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Decadal Survey (DS) CLARREO Workshop Report

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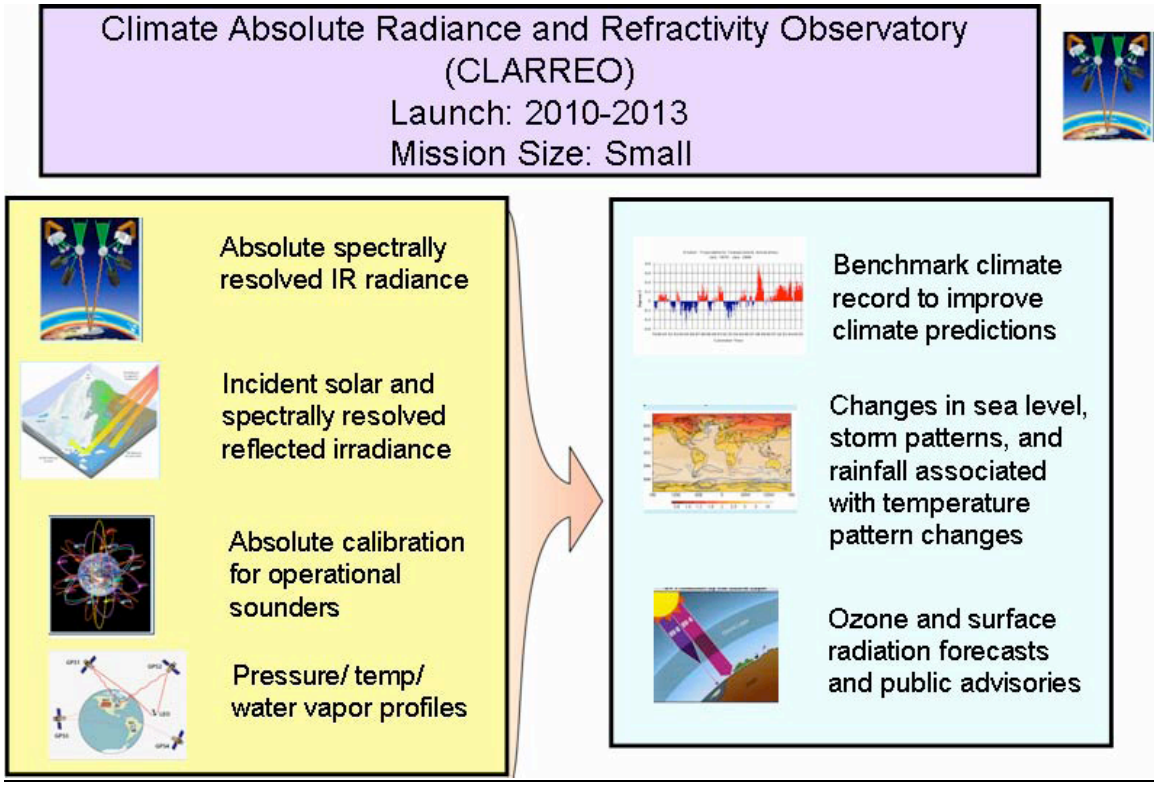
Website: http://map.nasa.gov/clarreo.html

1. Decadal Survey (DS) CLARREO Statement



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

Absolute spectrally resolved IR radiance

Incident solar and spectrally resolved reflected irradiance

Absolute calibration for operational sounders

Pressure/ temp/ water vapor profiles

Benchmark climate record to improve climate predictions

Changes in sea level, storm patterns, and rainfall associated with temperature pattern changes

Ozone and surface radiation forecasts and public advisories

CLARREO Mission Statement:
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. Appendix A provides the complete statement of the Decadal Survey CLARREO mission.

2. Introduction

The NASA CLARREO workshop held July 17-19 was one of four NASA workshops help in late June and July, 2007 to review the first four DS synthesized missions. As noted by the DS, these mission concepts are at different stages of maturity and the intent of the workshops was to help NASA organize its approach to implementation of DS recommendations. DS thematic panels developed 35 missions from 101 RFIs, from which the DS Executive Committee synthesized 17 missions, with suggested order. CLARREO was identified among the first four missions to be considered.

