An Instrument Concept for Atmospheric Infrared Sounding from Medium Earth Orbit

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Medium Earth Orbit (MEO) offers a unique vantage point for atmospheric infrared sounding. The orbit allows the entire globe to be covered each day with one satellite. The orbit is slow enough to allow multiple views of a single target to be made on each pass. This paper discusses the advantages in coverage and revisit rate from MEO for a particular concept for a Medium Earth Orbit Infrared Atmospheric Sounder (MIRIS). The requirements for this instrument in terms of spectral range, spatial resolution, field of view, and calibration are presented as well as the radiometric performance expectations.

I. Introduction

NASA and NOAA are in the planning stages for their future satellite systems to address weather and climate needs of the next two decades. As part of this effort, JPL has been tasked to investigate the use instruments in Medium Earth Orbit as a potential way of improving performance and/or saving program costs. This paper addresses the requirements for a combined imager and sounder to fly on the MEO platform to address a wide range of requirements for weather and climate. The requirements are well within the technology available today. Performance predictions are also presented that meet the majority of requirements anticipated from the system.

Wide field low earth orbit (LEO) imagers like the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS)[1] on Aqua acquire one image per day of any point on the ground. For the GEO instruments revisit is only limited by the acquisition time of the sensor and can be as much as once every 15 minutes, but coverage is extremely limited. New MEO satellites at an altitude of 10,500 km have been studied that provide full global coverage, and since the orbit is slower more scans of the image can be performed in a given pass of the satellite. The additional observations allow motion to be observed in the data products and should improve regional forecasts models worldwide.

The MEO instruments can be smaller than GEO since the orbit is more than 3x closer allowing smaller apertures for a given resolution. Instrument design requirements and performance predictions are presented for an advanced grating Medium Earth Orbit Infrared Imaging Spectrometer (MIRIS) to meet requirements of the weather and climate communities beyond 2010. We find that the design requirements for MIRIS are well within the capabilities for remote sensors currently in existence and expected in the next decade.

II. Requirements

Although there are no "official" requirements for MIRIS, we can use performance of prior systems and requirements for known future systems in the conceptual design of the instrument. MODIS and AIRS have set a standard for imager and sounder performance that form the basis of numerous important NASA earth science investigations today. The GOES-R Hyperspectral Environmental Suite (HES) and Advanced Baseline Imager (ABI) will provide a similar set of capabilities as their LEO counterparts when launched in 2012.

A. Orbit Requirements

The context of this study is limited to MEO orbits. The MEO orbit we selected is a 10,400 km orbit which corresponds to a drop in the radiation levels in this region. In this paper, we use a 55° inclination to provide global coverage including the polar regions. A single satellite is considered for now. Additional satellites will improve coverage times, and is discussed in a companion paper[2]. A map of the swath covered by this orbit is shown in Fig. 1 along with a single orbit from LEO and the coverage from GEO. In these figures, we limit the Local Zenith Angle

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(LZA) to 50°; beyond this the retrievals will be degraded considerably. We considerably better coverage with the MEO orbit than either the LEO or GEO options. Table 1 lists the orbital imaging parameters for the system.

