Measurement approach and design of the CubeSat infrared atmospheric sounder (CIRAS)

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ABSTRACT

The CubeSat Infrared Atmospheric Sounder (CIRAS) will measure upwelling infrared radiation of the Earth in the MWIR region of the spectrum from space on a CubeSat. The observed radiances can be assimilated into weather forecast models and be used to retrieve lower tropospheric temperature and water vapor for climate studies. Multiple units can be flown to improve temporal coverage or in formation to provide new data products including 3D motion vector winds. CIRAS incorporates key new instrument technologies including a 2D array of High Operating Temperature Barrier Infrared Detector (HOT-BIRD) material, selected for its high uniformity, low cost, low noise and higher operating temperatures than traditional materials. The detectors are hybridized to a commercial ROIC and commercial camera electronics. The second key technology is an MWIR Grating Spectrometer (MGS) designed to provide imaging spectroscopy for atmospheric sounding in a CubeSat volume. The MGS has no moving parts and includes an immersion grating to reduce the volume and reduce distortion. The third key technology is an infrared blackbody fabricated with black silicon to have very high emissivity in a flat plate construction. JPL will also develop the mechanical, electronic and thermal subsystems for CIRAS, while the spacecraft will be a commercially available CubeSat. The integrated system will be a complete 6U CubeSat capable of measuring temperature and water vapor profiles with good lower tropospheric sensitivity. The CIRAS is the first step towards the development of an Earth Observation Nanosatellite Infrared (EON-IR) capable of meeting the replacement needs of the CrIS on JPSS.

Keywords: Infrared, Sounding, CubeSat, Grating, Spectrometer

1. INTRODUCTION

Hyperspectral radiances measured from Low Earth Orbiting (LEO) infrared (IR) sounders including the NASA Atmospheric Infrared Sounder (AIRS)[1] on Aqua, and the Cross-track Infrared Sounder (CrIS) on the Joint Polar Satellite System (JPSS) have among the highest impact of any measurement type when assimilated into operational weather forecast models[2,3,4]. LEO IR sounder radiances are used to retrieve temperature and moisture profiles with high vertical accuracy.[5] AIRS profiles have been used to validate water vapor distributions in climate models and confirm positive water vapor feedback to global warming.[6,7]

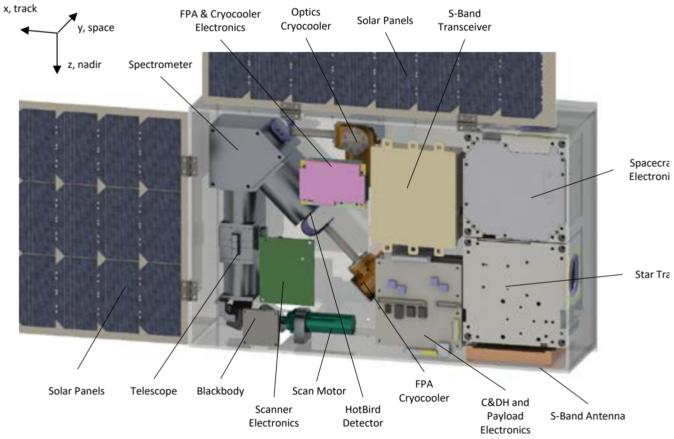


Figure 1. The CubeSat Infrared Atmospheric Sounder (CIRAS)

Figure 1 shows a conceptual layout of the CIRAS instrument[8]. Key objectives of CIRAS are to demonstrate technologies for reducing the cost of future IR sounders, help mitigate a gap in hyperspectral IR sounder coverage in the event of a loss of one of the current IR sounders, offer the opportunity for IR sounding data from new orbits, and maintain continuity of current IR sounders into the future. NASA has funded the CIRAS under the Inflight Validation of Earth Science Technology (InVEST) program under the Earth Science Technology Office (ESTO). The CIRAS is currently under development at NASA JPL and is scheduled for launch in mid to late 2018. The payload uses a mix of commercial and custom hardware. The key new technologies (spectrometer, focal plane, black silicon) are custom but almost everything else is commercial or based on commercial designs. The CIRAS spacecraft will be a commercial 6U CubeSat, the vendor of which will be selected in late 2016.

