Evolution of Satellite Imagers and Sounders for Low Earth Orbit and Technology Directions at NASA

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ABSTRACT

Imagers and Sounders for Low Earth Orbit (LEO) provide fundamental global daily observations of the Earth System for scientists, researchers, and operational weather agencies. The imager provides the nominal 1-2 km spatial resolution images with global coverage in multiple spectral bands for a wide range of uses including ocean color, vegetation indices, aerosol, snow and cloud properties, and sea surface temperature. The sounder provides vertical profiles of atmospheric temperature, water vapor cloud properties, and trace gases including ozone, carbon monoxide, methane and carbon dioxide. Performance capabilities of these systems has evolved with the optical and sensing technologies of the decade. Individual detectors were incorporated on some of the first imagers and sounders that evolved to linear array technology in the '80's. Signal-to-noise constraints limited these systems to either broad spectral resolution as in the case of the imager, or low spatial resolution as in the case of the sounder. Today's area 2-dimensional large format array technology enables high spatial and high spectral resolution to be incorporated into a single instrument. This places new constraints on the design of these systems and enables new capabilities for scientists to examine the complex processes governing the Earth System.

Keywords: Imager, Sounder, Remote Sensing, Hyperspectral

1. INTRODUCTION

The Advanced Very High Resolution Radiometer (AVHRR) imager and High Resolution Infrared Sounder (HIRS) on the TIROS spacecraft designed in the 1970's used individual detector elements and simple filter and imaging optics to achieve the best spatial and spectral resolution possible while maintaining good signal-to-noise ratio. High resolution linear detector arrays mounted on large format Focal Plane Assemblies in the 1980's combined with optical and filter advancements enabled higher spatial and spectral resolution observations as in the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS) instruments on the NASA Earth Observing System Aqua spacecraft. Similar technologies are used on the Visible/Infrared Imager Radiometer Suite (VIIRS), and Cross-track Infrared Sounder (CrIS) on NPOESS.

The current state-of-the art large format detector arrays and wide field optics now available within industry allow imaging and spectrometry to be acquired simultaneously at high spatial and high spectral resolution. For example, NASA has been working on measurement and instrument requirements for two candidate instruments to meet the future sounder and imager requirements, one for the UV/VIS/NIR/SWIR called the Ocean Radiometer for Carbon Assessment (ORCA) for ocean color applications and the other for the SWIR/MWIR/LWIR, the Advanced Remote-Sensing Imaging Emission Sounder (ARIES) low Earth sounder. Both instruments measure at approximately 1km spatial resolution and observe the hyperspectral reflected and emitted radiance from the atmosphere, providing maximum synergy of the two spectral regions. Together they constitute a powerful imaging and sounding facility to meet a wide range of current and future earth science and operational weather forecast needs.

2. HISTORY OF IMAGERS AND SOUNDERS AT NASA

Remote sensing of the atmosphere from space for weather and climate began in the early 1960's and 1970's with the TIROS and NIMBUS spacecraft[1]. A listing of US imagers and sounders flown or scheduled by NASA post 1964 is shown Table 1. For an excellent history of NOAA's satellite program see reference 1. The "imagers" and "sounders" as they eventually were called are designed to measure the upwelling radiance in the 0.4-15 micron spectral range. They

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are primarily global mappers with moderate to low spatial and spectral resolution. Resolution was limited by infrared detector technology and communications data rate. Imagers and sounders usually fly together with the imager providing cloud and surface information (vegetation, surface temperature, etc.) and the sounder providing atmospheric temperature and water vapor profiles but at lower spatial resolution. The AVHRR and the HIRS were flown on virtually all of the NOAA series of operational weather satellites in the 1980's and 1990's and paved the way for operational use of imagers and sounders. The MODIS and AIRS are the experimental and operational imagers and sounders in use today. The VIIRS and CrIS are scheduled for first launch in late 2011 on the National Polar Orbiting Environmental Satellite System (NPOESS) Preparatory Project (NPP) spacecraft, the precursor of the Joint Polar Satellite System.

Table 1. NASA Imagers and Sounders for Low Earth Orbit[2].

Imagers			
Acronyms	Instruments	Satellites	Launch Year
VIIRS	Visible Infrared Imager Radiometer Suite	NPP, NPOESS	2011(est)
MODIS	Moderate Resolution Imaging Spectroradiometer	Terra, Aqua	1999, 2002
SeaWiFS	Sea-Viewing Wide Field Sensor	Orbview-2	1997
AVHRR	Advanced Very High Resolution Radiometer	Tiros-N, NOAA-X	1978
CZCS	Coastal Zone Color Scanner	Nimbus 7	1978
SCMR	Surface Composition Mapping Radiometer	Nimbus 5	1972
THIR	Temp.-Humidity Infrared Radiometer	Nimbus 4 – 7	1970-1978
IDCS	Image Dissector Camera System	Nimbus 3 and 4	1969,1970
MRIR	Medium Resolution Infrared Radiometer	Nimbus 2 and 3	1966, 1969
AVCS	Advanced Vidicon Camera System	Nimbus 1 and 2	1964, 1966
HRIR	High Resolution Infrared Radiometer	Nimbus 1, 2, 3	1964-1969
Sounders			
Acronyms	Instruments	Satellites	Launch Year
CrIS	Cross-track Infrared Sounder	NPP, NPOESS	2011(est.)
AIRS	Atmospheric Infrared Sounder	Aqua	2002
HIRS	High Resolution Infrared Sounder	Nimbus 6, NOAA-X	1975
SAMS	Stratospheric and Mesospheric Sounder	Nimbus 7	1978
LIMS	Limb Infrared Monitor of the Stratosphere	Nimbus 7	1978
LRIR	Limb Radiance Inversion Radiometer	Nimbus 6	1975
PMR	Pressure Modulated Radiometer	Nimbus 6	1975
ITPR	Infrared Temperature Profiling Radiometer	Nimbus 5	1972
SCR	Selective Chopper Radiometer	Nimbus 4 and 5	1970, 1972

