

Climate Quality Broadband and Narrowband Solar Reflected Radiance Calibration Between Sensors in Orbit

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ABSTRACT

As the potential impacts of global climate change become more clear [1], the need to determine the accuracy of climate prediction over decade-to-century time scales has become an urgent and critical challenge. The most critical tests of climate model predictions will occur using observations of decadal changes in climate forcing, response, and feedback variables. Many of these key climate variables are observed by remotely sensing the global distribution of reflected solar spectral and broadband radiance. These "reflected solar" variables include aerosols, clouds, radiative fluxes, snow, ice, vegetation, ocean color, and land cover. Achieving sufficient satellite instrument accuracy, stability, and overlap to rigorously observe decadal change signals has proven very difficult in most cases and has not yet been achieved in others [2].

One of the earliest efforts to make climate quality observations was for Earth Radiation Budget: Nimbus 6/7 in the late 1970s, ERBE in the 1980s/90s, and CERES in 2000s are examples of the most complete global records. The recent CERES data products have carried out the most extensive intercomparisons because of the need to merge data from up to 11 instruments (CERES, MODIS, geostationary imagers) on 7 spacecraft (Terra, Aqua, and 5 geostationary) for any given month. In order to achieve climate calibration for cloud feedbacks, the radiative effect of clear-sky, all-sky, and cloud radiative effect must all be made with very high stability and accuracy. For shortwave solar reflected flux, even the 1% CERES broadband absolute accuracy ($1-\sigma$ confidence bound) is not sufficient to allow gaps in the radiation record for decadal climate change. Typical absolute accuracy for the best narrowband sensors like SeaWiFS, MISR, and MODIS range from 2 to 4% ($1-\sigma$). IPCC greenhouse gas radiative forcing is $\sim 0.6 \text{ Wm}^{-2}$ per decade or 0.6% of the global mean shortwave reflected flux, so that a 50% cloud feedback would change the global reflected flux by $\sim 0.3 \text{ Wm}^{-2}$ or 0.3% per decade in broadband SW calibration change. Recent results comparing CERES reflected flux changes with MODIS, MISR, and SeaWiFS narrowband changes concluded that only SeaWiFS and CERES were approaching sufficient stability in calibration for decadal climate change [3].

Results using deep convective clouds in the optically thick limit as a stability target may prove very

effective for improving past data sets like ISCCP. Results for intercalibration of geostationary imagers to CERES using an entire month of regional nearly coincident data demonstrates new approaches to constraining the calibration of current geostationary imagers.

The new Decadal Survey Mission CLARREO is examining future approaches to a "NIST-in-Orbit" approach of very high absolute accuracy reference radiometers that cover the full solar and infrared spectrum at high spectral resolution but at low spatial resolution. Sampling studies have shown that a precessing CLARREO mission could calibrate other geo and leo reflected solar radiation and thermal infrared sensors.

Index Terms— Meteorology, Remote Sensing, Calibration.

1. INTRODUCTION

This paper summarizes new approaches to inter-calibration of satellite remote sensors at climate change accuracy in the solar reflected and thermal infrared portion of the spectrum from roughly 0.3 to 100 μm wavelengths. The accuracy goals for decadal climate change from global remote sensing satellite data have been summarized in a recent interagency report [2] as 0.2% for reflectance at solar wavelengths and as 0.1K for brightness temperature at infrared wavelengths. The values are at 95% confidence levels or higher. These are extremely difficult levels to reach and are an order of magnitude more stringent than typical requirements for process studies or for weather prediction.

The recent NRC Decadal Survey for Earth Sciences [4] proposed a new approach called CLARREO (Climate Absolute Radiance and Refractivity Observatory). CLARREO plans high spectral resolution infrared and solar spectral radiances at absolute accuracies needed to rigorously observe climate change. The mission is currently in pre-phase A studies to define mission requirements. For some climate change variables like global average temperature and water vapor profiles, CLARREO should be able to directly observe decadal climate change. For other variables with more challenging sampling, CLARREO may reach its objectives by providing a calibration observatory in orbit that in turn calibrates other sensors: in effect a "NIST

in Orbit". It is this later application of CLARREO that is the subject of this paper.

