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Transient thermal envelope for rovers and sample collecting devices on the Moon

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Abstract

The requirements for the design of rovers and sample collecting devices for the Moon are driven by the harsh and diverse thermal lunar environment. Local lunar surface temperatures are governed by boulders and craters. The present work quantifies the changes in solar and infrared heat fluxes $\dot{q}_{Sol}$ and $\dot{q}_{IR}$ impinging on a rover or a sample collecting device, on the surface of the Moon, by combining lunar surface models, spacecraft and manipulator models, and transient thermal calculations.

The interaction between a rover, boulders, and craters was simulated for three solar elevation angles ($\theta = 2°$, $10°$, and $90°$), resembling lunar surface temperatures of $T_{reg} = 170$, 248, and 392 K, respectively. Infrared and solar heat fluxes for paths in the vicinity of a single boulder, a field of five boulders, and a single crater were compared to a path on an unobstructed surface. The same heat fluxes were applied to closed and open sample collecting devices to investigate the temperature development of the transported regolith sample.

The results show how total received infrared heat on a rover may increase by up to 331%, over the course of a transit in front of sunlit boulders compared to the same transit over an unobstructed plane. Temporary this leads to a 12-fold increased infrared heat flux at closest distance to the obstacle. A transit through a small bowl shaped crater on the other hand may decrease total received solar heat by as much as 86%. Relative as well as absolute influence of surface features on received heat fluxes increases significantly towards smaller solar elevation angles. The temperature of pristine samples, transported in closed or open sample collecting devices, increase from 120 to 150 K within 1 to 1.3 h if exposed to direct solar illumination and infrared heat. Protection from solar illumination yields in 8-fold and 5-fold increased transport times for closed and open sample devices, respectively. Closed sample transporters dampen short exposure times to solar illumination but also lead to higher sample end temperatures in the same period. The degradation of absorptivity and emissivity, due to coverage with dust or scratches obtained during operation, will significantly alter the sample temperature in a negative manner.

The results indicate that transient thermal analyses, that take into account the local lunar environment, are feasible and permit more detailed thermal envelopes for future rover missions to the surface of the Moon.

Keywords: Lunar rovers; Manipulators; Volatile sample stability; Thermal analysis; Dynamic simulations

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1. Introduction

Most space-faring nations show an increasing interest in missions to the lunar surface. Beside the recently landed Chinese Chang e3 mission, there is the planned Japanese SELENE-2 (Hashimoto et al., 2011), the Russian Luna-Glob (Luna-25), Luna-Resurs (Luna 27), and the Indian Chandrayan-2 (Goswami and Annadurai, 2011). In addition to governmental programs, there is an emerging private sector of Moon missions initiated through the Google Lunar X-Prize competition in 2010. In November

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Signs and Symbols

$\dot{q}_{Sol}$ $[\mathrm{W \cdot m^{-2}}]$ solar heat flux	θ [°] solar elevation angle
$\dot{q}_{IR}$ $[\mathrm{W \cdot m^{-2}}]$ infrared heat flux	c_p $[\mathrm{J \cdot kg^{-1} \cdot K^{-1}}]$ specific heat capacity
T_{cr} [K] critical sample threshold temperature	k $[\mathrm{W \cdot m^{-1} \cdot K^{-1}}]$ thermal conductivity
T_{reg} [K] lunar surface temperature	

2014, still 18 out of initially 33 teams actively pursued the target of landing on the Moon before the end of 2015.

