ACHIEVING CLIMATE CHANGE ABSOLUTE ACCURACY IN ORBIT

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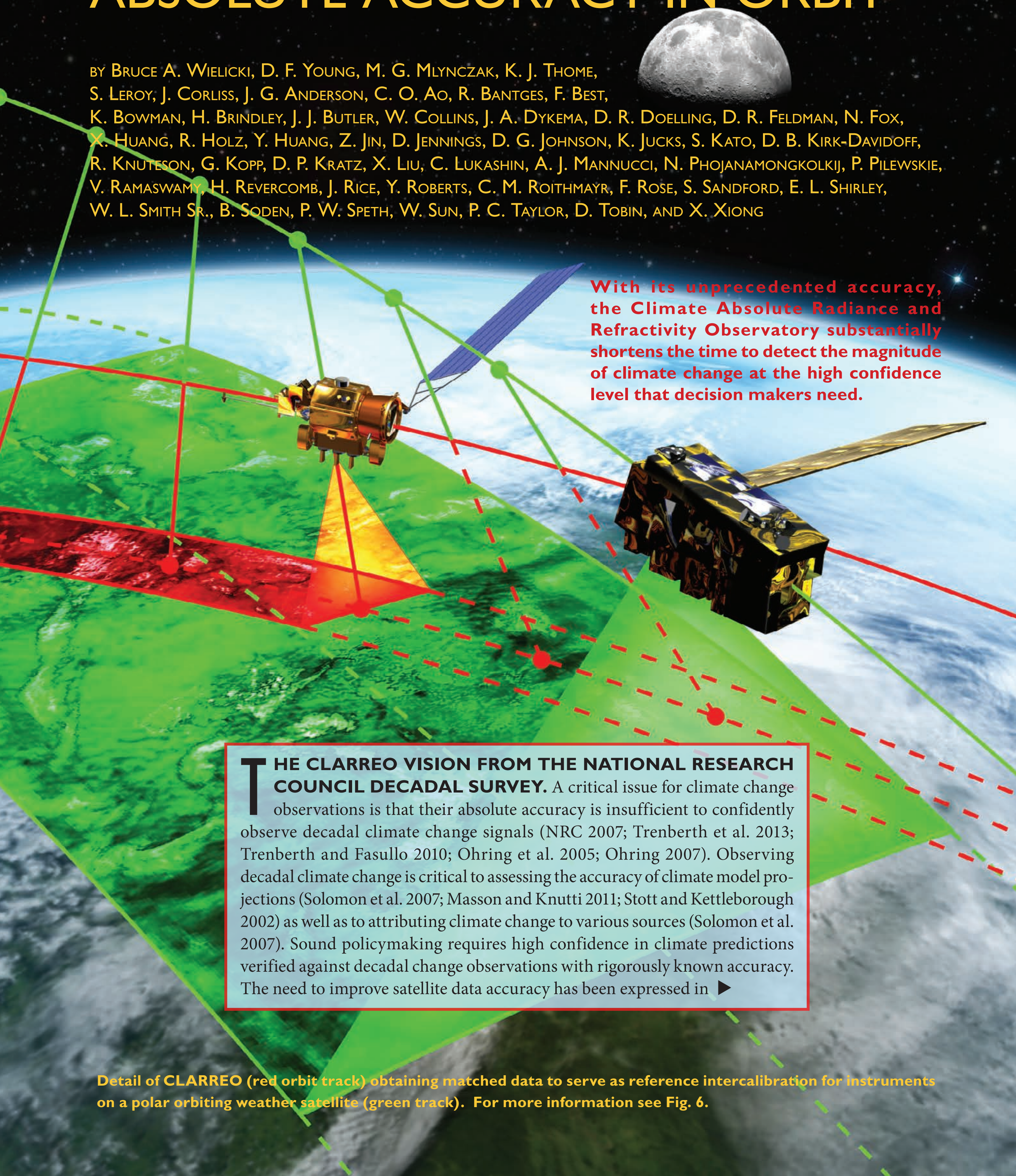

With its unprecedented accuracy, the Climate Absolute Radiance and Refractivity Observatory substantially shortens the time to detect the magnitude of climate change at the high confidence level that decision makers need.

THE CLARREO VISION FROM THE NATIONAL RESEARCH COUNCIL DECADAL SURVEY. A critical issue for climate change observations is that their absolute accuracy is insufficient to confidently observe decadal climate change signals (NRC 2007; Trenberth et al. 2013; Trenberth and Fasullo 2010; Ohring et al. 2005; Ohring 2007). Observing decadal climate change is critical to assessing the accuracy of climate model projections (Solomon et al. 2007; Masson and Knutti 2011; Stott and Kettleborough 2002) as well as to attributing climate change to various sources (Solomon et al. 2007). Sound policymaking requires high confidence in climate predictions verified against decadal change observations with rigorously known accuracy. The need to improve satellite data accuracy has been expressed in ▶

Detail of CLARREO (red orbit track) obtaining matched data to serve as reference intercalibration for instruments on a polar orbiting weather satellite (green track). For more information see Fig. 6.

U.S. interagency reports (Ohring et al. 2005; Ohring 2007) and international observing system plans (GEO 2005; GCOS 2011) and the Global Space-Based Intercalibration System (GSICS; GSICS 2006; Goldberg et al. 2011). Common challenges identified in these documents include uncertain long-term calibration drift, insufficient absolute accuracy, gaps in observations, and increased uncertainty even for overlapped and intercalibrated instruments (GEO 2010).

The Climate Absolute Radiance and Refractivity Observatory (CLARREO; http://clarreo.larc.nasa.gov) addresses these concerns by providing improved absolute accuracy in global satellite observations that can be traced continuously on orbit to international physical standards such as the Système Internationale (SI) standards for seconds, kelvins, and watts. Thus, CLARREO should lead to different observing strategies than have been employed in previous weather and climate satellites. We will summarize this new perspective on satellite-based observations, which we expect will be applicable to climate change observations in general.

CLARREO aims to provide highly accurate and SI-traceable decadal change observations sensitive to the most critical but least understood climate forcings, responses, and feedbacks. The required accuracy is determined by the projected decadal changes and the need to detect anthropogenic forced changes against the background natural variability. Because of the focus on longer time scales, CLARREO measurement requirements are determined not by instantaneous instrument noise levels, but instead by the long-term absolute accuracy sufficient to detect large-scale decadal changes (global, zonal, annual, and seasonal). The result is the creation of climate change benchmark measurements defined by three fundamental characteristics:

- Traceable to fundamental SI standards and robust to gaps in the measurement record;
- Time/space/angle sampling sufficient to reduce aliasing bias error in global decadal change observations to well below predicted decadal climate change and below natural climate variability; and
- Sufficient information content and accuracy to determine decadal trends in essential climate change variables.

The National Research Council (NRC) decadal survey defined three types of CLARREO benchmark measurements. The first is spectrally resolved infrared radiance (IR) emitted from Earth to space determined with an accuracy of 0.065 K ($k = 2$, or 95% confidence[1]). The infrared spectra are traced to the SI standard for the kelvin. The second benchmark is the phase delay rate of the signal from the low-Earth-orbit

[1] In discussing absolute accuracy, the metrology community uses a coverage factor k (BIPM 2008; Datla et al. 2009) that can be thought of simply as a more generalized version of a statistical confidence bound analogous to a Gaussian standard deviation (σ). A value of $k = 1$ is analogous to a 1σ confidence bound, $k = 2$ to a 2σ bound. We use k instead of σ to establish a rigorous tie between the climate and metrology communities. This interdisciplinary link is increasingly important in future climate change studies (WMO/BIPM 2010). Use of NIST-recommended methods of evaluating and reporting uncertainty is essential to CLARREO science objectives.

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Global Navigation Satellite System radio occultation system (GNSS-RO, or simply RO) occulted by the atmosphere, with an accuracy of 0.06% ($k = 2$) for a range of altitudes from 5 to 20 km in the atmosphere. The measurement is traced to the SI standard for the second. The third benchmark measurement is spectrally resolved nadir reflectance of solar radiation (RS) from Earth to space determined with an accuracy of 0.3% ($k = 2$). The percentage is relative to the mean spectral reflectance of the Earth of about 0.3. While solar spectral reflectance is a measurement relative to solar spectral irradiance, use of the solar spectral irradiance observations made by the Total Solar Irradiance Spectrometer (TSIS) enables traceability to the SI standards for the watt.

IR, RS, and RO measurements provide information on the most critical but least understood climate forcings, responses, and feedbacks associated with the vertical distribution of atmospheric temperature and water vapor (IR/RS/RO), broadband reflected (RS) and emitted (IR) radiative fluxes, cloud properties (IR/RS), and surface albedo (RS), temperature (IR), and emissivity (IR).

CLARREO enables two new approaches to climate analysis: *benchmark spectral fingerprinting* and *reference intercalibration*. Spectral fingerprinting signals directly measured by CLARREO allow determination of climate response and feedbacks (Leroy and Anderson 2010; Leroy et al. 2008a; Huang et al. 2010a,b; Feldman et al. 2011a,b; Jin et al. 2011; Kato et al. 2011; Roberts et al. 2011). The second approach uses CLARREO spectra to calibrate satellite instruments that do not reach decadal change absolute accuracy requirements. These include current and future instruments such as the Cross-Track Infrared Sounder (CrIS), Infrared Atmospheric Sounding Interferometer (IASI), Clouds and the Earth's Radiant Energy System (CERES), Visible Infrared Imager Radiometer Suite (VIIRS), Landsat, and all geostationary satellite radiometers. In this approach, CLARREO is an SI-traceable reference standard in orbit, providing reference intercalibration for other instruments to support efforts such as GSICS (Goldberg et al. 2011). These other instruments can then more accurately observe decadal climate changes and can also build long-term data records by bridging data gaps and reducing dependence on assumptions of stability and of uninterrupted overlap. Note that CLARREO does not include passive microwave observations given the lack of sufficiently accurate SI standards in this spectral region.

The National Aeronautics and Space Administration's (NASA's) current budget profile includes a CLARREO launch no earlier than 2022 for the baseline mission, but studies of other options are underway (see the section "Future directions").

RELATIONSHIP TO MAJOR CHALLENGES IN CLIMATE SCIENCE AND PREDICTION.

