Measuring the Earth's Surface Mineral Dust Source Composition for Radiative Forcing and Related Earth System Impacts

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Description: Mineral dust impacts direct & indirect forcing, tropospheric chemistry, ecosystem fertilization, human health & safety. Global source composition is poorly constrained by <5000 mineral analyses. Global spectroscopic measurement of surface mineralogy closes this gap to advance understanding & Earth system modelling of current & future impacts

Theme IV. Climate Variability and Change: Seasonal to Centennial. Forcings and Feedbacks of the Ocean, Atmosphere, Land, and Cryosphere within the Coupled Climate System

1. The Science and Application Target

Mineral dust emitted from the surface (Fig. 1) impacts climate variability and change through direct radiative forcing (RF) over arid and semi-arid regions around the globe. This is where shifts in climate have a significant impact on agriculture, precipitation, and desert encroachment. Dust particles contribute to both positive and negative forcing, depending on the composition of the particles (Fig. 2) which is a function of the mineralogy of source regions. Dust particles are also the primary source of ice nuclei (Atkinson et al., 2013; Cziczo et al., 2013), and thus can modify cloud properties. Desert dust particles are also the primary source of iron deposition to the ocean (Jickells et al., 2005). However, for all these interactions, not all types of dust are equally important, and the chemical composition or mineralogy is of primary importance (Atkinson et al., 2013; Shi et al., 2012; Sokolik and Toon, 1999). For direct radiative interactions in the atmosphere and when deposited on snow, the amount of iron, especially changes the absorption, and the climate impact (e.g. Sokolik and Toon, 1999; Painter et al., 2007; Scanza et al., 2015). Iron and phosphorus deposition modulates ocean biogeochemistry, and can be just as important as changes in climate for changing ocean productivity (Mahowald et al., 2011). The mineralogy matters greatly for these impacts, as some iron species are more bioavailable in the ocean than other iron (Shi et al., 2012). Because desert dust is sensitive to climate and land use, anthropogenic changes in dust sources can be forcing change in both climate and biogeochemistry (e.g. Ginoux et al., 2012; Mahowald et al., 2010). Currently poor knowledge of mineral dust source composition (MDSC) limits the skill of Earth System models to predict dust climate and biogeochemistry impacts around the globe.

The current challenge is that the MDSC is assumed to relate to soil types provided by a global atlas (e.g., Claquin et al., 1999). This relation is based upon massive extrapolation due to limited sampling of soil mineralogy (<5000 samples) and neglects mineral variations between regions of identical soil type. Also, these measurements are based on wet sedimentation ("wet sieving") techniques that disturb the soil samples, breaking the aggregates that are found in the original, undispersed soil that is subject to wind erosion. New, global observations of dust source and adjacent lands are need to provide direct and comprehensive measurements of the mineralogy of dust source regions, targeting at least the ten key minerals identified by the Earth system modeling community (Claquin et al., 1999; Nickovic et al., 2012; Journet et al., 2014).

Earth system models in use today are ready to accept and in need of accurate MDSC. For example, NASA GISS ModelE2 (Miller et al. 2006; Schmidt et al., 2014) and NCAR CESM (Hurrell et al, 2013), with the embedded atmospheric model CAM5 (Neale et al., 2012, Mahowald et al., 2006). Both models contribute to the Climate Model Inter comparison Projects (CMIP), used in the Assessment reports of the IPCC. Comparisons of current model predictions with in situ dust sampling do not match well (Scanza et al., 2015, Perlwitz et al., 2015a, b), underscoring the need for comprehensive and direct measurement of MDSC. Improved representations of emitted mineral dust aerosol composition would lead to more accurate predictions of AOD, RF, ice nuclei, dust deposition and related impacts around the globe. Furthermore, these measurements would improve studies of the feedback between climate change and the evolution of surface conditions (e.g., desert encroachment and greening) under future climate scenarios.

Beyond global impacts, the arid regions of the Earth are vulnerable to small shifts in climate and the related impacts of surface emitted mineral dust. For example, the largest changes in precipitation recorded in the 20th Century have occurred over the Sahel region of North Africa (e.g. Stocker et al., 2013). Climate modeling demonstrates that the incorporation of realistic mineral dust models improves predictions of temperature and precipitation changes over arid regions (e.g., Miller and Tegen, 1998; Yoshioka et al., 2007; Mahowald et al., 2010) along with weather forecasts (Perez et al. 2006), and the impact of dust is a function of the mineralogy and spatial distribution of soils in dust source regions (e.g. Perlwitz et al., 2001; Ginoux et al., 2012; Ward et al., 2014; Miller et al., 2014; Scanza et al., 2015).