Goals of the workshops include:

(1) Identify science goals that lead to specific mission requirements/definition, and noting compromises made during the mission synthesis that may lead to mission constraints.

(2) Identify related satellite instrument measurements available during these missions from research and operational missions either necessary for mission success or complimentary.

(3) Assess the impact of NPOESS de-manifested missions/measurements, especially if multi-mission 'constellation' measurements are necessary to satisfy science goals.

With regard to (3), the DS CLARREO synthesis identified a requirement that TSIS and CERES instruments be supported and flown operationally by NOAA. The workshop participants supported this requirement at the outset. The workshop discussion then proceeded without further discussion regarding details of how that would actually get implemented by NASA-NOAA. There was discussion of the CERES requirement for NPOESS measurements at the same level of accuracy/precision as the TRMM, Terra and Aqua for ancillary measurements necessary to achieve the CERES deliverable of OLR.

In section 3 below, principal science goals are identified. However, there was long and contentious discussion regarding specific science goals and related specific measurement requirements, as well as ultimate 'customers' for CLARREO data products.

As this workshop was the first opportunity to review the CLARREO synthesis mission and because there has been no formal NASA advanced concept mission study with detailed costs traded among science goals and practical systems engineering reality, no final consensus was reached regarding (1) above.

In response to (2) above, there was considerable discussion on this topic, particularly with regard to a requirement to measure diurnal variability. It was agreed that further study was necessary to resolve whether or not complimentary measurements by existing/planned satellite measurements might satisfy this requirement and reduce the number of specific CLARREO satellites required.

References and workshop information are on the CLARREO website and are not cited separately here.

3. Science Supported by DS CLARREO mission

CLARREO is a Highly Leveraged Interdisciplinary Climate Change Mission

- Accurate decadal-length records are essential for climate change detection, attribution, and for testing climate prediction accuracy. They represent the most critical test of uncertainty in future climate change prediction.
- While process study missions (e.g. CALIPSO/CloudSat) are critical to improve underlying climate model physics (e.g. clouds), decadal change observations are critical to determine the impact of those climate model improvements on the accuracy of predicting future climate change. Both elements are critical, and CLARREO is the major Decadal Study mission addressing serious accuracy issues in decadal climate change observation.
- The CLARREO mission is unique in its broad interdisciplinary impact on climate change science: the other NRC Decadal Survey missions are primarily focused on one climate process or discipline.
- CLARREO provides new solar reflected and infrared emitted high spectral resolution benchmark radiance climate data records that can be used to test climate model predictions, improve climate change fingerprinting, and attribution.
- CLARREO provides an orbiting calibration observatory that can be used to calibrate other solar and infrared space-borne sensors (e.g. VIIRS, CrIS, Landsat, Geostationary, CERES) and thereby improve to climate accuracy a wide range of sensors across the GEO observing system. It also improves the scientific value of all of these instruments.
- Key climate variable decadal records impacted by CLARREO include: atmospheric temperature and water vapor profiles, land and sea surface temperatures, cloud properties, radiation budget including Earths albedo, vegetation, surface snow and ice properties, ocean color, and aerosols. The data is also relevant to greenhouse gas monitoring.
- The absolute accuracy of CLARREO, when used to calibrate other sensors in orbit can dramatically reduce the impact of data gaps on decadal change data records across many climate variables.
- CLARREO provides the first spectrally resolved climate observation of

the Far-Infrared spectrum from 15 to 50 micron wavelengths, where half of the thermal infrared emission of the earth to space occurs, and the source of almost all of the Earth's water vapor greenhouse effect.

- CLARREO's ability to calibrate other instruments across the full solar and infrared spectrum can change the future prioritization of different elements of instrument pre-launch characterization (e.g. spectral response), stability, and calibration, thereby resulting in increased programmatic flexibility and savings.

