Response and Discussion of IR Breakout Discussion
Recap of CLARREO Workshop
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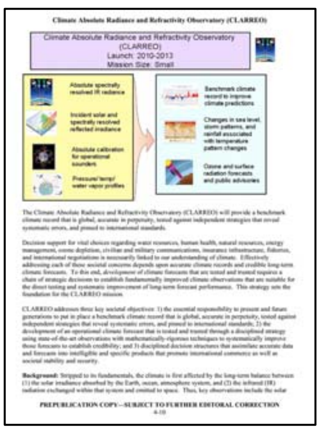
IR Breakout Discussion Recap

- *The discussion started (again) with a discussion of what are the science requirements (questions) and what are the instrument requirements. Part of this is due to the ambiguity between the ES and Chapter 9. Part is due to the fact that the ES only defines the instrument requirements.*
    - *Earlier presentations discuss the tight and integral relationship between the science and instrument requirements without fully describing what the instrument requirements are.*

Response: This is a key topic, since setting high level requirements was established as a major goal of the CLARREO workshop, and is essential to proceeding with more detailed mission design efforts. First, we believe that both the high level science/societal requirements and the mission/instrument requirements for the CLARREO benchmark concept are reasonably well defined in Section 4 of the NRC Decadal Survey (*Summary of Recommended Missions*, pages 4-10 to 4-12) and by the ASIC3 report edited by George Ohring. Although there are various viewpoints represented in the Decadal Survey, the science and instrument requirements we are supporting are consistent with the CLARREO mission recommended in the Decadal Survey.


Climate Absolute Radiance and Refractivity Observatory (CLARREO)

Climate Absolute Radiance and Refractivity Observatory (CLARREO)
Launch: 2010-2013
Mission Size: Small

The Climate Absolute Radiance and Refractivity Observatory (CLARREO) will provide a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards.

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The CLARREO Workshop presentations defined with considerable clarity how the objectives and the prioritization laid out by the Decadal Survey are traced directly to the instrument requirements in the IR/GPS component of CLARREO:

NRC Final Report:

- Recommends a path forward that restores U.S. leadership in Earth science and applications and averts the potential collapse of the system of environmental satellites
- Presents an integrated suite of missions
    - Panel recommendations rolled-up
    - Missions sequenced
    - Overall cost matched to anticipated resources plus reasonable growth
- Highest priorities of each panel preserved
- Some guidance on how to handle budget or technology development problems

The NRC found that fundamental improvements were needed to establish a disciplined structure linking:

- Decision processes that serve societal objectives
- The analyses, forecasts and models that provide timely and coherent input to those decision processes, and
- Observations selected to test and systematically improve those forecasts

The prioritization process for mission selection involved eight criteria used to set relative rankings:

- Contribution to the most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration)
- Contribution to applications and policy making (societal benefits)
- Contribution to long-term observational record of the Earth
- Ability to complement other observational systems, including national and international plans
- Affordability (cost consideration, either total costs for mission or costs per year)
- Degree of readiness (technical, resources, people)
- Risk mitigation and strategic redundancy (backup of other critical systems)
- Significant contribution to more than one thematic application or scientific discipline

Driven by the prioritization process that was applied across all disciplines within the NRC Decadal Survey purview, CLARREO emerged as a top priority for a new start:

NRC Final Report: CLARREO addresses three key Societal Objectives:

1. The essential responsibility to present and future generations to put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards
2. The development of an operational climate forecast that is tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically rigorous techniques to systematically improve those forecasts to establish credibility
3. Disciplined decision structure that assimilates accurate data and forecasts into intelligible and specific products that promote international commerce as well as societal stability and security

NRC Final Report: Mission and Payload

- The mission is built upon three satellites, each of which requires a specific orbit, and each of which includes an occultation GNSS receiver. In the first category of climate benchmark radiance measurements, two of the satellites contain redundant interferometers that have a spectral resolution of 1 cm^{-1}, and encompass the thermal infrared from 200 to 2000 cm^{-1}, are in true 90° polar orbits to provide a full scan of the diurnal harmonics as well as high latitude coverage from low Earth orbit,
- The components of the CLARREO mission include (1) two small satellites to obtain absolute, spectrally resolved radiance in the thermal IR and a GPS receiver for radio occultation; (2) a third small satellite to continue the IR absolute

spectrally resolved radiance measurements but with the addition of benchmark observations to obtain the reflected solar irradiance and a GPS receiver; and (3) re-flight of the incident solar irradiance and CERES broadband instruments on NPP and NPOESS

The ability of this CLARREO mission to calibrate passive sensors on-orbit via SI traceability and to address sampling issues without subsidiary information is a notable departure from the current strategy pursued for climate satellite records. The necessity for this departure was recognized by the NRC as follows:

NRC Objective: Global Benchmark Climate Record

Benchmark Observations: What are they?

The NRC Decadal Survey recognized that ***when the global climate record emerges as a significant contributor to public policy (societal) decisions, that record will be attacked relentlessly.*** If the climate record cannot stand up to those attacks, the record cannot effectively serve society. Recognition of this led to the requirement that the design of climate observing and monitoring systems from space must ensure the establishment of global, long-term climate records, which are of *high accuracy*, tested for systematic errors on-orbit, and tied to irrefutable standards such as those maintained in the U.S. by the National Institute of Standards and Technology

For the NRC report, this mission definition was essential for the prioritization process that fully considered scientific/societal impact, cost, ability to complement other systems, degree of readiness, risk mitigation, and contributions to other thematic areas. The ASIC3 report also chose a CLARREO-like mission as one of its high priority recommendations based on similar requirements. Once the context of responsiveness to societal objectives is understood, the path leading all the way to details of instrument design may be defined. A summary of requirements flowdown from high level science requirements to data products to mission and payload requirements for the IR and GPS components is included below.

Science Requirements

1. The first order requirement is to initiate a new generation of high accuracy, SI traceable on-orbit, climate benchmark measurements that will be continued in perpetuity, systematically improved and open for cross check and verification.
2. A closely associated primary requirement is the testing and systematic improvements of climate forecast models using a strategic balance between prioritization of new benchmark climate observations and mathematical tools that link those observations to climate forecast model testing.
3. A secondary requirement is to provide benchmark observations for the intercalibration of other space-borne sensors.

CLARREO Concept and Rationale

1. Absolute Spectrally Resolved Radiance (ASRR) in the IR in combination with GNSS radio occultation constitutes a powerful observational foundation with the appropriate technology readiness in order to provide the desired climate benchmark products. These observations can be made very accurately and have very high information content.

2. The systematic testing and improvement of decadal climate forecast models is mathematically linked to the data vectors provided by ASRR and GNSS such that both climate trends and the gain terms in climate feedback and radiative forcing can be observed.
3. An ASRR dataset will provide the reference for intercalibation of other IR imagers and sounders.

Data products

The data products are formed from observations of nadir viewing Absolute Spectrally Resolved Radiance (ASRR) and GPS refractivity. Key characteristics of the ASRR products are:

- Annual gridded (e.g., 15 × 30 deg) mean radiance spectra
- independent of time-of-day sampling
- on-orbit SI traceable accuracy of 0.1 K 2-sigma, provable on-orbit
- 0.5 wavenumber (± 1 cm MaxOPD) spectral resolution
- continuous spectral coverage from 200 to 3000 wavenumbers
- for a period of 5 years

This data product meets the primary CLARREO objective of determining long-term trends, traceable on-orbit to international standards, for climate model testing. CLARREO can satisfy other climate objectives that require data products corresponding to shorter timescales. Secondary CLARREO data products can also be produced with similar accuracy, on regional spatial scales, for timescales as short as two months. Thus the primary CLARREO data product of annual averages is supplemented by additional accurate radiance products on intermediate timescales and climate-relevant spatial scales.

