The CubeSat Infrared Atmospheric Sounder (CIRAS), Pathfinder for the Earth Observing Nanosatellite-Infrared (EON-IR)

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ABSTRACT

The CubeSat Infrared Atmospheric Sounder (CIRAS) will measure upwelling infrared radiation of the Earth in the Midwave Infrared (MWIR) region of the spectrum from space on a CubeSat. CIRAS will demonstrate two new infrared sounding technologies. The first is 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 Readout Integrated Circuit (ROIC) and commercial camera electronics. The second technology is an MWIR Grating Spectrometer (MGS) to be designed and developed by Ball Aerospace to provide imaging spectroscopy for atmospheric sounding in a CubeSat volume. The MGS has no moving parts and is based on heritage spectrometers including the Ball Aerospace Spaceborne Infrared Atmospheric Sounder for GEO (SIRAS-G) IIP of 2007. JPL will develop the mechanical, electronic and thermal subsystems for CIRAS. 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 Observing Nanosatellite Infrared (EON-IR) for potential use in a future operational forecasting system.

BACKGROUND

Numerical Weather Prediction (NWP) centers worldwide have demonstrated the value of hyperspectral infrared sounders to improving weather forecasts. The Atmospheric Infrared Sounder (AIRS) on the NASA Earth Observing System Aqua Spacecraft was the first hyperspectral infrared sounder to be used for operational forecast improvement. IR sounder radiances are assimilated into Global Circulation Models and NWP centers worldwide including the National Center for Environmental Prediction (NCEP), the European Center for Medium-Range Weather Forecast (ECMWF) and the UK Met Office. Six hours of forecast model improvement on the 5 day forecast has been achieved by assimilating AIRS data at NCEP and ECMWF by assimilating only 1 in 18 footprints.[1] An additional 5 hours of improvement on the 5 day forecast or more has been shown to be possible using cloud cleared radiances[2]. The AIRS and the Infrared Atmospheric Sounding Interferometer (IASI) impacts to operational 24-

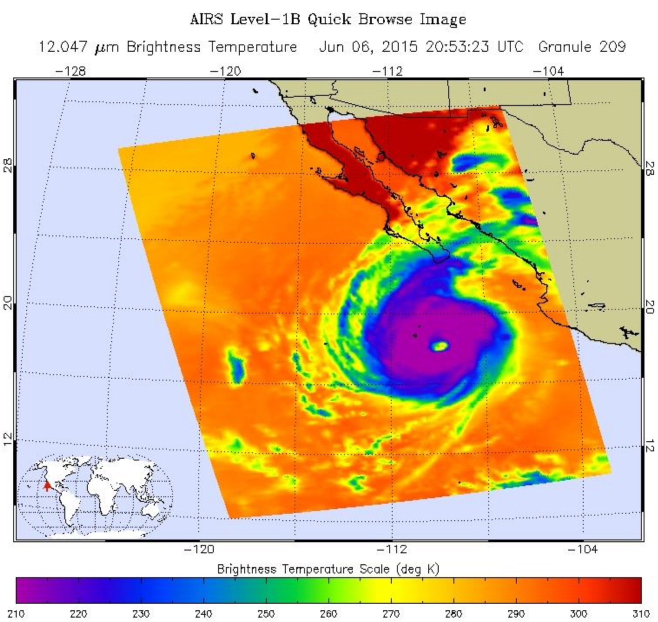

Figure 1. Wide swath scanning of the IR sounders enable daily revisit of severe weather events. E. Olsen (JPL)

hour forecasts at ECMWF are roughly comparable and are second only to the collective impact of four AMSU units[3]. Finally, the Cross-track Infrared Sounder (CrIS) on the Joint Polar Satellite System (JPSS) has demonstrated comparable performance to the AIRS and IASI. The sounders have a wide field of view enabling coverage of the full context of severe weather events (See Figure 1).

While the data from AIRS is assimilated into the operational forecasts at NCEP today, AIRS is expected to complete its mission when the Aqua spacecraft runs out of fuel in the 2022 timeframe. We can expect CrIS and IASI instruments and their nearly identical replacements to be operational into the late 2030's. 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 Observing Nanosatellite - IR (EON-IR) as a low cost-to-orbit way to mitigate a potential gap[4] in data of the CrIS on JPSS. A key objective of CIRAS is to demonstrate the technologies needed for an operational IR sounder, like EON-IR. In that respect, CIRAS is a pathfinder for EON-IR.

