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Mars radar clutter and surface roughness characteristics from MARSIS data

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Radar sounder studies of icy, sedimentary, and volcanic settings can be affected by reflections from surface topography surrounding the sensor nadir location. These off-nadir "clutter" returns appear at similar time delays to subsurface echoes and complicate geologic interpretation. Additionally, broadening of the radar echo in delay by surface returns sets a limit on the detectability of subsurface interfaces. We use MARSIS 4 MHz data to study variations in the nadir and off-nadir clutter echoes, from about 300 km to 1000 km altitude, *R*, for a wide range of surface roughness. This analysis uses a new method of characterizing ionospheric attenuation to merge observations over a range of solar zenith angle and date. Mirror-like reflections should scale as R^{-2}, but the observed 4 MHz nadir echoes often decline by a somewhat smaller power-law factor because MARSIS on-board processing increases the number of summed pulses with altitude. Prior predictions of the contributions from clutter suggest a steeper decline with *R* than the nadir echoes, but in very rough areas the ratio of off-nadir returns to nadir echoes shows instead an increase of about $R^{1/2}$ with altitude. This is likely due in part to an increase in backscatter from the surface as the radar incidence angle at some round-trip time delay declines with increasing *R*. It is possible that nadir and clutter echo properties in other planetary sounding observations, including RIME and REASON flyby data for Europa, will vary in the same way with altitude, but there may be differences in the nature and scale of target roughness (e.g., icy versus rocky surfaces). We present global maps of the ionosphere- and altitude-corrected nadir echo strength, and of a "clutter" parameter based on the ratio of off-nadir to nadir echoes. The clutter map offers a view of surface roughness at ~75 m length scale, bridging the spatial-scale gap between SHARAD roughness estimates and MOLA-derived parameters.

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1. Introduction

The use of radar sounding for planetary subsurface studies has expanded dramatically in the past decade. The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument on the Mars Express mission (Picardi et al., 2004; Jordan et al., 2009), the Shallow Radar (SHARAD) sounder on the Mars Reconnaissance Orbiter (Seu et al., 2007) and the Lunar Radar Sounder (LRS) on the Kaguya spacecraft (Ono et al., 2008) reveal subsurface layering in icy, sedimentary, and volcanic settings. By the 2020s, the Jupiter Icy Moons Explorer (JUICE) and Europa Clipper missions will use the Radar for Icy Moon Exploration (RIME) (Bruzzone et al., 2011; 2015) and the Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON) (Aglyamov et al., 2017; Blankenship et al., 2009) instruments to make the first subsurface investigations of Europa and Ganymede.

In radar sounding, a radio signal is transmitted toward the surface, and the sensor receives the reflected echoes (including those from the subsurface) as a function of time delay. The transmitted pulse is typically a swept-frequency signal that yields a time resolution, τ, proportional to the inverse of the signal bandwidth rather than the duration of the actual pulse. The successive pulse echo records are placed in order along the spacecraft nadir ground track to form a two-dimensional radargram plot in horizontal distance and round-trip delay. Spatial resolution along the ground track is improved by synthetic aperture processing based on frequency shifts caused by the spacecraft motion, but the cross-track spatial resolution cell dimensions are controlled only by the sensor viewing geometry and the time-delay resolution of the pulse.

Surface and subsurface dielectric interfaces, smooth at the scale of the radar wavelength, have echoes with narrow angular scattering patterns perpendicular to the interface. The contributing region for a coherent, specular reflection is limited to approximately

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the circular first Fresnel zone, since echoes from areas at greater distance from the nadir mutually interfere. In geologic settings, the surface and subsurface interfaces are rarely perfectly smooth even at the longer radar wavelengths used in sounding. This roughness diminishes the nadir coherent echo (eventually to a negligible level) and adds an increasing component with a broader angular scattering lobe that diminishes with greater round-trip time delay (e.g., Barrick and Peake, 1967). The rate of this decay is often used to infer surface roughness properties, and places a lower limit for detection of subsurface reflections at particular values of round-trip delay.

Given its influence on subsurface geology studies, it is important to characterize the nature of clutter and how it behaves as a function of radar observing geometry. In particular, we need to understand what might be expected in Europa studies that rely on flybys for sounding over a large range of sensor-surface distance. In this paper, we study nadir and off-nadir echoes in MARSIS data collected over a range of surface roughness and spacecraft altitude. We note at the outset that this study examines clutter produced by numerous terrain features within a resolution cell, not discrete clutter features like ridges or valley walls. Discrete features will exhibit a "move-out" in delay with sensor altitude (Peeples et al., 1978), and are often readily identified from topographic data. Section 2 presents the basic geometric considerations in radar sounding, and the possible dependence of nadir returns (surface and subsurface interfaces) and clutter components on altitude. Section 3 uses MARSIS data to explore the actual scattering behavior of different landforms, with application of a methodology to mitigate the effects of ionospheric attenuation. Section 4 applies the altitude and ionospheric corrections to create global maps of the nadir echo and a clutter-strength parameter indicative of surface roughness. Section 5 addresses some implications of the observations looking ahead to the jovian icy-moon sounders.

