The University of Wisconsin Space Science and Engineering Center Absolute Radiance Interferometer (ARI)

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ABSTRACT

A summary of the development of the Absolute Radiance Interferometer (ARI) at the University of Wisconsin Space Science and Engineering Center (UW-SSEC) will be presented. At the heart of the sensor is the ABB CLARREO Interferometer Test-Bed (CITB), based directly on the ABB Generic Flight Interferometer (GFI). This effort is funded under the NASA Instrument Incubator Program (IIP).

Keywords: CLARREO, FTS, infrared, Fourier transform spectrometer

1. INTRODUCTION

NASA has selected the Climate Absolute Radiance and Refractivity Observatory (CLARREO), a climate mission recommended by the 2007 Decadal Survey of the US National Research Council, as a potential new mission beginning in 2010. CLARREO will measure spectrally resolved radiance from the earth and atmospheric bending of GPS signals related to atmospheric structure (refractivity) as benchmark measurements of long-term climate change trends.

To reduce the time to unequivocally resolve climate trends, IR radiance spectra and GPS refractivity were selected as quantities with high information content that can be measured with high calibration accuracy referenced to international standards provided on orbit (SI-traceable measurements). For the infrared radiance spectra, a brightness temperature accuracy of 0.1 K, k = 3, confirmed on orbit is practical.

The challenge in the IR FTS sensor development for CLARREO is to achieve ultra-high accuracy (0.1 K, k = 3) with a design that can be flight qualified, has long design life, and is reasonably small and affordable. In this area, our approach is to make use of components with strong spaceflight heritage (direct analogs with high TRL) combined into a functional package for detailed performance testing.

A summary of the development of the Absolute Radiance Interferometer (ARI) at the University of Wisconsin Space Science and Engineering Center (UW-SSEC) is presented herein.

2. CLARREO

2.1 Overview

The NRC Decadal Survey, Earth Science Applications from Space: National Imperatives for the Next Decade and Beyond, states the principles on which new climate missions should be based: "Design of climate observing and monitoring systems from space must ensure the establishment of global, long-term climate records, which are of high accuracy, tested for systematic errors on-orbit, and tied to irrefutable standards." "For societal objectives that require long-term climate records, the accuracy of core benchmark observations must be verified against absolute standards on-orbit by fundamentally independent methods, such that the accuracy of the record archived today can be verified by future generations. Societal objectives also require a long-term record not susceptible to compromise by interruptions." [1].

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CLARREO emerged as a top priority, and is a Decadel Survey Tier 1 mission under development by NASA. CLARREO will provide a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards. A priority of the CLARREO scientific strategy is to measure absolute, spectrally-resolved radiance in the infrared with very high accuracy (0.1 K, k = 3 brightness temperature at scene temperature) using earth observing spectrometers in a low earth orbit. Both the radiative forcing of the atmosphere resulting from greenhouse gas emissions and aerosols and the response of the atmospheric variables clearly have a direct influence on the spectrally resolved signal of the outgoing radiance. Similarly, large differences among model projections of temperature, water vapor and cloud distributions imply, for each model, different predicted changes in absolute, spectrally resolved radiation. The spectrum of IR radiance, if observed accurately and over the full thermal band, carries decisive diagnostic signatures in frequency, spatial distribution and time.

The instruments for CLARREO also need to be as small and simple as possible. This goal is driven by the requirement for multiple spacecraft in orbits chosen to reduce temporal and spatial sampling biases to very tight limits (also < 0.1 K, k = 3), resulting in the overall uncertainty for climate assessment of < 0.1 K, k = 2. Relative simplicity also helps to make the system affordable and more likely to be continued decades into the future.

The required simplicity is achievable because of the large differences of the climate sampling problem from that of the typical remote sensing for weather research or operations. Studies show that, under the new CLARREO paradigm that emphasizes information content rather than calorimetry, the key climate information can be obtained with nadir only viewing, relatively large footprints (<100 km), and modest requirements on noise performance [2,3]. The key is to demonstrate ultra low combined measurement and sampling biases for the climate products that consist of annual averages of nadir radiance spectra averaged over 15º x 30º latitude/longitude regions and seasonal averages on larger spatial scales, of the order of 50º x 50º latitude/longitude regions. These striking differences from weather-driven requirements lead to very important reductions in sensor size, mass, and power that enable the novel climate accuracy requirements to be achieved with a relatively low demand on spacecraft resources and cost.

