CLARREO Climate Benchmarking, SI traceability, and Flowdown Requirements

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1. **Why we need CLARREO**
   *Serious gap in capability of existing systems to unequivocally detect long term climate trends with high sensitivity*

2. **Basic tenets and new paradigms for CLARREO**
   *Starting with discussion of key new capability needed*

3. **High-Level CLARREO requirements**
   *Examples consistent with Candidate NRC benchmark climate mission*
1. Why we need CLARREO

Serious gap in capability of existing systems to unequivocally detect long term climate trends with high sensitivity
• **Broadband**: CERES, ERBE, ERB, Suomi
  – Only US spaceborne systems specifically designed for climate trending
  – Have revealed the basics of the radiation budget and put necessary constraints on climate models, **but**
  – **Very limited information content**
    (Total Solar, Total Solar & IR, Total Window)
  – Results in severely limited ability to detect decadal climate change
OLR can miss important changes
Yi Huang thesis (Ramaswamy, advisor), 2008

AIRS=Nadir ± 5°
Model= GFDL GCM
Sept 2002-Oct 2003
All Skies
Ocean only

Differences in
Window &
Strat/upper Trop T
compensate
Water vapor &
mid Trop T

OLR agreement can be deceptive
CM2 25-yr Annual Mean Trends
Yi Huang thesis (Ramaswamy, advisor), 2008

Black dots indicate changes > 3 x standard deviation of unforced means

Note OLR Insensitivity to the trends in Ts, Atmospheric T, WV, and Clouds
Current System Limitations (2)

• **Filter Radiometer Sounders & Imagers:**
  HIRS, AVHRR…
  – Weather systems have served as valuable pathfinders for revealing climate processes and constraining climate models, **but**
  – **Very limited accuracy, even IR**
  – Spectral response uncertainty and inconsistency are major factors in IR
  – Results in severely limited ability to detect decadal climate change

• **Reflected solar radiance:**
  – **Accuracy generally limited to 2-3%**
Channel 2 (14.7 micron) indicates a gradual cooling of the lower stratosphere.

Channel 4 (14.2 micron) reveals a significant change in brightness temperature between the HIRS/2 and HIRS/3 instruments. HIRS/3 started with NOAA-15 satellite.

Intersatellite bias for channel 4, 8 and 12 can be as large as 5 K. Differences in overpass time, instrument response, and orbital drift contribute to some of this bias.

Leaves too much doubt about observed trends
Current System Limitations (3)

- **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
    - SI traceability post-launch limited to aircraft inter-comparisons (sounder-to-sounder comparisons useful, but do not have direct, timely connections to International Standards)
    - Inconsistent and incomplete spectral coverage among platforms
Aircraft is key approach for direct radiance validation of EOS & NPOESS

Fantastic Agreement, but 3-sigma uncertainty in validation is at least 0.5 K**

(70% chance error <0.16 K)

