Concepts for next generation grating spectrometer imaging atmospheric sounders from LEO and GEO

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ABSTRACT

Spaceborne infrared atmospheric sounders measure the spectrum of the upwelling radiance in the infrared with ultra-high spectral resolution. The resolution is sufficient to measure absorption features of atmospheric constituents enabling retrieval of atmospheric temperature and water vapor profiles, surface emission and atmospheric constituents. The Atmospheric Infrared Sounder (AIRS) on Aqua launched in May of 2002 was the first hyperspectral infrared sounder designed for this purpose and is still operational today. AIRS has been followed by the Infrared Atmospheric Sounding Interferometer (IASI) on MetOp A and B, and the Cross-track Infrared Sounder (CrIS) on Suomi NPP and JPSS. All instruments are operating well improving weather forecast and providing a wealth of information about the atmosphere. Additional CrIS and IASI instruments are expected to be launched providing data of this type into the late 2030's. AIRS, CrIS and IASI are all Low Earth Orbit (LEO) instruments with nominal spatial resolutions of 14km. Future IR sounders must achieve higher spatial and temporal resolution to match improvements in forecast models and be less costly to match anticipated future budget pressures. Higher temporal resolution can be achieved in several ways including operation in Geostationary Earth Orbit (GEO) or in constellations of SmallSats and CubeSats. Higher spatial resolution can be achieved using larger format focal plane assemblies in the instruments and larger aperture telescopes. Grating spectrometers are well suited to large format FPAs by allowing a wide field of view in a compact package. Concepts for next generation grating spectrometer IR sounders that have been developed over the years at JPL are presented along with technology advancements made to enable these concepts to achieve their stated goals.

Keywords: sounder, hyperspectral, infrared, grating, spectrometer

1. INTRODUCTION

Hyperspectral infrared sounding of Earth's atmosphere began in the early 1990's with the flight of the High-Resolution Interferometer Sounder (HIS). The first spaceborne IR sounder in LEO was the Atmospheric Infrared Sounder (AIRS) on Aqua in 2002[1,2]. The AIRS was intended for improving weather forecast and as such was rapidly assimilated into the operational forecast with considerable success showing more than 6 hours improvement on the 5 day operational forecast. AIRS was also a technology demonstration, having proved the feasibility of long-wavelength HgCdTe, active Split Sterling pulse-tube cryocoolers, dielectric filters and grating technologies that have been employed in numerous space systems since AIRS. Since AIRS, both the NOAA-led development of the Cross-track Infrared Sounder (CrIS) and the EUMETSAT Infrared Atmospheric Sounder Interferometer (IASI) have been launched on multiple platforms with great success in supporting operational weather forecasting. EUMETSAT is developing a Fourier Transform Spectrometer (FTS) IR sounder (IRS) for GEO and the Chinese have launched a geostationary FTS IR sounder called the Geostationary Interferometric Infrared Sounder (GIIRS). Although the US has not successfully launched a hyperspectral IR sounder from GEO, the Geostationary Imaging Fourier Transform Spectrometer (GIFTS) was developed but never flown. When looking to the future of IR sounding, we can count on continued operation of the operational suite of LEO instruments including CrIS and IASI until the late 2030's and continued development and deployment of new GEO IR sounders.

Advancements in CubeSats also enables smaller IR sounders to be demonstrated in LEO and possibly implemented into operations to meet complementary requirements such as providing data at different times of day not currently provided by the operational LEO sounders. NASA and NOAA have been working together to study the value of these CubeSats and demonstrate technology. In 2015, NASA started development of the CubeSat Infrared Atmospheric Sounder (CIRAS) as part of the Earth Science Technology Office (ESTO) Inflight Validation of Earth Science Technologies (InVEST) program. Although cancelled after one year due to projected cost overruns, the design was complete and several technologies demonstrated in hardware indicating that this technology is viable for future applications. NOAA has supported studies at JPL in 2015 and 2016 of the feasibility of the design of IR sounding CubeSats for operational applications.

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2. TECHNOLOGY ADVANCEMENTS

Technology supporting infrared grating spectrometer systems has made great progress in the last three decades. Figure 1 shows the technology evolution as is relates to instrument concepts developed over the years. In the 1990's when the AIRS was developed, the state-of-the-art in infrared detector technology was limited to very small area arrays or linear arrays, particularly at longer wavelengths. The optical designs were typically all or mostly reflective and cryocoolers were immature. AIRS demonstrated the first split sterling pulse tube cryocooler, developed by Northrop Grumman. The cryocoolers were redundant and had no parts that can wear out. The success of the AIRS technology demonstration is reflected in the fact that the AIRS instrument is still operational today after over 16 years in orbit.