In addition, the CLARREO SI traceable radiances will provide a source of absolute calibration for a wide range of visible and IR Earth observing sensors, greatly increasing their value for climate monitoring.

2.2 IR Measurement Requirements Summary

The primary drivers of the infrared requirements include

- Information Content: To unequivocally detect change and refine climate models, it is necessary to capture the spectral signatures of regional and seasonal climate change that can be associated with physical climate forcing and response mechanisms.
- Absolute Accuracy: To achieve the goal of resolving a climate change signal in the decadal time frame, the absolute accuracy for the infrared measurements must be less than 0.1 K, k = 2 brightness temperature for combined measurement and sampling uncertainty as applied to annual averages of 15ºx30º latitude/longitude regions.
- Calibration transfer to other spaceborne IR sensors: To enhance the value of IR Earth observing sensors for climate process studies, a CLARREO IR measurement accuracy approaching 0.1 K (k = 3) is required (for Simultaneous Nadir Overpass).

The above drivers, and the results of several other key studies, were used to derive the infrared measurement requirements (Table 1). These requirements have been used as a basis for the UW-SSEC Absolute Radiance Interferometer design.

Modern spaceborne, aircraft and ground-based spectrometers demonstrate great strides in calibration accuracy and the technical heritage of these instruments provide a strong foundation for the CLARREO spectrally resolved sensors. However, currently planned measurements cannot perform the CLARREO mission; the CLARREO measurements require higher accuracy, must be proven in orbit, and need to be coupled with unbiased spatial and temporal sampling.

Requirement	Value
Spectral Coverage	3-50 µm (200 - 3000 cm^{-1})
Spectral Resolution	0.5 cm^{-1} unapodized (1 cm max OPD)
Noise: NEdT(10 sec)	< 1.5 K for climate record, < 1.0 K for cal transfer
Spatial Footprint & Angular Sampling	100 km or less, nadir only
Pre-launch Calibration/Validation	Characterization against NIST primary infrared standards and evaluation of flight blackbodies with NIST facilities
On-orbit Calibration	Onboard warm blackbody reference (~300K), with phase change temperature calibration, plus space view, supplemented with characterization testing
Calibration Validation, On-orbit	On-orbit, variable-temperature standard blackbody, referenced to absolute physical standards

Table 1: Infrared measurement requirements for the UW-SSEC Absolute Radiance Interferometer (ARI)

3. THE UW-SSEC ABSOLUTE RADIANCE INTERFEROMETER (ARI)

3.1 Overview

The University of Wisconsin-Madison Space Science and Engineering Center (UW-SSEC) and Harvard University (HU) submitted a successful joint proposal entitled "A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for the CLARREO Mission" to the NASA Instrument Incubator Program (IIP). The UW-SSEC / HU team has a long history with the scientific and measurement concepts that have formed the foundation for CLARREO [2-8].

The objective of this effort is to develop and demonstrate the technologies needed to measure IR spectrally resolved radiances with ultra high accuracy for the CLARREO climate benchmark. The effort combines the development of fundamentally new devices including (1) an On-orbit Absolute Radiance Standard (OARS), a high emissivity blackbody source that uses multiple miniature phase-change cells to provide a revolutionary on-orbit standard with absolute temperature accuracy proven over a wide range of temperatures; (2) On-orbit Cavity Emissivity Modules (OCEMs), providing a source (quantum cascade laser, QCL, or "Heated Halo") to measure any change in the cavity emissivity of the OARS and calibration reference sources; and (3) an On-orbit Spectral Response Module (OSRM), a source for spectral response measurements using a nearly monochromatic QCL source configured to uniformly fill the sensor field-of-view. These new technologies are combined with the advancement of Dual Absolute Radiance Interferometers (DARI), one of which is the UW-SSEC ARI, providing spectral coverage from 3.3 to 50µm that can be inter-compared to dissect any unexpected systematic errors in overlapping spectral regions.

