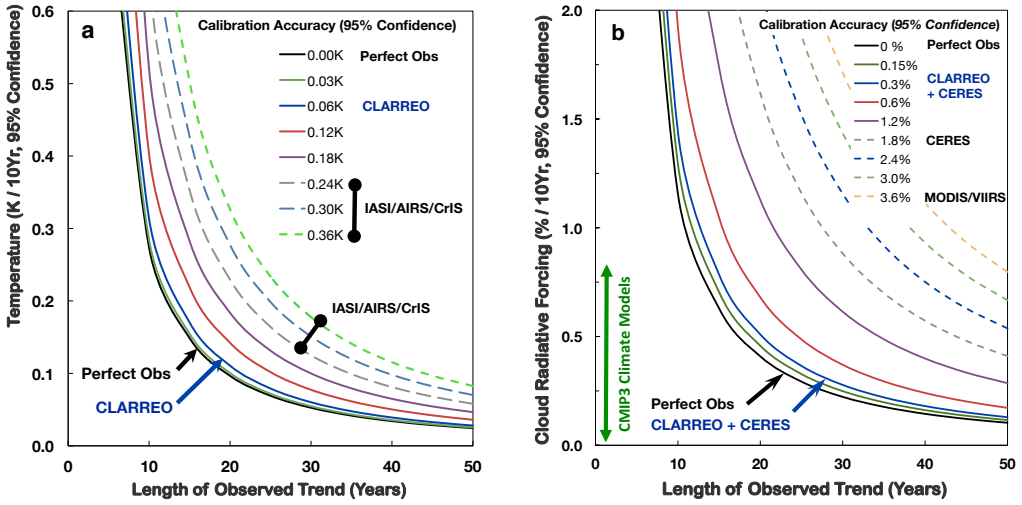
February 5, 2014

CLARREO Mission - Earth's Climate Change Observations

Executive Summary by the CLARREO Science Definition Team

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) is a high priority, NASA Decadal Survey mission recommended by the National Research Council [Wielicki et al., 2013]. The mission represents a calibration laboratory in orbit for the purpose of accurately measuring and attributing climate change. CLARREO observations establish new climate change benchmarks with high absolute radiometric accuracy and high statistical confidence across a wide range of essential climate variables. The CLARREO benchmarks are derived from measurements of the Earth/atmosphere reflectance (0.32 to 2.3 μm) and the thermal infrared (5 to 50 μm) spectra, and radio occultation from which accurate temperature profiles are derived. CLARREO's inherently high absolute accuracy will be verified and traceable on-orbit to *Système Internationale* (SI) units. The mission provides the first orbiting reference calibration standard for other radiometric sensors, essentially serving as a *NIST in orbit*[1]. This will significantly improve the accuracy and relevance of numerous spaceborne instruments for decadal climate change.



(a) Temperature trend and uncertainty.

(b) Cloud Feedback trend and accuracy.

Figures (a) and (b) show the relationship between absolute calibration accuracy and the accuracy of decadal climate change trends. The results are shown for a perfect observing system as well as varying levels of instrument absolute calibration. The relationship between infrared (IR) spectra accuracy and temperature trends is shown in (a), while the relationship between reflected solar (RS) spectra accuracy and changes in cloud feedback is shown in (b). This illustrates the dramatic effect of measurement accuracy on both climate trend accuracy (vertical axis) as well as the time to detect trends. CLARREO's accuracy is a factor of 5 to 10 better than the absolute accuracy of current instruments in the RS, and a factor from 2 to 3 of existing IR instruments. Accuracy improvements beyond CLARREO have little difference when compared to a perfect observing system, which is shown by the black line in both figures.