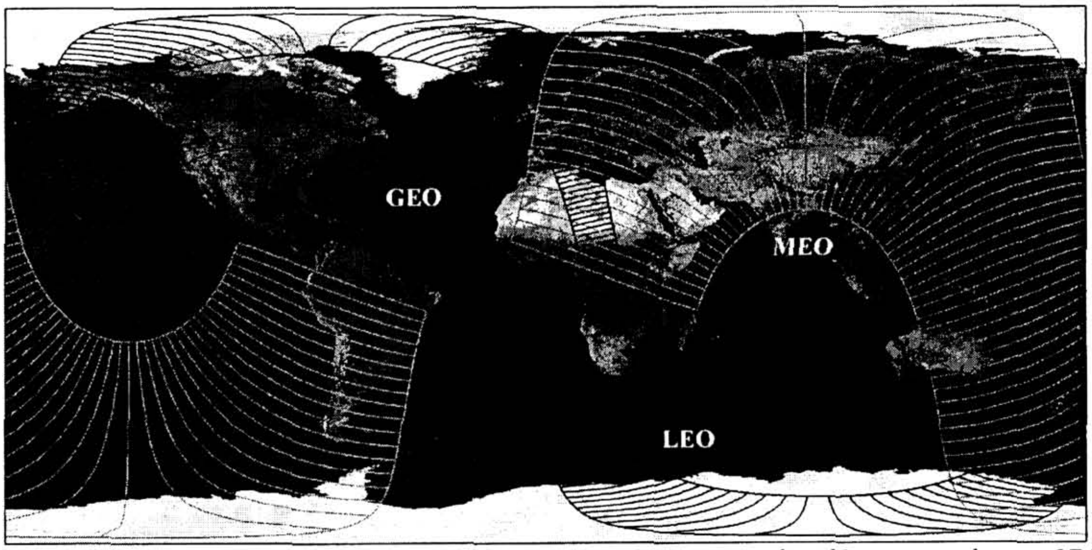

Figure 1. Coverage for a single orbit from LEO, MEO and GEO. *Swath width corresponds to an LZA of ±50°.*

B. Imaging Requirements

The basic requirements for imaging are derived from a wide variety of sources. Firstly the HES requires 4 km nominal spatial resolution and ABI requires 1km. Secondly, MODIS infrared bands have a 1km spatial resolution and AIRS has a 13.5 km spatial resolution. Our objective is to *provide the highest spatial resolution* possible while minimizing instrument size. We are also providing "hyperspectral" capability at this spatial resolution so we must consider data rate. We selected 2km as the design spatial resolution as a compromise. This results in a modest aperture size of 20 cm and keeps the instantaneous data rate under 1Gbps. The swath width of 7940 km corresponds to an LZA just above the 50° requirement. The scan time is 2 minutes, which is very long compared to the 1.47s and 2.67 seconds of MODIS and AIRS respectively. This may imply tight pointing requirements on the spacecraft Our resulting dwell time of 40 ms is long enough to provide good sensitivity as will be shown later in this paper. Scanning a 2000 x 3000 km region (hurricane and surrounding region) is performed in under 10 minutes at full spectral resolution. Full disk can be achieved in 1.8 hrs at full spatial and spectral resolution with this approach. Faster scan rates are possible with spectral and spatial aggregation, or with a larger Focal Plane Array.

Table 1. Orbit and Imaging Requirements for MIRIS

Orbit		
Orbit Altitude	10400	km
Orbit Inclination	55	deg
Orbital Period	6.01	hrs
Imaging (IR)		
Ground Projection	2	km
IFOV	0.19	m rads
Dwell Time	0.04	s
Cross-Scan Swath Width	0.71	±deg
Cross-Scan Swath Width	256.06	km
Along-Scan Swath Width	17.78	±deg
Along-Scan Swath Width	7937.21	km
LZA	53.43	±deg
Scan Efficiency	80	%
Scan Time	129.06	s
Scan Rate	0.28	deg/s
1000x1000km	1.57	min
2000x3000km	9.68	min
Full Disk	1.80	hrs