3.2 Operational Concept for Assuring High Accuracy On-orbit

On-orbit, the UW-ARI would be radiometrically calibrated using views of a dedicated blackbody reference and space. For laboratory testing during the IIP development, the space reference will be replaced by a second dedicated blackbody reference. The FTS will also be designed to minimize potential biases related to non-linear response and polarization effects, allowing the 0.1 K, k = 3 measurement accuracy requirement to be met (Figure 2). On-orbit tests to demonstrate that linearity and polarization characteristics do not change are also planned.

A Gold 45º scene mirror is used to select viewing targets (Figure 2 and Figure 3). The target options are the nadir earth view defined to be 0º, standard calibration views of the onboard calibration source at 90º and space at 180º, the OARS at -90º, a second space view for polarization characterization at -135º, and finally the OSRM for ILS monitoring at 135º. The normal operational concept is very simple. To collect the primary climate record, sequential views of the earth are separated by several samples of the calibration blackbody and the primary space view. Much less frequently, views of the OARS are collected over the full range of earth scene brightness temperatures. The other scenes that are also viewed infrequently include (1) the secondary space view, (2) the OARS with emissivity monitoring sources of the OCEM turned on, and (3) the OSRM.

The calibration advantages of high spectral resolution [9] are very important to achieving CLARREO goals. The spectral resolution for CLARREO (0.5 cm^{-1} unapodized) has been chosen for the information content it provides on the vertical structure of the atmosphere, for the lineshape and position determination, and for this calibration advantage. A very stable metrology laser will be used to make the interferometer spectral calibration highly stable, but the absolute spectral calibration will be derived from atmospheric spectra themselves as has been demonstrated with AIRS [10], Scanning HIS [11], NAST-I, and IASI. The fundamental physics that determines line positions will not be altered by climate change, and line positions are known with very high accuracy. We have demonstrated the capability to calibrate from the atmosphere with an accuracy exceeding 1 ppm.

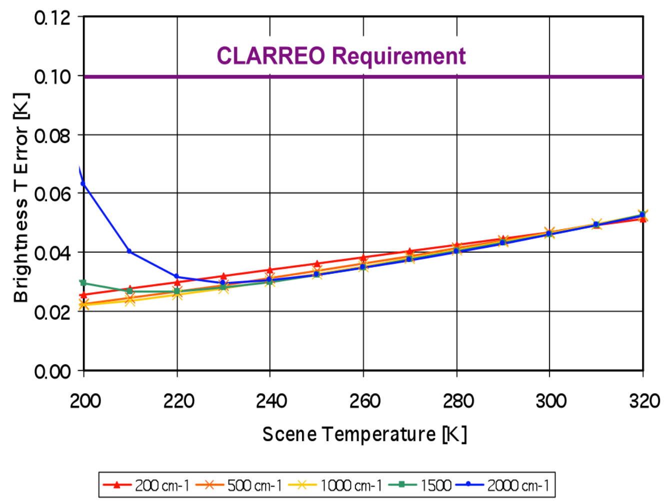

Figure 1: Estimated k = 3 calibrated brightness temperature uncertainty shown as a function of scene brightness temperature, based on use of the AASI. The uncertainty of the blackbody radiating temperature (45 mK, k = 3) dominates, except for large wavenumbers at cold temperatures where the assumed telescope temperature change of 20 mK between earth and calibration views becomes important. We assumed an emissivity of 0.999 with 0.0006 uncertainty and a blackbody temperature of 300 K, while the instrument is at 285 K.

The UW-SSEC ARI is comprised of

- Fore and aft optics designed specifically for high radiometric accuracy
- A cube corner, rocking arm interferometer with a diode laser-based metrology system
- A Cooled semi-conductor detector and dewar assembly
- A DTGS pyrolectric detector assembly
- A very small pulse-tube mechanical cooler for the semi-conductor detector / dewar subassembly

Each are chosen for their strong spaceflight heritage such that detailed performance testing can be conducted on a system with a clear path to space. For compatibility with an IIP budgets, the electronics are not flight designs.