3. NASA MODIS AND AIRS

3.1 The Moderate Resolution Imaging Spectroradiometer (MODIS)

The MODIS builds upon the measurement approach of the AVHRR but with more advanced technologies of the 80's to provide global daily visible through infrared imagery at moderate to high spatial resolution. MODIS was developed by Raytheon in Goleta, California. The MODIS has 36 bands ranging in wavelength from 0.4 – 14.4 μm, 16 in the Vis/NIR, and 20 in the Infrared. Two panchromatic bands image at 250 m resolution. 2 Vis/NIR and 3 SWIR bands operate at 500 m and the remainders operate at 1 km. Table 2 gives the general properties of MODIS and several other imagers mentioned above. MODIS scans ±55° from a sun-synchronous orbit of 705 km, tracing a swath of 2330 km cross-track[3]. This wide swath provides global daily coverage for over 95% of the Earth Surface daily.

The MODIS was originally conceived as a system composed of two instruments called MODIS-N (nadir) and MODIS-T(tilt), which were slated for flight on the EOS-AM platforms. MODIS-T was designed basically as an advanced ocean color sensor with the ability to tilt to avoid sunglint. MODIS-T also was a hyperspectral instrument with 15nm spectral resolution in the 0.4-0.88 micron region. The MODIS-T instrument was eventually removed from further development as the budget for EOS became more constrained.

The MODIS wide swath and moderate spatial resolution make it ideal for global earth system science for a wide range of products including Ocean Color, Vegetation Indices, Water Vapor, Aerosols, Clouds and Surface Albedo in the reflective bands and Surface Emissivity and Temperature, Atmospheric Temperature and Water Vapor, and Cloud Properties for the emissive bands[4].

For a discussion on ocean color, a comparison of SeaWiFS and MODIS is instructive. Both have achieved their mission objectives for ocean biogeochemistry, but in different ways from a design and technology perspective. Based on the experience from the Nimbus-7 Coastal Zone Color Scanner (CZCS, the ocean color band sets of SeaWiFS and MODIS (Terra and Aqua) were expanded to eight and nine bands, respectively, including two NIR bands for aerosol corrections. The most important difference in the ocean color band sets is the MODIS chlorophyll-a fluorescence band at 678 nm (Figure 1)[5]. After launch, it was found that the MODIS SWIR bands at 1240, 1640, and 2135 nm could be used for aerosol corrections over highly turbid waters such as often found in estuaries and near-shore waters. As a result, future ocean color instruments for the Aerosol, Clouds, and Ocean Ecosystem (ACE) and Pre-ACE (PACE) missions will have high performance SWIR bands for this purpose.

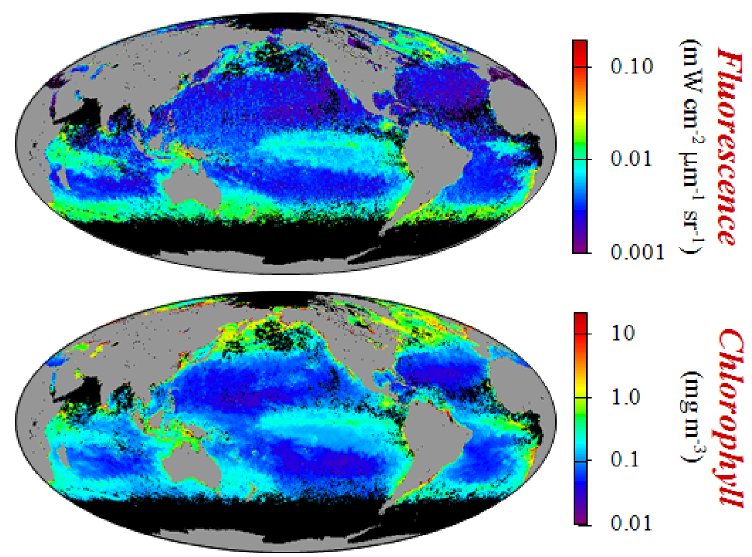


Figure 1. Monthly global composite of MODIS chlorophyll-a and fluorescence. The fluorescence provides information on phytoplankton physiology such as iron stress[5]. Iron is an essential nutrient for phytoplankton growth and much of the global ocean is “iron-limited”, i.e., insufficient iron concentrations for optimum growth. The chlorophyll-a fluorescence band will be a requirement for the ocean radiometer on PACE and ACE.