The MDSC science target presented here is addressed with two Quantified Earth Science Objectives (QESOs). QESO1 is to (i) accurately measure the type and abundance of key surface minerals available for dust emission over 28×10^6 km^2 of the surface (arid and semi-arid regions), (ii) demonstrate improved model performance, and (iii) update climate RF predictions, cloud properties and ocean biogeochemistry in dust impacted regions of the Earth. Historic data indicate that natural (non-anthropogenic) dust loading has almost doubled over the 20th century, and this trend is expected to continue into the future (Mahowald et al. 2010, Mulitza et al. 2010), due at least partly to direct land use (Ginoux et al., 2012). This motivates QESO2 that is to measure surface composition of agricultural and sparsely-vegetated lands bordering arid regions ($>4 \times 10^6$ km^2) to predict the evolution of new dust sources, and related Earth system impacts, under future climate scenarios.

In addition to direct climate forcing, mineral dust affects indirect RF through cloud formation as well as changes in the albedo and melting of snow/ice. Based on their chemistry, the minerals in dust react and modify tropospheric photochemistry and acidic deposition (Dentener et al., 1996; Martin et al., 2003). Mineral dust aerosols affect ocean and terrestrial ecosystem biogeochemical cycling by supplying limiting nutrients such as iron and phosphorus (Jickells et al., 2005). In populated regions, mineral dust is a natural hazard that affects human health and safety. Additional Earth system processes impacted by mineral dust emitted from the Earth's surface are given in Table 1.

This MDSC target advances the goals of NASA climate research and the IPCC (Myhre et al., 2013) as well as advancing elements of atmospheric composition and Earth surface research by characterizing the sources of radiatively active mineral dust emitted from the Earth's surface, understanding and predicting the impact of mineral dust on regional and global RF, and advancing the capabilities of Earth system modeling.

2. The geophysical variables

To achieve the science target, the type and relative abundance of the key dust source minerals need to be measured comprehensively for the arid and semi-arid regions of the Earth. This now feasible with modern spectroscopic measurements (Fig. 3). These new measurements would be incorporated into Earth system models that require consideration of the mineralogy of dust source regions (e.g., Claquin et al., 1999; Nickovic et al., 2012; Journet et al., 2014), saltation and emission of dust particles to the atmosphere (e.g., Zender et al., 2003a, b; Okin, 2005; Kok et al., 2014a, b; Perlwitz et al., 2015a, b), transport and dispersion of dust plumes (Knippertz and Todd, 2012; Choobari et al., 2014, and references therein), radiative properties of dust particles (e.g., Sokolik and Toon, 1999; Miller et al., 2006; Albani et al., 2014; Scanza et al., 2015;) and, finally, deposition of the dust (Zender at al., 2003a).

At least two leading Earth system modeling frameworks are readily available to accept these measurements: (1) NASA/GISS ModelE2 (Miller et al. 2006; Schmidt et al., 2014) and (2) NCAR CESM (Hurrell et al, 2013), with the embedded atmospheric model CAM5 (Neale et al., 2012, Mahowald et al., 2006). Both models contribute to the Climate Model Inter comparison Projects (CMIP), coordinated by the IPCC. The MDSC products can initialize dust emission models that in-corporate physically-based processes to estimate the composition and mass fraction of dust particles emitted into the atmosphere.

To achieve the two QESOs for this science target, NASA GISS ModelE2 and NCAR CESM would be initialized based on the new MDSC product. Hindcasts of total AOD could then be compared with archives of AOD derived from satellite and ground-based observations (e.g., Li et al., 2004; Patadia et al., 2009; Ginoux et al., 2012; Scanza et al. 2015). Further validation tests can compare hindcasts of dust deposition to in situ deposition records (Scanza et al., 2015, Perl-witz et al., 2015b). Following this validation phase, the models would be run to quantify the improved predictions of regional and global RF with incorporation of these new direct MDSC measurements.

To evaluate the impact on predictions of new dust source regions (QESO2), such as lands at risk for desert encroachment, the initial surface composition can be based on these new MDSC products. This would allow modelers to evaluate range of IPCC climate scenarios as well as various scenarios for land use change (Ginoux et al. 2012; Ward et al. 2014, Seager et al., 2007, 2014; Mahowald 2007), and analyze to assess future RF impacts regionally and globally. Regionally, dust RF can dominate RF and significantly impact regional climate including precipitation (Miller et al., 2014, Yoshioka et al., 2007, Miller et al., 2004).

