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# The University of Wisconsin Space Science and Engineering Center Absolute Radiance Interferometer (ARI): Instrument Overview and Radiometric Performance

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## ABSTRACT

Spectrally resolved infrared (IR) and far infrared (FIR) radiances measured from orbit with extremely high absolute accuracy are a critical observation for future climate benchmark missions. For the infrared radiance spectra, it has been determined that a measurement accuracy, expressed as an equivalent brightness temperature error, of 0.1 K ( $k = 3$ ) confirmed on orbit is required for signal detection above natural variability for decadal climate signatures [1, 2].

The challenge in the sensor development for a climate benchmark measurement mission is to achieve ultra-high accuracy with a design that can be flight qualified, has long design life, and is reasonably small, simple, and affordable. The required simplicity is achievable due to the large differences in the sampling and noise requirements for the benchmark climate measurement from those of the typical remote sensing infrared sounders for weather research or operational weather prediction.

The University of Wisconsin Space Science and Engineering Center, with funding from the NASA Instrument Incubator Program (IIP), developed the Absolute Radiance Interferometer (ARI), which is designed to meet the uncertainty requirements needed to establish spectrally resolved thermal infrared climate benchmark measurements from space. The ARI is a prototype instrument designed to have a short upgrade path to a spaceflight instrument.

Recent vacuum testing of the ARI, conducted under funding from the NASA Earth Science Technology Office, has demonstrated the capability to meet the 0.1 K ( $k = 3$ ) uncertainty requirement on-orbit. An overview of the instrument design and summary of the radiometric performance verification of the UW-SSEC ARI will be presented.

**Keywords:** FTS, Fourier Transform Spectrometer, Climate Benchmark Measurement, IR, FIR

## 1. INTRODUCTION

The objective of this effort is to develop and demonstrate the technologies needed to measure spectrally resolved infrared (IR) and far infrared (FIR) radiances from orbit with the ultra high accuracy ( $< 0.1$  K,  $k = 3$ , brightness temperature at scene temperature) required for a climate benchmark mission.

The climate benchmark measurement paradigm and accuracy requirement for the IR and FIR is defined in the ASIC3 (Achieving Satellite Instrument Calibration For Climate Change) report [2], and the US National Research Council Decadal Survey [1]. Furthermore, the Decadal Survey proceeded to define the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission and recommended it as a highest priority. 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.

A simple instrument design is key to achieving the ultra-high absolute accuracy requirements associated with infrared spectral radiances. The required simplicity is achievable due to the large differences in the sampling and noise

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requirements for the benchmark climate measurement from those of the typical remote sensing infrared sounders for weather research or operational weather prediction. Studies show that for the climate benchmark measurement paradigm, which 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 [3, 4]. The key is to demonstrate extremely low combined measurement and sampling biases for the climate product, which consists of annual averages of nadir radiance spectra over large 15° zonal regions. The 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. The SI traceable infrared radiances will also provide a source of on-orbit absolute calibration for a wide range of Earth observing sensors, greatly increasing their value for climate monitoring.

As noted, for the infrared radiance spectra, it has been determined that a measurement accuracy, expressed as an equivalent brightness temperature error, of 0.1 K ( $k = 3$ ) confirmed on orbit is required [1, 2, 5, 6].

## 2. THE ABSOLUTE RADIANCE INTERFEROMETER (ARI)

The ARI development is a component of a larger project being undertaken at the University of Wisconsin Space Science and Engineering Center (UW-SSEC), in partnership with Harvard University (HU). The project was funded by a NASA Instrument Incubator Program (IIP) grant “A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for the CLARREO Mission”. The NASA Earth Sciences Technology Office (ESTO) provided further support for the vacuum testing.

The project combines the development of fundamentally new devices including (1) the On-orbit Absolute Radiance Standard (OARS), a high emissivity blackbody source that uses multiple miniature phase-change cells to provide a revolutionary in situ standard with absolute temperature accuracy proven over a wide range of temperatures. The OARS is a source that will be used to maintain SI traceability of the radiance spectra measured by the calibrated interferometer sensor [7-9]; (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 [10-13]; (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, and (4) the Absolute Radiance Interferometer (ARI) for measuring spectrally resolved radiances with a spectral coverage of 200 – 2500  $\text{cm}^{-1}$  at 0.5  $\text{cm}^{-1}$  spectral resolution and a radiometric accuracy of < 0.1 K,  $k = 3$ , brightness temperature at scene temperature [14-18].