Maintaining continuity of these important weather forecasting and climate data sets is critical to NASA and NOAA. NOAA has identified the need for an Earth Observation Nanosatellite - IR (EON-IR) as a low cost-to-orbit way to mitigate a potential gap[9] in data of the CrIS on JPSS and offer new orbit opportunities. CIRAS will demonstrate the MWIR portion of EON-IR. The LWIR may not be required for some applications, but development of the LWIR spectrometer and detector has been proposed under the NASA ESTO Instrument Incubator Program (IIP).

2. SOUNDING REQUIREMENTS

Table 1 shows the performance capability of AIRS (similar for CrIS) compared to the requirements for CIRAS. The legacy sounders and CIRAS achieve relatively low spatial resolution, 13.5 km, but have a broad swath for global daily revisit. CIRAS orbit altitude is lower than AIRS and CrIS (between 450-600 km) contributing to a reduced swath. The pixel aggregation approach for CIRAS allows the same resolution to be achieved for any orbit altitude.

Table 1. AIRS Performance and CIRAS Requirements. CIRAS focuses on the lower troposphere.

Parameter	AIRS Performance	CIRAS Requirement
Vertical Range	0-<100mb	0-500 mb
Temperature Profile	≤1.5 K/km	≤1.5 K/km
Humidity Accuracy	15%/2km	20%/2km
Spectral Range	3.7-15.4μm	4.08-5.13μm
Spectral Resolution	≤0.5-2.2cm^{-1}	≤ 1.2-2 cm^{-1}
Spatial Res. (nadir)	13.5 km	13.5 km
Scan Range	1750 km	1100 km
NEdT	0.1-1.0K	<0.25K
Size	1.4 x 0.8 x 0.8 m^3	6U
Mass	177 kg	10 kg
Power	256W	40 W

The spectral resolution of CIRAS is comparable to legacy sounders in this band providing similar vertical resolution in the lower troposphere[8]. The band includes 2 temperature sounding branches and goes well into the water continuum. Spectral range and resolution for CIRAS and the legacy sounders in this region are shown in Figure 2 along with a typical spectrum of the atmosphere (after convolution with the CIRAS Spectral Response Function (SRF)), highlighting the water vapor lines and CO2 branch used for temperature sounding. We also show the AIRS channels used by the UK Met Office for data assimilation[10].

A key requirement for CIRAS is that it fit in a low cost CubeSat. This is intended to reduce the overall cost of the payload, satellite and launch making it useful as gap mitigation system or to augment the currently available orbits. To meet a CubeSat volume we focus CIRAS on retrieval of temperature and water vapor profiles from the surface to the mid troposphere, important for weather and climate studies, requiring only MWIR wavelengths for a smaller aperture, higher detector operating temperature and lower power operation.

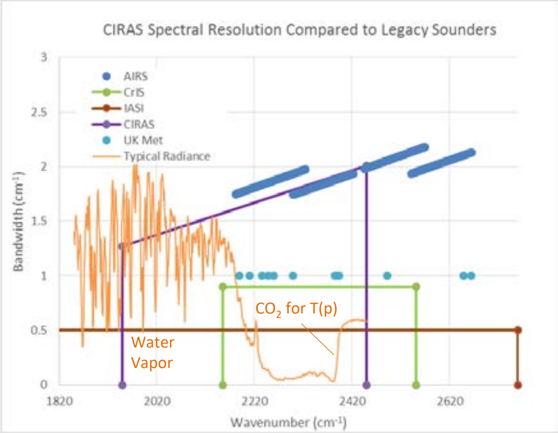


Figure 2. Spectral Resolution and Coverage for CIRAS compared to legacy IR sounders

The legacy sounders achieve temperature sounding well into the stratosphere using the LWIR, although similar data in the stratosphere is achieved from microwave sensors. Addition of the LWIR is possible in future instruments with additional volume and power.