3. Key requirements on the measurement

To achieve the science target, comprehensive measurement of ten key minerals identified by the Earth system modeling community (Claquin et al., 1999; Nickovic et al., 2012; Journet et al., 2014) is required. These are hematite, goethite, illite, vermiculite, calcite, dolomite, montmorillonite, kaolinite, chlorite, and gypsum each with a unique spectral signature tied to its composition (Fig. 4). The modeling of mineral dust is based on the fractional abundance of component minerals, and changes in the abundance of individual components will constrain the abundance of the remaining components, such as quartz and feldspar. Currently, remote spectroscopic mapping of dust source regions is the only feasible path to measure the occurrence relative abundance of the key dust source minerals with sufficient detail and global arid land coverage. Complete measurement of the spectral range from 410 to 2450 nm is required to capture the diagnostic absorptions of the minerals (Fig. 4). Spectral sampling of ≤15 nm, response function width ≤20 nm, and ≤5% spectral calibration uncertainty are required to discriminate overlapping absorption features (Swayze et al., 2003). This spectral range captures the atmospheric features used in the atmospheric correction (Thompson et al., 2015), aerosol and cloud screening (Thompson et al. 2014, 2016). To screen for non-dust source surface materials, the spectral features of green and non-photosynthetic vegetation are captured in this range as well.

To encompass the brightness of arid dust source regions, the radiometric range of the spectroscopic measurement is required to extend to ≥80% of a Lambertian reflectance target under direct illumination. Radiometric calibration of ≤10% uncertainty enables radiative transfer model-based atmospheric correction. The required precision of the measurements is established to provide sensitivity to 1% changes in the depth of absorption features in mineral spectra (Fig. 5). This sensitivity can be enhanced with optional aggregation from the nominal spatial sampling of 30 m to 100 m sampling.

A spatial sampling ≤100 m is required to characterize surface mineralogy in small fallow agricultural fields and exposed areas, and initialize predictions of the evolution of dust sources in regions vulnerable to desert encroachment (QESO2). Additionally, this spatial scale provides the detail for accurate aggregation and abundance estimation for the constraint of the dust mission elements in the Earth system models.

The coverage requirement for the science target is to measure the required mineralogy for ≥80% of the arid dust source and adjacent regions of the Earth identified by the WMO (Fig. 6) corresponding to 28×10^{6} km^{2} of the terrestrial surface. Based on related land cover classifications, an additional area of 4×10^{6} km^{2} is required for QESO2 corresponding to adjacent areas at risk for desertification that could potentially become future mineral dust sources.

The key requirements to achieve the science target and related QESOs are summarized in in the Science Traceability Matrix (Table 2).

4. Affordability

The measurements can be achieved affordably in the decadal timeframe, due to investments in response to global terrestrial/coastal coverage missions outlined in the 2007 NRC Decadal Survey (NRC 2007) and NRC *Landsat and Beyond* report (NRC 2013) and other initiatives. These measurements would build on a legacy of airborne instruments such as AIS (Vane et al, 1984), AVIRIS (Green et al., 1998), and AVIRIS-NG (Hamlin et al., 2011), and space-based instruments such as NIMS (Carlson et al., 1992), VIMS (Brown et al., 2004), Deep Impact (Hampton et al., 2005), CRISM (Murchie et al., 2007), EO-1 Hyperion (Ungar et al, 2003, Middleton et al., 2013), M3 (Green et al., 2011) and MISE, the imaging spectrometer now being developed for NASA's Europa mission.

NASA-guided engineering studies in 2014 and 2015 show that a wide swath VSWIR (380 to 2510 nm @ ≤10 nm sampling) (Fig. 7) imaging spectrometer instrument with a 185 km swath, 30 m spatial sampling and 16 day revisit with high signal-to-noise ratio and the required spectroscopic uniformity can be implemented affordably for a three year mission with mass (98 kg), power (112 W), and volume compatible with a Pegasus class launch or rideshare (Fig. 8).

The key for this measurement is an optically fast spectrometer providing high SNR and a design that can accommodate the full spectral and spatial ranges (Mouroulis et al., 2016). A scalable prototype F/1.8 full VSWIR spectrometer (van Gorp et al., 2014) has been developed, aligned, and is being qualified (Fig. 9).

Data rate and volume challenges have been addressed by development and testing of a lossless compression algorithm for spectral measurements (Klimesh et al., 2006, Aranki et al., 1009ab, Keymeulen et al., 2014). This algorithm is now a CCSDS standard (CCSDS 2015). With compression and the current Ka band downlink offered by KSAT and others, measurements for all dust source and potential dust source regions can be downlinked (Fig. 10).

Algorithms for calibration (Green et al., 1998) and atmospheric correction (Gao et al., 1993, 2009, Thompson et al., 2014, 2016) of large diverse data sets have been benchmarked as part of the HyspIRI preparatory campaign (Lee et al., 2015) as well as for the AVIRIS-NG India and Greenland campaigns and elsewhere. To enhance affordability and accelerate measurement availability, there is good potential for international partnerships. Efficient and accurate software for estimating surface mineralogy, such as the Tetracorder method shown in Fig. 3 (Clark et al., 2003), has been refined and field-validated over decades of use in airborne and planetary science applications.

