Accurate Inter-Calibration of Spaceborne Reflected Solar Sensors

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1. Accurate inter-calibration of spaceborne Reflected Solar sensors is a key challenge for Earth System Science

Calibration accuracy and consistency are the key on-orbit performance metrics for the Earth observing sensors and the system as a whole. The challenge is well recognized by the science community, both nationally and internationally. The accuracy and consistency of measurements across multiple spaceborne instruments in low Earth and geostationary orbits (LEO and GEO, respectively) are directly connected to the information content and scientific understanding from observing complex systems such as Earth's weather and climate. Recent results have demonstrated the quantitative impacts of observational accuracy on the science data products [Lyapustin et al., 2014] and the ability to detect climate change trends for several Essential Climate Variables – Earth radiation budget, cloud feedback, and long-term trends in cloud parameters [Wielicki et al., 2013; Shea et al., 2015].

a. Existing and planned U.S. and international programs: Several U.S. agencies – NASA, NOAA, and USGS – participate in inter-calibration efforts for LEO and GEO reflected solar sensors. Current activities rely on available assets such as referencing geostationary imagers to MODIS measurements, using lunar irradiance model predictions, and vicarious inter-calibrations using stable surface sites (e.g. Libyan desert, Dome C). The international inter-calibration effort is coordinated by the Global Space-based Inter-Calibration System (GSICS), with participation by U.S., European, and many other international satellite operators. The current state-of-the-art inter-calibration accuracy for reflected solar sensors is 3 – 5 % ($k = 1$)[1] due to a lack of adequate on-orbit reference sources, sampling, and

[1] We use coverage factor k to establish a rigorous tie between the Earth Science and metrology communities. In the case of a Gaussian distribution, $k = 1$ is the same 68% confidence level as for 1σ [BIPM 2008].

methodology in terms of calibration traceability. This accuracy is far from sufficient for a climate observing system [Wielicki et al., 2013]. Significant improvement of inter-calibration accuracy would extend geographical and temporal coverage far beyond the capabilities of an individual spacecraft to dozens of instruments already on-orbit. The following missions will have a significant impact on the inter-calibration quality by providing on-orbit reference standards:

(1) Total and Spectral Solar Irradiance Sensor (TSIS) will acquire accurate measurements of total and spectral solar irradiance (TSI and SSI, respectively). Both parameters are not only critical to understanding Earth energy budget and atmosphere response, but they will provide on-orbit reference for accurate calibration and inter-calibration of various sensors. The launch and deployment on the International Space Station (ISS) is scheduled for August 2017.

(2) Climate Absolute Radiance and Refractivity Observatory (CLARREO) was recommended by the NRC Decadal Survey in 2007 [NRC, 2007] as a Tier-1 mission. The accurate inter-calibration of reflected solar sensors in LEO and GEO is a major and unique requirement for the CLARREO mission design – its reference accuracy is set to 0.15% ($k = 1$). Extensive studies by the Science Team have demonstrated the feasibility of the CLARREO inter-calibration approach [Lukashin et al., 2013; Roithmayr et al., 2014; Wielicki et al. 2015]. Additionally, CLARREO will be able to characterize stable surface sites (e.g. Libyan desert, Dome C) with high accuracy, thus improving the ability for vicarious calibration. CLARREO passed MCR in November 2010, and is currently in pre-formulation with a high technology readiness level. In the FY16 President's Budget request, the CLARREO Pathfinder is included as a demonstration mission on the ISS.

