Hyperspectral Detail Meets Radiometric Accuracy: A Foundational Reflected Solar Capability for the Coming Decade

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Synopsis: Hyperspectral Earth-reflected solar measurements contain rich, detailed information about clouds, aerosols, and the atmosphere. This information compounds when paired with high, SI-traceable radiometric accuracy. Unlike spectral resolution, which can be resampled to coarser spectral resolutions, radiometric accuracy cannot be recovered once a measurement is made, making the choice to invest in this capability now a decision with lasting consequences for the climate record. CLARREO Pathfinder is demonstrating that this combination of hyperspectral sampling and benchmark-quality accuracy is achievable today, but no follow-on mission is currently planned within NASA's Earth Science Division portfolio, and the recent cancellation of the European Space Agency TRUTHS mission has heightened the urgency of sustaining this capability. We recommend prioritizing investment in a follow-on to CLARREO Pathfinder, along with dedicated support for the science community to fully exploit these measurements. This capability would reduce long-standing uncertainties in cloud feedback, aerosol forcing, and global energy imbalance, while providing a degradation-resistant, gap-resilient calibration foundation for the broader Earth observing system. Building on flight-proven technology and an engaged science community, this is a near-term, fiscally realistic opportunity to secure a foundational Earth observation capability for the coming decade.

1. Introduction

Hyperspectral Earth-reflected solar radiation (spectrally-resolved spectral data with contiguous, overlapping wavelength channels spanning the visible and near-infrared) contains detailed information about clouds, aerosols, surface characteristics, and the atmosphere (e.g. Stephens et al., 2021). High radiometric accuracy augments the value of these measurements to detect changes in the Earth system and attribute those changes to driving geophysical variables (Shea et al., 2022). High absolute accuracy and hyperspectral sampling are each individually valuable in measurements of reflected solar radiation, but they are unequal in one critical way: high spectral resolution can be resampled to emulate any multispectral instrument; whereas radiometric accuracy cannot be fully recovered once an observation is made. This distinction means that because SI-traceable accuracy is intrinsic to the measurement itself rather than reliant on continuity with prior sensors, it offers a resilient, degradation-resistant foundation for climate records, unlike traditional approaches that depend on overlapping missions to transfer calibration from sensor to sensor. The recently launched Calibration Absolute Radiance and Refractivity Observatory Pathfinder (CLARREO Pathfinder) (Shea et al., 2020) contains both attributes and therefore can provide a prototype of benchmark measurements, but no similar follow-on missions are currently planned within the NASA Earth Science Division (ESD) portfolio.

CLARREO Pathfinder is demonstrating that such a measurement is achievable today; however, CLARREO Pathfinder's location on the International Space Station (ISS) limits the ability of the instrument to obtain global coverage because the 51.6° orbital inclination does not enable polar observation. Implementing a follow-on of the CLARREO Pathfinder mission would deliver near-term atmospheric science value, reducing uncertainties in atmospheric retrievals and radiative imbalance attribution, while providing a calibration foundation the broader Earth observing system can leverage. The powerful combination of high accuracy and hyperspectral sampling is a capability NASA cannot afford to lose over the coming decade because of its immense value for improving our understanding of the atmosphere and maintaining NASA's gold standard calibration leadership.

We recommend investing in high-accuracy, hyperspectral reflected solar measurements and support for the science community to exploit the wealth of information in these measurements in the decadal plan for NASA's ESD. With the recent launch of CLARREO Pathfinder, the technology and measurement approaches are being demonstrated, an active science community is available to work with the data, and continuing the measurement protects a record whose value compounds over time.

2. The Societal and Scientific Imperative for Climate-Quality Radiometry

The need for SI-traceable, climate-quality accuracy in space-based Earth observations has been identified as a critical capability among the international science community for the past several decades (e.g. Goody et al., 1998; Ohring et al., 2007; Boesch et al., 2022; WMO BIPM, 2023). The 2022-2031 U.S. Global Change Research Program (USGCRP) strategic plan states that the "demand for authoritative information to support decision-making at local to global scales is growing, and needs are becoming more specific and complex." This statement, which is also quoted in NASA's Earth Science to Action strategy, succinctly captures the importance of high accuracy measurements, which provide "authoritative information" and hyperspectral measurements, which provide rich information about the Earth system. Together these characteristics support addressing increasingly specific and complex problems such as constraining cloud feedback, quantifying aerosol radiative forcing, and closing global energy imbalance, three long-standing sources of uncertainty in Earth's climate system.

A report written following the 2019 workshop jointly held by the Committee on Earth Observing Satellites (CEOS) and the Global Space-Based Intercalibration System (GSICS) acknowledged that current reflected solar satellite observations carry absolute uncertainties that are about five times greater than recommended SI-traceable climate-quality uncertainty requirements (Boesch et al., 2022), generally defined as better than 1% (1-sigma) absolute uncertainty in Earth reflectance, a barrier that is finally being breached by CLARREO Pathfinder reflectance measurements (Shea et al., 2020).