CLARREO represents an entirely new paradigm for remote sensing observations. Currently satellite instruments are designed to attack one or a few climate variables, and most commonly try to advance climate the science by providing improved sampling of space (MODIS), time (GOES), spectral (AIRS), angular (CERES), or vertical (CALIPSO) dimensions. These are all key contributions, but typically fall short of critical decadal change accuracy. CLARREO attacks instead calibration accuracy across the solar and infrared spectrum. It does so by sacrificing other dimensions (space, angle, time). But this unique focus on climate change absolute accuracy across the relevant spectrum for climate change gives CLARREO the potential to lift the value of a wide range of observations which normally lack the accuracy needed for decadal climate change. In this sense, CLARREO is an interdisciplinary satellite mission with a unique ability to anchor much of the climate observing system. In the same way, CLARREO is an enabling mission: it allows other missions to exceed their original capabilities.

2. THE 8-DIMENSIONAL CHALLENGE

Inter-calibration of sensors in orbit on two different spacecraft at climate accuracy requires rigorous matching in an 8-dimensional space: time, latitude, longitude, vertical, solar zenith angle, viewing azimuth angle, viewing zenith angle, and wavelength. Significant errors in any of the above can lead to both random and systematic differences that will alias or corrupt the accuracy beyond that required for climate change.

Well known examples of these issues include diurnal cycle aliasing, field of view mismatch, radiation anisotropy, wavelength mismatch, and parallax issues. The difficulty suggests that careful analysis is needed for all of these sampling issues, with a strategy developed that can overcome all of them. In general, the challenge is not to reach a "perfect" match in all 8-dimensional space, but to determine how close a match is required, and how many calibration matches are required in order to verify inter-calibration at a given confidence level. The sections below will summarize calibration matching requirements for each of these dimensions, estimate overall sampling requirements, and discuss optimal satellite orbits for CLARREO to serve as a calibration observatory.

3. HORIZONTAL SPATIAL MATCHING

The large spatial variability of Earth's solar reflected and thermal infrared emission to space require careful matching of instrument fields of view (FOV). Instrument FOVs vary greatly and range from ~ 10 meters (land imagers) to ~ 1 km (global imagers) to ~ 15 km (infrared sounders and radiation budget sensors). All instruments in turn have spatial response function that is roughly a 2-D gaussian based on its optics and electronic filtering. The best way to match a diverse range of instruments is to have a sufficiently large

calibrator FOV that all other instruments can be convolved to match it very accurately. CERES data products, for example, accomplish this by convolving the CERES spatial response function for each 20-km CERES FOV (nadir diameter) with near simultaneous higher spatial resolution 1-km MODIS imager data. Experience suggests that the calibrator FOV should be at least 3 to 10 times as large as the smaller FOV to allow tight spatial matching. This approach also requires accurate knowledge from ground characterization of the calibrator spatial response function.

In order to examine the sensitivity of spatial matching noise to FOV size during inter-calibration, 3 months of NOAA 17 and NOAA 18 AVHRR GAC visible channel data (0.65 μm) were used at orbital crossings of these two low earth orbit spacecraft [5]. This sensor was chosen because the spectral response of the channels is the same (eliminating spectral differences). The visible channels were chosen because they have the largest spatial variability and therefore represent a worst case test. Three months of orbit crossings were chosen, with time simultaneity required to be 6 minutes or less. Angle matching (viewing azimuth angle and zenith angle) were required to be within 1 degree or less. The tight angle/spectral/time requirements were made to isolate spatial variability effects. These requirements led to 450 orbit matches for inter-calibration over the 3 month period from March through May of 2007. The GAC data ~ 4-km spatial resolution. The data from each satellite was averaged over different diameter regions centered on the orbit crossing point of optimal angle/time/space match. The diameter of the averaging region was varied from 12.5 km to 150 km, a factor of 3 to 30 times larger than the GAC FOV.

