



Progression of NASA's Climate Absolute Radiance & Refractivity Observatory (CLARREO) Mission

AGU

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- **The Climate Observing Challenge**
- **Critical Problems CLARREO Helps Solve**
- **Evolution of the Mission Architecture**
 - ✓ *Mission Concept Review (2010)*
 - ✓ *International Space Station Concept (2013)*
 - ✓ *Smaller Mission Class Concept (2014)*
- **Contributions of the Science Definition Team – Science Value**
- **Next steps**



The Climate Observing Challenge

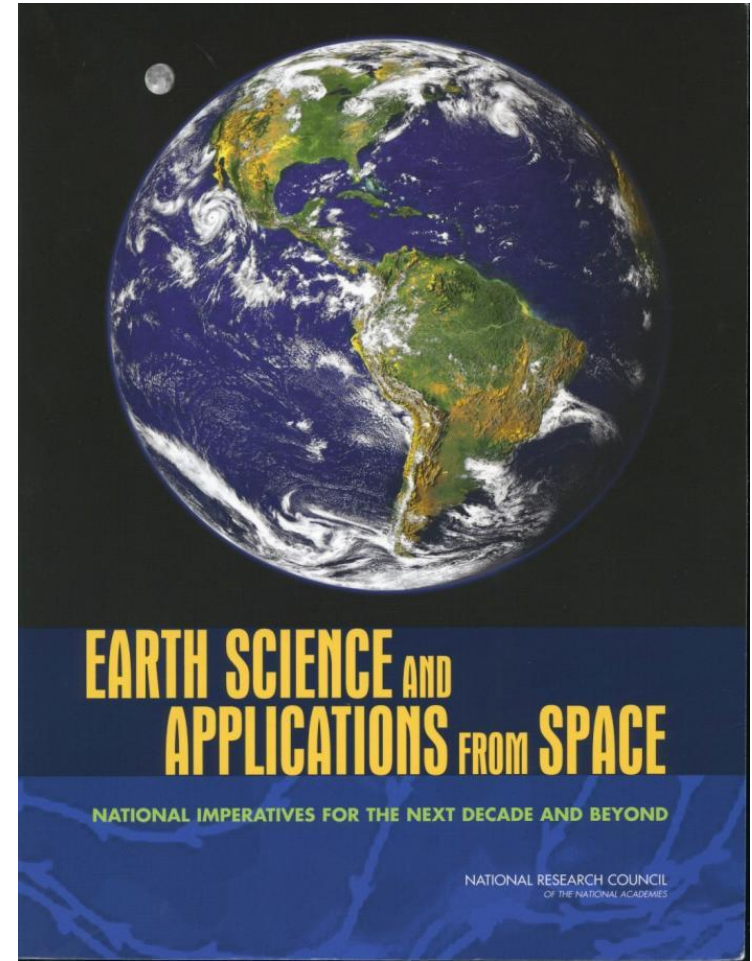


- “Global climate change presents us with a complex and inextricably-linked mix of environmental, economic, security, and political issues for all nations on the planet. It is a long-term, century-to-millennial problem, the outcomes of which directly depend on the soundness of decisions being made today.” (OSTP-USGEO Report on Earth Observations 2010)
- Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. (IPCC Climate Change Report 2014)
- Observations must be sustained into the future to evaluate how the climate is changing so that informed decisions can be made on prevention, mitigation, and adaptation strategies. (Global Observing System for Climate in Support of the UNFCCC 2010)
- Gaps in our ability to observe these changes will lead to deficiencies in our understanding and our ability to develop an effective response.



CLARREO = Climate Absolute Radiance and Refractivity Observatory

- CLARREO was recommended as a top priority for NASA by the National Academy of Science
 - The 2007 Decadal Survey concluded that the single most critical issue for current climate change observations was their **lack of accuracy** and low confidence in observing the **small climate change signals** over long decade time scales.



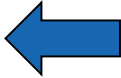
Science Impact: Critical Problems CLARREO Solves



- **Improve assessment of climate predictions for public policy**
 - CLARREO will measure solar reflected and infrared emitted high spectral resolution benchmark radiance climate data records that can be used to test climate model predictions, improve climate change fingerprinting, and attribution
- **Provide climate-accuracy calibration for operational sensors**
 - An orbiting calibration observatory that can be used to calibrate other solar and infrared space-borne sensors and thereby improve climate accuracy of a wide range of sensor measurements across the Earth observing system
- **Dramatically reduce the effects of data gaps**
 - The absolute accuracy of CLARREO, when used to calibrate other sensors in orbit can dramatically reduce the impact of data gaps on decadal change data records across many climate variables
- **Provide the first space-based measurements of the Earth's far infrared spectrum**
 - Opens a new window to 50% of Earth's IR spectrum with key information on water vapor feedback, cirrus radiative forcing, and the natural greenhouse effect



CLARREO's contributions to the climate observing system

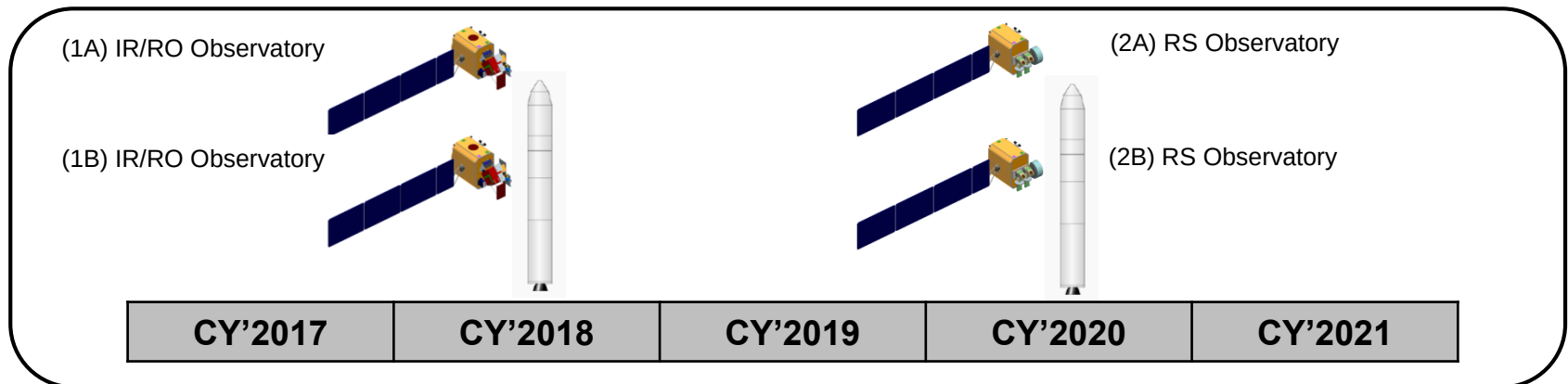
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Mission Concept Review (2010)

