Performance expectations for future moderate resolution visible and infrared space instruments based on AIRS and MODIS in-flight experience

Thomas S. Pagano[a], Steven E. Broberg[a], Hartmut H. Aumann[a], Richard L. Baron[a]

[a]Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, CA

ABSTRACT

Lessons learned from the Atmospheric Infrared Sounder (AIRS) and the Moderate Resolution Imaging Spectroradiometer (MODIS) projects highlight areas where further technology development is needed to address future land, ocean and atmospheric measurement needs. Although not established as requirements at this time, it is anticipated that scientists will expect improvements in the areas of spatial, spectral, radiometric, polarimetric, temporal and calibration performance for future sensors. This paper addresses each of these performance areas and provides lessons learned from MODIS and AIRS. We also present expectations in performance of the system based on information from NASA Instrument Incubator Program and industry reports. Tradeoffs are presented vs orbit altitude (LEO, MEO and GEO) and provide a "systems" perspective to future measurement concepts.

Keywords: AIRS, MODIS, Atmosphere, Sounding, Infrared, Spectrometer

1. INTRODUCTION

NASA's successful Earth Observing System (EOS) program has provided a wealth of scientific and technical information for the remote sensing community. In particular, the Atmospheric Infrared Sounder (AIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS), the two "facility" instruments on the EOS Aqua spacecraft address a wide range of requirements for Earth science[1]. The AIRS instrument, along with its companion instrument the Advanced Microwave Sounding Unit (AMSU) provide daily global maps of temperature and water vapor profiles with accuracies approaching that of radiosondes[2]. AIRS calibrated radiances are distributed by NOAA and assimilated daily by National Weather Prediction Centers worldwide. MODIS provides global maps of global vegetation indices, sea surface temperature, atmospheric water vapor, forest fires, clouds and a myriad of other important quantities for Earth Science[3]. Together MODIS and AIRS provide a comprehensive look at the Earth, complementing each other in every way. MODIS provides a moderate spatial resolution, 1km, product in the infrared, with channels at 0.5 km and 0.25 km in the visible, and with broad spectral channels ranging in resolution ($\lambda/\Delta\lambda$) from 20 to 50. AIRS provides a low spatial resolution of 13.5 km in the infrared with high spectral resolution ranging in excess of 1200. AIRS also has 4 visible and near infrared bands at a spatial resolution of 2.3 km, mostly for cloud detection. The need for higher spectral resolution on MODIS and higher spatial resolution on AIRS calls for an advanced system capable of doing both missions, primarily in the infrared. We restrict the study of this paper to the infrared since the visible is best done in a separate instrument; this is explained in section 3.1. Advancements in remote sensing technology will allow us to achieve a level of performance that surpasses either MODIS or AIRS infrared performance in a single instrument. The combined high spatial and spectral resolution will provide meteorologists with the type of data needed to improve weather forecasting and scientists with the spatial and spectral fidelity needed to improve measurement accuracy.

When we look to the future, we must consider the other instruments in the pipeline. The Integrated Program Office (NASA/NOAA/DoD) is developing the National Polar Orbiting Environmental Satellite System (NPOESS) imager (Visible/Infrared Imager Radiometer Suite, VIIRS) and sounder (Crosstrack Infrared Sounder, CrIS). These instruments will basically continue the AIRS and MODIS measurements without significant enhancements. Our primary goal here is to achieve AIRS spectral resolution at MODIS spatial resolution which neither of these instruments will even approach. NOAA is also developing the Geostationary Operational Environmental Satellite (GOES-R) imager and sounder instruments. The GOES-R HES will have improved spatial resolution of 4km, but will not have the global coverage.

Figure 1 shows the currently flying and next generation imaging and sounding instruments planned for NASA and NOAA. There are two reasons for pursuing a next generation system. Firstly, virtually none of these systems provide the high spatial and high spectral resolution in a single system. That is, the hyperspectral information is always at the low spatial resolution. This prevents atmospheric sounding and composition determination at the high spatial resolution. Secondly, these systems are complex and costly, and we must examine the best value to the government that can be obtained in the post-GOES-R timeframe by use of advanced technologies.