Figures

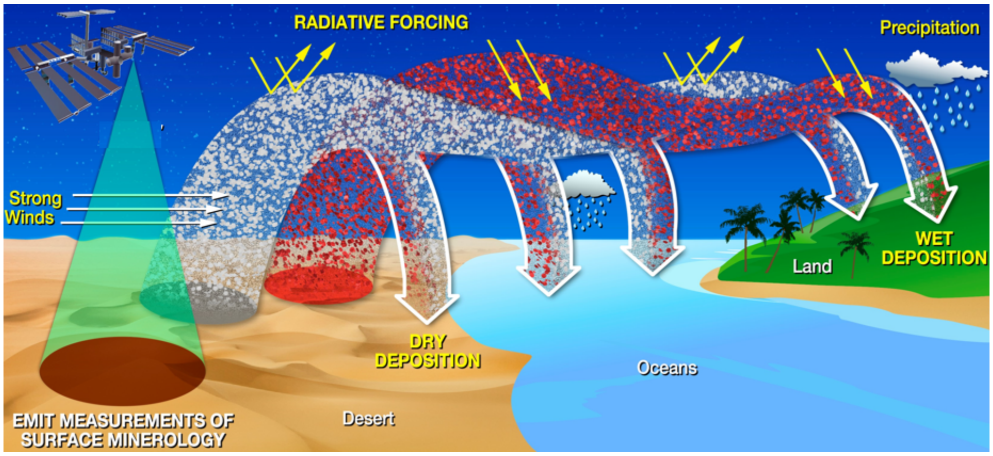

Figure 1. Modeling the role of mineral dust in RF requires consideration of the generation, emission, radiative properties, and deposition of dust particles. The composition of dust aerosol can be traced back to the source region on the surface. Dust particles can reflect (white) or absorb (red) solar radiation, based on the composition of the particles. In addition to direct radiative forcing, mineral dust impacts the Earth system by modifying cloud properties, enhancing snow/ice melt, changing precipitation patterns, modifying atmospheric composition, supplying nutrients to terrestrial and aquatic ecosystems as well as direct societal impacts to air quality, visibility, and respiratory health.

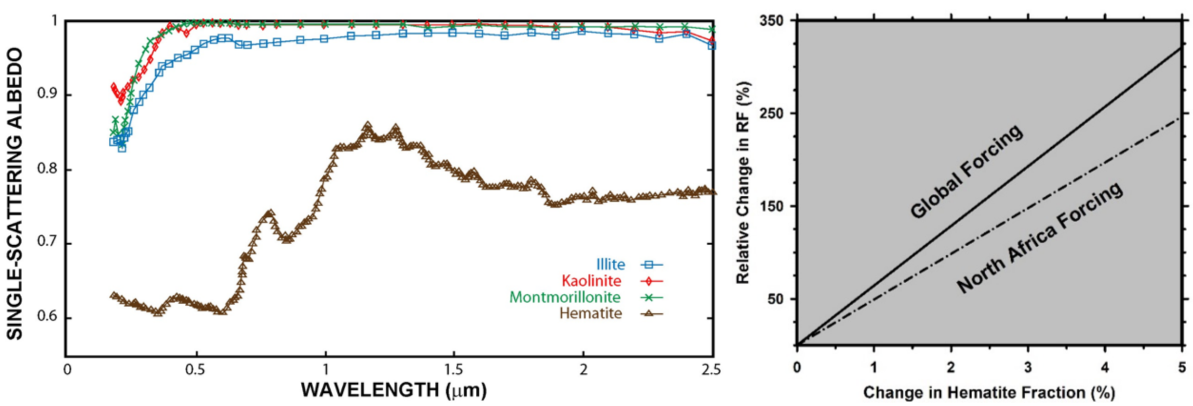

Figure 2. (left) Mineral composition is a key control of SSA, which describes how particles scatter and absorb energy. Iron-bearing minerals (represented here by hematite) are strong absorbers (SSA < 1.0) in the solar spectral region, while clay minerals (illite, kaolinite, and montmorillonite) are strong scatters (SSA ≈ 1.0). Particle radius is 0.5 mm. Figure modified from Sokolik and Toon (1999). (right) The relative abundance of hematite in dust source regions has a significant impact on dust-related radiative forcing. A 2% increase in the hematite content of soils results in increases of 130% and 100% in simulations of global forcing (solid line) and regional forcing over North Africa (broken line), respectively. Modeling results courtesy of R. Scanza, Cornell.

