Monitoring Earth's shortwave reflectance: GEO instrument concept

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Abstract— **In this paper we present a GEO instrument concept dedicated to monitoring the Earth's global spectral reflectance with a high revisit rate.**

Based on our measurement goals, the ideal instrument needs to be highly sensitive (SNR>100) and to achieve global coverage with spectral sampling (≤10nm) and spatial sampling (≤1km) over a large bandwidth (380-2510 nm) with a revisit time (≥3×/day) sufficient to fully measure the spectral-radiometric-spatial evolution of clouds and confounding factor during daytime. After a brief study of existing instruments and their capabilities, we choose to use a GEO constellation of up to 6 satellites as a platform for this instrument concept in order to achieve the revisit time requirement with a single launch.

We derive the main parameters of the instrument and show the above requirements can be fulfilled while retaining an instrument architecture as compact as possible by controlling the telescope aperture size and using a passively cooled detector.

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1. INTRODUCTION

An ideal system to monitor and attribute changes in Earth's shortwave reflected radiation must capture diurnal, seasonal and regional variations with global coverage. With sufficient sensitivity, this same system would detect small variations induced by Solar Radiation Management (SRM). To do so, long term baseline measurements over several years are needed to properly discriminate anthropogenic forcings from natural forcings. In addition, characterization of the aerosol species in the atmosphere as well as the determination of their effect on the spectral reflectance requires an instrument with sufficient spectral sampling and a range covering at least visible to shortwave infrared wavelengths.

SRM geoengineering has been proposed as a potential climate intervention option using methods such as stratospheric aerosol injection and marine cloud brightening [1,2]. Science-based decisions regarding risk assessments from field studies and eventual SRM activity will require observational data. However, to access the impact and effectiveness of any such effort, a global measurement system is needed that is capable of detecting changes in the Earth's shortwave reflected radiation with spatial, temporal and spectral sampling sufficient to attribute those changes to intentional perturbations over the natural variability background. Though many space-based instruments measure the Earth reflectance and aerosols, none achieve global coverage with high spectral resolution (≤10nm) and high spatial resolution (≤1km) with a revisit time (≥3×/day) sufficient to measure the evolution of clouds during daytime.

For cloud resolved measurements with a global coverage, a LEO satellite system seems to be an ideal platform for the instrument but requires the use of several orbital planes and thus several launches to achieve a revisit time of the order of 3 hours during daytime [3]. On the other hand, a single launch could carry up to 6 GEO satellites at a time and achieve stereoscopic global coverage with a 2 hour revisit at the cost of a comparatively larger optical system for the instrument [3]. Concepts for LEO instruments already exist so this paper focuses on the trade-off analysis and design effort of a hyperspectral instrument concept designed to be the primary payload of a GEO satellite constellation. We also outline possible additional instrument capabilities or synergies with existing instruments that could attribute more precisely the measured shortwave radiation change.

2. MEASUREMENT GOALS

We have identified three primary measurement goals for monitoring Earth's global spectral reflectance. In this section,

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we briefly present these goals and how they translate to requirements for our instrument concept.

Natural variability

The detection and attribution of intentional or unintentional anthropogenic changes of spectral reflectance within the larger annual, seasonal or even local natural variability requires a long term baseline measurement. Therefore we have designed a highly sensitive (0.2 W/m²) global measurement plan spanning several years. The sensitivity is enough to detect and assess the impact of many field experiments [4].

Attribution

Whenever a forcing of the spectral reflectance is identified, the aerosol species and the type of spectral reflectance modification linked to the forcing should be identified. To do so, a high spectral resolution measurement (10 nm) over a broad spectral range covering the visible to near-infrared wavelengths (380-2510nm) is needed with a signal to noise ratio higher than 100. For example, this resolution and spectral coverage can detect and identify black carbon in ship tracks or sulfate aerosols from volcanic or intentional injection [4,5].