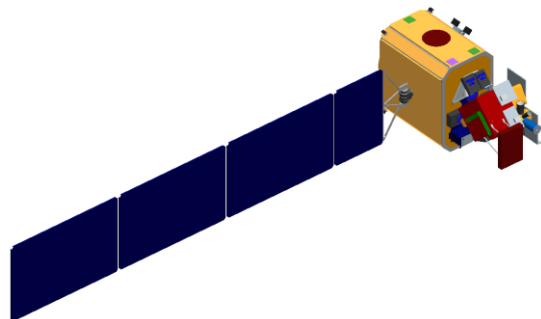


- Three instruments (two copies of each)
 - Infrared (IR) Spectrometer
 - Reflected Solar (RS) Spectrometer
 - Global Navigation Satellite System-Radio Occultation (GNSS-RO)
- Four observatories, two dual-manifested launches
 - July 2018: Two Infrared (IR) Observatories, each with GNSS-RO
 - May 2020: Two Reflected Solar (RS) Observatories
- 609 km polar orbits (90° inclination)



Flexible mission architecture defined

Infrared Observatory



**Infrared (IR)
Instrument**

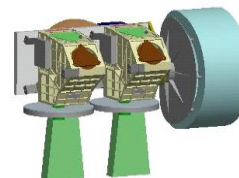
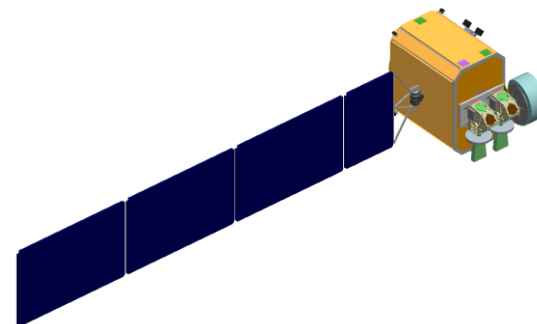
- FTS
- CBE Mass: 76 kg
- CBE OA Power: 124 W
- Data Rate: 228 kbps
- Data Volume: 20 Gb/day



**GNSS-RO
Instrument**

- GNSS Receiver / Antennas
- CBE Mass: 18 kg
- CBE OA Power: 35 W
- Data Rate: 119 kbps
- Data Volume: 10 Gb/day

Reflected Solar Observatory



**Reflected Solar (RS)
Instrument**

- Two Grating Spectrometers
- CBE Mass: 69 kg
- CBE OA Power: 96 W
- Data Rate: 0.4 to 72 Mbps
- Data Volume: 69 Gb/day



**Gimbal for RS
Instrument**

- Single-axis of rotation
- CBE Mass: 14 kg
- CBE OA Power: 17 W
- Data Rate: <5 kbps
- Data Volume: 300 Mb/day

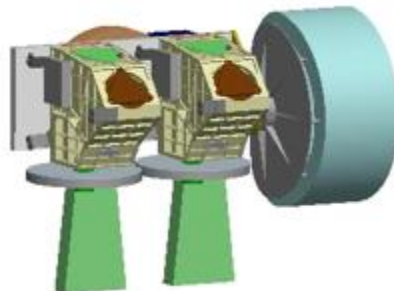




Infrared (IR) Instrument

Fourier Transform Spectrometer

- Systematic error less than 0.1K ($k=3$)
- 200 – 2000 cm^{-1} contiguous spectral coverage
- 0.5 cm^{-1} unapodized spectral resolution
- 25 km nadir fov, 1 earth sample every 200 km
- Mass: 76 Kg
- Power: 124 W



Reflected Solar (RS) Instrument

Two Grating Spectrometers Gimbal-mounted (1-axis)

- Systematic error less than 0.3% ($k=2$) of earth mean reflectance
- 320 – 2300 nm contiguous spectral coverage
- 4 nm sampling, 8 nm res
- 300 m fov, 100 km swath
- Mass: 67 Kg
- Power: 96 W
- Power and Mass are total for both spectrometers



GNSS Radio Occultation Receiver

GNSS Receiver, POD Antenna, RO Antennae

- Refractivity uncertainty 0.03% ($k=1$) for 5 to 20 km altitude range. (Equivalent to 0.1K ($k=3$) for temperature)
- 1000 occultations/day
- Mass: 18 Kg
- Power: 35 W



Calibration verified on-orbit and traceable to international standards

MCR Board Consensus



- The project team successfully demonstrated the need for the CLARREO mission, defined the mission objectives for the proposed mission and presented a feasible mission concept for meeting those objectives within the imposed funding constraints.
- All of the MCR-specific review criteria were satisfied.

The MCR Board believes that the CLARREO project has successfully demonstrated MCR maturity and should be approved to proceed to Phase A. ✓

- And, then in Feb. 2011... the President's budget was released dramatically reducing the funding profile for Earth Science and putting CLARREO in extended Pre-Phase A.