Early in the 2000's, advancements in optics, detectors and cryocoolers took place that were used to develop new instrument designs to follow AIRS. In 2000, Ball Aerospace, with JPL leadership, successfully demonstrated an LWIR (12-15.4µm) all refractive grating spectrometer called the Spaceborne Infrared Atmospheric Sounder (SIRAS) as part of the NASA Instrument Incubator Program (IIP)[3]. The SIRAS demonstrated wide field of view hyperspectral imaging spectrometery in a compact package. Around the same time, Teledyne demonstrated a large format IR FPA of PV HgCdTe called CHROMA that can provide as high as 480 x 1280 pixels with very high frame rate and high full well. Northrop Grumman also developed a compact version of their pulse tube cooler. These technologies were incorporated into an instrument concept called the Moderate resolution InfraRed Imaging Sounder (MIRIS) that combined the capabilities of the Visible Infrared Imaging Radiometer Suite (VIIRS) infrared channels and CrIS in a single instrument, offering constant resolution imaging like VIIRS simultaneously with up to 2km spatial resolution MWIR and LWIR soundings[4].

Around the middle of the current decade, JPL developed processes to further reduce the size and cost of IR sounders. It was found that placement of the grating on the back side of a high index material can reduce the volume of IR grating spectrometers. Called an immersion grating, JPL has demonstrated several of these devices in laboratory prototype spectrometers. The immersion grating was incorporated into the CIRAS design enabling the spectrometer to fit in a 6U CubeSat. Earlier in this decade, JPL demonstrated a new detector material called the High Operating Temperature-Barrier Infrared Detector (HOT-BIRD) that has the performance of HgCdTe, but with much higher uniformity and operability, enabling operation at warmer temperatures. When these technologies are combined with new commercial miniature cryocoolers and compact electronics, we are now able to provide AIRS-like performance in the MWIR in a CubeSat form factor.

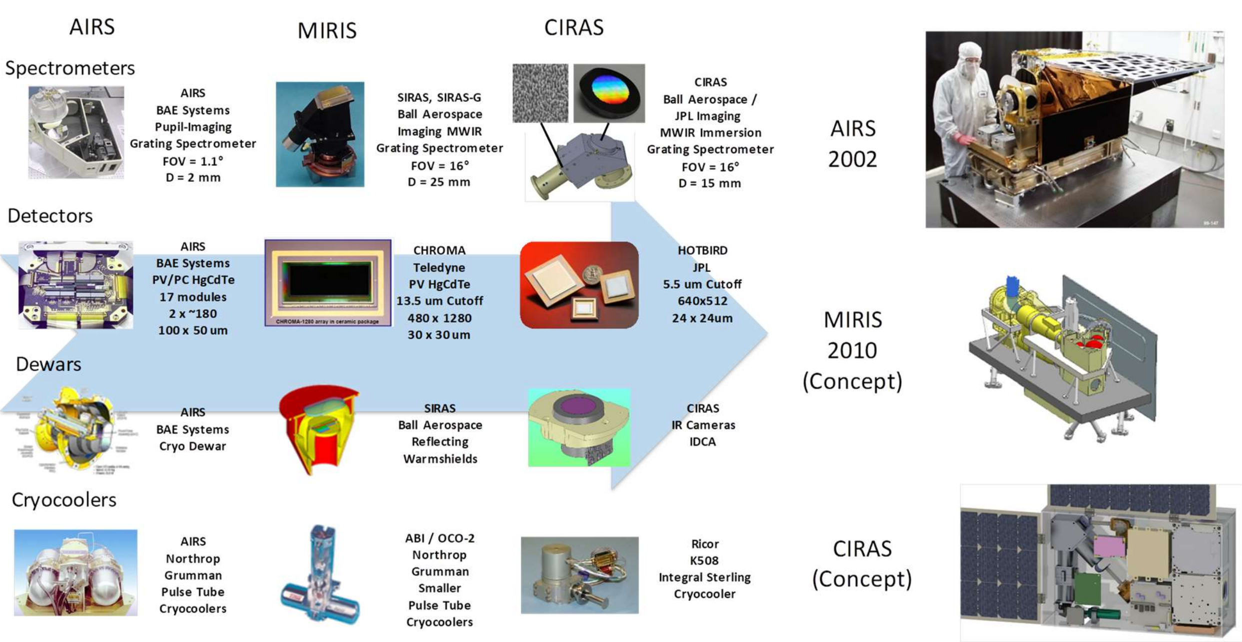

Figure 1. Technology advancements since AIRS enable smaller and more capable IR sounders.