A solid model of the instrument is shown in Figure 1. Photos of the completed ARI sensor and On-orbit Test and Verification (OTV) module are provided in Figure 2.

The UW-SSEC ARI is comprised of the following subsystems:

- Ultra-high accuracy blackbody calibration reference sources;
- A scene selection mirror assembly;
- Fore optics designed specifically for high radiometric accuracy;
- A 4-port cube corner, rocking arm interferometer with a diode laser based metrology system;
- Two aft optics assemblies, 1 at each output port of the interferometer;
- A 77 K multiple semi-conductor detector (450 – 3000  $\text{cm}^{-1}$ ) and dewar assembly;
- A very small mechanical cooler for the semi-conductor detector and dewar subassembly;
- A DTGS pyroelectric detector (200 – 1400  $\text{cm}^{-1}$ ) assembly.

The subsystems are chosen for their strong spaceflight heritage such that detailed performance testing can be conducted on a system with a clear and short path to space. For compatibility with an IIP budget and schedule, the electronics are not flight designs. Details of the instrument design, operational concept, and key trade-studies are presented in prior papers [14, 16, 17].

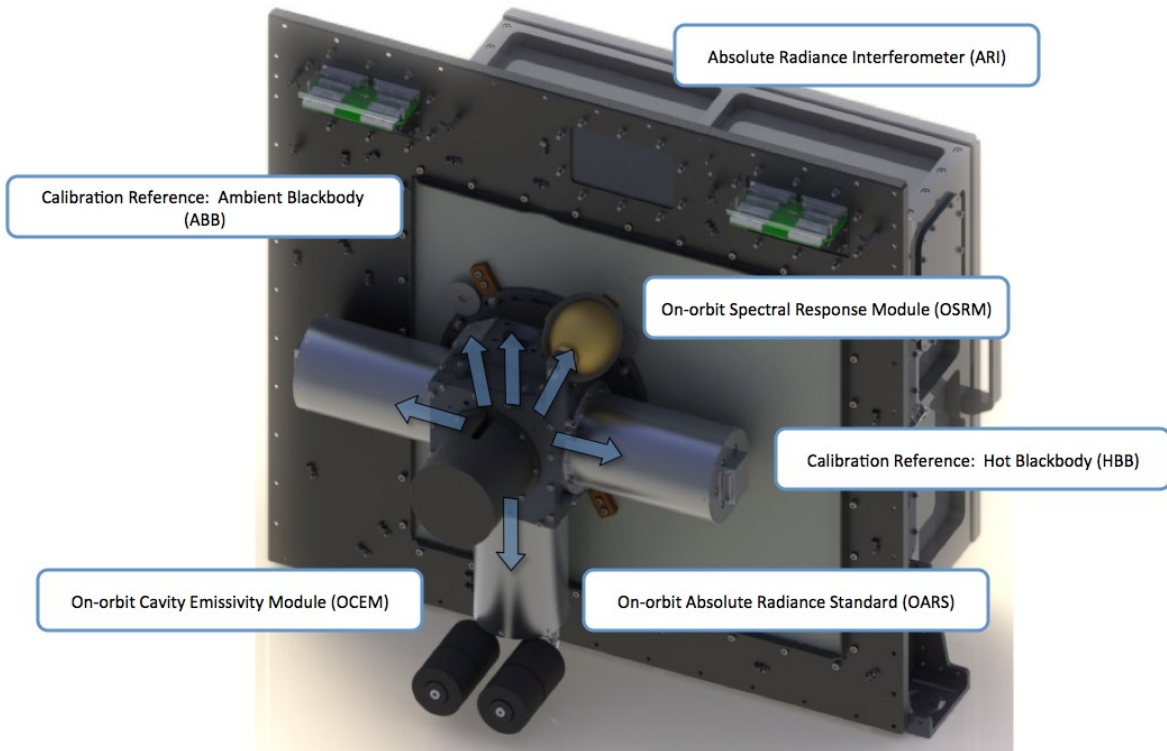


Figure 1: Technology developments completed under the NASA IIP funded proposal “A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for the CLARREO Mission”.