Response to a really bad day



Every strike brings me closer to the next home run. *Babe Ruth*



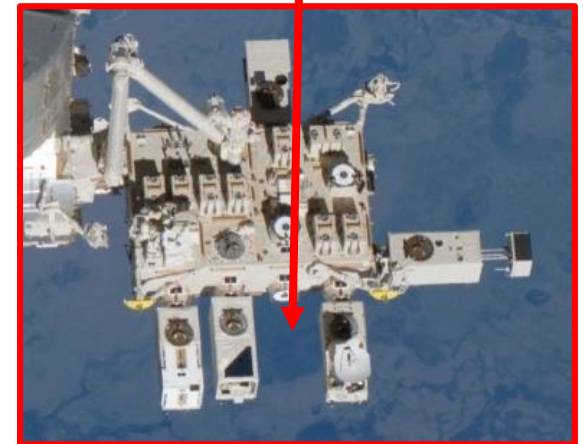
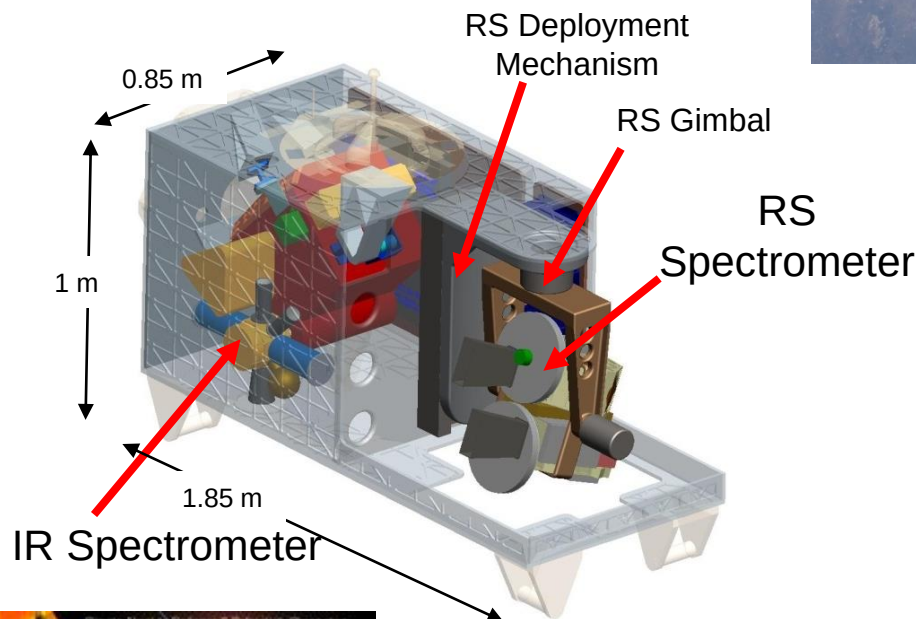
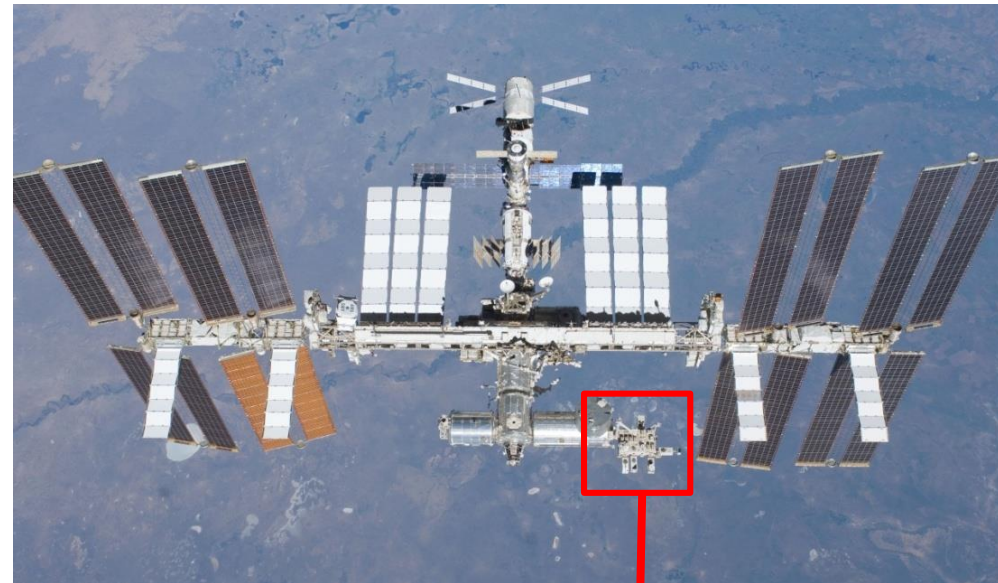
ISS Implementation Options (2013)



Mission Concept Readily Accommodated on the ISS

CLARREO ISS
Concept Design 2013

- Selected the Japanese Experiment Module Exposed Facility (JEM-EF) for this study
 - Other sites viable, but ram-side of JEM-EF is optimal for maximizing viewing opportunities
- Both instruments fit into one box occupying one experiment location

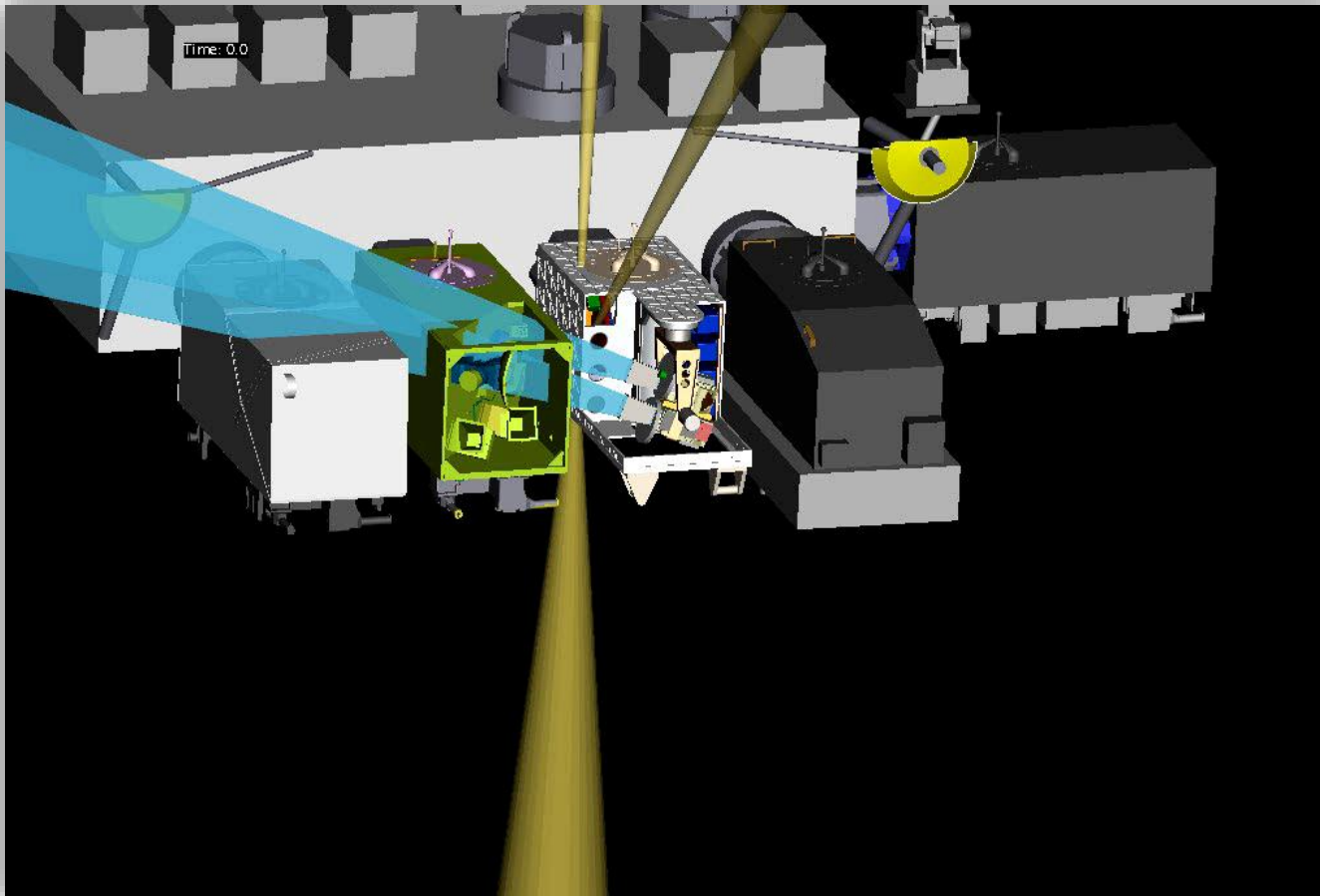


CLARREO-ISS Accommodation Compliance Matrix

CLARREO ISS
Concept Design 2013

	JEM-EF Site Capabilities	CLARREO-ISS Design Summary
Mass	550 kg (standard site)	~453 kg with GFE (~20% margin)
Power	3 kW (standard site)	~250 W (1100% margin)
Thermal	3 kW (fluid cooling loop)	~250 W
Data Rate	1 Mbps (MIL-STD-1553) 10 Mbps (10 Base-T Ethernet) 43 Mbps (Shared-Negotiated) NTSC Video	~640 kbps to ~72 Mbps (Highest rate due to RS during solar calibration requires data buffering at the payload)
Data Volume	Negotiable – Up to 1.5 TB	~90 Gb/day
Volume	0.8 x 1.0 x 1.85 m	Complies (stowed)





Preliminary studies show that the mass, power, volume, and thermal requirements are within a reasonable ISS design space.