3. CURRENT IR SOUNDING CAPABILITY

Table 1 lists the primary characteristics of the LEO infrared sounders currently in orbit today that are fully operational. The first of these, AIRS, is expected to last the life of the spacecraft to 2022. In addition to operation on Suomi NPP, CrIS is scheduled for manifest on JPSS-1, 2, 3 and 4, taking it out to the late 2030 timeframe. IASI is currently operational on Metop A and B and planned for operation on Metop C taking it through the 2024 timeframe; after this time, the EUMETSAT Polar System Second Generation (EPS-SG) will continue the measurement, but with a next generation infrared sounder.

Table 1. Characteristics of currently operational LEO hyperspectral infrared sounders in orbit today

Sounder Comparison	AIRS	IASI	CrIS
Spatial			
Orbit Altitude	705 km	817 km	824 km
Scan Range	±49.5°	±48.3°	±48.3°
Horizontal Resolution	13.5 km	12 km	14 km
Spectral			
Method	Grating	FTS	FTS
Nominal Resolution	0.5-2.5 cm^{-1}	0.5 cm^{-1}	0.9 cm^{-1}
0.4 - 1.0 um	4	n/a	n/a
1.0 - 3.0 um	n/a	n/a	n/a
3.0 - 5.2 um	3.7-4.6 µm (514)	3.6-5.2 µm (3348)	3.9-4.6 µm (632)
5.2 - 8.2um	6.2-8.2 µm (602)	5.2-8.2 µm (2814)	5.7-8.2 µm (864)
8.2 - 12.5 um	8.8-12.7 µm (821)	8.2-12.5 µm (1678)	9.1-12.0 µm (472)
12.5 - 15.5 um	12.7-15.4 µm (441)	12.5-15.5 µm (620)	12.0-15.4 µm (240)
Total Channels	2382	8460	2208
Radiometric			
NEdT	0.07-0.7K	0.25-0.5K	0.1-1.0K
Resources			
Size	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
Mass	177 kg	236 kg	165 kg
Power	256 W	210 W	117 W
Max Data Rate	1.3 Mbps	1.5 Mbps	1.5 Mbps

The first US development of a GEO IR sounder was sponsored by the NASA New Millenium Program out of NASA LaRC in early 2000s called the GIFTS or Geosynchronous Imaging Fourier Transform Spectrometer. GIFTS was originally scheduled for launch in 2004 as— GIFTS-IOMI (Indian Ocean METOC) on EO3, but eventually was cancelled in 2008 with the cancellation of the NMP project. GIFTS never flew but a fully functional engineering model is in place at Space Development Laboratories (SDL) in Logan Utah. As mentioned above, we can look forward to the Chinese GIIRS and EUMETSAT IRS to provide the first and second geostationary IR sounding measurements.

3.1 Physical Phenomena Observed

Infrared sounders in LEO orbit including AIRS, CrIS and IASI, measure the upwelling radiance in the infrared. In addition to atmospheric temperature and water vapor profiles from the surface to the upper troposphere or stratosphere, these instruments measure surface temperature, cloud properties, aerosols, and trace gases such as ozone, carbon monoxide, methane, ammonia and carbon dioxide. Figure 2 shows a typical spectrum from the AIRS and the constituents contributing to the absorption features observed. Not all species in this figure are retrieved today.

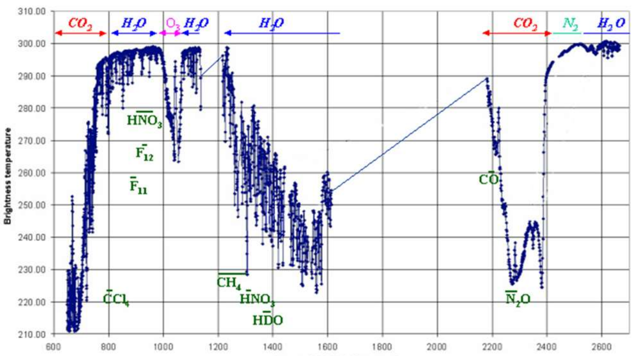

Figure 2. AIRS spectrum and atmospheric constituents. Temperature profiles are retrieved by sounding along the large CO_2 branches at 700 cm^{-1} and 2400 cm^{-1}.

The radiances from the IR sounders have among the highest impact of any measurement type when assimilated into operational weather forecast models[5]. LEO IR sounder radiances are used to retrieve temperature and moisture profiles with high vertical accuracy[6]. AIRS profiles have been used to validate water vapor distributions in climate models and confirm positive water vapor feedback to global warming[7].

