CHARACTERIZATION OF LUNAR SURFACE THERMAL ENVIRONMENT AND PHYSICAL PROPERTIES USING ADVANCED THERMOPILE ARRAYS. B. T. Greenhagen[1], J. T. S. Cahill[1], M. Kenyon[2], G. Mariani[2], P. O. Hayne[3], P. G. Lucey[4], J. P. Williams[5], and D. A. Paige[5], [1]Johns Hopkins Applied Physics Laboratory, [2]Jet Propulsion Laboratory, Caltech, [3]University of Colorado Boulder, [4]University of Hawaii at Manoa, [5]University of California, Los Angeles (Email: benjamin.greenhagen@jhuapl.edu).

Introduction: The lunar thermal environment is extreme with equatorial regions experiencing diurnal temperatures of 100 to 400K, while permanently shadowed regions near the poles are limited to only 30-60K each day. Characterization of the surface requires high quality thermal imaging with an ability to obtain highly accurate temperature measurements across the full range of thermal environments present on the Moon. To meet these requirements, our investigation will utilize instruments with all reflective optics with advanced thermal infrared detectors. Specifically, we will utilize the same thermopile technology successfully employed at the Moon by the Diviner Lunar Radiometer (Diviner) on the Lunar Reconnaissance Orbiter (LRO) and at Mars by the Mars Climate Sounder (MCS) on the Mars Reconnaissance Orbiter (MRO).

Objectives: Deployment and operation by crew enables the rapid acquisition of thermal images and panoramas, which can be used to characterize the surface and assess traverses in terms of scientific interest and potential hazards. Potential investigations would broadly fit in the following four areas, with appropriate modifications for specific lander locations:

1) Characterize the diurnal (and seasonal for polar) thermal environment of the landing site.
2) Map and characterize any nearby cold traps (at scales down to cms) where water-ice may be thermally stable on the lunar surface or in the subsurface.
3) Characterize the local thermophysical properties, including the distribution and abundance of rocks.
4) Characterize local compositional properties and abundance of silicates, oxides, and volatiles.

Our approach is based on the fact that the thermal infrared provides both unique and complementary information on environment, physical properties, and composition that are critical for addressing priority lunar science questions identified in the Scientific Context for the Exploration of the Moon (SCEM) and other community reports. Therefore, it is critical that a highly capable thermal infrared instrument be available for future lunar surface exploration.

Thermal Environment. At the most basic level, and like all thermal infrared radiometers, our instrument is a thermometer. Although the surface expression of temperature is a balance between endogenic and exogenic sources, we know from existing lunar measurements that the actual thermal behavior is quite complex, including significant effects from topography, thermophysical properties, and albedo at a wide range of spatial scales [e.g. 1-6]. To fully characterize the diurnal thermal environment, the minimum detectable temperature of our instrument must be lower than the lowest temperature at the landing site. Thermopiles offer the only demonstrated means of measuring lunar PSR temperatures with a non-cryogenic detector, which significantly lessens power consumption requirements.

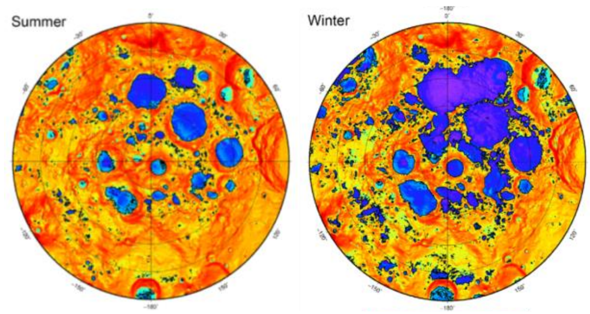

Figure 1: *Seasons vastly increase the area available for cold trapping near the lunar poles. Diviner maximum temperatures of the south pole 85°-90° S split into summer (left) and winter (right) seasons. The contours marks 110 K [6].*

Cold Traps: The lunar polar regions contain particularly interesting thermal environments due to their importance for cold-trapping volatiles. The permanently shadowed regions (PSRs) and seasonally temporarily shadowed regions (TSRs) may be key reservoirs for water-ice (Figure 1). Next-generation thermopile detectors are more sensitive than those used in Diviner, which has already provided unprecedented thermal maps of the lunar polar regions at scales of hundreds of meters [1,6]. Therefore, our instrument would be capable of accurately measuring temperatures below 50 K at cm-scales in the lander vicinity. Understanding the difference between accessible, sub-meter-scale permanently shadowed regions and diurnally shadowed regions is critical to understanding volatile stability, sources, and potential resources, and is only readily identified by their temperature.