Smaller Mission Class Option (2014)



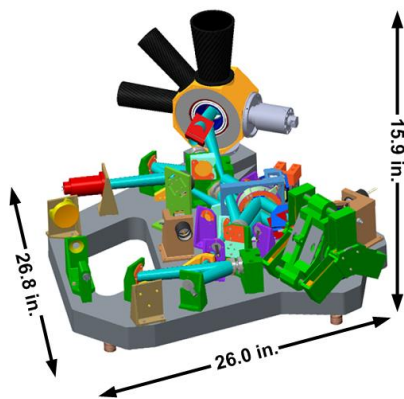
Technical Maturity



- **Earth Venture Solicitations (EV-2 and EVI-1)**
 - CLARREO-like instruments assessed at TRL 6 or higher; Reflected Solar concept received low risk rating
- **RS and IR Calibration Demonstration Breadboards developed and in test.**
 - Successfully demonstrated the measurement approach.
 - incorporated NIST calibration advancements (FY13-14).
- **Concurrent Earth Science Technology Office investments**
 - Successfully matured the required technologies to TRL=6.

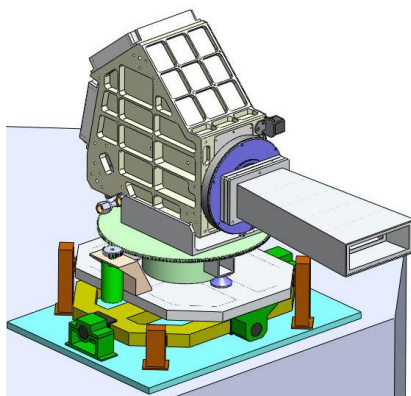


- Focus on smaller, lower cost instrument designs



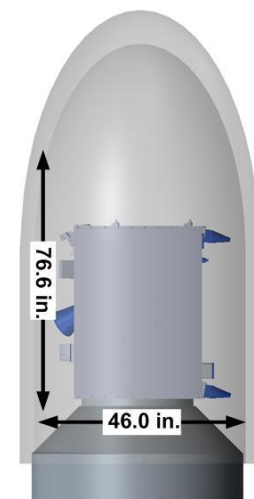
Compact IR Instrument

- Compared to MCR design:
 - Mass reduced from 76 kg to 49 kg CBE, not including payload adapter ring.
 - Power reduced from 124W avg, 233W peak to 75W avg, 100W peak.



One-box approach to RS instrument

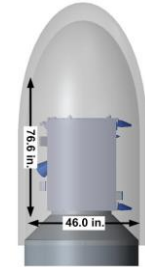
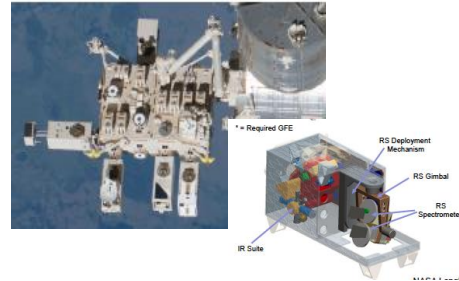
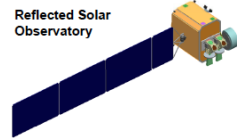
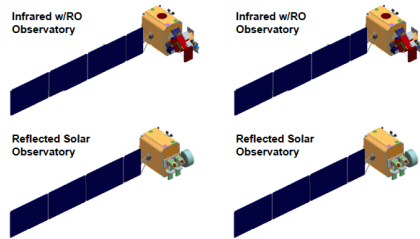
- Compared to MCR design:
 - Instrument mass reduces from 77 kg to 35 kg CBE
 - Power reductions still being evaluated but not expected to change significantly due to data rates and pointing requirements essentially identical as MCR design



IR Instrument
SSTL-150 Bus and
Pegasus Launch Vehicle



CLARREO Alternate Mission Options



MCR Concept
(100% Science)

**\$950M- 1.2B Est.
Total Cost**

**6 instruments,
4 small (or 2 medium
spacecraft),
2 launches**

Baseline

MCR Minimum
Mission Concept
(62% Science)

**~\$675M
+ Launch**

**3 instruments,
1 medium-sized
spacecraft,
1 launch**

**Cost Reduction
~\$325M +
Launch Vehicle**

ISS Mission
Concept
(73% Science)

**~\$400M
Total Cost**

**2 instruments on
ISS, RO is obtained
from COSMIC-2
(LRD 2023)**

**Cost Reduction
~\$600M**

Smaller Mission
Class (Single
Instrument Only)

**~\$200 M
Total Cost**

**Lower cost, smaller
instruments (either
IR or RS).**

**Cost Reduction
~\$800M**

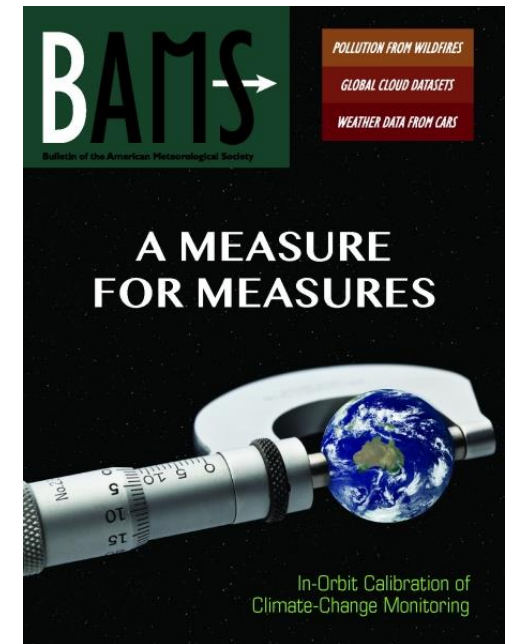
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- **Summary**



Contributions of the Science Definition Team (2011-2014)



- Despite the fact that CLARREO is not on-orbit the SDT is making important contributions to the tools/methods that help us understand and assess climate trends → improve predictions
- 26 journal papers published/in press in 2014. In total, 105 papers (to date) have been included in <https://esdpubs.nasa.gov/>
- Published CLARREO mission paper (20 pgs) as **cover article** in Bulletin of the American Meteorological Society (BAMS, Oct 2013).

