Final Technical Report
University Of Wisconsin-Madison

(To be completed by RSP or the Department)

Project Title:	**A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for The CLARREO Mission**
Award Number:	**NNX08AN35G**
UW Account Number:	**PRJ15PI**
For the Period of:	**6/25/2008 to 3/15/2012**
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(To be completed by the Principal Investigator)

<u>Inventions Report:</u>

☒ No Inventions resulted from this award
☐ Yes

Inventory Report:

☒ No federally owned equipment is in the custody of the PI
☐ Yes

Publications:

P. Jonathan Gero, John A. Dykema, James G. Anderson, and Stephen S. Leroy, "On-orbit characterization of blackbody emissivity and spectrometer instrument line-shape using quantum cascade laser based reflectometry," *Proc. SPIE 7081, 70810Q (2008)*

Fred A. Best, Douglas P. Adler, Scott D. Ellington, Donald J. Thielman, and Henry E. Revercomb, "On-orbit absolute calibration of temperature with application to the CLARREO mission," *Proc. SPIE 7081, 70810O (2008)* .

Gero, P. J., John A. Dykema, James G. Anderson, "On-Orbit Characterization of Blackbody Emissivity and Spectrometer Instrument Line-Shape Using Quantum Cascade Laser Based Reflectometry," *OSA Hyperspectral Imaging and Sensing of the Environment (HISE) Meeting April 26-30, 2009, Vancouver, British Columbia Canada.*

Revercomb, Hank E., Fred A. Best, John A. Dykema, Joe Taylor, David C. Tobin, Robert O. Knuteson, Douglas Adler, Mark Mulligan, "High Spectral Resolution IR Instrument Developments for CLARREO," *OSA Hyperspectral Imaging and Sensing of the Environment (HISE) Meeting April 26-30, 2009, Vancouver, British Columbia Canada.*

Dykema, John A., Stephen Leroy, Yi Huang, James G. Anderson, "CLARREO Science Applications: Infrared Spectra with On-Orbit SI Traceability for Climate," *OSA Hyperspectral Imaging and Sensing of the Environment (HISE) Meeting April 26-30, 2009, Vancouver, British Columbia Canada.*

Anderson, James, John Dykema, Stephen Leroy, "High Accuracy Observations of Spectrally Resolved IR Radiance from Earth Orbit: Setting the Time Scale in the Energy-Climate Debate," *OSA Hyperspectral Imaging and Sensing of the Environment (HISE) Meeting April 26-30, 2009, Vancouver, British Columbia Canada.*

Hank Revercomb, Fred A Best, David C Tobin, Robert O. Knuteson, Joe K Taylor, Dan LaPorte, Steve Dutcher, Jonathan Gero, Doug Adler, Mark Mulligan, "Absolute Calibration of IR Atmospheric Spectra: Background and New Paradigms for the CLARREO Climate Benchmark Mission," *31st Review of Atmospheric Transmission Models Meeting National Heritage Museum Lexington, MA, 16-17 June 2009.*

Dykema, J.A., H.E. Revercomb and J.G Anderson, (2009), GC52A-05, "Experimental Basis for Robust On-orbit Uncertainty Estimates for CLARREO InfraRed Sensors," *Eos Trans. AGU, 90(52), Fall Meet. Suppl., Abstract GC52A-05.*

P. Jonathan Gero, Joseph K. Taylor, Fred A. Best, Henry E. Revercomb, Robert O. Knuteson, David C. Tobin, Douglas P. Adler, Nick N. Ciganovich, Steven Dutcher, Raymond K. Garcia, "On-orbit Traceable Blackbody Emissivity Measurements Using the Heated Halo Method," *AGU 2009 Fall Meeting*.

Joe K. Taylor, Henry E. Revercomb, Frederic J Grandmont, Henry Buijs, P. Jonathan Gero, Fred A. Best, David C. Tobin, Robert O. Knuteson, Daniel D. LaPorte, "A New Class of Advanced Accuracy Satellite Instrumentation (AASI) for the CLARREO Mission: Interferometer Test-bed Trade studies and Selection" *AGU 2009 Fall Meeting*.