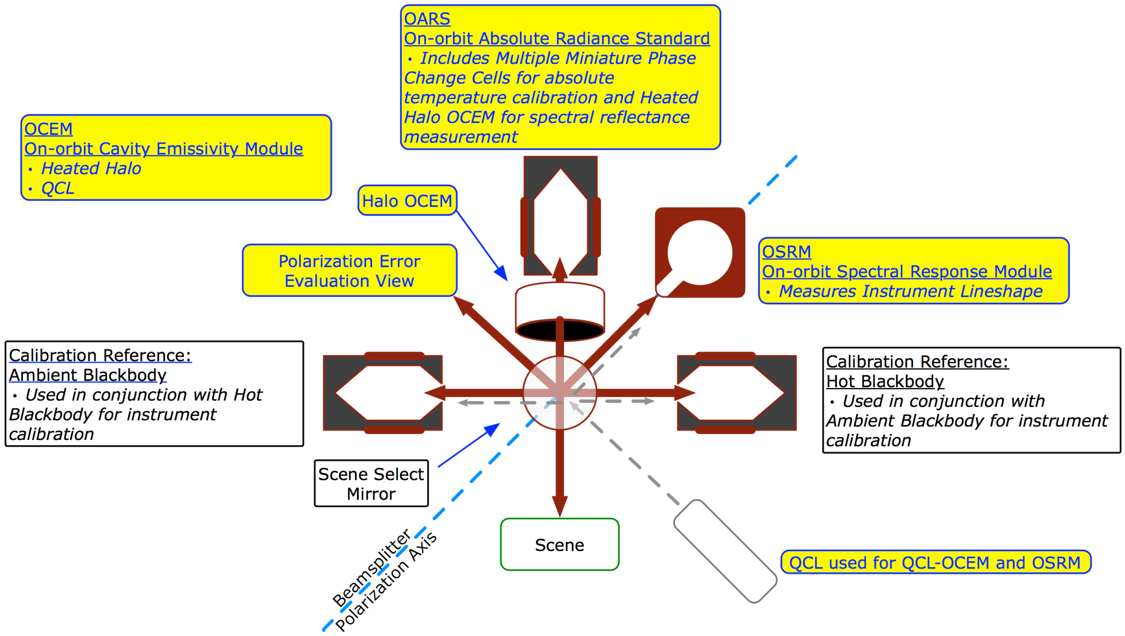

Figure 2: Laboratory viewing configuration, optimized to provide immunity to polarization effects.

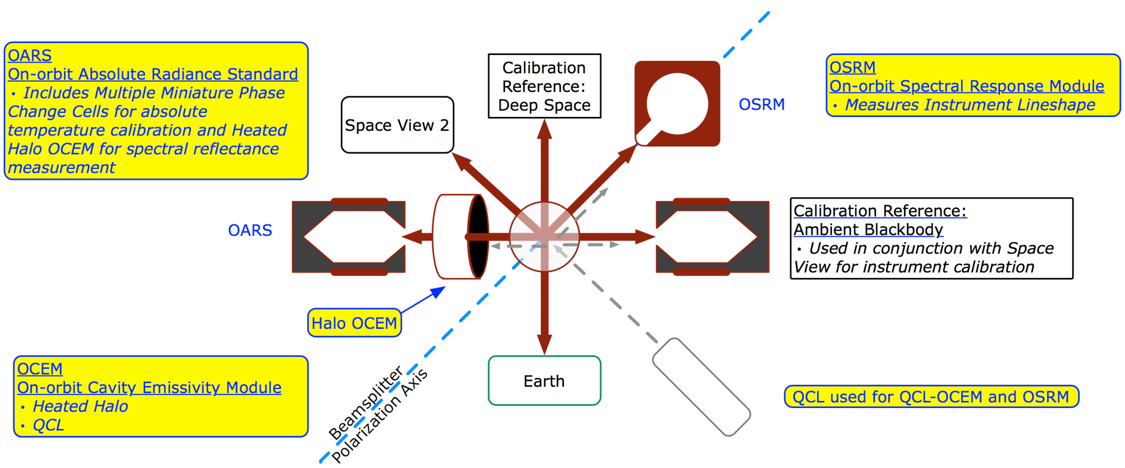

Figure 3: Flight viewing configuration, optimized to provide immunity to polarization effects.

