Artemis Terrestrial Ecosystem Observatory (ATEO)

K. F. Huemmrich and P. E. Campbell
Joint Center for Earth Systems Technology, University of Maryland Baltimore County, Code 618, NASA Goddard Space flight Center, Greenbelt, MD 20771, huemmric@umbc.edu

Objectives: As humans advance into the solar system, it is critical for us not to forget to look back at our home, the Earth. The capture of an image of the Earthrise over the lunar surface was one of the most important achievements of Apollo-8. Artemis has the potential to build upon that legacy.

We propose to advance global understanding of the dynamics in terrestrial ecosystem function, photosynthesis and environmental stress responses using vegetation spectral reflectance and fluorescence observations collected from a lunar observatory. The Artemis Terrestrial Ecosystem Observatory (ATEO) would use optical signals to describe terrestrial ecosystem photosynthesis, stress responses, and key ecosystem functional and biophysical characteristics at diurnal/seasonal time scales for most of the Earth's land areas at a spatial scale appropriate for existing global ecosystem models

The Earth view from the moon makes it possible for a single observatory to observe both diurnal and seasonal changes for most vegetated terrestrial environments. Thus, ATEO would provide global observations collected throughout the year to describe the two key temporal variables of seasonal change and diurnal variability. Observations would be at spatial scales relevant to global ecosystem models (10-15 km).

Approach: To accurately quantify plant photosynthesis and stress responses, ATEO would provide a full description of the energy pathways of sunlight absorbed by chlorophyll (Chl) in ecosystems. The absorbed sunlight by Chl can be determined from reflectance wavelengths across the visible through shortwave infrared spectra, as the fraction of photosynthetically active ration absorbed by chlorophyll (fAPARchl). The energized Chl molecules release energy as they return to the ground state, and this energy is either used for photochemistry (leading to carbon fixation); or is actively discarded for photoprotection as heat in the form of non-photochemical quenching (NPQ) or as chlorophyll fluorescence emissions.

Chlorophyll absorption, fluorescence, and pigment change associated with NPQ can be characterized through optical signals. Chlorophyll fluorescence, in the form of Solar Induced Fluorescence (SIF), can be directly measured in narrow Fraunhofer lines. The SIF signal is small, representing only a few percent of the reflected radiance. SIF spectra from chlorophyll has two peaks: red and far-red spectral bands that are associated with Photosystem II and PS I, respectively. SIF has successfully been measured from satellite by looking in Fraunhoufer lines using spectrometers with narrow spectral bands (<0.3 nm).

The energy dissipated by NPQ can be inferred from changes in spectral reflectance. For example, the Photochemical Reflectance Index (PRI) which uses narrow spectral bands can detect changes in xanthophyll cycle pigments associated with NPQ, however presently there is little data on global spatial and temporal variability in PRI. Further, spectral reflectance can describe leaf pigment concentrations (chlorophyll, carotenoids, anthocyanins) along with other foliar physical and chemical traits useful for understanding ecosystem processes and model parameterization.

Photosynthetic dynamics range from short-term (seconds to hours) up through seasonal time periods. Measurements of Chl and other pigments from spectral reflectance can provide information on the photoprotective processes that plants use to mange longer-term (days to weeks) stress conditions while estimations of vegetation nutrients (e.g. nitrogen) and water content describe constraints on canopy/ecosystem photosynthesis. The optical signals provide a description of photosynthesis that is independent of most ecosystem models and their inputs (e.g. meteorological data), thus this type of modeling based on optical signals will provide an independent source of data for the development and testing of many other types of ecosystem models.

Why view the Earth from the moon? From the vantage point of the moon, most of the Earth's terrestrial vegetated regions may be viewed within a single day. Observations can be made of locations on the Earth at different times of the day and at multiple times of the year. Through the lunar month there are views of the Earth at different phases and the Earth's rotation provides views of all longitudes under consistent solar illumination angles. When observing the full disk of the Earth – the East-West direction also represents time differences on the surface, thus, 5-6 hours of change can be captured in a single Earth view.

