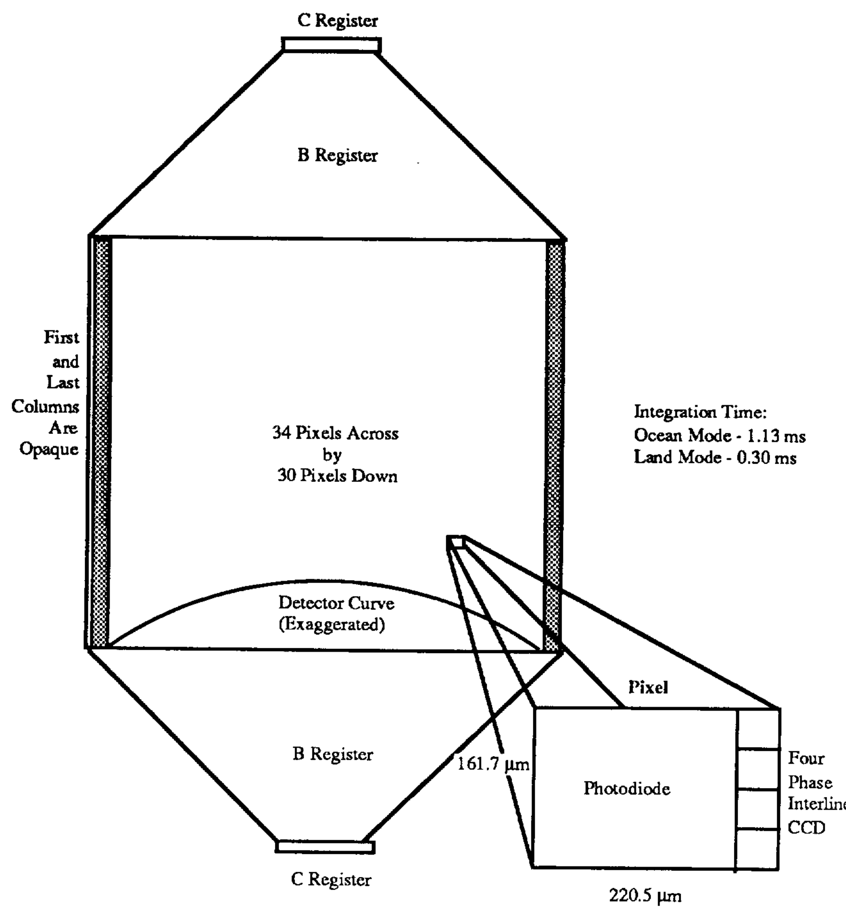

Figure 3. Detector Layout.

integration time (100% of dwell time) and 0.30 ms are used for the land integration time. The drain structure is used for two purposes. First, while in the ocean mode, the MODIS-T instrument will at times image clouds with radiances over five times the saturation of the CCD. The drain structure will remove the excess electrons from the photodiode, thereby eliminating "image memory" problems. Secondly, the drain structure will be used in the land mode to remove electrons from the photodiode during the 0.83 ms that the detector does not integrate. The detector chip is mounted to a thermal electric cooler and will be maintained in orbit at 253 ±0.1K.

Radiometric analysis of the instrument performance utilizes the standard signal to noise ratio equations:

$$\mathbf{S} = \mathbf{R} \cdot \Delta\lambda \cdot \frac{\lambda}{\mathbf{hc}} \, \mathbf{A_o} \cdot \Omega_\mathbf{d} \cdot \mathbf{T_o} \cdot \mathbf{T_i} \cdot \eta$$

and

$$\mathbf{SNR} = \frac{\mathbf{S}}{\sqrt{N_{shot}^2 + N_{read}^2 + N_{quantizer}^2}}$$

Where:

S = Integrated sensor signal [electrons]

R = Spectral radiance $\left[\frac{\text{mW}}{\text{cm}^2 \cdot \text{ster} \cdot \mu\text{m}}\right]$