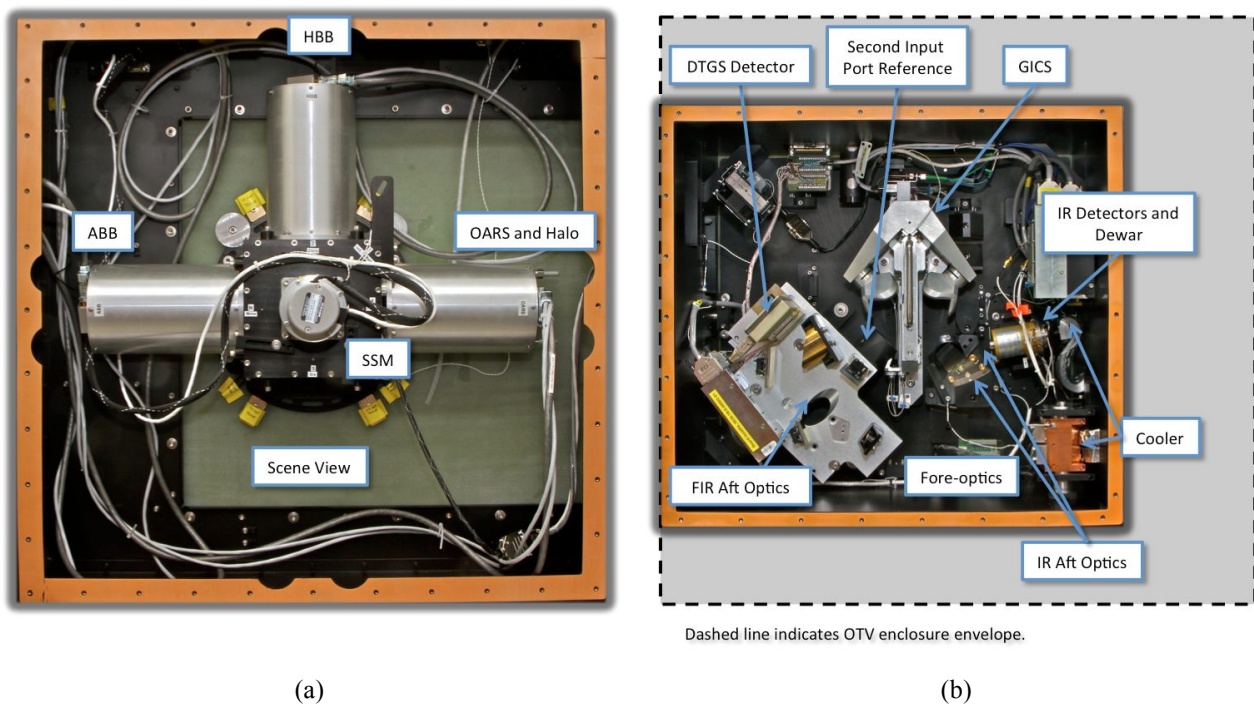


Figure 2: (a) Front view of the completed ARI sensor prototype. (b) Internal view of the completed ARI sensor prototype.

On-orbit, the sensor will be radiometrically calibrated using views of a dedicated onboard full-aperture blackbody reference and space. For laboratory and vacuum testing, the space reference is replaced by a second dedicated blackbody reference. The sensor has been designed to minimize potential biases related to non-linear response and polarization effects.

The ARI reference blackbodies are based on the UW SSEC Geostationary Imaging FTS (GIFTS) blackbody design [19]. Minor design modifications were made for the OARS, along with the addition of multiple miniature phase-change cells. The OARS uses transient temperature melt signatures from three (or more) different phase change materials to provide absolute calibration for the blackbody thermistor sensors covering a wide, continuous range of temperatures [7-9]. The system uses very small masses of phase change material (<1 g), making it well suited for spaceflight application.

