CLARREO Extended Pre-Phase A White Paper

Final Version, March 28, 2011

1. Background

1.1 Document Purpose

The Climate Absolute Radiance And Refractivity Observatory (CLARREO) mission is one of the Tier 1 missions recommended by the 2007 Earth Science Decadal Survey. NASA has conducted Pre-Phase A science and mission planning for CLARREO from 2008-2010. The mission successfully completed its Mission Concept Review (MCR) in November of 2010, and had planned to move into Phase A early in 2011. On February 14, 2011, the President's new budget for NASA eliminated the previous funding profile for the CLARREO and Deformation, Ecosystem Structure and Dynamics of Ice (DESDynI) missions. The new budget guidance was for the CLARREO mission to enter an extended Pre-Phase A and to examine other ways to achieve some portion of the CLARREO science in the near term through alternative mission concepts, instruments of opportunity or aircraft; international collaboration, interagency collaboration, or other mission implementations. This effort will also serve to advance the science and could identify options for achieving the full CLARREO objectives in the future.

A meeting was held at NASA HQ on February 28, 2011 to discuss the path forward. The meeting was attended by the CLARREO leadership team and members of the NASA HQ Earth Science Division (ESD). At this meeting, the CLARREO team was tasked to produce a white paper suggesting the best path forward given the new guidance. This white paper should consider three major resource elements including procurement, the ROSES selected CLARREO Science Definition Team (SDT), and NASA civil service staff. The plan should include FY12 through FY15. The plan should assume that the ROSES CLARREO SDT would receive its $1.6M of FY11 funding as planned, but that FY12-FY15 funding levels were not yet set and would need to demonstrate utility and deliverables to both the ESD Flight Projects and Research and Analysis (R&A) Programs.

The present document provides the white paper requested at the February 28, 2011 meeting.

1.2 CLARREO Science Summary

The CLARREO mission addresses the need to rigorously observe climate change over decadal time scales and to use decadal change observations as the most critical method to determine the accuracy of climate change projections such as those in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Climate predictions verified against decadal change observations with rigorously known accuracy are critical in order to enable sound policy decisions.

SCIENCE OBJECTIVE: Make highly accurate and SI-traceable decadal change observations sensitive to the most critical but least understood climate radiative forcings, responses, and feedbacks.

The NRC Decadal Survey (NRC, 2007) concluded that the single most critical issue for current climate change observations was their lack of accuracy and low confidence in observing the small climate change signals over decade time scales. The CLARREO breakthrough in observation of climate change on decadal scales is to achieve the required levels of accuracy and traceability to SI standards for a set of observations sensitive to a wide range of key climate change observations. These accuracy levels are determined by the projected decadal changes due to anthropogenic forcing along with the background natural variability above which such changes must be detected. Therefore, CLARREO measurement requirements are determined not by instantaneous accuracy, but instead by the accuracy sufficient to detect large time/space scale decadal changes (global, zonal, annual, and seasonal).

The result is the creation of climate change benchmark measurements defined by three fundamental characteristics.

- *Traceability to fundamental SI standards at the accuracy level required to resolve decadal climate change signals, and to be robust to gaps in the climate measurement record.*

- *Time/space/angle sampling sufficient to reduce aliasing bias error in global decadal change observations to levels well below predicted decadal climate change signals and below natural variability of the climate system.*

- *Sufficient information content in the observation to infer climate change in the key climate change variable(s) of interest.*

A summary of the CLARREO benchmark measurements is given below:

- The CLARREO infrared (IR) SI traceable benchmark measurement is the Absolute Spectrally Resolved Radiance Emitted from Earth to Space determined with an accuracy of 0.1K (k=3)*. The measurement is traced to the SI standards for the Kelvin and the Watt.
- The CLARREO Global Navigation Satellite Systems Radio Occultation system (GNSS-RO) SI traceable benchmark measurement is the phase delay rate of the transmitted signal occulted by the atmosphere from low Earth orbit. The measurement is traced to the SI standard for the second.
- The CLARREO reflected solar (RS) SI traceable benchmark measurement is the Absolute Spectrally Resolved Nadir Reflectance of Solar Radiation from Earth to Space determined with an accuracy of 0.3% (k=2). The percentage is relative to the mean spectral reflectance of the Earth. While spectral reflectance is a

---

* The coverage factor (k) can be thought of most simply as a more generalized version of a statistical confidence bound. A value of *k=1* is analogous to a 1σ confidence bound, *k=2* to 2σ, and *k=3* to 3σ. Note that for CLARREO, the selection of whether to specify the accuracy requirement as *k=1,2, or 3* is primarily one of convenience to keep the requirements as single digits that are more easily remembered. For example, the 0.1K (*k=3*) IR accuracy requirement could have been specified as 0.07 (*k=2*), or the 0.3% (*k=2*) RS requirement could have been specified as 0.15% (*k=1*).

measurement relative to solar spectral irradiance, use of the TSIS spectral solar irradiance observations enables traceability to the SI standard for the Watt.