$\Delta\lambda$ = Bandwidth of spectral channel [μm]

$\frac{\lambda}{hc}$ = Number of photons per unit energy $\left[\frac{\text{photons}}{\text{W} \cdot \text{sec}}\right]$

A_o = Entrance aperture area [cm^2]

Ω_d = Pixel instantaneous solid angle [ster]

T_o = Optical transmission

T_i = Integration time [sec]

η = Quantum efficiency $\left[\frac{\text{electrons}}{\text{photon}}\right]$

A interactive spreadsheet was developed to calculate the signal to noise ratios (SNR), determine the instrument entrance aperture area, determine the land integration time and to size the photodiode, CCD and dead space for each spectral channel. Inputs to the spreadsheet include at instrument radiances and SNR requirements, optical transmission, quantum efficiency, read noise, dark current and pixel solid area. The worst case land or ocean maximum radiances size and optimize each spectral channel (ocean uses the full integration time - land integration time is a variable). The photodiode width determines the spectral channel full width half maximum bandwidth of each channel. The CCD area determines the electron full well capacity. The land maximum radiances determine the land quantizer noise. Using land typical radiances, the land integration time is varied until the land SNR requirements are met in every channel. The detector photodiode/CCD size are reoptimized and the quantizer noise recalculated every time the land integration time is changed. The ocean maximum

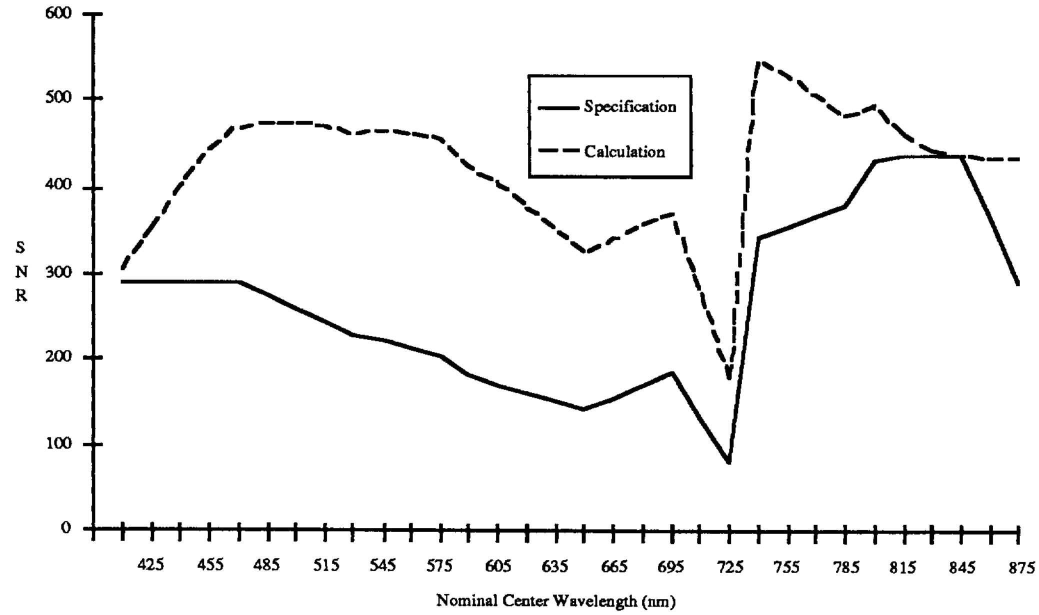

Figure 4. Land Signal-to-Noise Ratio and Requirements.

radiances determine the ocean quantizer noise. Ocean maximum radiances are then used to determine ocean SNRs. The instrument entrance aperture area is adjusted based on the ocean SNRs and the entire spreadsheet calculation run again until ocean and land SNR requirements are met.