3. DESIGN APPROACH

3.1 System Overview

A block diagram of the CIRAS is shown in Figure 3. The CIRAS payload includes a scan mirror capable of rotating 360° to view Earth, cold space and an internal blackbody for calibration. The blackbody is a simple flat plate composed of black silicon, heat sunk and instrumented with a temperature sensor, and provides high emissivity and durability in a compact design. Energy from the scan mirror is collected using an all-refractive telescope. Energy from the telescope is focused onto the entrance slit of an all refractive MWIR Grating Spectrometer (MGS). The MGS covers the 4.08-5.13

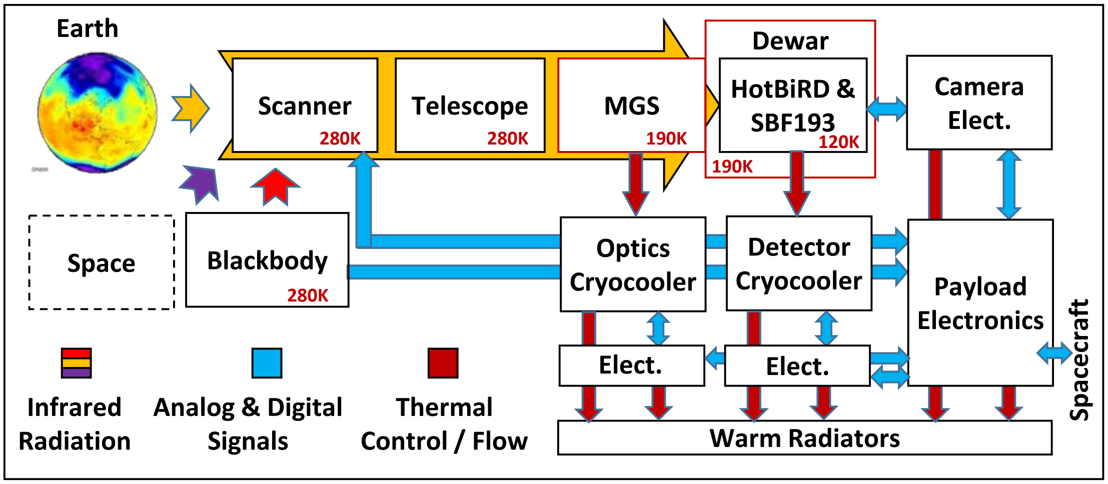


Figure 3. Block diagram of the CIRAS instrument. Items in red are targeted to be advanced in TRL.

µm spectral range in 625 channels and employs an immersion grating to reduce size and distortion. The CIRAS optics will be developed by Ball Aerospace of Boulder Co. The telescope and spectrometer are cooled to 190K using an active commercial cryocooler heat sunk to radiators on the spacecraft. The specific cryocooler has not yet been selected. The spectrometer disperses the energy across the spectral range and produces a 2-dimensional image at the focal plane with one direction spatial (504 pixels) and the other spectral (625 channels). The detector array uses the JPL HOT-BIRD photosensitive material mounted on a Lockheed Martin Santa Barbara Focalplane (SBF) 193 Readout Integrated Circuit (ROIC). The ROIC is mounted in a standard Integrated Cooler Dewar Assembly (ICDA). The dewar contains a cold filter mounted close to the focal plane, and a window at the interface between the dewar and the optics. The detector is cooled to 120K using a second commercial cryocooler heat sunk to the warm radiator. Clocks, biases and A/D conversion are performed using commercial electronics. Payload electronics provide the interface between the scanner, camera, cryocoolers, blackbody and spacecraft electronics. Electronics, cryocooler and spacecraft waste heat is dissipated in warm temperature radiators on all remaining surfaces except nadir and anti-nadir.