3.3 The Interferometer Core

At the heart of the UW-SSEC ARI sensor is the ABB CLARREO Interferometer Test-Bed (CITB), based directly on the ABB Generic Flight Interferometer (GFI). The challenge in the FTS sensor development for CLARREO is to achieve ultra-high accuracy (0.1 K, k = 3) with a design that can be flight qualified, has long design life, and is reasonably small and affordable.

ABB has participated in many recent mission definitions involving FTS. Strong similarities in the requirements at the level of the interferometer module resulted in ABB to pursue developing a generic flight architecture, the Generic Flight Interferometer (GFI). The GFI includes an Opto-Mechanical Assembly (OMA) that consists of an interferometer module equipped with a metrology assembly. The OMA is entirely free of electronic components apart from the interferometer scanning actuator. A 6U control card that conveys the functionality of metrology detection, laser source, actuator drive, servo control, housekeeping, telemetry and command/data handling complements this Opto-Mechanical Assembly (OMA). The OMA architecture draws its heritage from a commercial instrument (Bomem MB Series) which heritage dates back to the mid 1980's. This instrument is known for its exquisite response stability and is used in production plants around the world to provide critical concentration measurement as control feedback for industrial fabrication processes. The ACE-SCISAT FTS was the first to implement a space design based on this architecture. Launched in 2003, ACE continues to operate today (2010), well beyond its design life-time requirement of 2 years. More recently the TANSO-FTS onboard IBUKI (GOSAT) launched in 2009 by JAXA was also based on an evolution of the ACE-FTS and MB Series. The GFI thus represents a third generation of flight interferometers and includes some of the latest technology developed for commercial applications.

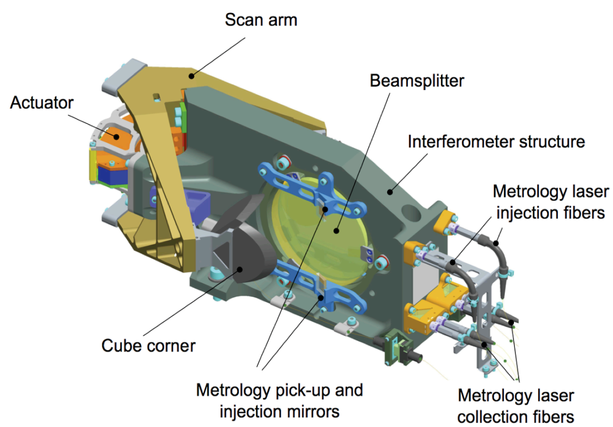

Figure 4: ABB Generic Flight Interferometer (GFI).

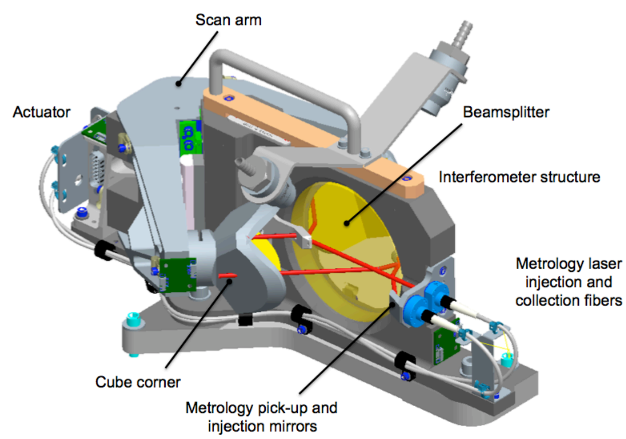

Figure 5: ABB CLARREO Interferometer Test Bed (CITB); also referred to as ABB Generic Interferometer for Climate Studies (GICS)

To meet the UW-SSEC ARI requirements, only small adaptations of the GFI architecture were required. The resulting interferometer core is the ABB CLARREO Interferometer Test Bed (CITB) (also referred to as the ABB Generic Interferometer for Climate Studies [GICS]). The key differences from the GFI are:

- The beamsplitter substrate and coatings have been replaced with materials that maximize efficiency over the 3 – 50 μm range.
- Mounting of the beamsplitter has been optimized for CsI beamsplitter
- A self-compensated beamsplitter design is used instead of a substrate and compensator design.
- CITB: 4-port configuration, GFI: 2-port configuration.
- Laser metrology components have been relocated for compatibility with 4-port operation.
- Replicated monolithic cube corners are used in the CITB.
- Due to cost considerations, the GFI flight electronics have been replaced with modified commercial electronics and software for the IIP demonstration.