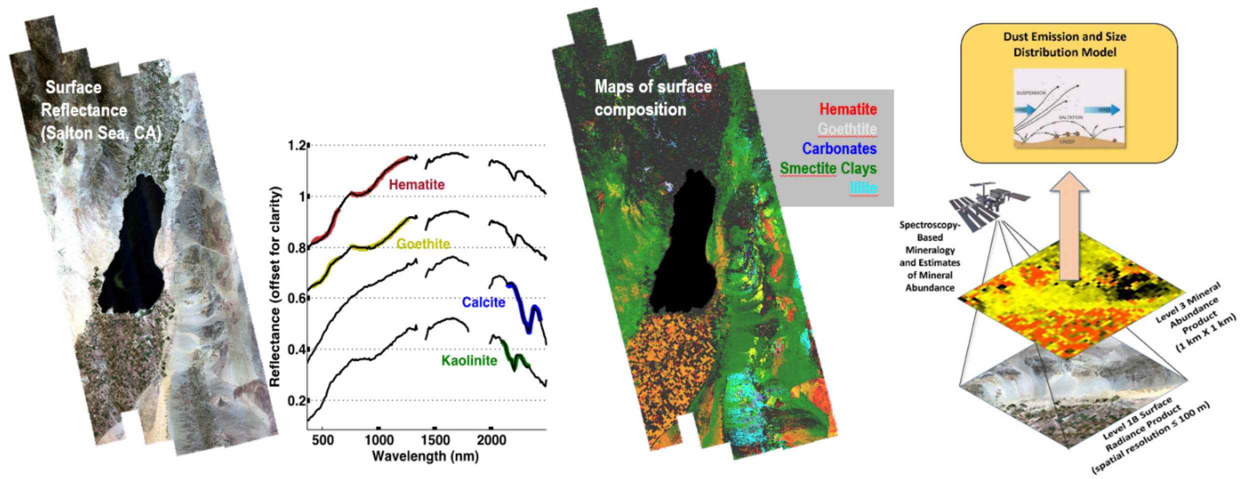

Figure 3. (left) Example spectroscopic mineral composition maps of the Salton Sea dust source region in California from the NASA HyspIRI preparatory airborne campaign. The strength and shape of the absorption is used to identify the mineral and estimate the abundance. The residuals of the spectral fit provide the basis for certainty estimation and are reported together with the mineral products. (right) To address this science target, the products can be aggregated and input into dust emission models that estimate the mass fractions of dust particles emitted into the atmosphere to address the QESOs and advance modeling of Earth's dust cycle.

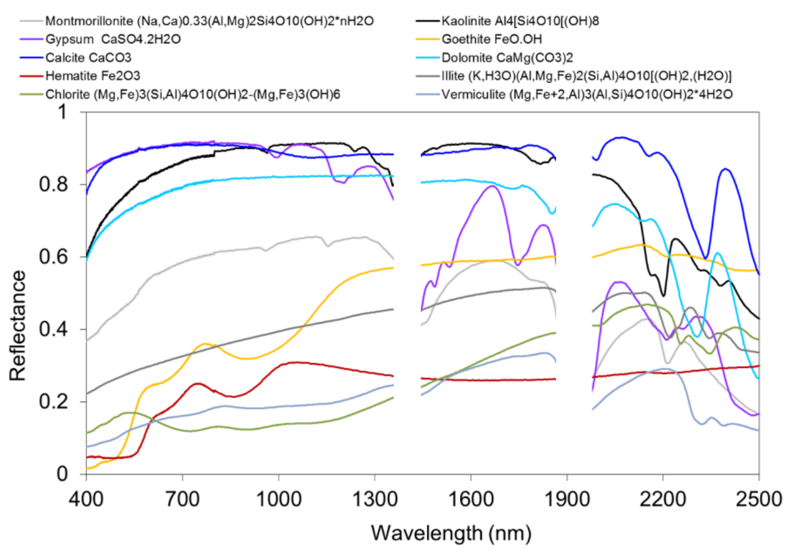

Figure 4. Measured reflectance spectra of the ten key dust source minerals showing the absorption features in the range from 450 to 2450 nm. These absorption features tied to composition are the basis for achieving this science target with imaging spectroscopy measurements of the arid land regions of the Earth.