4. Breakout Summaries

4.1 Summary of CLARREO Solar Working Group

Discussion leads: Norman Loeb (LaRC), Joe Rice (NIST), Peter Pilewskie (CU/LASP)

The solar working group met during the afternoon of the second day of the CLARREO meeting and during the first part of the morning on the third day. The discussion was quite positive overall and clarified many questions concerning CLARREO goals, sampling needs, and instrument requirements. Following is a brief summary of the discussion that took place during the solar working group meeting.

CLARREO Goals

The solar working group agreed that the main objective of the CLARREO mission in the solar portion of the spectrum is:

> *To enable rigorous detection of decadal climate change in the key climate variables remotely sensed by satellites (e.g., solar irradiance, cloud & aerosols properties, radiation budget, vegetation, ocean color, snow & ice).*

This science will be achieved by using CLARREO as an orbiting calibration standards laboratory designed and optimized for calibration of sensors on operational and research missions that will then provide the global space/time sampling needed for climate change detection. CLARREO will provide the SI traceable accuracy in orbit for these sensors at absolute accuracy levels sufficient to observe decadal climate change at a signal-to-noise level of at least 5:1 (Ohring et al., 2005). These goals are consistent with three recent reports on satellite calibration requirements:

i) NASA/NOAA/NIST/NPOESS Satellite Climate Calibration Workshop (Ohring et al., 2005, NISTIR 7047);

ii) Global Climate Observing System (GCOS) international report;

iii) Achieving Satellite Instrument Calibration for Climate Change (ASIC^3).

The goals are also in line with the Global Space-based Inter-Calibration System (GSICS), a new World Meteorological Organization (WMO) program whose overarching goal is the ensure the comparability of satellite measurements provided at different times, by different instruments under the responsibility of different satellite operators.

While the solar working group discussions were tilted toward the satellite calibration observatory (or "NIST- in-orbit") concept as described in the Decadal Survey, the group recognized that the data will provide the "global climate benchmark" of reflected solar radiation measurements, albeit with larger sampling challenges than at infrared wavelengths. The group viewed the satellite calibration observatory and global climate benchmark CLARREO goals as being complementary. In fact, the absolute radiometry requirements for the satellite calibration observatory are the same as the radiance benchmark requirements. The group recommended that further modeling and sampling studies be carried out to clarify the optimal sampling strategy to use the solar wavelength observations of CLARREO as a spectral radiance benchmark. That study should take into account the duty cycle for the CLARREO inter-calibration activities, estimated to be < 5%.

Accuracy requirement

Climate accuracy requirements for variables determined from reflected solar radiation are shown in Table 1, expressed as stability per decade (see ASIC^3 report). The objective is to calibrate operational and research satellite instruments with CLARREO to enable these levels of stability to be achieved by the satellite observing system.

Variable	Stability/Decade (Instrument gain change in %)
SW cloud radiative forcing (cloud feedback)	0.25
Visible cloud optical depth (cloud feedback	0.40
Cloud particle size (1.6mm and 2.1mm wavelength)	0.50
Vegetation	0.80
Ocean color	1.00
Surface albedo	1.00
Aerosols (gain)	1.50
Aerosols (polarization)	0.25

Table 1 Accuracy requirement by variable.

SI Traceability

SI Traceability is achieved in essence by transferring the full calibration and traceability chain employed in terrestrial national standards laboratories such as NPL and NIST into orbit. For example, from the primary standard cryogenic radiometer (in the case of TRUTHS) through to the calibration of spectral radiance of the full aperture of an Earth viewing imager. It meets these objectives largely through the use of existing developed technologies and instruments (e.g., TRUTHS concept, which is traceable to SI through Cryogenic Solar Absolute Radiometer (CSAR) in space (as on ground)). SI-traceable reference targets such as the sun and the moon will also be used for redundancy.

