A New Class of Advanced Accuracy Satellite Instrumentation for Earth Observation
(UW-Harvard project, NASA Instrument Incubator Program)

Hank Revercomb
University of Wisconsin-Madison,
Space Science and Engineering Center

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The need for high spectral resolution observations for Climate benchmarking (a la CLARREO) motivates the drive for High accuracy

- For climate, we have been making broadband total radiance and flux measurements for 50 years, starting with Verner Suomi and Robert Parent’s 1st experiment to look at the Earth from space.
- To unequivocally resolve key climate trends on the decadal time scale, we need a new approach with higher information content.
- Spectrally resolved IR radiance measurements combined with SI-traceable on-orbit standards can deliver the needed information content with proven accuracy (when sampling biases are controlled by orbit choice).
- Broad spectral coverage, including much of the Far-IR, is important for optimizing information content.
October 1959 - October 2009

Suomi/Parent Radiometer

Explorer VII

50 YEARS

50 years celebrated 2 November 2009, Madison, Wisconsin
CM2 25-yr Annual Mean Trends
Yi Huang, McGill University

Note OLR insensitivity to trends in T, WV, and Clouds

Black dots indicate changes > 3 x standard deviation of unforced means
IR Accuracy Requirements for Climate Benchmarking

**Radiance Accuracy:** <0.1 K 2-sigma brightness T for combined measurement and sampling uncertainty for annual averages of 15° zones (each <0.1 K 3-sigma) to approach goal of resolving a climate change signal in the decadal time frame

**On-orbit Verification and Test:** Provide an On-orbit Absolute Radiance/Brightness Temperature Standard with an accuracy of <0.1 K 3-sigma to provide SI traceability of on-orbit measurements
• Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO

• NASA Instrument Incubator Program (IIP) achievements demonstrate On-orbit Verification and Test System
Current System Capabilities

• **New High Resolution IR Sounders:** AIRS, IASI, CrIS…
  – Tremendous advance in information content & accuracy
  – Huge advance for climate process studies, offering
    • High vertical resolution T and WV profiling
    • Trace gas distributions
    • Cloud and surface properties
  – Provide a solid foundation for CLARREO IR feasibility
  – **But, not optimized for unequivocal decadal trending**
    • Biased diurnal sampling
    • Inconsistent and incomplete spectral coverage among platforms
    • Accuracy can be improved (by factor of 4-5)
    • SI traceability post-launch limited to aircraft inter-comparisons
      (sounder-to-sounder comparisons useful, but do not have direct, timely connections to International Standards)
CrIS FM1 In-flight Radiometric Uncertainty:
versus scene temperature for all FOVs for ~mid-band spectral channels

Generally < 0.2 K 3-sigma for all scene temperatures

Non-linearity causing prominent FOV dependence (color coded)
will be reduced significantly by in-flight FOV inter-comparisons

UW Scanning HIS

Provides Sounder Inflight Validation

Ambient Blackbody

Hot Blackbody

Scene Mirror Motor

Interferometer & Optics

Electronics

S-HIS on Global Hawk-2011-HS3 (Hurricane & Severe Storm Sentinel)

CO

N₂O

CH₄

CO

CO₂

Longwave

Midwave

Shortwave

CO₂

O₃

N₂O

CH₄

H₂O

CO

CO₂

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Slide 9
**Formal 3-sigma absolute uncertainties, similar to that detailed for AERI in Best et al. CALCON 2003**

- $T_{\text{ABB}} = 260$ K
- $T_{\text{HBB}} = 310$ K
- $\sigma T_{\text{BB}} = 0.10$ K
- $\sigma \varepsilon_{\text{BB}} = 0.0010$
- $\sigma T_{\text{refl}} = 5$ K
- 10% nonlinearity

S-HIS Absolute Radiometric Uncertainty for typical Earth scene spectrum
End-to-end S-HIS radiance evaluations conducted under S-HIS flight-like conditions with NIST transfer sensor (TXR) such that S-HIS satellite validation & AERI observations are traceable to the NIST radiance scale.

Results for TXR 10 μm Channel

- AERI minus TXR mean = -22 mK (well < 3-sigma uncertainties)
- AERI minus S-HIS mean = -60 ± 90 mK
- mean S-HIS-TXR = 38 mK (well < 3-sigma uncertainties)
Aircraft is key approach for direct radiance validation of EOS & NPOESS, and will be key to CLARREO validation also.
**IASI Midwave Validation**

**Mean spectra**

- **IASI, NAST-I, SHIS**
- **BT (K)**
- **Diff (K)**

**IASI minus NAST-I, IASI minus SHIS**
- (using double obs-calc method)
- NAST-I: 0.12 K, 0.04 K, -0.19 K
- S-HIS: 0.20 K, 0.03 K, -0.08 K
< 0.1 K 3-sigma brightness T accuracy is achievable by applying proven techniques with simplified instrument design (nadir only, high S/N not needed, can avoid polarization errors & minimize non-linearity)

Calibration Uncertainty (Including 0.03% non-linearity)

Brightness T Error [K 3-sigma]

200 cm-1 800 cm-1 1600 cm-1 2000 2600 cm-1

Residual Nonlinearity = 0.03%

\( dT_{\text{ict}} = 0.045 \) K, \( E_{\text{ict}} = 0.999 \pm 0.0006 \), \( T_{\text{bg}} = 290 \pm 2 \) K