Mission and Payload Requirements

1. The mission will include three satellites. To provide complete and unbiased spatial and temporal coverage, three 90 degree polar orbits spaced by 60 degrees in orbital plane are important for achieving both the societal and scientific objectives of CLARREO. This choice gives true global coverage and all local times are covered every two months, thereby minimizing diurnal sampling biases. The orbit altitude is approximately 750 km to ensure adequate mission lifetime.
2. A nadir viewing spectrally resolved IR sensor with on-orbit SI traceability is included on each satellite.
3. A GPS receiver will also be included on each satellite.
4. Cost consistent with Decadal Survey recommendations

IR Instrument Requirements

1. Instrument Architecture: SI traceable, absolute calibration on orbit, by the logic of fundamental metrology, requires the determination of systematic error on-orbit. Determination of systematic error in turn requires an independent determination of each term in the error budget. For the determination of absolute spectrally resolved radiance in the thermal infrared this requires:
    a. Redundant spectrometers that engage multiple cross checks defining traceability to the international definition of thermal infrared radiance on-orbit to reveal systematic errors

b. Absolute thermometry such as the phase transition of an element embedded in multiple blackbodies for each spectrometer
c. Direct determination of blackbody emissivity
d. Direct determination of instrument line shape applicable across the spectrum
e. Direct measurement of instrument polarization
f. Detector chain linearity determination
g. Foundation of continuous calibration of flight subsystems against NIST primary infrared standards and evaluation of flight blackbodies in NIST facilities

2. Spectrometer Design: Fourier transform spectrometer. This requirement follows from the need for simplicity, broad Nyquist sampled spectral coverage, redundant spectrometers on the same spacecraft, instrument line shape determination across the full spectrum, polarization determination.
3. Spatial Footprint and Angular Sampling: Order of 50–100 km, nadir viewing only. This requirement arises from the fact that long-term trends in outgoing longwave radiance have course spatial structure; the influence of clouds included. While arguments have been put forward for cloud clearing, which requires much finer horizontal resolution, for the objectives of climate (in sharp contrast to those of weather forecast initialization), a small observing footprint is both unnecessary and ill-advised for several reasons. First, the climate system evolves in time as a coupled system that links secular trends in temperature, water vapor, clouds structure, etc. Both for the climate record and for the testing of climate forecast models, it is the coupled response of temperature, water vapor and cloud structures, as manifest in the spectrally resolved radiance emitted from Earth to space in combination with atmospheric refractivity derived from GPS, that constitutes the fundamental data product for climate. Optimal detection provides a unique determination of the secular trends in these climate variables and the dominant feedback terms and can be used to examine how those coupling terms depend on the degree of cloudy vs. clear conditions - if that is the objective. Second, a benchmark of cloud-cleared radiance requires on-board proof of the *accuracy* of the cloud-clearing process. To this day, we have little to no idea what the accuracy of the cloud clearing process is, entirely because there is no SI traceable pathway to prove it. It is highly unlikely that cloud-clearing can be accomplished with an accuracy of 0.1 K 2σ. Third, attempting to achieve high horizontal spatial resolution adversely affects a number of design elements in the architecture of high accuracy spectrally resolved radiance measurements for both climate benchmark observations and for climate forecast testing.
4. Spectral Resolution and Sampling: Order 1 cm^{-1} with Nyquist sampling across interferogram
5. Spectral Range: 200–3000 cm^{-1} the spectrum coverage is meant to include broad coverage of key parts of the infrared spectrum that contain significant information about the state of the atmosphere and that can be observed with high accuracy.
6. Pointing Accuracy and Knowledge: Within 5° of nadir; < 0.1° uncertainty
7. Temporal Resolution and Sampling: < 15 sec resolution and < 60 sec intervals
8. Detectors: The design includes two spectrometers, one with pyroelectric detectors to cover the far to mid infrared, and the other with photovoltaic MCT and InSb detectors for coverage of the long to shortwave IR with better noise performance. The detectors are chosen to meet NEΔT requirements with a high level of linearity. Unlike most applications, detector sensitivity is not a major issue for this application. Many samples

will be averaged, making noise requirements (NEΔT < 1.5 K for climate products and < 0.6 for intercomparisons) reasonably easy to achieve using pyroelectric detectors for 200 to 2000 cm^{-1}, photovoltaic MCT for 650 to 2000 and sandwiched InSb from 1825 → 3000 cm^{-1}

9. Blackbody Design: Two blackbodies for each spectrometer, plus deep space view. Each blackbody equipped with phase transition cells for a range of absolute temperatures and direct emissivity measurements on-orbit. One of the blackbodies would be a warm blackbody reference (~ 300 K); the other would be a variable temperature reference with a range 200–320 K.
10. On-Orbit Performance Characterization: Absolute temperature, cavity emissivity, instrument line shape, linearity, polarization, and stray light

Material in several workshop presentations contained the results of studies supporting these requirements.

Final Note: These requirements along with the current state of technical readiness provide a firm basis for proceding to a Phase A study for the IR/GPS CLARREO Mission.

IR Breakout Discussion Recap (cont.)

- *We agreed that it the mission is more simple if it is primarily a climate benchmark, with contributions to constraining the physics of models with cross correlation with operational sounders a secondary function.*
- *There was much discussion (with an understanding that people will maintain differing opinions) about using the sounders as part of the past and future climate record (in coordination with CLARREO); is this a proper primary emphasis?*

Response: In the absence of a detailed analysis, it may appear that there is an inherent conflict between the *primary objectives* of NRC Decadal Survey CLARREO mission:

- First order objective is to initiate a new generation of high accuracy, SI traceable on-orbit, climate benchmark measurements that will be continued in perpetuity, systematically improved and open for cross check and verification.
- A closely associated primary objective is the testing and systematic improvements of climate forecast models using a strategic balance between prioritization of new benchmark climate observations and mathematical tools that link those observations to climate forecast model testing.

and the *secondary objective*, the objective of intercalibrating other IR sounders. But, in fact, the analyses presented independently by Kirk-Davidoff (University of Maryland) and by Tobin (University of Wisconsin) demonstrated beyond any doubt the following.

Kirk-Davidoff Conclusions:

- Observational coverage of the semidiurnal (twice per day) component of the diurnal cycle is a critical issue for a climate benchmark.
- A precessing orbit is of value as long as an integral number of nodal precession cycles occurs per year.
- Three 90° polar orbits is key to a resilient global benchmark mission.

Tobin Conclusions:

1. Using CLARREO FOVs with spatial standard deviations less than 2 K, the uncertainty in the monthly mean brightness temperature differences (CLARREO minus IASI, CLARREO minus CrIS) due to differences in spatial and temporal sampling are less than 0.02 K.
2. To meet a monthly inter-calibration accuracy of 0.1 K 3σ, the maximum allowable instrument noise for individual CLARREO FOV is approximately 0.6 K, with no assumed spectral averaging. This assumes single channel calibration with no noise filtering or spectral averaging and three CLARREO satellites with sampling frequency of 10 seconds
3. The number of usable monthly CLARREO Fields of view (BT STD < 2 K and 10 second sampling) during 2006 does not vary significantly by month with the number of FOV between 400–500. As result, the monthly CLARREO noise requirement (0.6 K) for intercalibration remains consistent during the year.

Kirk-Davidoff/Tobin Conclusions for Establishing the Benchmark Climate Record:

- To meet the primary requirement of obtaining an SI traceable benchmark of thermal radiance spectra, three 90° polar orbits spaced by 60° in orbital plane are needed. This choice gives true global coverage and all local times are covered every two months, thereby minimizing diurnal sampling biases.

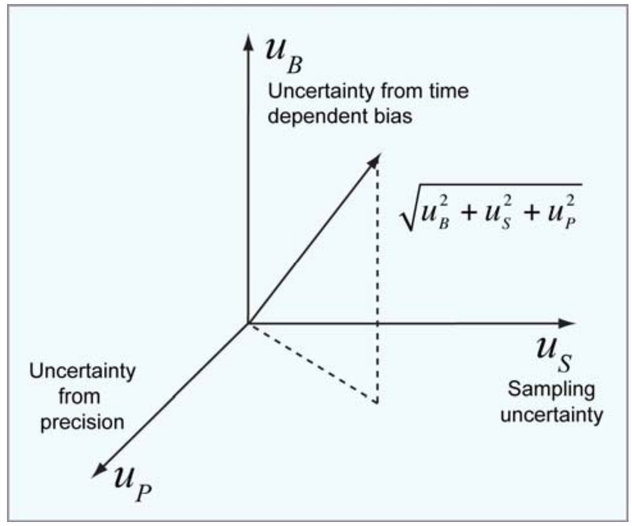
- The orbital configuration recommended by Kirk-Davidoff is already sufficient to intercalibrate other IR sensors to 0.1K (3σ) on a monthly basis over a broad dynamic range of temperatures with an NEΔT of 0.6K. This fully considers all spatial and temporal atmospheric variability(as contained in the MODIS data) – including clouds. This was clearly laid out in Dave Tobin's presentation at the Workshop. The best strategy for the objective of intercalibrating of other IR sounders, therefore, is to employ the three CLARREO IR/GPS satellites to establish the climate record, then establish the bias between CLARREO and the other sounders using SNO and Climate Target domains.

It should be noted that the response given here is specific to the IR; workshop presentations clearly demonstrated that the temporal and spatial sampling required for the climate and intercalibration objectives are significantly different for the IR and the solar/visible measurement objectives.

Final Note: These represent extremely important conclusions that are, in the absence of detailed calculations, not intuitively obvious. But in addition, it was clear from the open discussion at the workshop on the second and third day, that a number of the members of the IR/GPS breakout session didn't understand the Kirk-Davidoff/Tobin presentations. This lack of understanding has important ramifications because it implies both confusion over issues that are in fact settled and it also refuels the old apparent conflict between (a) setting the benchmark climate record in place and (b) determining the bias between that SI traceable record from CLARREO and the other IR sounders such as AIRS, CrIS and IASI. This should not be allowed to persist. With respect to the issue of how useful AIRS, IASI and CrIS are in conjunction with CLARREO, two conclusions emerge: (1) *AIRS, IASI, and CrIS are intended to be process-study instruments and weather forecast initialization systems while CLARREO is narrowly targeted as a benchmark instrument.* Both are necessary. (2) The study by Tobin indicates that AIRS, IASI, and CrIS can be calibrated against CLARREO on a monthly basis. But the study by Kirk-Davidoff indicates that their benchmark capability is, even after calibration, limited by orbit selection.