CLARREO decadal change observations are also needed to reduce uncertainties in the climate feedbacks that drive uncertainty in climate sensitivity. These feedbacks (from largest to smallest uncertainty) are from clouds, lapse rate/water vapor, and snow/ice albedo (Solomon et al. 2007; Soden and Held 2006; Bony et al. 2006; Roe and Baker 2007). In addition, CLARREO will help quantify radiative forcing from anthropogenic changes in land albedo, will quantitatively confirm the effect of greenhouse gases on infrared emissions to space, and will make modest contributions to improving aerosol direct radiative forcing.

CLARREO employs recent advances in metrology for more accurately calibrated solar and infrared instruments, and uses better radio occultation to improve capabilities to probe the atmosphere (see "Mission and instrument design" sidebar). CLARREO also measures with high spectral resolution over 95% of the spectrum of Earth's thermal emitted radiation (200–2000 cm^{-1} or 5–50-μm wavelength) and solar reflected radiation (350–2300 nm) for the first time. This is the spectrum of energy that radiatively forces climate change and feedbacks. Because its spectral range spans many other instruments, CLARREO is a metrology laboratory in orbit, anchoring the global satellite monitoring system.

While most satellite missions strive for smaller spatial scales to improve understanding of Earth processes (Stephens et al. 2002, Winker et al. 2010), a climate change metrology mission like CLARREO must focus on larger scales—for example, the spatial patterns of critical climate feedbacks (Fig. 1). Climate models show that these feedbacks occur on spatial scales of 2,000 km or larger and are often very zonal in nature.

The Intergovernmental Panel on Climate Change (IPCC) typically uses a 5-yr running mean filter on decadal time series (Solomon et al. 2007) to reduce the impact of the typical (3–5-yr period) natural variability from El Niño–Southern Oscillation (ENSO) events. As a result, CLARREO focuses primarily on observing annual and longer time scales, with an initial benchmark climate record of at least 5 years. Chung et al. (2012) confirm that a 5-yr running mean is a lower bound on the duration needed to accurately

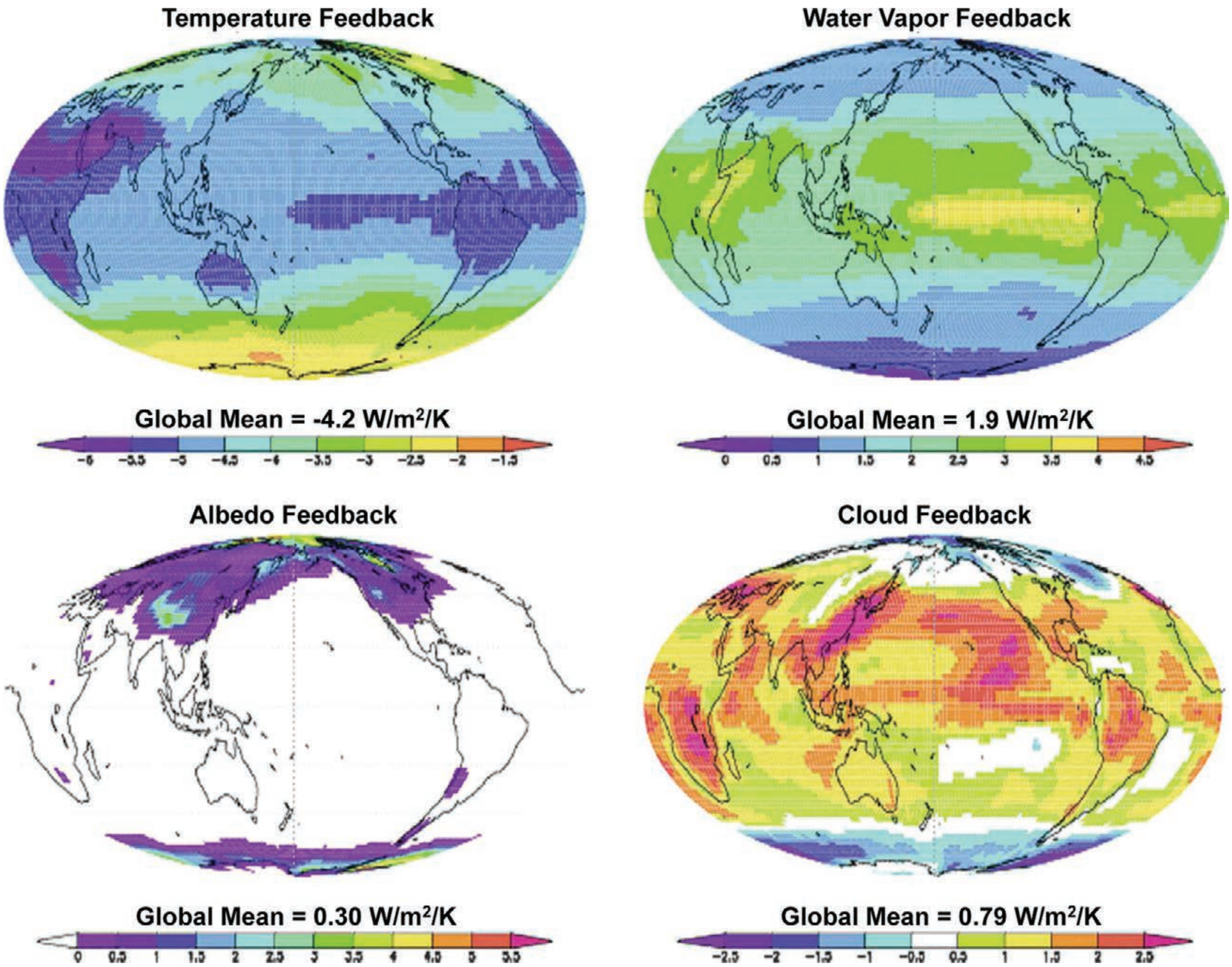

Fig. 1. IPCC Fourth Assessment Report (AR4) climate model ensemble means of decadal feedback for temperature, water vapor, surface albedo, and clouds (Soden et al. 2008). Only very large spatial scales of 2000 km and larger are driving sensitivity of the climate system to anthropogenic forcing, and thus CLARREO's focus is large scale.

MISSION AND INSTRUMENT DESIGN

CLARREO requirements (Table 1) were used to develop instrument designs, with the additional goal of reducing instrument size to minimize mass, power, and cost. A wide range of mission orbits, spacecraft, and launch vehicle designs were considered to optimize the requirements. Prototype designs were developed for all of the instruments, with similar designs being used to verify calibration accuracy tests in collaboration with NIST.

The CLARREO instruments are much smaller than typical weather instruments such as VIIRS (252 kg), CrIS (152 kg), and IASI (210 kg). This allows small spacecraft and launch vehicles. The entire suite of CLARREO instruments would require a satellite with mass of only one-third to one-sixth that of the flagship missions *Terra*, *Aqua*, or NPP.

CLARREO instrument design represents an advance in absolute calibration over existing instruments. Figure 2a demonstrates how this is achieved for the thermal infrared interferometer, including independent deep cavity blackbodies with multiple phase change cells for temperature accuracy; an infrared quantum cascade laser to monitor blackbody emissivity as well as spectral response; multiple deep space views to verify polarization sensitivity; and a heated halo on the blackbody to independently verify blackbody emissivity (Anderson et al. 2004; Dykema and Anderson 2006; Gero et al. 2008, 2012; Best et al. 2008). Figure 2b demonstrates the approach for the reflected solar spectrometer and its use of the moon as a reference for stability in orbit, the sun with multiple attenuators to verify instrument nonlinearity of gain across the Earth viewing dynamic range, and the ability to directly scan deep space to verify instrument offsets (Espejo et al. 2011; Fox et al. 2011). Spectral response is verified using solar spectral absorption line features. One critical difference quantify feedbacks in coupled ocean–atmosphere models. CLARREO's long-term focus depends on thousands of observations and hence on *accuracy*, whereas weather and climate process missions depend on instantaneous observations and hence their *precision*. Averaging measured spectra over large time and space domains reduces uncertainty due to uncorrelated random instrument noise to an insignificant level over time. Thus, on annual and longer time scales the main uncertainty in the measured CLARREO radiances is due to systematic uncertainty, not random noise.

This tolerance for moderate random instrument noise allows CLARREO to use smaller instruments

Table 1. Instrument and mission requirements. NEDT = noise equivalent differential temperature. FTS = Fourier transform spectrometer. S/N = signal-to-noise ratio. TRIG = Tri GPS GNSS RO Sensor. RAAN = right ascension of ascending node.

IR spectrometer	RS spectrometer	GNSS radio occultation	Spacecraft orbit
Systematic error <0.06 K (k = 2)	Systematic error <0.3% (k = 2) of Earth mean reflectance	Systematic error <0.06% refractivity (k = 2) for 5–20 km	90° ± 0.1° orbit for full diurnal sampling twice per year
200–2000 cm^{-1} spectral coverage	320–2300-nm spectral coverage	GPS and Galileo GNSS frequencies	Global coverage 90° inclination
0.5 cm^{-1} unapodized spectral resolution	4-nm spectral samples; 8-nm resolution	5–20-km altitude range refractivity	609 ± 0.2-km altitude, 61-day repeat
NEDT < 10 K for 200–600 cm^{-1}, and >1600 cm^{-1}, all others <2 K	S/N > 33 for 0.3 scene reflectance, at a solar zenith angle of 75°. S/N > 25 for λ > 900 nm	>1000 occultations per day to control sampling noise	RAAN of 0° or 180° to optimize reference intercalibration
25–100-km nadir FOV	0.5-km nadir FOVs for a 100-km-wide swath		5-yr initial mission record length
<200 km between successive spectra along the ground track	Polarization sensitivity <0.5% (k = 2) for λ < 1000 nm, <0.75% (k = 2) for λ > 1000 nm		Orbits repeat exactly each year to avoid diurnal/seasonal cycle aliasing
Nadir pointing, with systematic error <0.2°	Pointable in azimuth and elevation for solar, lunar, reference intercalibration views		RS and IR fly on same spacecraft or in close formation
Prototype design: 4-port FTS, 76-kg mass, 124-W avg power, 2.5 GB day^{-1}	Prototype design: Dual Grating Spectrometer, 69-kg total mass, 96-W avg power, 30 GB day^{-1}	Prototype design: TRIG receiver, 18-kg mass, 35-W avg. power, 1.2 GB day^{-1}	IR/RO- or RS-fueled spacecraft mass 370 kg, can fit on small launch vehicles

from other instruments in orbit is that the entire instrument can point at the Earth, sun (every 2 weeks), moon (monthly at 5°–10° phase angle), or deep space. This eliminates the need for scanning mirrors with angle-dependent calibration uncertainties, and allows the use of depolarizers to reduce polarization sensitivity to the required levels. Scanning the instrument view across lunar and solar disks provides images suitable for verifying stray light performance. Finally, any future improvements in the absolute reflectance of the lunar surface can be used to tie the CLARREO solar spectrometer results to future improvements in calibration beyond CLARREO, even should these improvements come 10 or even 30 years from now (Kieffer 1997; Kieffer and Stone 2005). Note that the calibration of the reflected solar is in terms of reflectance units, which can be converted to absolute radiance using the spectral total solar irradiance provided by instruments such as TSIS with an expected absolute accuracy of 0.25% (Richard et al. 2011).