2. Geometric and surface scattering aspects of radar sounding

For simplicity, we describe radar sounder echoes as a mix of a nadir reflection and off-nadir clutter signals that arise from particular delay cells of the measurements. We further assume the monostatic case of a co-located transmitter and receiver. The signal from the transmitter experiences a geometric spreading loss as the inverse square of the range or altitude, R (Fig. 1). The spreading loss of the reflected signal depends upon the nature of the scattering. For the nadir echo from a flat, specular plate there is no increase in spreading loss, so the total round-trip loss is of order R^{-2} (Peters et al., 2005; Schroeder et al., 2016). If the clutter arises from a small number of tilted facets that are large with respect to the radar wavelength, λ, then the total loss may also be close to this −2 power-law. A field of "diffuse" scatterers or facets smaller than about the radar wavelength, however, will experience an R^{-2} spreading loss for a net behavior of order R^{-4}. This latter scenario is often termed quasi-specular scattering, since some degree of coherent reflection occurs only for favorably tilted facets that add incoherently over a resolution cell (e.g., Hagfors, 1964).

The region of a near-planar surface that strongly contributes to the coherent echo is limited to the Fresnel zone radius:

$$r_F = \sqrt{\frac{R\lambda}{2}} \tag{1}$$

so the Fresnel zone area is proportional to R. Sounder data processing often aims for an along-track Doppler-processing aperture of approximately $2r_F$. Off-nadir signals come from discrete areas of the surface defined by the sensor range, the delay resolution τ, and the along-track resolution set by synthetic aperture processing. At some chosen incidence angle with respect to a mean plane surface, ϕ, the cross-track illuminated area of a cell is independent of the range:

$$\Delta x = \frac{c\tau}{2sin\phi} \tag{2}$$

Plots of echo power versus incidence angle are often used to characterize the scattering properties of a rough surface, and Eq. 2 shows that we may compare echoes at different R, but constant ϕ, without considering the cross-track illuminated area.

This initial look suggests that nadir echoes diminish with altitude as R^{-2}, and the clutter echoes decline as some higher power up to R^{-4}. Within the MARSIS on-board processing, however, there is an additional contribution to the final observed signal strength. As the altitude rises, the synthetic-aperture processing increases the number of echo pulses, N, to keep pace with the expanding Fresnel zone. Coherent summation over these pulses, once they are shifted in phase to "focus" the returns to the nadir location at the center of the aperture, yields an increase in echo strength proportional to N. If this increase in N is approximately linear with the Fresnel zone diameter (Eq. 1), then the coherent gain increases as $R^{1/2}$ and the overall nadir returns scale as $R^{-3/2}$. A collection of diffuse off-nadir scatterers with random phase would gain only a factor of $N^{1/2}$, and thus an improvement of $R^{1/4}$ in the total round-trip losses.

MARSIS onboard Doppler filtering yields an along-track spatial footprint, Δy, close to the Fresnel zone diameter, which increases by a factor of $\sqrt{R}$ with altitude. The region contributing to the echo at a fixed delay (rather than fixed ϕ) relative to the peak surface return moves outward from the nadir, increases along the cross-track dimension as $\sqrt{R}$, and has a lower incidence angle, with increasing R. The change in incidence angle may lead to an increase in the echo, since rough surface backscatter typically increases with lower ϕ. The degree to which this occurs depends upon the angular scattering function of the surface, which can be highly variable within a few degrees of the nadir direction. Such behavior will further lower the power-law decline of the clutter.

The net change in area for an off-nadir scattering cell at some time delay relative to the nadir echo arrival (i.e., fixed probing depth in the subsurface) is thus proportional to R (Fig. 1). If the off-nadir terrain is made up of diffuse, quasi-specular facets (less than a few λ), then this increase in area cancels a factor of R^{-1} in the geometric spreading loss. The clutter echoes thus scale with a power-law dependence between R^{-3} (fully diffuse returns that benefit from the increase in area) and R^{-2} (tilted facets that extend to a significant fraction of the Fresnel zone, which exhibit minimal spreading loss). The on-board coherent summation of pulses will cancel a factor of $R^{-1/4}$ to $R^{-1/2}$, respectively, and the incidence angle change will provide a further, though uncertain, mitigation.

The behavior of nadir and clutter echoes beyond these simple predictions is not well established from actual sounder data. Given the complexities in scattering area, angular scattering function, and possible coherent scattering effects within off-nadir cells, a phenomenological first look at the echo behaviors with altitude and terrain roughness is needed. In the next section, we use MARSIS data to examine actual variations in power versus delay and incidence angle as a function of altitude.

3. MARSIS echo variations with altitude

3.1. Methodology

The MARSIS sounder on the Mars Express mission operates from an elliptical orbit that revisits sites on the surface at distances from about 250 km to 1200 km (Picardi et al., 2004). In contrast, the SHARAD sounder on the Mars Reconnaissance Orbiter ranges only over ∼250 km–∼320 km altitude (Seu et al., 2007). MARSIS data can thus be used to examine the behavior of the