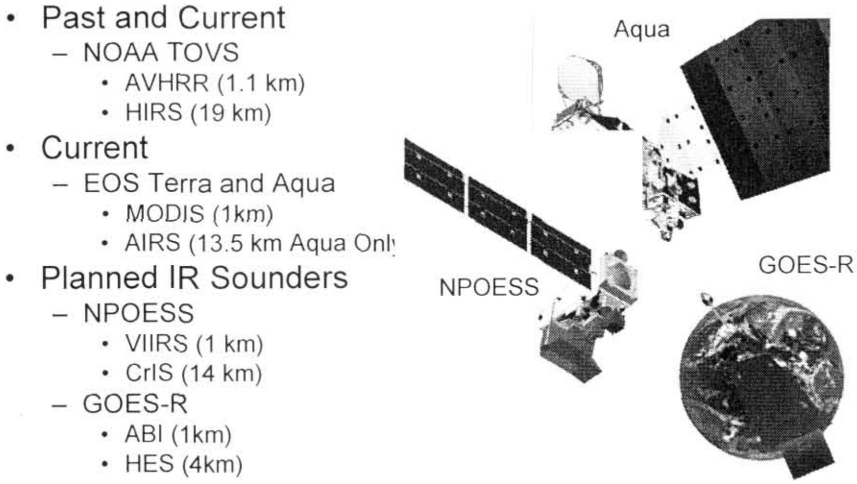

Figure 1. Past, Current and Planned Moderate-Resolution-Class Global Imagers and Sounders

2. REQUIREMENTS

2.1 Moderate Spatial and High Spectral Resolution

Our fundamental assertion is that there will be a need for moderate (1km) spatial resolution and high spectral resolution ($\lambda/\Delta\lambda \sim 1000$) infrared imagery from space in the future. The infrared sounder would significantly benefit from higher spatial resolution. First, the inhomogeneity of the scene in a field-of-view adds to the uncertainty of any retrieval of atmospheric state, particularly over land or where small clouds and high surface variability are present. The improved spatial resolution will improve the accuracy of the temperature and water vapor soundings. Additionally, multiple soundings can be aggregated spatially if needed for a number of reasons from reducing noise to new techniques for cloud clearing. Improved sensitivity is extremely important for retrieval of trace gases; improved spatial resolution will allow combining measurements spatially to achieve improved sensitivity, assuming each measurement has the high sensitivity of the larger footprint in the current system, which is indeed the case as we will show later in this paper. Improved spatial resolution will also greatly benefit forecasting the tracks of hurricanes and even open up the possibility of measuring and predicting tornados. Figure 2 shows an example of imagery from MODIS and AIRS of hurricanes that demonstrate the significantly higher spatial information content in the MODIS. The higher spectral resolution of AIRS allows a three dimensional temperature profiles of the storm and surrounding region to be made to improve forecasting accuracy[2].

From the MODIS point of view, the MODIS infrared products would benefit from improved spectral resolution. Sea Surface Temperature (SST) products would improve as better correction can be made for water vapor absorption as the atmospheric temperature and water vapor state can then be retrieved simultaneously with SST. Improved observation of fires will be accompanied by measurement of the trace gases in the plume. Figure 3 (left) shows an image from MODIS of the wildfires in San Diego in 2003. Figure 3 (right) shows the AIRS ability to extract SO_2 from the Mt. Etna eruption in 2003.

