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Title:
Local to Global Remote Sensing of Surface and Atmospheric Chemistry

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A more complete understanding of our environment on planet Earth requires understanding of the chemistry of the Earth system, including solid surface, liquid, the cryosphere and the atmosphere. Remote chemical mapping of the surface and atmosphere can only be done with imaging spectrometers.

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?

With the large human population on the Earth, we face new challenges to the environment at all scales from local to global, surface to atmosphere. The environmental impacts result from many sources, including industrial applications, expanding populations, to war. Impacts can be local, including small scale environmental disasters (e.g. the World Trade Center disaster), regional (the 2010 Gulf of Mexico Deepwater Horizon oil spill, deforestation in the Amazon and other regions around the world, including the current wars in the middle east, all of which can have global impacts on the Earth system. With the warming planet, the chemical changes of the Earth's system, from changing surfaces (including changing albedo from deforestation, farming, pollution, etc.) to changing atmospheric chemistry (pollution, CO_2, water vapor, other trace gases) affect the radiative heat balance of the system.

The only way to measure chemistry on local to global scales is by spectroscopic remote sensing. To date, global remote sensing has been limited to broad-band and multispectral systems. Such systems can show something is changing, but why? Only by understanding the chemistry of the system can we really understand the why. The real problems in identifying chemistry with remote sensing is that there is no “one band, one chemical/property.” Every material absorbs and scatters at multiple wavelengths, and only spectroscopy with sufficient spectral resolution and spectral range can untangle the overlapping signatures from multiple materials (e.g. Clark 1999, Clark *et al*., 2003, Swayze *et al.*, 2003). The albedo of the Earth's surface changes with sun altitude and atmospheric conditions, so only with full spectral range measurements can we understand the complete radiative balance of the Earth as a system and its changing nature, from diurnal to seasonal to decadal and beyond.

Planetary scientists are sending imaging spectrometers on virtually every mission, with amazing discoveries made all over the Solar System. For example, the detection of widespread water on the surface of the Moon was only possible with an imaging spectrometer. The detection went against prevailing theories that the Moon was dry. The discoveries made throughout the Solar System with spectroscopy have been filled with surprises and the corresponding new chemical insights fills many books. Our understanding of the radiative heat balance in the atmosphere is based on the spectroscopic absorptions and scattering in the atmosphere, yet we have no such instrumentation in Earth orbit to measure the chemistry of the Earth's surface on regional to global scales. The use of multispectral sensing is simply inadequate to understand the myriad of environmental problems now facing the Earth system. Multispectral sensing has too many false positives and negatives due to inadequate sensing of the complex absorptions and scattering in the spectral response of the Earth's many surface materials (e.g. Clark *et al.*, 2003).

For example, consider the 2010 Deepwater Horizon oil spill. The spill was regional, making it difficult to cover by aircraft. A satellite with a wide swath was needed. Further, a system with the spectral resolution to resolve the absorptions in the oil and distinguishing them from those in liquid water and water vapor was critical to assess the amount of oil on the ocean's surface (Clark *et al*., 2010). No such satellite existed and AVIRIS was flown periodically for over 4 months to get a statistical sampling. A wide swath satellite imaging spectrometer with repeat coverage of a few days was needed. And this is just one of multiple environmental disasters around the world each year.

Understanding climate change requires a better understanding of the spectral response of the Earth's changing surface, including sources of dust, air pollution, natural and man-made sources of carbon dioxide, methane, and other greenhouse gases in the atmosphere. The spectral albedo of the polar regions is critical to understanding the radiative heat balance. Changes in snow and ice grain size can have a large change in IR albedo that is not obvious at visible wavelengths and grain size effects can have a larger effect than small amounts of carbon soot in the snow pack on the radiative heat balance (Tedesco et al., 2015). The full solar reflected light range (0.3 to 3 microns) is needed with spectral resolution to resolve ice features sufficient to characterize grain size and carbon contamination is needed to fully understand the the changing polar regions.

The list of Earth system challenges goes on and are too numerous to list. It is clear that the myriad of problems on such large scales can only be characterized well with imaging spectrometers with sufficient spectral range, surface spatial resolution, and repeat coverage.

Why are these challenge/questions timely to address now especially with respect to readiness?

While we needed high spectral and spatial resolution imaging spectrometers in orbit decades ago, the large data volume, computer power, storage to manage the data and the immaturity of analysis algorithms made such satellite instruments difficult on all levels, from instrumentation, detectors, data flow to the ground, and generation of useful data products. But with the advancement on all these fronts, such imaging systems are now practical, though still a challenge that will push limits. Foremost in technology now is the advancement in sensors and computer technology. The advancement in computer technology has also enabled maturity of imaging spectroscopy analysis algorithms (e.g. Clark et al, 2003, 2010, 2014; Schaepman et al., 2009 and references therein). It is now feasible to analyze imaging spectrometer data in near real time, producing maps of thousands of compounds. Such a data set would show new insights into the changing chemistry of the Earth's surface and atmosphere as a function of time on local to global scales.

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

Only space satellite based systems can provide global coverage on short time scales (days to weeks) and with wide swath widths (hundreds of km) for rapid assessments of large regional events.

In order to balance data volume with technology to acquire, transmit and process the massive data volumes from imaging spectrometers and with enough spectral and spatial resolution to untangle complex chemistry in the Earth system, the following strategy makes it feasible to make major advances in Earth system science. A four component strategy:

1) High spatial resolution multispectral imager covering the reflected solar spectral range (0.3 to 3 microns) with at least 15 meters/pixel in several bands (not less than 5 bands) plus several bands in the thermal range (8 to 16 microns) with at least 60-meters/pixel spatial resolution. Global coverage at least every week

2) Moderate spatial resolution, wide swath imaging spectrometer (0.3 to 3 microns), at least 5 nm sampling with 5 to 7 nm bandpass, 60 meters/pixel or better. Global coverage every week.

3) High spatial resolution imaging spectrometer (0.3 to 3 microns) at least 5 nm sampling with 5 to 7 nm bandpass, 20 meters/pixel. Swath width of tens of kilometers. Steerable to point at local areas and make emisssion-phase function measurements.

4) High spectral resolution profiling (or spatial jail bar) spectrometer. Footprint matches #2, spectral range 0.3 to 20 microns, spectral resolving power > 3000 in the reflected solar range, and at least 4 wavenumber in the thermal. Minimum one along track profile centered on #1 and #2, ideally multiple profiles across track (jail bars).

The high resolution profiling spectrometer enables details of atmospheric and surface chemistry to be determined on a fine scale, and enables extension of the moderate resolution imaging spectrometer to resolve issues with unresolved spectral components, thus extending chemical mapping with higher precision. The high resolution multispectral images extends moderate resolution imaging spectrometer compositional maps to higher spatial resolutions.

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