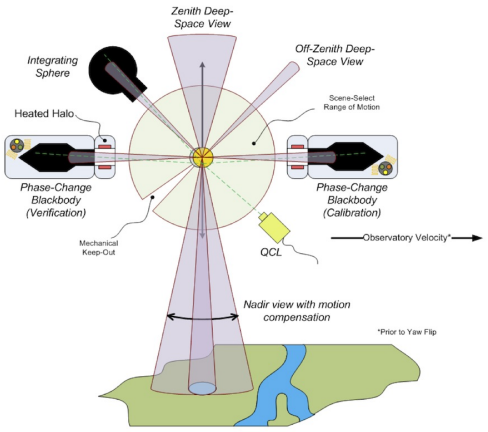
CLARREO Climate Change Observations: The climate benchmarks established by CLARREO are critical for assessing changes in the Earth system as society works to meet the challenge of optimizing strategies for mitigating and adapting to climate change. The most critical tests of climate model predictive capability are observations of decadal change - CLARREO data will be used for this purpose. CLARREO will serve as a cornerstone of the climate observing system through its provision

[1]National Institute of Standards and Technology.

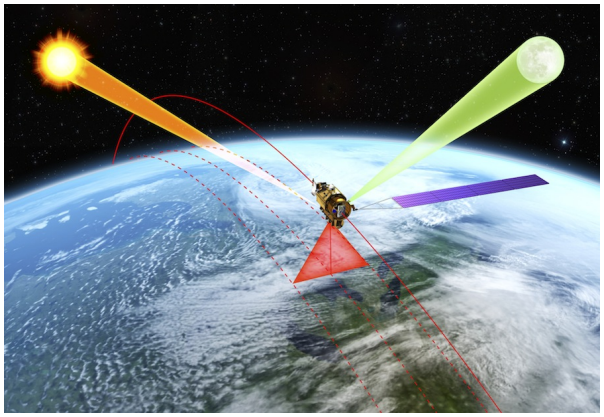
of accurate observations from which climate change can be assessed and validated for decades into the future.

CLARREO Near Term Impacts: 1) CLARREO provides the first measurement of Earth's far-IR spectrum (from 15 to 50 μm wavelength), at climate accuracy, enabling a fundamental test of climate models by determining the water vapor and CO_2 greenhouse effects simultaneously. The far-infrared includes 50% of the Earth's infrared energy emitted to space and contains most of the water vapor greenhouse effect. 2) CLARREO's ability to establish a reference calibration standard for the infrared and reflected solar radiometers in Earth orbit (CrIS, IASI, CERES, VIIRS, Landsat, and all geostationary satellite radiometers) will improve the analysis of a wide range of Earth observations, including more accurate bias corrections in weather assimilation and weather prediction, and will enable more consistent land process and atmospheric-state observations, aerosols, and ocean and land surface temperatures. 3) The mission's near term benefits include accurate spectral surface reflectance for selected sites and advanced hyperspectral retrievals.

CLARREO Societal Benefits: CLARREO provides the data necessary to accelerate decisions on public policy concerning climate change by 15 to 20 years. Earlier and better informed decisions provide a large economic benefit to the United States and the world, estimated to be $\sim$ \$12 Trillion over the next 40 to 60 years[2][Cooke et al., 2013]. CLARREO establishes a record with the high accuracy and information content necessary to detect long-term climate change trends and to test and systematically improve climate predictions. By reducing climate prediction uncertainties, CLARREO impacts: civil Government and military planning (i.e., Navy bases), disaster mitigation, response, and recovery (i.e., insurance industry), and U.S. international policy decisions.



(c) CLARREO IR measurements on-orbit.



(d) CLARREO RS measurements on-orbit.

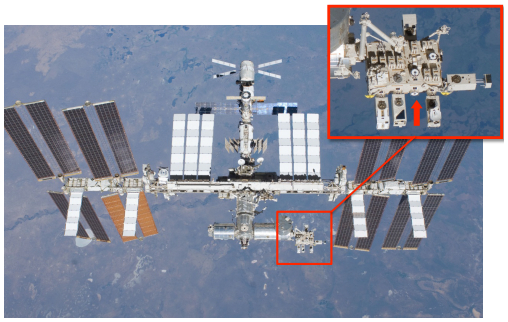
CLARREO Technical Readiness: CLARREO successfully passed its NASA Mission Concept Review in November 2010, with recommendation to proceed to the next stage in development prior to a NASA budget decrease in February 2011. The CLARREO InfraRed (IR) Spectrometer, Reflected Solar (RS) Spectrometer, and Radio Occultation (RO) instruments are mature, achieving Technology Readiness Levels of 6 and higher. One of the most critical aspects of CLARREO instrument design is the advance in absolute calibration and in control of parameters susceptible to drift and error on-orbit. CLARREO's accuracy goals for IR brightness temperature and reflectance measurements are 0.1K ($k = 3$) and 0.3% ($k = 2$), respectively[3]. The infrared calibration, Figure (c), relies on phase change cells at $-39°$, $0°$, and $30°$C to verify thermistor accuracy, a quantum cascade laser and heated halos to verify blackbody emissivity, optics design to verify polarization sensitivity, and