Sampling Needs

To meet the climate accuracy goals defined in the ASIC[3] and earlier reports, CLARREO must not only be highly accurate, stable, well characterized, and have a means of tracking stability on orbit, but it must also have the appropriate characteristics to enable calibration of operational and research satellite instruments. Much of the discussion in the solar working group centered on the spectral, spatial, angular, temporal requirements for CLARREO in addition to the need for pointing capability, specific orbits, and sampling coverage. The requirements for these are summarized in Table 2 along with further studies the group felt were needed to better define the requirements. The following summarizes the discussion that took place concerning each item in Table 2.

Spectral Sampling

The main driver for the spectral sampling requirement is the need to convolve CLARREO spectra with the spectral response functions of the various instruments being calibrated by CLARREO. It was felt that a 5-10 nm spectral resolution, with a sampling resolution of 25% of the spectral resolution of the CLARREO instrument would be sufficient. With few exceptions, solar reflectance earth viewing sensors have spectral response widths of 20nm or larger. It was also noted that some studies (e.g., with MODTRAN spectra) would be needed to assess the trade-off between spectral resolution and accuracy, especially near absorption features. A key question is the accuracy with which it would be possible to separate spectral shifts from radiance calibration in instruments with poorly characterized spectral response functions, or from changing spectral response functions between instrument versions such as MODIS to VIIRS. Determination of the impact of spectral response changes on climate change signals would require CLARREO spectra in a wide range of climate regimes and spectral scenes. This need is also consistent with the CLARREO interest in providing a spectral radiance benchmark. The required spectral range of 0.38-2.5 mm follows directly from what is currently achievable with a TRUTHS type of calibration system, the wavelength range covered by narrowband and broadband radiation sensors to be calibrated, and with covering more than 95% of the energy the earth reflects to space. The coverage will also meet the needs of a radiance benchmark. However, several participants expressed the need to also provide highly calibrated measurements near 3.7 mm where particle size retrievals are often made. It was felt that this wavelength range needs further study and is more appropriately addressed by the IR group.

The group discussed whether the spectral resolution and coverage of CLARREO in the solar spectrum should be sufficient for calibration of atmospheric chemistry instruments such as ozone (0.3 to 0.4 mm) or oxygen A-band (CO_2). It was noted that the primary mission for CLARREO was not chemistry and that the much higher spectral resolution and coverage that would be required would greatly increase the complexity and cost of the CLARREO solar reflectance measurements. Given the desire for a small cost effective mission, chemistry requirements were not included in the trade space.

The group also discussed the need for polarization measurements. This need arises from three different perspectives. First, the CLARREO spectral radiance should be insensitive to polarization of the incident radiation field. Second, since the Earth-viewing solar wavelength sensors that TRUTHS will be calibrating may be sensitive to polarization, it will be necessary to characterize the polarization in scenes used for calibration. Third, some instruments used to study aerosols rely on polarization as a key observation. Nigel Fox pointed out that the TRUTHS design envisioned characterizing overall scene spectral polarization by putting stripes on the imager so that you could have some S and P polarization state information across the FOV. He indicated that the plan was also to have a small number (~4) of polarised filter radiometers with wide FOV (~20 km to 100 km (TBD)) that could simultaneously view the Earth alongside the imager and similarly be traceably calibrated in orbit. The optimal design for CLARREO polarization spectral sensing needs further clarification.

Spatial Sampling

The ideal CLARREO spatial sampling was determined to be 1-km IFOV over a 100-km swath. This would permit calibration of moderate-spatial resolution instruments by averaging over 100-km regions observed by both CLARREO and the instrument being calibrated within a few minutes of one another. For instruments with coarser spatial scales (e.g., radiation budget instruments), the 1-km CLARREO pixel data could be spatially averaged into the larger footprint of the instrument being calibrated (after weighting by the instrument point-spread function). Some further study was identified to ensure that the proposed intercalibration strategy would also be effective when calibrating very high-resolution instruments (e.g., for land applications) and if there were any benefits (within a trade-off against cost) for higher spatial resolutions of 100/250 m. Another motivation for needing a 1-km IFOV is to be able to resolve the moon in the IFOV. The 1-km resolution is the minimum IFOV for lunar viewing as demonstrated by the recent SeaWiFS use of lunar stability monitoring. The lunar diameter as viewed from a low-earth orbiting mission like CLARREO is roughly equivalent to a 6km IFOV.