Not all requirements from the current operational IR sounders need to be satisfied in the EON-IR. The primary requirement to meet is the ability to provide radiances with sensitivity to temperature and water vapor profiles in the lower troposphere (below 500 mb). It is also recognized that the spatial coverage will depend on the orbit of the CubeSat, and that the CubeSat need not be placed in the same orbit as the operational sounders. This would enable sounding information at times that are currently not available (e.g. early morning). EON-IR would also provide a substantial cost saving (over 10x) compared to the current operational sounders, and can provide for new architectures, including a constellation for near-real-time global coverage of atmospheric humidity and temperature. Finally, with an improvement in the spatial resolution (zoom mode) and 3 tandem formation satellites in formation separated by 5-10 minutes, the EON-IR would be able to measure atmospheric motion vector winds in 3D using the water vapor profiles retrieved. EON-IR offers robustness to loss of failure and options for alternate orbits that complement the existing suite of sounders and pave the way for a future lower-cost, more robust observing system. CIRAS is the pathfinder mission to demonstrate several of these capabilities.

CIRAS REQUIREMENTS

A comparison of measurement and resource capabilities the legacy sounders, AIRS, IASI, CrIS and requirements for CIRAS is shown in Table 1. CIRAS is designed for a Low Earth Orbit (LEO) that is most likely lower than the legacy sounders. A wide field scan range is possible from the instrument but will result in a shorter swath than the legacy sounders. CIRAS has one band, discussed below, and is significantly smaller and lighter.

Spectral Resolution and Range

The CIRAS is designed to operate in the MWIR from 1950-2450 cm^{-1} to reduce size, cost and resource requirements of the IR sounders. This region was selected since it contains both temperature sounding and water vapor sounding spectroscopic lines, and the

Table 1. Comparison of Measurement and Resource Capabilities for Legacy Sounders and CIRAS

	AIRS	IASI	CrIS	CICAS
Spatial				
Orbit Altitude	705 km	817 km	824 km	450-600 km
Scan Range	±49.5°	±48.3°	±48.3°	±6.2°, ±41.6°
Spatial Resolution	13.5 km	12 km	14 km	3 km, 13.5 km
Spectral				
Method	Grating	FTS	FTS	Grating
Nominal Resolution	0.5-2.5 cm^{-1}	0.5 cm^{-1}	1.0-5.0 cm^{-1}	1.3-2.0 cm^{-1}
0.4 - 1.0 µm	4	n/a	n/a	n/a
1.0 - 3.0 µm	n/a	n/a	n/a	n/a
3.0 - 5.2 µm	3.7-4.6 µm (514)	3.6-5.2 µm (3348)	3.9-4.6 µm (632)	4.08-5.13 µm (625)
5.2 - 8.2 µm	6.2-8.2 µm (602)	5.2-8.2 µm (2814)	5.7-8.2 µm (864)	n/a
8.2 - 12.5 µm	8.8-12.7 µm (821)	8.2-12.5 µm (1678)	9.1-12.0 µm (472)	n/a
12.5 - 15.5 µm	12.7-15.4 µm (441)	12.5-15.5 µm (620)	12.0-15.4 µm (240)	n/a
Total Channels	2382	8460	2208	625
Radiometric				
NEdT @ 250K	0.07-0.7K	0.25-0.5K	0.1-1.0K	0.2K - 0.6K
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	0.1 x 0.2 x 0.3 m^3
Mass	177 kg	236 kg	165 kg	14 kg
Power	256 W	210 W	117 W	40 W
Max Data Rate	1.3 Mbps	1.5 Mbps	1.5 Mbps	0.32 Mbps