IR Breakout Discussion Recap (cont.)

- *There was also discussion as to the requirement of precision, to go along with the absolute accuracy as defined in the ES and the day one discussion.*



Response: Consideration of the requirements for *precision* as opposed to *accuracy* is most effectively cast in terms of the orthogonal axes displayed in the adjacent figure and they encompass a lesson of great importance for the achievement of Climate Benchmark Observations. The vertical axis represents the (2σ) measurement uncertainty (u_B) against an SI traceable on-orbit standard—it is the *accuracy of the instrument* used to make the SI observation. The (2σ) *sampling* uncertainty, u_S, is the bias introduced by the method of sampling—in the case of CLARREO the selection of orbits, crossing times, etc. and is an error with as serious potential consequences as the bias resulting from an inability to establish an SI traceable standard on-orbit. The (2σ) uncertainty from precision, u_P, is the uncertainty resulting from issues such as the NEΔT of the instrument's detectors, choice of footprint size, etc.

The important and recurring issue here is that it is the simultaneous specification of the contribution of *all three axes*—the calculation of the amplitude of the vector in the above diagram—that constitutes the figure of merit for climate benchmark observations. The NRC Decadal Survey called for climate benchmarks with an uncertainty of 0.1 K (2*σ*). That translates, by the representation of the figure above, to mean that the (2σ) combined uncertainty, sqrt(u_B^2 + u_S^2 + u_P^2), is equal to or less than 0.1 K.

So, recognizing that one of these axes cannot be taken out of the context of the others when setting a CLARREO strategy, we consider here uncertainties resulting the precision axis, u_P; the issue addressed in the IR Breakout Discussion Recap highlighted above.. u_P is related to the single sample noise, NEΔT, and is random in nature. Noise is important for setting the climate benchmark record, but not especially demanding given the large number of individual samples included in the annual, gridded, climate product. The requirements on NEΔT for a CLARREO system with the *sole* objective of setting in place the long-term climate record are a NEΔT of ~ 1.5 K for a 10 second sample interval. Note that a CLARREO instrument combination (two or more small interferometers on each satellite) provides ~ 3×10^6 spectra/yr. It is also important to recognize that by using two or more interferometers on the same CLARREO spacecraft—a key part of the strategy to critique systematic errors on-orbit—the detectors can be selected for (1) linearity and full spectral coverage on the one hand (DTGS) and (2) low NEΔT on the other (MCT).

The requirement to intercalibrate other operational infrared spectrometers leads to a somewhat more stringent requirement on precision. Our simulation using a year of MODIS data and a month of 15 minute interval SEVERI data show that a noise performance of better than 0.6

K for window channels for a 10 second sampling interval are adequate for validating radiances to better than 0.1 K 3σ in a month with CLARREO in three 90º polar orbits. As a consequence the requirements placed on instrument Precision are driven by requirements placed on the system by the method of Simultaneous Nadir Overpass intercalibration of other IR sounders rather than the need for Precision in setting the global benchmark climate in place.

IR Breakout Discussion Recap (cont.)

• All agree that extending to the far infrared is an important and essential feature of the IR component of CLARREO.

Response: A clear case was made at the Workshop (and in the NRC Decadal Survey) to extend the spectral coverage of CLARREO beyond 650 cm^{-1} to encompass the rotational spectrum of water and a clear case was made to provide continuous (uninterrupted) coverage over the entire spectral interval. It is also, quite obviously, a requirement to achieve this within the constraints of 0.1 K (2σ) uncertainty, which together pose the question: How far into the "far infrared"? So the spectral coverage of the CLARREO instruments is a trade-space that must simultaneously consider:

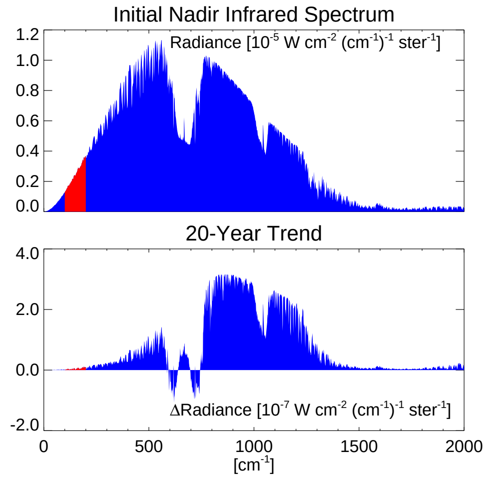
1. Attainment of the NRC objectives of 0.1 K (2σ) uncertainty in the benchmark global climate record;
2. The effective testing of climate forecast models;
3. The cost implications of extending the spectral coverage;
4. The impact on overall instrument accuracy by extending the spectral coverage; and
5. The amount of independent information contained in the spectral interval to be added.

Taking the CLARREO mission as defined in the NRC Decadal Survey Executive Summary (and the subsequent four chapters):

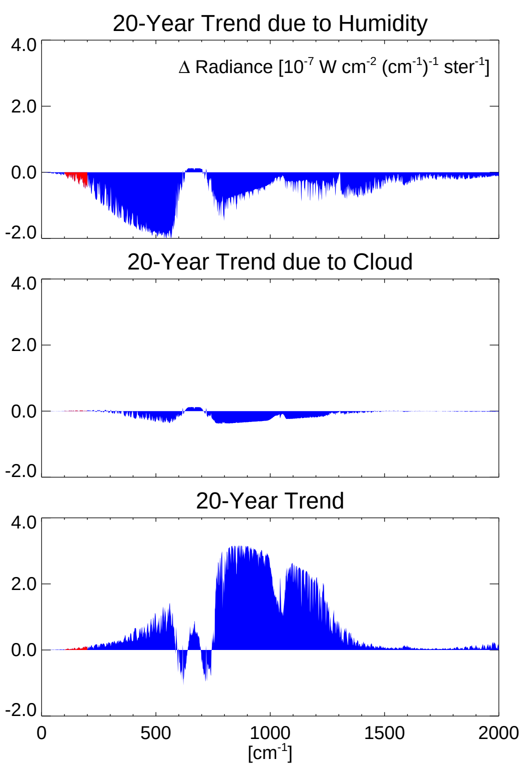
> *"The mission is built upon three satellites, each of which requires a specific orbit, and each of which includes an occultation GNSS receiver. In the first category of climate benchmark radiance measurements, two of the satellites contain redundant interferometers that have a spectral resolution of 1 cm^{-1}, and encompass the thermal infrared from 200 to 2000 cm^{-1}, are in true 90° polar orbits to provide a full scan of the diurnal harmonics as well as high latitude coverage from low Earth orbit, and each of the interferometers have an internal scene selection that includes redundant blackbodies with programmable temperatures and an external scene selection that includes deep space viewing for radiance zeroing and nadir viewing with a 100 km footprint for Earth observations."*

We consider the arguments for extending the spectral range of coverage beyond 2000 cm^{-1} on the one hand, and beyond 200 cm^{-1} on the other. The arguments are very different in the two cases. First, extending beyond 2000 cm^{-1}, a region that lies well beyond the shortwave extent of the thermal IR emission from the Earth to space, would be primarily for the purpose of picking up additional rotational/vibrational transitions in CO_2 and water for the calibration of sounders such as IASI and CrIS with limited impact on CLARREO instrument design. The 2000–3000 cm^{-1} region would be incorporated using an InSb detector in a sandwich configuration with the primary MCT detector; an addition that would not compromise the instrument accuracy. The cost impact would be small, but not zero.

To investigate the information content in the far-infrared relevant to climate trend detection and climate model testing, the optimal filtering framework may be employed. In particular, there is the question of whether spectral coverage should extend to 100 cm^{-1} or 200 cm^{-1}? In terms of the radiation budget, the spectral region between 100 cm^{-1} and 200 cm^{-1} contains about 3% of the total radiant energy based on the annual average all-sky midlatitude spectrum (upper panel). It contains a smaller fraction of the total energy in the all-sky radiation trend simulated by 20 years of 1% yr^{-1} CO_2 increases (lower panel), around 1.5%.