Henry E. Revercomb, Fred A. Best, David C. Tobin, Robert O. Knuteson, Joe K. Taylor, P. Jonathon Gero, Douglas Adler, Mark Mulligan, "CLARREO IR Spectra: Achieving 0.1 K 3-sigma," *AGU 2009 Fall Meeting*.

Fred A. Best, Douglas P. Adler, Claire Pettersen, Henry E. Revercomb, John H. Perepezko, "On-Orbit Absolute Temperature Calibration Using Multiple Phase Change Materials," *AGU 2009 Fall Meeting*.

Revercomb, H. E., and Coauthors, 2010, "The Path to accurately calibrated FTIR: Progress from the University of Wisconsin HIS aircraft instruments, to the ground-based AERI, to spaceborne atmospheric sounding instruments (AIRS, IASI, CrIS), and onward to the NASA CLARREO climate benchmark mission," *Proc. Workshop on Infrared Remote Sensing Applications*, Quebec, QC, Canada, ABB.

Taylor, J. K., and Coauthors, 2010: "The University of Wisconsin Space Science and Engineering Center Absolute Radiance Interferometer," *Proc. Workshop on Infrared Remote Sensing Applications, Quebec, QC, Canada, ABB.*

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Henry E. Revercomb, Fred A. Best, Robert O. Knuteson, David C. Tobin, Joe K. Taylor, Robert E. Holz, P. Jonathon Gero, "The CLARREO benchmark climate mission: achieving high accuracy with high spectral resolution IR observations" (Invited Paper), *SPIE Asia-Pacific Remote Sensing conference held in Incheon, Korea, 11-14* October 2010.

Fred A. Best, Douglas P. Adler, Claire Pettersen, Henry E. Revercomb, John H. Perepezko, "On-orbit absolute temperature calibration using multiple phase change materials: overview of recent technology advancements," *SPIE Asia-Pacific Remote Sensing conference held in Incheon, Korea,* 11-14 October 2010.

Joe K. Taylor, Henry E. Revercomb, Univ. of Wisconsin-Madison (United States); Henry L. Buijs, Frederic J. Grandmont, ABB-Bomem Inc. (Canada); P. Jonathon Gero, Fred A. Best, David C. Tobin, Robert O. Knuteson, Daniel D. LaPorte, Richard Cline, Mark Schwarz, Jeff Wong, "The University of Wisconsin Space Science and Engineering Center absolute radiance interferometer (ARI)," *SPIE Asia-Pacific Remote Sensing conference held in Incheon, Korea,* 11-14 October 2010.

P. Jonathon Gero, Joe K. Taylor, Fred A. Best, Henry E. Revercomb, Robert O. Knuteson, David C. Tobin, Douglas P. Adler, Nick N. Ciganovich, Steven T. Dutcher, Raymond K. Garcia, "On-orbit absolute blackbody emissivity determination using the heated halo method," *SPIE Asia-Pacific Remote Sensing conference held in Incheon, Korea,* 11-14 October 2010.

Best, F.A., et al., 2011, “On-Orbit Absolute Radiance Standard for Future IR Remote Sensing Instruments,” *NASA 2011 Earth Science Technology Forum, Pasadena, CA.*

Best, F.A., Adler, D.P., Pettersen, C., Revercomb, H.E., Gero, P.J., Taylor, J.K., Knuteson, R.O., and Perepezko, J.H., “On-Orbit Absolute Radiance Standard for Future IR Remote Sensing Instruments,” *11th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD)*, 19–23 September.

Gero, J., J. Taylor, F. Best, H. Revercomb, R. Knuteson, D. Tobin, D.P. Adler, N. Ciganovich, S. Dutcher, R. Garcia, 2011, “On-orbit Absolute Blackbody Emissivity Determination Using the Heated Halo Method, *Proc. OSA Optics & Photonics Congress*, FMA3.

Gero, J., J. Taylor, F. Best, H. Revercomb, R. Knuteson, D. Tobin, D.P. Adler, N. Ciganovich, S. Dutcher, R. Garcia, 2011, “On-orbit Absolute Blackbody Emissivity Determination Using the Heated Halo Method,” *Metrologia* .