The CLARREO suite of measurements is designed to provide an integrated view of the entire climate system. In particular, these measurements are designed to provide information on the most critical but least understood climate forcings, responses and feedbacks associated with the vertical distribution of atmospheric temperature and water vapor, broadband reflected and emitted radiative fluxes, cloud properties, surface albedo, temperature, and emissivity (Figure 1)

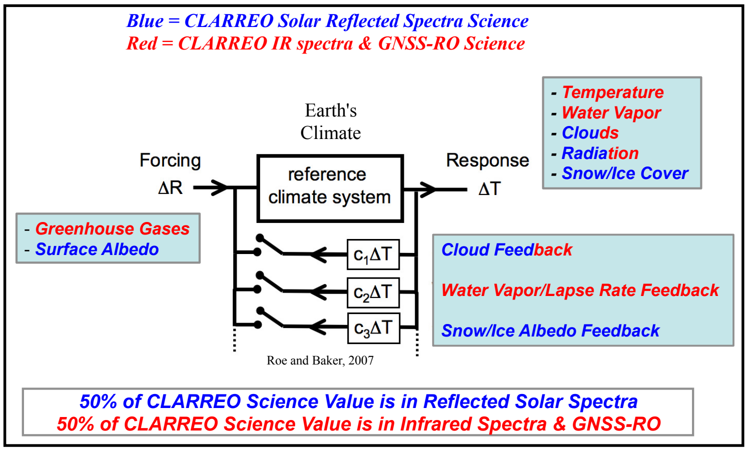

Figure 1: CLARREO RS, IR, and RO science contributions. Red text highlights contributions of IR/RO instruments, and blue text highlights contributions of the RS instrument. Climate forcing contributions (left), climate response (upper right), and climate feedbacks (lower right) are shown with text colored proportional to the relative impact of the CLARREO instruments on the science.

Having obtained an observational record that meets the benchmark requirements described in the previous section, investigators will undertake analyses to achieve the two independent CLARREO goals: unambiguously documenting changes in the climate system, and testing and improving climate forecasts.

While there are many existing ways to approach climate analysis, CLARREO is designed to enable two new approaches in particular: Benchmark Measurement Fingerprinting, and Reference Inter-calibration. First, the optimal detection method makes use of spectral fingerprinting signals directly measured by the CLARREO instruments to determine climate response and climate system feedbacks. The second approach is to calibrate operational satellite system instruments that do not reach decadal change absolute accuracy to CLARREO spectra. These include current and future instruments such as CrIS, IASI, CERES, VIIRS, Landsat, and all geostationary satellite radiometers. In this approach, CLARREO serves as an SI traceable reference standard in orbit, and provides Reference Inter-calibration for these other instruments. Data from these other instruments with calibration improved by CLARREO for decadal change are then used to accurately retrieve changes in properties of the climate system on decade time scales.

1.3 New CLARREO Guidance for 2012 - 2016: Baseline and Threshold Approach Definition.

The current guidance to the CLARREO team for 2012 and beyond is a procurement budget of \$2.0M per year. The recently selected Science Definition Team has been fully funded by CLARREO Project funds for the first year (March 2011 through February 2012). Funding level for the SDT beyond this period is still open for decision based on its relevance to not only the

NRC CLARREO mission refocus but also to the overall ESD Research and Analysis program as defined in the annual ROSES calls for proposals.

The CLARREO project in support of this guidance has provided the science, engineering, and organizational structure for both a baseline and threshold level of activity. The overall goals and approach to these options is defined below:

a) The **baseline** is designed to refocus the CLARREO science and engineering effort on less expensive options that could capture smaller but significant portions of the original CLARREO science goals. The baseline scenario is derived from a bottoms up analysis of the science and engineering tasks needed to support this refocus of CLARREO into an extended Pre-Phase A study period. While the science study scope of alternative options has expanded beyond that anticipated in the Phase A CLARREO SDT, the pace of the studies has been slowed so that a larger science team is not required. The baseline limits activities to the highest priorities identified in the previous 3 years of Pre-Phase A activities. The baseline also considers the relevance and contribution of these science studies to the broader R&A program distinct from their relevance to the mission-specific CLARREO objectives. This is an important element for understanding the CLARREO SDT funding and what portions of it support the broader NASA Earth Science R&A program. The baseline includes publication and capture of CLARREO science and engineering work to date (the MCR concept) and publication of a final report sufficient for the Second Earth Science Decadal Survey (e.g. 2014 to 2016 with dates TBD) to consider a range of options for portions or all of the CLARREO science. The baseline activities will use the Science Value Matrix developed by the CLARREO team for its MCR mission trades in exploring, prioritizing, and understanding the relative value/cost of varying mission options. The baseline approach is a balance between minimizing funding/staffing levels and retaining a small viable integrated science and engineering team that is capable of recovering some significant part of the CLARREO science goals in the near term and the full CLARREO science in the longer term. The baseline is described in Sections 2 through 5.

b) The **threshold** assumes that no R&A funding is provided for the SDT in FY12 and beyond, and all procurement funding must fit the $2.0M guidance. The threshold is ultimately a funding level of effort, and will lose capabilities from the baseline approach. This document summarizes the losses encountered in this approach, and which capabilities can be retained. The bottoms-up analysis of the baseline approach was examined to choose elements to eliminate for the threshold approach until the budget limit was reached. This is considered a very high-risk approach to recovering some significant part of the CLARREO science goals. The guidance from NASA HQ is that no CLARREO external SDT members will be deselected in this plan: that ROSES selections are a serious commitment with the general science community. The impacts of descoping to the threshold budget are provided in Section 6.