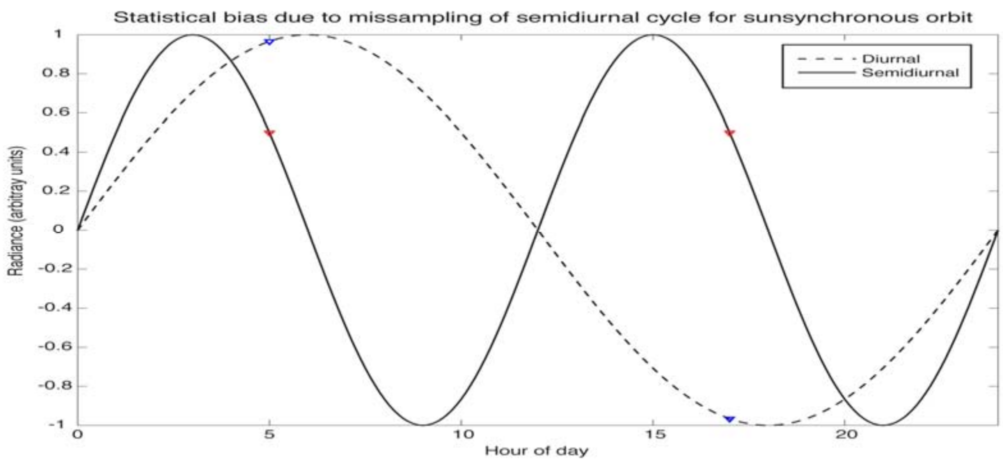
The relevant question for model testing, however, is information content, rather than OLR fraction. The information content may be analyzed through examination of the radiative signatures due to clouds and water vapor in the context of optimal fingerprinting. Optimal fingerprinting derives most of its information from aspects of signals that differentiate those signal shapes from natural variability and distinguish the spectrally resolved signatures from one another. Exactly how useful the 100–200 cm^{-1} spectral region is in optimal detection has yet to be determined. We already know that the spectral range from 200 to 2000 cm^{-1} is adequate for detecting radiance trends resulting from temperature and humidity.



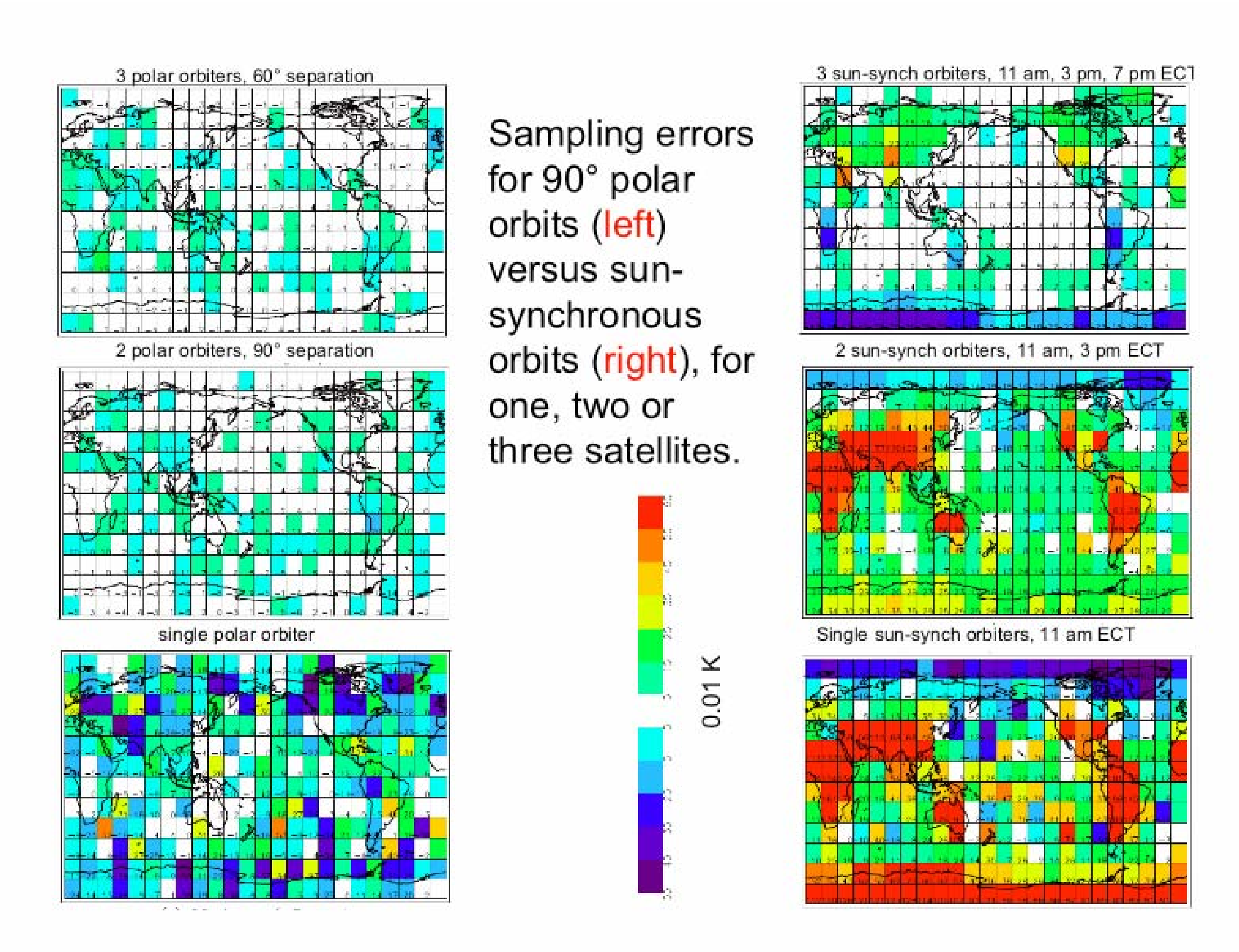
IR Breakout Discussion Recap (cont.)

- *To fully address the diurnal and semi-diurnal cycle, 3 polar orbits are ideal.*
  - *Only using two would be useful, but begins to degrade the statistics of separating natural variability from trends.*
  - *Only one would not achieve this.*
  - *Multiple sun sync orbits give useful, but non-ideal sampling of the diurnal cycle.*

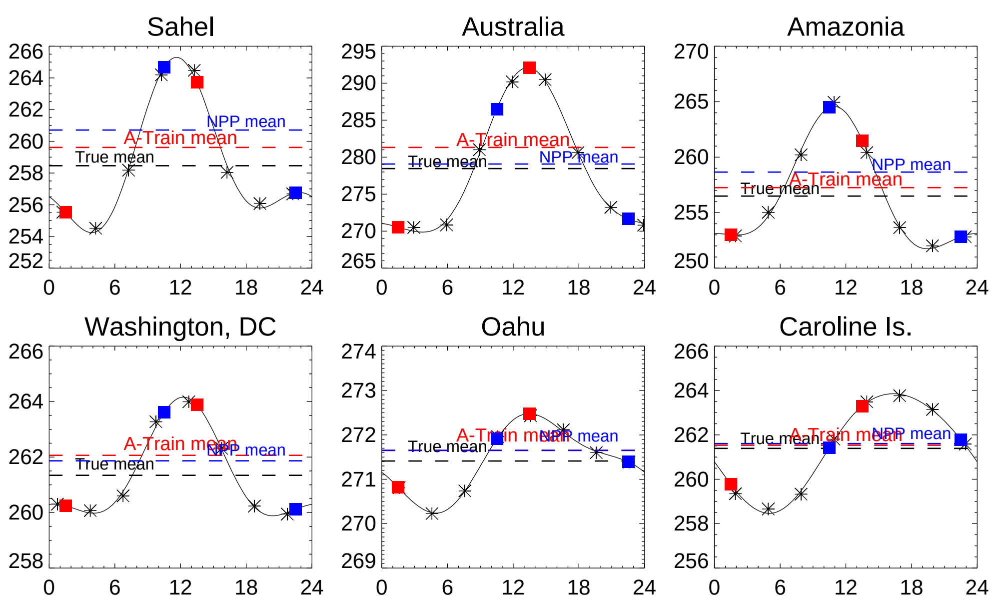
Response: First it should be emphasized that it is not a matter of three true 90º polar orbits being "ideal", but rather it is a matter of achieving the objectives of 0.1 K total uncertainty that demands, as was pointed out above, simultaneous consideration of the combined uncertainties from instrument bias, measurement precision, and sampling bias. Three true 90º polar orbits is the most robust possible configuration to reduce the sampling bias to below 0.1 K. As Leroy and Kirk-Davidoff have demonstrated in the literature [Leroy, 2001: *J. Climate,* **14**, 4330–4337; Kirk-Davidoff *et al.,* 2005: *J. Climate,* **18**, 810–822], it is the semi-diurnal and higher harmonics of the diurnal cycle in radiance that create the dominant sampling bias. As shown in the diagram below, the diurnal component cancels in recovering the climatological mean from a sun-synchronous orbit, but the semi-diurnal component does not.



The following figure from Kirk-Davidoff's Workshop presentation demonstrates that a single 90º orbit captures annual average 11µ radiance over approximately 30–40% of the Earth's surface with a sampling error of < 0.1 K. The addition of two other 90º polar orbits spaced 60º in ascending node enable accurate sampling over virtually the entire globe and over time scales much less than one year by covering the diurnal *and semi-diurnal* cycle. This strategy works even when the phase and amplitude of the semi-diurnal cycle is spatially non-uniform. Such spatial non-uniformity, on the other hand, is crippling for sun-sync orbitors. But it is also critical to recognize that there is an important redundancy intrinsic to the three satellite, 90º polar orbit architecture, and that is the redundancy/cross checking that emerges from the proper semi-diurnal sampling—a key consideration for the NRC societal objectives.



This is captured in the analysis by Leroy presented at the CLARREO Workshop, shown in the figure below.