Solar Radiation Management

We aim to detect and assess the impact of Solar Radiation Management experiments such as stratospheric aerosol injection, marine cloud brightening, or cirrus cloud seeding [4,6]. In particular, marine cloud brightening generates clouds of 1 km scale with a typical lifetime of 6 hours [7]. This corresponds to a spatial resolution requirement of 1 km or less, and a revisit time of 3 hours or less to allow for at least 2 measurements during the cloud lifetime.

All of these requirements are listed in the table 1.

Table 1 – Main requirements for an instrument monitoring global spectral reflectance.

Parameter	Value
Wavelength range	380-2510 nm
Spectral resolution	10 nm
Signal to noise ratio	>100
Coverage	Global
Spatial resolution	1km
Revisit	<3 hours (daytime)
Mission lifetime	> 2 years

3. TRADE-OFF ANALYSIS

In order to identify the best instrument design possible to monitor global spectral reflectance, we studied the numerous existing instruments dedicated to Earth observation in the visible to near-infrared. In this section, we analyze of these existing instruments in light of our set of requirements and present the geosynchronous mission concept that could host an instrument designed for global spectral reflectance.

Existing instruments

There are many existing satellites that can measure aerosols, clouds, or some combination of the two. Specifically, CALIOP, MODIS, POLDER, OMI and Hyperion are instruments aboard Low Earth Orbit (LEO) satellites for Earth observation and have excellent characterization of aerosols. Taking advantage of a near polar sun-synchronous orbit, these instruments achieve a global coverage but only with a global revisit of 1-16 days. This revisit time is highly dependent on their spatial resolution since it is set by their swath width, which means that the instruments that do satisfy our 1 km spatial resolution requirement have the longest revisit times as illustrated in figure 1.

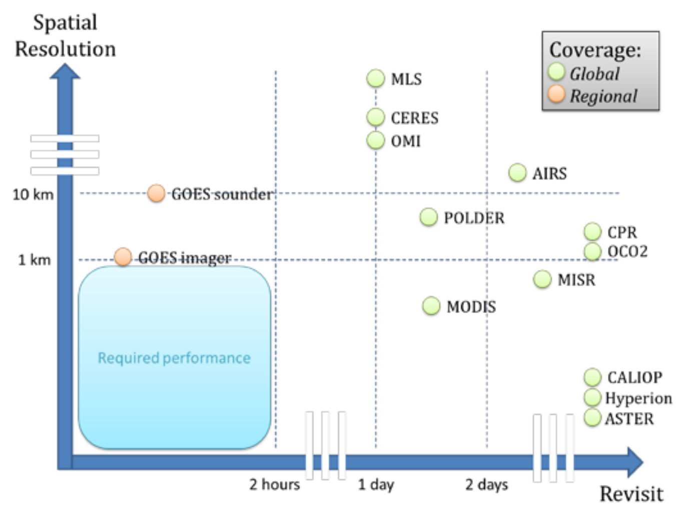

Figure 1 – Plot showing the spatial resolution, revisit time and coverage of existing Earth observation instruments compared to our required performance.

Geostationary weather satellites like the Geostationary Operational Environmental Satellite (GOES) series have a revisit time lower than 2 hours but do not achieve global coverage since they are dedicated to the observation of weather patterns in northern America and use a constellation of only 2 satellites at a time to do so [8]. The instruments aboard geostationary satellites have access to both the spatial resolution, revisit time and global coverage needed to fulfill our requirements if we consider a constellation of at least 3 satellites. However, figure 2 shows that existing instruments aboard current weather satellites like GEOS have insufficient channels to achieve the required spectral resolution.