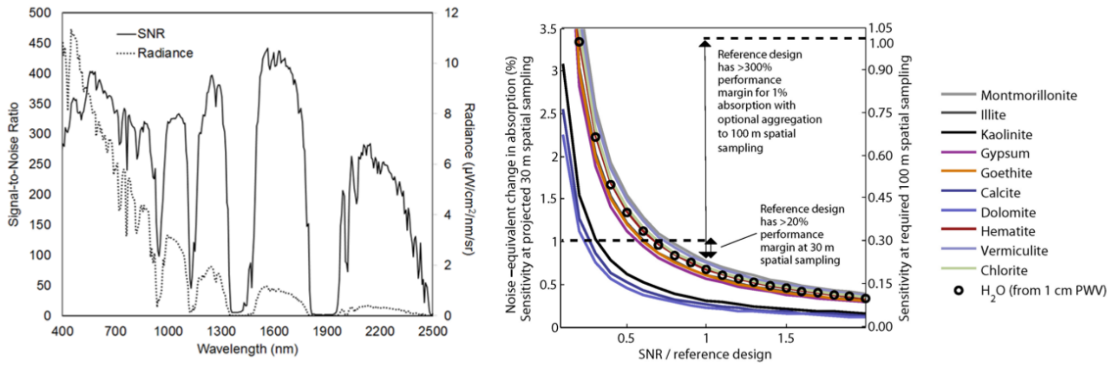

Figure 5. (left) Radiance spectrum and reference signal-to-noise ratio that enables measurement of absorption features for mineral source composition and abundance estimation. (right) Noise equivalent change in absorption sensitivity for the ten key minerals. Sensitivity to water vapor is also assessed in relation to retrieval for atmospheric correction.

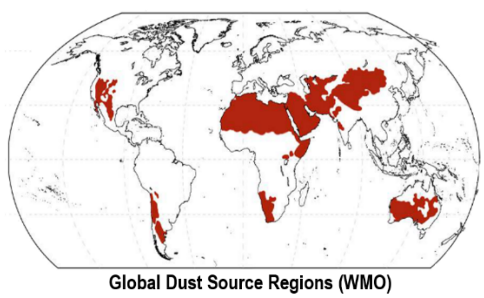

Figure 6. Current dust source regions of the Earth identified by the World Meteorological Organization.

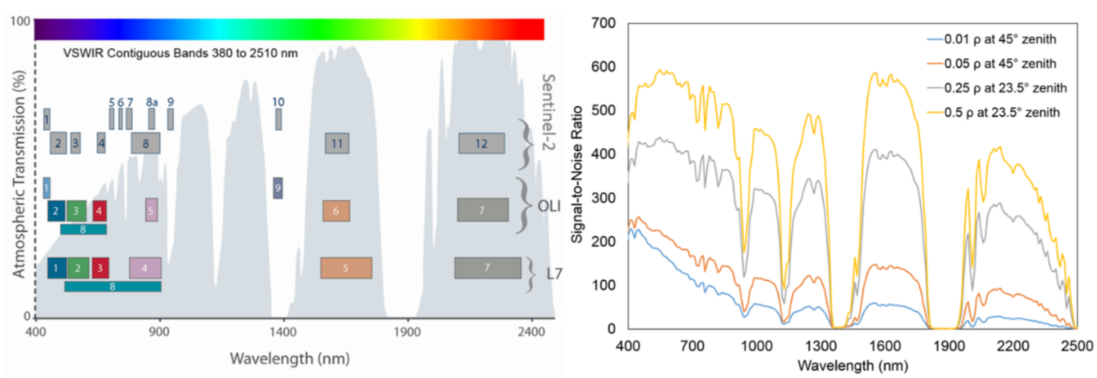

Figure 7. (left) Contiguous spectral coverage from 380 to 2510 nm showing overlap with Landsat and Sentinal-2 bands. (right) Signal-to-noise ratio for 30 m sampling with F/1.8 VSWIR Dyson imaging spectrometer for a range of reference radiances.