Taylor, J.K., H.E. Revercomb, H. Buijs, F.J. Grandmont, P.J. Gero, F.A. Best, D.C. Tobin, R.O. Knuteson, D.D. LaPorte, R. Cline, M. Schwarz, J. Wong, 2011, “The University of Wisconsin Space Science and Engineering Center Absolute Radiance Interferometer (ARI), *11th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD),* 19–23 September.

Revercomb, H. E. CLARREO IR Spectra, “Achieving 0.1 K 3-sigma (SI-traceable uncertainty analyses and Post-launch Validation),” *CLARREO Science Team Meeting*, Madison, WI; October 12-14, 2011.

John Dykema, Mark Witinski, and James Anderson, 2011, "Testing Space-based Infrared Sensors for Systematic Errors,” *Fourier Transform Spectroscopy (FTS),* Toronto, Canada, July 10, 2011.

Gero, P. Jonathan, John A. Dykema, James G. Anderson, 2009, “A Quantum Cascade Laser–Based Reflectometer for On-Orbit Blackbody Cavity Monitoring,” *J. Atmos. Oceanic Technol., 26, 1596–1604.*

Summary of Technical Effort: (Usually several paragraphs. Please feel free to attach additional pages if you wish.)

Overall Summary

- A new class of Advanced Accuracy Satellite Instrumentation (AASI) that provides for On-orbit Verification and Testing of IR radiances has been advanced from TRL3 to TRL6 under this NASA ESTO Instrument Incubator Program.
- IIP Advances have been conveyed to LaRC for integration into CLARREO plans.
- This capability should be implemented at the heart of a new mission to provide a fundamental Climate Benchmark and an Infrared Inter-calibration resource as soon as possible.
- New activities for advancing the foundation for CLARREO, Zeus, and other future NASA missions have been identified that warrant new ESTO support.

Key Activities and Findings of the Effort: Phase Change Technology

- Defined baseline geometry for phase change material housings, based on thermal modeling, melt signature testing, and material compatibility tests [Ga/SS, (9 mo.) ΔMP<1mK; H_2O/SS, (18 mo.) ΔMP <1mK].
- Developed the capability to measure mechanical strain in the housings during freeze events. *Gallium and water expand upon freezing leading to a build-up of pressure that will induce stresses in the confining housings*.
- Verified that strains built up in the housings during Gallium freeze events are at safe levels compared to intrinsic housing material strength. *Tests with water will be conducted next, but are not expected to be a problem due to transformation of ice into higher melting phases when under higher pressures. Hg shrinks upon freezing*.
- Developed baseline life-cycle temperature history for the phase change cells, *including time at various temperatures and number of freeze cycles.*
- Developed accelerated life-test scenarios to test for unwanted housing material diffusion into the melt materials (this would alter melt temperature). *Equivalent life-test scenarios of the phase change cells are based on the Arrhenius reaction rate equation. These tests will be conducted at higher temperatures but at far shorter times than the expected multi-year service-life.*
- Developed a phase change cell test bed. With a single configuration the test bed can:
- Accommodated multiple phase change cells all tested at one time.
- Ran one full cycle from -80 °C to +50 °C to -80 °C in 2 hours.
- Provided accurate temperature control for time at temperature tests (multiple days at up to +80 °C).
- Conduceted melt signature tests on system that is scalable and easy to reproduce.
- Developed an approach for temperature metrology system that is consistent with above.
- Developed relationship to help bound the depression of melt temperatures with varying amounts of contamination (from containment material dissolution).
- A sensitivity analysis was performed to relate the amounts of contamination (ppm levels) needed to change melt point temperatures (mK). The simplest method to look for contamination appears to be from the melt signature. The analysis is useful in estimating contamination levels.
- A more accurate capability was been identified to look for melt material contamination based on X-ray Fluorescence (Bruker).
- Developed strategy using SEM examination to inspect the melt housings for evidence of cracking, melt diffusion, and liquid metal embrittlement.
- Designed and ran Accelerated Life Test-1.
- Wrote a proposal that was accepted to demonstrate our phase change cell performance on the Space Station. *Testing and analysis were performed to show that our phase change cells would work with a test platform being developed by USU/SDL.*
- Supported the CLARREO IR Instrument Integrated Design Lab (IDL) at NASA GSFC. *There is significant synergy between our IIP work and the IDL design, and follow-on efforts to improve this design.*
- Continued to work with NIST to refine the emissivity measurements of both the Harvard and UW blackbodies.
- Continued to work with NIST personnel to perform refined emissivity measurements of

an AERI and Harvard Blackbodies using NIST facilities.