Angular Sampling

Initially it was proposed to restrict the angular coverage to the nadir-to-45 deg range, but because some instruments (e.g., MISR) can observe to 70 deg in the alongtrack direction, the group decided to extend the range to 70 deg. The group also expressed a need to be able to view the moon over a 5-90 deg phase angle range.

Pointing Capability

The group concluded that a pointing capability is critical to CLARREO's ability to calibrate other instruments at climate accuracy. The inter-calibration involves not only matching samples in space and time, but also in viewing geometry. That is, CLARREO must observe a scene from the same view angle as the instrument being calibrated. A nadir-only CLARREO would severely limit the number of matches available and likely wouldn't meet the accuracy goals listed in Table 1. The rate at which CLARREO needs to point was determined to be approximately 2-deg per sec. This is tied to how much dwell time CLARREO would have to align its viewing geometry with other instruments, which in turn, is related to the orbit altitude and inclination. CLARREO would also need a pointing control of 0.5 deg to reduce anisotropy error, and a pointing knowledge of 0.5 arc min to meet the requirement to observe the moon.

Temporal Sampling

The temporal requirement is driven by the need to calibrate satellite instruments at equator -to-polar latitudes approximately every 3 months. The equator-to-pole requirement is driven by the need to verify calibration accuracy in a full range of climate regimes, especially to verify spectral response functions of filter instruments like MODIS, VIIRS, GOES, and CERES. The 3-month time period is driven by the need to resolve any rapid shifts in instrument calibration, as well as the ability to do the calibration while the instrument gain is relatively constant. Some imager reflectance channels have been shown to change gain by 1 to 3 percent per year. While the change is smooth over time, it is not exactly linear, so the magnitude of change during a calibration period should be small. A secondary reason for the 3-month calibration period is to achieve more than one precession cycle per year so that annual thermal cycles of instrument and spacecraft temperature are constant from year to year. It was noted that the cavity detectors used in SORCE and TRUTHS designs are designed to be insensitive to thermal environment, but if a consistent thermal environment from year to year can be assured without significant mission cost, it would be useful.

Orbit

As stated in the Decadal Survey (Chapter 9), the calibration observatory requires 3 satellites: two precessing orbits separated by six hours with a third ready to launch upon failure of one of the other two. An inclination of 74 deg is found to be a compromise between sampling the polar ice sheets and tropics. The question as to whether or not climate accuracy could be achieved with just one CLARREO satellite with pointing capability is unclear and requires further study.

As noted above, the orbital altitude of CLARREO needs to differ from that of the instrument being calibrated to provide sufficient dwell time for matching in angle: you gain approximately 40 sec of time per 100 km orbit difference. Given that many of the satellite instruments CLARREO is targeting for calibration are flying at altitudes between 700 (e.g. Terra, Aqua) and 840 km (e.g. NPOESS), it was felt that CLARREO should fly between 500 and 600 km, which would provide a few minutes of time for matching. The consensus of the group was that the cost and other difficulties of mid-Earth orbits (MEO) make this a less attractive option.

Sampling Coverage

The sampling coverage (spectral, temporal, and spatial) needs to be sufficient to allow separating changing instrument spectral response in climate data records (e.g. changes from MODIS to VIIRS), and to serve as a spectral radiance benchmark. These requirements will drive data rate and associated cost. Related to this is the CLARREO duty cycle: would data need to be collected continuously or just when inter-calibrating with other instruments? If CLARREO collects data less than 5% of the time (e.g., when inter-calibrating other instruments), the high data volume associated with full spectral and spatial resolution may be quite manageable. For spectral benchmark purposes, the average 100km spatial scale spectral radiance could be saved 100% of the time without driving total data volume or storage requirements.