Thermophysical Properties. Measurement of variations in temperature with time, principally over the lunar diurnal cycle, is key to understanding the thermophysical properties of the surface. Invariably a scene is composed of a surface exhibiting many temperatures both due to variation in the local incidence angle of the Sun, and by differences in thermophysical properties and albedo. Because of the temperature variations, the spectrum of a pixel that includes these many temperatures will deviate from the spectrum of a pure blackbody. Therefore, multispectral measurements can be used to detect temperature units at the subpixel level. For example, in the case of Moon the relative abundance of rocks and soil [2], regolith thermal inertia [5], and surface roughness [4] has been determined from multispectral measurements used to characterize the deviation from pure blackbody behavior.

Composition: Most geologic and cryogenic materials have strong absorption and transmission features in the mid- and/or far-infrared that can be used to determine the bulk composition of the surfaces where they are found. Diviner used three narrow mid-infrared passbands near 8 microns to characterize the bulk silicate mineralogy found on the lunar surface, including a high concentration of silica and iron found in localized volcanic features [e.g. 7-9]. Compositional constraints from thermal-infrared techniques would be much stronger with additional spectral information from the lunar surface. To measure compositional properties requires multiple passband channels at specific wavelengths where materials with lunar compositions can be discriminated.

Instrumentation: Given the focus on polar exploration and the excellent performance of thermopiles for this environment, our instrument is based on this technology. Continued development since MCS and Diviner has led to higher density arrays that will fly in 2020 on the Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE) mission and that were also previously advanced to TRL 6 for the harsh thermal and radiation environment found at Europa via ICEE funding. The specific instrument implementation is flexible depending on the opportunity and programmatic risk posture (Table 1).

Near Build-to-Print Copy of Diviner. The simplest implementation would be to re-fly Diviner with small modifications in the filter passbands to reflect the science objectives of the landing site. Diviner's dual actuators give it the ability to scan and image any proximal scene, which it demonstrated on orbit by taking a "portrait" of LRO. However, this is also the highest mass and cost option and would offer more limited spatial resolution.

Advanced Articulating Pushbroom Imager. Investments in thermopile technology have resulted in larger format arrays at varying levels of development from TRL4 (128x64) through TRL8 (64x8). These advanced arrays enable higher spatial resolution for similar scale optics. The new arrays are also compatible with single telescope systems and flight proven, lower-mass articulation systems, which provides a significant reduction in mass and cost while providing superior performance.

Wide Field of View Full-Frame Imager. The technologies required to produce a full 2D thermopile array without the gaps between elements used in the pushbroom designs has been demonstrated to TRL4. An instrument built around this technology could be paired with a filter wheel and wide field of view optics to provide a unique combination of capabilities and enable the rapid acquisition and interpretation of thermal data.

Accommodation: Thermopile instruments (Table 2) can be designed to arrange of accommodation requirements from fixed locations on landers or rovers for the articulating versions to suit-mounted or handheld for the full-frame imager.

Table 1: Instrument Architectures

	Diviner	Advanced Articulating Pushbroom Imager	Wide FOV Full-Frame Imager
Mass	10 kg	<5 kg	<3 kg
Power	12 W	<10 W	<7.5 W
Detector	Dual Telescope 21x6 & 21x3	64x8 to 128x64	2D 128x64 (no gaps)
IFOV	3.4 x 6.7 mrad	<1 mrad	5.4 mrad
Spectral Range	0.3 to 400 microns	0.3 to 200 microns	0.3 to 200 microns
Spectral Channels	9	8 to 16+	6 to 10

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