The original CLARREO decadal survey mission called for three spacecraft at 90° inclination (NRC 2007; Kirk-Davidoff et al. 2005) to assure full 24-h diurnal sampling accuracy on regional, zonal, and global averages. The more recent development of the CLARREO accuracy requirements referenced to natural variability, combined with additional orbital sampling studies for IR and RS, demonstrated that the mission could be reduced to a single 90° orbit, significantly reducing mission cost. The 90° orbit is unique to CLARREO and assures full diurnal cycle sampling for spectral fingerprints as well as full reference intercalibration sampling over all climate regimes and all satellite orbit thermal conditions.

with smaller optics and less cooling of detectors. This enables CLARREO to utilize existing pyroelectric detectors sensitive in the far infrared (15–50 μm) that operate near room temperature (Anderson et al. 2004). Reduced optical and cooling system requirements lead to much smaller, lighter, lower-power, and lower-cost instruments. Smaller instruments can use smaller spacecraft and launch vehicles, all of which drive down costs. A mission focused on high absolute accuracy for decadal change results in a very different design from those for weather or climate processes. In fact, prior to CLARREO, NASA had never accommodated such requirements. New requirements methods had to be developed based on information discussed in this paper.

WHAT ACCURACY IS NEEDED FOR CLIMATE CHANGE OBSERVATIONS? With its absolute accuracy, CLARREO data will be relevant to decadal change observations not only 10 years but even 100 years from the start of CLARREO observations. As a result, unlike most missions, CLARREO must consider the impact of its science requirements decades from now. This suggests that requirement metrics be stated in terms of accuracy of decadal change and in terms of time to detect climate change. The former is more relevant to climate model testing, while the latter is more relevant to societal decision making.

But how do we decide what accuracy is needed? What metrics do we use? In general, scientists have struggled in making climate monitoring requirements more rigorous (Ohring et al. 2005). The science diversity of the CLARREO mission (reflected solar, thermal infrared, and radio occultation), along with recent budget challenges, demanded a rigorous approach. We now describe what evolved from CLARREO science team deliberations—an approach potentially applicable to a wide range of decadal climate change observations.

The critical insight is that even a perfect observing system for measuring long-term forcing and climate response is fundamentally limited by the noise of natural variability (Leroy et al. 2008b). Such variability includes a range of time scales: ENSO (3–5 yr), solar irradiance and sunspot cycles (11 yr), and the Arctic Oscillation, North Atlantic Oscillation, and Pacific decadal oscillation (10–30 yr). ENSO's importance is recognized by the IPCC with the aforementioned 5-yr running means for comparisons of decadal change datasets (Solomon et al. 2007). While ensemble techniques can reduce noise from natural variability in climate model predictions or hindcasts, all observed trends are subject to the confounding noise of natural variability. This means that there is a "floor" for required accuracy in climate trends: the observations need to have uncertainties smaller than, but of comparable magnitude to, natural variability. The key, therefore, is to quantify the relationship between natural variability and observing system accuracy (see the sidebar on "Quantifying climate change accuracy goals").

Even though climate changes are not simply linear trends, statistical trend analysis (Leroy et al. 2008a,b; Weatherhead et al. 1998; von Storch and Zwiers 1999)

Table 2. Sources of climate trend uncertainty using global annual mean observations. Uncertainty sources for Figs. 3a and 3b results using Eqs. (1), (2), and (A2). Values for natural variability are derived using 10 years of CERES observations (Wielicki et al. 1996), calibration uncertainties are the absolute accuracy goals for CLARREO (Table 1), orbit sampling uncertainties are derived using a single CLARREO 90° inclination polar orbit flown over 10 years of CERES SYN1deg-3Hour synoptic radiative fluxes and clouds observations interpolated to hourly and subsampled to nadir-only CLARREO orbit observations (Table 1), and instrument noise values are the CLARREO mission specifications (Table 1) for averages at global annual scales. For natural variability, a Student's *t* distribution is used to account for the relatively short 10-yr record. CERES is chosen as one of the most stable instruments in orbit (Loeb et al. 2007). The 10-yr record is sufficient to capture the dominant ENSO variability but short enough to avoid being dominated by decadal climate change. Infrared values are from CERES 8- to 10-μm window channel, and reflected solar cloud radiative forcing (CRF) from the broadband shortwave channel.

	IR/RO temperature trends		RS CRF trends	
Uncertainty source	σ (K)	τ (yr)	σ (CRF) (%)	τ (yr)
Natural variability	0.085	2.3	0.60	0.8
Calibration uncertainty	0.03	5	0.15	5
Orbit sampling uncertainty	0.018	1	0.21	1
Instrument noise uncertainty	0.005	1	<0.01	1

is useful for robust comparison of the impact of different error sources and thus for critical insights into mission science requirements.

We now give an example of how to use climate trend uncertainty in determining the absolute accuracy requirement of CLARREO's infrared and reflected solar spectrometers. These spectrometers will represent the greatest advance in accuracy over current instruments in orbit.

We first consider the accuracy of temperature trends using the infrared spectrometer. Depending on the infrared wavelengths chosen, trends could be examined for near-surface midtroposphere, or stratosphere temperatures (Leroy et al. 2008a; Huang et al. 2010a,b). The trend uncertainty δm (see equation in appendix A and sources listed in Table 2) includes natural variability, absolute calibration uncertainty, instrument noise, and orbit sampling uncertainty. Figure 3a demonstrates several key points about climate observations. First, trend accuracy increases with the length of the climate record, even for a perfect observing system, because of the need to average out noise in the climate system. Note that the IPCC predicted a global surface air temperature and tropospheric air temperature increase for the next few decades of roughly 0.2 K decade^{-1}. A climate record of 12 years is required to reach a trend uncertainty of 0.2 K decade^{-1} at 95% confidence, *even for a perfect observing system*. This shows dramatically the necessity of long climate records in understanding climate trends. To reach a 95% confidence level of 0.1 K decade^{-1} (i.e., smaller than the expected trend) requires a 20-yr climate record for perfect observations and 22 years with CLARREO accuracy. These results reaffirm that records shorter than 20 years contain little information on global temperature trends.

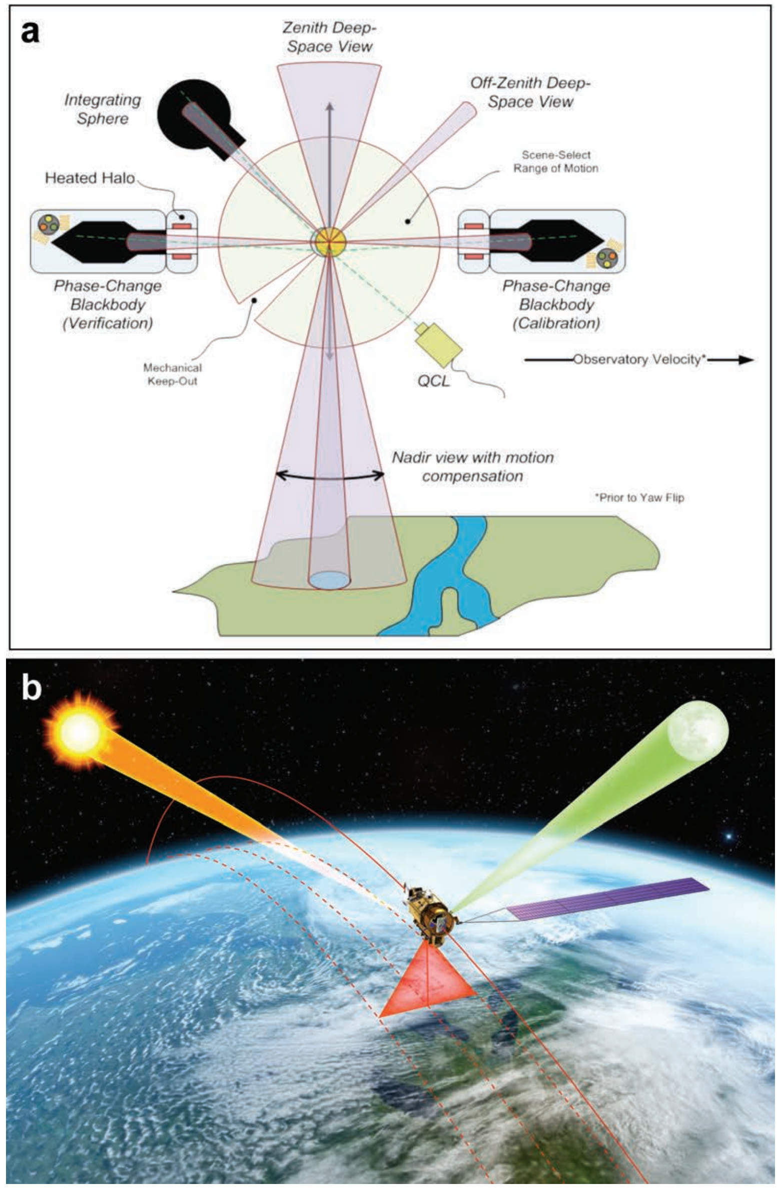

Fig. 2. CLARREO concepts for improved SI-traceable absolute accuracy in orbit. (a) The infrared relies on phase change cells at –39°, 0°, and 30°C to verify thermistor accuracy, quantum cascade laser and heated halos to verify blackbody emissivity, optics design to verify polarization sensitivity, and the quantum cascade laser with integrating sphere to verify instrument spectral response. (b) The verification of nadir spectral reflectance accuracy relies on rotating the entire instrument to view the moon at constant phase angle as a single-level stable reflectance source [similar to the Sea-viewing Wide Field-of-View Sensor (SeaWiFS)], the sun in combination with filters and precision apertures for nonlinearity determination, and the use of depolarizers to control polarization sensitivity.