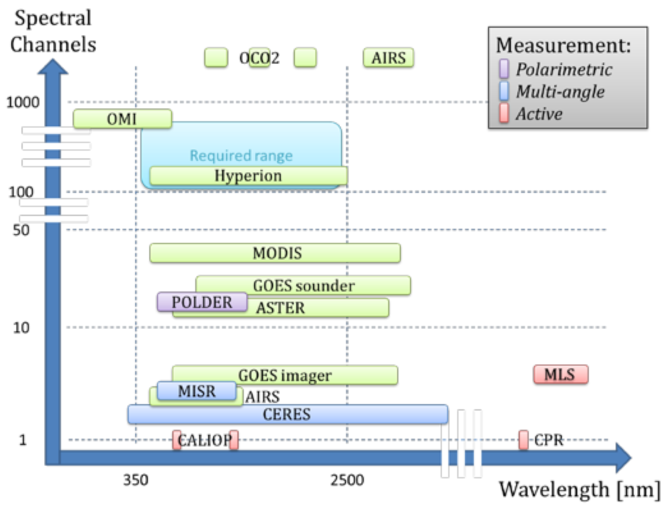

Figure 2 – Plot showing the number of spectral channels and wavelength range of existing Earth observation instruments compared to our required performance.

As illustrated in figure 2, the proposed requirements are well within the wavelength range of many existing instruments but only Hyperion has a satisfactory number of channels. However, Hyperion is part of the Earth Observing-1 (EO-1) mission on a near polar LEO orbit with a 16 day revisit and used for targeted observing only.

None of the existing instruments capture the Earth spectral reflectance signature in the visible with both the spectral resolution and the revisit time that is needed. Although they lack spectral or spatial coverage, existing instruments are very good at measuring specific things (ozone, SO2, water vapor) once every few days and should therefore be considered for data synergy or cross calibration for our measurement concept.

GEO satellite constellation concept

To be able to achieve both global coverage and a revisit time of 2 hours during the daytime, a LEO satellite system requires the use of several orbital planes and thus several launches to achieve a revisit time of the order of 2 hours during daytime [3] whereas a GEO satellite system of up to 6 satellite would require a single launch [3]. In this paper, we chose to focus our trade off analysis and design effort on a hyperspectral instrument concept designed to be the primary payload of a GEO satellite constellation.

With the opportunity to launch up to 6 satellites with one rocket, a constellation of 6 satellites can be considered. In this case, up to 84% of the globe can be covered with a coverage requirement of ± 50˚ latitude and ± 60˚ longitude. This corresponds to a field of regard requirement of 14.7˚×16.0˚ regard for each instrument of the constellation.
Furthermore the scanning strategy of each adjoining satellites can be synchronized to scan overlapping areas at the same time. The near global coverage would then be achieved with stereoscopic views of each region which would add a vertical resolution of clouds of 2 km to the data set.

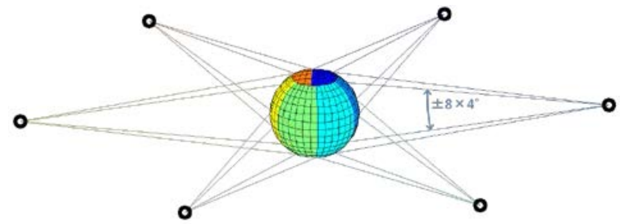

Figure 3 – 6 satellite GEO constellation concept.

4. Instrument Concept

In this section, we present the instrument concept designed as the primary payload of a dedicated 6 GEO satellite constellation aiming to fulfill all the requirements set by our goals for monitoring global spectral reflectance.

Optical system parameters

Based on the geometry from geosynchronous orbit, the variation of the ground sampling distance (GSD), can be calculated to derive the best the instantaneous field of view (IFOV) for the instrument. We are aiming for a spatial resolution of the order of 1 km for the total ±50˚ latitude and ±60˚ longitude coverage. An IFOV of 17.1 µrad allows us to obtain a GSD lower than 1.25 km for 87% of the total coverage with a value of 620 m at nadir as illustrated in figure 4.