Expected Calibration Accuracy

Equally achievable in Far-IR
• Background on IR Accuracy: Calibration and Validation of current sounders supports 0.1 K 3-sigma being achievable for CLARREO

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Flight-like Breadboard Configuration

ABB Interferometer (corner cube, wishbone, CsI beam-splitter)

Pyroelectric Far IR Detector & all reflective Aft Optics

Calibrated FTS

Fore Optics - all reflective

Cryogenic Detector/Dewar & Aft Optics

Internal Input Port 2 Source

see Joe Taylor’s talk

Taylor, J.K., et al., 2011: NEWRAD
Taylor, J., et al. 2010: SPIE
On-Orbit Verification & Test System

OARS: On-orbit Absolute Radiance Standard

OSRM: On-orbit Spectral Response Module (QCL source)

- 3 cm aperture Sources
- 45° Gold Scene Select Mirror
- 2 Blackbodies for Calibration
On-Orbit Absolute Radiance Standard allowing calibration testing throughout mission

OARS
Variable T Blackbody

Heated Halo

Melt Cells

Blackbody Cavity (aft view)

Thermistor

Melt Material

Cavity Surface Annulare Z360

Thermistor Heater

Cavity Aperture

Aluminum Enclosure

Aluminum Cavity

Glass-filled Noryl Cavity Support Tube / Thermal Isolator

Glass-finished Noryl Base

Gage of SP-49

Mechanical Support for Enclosure

Base Thermistor

-40 °C -20 °C 0 °C 20 °C 40 °C

-38.87 °C Mercury

0.00 °C Water

29.77 °C Gallium

Expected OARS Emissivity, Heated Halo Results, and NIST Validation

High Emissivity, Measured On-orbit with halo and QCL source

see Jon Gero’s talk

Absolute Temperature Calibration Using Multiple Phase Change Materials

See Jonathan Gero, et al. AGU Poster GC43A-0792

On-Orbit Traceable Blackbody Emissivity Measurements Using the Heated Halo Method

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see Fred Best’s talk
On-orbit Verification Uncertainty

OVTS Uncertainty

Brightness T Error [K, k=3]

Scene Temperature [K]

dT_{oars} = 45 \text{ mK}, \ E_{oars} = 0.999 \pm 0.0006^*, \ T_{bg} = 290 \pm 2 \text{ K}

*uncertainty for low T, high wavenumbers reduced via T/V Testing with high E references
UW Breadboard ARI-1
Results Summary

ABB Bomem Interferometer

AERI Front-End With Blackbodies

Pyroelectric Detector

Madison Sky
21 Jan 2011
New Test Results

1. Longwave Emissivity Measurement
2. Pyroelectric Linearity
3. Ice Body Calibration
Far IR falloff is expected for Z306 paint—plan to use Graphene impregnated Z306 to reduce this effect (see LaRC test data).

Very good agreement with model.

Responsivity averaged to prevent bias errors from low S/N.

Shows that excellent measurements are possible even with pyroelectric noise level. See Jon Gero’s talk.
Pyroelectric Linearity

Out of band estimate: 0.01% of peak

Pyro & electronics are very linear!

(Dry air purge, ~50 hour dwell)
Pyroelectric Linearity: Estimate

Rough quantitative estimate shows high degree of linearity even for raw spectrum—effects on calibrated spectra are smaller

Pyroelectric detector is well suited to CLARREO
Ice Body Calibration Test

- Demanding ambient lab test
- Calibration Blackbody T’s: 298 K & 317 K
- Extrapolating to 273.15 K

Same Blackbody characteristics would give < 0.1 K 3-sigma accuracy with a space view on-orbit
Ice Body Calibration Test Result

- Expected Accuracy is realized
- Grayed area is affected by room water vapor
- Extrapolating enhances noise (see 298 K comparison)

12 hours test time
Conclusions

• Proven results from high spectral resolution measurements and the recent UW/Harvard IIP developments demonstrate readiness for an IR Climate Benchmark Mission

• NASA Earth Venture-2 provides the first opportunity for getting this compelling mission into space
Science and Society: High Accuracy Measurements for Climate and Weather

Mission Overview

Named for the god of sky and weather, law, order, and fate, the Zeus mission will harness advances in the physics of high accuracy measurements from Earth orbit to establish a benchmark observation of global climate. Zeus will observe spectrally resolved infrared radiances from a 90° polar orbit, creating a dataset with high information content.

EV-2 could provide the members of this community with a very exciting data set to analyze and evaluate.
4 Major Elements have set the stage for Zeus

**Element I**

**NASA Science Mission Directorate:**
Advance Earth system science to meet the challenges of climate and environmental change.
1. How is the Earth system changing? (characterize)
2. What are the sources of change? (understand)
3. How will the Earth system change in the future? (predict)

**Element II**

**NRC Decadal Survey Tier 1:**
Address climate prediction, sea level rise, and climate-weather coupling.
1. Need for benchmark climate record that is global, accurate in perpetuity, tested against independent strategies,
2. Development of tested and trusted operational climate forecast,
3. Disciplined decision structures that assimilate accurate data and forecast.

**Element III**

**NRC Decadal Survey Venture Class:**
Restore more frequent launch opportunities to facilitate innovative ideas and technologies. Create a new Venture Class low-cost research and applications mission.

**Element IV**

**NASA Instrument Incubator Program:**
Develop an extensive infrastructure leading to the production of the Engineering Demonstration Unit for the Zeus high accuracy calibrated interferometer and on-orbit verification system.