1.4 The Need for an Integrated Science, Mission Design, and Calibration Demonstration System Team to Meet HQ Guidance on CLARREO

The previous CLARREO Pre-Phase A effort was a highly integrated approach to the mission science, trades, and design with funding and staff required for the formulation of a large mission.

We propose a much smaller effort in the extended Pre-Phase A CLARREO plan that maintains the advantage of an integrated view of the mission science trades, engineering trades, SI traceability risk reduction, and the ability to respond to a wide range of ways to recapture some part of the CLARREO science. The basic idea is to ramp down to zero, all engineering Phase A activities, but to maintain a core team sufficient to be successful in the broader trade space of the new extended Pre-Phase A studies. Key engineering staff for example might be only used for 0.3 FTE or even less in this plan, as needed for specific tasks. The concept is to take advantage of the last 3 years of experience of the relevant science and engineering staff with the CLARREO mission goals and previous trades. This experience leads to a much more efficient and effective ability to respond to alternative approaches. Starting up new staff at each new opportunity would be much more costly in time and resources. Langley management supports this approach to greatly reducing costs and staff, but to maintaining a flexible experienced core group for the extended Pre-Phase A work in 2012 through 2015.

Because NASA LaRC and NASA GSFC do not have all of the expertise required to accomplish these goals, the recently selected CLARREO SDT is a critical part of the integrated team. In turn, the SDT by itself is missing many of the critical science and engineering skills that exist at LaRC and GSFC. Only an integrated team approach will be both effective and efficient.

The value of this integrated approach is validated by the report from the CLARREO MCR Review Board. Dennon Clardy, the Mission Concept Review Board Chair, gave the CLARREO team especially high marks for the working relationship among its scientists, project managers and engineers. "I've seen projects already up and running that don't have the strong working relationship between the science team and project managers and engineers that you do," said Clardy, of NASA's Marshall Space Flight Center in Huntsville, Ala. The panel also praised the project for "exploring a variety of mission concepts and [having] done an excellent job of defining a feasible concept within a constrained funding profile & launch date." We propose to continue this successful approach in the extended Pre-Phase A studies.

1.5 Organizational Structure and Management

The organizational structure for the extended Pre-Phase A CLARREO effort is simplified from that planned for the mission and is shown in Figure 2. There is a small project management

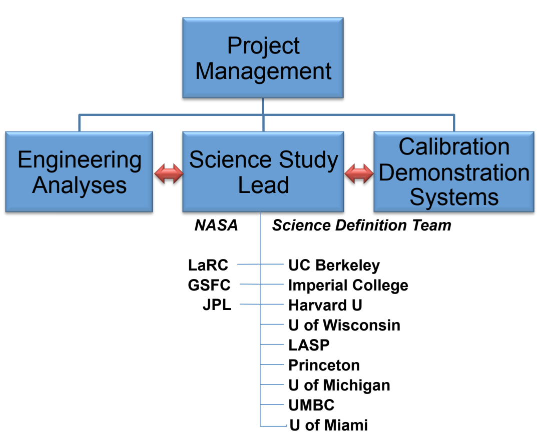

Figure 2. CLARREO Extended Pre-Phase A Organizational Structure

function that oversees the integration of the science studies, engineering analyses for mission and instrument options, and the Calibration Demonstration Systems that are key to eliminating the SI traceability risk. NASA LaRC will remain the lead center for the CLARREO extended Pre-Phase A team.

2.0 Science Trade Studies

2.1 Science Goals

There are two overarching science goals during the extended Pre-Phase A period:

- *Advance the CLARREO RS, IR, and RO climate change science.*

- *Determine the impact of alternate mission concepts on CLARREO science and thereby enable science value/cost trades through use of the CLARREO Science Value Matrix approach.*

The first of these two overarching science goals is in essence an R&A type science investigation that joins the science expertise of the external competed SDT with the LaRC and GSFC internal science expertise. The SDT was selected to complement the LaRC and GSFC science and thereby achieve the depth and breadth required for the CLARREO science investigations. Over 80% (83%) of the selected SDT funding was focused on R&A type CLARREO science. Only 17% or $275K was focused on instrument-specific SI traceability in the IR, RS, and RO. The remaining studies were broader climate science investigations including climate change Observing System Simulation Experiments (OSSEs), climate change spectral fingerprinting, Reference Intercalibration of a range of spaceborne IR and RS sensors at climate change accuracy, GNSS RO algorithm improvements for climate change at altitudes below 5km and above 20km altitude, new studies of the stability of satellite retrieval algorithms for decadal change, and orbital sampling impacts on accuracy of climate change spectral fingerprints and on Reference Intercalibration. These are all studies that will appear in the peer reviewed journal literature and can advance climate science in general, similar to the rest of the R&A program. Table 1 summarizes the CLARREO SDT investigators and studies.

