CLARREO Pathfinder Mission: Calibrating Climate Observing Systems of the Future

Bruce A. Wielicki, Yolanda Shea, Constantine Lukashin, Gary Feldman
NASA Langley, Hampton, VA
Peter Pilewskie, Greg Kopp, Paul Smith, Greg Ucker
University of Colorado LASP, Boulder, CO
CLARREO Pathfinder Team

SI Traceable Space-based Climate Observing System Workshop
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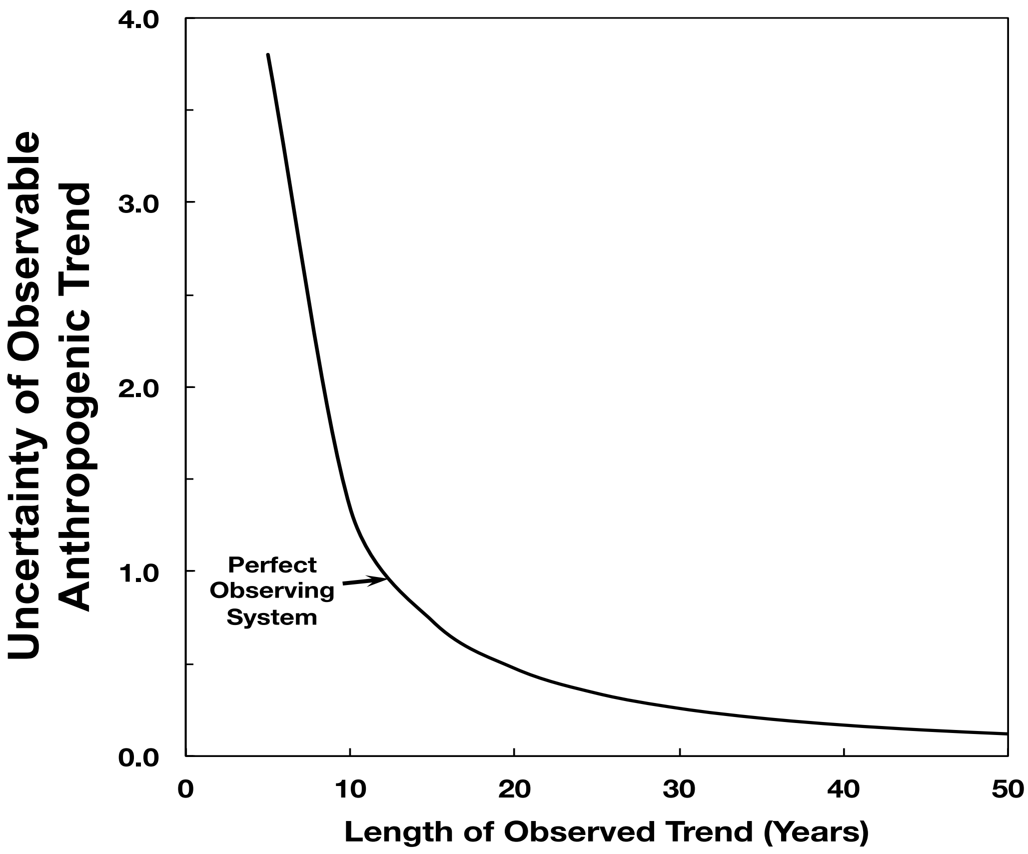
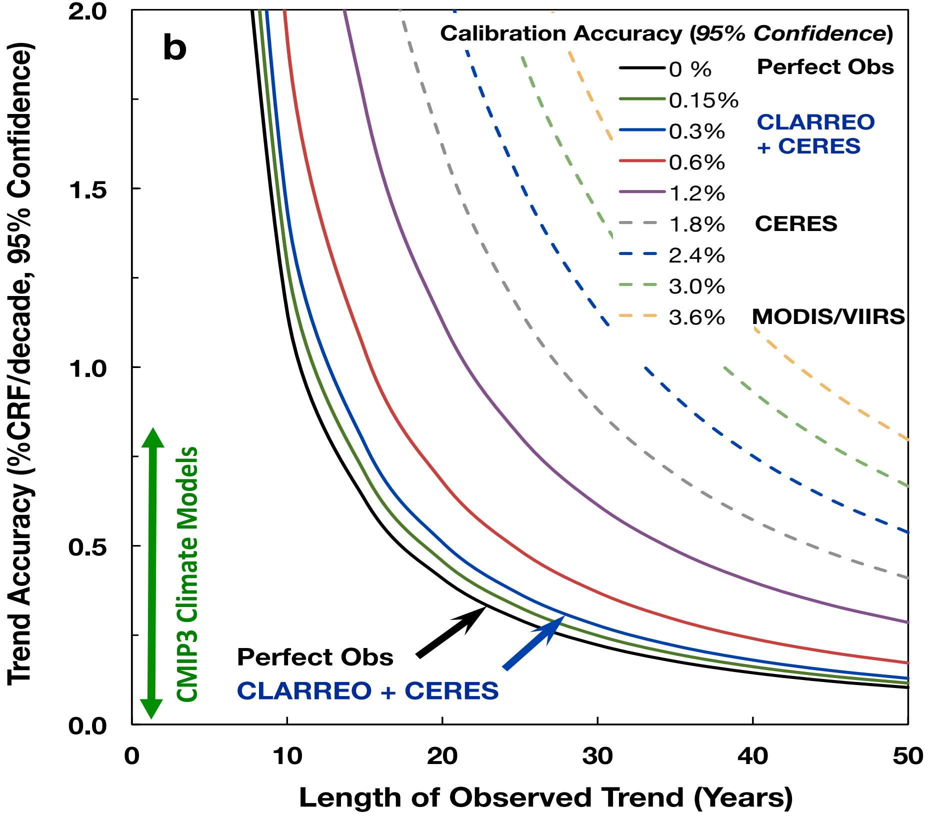
Climate Observation Accuracy Requirements



The length of time required to detect a climate trend caused by human activities is determined by:

- *Natural variability*
- *The magnitude of human driven climate change*
- *The accuracy of the observing system*

Reflected Solar Accuracy and Climate Trends



Climate Sensitivity Uncertainty is a factor of 4 (IPCC, 90% conf) which = *factor of 16 uncertainty in climate change economic impacts*

Climate Sensitivity Uncertainty = Cloud Feedback Uncertainty = Low Cloud Feedback = *Changes in SW CRF/decade (y-axis of figure)*

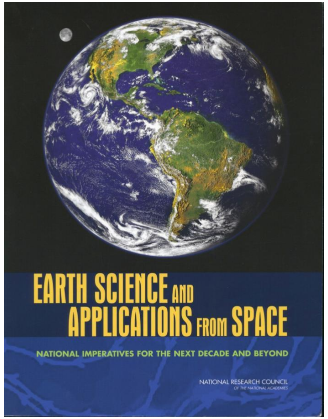
Higher Accuracy Observations = CLARREO reference intercal of CERES = *narrowed uncertainty 15 to 20 years earlier*

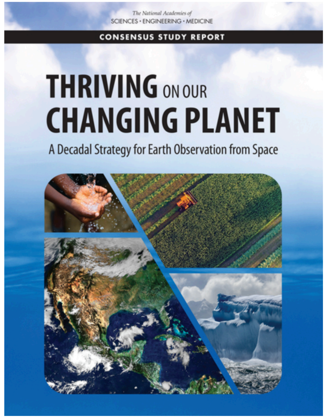
Wielicki et al. 2013, Bulletin of the American Meteorological Society

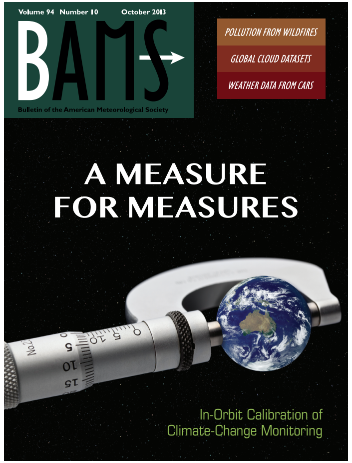
CLARREO Mission – What and Why

- CLARREO = Climate Absolute Radiance and Refractivity Observatory
- Calibration Reference Spectrometers for national and international climate observing systems in orbit (Tier 1 Decadal Survey Mission)
- Reflected solar and infrared spectrometers enabling calibration across the entire solar and infrared spectrum of space instruments (e.g. CERES, VIIRS, CrIS, Landsat, geostationary imagers and sounders)
- Advance accuracy a factor of 5 to 10 for observing global climate change from space (e.g. climate sensitivity/cloud feedback)
- Higher accuracy enables earlier more accurate predictions of future climate change (15 to 20 years)
- Reduced prediction uncertainty leads to better societal decisions and economic outcomes.
- CLARREO will be a critical calibration anchor of the first international climate observing system (currently we have none)
- *Economic value of a more accurate climate observing system using CLARREO as the example estimated at $10 Trillion U.S. dollars (Cooke et al., 2014). ROI $50:$1 if triple global climate observation effort (true climate observing system)*