Absolute calibration accuracy has a dramatic effect on climate trends (Fig. 3a). The CLARREO requirement is 0.06 K (k = 2) or equivalently 0.1 K (k = 3). At this absolute accuracy even short gaps do not significantly affect the climate record's accuracy (Leroy et al. 2008b). In fact, the trend accuracy is very close to that of a perfect observing system. Improving the CLARREO accuracy by a factor of 2 to 0.03 K ($k = 2$) has little effect and clearly reaches the point of diminishing returns. But degrading the CLARREO accuracy by a factor of 2 to a value of 0.12 K ($k = 2$) would degrade trend accuracy by more than 20%, and would increase from 22 to 26 years the time to detect a trend of 0.1 K at 95% confidence. Figure 3a shows that every degradation of calibration absolute accuracy by an additional 0.06 K delays the time to detect such a trend by 5 more years.

The absolute accuracy of weather spectrometers such as the Atmospheric Infrared Sounder (AIRS), IASI, and CrIS ranges from 0.2 to 0.4 K ($k = 2$) (Hilton et al. 2012; EUMETSAT 2011). For these instruments we rely on much weaker constraints for climate trends: instruments must typically overlap for a year or more (Loeb et al. 2009), and we must assume instrument calibration stability (Ohring et al. 2005; Ohring 2007). Figure 3 makes a worst-case assumption of either short gaps and/or instrument calibration drifts at the level of the absolute accuracy uncertainty defined for each instrument. This conservative approach is necessary for a result as critical as climate change. We conclude that absolute accuracy and long climate records are essential to highly robust climate trend observations.

Figure 3b shows the analogous result for the reflected solar spectrometer. Again, absolute calibration

QUANTIFYING CLIMATE CHANGE ACCURACY GOALS

In our example for CLARREO, we define an uncertainty factor U_a for climate trend accuracy. This uncertainty factor is the ratio of trend uncertainty for a real climate observing system to the trend uncertainty of a perfect observing system limited only by natural variability. The factor is unitless and can be applied generally to any climate variable: solar irradiance, reflected flux, surface temperature, spectral radiance, or sea ice extent. A perfect observing system would have a U_a value of 1.0. The value of U_a for any real observing system will exceed 1.0 because of uncertainties. Using the results of Leroy et al. (2008b) on the relationship between trend uncertainty for natural variability and uncertainty for the observing system, we can determine the accuracy uncertainty factor U_a as

$$U_a = \left(1 + \frac{\sigma^2_{\text{cal}}\tau_{\text{cal}} + \sigma^2_{\text{inst-noise}}\tau_{\text{inst-noise}} + \sigma^2_{\text{orbit}}\tau_{\text{orbit}}}{\sigma^2_{\text{var}}\tau_{\text{var}}}\right)^{1/2}, \quad (1)$$

where σ^2_{var} is the variance of natural variability for the climate variable of interest, τ_{var} is the autocorrelation time scale for natural variability [which for global annual 500-hPa temperature variability was shown by Leroy et al. (2008b) to be ~1.5 yr], σ^2_{cal} is the variance of the uncertainty in absolute calibration of the orbiting climate instrument performing the observation, τ_{cal} is the absolute calibration time scale (typically instrument lifetime), and the remaining observing uncertainties are for instrument noise and orbit sampling. Instrument noise time scale is very short, while orbit-related sampling uncertainty tends to be determined by the climate record time sampling interval, typically monthly, seasonal, or annual. Note that additional error sources can be added to the numerator in Eq. (1) as appropriate for each climate observation. Equation (1) is derived in appendix A.

The expression for U_a provides a powerful tool for understanding the trade space of climate monitoring observing system design versus system cost. It enters almost all expressions for uncertainty in trend determination, whether it is the difference between two missions broadly separated in time, the slope of a continuous time series of data, or even quadratic and higher-order fitting to a long time series of data. The autocorrelation time scale τ for each uncertainty source essentially determines the number of independent samples n that will exist for any climate record of length Δt. If we consider the case of undetectable, slow instrument calibration drifts in orbit, or the case of changing absolute accuracy of instruments with gaps between their deployments, the resulting relevant time scale for τ_{cal} is the instrument lifetime on orbit, typically about 5 years. Using Eq. (1) we can see that, compared to orbit sampling time scales for annual mean time series, calibration drifts will in general have much more impact on climate trend uncertainty, except if the orbit sampling uncertainty is caused by a slow systematic drift in the time of day of the observations, as seen in the National Oceanic and Atmospheric Administration (NOAA) polar orbit data in the 1980s and 1990s. Modern polar orbiters, however, are designed to maintain time of day and eliminate this long time scale. Examination of Eq. (1) shows that the key metric for any individual error source is the ratio $(\sigma_i^2\tau_i)/(\sigma^2_{\text{var}}\tau_{\text{var}})$. As long as this ratio is significantly less than 1, then its impact on the observation of climate trends will be small. Equation (1) also allows the climate observing system to rigorously trade the value of decreasing one error such as calibration accuracy versus another such as orbit sampling. For all CLARREO mission observations (reflected solar, thermal infrared, and radio occultation), U_a was required to be less than 1.2. In other words, CLARREO is designed to observe climate trends to within 20% of the accuracy of a perfect observing system. This method of setting requirements allows a consistent treatment across diverse climate variables, each with their own estimates of natural variability. The method also avoids the costs of pursuing perfection that may add little value to observing trends, and provides a quantitative floor for climate accuracy. In particular, Eq. (1) shows (see also Fig. 3) that when error sources are a factor of 2–3 below the level of natural variability, further increase in accuracy yields greatly diminished benefit.

uncertainty dominates the accuracy of global average trends. Uncertainty in climate sensitivity is driven primarily by uncertainty in cloud feedback, which in turn is driven primarily by low cloud changes varying Earth's albedo (Solomon et al. 2007; Bony et al. 2006; Soden et al. 2008). We can derive a simple metric of cloud feedback for reflected solar by considering the trend in global mean shortwave cloud radiative forcing (SW CRF) (Soden et al. 2008; Loeb et al. 2007). Global mean SW CRF is simply the difference between all-sky and clear-sky reflected flux.

As for temperature trends (Fig. 3a), the perfect observing system again shows the need for long climate records for accurate trends in SW CRF (Fig. 3b).

What about time to detect trends? Using Leroy et al. (2008b) we can define an analogous uncertainty factor U_t—the ratio of the time to detect a trend using a real observing system to the time to detect a trend using a perfect observing system. Such a ratio can be defined for any climate variable or statistical confidence bound desired. Again extending the results from Leroy et al. (2008b),

$$U_t = \left(1 + \frac{\sigma^2_{\text{cal}}\tau_{\text{cal}} + \sigma^2_{\text{inst-noise}}\tau_{\text{inst-noise}} + \sigma^2_{\text{orbit}}\tau_{\text{orbit}}}{\sigma^2_{\text{var}}\tau_{\text{var}}}\right)^{1/3}. \quad (2)$$

The only difference between Eqs. (1) and (2) is that the square root on the right side of the equation becomes a cube root. Since U_a and U_t are always greater than 1, and are usually near 1, Eqs. (1) and (2) show that

$$(U_t - 1) \approx \frac{2}{3}(U_a - 1). \quad (3)$$

Another way of interpreting Eq. (3) is that the degradation of trend accuracy for time to detect trends is only two-thirds of the degradation for accuracy in trends. For example, the CLARREO requirement that $U_a < 1.2$ equivalently requires that $U_t < 1.13$. How do we interpret the meaning of $U_t = 1.13$? If a perfect observing system could detect a temperature trend with 95% confidence in 20 years, then the CLARREO observing system could detect the same trend with 95% confidence in 23 years (13% more time).

These equations give a simple but powerful way to understand the value of observing system accuracy for both climate trend accuracy (e.g., tests of climate predictions) and time to detect trends (e.g., public policy decisions). They also provide a way to compare consistent metrics across a wide range of climate variables, as well as a wide range of sources of uncertainty in climate observations. We strongly encourage use of this approach to more rigorously understand and optimize climate observation requirements across the wide range of essential climate variables (ECVs) (GCOS 2011). This is especially important given the limited resources available for global climate observations (Trenberth et al. 2013).