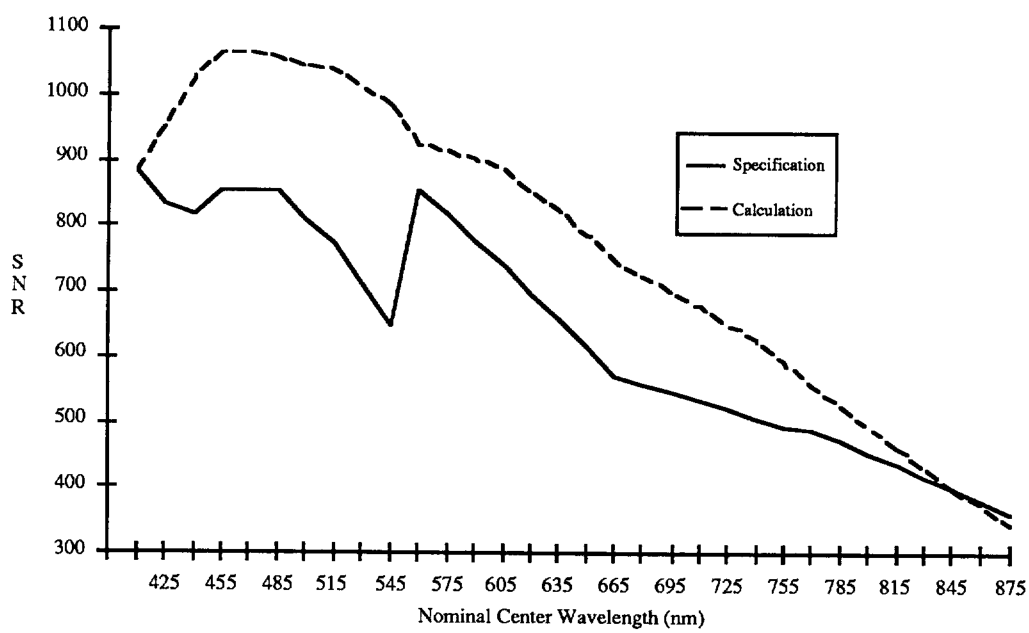

Figure 5. Ocean Signal-to-Noise Ratio and Requirements.

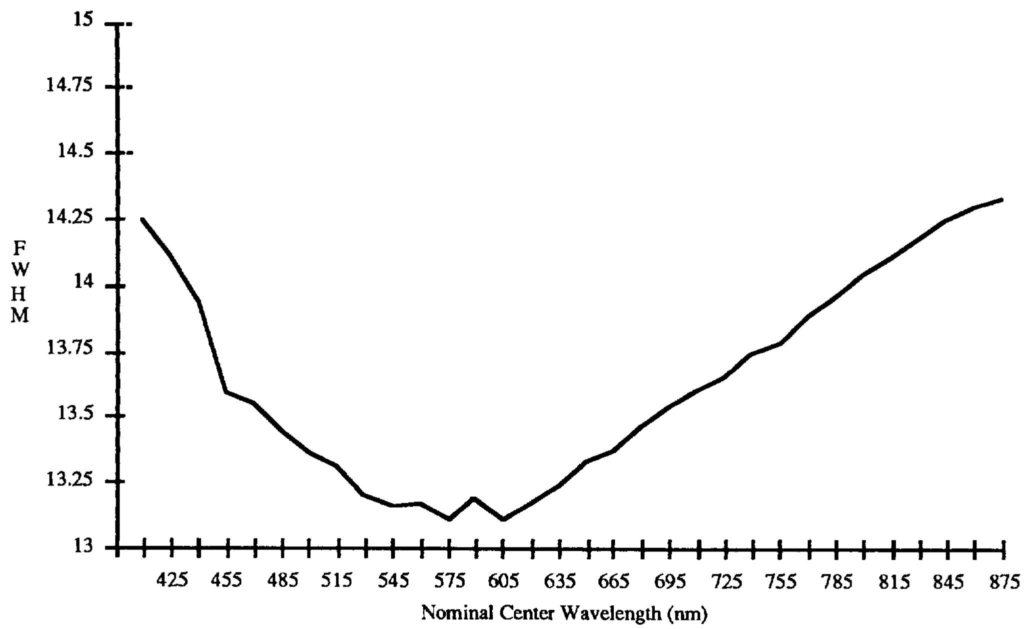

Figure 6. Full Width Half Maximum Bandwidths.