Most of the CLARREO science studies were in the early stages of development during the initial CLARREO Pre-Phase A, and there is a need to both document those studies in the peer reviewed literature as well as to extend them to more rigorous and complete levels. The climate change OSSEs have already produced significant results (Figure 3), but still need extensions from ocean mixed layer climate models to fully coupled ocean atmosphere models, extensions from normal and doubled CO_2 tests of climate change to more realistic IPCC type scenarios with realistic natural variability, extensions to combined infrared, reflected solar, and radio occultation simulations, and finally extension to a wider range of climate model climate sensitivity to verify the ability to observe low versus high climate sensitivity from CLARREO-like observations.

Similar extensions to more realistic conditions are needed to improve the rigor and confidence of the other studies including Spectral Fingerprinting and Reference Intercalibration of operational sensors. Finally, a new category of studies was identified as a missing element in climate research: the stability over decades of infrared and reflected solar satellite retrieval algorithms for climate change. The added rigor of these studies is key to retiring risks in achieving CLARREO science goals while advancing the science of climate trend detection. The science community is rightfully skeptical of new ideas, and CLARREO is very much a new concept for climate change science. The extended Pre-Phase A science studies will work at a reduced pace to confidently reduce those risks.

PI	Organization	Research Objectives
Ao	Jet Propulsion Laboratory	SI-Traceability analysis for GNSS RO Ionospheric residual errors and stratospheric retrieval Lower troposphere bias and depth penetration GNSS RO climate data analysis
Brindley	Imperial College London	Assessment of natural variability in the resolved infrared spectrum and the emergence of climate change signals Analysis of satellite sampling and instrument characteristics in trend detection
Collins	UC Berkeley	Continued OSSE execution; Detection and Attribution Analysis Comparison of variability in SCIAMACHY data / OSSE variability Testing time-to-detection results based on OSSE spectra. Simulating infrared and solar spectra Expansion of the OSSE infrastructure to different climate models
Dykema	Harvard University	SI traceable uncertainty analysis of IR measurements Formulation of IR calibration and validation plans
Huang	University of Michigan	Simulations of IR spectra using high-resolution climate models Using CLARREO data to test and validate global climate models
Leroy	Harvard University	Evaluate climate signal pattern uncertainty using perturbed physics ensembles Investigate transient climate change and detection times Next generation radiance simulation / performance evaluation for joint IR, RO, RS trend detection Climate use of GNSS RO Finalize the error budget for the upper troposphere Investigate possible RO benchmarking of the lower troposphere, 0–5 km Investigate possible RO benchmarking of the stratosphere, 20–50 km Contribute a spatially-dependent cumulative error budget
Pilewskie	University of Colorado	Trend Detection in RS Spectral Radiances
Revercomb	University of Wisconsin-Madison	IR SI-traceable uncertainty analyses and post-launch validation approaches Defining approaches for using CLARREO data for testing and improving climate projections Retrieval stability for climate trend analyses IR Intercalibration assessment studies
Soden	Univ. of Miami	Radiative Kernels as a Tool for Diagnosing Climate Feedbacks
Strow	University of Maryland Baltimore County	Evaluate accuracy of in-orbit spectral calibration, or validation, of CLARREO Accuracy and stability of the CLARREO spectral calibration Explore ways to determine climate trends from hyperspectral data retrievals
Xiong	NASA GSFC	RS Intercalibration assessment studies SI-Traceable uncertainty analyses for RS

Table 1. CLARREO Science Definition Team: Principal Investigators, Organizations, and Research Objectives.

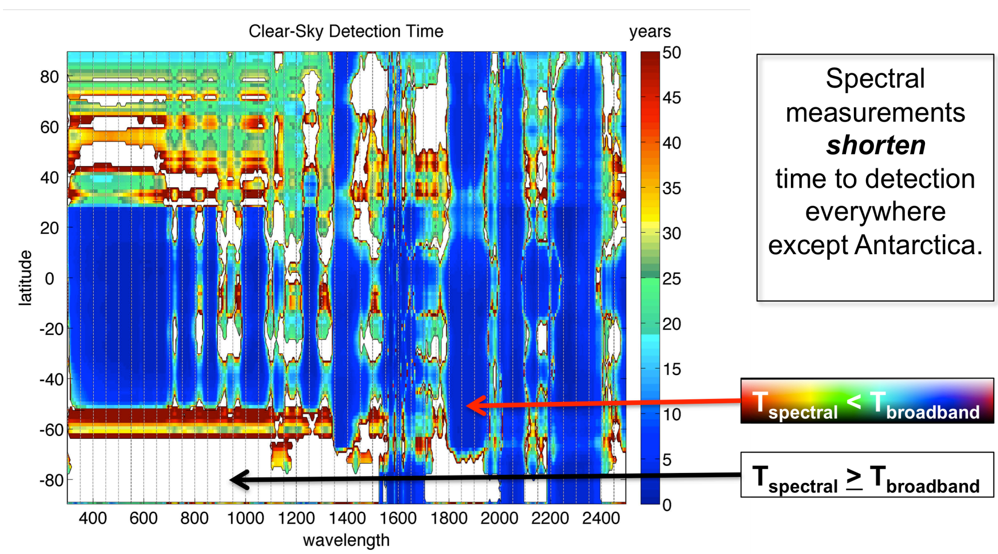

Figure 3. Climate OSSE results for reflected solar clear-sky climate change spectral fingerprints showing reduction in the time to detect climate change at a 95% confidence level (Collin, et al., 2010).