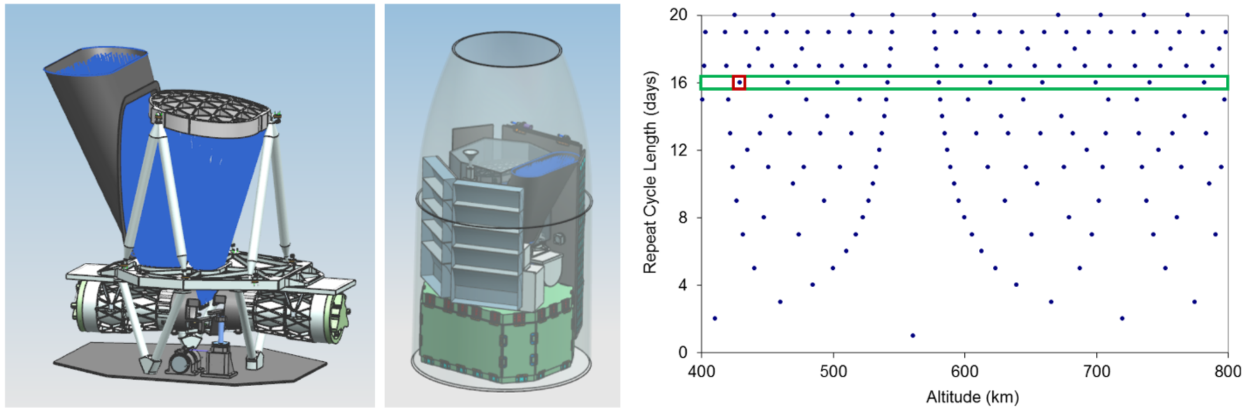

Figure 8. (left) Opto-mechanical configuration with one telescope feeding two field split wide swath F/1.8 VSWIR Dyson spectrometer providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options showing an altitude of 429 km with a fueled spacecraft supports the three year mission with the affordable Pegasus launch or rideshare. Higher orbits are viable with a larger launch vehicle.

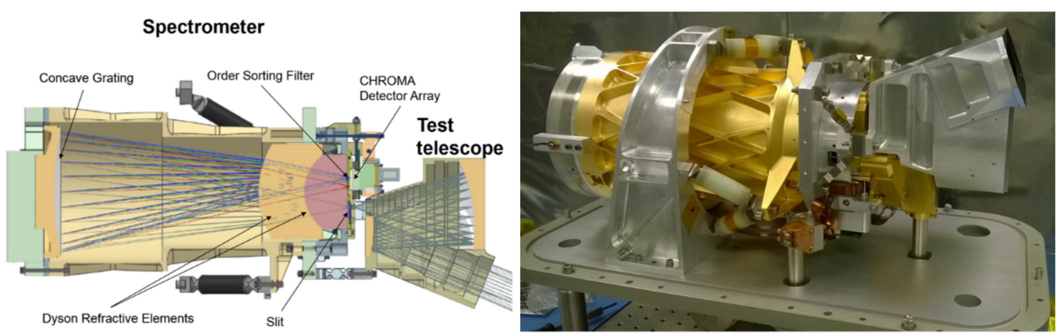

Figure 9. Design of a wide swath F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Dyson imaging spectrometer in qualification that uses a full spectral range HgCdTe detector array.

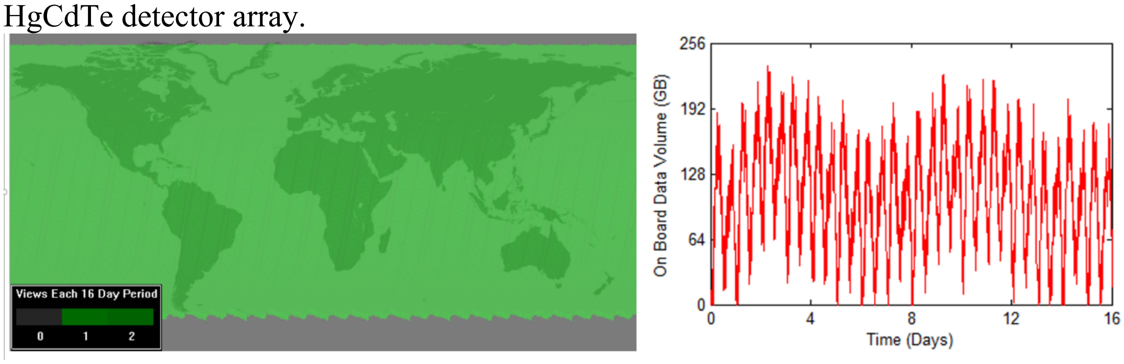

Figure 10. (left) Global illuminated surface coverage every 16 days. (right) On-board data storage usage for illuminated terrestrial/coastal regions with downlink using Ka Band (<900 mb/s) to KSAT Svalbard and Troll stations. Oceans and ice sheets can be spatially averaged for downlink.

Tables

Table 1. Mineral dust impacts a broad range of physical and chemical Earth system processes.

Process	Example References
Direct radiative forcing	Tegen et al., 1996; Sokolik and Toon, 1999; Dufresne et al., 2002, Boucher 2013
Indirect radiative forcing by modifying cloud properties	Kauffman et al., 2005, Forster et al., 2007, Mahowald et al., 2013, Rosenfeld et al., 2001, Atkinson et al., 2013, DeMott et al.,2003, Mahowald and Kiehl, 2003
Melting of snow/ice	Krinner et al., 2006, Painter et al. 2007, 2012
Modification of regional precipitation	Miller et al., 2004, 2014; Yoshioka et al., 2007
Modification of atmospheric sulfur cycle and mitigation of acidic aerosol deposition	Dentener et al. 2006; Vet et al. 2014
Modification of tropospheric ozone through nitrogen uptake	Bian et al. 2003; Dentener; Crutzen 1993; Dentener et al. 1996
Modification of carbon cycle through supply of iron to aquatic ecosystems	Jickells et al., 2005, Krishnamurthy et al., 2009, (Mahowald et al., 2010), Okin et al. 2011
Modification of carbon cycle through supply of phosphorous to terrestrial ecosystems	Swap et al., 1992, Okin et al., 2004, Yu et al., 2015
Impacts on air quality, visibility, and respiratory health	Gills, 1996; Prospero, 1999; Morman 2013; Buck et al., 2013; Metcalf et al, 2015; Mahowald et al. 2007; Huszar and Piper, 1989

Table 2. Flow of key requirements from science target to objective to measurement approach.