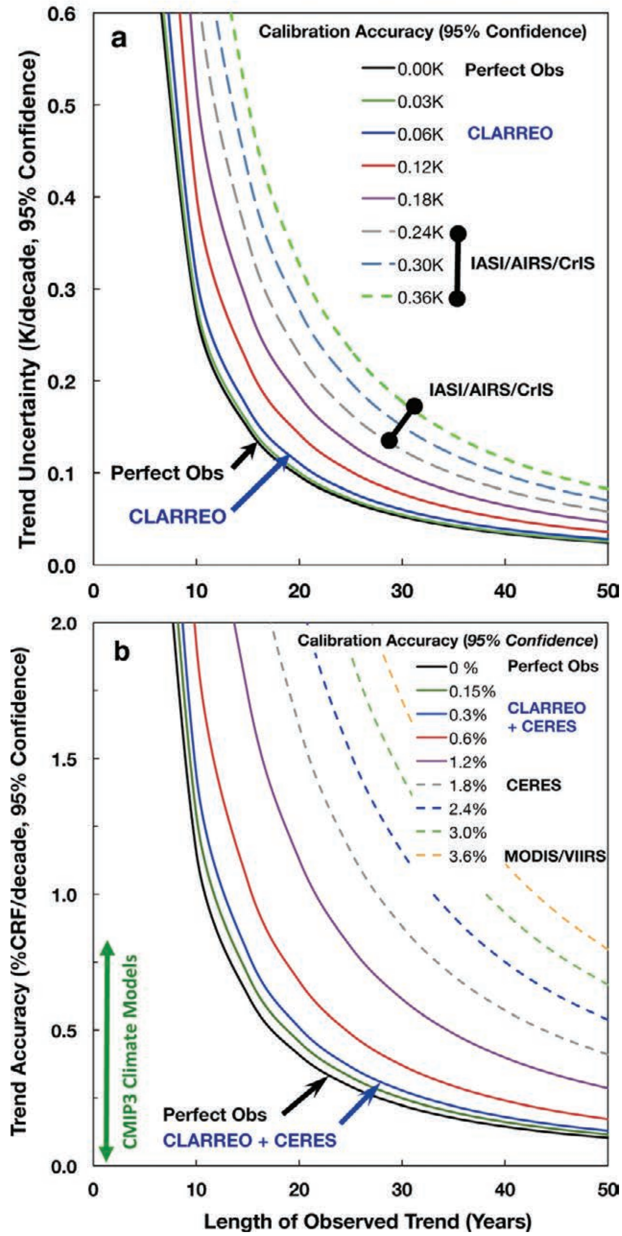

Fig. 3. The relationship between absolute calibration accuracy and the accuracy of global average decadal climate change trends. Trend accuracy shown for a perfect observing system (black), varying levels of instrument absolute accuracy (solid color lines) for possible CLARREO requirements, and current instruments in orbit (dashed lines). Shown are (a) the relationship between infrared spectra accuracy and temperature trends and (b) the relationship between reflected solar spectra and changes in broadband CRF and cloud feedback. The figures show the dramatic effect of instrument accuracy on both climate trend accuracy (vertical axis) as well as the time to detect trends (horizontal axis). The green vertical line for reflected solar shows the range of CMIP3 climate model simulations (Soden and Vecchi 2011). Larger values of decadal change in SW CRF indicate larger values of cloud feedback (Soden et al. 2008).

Most climate models predict low clouds as a positive feedback that can be observed as decadal changes in SW CRF (Soden et al. 2008; Soden and Vecchi 2011). Future observations will be required to greatly reduce uncertainty in climate sensitivity (currently almost a factor of 3) for clearer understanding of climate change risks over the next century, as well as to monitor as rapidly as possible the future effectiveness of any future carbon emission controls (Trenberth et al. 2013). Studies of the economic impacts of climate change conclude that a factor of 3 uncertainty in climate sensitivity leads to roughly a factor of 9 uncertainty in economic impacts, a quadratic relationship (Interagency Working Group on the Social Cost of Carbon 2010). A decadal change in SW CRF of 1% decade^{-1} changes the Earth's radiation balance as much as the anthropogenic radiative forcing of 0.5 W m^{-2} decade^{-1} expected over the next few decades (Solomon et al. 2007). Figure 3b shows that a signal this large would take 12 years to detect with a perfect observing system. A smaller cloud feedback of half this magnitude (0.5% decade^{-1}) would require 17 years of observations at 95% confidence for a perfect observing system, and 20 years with a CLARREO accuracy of 0.3% (k = 2).

As for the infrared example, the CLARREO accuracy requirement for the reflected solar spectrometer of 0.3% (k = 2) is nearly as accurate as a perfect observing system. But just as for the infrared, as the accuracy degrades from the CLARREO requirement, the accuracy of trends and the time to detect trends decays rapidly. Current instruments in orbit include CERES (2%) and the Moderate Resolution Imaging Spectroradiometer (MODIS; 4%) for k = 2 absolute accuracy. Both of these instruments rely on extensive overlap and assumptions about stability on orbit (Loeb et al. 2007). Any gaps essentially restart the climate record from zero because absolute accuracy differences exceed climate change signals. (Loeb et al. 2009).

Achieving the accuracy in SW CRF decadal change shown in Fig. 3b requires CLARREO to provide reference intercalibration to CERES broadband radiances, while CERES provides the angular sampling critical to accurate radiative fluxes (Loeb et al. 2003). Achieving accuracy in the decadal change of critical cloud properties related to SW CRF such as cloud optical depth similarly requires CLARREO to provide reference intercalibration to global cloud imagers such as VIIRS. Verifying that climate models produce the right cloud feedback with the correct physics requires both CLARREO-calibrated CERES and VIIRS observations.

CLARREO requires 0.06% (k = 2) accuracy for RO in the ~5–20-km altitude range. As with RS and IR, this requirement is derived from an estimate of natural variability, in this case taken from RO simulations using the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-Interim; Dee et al. 2011) from 2000 through 2008. Unlike RS and IR, random sampling error dominates the uncertainty at this altitude and leads to a requirement of at least 1000 soundings daily (see Table 1).

Natural variability cannot be known exactly. This uncertainty is partially due to the short observational records, the nonstationarity of recent climate, and unresolved contributions of multidecadal oscillations (Swanson et al. 2009; DelSole et al. 2011; Huber and Knutti, 2011; Leroy et al. 2008b; Foster and Rahmstorf 2011). An exact knowledge of natural variability, however, is not required for setting instrument accuracy requirements. Consider the CLARREO goal of accuracy within 20% of a perfect observing system, U_a = 1.2, where U_a is the ratio of climate trend accuracy of an actual observing system to that of a perfect observing system (see sidebar "Quantifying climate change accuracy goals" for equations and discussion). Absolute calibration dominates the observational uncertainty for global and zonal trends. To achieve U_a = 1.2, we can use Eq. (1)[2] from the sidebar "Quantifying Climate Change Accuracy Goals" to determine that, even if the variance of natural variability (σ_{var}) is increased by 50%, U_a will only decrease from 1.2 to 1.1. Alternatively, a 30% decrease in σ_{var} will only cause a 15% change in U_a from 1.2 to 1.4. Thus, it is sufficient to know the magnitude of natural variability to within 30%–50%, and using 100-yr-long preindustrial coupled ocean–atmosphere climate model simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) we find variations of 30%–50% above and below our values in Table 2.

Since Figs. 3a and 3b are for global temperature trends, the following question arises: How well do these concepts apply at zonal, regional, or other scales? This question is especially relevant to observing and comparing tropical and polar trends, or land versus ocean trends. For global mean time series using monthly, seasonal, and annual time averaging we found almost no differences in the results as differences in variance compensated changes in autocorrelation time. For annual zonal

[2] In other words, we require $\left(\sigma^2_{cal}\tau_{cal}\right) / \left(\sigma^2_{var}\tau_{var}\right) \le 0.44$.

(10°) and regional (10° latitude × 30° longitude) scales, temperature, and CRF natural variability increased by factors of 3 from global to zonal and 9 from global to regional. As a result, regional trends must be much larger than global trends to be detected above natural variability. Because CLARREO has only nadir views, orbit sampling and instrument noise uncertainties increase at these smaller spatial scales; but relative to natural variability, the increase is slow enough to ensure the same $U_a < 1.2$ found for the global average. The balance of the sources of instrument uncertainty in Eq. (1) varies with time/space scale, but the overall uncertainty is similar. We conclude that, for the large time/space scales typical of global climate change (Soden et al. 2008), a single metric of climate change accuracy is sufficient to design a consistent set of mission and instrument requirements.

At much smaller spatial scales such as 100–1000 km, orbit sampling will be increasingly important, and a nadir-viewing instrument cannot meet the sampling requirements. The more traditional instruments such as MODIS, VIIRS, Advanced Very High Resolution Radiometer (AVHRR), CrIS, IASI, and CERES can meet those requirements when they are intercalibrated against the CLARREO spectrometers (see more on this topic below).

CLIMATE CHANGE OBSERVING SYSTEM SIMULATION EXPERIMENTS. At times the simple view presented above will miss some aspects of a key climate observation. An example is climate change spectral fingerprinting. For example, with CLARREO we will use the decadal change in Earth's emitted infrared spectra and reflected solar spectra to "fingerprint" signals of climate change (Goody et al. 1998; Huang et al. 2010a,b; Feldman et al. 2011a,b; Jin et al. 2011; Kato et al. 2011, Roberts et al. 2011) in temperatures at various levels, water vapor, cloud properties, surface vegetation, snow/ice cover, or the effects of greenhouse gases on thermal emission. The effects are broad because they include the entire spectrum of Earth's reflected and emitted radiation.

Since climate change is primarily driven by changes in planetary radiation, different portions of the Earth's spectrum respond in climate change scenarios. These same spectral regions have been used for instantaneous satellite retrievals of geophysical properties as well as radiance constraints for numerical weather prediction and climate reanalysis (Kalnay et al. 1996; Derber and Wu, 1998; McNally et al. 2006). For climate change spectral fingerprinting, spectra are averaged over space and time. The advantage of this new approach is to eliminate the instantaneous nonlinear retrieval step, and to provide an alternative to reanalyses. While reanalyses are useful in many ways, they continue to struggle to achieve highly accurate climate trend observations (Dee 2011; Saha et al. 2010; Thorne and Vose 2010; Rienecker et al. 2011).

To use time–space-averaged spectra to fingerprint climate change, the spectral changes must be sufficiently linear with changes in geophysical variables, so that averaging does not corrupt climate change signals. Since the instantaneous retrievals from spectra are nonlinear, this might appear to be a poor assumption. The small time and space scales of weather involve large changes in temperature, humidity, and clouds, so linearity can be a poor assumption. Climate change, however, consists of very small changes in distributions of geophysical variables, much like the small change approximations used for Taylor expansions of nonlinear mathematical equations. Typical decadal changes are much less than 1% and clearly are small perturbations. Thus, linearity is likely valid at large time and space scales but the degree of linearity must be verified. Our simple Eq. (1) in the sidebar "Quantifying climate change accuracy goals" does not answer this more sophisticated question, but a climate observing system simulation experiment (OSSE) can. We first define climate OSSEs, and then show examples of how such experiments increase understanding of climate observation requirements.