Spacecraft returning to the surface of the Moon encounter a demanding thermal environment. The lunar thermal environment is governed by radiative heat transfer, originating from the Sun and the lunar surface. The lunar surface temperature varies in a range from 25 to 390 K (Paige et al., 2010), depending on the solar elevation angle, exposure time, and local material properties. For thermal engineers it is demanding to maintain the operational temperature of a piece of equipment placed in this thermal environment, or to secure precious volatile elements in scientific instruments. Thermal control engineering for the Moon largely is based on simplified models of the lunar surface. These models do not take into account the relative movement between the investigated object and the surface of the Moon. Yet, lessons learned from past missions indicated an impact from local surface features such as boulders and craters on spacecraft and instruments. The Mobile Payload Element (MPE) serves as an example for a lunar exploration vehicle. It was developed as a sample fetching rover for the ESA Lunar Lander mission, which was stopped in 2012. The MPE uses a closed containment (mole) for the collection and transport of scientifically interesting lunar soil samples. As a further option, an open containment (scoop) is investigated as part of this work.

2. Background & motivation

The Moon still poses many geological, geochemical, geophysical, astronomical, as well as physiological, and life science related research questions (Jaumann et al., 2012; Crawford et al., 2012). Of special interest are volatile elements that were detected in cold traps at the lunar poles (Colaprete et al., 2010) and water, which was found in lunar regolith (Pieters et al., 2009; Greenwood et al., 2011). Investigation of those soil samples will involve rovers to enter the scientifically interesting sites and expand the operational radius of landers. The rovers will be equipped with sampling devices in order to transport the soil samples from the sample site to the lander. Such sampling devices can be scoops at the tip of manipulators (e.g. such as on the Mars Phoenix lander or Curiosity), or ground penetrating devices, so-called moles (Richter et al., 2004; Grygorczuk et al., 2009; Lange et al., 2010).

In the past, thermal problems were recorded concerning the operation of rovers and equipment during the US Surveyor, Apollo, and Soviet Luna missions. Only three of the five successful Surveyor landers (Fig. 1a) survived the first lunar night. During lunar morning and afternoon the temperatures onboard the Surveyor landers were in some places 25 K higher than initially predicted. This fact was suspected to originate from the impact of nearby boulders (JPL, 1969). During the Apollo era thermal problems were encountered for example on the Mobile Equipment Transporter (Gilmore, 2002) (Fig. 1b), the Apollo Lunar Surface Experiments Package (ALSEP) instruments (Gaier, 2005; Harris, 1998) (Fig. 1c), or the lunar roving vehicles (LRV) during Apollo 15, 16, and 17 (Gaier and Jaworske, 2007) (Fig. 2b). The Soviet Lunokhod rovers 1&2 (Fig. 2a) operated for 11 lunar days (~11 months – Lunokhod-1) and 4 lunar days, respectively (Lunokhod-2) (Ivankov, 2013a,b). Especially in case of Lunokhod-2 it was suspected that thermal problems led to a shorter lifetime (Ivankov, 2013b).

Current lunar mission design teams acknowledge the demanding thermal environment by thoroughly investigating concepts to sustain or avoid thermal extremes on the Moon. For the survival of a rover in the long phases of the cold lunar nights several methods are considered. These methods are to hibernate (Hashimoto et al., 2011), to use radioisotope thermoelectric generators (Bartlett et al., 2008), radioisotope heater units (RHUs), or to avoid prolonged shadows (Haarmann et al., 2012; Della Torre et al., 2010; Gump and Thornton, 2011). Methods to survive times of extremely high lunar surface temperatures include heat rejection via radiators or heat storage in phase change material. Transport of heat is achieved e.g. by pumped fluid loops or heat pipes.

Rover and instrument designs for the surface of atmosphere-less bodies must be based on detailed thermal analysis, performed with advanced time-marching numerical methods (Ball, 2007). Such methods are lumped thermal node networks and ray tracing algorithms, in conjunction with numerical solvers. Simulations on small exploration rovers already revealed qualitatively that there will be a contribution of boulders to the local thermal environment (Barraclough et al., 2009).

There is a lack of understanding how the local thermal environment impacts the transport of pristine lunar soil samples, which is a central objective of those upcoming missions. Hence, the present work focuses on the quantification of thermal environments for rovers, the derivation of general trends for rovers, and the quantification of the temporal development of soil sample temperatures in sampling devices.