The recent European Space Agency Traceable Radiometry Underpinning Terrestrial-and Helio-Studies (TRUTHS) mission concept was also built upon the value of high accuracy hyperspectral measurements (Fox et al., 2020). There was promise in the potential for CLARREO Pathfinder and TRUTHS to overlap to demonstrate independent verification of such observations, an important feature of a resilient Earth system monitoring program. However, with the TRUTHS cancellation, the longevity of this capability is now at risk, lending urgency to sustaining it within the NASA Earth Science Division portfolio.

Because radiometric uncertainty cannot be fully recovered after a measurement is taken, designing a system to attain a given level of accuracy is critical. The choice to sustain or forgo this measurement in the coming decade determines whether the resulting record can ever meet the sustained accuracy upon which future science and societal decisions depend (Boesch et al., 2022).

We strongly recommend continuing the class of measurement demonstrated by CLARREO Pathfinder: contiguous spectral sampling across the reflected solar spectral range at high SI-traceable accuracy. Doing so will advance our understanding of the Atmosphere by providing reliable, information-packed measurements that can support the reduction of long-standing uncertainties in cloud properties (and cloud feedback), aerosol forcing, and global energy imbalance.

3. High Accuracy Hyperspectral Observations for Atmospheric Studies

The synergy between high accuracy and hyperspectral sampling has the potential to significantly advance studies of the atmosphere in the coming decade. Previous studies have shown the value of hyperspectral sampling of TOA measurements to improve our understanding of Earth's atmosphere and its variability (e.g. Roberts et al., 2011, 2013; Feldman et al., 2011, 2013; Stephens et al., 2015). While hyperspectral sampling itself enables identification of different Earth system components and processes, the combination with high accuracy also enables unambiguous climate term trend detection and climate model validation. Such measurements can be classified as climate benchmark measurements, which are those that attain and maintain absolute accuracy in space and the spectral resolution sufficient to capture and attribute the variability of the Earth's climate system (Goody et al., 1998). However, NASA's Earth observing portfolio does not currently include a plan for sustained benchmark measurements.

Other current Earth science missions fulfill elements of this capability but are unable to fully satisfy the requirements for benchmark measurements. For example, while the Plankton, Aerosol, Cloud, Ocean Ecosystem (PACE) mission (Werdell et al., 2019), provides novel data through the combination of its imager and polarimeters, its hyperspectral sampling degrades to multispectral beyond 940 nm, and it lacks the degradation-resistant calibration accuracy needed to provide a benchmark measurement. Likewise, the Earth Surface Mineral Dust Source Investigation (EMIT) mission (Green et al., 2021) has a spectral range and resolution comparable to CLARREO Pathfinder, but without an onboard calibration system its estimated 2% absolute uncertainty is insufficient to confidently monitor climate-relevant variability. We propose the sustainment of CLARREO Pathfinder-like measurements as a complement to existing Earth observing capabilities that serve other spheres, including Biosphere and Geosphere. There are features that missions such as PACE, EMIT, and the Visible Infrared Imaging Radiometer Suite (VIIRS) (Cao et al., 2018) provide that CLARREO Pathfinder does not (e.g. polarimetry, high spatial resolution, and near-global daily coverage, respectively). However, CLARREO Pathfinder measurements and a similar follow-on would uniquely have the characteristics of a shortwave climate benchmark and would also serve to advance ocean biology and land surface science, for example, through improved atmospheric correction over both ocean and land surfaces.

3.1. The Unique Value of Hyperspectral Sampling

Hyperspectral measurements enable attribution of underlying physical drivers of Earth system variability observed by broadband sensors. For example, hyperspectral data provide insight into the physical mechanisms that support all-sky (Stephens et al., 2015) and clear-sky hemispheric symmetry (Diamond et al., 2022). Hyperspectral measurements can also reveal variability masked by broadband measurements. Gristey et al. (2019) showed that hyperspectral shortwave cloud radiative effect (SWCRE) revealed compensating signals in the near-infrared (NIR), such as those from ice clouds and vertically distributed thin liquid clouds, which cancel each other out in broadband SWCRE and thus appear very similar despite representing physically distinct cloud populations.

In addition to radiative process attribution, the wealth of information in hyperspectral measurements can be exploited to develop robust cloud and aerosol retrieval algorithms as powerful complements to existing multispectral products. Examples of retrievals that can benefit from the information in hyperspectral measurements are as follows:

- Effective particle size profiles in liquid water clouds (e.g. King and Vaughan, 2012; Buggee and Pilewskie, 2026);
- Increased information content in ice cloud optical retrievals compared to multispectral retrievals (Mast and Yang, 2024);
- Thermodynamic phase discrimination in clouds (Pilewskie and Twomey, 1987);
- Improved scene discrimination, which in turn strengthens the overall robustness of cloud and aerosol retrievals; and
- Aerosol size information and the partitioning of aerosol optical depth between fine and coarse modes.