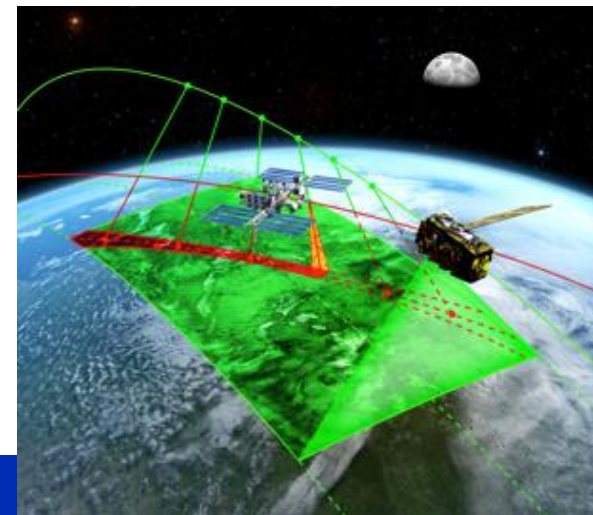


- **Infrared and Reflected Solar Benchmark**

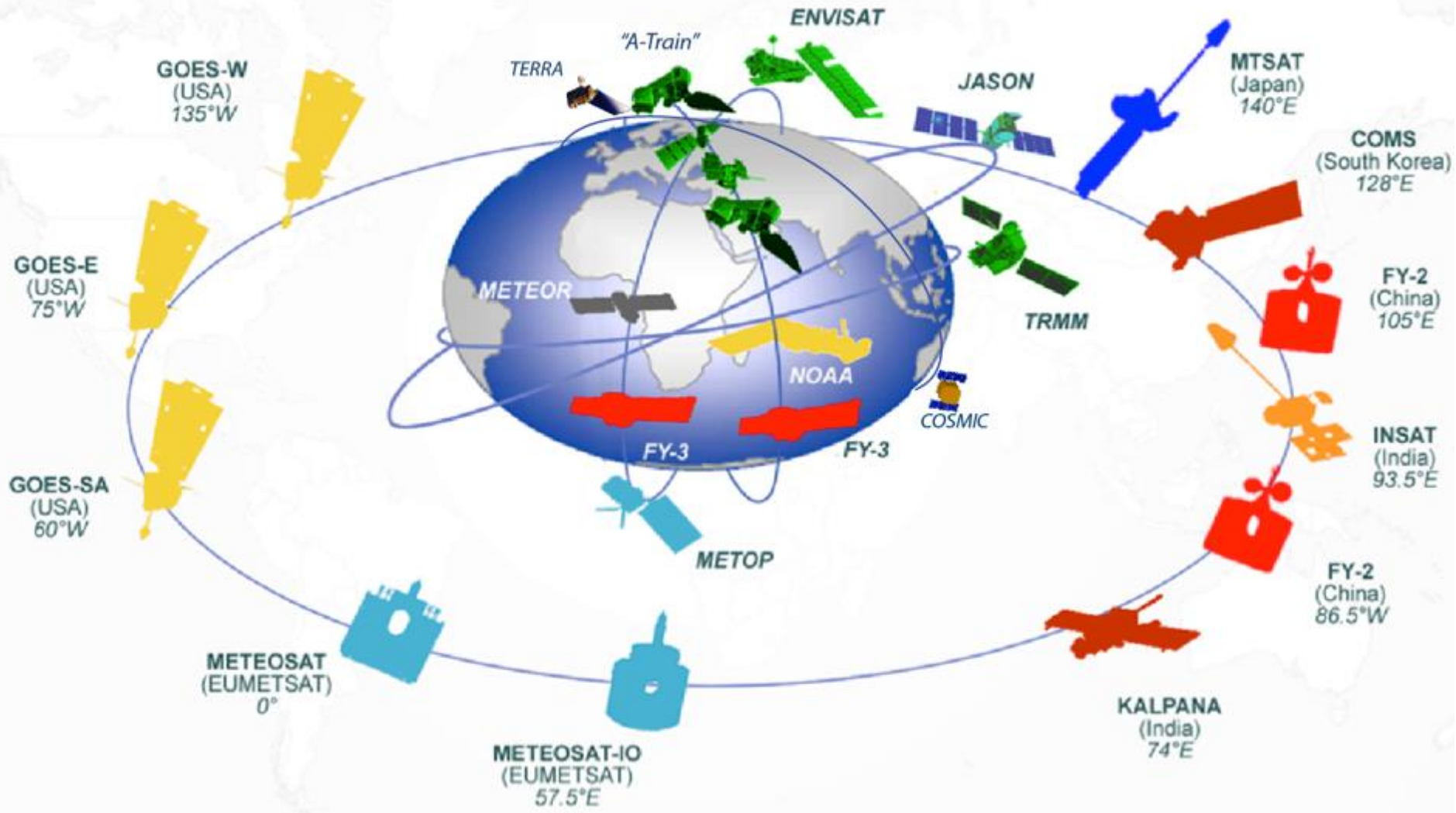
- Developed IR and RS radiometric and spectral calibration methodologies/tools. Applied knowledge to VIIRS, RBI, CrIS, Landsat calibration efforts.
 - *Impact:* Demonstration of first on-orbit SI traceable calibration methods to achieve accuracies 5 to 10x higher than current IR and RS instruments. Put the lunar spectral irradiance on an SI traceable scale with 10 to 20 times the current accuracy of 5 to 10 % (1 sigma). First far-infrared measurements since Nimbus.