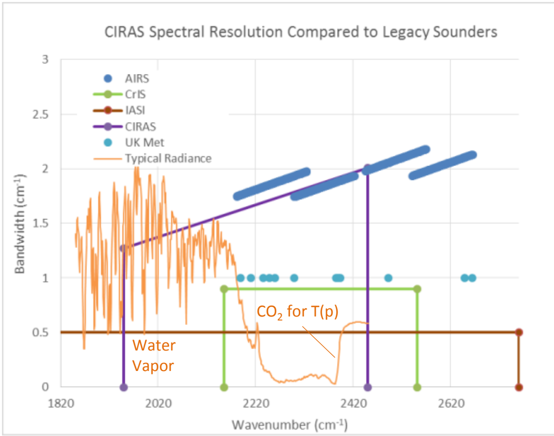

Figure 2. Spectral Resolution and Coverage for CIRAS compared to legacy IR sounders

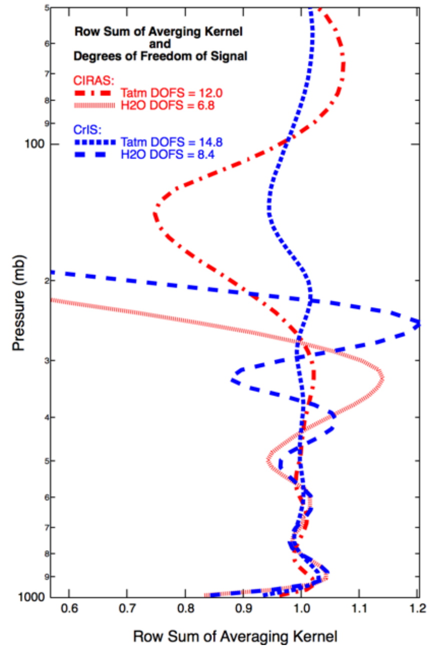

Figure 3. Row sum of AK shows CIRAS has good lower tropospheric sensitivity.

detectors can operate at higher temperatures than the Longwave Infrared (LWIR). 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.

CIRAS spectral resolution is comparable to AIRS in the temperature sounding region. Note: AIRS and CrIS do not sound in the 5 µm water band (2000 cm^{-1}) since they use longer wavelengths for water vapor. The CIRAS spectral resolution improves naturally in the water vapor band (since gratings operate with constant spectral bandwidth in wavelength domain). This improvement preserves information content and allows us to resolve the lines.

Legacy sounders also have the Longwave Infrared (LWIR) for temperature sounding. A concern with using only the MWIR region of the spectrum for temperature sounding is contamination by solar reflected energy between 4 and 4.5µm. However, the AIRS temperature profile retrieval algorithm has successfully dealt with the solar reflected component by separately solving for shortwave emissivity and reflectivity[5]. Despite not having LWIR sensing capability, the CIRAS spectral band is expected to provide comparable temperature sounding to legacy sounders in the lower troposphere.

An earlier study showed that the degrees of freedom of signal (DOFS) for AIRS is comparable to a midwave sounder using a similar band to CIRAS[6]. In this early study, the DOFS for temperature were nearly the same, but the water vapor showed better lower tropospheric sensitivity and poorer upper tropospheric sensitivity. A more recent study of the information content of CIRAS for this paper leads us to the same conclusion. Figure 3 shows the row sum of the Averaging Kernels (AK) for CIRAS compared to CrIS for temperature and water vapor. The row sum of the averaging kernel matrix is an estimation of the sensitivity of the retrieval to changes in the atmospheric state, although it lacks the vertical resolution information or cross-species sensitivities found in the full averaging kernel. The Degrees of Freedom of Signal (DOFS) is the trace of the averaging kernel for each species, and is a measure of the information content of the retrieval. Calculations shown here are for comparison purposes, using idealized systems over mid-latitude ocean in clear sky, and assumed summertime atmospheric states and "a priori" covariances. All channels were used. Effects from the spectral resolution and expected noise are included, but systematic errors are not.

Spatial Resolution and Coverage

CIRAS is designed to match and exceed legacy sounder spatial resolution requirements. Table 1 shows the comparison of the nominal spatial resolution. CIRAS can achieve a nominal 13.5 km spatial resolution from any orbit. This is achieved by adjusting the pixel binning along-track and scan rate and number of frames averaged for the cross-track direction. Figure 4 shows the binning configuration and projection of the slit on to the focal plane for the nominal resolution. CIRAS maintains a constant frame rate and integration time