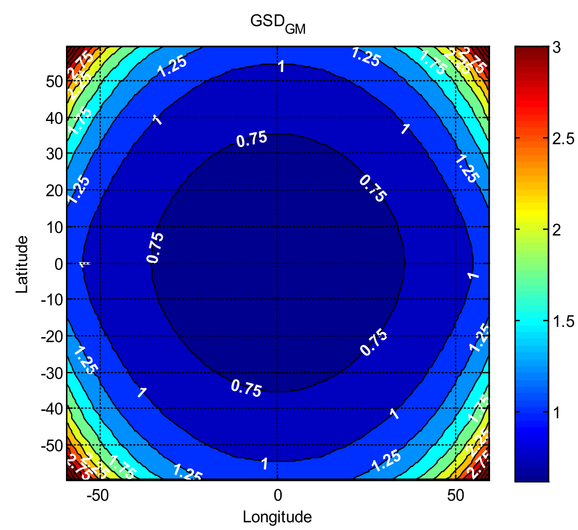

Figure 4 - Ground Sampling Distance (GSD) variation viewed from a geosynchronous orbit for ±60˚ latitude and ±60˚ longitude for an instantaneous field of view (IFOV) of 17.1 µrad.

Once the IFOV is set, the corresponding focal length is calculated according to the orbit value. In the case of a geosynchronous satellite, we obtain an ideal focal length of 1750 mm.

The ideal focal number and the corresponding entrance pupil diameter are then calculated by matching the maximum spot size set by the diffraction limit to the focal plane array pixel size. This requirement on the maximum spot size will insure that both the spatial and the spectral information are correctly allocated. For this design, a diffraction limited spot size corresponding to a pixel pitch of 30 µm at a maximum wavelength of 2.5 µm corresponds to a focal number of 5. This corresponds to an entrance pupil diameter of 350 mm.

Table 2 - Main optical system parameters.

Parameter	Value
IFOV	17.1 µrad (GSD = 0.62 km at Nadir)
FOV	1.26˚ (1280 spatial pixels)
Focal length	1750 mm
Entrance pupil diameter	350 mm
Focal number	5

To obtain a compact high uniformity (>90%) and high signal to noise ratio (S/N) design, we designed a modified Cassegrain telescope with a refractive corrector that provides wide field and a telecentric output for matching an Offner grating spectrometer without increasing the overall volume of the instrument (Figure 5).

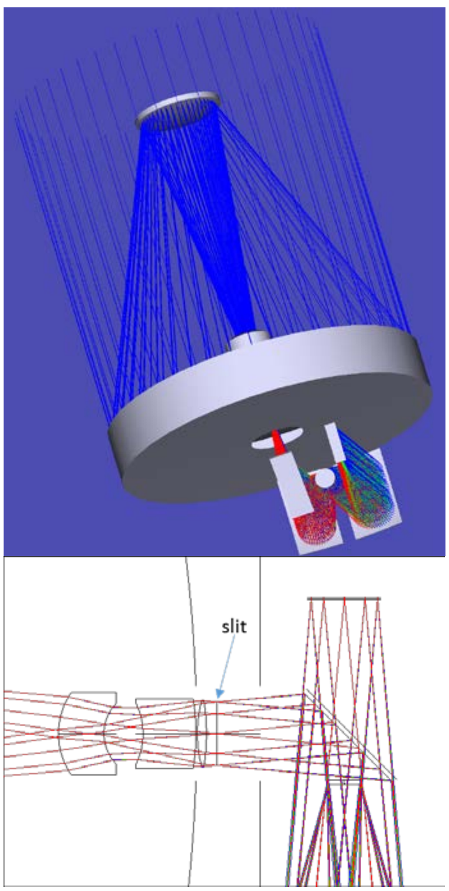

Figure 5 - Optical design including a modified Cassegrain telescope with a refractive corrector and a high uniformity Offner spectrometer.

The refractive corrector design employs only low-index materials with full transmission over the entire spectral range, and is thermally insensitive so it does not affect the athermalization of the telescope. At the same time, the refractive corrector can provide a focus compensation mechanism if needed, and critically, has very small chromatic aberration of less than 1.5 µm or 5% of a pixel for all fields and wavelengths. The telescope central obscuration corresponds to only 8% of the area but it is estimated to 12% once the structure is added. While the Offner design draws heritage from UCIS [9], the Moon Mineralogy Mapper [10], and the airborne NGIS [11].