Climate OSSEs are based entirely on climate models' simulations. Models—not Earth, but Earth-like in their physics—have many advantages for conceptual testing of observing systems: the model

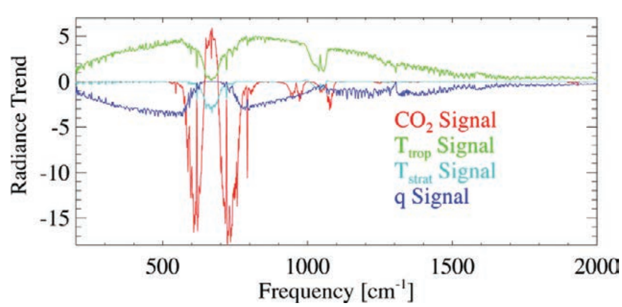

Fig. 4. Global average spectral infrared fingerprints of climate change trends based on the first 50 years of an IPCC Special Report on Emissions Scenarios (SRES) A1b climate change scenario (from Fig. 1 of Leroy et al. 2008a). Each climate variable changes individually while holding all other variables fixed: CO_2 shows the effect of increased carbon dioxide, T_{trop} shows the effect of tropospheric temperature, T_{strat} shows stratospheric temperature, and q shows tropospheric water vapor. Radiance trend units are 10^{-5} W m^{-2} (cm^{-1})$^{-1}$ ster^{-1} yr^{-1}.

climate change is known exactly, the model anthropogenic forcings (if included) are known exactly, and the output "data" are known exactly and have no gaps, sampling uncertainties, or drifting instrument calibration issues. A climate OSSE, then, uses simulations of climate change over decades to test the value of a particular observing system. An example is to understand the value of observations to determine the different feedbacks that contribute to climate sensitivity. Figure 1 from Soden et al. (2008) shows one type of climate OSSE, using the spatial patterns of climate feedbacks to understand the required spatial resolution of decadal climate change observations. The figure shows that climate feedbacks occur on the scale of thousands of kilometers and are often zonal in structure.

While understanding spatial sampling requirements is a good first step, CLARREO needed a different approach to understand the ability of spectral fingerprinting to observe climate change and to rigorously test climate model predictions. The climate OSSE approach uses climate model output histories to drive high-spectral-resolution radiative transfer models that could simulate the CLARREO infrared and reflected solar spectra on regional scales as well as monthly, decadal, and even centennial scales. This effort began with pioneering efforts in the infrared spectra (Leroy et al. 2008b; Huang and Ramaswamy 2009; Huang et al. 2010a,b, 2011). Figure 4 shows an example of the thermal infrared climate change spectral fingerprints for a range of climate variables for tropical clear-sky conditions: atmospheric carbon dioxide concentration, tropospheric and stratospheric air temperatures, and tropospheric water vapor (Leroy et al. 2008a). The examples are developed from the first 50 years of a climate model simulation using the IPCC A1B emissions scenario. Most of the climate change spectral fingerprint signals occur in the spectrum between 200 and 2000 cm^{-1}, which includes over 95% of the infrared energy emitted to space. The spectral fingerprints demonstrate the diversity of climate change signals and do not require satellite nonlinear retrievals to observe. Future climate models could directly predict the amplitude and shape of such fingerprints both for natural and anthropogenic climate change, and then use these as a test against climate observations (Leroy et al. 2008a; Kato et al. 2011).

Climate model OSSE results were also used to test the linearity of the infrared spectral fingerprints, showing climate change nonlinearities below 1% at most wavelengths (see appendix B). Finally, the climate OSSEs provide methods to determine the ability of infrared spectral fingerprints to determine cloud feedbacks, which have been shown to be more effective for high clouds than for low clouds (Huang et al. 2010a,b; Kato et al. 2011).

CLARREO climate OSSEs have also been carried out for the reflected solar spectra (Feldman et al. 2011a,b). The spectral fingerprints in Fig. 5a show the signals of polar snow and ice changes, water vapor changes, and cloud changes. Clear-sky and cloudiness changes can be separated by considering all-sky and clear-sky-only spectral fingerprints (Feldman et al. 2011a,b). Given the critical importance of determining the time needed to detect climate change above natural variability, climate OSSEs can also use unforced control runs to determine the climate model natural variability level, and then use this when determining the time to detect trends. For example, Fig. 5b shows that the time to detect trends is a strong function of latitude and wavelength. Water vapor trends can be detected near 2300 nm in as little as 5–7 years, while cloud and surface trends vary from 10 to 30 years. The CLARREO climate OSSEs have proven extremely useful in these early results. Next steps include adding the satellite orbits, along with combined RS, IR, and GNSS-RO spectral fingerprint testing of observations in the same climate model simulations. Climate OSSEs have already shown that combining IR and RO significantly improves discrimination of climate change fingerprints (Huang et al. 2010a). Finally, climate OSSEs should explore a wide range of climate models with varying physics such as perturbed physics ensembles (Murphy et al. 2004) or model ensembles of opportunity such as the Coupled Model Intercomparison Project (Taylor et al. 2012) in order to better establish uncertainty in the results.

Many climate observation systems would greatly benefit from climate OSSEs to improve understanding of the observation requirements, as well as the trade space for prioritization of different observational approaches. Given the severe cost-constraining environment for new climate observations, climate OSSEs represent a critical tool to more effectively and more efficiently plan climate observing systems.

IN-ORBIT REFERENCE CALIBRATION STANDARD FOR OTHER SATELLITE SENSORS. In addition to the major advances in metrology over the last 20 years (Brown et al. 2006; Fox et al. 2011; Dykema and Anderson 2006), there have been major advances in methodologies and techniques to intercalibrate satellite sensors in orbit. The critical need for sensor intercalibration has led to an international effort called the Global Space-Based Intercalibration System (Goldberg et al. 2011). However, GSICS has a major limitation: the lack of high-accuracy reference radiometers. Intercalibrating two instruments in orbit is useful, but at least one of the radiometers should be a reference traceable to international standards at climate change accuracy (Goldberg et al. 2011).

A second major challenge is that the reflected solar instruments [e.g., Geostationary Operational Environmental Satellite (GOES), MODIS, AVHRR, VIIRS, CERES, Geostationary Earth Radiation Budget (GERB), and Landsat] all have very different spectral response functions. This means that the accuracy of even relative intercalibration between these instruments is typically limited to a few percent, as each instrument views a different part of the reflected spectrum. Unfortunately, this uncertainty is a factor of 10 worse than the 0.3% (k = 2) accuracy requirement for reflected solar climate change observations we have discussed.

A third limitation is that the polarization sensitivity of reflected solar imagers like MODIS or VIIRS varies with instrument scan angle (i.e., scanning mirror angle), making the usual intercalibration approach—simultaneous nadir overpasses (SNOs)—incomplete. Unfortunately, SNO is the current state of the art for most instruments because orbit geometry, combined with the typical fixed cross-track scan, limits matching of time, space, and angle to nadir views only. The CERES instrument with both azimuthal and elevation rotation (a biaxial scan) demonstrated the possibility of angle/time/space-matched observations for a wide range of conditions when satellites cross orbits (Haeffelin et al. 2001; Clerbaux et al. 2009).

The limitations for today's instruments are not inherent for future instruments. CLARREO uses lessons from GSICS and CERES to address the major limitations in several ways. First, CLARREO provides a factor of 4–10 improvement in absolute accuracy over current Earth-viewing RS and IR instruments, which is necessary for a reference radiometer anchoring GSICS calibrations. Second, CLARREO uses sufficiently high resolution and broad spectral coverage to accurately match the spectral response function of the major reflected solar or infrared instruments, including CrIS, AIRS, IASI, MODIS, VIIRS, AVHRR, Landsat, and CERES, as well as geostationary imagers and sounders (Doelling et al. 2012, Tobin et al. 2006). Third, the CLARREO reflected solar spectrometer adds biaxial scan capability, allowing matched time/space/angle observations during orbit crossings with another satellite. Fourth, CLARREO provides solar spectral reflectances with polarization sensitivity of less than 0.5%, (k = 2) below 1000 nm, and less than 0.75% (k = 2) above 1000 nm—better accuracy than

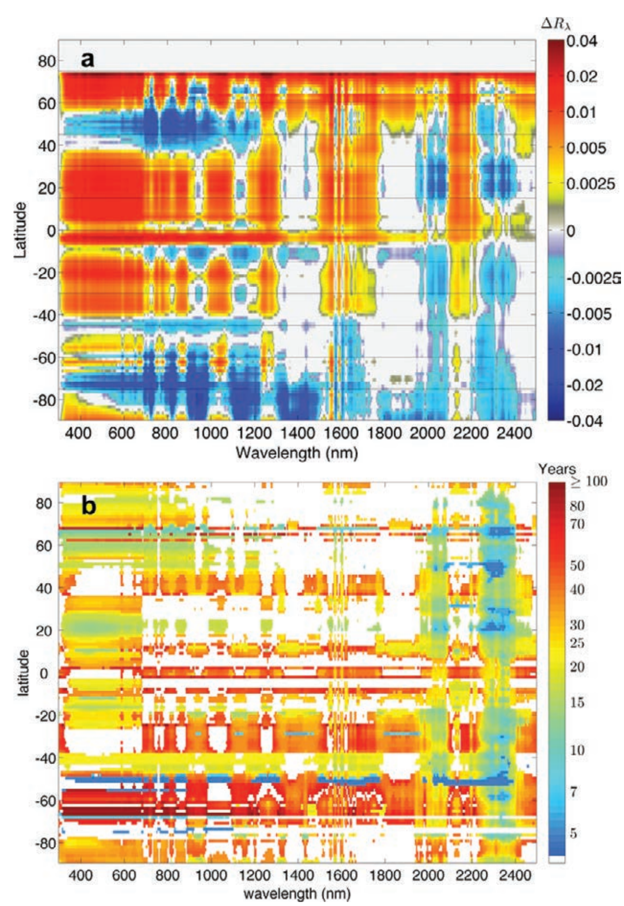

Fig. 5. A simulation of CLARREO zonal mean spectral nadir all-sky reflectance changes (Feldman et al. 2011a) using the National Center for Atmospheric Research (NCAR) Community Climate System Model, version 3 (CCSM3) climate model output for the IPCC AR4 A2 anthropogenic climate change scenario, adding much more sophisticated surface, cloud, and atmosphere solar scattering, including the 4-nm CLARREO spectral resolution used to resolve climate change signals. (a) The latitudinal dependence of spectral climate change signals from the ultraviolet (350 nm) to the near infrared (2500 nm)—encompassing 96% of the solar energy reflected back to space, and shows climate change anomalies for December–February (DJF) of the 2050s decade vs the 2000s decade. Clear regions indicate signals below the level of natural variability at 95% confidence. (b) Estimates of natural variability are used in combination with the climate change signals in (a) in order to quantify time to detect climate trends. In clear regions times to detect spectral trends are similar to those for broadband reflected solar radiation; colored regions have shorter time to detect trends.