Figures 4 and 5 contain plots of the land and ocean required and calculated SNRs. Figure 6 contains a plot of the calculated bandwidth of the 30 spectral channels. Figure 7 contains a plot of the CCD full well utilization which shows that the ocean drives the first few spectral channels and the land drives the remaining channels.

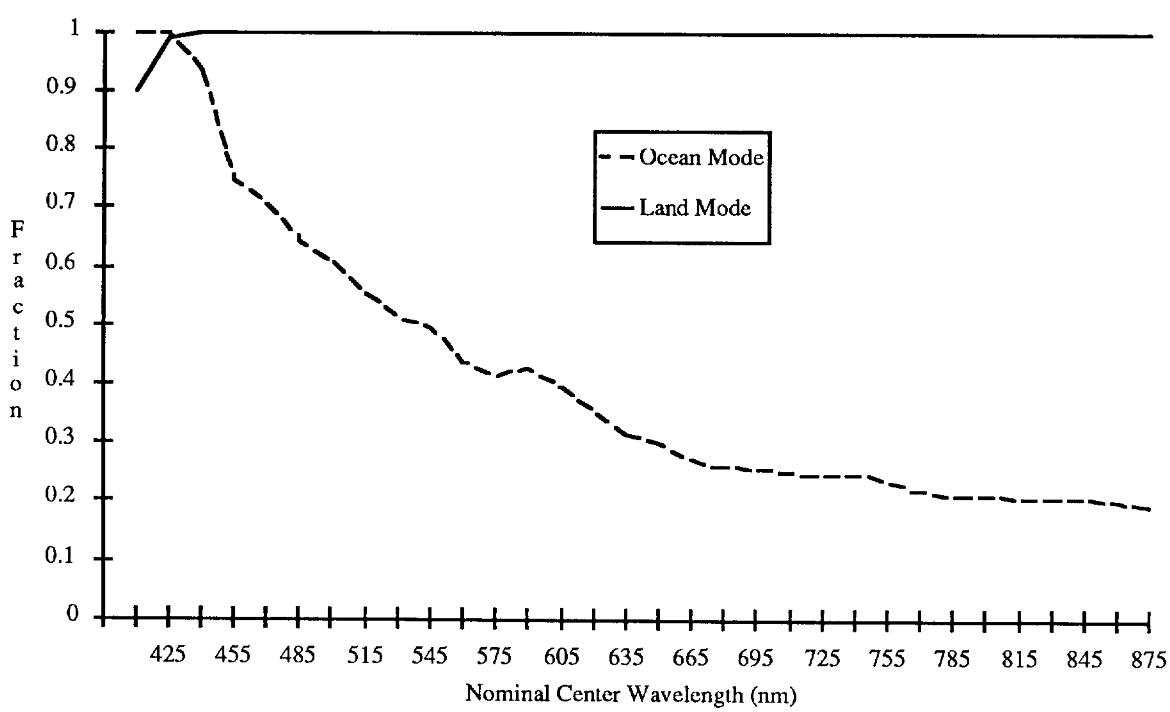

Figure 7. CCD Full Well Utilization.