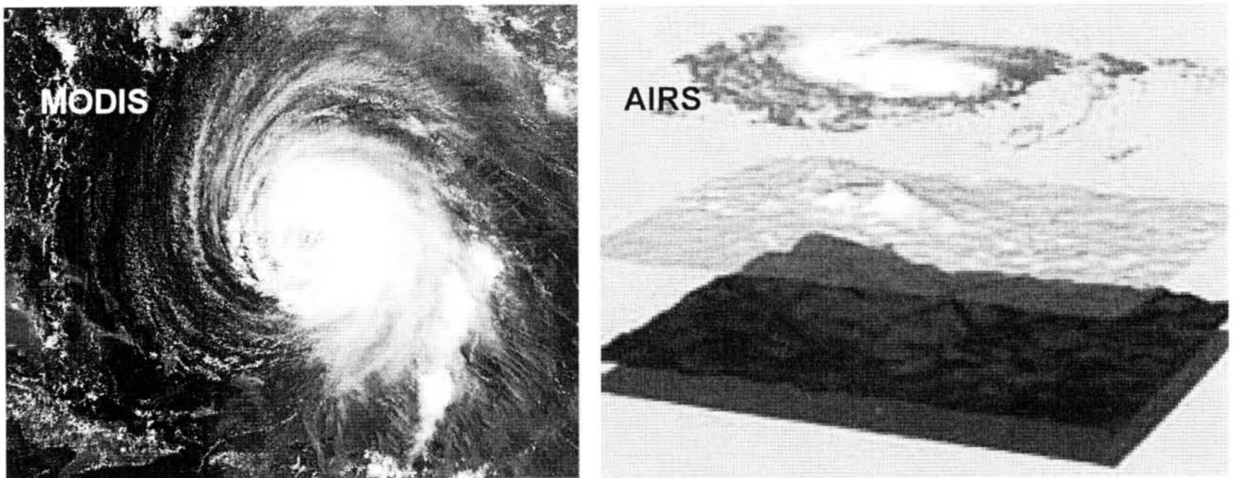

Figure 2. (Left) MODIS provides excellent spatial resolution of hurricane Isabel. (Right) AIRS provides thermal information in 3 dimensions in this isotherm of Supertyphoon Pongsona.

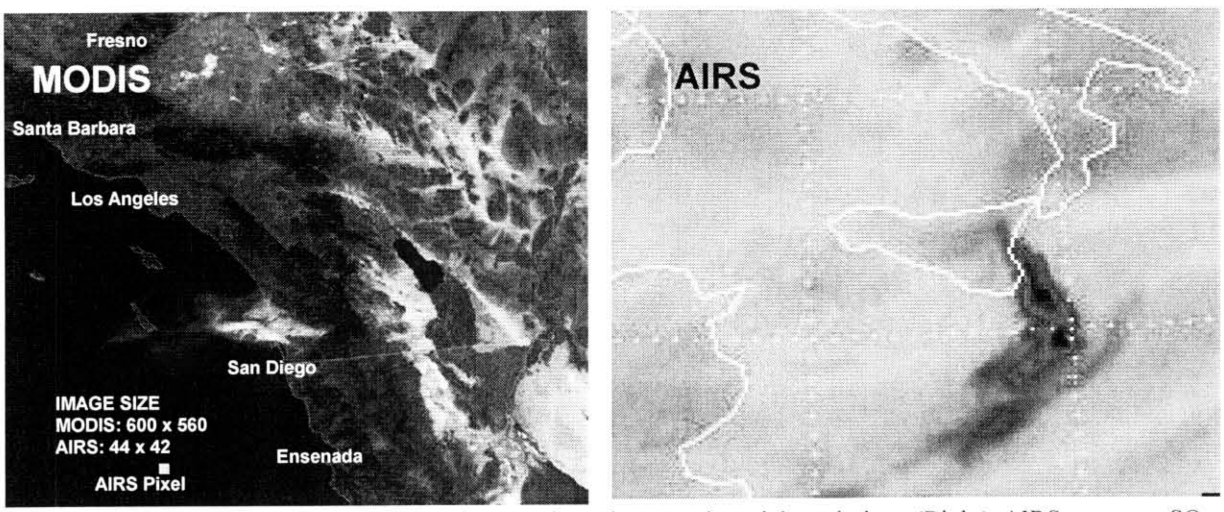

Figure 3. (Left) MODIS image of wildfires in San Diego show good spatial resolution. (Right) AIRS measures SO_2 from Mt. Etna eruption

2.2 LEO and MEO Orbit

NASA and NOAA are in the planning stages for their future satellite systems to address weather and climate needs beyond the next decade. Figure 4 shows schematically the relationship between coverage and temporal revisit for one satellite in each of the three orbits, LEO, MEO and GEO. LEO offers very good global coverage, while GEO offers good temporal revisit. Regional models currently rely on the GEO data due to its good revisit, while Global Circulation Models (GCMs) rely on the LEO data. In the future it is anticipated that improved coverage and temporal revisit will be necessary for both models. A single MEO brings us in the right direction, while a constellation[3] may be the ultimate solution someday.

