CLARREO Infrared Instrument Suite
CLARREO RO Instrument Suite

CLARREO IR Instrument Team
CLARREO RO Instrument Team

Presenting: Marty Mlynczak

May 17 2011
Level 2 IR Instrument Requirements

• Spectral Range: 200 to 2000 cm\(^{-1}\) (2760 cm\(^{-1}\) goal)
  – Rationale:
    ▪ Spectral Range for Climate Benchmark and Fingerprinting
    ▪ Spectral Range for Reference Intercalibration of Longwave Broadband Sensors (CERES; GERB; Megha-Tropiques)

• Spectral Resolution: 0.5 cm\(^{-1}\) unapodized
  – Rationale:
    ▪ Ability to resolve effects of temperature and water vapor as functions of altitude

• Systematic Uncertainty: 0.100 Kelvin (coverage factor k=3)
  – Rationale:
    ▪ Driven by interannual variability of IR spectra

• IFOV: No less than 25 km
  – Rationale:
    ▪ Enables climate record, reference intercalibration

• Ground Sampling: One calibrated spectrum every 200 km or less
  – Rationale:
    ▪ Nyquist samples the autocorrelation length of the radiation field
Far-IR and natural variability are significant
IR Concept Consists of Electro-Optical and Calibration-Verification Modules

Verification System Enables on-Orbit SI Traceability
Verification System Provides SI Traceability

• Maintaining SI traceability requires quantifying errors and verifying accuracy on orbit
• This requirement is partially met through traditional methods:
  • Frequent views of ambient blackbody and deep space for radiance calibration and estimates of instrument drift
  • Multiple temperature sensors used to detect and correct for changes in offset
  • Detector nonlinearity characterized during preflight calibration
• Requirement fully satisfied by using on-orbit verification system to:
  • Quantify sources of bias that affect calibration accuracy
    • Polarization effects
    • Instrument line shape
  • Verify accuracy through measurements of a known source
    • Variable temperature blackbody that is not used for instrument calibration

SI Traceability: Unbroken chain of comparison with stated uncertainties
On-Orbit Calibration of the Verification BB

SI (Kelvin)-Based IR Radiance Scale Realization

\[ L_{BB}(\nu, T_{BB}) = \varepsilon_{BB}(\nu) \times \frac{2h\nu^3}{c^2} \times \frac{1}{(e^{(h\nu/kT_{BB})} - 1)} \]

**Planck Equation**

Emissivity

Temperature

Cavity Emissivity Measurement

Quantum Cascade Laser (QCL)

Heated Baffle

3 Phase Change Cells
Provide SI Traceable Fixed Points (-40°C, 0°C, 30°C)

Phase Change Cells

On-orbit, SI traceable measurements of temperature and emissivity
Meeting Level 1 Requirements

SI Traceability: Unbroken chain of comparisons with stated uncertainties

Estimated $k=3$ uncertainties at 1000 cm$^{-1}$ for scene temperature of 250K, with calibration BB at 270K

Combined Type B Uncertainty 54 mK

Calibration Blackbody Radiance 31 mK

Space View Radiance < 1 mK

Gain Nonlinearity 29 mK

FTS Uncertainty Terms 33 mK

Total Combined Uncertainty 54 mK

Annual Type A Uncertainty < 1 mK

IR Level 1 Requirement 100 mK, $k=3$

Modeling work to date shows ability to meet level 1 & level 2 requirements
Technology Development Plan Leverages Hardware Matured Through Breadboard and IIP Programs
IR Instrument Suite

- Metrology Laser Radiator
- QCL Radiator
- IR Instrument Mount
- IR FTS Scan Mechanism
- IR Scene Select Assembly
- IR Bench Radiator
- Cryo-Cooler Radiator
- Blackbody Radiator
- Cryo-Cooler
- Far IR Detector Optical Assembly
- Mid IR Detector Optical Assembly
- IR Instrument Mount
- Verification Assembly
## Infrared Instrument Comparison