But what is critical to the CLARREO strategy, in addition to showing the superiority of the true 90º polar orbit, is that while the ability to recover the climate mean from an increasing number of sun-sync orbits improves, there is a dramatic degradation in the sampling bias in going from three to two satellites in the benchmark constellation. Thus, the loss of a single satellite from a three satellite sun-sync combination profoundly compromises the ability of the climate mission, whereas the resilience of the mission, if launched into the true 90º polar orbit, is far higher.

In the published literature, others have accounted for the semidiurnal cycle bias with data from geostationary satellites or the output of climate models. The former has proven problematic because of limb darkening/brightening in geostationary satellite data. The latter is at odds with the philosophy of climate benchmarking: sampling accuracy must be observationally demonstrated just as instrument accuracy is. Using the semidiurnal cycle generated by a climate model is insufficient because, not only does the diurnal (and semidiurnal) cycle remain unobserved, a climate model's representation of it cannot be trusted to 0.1 K accuracy.

This leads to the following conclusions:

- Observational coverage of the semidiurnal (twice per day) component of the diurnal cycle is a critical issue for a climate benchmark.
- A precessing orbit is of value as long as an integral number of nodal precession cycles occurs per year.
- Three 90° polar orbits is key to a resilient global benchmark mission – one that can withstand the loss of a satellite.
- Multiple sun-sync orbits will not meet the NRC Decadal Survey objectives within the cost constraints of the CLARREO mission.

Final Note: Results presented at the Workshop clearly demonstrated that fewer than three orbits in any configuration inhibits our ability to distinguish long-term secular trends from long-term modulation of the semi-diurnal cycle. This effect is significantly minimized by deployment in true 90º orbits rather than sun-sync orbits. Multiple sun-sync orbits give useful (but highly compromised) sampling of the diurnal cycle *only if there are three or more sun-sync orbits spaced four hours in local time.*

IR Breakout Discussion Recap (cont.)

Why do we stop at 200 or 2400 cm^{-1}?

- *Without seeing any optimal fingerprinting studies beyond these defined limits, it's unclear why they are set as instrument drivers.*
- *Most think that getting the 100 to 200 cm^{-1} range is critical for understanding the climate feedbacks in the UT.*

- *There was not much need for discussion of a 1 cm OPD as most agreed it's probably in the right ballpark.*

Response: First of all, there was general agreement that a climate benchmark in the thermal infrared must require continuous spectral coverage, even though some uncertainty remains in the extent of that coverage. Not obtaining continuous spectral coverage at this point in time limits all future generations' ability to compare to the present climate. Discussion of the trade-space that must simultaneously be considered in the selection of spectral coverage was treated in previous bullets. While it is clear that analysis of the 100–200 cm^{-1} region is important for mechanistic studies of middle/upper troposphere heating and cooling rates and for refinement of radiative transfer processes in the rotational spectrum of water and in the union of the continuum and the rotational lines of water in that spectral region, these studies are a distinct and separable issue from that of setting in place a high accuracy climate benchmark record that is SI traceable on-orbit. The latter issue requires careful consideration of the impact on *overall* instrument accuracy resulting from extending the spectral coverage, the amount of independent information contained in the spectral interval to be added, and the cost implications of extending the spectral coverage.

Well, perhaps "Most think that getting the 100 to 200 cm^{-1} range is critical for understanding the climate feedbacks in the UT" , but no objective analysis or quantitative study has been presented, published, or discussed in any forum on this matter. Based on our efforts in optimal detection, we remain highly skeptical of this statement. The reason for this skepticism is that climate feedbacks, in the testing of Climate Forecast Models is represented as the Sensitivity by which the Forcing is multiplied to obtain the Response as shown in the figure below (presented at the Workshop). The Planck response is identified independently from the gain terms, γ_i, that represent the feedbacks from changes in water vapor, clouds, lapse rate, etc. The powerful aspect of the IR is that it captures these gain terms directly from observations of the atmosphere, as shown in the second figure, and therefore tests directly the climate forecast's ability to calculate the feedbacks. But notice that the spectral information, shown in the second figure, is contained in the region between 200 and 2000 cm^{-1}. Extension from 2000 cm^{-1} to 3000 cm^{-1} should be included because it provides unique spectral signatures (including the ν_3 band of CO_2 with enhanced sensitivity to lower atmospheric structure, CO, and reflected solar radiation) and it is easily accomplished within the existing sensor designs. What information is gained by extension to the high and low frequency ends of the spectrum can be determined by an optimal detection study as part of a phase A study.

Testing Climate Models

Response = Forcing × Sensitivity

$$\Delta T = \Delta F_{\text{rad}} \times \left(\Gamma - \sum_i \gamma_i^{\text{LW}} - \sum_i \gamma_i^{\text{SW}} \right)^{-1}$$

$$\Gamma = \Delta F_{\text{RAD}} / \Delta T$$

Planck response to radiative forcing ΔF_{RAD}

Stefan-Boltzmann

$$F = \varepsilon \sigma T^4$$

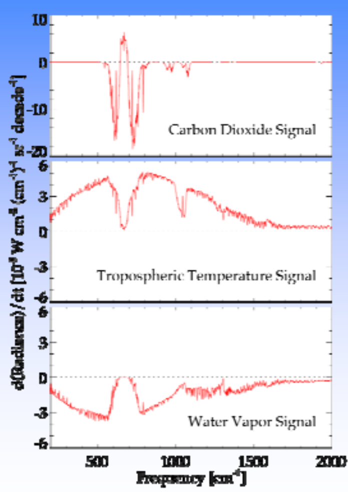
$$\Delta F_{\text{RAD}} / \Delta T = 4 \varepsilon \sigma T^3 = \Gamma$$

$$\gamma_i = \left(\frac{\partial F}{\partial x_i} \right) \left(\frac{dx_i}{dT} \right)$$

γ_1 = 1.7 w/m^2-K (water vapor)
γ_2 = –0.3 w/m^2-K (lapse rate)
γ_3 = 0.5 w/m^2-K (clouds)
γ_4 = 0.5 w/m^2-K (surface albedo in cryosphere)

35

Information in Infrared



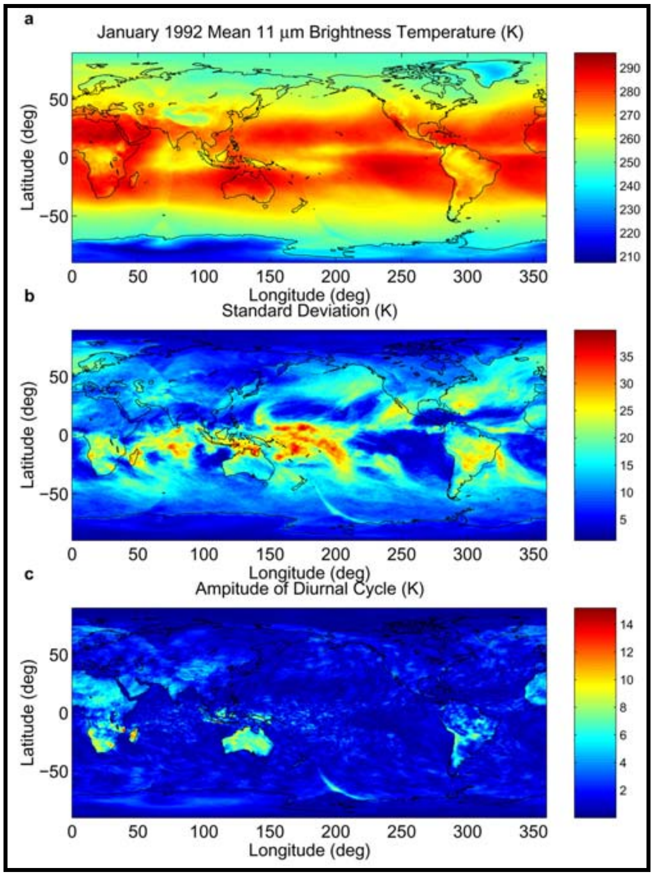
Obtain part of feedbacks

$$\gamma_i = \left(\frac{\partial F}{\partial x_i} \right) \frac{dx_i}{dt} \times \left(\frac{dT}{dt} \right)^{-1}$$

37

IR Breakout Discussion Recap (cont.)