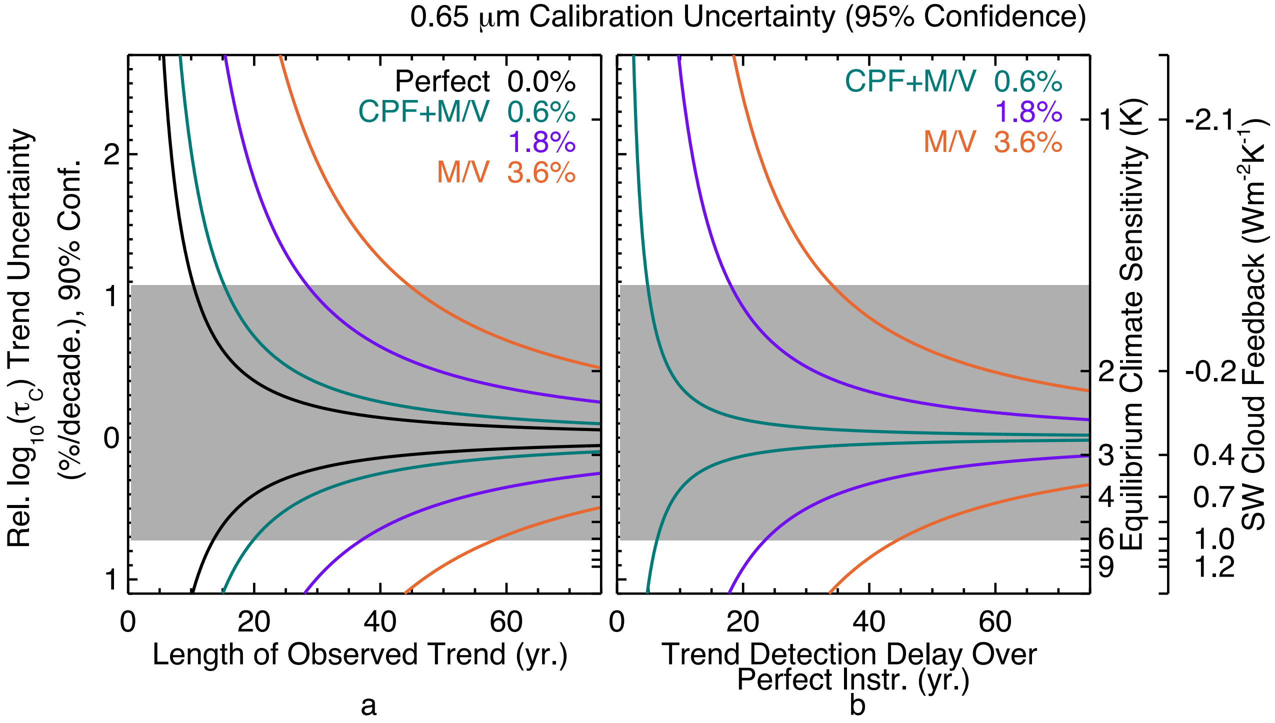
http://clarreo.larc.nasa.gov/







Cloud Optical Depth Trend Uncertainty and Climate Sensitivity



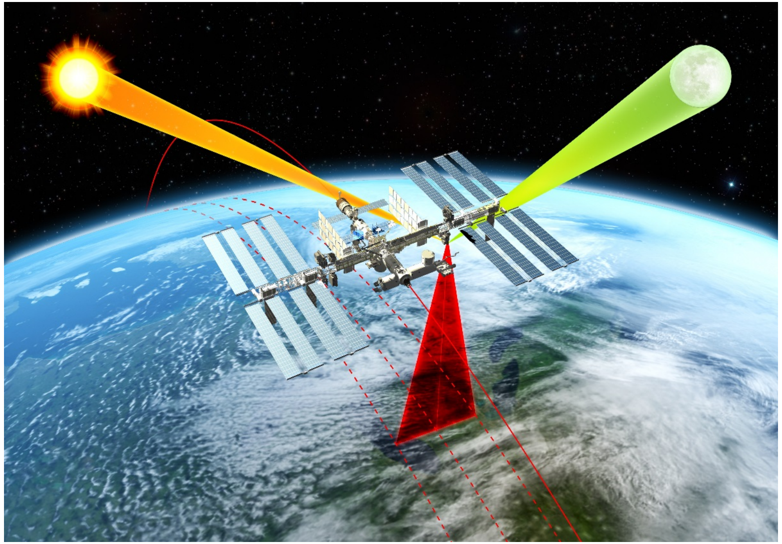
Gray Shaded Region: 90% Confidence Interval in climate sensitivity

Higher accuracy advances results by 20 to 40 years

Shea et al. *2017, J. Climate*

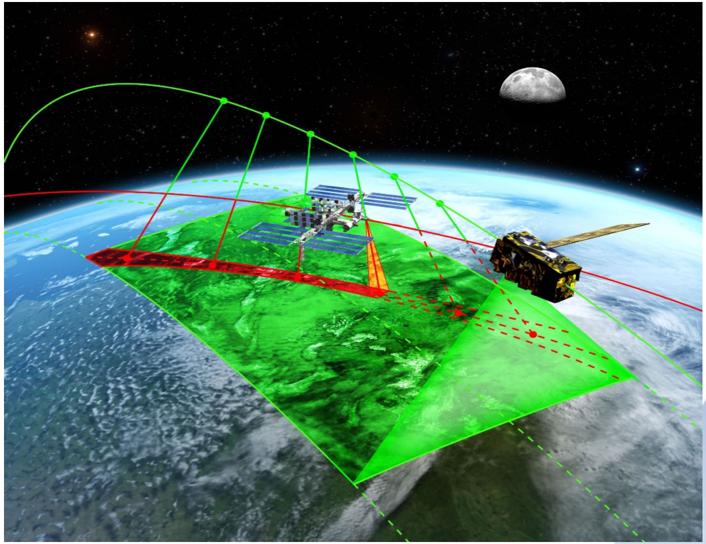
CLARREO Pathfinder: Baseline Objectives

Demonstrate high accuracy SI-Traceable Calibration



Objective #1: Demonstrate the ability to conduct, on-orbit, SI-Traceable calibration of measured scene spectral reflectance with an advanced accuracy over current on-orbit sensors using a reflected solar spectrometer flying on the International Space Station.

Demonstrate Reference Inter-Calibration Capabilities



Objective #2: Demonstrate the ability to use that improved accuracy to serve as an in orbit reference spectrometer for advanced inter-calibration of other key satellite sensors across the reflected solar spectrum (350-2300 nm).

Level 1 Requirements Summary

Demonstration Parameter	Measurement Uncertainty	
	Baseline Objective*	Threshold Requirement**
Spectrally-Resolved Earth Reflectance (350 – 2300 nm): SI-Traceable, referenced to spectral solar irradiance	≤ 0.3% (k = 1)	≤ 0.6% (k = 1)
Spectrally-Integrated Earth Reflectance (350 – 2300 nm): SI-traceable broadband (350 - 2300 nm) spectrally-integrated Earth reflectance with spectral accuracy weighted using global average Earth spectrally reflected energy	≤ 0.3% (k = 1)	≤ 0.6% (k = 1)
On-Orbit Inter-Calibration: Demonstrate the ability to Inter-Calibrate with CERES/RBI short wave channel and VIIRS reflectance bands	≤ 0.3% (k = 1)	≤ 0.6% (k = 1)

* *Baseline Objective is within a factor of 2 of full CLARREO Tier-1 Decadal Survey Mission Requirements*

** *Threshold requirement is a factor of 2 (CERES) to 4 (VIIRS) better than current capabilities.*

Support for the CLARREO Mission

- Called for by Global Space-based InterCalibration System (GSICS)
  - Part of the World Meteorological Organization (WMO) and the World Climate Research Program (WCRP)
- Letter to Dr. Freilich from Director of Space for WMO: CLARREO needed to support climate change calibration from space
- WMO 2040 WIGOS: plan for a 2040 observation system
- Global Climate Observing System (GCOS) under WCRP
- CEOS/CGMS/WMO "Strategy Towards an Architecture for Climate Monitoring from Space" (2013)
- U.S. Academy of Sciences 2015 report titled "Continuity of NASA Earth Observations from Space: A Value Framework", 2007 and 2017 Earth Science Decadal Surveys