SeaWiFS and MODIS are scanners, although their designs are quite different. Each achieved wide swath data to meet a two-day global coverage requirement. The SeaWiFS scanning mechanism included a rotating telescope and half-angle mirror. Its focal planes had four detectors for each band which were summed in a time-delay-integration (TDI) scheme. Also, one of the four detectors had a very high radiance range to avoid saturation over clouds resulting in a bilinear gain without gain switching. MODIS employed a large rotating mirror (both mirror sides were used) and each band had ten detectors. Each MODIS scan captured the equivalent of about 9 SeaWiFS scans. The TDI scheme of SeaWiFS increased signal-to-noise (SNR) to meet its performance requirements. The slower MODIS scan rate allowed for longer dwell times to achieve its SNR specifications which were higher than those of SeaWiFS. The high MODIS SNRs came at the price of image striping and 10 times the number of detector gains to calibrate and track on orbit. Also, MODIS, being an interdisciplinary sensor, did not tilt to avoid sunglint resulting in significant ocean color data loss and did not incorporate a polarization scrambler as did SeaWiFS. Despite these differences, both designs have proven to be highly robust and produce global time series of water-leaving radiance, chlorophyll-a, and other parameters of comparable quality. Having the three sensors on orbit simultaneously has resulted in algorithm improvements for each sensor due to the ability to compare the derived product time series and explore the differences. For instance, MODIS Terra, in particular, has experienced very dramatic changes in response versus scan angle dependence and polarization sensitivity. Using global SeaWiFS data, these time-dependent changes were quantified, greatly improving the MODIS Terra derived products[6].

Finally, one of the most important methodological developments coming out of these program is the lunar calibration, i.e., imaging the moon once per month at a constant phase angle[7]. SeaWiFS achieves this with a spacecraft pitch maneuver. MODIS collects lunar data through the spaceview port, but at a much larger phase angle. This capability has been critical to tracking sensor degradation on orbit and will be a requirement for PACE and ACE.

Table 2: Characteristics of CZCS, SeaWiFS, AVHRR, MODIS, VIIRS and ORCA Imagers

Imager Comparison	CZCS[8]	SeaWiFS[7]	AVHRR[9]	MODIS[4]	VIIRS[10]	ORCA* (Concept)
Spatial						
Orbit Altitude	955 km	705 km	833 km	705 km	824 km	450 km
Swath Width	±40° + Tilt	±58.3° + Tilt	±55.4°	±55°	±56°	±58.3° + Tilt
Horizontal Resolution	0.83 km	1.1 km	1.1 km	0.25, 0.5, 1.0 km	0.4 km, 0.8 km Constant	1.0 km @ 20° tilt
Spectral	#Channels @ GSD (km)					
0.345 - 1.0 um	5 @ 0.83 km	8 @ 1.1 km	2 @ 1.1 km	2 @ 250 m, 2 @ 500m, 12 @ 1km	7 @ 0.7 km, 2 @ 0.4 km, DNB @ 0.7 km	108 (5 nm)
1.0 - 3.0 um	n/a	n/a	1 @ 1.1 km	3 @ 500 m, 1 @ 1 km	4 @ 0.7 km, 1 @ 0.4 km	3
3.0 - 5.0 um	n/a	n/a	1 @ 1.1 km	6 @ 1km	3 @ 0.7 km	n/a
5.0 - 8.0 um	n/a	n/a	n/a	2 @ 1 km	n/a	n/a
8.0 - 12.5 um	1 @ 0.83 km	n/a	2 @ 1.1 km	4 @ 1 km	3 @ 0.7 km, 1 @ 0.4 km	n/a
12.5 - 15.5 um	n/a	n/a	n/a	4 @ 1km	n/a	n/a
Total Channels	6	8	6	36	22	111
Radiometric						
SNR	100-150	TBD	>9:1	74-1087	119-416	150 - 3150
NEdT	0.2 K @ 270K	n/a	< 0.12K @ 300K	0.05K @ 300K 0.25K @ 250K	0.07K @ 300K 2.5K @ 250K	n/a
Resources						
Size	0.81 x 0.38 x 0.56 m	0.5 x 0.6 x 0.5 m	0.8 x 0.4 x 0.3 m	1.0 x 1.6 x 1.0 m	1.3 x 1.4 x 0.8 m	~ 1.0 x 0.7 x 0.7 m
Mass	42 kg	52 kg	33.2 kg	250 kg	270 kg	~ 140 kg
Power	50 W	61 W	27 W	220 W	240 W	~ 130 W
Max Data Rate	0.8 Mbps	0.665 Mbps	1.6 Mbps	11 Mbps	10.5 Mbps	~ 13 Mbps

* The 450 km altitude is the current ACE mission altitude. Five nm bands in the 0.345-1.0 µm range are aggregated to form the required 23 UV-NIR ACE and PACE multispectral bands (all multiples of 5 nm). SNRs are for the multispectral bands including the 3 required SWIR bands.