- **Reference Intercalibration**

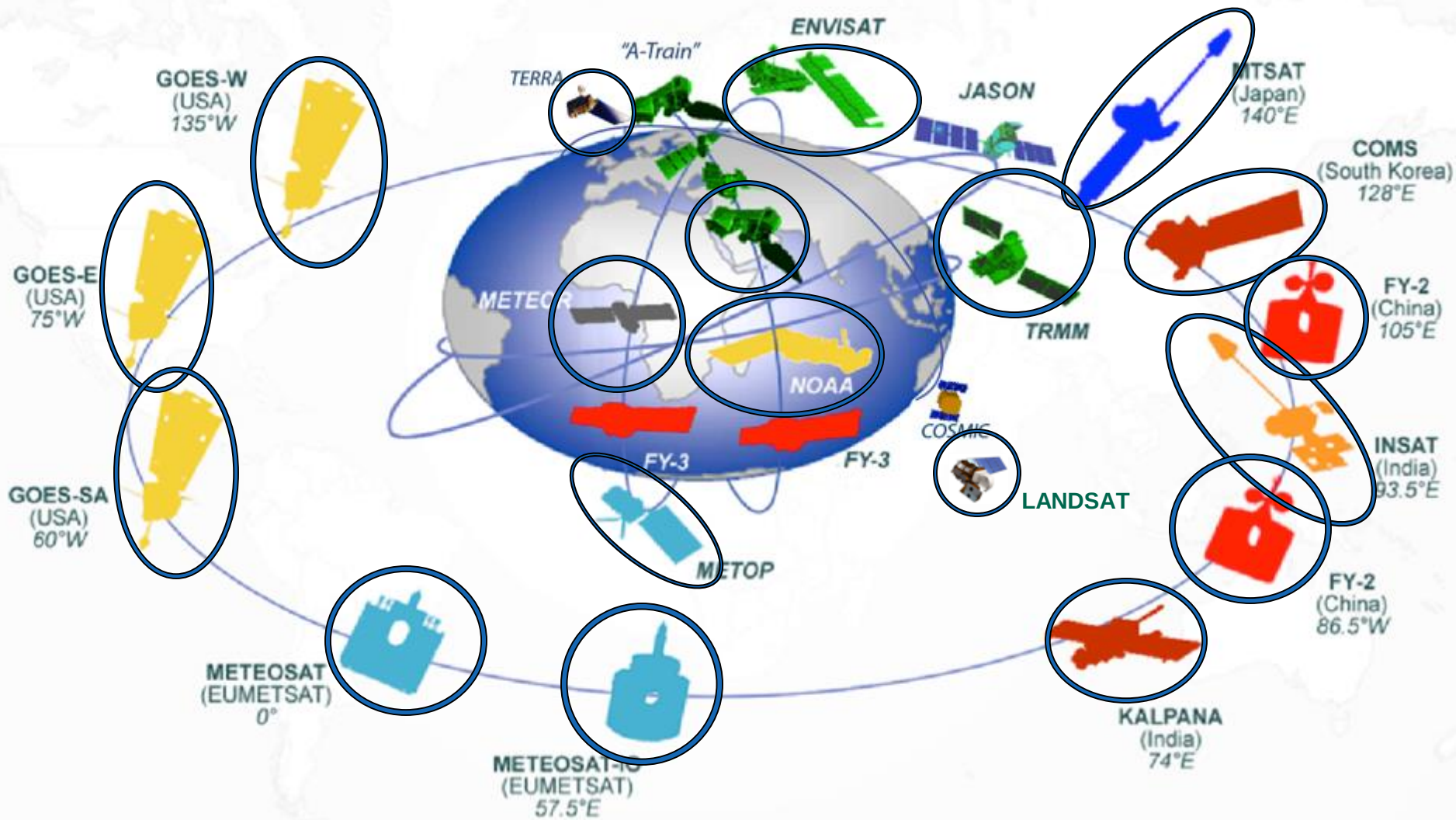
- Provided methodologies to enable CLARREO to tie 30 to 40 Earth viewing sensors in LEO and GEO orbits to higher accuracy standard on-orbit.
- Multi-instrument inter-calibration framework to be deployed at NASA/NOAA.
 - *Impact:* Provide on orbit crossings with NPP, JPSS1, METOP, Terra, Aqua, and geostationary satellites (5 for global coverage). Demonstrate the use of both IR and RS as reference instruments for intercalibration as part of GSICS (Global Space Based Inter-Calibration System).



Global Satellite Observations



Intercalibration to CLARREO for Climate Change Accuracy



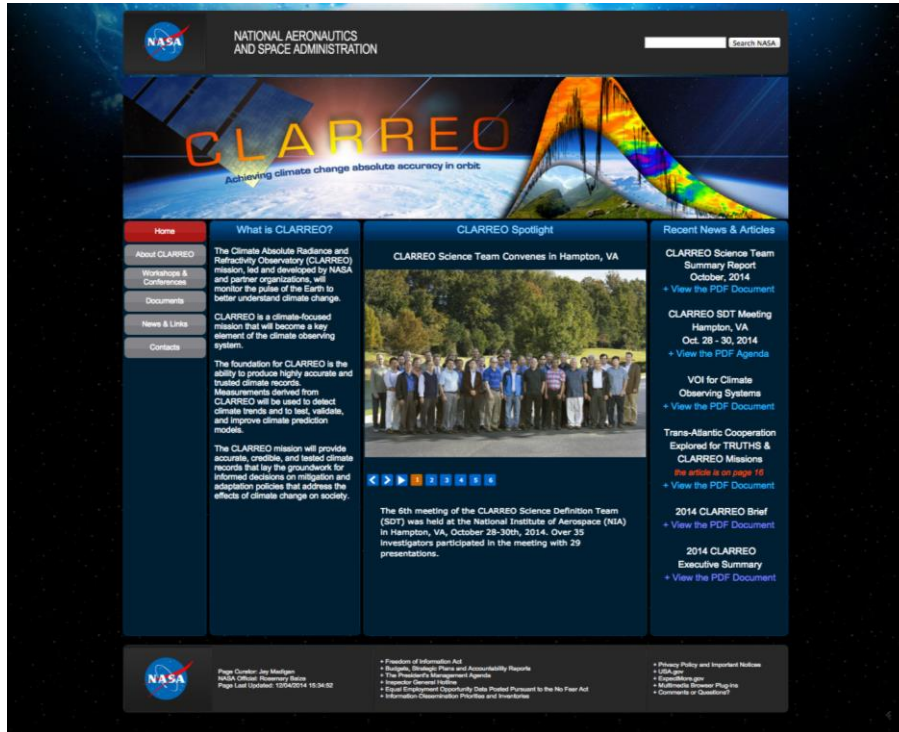
Intercalibration of 30 to 40 instruments in LEO and GEO orbits

- **Observing Systems Simulation Experiments (OSSEs)**
 - Developed first combined IR/RS CLARREO OSSEs (Feldman 2013). Use models as “perfect worlds” for application of CLARREO spectra.
 - Demonstrated CLARREO ability to discriminate between low and high sensitivity climate models, which is critical for climate science (WCRP Grand Challenge #1).
 - *Impact*: Modeling community utilizes CLARREO all-sky radiances for evaluation and assimilation. Sufficient data provide climate model tests.
- **Climate Trend Detection and Attribution**
 - Tested LW and SW Spectral Fingerprinting with real world and simulated observations
 - Retrieved atmospheric changes from hyperspectral data using Principal Component Radiative Transfer Modeling (25-30x speedup versus Modtran). Enabled larger number of simulations for examining signatures of climate change.
 - Goal: To find the spectral kernels that best represent the true radiative response in nature and use it to attribute changes seen in the observational data. Good correlations with CERES/MODIS and Sciamachy data sets.
 - *Impact*: Retrieve atmospheric changes from CLARREO hyperspectral datasets.



Would you like to learn more about CLARREO

Get online:



CLARREO Website:



Talk to
CLARREO team



Visit the CLARREO website:
<http://clarreo.larc.nasa.gov/>

Thank You!