Quantifying Objectives and Priorities

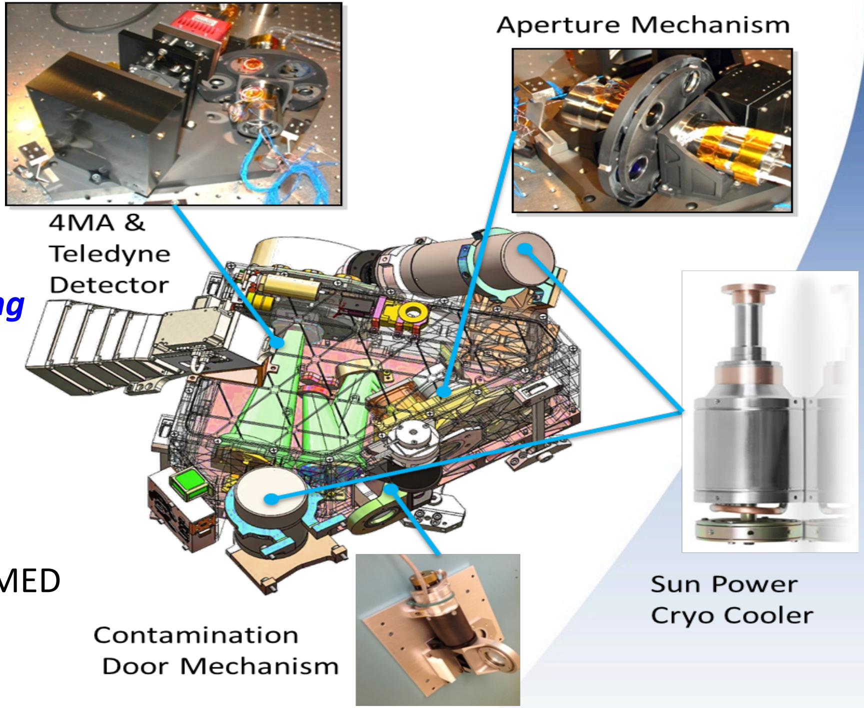
- CLARREO full mission developed a Science Value Matrix to clearly relate science value to mission, orbit, reliability, and instrument accuracy trades. Pathfinder relied on this to decide between a reflected solar and infrared spectrometer demonstration mission to ISS.
- Quantitative Earth science objectives and their relationship to measurement Utility and Quality were key concepts used and extended in the recent NRC Continuity Report for NASA
- Accuracy and time to detect climate change used as key quantitative metrics of Quality in the NRC Continuity report
- Quantitative science objectives were also used extensively for the Climate Science sections of the recent 2017 U.S. Academy of Science Decadal Survey

CLARREO Pathfinder Mission Summary

- **Demonstrate CLARREO calibration accuracy for the reflected solar spectrometer on the International Space Station**
- **Nominal launch is early 2023, nominal operations 1 year**
  - *ISS is holding an 18 month window, with a potential for up to 3 years on orbit.*
- **Class D low cost mission**
  - *Instrument design life 1 year at 85% probability, ~ 50% of achieving 4 yrs*
- **Demonstrate CLARREO level SI traceability in orbit**
- **Demonstrate CLARREO Reference Intercalibration for VIIRS and CERES**
- **Take intercalibration observations for additional sensors (LEO, GEO) but Pathfinder budget only covers L0 processing for these orbit crossings**
- **When success is demonstrated, request funding to process full data stream and additional instrument intercalibration events, as well as nadir spectral benchmarking observations.**
- **Currently approved planning budget: $120M including NASA HQ and project reserves (< an EV-M)**

CLARREO Pathfinder
Reflected Solar (RS) Spectrometer Description

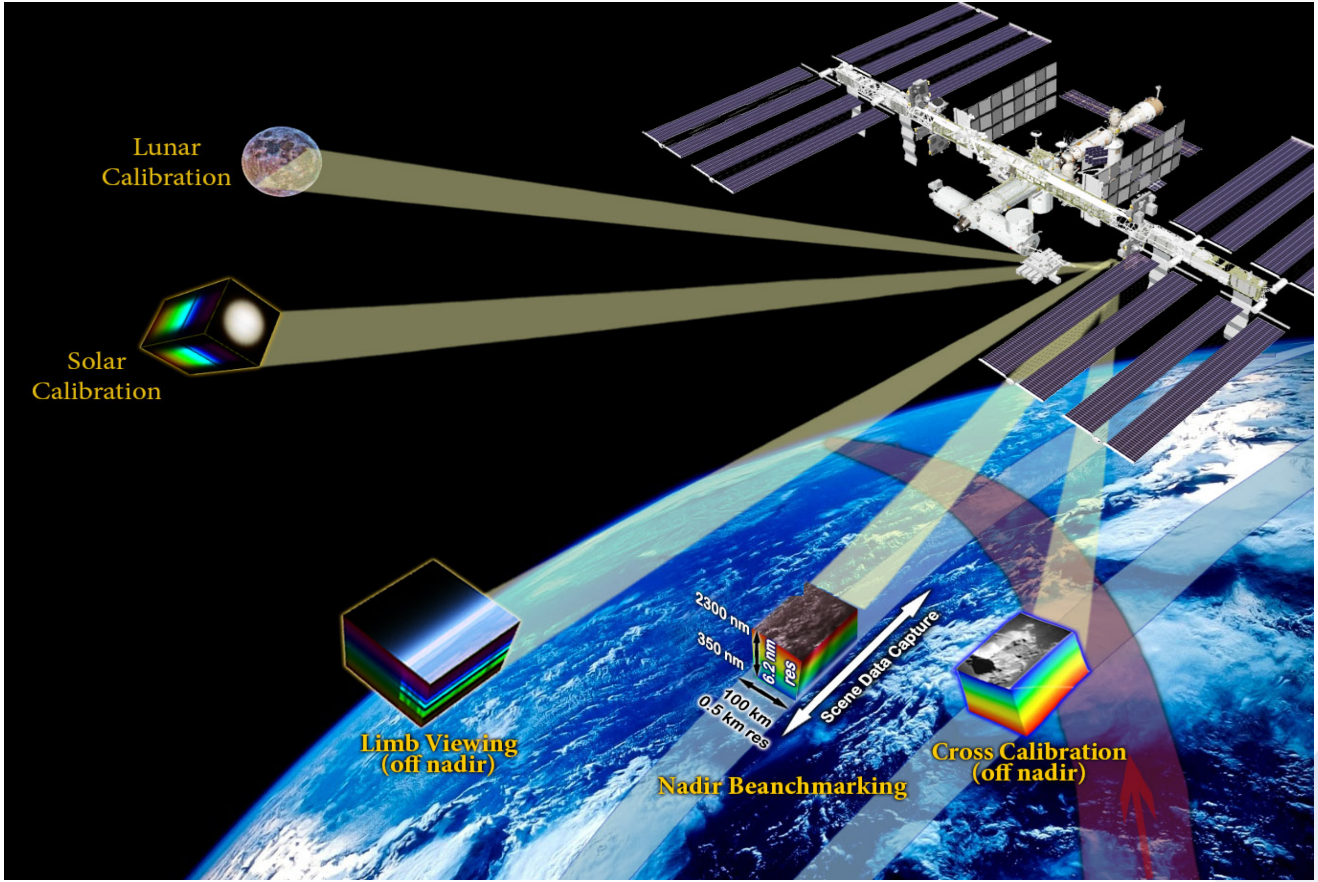
- **Based on Hyper-Spectral Imager for Climate Science (HySICS) instrument**
  - Developed by the ***University of Colorado Laboratory for Atmospheric and Space Physics (LASP)*** under NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP)
  - IIP Awards in 2007 and 2010
- **Push-broom Spectrometer**
  - 350-2300 nm contiguous spectral coverage
  - 3 nm spectral sampling, 6 nm resolution
  - 70 km cross-track swath width, 0.5 km pixels
  - ***2 Balloon flights demonstrated accuracies approaching CLARREO requirements for climate data records***
- **Two-Axis Pointing System enables solar / lunar / Earth viewing**
  - Active stabilization for use on ISS
  - Leverages significant design heritage – TSIS, GLORY, TIMED
  - *Balloon flight used Astrophysics WASP pointing system*