2.4 In Flight Calibration

Several methods will be used in flight to calibrate the MODIS-T instrument including artificial sources, electronic voltage levels and solar radiation. A dual integrating sphere will be viewed on the back scan of every rotation of the scan mirror. Solar radiation and a RF excited helium lamp can feed flux into these spheres. The sphere entrance port is located on the sun side of the platform, perpendicular to the earth and the velocity direction of the platform. The sun rotates about a 22° angle to this port from the south pole to the north pole (see Fig. 8). Detectors located within the integrating sphere monitor the output flux. Spectral lines from the helium source are used to monitor the spectral alignment of the instrument. There are five spectral lines in the helium source which fall in the MODIS-T spectral range. The output radiance from the integration sphere is collected by a Winston cone and imaged by a lens on to a diffuser plate located below the scan mirror. This diffuser plate tilts with the scan mechanism. Twenty detector frames of data can be taken of this diffuser plate on every back scan. An aperture wheel located an the sphere entrance port provides three different size apertures and a closed position. The scan mirror also views a dark target on the back scan and fifty frames of zero flux data are taken. Three levels of voltages are switched into the front end of the analog signal processing chain during the back scan. Two hundred samples of the three voltage levels are collected.

A full aperture diffuser plate can be deployed when the spacecraft is at the south pole. In the calibration position the plate will be located about 50 cm above the instrument, within the instrument

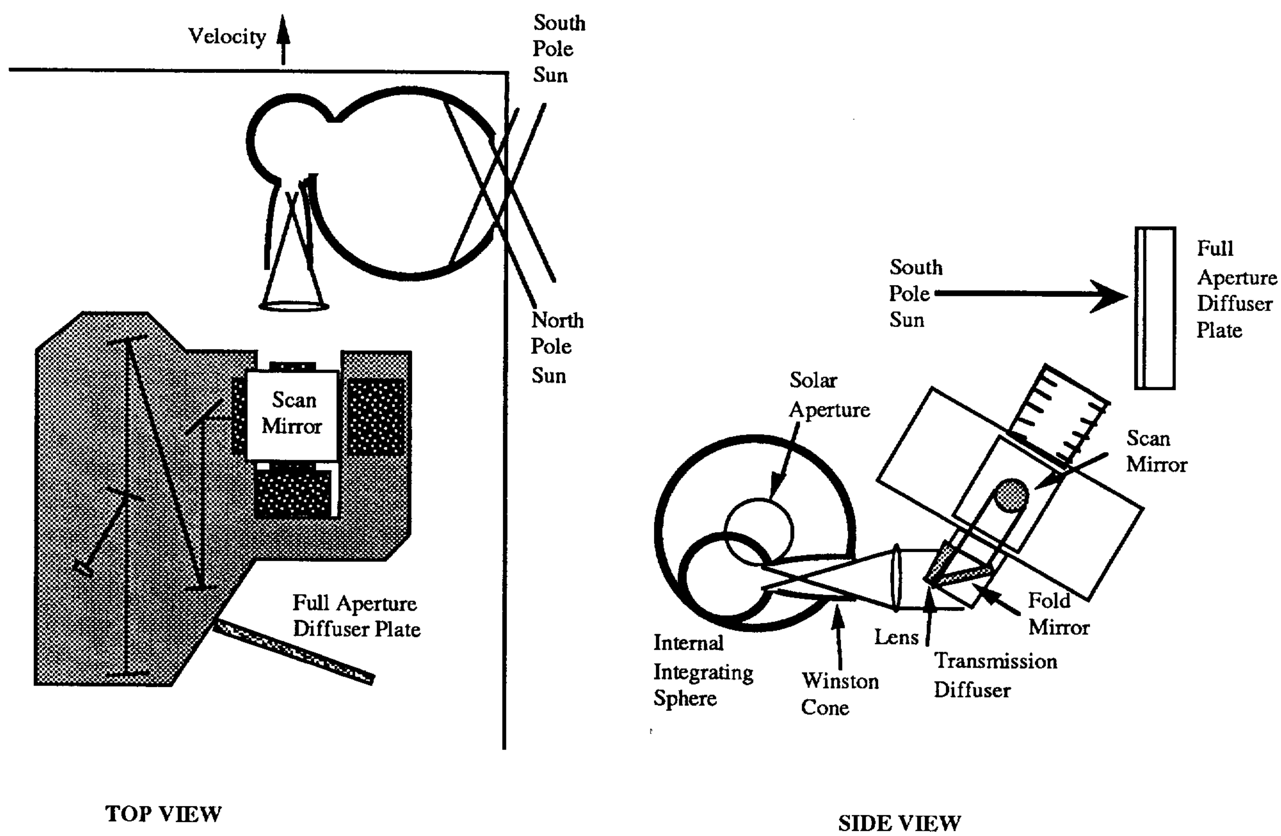

Figure 8. Flight Calibration System.