### 3. RADIOMETRIC PERFORMANCE

#### 3.1 Radiometric Calibration and Uncertainty

The complex calibration method is used for ARI radiometric calibration [20]. The uncertainty associated with the calibrated radiance may be estimated by calculating the combined uncertainty [21] for the complex calibration equation. The on-orbit, laboratory, and vacuum environments each present unique uncertainty conditions. Meeting the combined calibration and calibration verification uncertainty in the respective laboratory or vacuum calibration reference configurations and environments demonstrates the capability to meet the 0.1 K (factor  $k = 3$ ) uncertainty requirement on-orbit. The details of the radiometric calibration and uncertainty analysis, along with the predicted calibration and calibration verification uncertainty for the laboratory configuration are presented in separate papers [14, 16]. A summary of the predicted uncertainty for the on-orbit and vacuum configurations and environments are included in the following sections.

#### 3.2 Predicted Uncertainty: On-orbit

Figure 3(a) shows the radiometric uncertainty estimate, on-orbit, converted to equivalent brightness temperature. The calibration reference sources on-orbit are a space view target (ST) and the internal calibration target (ICT), which is near instrument (ambient) temperature. Uncertainty estimates are tabulated in Table 1. On-orbit validation uncertainty is also shown in Figure 3(a) with contributors included in Table 1. Combined calibration and calibration verification uncertainty is shown in Figure 3(b). The on-orbit temperatures and uncertainty estimates are based on past experience with the testing and analysis of flight sensors and thermal modeling of the flight environment. Based on the radiometric uncertainty analysis and the required calibration accuracy, the residual nonlinearity, expressed as a percentage error, should be limited to less than 0.03%

Table 1: Uncertainty estimates used in the radiometric uncertainty analysis. It has been assumed that the OARS emissivity and associated uncertainty is determined from laboratory testing with a very high emissivity source.

(\*  $\epsilon_{OARS} = 0.999 \pm 0.0006$  (200  $\text{cm}^{-1}$ ),  $\pm 0.0004$  (800  $\text{cm}^{-1}$ ),  $\pm 0.0002$  (1400  $\text{cm}^{-1}$ ),  $\pm 0.0001$  (2000  $\text{cm}^{-1}$ ),  $\pm 0.000075$  (2600  $\text{cm}^{-1}$ ))

|   | Temperature | Uncertainty |
|---|-------------|-------------|
| Cold Cal Ref (Space Target)             | 4 K         | 0 K         |
| Hot Cal Ref (Internal Cal Target)       | 295 K       | 0.045 K     |
| Verification Target (OARS)              | 230 – 320 K | 0.045 K     |
| Reflected Radiance, Cold Cal Ref        | 290 K       | 0 K         |
| Reflected Radiance, Hot Cal Ref         | 290 K       | 4 K         |
| Reflected Radiance, Verification Target | 290 K       | 4 K         |
|   | Emissivity  | Uncertainty |
| Cold Cal Ref (Space Target)             | 1           | 0           |
| Hot Cal Ref (Internal Cal Target)       | 0.999       | 0.0006      |
| Verification Target (OARS)              | 0.999       | 0.0006*     |