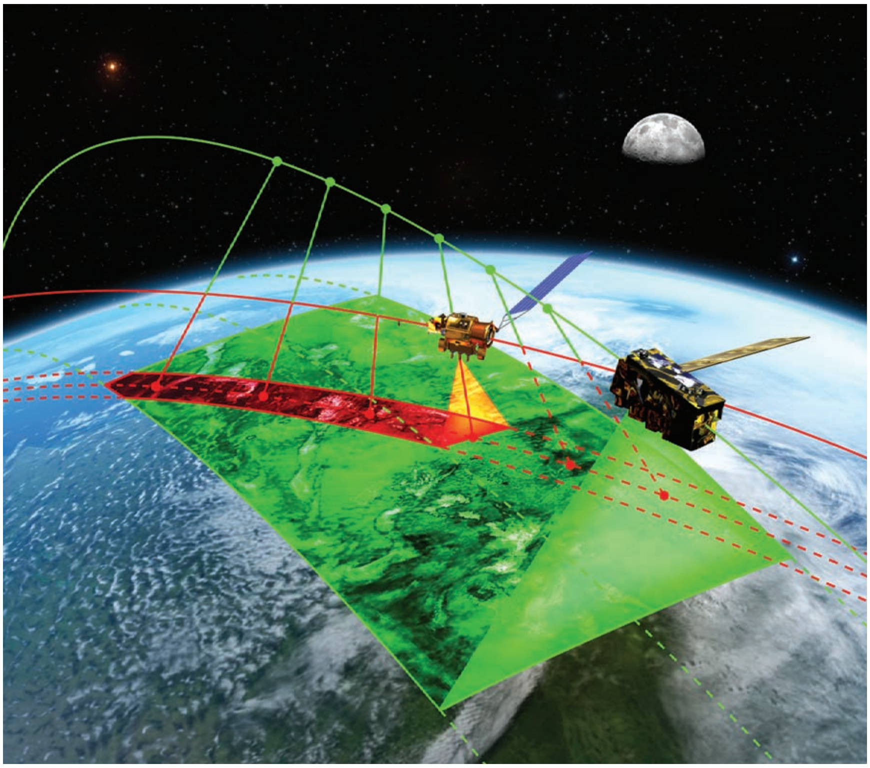

Fig. 6. As the CLARREO orbit (red; 609-km altitude, 90° inclination) crosses that of a satellite such as NPP or MetOp (green) (827-km altitude, 1330 LT sun-synchronous orbit with 98.7° orbit inclination) with an operational sensor, the CLARREO infrared and reflected solar spectrometers gather data matched in time, space, and angle of view to provide reference intercalibration SI-traceable spectra for operational sensors that cannot achieve climate change accuracy directly. As a metrology transfer standard in orbit, CLARREO is an anchor for the climate observing system.

required for decadal climate change observations. Fifth, CLARREO has demonstrated that scene and viewing geometry-dependent polarization distribution models (PDMs) (Nadal and Breon 1999; Maignan et al. 2009) allow CLARREO to determine the scan-angle-dependent polarization sensitivity of imagers such as VIIRS, AVHRR, or geostationary imagers, as well as to enable those instruments to remove this scene-dependent polarization dependence (Lukashin et al. 2012). Sixth, the CLARREO 90° inclined polar orbit (see Table 1) slowly drifts through all 24 hours of local solar time over 6 months. This orbit allows reference intercalibration orbit crossings with satellites at all latitudes, which is important for verifying accuracy across all climate regimes, as well as for verifying if instruments have orbit-dependent calibration changes, especially from the different hot/cold parts of the orbit in or out of direct solar illumination. By contrast, sun-synchronous satellites only cross orbits at polar latitudes, which is another limitation of current GSICS methods. Simulations show that CLARREO reference intercalibration sampling is sufficient to determine instrument gains and offsets on a monthly time scale, while polarization sensitivity, nonlinearity, and orbit position dependence can be achieved on annual time scales.

In Fig. 6, CLARREO crosses under the Suomi National Polar-Orbiting Partnership (NPP) or Joint Polar Satellite System-1 (JPSS-1) orbit. CLARREO matches elevation and azimuth directions across the cross-track scans of CERES, VIIRS, and CrIS by setting the azimuth angle of the CLARREO instrument to match the NPP scan plane and then slowly rotates the CLARREO RS spectrometer (mounted on a gimbal) to match viewing zenith angles across the entire scan during the orbit crossing. The azimuth angle for this match varies from orbit crossing to orbit crossing but is essentially constant for any single orbit crossing (Roithmayr and Speth 2012).

The time available for the matching scan is directly proportional to the orbit altitude separation of the two spacecraft. Spacecraft at the same altitude have only a few seconds to obtain the entire scan swath, while several minutes are available for an orbit separation of 100 km or more (Roithmayr and Speth 2012). For this reason, the CLARREO design orbit altitude is ~600 km—sufficiently high to minimize fuel use for orbit control, sufficiently low to minimize launch vehicle requirement for mass to orbit, and well below the typical polar orbiter altitudes of ~825 km [NPP, JPSS, and the Meterological Operational Satellite (METOP)] to increase the matched scan angle intercalibration time. Thus, the orbit selection and gimbal azimuth/elevation-pointing capability will allow CLARREO to increase reference intercalibration sampling by more than a factor of 100 compared to current GSICS capabilities, whereas typical SNOs restrict polar-orbiting satellites to the polar regions and geostationary satellites to the equator.

Simulations of these orbit crossings have been carried out to determine requirements for spatial matching, angle-of-view matching, and time matching for reference intercalibration to reach the CLARREO levels of accuracy for IR and RS. We conclude that the intercalibration uncertainty is comparable to the CLARREO instrument calibration uncertainty, and consistent with the decadal change accuracy goals derived in Eqs. (1) and (2).

Reference intercalibration for the infrared channels is discussed here, while the reflected solar case can be found in appendix C. For the infrared, the strategy is to use nadir-to-nadir orbit crossing matches of CLARREO with weather sounding spectrometers such as AIRS, CrIS, and IASI. Nadir is sufficient given the much lower sensitivity of the infrared spectrometers to angle-dependent polarization. Studies for space/time matching using AVHRR to AVHRR overpasses (Wielicki et al. 2008), as well as AIRS/MODIS/IASI orbital crossings (Tobin et al. 2006), show that a CLARREO field of view (FOV) ranging from 25 to 100 km would give sufficient spatial matching.

The effect of spatial matching errors for varying CLARREO FOV sizes was simulated using the MODIS 11-μm window channel 1-km data as a worst-case scenario and then simulating the CLARREO, AIRS, IASI, and CrIS field-of-view patterns during simulated orbital overpasses. Time matching was also studied and determined to require simultaneity within 30 min, along with angle matching of about 5°. As expected, all of the results showed much less variability with time/space/angle for the thermal infrared when compared to the reflected solar wavelengths, thereby simplifying the intercalibration requirements relative to the reflected solar.

Spectral matching in the infrared can be accomplished with high accuracy given the CLARREO 0.5 cm^{-1} unapodized spectral resolution. Instrument noise was also varied in these studies, given that CLARREO instrument noise at wavelengths overlapping the AIRS/IASI/CrIS/VIIRS wavelengths varies from 0.5 to 2 K. The intercalibration studies concluded that CLARREO would achieve sufficient sampling and angle/time/space/wavelength matching for determining infrared instrument offsets, gains, and instrument nonlinearity, as well as for intercalibrating as a function of orbit position to test any residual thermal environment issues from cold to hot sides of the orbit.

These early studies conclude that CLARREO can provide the in-orbit "reference radiometer" for other reflected solar and thermal infrared radiometers. GSICS has confirmed the critical need for such a mission, and CLARREO could greatly improve the accuracy and relevance of a wide range of instruments for decadal climate change. (The sidebar "Impacts on Earth Science beyond long-term climate change monitoring" summarizes CLARREO science impacts beyond climate change.)

FUTURE DIRECTIONS. In November 2010, CLARREO successfully passed its mission concept review: a major milestone required before moving to formal mission implementation (see the sidebar "Mission and instrument design"). Launches were planned for 2018 and 2020. Unfortunately, in early 2011, reductions in NASA's Earth science budget required that the launch be delayed to no earlier than 2022. While this is unfortunate, space missions

IMPACTS ON EARTH SCIENCE BEYOND LONG-TERM CLIMATE CHANGE MONITORING

Some of the benefits of CLARREO can be realized in the first few years of the mission and do not require the decades needed to detect climate change. We will give two key examples.

First, CLARREO will provide the first full infrared spectral observations from space, including the first spectral observations of the far infrared from 200 to 650 cm^{-1} (15–50-μm wavelength). The far infrared includes 50% of the Earth's infrared energy emitted to space and contains most of the Earth's water vapor greenhouse effect (Mlynczak et al. 2006). As a result, this spectral region dominates the physics of the water vapor feedback in climate but has yet to be observed from space to verify climate model simulations of these processes. The effect of clouds in the far infrared also remains unobserved in high-resolution spectra, and radiative transfer model discrepancies have been identified in the limited number of far-infrared measurements that have been made in the presence of clouds (Cox et al. 2010).

Second, the ability to provide a reference standard for intercalibration for the infrared and reflected solar radiometers in Earth orbit will improve the analysis of a wide range of Earth observations, including more accurate bias corrections in weather assimilation and weather prediction, and enable more consistent land process observations, atmospheric-state observations, aerosols, atmospheric chemistry, and ocean and land surface temperatures. CLARREO does not replace any of these observations, but instead makes them all more capable.

are often delayed because of cost overruns of earlier missions or changes in NASA budget plans.

Currently, CLARREO remains in prephase-A studies designed to further advance the science and reduce technology development risks. A new CLARREO Science Definition Team, selected in January 2011, will continue advancing CLARREO climate OSSEs and simulations using existing data sources. The delay will also allow engineering teams to design, build, and test calibration demonstration systems for both the RS and IR spectrometers. These systems will reduce development risks by demonstrating CLARREO-like spectrometer calibration performance using the planned methodologies and verification of accuracy in collaboration with National Institute of Standards and Technology (NIST) researchers. Given the difficult budget environment, studies are also underway to look for further ways to reduce cost, such as use of the International Space Station (ISS) or small Venture Class missions, while achieving most of the CLARREO science objectives. The ISS mission option could achieve 70% of the baseline mission science at a cost of 40% of the baseline mission, or $430 million in real year dollars, the cost of a small NASA mission. From a technology readiness standpoint, this alternative mission option could be ready for launch by 2019, but this is not in the current NASA budget.