field of view with the scan mirror at the 30° aft tilt position and orientated normal to the sun. One half of the diffuser surface has a reflectance of about 90% (land use), the other half has a reflectance of about 25% (ocean use). One hundred frames of solar diffuse radiation data will be collected for each earth scan. The diffuser plate will be stowed while not in use for contamination protection.

2.5 Electronics

All the electronics except for the detector are fully redundant. There are a total of six electronic boxes: command and data handling, power distribution unit, mechanism control, detector drive, analog processing and detector power supply. The command and data handling (C & DH) unit collects and transmits the image data, the housekeeping and calibration data. It makes instrument temperature, voltage and current measurements and provides platform ancillary data. The C & DH provides command verification and execution, and timing for the instrument. The power distribution unit converts the platform provided 120 volt DC to voltages used by the instrument and distributes the power to secondary convertors located with the subsystem enclosures. The mechanism control electronics run the four instrument mechanisms (scan, tilt, diffuser, aperture wheel) as well as three launch locks. The detector drive electronics provide the timing and clock drivers to operate the four

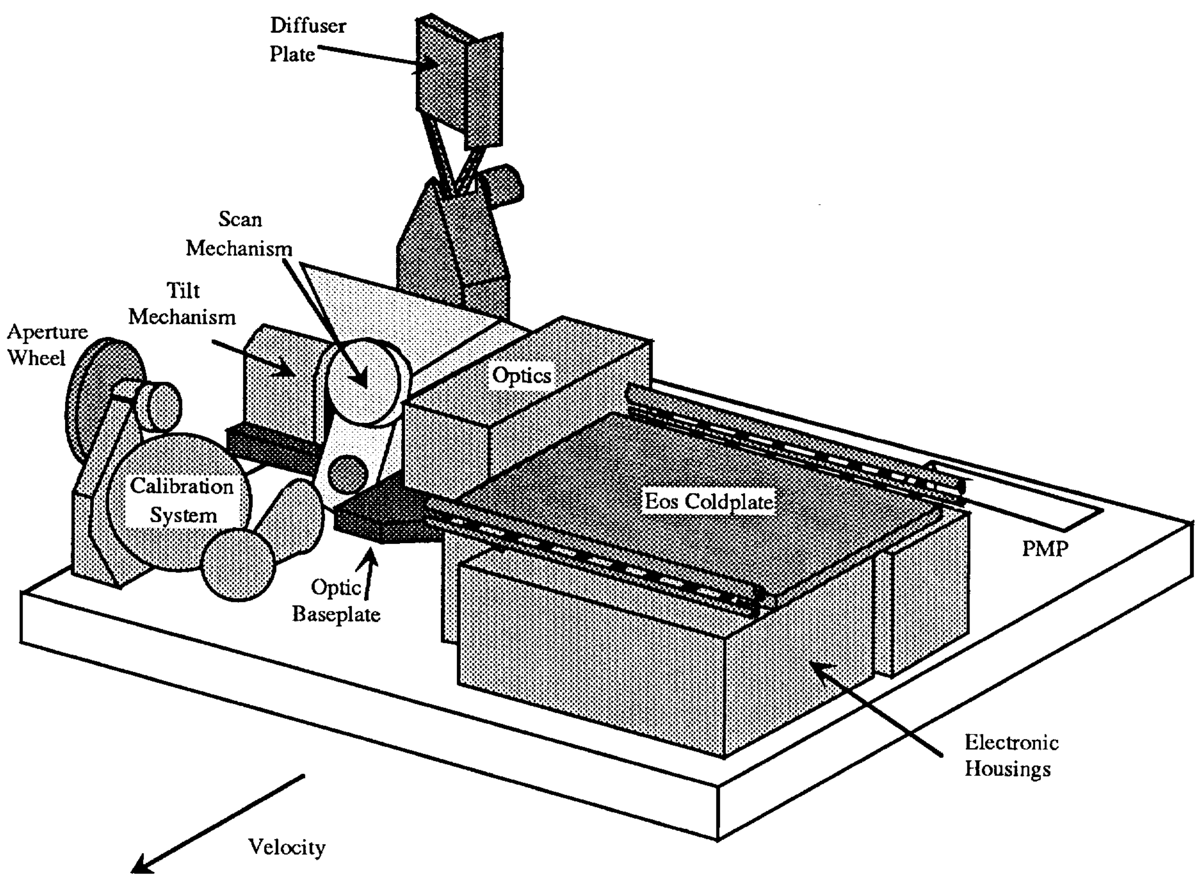

Figure 9. MODIS-T Instrument Mounted to the Eos Payload Mounting Plate.

phase photodiode CCD in both the land and oceans modes. The analog signal processing electronics provides amplification, correlated double sampling and 12 bit linear analog to digital conversion of the detector array output.

Thermal analysis was performed to determine the optimum method for maintaining the electronic packages within their proper operating temperature ranges. The platform provided capillary pumped loop cold plate and various fin radiators were analyzed. The cold plate was found to be superior. The electronics boxes will mount directly to but thermal isolated from the Eos platform The cold plate will mount to the top of the electronic housings. All electronic housings are 25.4 cm high. Figure 9 depicts the MODIS-T instrument as mounted to the Eos Payload Mounting Plate (PMP).

3. MODIS-T OPERATION MODES