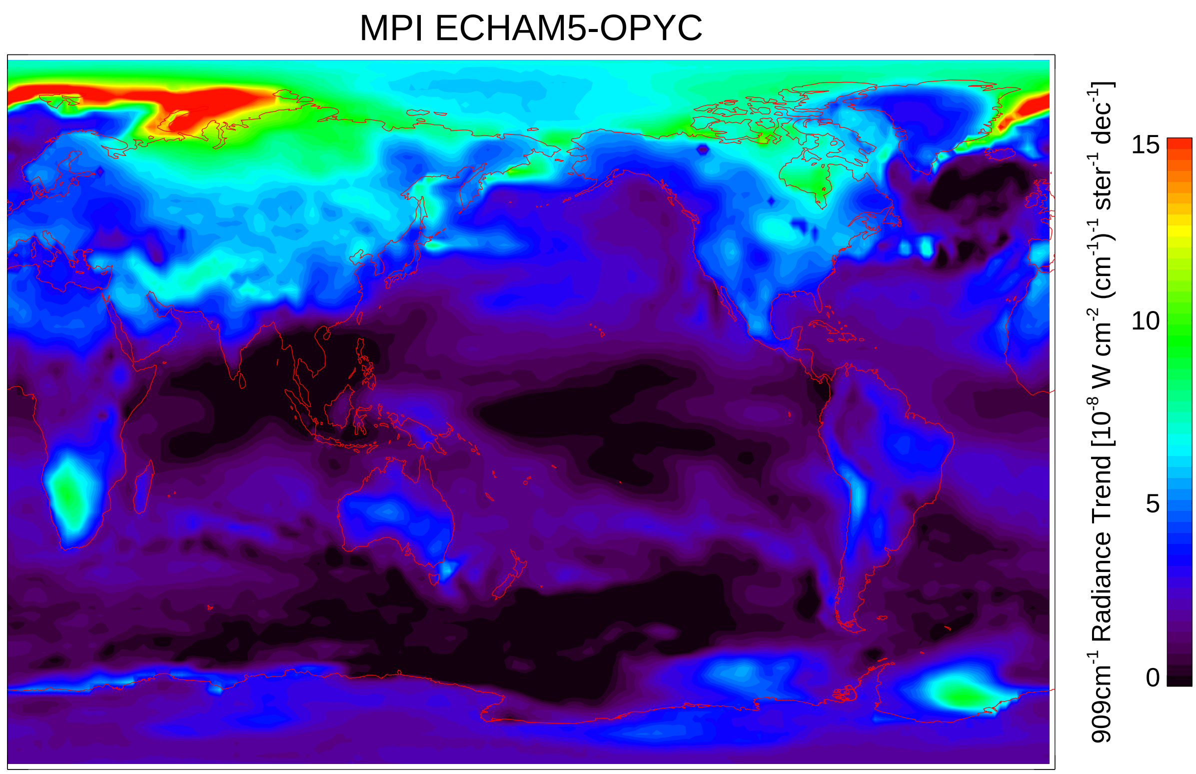
- *We had a hard time knowing whether a 100 km, or a smaller footprint is ideal. This deserves much more study by the community.*



Priority: Orbit choice. Salby cloud imagery data at 11μm

Response: Since the CLARREO climate product is composed of mean radiance spectra, with ensembles taken over long time periods (e.g. monthly to annual) and large geographic regions (e.g. 15 deg by 30 deg), footprint size is not a driver for the CLARREO design. While increasing the spatial resolution by decreasing the footprint of IR sounders designed for weather forecast initialization has always been a design goal for systems intended explicitly for weather objectives, for the establishment of a high accuracy, global benchmark climate record, the objectives are very different. There are many ways of representing the sharp contrast between weather and climate objectives in the determination of footprint size, but an effective starting point is to consider the cloud imagery data of Salby, wherein the monthly mean temperature, standard deviation, and amplitude of the diurnal cycle at 11 μm can be determined from the Salby data, as was done in Anderson *et al.* (2004), with the results shown here for a typical year (January 1992).

Although the intrinsic resolution of these data is 0.35º in latitude and 0.70º in longitude, it is clear that even for the monthly mean, a footprint size of 100 km easily resolves the desired features. At another level, the semi-diurnal cycle bias at 11μm displayed from the work of Stephen Leroy presented at the Workshop is shown in the figure below, again showing that there is little need for climate objectives of a footprint less than 100 km in diameter.



Detailed consideration of:

- Long-term climate science objectives
- Intercalibration goals
- Simplified optical design for on-orbit SI traceability
- Minimizing footprint spatial inhomogeneity for spectral calibration

yields the following conclusions:

- Obtaining radiative forcing and response for model testing: spatial structure of these signals is coarse for annual averages and long-term trends; 100 km footprint diameter is easily adequate for these objectives.
- Intercalibration: averaging over footprint inhomogeneity improves result and improves coverage, as shown in the Tobin study incorporating MODIS data and the IASI footprint pattern.
- Footprint inhomogeneity complicates spectral calibration; initial IASI results show this can be accounted for.

IR Breakout Discussion Recap (cont.)

- *Primary data product from spectrometer*
  - *Annual mean brightness radiance T @15 degree grid of 0.1 K*
  - *Sufficient spectral information to identify causes of changes in brightness temperature (techniques LIKE optimal fingerprinting).*
  - *Minimum 5 year data record.*
- *Secondary product from spectrometer*
  - *Intercalibration of operational sounders*
  - *Weather people would like temperatures at this accuracy as well.*
- *Open Issues*
  - *nEdT needs to be sufficient to characterize on orbit systematic errors, tighter than required to meet CLIMATE science goals.*
  - *Future discussion/studies are required to determine this requirement.*
- *Spectral range*
  - *200 to 2000 is a nominal starting point (in ES), needs to be refined based on optimal results from optimal fingerprinting.*
  - *100-3300 in chapter 9*
- *100 km FOV*
  - *Sufficient for annual gridded means*
  - *Some discussion as to whether this is sufficient for intercalibration with operational sounders, or even aircraft comparisons.*
- *Instrument type? Most agreed that an FTS is a robust way to do these measurements, but other types of spectrometers may meet the requirements as well.*

Response: Given that CLARREO addresses the key Societal Objectives to: (1) put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards, and (2) development of an operational climate forecast that is tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically rigorous techniques to systematically improve those forecasts to establish credibility, it follows that the *primary data* products from the spectrometer should include:

- High accuracy (0.1 K; 3σ), spectrally resolved (1 cm^{-1}), radiance extending from 200–3000 cm^{-1} emitted from the Earth to space obtained in the nadir from low Earth orbit such that some 1×10^6 such spectra are obtained each year from orbits selected to minimize sampling bias.
- By achieving very high accuracy (absolute) for combined measurement and sampling uncertainty (< 0.1 K 2σ brightness temperature for 15º × 30º latitude/longitude regional, annual means) that the long-term trend can be definitively separated from more rapid variations on the 10–20 year time frame, a capability that will also allow seasonal variations over larger spatial regions to be studied at comparable accuracies.
- The primary data product—the ensemble of absolute spectrally resolved radiance spectra must be such that systematic testing and improvement of decadal climate forecast models is

mathematically linked to the data vectors provided by the spectra obtained such that both trends and the gain terms in climate feedback can be observed.

- The global benchmark climate record initiated by the first three CLARREO IR/GPS missions should cover a period of seven years.

The *secondary data products* include the use of CLARREO to establish an SI traceable observation of absolute spectrally resolved radiance in order to determine the instrument bias in IR sounders such as CrIS, IASI, etc. As the Kirk-Davidoff/Tobin presentations made clear at the Workshop, the best strategy for the objective of intercalibrating of other IR sounders is to employ the three CLARREO IR/GPS satellites to establish the climate record, then establish the bias between CLARREO and the other sounders using SNO and Climate Target domains. There is also no doubt that weather forecast initialization, which now makes heavy use of data assimilation techniques, would be very considerably aided by the removal of "fudge factors" from the various IR sounders that make up the global observation system.

With respect to "Open Issues," there is little doubt that the NEΔT requirements are the least demanding requirement, including the requirements to characterize on-orbit systematic errors. The "Spectral Range" and "100 km FOV" are treated in previous sections.

Final Note: We note again that it doesn't seem as though there was a general understanding of the work presented by Tobin at the Workshop on strategies for intercalibration of other IR sounders with CLARREO. He demonstrated, using *real data with clouds* (!!), that other IR instruments can be intercalibrated with CLARREO to within 0.1 K on a monthly basis with an NEΔT of 0.6 K—and this was done at 11μ where the highest variability is present in the radiance emitted to space! His presentation at the Workshop should be carefully reviewed if there is any confusion on this point. Many of these questions were specifically answered in the detailed study presented by Tobin.

IR Breakout Discussion Recap (cont.)

- *How does one validate an instrument that is designed to BE the benchmark?*
    - *Most existing instruments are not designed to have that absolute accuracy along with traceability since this is supposed to be a new paradigm.*
    - *Because CLARREO is a climate monitoring instrument, where statistics are required more than high precision and small footprint of an instrument that is primarily a sounder, numerous intercomparisons with an aircraft are required for a proof of the delivered data product. Can this really be done? Should it be done?*
    - *How does one fully understand the instrument characteristics in flight with an instrument where absolute accuracy drives the design much more so than precision (as driven by the science questions/cost/etc.).*
    - *Is the second tunable blackbody good enough verification of the absolute calibration on orbit? What happens if radiances from this second blackbody don't agree with the first in flight?*

Response: This subject was addressed in a number of presentations at the CLARREO Workshop, and was introduced by George Ohring in the discussion of the ASIC 3 Report. At the same time the NRC was engaged in the setting of priorities for Earth Sciences with the ESAS

Decadal Survey, a major effort was underway to investigate the fundamental metrology behind satellite observations as they are applied to global climate observations.