3. TECHNOLOGY APPROACH

Figure 5 illustrates the principle of the technology approach. The MODIS and the AIRS infrared operate basically in the same spectral region. What we propose to do is use the wide field refractive optics technology of MODIS in a grating spectrometer system, like AIRS, to create a hyperspectral imaging spectrometer. MODIS advanced the state of the art of refractive optics for space applications in the infrared by developing advanced materials and coatings. New designs for advanced spectrometers have been developed in the NASA Instrument Incubator Program that employ these materials to achieve a very wide field system. The wide field-of-view of the spectrometer allows us to go to a very slow scan or even pushbroom, increasing the dwell time and enabling smaller IFOVs for improved spatial resolution. The wide field also allows a large number of spectral channels to be collected behind the grating.

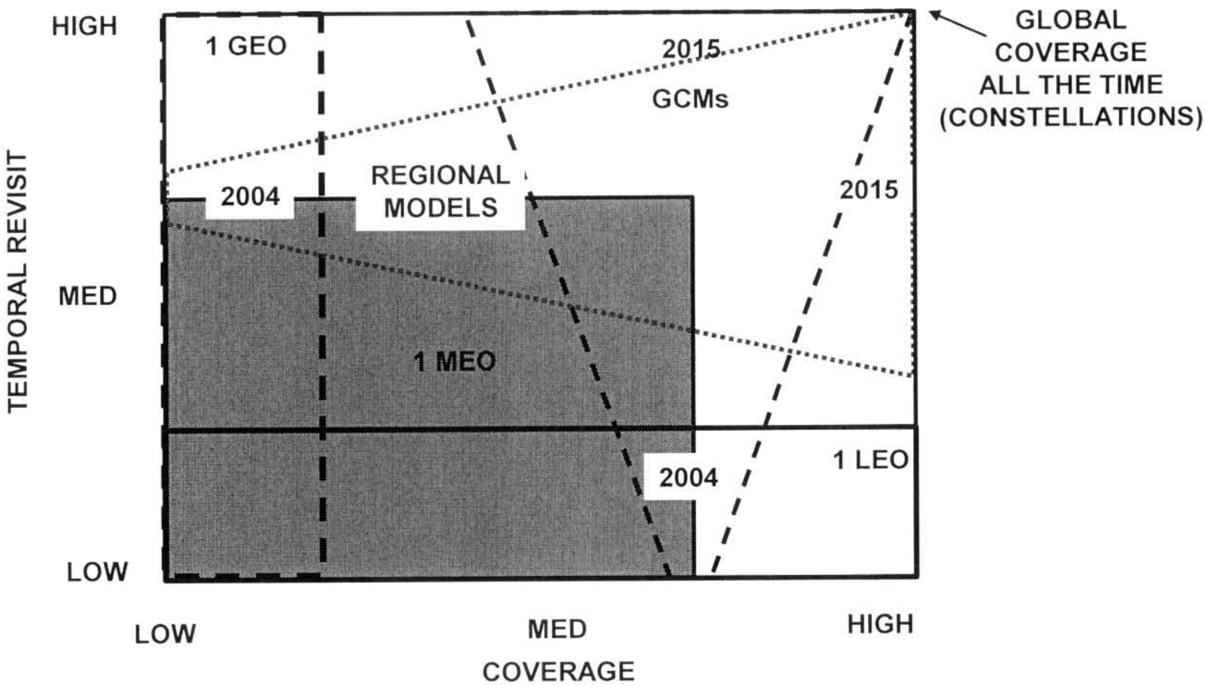

Figure 4. LEO, MEO and GEO have different coverage and temporal revisit. Future needs will benefit from MEO orbits and in fact constellations may be the best option in the future.