The value of top-of-atmosphere (TOA) hyperspectral measurements is further amplified when paired with ground-based hyperspectral networks. Riihimaki et al. (2021) showed that ground-based sensors, with their high temporal resolution, excel at capturing the rapid evolution of cloud and aerosol properties in response to changing meteorological conditions. When space-based and ground-based hyperspectral observations are used together, they can provide independent validation of satellite-retrieved cloud properties, support more accurate atmospheric correction, and enable rigorous radiative closure experiments.

3.2. High Accuracy Compounds the Value of Hyperspectral Sampling

The combination of high accuracy and hyperspectral sampling yields more climate information than either attribute can deliver alone (Shea et al., 2022). High absolute accuracy ensures that spectral variations can be confidently attributed to geophysical processes rather than instrument artifacts, unlocking the full potential of the spectral data (Shea et al., 2026).

This compounding benefit has been illustrated through cloud retrieval applications. For example, Buggee and Pilewskie (2025) found that lower radiometric uncertainty reduces error in water cloud effective particle size profiles more effectively than increasing the number of wavelength bands used in the retrieval. Additionally, synthetic experiments using a newly developed optimal estimation-based ice cloud optical property hyperspectral retrieval further confirm that increasing spectral channels and reducing instrument uncertainty improves the accuracy of retrieved cloud optical depth and effective particle size (Mast et al., In Prep).

Beyond retrievals, high-accuracy hyperspectral measurements can serve as a rigorous validation source for climate model output (Goody et al., 1998). For example, high accuracy shortwave spectral reflectance can be used to distinguish between climate model outcomes with varying cloud feedback strengths on shorter timeframes than comparably accurate broadband measurements (Feldman et al., 2011). This rich spectral information can provide a stringent physical constraint for climate models (e.g. Roberts et al., 2013).

4. Defining the Foundational Capability for the Coming Decade

Our recommended requirements for this concept in Table 1 are derived from the characteristics of the original CLARREO mission concept (Wielicki et al., 2013) and the currently implemented CLARREO Pathfinder mission (Shea et al., 2020).

4.1. Core Recommended Requirements

The requirements summarized in Table 1 are expanded upon below.

- **Spectral range:** The recommended spectral range spans the visible and near-infrared and is needed to capture cloud, aerosol, atmosphere, and surface properties simultaneously, making atmosphere-focused retrievals more robust, and enabling the measurement to be used as a climate benchmark for reflected solar radiation.
- **Spectral sampling/resolution:** The spectral resolution requirement stated is the Full-Width at Half-Maximum (FWHM) of the spectral response function. The spectral sampling resolution would ideally be at Nyquist sampling (estimated as FWHM/2). This spectral resolution and sampling are needed to resolve spectral variability for retrievals to exploit and provide the rich information about the Earth system needed for a climate benchmark.
- **Radiometric Uncertainty:** Attaining high SI-traceable absolute accuracy and maintaining that accuracy throughout the lifetime of a mission guarantees stable measurements for the rigorous monitoring of Earth system variability and establishment of an Earth system benchmark. Prior studies have quantified the impact of radiometric uncertainty on decadal trend-detection sensitivity (Wielicki et al. 2013; Shea et al., 2017). We recommend that this capability leverage degradation-resistant on-orbit calibration and measurement approaches that enable the achievement and maintenance of Earth-reflectance uncertainty to better than 1%.
- **Spatial sampling:** The recommended spatial resolution is comparable to multispectral sensors (e.g. the moderate resolution bands of MODIS and VIIRS) and can be used to support cloud, aerosol, and atmosphere retrievals. An important related trade space that warrants further investigation is the signal-to-noise ratio (SNR). A climate benchmark is relevant at zonal and

global scales, where spatial and temporal averaging can be used to improve effective SNR without compromising scientific objectives. However, if regional-scale applications are prioritized alongside constructing a global climate benchmark, the SNR requirements, and their relationship to spatial sampling and integration time, should be reassessed to ensure the measurement remains useful across relevant spatial scales.

- **Polar orbit:** A 90° orbit enables global coverage and full diurnal sampling twice per year. Global TOA coverage also supports global spectral radiative balance closure studies and the creation of a complete set of Earth system benchmark measurements. Placing a follow-on sensor in a polar orbit resolves a key limitation of CLARREO Pathfinder on ISS.