The CITB is a vacuum compatible interferometer. The IIP demonstration unit has a mass of < 7 kg (Opto-Mechanical Assembly), and the power requirements for the flight design are 18 W average, 23 W peak. Again, for cost considerations modified COTS electronics are used for the IIP demonstration. While new coating recipes with optimized FIR performance are in development as part of joint ABB and Laval University R&D project, to minimize schedule risk for IIP the CITB uses a modified ABB production unit coating. Modulation efficiency and speed stability were the two primary performance tests conducted on the CITB at ABB-Bomem. The results of these tests are shown in Figure 7 and Figure 8 respectively.

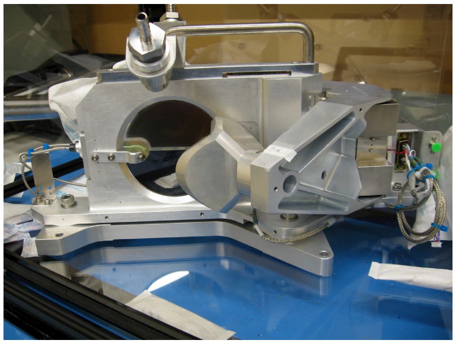

Figure 6: CITB under test at ABB-Bomem.

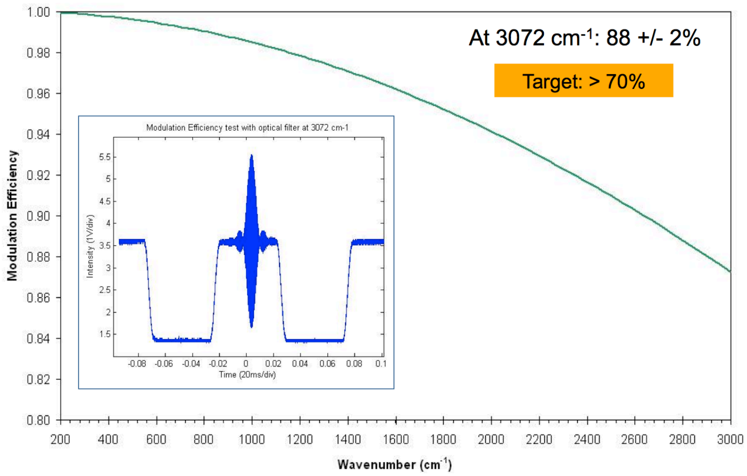

Figure 7: Modulation efficiency as measured at ABB-Bomem.

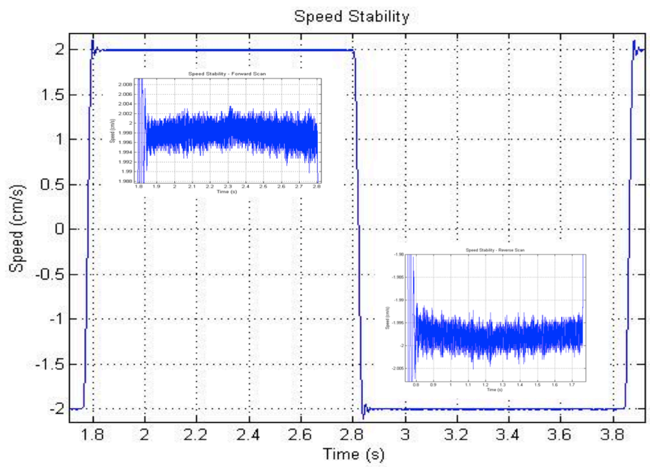

Figure 8: At 2 cm/s: ~0.13% RMS speed stability (1 σ); Target: 1%.