These features allow us to achieve an excellent optical performance that is kept uniform by design over all wavelengths as illustrated in figure 6. To do so, we deliberately introduced aberrations at the short wavelengths to balance the diffraction at longer wavelengths and increase uniformity [12].

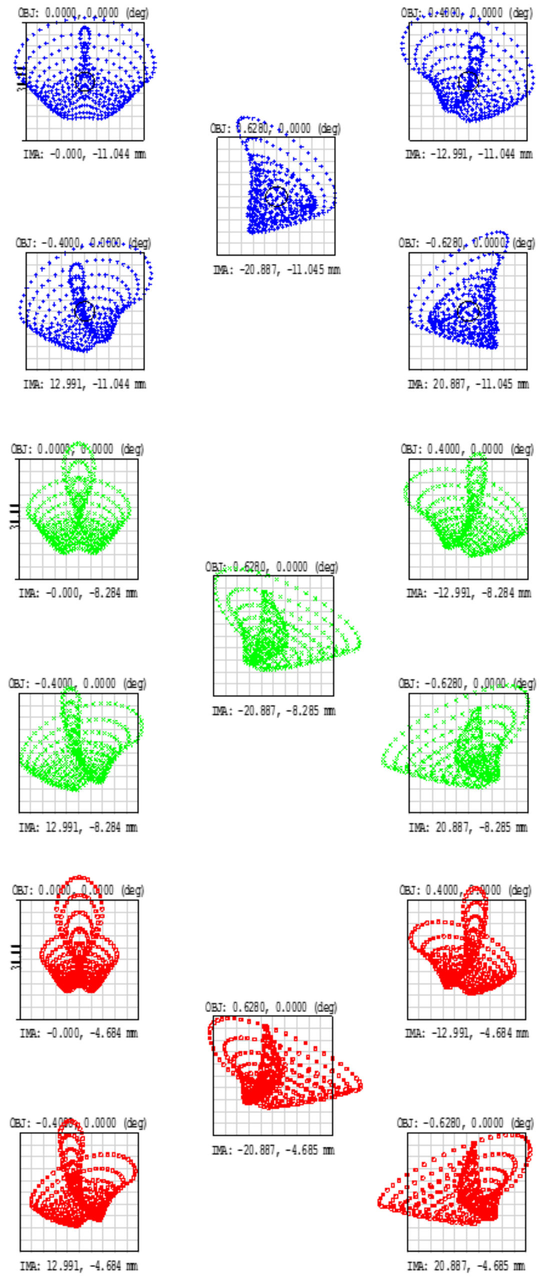

Figure 6 – Full optical system spot diagrams compared to the pixel size (30µm) for the extreme and middle wavelengths of the total range: 380nm (blue), 1300nm (green), 2500nm (red).

Focal plane array

For this instrument concept, we need a space qualified detector covering our required wavelength range with enough sensitivity and an array large enough to accommodate the 213 required spectral channels and enough spatial pixels to obtain a large swath. Another requirement on the detector to keep the instrument size, mass and power consumption reasonable is for an operation temperature that does not require active cooling.

The Teledyne Imaging sensor CHROMA satisfies all these requirements and allows the use of correlated double sampling at the pixel level to correct for bias. The expected signal to noise ratio (S/N) of the instrument based on the detector and optical system characteristics is illustrated in figure 7 for an integration time compatible with our 2 hour revisit requirement. The required signal to noise ratio (S/N>100) is thus exceeded for all the atmospheric windows in the wavelength range for radiance levels higher than 10%. The balanced SNR across the 2.5 octave from 380 to 2510 nm is achieved with an efficiency tuned electron-beam-lithography convex grating of the type flown in the Offner spectrometer of the Moon Mineralogy Mapper [13].