3.2 The Atmospheric Infrared Sounder (AIRS)

The Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared spectrometer with global coverage designed to measure global temperature and water vapor profiles on a daily basis. AIRS was developed by BAE Systems of Lexington Massachusetts under the direction of NASA JPL. AIRS measures 2378 infrared channels from 3.7-15.4 µm with a horizontal spatial resolution of nominally 13.5 km at nadir and scanning ±49.5°. Table 3 gives the characteristics of AIRS compared to other sounders. The high spectral resolution, low spatial resolution but global coverage provides a unique perspective for global weather prediction and climate modeling. Only with hyperspectral resolution is it possible to measure the vertical profile of temperature and water vapor with enough precision to determine the partition of the outgoing radiation in the thermal infrared. The partition of energy is important to determine the role of clouds and water vapor in the radiative feedbacks to global warming.

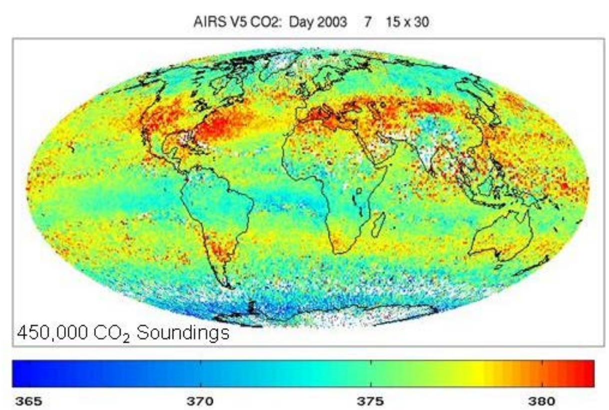


Figure 2. AIRS Mid-Tropospheric Carbon Dioxide for July 2003. These data aid in understanding global distribution and transport of CO_2 in support of climate modeling.

The AIRS retrieves the vertical profile of atmospheric temperature in a way very similar to the prior instruments, (e.g. HIRS), by "sounding" along the CO_2 R Branch. The difference is that the AIRS uses numerous high spectral resolution channels rather than the few broader channels from the prior instruments. A temperature profile is achieved with an accuracy of 1K/km from the surface to about 30 mb. Another difference is in the method of cloud clearing. A unique approach to cloud clearing results in successful retrievals up to 80% cloud cover. Water vapor profiles are then retrieved using water sensitive channels with weighting functions that peak at different altitudes. The retrieved water vapor profile is accurate to about 15% / 2 km.

Table 3: Characteristics of HIRS-4, AIRS, IASI, CrIS and ARIES Sounders

Sounder Comparison	HIRS-4	AIRS	IASI	CrIS	ARIES
Spatial					
Orbit Altitude	833 km	705 km	817 km	824 km	705 km
Scan Range	±49.5°	±49.5°	±48.3°	±48.3°	±30°, ±55°
Horizontal Resolution	10 km	13.5 km	12 km	14 km	1, 2 km
Spectral	#Channels @ GSD (km)				
Method	Filter Wheel	Grating	FTS	FTS	Grating
Nominal Resolution	3-100 cm^{-1}	0.5-2.5 cm^{-1}	0.5 cm^{-1}	1.0-5.0 cm^{-1}	0.5-2.0 cm^{-1}
0.4 - 1.0 um	1	4	n/a	n/a	n/a
1.0 - 3.0 um	n/a	n/a	n/a	n/a	n/a
3.0 - 5.0 um	3.7-4.6 μm (7)	3.7-4.6 μm (514)	3.6-5.0 μm (1520)	3.9-4.6 μm (158)	3.4-4.7 μm (1024)
5.0 - 8.7um	6.5-7.3 μm (2)	6.2-8.2 μm (602)	5.0-8.2 μm (1561)	5.7-8.2 μm (432)	6.2-8.7 μm (1024)
8.7 - 12.5 um	9.7-12.4 μm (3)	8.8-12.7 μm (821)	8.2-12.5 μm (839)	9.1-12.0 μm (420)	8.7-11.4 μm (1024)
12.5 - 15.5 um	13.3-15.0 μm (7)	12.7-15.4 μm (441)	12.5-15.5 μm (310)	12.0-15.4 μm (294)	11.4-15.4 μm (1024)
Total Channels	20	2382	4230	1305	4096
Radiometric	@ 250K				
NEdT	0.2-2.4K	0.07-0.7K	0.25-0.5K	0.1-1.0K	0.2 K
Resources					
Size	0.4 x 0.5 x 0.7 m^3	1.4 x 0.8 x 0.8 m^3	1.2 x 1.1 x 1.3 m^3	0.9 x 0.9 x 0.7 m^3	0.4 x 0.4 x 1.0 m^3
Mass	35 kg	177 kg	236 kg	145 kg	100 kg
Power	24 W	256 W	210 W	105 W	150 W
Max Data Rate	2.88 kbps	1.3 Mbps	1.5 Mbps	1.5 Mbps	60 Mbps

Currently radiances from the AIRS are assimilated by the NOAA/NCEP weather prediction models and distributed to NWP centers worldwide for operational forecasting. Over 11 hours improvement in the 5 day forecast has been demonstrated. Temperature and water vapor profiles are not yet assimilated by the forecast centers but are widely used by researchers for the study of weather and climate processes and validation of weather and climate models[11] [12].