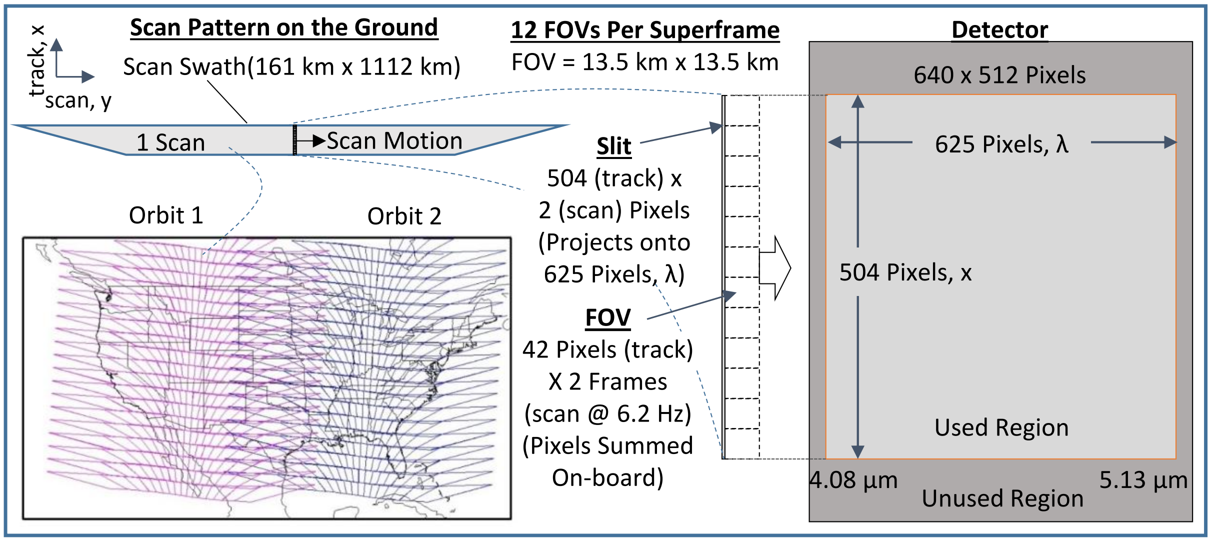

Figure 4. CIRAS uses pixel and frame binning and an adjustable scan rate to achieve 3km (Zoom) or 13.5 km (Global) FOVs from any orbit (13.5 km FOV from 600km orbit altitude shown).

keeping internal functions of the instrument common between the two modes. The scan pattern for CIRAS rotates the slit with scan angle. The pattern is deterministic and isn't expected to pose a problem.

CIRAS can also adjust the scan rate and number of pixels along-track and frames cross-track averaged to achieve a 3 km footprint. We call this "zoom" mode. The instrument cannot download this entire data volume, and is therefore limited to a swath of about 160 km. In addition to higher spatial resolution, Zoom mode can target anywhere in the full swath of Global Mode. The higher spatial resolution will enable more soundings per unit area than the current operational sounders, and allow more clear observations. CIRAS will be the highest spatial resolution hyperspectral IR sounder to fly in space. This mode will demonstrate the value of higher spatial resolution IR sounding for future science and operational weather missions. This mode will be possible with the EON-IR given successful demonstration of this technology.

Radiometric Sensitivity

The radiometric sensitivity of the IR sounders in the temperature sounding band must be better than 0.2K at 280K. The AIRS and CIRAS are grating spectrometers and have good sensitivity in this region for temperature sounding. CrIS also has good sensitivity in this region, but like the other legacy sounders use the long wavelength region for temperature sounding as mentioned above. Figure 5 shows the predicted NEdT for CIRAS in Global and Zoom modes compared to the legacy sounders in this spectral region. The Zoom mode NEdT is higher due to fewer pixels to average in the along-track direction.

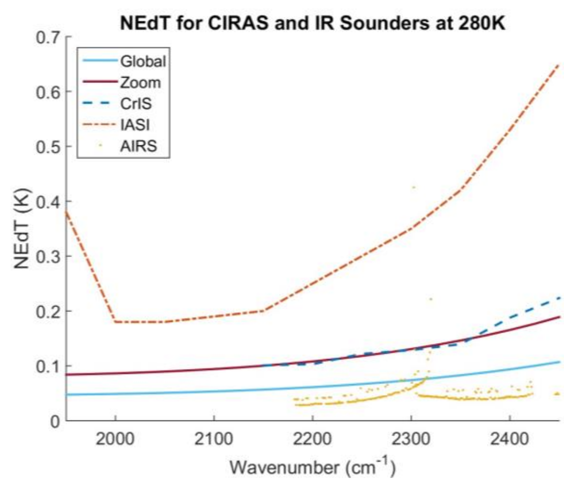

Figure 5. CIRAS NEdT at 280K compared to legacy IR sounders.