- Accelerated Life Test (ALT) developed with dissolution environment equivalent to full life exposure, but limited cycling to reduce test time. Intent is to accelerate discovery of fundamental compatibility and containment issues, full life cycle tests will be run for verification as development progresses. *Gallium critical due to LME potential, water is sensitive to dissolution contamination.*
- Gallium testing completed – ALT I and ALT II.
- ALT I showed good results with no evidence of LME or contamination (Year 1 Review).
- Gallium results show no significant melt temperature changes pre vs. post ALT I.
- Completed ALT II testing.
- Welded housings with gallium in contact with weld zone.
- Melt signature results pre and post test were within 1 mK.
- Conducted water testing – ALT I, ALT II, and ALT III.
- As reported in Year-1 Review, ALT I water melt temperature results showed wide scatter and depression of melt point - investigation indicated process contamination.
- For ALT II, changed preparation procedure and housing plug material:
    - Melt signature results pre and post test were within 10 mK.
    - Analyses of housings and melt material conducted.
    - ALT III with water in welded housings completed.
- Completed mercury testing – ALT I and ALT II
    - Identified relevant Hg safety issues and developed procedures for handling and testing.
    - ALT I melt signature results pre and post test were within 0.5 mK.
    - Completed ALT II testing.
- Welded and tested housings with gallium in contact with weld zone.
- Developed laser welding process to seal melt housings
- Housings containing gallium, water, and mercury were successfully laser welded. Gallium and mercury centrifuged into full contact with weld zone, and ALT II conducted and verified there was no weld damage, melt contamination, or housing LME. ALT with water in welded housings were completed.
- Investigated methods to verify leak rates under vacuum.
- Conducting testing with gallium eutectics. Eutectic is planned for use in funded ISS microgravity melt experiment to replace mercury, to allow demonstration of 3-point calibration. Melt signature results for Ga-In, Ga-In-Sn, and Ga-Sn are highly repeatable and reliable.
- Completed Full Accelerated Life Test on Welded Melt Cells [TRL 4]. Completed full accelerated life testing on Ga, H_2O, and Hg in welded housings. Previous Life Testing was abbreviated for expedited initial screening. Pre and post melt signatures are within 5 mK (3 sigma). Mechanical integrity was maintained in the housings and welds.
- Integrated Melt Cells Into Blackbody and Obtained Melt Signatures [TRL 5]. Integrated Ga, H20, and Hg welded Melt Cells into breadboard blackbody and obtained high quality melt signatures.
- Examined a melt cell housing weld cross-section using SEM/EDS (energy dispersive spectroscopy) to confirm expected weld structure, particularly the absence of MnO.
- Completed Shortened Accelerated Life Test on ISS Candidate melt cells. ISS Melt

materials are Ga, GaSn (Eutectic), and H20+AgI. These materials were chosen to be compatible with the ISS Test capabilities (lowest temperature achievable is -10°C). Ga has been proven with Full Accelerated Life testing. GaSn Eutectic (MP=20.42°C).