The infrared spectrum of the atmosphere has many gas absorption features detectable at the AIRS spectral resolution. Gases imaged by AIRS on a daily basis are stratospheric ozone, mid-to-lower tropospheric carbon monoxide, upper tropospheric methane and mid-tropospheric carbon dioxide (see Figure 2)[13].

4. THE NPOESS VIIRS AND CRIS

The NASA MODIS and AIRS requirements were designed to support earth system science including climate prediction, operational weather forecasting (in conjunction with NOAA), and hazard applications. Early in the development cycle, agreements were made between NASA and NOAA to transition these sensors into operations at some point in the future. Originally NASA planned to launch 6 of the MODIS instruments and 3 of the AIRS instruments as part of a long-term strategy for measuring climate over a 15 year period as part of the Mission to Planet Earth (MTPE) Program.

However, in 1994 in an effort to reduce cost of future satellite systems, the joint NOAA, Air Force and NASA Integrated Program Office (IPO) was formed to manage the National Polar Orbiting Environmental Satellite System (NPOESS). A new set of requirements for the imagers and sounders were developed solely to meet weather forecasting and field operations requirements for imaging and sounding at greatly reduced cost to the government. Key Air Force requirements included constant resolution for the imager across the scan line as well as the ability to image under low-light conditions. For the sounder, requirements included the mandatory use of a Fourier Transform Spectrometer. These requirements were impossible to meet with the existing MODIS and AIRS designs and contracts were awarded to Raytheon and ITT under the management of the Air Force in 2002 for the VIIRS and CrIS respectively; the same year as the launch of MODIS and AIRS on Aqua (May 4, 2002). Delivery of the new sensors was completed in 2010 with some improvements and some deficiencies compared to MODIS and AIRS but with non-recurring cost well in excess of expectations and of the NASA predecessors. The first VIIRS and CrIS will launch on the NPOESS Preparatory Project (NPP) satellite currently scheduled for Fall of 2011.

More recently, the Obama administration recognized the problems with the NPOESS program and announced a restructuring. NASA and NOAA were given the responsibility of managing the satellites for the afternoon orbit, and the Air Force the morning orbit. With this, NASA and NOAA formed the Joint Polar Satellite System (JPSS) program office. While this does not affect the instruments on NPP and C1 (now called J1), it is possible the requirements and performance could change for subsequent units.

It is important to identify that the VIIRS and CrIS were not designed or intended to meet requirements of the scientific research community, but to meet requirements compatible with delivery of "operational" data products, i.e. products that are used for operations including weather prediction for NOAA and battlefield operations for the Air Force. These products have been demonstrated on the heritage instruments. The ability to develop new "research" products from these instruments depends on the stability, accuracy and sensitivity of the instruments and the comprehensiveness of the pre-flight test program. Requirements for enabling scientific research with CrIS and VIIRS instruments is still under discussion.

4.1 The Visible Infrared Imager Radiometer Suite (VIIRS)

A comparison of the VIIRS with the MODIS and prior instruments is given in Table 2. The VIIRS has fewer channels than MODIS, (22 in VIIRS, vs 36 in MODIS). The most notable difference is in the imaging performance; the VIIRS has nearly constant resolution across the scan line. The channels selected are primarily for surface and cloud imaging making VIIRS an overall better surface imager. Water vapor channels (5-8 μm), and temperature sounding channels (12.5-15.5 μm) are eliminated. VIIRS uses a continuously rotating telescope to reduce stray light, whereas MODIS uses a continuously rotating paddle-wheel mirror. The first VIIRS instrument is complete and integrated on the NPP spacecraft. Although the majority of the requirements are satisfied, the VIIRS on NPP suffers from crosstalk and scattered light on internal filters that impact the accuracy and sensitivity of several products. Improvements are planned for the second and subsequent flight units.

The requirements for VIIRS are driven by meeting "Environmental Data Records" (EDR's). There are 24 EDR's for VIIRS including precipitable water, suspended matter, aerosol optical thickness, aerosol particle size, 7 cloud products, active fires, surface albedo, land surface temperature, soil moisture, surface type, vegetation type, sea surface temperature (SST), ocean color and chlorophyll, net heat flux, sea ice characterization, ice surface temperature, and snow cover and depth[14]. Ocean color and chlorophyll products may be problematic in the NPP instrument due to spectral crosstalk. This is expected to be improved for subsequent units. Since the primary channels on VIIRS are surface channels, products like SST, land surface reflectance, surface albedo, and vegetation should work well but may have algorithmic differences from MODIS. Imaging of active fires will be limited from VIIRS since it does not have the fire detection bands of MODIS.