3.2 Imaging and Scanning

The CIRAS employs pixel and frame averaging to achieve the desired size of the Field of View (FOV). The system can achieve low spatial resolution (13.5 km) with global coverage in “Global” mode, or high spatial resolution (3km) in a narrow swath in “Zoom” mode. Orbit, imaging and scan parameters are shown in table 2. The process is diagramed in Figure 4 for the Global mode case. The CIRAS focal plane layout is shown to the right. One dimension is used for the spectrum and corresponds to the direction perpendicular to the length of the slit. The second dimension is used for spatial information, projecting a line onto the ground at nadir. A total of 625 channels and 506 spatial detector elements (pixels) are used respectively. In Global mode, the CIRAS adds 42 pixels along track and averages 2 frames while scanning cross-track to make a single FOV. The 42 pixels are averaged for every spectral channel. Different pixels can be summed to co-register spatial and spectral information if needed. The slit projection is scanned cross-track, mapping the earth as the satellite moves along the track direction. The scan rate and sampling rate are adjusted to achieve 2 frames of data every 13.5 km footprint.

In Zoom mode, the sensor will be able to achieve 3 km spatial resolution over a 161 km swath. In this mode, only 9 pixels and 3 frames are averaged per FOV. The additional frame is needed to

Table 2. CIRAS Nominal Orbit, Imaging and Scanning Parameters

Orbit	Global	Zoom
Altitude (km)	600	600
Inclination (deg)	98.7	98.7
Ground Vel. (km/s)	6.91	6.91
Imaging	Global	Zoom
FOV (km)	13.5	3
N_FOVs_trk	12	56
N_Pixels trk	504	504
Pixels/FOV trk	42	9
Frames/FOV xtrk	2	3
Scanning	Global	Zoom
Scan Efficiency	0.9	0.9
Swath trk (km)	161	161
Swath xtrk (+/-deg)	41.6	6.18
Swath xtrk (km)	1112	130
Active Scan Time (s)	20.8	20.8
Scan Rate (r/s)	0.0699	0.0104
Tdwell (s)	0.322	0.482
Integration Time (s)	0.161	0.161

improve SNR at the expense of a reduced swath. Wider swath in zoom mode may be possible depending on actual noise from the instrument and available data rate.

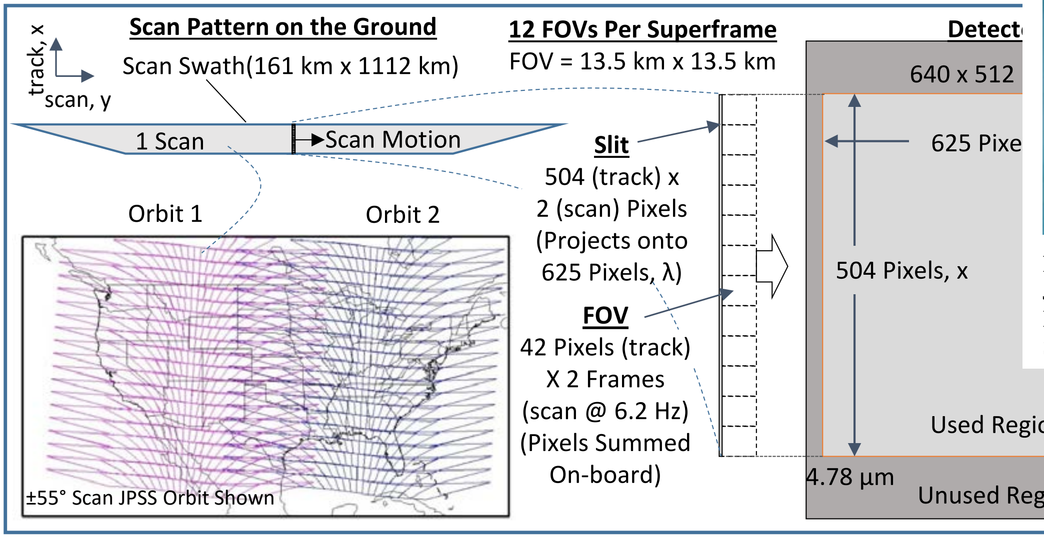


Figure 5. JPL/Ball SIRAS IIP-2000 LWIR Spectrometer.