3.2 SDR Performance Metrics and Relationship to EDRs

3.2.1 SDR Performance

The infrared sounders have very high spectral resolution, $\lambda/\Delta\lambda > 1000$, making them starved for signal. The legacy sounders include cryogenic cooling of the infrared detectors to achieve radiometric sensitivity, with more cooling required for the longest wavelength bands. Different methods were employed to achieve the spectral separation with AIRS using a grating spectrometer and IASI and CrIS using a FTS. While there was considerable dialogue in the community as to the advantages and disadvantages of the different approaches, the bottom line is that, in the end, both methods are working very well in operations and are comparable in cost. Nevertheless, there are several instrumental artifacts that must be avoided to make the SDRs and EDRs useful.

Detector noise properties can be a significant issue for IR sounders. AIRS has 2378 channels in the infrared (2 detectors each for most for redundancy). Not all detectors have the same noise properties. In fact, about 5% of them are either dead, very noisy, or have non-Gaussian noise. On average, one detector every month goes out due to radiation damage in orbit. To mitigate this, the AIRS project regularly updates the redundancy configuration recovering most of the detectors that were lost. Future grating spectrometer systems will use many more than 2 detectors per channel, allowing full operation for all channels throughout the mission. The CrIS instrument on NPP has almost all detectors working properly, with just one MWIR channel as noisy. The non-Gaussian noise properties exhibited by some of the AIRS detectors has not been an issue for data assimilation to date. Each channel in the spectrum has noise independent of the other in a grating system, while the noise is correlated in an FTS as in CrIS. Care must be taken in all IR sounder systems to define the noise covariance matrix.

Spectral stability is critical to maintaining accuracy in hyperspectral IR sounders. The spectral resolution is high enough that small shifts in frequency can result in large changes in radiance as the channel sees different parts of absorption features. Methods are in place to calibrate the spectrum in orbit to better than 0.2 ppm[8], however this takes time to calibrate so spectral stability is critical. Temperature control is required for the grating spectrometers, and a metrology laser is required for the FTS.

Spatial inhomogeneity effects can impact EDRs. Ideally, instrument spatial response does not produce artifacts in the spectra, however, due to the design of the instrument, artifacts are possible. The AIRS pupil imaging scheme results in discontinuities in the spectrum at detector array module boundaries when viewing high contrast scenes (e.g. clouds in the scene). Discontinuities also exist in IASI and CrIS at band boundaries (3 bands), and the noise amongst the multiple FOVs behaves differently in the instruments. These artifacts could impact retrieval accuracy in cloudy scenes. At this time NWP centers assimilate primarily clear soundings. Higher spatial resolution systems in the future will mitigate this problem by allowing more cloud free soundings per unit area.

Most scenes are unpolarized in the infrared, except over ocean at extreme view angles. Nevertheless, polarization can impact radiometry. This happens when the scan mirror polarization interacts with that of the spectrometer to create a polarizer/analyzer modulation effect with scan angle. Both AIRS and CrIS have seen this effect and have algorithms for correction[9].

3.2.2 Sounder EDRs

As an example of the type of EDRs achieved from the IR sounders, the AIRS standard deliverable products from Version 6.0 are given in Table 2. The performance of the product is listed in the third column. The products are divided into three types. Core radiances that consist of calibrated and geolocated upwelling radiances at the native resolution of the instrument (15 km). The second type of data are the Core Geophysical (Level 2) products. These products are geolocated geophysical quantities, usually offered on the scale of approximately 45 km at nadir. The third type of products are research products (at a low state of validation). Level 3 products are gridded spatially (1 degree latitude and longitude bins) and temporally (1 day, 8 day and monthly) and usually contain all standard Level 2 products. Level 3 products are produced for all geophysical variables. In addition to the products identified in the table, it is expected that a 3-satellite constellation of CubeSat IR Sounders operated would produce good Atmospheric Motion Vector (AMV) winds.

Table 2. Example of data products from a fully operational IR sounder (AIRS).

AIRS Product	Product Type	Accuracy (V5)
Core: Radiances		
AIRS IR Radiance	L1B-AIRS	<0.2K @ 250K
AIRS VIS/NIR Radiance	L1B-VIS	15-20%
Core: Geophysical		
Cloud Cleared IR Radiance	L2	1.0 K
Sea Surface Temperature	L2	1.0 K
Land Surface Temperature	L2	2-3 K
Temperature Profile	L2	1 K / km
Water Vapor Profile	L2	15% / 2km
Total Precipitable Water	L2	5%
Fractional Cloud Cover	L2	20%
Cloud Top Height	L2	1 km
Cloud Top Temperature	L2	2.0 K
Carbon Monoxide	L2	15%
Carbon Dioxide (Mid-Troposphere)	Post-Proc	1-2 ppm
Total Ozone Column	L2	5%
Ozone Profile	L2	20%
Land Surface Emissivity	L2	10%
IR Dust	L1B-Flag	0.5 K
Research Products		
Methane	L2	2%
OLR	L2-Support	5 W/m^2
HNO3	L1B-Post	0.2 DU
Sulfur Dioxide	L1B-Flag	1 DU

4. FUTURE CONCEPTS

Future concepts for infrared sounders will depend on the desired spatial, spectral and temporal resolution from the instruments. We start with examining the trade space and concepts for LEO sounders then discuss considerations for next generation GEO sounders.