4.2 The Crosstrack Infrared Sounder (CrIS)

Table 4 compares the major features of the CrIS and AIRS instruments. CrIS requirements are very similar to AIRS, with nearly the same spectral region. CrIS uses a Fourier Transform Spectrometer (FTS) with unapodized spectral resolution comparable to AIRS. Apodization ("removal of the foot" of the sinc function response of the FTS) reduces the spectral resolution by about a factor of 2. CrIS has three bands (objectives and focal plane assemblies), each consisting of a 3x3 array of detectors each sharing a common interferometer in the object space of the optical system: shortwave (SW), midwave (MW) and longwave (LW). The FTS includes a dynamic alignment system to keep the mirrors parallel and minimize the effects of vibration. A step-stare pointing mirror produces an effective stabilized image on the ground during which time the interferometer completes its scan. The CrIS instrument meets most of its requirements, with good radiometric sensitivity, spectral and spatial performance. Manufacturing errors with the Internal Calibration Target (ICT) resulted in a lower than expected emissivity of approximately >0.97 vs requirement of >0.995. Radiometric errors associated with this are mitigated using a thermal model of the baffle region surrounding the blackbody to compute the reflected energy off the blackbody. The model is sufficient for meeting specifications but may impact the ability to measure small changes associated with climate variability and processes. A modification to the ICT is under consideration for the second and subsequent CrIS units.

Key EDR's for CrIS include Atmospheric Vertical Temperature Profile and Atmospheric Vertical Moisture Profile. Atmospheric Vertical Pressure Profile is derived from these two quantities and is also a key EDR. Ozone is also provided as an "intermediate product". The reduced spectral resolution associated with the apodization makes retrieval of Carbon Monoxide and Carbon Dioxide uncertain with CrIS as currently configured. Since the FTS acquires data at full OPD for all bands higher resolution data are possible for the SW and MW spectrometers. This should help the retrieval of Carbon Monoxide but will not help the Carbon Dioxide product which uses the LW. To download this data does not require a hardware modification to the instrument and is currently under investigation.

5. NEW IMAGER AND SOUNDER TECHNOLOGY DIRECTIONS AT NASA

Much has been learned over the last two decades in both science and technology since the MODIS and AIRS instruments were developed. New requirements for higher spatial and spectral resolution are driven by the demand from the science community and the public for higher information content. Scientists require hyperspectral information of the surface or atmosphere to improve classification and sensitivity of retrieved products. Improved horizontal resolution Earth system models have been shown to greatly improve prediction of weather and climate and seasonal behavior of other ground and atmospheric geophysical variables. These new high resolution models require observations with matching spatial resolution for validation and initialization of model state[15].

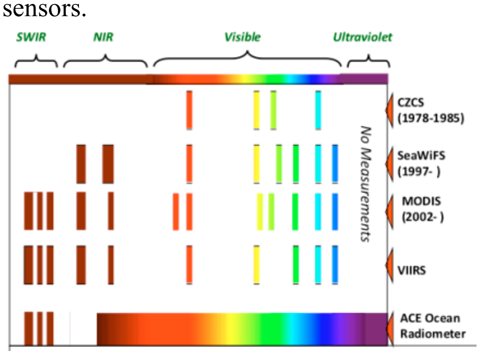
Higher resolution sensors are now possible with advanced high density 2-dimensional focal plane detector arrays that allow more information to be gathered by the optical sensors in a given amount of time. Advanced optical systems make use of these arrays by packing in the highest spatial and spectral information possible. Miniature cryogenic coolers, high density electronics, and composite materials enable a higher level of opto-mechanical, thermal and electronic performance in a smaller volume. These and other advancements are driven by the commercial and defense industries and government technology development programs such as the NASA Instrument Incubator Program (IIP).

In the next two sections we describe a new class of imager and sounder born out of the NASA IIP. The Ocean Radiometer for Carbon Assessment (ORCA) provides hyperspectral imaging in the solar reflective region of the spectrum, while the Advanced Remote-sensing Imaging Emission Sounder (ARIES) measures the thermal infrared emission spectrum. Together they enable the entire MODIS and AIRS science capability with the breakthrough in hyperspectral and high spatial resolution needed to meet the future needs of the imaging and sounding user communities. A new paradigm with these two instruments is that instead of having visible through longwave infrared on a single instrument (both AIRS and MODIS), the two instruments separate out the visible from the longer wavelength infrared. For the ORCA, a polarization scrambler is possible since there is no infrared. This greatly improves calibration accuracy. For the ARIES, a gold mirror can be used since there is no visible imaging requirements. This also improves calibration accuracy associated with infrared polarization emission from the mirror. With both instruments boresighted on the same platform, all imaging and sounding requirements are satisfied at high spatial resolution.

5.1 The Ocean Radiometer for Carbon Assessment (ORCA)

In 2000-2001, NASA conducted an evaluation of what sensors would be required for carbon budget research[16]. One of the recommendations was for an advanced ocean color sensor to follow SeaWiFS and MODIS. GSFC initiated work on an advanced sensor at that time in anticipation of an Earth System Science Pathfinder (ESSP) mission. While the ESSP solicitation was never released, GSFC has continued work on the instrument concept which became the Ocean Radiometer for Carbon Assessment (ORCA). Early in the development, the ORCA team decided to build on the SeaWiFS design, particularly the rotating telescope/half-angle mirror/polarization scrambler fore optics. This design provides a wide seamless swath, minimizes exposure to contaminants, and essentially eliminates polarization sensitivity (SeaWiFS testing showed a 0.25% level of sensitivity). The SeaWiFS scan mechanism continues to work flawlessly after 13 years on orbit. Initial requirements included 19 multispectral bands. Design studies showed that the SeaWiFS aft-optics could not be effectively expanded to 19 bands, so spectrometer designs were considered, both prism and grating-based. Reflective gratings were chosen and the spectrum was divided into two domains, UV-visible (345-570 nm) and visible-NIR (570-885 nm). The detector arrays are silicon CCDs. The implementation avoids stripping such as seen in sensors such as MODIS, MERIS, and OCM and simplifies calibration (prelaunch and on-orbit).