An open question is whether CLARREO should characterize targets around the Earth (e.g., specific climate regimes, ground sites with wide range of instrumentation such as ARM). It was felt by some that this would be a good idea and such data would also serve process-oriented studies as well (e.g., closure studies).

Collaborations

The group agreed that CLARREO will require international collaborations (e.g., TRUTHS) amongst scientists and engineers from both CLARREO and the operational and research missions whose instruments CLARREO will calibrate and that the CLARREO mission fits well within frameworks such as GEOSS and CEOS. These collaborations will span a range of activities (e.g., from decisions about instrument design/cost issues to analysis of climate data records from instruments calibrated by CLARREO). Everyone agreed that CLARREO must have an open data policy.

Category	Requirement	Req'd Further Studies
Spectral	0.38-2.5 mm (5-10 nm spectral resolution, sampled to ~25% of spectral res); Characterize solar measurement instrumentation for polarization	- Convolve spectra over instrument spectral response (e.g., MODIS) vs accuracy requirement. - Accuracy requirement as a function of wavelength. - Clarify polarization requirement
Spatial	~1 km IFOV resolution over 100-km swath; Avg over 100-km regions for intercalib. with other instruments	- Scene simulation study for IFOV (e.g., land applications).
Angular	0-70° with full azimuth range; Ability to view the moon (phase angles 5° to 90°)	
Pointing capability	~2° per sec; Pointing control of 0.5°*; Pointing knowledge: 0.5 arc min (lunar cal requirement)	- Clarify pointing time interval versus orbit altitude and inclination
Temporal	Calibrate at equatorial-to-polar latitudes; precess across all hours of the day every 3 months	- 1 vs 2 satellite sampling to meet sampling requirements
Orbit	Nominally 600 km	- Linked to pointing capability study
Sampling Coverage	Ability to account for changing instrument spectral response in climate data records, and to provide a spectral radiance benchmark	- Clarify according to sampling requirements vs cost
Collabor-ations	International ; Calibration of sensors on operational and research missions; Analysis of climate data records from instruments calibrated by CLARREO; Open data policy	- TRUTHS - CEOS-GSICS

Table 2 CLARREO requirements discussed during solar breakout session of CLARREO workshop.
*Derived from the anisotropy of radiation fields (1-sigma)

4.2 Summary of CLARREO IR Working Group

Discussion leads: Ken Jucks(NASA HQ), Dave Johnson (LaRC), Larrabee Strow (UMBC), Dan Kirk-Davidoff (UMD)

In order to properly discuss the requirements for an infrared spectrometer, it was important to discuss the science drivers for this portion of the CLARREO mission. The Synthesis Summary stressed the need to do climate observations and not add requirements to the mission for atmospheric sounding as done by current EOS instruments and CrIS on NPP.

The discussion concentrated on the type of observations to first and foremost define a robust and achievable benchmark set of measurements for observing future trends in atmospheric/climate change, and not as a sounder, e.g. AIRS, two key points became obvious to the discussion: 1) the type of spectrometer can and should be much smaller and simpler in design than the current operational sounders; and 2) the adaptation of current and future sounding instruments into a climate record that includes the initial CLARREO instrumentation is far from straight forward. Some thought that it is absolutely required to do so, and others thought that there is no point to even try, given that they do not have the same on-board calibration standards being considered for CLARREO.

There was near unanimous agreement that putting a spectrally resolved radiometer into space with SI traceable calibration standards on board is important. The group could all see that such observations have many of potential uses, even without a clear path as to how the climate modeling community may end up using a CLARREO data set. There was also considerable discussion, with no real resolution, about what the required precision should be for such instruments. For sounders, precision has a higher priority than absolute accuracy for many applications. For Climate studies, the opposite is true. However, in order to fully understand the systematics of the instrument in orbit, and prove to the community that the systematics are well understood and do not affect the absolute radiances being delivered, high precision may be required. No hard numbers were, or really could be, discussed at this time given the lack of a public feasibility study.