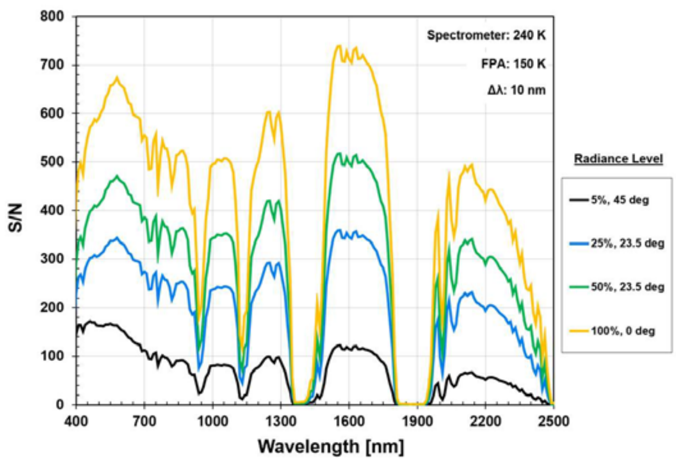

Figure 7 - Expected signal to noise ratio (S/N) of the spectrometer design for different radiance levels based on the instrument characteristics for 2 reads performed in 18.9 ms and a focal plane temperature of 150 K.

Table 3 - Main characteristics of the Teledyne Imaging sensor CHROMA focal plane array.

Characteristic	Value
Detector technology	Mercury Cadmium Telluride
Array size	1280×480 pixels
Pixel pitch	30 µm
Full well	10^6 electrons
Readout noise	110 electrons
Readout mode	Integrate while read
Integration time	18.9 ms
Digitalization	14 bits
Operation temperature	~150 K
Power dissipation	180 mW

Scanning strategy

A covered area of ±50˚ latitude and ±60˚ longitude from geosynchronous orbit corresponds to a total field of view of 14.7˚×16.0˚ to cover with a revisit of 2 hours. With its 1280 spatial pixels and an IFOV of 17 µrad, the field of view of the instrument is 1.26˚. In order to obtain the required coverage, the instrument will include a scanning mirror to scan Earth in a North to South motion in a series of 13 strips with the East to West motion performed by the satellite.

With this scanning strategy and the 2 hour revisit requirement, the maximum integration time per spectrum is set to 37.8 ms which is two times more available time than the 18.9 ms needed to obtain the S/N plotted in figure 7. This means there is enough time to perform two additional reads and either: i) choose to increase the S/N further by a factor $\sqrt{2}$ with averaging, or ii) refine the spatial resolution by a factor ~0.6 by reading every half pixel of equivalent ground motion, or iii) add a basic polarimetric capability to the instrument by switching two perpendicularly polarized filters in front of the spectrometer entrance slit between the two reads.

With an available downlink rate of 120 Mbits/s and the JPL 6 to 1 loss-less data compression technology [14], the total data volume per day of 60.62 GB for one read can be downlinked in less than 1 hour 15 minutes. Doubling the data volume by adding a second read can therefore be considered.

Table 4 - Main parameters of the scanning strategy.

Parameter	Value
Scanning motion	North-South with a scan mirror East-West with spacecraft motion
Number of scans per revisit	13 North-South scans
Number of spectra per scan	14660 (less near limb)
Data volume per scan	6.99 GB (uncompressed)
Number of revisits during daylight	4 (e.g. 9am, 11am, 1pm, 3pm local time) (satellite operated from 8am to 4pm)
Total data volume per day	363.72 GB (60.62 GB with 6:1 compression)
Downlink rate	~120 Mbits/s
Downlink time	~1h 7 min (with 6:1 loss-less compression)

Calibration and thermal architecture

The scanning mirror will be used for calibration as well as scanning the scene. For the flat field correction, pointing the mirror towards a diffuse surface reflecting the sunlight will be done once a day and an additional correction will be performed once a month using the Moon as a target. For the dark current correction, the mirror will be pointing towards deep space around the view of Earth. An ideal period for this correction is once per revisit, which would only an additional step to the scanning of the target for the scan mirror.

The calibration data volume per day equivalent to 5 dark current corrections and 1 flat field is 6.45 MB.

A passive architecture is sufficient to cool down the focal plane array at 150 K and the spectrometer assembly at 180 K. We will therefore adopt a passive thermal architecture inherited of the M³ (Moon Mineralogy Mapper) instrument [13].