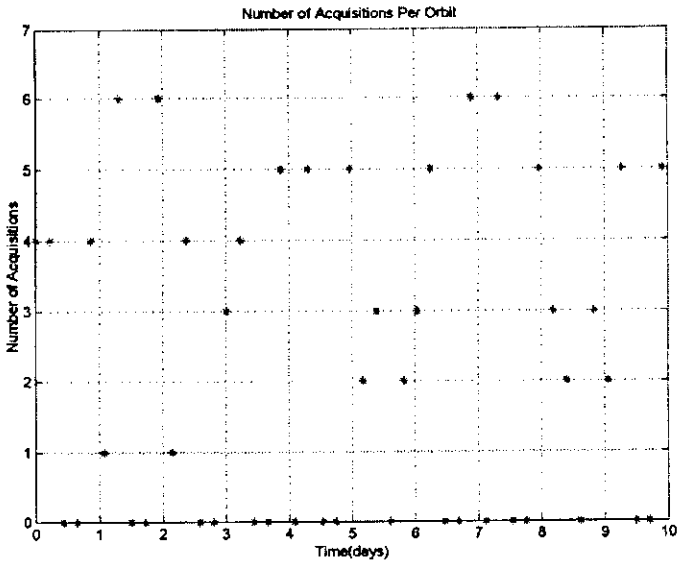

Figure 2. MIRIS Revisit Intevals. *The number of acquisitions of a 2000 x 3000 km region is plotted for each orbit over a 10 day period.*

Figure 2 shows results the number of acquisitions of a 2000 x 3000 km region for every orbit in a 10 day period. We see that the MIRIS in the MEO orbit gives as many as 6 acquisitions for a single orbit, and up to two encounters per day. This is significantly better than LEO instruments which are lucky to get one good image of a region this size per day. GEO orbits can do better than this, but for a very small region. With the multiple acquisitions, of sounder data, a three dimensional movie of the temperature profile and water vapor profiles can be made. This will allow wind speed to be calculated as well as provide information on the dynamics of the storm.

C. Spectral Requirements

Table 2 gives the spectral and spatial requirements for HES and the corresponding derived requirement for MIRIS. HES spectral range and resolution were selected because they are similar to the AIRS spectral requirements and, through band synthesis, we can generate bands for MODIS and ABI. The HES band 4 and 7 are not included because we can synthesize them with the spectrometers from the corresponding spectral region. Optical requirements to meet the MIRIS requirements below are presented in the next section.

Table 2. HES Spectral and Spatial Requirements and MIRIS Derived Requirements.

HES Design Requirements

Band	Number	From (cm^{-1})	To (cm^{-1})	From (um)	To (um)	Resolution ($\lambda/\Delta\lambda$)	Number of Channels	GSD (km)
LWIR	1	650	1200	8.33	15.38	1329	-	4.00
MWIR Opt1	2	1650	2150	4.65	6.06	1520	-	4.00
MWIR Opt2	2	1210	1740	5.74	8.26	1180	-	4.00
SWIR	3	2150	2250	4.65	4.44	880	-	4.00
VIS	4	NA	NA	0.52	0.70	0.18 um	1	2.00
Refl. Solar < 1	5	NA	NA	0.4	1.00	43	-	0.30
Refl. Solar > 1	6	NA	NA	1	2.29	45	-	1.20
LWIR	7	813	893	11.2	12.8	0.8 um	1	2

MIRIS Instrument Requirements

Band	Number	From (cm^{-1})	To (cm^{-1})	From (um)	To (um)	Resolution ($\lambda/\Delta\lambda$)	Number of Channels	GSD (km)
LWIR	1a	650	833	12.00	15.38	1062	573	2.00
LWIR	1b	833	1200	8.33	12.00	1237	941	2.00
MWIR Opt2	2	1210	1740	5.75	8.26	1162	858	2.00
SWIR	3	2150	2720	3.68	4.65	1052	497	2.00
Refl. Solar < 1	5	NA	NA	0.40	1.00	603	1055	0.50
Refl. Solar > 1	6	NA	NA	1.00	2.22	343	531	1.00

III. Instrument Approach

The MIRIS will be similar to most other sensors involving a scanner, telescope, spectrometer, electronics, and thermal control system. The thermal control is probably the most novel aspect that results from the MEO orbit. The position of the sun relative to the spacecraft changes with every orbit, complicating the design. The thermal design of the MIRIS instrument is under development and results are not presented at this time. The following sections present requirements and design considerations for each of the major modules of the MIRIS.

D. Scanner

We expect the scanner to be a 45 degree "barrel roll" in the E/W scan direction as for AIRS. Because this produces an image rotation, we are going to require that all channels image through the same entrance slit. The optical point spread function will rotate with scan as it does on AIRS currently. This should not affect retrievals since all channels will rotate together. Polarization effects with image rotation have been characterized for AIRS (ref. 4).