MODIS-T will collect earth scan data only during the sunlit portion of the orbit. The shadow portion of the orbit will be used to obtain internal calibration data from dark targets and the RF excited helium source. The MODIS-T uses five operation modes: an ocean mode, a land mode, BRDF mode, a radiometric calibration mode and a spectral calibration mode. The ocean mode will be the predominately used mode.

In the ocean mode, the instrument will tilt to the 20° aft position during the shadow portion of the orbit. At the sub-solar point of the sunlit orbit, the instrument will tilt to the 20° forward position. This scenario will be then repeated every orbit. In this mode, when the spacecraft is crossing the south pole, the instrument can tilt to the 30° forward position and the solar diffuser can be deployed and solar data collected. The detector system will use 100% of the available dwell time.

In the land mode, the instrument can be titlted to any desired position for data taking. The detector system will be set to integrate for 0.30 ms. Solar calibration can be performed at the south pole.

In the BRDF (Bidirectional Reflectance Distribution Function) mode, a single scan will be made at a desired forward look angle of 50 degrees or less forward. During the MODIS-T backscan, the look angle will be decrease by the along track FOV and the original earth line scanned again. This scenario will be repeated until the desired aft look angle (≥50°) is reached. The detector system will be set for the land mode.

In the radiometric calibration mode, the dual solar integration sphere aperture wheel will be commanded to one of the open positions. Data will be obtained for several scans of the integration sphere. The aperture wheel will then be rotated to the next smaller size opening and several scans of data taken. The above will then be repeated for the smallest size aperture opening. This mode can be implemented only on the the sunlit portion of the orbit and can be in conjunction with any of the land or ocean modes in which the instrument tilt is within the range of forward 30° to aft 20°.

In the spectral calibration mode, the RF excited source will be turned on and data will be obtained for several scans of the integration sphere. This mode can be implemented on the sunlit or dark portion of the orbit. On the sunlit portion of the orbit, it can be in conjunction with any of the land or ocean modes in which the instrument tilt is within the range of forward 30° to aft 20°.

4. ACKNOWLEDGEMENTS

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