Figure 4. Scan pattern and projection on the ground and detector for CIRAS in global mode in a 600 km orbit. CIRAS makes 12 Fields of View (FOVs) by averaging 2 frames and 42 pixels along track per FOV.

3.3 CIRAS Optics

The CIRAS optical design includes the all refractive wide field telescope and the MWIR Grating Spectrometer (MGS). The all refractive design with multiple elements enables good image and color correction over a large, two dimensional field of view. The CIRAS is based on designs developed by JPL and Ball Aerospace in the late 1990's and mid 2000's. The Spaceborne Infrared Atmospheric Sounder (SIRAS)[11]. and SIRAS-Geosynchronous Earth Orbit (SIRAS-G) demonstrated wide field all refractive grating spectrometer systems operating in the LWIR and MWIR respectively with spectral resolution and field of view comparable to the CIRAS. Figure 5 shows the SIRAS LWIR spectrometer developed by Ball Aerospace and JPL in 2000. CIRAS is much smaller and simpler than the SIRAS spectrometers and will also be developed at Ball Aerospace with the immersion grating and entrance slit developed at JPL. A silicon immersion grating similar to that required for CIRAS has been developed in the JPL Micro Devices Laboratory (MDL) for the OCO-WF RTD program. Measurements show the diffracted beam at the predicted angles and required efficiencies, demonstrating JPL's ability to develop TRL 5 immersion gratings for CIRAS.

Two important requirements of spectrometer optical performance are the spectral 'smile' (<2 pixels) and keystone geometrical distortions (<2 pixels), resulting from anamorphic magnification (beam compression) of the diffracted beam. Anamorphic magnification also may cause Point Spread Function (PSF) elongation in the spectral direction, which reduces spectral resolving power. The symmetry of the design and the use of the immersion grating minimizes distortions. The resulting spectral 'smile' across the spectrum is less than 1 pixel, and the keystone distortion is also less than 1 pixel. The diffraction PSF remains concentric and uniform in spatial and spectral directions, resulting in uniform resolution across the FPA. The PSF cross-section follows a diffraction limited power distribution within the focal spot at the FPA, with a spot diameter of ~31 µm, or 1.3 pixels. Additional considerations in the design and build will include operating temperature, design athermalization, stray light, ghosting, and fringing.

3.4 HOT-BIRD Detectors

CIRAS will use the recently invented JPL High Operating Temperature Barrier Infrared Detector (HOT-BIRD) technology based on III-V compounds. HOT-BIRD offers a breakthrough solution for the realization of lower development cost, while reducing dark current and improving uniformity and operability compared to II-VI material (MCT). Low 1/f noise and high temporal stability allows CIRAS to use a slow scan for better sensitivity and less frequent calibrations. Using the HOT-BIRD material, JPL has fabricated a variety