The second of the two overarching science goals is to greatly broaden the science trade space from that considered for the original CLARREO Decadal Survey mission. The new NASA HQ guidance directs the team to focus on much smaller elements of the CLARREO science: not the full mission. The guidance is also to enable other ways to achieve parts of the CLARREO science by means of a small mission, an instrument of opportunity, international collaborations, or even a sub-orbital campaign. For the next several years at least, we are changing from the full CLARREO science vision to something much smaller.

There are many ways such smaller pieces of CLARREO science could be carved off: and this greatly expands the CLARREO trade space for both science and engineering studies. It will require several years to explore them, and some will be resolved more quickly than others. Priority will be given to approaches depending on how they would fit opportunities coming up in the next several years: To support these possibilities, the CLARREO science must explore a wider range of less capable but also less expensive orbits and platforms including the International Space Station, Iridium, sunsynchronous orbits of opportunity (e.g. DoD ESPA ring, NOAA, EUMETSAT), and shared launch options with either other U.S. agencies or international collaboration. Because many of these options require even smaller instruments than the ~75kg CLARREO had planned for the IR or RS spectrometer, there will also be a need to evaluate much smaller, lighter, lower power, but less capable options: again to achieve a portion of the CLARREO science. Examples of such reductions in instrument capability will include decreased spectral resolution and spectral coverage, increased instrument noise, and decreased SI traceable absolute accuracy.

While this new trade space is larger than the original CLARREO Pre-Phase A research, the CLARREO team has also developed an extensive range of analysis tools that will help in the effort. In particular, the Science Value Matrix tool will be expanded to include the broader trade space and will be used extensively to explore the relative value of a range of options to capture parts of the CLARREO science. This tool was used very successfully in developing the MCR concept and to meet challenging budget profile restrictions on the MCR mission. The tool was recommended by the MCR board and the recent chairs of the Decadal Survey as a powerful new method to more objectively carry out science value/cost trades in the context of the CLARREO decadal change science goals. CLARREO will continue to expand this capability in this extended Pre-Phase A work and use it to navigate the large potential trade space of partial CLARREO science.

2.2 Science Deliverables

As for most science studies, the primary deliverables are knowledge published in journal articles and reports. A key goal of the extended Pre-Phase A science team activities will be to document the activities of both previous and future science studies. Much of the previous work remains to be documented in the peer review literature given the focus on the push to MCR. New options will also have to be documented in journals, including the Science Value Matrix used to evaluate them.

But an integrated view of alternative CLARREO approaches for partial science will also require something more than a collection of journal papers, each of which by their very nature needs to typically be focused on a narrow topic. The space science community in the past used a concept known informally as the "Blue Books" because of their blue report covers. These reports captured the science and engineering trades for possible mission designs in a more integrated view. Toward the end of this CLARREO extended Pre-Phase A activity we have designed an equivalent broad report on the strengths and weaknesses of the varying approaches to portions of the CLARREO science. Such a document would be extremely valuable to the next Earth Science Decadal Survey in evaluating the cost/benefit of all or part of the CLARREO science.

2.3 Science Tasks

The goals above have been considered in developing a bottoms-up plan for the extended Pre-Phase A science tasks. These tasks are based on experience in the previous Pre-Phase A work, and a consideration of the types of other options possible at much lower cost (orbits, instrument reduction of capability, etc). The tasks are designed to get the final answer in the shortest time with the available resources, by prioritizing the efforts and phasing them over 2012 through 2015 to get to a clear understanding of a much wider trade space for partial CLARREO science. In some cases opportunities may arise that will not yet have science answers. This cannot be avoided with a much lower level of effort spread out over a longer time. Nevertheless, the tasks as planned take advantage of the developed CLARREO team experience, the new SDT capability, and an initial understanding of potential engineering options. Table 2 summarizes the tasks at a high level and shows how they tie into current 2011 activities. Further levels of detail on the tasks can be provided if desired.