Scan ranges, rates and efficiency assumptions are given in Table 1. These requirements should be easily met by modern scan control systems. The scan controller should be easily programmable, to allow a change in scan range. This will permit more frequent images to be made over a smaller area. Scan rate should also be programmable to allow faster acquisition at reduced SNR. The reduced SNR from the shorter dwell times can be recovered using channel aggregation (as for the MODIS applications).

E. Telescope

Table 3 gives the diffraction limited aperture vs. orbit altitude for a 2 km and 10 km footprint. To achieve 2 km spatial resolution from GEO, requires a 65 cm aperture, while from MEO requires only a 19 cm aperture. This factor of 3 in aperture scales to significant cost savings in the instrument. Optical elements are smaller, calibrators and test equipment are smaller. The apertures were calculated by requiring a system MTF of 0.3 at Nyquist (as for MODIS), assuming diffraction limited performance of the optical system.

The telescope selected for MIRIS is a 20.0 cm aperture f/2.6 with a 3.07x magnification. Special athermal materials will be required. The FOV is kept small, to ±0.71°; this should keep the size of the secondary small, potentially allowing a smaller centered design.

Table 3. Diffraction Limited Aperture vs Orbit Altitude

Orbit	Altitude (x1000km)	2.00 km Aperture (cm)	10.00 km Aperture (cm)	50degLZA Swath (±deg)	Swath (km)
LEO	0.705	1.29	0.47	43.61	1421.73
MEO	10.4	19.03	6.97	16.93	7362.49
GEO	35.8	65.51	23.98	6.65	9650.75

F. Spectrometer

Requirements for MIRIS can be met using a grating spectrometer system. The AIRS approach uses a single grating to achieve the entire spectral range, with a single IFOV dispersing into line arrays for each spectral region. MIRIS requires 128 IFOV's for the infrared bands, dispersing on to four individual area array focal plane assemblies. Table 4 gives the spectrometer design requirements for the MIRIS optical system. There are six different spectral regions, but the grating parameters are chosen to allow sharing a spectrometer using multiple grating orders. One approach developed by JPL, shown in Fig. 3, uses two IR Offner spectrometers, and one each for Reflective Solar Bands (RSB) < 1 um and > 1 um. The entrance slit of 0.592 mrads is the cross-scan IFOV dimension, equaling the along-scan IFOV identified in Table 1 times the 3.08x magnification of the telescope.

G. Focal Plane Assemblies

There are a large number of spectral channels in the MIRIS instrument. Table 5 shows the MIRIS Focal Plane Assembly (FPA) geometry. All of the IR arrays have 128 elements in the "spatial direction" with 100 um pixels. These can be replaced by 256 elements of 50 um pixels allowing a square pixel geometry and oversampling spatially. Similarly for the VIS, and the SWIR FPAs, the spatial direction can be oversampled by 2x to allow the pixel geometry to match the spectral direction. This oversampling facilitates resampling if there is an alignment

Table 4. MIRIS Grating Spectrometer Derived Requirements. *Six spectral regions use two gratings in multiple orders. Detectors are half the size of the entrance slit.*

