Thermal Infrared Data of the Earth and Lunar Surface (from the Lunar Surface).

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Introduction: The overarching goal of NASA Earth Science research is to make global observations to map the connections between Earth's vital processes and the effects of ongoing natural and human-caused change. To advance this goal, spaceborne data are critical to model and monitor both short and longer-term processes, thus allowing a deeper understanding of those changes. Much of the data needed for this research are collected by an array of low Earth orbiting (LEO) and geostationary (GEO) satellite-based instruments. However, these platforms do not allow whole-Earth views, including the polar regions, at the rapid time-scales required for many of these processes. Nor is there an ability to track changes as the Earth rotates through the view of the instrument, something that is possible for extended periods from the lunar surface.

Data Possibilities: An "Earth Observatory" at the lunar south pole, particularly if placed at a higher topographic location such as the region between Malapert and Nobile craters, would offer a unique, stable, and serviceable platform. The rotation of Earth as seen from this position provides unprecedented temporal views of transient phenomena, and data from these instruments could address a range of Earth Science objectives over time. The observational geometry enables new solid earth, ecosystem and climate monitoring possibilities, all factors mentioned in the 2018 Decadal Survey for Earth Science [1]. For example, high temporal frequency data coupled with the ability to observe a given location for up to 12 hours (including the polar regions due to the Earth's orbital precession) enables detection and analysis of processes such as ice shelf disintegration, sea ice change, and snow cover cycles at scales not possible now with GEO-based instruments. It would also provide data for time-dependent atmospheric composition and natural hazards (i.e., global mapping of emissions, long-range transport of volcanic plumes, greenhouse gases sources and sinks). Finally, limb views of the Earth provide numerous occultation opportunities for observing the vertical structure of the Earth's atmosphere.

Instruments at this location could acquire global, continuous, unique observations at both full-spectrum, low-spatial resolution as well as multi-spectral, high-spatial resolution. Further, they could provide a synoptic-view instrument synergy among multiple LEO and GEO satellites for cooperative operations, enhanced calibration, and science.

Constraints: The Moon is ~ 9.5 times further from Earth than GEO satellites, which makes acquiring data with useful spatial scales required for smaller-scale processes more difficult. Therefore, larger telescopes would likely be required. Additionally, depending on the final location of any lunar south pole based instrument, the Earth would only be visible for several weeks at a time, limiting data records. However, during those times, the instruments could be trained on the lunar surface in longer duration survey modes, for example. These data would become useful for planetary surface science, thermophysics, and monitoring of human habitation and operations, for example.

Concepts: Thermal infrared (TIR) data provide fundamental information on common terrestrial rocks and minerals, atmospheric chemistry, as well as surface temperature. These data have been acquired from numerous instruments in Earth, Mars, and lunar orbits in the past. For example, thermally-elevated features on Earth (e.g., volcanic, fire, and anthropogenic activity) are currently monitored at medium spatial resolution with LEO-based TIR instruments such as MODIS and VIIRS and at higher resolutions from ASTER, TIRS and ECOSTRESS. GEO-based TIR sensors do provide much better temporal scales of larger-scale dynamic processes (Fig. 1), but with the limitation of only one Earth-view and data that are increasingly distorted at higher latitudes. Furthermore, these sensors are not able to capture data at the time scales required for scientific and hazard analysis in near-real time; nor can they track a specific event as the Earth rotates.

We suggest that a lunar surface-based pair of high-heritage TIR instruments capturing spectral and image-based data of the Earth could achieve the needed temporal, spatial, and spectral resolutions required. For example, TIR instruments in Earth and Mars orbits have shown the scientific importance of these data (Fig. 1) and an observation of the Earth from a greater distance (Fig. 2) by the OTES instrument on the OSIRIS-REx Mission confirm that these measurements are possible and indeed quite useful [2]. Arizona State University has developed two distinct classes of infrared instruments that could meet this need. These are currently operational (e.g., Mars Odyssey THEMIS IR imager; OSIRIS-REx OTES spectrometer); recently-launched (e.g., UAE Hope EMIRS spectrometer), or are in development (e.g., Europa Clipper E-THEMIS IR imager).