[2]Using the U.S. Interagency Memo of the Social Cost of Carbon (2010), CLARREO's value has been estimated at about \$20 Trillion for a 2.5% discount rate, \$12 Trillion for a 3% discount rate, or \$3 Trillion for a 5% discount rate.

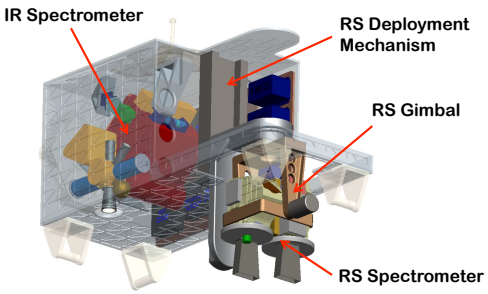
[3]We use general coverage factor k instead of σ to establish a more rigorous tie between the climate and metrology research communities. In the case of a Gaussian distribution, $k = 2$ is the same confidence level, 95%, as for 2σ.

a quantum cascade laser with integrating sphere to verify instrument spectral response. The verification of Earth's spectral reflectance accuracy on orbit, Figure (d), relies on rotating the entire instrument to view the moon at a constant phase angle as a single-level stable reflectance source, the sun in combination with filters and precision apertures for nonlinearity determination, and the use of depolarizers to limit instrument sensitivity to polarization.

CLARREO Baseline and Minimum Mission Options (MCR): Development of the CLARREO accuracy requirements, combined with additional orbital sampling studies for IR, RS, and RO, demonstrated that the CLARREO Baseline Mission can achieve its 100% of the science by flying 6 instruments in two 90° inclination polar orbits. This orbit choice is well-suited to CLARREO's requirements and assures full diurnal cycle sampling for spectral fingerprints as well as full reference inter-calibration sampling over all climate regimes and all satellite orbit thermal conditions. The CLARREO Minimum Mission with 3 instruments in a single 90° inclination polar orbit could achieve 62% of the Baseline Mission science at a significantly reduced cost (see Table).



(e) Example of CLARREO location on the ISS.



(f) Configuration of CLARREO payload.

CLARREO ISS Mission Option: A mission concept to fly two CLARREO instruments, RS and IR spectrometers, on the International Space Station (ISS) as shown in Figures (e) and (f). Because of the higher reliability of the ISS as a spacecraft, thereby allowing a longer climate record, this option offers the best overall science value of 73% for the lowest cost (see Table). Due to the ISS 52° inclination orbit, CLARREO will not have coverage of Earth's polar regions, however, flying in a precessing orbit will significantly enhance sampling for inter-calibration of existing sensors. In this mission option, the radio occultation data is acquired from the COSMIC constellations.

Mission Option	Relative Science Value	Cost Estimate ($RYM)
MCR Baseline Mission: 6 instruments, 4 smaller or 2 larger SC in 2 P90 orbits	100%	~ $800 + Launch Vehicles
MCR Minimum Mission: 3 instruments, one SC in a single P90 orbit	62%	~ $675 + Launch Vehicle
ISS Mission Concept: 2 instruments on ISS, RO data from COSMIC	73%	~ $400 Includes Launch Cost EV-2 ISS full cost guidelines

CLARREO Essential References:

◇ Wielicki et al., October 2013: "Achieving Climate Change Absolute Accuracy in Orbit," *Bull. Amer. Meteor. Soc.*, pp. 1519–1539, DOI 10.1175/BAMS-D-12-00149.1

◇ Cooke et al., 2013: "Value of Information for Climate Observing Systems," *Environ. Syst. Decis.*, 12 pp., DOI 10.1007/s10669-013-9451-8

◇ CLARREO official website *http://clarreo.larc.nasa.gov*