MIRIS Spectrometer Requirements Objective		Spect1 LW 1a	Spect1 LW 1b	Spect2 MW2 2 (option 2)	Spect2 SW 3 + Goal	Spect3 RSB 1 5	Spect3 RSB 2 6
vn_min	(cm-1)	650	833	1210	2150	10000	4500
vn_max	(cm-1)	833	1200	1740	2720	25000	10000
wl_min	(μm)	**12.00**	**8.33**	**5.75**	**3.68**	**0.40**	**1.00**
wl_max	(μm)	**15.38**	**12.00**	**8.26**	**4.65**	**1.00**	**2.22**
Sampling	(-)	2323	2607	2387	2124	1231	700
Resolution	(-)	1062	1237	1162	1052	603	343
Ruling	(μm)	**40**	**40**	**20**	**20**	**20**	**20**
Order	(-)	**2**	**3**	**2**	**3**	**2**	**1**
Blaze WL	(μm)	27.39	30.51	14.01	12.49	1.40	1.61
Blaze Angle	(deg)	21.86	24.09	22.31	20.13	2.71	3.10
Grating Inc	(r)	0.79	0.79	0.79	0.79	0.79	0.79
Avg Disp	(rads/μm)	0.0502	0.0758	0.1008	0.1509	0.1300	0.0643
FOV	(deg)	9.720	15.955	14.539	8.429	4.470	4.503
IFOV_det	(mr)	**0.296**	**0.296**	**0.296**	**0.296**	**0.074**	**0.148**
IFOV_slit	(mr)	**0.592**	**0.592**	**0.592**	**0.592**	**0.148**	**0.296**
EFL	(cm)	16.90	16.90	16.90	16.90	16.90	16.90
F-Number	(-)	**2.60**	**2.60**	**2.60**	**2.60**	**2.60**	**2.60**
Aperture Size	(cm)	6.50	6.50	6.50	6.50	6.50	6.50
Diff'n Res.	(mr)	0.2570	0.1909	0.1315	0.0782	0.0131	0.0302
det_Size	(μm)	**50.00**	**50.00**	**50.00**	**50.00**	**12.50**	**25.00**
No. Channels	(-)	573	941	858	497	1055	531
FPA-Length	(cm)	2.87	4.71	4.29	2.49	1.32	1.33

problem between spectrometers. If SNR is a problem, additional dwell time can be obtained by increasing the array dimension in the cross-scan direction to slow down the scan and increase dwell time. The optics will need to accommodate the additional field of view, however and this may impact the telescope design. For the analysis presented here, all IR FPAs are assumed to be HgCdTe, operating at 60K. The SWIR FPA is assumed to be HgCdTe also operating at 60K, but the VIS FPA is assumed to be silicon detector technology bumped to silicon ROICs operating at 0 C.

Alternate FPA technology including QWIP infrared detectors[4] and CCDs for the RSB < 1 um should be considered for future designs. By allowing a larger array format, or cooling detectors to a lower operating temperature these technologies indeed become viable.

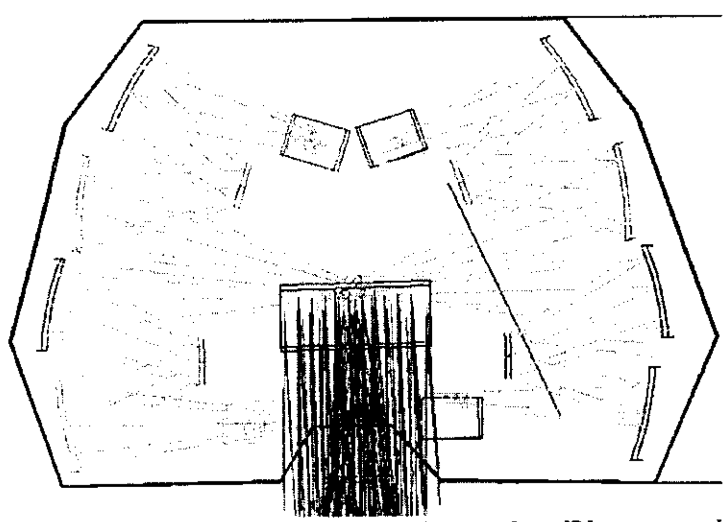

Figure 3. 4-Candidate Spectrometer Approach. *JPL conceptual design uses 4 Offner spectrometers, one for bands 1a and 1b, another for 2 and 3, and one each for spectrometers 5 and 6.*