4.1 Future LEO Grating Spectrometer Sounder Concepts

At this time there are no funded LEO IR sounder new instrument development programs at NASA. This section covers two concepts for advanced sounders using grating spectrometers developed at JPL under studies for NASA and NOAA.

4.1.1 Physical Limitations in LEO

For a given radiometric sensitivity (i.e. Noise Equivalent Temperature Differential, NEdT), a tradeoff exists between the sensor aperture and the integration time, which is related to the size of the detector array and field of view of the optics along track. Figure 3 shows the trade for IR sounders of different configurations in LEO. The curves represent the required aperture size vs field of view to achieve a constant NEdT. There are curves for MWIR+LWIR (like the legacy sounders) but at multiple spatial

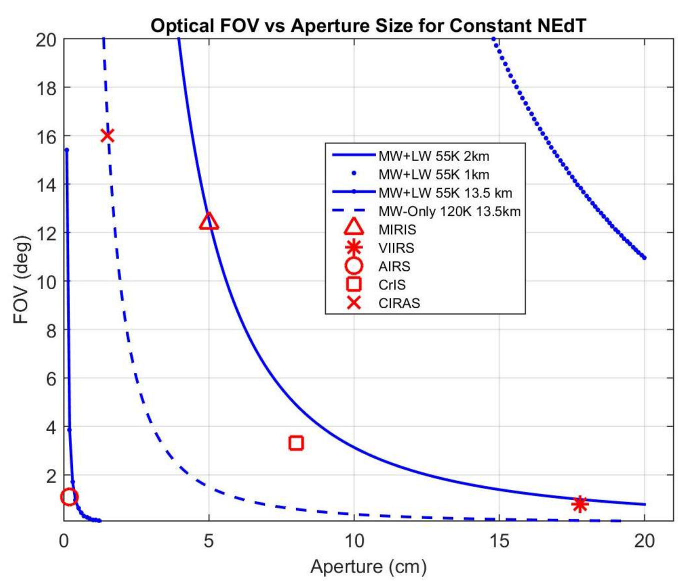

Figure 3. Optical Field of View along track vs aperture size for LEO sounders and where certain sensors fall in the trade space

resolutions, and MWIR-Only at the legacy spatial resolution of 13.5km.

The curves show that the wider the field of view along track (more time to scan and longer integration time), the smaller the aperture needs to be. AIRS falls on the first curve with an effective pupil diameter of about 0.3 cm, but used an aperture sharing technique (pupil imaging and afocal relays) for each of the individual detector modules requiring a larger mirror. AIRS detectors operate at about 59K as needed for the quality of the IR detectors at the time. CrIS detectors operate at about 80K, but has far fewer detectors (27) allowing selection of the best quality elements.

The CIRAS achieves MWIR-Only sounding operating the detectors at 120K and falls on a different curve because of the operating temperature and band. CIRAS pushes the aperture to the smallest possible by achieving a very wide 16° field of view along track. The scan is slow, about 20.8s to complete ±49.6º. The large format FPA makes this possible.

The third curve in the figure corresponds to the same trade for 2km spatial resolution and a FPA running at 55K to capture the LWIR. This curve represents what would be needed to meet the needs of the next generation of sounders requiring higher spatial resolution. This curve includes the aperture and FOV for the MIRIS (which achieves 2 km IR sounding, and 250m x 500m imaging like VIIRS), and the aperture and field of view of VIIRS for reference.

It can be seen from these curves that the systems with the largest field of view achieve the smallest aperture. Aperture size translates into instrument and mission cost. The wide field of view requires large format FPAs and wide field of view optics. Fourier Transform Spectrometer (FTS) systems have difficulty with a wide field of view due to significant shifting of the spectral response across the field. Gratings can achieve the wider field at the expense of more detectors and greater cooling load.

None of the current operational infrared sounders take advantage of large format FPA technology and wide field of view optics. Designs were limited by FPA technology available at the time. Future instruments can take advantage of the larger FPA technology reducing instrument size and overall costs in most cases.