Calibration Risk Mitigation and Resolution

- **IIP demonstrated threshold requirement accuracy for 95% of the spectrum**:
  - Limiting factor was stray light from the lower quality grating that could be afforded under a small IIP budget.
  - Flight instrument will use a higher quality sinusoidal holographic grating to reach baseline objective level of accuracy across the full spectrum.
  - Journal paper published that documents accuracy achieved in HySICS balloon flight (Kopp et al., 2017)
- **Independent verification of new accuracy level:**
  - GSFC reflected solar calibration group (Thome, McCorkel) are supported to provide an independent calibration.
  - Uses GSFC GLAMR (Goddard Laser for Absolute Measurement of Radiance) version of NIST Traveling SIRCUS (Spectral irradiance and radiance responsivity calibrations using uniform sources) calibration methodology. CLARREO pre-formulation contributed to the GLAMR development.
  - LASP characterizes on the ground and calibrates in orbit (solar/lunar).
  - GSFC calibrates on the ground and uses in orbit solar and lunar views to determine changes of calibration ground to orbit and in orbit.
  - NIST will be supported to provide calibration uncertainty reviews.

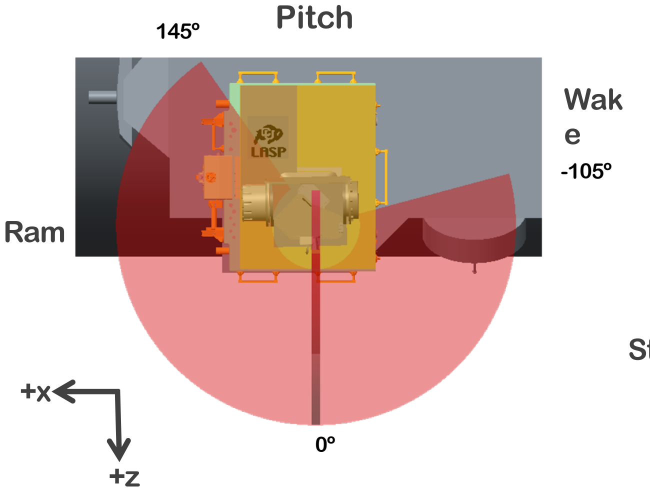
Viewing Modes

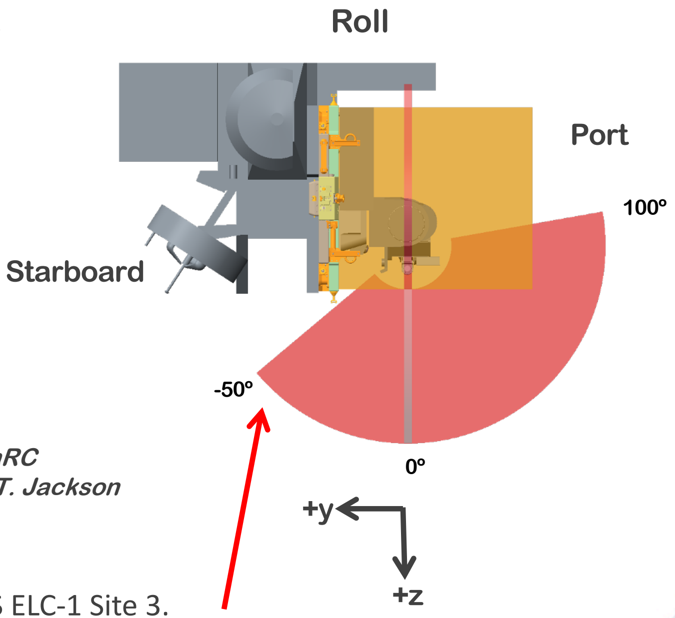


University of Colorado LASP Visualization

RS Instrument Field-of-Regard: Pointing for Solar, Lunar, Inter-calibration

Accommodations on ISS at Express Logistics Carrier #1 (ELC-1) Site 3 provides adequate viewing to meet CLARREO Pathfinder mission objectives.