As possible lunar examples, the E-THEMIS instrument utilizes a 1200 x 1280 pixel, uncooled microbolometer array that has completed flight environmental testing and is qualified for the extreme Europa environment. This imager is 23 x 31 x 30 cm in size, weighs 12 kg (without Europa shielding mass), and uses 38 W during imaging. The multi-spectral three-mirror imager has a small (8 cm) effective aperture telescope constrained to meet the Clipper mass limitation, providing 0.11 mrad individual field of view resolution. This existing instrument design would produce 40 km/pixel TIR data of the Earth from the Moon. Such an imager would observe the full Earth disk in a single image. A modified telescope design could provide much higher resolution imaging allowing a particular target location to be tracked throughout the 12-hour period that it would be in view [3]. In contrast to the TIR imager, the OTES IR spectrometer collects hyperspectral TIR data from 6 to 100 µm at 8.6 cm^{-1} spectral sampling, and has an 8.3 mrad individual field of view [4]. It has a 15-cm aperture, weighs 6.3 kg, is 37.5 x 28.9 x 52.2 cm in size, and uses 10.8 W during operation. An identical instrument is also being built at ASU for the NASA Discovery Lucy mission, and a similar spectrometer is aboard the UAE Hope mission, now in transit to Mars.

Instruments nearly identical to (or slightly modified from) these, deployed as part of an initial suite either on the lunar surface or the Deep Space Gateway could also upgradeable over time. Instrument deployment would be easily phased, upgrading over time from their current flight-heritage designs to a higher spectral and spatial instruments. This would require astronaut or robotic involvement to upgrade focal plane arrays, incorporate new technologies, operate in research mode, and provide real-time link between GEO and LEO observations. Full Earth views are critical for such a concept to be fully realized, but the telescopes could be enlarged to 30-50 cm and achieve spatial resolution similar to that of GEO data. Furthermore, if deployed at the south pole, these instruments could also be dedicated to lunar surface science and operations for approximately half the time that the Earth is not being observed.

References: [1] National Academies of Sciences, Engineering, and Medicine (2018) *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Washington, DC: The National Academies Press. [2] Christensen P. R. (2016) Looking Forward – A Next Generation of Thermal Infrared Planetary Instruments, *AGU Fall Mtg., P33H-01*. [3] Ramsey, M. S. (2007) *Earth Science Report, NASA Advisory Council Workshop on "Science Associated with the Lunar Exploration Architecture"*. [4] Christensen, P. R., et al. (2018), The OSIRIS-REx Thermal Emission Spectrometer (OTES) Instrument, *Space Sci. Rev., 214:87*.

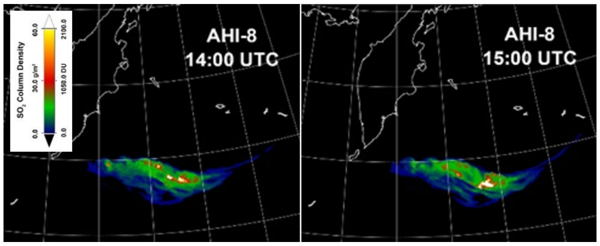

Figure 1. Example of modeling SO_2 in the volcanic plume from the Raikoke eruption on 22 June 2019 (courtesy of V. Realmuto, JPL). These data were acquired from the GEO-based AHI-8 TIR instrument. Similar monitoring of dynamic processes is possible from the lunar surface at even higher temporal scales.

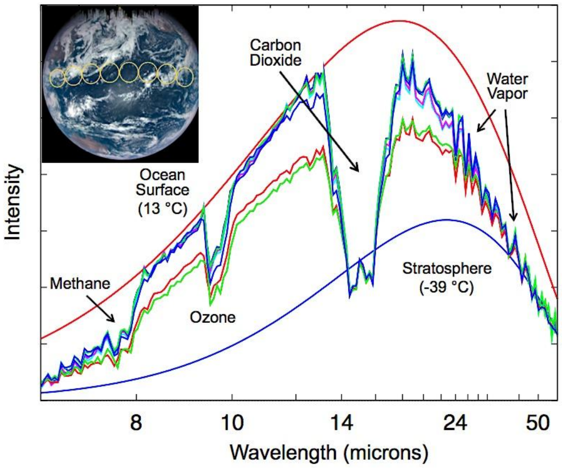

Figure 2. Thermal infrared emissivity data acquired on 22 September 2018 by the OTES instrument on the OSIRIS-REx mission. The data were collected during the closest approach of the spacecraft to Earth as it transited to the asteroid Bennu. The yellow circles, each about 1,000 km in diameter, indicate the instrument spot size at that Earth-spacecraft distance. Similar spatial resolution (or better) spectral data could be acquired from the lunar surface depending on the final instrument configuration.