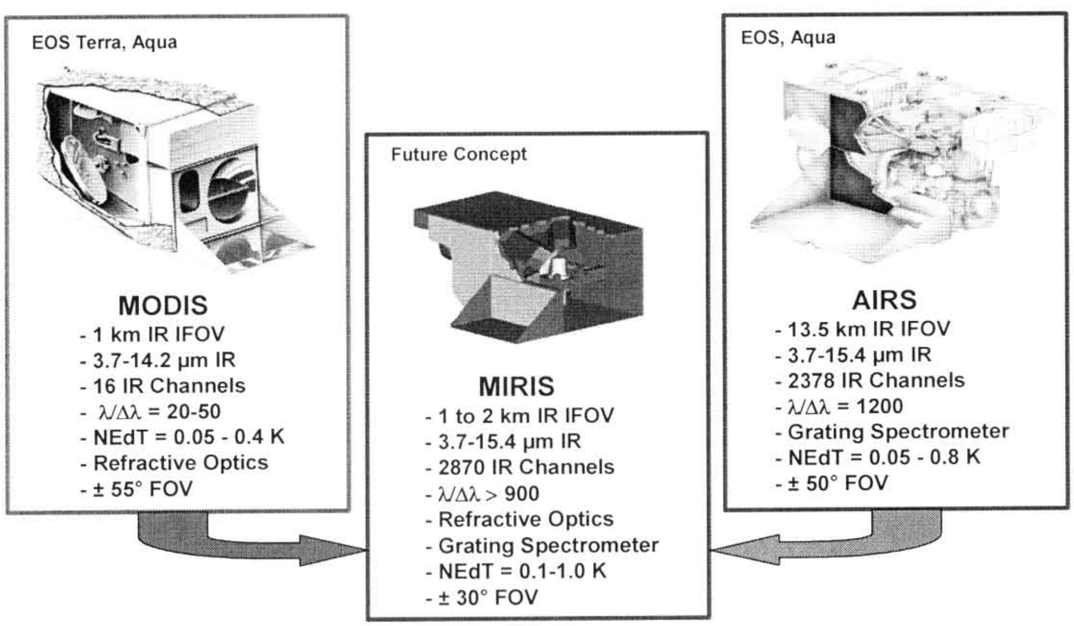

Figure 5. New requirements and capabilities of new technology may lead to a combined infrared imager/sounder instrument for future missions.

3.1 Separate VIS/NIR/SWIR and IR Instruments

One major complication in the development of the MODIS instrument was the need to achieve visible through long wavelength infrared in a single instrument. This required development of advanced optical coatings for the scan mirror, out-of-band blocking filters and dichroic beamsplitters. The MODIS uses a beryllium scan mirror coated with silver and the FSS99 coating developed by Denton Vacuum that provided good reflectance from 0.4 μm to 14.4 μm. The problem with this method is that the reflectance and polarization varies with scan angle. The MODIS mirrors have as much as 8% polarization at 8 μm at an angle of incidence of 60° and almost none at normal incidence. Degradation of the mirror in orbit caused problems with the scan angle dependence of both the reflective and infrared bands[5,6]. The AIRS instrument used a similar mirror also developed by the same manufacturer that is believed to be responsible for a 10% degradation in instrument response in the 0.44 μm visible band. Although more stable coatings are believed to exist from this manufacturer today, the complication of polarization still remains. For this reason, we recommend all future instruments that address the MODIS VIS/NIR/SWIR requirements contain a depolarizer. This approach was used on SeaWiFS with considerable success[7]. In SeaWiFS, the "polarization scrambler" is placed between the primary mirror and the half angle mirror in the rotating telescope. If a polarization scrambler, or depolarizer is used in the telescope, it will complicate the infrared response. No depolarizer that operates from the visible through the long wavelength infrared is available today as far as this author is aware. Putting the VIS/NIR/SWIR in a separate instrument not only allows for better flexibility in using a depolarizer, it greatly simplifies the design of the infrared instrument. Instead of the need for wide band coatings, standard coatings such as gold can be used for the mirrors. Gold exhibits good reflectance and low polarization in the region of interest.