Figure 1 shows the spatial matching noise found as a function of averaging area in percent of the radiance for each match. The values are one standard deviation of the noise.

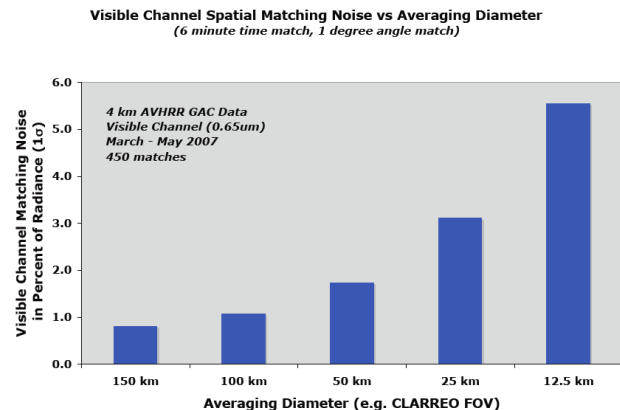


Figure 1. Spatial matching noise as a function of averaging area for 4-km AVHRR GAC visible channel (0.65 μm) data.

The results show that at least a 100-km fov size is needed to reduce spatial matching noise to 1% or below. If smaller FOVs are used the noise increases due to the inability to exactly match the spatial regions and their underlying variability. As mismatch noise grows, the number of

samples needed to intercalibrate will also rapidly grow. For example, a 25-km fov with 3% sampling noise would require 9 times as many orbit crossing matches to reach the same inter-calibration confidence as a 100-km FOV. Note that the nominal CLARREO FOV diameter suggested in the NRC Decadal Survey was 100-km. Fortunately, spatial matching noise is inherently random in nature, and therefore aliasing of bias errors is not as critical as other matches.

While not shown, the same study was performed for the AVHRR 11 μm infrared window channels. In terms of brightness temperature noise, the 25-km FOV gave 1.2K (1σ) noise, while the 100-km FOV match gave a much lower 0.4K noise. The relative factor of 3 decrease in noise for increasing FOV size was similar to that seen for the visible channel results in Figure 1. Note that since other wavelengths of solar (e.g. UV) and infrared (e.g. CO₂ or H₂O absorption sounding bands) will show smaller variability. As a result the AVHRR visible and infrared window channel results can be used to set requirements which will then apply for all solar and infrared spectral regions.

4. TIME MATCHING

The same AVHRR data used to examine spatial matching was also used to examine time matching requirements. In this case, the orbital matches were selected with varying time matching criteria (maximum mismatch allowed) of as little as 1.5 minutes to as much as 12 minutes. Since low earth orbits have periods of ~ 100 minutes, 12 minute time simultaneity would occur in roughly 24% of orbit crossings for any two leo satellites. The exception to this rule will be satellites locked in formation such as the A-train. These missions can achieve either zero or 100% simultaneity depending on the time requirement. Figure 2 shows the AVHRR orbit crossing results as a function of time simultaneity of orbit crossings for the 100-km FOV size that resulted in 1% spatial matching noise in Fig. 1. The visible channel is used as the worst case scenario. Note that solar zenith angle corrections are made so that simple changes in solar illumination do not dominate the results.

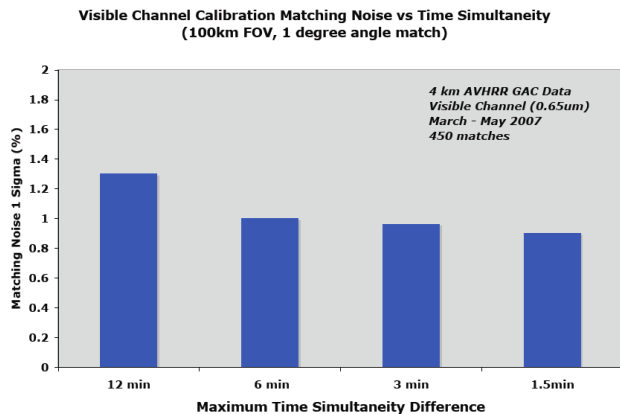


Figure 2. Time matching noise for 100-km FOV at 0.65 μm .

