**Title (150 character limit):** Constellation approaches to assessing earth radiation imbalance

**White Paper Description (350 character limit):** Measuring earth radiation imbalance is a challenge requiring stable, accurate sensors sampling multiple geometries and local times. Current measurements achieve this by supplementing low-earth orbit data with models and ancillary data. Achieving, however, accuracies of 0.5 W/m2 (daily means) and 0.1 W/m2 (annual) requires alternate approaches.

**File of White Paper (1500 word limit):**

**Constellation approaches to assessing earth radiation imbalance**

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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 expected to require significant societal changes to avoid dire consequences for future generations. The radiation imbalance of the earth-atmosphere system is a fundamental signal of climate change and requires measurements that are global, long-lasting and highly accurate. Only with such measurements can we tease out long-term climate change trends and determine the accuracy of climate change projections.

The recommendation in this white paper is for a space-based approach to more direct measurements of the radiation imbalance that is a key indicator in changes in the global climate. The major point in this white paper is that there is a critical need for radiation imbalance measurements and that and improved measurement approach independent of past space-based retrievals is necessary to achieve the accuracy required to make informed policy decisions. One possible sampling scheme for radiation imbalance retrievals is through a constellation approach with a fleet of wide-angle viewing, broadband sensors in various orbital inclinations and altitudes to achieve the angular, temporal, and spatial range of sampling needed to measure the imbalance more directly than done with sun-synchronous or mid-inclination only systems. Note, that it is not the goal of this white paper to propose a specific satellite mission, but to advocate for a different method to measure radiation imbalance. The constellation approach is one way to do this and serves as an illustration.

*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 compliment of Earth observing systems includes radiation budget measurements that make use of mid-inclination and sun-synchronous low-earth orbits. The radiation budget is inferred from global measurements of upwelling total, shortwave, and longwave broadband radiances supplemented by ancillary data from ground-based and model-based sources, and implementing conversion factors to transform radiances to fluxes. The existing systems lack the proven absolute accuracy necessary to evaluate the radiation budget imbalance or even track its relative temporal variability.

NASA’s planned CLARREO (Climate Absolute Radiance and Refractivity Observatory) attempts to address both the sampling and accuracy issue while also providing a spectral knowledge that will be important for understanding the earth climate system. Including broadband measurements of upwelling radiation from a constellation of sensors designed to sample spatially and temporally in a much different fashion than CLARREO would provide supplementary information that ensures the sampling fidelity of CLARREO.

*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 current lack of globally-based, wide-angle radiation measurements from space has led to a range of innovative approaches to determine radiation imbalance. The Clouds and the Earth's Radiant Energy System (CERES) processing approach is one example. Another has been the use of an international array of Argo floats, measuring ocean heat content to a depth of 2000 m. By 2006 there were about 3000 floats covering most of the world ocean. These floats allowed estimates during the 6-year period of 2005-2010 that the upper 2 km of the world ocean gained energy at a rate 0.41 W/m2 averaged over the planet.

Incorporating a global set of wide-angle measurements from space has the potential to provide direct radiation imbalance estimates, and will enhance the science value of already-existing data sets. An improved set of sensors with known SI-traceability and suitable stability and precision will allow key climate questions to be answered.

*c. The anticipated scientific and societal benefits*

Observed planetary energy gain during the recent strong solar minimum reveals that solar forcing of climate, though significant, is being overwhelmed by a much larger net human-made climate forcing. The indirectly inferred radiation imbalance confirms that, if other climate forcings are fixed, atmospheric CO2 must be reduced to about 350 ppm or less to stop global warming.

When many climate models contributing to the the Intergovernmental Panel on Climate Change employed aerosol forcings in the range -0.5 to -1.1 Wm-2, they achieved good agreement with observed global warming over the past century, suggesting that the aerosol forcing is only moderate. However, an ambiguity remains among the climate models. Most of the models used in IPCC mix heat efficiently into the intermediate and deep ocean, requiring thus a large climate forcing (~2 Wm-2) to warm Earth's surface by the observed 0.8°C over the past century. Was the ocean mixing heat into the deeper ocean less efficiently, the net climate forcing needed to match observed global warming would have been smaller.

An accurately-measured Earth radiation imbalance provides a way to resolve this ambiguity. The case of rapid ocean mixing and small aerosol forcing requires a large planetary radiation imbalance to yield the observed surface warming. Quantifying the imbalance at a level that permits attribution of the dominant causes of warming provides exactly the information policy makers need to determine whether society attempts to mitigate warming or rather concentrates on understanding the impacts that warming will have.

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

The CLARREO Science Definition Team and CERES science users would be the starting point for understanding the spaceborne capabilities described in this white paper. These two teams include both the government and academic sectors. It is essential to include also the Argo buoy teams for their expertise in assessing radiation imbalance. Ensuring the climate modeling community is also engaged is important to refine the information that is needed to address the radiation imbalance question rather than recommending a specific measurement and sensor approach.

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

Beyond the fact that climate change is one of the dominant issues affecting mankind in the next several decades, the confluence of several key factors in recent years to points towards the need to refine our methods for measuring the earth radiation imbalance. First, certain successes of past radiation budget measurements provide guidance on where we can improve our measurement approaches. The CLARREO mission is a direct result of that. Second, the importance of making highly accurate and SI-traceable measurements is now recognized and, more importantly, the techniques for doing so are becoming better understood. Third, the design of on-orbit sensors has improved to a technical readiness level where implementing high-accuracy on orbit can be proven to be achievable. Four, the success of the A-train and other constellation approaches combined with an improved ability to makes smaller sensor packages gives confidence that a fleet of radiation imbalance sensors can be readily developed and deployed. Finally, sensor harmonization methods have been developed in the past decade making it feasible to put a fleet of sensors onto a single radiometric scale allowing the data from a fleet of sensors to be used for radiation imbalance retrievals.

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

As stated above, attempts to determine the radiation imbalance from non-space-based data have been underway for a while, but those approaches are not fully global in there sampling. By nature, the radiation imbalance is a global quantity that relates to shortwave and longwave radiation directed from Earth to space. Any assets measuring radiative flux deployed at other vantage points such as ground or somewhere within the atmosphere, would not only suffer huge coverage gaps, but would also measure radiative quantities that would be hard to relate to the radiation imbalance.