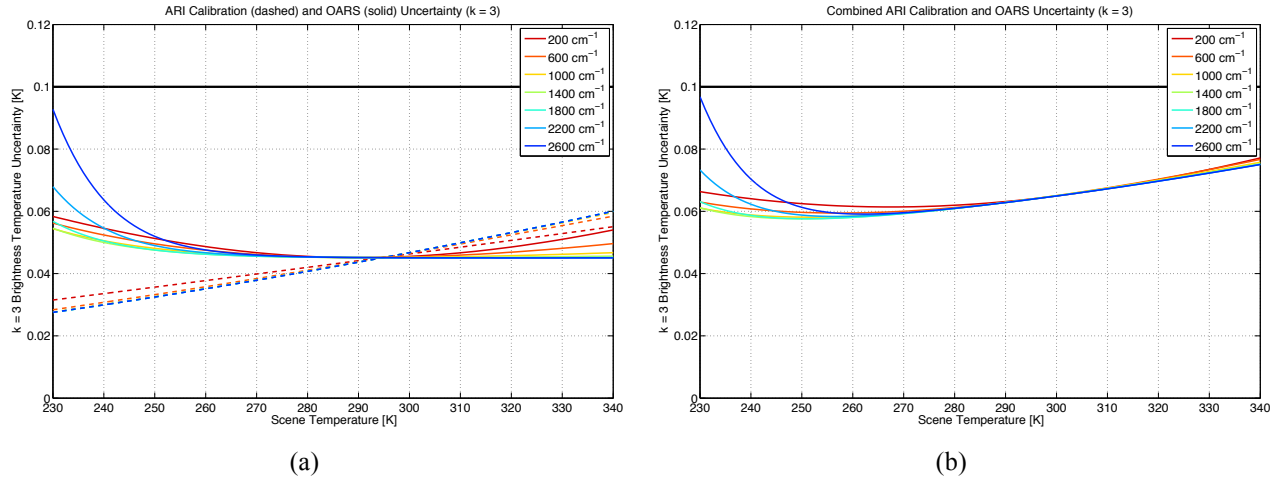


Figure 3: Predicted on-orbit radiometric calibration uncertainty; (a) calibration and OARS, (b) combined.

### 3.3 Predicted Uncertainty: Vacuum Environment

An ambient (or slightly warm biased) onboard blackbody and space view are used for calibration references on-orbit. For vacuum testing, a cold calibration blackbody and a warm-biased calibration blackbody are used as calibration reference sources. The primary challenges associated with the vacuum calibration reference configuration and demonstration include:

- Increased uncertainty associated with a blackbody compared to that of a space view. A true space view has no reflected radiance or emissivity uncertainty contributions;
- Increased uncertainty associated with the emissivity of OARS verification blackbody. For the on-orbit analysis, it was assumed that the OARS emissivity and associated uncertainty is determined from laboratory testing with a very high emissivity source, resulting in reduced emissivity uncertainty for the OARS with increasing wavenumber. This characterization is outside the scope of the IIP demonstration.

The impact of the calibration reference configuration can be estimated by calculating the combined uncertainty for the calibrated radiance for the vacuum configuration and expected conditions. Uncertainty estimates for the vacuum configuration and environment are provided in Table 2. Figure 4(a) shows the radiometric uncertainties for the ARI calibration and OARS predicted radiance for the vacuum configuration, converted to equivalent brightness temperature. Figure 4(b) shows the combined radiometric calibration and calibration verification uncertainty estimate for the expected vacuum configuration and conditions. Meeting the combined calibration and calibration verification uncertainty in the vacuum calibration reference configuration and vacuum environment demonstrates the capability to meet the 0.1 K ( $k = 3$ ) uncertainty requirement on-orbit.

Table 2: Uncertainty estimates used in the radiometric uncertainty analysis for vacuum configuration.

|   | Temperature | Uncertainty |
|---|-------------|-------------|
| Cold Cal Ref (Ambient Blackbody)        | 215 K       | 0.045 K     |
| Hot Cal Ref (Hot Blackbody)             | 300 K       | 0.045 K     |
| Verification Target (OARS)              | 213 – 333 K | 0.045 K     |
| Reflected Radiance, Cold Cal Ref        | 295 K       | 4 K         |
| Reflected Radiance, Hot Cal Ref         | 295 K       | 4 K         |
| Reflected Radiance, Verification Target | 295 K       | 4 K         |
|   | Emissivity  | Uncertainty |
| Cold Cal Ref (Ambient Blackbody)        | 0.999       | 0.0006      |
| Hot Cal Ref (Hot Blackbody)             | 0.999       | 0.0006      |
| Verification Target (OARS)              | 0.999       | 0.0006      |