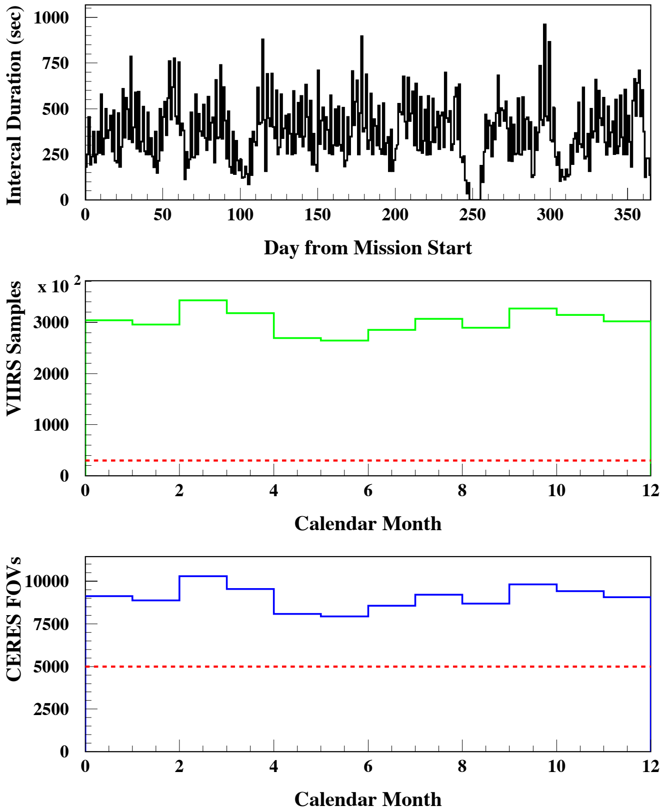




Accommodation studies by the NASA LaRC Engineering team: J. Leckey, C. Boyer, T. Jackson

- Gimbal configuration: pitch - roll
- Approximate gimbal range of motion at ISS ELC-1 Site 3.
- Not all pointing angles are available due to ISS accommodation.

Inter-Calibration of Sensors: VIIRS and CERES Sampling



Simulation ISS ELC-1 Site 3:

- 10 minutes time matching
- Instrument field-of-regard
- Instrument FOV = 10º
- Instrument FOV obscuration = 0%
- Event duration > 30 seconds
- SZA < 75º
- N good events = 1163

VIIRS:
100 samples every 5 seconds

- - - Sampling requirements

CERES:
3 FOVs every 5 seconds

Conclusion: sampling is sufficient
- 45% margin for CERES,
- factor of 10 margin for VIIRS

CLARREO Pathfinder Mission Status

- **PDR and Key Decision Point C successfully passed in 2019**
- **CDR planned for February 2020**
- **Mission Team:**
  - *Mission management and inter-calibration demonstration: NASA Langley*
  - *NASA HQ Mission oversight: Earth Systematic Missions Program Office*
  - *Instrument design, build, test, and calibration demonstration: CU LASP*
  - *Independent instrument calibration: NASA GSFC*
  - *Independent instrument calibration reviews: NIST*
- **Mission Science Team solicitation: 2021?**

Summary

- **Two major sources of uncertainty in anthropogenic climate change trends**
  - *Natural variability (e.g. ENSO, PDO)*
  - *Observing system uncertainty (e.g. calibration shifts or drifts)*

- **Higher accuracy observations can accelerate time to detect climate change trends at a desired uncertainty level by 15 to 20 years**
  - *Example: higher accuracy cloud radiative forcing trends for cloud feedback to narrow uncertainty in climate sensitivity*

- **Aids societal decision making to optimize mitigation and adaptation costs**

- **3 recent studies of the economic value of higher accuracy climate obs:**
  - *Cooke et al., J. Environ. Systems and Decisions, 2014;*
  - *Cooke et al., Climate Policy, 2015;*
  - *Hope, Phil. Trans. Roy. Soc., 2015*

- **Economic Value: $10 to $20 Trillion U.S. dollars in Net Present Value**
  - *For full climate observing system (3X current investment) 50:1 return on investment*
  - *CLARREO Pathfinder is a critical initial step toward a true climate observing system*

Further Information

- **CLARREO Mission Overview: Wielicki et al. 2013, BAMS cover article**
- **Need for Higher Accuracy Climate Observations and Their Large Economic value**
  - Cooke et al., *J. Environ. Systems and Decisions*, 2014
  - Cooke et al. *Climate Policy*, 2015
  - Cooke et al. *Environmental Modeling and Assessment, 2019*
  - Weatherhead et al. *AGU Earth's Future*, 2017
- **HySICS Instrument Calibration Journal Paper**
  - Kopp et al., *Geosci. Instrum. Method. Data Syst.*, 2017
- **CLARREO Web site:** http://clarreo.larc.nasa.gov
- **CLARREO Pathfinder Report (~ 74 page summary):**
  - http://clarreo.larc.nasa.gov/pdf/CLARREO_Pathfinder_Report.pdf
- **CLARREO Science Team Report (~200 page summary of mission science, instruments, orbits, options, costs):**
  - http://clarreo.larc.nasa.gov/pdf/CLARREO_Science_Team_Report.pdf
- **CLARREO related/funded journal papers: >140 papers, >1300 citations**
  - List at: http://clarreo.larc.nasa.gov/docs-references-A-F.html

Backup Slides

Further Information: Google “CLARREO NASA”

- Mission Overview: Wielicki et al. 2013, BAMS cover article
- Economic value of higher accuracy climate obs: Cooke et al., J. Environ. Systems and Decisions, 2014; Cooke et al. Climate Policy, 2015, Cooke et al.
- CLARREO Web site: http://clarreo.larc.nasa.gov. Soon to be a new updated CLARREO Pathfinder website (~ October, 2019)
- CLARREO Science Team Report (~200 page summary of mission science, instruments, orbits, options, costs), CLARREO Pathfinder mission summary: http://clarreo.larc.nasa.gov
- CLARREO related/funded journal papers: >140 papers, >1300 citations, list can be found at: http://clarreo.larc.nasa.gov
- CLARREO Science Team Meeting Presentations: http://clarreo.larc.nasa.gov
- CLARREO conference presentations: a wide range of venues, U.S. and international

Determining the Accuracy of Decadal Change Trends and Time to Detect Trends

- A perfect climate observing system is limited in trend accuracy only by climate system natural variability (e.g. ENSO) (Leroy et al, 2008).