Efforts are also underway for international collaboration in CLARREO-like missions. Establishing SI-traceable standards in orbit is similar to establishing metrological standards here on Earth. International standards require independent verification. Therefore, the long-term vision is for at least one international version of CLARREO for independent verification of the U.S. mission. The CLARREO team has been collaborating with two mission proposal groups in Europe: the Traceable Radiometry Underpinning Terrestrial and Helio Studies (TRUTHS) mission (Fox et al. 2011) for high-accuracy solar reflected spectra and the Far Infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission for high-accuracy thermal infrared spectra. While the CLARREO team is the farthest along in development at this time, future collaboration will be key to achieving the accuracy for global climate change data that the world so critically needs.

These missions represent a new era of climate change accuracy viewing the entire globe, and provide a foundation for the first true global climate observing system. Imagine if we had achieved these levels of observation accuracy from the origin of global satellite observations in the late 1960s and early 1970s. We would now have a highly accurate climate change record of over 40 years for a diverse set of essential climate variables. While the technology to achieve this vision did not exist in the 1970s, it has been developed in the last decade. Hopefully we can have the foresight to provide that accuracy to future climate scientists, thereby helping them improve understanding of the trajectory of the climate system.

ACKNOWLEDGMENTS. We thank several reviewers for providing comments that significantly improved the clarity and presentation of the paper. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

APPENDIX A: CLIMATE TREND UNCERTAINTY. The accuracy of climate trends relative to a perfect climate observing system can be determined following a simple extension of the methodology of Leroy et al. (2008b). In particular, we can define a climate trend uncertainty factor U_a as the ratio of the accuracy of an actual observing system like CLARREO to that of a perfect observing system. This uncertainty factor is given by $U_a = (\delta m/\delta m_p)$, where δm is the accuracy of a climate trend with the CLARREO observations, and δm_p is the accuracy of the same climate trend for a perfect observing system. From Leroy et al. (2008b) we can show that

$$(\delta m_p)^2 = 12(\Delta t)^{-3}(\sigma_{\mathrm{var}}^2 \tau_{\mathrm{var}}), \quad \text{(A1)}$$

and

$$(\delta m)^2 = 12(\Delta t)^{-3}(\sigma_{\mathrm{var}}^2 \tau_{\mathrm{var}} + \Sigma \sigma_i^2 \tau_i). \quad \text{(A2)}$$

Using Eqs. (A1) and (A2) and the definition of U_a, we can show that

$$U_a = (1 + \Sigma f_i^2)^{0.5}, \quad \text{(A3)}$$

where

$$f_i^2 = (\sigma_i^2 \tau_i) / (\sigma_{\mathrm{var}}^2 \tau_{\mathrm{var}}). \quad \text{(A4)}$$

In Eq. (A1)–(A4), σ_{var}^2 is the variance of the natural variability of the climate system for the variable of interest (SW CRF, spectral nadir reflectance, cloud cover, etc.); τ_{var} is the autocorrelation time for natural variability (Leroy et al. (2008b), $\sigma_i^2 \tau_i$ are the same two quantities for the variance and time scale of observation error source, respectively; *i*, and Δt is the length of the climate time series. The units of the trend uncertainty provided by Eqs. (A1) and (A2) are defined by the units used in σ_{var}, τ_{var}, and Δt. For example, use of the values from Table 2 will provide a trend uncertainty in temperature per year.

The autocorrelation time is a measure of the time between independent samples in a time series of measurements. The number of independent samples, in turn, governs the uncertainty due to noise in the measurement. Therefore, longer time-scale error sources have a larger impact on uncertainty than shorter time scales. A key error source for decadal change is calibration accuracy, and its time scale is taken as the instrument lifetime on orbit (Leroy et al. 2008b). The reason for this choice is that accuracy of an instrument can vary over time, while systematic errors are also likely to be present that are intrinsic to the instrument design itself and its limitations. As a result, for climate change we must consider the worst possible case that provides a calibration time scale of the life of the instrument, taken here as 60 months for CLARREO. For natural variability, the value of τ can be derived as in Leroy et al. (2008b) or as in Weatherhead et al. (1998) (used in this study), where τ is given by $\tau = (1 + \rho)/(1 - \rho)$, where ρ is the lag-1 autocorrelation. For this study we compared both methods and found similar results to within about 20%.

Finally, we can define an uncertainty factor U_t for climate trend detection. This uncertainty factor is the ratio of the time to detect climate trends at any confidence level for the CLARREO observing system to that of a perfect observing system. The result also can be derived from Leroy et al. (2008b) using analogous definitions to Eqs. (A1)–(A4), and is given simply by

$$U_t = (1 + \sum f_i^2)^{1/3}. \tag{A5}$$

Equations (A1)–(A5) provide a powerful method to understand the trade space of climate trend accuracy, detection, and observing system uncertainties.

APPENDIX B: SPECTRAL FINGERPRINT LINEARITY. Climate model OSSE results were also used to test the linearity of the infrared spectral fingerprints and this is shown in Fig. B1. The linearity is tested by determining the infrared spectra changes to the simple sum of nine individual climate change variables (those used in Fig. 4 and additional cloud property changes) versus the full climate system with all nine variables changing at the same time. The difference from exact linearity is typically a few percent at each wavelength, with only a few wavelengths reaching 5% in the strong absorption lines within the 15-μm band of CO_2 near 650 cm^{-1}. The difference is so small that the two lines essentially overlap. The small difference is shown in the dotted offset line for clarity. The linearity of spectral signals has also been demonstrated from instantaneous observations

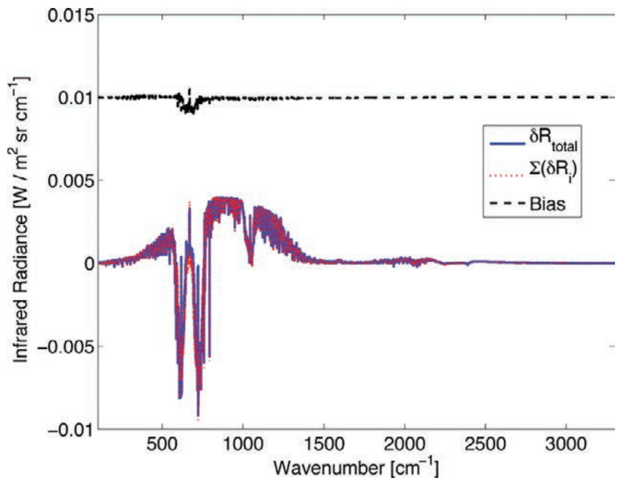

FIG. B1. The figure shows the high degree of linearity of the global spectral fingerprints, with the blue line (δR_{total}) showing the result for all climate changes together (temperature, water vapor, CO_2, and clouds), while the red line [$\Sigma(\delta R_i)$] gives the result of simple addition of the fingerprint changes of each individual climate variable. The difference between the two is offset and shows nonlinearity for climate change signals below 1% at most wavelengths, reaching 5% only in the most highly absorbing CO_2 wavelengths (from Fig. 4 in Huang et al. 2010b).

averaged to larger time and space scales (Kato et al. 2011). A similar study for reflected solar spectral fingerprints (Jin et al. 2011) has also verified a very high degree of linearity for climate change signals, similar to the results for the thermal infrared spectra shown in Fig. B1.

APPENDIX C: REFERENCE INTERCALIBRATION FOR REFLECTED SOLAR. The most severe requirements for climate change accuracy reference intercalibration are for the reflected solar intercalibration, caused by the larger spatial and angular variability of reflected solar radiation. A study using AVHRR orbit crossings (Wielicki et al. 2008) showed that space/time/angle matching noise could be reduced to 1% relative for reflected solar intercalibration if time simultaneity is 5 min or less, angle matching in viewing zenith and azimuth angles is within 1° or less, and spatial averaging areas are matched to within 5% of their diameter. Matching criteria for infrared intercalibration are about a factor of 5 less severe (Wielicki et al. 2008).

Orbital simulations of CLARREO orbit crossings and instrument simulations of space/time/angle matching of the CLARREO RS spectrometer with cross-track scanning instruments like VIIRS and CERES were then carried out to verify sufficient sampling and scene diversity to limit the uncertainty contribution for reference intercalibration to less than 0.3% ($k = 2$). The sampling requirements include the ability to verify offset (i.e., zero level), gain, nonlinearity (calibrate at different levels of dynamic range from dark to bright targets), and scan-angle-dependent polarization dependence.

Since the CLARREO spectrometer has an FOV size of 0.5 km, the observations are spatially averaged to 10 km for matching the VIIRS imager and at the inherent 25-km FOV diameter for matching CERES. VIIRS scan-angle-calibration dependence including polarization dependence is performed every 10° in the VIIRS instrument scan angle. Polarization distribution models (PDMs) are used to sort intercalibration samples between highly polarizing targets such as clear ocean and low polarizing targets such as optically thick cloud or snow and ice surfaces (Lukashin et al. 2012). The simulations use realistic probability distributions of Earth scenes based on MODIS cloud property retrievals used for the CERES 20-km instantaneous FOV Single Satellite Footprint (SSF) data product (Wielicki et al. 1996; Lukashin et al. 2012). Polarization simulations use PDMs developed from multiangle, multispectral Polarization and Anisotropy of Reflectances for Atmospheric Sciences Coupled with Observations from a Lidar (PARASOL) observations (Lukashin et al. 2012; Nadal and Breon 1999; Maignan et al. 2009). High spectral, low-spatial-resolution Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) observations are used to simulate CLARREO reflected solar spectra for realistic Earth scene types (Lukashin et al. 2012). The results from this analysis demonstrate that the advances in CLARREO orbits, pointing control, instrument accuracy, and polarization analysis can achieve the required intercalibration accuracy of 0.3% ($k = 2$) for both the future low Earth orbit and geostationary satellite instruments.

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