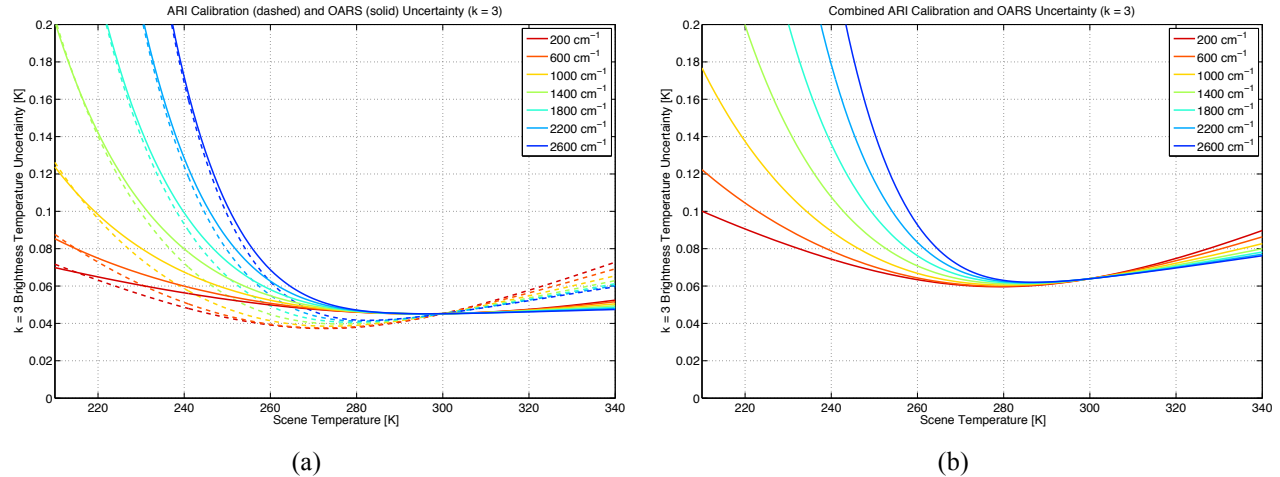


Figure 4: Predicted radiometric calibration uncertainty in the vacuum configuration and environment; (a) calibration and OARS, (b) combined.

### 3.4 Radiometric Calibration Verification Results

Calibration verification was successfully completed in both the laboratory and vacuum calibration configuration and environment. Vacuum calibration verification was completed using the OARS verification source at temperature setpoints of approximately 216K, 233K, 253K, 273K, 293K, 313K, and 333K (refer to Figure 5). An example of the calibration verification results at 800  $\text{cm}^{-1}$  (700 – 900  $\text{cm}^{-1}$  average), expressed as differences in observed and predicted brightness temperatures for the LW MCT detector with nonlinearity correction, and the DTGS detector are shown in Figure 6 and Figure 7. Detailed results are presented by Taylor in a separate paper [14].

To maintain compatibility with the IIP demonstration schedule and budget, readily available commercial options were selected for the signal chain electronics and the FIR deuterated triglycine sulfate (DTGS) pyroelectric detector, and an existing UW-SSEC detector and dewar assembly was used. The existing UW-SSEC detector dewar assembly houses a shortwave Indium Antimonide (InSb), and three photoconductive (PC) Mercury-Cadmium-Telluride (HgCdTe or MCT) detectors providing spectral coverage from 420 – 3300  $\text{cm}^{-1}$  (extended longwave MCT: 400 – 1600  $\text{cm}^{-1}$ , longwave MCT: 550 – 1700  $\text{cm}^{-1}$ , midwave MCT: 800 – 1820  $\text{cm}^{-1}$ , shortwave InSb: 1820 – 3300  $\text{cm}^{-1}$ ). For the ARI demonstration the longwave MCT and FIR DTGS detector channels were used.

The photovoltaic (PV) InSb detector exhibits an extremely linear response, and test and analysis of the DTGS detector indicate its nonlinearity, including signal chain electronics, to be less than 0.01%. The nonlinear response of photoconductive (PC) MCT detectors is well established, with a typical nonlinear behavior ranging from a few percent to more than 20% deviation from linearity at maximum flux intensities. Accordingly, a nonlinearity correction needs to be applied to the MCT detectors prior to radiometric calibration.