- Researched and tested H2O+AgI dopant, and demonstrated this controls undercooling to be within ISS test set capabilities. Conducted extensive supercooling tests to confirm that water freezes above the limit of the ISS test apparatus
- Optimized the SDL Experiment Support Package for UW Melt Cell Demonstration on ISS. Changed thermal couplings to improve the quality of melt signatures and to obtain lower temperatures for supercooled freezes (GaSn and H2O). Modified electronics to improve temperature readout stability.
- Obtained quality signatures in Optimized ISS Configuration using lab temperature controllers and resistance readouts
- Conducted vibration testing on ISS Phase Change Cells. No change in melt behavior was observed as a result of the test, which was conducted at the expected ISS launch levels.
- Obtained quality signatures with the Optimized UW ISS Configuration using SDL electronics in manual debug mode. Testing included operation with simulated on-orbit thermal fluctuations.
- Revised SDL ISS software to implement the UW developed melt algorithms used previously in manual debug mode.
- Conducted accelerated life testing on Miniature Phase Change Cells (Ga, H_2O, Hg) that used thermally conductive epoxy in place of conductive paste for coupling to a cavity simulator. Signatures taken before and after the accelerated life test showed no change in melt behavior
- Completed detailed design of the OARS for use in a laboratory environment
- Completed detailed design of the HBB and ABB for use in the Absolute Radiance Interferometer Prototype
- Calibrated thermistors for use in the OARS, HBB, and ABB using a Hart Scientific calibrated temperature probe with an accuracy of 5 mK (k=3)
- Fabricated and characterized Ga, H_2O, and Hg miniature phase change cells for use in the OARS
- Fabricated, assembled and characterized the OARS, HBB, and ABB
- Integrated the OARS, including phase change cells and Heated Halo, to the ARI, along with HBB and ABB, and conducted end-to-end system testing [TRL 6].

Key Activities and Findings of the Effort: Heated Halo Cavity Emissivity Measurement

- Configured UW aircraft instrument Scanning-High-resolution Interferometer Sounder (S-HIS) in UW laboratory for Heated Halo test and obtained preliminary measurements.
- Primary "lessons learned" for CLARREO is the importance of controlling stray light contributions in the heated halo test.
- Results of this preliminary testing will be used as input to a refined halo design for the next phase of testing.
- A purge box was constructed to eliminate absorption features in the emissivity spectra due to ambient air.
- The optical system was improved to better control stray light. The resulting emissivity spectrum now agrees with the Monte Carlo model calculation.

- Agreement between UW, NIST measurements and model results validates the process for emissivity measurement with the Heated Halo.
- Designed Next Generation Heated Halos leading to TRL advancement to level 5 and 6.
- Generation 2 incorporates a conical design and improved mechanical integration with the blackbody. Optical performance is comparable to Gen. 1.
- Generation 3 is conical, smaller, and fully mechanically integrated to the OARS. Optical performance is optimized by matching with fore-optics.
- Integrate Heated Halo Generation 2 with ARI Breadboard 1. This allows emissivity measurements out to 50 μm (200 cm^{-1}) with pyroelectric detector.

- Compact conical flight-like design, fully integrated with OARS. The ARI prototype allows emissivity measurement with multiple detectors
- Spectral emissivity measurement demonstrated in relevant environment — TRL 6
- Emissivity measurements are in agreement within various generations of Heated Halo results as well as NIST results
- Attained emissivity measurement uncertainty meets the requirements for CLARREO / Zeus.

Key Activities and Findings of the Effort: Quantum Cascade Laser (QCL)

- Verified environmental performance of QCL subsystem sufficient for integration into DARI-LW system for system-level environmental test.
- Conducted environmental test as part of integrated system and tested OCEM-QCL and OSRM functions.
- Specified and ordered aspheric lens to increase collected power but not necessary to functional check of LCAB.
- Added integrating sphere accessories that include port reducer to test impact of reduction in effective FOV size on ILS for DARI testbed.

Key Activities and Findings of the Effort: Absolute Radiance Interferometer at UW

- Defined top-level FTS module requirements and identified two existing ABB interferometer core solutions that would meet or exceed requirements: ABB GOSAT FTS / ACE-FTS Hybrid Breadboard Unit (Tokyo design); and the ABB Generic Flight Interferometer (GFI). Both interferometer cores: minimize non-recurring engineering costs by leveraging existing ABB designs and utilize ABB COTS electronics and software. Also both are designs with extensive space flight heritage and/or flight qualification
- Selected GFI, based primarily on similarity of spectral resolution requirement.
- Defined and resolved top-level interferometer trades, and defined major subsystems and interfaces (synergy with IDL effort). Also developed top-level cooler requirements working with vendor.
- Brought Interferometer and Cooler approach to CLARREO IR IDL exercise
- ABB/Bomem proposal received
- Internal ABB Kick-off held on October 1st, 2009, project milestones met:
    - Internal Design Review held on December 1st, 2009.
    - ABB: Procurement phase completed Feb 2010