**Contributions from Sampling, Representativeness, Noise, Double differences, as well as S-HIS Accuracy
## Properties Comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>AIRS</th>
<th>IASI</th>
<th>CrIS</th>
<th>CLARREO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Radiometric Cal.</strong></td>
<td>1. &lt; 0.3 K at scene T</td>
<td>1. &lt; 0.5 K at scene T</td>
<td>1. &lt; 0.4 K at scene T</td>
<td><strong>Verified on orbit!</strong></td>
</tr>
<tr>
<td>2. BB emissivity</td>
<td>&gt;0.999</td>
<td>&gt;0.996</td>
<td>&gt;0.995</td>
<td>1. &lt; 0.1 K 3-σ at scene T</td>
</tr>
<tr>
<td>3. Blackbody T error</td>
<td>&lt;0.05 K</td>
<td>&lt;0.08 K</td>
<td>&lt;0.08 K</td>
<td>2. &gt;0.999</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. &lt;0.045 K 3-σ</td>
</tr>
<tr>
<td><strong>Spectral Calibration</strong></td>
<td>1. Atmospheric lines</td>
<td>1. →</td>
<td>1. →</td>
<td>1. →</td>
</tr>
<tr>
<td>2. Stability</td>
<td>2. ΔT control of spectrometer/aft optics (2.2% Δν shift/K)</td>
<td>2. Stable laser controls interferogram sampling (&lt; 1ppm over 6 months)</td>
<td>2. (&amp;/or Ne source)</td>
<td>2. →</td>
</tr>
<tr>
<td>3. Instrument Line Shape (ILS) knowledge</td>
<td>3. Prelaunch tests with FTS source</td>
<td>3. fundamental instrument design, verified with laser sources in ground testing</td>
<td>3. →</td>
<td>3. On-orbit ILS Source</td>
</tr>
<tr>
<td><strong>Linearity</strong></td>
<td>&lt;0.3% over much of spectrum, &lt; ~1% peak; error assumed &lt; 0.05 K after correction</td>
<td>&lt;1% longwave, negligible MW- &amp; SW error &lt; ~0.15 K after correction stability verifiable in orbit from out of band features</td>
<td>&lt;1% longwave &amp; MW negligible SW error &lt; ~0.1 K after correction stability verifiable in orbit from out of band features</td>
<td>Very small for DTGS and InSb, longwave goal &lt;&lt;0.1 % verified in orbit</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>±worst case 0.4K (9 &amp; 15 μm); error assumed &lt; 0.07 K after correction</td>
<td>&lt;0.2% (“paddle wheel” gold scene mirror overcoated) uncorrected error &lt; 0.2 K correction confirmed with dual space views</td>
<td>&lt;0.05% (45º gold scene mirror with overcoating) error &lt; 0.04 K even uncorrected</td>
<td>Nominally zero (by design, nadir only) verified in orbit with dual space views</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>166 kg</td>
<td>200 kg</td>
<td>133 kg</td>
<td>TBD&lt;35 kg each</td>
</tr>
<tr>
<td><strong>Power (W)</strong></td>
<td>256 W</td>
<td>200 W</td>
<td>106 W</td>
<td>TBD&lt;60 W Far IR FTS</td>
</tr>
</tbody>
</table>

CLARREO accuracy will be proven with SI standards on-orbit & better by ~ x5
2. Basic tenets and new paradigms for CLARREO
A new type of mission focused on decadal time scales: measuring trends and testing model predictions

Integral part of major existing & planned research (EOS+) and operational systems for characterizing climate

From CLARREO Science Questions Document, 9 Oct ‘08
1) **High information content**, rather than just monitoring total radiative energy budget (i.e. spectrally resolved radiances covering large parts of the spectrum as a product, rather than Total IR or Solar fluxes)

2) **Very high absolute accuracy, with measurement accuracy proven on orbit** (stability not sufficient)
   a) minimizes climate change detection time and
   b) relieves the need for mission overlap
   (Must consider Total Accuracy = RSS of Spatial/ Temporal biases and measurement accuracy)

3) **Commitment to ongoing Benchmark Missions**
   e.g. 5-8 year lifetime every 8-10 years (TBD by studies)
   (Data for Model trend evaluation is needed for the foreseeable future—therefore, affordability is a key ingredient)
Radiance Accuracy: <0.1 K 2-sigma brightness T for combined measurement and sampling uncertainty (each <0.1 K 3-sigma) for annual averages of large regions (to approach goal of resolving a climate change signal in the decadal time frame)

To avoid bias, use direct observable (Radiance) to assess climate, not FOV by FOV retrievals
Stratosphere (668 cm⁻¹) from 2007 near nadir AIRS

CLARREO proxy data from AIRS: see Knuteson talk (Wed) & Dutcher poster
Upper Troposphere (720 cm\(^{-1}\)) from 2007 near nadir AIRS
Window (911 cm\(^{-1}\)) from 2007 near nadir AIRS
Key Advances needed from Dedicated Climate System (CLARREO)

- High information content, targeted for climate trend sensitivity (e.g. for emission spectra, include far IR; consider polarization for solar)
- Highest possible accuracy, proven with on-orbit SI traceability
- Unbiased diurnal sampling and complete global coverage using specialized orbits
- Consistent spectral coverage among platforms
- System designed for affordability, allowing continuation of benchmark for many decades
- Synergistic combination of measurements with SI-traceable data sets: e.g. Spectrally resolved IR radiance, GPS, & solar radiance
Example of IR & GPS synergy for CLARREO using CM2 20-yr IR Trend Contributors
Yi Huang thesis (Ramaswamy, advisor), 2008


Cancelation of Temperature and Water Vapor Effects
can be easily separated using GPS with IR observations
-valid for CO₂ also
3. High-Level CLARREO Requirements

Examples consistent with candidate NRC benchmark climate mission
Flow-Down IR Requirements (1)