3.4 Sensor Configurations

Testing of the UW-SSEC ARI will be completed using two sensor configurations, Breadboard 1 and Breadboard 2. Use of the two defined system configurations will

- Allow immediate testing of instrument breadboard upon interferometer delivery
- Allow design and development of Breadboard 2 ("Prototype") while Breadboard 1 undergoes testing
- Mitigate schedule impact due to unforeseen delivery delays
- Provide Assembly, Integration, and Test (AIT) flexibility

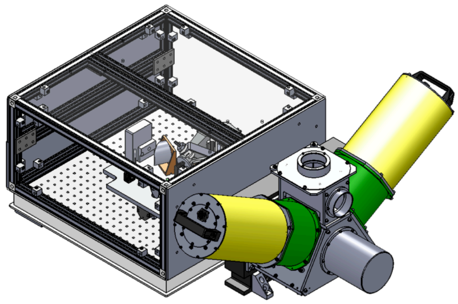

Figure 9: UW-SSEC Absolute Radiance Interferometer (ARI), Breadboard 1.

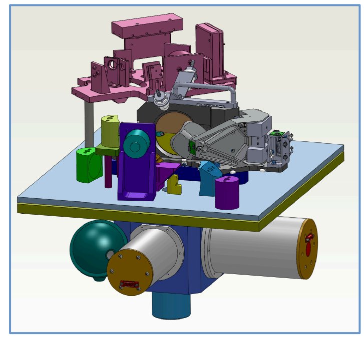

Figure 10: UW-SSEC ARI, Breadboard 2 (Enclosure not shown).

Table 2: Key subsystems for UW-ARI Breadboard 1 and Breadboard 2.

	UW-SSEC ARI Breadboard 1	**UW-SSEC ARI Breadboard 2**
Fore-optics	None	UW-SSEC ARI prototype
Interferometer Core	ABB CITB	ABB CITB
Output Port 1	• ABB delivered Aft optics (ABB AERI based) • ABB delivered FIR detector module (DTGS Pyroelectric)	• ABB delivered Aft optics (ABB AERI based) • ABB delivered FIR detector module (DTGS Pyroelectric)
Output Port 2	Not used	• UW-ARI Prototype • 2 channel Cooled Detector –Dewar • NGST Pulse Tube Cooler
Enclosure	COTS, frame and panel	UW-SSEC ARI Prototype
Optical Bench	COTS	UW-SSEC ARI Prototype
Calibration References and Scene Select Module	Existing UW-SSEC AERI (Atmospheric Emitted Radiance Interferometer)	UW-SSEC ARI Prototype
External Blackbody / OARS	Existing UW-AERI	OARS 1" Aperture
Halo OCEM	Generation 2	Generation 3

3.5 Optics, Cooler, and Detectors

An all-reflective fore-optics design consisting of Gold coated diamond turned Aluminum elements will be used in the ARI. To minimize undesirable polarization effects, no protective or antireflective coatings will be applied to the gold coated mirrors. The fore-optics design was driven by the following considerations

- Optimize interferometer throughput
- Maximize Stray light control
- Minimize instrument mass and volume
- Optimize heated halo fill factor (and sensitivity)
- Desired compatibility with 1" aperture Blackbody
- Allow 'tuning' of polarization null locations

NGST is developing a small scale pulse tube microcooler with significant space flight heritage, including AIRS. This cooler will be used on the UW IIP CLARREO ARI, and is suitable for use by CLARREO. The same scaling relationships successfully used previously in scaling the HEC compressor up to a 26cc compressor and down to a 1.8cc compressor were used to produce the design for this 0.65cc compressor. A developmental coldhead optimized for the small swept volume and high resonant frequency of the small compressor has been designed, built and tested by NGST.

Details of the optical design, detector-dewar and cooler subsystem, the On-orbit Absolute Radiance Standard, and the Halo OCEM will be presented in future papers.