The results show a smaller dependence on time simultaneity with little difference between 1.5 and 6 minutes, but degradation building at 12 minutes. In fact, the time simultaneity requirement is dependent on the spatial FOV considered. At 100-km matching scale, cloud systems can only move a small distance across the 100-km calibration averaging domain. For example, a 10 m/s wind operating over 6 minutes is the equivalent of 3.6 km advection distance, which is a small fraction of the 100-km region. But if a 12-km FOV had been chosen: this advection would cause a much larger amount of noise. As a result, the space/time matching requirements are interlinked. As FOV increases, the time simultaneity requirement relaxes. Very large time changes, however, would result in aliasing from systematic changes in radiation fields with the diurnal cycle such as surface heating and cloud dynamics.

5. ANGLE MATCHING

Infrared and especially solar reflectance spectra show a large anisotropy in radiation fields. The effect varies from 20% for typical infrared radiance (limb darkening) to factors of 2 to 10 for solar reflectance (limb brightening, ocean specular reflectance). Recently, the CERES mission flew broadband solar and infrared instruments designed to sample the entire hemisphere of Earth's reflected and solar radiation fields for a full range of solar zenith angle, latitude, and scene conditions [6]. This data represents the most complete observation set of radiation anisotropy in thermal infrared and solar spectral regions. The data set allows a determination from observations of the amount of angle matching required to avoid both random and bias errors for inter-calibration of sensors.

Figure 3 shows an analysis of the effect of angle matching error for solar reflected radiances, the worst case scenario. The results are shown in percentage of broadband reflected solar flux for tropics only, and for global conditions. Global conditions would be representative of inter-calibration using orbit crossings at a wide range of latitudes such as leo orbiters. Tropical conditions would be representative of orbit crossings of CLARREO under geostationary satellites.

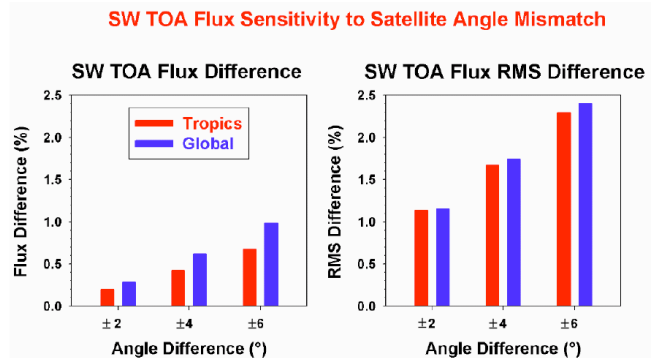


Figure 3. Angle sampling bias errors (left panel) and random errors (right panel) for solar reflected radiance calibration.

The results show that angle matching is even more critical than space and time matching. Angle matching within 2 degrees leaves bias errors of 0.2 to 0.3%, suggesting a climate calibration requirement of 1 degree or better angle match. Angle matching within 2 degrees causes a random noise of 1%, roughly similar to the 100-km fov spatial matching noise. The noise and bias error increase almost linearly in the angle matching requirement. Both bias and noise suggest a 1-degree angle match requirement. As for the time simultaneity test, the results in Fig. 3 include correction for solar zenith angle changes, so that the bias and random errors are the result of anisotropy variations, not the result of changing solar insolation level.