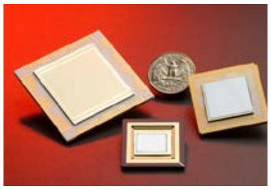


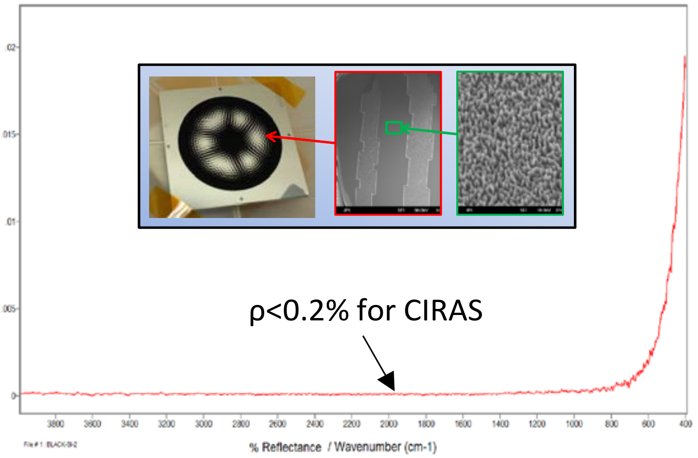
Figure 6. HOT-BIRD Detectors Made at JPL

of MWIR and LWIR FPAs with different pixel pitches (12µm and above) and formats (up 1Kx1K), see Figure 6. These FPAs showed excellent image quality with median NEDT of < 28mK and uniformity of 99.9%. These results clearly demonstrate that the HOT-BIRD technology has been advanced to TRL 6 and can be consistently delivered to space flight instruments including CIRAS.

3.5 Black Silicon Blackbody and Slit

AIRS used a wedge calibration blackbody, which is excellent and robust, but large. In order to save space the CIRAS calibration target (blackbody) is a flat plate coated with a JPL developed black silicon process. The result is a broadband black surface, exhibiting less than 0.15% reflectance at a wavelength of 5 microns. (Figure 7). The calibration target will be mounted to an aluminum block with a temperature sensor and operate at ambient temperatures. Temperature sensing accuracy is expected to be better than the 0.25K requirement. Black silicon for stray light absorption is currently being used on a number of flight spectrometers, and within the coronagraph for WFIRST-AFTA. The entrance slit will use precision micro machined fabrication and black silicon texturing techniques used on OCO-2, HyTES, UCIS, HyspIRI, MaRS2, PRISM and NEON.

Figure 7. Cryo-etched Black Si reflectance. Inset: WFIRST-AFTA high contrast apodizer



The remaining subsystems for CIRAS including the scanner, cryocoolers, thermal control system, electronics and spacecraft are undergoing design trades at this time and will be the subject of future reports. These systems (except thermal) involve extensive use of commercial technology and are relatively low risk.

4. PREDICTED PERFORMANCE

Spectral: The spectral resolution of CIRAS is calculated to be 3.3 nm at FWHM across the band (1.2-2.0 cm^{-1}) based on the dispersion and slit width. The shape of the response is defined by the convolution of the slit response (2 pixels), the detector response (1 pixel), and the optics blur function. The resulting spatial response is multiplied by the dispersion to give the spectral bandpass. The individual contributors to the total spectral response, and the total bandwidth are plotted in Figure 8. 2x Nyquist sampling is performed enabling resampling of the spectrum to a common grid. Additional requirements for keystone and distortion are also satisfied by the optical design.

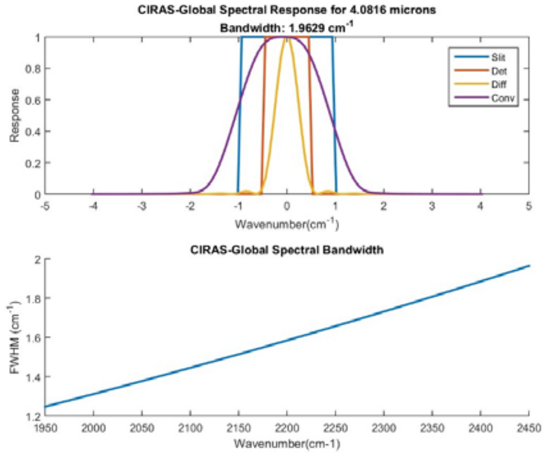


Figure 8. (Top) Contributors to the total (convolved) spectral response for CIRAS. (Bottom) FWHM of the spectral response function (bandwidth).