4.1.2 LEO CubeSat IR Sounder

CIRAS is an instrument approach to achieve temperature and water vapor profiles using hyperspectral infrared in a 6U CubeSat[10,11]. Although originally intended to fly in space but descoped due to cost reasons, much was learned about the design and development of the CIRAS approach during the first year, including detailed design of the instrument and spacecraft, and technology demonstration of key subsystems.

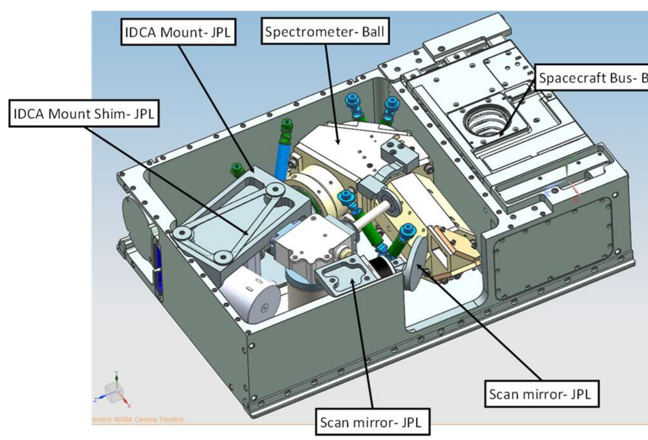

Figure 4. The CubeSat Infrared Atmospheric Sounder (CIRAS) MWIR sounder concept

The CIRAS instrument employs wide field optics and large format FPAs to minimize size and cost. Industry partners include Ball Aerospace, IRCameras, and Blue Canyon Technologies (BCT). Figure 4 shows a conceptual layout of the CIRAS instrument and the major subsystems. The CIRAS is designed with three key JPL Microdevices Laboratory (MDL) technologies: 1) HOT-BIRD detectors, 2) MWIR Grating Spectrometer (immersion grating), 3) Black Silicon Blackbody. At this time, the design is near or at completion for all subsystems. Hardware subsystems developed to completion include the HOT-BIRD Focal Plane Assemblies (FPAs), the FPA out of band blocking filters, the Integrated Dewar Cryocooler Assembly (IDCA) (IR Cameras), the Camera Electronics, the cryocoolers and the cryocooler electronics. Assemblies still in breadboard stage include the Payload Electronics including the motor driver, housekeeping and power conversion. Assemblies at the final design stage include the Optics (Ball Aerospace) and the Spacecraft (BCT), both of which had their Final/Critical Design Reviews. The CIRAS mechanical design is complete at the PDR stage having completed the CAD design and structural analyses on the optics mounts (bipods), but not on the other mounts. Slits for the spectrometer were fabricated (from black silicon) and the grating substrates were fabricated and AR coated.

Currently there are two Observing System Simulation Experiments (OSSEs), one sponsored by NOAA performed at the University of Wisconsin, and another sponsored by NASA performed at the Global Modelling and Assimilation Office

(GMAO) at GSFC to evaluate the impact of assimilation of MWIR-Only radiances on forecast accuracy. Simulations of retrievals using the MWIR Only in AIRS have shown good results in the lower troposphere[12]. Maturation of the radiative transfer models and additional assimilation studies are needed in the MWIR to make full use of this band that currently exists in the IR sounders today.

The CIRAS can be used in multiple ways in a future observing system. First, it can serve as a low-cost gap mitigation measure in the event of failure of CrIS on JPSS. It can provide IR sounding data in different orbits, and with more rapid revisit. The CIRAS instruments can be used in a 3-satellite constellation designed to measure IR water vapor AMV winds in 3D. The retrieval process would be similar to MODIS AMVs, but with 3D information due to the sounder vertical resolution in water vapor (vs MODIS total column) and better coverage due to overlap at all latitudes.

4.1.3 LEO High Spatial Resolution IR Sounder

The infrared portion of VIIRS and the CrIS requirements can be met with a single instrument called the Moderate resolution InfraRed Imaging Sounder (MIRIS)[13] shown in Figure 5. A 2013 study performed by JPL for NOAA developed a concept for the MIRIS incorporating two all refractive telescope/grating spectrometers. The concept has 250 m x 500 m spatial resolution imaging with sufficient sensitivity to achieve hyperspectral infrared sounding at 2 km x 2 km resolution.

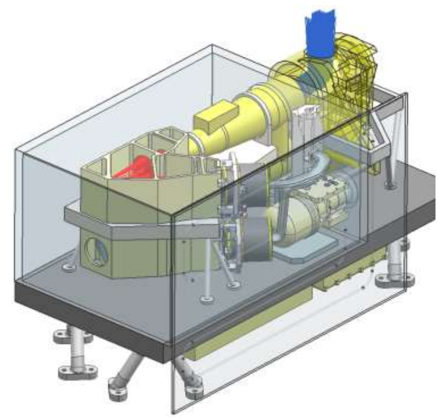

Figure 5. Moderate-resolution InfraRed Imaging Sounder (MIRIS) provides VIIRS-like imaging and CrIS-like sounding at 2 km GSD.