<table>
<thead>
<tr>
<th>Class</th>
<th>Instrument</th>
<th>Mass (kg)</th>
<th>Pwr (W)</th>
<th>Vol (m³)</th>
<th>Spectral Band (µm)</th>
<th>Spectral Rsln (cm⁻¹)</th>
<th>Absolute Accuracy (K)</th>
<th>IFOV (km); Swath Width (km)</th>
<th>Detector Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Explorer</td>
<td>Voyager IRIS</td>
<td>18</td>
<td>14</td>
<td></td>
<td>4-55</td>
<td>4.3</td>
<td>0.4-1.7</td>
<td>N/A</td>
<td>Single element</td>
</tr>
<tr>
<td></td>
<td>CIRS</td>
<td>39</td>
<td>33</td>
<td>0.35</td>
<td>7-1000</td>
<td>0.5 - 20</td>
<td>1.9-6.2</td>
<td>N/A</td>
<td>2 FIR detectors; 2 1x10 MIR arrays</td>
</tr>
<tr>
<td></td>
<td>ACE</td>
<td>41</td>
<td>37</td>
<td>0.17</td>
<td>2.3-13.3</td>
<td>0.02-1.0</td>
<td></td>
<td>Solar occult</td>
<td>Two single-element</td>
</tr>
<tr>
<td></td>
<td>CLARREO IR Suite*</td>
<td>76</td>
<td>124</td>
<td>0.28</td>
<td>5 – 50</td>
<td>0.5</td>
<td>0.1 K (k=3)</td>
<td>25 nadir only</td>
<td>Three single-element</td>
</tr>
<tr>
<td></td>
<td>CrIS</td>
<td>165</td>
<td>123</td>
<td>0.60</td>
<td>4 – 15</td>
<td>0.62-2.5</td>
<td>0.3 K</td>
<td>14 +/- 1000</td>
<td>Three 3x3 arrays</td>
</tr>
<tr>
<td>Sounders</td>
<td>AIRS (Grating)</td>
<td>177</td>
<td>220</td>
<td>1.75</td>
<td>4 – 15</td>
<td>0.5-2.5</td>
<td>0.3 K</td>
<td>13.5 +/- 900</td>
<td>2378 element array</td>
</tr>
<tr>
<td></td>
<td>IASI</td>
<td>236</td>
<td>210</td>
<td>1.71</td>
<td>4 – 15</td>
<td>0.25</td>
<td>0.5 K</td>
<td>12 +/- 1000</td>
<td>Three 2x2 arrays</td>
</tr>
</tbody>
</table>

*CLARREO is verified on-orbit to SI standards*
IR Suite Accommodations

<table>
<thead>
<tr>
<th>Mass</th>
<th>Avg. Power</th>
<th>Peak Power</th>
<th>Data Rate</th>
<th>Data Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>76 kg</td>
<td>124 W</td>
<td>233 W</td>
<td>228 kb/sec</td>
<td>20 Gb/day</td>
</tr>
</tbody>
</table>

NOTES:
(1) “Ram” and “Wake” are relative terms due to the biannual yaw flips.
(2) “IR Zenith” and “IR Nadir” ROR accounts for ±5° pointing needed for motion compensation in zenith and nadir views.

IR Suite Fields-of-Regard

IR Zenith
Parallel to S/C -Z
±6.2° in S/C XZ plane
±1.2° in S/C YZ plane

IR Off-Zenith
±1.2° cone angle
Centered 45° with respect to “IR Zenith” in S/C XZ plane

IR Nadir
Parallel to S/C +Z
±6.2° in S/C XZ plane
±1.2° in S/C YZ plane

S/C -X (Wake)
S/C -Z (Zenith)
S/C +X (Ram)
S/C +Z (Nadir)
Ongoing Pre-Phase A Activities

• Developing IR Calibration Demonstration System (CDS)
  – Validate instrument model
  – Demonstrate required measurement accuracy

• Technology development
  – Complete IIPs (AASI, CORSAIR)
  – Compare UW Breadboard, CDS (strongly desired; seeking funding)
Summary

• IR Instrument Suite Concept meets the science objectives and is feasible
  – Infrared Fourier transform spectrometer
  – Calibration methodology (preflight and on orbit)
  – Verification system

• Instrument design concept is viable
  – Uncertainty budget is defined
  – Key trade studies have been completed

• Plans to continue assessment of calibration systems
  – Complete the IIPs
  – Complete the CDS
GNSS – RO Instrument Summary

Thanks to the TriG Team at JPL for the status update!
GNSS-RO Requirements

Level 1 Science Requirements

Baseline Accurate and Traceable
• Observations shall have their accuracy uncertainty traceable to SI standards

Atmospheric Refractivity Baseline Science Measurement
• Spatial and temporal sampling sufficient to provide global coverage and to reduce sampling biases
• Changes in annual means of refractivity with an uncertainty of 0.03% (k=1, over 90% TBR of the zones) for 5-20 km altitude

Draft Level 2 GNSS-RO Measurement Requirements

• Phase Delay Rate Uncertainty: \( \leq 0.5 \text{ mm/s (from all error sources)} \)
  \textit{Required to achieve 0.03\% refractivity uncertainty}

• Sampling Density: \( 1000 \text{ occultations/day} \)
  \textit{Required to achieve 0.03\% refractivity uncertainty}
GNSS-RO Instrument Accommodations

<table>
<thead>
<tr>
<th>Mass</th>
<th>Avg. Power</th>
<th>Peak Power</th>
<th>Data Rate</th>
<th>Data Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 kg</td>
<td>35 W</td>
<td>40 W</td>
<td>119 kb/sec</td>
<td>10 Gb/day</td>
</tr>
</tbody>
</table>

GNSS-RO Antenna Fields-of-View
GNSS-RO Preliminary Error Budget

**Troposphere (5-20km)**
Testing that requirements are met for this region to be done at 18km.

<table>
<thead>
<tr>
<th>Phase rate error (mm/s)</th>
<th>Refractivity error (%)</th>
</tr>
</thead>
</table>