4. SUMMARY

An excellent, low cost, climate benchmark mission has been defined, and the proposed IR measurement requirements are supported by excellent technical readiness. The UW-SSEC ARI and On-orbit Test and Validation (OT/V) module will allow us to demonstrate the technology necessary to measure IR spectrally resolved radiances (3.3 – 50 μm) with ultra high accuracy (< 0.1 K, k = 3 brightness temperature at scene temperature) for the CLARREO benchmark climate mission. The UW-SSEC ARI subsystems have been selected and developed to provide a system with a clear path to space.

REFERENCES

[1] National Research Council (NRC), [Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond], The National Academies Press, Washington, D.C., 64 (2007).

[2] Anderson, J. G., J. A. Dykema, R. M. Goody, H. Hu and D. B. Kirk-Davidoff, "Absolute, spectrally-resolved, thermal radiance: a benchmark for climate monitoring from space", J. Quant. Spectrosc. & Rad. Transf. 85(3–4), 367–383 (2004).

[3] Kirk-Davidoff, D., R. Goody and J. Anderson, "Analysis of sampling errors for climate monitoring satellites", J. Climate 18(6), 810–822 (2005).

[4] Revercomb, Henry E., Daniel D. LaPorte, William L. Smith, Henry Buijs, David G. Murcray, Frank J. Murcray and Lawrence A. Sromovsky, "High-altitude aircraft measurements of upwelling IR radiance: Prelude to FTIR from geosynchronous satellite, International Conference on Fourier Transform Spectroscopy", Mikrochimica Acta 2(1), 439–444 (1988).

[5] Revercomb, H. E., D. C. Tobin, R. O. Knuteson, F. A. Best, P. van Delst, D. D. LaPorte, S. D. Ellington, M. W. Werner, R. G. Dedecker, R. K. Garcia, N. N. Ciganovich, H. B. Howell, S. Dutcher, and J. K. Taylor, "FTS Calibration: Demonstrated Absolute Accuracy for IR Remote Sensing and Future for Monitoring Climate", Fourier Transform Spectroscopy/ Hyperspectral Imaging and Sounding of the Environment, Technical Digest (CD) (Optical Society of America, 2005), FMD1 (2005).

[6] Revercomb, H. E., J. G. Anderson, F. Best, D. Tobin, R. Knuteson, J. Taylor, R. Holz, Douglas Adler, M. Mulligan, J. O'Connell, J. Rice, High Accuracy, "Spectrally Resolved IR Radiances for the CLARREO Climate Mission", 2007 CALCON Technical Conference, (2007).

[7] Ohring, G., J. Tansock, W. Emery, J. Butler, L, Flynn, F. Weng, K. St. Germain, B. Wielicki, C. Cao, M. Goldberg, J. Xiong, G. Fraser, D. Kunkee, D. Winker, L. Miller, S. Ungar, D. Tobin, J. G. Anderson, D. Pollock, S. Shipley, A. Thurgood, G. Kopp, P. Ardanuy, T. Stone, G. Bingham, R. Datla, J. Dykema, T. Iguchi, S. Leroy, and H. Revercomb (2007), "Achieving Satellite Instrument Calibration for Climate Change (ASIC3)", Eos Trans. AGU 88(11), (2007).

[8] Best, F.A., Adler, D.P., Ellington, S.D., Thielman, D.J., Revercomb, H.E., and Anderson, J.G.; "On-orbit Absolute Temperature Calibration for CLARREO (NASA's New Climate Mission)", Proceedings of the 2007 Conference on Characterization and Radiometric Calibration for Remote Sensing, Utah State University, Space Dynamics Laboratory, Logan, Utah, (2007).

[9] Goody, R. and R. Haskins, "1998: Calibration of Radiances from Space", J. Climate 11, 754-758 (1998).

[10] Strow L. L., S. E. Hannon, S. De-Souza Machado, H. E. Motteler, D. C. Tobin (2006), "Validation of the Atmospheric Infrared Sounder radiative transfer algorithm", J. Geophys. Res. 111, D09S06, (2006).

[11] Tobin, D. C., H. E. Revercomb, R. O. Knuteson, "On-orbit Spectral Calibration of the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS)", 2003 CALCON Technical Conference, Characterization and Radiometric Calibration for Remote Sensing, Space Dynamics Laboratory / Utah State University, Logan, Utah, 15-18 September, (2003).