3.2 System Design Concept

Table 1 gives the overall design parameters to meet a combined imager sounder instrument for two different orbit altitudes. The LEO configuration uses a 1mr IFOV from 705.3 km to give a 0.705 km footprint at nadir. We assume a whiskbroom approach, and achieve a 20 ms dwell time. This is the same dwell time achieved by AIRS. The field-of view cross-track is approximately ±30° achieved by scanning for a total swath of 841 km. This is considerably smaller than MODIS or AIRS, but it is assumed that the system can point to regions of interest to ±55°. The optics in this approach shows a very small aperture of 29.4 mm, where the diffraction limit is 36.6 mm. The added diffraction helps the scrambling of the spectral information in the IFOV, at the expense of a small amount of signal.

Parameters for Medium Earth Orbit are also shown in the table. The spatial resolution is set at 2 km rather than <1km to keep the instrument aperture size down. This results in a 200 mm aperture, and a slower system at f/2.6. A 1 km system can be easily accommodated at the expense of MTF if desired. Since the object space field of view is much lower from MEO, we can use a 3x magnification to keep the aperture of the spectrometer down without a major hit to the field of view.

Table 1. Conceptual Design Parameters for a Combined Imager/Sounder

	SIRAS-L	MIRIS3	
Orbit			
Orbit Altitude	705.3	10400	km
Orbit Inclination	98.8	55	deg
Orbital Period	1.65	6.01	hrs
Imaging			
Ground Projection	0.7053	2	km
IFOV	1.00	0.19	m rads
Dwell Time	0.02	0.04	s
Cross-Scan Swath Width	7.33	0.71	±deg
Cross-Scan Swath Width	181.72	256.06	km
Along-Scan Swath Width	30.31	17.78	±deg
Along-Scan Swath Width	841.56	7937.21	km
LZA	34.09	53.43	±deg
Scan Efficiency	80	80	%
Scan Time	21.16	129.06	s
Scan Rate	2.86	0.28	deg/s
Telescope			
Telescope Aperture	29.40	200.00	mm
Diffraction Ltd EPD	36.60	190.32	mm
System F/#	1.7	2.6	
Magnification	1.00	3.08	
FOV	7.33	0.71	±deg
FPA			
Number of Spectral Ch	2870	2870	
Number Cross-Scan	128	256	
Spectrometer			
Spectrometer Aperture	29.40	65.00	mm

The FPA requirements are not particularly challenging. The number of elements per array is within current capabilities. The full well signal levels for a grating system are much lower than for an interferometric approach and the rates are not as high. FPAs are assumed to operate at 60K with the optical bench at 160K both very close to the AIRS operating temperatures.

3.3 Wide Field Spectrometers

JPL has been working on a combined imager/sounder for some time. We started with an instrument concept called the Spaceborne Infrared Atmospheric Sounder, SIRAS, in 1998 as an instrument concept. A SIRAS LWIR spectrometer was developed by Ball Aerospace and Technologies Corporation (BATC) under JPL management and systems engineering as part of the Instrument Incubator Program (IIP)[8] and completed in 2001. The SIRAS spectrometers have very wide fields-of-view to give broad spectral range and wide field imaging for pushbroom or very slow whiskbroom scanning. This is very important in that we get the maximum amount of spectral and spatial information possible in the wide field design. Today, SIRAS is in the middle of its 2nd IIP as a concept for Geosynchronous orbit[9], as BATC demonstrates the SIRAS spectrometer with an area array focal plane assembly. Reference 9 discusses the SIRAS including the spectrometer design assumptions that are used in the performance predictions presented in section 4. The spectrometers use flat gratings operating in low orders. Four spectrometers are used to cover the AIRS and MODIS spectral ranges.