For the discussion of the instrument requirements necessary to meet the climate benchmark, as noted in the plenary discussion and in the Synthesis Summary, the session targeted three general topics: (a) orbits and footprints for climate studies; (b) spectrometer optical requirements; and (c) calibration and validation requirements. This was followed by a brief discussion of potential cost drivers and spacecraft options.

Orbits and Statistics for covering the diurnal cycle and natural variability

This discussion started out with a presentation by Daniel Kirk-Davidoff based on a publication he led on the orbits required to both fully sample the semi-diurnal cycle of the outgoing longwave radiances (OLR), and maximize overlap with sounders that are in sun synchronous orbits. This study clearly shows that the most ideal configuration has three instruments in polar orbits separated by 60 degree declinations. The study further states that reducing the number of satellites and/or shifting to sun sync orbits reduces both the sampling of the semi-diurnal cycle and the statistics of overlap with the existing sounders. Many voiced their concern about whether the science gained by having 3 individual orbiters was really a requirement for such a mission. There may be other less expensive options for sampling the diurnal cycle. This is an area that requires significant future investigation as this mission concept evolves.

Footprint size

As we discussed why the Decadal Survey indicated a 100 km footprint, it became clear that this was being driven as much by one concept of what one set of currently available technology can deliver as opposed to any clear scientific requirement. There are many parameters and instrumental characteristics that affect and are affected by the footprint size. Much of this is driven by the sensitivity of the detectors used, the fore-optics, the throughput of the spectrometer, and any desire to sound homogeneous footprints for validation purposes. For the most part, the group recognized that the phase space driving this requirement is broad, and that final footprint size will be driven by many issues as the concept evolves.

Wavelength Range

There are different numbers for what the desired wavelength range for the IR radiometers should have in different parts of the Decadal Survey. The Executive Summary calls for 200 to 2000 cm^{-1}, but a broader range is indicated in Chapter 9. The tradeoff here is that the former range covers MOST of the OLR. But all agree that there is considerable climate information at wavelengths at both ends that would be scientifically useful. Not measuring them now sets a limit on what is used for any successive climate record satellites that use similar on-board absolute calibration schemes. Most recognized that technology issues with both optics and detectors might have driven the smaller range in the Executive Summary. These issues may be overcome by some of the ongoing technology studies currently in progress by some of the groups in attendance.

For frequency resolution, all were in agreement that the best tradeoff between instrument simplicity and scientific return was best met with a frequency resolution of 1 cm^{-1} (or 1 cm optical path difference in FTS language).

Overall Spectrometer requirements

In order for the entire group to understand what the requirements are for a minimal instrument that meets the requirements for establishing a benchmark climate radiance record, we discussed individual aspects of the instrument characteristics and science objectives. These are summarized here:

- Primary data product from spectrometer
  - Annual or seasonal mean spectrally resolved brightness radiances temperatures in roughly 15 degree grid that have an absolute and relative accuracy of 0.1 K or better
  - Spectrometer needs to have sufficient spectral information to identify causes of changes in brightness temperature (using techniques LIKE optimal fingerprinting).
  - A minimum of a 5 year data record is needed to start and establish such a record.
- Secondary product from spectrometer
  - Inter-calibration of operational sounders with the CLARREO radiometers.
  - Weather community would like individual spectrally resolved temperatures with a 0.1 K precision as well.
- Open Issues
  - nEdT (detector sensitivity) needs to be sufficient to characterize on orbit the systematic errors. These requirements are tighter than required to meet CLIMATE science goals (and not addressed in Decadal Survey).
  - Future discussion/studies are required to investigate this requirement.
- Spectral range
  - 200 to 2000 cm^{-1} is a nominal starting point (in ES), needs to be refined based on optimal results from optimal fingerprinting.
  - 100-3300 cm^{-1} in chapter 9. Most in the workshop would like at least 100 to 2400 cm^{-1}.

- 100 km FOV
  - This is sufficient for annual or seasonal gridded mean radiances.
  - Some discussion as to whether this is sufficient for inter-calibration 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.