Table 3. Estimated Resource Requirements for MIRIS

Parameter	Value
Size	1.0 x 0.5 x 0.5 m
Mass	100 kg
Power	150 W
Data Rate	< 40 Mbps

The MIRIS includes a single scanner mounted on a 2-axis gimbal allowing along-track scanning as well as the standard cross-track scanning. This allows pointing and tracking a single target for improved sensitivity. The energy from the scanner is collected via a single 50 mm Effective Pupil Diameter (EPD) reflective telescope and directed to two individual grating spectrometers (corresponding to the two spectral bands) via dichroic beamsplitters. The grating spectrometers disperse the energy into the individual spectral channels at the detector array. Spectrometer designs have been developed and show no insurmountable challenges. The system includes large format Teledyne CHROMA commercial detector arrays (480 x 640), 2 per band to achieve 960 channels covering the spectral ranges 3.76 µm–5.13 µm, and 8.0 µm– 15.4 µm, and active cooling using the NGC Pulse Tube Cooler. Passive radiators are not shown but place additional requirements on the orientation of the spacecraft. A sun synchronous orbit is required with a clear view to space as is currently available for the legacy instruments. Resource requirements for MIRIS are given in Table 3.

The MIRIS approach was cited in a white paper submitted to the 2017 NRC Decadal Survey for Earth Observation from Space[14]. The RFI response, number 31, is titled "High resolution atmospheric temperature and water vapor observations to improve drought and vector borne disease predictions and weather forecasting". MIRIS will address how local near surface atmospheric temperature and humidity are controlled by fine-scale variations in emissivity and topography and address processes relevant to agriculture, human health monitoring, drought, fire and weather forecasting. MIRIS most likely fits under the "Planetary Boundary Layer" targeted observable, but could also address "Greenhouse Gases" and "Ozone and Trace Gases".

4.2 Future GEO Grating Spectrometer IR Sounder Concept

The atmospheric sounding community has identified the value of a high-spectral and high-temporal resolution infrared sounding for "monitoring the mesoscale environment for severe weather forecasting and other applications"[15]. The Geosynchronous Interferometric Infrared Sounder (GIIRS) on Feng Yun-4 (FY-4) satellite, launched in December of 2016 is the first hyperspectral infrared sounder in GEO with a spatial resolution of 8km and spectral resolution of 0.625 cm^{-1}. A study was performed by three industry contractors in the mid 2000s of a Hyperspectral Environmental Suite (HES). The requirements for the instruments called for hyperspectral infrared for atmospheric sounding and multispectral visible imaging for ocean color[16]. HES was cancelled, but we use HES requirements to develop concepts for next-gen IR GEO sounders.

In this section we present a few considerations on the physical limitations of sounding from GEO followed by a concept developed at JPL to augment a GEO Imager with hyperspectral sounding capability.

4.2.1 Physical Limitations

Physical limitations for GEO sounding are primarily driven by spectral resolution and radiometric sensitivity, (Noise Equivalent Differential Temperature (NEdT)). Requirements on spatial and temporal resolution are the next most difficult due to the distance from the Earth and need to scan wide fields in a short amount of time.

Spectral: Spectral resolution requirements are high ($\lambda/\Delta\lambda$ > 1000:1) across the spectrum, and can be achieved using a high spectral resolution spectrometer (e.g. grating or FTS). The spectrometers can be complex, requiring moving and active parts (in the case of the FTS), or large numbers of detectors (at least 1 for each channel) in the grating. Schmit et al. (2007) discuss tradeoffs of spectral resolution and vertical resolution[17].

MWIR-Only Sounding: In addition to the full band capability, good temperature and water vapor performance can be achieved with just the MWIR region of the spectrum[12]. Prior studies have shown that theoretically MWIR-only sounding can achieve most of the sensitivity as full band sounding for temperature and water vapor in the lower troposphere and under ideal circumstances. While the Atmospheric Infrared Sounder (AIRS) on Aqua uses the MWIR band for temperature sounding in their V6 retrieval (with similar spectral resolution), there still are challenges with solar reflected energy that must be resolved before MWIR sounding can be used operationally at National Weather Prediction (NWP) centers. With the current interest and investment to solve this problem and make use of smaller instruments like CIRAS, these issues should be resolved in the timeframe of the flight of the future instruments that would choose to fly MWIR only.