3.4. Alternate Orbits

JPL was tasked by NOAA to investigate the use of meteorological instruments in Medium Earth Orbit as a potential way of improving performance and/or saving program costs in the post GOES-R timeframe. Early results from this effort show that an instrument concept is possible to meet the majority of the infrared requirements, but that the VIS/NIR/SWIR performance is lagging that of MODIS[10]. The MEO orbit offers a very wide swath width as well as a slower orbit. The slow, 6 hour orbit allows as many as 6 frames of a 2000x3000 km region to be made on a single pass. (Each frame takes 10 minutes and the region is in view for about 1 hr.) The orbit is such that this can be done twice per day. This is much better revisit than for the LEO, and provides the global coverage not available from GEO. The tradeoff is that a larger telescope is required than for LEO. Constellations of MEO sensors may obviate the need for LEO and GEO systems in the future.

4. PERFORMANCE EXPECTATIONS

4.1 Spectral Resolution and Radiometric Sensitivity

The LEO or MEO designs offer comparable spectral performance (Figure 6 (left)) because the spectral response is defined by the spectrometer. Selection of grating ruling and size of the entrance slit and detectors results in a spectral resolution of greater than 900 for all frequencies. The NEdTs, shown in Figure 6 (right) are also comparable to AIRS, but slightly worse for the SIRAS case due to much higher spatial resolution and wider scan. Design optimization is necessary but requires science team involvement. This is an ongoing activity and the early results are indeed favorable.

Radiometric and spectral stability should be very good for these systems, as a gold mirror will mitigate polarization effects on instrument variability. Also we assume the spectrometers will be temperature controlled as done on AIRS to minimize radiometric or spectral drift due to thermal variations[11].

We expect there to be a small amount (<50% of a resolution element per the requirement) of spectral smile[9]. Smile means that every detector in the spatial direction for a given channel sees a slightly different frequency. This will result in the need for a different radiative transfer algorithm (RTA) for each spatial footprint since the spectral response will differ slightly. We need to expect this as any future system with more than one detector will experience this. What it means is a more complicated RTA program. Discussions with the AIRS Science Team indicate that this should not be a significant problem.

4.2 Spatial Response

Table 1 gave the spatial response of the system to be 0.705 km for the SIRAS LEO concept and 2km for the MIRIS MEO concept. These resolutions are consistent with an MTF at Nyquist of 0.3. This is due to the use of an integration time equaling the dwell time and assuming diffraction limited optical performance. The SIRAS spectrometers indeed had a near diffraction limited performance when measured during the IIP testing phase in 2003[8]. The Field-of-View of the system is limited to ±30° for the SIRAS in LEO, but the MIRIS is a full field mapper. MIRIS maps to an LZA of 54°, which is higher than the rule-of-thumb of 50° for ideal sounding conditions.