CLARREO Refocus Activities and Deliverables

Deliverables are shown in bold text

Science Study Focus Area	**Organizations**	**2011**	**2012**	**2013**	**2014**	**2015**
IR SI Traceability	LaRC/NIST/UW/Harvard/UK/Italy	SI Design	CDS Analysis	Dev Inst Model	**Test Inst Model**	**Final Report**
RS SI Traceability	GSFC/NIST/LASP/UK-NPL	SI Design	CDS Analysis	Dev Inst Model	**Test Inst Model**	**Final Report**
IR Spectral Inst. Reductions: Capability/Cost	LaRC/GSFC/UW/Harvard	Limit Spectral	Vary Accuracy	Alt Methods	**Alt Methods**	**Final Report**
RS Spectral Inst. Reductions: Capability/Cost	GSFC/LASP	Limit Spectral	Vary Accuracy	Alt Methods	**Alt Methods**	**Final Report**
Decadal Change Climate OSSEs	UC Berkeley/U Michigan/Canada	IR/RS/RO	Alt Orbits	Clim. Sensitivity	AR5/CFMIP	**Final Report**
Climate Change Spectral Fingerprinting	LaRC/Berkeley/LASP/Miami	Fast RS code	IR/RS/RO	Nonlinearities	Cloud Amt/Prop	**Final Report**
Climate Change Reference Intercalibration	LaRC/GSFC/UW/NOAA/GSICS	Alt Orbits	Polariz Models	Alt Methods	**Alt Methods**	**Final Report**
Suborbital Options for IR Reference Intercal	UW/LaRC/NIST	Aircraft	Aircraft	Airships	Airships	**Final Report**
Suborbital Options for RS Reference Intercal	LASP/LaRC/NIST	Aircraft	Aircraft	Airships	Airships	**Final Report**
Decadal Stability of Retrieval Algorithms	LaRC/UMd	IR tests	IR/RS tests	IR/RS Methods	**IR/RS Methods**	**Final Report**
Orbital Sampling for Spectral Fingerprinting	LaRC	Alt Orbits	Natural Var	Alt Methods	**Alt Methods**	**Final Report**
Orbital Sampling for Reference Intercalibration	LaRC	Alt Orbits	Natural Var	Alt Methods	**Alt Methods**	**Final Report**
GNSS-RO Improvements for climate change	Harvard/JPL/LaRC	< 5 km	< 5 km	> 20km	> 20 km	**Final Report**
Data Systems to Support Studies	Pleiades Supercomputer/ASDC	OSSEs/Analysis	OSSEs/Analysis	OSSEs/Analysis	OSSEs/Analysis	
Documentation: Journal Papers, Reports		**All**	**All**	**All**	**All**	**All**
CDS Focus Area						
IR Calibration Demonstration System (CDS)	LaRC/GSFC/NIST	Assemble	**Complete/Cal**	Cal/Cap Trades	Cal/Cap Trades	**Final Report**
RS Calibration Demonstration System (CDS)	GSFC/NIST	Assemble	**Complete/Cal**	Cal/Cap Trades	Cal/Cap Trades	**Final Report**
Engineering Focus Area						
Reduced IR Instrument Studies	LaRC/GSFC	Preliminary Design / Cost	Accommodation Assessment	Science Value Assessment	Science Analysis / Design Update	**Final Report**
Reduced RS Insrument Studies	GSFC/LaRC	Preliminary Design / Cost	Accommodation Assessment	Science Value Assessment	Science Analysis / Design Update	**Final Report**
Accomodation and Access to Space Analyses	LaRC	Identify Options	Cost Analysis / Verification	Science Analysis / Design Update	Finalize options and costs	**Final Report**

Table 2. CLARREO Extended Pre-Phase A Science Tasks and Deliverables (2011 - 2015)

Table 2 breaks down the studies required by major focus areas (column 1) that were developed as part of CLARREO Pre-Phase A work to date. The organizations column lists the key organizations involved in aspects of those studies. The final columns are ordered by year and summarize the focus of the studies in each year.

3.0 Engineering Trade Studies

3.1 Engineering Goals

The engineering trades use a focused and agile team to study multiple mission options for implementing portions of the foundational CLARREO science at low cost on alternative platforms. This team will incorporate the scope of the Science Value Matrix within the new engineering trade space to provide a quantitative assessment of the new options. The team's goal is to develop options that maximize the science benefit/cost ratio, minimize the risk, and have sufficient technical definition on each option in order to respond quickly to potential flight opportunities. The engineering team will iterate conceptual designs with the science team as the science analysis matures and incorporate the results from the testing of the Calibration Demonstration Systems. Sufficient technical definition requires completing the instrument technology maturation, risk reduction, and SI traceability demonstration via the infrared and reflected solar Calibration Demonstration Systems.

The trade space includes developing less complex instruments covering reduced portions of the total measurement spectra that could fly on multiple low cost candidate platforms. The candidate platforms are likely to include International Space Station, commercial spacecraft with available space, interagency or international spacecraft with available space, small dedicated spacecraft, and possibly high altitude aircraft campaigns.

This effort will also include identifying and analyzing options for access to space, such as dedicated launches on emerging vehicles, shared or co-manifested launches, and candidate host spacecraft.

3.2 Engineering Deliverables

The deliverables will be System Engineering Reports (SER) that cover the following topics

a. Mission Analysis and Design
b. Engineering portion of Science Value Matrix update
c. Instrument Conceptual Design study results
d. Instrument Accommodation Analysis Studies
e. Calibration Demonstration Test Report(s)
f. Access to Space Opportunities

These reports will be produced as the studies are developed, and will be integrated in the final "Blue Book" report.