- Degradation of accuracy of an actual climate observing system relative to a perfect one (fractional error F_a in accuracy) is given by:

$$F_a = (1 + \Sigma f^{2}_{i})^{1/2} - 1 \text{ , where } f^{2}_{i} = \sigma^{2}_{i} \tau_i / \sigma^{2}_{var} \tau_{var}$$

for linear trends where σ is standard deviation, τ is autocorrelation time, σ_{var} is natural variability, and σ_i is one of the CLARREO error sources.

- Degradation of the time to detect climate trends relative to a perfect observing system (fractional error in detection time F_t) is similarly given by:

$$F_t = (1 + \Sigma f^{2}_{i})^{1/3} - 1$$

Degradation in time to detect trends is only ⅔ of degradation in accuracy.

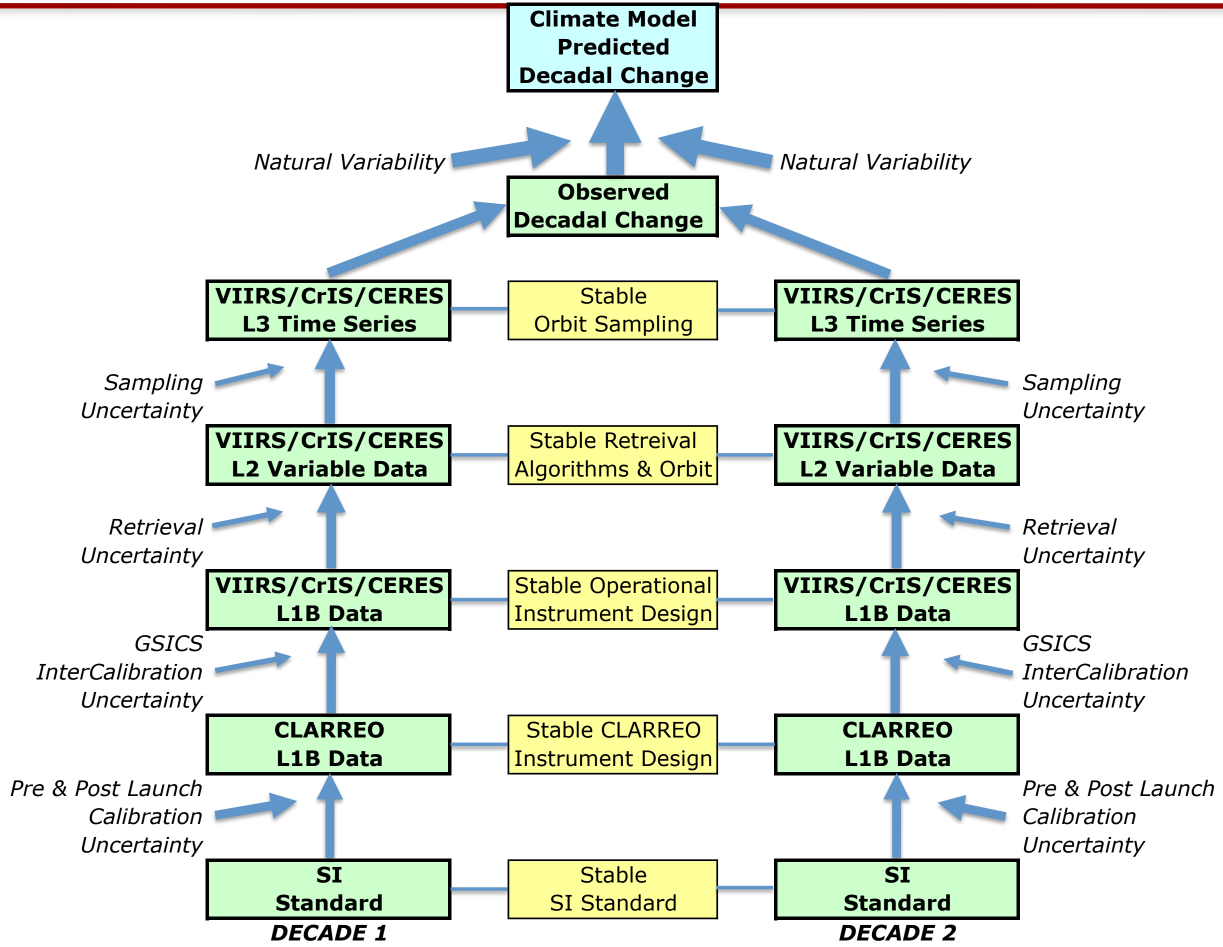
Decadal Change Trends

- The absolute accuracy of climate change observations is required *only at large time and space scales such as zonal annual, not at instantaneous field of view. Therefore all errors in climate change observation error budgets are determined over many 1000s of observations: never 1, or even a few.*