    - Integration completed March 2010
    - Testing completed at ABB March 2010
    - Unit ready for delivery April 1st, 2010.
- Added Aft optics and detector subsystem to ABB interferometer.
- ABB measured performance:
    - Modulation efficiency: 88 ± 2% (target: > 70%)
    - Velocity variation: At 2 cm/s: ~0.13% RMS speed stability (1 □) (target: <1%)
    - Interferometer delivered Oct 2010 and integrated into Breadboard 1.

- ABB interferometer and aft optics integrated.
- Second port stable reference designed and integrated.
- Detector temperature control system designed, integrated, and tested.
- Data acquisition system completed and tested.
- Detector performance characterized.
- Interferometer characterization testing complete.
- "Config A" Fore-optics Optical design complete and "locked" and used for dry-run RFQ to optical vendors (determine costs, procurement time, machinability of surfaces, interested vendors).
- "Config B" Fore-optics design completed. Reduced the number of optical elements from Config A to achieve same design goals.
- Thorough optimization process and stray light analysis completed.
- Detailed drawings approved, RFQ completed, order issued.
- ABB E-AERI aft optics system with DTGS detector delivered and integrated into Breadboard 1. The system includes FIR detector module and compatible with existing AERI detector and dewar module. This mitigates impact of unforeseen schedule delays for UW designed aft optics and custom detector/dewar (TIR) and/or second FIR detector assembly (UW-SSEC design). The alignment and assembly were completed at ABB prior to delivery to UW.
- Breadboard 1 Testing Completed:
    - FIR Detector and aft optics testing and characterization
    - Linearity
    - Noise Performance
    - Interferometer performance characterization
    - Near Field Response Maps
    - Spectral Calibration Verification
    - Radiometric Calibration Analysis (External BB)
    - OCEM Heated Halo (Halo Gen 2)
    - Clear sky zenith data collected; comparison vs radiosonde
- Sensor Prototype (Breadboard 2) was configured:
    - Sensor structure and enclosure assembled
    - Interferometer Core and FIR aft optics transferred to Sensor Prototype
    - Fore-optics installed
    - IR Aft optics, detector-dewar assembly, and cooler installed
    - Optical alignment and throughput of system verified
    - Near field response at scene select assembly ports mapped and verified vs. optical models (FRED and Zemax)

  - Data acquisition and calibration system AIT completed
  - Electronics Rack re-configured for Breadboard 2.
  - Ingest and control software modified for Breadboard 2.
- Integrate components into Prototype and test in relevant environment. [12/11, TRL 5]
- End-to-end system test with OTV Module in simulated on-orbit thermal environment [2/12, TRL 6]

Roadmap for Implementation of NASA ESTO IIP Technology

- **Goal:** Flight of UW/Harvard IIP developments on Climate Benchmark Mission ASAP, thereby fulfilling a major part of the NASA commitment to Tier 1 DS missions
- **Background:** The IIP Prototype at UW was designed to serve as an Engineering Development Unit (EDU) for a flight program. Its key new technologies include the Absolute Radiance Interferometer (ARI) and the On-orbit Verification and Test System (OVTS), consisting of the OARS, OCEM, and OSRM. As shown here today, all have now been brought up to TRL 6.
- **The next step:** Extending and augmenting the funding for this IIP for another year would allow system refinement, integration, and testing to enhance readiness/ reduce risk for a critically important flight mission. Incremental investment in this proven team would be an efficient way to multiply the value of this successful IIP.
- **Specific Task examples:**
  - Integrate upgraded Harvard QCL into UW ARI Prototype
  - Upgrade cooled MCT/InSb package for improved noise performance
  - Substantially extend system testing, including (1) refined performance characterization (2) outside sky viewing, (3) ILS measurement demonstration, & (4) integrated halo and QCL emissivity tests