Additionally, the 4-port configuration of the interferometer allows direct comparison between the two output ports of detector response in overlapping spectral regions. The DTGS detector and MCT detectors, located at opposite output ports, have simultaneous and overlapping spectral coverage from 450  $\text{cm}^{-1}$  to 1800  $\text{cm}^{-1}$ .

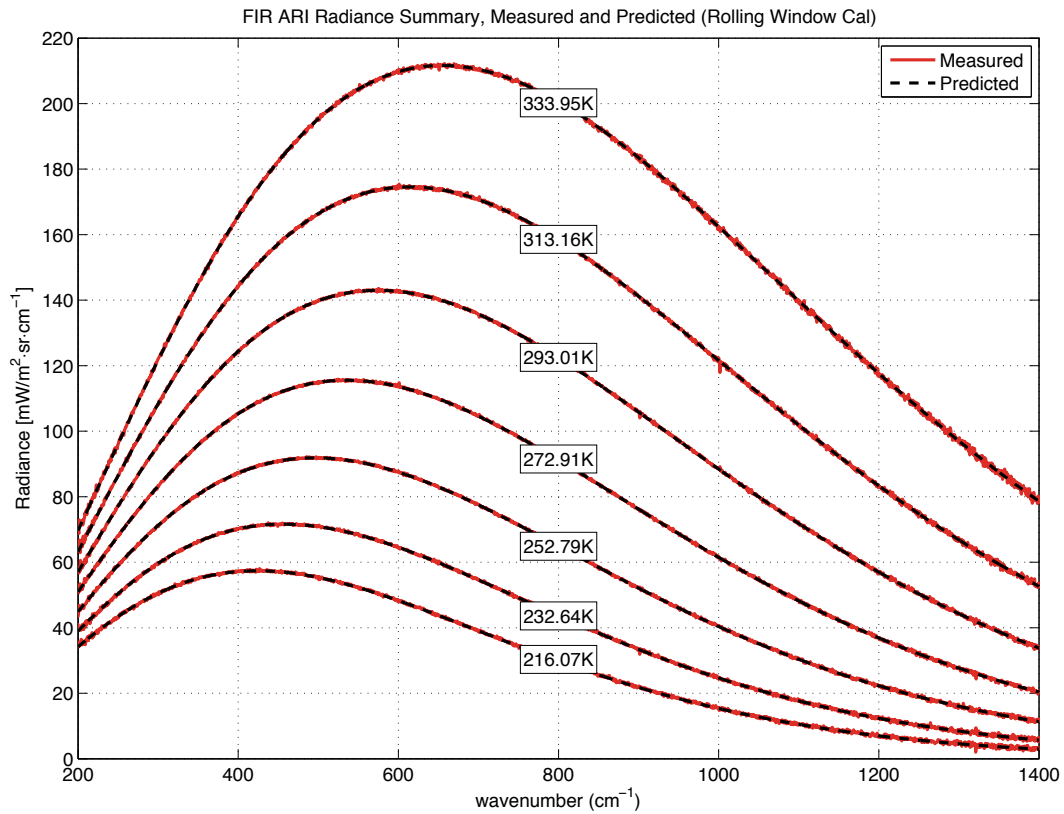


Figure 5: Radiance summary for the ARI DTGS channel calibration verification conducted under vacuum. The OARS was operated over a range of temperatures from approximately 216 K to 334 K.