<table>
<tr><th rowspan="2">Science Target</th><th rowspan="2">Science Objectives</th><th colspan="2">Scientific Measurement Requirements</th><th colspan="2">Instrument Performance</th><th rowspan="2">Mission Requirements</th></tr>
<tr><th>Physical Parameters</th><th>Observables</th><th>Parameter</th><th>Reqts</th></tr>
<tr><td rowspan="3">Advance NASA's Climate, Atmospheric Composition and Earth Surface Research Goals:
• Characterize the Emissions of Radiatively-Active Mineral Dust from the Earth's Surface
• Describe and Predict the Role of Mineral Dust in Radiative Forcing
• Refine/Augment Earth System Modeling Capabilities
• Earth Surface and Atmosphere Interactions
http://science.nasa.gov/earth-science/focus-areas/
• Reduce mineral dust RF uncertainty identified in the IPCC AR5</td><td>(QESO1) Acquire a comprehensive inventory of key surface minerals available for dust emission in arid regions, based on ≥28 X 10^6 km^2 of the surface, demonstrate improved model skill, and update climate RF predictions in dust impacted regions of the Earth.</td><td rowspan="3">Occurrence and fractional abundance (0-1.0 with uncertainty) of dust source minerals expressed at the surface of arid dust source regions and adjacent land at risk for desertification:
• Montmorillonite
• Kaolinite
• Gypsum
• Goethite
• Calcite
• Dolomite
• Hematite
• Illite
• Chlorite
• Vermiculite
Confounding factors:
• Fractional surface cover for green and non-photosynthetic vegetation
• Identification and flagging of other materials (water, snow, human infrastructure)</td><td>Top of Atmosphere Radiance Spectra
Spectral Characteristics
• Mineral Composition with uncertainty:
– Iron: 450–1250 nm
– Sulfates, Clays & Carbonates: 1450–2450 nm
• Atmospheric correction:
– Aerosols: 410–780nm
– Water vapor: 880–1250 nm
– Cirrus clouds: 1360–1400 & 1845–1905 nm
• Surface vegetation cover
– Pigments/red edge: 450–800 nm
– Non-photosynthetic components: 2000–2350 nm</td><td>Spectral Requirements:
Minimum Wavelength (nm)
Maximum Wavelength (nm)
Sampling (nm)
FWHM (nm)
Spectral calibration uncertainty (%)</td><td>
≤ 410
≥ 2,450
≤ 15
≤ 20
≤ 5</td><td rowspan="3">Coverage:
Single cloud-free measurement for ≥80% of arid dust source and adjacent lands when local solar elevation ≥ 45°
Orbit Altitude:
350 - 750 km
Mission Lifetime:
≥At least 1 year</td></tr>
<tr><td rowspan="2">(QESO2) Measure surface mineral composition available for new dust sources in agricultural and sparsely vegetated lands that border source regions (≥4 X 10^6 km^2), and predict evolution of dust sources and related RF under future climate scenarios.</td><td>Spatial Characteristics
• Spatial resolution sufficient to resolve hectare-scale features (100x100 m)
– Mineralogy of fallow fields and small exposed areas
– Continuity with Landsat, Hyperion, and ASTER data records
– Robust aggregation to L3 and Earth System model grids
• Geolocation knowledge sufficient to composite, aggregate and tie to digital elevation data use in dust models.
• Swath sufficient to measure required areas in a one year period</td><td>Spatial Requirements:
Sampling @ nadir (m)
FWHM @ nadir (m)
Knowledge (m) post processing
Swath (samples)
Field of Regard (°)</td><td>
≤ 100
≤ 125
≤ 100
≥ 1000
≥ 30</td></tr>
<tr><td>Radiometric Characteristics
• Avoid saturation over highly reflective surfaces (≥ 80%)
• Accurate radiometry for atmospheric correction (≤10% uncertainty)
• 1% precision in depth of absorption features in accessible mineral absorption spectral regions</td><td>Radiometric Requirements:
Range (% of max Lambertian)
Radiometric uncertainty (%)
Precision (SNR vs band depth)</td><td>
0 to ≥ 80%
≤ 10%
Figure 5.</td></tr>
</table>

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