- **Spectral Coverage & Resolution:**
  3-50 μm or 200-3000 cm\(^{-1}\) with \(\Delta \nu = 0.5\) cm\(^{-1}\)
  (includes Far IR to capture most of the information content and emitted energy)
Flow-Down IR Requirements (2)

• **Spatial Footprint & Angular Sampling:**
  Order 100 km or less, nadir only
  (no strong sensitivity to footprint size, nadir only captures information content)

• **Temporal Resolution and Sampling:**
  < 15 sec resolution and < 15 sec intervals
  (adequate to reduce sampling errors and noise)

Not trying to compete with sounders—
that role for weather and climate is being done very well—
Filling a need to further reduce overall biases to get
decadal trends as soon as possible
CLARREO from AIRS, 2006, 13.5 km footprints

Annual Mean of 11 µm Brightness Temperature

Std. Dev. of 11µm Brightness Temperature

2º x 2º bins
CLARREO from AIRS, 2006, 13.5 & 100 km footprints

100 km

13.5 km

Std. Dev. of 11μm Brightness Temperature

2° x 2° bins
2006 Annual
911 cm⁻¹, window
10°x15° bins

Mean

Average Brightness Temperature for wavenumber=911.24

13.5 km FOV

Standard Deviation

India
2006 Annual
911 cm\(^{-1}\), window
10°x15° bins

Average Brightness Temperature for wavenumber=911.24

100 km FOV

Mean

Standard Deviation

Climate Content Preserved
2006 Annual
911 cm\(^{-1}\), window
10\(^\circ\)x15\(^\circ\) bins

Mean

Average Brightness Temperature for wavenumber=911.24

Standard Deviation

Africa: West Central

13.5 km FOV
2006 Annual
911 cm\(^{-1}\), window
10°x15° bins

Mean

Standard Deviation

Africa: West Central

Climate Content Preserved
2006 Annual
911 cm⁻¹, window
10°x15° bins

13.5 km FOV

Mean

Standard Deviation

Florida
2006 Annual
911 cm\(^{-1}\), window
10ºx15º bins

Average Brightness Temperature for wavenumber=911.24

100 km FOV

Florida

Climate Content Preserved
CLARREO does not need cloud clearing—already done well by high resolution sounders for understanding processes.
CM2 Annual Mean Spectral 25-yr Trend
Yi Huang thesis (Ramaswamy, advisor), 2008

a). cl-r-sky Global ocean annual mean radiance change

b). all-sky Global ocean annual mean radiance change

Black dots indicate changes > 3 x standard deviation of unforced means
Flow-Down IR Requirements (3)

- **Orbits:** Configuration of 3 90° inclination orbits spaced 60° apart is best current option (to minimize sampling biases that RSS with measurement uncertainty & achieve global coverage with nadir only views)
CLARREO from AIRS, 2006, 13.5 km footprints

Annual Mean of 11 µm Brightness Temperature

Std. Dev. of 11 µm Brightness Temperature

2° x 2° bins
Flow-Down IR Requirements (4)

• **Validation, On-orbit:**
  Variable-temperature Standard Blackbody, with on-orbit absolute T calibration and reflectivity measurement (to maintain SI measurements on orbit)
A New Class of Advanced Accuracy Satellite Instrumentation for CLARREO

Viewing configuration providing immunity to polarization effects.

see Best talk: UW / Harvard IIP, Wednesday

New Developments
Flow-Down IR Requirements (5)

• Cross-Calibration with other systems:
  Calibration assessment and improvement of other observations at close to CLARREO accuracy

see Tobin, Holz talk, Thursday
Summary

- A new spaceflight system optimized to benchmark the climate of the earth and establish longterm trends is urgently needed.
- The CLARREO approach evokes new paradigms to define such a system.
- Unbiased sampling strategy is a key part of CLARREO overall accuracy.
- Existing high spectral resolution IR instruments demonstrate the technical readiness to proceed with major components of CLARREO very expeditiously.
- One key is an on-orbit calibration validation reference source, and an exciting new approach for on-orbit temperature calibration is now available for assuring the accuracy of that reference.
CLARREO type Benchmark Record
from CM2 Annual Mean Spectral 25-yr Trend
Yi Huang thesis (Ramaswamy, advisor), 2008

CLARREO could have captured this benchmark record.
Let’s make sure we start as soon as possible!