Figure 3. Comparison of ACE ocean radiometer spectral coverage and heritage sensors.



In 2008, the Decadal Survey Aerosol, Cloud, and Ecology (ACE) mission working group was formed and is composed of the aerosol, cloud, ocean ecology, aerosol-ocean interaction, and suborbital subgroups. The ocean group has added seven multispectral bands (three in the SWIR) to the original nineteen ORCA bands and 5 nm spectral resolution from 350-775 nm. Figure 3 shows the comparison of the ACE ocean radiometer spectral coverage versus the heritage sensors. The requirements also include no saturation in any band and polarization sensivity below 1.0% in all bands.

ORCA already had the hyperspectral resolution and bandwidth in the UV-NIR required for ACE, but the three descrete SWIR bands had to be added with separate optics and InGaAs detectors. The issue of throughput from 345 to 2135nm has been addressed using advanced coatings and high performance detector arrays available from commercial sources. The detector arrays will be custom designs to accommodate the high data rates, but rely on well-established techniques. Modeling using optical component test data (testing at GSFC) and vendor provided detector performance data show that ORCA will exceed all SNR requirements without saturation. A comparison of model ORCA and MODIS SNRs at typical TOA ocean radiances indicates that ORCA substantially outperforms MODIS in the visible and SWIR. The ORCA design emphasizes stray light rejection. Stray light around bright clouds in SeaWiFS and MODIS has required the cloud masks to be dilated significantly at the expense of coverage. Currently, ORCA is in development under the NASA Instrument Incubator Program. Under this funding, the emphasis has been on the optical design and performance and on the telescope/HAM mechanisms. Funding is being sought to incorporate the custom manufactured flight-like detector arrays, electronics and data system. In parallel with the design, test protocols reflecting the performance requirements are being developed in collaboration with staff at the National Institute of Standards and Technology (NIST). This activity seeks to ensure that testing will be timely, accurate, unambiguous, and complete should ORCA be selected for the PACE mission.

5.2 The Advanced Remote-sensing Imaging Emission Sounder (ARIES)

Hyperspectral infrared spectrometers like AIRS have demonstrated positive forecast improvement when assimilated into weather prediction models at major Numerical Weather Prediction (NWP) centers worldwide. AIRS has also been extremely valuable in understanding processes affecting climate, particularly with respect to water vapor and clouds and atmospheric composition of key greenhouse gases including CO2, CH4, O3 and CO. Additional forecast impact is anticipated from the IR sounders as computing power at the NWP centers improves, but we are already seeing the limitations in these systems associated with the low (13.5 km) horizontal spatial resolution (HSR). A significant reduction in yield and accuracy occurs over land in the boundary layer indicative of lack of knowledge of the surface emissivity. Unfortunately NWP models also have the lowest accuracy in the boundary layer where the sounders could have the most impact. Additionally, climate models require good knowledge of the surface atmosphere exchange of water vapor and of cloud process studies requiring higher HSR. Advancements in both modeling and observations is required to improve weather and climate prediction and improve regional and local environmental decision making.

5.2.1 Technology Advancements

Requirements and design concepts for an advanced low-earth sounder, or the Advanced Remote-sensing Imaging Emission Sounder (ARIES) to achieve 1km horizontal spatial resolution with spectral resolution better than AIRS are being developed at NASA JPL[17]. Table 3 lists some of the key requirements for ARIES compared to the current and heritage systems. ARIES uses large format focal plane arrays to slow the scan rate and improve dwell time allowing a smaller instantaneous fields of view. Wide field optics image the large focal planes onto the scene collecting maximum illumination area while minimizing aperture size. The NASA Instrument Incubator Program funded the development of wide field optical systems including the Spaceborne Infrared Atmospheric Sounder (SIRAS)[18], and SIRAS-G[19]. The former being the original longwave wide field grating spectrometer tested with a linear array, and the latter being a shortwave version with an area array. These optical systems enable 2 dimensional imaging of spatial and spectral information covering over 10 degrees in each direction. When used with a 1024 square array on 20 micron pitch, we can achieve 1024 spectral samples and 128 spatial samples (aggregating 8 pixels to make 1km). While the concept development is still in its early stages, we can also examine the benefits of the ARIES to weather forecasting, climate modeling and greenhouse gas observations.