3.3 Engineering Tasks

This section summarizes the tasks for developing alternative mission concepts and iterating those concepts with the science tasks.

3.3.1 Study oversight and management

Study oversight and management will provide preliminary planning, cost estimation capability and schedule development for alternative mission concepts. It will develop acquisition and procurement strategies for rapid implementation when flight opportunities arise.

3.3.2 Orbit analysis and flight dynamics

The study will assess the sampling and coverage from alternative orbits, including Reference Intercalibration opportunities from the alternative orbits. The results of this analysis will inform the science value analysis, the orbit sampling studies for spectral fingerprinting and reference calibration, and instrument conceptual design studies.

3.3.3 Instrument conceptual designs

The team will generate conceptual designs for less complex instruments, analyze the measurement performance of those designs, and incorporate the reduced performance projections in the science value analysis. Design concepts include, but are not limited to:

a. IR instrument (5 to 50 μm). There are four reduced performance concepts for an IR instrument that extends spectral coverage into the far infrared (Far-IR) that coincide with the science studies for reduced spectral coverage and reduced accuracy. Two concepts are reduced measurement accuracy instruments based on enhancements to the NIMBUS Infrared Interferometer Spectrometer (IRIS) instrument design with masses in the 20 to 30 kg ranges. Two concepts are reduced spectral coverage based on descopes to the CLARREO MCR design with masses in the 60 to 70 kg range. These two concepts focus on better accuracy in the Far-IR with reduced accuracy in other wavelengths. Potential design options include: 1) elimination of the cryocooler and the use of thermopile or pyroelectric detectors; 2) simplifying the instrument optical designs; 3) simplifying the instrument calibration and verification system while keeping key portions of the SI-traceability elements, such as the phase change blackbody; 4) accepting higher uncertainty than the CLARREO MCR instrument design after evaluating if the accuracy can be reduced for a shorter mission duration of 1 to 3 years.

b. RS instrument (320 to 2300 nm). There are two reduced performance options that coincide with the science studies for reduced spectral coverage and reduced accuracy. These include a simplified RS optical design and reduced spectral coverage and resolution. Potential design options include: 1) simplifying the calibration and verification system while retaining key portions of the SI-traceability elements; 2) accepting higher uncertainty than the CLARREO MCR instrument design after evaluating whether the accuracy can be reduced for a 1 to 3 year mission duration.

c. GNSS-RO: Study the use of GNSS-RO from existing missions.

3.3.4 Host spacecraft identification and accommodations studies

This study will assess the instrument accommodation resource requirements, evaluate fields of view and footprints, and assess the Reference Intercalibration opportunities for each alternative instrument developed in task 3.3.3. It will assess at a minimum the suitability of the following host platforms:

a. International Space Station
b. Small dedicated spacecraft (e.g. ESPA ring compatible)
c. Iridium
d. Joint Polar Satellite System (JPSS)
e. International missions as identified

3.3.5 Access to space opportunities identification and assessment

This task will identify and assess creative low cost opportunities for access to space, including both dedicated launch vehicles and ride sharing opportunities. It will document both a technical assessment of the suitability and the process to generate MOA's required for identified opportunities to secure commitments for those opportunities. These opportunities include, at present, a reimbursable ride with the Space Test Program (either an ESPA ring or a shared Minotaur IV launch), and international partnerships (TBD).

4.0 Calibration Demonstration System Studies

4.1 Goals

One of the major objectives of CLARREO is to advance the accuracy of SI traceable absolute calibration at infrared (5 to 50 μm) and reflected solar wavelengths (320 to 2300 nm). This advance is required to reach the on-orbit absolute accuracy required to allow climate change observations to survive data gaps and to detect climate change as rapidly as possible. These accuracy requirements are set by the need to rigorously observe climate change to within the uncertainty of the limit of natural variability. This accuracy has been shown to be 0.1K (k=3) for the infrared spectrum and 0.3% (k=2) for the reflected solar spectrum (see section 7.0 for details). These levels take advantage of improvements by NIST and other metrology labs of SI traceable accuracy over the last decade, as well as advances currently underway at NIST such as in the Far-Infrared wavelength region between 15 to 50 μm. The lack of this accuracy was identified by the NRC decadal survey as one of the critical shortcomings of current satellite-based global climate change observations.

While many of these capabilities exist at NIST in the laboratory, we need to demonstrate that it can move successfully from NIST to NASA and/or instrument vendor capabilities for future spaceborne instruments. This demonstration is one of the key risks that the CLARREO project was working to retire. Calibration Demonstration Systems (CDS) have been in design and construction in 2010/2011 and have leveraged almost $20M in prior ESTO funding. This leveraging includes hardware from the current IIP (CORSAIR) used in the IR CDS system. The IR CDS has been in construction at NASA Langley, while the RS CDS has been in construction at NASA GSFC. The centers were selected based on their extensive past experience with instrument development and calibration for these types of spaceborne instruments. They were also selected based on the need to include government-based verification of the critical climate change verification of CLARREO spectrometers, even if those spectrometers were built by other organizations. SI traceability at climate change accuracy must be a completely open scientific process that extends beyond proprietary interests and needs of private corporations.