Validation/Calibration of the IR CLARREO

The discussion of how to validate an instrument on orbit that is designed to be the benchmark for all past and future climate monitoring spectrally resolved radiometers left more questions than conclusions. Much of this hinges on the discussions earlier of what the instrument requirements are, how one proves the emissivity and temperature of the blackbodies, proves that the stray light issues are properly controlled, and proves that any off axis issues in the chosen radiometer are properly understood and modeled. This requires that both the ground calibration and in-flight calibration procedures are sufficient to characterize these issues. There was also discussion about how one goes about designing a field campaign to validate an instrument with a much larger field of view than most Earth observing systems and is designed more for accuracy than precision. Can enough statistics be obtained to do this? There was also discussion of what happens if the results from the radiances from the two on board blackbodies do not agree. Are the multiple radiometers proposed for each satellite good enough validation? All of these remain open questions.

Costs

Using current NASA costing metrics, there is no way to fly 3 satellites alone (not including the spectrometers themselves) within the $200M listed in the Decadal Survey. The only way to fit it in is to either remove the cost of the launch vehicles from the costing metric (not likely) or to find lower cost launch vehicles. The group from Southwest Research Institute proposed some DARPA funded vehicles that may be of use for CLARREO. But we don’t yet know if they will become available within the next decade to NASA and whether NASA would approve of their use. We also don’t know what the final cost of these vehicles may be.

No group was willing to estimate the cost of each spectrometer unit would be since it’s early in the discussion of the mission concept.

However, related spectrometers for recently proposed Mars missions were budgeted at $15M. This is a good starting point for the discussion of cost. The spectrometer for CLARREO may be simpler than those proposed for the Mars mission, but the in-flight calibration and advanced blackbodies may add cost. The Executive Summary of the Decadal Survey called for 6 spectrometers, 2 on each of the 3 polar orbiting satellites.

5. Potential Partnerships

International Participation/opportunity

Both Claude Camy-Peyret (IASI) and Nigel Fox (TRUTHS – UK [NPL]) were enthusiastic about wanting to internationalize the CLARREO mission, especially because international standards in orbit are a requirement if these standards are to be accepted.

Potential NSF participation

Rob Kurczinski for U. of Arizona attended the meeting. He was recently awarded a large NSF grant, ATOMMS: Active Temperature, Ozone, Moisture Microwave Spectrometer (ATOMMS) is LEO-LEO Occultation Observing System. Rob moved from JPL a few years ago. NASA has interacted with Rob and is providing a platform for flight tests. NASA will provide an opportunity to instrument the two NASA WB57s with ATOMMS instruments.

ATOMMS development may be accelerated as a result of the CLARREO workshop. NSF may well become a partner, if ATOMMS is developed on schedule and satisfies CLARREO measurement requirements.

6. Challenges

Issues for testing climate model integration to observations

- What tests are necessary and sufficient for accurate predictions?
- How are observables and sensitivity fundamentally related?
- We need empirical estimates of sensitivity that are robust to uncertainties in historical forcing.
- Fluctuation-dissipation theory links sensitivity to 2nd-order statistics (lagged correlations) of observables. This theory is not utilized in current assessments.
- Observational and model capabilities should be designed with tests of this theory as a top priority.

Issues for solar backscatter Observations

- Further modeling and sampling studies should be carried out to clarify the optimal sampling strategy in order to use the solar wavelength observations of CLARREO as a spectral radiance benchmark.
- Table 2

Issues for IR Observations

- The desired spectral range and spatial resolution needs to be defined by the science return for both the future climate record and climate signatures. The Decadal Survey appears to have defined these by simple, not state of the art, instrumentation.
- The scientific need to have 3 polar orbiting satellites to fully characterize the semi-diurnal signature for climate needs to be more fully defined.
- The precision of the radiances need to be sufficient to characterize and model the effects of instrumentation artifacts on the retrieved radiances. This is difficult to do with averaged radiances.
- How does one tie CLARREO radiances with larger footprints to those of the current observational sounders with smaller footprints and no in orbit SI traceable calibration?