**An observatory to establish a global benchmark of the current climate from space   
is crucial to advancing accurate decadal climate forecasting**

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*1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?*

A fundamental question for Earth System Science is: ***How is the climate of the Earth changing on decadal time scales*?** Quantitative, global answers to this question will form an important part of the foundation needed for very difficult governmental policy decisions that are now expected to require significant societal changes to avoid dire consequences for future generations. Therefore, a key challenge for NASA is ***to make spaceborne measurements with the information content and accuracy needed to quantify decadal scale climate trends for major regions all across the globe***. This White Paper addresses the first step urgently needed in the next decade: ***an observatory to establish a global benchmark of the current climate from space***. The term “benchmark” is used to convey an extremely accurate measure that provides a reference from which future benchmark observations can be judged to establish accurate trends. In simple terms, it is a global version of a stake used to mark the extent of a glacier.

This benchmarking objective was one of the principal drivers of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission that was chosen as one of four Tier 1 missions in the 2007 Decadal Survey. The key elements of CLARREO that in combination set it far apart from existing systems are (1) high information content about temperature and water vapor profile distributions, trace gases, and cloud and surface properties from measuring a large part of the reflected solar and the emitted radiance spectra at high spectral resolution, (2) state-of the-art measurement accuracy (0.4% reflected solar radiance, 0.1 K emitted brightness temperature, both 3-sigma) ***proven on-orbit*** with SI international reference standards, and (3) spatial sampling strategy chosen to minimize biases for regional climate products so as to not significantly degrade the measurement accuracy. Highlights include emission spectra that cover a major part of the Far IR spectrum (extending out to 50 microns, a region not sampled by existing spaceflight observations), new technologies specifically developed under NASA Instrument Incubator Program (IIP) efforts to verify expected accuracy on-orbit, the use of truly polar orbits (90 degree inclination) to reduce sampling biases, and inclusion of GPS radio-occultation observations for independent, highly accurate refractivity (0.1%, 3-sigma for 5-20 km altitude) constraints on temperature trends that are not influenced by carbon dioxide, ozone, or upper level water vapor trends.

*a. Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?*

The existing national and international complement of Earth observing systems does not include benchmarking measurements capable of unequivocally establishing how the climate is changing on decadal time scales. By acquiring observations with improved absolute accuracies, CLARREO benchmark measurements can quantify climate trends on shorter time scales.

Current systems used for climate observing fall into three general categories, (1) observing systems designed to study weather and climate processes, (2) systems to measure the trends of specific properties, and (3) Earth radiation budget observing systems. None of the Category 1 systems have the unbiased temporal and spatial sampling, the ultra-high measurement accuracy proven on-orbit, and the high information content about the climate state necessary to satisfy this key challenge. Category 2 systems like IceSat and Jason for observing changes in ice cover and sea level are very important, but do not provide the detailed global constraints needed to distinguish broader aspects of climate models such as radiative effects from cloud cover and land use changes.

While much has been learned from the series of Earth radiation budget systems (Category 3), it is now recognized that as currently implemented these systems are unable to address this crucial question. One of the key limitations is the lack of detailed information provided by these systems. Ever since the first radiation budget experiment flown by Verner Suomi on Explorer VII in 1959, these systems (ERB, ERBE, CERES) have provided measurements of broad-band reflected solar and infrared emitted fluxes or radiances. That is, these systems were designed to measure radiative properties integrated over the whole solar spectrum and the whole radiation spectrum (or at best, adding a large IR window band). The idea was essentially to do a calorimetry experiment whereby the incoming and outgoing energy balance was measured. While a sound concept, this approach does not capture most of the detailed information about climate present in the spectrally resolved radiation field and does not have the sensitivity to detect climate trends. In addition, these systems have not had the proven absolute accuracy necessary to establish a benchmark, and thereby have suffered significant uncertainties from temporal observing gaps.

The problem with relying on the NASA CLARREO program to accomplish this important role is that there is still no definite commitment to a mission budget or schedule. The investment required to conduct a cost constrained, but complete, CLARREO benchmark mission has been estimated by NASA in the range $400-500 M. Alternative international partnerships are also under consideration.

The good news about the CLARREO implementation effort is that a low cost, risk reduction mission ($77M) was included in the President’s 2016 Budget and has made it to the execution phase of the NASA Planning, Programming, Budgeting, and Execution (PPBE) process. This Pathfinder Mission has been designed for the International Space Station (ISS) and is expected to be able to demonstrate (1) the new technologies developed for CLARREO, (2) successful inter-calibration of radiances from other major scientific and operational instruments (to improve their calibrations and allow inclusion in benchmarking), and (3) the start of a significantly improved climate benchmark. This pathfinder mission would build extra confidence in the technologies and costs associated with the full mission. However, whether the pathfinder happens or not, there needs to be a commitment to start the full mission as soon as possible.

*b. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs*

The link between CLARREO benchmark data and a wide range of other data types is the climate model. Conventional and spaceborne data are used to initialize climate models and the measurements from the original and subsequent benchmarks will be used to test model validity. This is the process by which climate forecasts will be continuously improved over the decades of the next century.

*c. The anticipated scientific and societal benefits*

Dealing with climate change is certainly expected to be one of society’s largest challenges in the current century. Our understanding of the climate threat and progress made by societal changes is going to depend on having forecasts from climate models that are as accurate as possible. Knowledge of model accuracy will depend on having data that can be used for thorough testing of these models. The observations themselves will provide definitive proof that change is happening, along with how and where.

*d. The science communities that would be involved.*

The NASA funded CLARREO Science Definition Team is representative of the diverse range of science communities that should be involved. The team includes people from NASA, NOAA and NIST government laboratories, and universities with representation of talent related to scientific data analysis, mission planning, remote sensing, instrument design, metrology, radiative transfer, climate modeling, and climate change.

*2. Why are these challenges/questions timely to address now especially with respect to readiness?*

Clearly Earth System Science observations have already begun to find irrefutable evidence that significant changes are occurring in certain aspects of the climate of Earth. Therefore, now is the time to lay down a sensitive benchmark from which to take the full measure of global changes.

# Fortunately, a robust approach for providing an observatory to benchmark the climate has been developed by the NASA CLARREO program that marshalled NASA and community research in support of the climate mission defined in the 2007 Decadal Survey. Over the last decade extensive preparations for the required observatory have brought the scientific basis, the required new technologies, and the detailed design to a high level of readiness. The paper laying out the scientific basis and design of the mission (Wielicki, et al., Achieving Climate Change Absolute Accuracy in Orbit, *BAMS*, 2013) won NASA Langley’s Henry J. E. Reid award for its best paper based on the importance of the problem, significance of the contribution, originality of the concept, and quality of the reporting. Also, development and testing efforts have brought all of the required new technologies to the NASA Technical Readiness Level (TRL) 6 required by mission Preliminary Design Review.

*3. Why are space-based observations fundamental to addressing these challenges/questions?*

The simplest rationale for requiring space-based observations is that the whole Earth needs to be monitored to test comparisons with global climate models. In addition, space-based observations are the only way to observe the fundamental reflected solar and emitted radiance spectra that depict the response of the Earth system to solar forcing and characterize key aspects of the resulting climate state.

The ability to conduct climate benchmarking to address this fundamental question and key challenge has been very well defined by the CLARREO program and related NASA supported developments and deserves a very strong recommendation for proceeding to execution from the 2017 Decadal Survey.