December 17, 2014

- Back-up



Scientific Value of Mission Concept



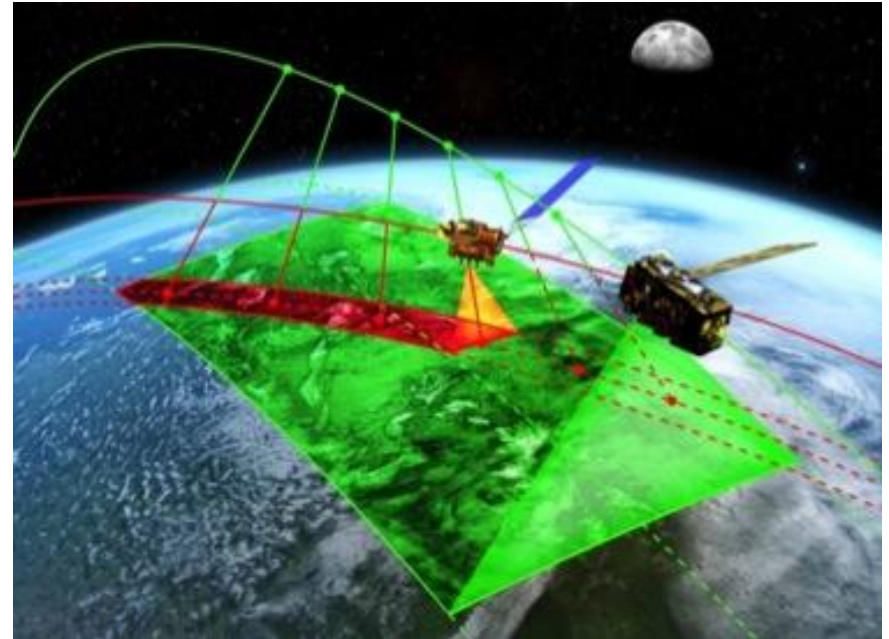
- Increases accuracy of climate observing system through reference intercalibration
 - The absolute accuracy reduces the need for overlap between successive instruments
- Reduces levels of uncertainty in climate change projections (15-20 years earlier)
- Lower cost implementation option may lead to initiating the climate record sooner
- Follow-on missions could continue the data record from free-flyers in different inclinations and altitudes (i.e., not locked in to ISS for follow-on)
- Provides spectral measurements in the far-IR, a region of the spectrum that has been largely unobserved from space
- Large number of SDT peer-reviewed journal publications: 72 papers posted to date (<https://esdpubs.nasa.gov/>)
- Developed methodology broadly applicable to understanding the economic value of climate science (http://clarreo.larc.nasa.gov/pdf/articles/VOI-ForClimateObservingSystems_Springer.pdf)
- Letters of support GSCIS, WMO, GCOS



CLARREO - Overview

Science Value:

- **Climate Benchmark** (*Decadal Survey Tier 1 mission*): Fills the critical need for unambiguous climate change measurements with a high level of accuracy (improved by factors of 5 to 10).
- Used to detect climate trends and to test, validate, and improve climate prediction models.
- **Standard for Intercalibration**: Provides a metrology laboratory in orbit for the purpose of accurately quantifying/attributing climate change.
- Benchmark for GSICS to tie 30 to 40 Earth viewing sensors in LEO and GEO orbits to a higher accuracy.
- **Discovery Science**: Provides the first spectral observations of Earth's far-infrared, which includes 50% of Earth's energy emitted to space.



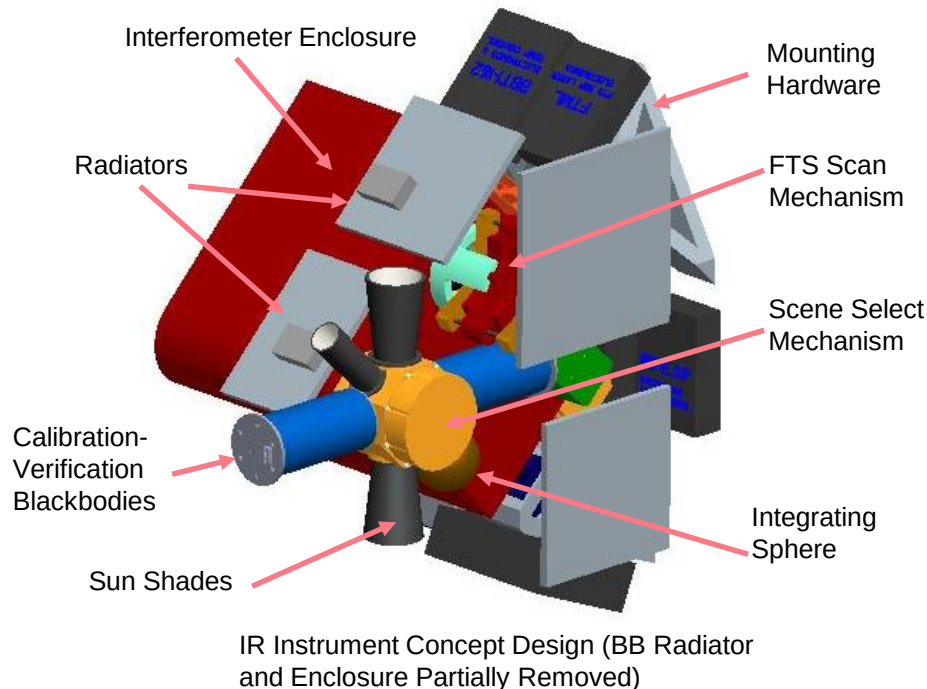
Study Status:

- Passed Mission Concept Review in Nov 2010. Currently in pre-phase A.
- Advanced measurement design maturity (all components now TRL 6) and incorporated NIST calibration approaches (FY13-14).
- CLARREO RS and IR payloads compatible with ISS hosting (FY13).
- Focus on lower cost, smaller instruments with ability to achieve required accuracy on-orbit (FY14).

Teaming:

- Project Team: LaRC, GSFC, JPL. Competitively selected SDT (7 Universities + NASA + International partners)
- Government Partners: NIST, NOAA
- UK NPL, Imperial College, NCEO
- WMO GSICS

IR Suite Overview



Baseline Instrument Package:

- *FTS, calibration-verification system, thermal management hardware, support structure, and electronics*
 - Mass: ~76 kg
 - Power: ~124 W
- *Instrument Dimension: ~88x70x80 cm³*
- *Data Rate: ~228 kb/sec*
- *Data Volume: ~20 Gb/day*

Instrument Description:

- *A Fourier Transform Spectrometer (FTS) for SI traceable measurements of the Mid and Far-IR spectrum of the Earth and atmosphere*
- *Utilizes one ambient black body, one phase-change black body, and deep space as on-orbit calibration sources accessible with a scene select mechanism which is also utilized for spacecraft motion compensation*
- *Uncooled pyroelectric detector for the Far-IR*
- *Two-actively cryocooled HgCdTe (MCT) detectors for the Mid-IR*

Characteristics:

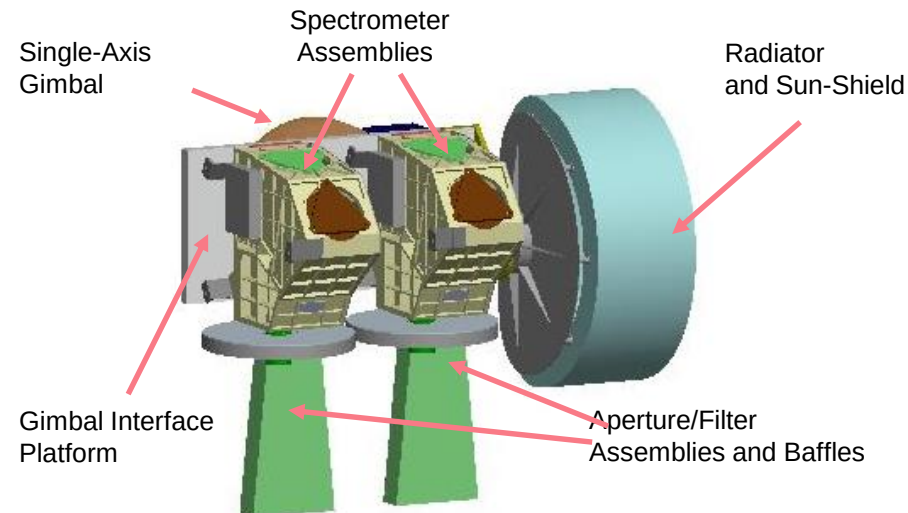
- *Radiance Scale Accuracy: 0.1 K 3 σ*
- *Spectral Range:*
 - ~ 5-50 μm (200-2000 cm^{-1})
- *Unapodized Resolution: 0.5 cm^{-1}*
- *Detectors:*
 - MCT #1: ~3 to 9 μm (1111-3333 cm^{-1})
 - MCT #2: ~8 to 16.5 μm (606-1250 cm^{-1})
 - Pyroelectric: ~15 to 50 μm (200-667 cm^{-1})
- *Footprint: ~25 km from 609 km*
- *Integration Period: ~ 8 seconds*

5/12/2014



NASA LaRC

Reflected Solar Suite Overview



Reflected Solar Suite Design Concept

Baseline Instrument Package:

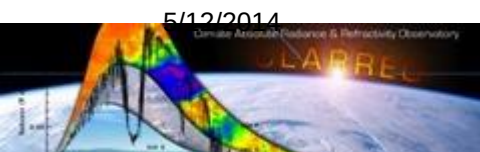
- Two spectrometers, interface platform, filter assemblies, thermal management, and electronics
 - Mass: ~70 kg
 - Average Power: ~96 W
- Dimension: ~0.92x0.74x0.40 m³
- Data Rate: (with 2x compression)
 - Solar Calibration: ~72 Mb/sec
 - Nadir Collection: <0.5 Mb/sec
- Data Volume: (with 2x compression)
 - Typical: ~66 Gb/day
 - Peak: ~69 Gb/day

Instrument Description:

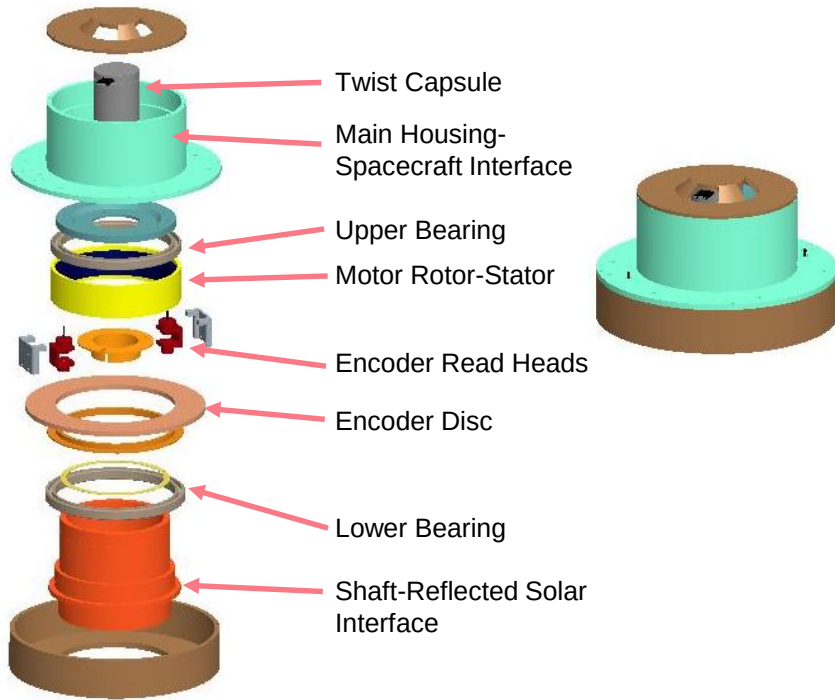
- A pair of pushbroom hyperspectral imagers with high spatial and spectral resolution
- Measures solar spectral reflectance of the Earth and its atmosphere relative to the solar irradiance spectrum
- Calibration of detectors obtained through precision apertures, neutral density filters, and perforated plates rotated via filter wheels
- Field of regard (FOR) achieved with combination of spacecraft bus motion and single-axis gimbal

Characteristics:

- Absolute reflectance measurement uncertainty of 0.3% at 2 σ confidence for the total integrated broadband reflected solar spectrum
- Polarization sensitivity <0.25% below 1000 nm and <0.75% at other wavelengths
- Spectral Range: 320 – 2300 nm
 - ~320 to ~640 nm ("Blue")
 - ~600 to ~2300 nm ("Red-NIR")
- Spectral Sampling: ~2 – 4 nm
- Swath Width: >100 km cross-track from 609 km
- Spatial Sampling : ~0.5 km at Nadir



Single-Axis Gimbal Overview



Single-Axis Gimbal Design Concept

Baseline Concept:

- *Gimbal, electronics, and cabling*
 - Mass: ~14 kg
 - Average Power: ~17 W
 - Peak Power: ~55 W
- *Dimension: ~0.2m x 0.3m diameter*
- *Data Rate: ~3.3 kb/sec*
- *Data Volume: ~280 Mb/day*

Description:

- *Provides cross-track pointing required by reflected solar suite for on-orbit calibration-verifications, reference intercalibrations, and benchmarking (nadir-collection) without additional optics*
- *Provides mechanical and electrical interfaces between the spacecraft bus and the reflected solar suite*
- *High-TRL components and similar gimbals have flight heritage*
- *Optical encoder provides shaft angle for closed-loop control and motor commutation*
- *Brushless DC motor provides zero-cogging and smooth drive torque*
- *Twist capsule used to carry gimbal and reflected solar signals and power across rotating interface*

Characteristics:

- *Range of Motion: +/- 180 degrees*
- *Angular Knowledge: < 20 arcsec*
- *Angular Control: < 72 arcsec*
- *Slew Rates: > 5 deg/sec*
- *Tracking Rates: Up to 5 deg/sec*
- *Acceleration: $\geq 1 \text{ deg/sec}^2$*

NASA LaRC

5/12/2014