Both missions, TSIS (funded) and CLARREO (in pre-formulation), can provide the capabilities necessary to make substantial progress in establishing accurate inter-calibration for reflected solar sensors in LEO and GEO. Additional investments to establish the Moon as an on-orbit high-accuracy calibration source would enable even broader inter-calibration opportunities as the lunar reflectance is practically invariable in time and can be directly measured by most Earth-observing instruments. Existing approaches to inter-calibrate spaceborne sensors against the Moon can achieve a stability of a tenth of a percent over 12 years [SeaWIFS; Eplee et al., 2012]. However, the current lunar calibration accuracy is limited to 5 – 10% ($k = 1$), depends on the photometric model of the Moon [Kieffer and Stone, 2005], and needs to be improved significantly. A new concept for a potential solution to this challenge is under development by a multi-agency and multi-center team with NASA Langley Research Center leading the effort:

(3) The ARCSTONE mission concept (under development), flying on a small satellite in LEO, will provide an orbiting spectrometer with accuracy sufficient to establish lunar spectral reflectance as an SI-traceable absolute calibration standard for past, current, and future Earth's weather and climate sensors.

B. INTEGRATION OF SPACE-BASED AND OTHER OBSERVATIONS: Space-based accurate inter-calibration of reflected solar sensors should be integrated with airborne and surface observations, providing validation of airborne and surface radiometric campaigns. Such integration can be achieved by near-coincident scheduled measurements from space, aircraft, and *in-situ* instrumentation. The implementation of multi-instrument data fusion requires the development and deployment of advanced frameworks capable of networking between relevant data centers [MIIC, Wielicki et al., 2015].

c. Anticipated scientific and societal benefits:

Long Term Impacts: An improved high-accuracy Earth Observing System (EOS) will provide the data necessary to accelerate decisions on public policy concerning climate change by 15 to 20 years. Earlier and better informed decisions provide a large economic benefit to the U.S. and the world, estimated to be ∼$12 trillion over the next 40 to 60 years[2] [Cooke et al., 2014]. By reducing the risk in climate prediction, an accurate EOS data will impact U.S. international policy, strategic planning by government agencies, operation and sustainment of key national assets, and risk assessment by the reinsurance industry.

Near Term Impacts: Establishing a high accuracy on-orbit inter-calibration standard for LEO and GEO sensors will reduce bias in the observations and geophysical parameters derived from them, improve consistency in land imaging constellations, and increase the accuracy of a wide variety of climate-relevant observations including land processes, atmospheric state variables, aerosols, and trace gases.

d. The science communities involved: The space-based inter-calibration of reflected solar sensors in LEO and GEO involves a large science community researching the fields of Earth's radiation budget, ocean color, cloud and aerosol and atmospheric processes, land use and vegetation, and Earth's climate.

2. Why is this challenge timely to address now ?

There are several arguments for the urgent implementation of accurate space-based inter-calibration of reflected solar sensors and improving the overall performance of the EOS:

(1) Growing societal importance of quantifying magnitude and rate of climate change.
(2) Necessity of establishing highly accurate climate data records.
(3) Previous investments into TSIS (scheduled) and CLARREO (in pre-formulation).

Delaying accuracy improvements of the climate observing system can result in additional adaptation/mitigation costs of hundreds of billions of dollars per year of delay [Cooke et al. 2014]. The technology to address this challenge exists and is ready.

3. Why are space-based observations fundamental to addressing this challenge ?

Space-based observations are truly fundamental for enabling the accurate inter-calibration of reflected solar sensors as the concept requires measurements above Earth's atmosphere to achieve global coverage, and to detect a wide variety of observed surface and atmosphere conditions (e.g cloud-free ocean/deserts/ice, deep convective clouds). To ensure sufficient inter-calibration sampling for multiple sensors in LEO and GEO, the inter-calibration reference source, such as CLARREO, has to fly in an optimized orbit – the current requirement is a 90° inclination polar orbit at 609 km altitude [Roithmayr et al., 2014; Wielicki et al., 2013]. To use the Moon as an accurate inter-calibration standard, it is essential to measure lunar reflectance from orbit to avoid large uncertainty in the absorption spectral regions, and the need for atmospheric corrections.

[2] Using the U.S. Interagency Memo of the Social Cost of Carbon (2010), highly accurate EOS value has been estimated at about $18 trillion for a 2.5% discount rate, $12 trillion for a 3% discount rate, or $3 trillion for a 5% discount rate.

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