THE CIRAS INSTRUMENT

Instrument Overview

The CIRAS payload (Figure 6) includes a scan mirror capable of rotating 360º to view Earth, cold space and an internal blackbody for calibration. The Scan Mirror Assembly consists of a single planar gold coated aluminum mirror mounted at 45º to the axis of a stepper motor. Gold provides low polarization and high reflectance in the CIRAS band. Footprint rotation is not a concern since all spectral channels share the same slit (same for AIRS), and slit rotation angle is

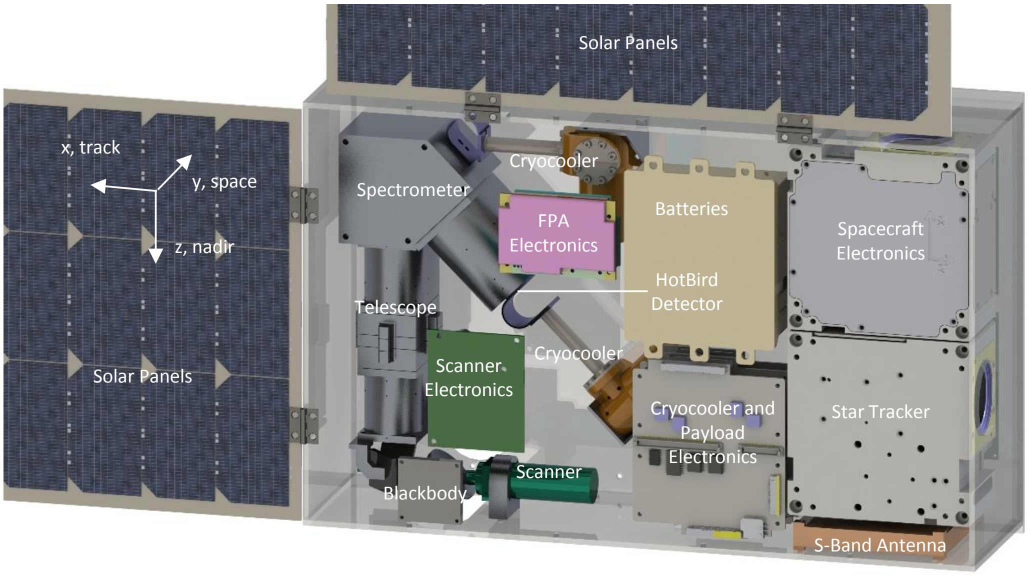

Figure 6. CIRAS Payload and Spacecraft

deterministic, making geolocation straightforward. 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 a 3-element all-refractive telescope. Energy from the telescope is focused onto the entrance slit of an all refractive MWIR Grating Spectrometer (MGS). The telescope and spectrometer are to be developed by Ball Aerospace. 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 custom Integrated Cooler Dewar Assembly (ICDA) to be developed by IR Cameras. 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 CIRAS subsystem electronics are primarily commercial. A payload electronics board will be developed to interface the various subsystems. Clocks, biases and A/D conversion are performed using military-grade electronics also provided by IR Cameras. JPL will develop the payload electronics to interface with the scanner, camera, cryocoolers, blackbody and spacecraft electronics.

Cooling of the spectrometer to 190K and the narrow spectral range of the filters minimize background loading on the detector. Use of a Ricor cryocooler for the optics is included in the current design but alternate coolers will be investigated. The detector is cooled to 120K also using a Ricor cryocooler, heat sunk to the warm radiator. Electronics, cryocooler and spacecraft waste heat is dissipated in warm temperature radiators on all remaining surfaces except nadir and anti-nadir.

CIRAS will be developed as a stand-alone payload with mechanical, thermal, and electrical interfaces to the spacecraft. Radiators will be detachable to allow easy integration of the payload and reattachment after integration with the spacecraft.