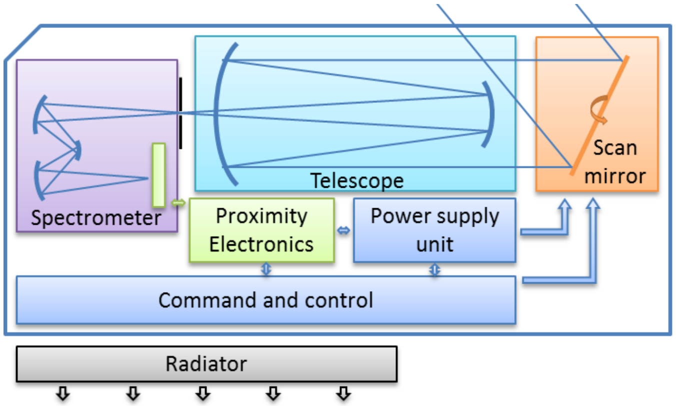

Figure 8 - Preliminary instrument block diagram.

5. CONCLUSION

We identified our measurement goals and showed that no existing instrument fulfilled them entirely. Therefore we created a new instrument concept dedicated to measuring Earth's shortwave reflectance and monitor Solar Radiation Management based on a GEO satellite constellation.

Using existing technologies and heritage architecture from JPL instruments, we were able to meet all the instrument requirements defined by our measurement goals while keeping the design as compact as possible.

6. ACKNOWLEDGEMENTS

This paper presents some of the results from a joint JPL-Boeing study dedicated to measuring spectral reflectance from space. This successful collaboration has identified the main objectives for monitoring Solar Radiation Management globally with both LEO and GEO satellites and provided potential observation solutions to this end.

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BIOGRAPHY

Dr. Brageot *received a B.S. (2007), a M.S. (2009) in fundamental physics and a M.S. (2009) in astronomical and space-based systems engineering from the University of Paris-Sud, and a Ph.D (2012) in instrumentation from the University of Aix-Marseille. After completing her thesis at the Laboratoire d'Astrophysique de Marseille, she continued her work on instrument design until December 2013 as a systems engineer and co-investigator of the THERMAP mid-infrared spectro-imager selected for the ESA space mission MarcoPolo-R. She is now a NASA Postdoctoral Program fellow at NASA's Jet Propulsion Laboratory where she works on instrument and detector performance assessment and optical design for several projects.*

Michael Mercury *received a B.S. and M.S. in Astronautical Engineering from the University of Southern California in 2008 and 2010 respectively. He has worked in mission formulation at NASA's Jet Propulsion Laboratory for 6 years as Systems Engineer, System Analyst and Contract Technical Manager. He has supported Team X as a Systems Engineer and the last three years has been the lead Systems Engineer on the HyspIRI mission as well as a recent Imaging Spectrometer proposal to Europa. He has been Contract Technical Manager for multiple spacecraft accommodation studies and developed Matlab tools for applications ranging from calculating a polarimiter's polarization rotation due to viewing geometry, to predicting flight times for large airborne campaigns.*

Robert Green's research interest is optical imaging spectroscopy with a focus on advanced instrumentation; model based spectroscopic inversions, as well as measurement calibration and validation. Robert has been Experiment Scientist for the NASA AVIRIS airborne imaging spectrometer since 1989. AVIRIS measurements have been used for many science discoveries and resulted in hundreds of journal articles. Robert is a science co-investigator on the CRISM imaging spectrometer for Mars and Instrument Scientist for the M3 imaging spectrometer that discovered water and hydroxyl compounds on the illuminated surface of the Moon. Robert is also co-lead for the NASA Earth Decadal Survey Mission HyspIRI that includes a global coverage imaging spectrometer for science and applications as well as investigation of climate change, impact, adaptation and vulnerability. He has been involved with the development of 5 space imaging spectrometer and more than 10 airborne and ground imaging spectrometer systems that use JPL's unique capabilities.

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