6. SPECTRAL WAVELENGTH MATCHING

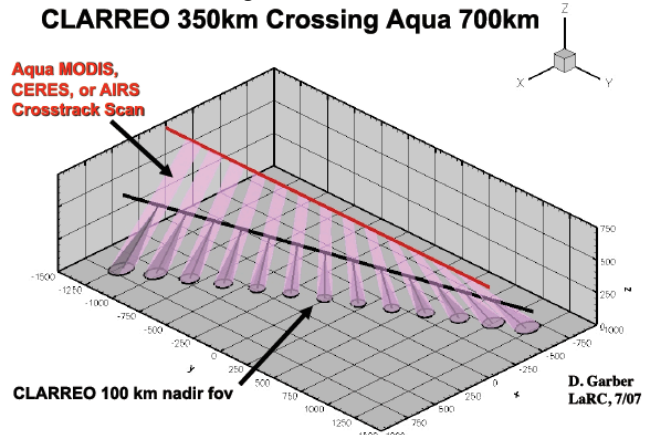
Radiance calibration of filter radiometers such as MODIS or Landsat requires a knowledge of their spectral response function from ground characterization. It also requires that the high accuracy spectral radiances measured by CLARREO have sufficient spectral resolution to allow accurate matching of spectral resolution. A criteria of a factor of 10 smaller than a filter response would lead to a spectral resolution of $\sim 2 \text{ cm}^{-1}$ in the infrared and 2 nm in the solar wavelength range. For interferometers (CrIS, IASI) and spectrometers (AIRS, SCHIAMACHY) spectral resolution can be matched by averaging or even more flexibly by tailored analysis of the interferometer data to match a different spectral resolution instrument.

Special consideration must be given to the ability to detect any change in instrument spectral response in orbit of either CLARREO or the instrument it is calibrating. This can vary from slowly spectrally variable transmission loss of optics in the solar at wavelengths below $0.5 \mu\text{m}$, by errors in ground characterization of filter radiometer spectral response, or by any changes in orbit of spectral response. CLARREO pre-phase A studies are underway to examine these potential effects by using high spectral resolution radiative transfer modeling, as well as high spectral resolution data sets such as AIRS and IASI for the infrared spectrum and SCHIAMACHY for the solar spectrum. These modeling and data studies will simulate a wide range of spectral matching errors and examine their impact on the ability to transfer calibration. The studies will also examine the impact of polarization, since some solar reflectance instruments are designed to observe polarized signals (APS, POLDER) while others have a sensitivity to polarization.

7. OPTIMAL CALIBRATION ORBITS

The above requirements to match in time, space, and angle suggest that orbital studies are needed to evaluate the effect of varying CLARREO orbits on the mission's ability to calibrate other leo or geo sensors. Because sun-synchronous orbits have nearly constant local time sampling, this suggests a CLARREO orbit which precesses through all local times of day. The angle matching requirement of 1 degree suggests an orbit with sufficiently high altitude that the 100-km field of view does not have too large a viewing

angle range. The need to match both viewing zenith and azimuth angle suggests that there may be a significant trade space between nadir only (few matches) and the ability to point the spacecraft or instrument to match viewing angles during orbit crossings and thereby obtain an order of magnitude increase in matches per orbit crossing. A simple schematic of a CLARREO mission flying below the Aqua mission is shown in Figure 4 below.



Time to Achieve Viewing Angle Matches:
40 seconds per 100km orbit altitude Difference: 140 seconds above

Figure 4. Example schematic of CLARREO orbit crossing with Aqua and angle/time/space matched 100-km FOVs.

An interesting result of the orbital simulations is that the time interval for intercalibration across a satellite swath during orbit crossings is a function of the altitude separation of the orbits. There is approximately 40 seconds of time for angle/space/time matched inter-calibration per 100-km orbit altitude difference. The combination of matching noise (number of samples), characterization of spectral wavelength matching (wide range of spectral scene types from equator to pole) and the desire to calibrate in a full range of climate regimes will all enter into design of the optimal CLARREO orbits for intercalibration. The nominal NRC Decadal Survey design is for 3 CLARREO orbits with 90 degree inclination which gives full equator to pole coverage and precesses through 24 hours of local time once per year.

8. REFERENCES

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