As a result of the above considerations, completion of assembly and testing of the Calibration Demonstration Systems for the IR and RS spectral regions is a critical element of the Pre-Phase A activities in support of both overarching science goals. The approach is to complete assembly in 2011, and then to ramp down staff and funding to allow a slower paced (and primarily CS labor) verification of the SI traceability to the level of the CLARREO science goals.

The IR and RS calibration demonstration systems will also be a critical risk reduction element of the studies of alternative approaches to achieving CLARREO objective. The systems will allow the testing and evaluation of alternate design or implementation approaches and components. They also provide a test-bed for detector technologies, non-linearity determination and uncertainties, and application of future technology developments and suggested spacecraft instrument design modifications.

4.2 Deliverables

The IR and RS calibration demonstration systems are deliverables with known and demonstrable measurement uncertainties. The IR CDS provides the path to meeting the +/- 0.1K (k=3) measurement requirement traceable to SI standards via calibrated ambient, cold, and variable temperature blackbodies with known uncertainties. The RS CDS demonstrates the path to develop an SI-traceable error budget for measuring solar reflectance to 0.3% (k=2) using solar irradiance as a reference. The RS CDS will use measurements of direct solar irradiance in order to demonstrate SI-traceability of reflectance through both source- and detector- based standards.

The calibration demonstration systems will be used to develop end-to-end instrument performance models and error budgets with measured uncertainty magnitudes and peer reviewed (NIST) measurement accuracy traceability chains.

4.3 Tasks

4.3.1 CDS Test Planning

The initial task during FY12 will involve the development of the CDS test plan, calibration process and procedures, and the instrument uncertainty model and SI traceability path

4.3.2 CDS Assembly

In FY 12, the team will complete the build of the CDS hardware and electronics by assembling and testing the subassemblies, and integrating the subassemblies into subsystems. The subsystems will be integrated into the full instrument system and tested.

4.3.3 CDS Operation

The integrated system will be used to acquire data in order to measure instrument uncertainties in order to validate the instrument uncertainty model and test the SI traceability. A peer review, including reviewers from NIST, of the instrument uncertainty model will be performed. Performance models will be used to feed science studies of impact of instrument design changes.

5.0 Staffing and Procurement: Baseline Extended Pre-Phase A CLARREO

This section redacted for general distribution.

6.0 Impacts of a $2.0M/Yr. Procurement Limit: Threshold Extended Pre-Phase A CLARREO

This section discusses the impacts of reducing from the Baseline Procurement Budget to the Threshold Procurement Budget of $2.0M/yr. The impacts are severe and the chance of recovering part of the CLARREO science through alternative mission options is significantly reduced. The Baseline budget was already slows down the pace of studies to decrease costs. Further reductions will require elimination of skills from the team that do not exist in the remaining members. The impacts of the Threshold vs. Baseline budgets include:

1. Elimination of completion and use of the Calibration Demonstration Systems for both the infrared and reflected solar spectra. This loss will seriously diminish the ability to evaluate the risk of achieving SI traceability at climate change accuracy and to evaluate the science value of reduced capability instruments.

2. Twenty five percent reduction in Climate OSSE studies by the SDT that will eliminate some of the key OSSE tests, and will greatly reduce development of postdoctorate skills to build this capability. This will also add substantial risk to any alternative mission designs.

3. Eliminate suborbital studies. These studies were not planned for in the original SDT and therefore were a new requirement to consider a broader trade space for obtaining portions of CLARREO science. They cannot be supported at the threshold level.

4. Eliminate studies of the stability over decade time scales of retrieval algorithms using reflected solar satellite data. These are critical to climate change studies and the total CLARREO decadal change uncertainty for Reference Intercalibration. CLARREO is the only mission that had identified this critical need, and such studies are not currently being carried out by the science community, the CLARREO selected SDT, or any other ROSES SDT studies. This key climate science extension would have to be eliminated for the Threshold budget.

5. Reduce Reference Intercalibration studies in the reflected solar by 50%. This is one of the most critical contributions of CLARREO but was not being covered by the SDT. Most of this work was covered by NASA LaRC support contractor staff, and about half of this effort would be eliminated by the Threshold budget. A proposal would be submitted to the planned ROSES satellite intercalibration announcement to attempt to recover some or all of this funding, but this is a high risk approach to solving this problem. If the ROSES proposal for Reference Intercalibration were not chosen, this would dramatically reduce the ability to study alternative mission concepts and to derive algorithms to be able to reach sufficient Reference Intercalibration at climate change accuracy. The primary issue is that the original CLARREO mission was designed to keep SI traceability as straightforward as possible. Use of other orbits and less capable instruments would require greatly expanded reliance on radiative transfer theory and on empirical anisotropic dependence models and polarization dependence models. In effect, the chain of traceability for Reference Intercalibration would add additional steps and additional algorithm development that would require extensive validation not required by the original CLARREO concept.