A key consideration underpinning a national strategy for obtaining climate quality observations from space involves a careful analysis of evolving scientific developments in three important sub-fields: (1) Metrology, the sub-field of physics that addresses measurement accuracy and traceability, as it is practiced at the National Institute of Standards and Technology and in the physics and chemical physics scientific literature; (2) instrument system development, innovative on-orbit calibration technology, orbit selection for climate, etc., for high accuracy observations from space that incorporate Systeme International (SI) traceable standards *on-orbit*; and (3) the Earth Science community that employs climate models, *in situ*, and remote observations to address the mechanistic coupling of dynamics, radiation and chemistry in the context of climate. These subfields highlight the distinct contributions that each makes to the development of high accuracy global climate observations from space.

Principles from metrology constitute the foundation for the concept of benchmarks as a critically important category of observations that are of fundamental importance to the establishment of a climate record. No climate monitoring system has been developed in this country; the NRC Decadal Survey and the ASIC3 Report set a new direction. As the ASIC3 Report makes clear, in order to accomplish this goal, it is necessary to establish a set of **Guiding Principles for Satellite Climate Observations**:

1. Methods of observing the most critical climate variables from space must be developed, each having accuracies that satisfy the requirements of climate (e.g., 0.1 K for temperature) and that are SI traceable on-orbit to absolute standards.

2. The fundamental requirements of climate must be recognized in the design of instruments that constitute the backbone of the national climate observation array: Optical Designs, Orbits, Calibration, etc.

3. Trust in the accuracy of key long-term climate observations must be built upon: (a) open access to the details of experimental execution; (b) publication in the scientific and technical literature; (c) individual scientific responsibility; and (d) continuity in laboratory, airborne, and satellite analyses that together dissect systematic errors.

4. The experimental design and execution of long-term climate observations must be cost effective, responsive to emerging knowledge, and adaptable to technological innovation.

5. Calibration and associated subsystem development resources must be given high priority and the analysis of accuracy achieved by the observing systems must be systematically critiqued over the period of decades. Fundamental development of calibration facilities at NIST must be supported with ongoing commitment.

6. Primary long-term climate observations must be global in coverage, must provide required accuracies in both horizontal and vertical structure, and must be free of interference from uncontrolled boundary conditions.

7. Climate forecast testing and improvement places specific demands upon the data vector produced by the climate observation and upon the mathematical structure used to couple the observations to the forecast. Thus, selection of the highest priority observations must be done in concert with an understanding of the structure of the forecast model.

8. A benchmark must be of a data type that is repeatable by future generations in such a way

that no adjustment of data and the breaking of SI traceability are necessary. This demands unequivocal spectral response functions, continuous spectral coverage, unimpeachable thermometry and emissivity, and a through error budget that is submitted to repeated and on-going criticism.

While the ASIC3 document addressed the fundamentals of high accuracy on-orbit for climate studies, the application of those Principles to CLARREO specifically take the following form, as discussed at the CLARREO Workshop. The instrument design must be driven by the identification of all factors required for success in achieving the measurement objective: that is, the production of calibrated infrared spectra, together with the necessary evidence to defend the claimed level of measurement accuracy. These elements are shown schematically in Figure X. They include:

- Minimized error sources;
- Calibration strategy yielding SI traceability;
- Systematic errors tests (diagnostics);
- Redundancy for measurement uncertainty evaluation;
- Laboratory testing against primary radiometric scales; and,
- Continued critical evaluation of design and operation.

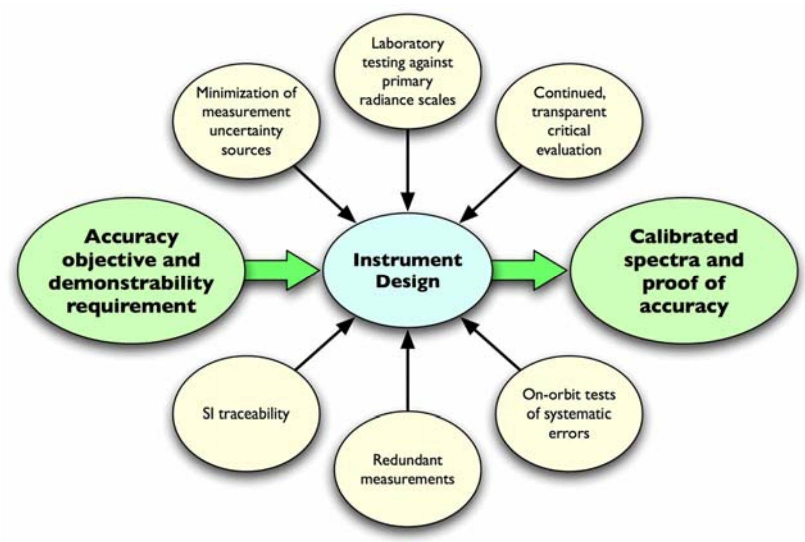


Figure X. The elements of the experimental strategy allow the instrumental design to achieve the measurement objectives for the infrared part of the CLARREO mission.

The experimental physics and technological basis for this approach are drawn from the work of many researchers over the course of decades. The fundamental instrument reference demands provably accurate temperature knowledge, thus engaging work in defining thermodynamic temperature and realizing a practical temperature scale with a rigorously understood and repeatable relationship to thermodynamic temperature. Combined with a deep cavity with a stable, low-reflectivity surface and homogeneous temperature distribution, these temperature measurements result in calibration blackbodies of sufficient accuracy. In addition to accurate blackbodies, meeting the measurement objectives requires calibration procedures to accurately quantify radiometric gain and offset and to account for self-emission. These calibration procedures rely on linear detectors and detector signal chains, which are obtained by choosing detector types that offer linear signal response at the molecular level. Additional sources of radiometric error arising from optical considerations include scattering, multiple reflections, polarization, and diffraction. Simplified optical designs which are optimized for climate minimize these uncertainties by reducing the number of optical elements, which diminishes the sensitivity to system alignment, compensates for thermal gradients, and reduces off-axis responsivity. Additionally, these simplified optical designs facilitate the inclusion of redundant calibrations, providing a practical method of testing radiometric accuracy on-orbit.

The instrument design available for CLARREO is informed by previous studies of small satellites, with an eye towards achieving reduced power and mass budgets to facilitate lower cost launches and constellations of multiple satellites. The value of spectral information and broad spectral coverage for climate studies has been considered in the choice of spectral resolution and spectral window. Studies of instrumentation with redundant calibrations as a means to irrefutably demonstrate accuracy on-orbit have been drawn upon to develop the calibration strategy. The value and shortcomings of flight intercomparisons have been evaluated to take full advantage of the utility of multiple interferometer instruments. The device physics and *in situ* performance of various detector types has been explored to aid in selection of detectors.

The application of the principles that dictate the CLARREO design also provide fundamentally new methods of on-orbit validation.

Two approaches will be used to validate the benchmark instrument observations, (1) the primary approach uses the new paradigm of in-flight validation with absolute standards as described above, and (2) the secondary approach applies recently demonstrated and proven techniques developed for AIRS and NPOESS as confirmation.

For the primary approach, as discussed in some detail at the workshop, the in-flight validation is accomplished with a new blackbody source design that can fill the CLARREO instrument aperture with accurately known radiances covering the full range of earth emitted brightness temperatures. The key properties of the source (temperature and emissivity) will be directly verified on orbit using a novel temperature calibration technique based on detecting multiple phase change transitions, and auxiliary sources that irradiate the blackbody allowing its reflectance to be monitored from the source on/off signal difference. This is a very direct approach, in accordance with the principles for SI traceability laid out in the ASIC 3 report. That is, the optical and thermodynamic properties of the blackbody, which are the fundamental linkage between the on-orbit calibration and the SI scale, are independently confirmed on-orbit. This method allows routine on-orbit testing with even higher accuracy than the normal thermal-vacuum testing performed before launch.

The verification of the traceability of the blackbodies on-orbit creates the foundation for testing the other systematic errors, a requirement to demonstrate that the sensor is in fact SI traceable. For example, the 45º view of deep space allows direct testing of the polarization effect. The ability of the second blackbody to dwell over the full range of Earth observation temperatures provides a direct test of signal chain linearity that supplements other well-established tests that have been demonstrated for interferometers. The redundancy of the multiple spectrometers, once the accuracy of the calibration system has been established, provides a unique set of diagnostics for determining other errors associated with the optical system. Again, this method of redundant calibration standards, independently verified for SI traceability, and tests of systematic error relevant to attaining 0.1K 3σ accuracy, replicates the thorough calibration tests employed in pre-launch for routine execution on-orbit.

The secondary approach would use several techniques developed by the community for EOS and NPOESS. The primary direct radiance validation would make use of high altitude aircraft observations, as is currently being done with the University of Wisconsin Scanning HIS instrument. As reported at the workshop, the aircraft instrument calibration uncertainty is itself verified using the NIST TXR transfer radiometer (<0.2 K 3-sigma for scene temperatures greater than about 240 K). To handle the large footprint size and sparse sampling characteristics of CLARREO, these comparisons would make use of the high spectral resolution sounding observations from AIRS and the new operational sounders (IASI and CrIS) to provide a transfer between the aircraft observations and CLARREO. Therefore, the actual aircraft comparisons would be made to sounder data, just as we are doing now. Our results from applications to AIRS and IASI show agreement to about 0.2 K and support a 3-sigma accuracy of the validation of better than about 0.4 K. While this approach is probably not capable of 0.1 K 3-sigma accuracy, it should definitely be performed to develop confidence in the new paradigm.