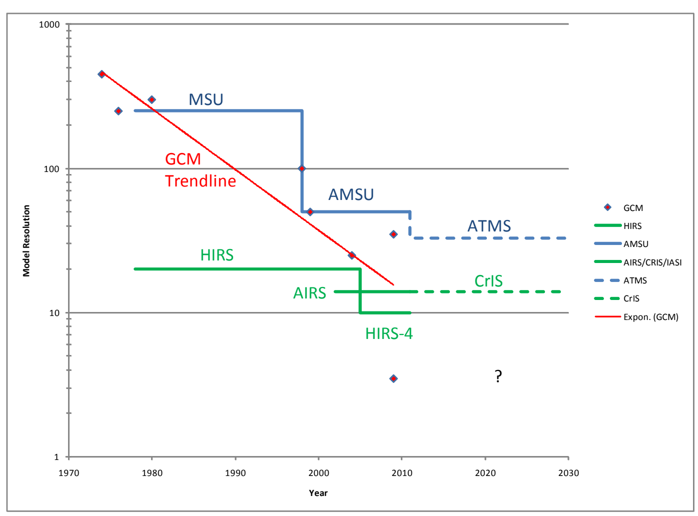


Figure 4. Model Resolution Advancements and Instrument Resolution

5.2.2 Matching Higher Resolution Weather and Climate Prediction Models

While it has been speculated that higher spatial resolution soundings will improve boundary layer sensitivity and improve forecast, it can be certain that there will be higher yield due to more observations per unit area and more cloud free observations. Analysis with MODIS data demonstrated an almost 3x improvement in yield going from 15 km to 1km[20]. The significantly higher yield from the ARIES has the potential to greatly improve weather forecast. LeMarshall et al. showed an improvement of 6 hours in the 5 day forecast with assimilation of all 18 FOV's of AIRS rather than 1 in 18 which was responsible for the 6 hour improvement already achieved.[21]

In addition to more observations per unit area, Weather and Climate models are achieving higher horizontal spatial resolution matching both an improved understanding of the what was traditionally sub-grid-scale physical processes and the capacity of today's computational systems to represent those processes. Figure 4 shows improvements in GCM resolution compared to infrared and microwave observations over the past three decades. The trendline projects that models will be operating at 1-2 km HSR within the next decade. A prior work demonstrates that validation of a model of a given resolution must have observations as good or better than the model itself in order to minimize errors due to the observations filtering out process in the model of spatial frequencies higher than the Nyquist frequency.[22]

5.2.3 Climate Processes: Water Vapor, Clouds and Greenhouse Gases

Infrared sounders have proven valuable in understanding the processes affecting water vapor transport and cloud formation in the atmosphere. For example, recent studies by Gettelman and Fu show using AIRS and model data that as surface temperatures increase, water vapor in the upper troposphere increases preserving a constant relative humidity and producing a positive feedback[23]. The question remains in how a positive water vapor feedback will react to make clouds. MODIS has proven highly effective in characterizing clouds with its 1km horizontal spatial resolution, however the added hyperspectral information in the AIRS has shown to be more capable of separating clouds into ice and liquid phases[24]. Discussions with the authors of this latter paper indicate that having the high spatial resolution of the MODIS combined with the hyperspectral resolution of the AIRS would provide a major advancement in understanding of sub-grid-scale cloud processes.

A final major side benefit of high spatial resolution sounding will be the ability to monitor sources and sinks of greenhouse gases and their progenitors including CO, CO2, and CH4 with unprecedented resolution and coverage. Currently the AIRS instrument has demonstrated the ability to observe carbon monoxide and methane at horizontal resolutions of 45 km, and carbon dioxide at horizontal resolutions of 200km all with global daily coverage[25]. The ARIES will have the ability to produce greenhouse gases at the scale of MODIS observations. The benefits include monitoring emissions from natural and anthropogenic burning, identifying sources and sinks of greenhouse gases for climate science and monitoring emissions for verification of compliance with government regulation and international treaty verification.

6. SUMMARY AND CONCLUSIONS

Imaging and sounding have been the fundamental workhorse instruments for global daily observations of the surface, oceans and atmosphere since the 1960's. They are used for scientific research, operational weather forecasting, hazard detection, military, and commercial applications. High spatial resolution imagers (< 1-2 km) traditionally require low spectral resolution ($\lambda/\Delta\lambda < 100$) while the high spectral resolution "sounders" ($\lambda/\Delta\lambda > 1000$) offer low spatial resolution (> 10 km). Today's semiconductor technology enables large format detector arrays that, when configured with wide field optics, enable high spatial resolution simultaneously with very high spectral resolution . Two NASA instrument concepts, the ORCA and the ARIES combine imaging and sounding while splitting the spectral range between them, greatly improving accuracy of each instrument and reducing cost and complexity. Scientist and operational forecasters can now examine the "regional" scale while preserving the global daily coverage that makes the imagers and sounders of such high value to the global community. The higher resolution will enable a whole new level of scientific research, improving observational accuracy, and meeting the needs of the next generation of researchers and their higher computing capability. It will improve operational weather forecast accuracy and give a better understanding of the processes affecting anthropogenic and natural climate change. It will enable the operational community to obtain the data sets currently only available at the global scale, but at a scale that will better support decision makers on the ground for hazard alert and emergency responsiveness. In general, the technology under development today by NASA, other US government agencies, and industry will lead to a major improvement in imaging and sounding accuracy and resolution to meet the future needs of the user community.

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