Table 5. Focal Plane Assembly Geometry

FPA		LW	LW	MW	SW	RSB 1	RSB 2	
Detector Size	Spatial	100	100	100	100	25	50	um
	Spectral	50	50	50	50	13	25	um
Number	Spatial	128	128	128	128	512	256	
	Spectral	573	941	858	497	1055	531	
Length	Spatial	1.28	1.28	1.28	1.28	1.28	1.28	cm
	Spectral	2.87	4.71	4.29	2.49	1.32	1.33	cm

H. Electronics

The main electronics functions are control of the scan mirror assembly and aperture doors, control of the active cooler for the FPAs, analog and digital supply and readout of the FPAs, gains, offsets, radiation circumvention and formatting. There are no active elements in the spectrometer, and no need for oversampling the FPA readout or on-board FFTs. Due to the large number of channels, we indeed expect the data rate to be high (Table 6), however pixel has a unique spectra without any signal processing. Radiation circumvention, as performed on AIRS[5], mitigates noise spikes caused by radiation in the South Atlantic Anomaly and should be part of any future system

Table 6. Data Rate Calculation

Parameter		LW2	LW1	MW	SW	RSB1	RSB2	Total
vn_min	(cm-1)	650	833	1210	2150	10000	4500	
vn_max	(cm-1)	833	1200	1740	2720	25000	10000	
wl_min	(μm)	12.00	8.33	5.75	3.68	0.40	1.00	
wl_max	(μm)	15.38	12.00	8.26	4.65	1.00	2.22	
Spectral Ch's		573	941	858	497	1055	531	4456
Spatial		128	128	128	128	512	256	
Integration Time	(s)	0.04	0.04	0.04	0.04	0.01	0.02	
Bits		14	14	14	14	14	14	
Rate	(Mbps)	**25.69**	**42.17**	**38.42**	**22.28**	**756.14**	**95.20**	**979.90**

IV. Performance Predictions

Spectral resolution and radiometric sensitivity were calculated for the design presented above. Spectral resolution is determined by multiplying the convolved optical IFOV with the dispersion of the grating. The IFOV is calculated by convolving the rectangular entrance slit with the rectangular exit slit and the diffraction limited point spread function. Results are shown in Fig. 4 and compared to the measured AIRS response and the requirements for HES.

Figure 5 shows the NEdT compared to AIRS and HES. This is the high spectral resolution NEdT, i.e. full spatial and spectral resolution. The performance of this design is comparable to AIRS and meets the majority of the HES requirements. The LWIR noncompliance should not be a major issue as the enhanced SWIR performance will preserve retrieval accuracy as is the case for AIRS. Figure 6 shows the RSB SNRs for 100% albedo. We see the design beats the requirement of 300:1 for all but the shortest and longest frequencies of the visible spectrometer.

At much lower albedos, the instrument performance reduces considerably. In Fig. 7, we compare the SNR of MODIS at typical radiances to the SNR of MIRIS at the spatial and spectral resolution of MODIS, we see the MODIS performance is considerably better. This is because MODIS has an aperture comparable to MIRIS (17.8 cm) yet is at a much closer to the Earth at an orbit altitude of 705 km. The MODIS IFOV is 1.42 mr while the MIRIS IFOV is 0.19 mr.. Overall the radiometric and spectral sensitivity of MIRIS appear reasonable for the future system.