Table 1. *Recommended Requirements for a Robust NASA High Accuracy Hyperspectral Capability*

Parameter	Requirement	Notes
Spectral Range	350-2500 nm	Exact bounds of spectral range can be flexible, but must be no shorter than 400 nm and include up to at least 2300 nm
Spectral Resolution	6-10 nm	Approximate full-width at half maximum of spectral response function. Enables cloud phase discrimination (and supports reference intercalibration)
Reflectance Radiometric Uncertainty	0.6% (1-sigma)	Can capture Earth system variability and provide a reliable benchmark. Also low polarization sensitivity (~0.5%)
Spatial Sampling	250-500 m	Moderate resolution comparable to other atmospheric imaging sensors; capable of resolving clouds; supports diverse intercalibration
Orbit	90° Polar orbit	Enables full diurnal sampling twice per year

Other Enabling Considerations

Gap-Resilient Continuity		
Sustainment	Demonstrated overlap for initial follow-on highly recommended.	Subsequent follow-ons can tolerate gaps with appropriate SI-traceable accuracy.
Synergy with Radiation Budget Observations		
Coordination with Other Key Measurements	Co-locate with Radiation Budget Observations	Enhanced scene attribution information compared to multispectral sampling

Requirements are derived from well-established studies in support of the 2007 Decadal Survey-recommended CLARREO mission (Wielicki et al., 2013). Several of the requirements outlined here are being demonstrated by the CLARREO Pathfinder mission, notably the radiometric uncertainty (with regular on orbit self-calibration), spectral range and resolution, spatial sampling, and polarization sensitivity. The development of these requirements is mature, and they can readily be applied to the definition of a future mission.

4.2. Other Enabling Considerations

Gap-Resilient Continuity

A key advantage of this measurement concept is that overlapping measurements with prior similar measurements is not essential for continuity. Traditionally, Earth system observation records have relied upon continuous overlapping missions to confirm that calibration has been transferred from sensor to sensor. However, ***the benchmark value of these proposed measurements comes from its absolute, SI-traceable accuracy, rather than inter-sensor continuity.*** Because the measurement is rigorously tied to an absolute reference and maintains benchmark-quality accuracy on orbit without reliance on overlap with a prior sensor, measurements from successive instruments are directly comparable. While we recommend overlap between an initial follow-on and CLARREO Pathfinder to empirically confirm this independence, subsequent missions can tolerate temporal gaps (Wielicki et al., 2013). The appropriate length of these gaps may need further study, especially as the Earth system continues to change.

Synergy with Radiation Budget Observations

While not a strict requirement, co-locating these hyperspectral measurements with broadband radiation budget observations provides an excellent opportunity to enhance scene attribution information relative to what multispectral imagers currently provide, and broadband measurements can offer an independent constraint for the hyperspectral measurements through radiative closure studies. This synergy would support the necessary continuity and scientific yield of radiation budget observations.

5. This Capability is Feasible within the Next Decade

Implementing this capability within the coming decade is highly feasible and represents a low-risk, high-reward investment for NASA. The technology is already proven. The recent launch and ongoing commissioning of CLARREO Pathfinder on the ISS demonstrates flight heritage (currently at TRL-8 with the expectation of demonstration TRL-9 by end of prime mission), significantly reducing the technical risk and cost for a follow-on mission. Lessons learned from the CLARREO Pathfinder build and pre-launch testing can be leveraged to streamline and improve future development.

However, the need for a dedicated follow-on is urgent. CLARREO Pathfinder has a nominal one-year mission life and even with the potential for extended operations (which is dependent upon NASA ESD decision and available resources) is ultimately constrained by the lifetime of the ISS. Additionally, the recent cancellation of the European TRUTHS mission has threatened the possibility of an international independent verification of this concept, leaving a critical gap in the global Earth observation strategy that NASA is uniquely positioned to fill.

A future mission can easily leverage commercial and international partnerships, particularly in the realm of intercalibration, which ties directly into national and global priorities. Furthermore, the workforce and science community is prepared. An active algorithm development community is already positioned to exploit CLARREO Pathfinder data, and the widespread multispectral community can easily leverage these measurements to further test and potentially enhance existing products.

A hyperspectral, high accuracy capability supports multiple Atmosphere-related science targets using existing heritage, and it offers an innovative, fiscally realistic path that delivers an exceptionally high science return on investment.

6. Summary

We strongly recommend the continuation of high-accuracy, hyperspectral reflected solar measurements in the upcoming decadal strategy. The science community has clearly articulated the need for authoritative, SI-traceable information to address increasingly complex Earth system challenges. CLARREO Pathfinder is paving the way, proving that this capability is achievable today and establishing a foundation that current sensors can leverage. By prioritizing a polar-orbiting follow-on, NASA can secure a degradation-resistant climate benchmark, reduce long-standing uncertainties in key parameters like cloud feedback, and provide a gap-resilient calibration standard for the entire Earth observing system. This is a near-term, achievable opportunity to protect and compound the value of our climate record for decades to come.

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