Radiometric: A radiometric sensitivity model was developed for CIRAS. Figure 9 shows the results of the model. All parameters are derived from the anticipated performance in orbit of the subsystems. 1/f noise is negligible at the calibration frequency of 20 mHz since the 1/f knee for the HOT-BIRD detectors is less than 0.1 mHz[12]. Correlated noise is primarily along the rows (spectral direction), and will removed by subtracting the average signal from several non-photo-active pixels in a given row in the ROIC. The results show an NEdT for all channels of <0.2K for a scene temperature of 280K. Analysis also shows sufficient dynamic range to image at 330K without saturation for the background and dark current expected. Radiometric accuracy for CIRAS is estimated to be less than 1.5%, or <0.5K @ 300K and is driven by the on-board blackbody temperature knowledge (<0.25K) and nonlinearity (<1%). Polarization is not a concern since the scene is unpolarized and a gold mirror will be used.

Spatial: The excellent image quality of the CIRAS optical system leads to the spatial resolution being driven by the pixel aggregation scheme and scan rate as discussed above. Both are programmable on orbit. We have chosen 13.5 km to meet requirements and build margin into the design, but with the system is capable of 3 km over a limited swath as mentioned above. Geolocation will be performed on the ground using a scan geometry model and CIRAS scene data with ground control points and spacecraft attitude as done on AIRS. Co-registration of the frequencies for a given ground position is achieved using a common slit and minimization of optical distortion.

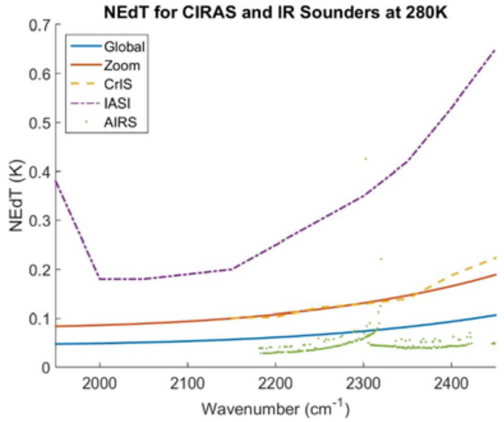


Figure 9. NEdT at 280K for CIRAS in Global and Zoom modes compared to AIRS, CrIS and IASI

Retrieval Accuracy: CIRAS builds on the lessons learned from AIRS V6 retrievals and performs temperature sounding using the MWIR. AIRS uses the LWIR for cloud clearing[5]. A sensitivity study was performed using Averaging Kernels that show CIRAS has good sensitivity of temperature and water vapor to about 400-300 mb[8]. While CIRAS will not provide sensitivity in the mid to upper troposphere, the high sensitivity in the mid-to-lower troposphere makes it still valuable as a sounder since this region is where most of the water vapor and clouds are, and where most of the weather occurs.

5. SUMMARY AND CONCLUSIONS

The CIRAS is a hyperspectral infrared sounder operating in the MWIR under development at JPL scheduled for launch in the mid 2018-2019 timeframe. CIRAS incorporates new technologies including a wide field spectrometer employing an immersion grating, HOT-BIRD detectors, and a Black-Silicon blackbody. These new technologies combined with commercial technologies in camera and payload electronics, scanning, cryocooling and the spacecraft enable the CIRAS to be developed at low cost and in a CubeSat configuration. Meeting legacy imaging requirements is straightforward, however CIRAS does not have the LWIR, making it sensitive to only the low-mid troposphere. This is the area of most value, however, to the forecast and science communities as it relates to weather and science applications (e.g. drought, vector borne disease habitat, etc.). Radiometric sensitivity for CIRAS also meets legacy requirements, but CIRAS has a zoom mode to allow 3 km spatial resolution imaging over a limited swath to view severe weather events or other areas of interest. Future CIRAS instruments can be used to mitigate a gap created by a loss of CrIS on JPSS and can be used in a constellation to achieve improved timeliness.

ACKNOWLEDGEMENTS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. © 2016 California Institute of Technology. Government sponsorship acknowledged.

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