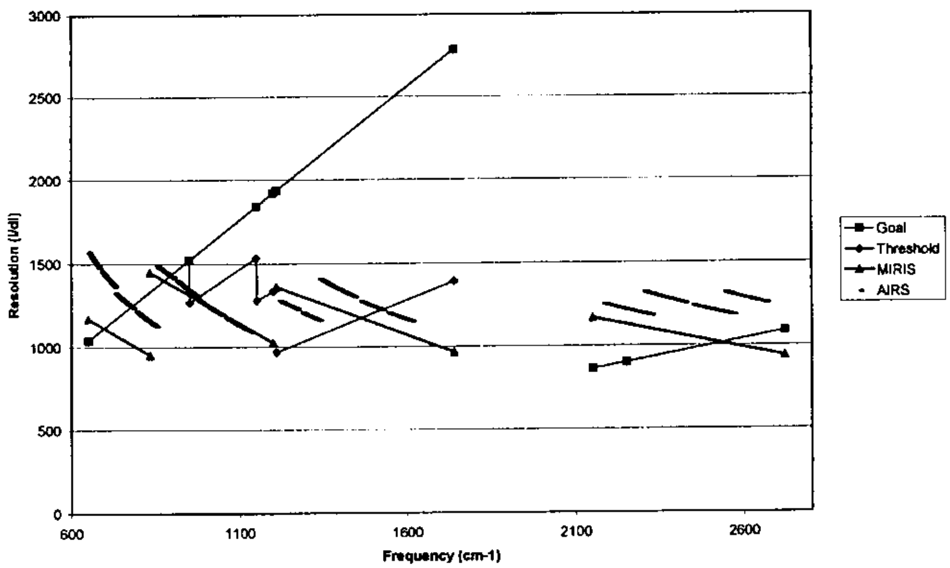

Figure 4. MIRIS Spectral Resolution. *Spectral Resolution is comparable to AIRS. Also shown are HES threshold and goal requirements.*

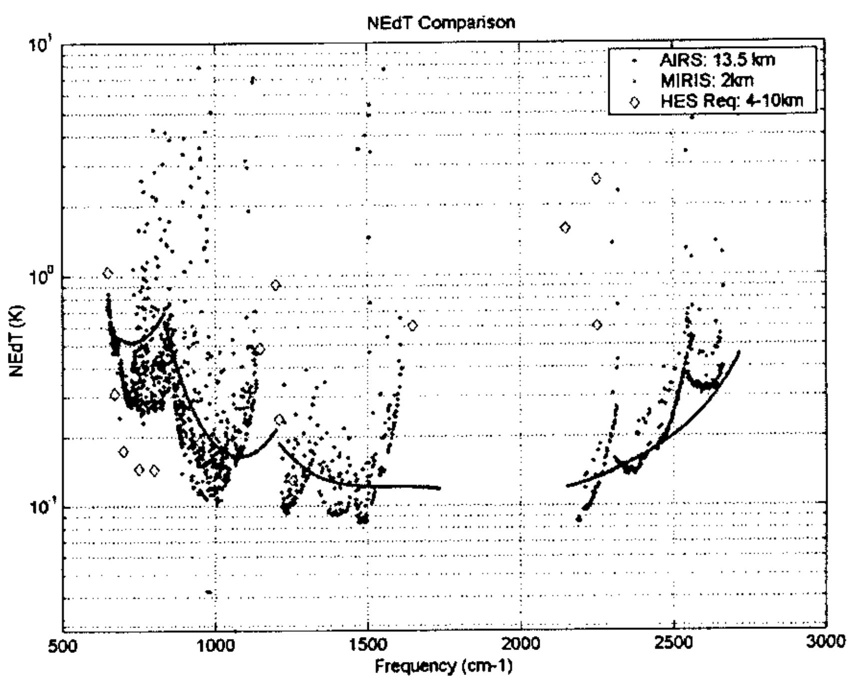

Figure 5. Noise Equivalent Temperature Differentials (NEdTs) *for MIRIS compared to HES Requirements (diamonds) and AIRS Actual (blue dots).*