The CIRAS spacecraft will be a commercial 6U system (industry procurement) with deployable solar panels and additional batteries. The spacecraft will provide communications, navigation, power and on-board processing and formatting of the raw data stream from the payload. The spacecraft structure will have custom features to allow a clear scan field of view and for mounting the payload components.

The payload development and test will take 20 months followed by spacecraft integration and test of 2 months. In-flight operations will take a minimum of 3 months after launch consisting of system activation, calibration and data acquisitions. CIRAS is TRL 5 upon entry and TRL 7 after flight demonstration.

KEY TECHNOLOGIES

MWIR Grating Spectrometer

CIRAS uses a 15 mm telescope that forms a telecentric image at the entrance slit of the spectrometer. Light passing through the slit is collimated by the collimator optics in the spectrometer, then dispersed by the diffraction grating in the MGS, and focused at the Focal Plane Assembly (FPA). The diffraction grating is built into the backside of a silicon substrate (immersion grating) to maximize dispersion and minimize distortion. The optical system includes fold mirrors to fit the layout within the CubeSat allocated volume. The entrance slit will use precision micro machined fabrication and black silicon deposition techniques used on several JPL flight projects. Optical materials will be selected to minimize distortion, and establish an athermal system capable of being aligned at room temperature and operated at 190K without refocus.

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, stray light, ghosting, and fringing.

HOTBIRD Detectors

The current MWIR detector/FPA market is dominated in volume by InSb that has cut-off wavelength of λ=5.6μm.[7] HgCdTe (MCT) detectors, with adjustable cut-off wavelength depending on the Cd fraction in the absorber material, are used for shorter and longer cut-off wavelengths in the MWIR and for very high end applications, such as the low illumination conditions needed here. Single element MWIR MCT detectors show high-performance operation, however, MCT focal plane arrays (FPAs) typically suffer from pixel-to-pixel non-uniformity and pixel operability issues. This requires lower operating temperatures for the FPA to achieve requirements for all pixels. While in principle, it is possible to select astronomy grade MCT FPAs with very good performance[8], this process involves fabrication and testing of a large number of FPAs. This approach is risky, time consuming and labor intensive resulting in a very high cost as well as in high risk of delivery delays.

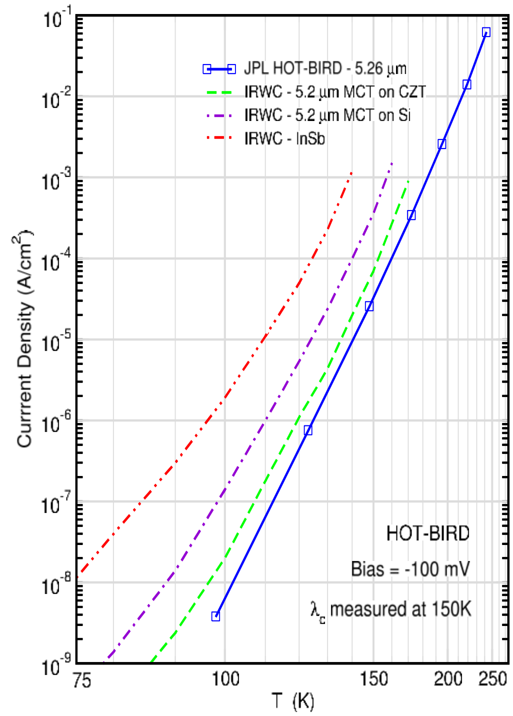

Figure 7. Dark current vs temperature for a JPL HOT-BIRD device compared to InSb and MCT.

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 (Figure 7) and improving uniformity and operability compared to II-VI material (MCT) (See table 2). Low 1/f noise and high temporal stability allows CIRAS to use a slow scan for better sensitivity and less frequent calibrations.

Table 2. Key figures of merit for InSb and MCT compared to HOT-BIRD in the MWIR

	InSb	MCT	HOT-BIRD
Wavelength Range	1.0 - 5.6	0.4-5.6	1.0 - 5.6
Operating Temp [K]	80K	110K	150K
Dark current[A/cm2]	<1E-5	<1E-5	<1E-5
QE at 5μm	>70%	>70%	>70%
Cost	Low	High	Low
Pixel Operability and Uniformity	High	Low-Medium	High
Pixel Blinkers	Very Low	High	Very Low

Black Silicon Blackbody

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. 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.