**Measurement Requirement A: Individual Sounding**

**Systematic**
- Retrieval Non-Linearity: 0.000, 0.0000%
- RO antenna phase center determination: 0.021, 0.0007%
- Atmospheric multipath: 0.000, 0.0000%
- Ionospheric residual: 0.300, 0.0100%
- LEO POD: 0.054, 0.0018%
- Clock accuracy: 0.030, 0.0010%
- Attitude knowledge: 0.024, 0.0008%
- Attitude rate knowledge: 0.150, 0.0050%
- Local multi-path: 0.240, 0.0080%
- **Total**: 0.418, 0.0139%

**Random**
- Instrument precision: 0.240, 0.0080%
- Ionospheric scintillation: 0.060, 0.0020%
- Gravity waves: 0.090, 0.0030%
- Clock precision: 0.099, 0.0033%
- **Total**: 0.281, 0.0094%

**Measurement Requirement B: Climatological Averaging**

**Systematic**
- Diurnal cycle: n/a, 0.0100%
- **Total**: n/a, 0.0100%

**Random**
- Sampling density: n/a, 0.0220%
- **Total**: n/a, 0.0220%

**Total systematic error (target)** 0.0170%
**Total systematic error** 0.0172%
**Total random error (target)** 0.0250%
**Total random error** 0.0239%
**Total error** 0.504, 0.0294%
**Requirements** 0.5, 0.03%

Error Budget Successfully Peer Reviewed by RO Community Experts

Mission Concept Review
JPL TriG Receiver

- Currently under development for Decadal Survey and COSMIC-2 missions
- Leverages previous GNSS-RO receivers
  - Provides capability to track signals of future GNSS constellations
  - Has improved radiation hardening
- Development schedule supports CLARREO
  - Engineering Models will be completed six months prior to CLARREO’s GNSS-RO Instrument SRR

### TriG Compatibility

<table>
<thead>
<tr>
<th>CLARREO Requirement</th>
<th>TriG Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track GPS and Galileo</td>
<td>GPS, Galileo, GLONASS</td>
</tr>
<tr>
<td>TID ~ 15 kRad</td>
<td>&gt; 40 kRad</td>
</tr>
<tr>
<td>Sample Rate=100 Hz</td>
<td>Sample Rate=100 Hz</td>
</tr>
<tr>
<td>Vertical Resolution=200 m</td>
<td>Vertical Resolution=100 m</td>
</tr>
<tr>
<td>Track 6 POD Satellites</td>
<td>Tracks 10 POD Satellites</td>
</tr>
<tr>
<td>Track 4 RO Satellites</td>
<td>Tracks up to 6 RO satellites</td>
</tr>
<tr>
<td>1553B or RS-422 Interface</td>
<td>RS-422 Interface</td>
</tr>
</tbody>
</table>
TriG Developments Since CLARREO MCR

Date: May 13, 2011

Jeff Tien, TriG Delivery Manager
Anthony J. Mannucci, RO Formulation
Jet Propulsion Laboratory, California Institute of Technology
TriG GNSS Receiver

Product: Engineering Model GNSS Science Receiver

**Key Applications:**
- Radio Occultation (RO)
- Precise Orbit Determination (POD)

- Designed to meet known/expected CLARREO requirements

**Customers:**
- COSMIC II (NOAA), Grace F/O, ICESat II, SWOT and missions of opportunity

13 May 2011
Recent Accomplishments

- Completed Preliminary Design Review (Dec 2011)
  - Key finding: Design is compliant with program requirements

- Completed preliminary design of the TriG EM Hardware

- Currently focusing on completing development in areas with highest technical risk:
  - Navigation and Science Processor Cards
  - RF Downconverter (RFDC) and Clock Distribution Card

- Completed radiation test on key RFIC (radio frequency front-end integrated circuit)

- Industrial partner (BroadReach Engineering) is currently on startup contract

TriG GNSS Receiver
• The GNSS-RO instrument concept meets the science requirements
  – Draft Level 2 measurements requirements have been derived
  – Preliminary error budget has guided the instrument design concept

• The GNSS-RO instrument concept is feasible
  – Radio occultation is a mature measurement technique that has been used since 1995 on numerous space missions
  – Technical searches have been conducted to determine the GNSS-RO state-of-the-art and to identify potential instrument suppliers

• GNSS-RO technology development (TriG) is proceeding
Backups
IR Level 1 Requirements

• **Accurate and Traceable:**
  – CLARREO shall make observations with verifiable on-orbit accuracy sufficient to resolve decadal change and to survive gaps in data sets;

  – Observations shall have their calibration traceable to SI standards in order to allow comparison with future measurements even if data gaps occur.

• **Infrared Science Measurement:** CLARREO shall obtain infrared radiance spectra of the Earth using nadir views from orbiting satellites. Establishing a climate benchmark and providing a reference for satellite intercalibration requires:
  – Broad spectral coverage of the earth emitted spectrum to quantify trends in climate state variables including temperature, atmospheric structure, composition, clouds, and surface properties;

  – Spectral resolution sufficient to resolve contributions from individual greenhouse gas species and to provide vertical structure information;

  – Radiance measurement bias that corresponds to < 0.1 K uncertainty in brightness temperature (k=3) for the range of expected earth scene temperatures and wavelengths relevant to climate.