Most previous satellite missions (e.g. MODIS, Landsat) studying ecosystem change focused on seasonal and longer-term responses related to changing green LAI and plant types. ATEO will advance the science describing both diurnal and seasonal changes in ecosystems focusing on biochemical changes.

Low Earth orbiting (LEO) satellites can provide global observations but, are limited in viewing diurnal change, particularly since most Earth-observing LEO satellites are in sun synchronous orbits thus having all overpasses at the same time. Geosynchronous (GEO) satellites can observe diurnal/seasonal change, but only for a limited spatial region. Only constellations of LEO or GEO satellites could provide the spatial/temporal coverage of ATEO.

Instruments: We propose two instruments, an Earth Imaging Spectrometer, an imaging spectrometer with 5-10 nm spectral resolution covering from 400-2400 nm to measure foliar pigments, nutrients, water content, and structural materials, and a Fluorescence Earth Imager, a spectrometer with high spectral resolution of 0.1-0.2 nm over 650-800 nm to measure red and far-red chlorophyll fluorescence necessary for describing activity in both Photosystems II and I. These instruments would be deployed on the lunar surface with a view of the Earth. The stability of a lunar observatory will allow long observation times that will improve instrument signal to noise even for a moderately-sized telescope.

Operations: From the vantage point of the moon, each month the instruments would be able to collect multiple days of Earth views under a range of solar phase angles. In a two-week period, Earth views would go from surface dawn, through midday, into the afternoon, and finally sunset under consistent view angles. This differs from missions in geosynchronous orbit, by enabling observation of the entire Earth with a single set of instruments to produce a new consistent diurnal-seasonal dataset. Further, by being in an orbit near the ecliptic, a lunar Earth observatory will view farther poleward during the high latitude summers when ecological activity in those regions are at their highest.

Meeting NASA Science Objectives: The 2018 NAS Earth Sciences Decadal Survey "Thriving on Our Changing Planet A Decadal Strategy for Earth Observation from Space" identified as Most Important science questions for Ecosystem Change (in *italics*):

(E-1) What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?

ATEO addresses functional changes at diurnal/seasonal time scales and global spatial scales.

(E-2) What are the fluxes (of carbon, water, nutrients, and energy) between ecosystems and the atmosphere, the ocean and the solid Earth, and how and why are they changing?

(E-3) What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing?

ATEO can characterize the dynamics of terrestrial ecosystem carbon fluxes relating them to plant physiology and responses to environmental and climatic conditions.

Secondary Activities: Along with the primary mission there are a number of secondary activities for the ATEO:

1) Support exobiology studies by providing full Earth reflectance spectra collected throughout the seasons at a range of phase angles. These spectra will provide a baseline of Earth's spectral characteristics to compare with observations from future exoplanet observatories in the search for Earth-like planets.

2) ATEO observations of total solar eclipses on the Earth provide natural experiments in the Kautsky Effect. The Kautsky Effect occurs following dramatic change in illumination, when there is a rapid rise in SIF emission, followed by a slow decline in SIF to a steady state under a stable illumination. Such observations from various ecosystems would provide the first large-area canopy-level evaluation of this effect leading to improved understanding of photosynthetic processes at this global modeling scale.

3) While ATEO would mostly be autonomous, there are benefits for it to be deployed with a human-tended station. Sensors on satellites often have solar diffusers, calibration standard panels, and/or calibration lamps, to characterize changes in instrument response over time. Unfortunately, on unmanned satellites these calibration standards can change over time with no way to describe that change, creating uncertainties in instrument calibration. Visiting crew could periodically swap out instrument calibration standards (e.g. solar diffusers), returning the old one to Earth for evaluation of change over time and replacing them with a new well-characterized standard, thus providing a significant improvement in data quality, and aid in the development of accurate measurement time series.

References and Review of Relevant Work

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