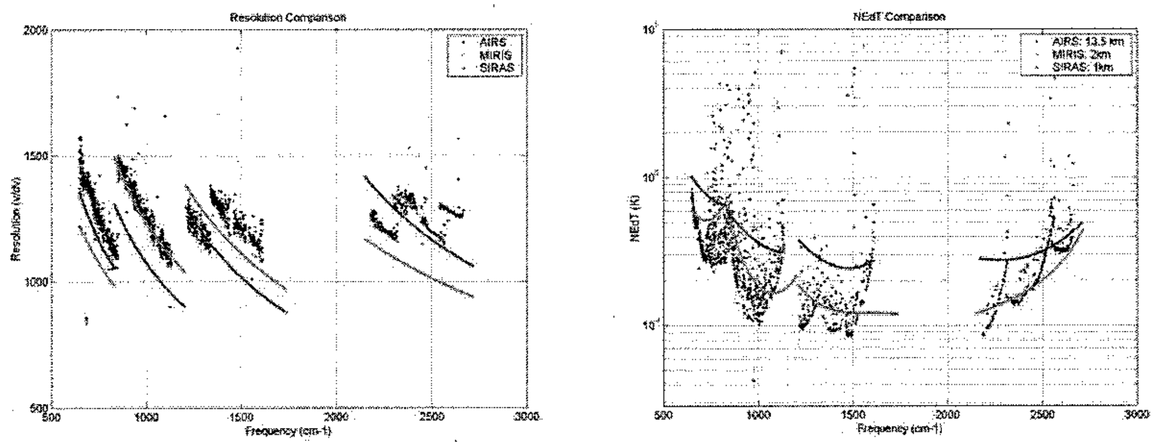

Figure 6. (Left) Spectral Resolution for AIRS compared to MIRIS and SIRAS. (Right) NEdT comparison of AIRS compared to MIRIS and SIRAS.

5. SUMMARY

Advancements in wide field optical technology and large format focal plane arrays allow much more information to be collected within a given amount of time. This allows us to reduce the IFOV from the AIRS 13.5 km to less than 1km in LEO and 2km in MEO and achieve a comparable level of performance. Lessons learned on AIRS and MODIS indicate that the IR and VIS/NIR/SWIR instruments should be separate. This will greatly simplify the design of future systems and most likely reduce cost and improve performance. Conceptual designs indicate that a combined AIRS and MODIS infrared system is feasible. This will lead to reduced development and operations cost and improve the accuracy of forecasts and climate science in the future.

6. ACKNOWLEDGEMENTS

The MODIS images in Figures 2 and 3 were obtained from the MODIS website at http://modis.gsfc.nasa.gov. The isotherm in Figure 1 was generated by Vince Realmuto at JPL. The SO2 image in Figure 2 was generated by Sung-Yung-Lee at JPL. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

7. REFERENCES

1. J.A. Benediktsson (ed.), "IEEE Transactions on Geoscience and Remote Sensing", Special Issue on the Aqua Spacecraft. Volume 41, Number 2, p. 253–441.
2. T. Pagano, et al., "AIRS/AMSU/HSB on EOS Aqua: First Year Post Launch Assessment", Proc. SPIE 5151-25, August, 2003

3. W. Barnes, T. Pagano, V. Solomonson, “Prelaunch Characteristics of the Moderate Resolution Imaging Spectroradiometer (MODIS) on EOS-AM1”, IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 4, July 1998
4. A. Gerber, D. Tralli, “Medium Earth Orbit (MEO) as an Operational Observation Venue for NOAA’s Environmental Satellites”, Proceedings of AIAA Space 2004 , AIAA-2004-5957, San Diego, CA, 2004
5. X. Xiong, J.-Qiang Sun, J. Esposito, B. Guenther, W. Barnes, “MODIS reflective solar bands calibration algorithm and on-orbit performance”, Proc. SPIE Vol. 4891, p. 95-104, Nov. 2003
6. X. Xiong, K. Chiang, B. Guenther, W. Barnes, “MODIS thermal emissive bands calibration algorithm and on-orbit performance”, Proc. SPIE Vol. 4891, p. 392-401, Nov. 2003
7. R. Eplee, Jr., R. Barnes, C. McClain, “SeaWiFS Detector and Gain Calibrations: Four Years of On-Orbit Stability”, Proc. SPIE Vol. 4814, p. 282-288, Sept 2002
8. S. Broberg, T. Pagano, H. Aumann, L. Strow, S. Gaiser, “Atmospheric Sounding at JPL: Current and Future Technologies”, Proc. SPIE Vol 5074-64, Mar. 2003.
9. T. Kampe, T. Pagano, “SIRAS-G, the Spaceborne Infrared Sounder for Geosynchronous Earth Orbit: a versatile concept for IR imaging spectrometry from geosynchronous orbit”, Proc. SPIE Vol 5157-20, Aug. 2003
10. T. Pagano, R. Baron, “An Instrument Concept for Atmospheric Infrared Sounding from Medium Earth Orbit”, Proceedings of AIAA Space 2004, AIAA-2004-5958, San Diego, CA, 2004
11. H. Aumann et al., “Sea Surface Temperature Measurements with AIRS: RTG.SST Comparison,” SPIE 5151-30, August 2003.