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Lunar ground penetrating radar: Minimizing potential data artifacts caused by signal interaction with a rover body

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Abstract

Ground-penetrating radar (GPR) is the leading geophysical candidate technology for future lunar missions aimed at mapping shallow stratigraphy (<5 m). The instrument's exploration depth and resolution capabilities in lunar materials, as well as its small size and light-weight components, make it a very attractive option from both a scientific and engineering perspective. However, the interaction between a GPR signal and the rover body is poorly understood and must be investigated prior to a space mission. In doing so, engineering and survey design strategies should be developed to enhance GPR performance in the context of the scientific question being asked. This paper explores the effects of a rover (simulated with a vertical metal plate) on GPR results for a range of heights above the surface and antenna configurations at two sites: (i) a standard GPR testing site with targets of known position, size, and material properties, and; (ii) a frozen lake for surface reflectivity experiments. Our results demonstrate that the GPR antenna configuration is a key variable dictating instrument design, with the XX polarization considered optimal for minimizing data artifact generation. These findings could thus be used to help guide design requirements for an eventual flight instrument.

Keywords: Ground-penetrating radar, Lunar rover; Moon; Polarization; Surface reflectivity

1. Introduction

Characterizing the Moon's shallow subsurface will provide important clues for understanding its geological history (Jaumann et al., 2012; Neal, 2009), mapping possible subterranean refuges (Haruyama et al., 2009; Robinson et al., 2012), and identifying potential resources in support of eventual human presence (Anand et al., 2012; Sanders and Larson, 2010). However, despite the wealth of data on lunar regolith properties having been returned from Earth-based (e.g. Campbell et al., 2010; Fa and Wieczorek, 2012), orbital (e.g. Ono et al., 2009; Spudis et al., 2010) and lunar surface-based measurements (Simmons et al., 1974), our understanding of its surface-adjacent structure and composition remains largely incomplete.

As part of a future landed mission, ground penetrating radar (GPR) has been identified as a candidate technology that could complement an instrument suite designed to address these gaps (Falkner et al., 2007; Heggy et al., 2009; Russell et al., 2011). GPR is a non-invasive geophysical technique that uses pulses of electromagnetic energy to provide a variety of information about the surface composition and subsurface structure, such as measuring dielectric properties and locating discrete targets within the subsurface (Slob et al., 2010). On the Moon, for example, a rover-mounted GPR could thus be extremely useful for

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surveying buried ejecta blocks (Russell et al., 2012), mapping lava tubes (Miyamoto et al., 2005), or identifying resource drilling targets (ten Kate et al., 2012).

A major challenge of mounting a GPR aboard a mobile platform involves elucidating possible interactions between the emitted GPR signal and the rover itself (e.g. Barfoot et al., 2003). Because metallic objects are nearly perfect reflectors of GPR energy, interference from the rover body will produce data artifacts that could mask subsurface returns of scientific importance. These effects will occur to some extent even for shielded antennas and will be enhanced when the antennas are elevated above the surface. Although non-conductive composite materials could be used in the rover body to somewhat mitigate the interference with the GPR signal, they are inferior to metallic bodies for withstanding shocks and vibrations over rough terrain. It is thus infeasible to expect that a rover could be made entirely of non-metallic materials. Thus, the overarching objective of this work is to perform basic experiments to investigate how the presence of a large metallic plate (designed to simulate the back of a rover) can affect GPR data under two different survey configurations: (i) when attempting to locate subsurface targets, and; (ii) when measuring the dielectric permittivity of the surface material. These experiments are intended to provide background for more extensive research that will include numerical modeling of a GPR signal in lunar substrates and a study of the impact of an actual rover on GPR responses. The results of this preliminary study demonstrate that optimal instrument orientation is dependent on the science question being asked, and thus highlight the need to clearly establish and address scientific mission requirements prior to flight instrument design.

2. Ground-penetrating radar for lunar exploration

The acquisition and interpretation of near-surface geological information on the Moon are the primary objectives of a rover-GPR instrument package. Subsurface mapping scenarios include local stratigraphic characterizations (e.g. thickness of lunar regolith, buried boulders, bedrock fractures), as well as the detection of refugia (Hörz, 1985) or resources (Anand et al., 2012) vital for human occupation of the moon.

To map underlying stratigraphy and targets, GPR relies on differences in the dielectric permittivity between materials. Given that wave propagation velocity through a medium is a direct function of the medium's dielectric permittivity value (ε), it is possible to use the signal's return time (t) to translate the GPR cross-section's time axis into a depth (d) axis using Eq. (1), where c is the speed of light in a vacuum and ε is the dielectric permittivity. In practice, this relationship must also take into account the finite separation between the transmitting and receiving antenna.

$$d = tc/(2\sqrt{\varepsilon}) \tag{1}$$

There are multiple methods to determine the dielectric permittivity, including trenching to a target of a known depth (e.g. Hinkel et al., 2001), as well as hyperbolic fitting and common midpoint (CMP) surveying (refer to Annan, 2005). For a lunar mission, however, trenching and CMP surveys will be infeasible. Thus, the preferred operation would be measurement of the surface reflectivity and hyperbolic fitting of scattering responses. The application of hyperbolic fitting is dependent on the presence of discrete targets and provides an average velocity between the ground surface and the top of the object. Surface reflectivity testing is optimally performed at a location that is sufficiently smooth (refer to the section on Study Sites) and provides an average dielectric permittivity estimate of a layer whose thickness is a function of the velocity and centre frequency of the electromagnetic wave (refer to Galagedara et al. (2005)).

For the surface reflectivity method an amplitude calibration is performed by using a large metal plate (i.e. a perfect electromagnetic reflector) to record reference amplitude from a target with known reflectivity. Subsequently, this value (A_m) is compared with the ground surface amplitude of adjacent terrain (A_r) to compute the surface reflectivity and infer the relative near-surface dielectric permittivity (ε) along the profile (e.g. Huissman et al., 2003; Redman et al., 2002) as shown in Eq. (2).

$$\varepsilon = [(1 + A_r/A_m)/(1 - A_r/A_m)]^2 \tag{2}$$

For a space mission, the GPR would be calibrated on Earth. This calibration approach to surface reflectivity measurements is simple and easy to implement. There are other analysis methods that are more complex and have also been shown to produce accurate and reliable results (Lambot et al., 2006), but they were not addressed in this study.

Energy reflected either directly from the rover or after reflection from the surface is expected to be the most significant source of data artifacts. Horizontal banding and multiple reflections (i.e. repeated reflections from one target at successively greater depths) between the rover and subsurface targets are of particular concern. This type of noise can be misinterpreted as stratigraphy or numerous buried objects (Radzevicius et al., 2000). The reflections from above-surface objects, however, can be reduced with an optimal antenna polarization configuration (van der Kruk and Slob, 2004). More specifically, the antenna polarization is defined in terms of principal electric field direction with respect to the line direction and the relative spatial relationship of the transmitting and receiving antennas (Fig. 1). Therefore, it is extremely important to assess optimal antenna configurations that would minimize data artifact generation for a given instrument concept.

3. Instrument concept

To satisfy future mission objectives consistent with a lunar ground-penetrating radar (LGPR) prototype project