For clarity, we briefly address each of the sub-bullets of this validation question:

- *Most existing instruments are not designed to have that absolute accuracy along with traceability since this is supposed to be a new paradigm.* Our approach to the CLARREO IR payload should be thought of as two separate elements: (1) instruments, including their calibration systems, that are designed to optimize absolute accuracy and with properties that can be tested in orbit (e.g. linearity, Instrument Line Shape, polarization sensitivity), and (2) a highly accurate validation source that does not rely on stability on-orbit (Temperature referenced to multiple phase changes and reflectivity monitored). Therefore, while the instruments use several independent techniques to assure absolute accuracy and to be testable on orbit, from a validation viewpoint what is really different is that a separate end-to-end validation source is being provided on-orbit.
- *Can aircraft intercomparison really be done? Should it be done? Can it be done?* — Yes. Should it be done? — Yes, but it is important that the aircraft observations are SI traceable to accuracies comparable to that of CLARREO. As explained above, using operational high resolution sounders as transfer between CLARREO and an aircraft instrument make this practical. Of course, this comparison will be limited to the spectral coverage of the sounders (IASI covers about 3–15.4 microns), but this provides a very useful test of calibration properties over the full range of atmospheric brightness temperatures.
- *How does one fully understand the instrument characteristics in flight with an instrument where absolute accuracy drives the design much more so than precision?*
  The end-to-end radiometric performance is tested extremely well by the separate on-orbit SI source. For observations of the SI source, spectral averaging can be used to reduce the observation time needed for noise reduction. From an instrument characterization point of view, some tests (linearity from the out of band signal for example) can be performed using large amounts of data, and are not contingent on noise performance. The inclusion of high performance MCT and/or InSb on one interferometer allows the application of performance tests that *are* contingent on noise performance.

- *Is the second tunable blackbody good enough verification of the absolute calibration on orbit? What happens if radiances from this second blackbody don't agree with the first in flight?*

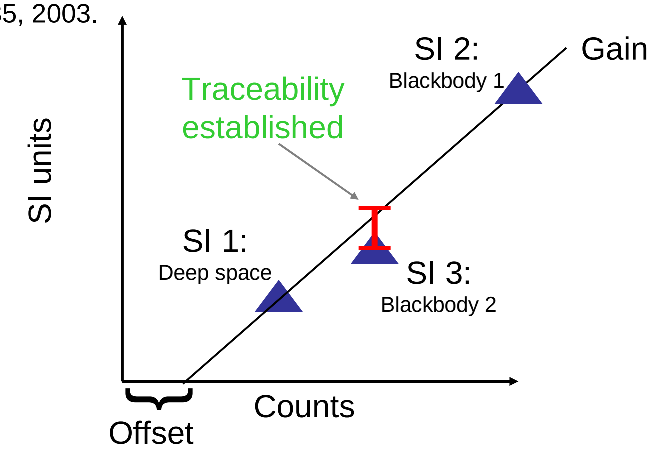
  As laid out above, there is a great deal more in the new CLARREO strategy than simply a "second tunable blackbody." Absolute thermometry is set using phase transition cells imbedded in the blackbodies, quantum cascade lasers and emission tube methods are used for independent cavity emissivity measurements, deep space scans are used for polarization measurements, and redundant interferometers, each with multiple blackbodies plus deep space, are used to interrogate systematic errors on-orbit. It is assumed in this design approach that there will be differences to adjudicate—that is the reason for strategically designed redundancy in the system architecture. It should also be emphasized that a key reason for joining absolute spectrally resolved radiance (ASRR) with GPS is that each is accurate against an SI traceable absolute scale to 0.1 K 3σ and thus there is, in this strategy, a fully independent cross check of accuracy achieved on-orbit. Trends obtained in the infrared spectra and the GPS occultation data should be scientifically consistent where the two deliver redundant information.

  We strongly support the need for aircraft flights. They provide independent information. If there should be a difference detected with the onboard validation source, careful analyses of the spectral and radiance dependencies of any radiance differences should be able to focus in on the cause. For example, the differences could be indicative of a very slow change in the emissivity of the calibration cavity. Depending on the detailed design, this might be directly testable, or tests on the validation source might be relied on. Then, the basic calibration could be corrected. The CLARREO system concept includes many more options to resolve such quandaries than any system flown to date.

Final Note: When a new design strategy for high accuracy IR radiance observations is applied to the climate problem, a system with on-orbit SI sources for sensor calibration validation, capability for on-orbit sensor and source characterization testing, and redundant on-orbit cross checks—principles reviewed by Pollock *et al.* [2003]—emerges. The foundation is expressed in the simple conclusion from Pollock *et al.,* "***To report the data from a remote sensor as being SI implies the sensor bias is more than an assumed unknown or unexplored uncertainty. The hypothesis that the remote sensor is calibrated must be tested***." Best current practices for IR spaceflight sensors would follow this practice for ground testing, but assume stability in space. For CLARREO, having an on-orbit SI source that can be maintained on orbit (using multiple phase change temperature calibration and reflection measurements) allows routine testing that the sensor data is SI (shows agreement within expected uncertainty with a source traceable to SI units). Having the capability for on-orbit characterization will allow any changes of key sensor properties to be identified (e.g. linearity changes from out of band measurements) and used to update the calibration. This process will allow SI traceability to be maintained on-orbit as subtle changes occur. Further, having multiple interferometers provides critical cross-checking to reveal systematic errors. All of these strategies support the new paradigm for climate measurements of assuring SI data with an uncertainty of < 0.1 K 3-sigma for the duration of the mission. In fact, the most crucial tests will be performed in space, but more conventional validation testing is necessary in addition.

Achieving SI traceability

- SI traceability *on-orbit* requires one additional SI traceable standard: Pollock, D. B., T. L. Murdock, R. U. Datla, and A. Thompson, Data uncertainty traced to SI units. Results reported in the International System of Units, *International Journal of Remote Sensing, 24*(2), 225-235, 2003.



IR Breakout Discussion Recap (cont.)

Costs?

- *Spacecraft costs are a serious impediment to meeting the $200M mission cost.*
- *Options exist that may decrease the costs, but are not yet NASA qualified.*
- *If launch costs are not part of the equation (or at least a small part), then one could build the desired number of spectrometers. This is not the current metric.*
- *If current spacecraft costs are required, staying within the budget is not possible. Costing matrix studies were not presented.*
- *We did not get to potential international collaborations. This avenue needs pursuit.*

Response: While it is true that launch costs (as opposed to spacecraft costs) are a serious impediment to meeting the $200M mission costs for CLARREO, it is also true that launch costs are a serious impediment to meeting the mission costs of nearly every NASA/NOAA/NPOESS mission now on the boards. However, on the timescale of the first CLARREO launch (2011–12), the emerging availability of the Space X Falcon 1e vehicle, under support of DARPA, has the capability of solving a manifold of NASA launch vehicle issues. This issue is addressed for CLARREO in the adjoining figure from Bill Gibson's presentation at the CLARREO Workshop. With the Falcon 1e, the launch costs for three of the CLARREO IR/GPS payloads would be roughly $30M, leaving $170M for other mission costs. With one Pegasus XL (@ $40M ea) and two Falcon 1e vehicles, the launch costs would be $60M, leaving $140M for other mission costs. These are all options that would provide ample margin for the IR/GPS mission. Given the advanced point of development of Falcon 1e and the highly simplified design (liquid oxygen and kerosene) in combination with DARPA support, there are two conclusions:

1. It would be wise for NASA to put its weight behind the continued deployment of the Falcon 1e as it is a critical factor in the planning of nearly all the NRC Decadal Survey priority missions, and
2. Putting high priority mission development on hold for a launch vehicle that is both nearly ready for operational launches and will not be required for CLARREO until 2011, would seem unwise.

Arrhenius/CLARRO SpaceX Falcon 1e Launch Summary

- Falcon 1e is a 2-stage, liquid oxygen/kerosene fueled expendable launch vehicle.
- With a 2 burn launch profile, Falcon 1e can take 450 kg to a 750 km. 90 degree inclination orbit.
- Falcon 1e Fairing payload accommodation:
  - Width: 155cm (dia) Arrhenius/CLARREO margin: 27%.
  - Height (non-tapering): 175cm; Arrhenius/CLARREO margin: 36%.
- Separation system: 98.6 cm motorized Lightband shock-less.
- Falcon 1e availability: 2009 at a cost of $8.5M.
- Falcon status:
  - 2 launches of Falcon 1.
    - 1st aborted @ ~T+34s , 2nd aborted @ ~T+475s due to an upper-stage control anomaly attributed to LOX slosh.