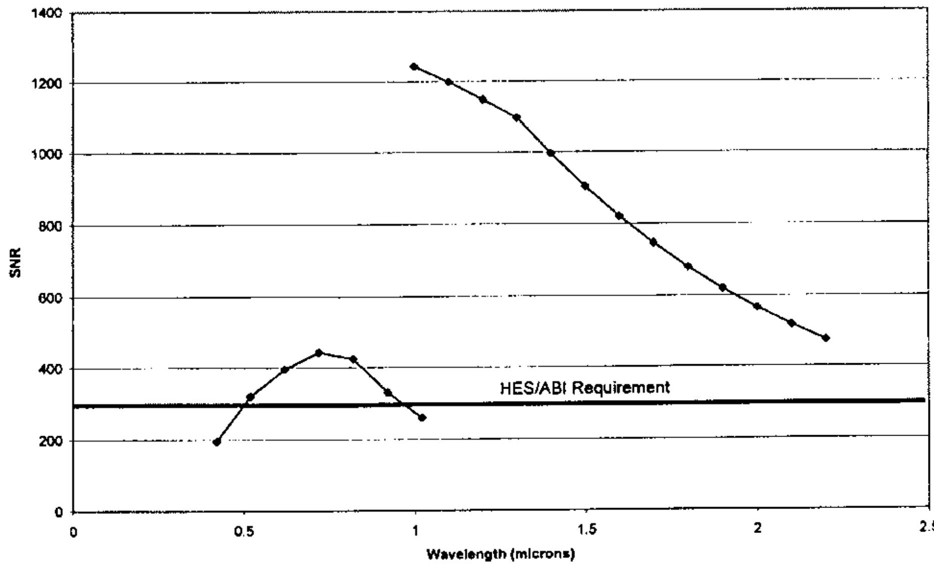

Figure 6. Reflective Solar Band SNR compared to HES CW requirements.

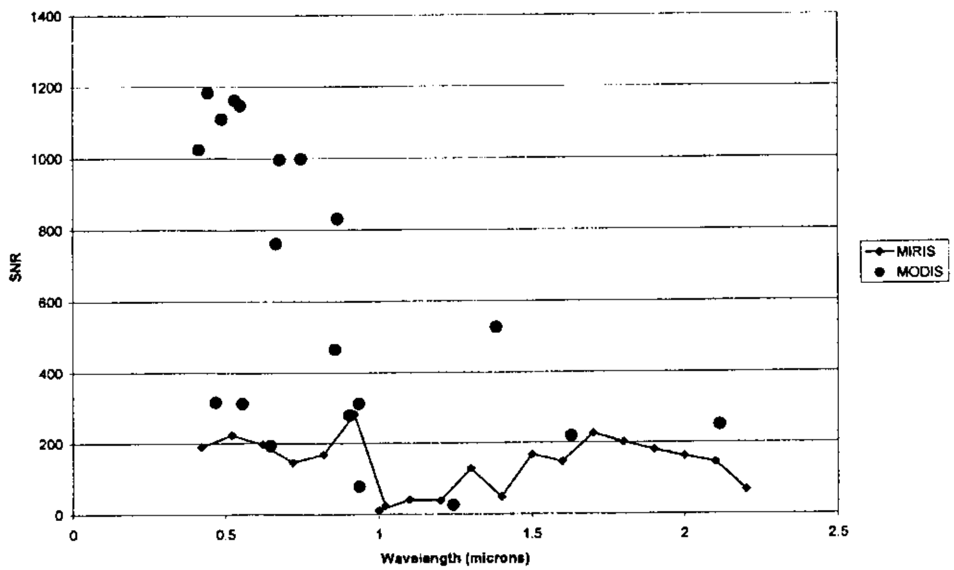

Figure 7. SNR for MIRIS compared to MODIS. *MIRIS does not have as good an SNR as MODIS in the ocean color bands since the MODIS IFOV is so much larger due to the lower orbit.*

V. Conclusions

Medium Earth Orbit offers better revisit than LEO, and is closer than GEO making instruments smaller. The unusal orbit will complicate thermal control for the future infrared sounders, and thermal control should be a topic of future technology demonstration programs. A point design for an advanced thermal sounder for MEO meets the majority of requirements for HES, AIRS, ABI and MODIS. We see a deficiency in the SNR of the MEO when compared to MODIS that requires additional investigation. The high spectral resolution from the visible channels through the long-wavelength infrared will meet the majority of science needs which rely on this spectral range for information. Although MEO instruments are not expected to replace the LEO and GEO systems entirely, they offer exceptional performance with a reasonable instrument cost. Constellations of MEO instruments provides an added "real-time-global" dimension that may offer considerable advantages for weather prediction.

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