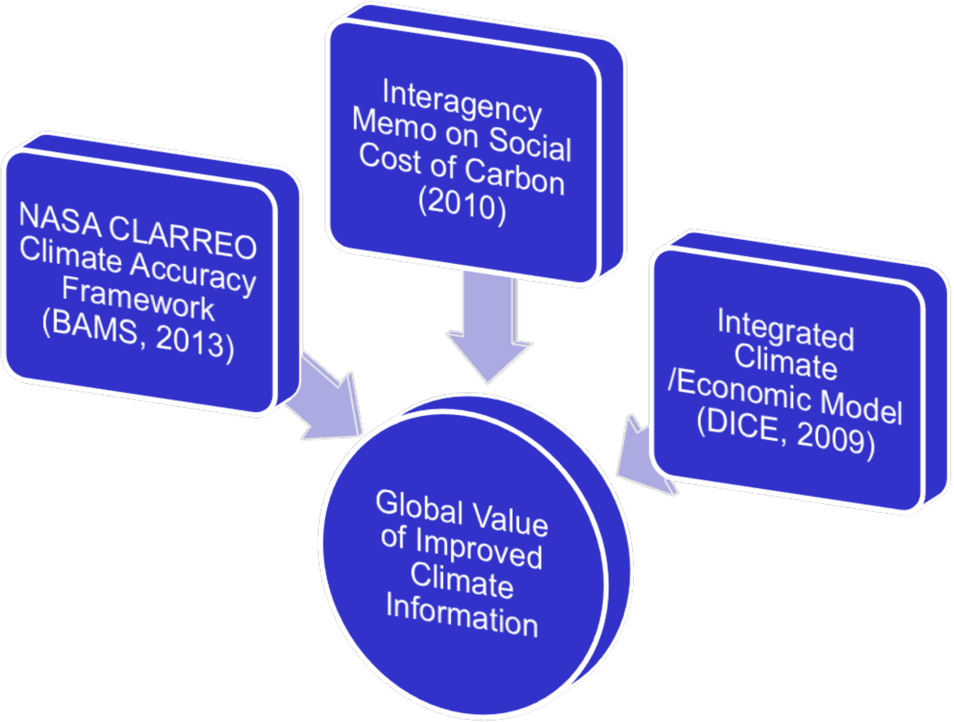
- Climate change requirements can be very different than a typical NASA Earth Science process mission interested in retrievals at instantaneous fields of view at high space/time resolution, *where instrument noise issues may dominate instantaneous retrievals*

- *So what accuracy relative to a perfect observing system is needed?*

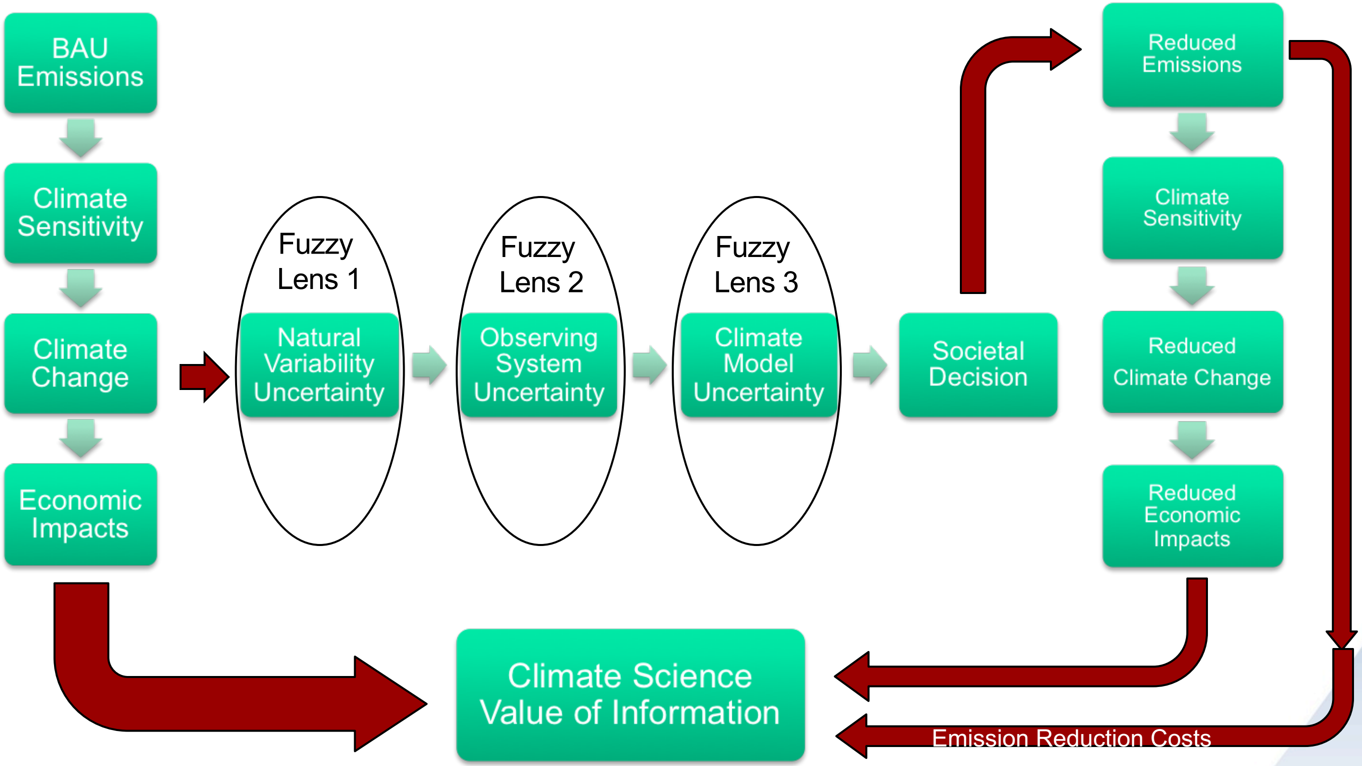
Decadal Change Reference Intercalibration Benchmarks: Tracing Mission Requirements



invest in climate science?



Value of Information Estimation Method



VOI vs. Discount Rate

Run 1000s of economic simulations and then average over the full IPCC distribution of possible climate sensitivity

Discount Rate	CLARREO/Improved Climate Observations VOI (US 2015 dollars, net present value)
2.5%	$17.6 T
3%	$11.7 T
5%	$3.1 T

Additional Cost of an advanced climate observing system:
~ $10B/yr worldwide
Cost for 30 years of such observations is ~ $200 to $250B (NPV)

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Advanced Climate Observing System:

Return on Investment: $50 per $1

Results and Sensitivity to Assumptions

World Wide Economic Benefits

Parameter Change	CLARREO/Improved Climate Observations VOI (Trillion US 2015 dollars, NPV) 3% discount rate
Baseline*	$11.7 T
BAU => AER	$9.8 T
0.3C/decade trigger	$14.4 T
2030 launch	$9.1 T

* Baseline uses 0.2C/decade trigger, 95% confidence in trend, BAU => DICE optimal emissions, 2020 launch

- Delaying launch by 10 years reduces benefit by $2.6 T