Table 4. CIRAS Payload Power

Subsystem	Power (W)
Spacecraft	5
Instrument Elects.	5
FPA Cooler + Electronics	21.5
Optics Cooler + Electronics	3.5
Scanner	2.5
Total	**37.5**

RESOURCE REQUIREMENTS

A preliminary estimate of the resource requirements for CIRAS have been established. This will allow sizing of the spacecraft for CIRAS as well as the data management system.

Mass

Table 3 lists the mass of the key subsystems for the CIRAS. The total mass is less than 9kg at this time.

Table 3. CIRAS Payload Mass

CIRAS Mass Estimate	Mass (g)
Spacecraft	**5928.9**
Mechanical/Structure	1798.3
Spacecraft Bus	1710.0
Telecom	490.6
EPS	1820.0
Thermal	110.0
Instrument	**2519.9**
Optics	38.0
Housing	102.7
Housing Cover	28.4
Compressor	600.0
Cooler Cold Head	240.0
Ricor Cooler	222.0
Ricor Cooler Elex	72.0
Scan Mirror/Bracket	120.0
Scan Motor	136.8
Blackbody	120.0
IR Camera	600.0
Bracket	120.0
Electronics	120.0
Total	**8448.8**

The maximum mass for the CubeSat is 14kg, leaving sufficient margin for spacecraft subsystems and margin.

Power

An estimate of the payload power dissipation is given in Table 4. The power for CIRAS is driven by the cryocooler for the focal plane assembly. Total power is estimated to be 37.5 W.

Data Rate

The raw data rate for the CIRAS is 13.7 Mbps in global mode. Assuming pixel binning and frame averaging to achieve the nominal resolution and 6x compression through data selection (when data are acquired and which subset of the 625 channels are downloaded), the orbital average data rate is 0.33 Mbps. This gives approximately 0.32 Gb of data per orbit. We estimate that 1Gb per orbit can be downloaded assuming a ground station in view for that orbit.

SUMMARY AND CONCLUSIONS

The CubeSat Infrared Atmospheric Sounder (CIRAS) will demonstrate key spectroscope and detection technologies for atmospheric sounding in the MWIR. CIRAS will measure radiances corresponding to temperature and water vapor profiles in the lower troposphere with comparable sensitivity as the legacy operational sounders. Upper tropospheric temperature and water vapor and atmospheric composition products other than CO (e.g. O3) require the LWIR and will also require technology demonstration. A complete MWIR and LWIR system is required to meet all the CrIS requirements on JPSS and would require a 12U CubeSat or flying 2 6U CubeSats in formation. CIRAS may serve as the EON-IR without the LWIR if other sensors can make these measurements (e.g. the microwave sounders for upper tropospheric temperature and water vapor, and NASA's composition sounders).

CIRAS will have two operating modes including global and zoom. Global mode will provide wide swath at 13.5 km resolution, while the zoom mode will acquire data at 3 km spatial resolution (with higher NEdT) over a limited area. CIRAS will be the first to demonstrate high spatial resolution hyperspectral infrared temperature and water vapor sounding from space.

CIRAS includes an MWIR grating spectrometer built with an immersion grating to minimize spectrometer size, and black-silicon for the entrance slit. CIRAS will be the first to fly the HOTBIRD MWIR detector material in space. This material offers good sensitivity, uniformity, and operability and is relatively lower cost to fabricate. CIRAS will use a commercial 6U spacecraft and will require high power (37.5W), posing challenges for power management and heat dissipation. Data selection will be required to reduce data downlink volume to be compatible with the data transmission system of the CIRAS; most likely an S-Band transmitter.

CIRAS started development June 1, 2016 and is expected to be completed by the end of 2017 or early 2018 with a launch in mid to late 2018. Mission duration is only required to be 3 months to demonstrate the technologies, but a much longer life is expected.

Finally, CIRAS will demonstrate the viability of CubeSat compatible technologies that can be used for science missions. A successful CIRAS mission will add to the body of evidence that is growing today that CubeSats can make measurements suitable for operational weather and science missions.

ACKNOWLEDGMENTS

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