Spatial: HES requirements call for 5 km in Severe Weather/Mesoscale (SW/M) mode and 10 km in Full Disk mode. The concepts we explored offer HES-like resolution mostly limited by spectral resolution and radiometric sensitivity (NEdT). The diffraction limited aperture for a 5 km GSD at 15.4 microns is 13.5 cm, much smaller than the GEO imagers but much bigger than that required for LEO sounders.

Temporal: The acquisition time requirement for HES is 3 hours to acquire 2.5 full disk plus coastal waters images, or less than 1 hour per full disk acquisition. The longer acquisition time enables meeting the NEdT without driving aperture beyond the diffraction limit.

4.2.2 Geostationary Earth Multispectral Mapper-Sounder (GEMM-S).

In 2014, JPL developed a concept for a Geostationary Earth Multispectral Mapper (GEMM) that met the majority of the ABI requirements but in a package small enough to fit as a hosted payload on a communications satellite. An augmentation to the GEMM imager instrument concept was developed to include an IR sounder (Figure 6). The GEMM Sounder (GEMM-S) includes an MWIR-only grating spectrometer at the MWIR focal plane of the primary imaging telescope of the GEMM. The spectrometer would operate under 4x magnification making it small but with a wide field of view. The spectrometer includes an immersion grating and would be very similar to the CIRAS spectrometer, covering the same band and spectral resolution (see above).

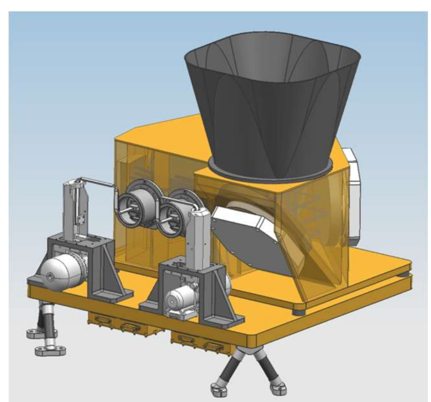

Figure 6. Geostationary Earth Multispectral Mapper-Sounder contains an MWIR grating spectrometer sounder

The GEMM-S meets HES sounding requirements in the MWIR but has no LWIR channels. Spatial and temporal requirements are met with 15-30 min updates possible, allowing sounding to be performed with minimal impact to imagery acquisition. With a 20 Mbps data rate, the 625 sounding channels can be downloaded at a spatial resolution of 5 km over the period of 1 hour. A data acquisition scheme and spectral binning approach should allow generation of both imaging and sounding products from the same data set. The data rate would be correspondingly higher with imaging provided simultaneously. The GEMM-S concept has a volume of 0.8 x 0.8 x 0.65 m, weighs 160 kg and consumes 310W.

5. SUMMARY

Infrared atmospheric sounders in LEO provide among the highest contribution to reducing error in global operational forecast models of any instrument type. They measure temperature and water vapor profiles with high vertical resolution and can be made to have high spatial resolution with state-of-the-art large format focal plane technologies, or be made considerably smaller such as with CIRAS. MWIR-only sounding as done in CIRAS can provide a significant reduction in size, mass, power and cost, and provides good vertical resolution and sensitivity throughout the low-to-mid troposphere but can be impacted by solar reflection. The JPL MIRIS concept developed for NOAA in 2013 provides full spectrum capability (MWIR-LWIR) with a horizontal spatial resolution of 2km in sounding mode, offering next-generation sounding capability to meet the needs identified in the NRC 2017 Decadal Survey for Planetary Boundary Layer and Greenhouse Gas measurements. MIRIS also meets the thermal imaging requirements of the VIIRS. While the US has not yet achieved a program to develop a geostationary hyperspectral infrared sounder, the Chinese have launched their first instrument with the GIIRS. The EUMETSAT IRS for GEO sounding is under development. Both GIIRS and IRS are FTS systems like the CrIS and IASI, but grating spectrometer systems are equally viable for these applications. The GEMM-S concept for GEO sounding employs an MWIR-Only grating spectrometer to achieve a low-cost modification to a GEO imager such as the JPL GEMM hosted payload concept.

The tradeoffs in cost, sensitivity, spatial coverage and resolution, and spectral range and resolution between the two types of spectrometers (gratings and FTS) will usually dictate the preferred approach, but at this time both approaches are viable for IR sounding. With the advent of large format focal plane assemblies, grating spectrometers can offer wider field of view than FTS instruments, leading to a smaller overall instrument package. As requirements for imaging and sounding merge to provide high spatial resolution sounders (or hyperspectral imagers) in the infrared, the grating spectrometer solutions presented here offer numerous advantages in size, mass, power, complexity and cost.

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