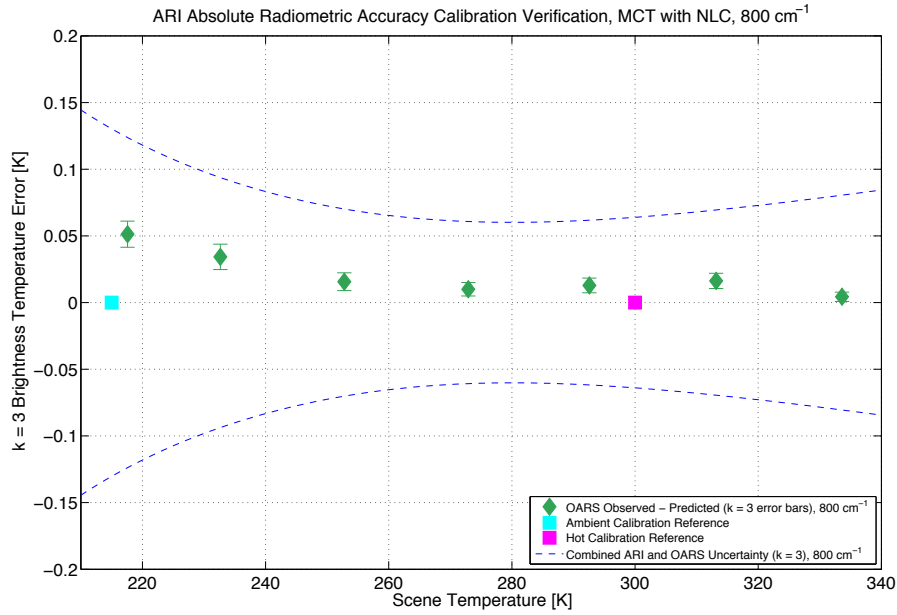


Figure 6: ARI vacuum calibration verification results for the longwave detector with nonlinearity correction,  $800\text{ cm}^{-1}$ . Total (calibration and calibration verification) radiometric uncertainty is shown in blue dashed lines. Meeting these uncertainty bounds in the vacuum environment demonstrates the capability to meet the  $0.1\text{ K}$  ( $k = 3$ ) uncertainty requirement on-orbit.

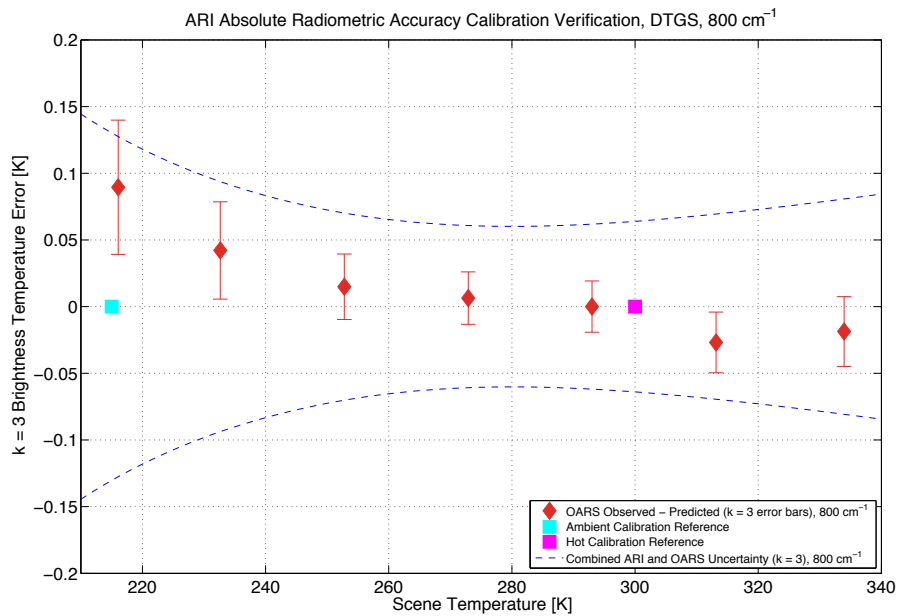


Figure 7: ARI vacuum calibration verification results for the far infrared (DTGS) detector,  $800\text{ cm}^{-1}$ . Total (calibration and calibration verification) radiometric uncertainty is shown in blue dashed lines. Meeting these uncertainty bounds in the vacuum environment demonstrates the capability to meet the  $0.1\text{ K}$  ( $k = 3$ ) uncertainty requirement on-orbit.

## 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 Verification (OTV) module have demonstrated the technology necessary to measure infrared spectrally resolved radiances (3.3 – 50  $\mu\text{m}$ ) with ultra high accuracy ( $< 0.1$  K,  $k = 3$  brightness temperature at scene temperature) required for a benchmark climate mission. The UW-SSEC ARI and OTV subsystems have been selected and developed to provide an instrument prototype with a clear path to space, and the prototype has received a NASA technological readiness level (TRL) rating of 6.

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