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Radar scattering by boulders studied using geometric optics

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ABSTRACT

We simulate radar scattering from meter-scale boulders of ice and rock using an algorithm of geometric optics. The scattering particles are Gaussian-random-sphere particles with different levels of irregularity. We study the effect of particle size, geometry, and material on the radar albedo and circular polarization ratio at microwaves concentrating on the S-band wavelength of 12.6 cm. We show that increased absorption causes the radar albedos in both polarization states to attenuate exponentially when the contribution of the internally scattered waves decreases. Consequently, also the polarization ratio decreases. Semi-empirical models for the radar albedos are derived.

1. Introduction

Planetary radar astronomy is a powerful branch among the planetary observation methods. It is capable of deducing some of the dynamical and physical properties of a planetary target on a level that is unreachable for other techniques. The strength as an observation technique arises from the full control of the illuminating radiation: the radar transmits a signal with well-known characteristics and receives a more or less transformed echo. The comparison of the two signals provides the observer with implications on the physical and dynamical properties of the target.

In this paper, we study what physical properties of the target can be deduced from the echo in terms of intensity and polarization. The parameters that we concentrate on are the radar albedo (i.e., the radar reflectivity) and the polarization ratios, i.e., the linear or the circular polarization ratio. The linear and circular polarization ratios are theoretically related, so we concentrate here only on the more commonly used circular polarization.

In practice, the circular-polarization ratio is the ratio of the integrated echo power in time delay and Doppler frequency in the two states of the circular polarization: the same-circular (SC) polarization state relative to the transmitted wave divided by the opposite-sense circular polarization (OC). The advantage of the circular polarization over linear is the effect of the atmosphere: the charged small particles of the atmosphere have a rotating effect on the polarization of the penetrating waves and, therefore, may be a more significant source of error for the linearly polarized radiation.

For single spherical particles or with a normal incidence to a planar interface between two homogeneous media, the polarization ratios at backscattering are equal to zero. An increased polarization ratio implies multiple scattering, or as commonly interpreted in practice, wavelength-scale surface roughness (e.g., Benner et al., 2008; Harmon et al., 1989; Magri et al., 2001; Ostro et al., 2002). In essence, typical planetary radar transmitter frequencies are within the range 430–8460 MHz, which corresponds to the wavelengths of 3.5–70 cm.

The images taken by, for example, Hayabusa of asteroid (25143) Itokawa show a surface full of large boulders (Fig. 1). According to the Brazil-nut effect introduced by Möbius et al. (2001), large boulders tend to rise to the surface from below as a result of collisions. Nevertheless, there is a wide variety in the number densities of boulders on asteroid surfaces.

In order to demonstrate typical observed values of the radar albedo (in the opposite-circular polarization) and the circular-polarization ratio, Fig. 2 illustrates observational data for asteroids, for which both the circular-polarization ratio and the radar albedo have been published. The data have been obtained mainly from Neese et al. (2012) with some additions from Shepard et al. (2015).

The image shows that the highest radar albedos can be related with the metallic M and X types and the highest polarization ratios with the E and V types. For comets, the OC radar albedo is within [0, 0.1] and the circular-polarization ratio is within [0.1, 0.5]

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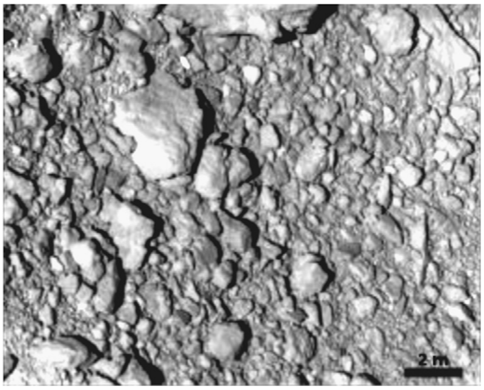

Fig. 1. The surface of asteroid Itokawa imaged by Hayabusa. Photo credits: JAXA/ISAS/Univ. Tokyo.

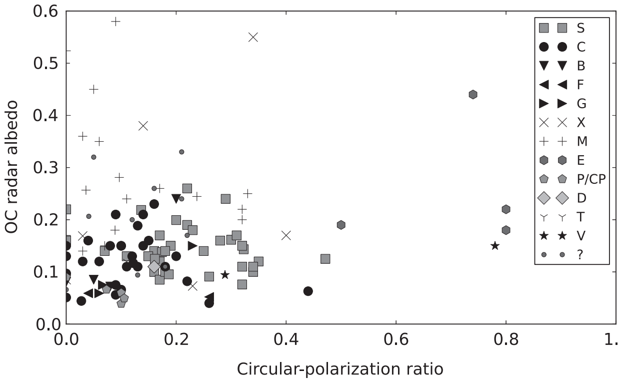

Fig. 2. The radar properties of asteroids of different taxonomic types. The data have been obtained mainly from Neese et al. (2012) with some additions from Shepard et al. (2015).

(Harmon et al., 2004). For the icy Galilean moons Europa, Ganymedes, and Callisto, the OC radar albedo is 1.0, 0.6, and 0.3, and the circular-polarization ratio is 1.5, 1.4, and 1.2, respectively (Campbell et al., 1978; Ostro et al., 1992. The distinctly high radar albedos and polarization ratios of the Galilean moons have been explained with the coherent-backscattering effect (Black et al., 2001; Akkermans et al., 1986).

It is a well-known fact that, for ensembles of non-spherical particles, the polarization ratios increase, but the effect of the geometric irregularity is not unambiguous. How the particle shape affects the circular- or linear-polarization ratio has been studied, for example, by Virkki et al. (2013), Zubko and Kokhanovsky (2012), Mishchenko and Hovenier (1995), and Mishchenko and Sassen (1998). The studies show that regular but non-spherical particles in random orientations, such as spheroids, cylinders, Chebyshev particles, and aggregates of spheres, show resonance effects in either the linear or circular polarization ratio that depend on the material and the size of the particles.

In this paper, we concentrate on the effect that large-scale, irregularly-shaped planetary surface material has on the radar scattering. We also study how the absorption of the material affects the radar scattering. It is known that the radar signal is able to penetrate into the surface up to ten times the wavelength. Thus, it is also possible that the echo receives significant contribution from structures below the surface. The penetration depth depends on the absorption of the material. However, the effect of absorption has not been systematically studied before, and is often omitted completely.

To outline the paper, Section 2 gives a brief overview of the relevant scattering theory in terms of the intensity, polarization, and the scattering matrix. In Section 3, we describe the numerical model, post-processing of the numerical data, and the geometry of the Gaussian-random-sphere particles. Here, we also present the values that we selected for the shape parameters, sizes, and materials of the particles. In Section 4, we illustrate and discuss the differences in the radar scattering of the particles due to different parameter choices. And, in Section 5, we summarize the conclusions for the presented results and discuss future work that will be required in order to explain specific radar observations of small objects of the Solar System.

2. Scattering theory

2.1. Scattering matrix

The intensity and the polarization of an electromagnetic wave can be presented using the Stokes vector $\mathbf{I} = [I, Q, U, V]^T$, where I stands for the intensity, Q and U stand for the linear polarization, and V stands for the circular polarization. The ensemble-averaged 4×4 scattering matrix $\mathbf{S}$ relates the incident and scattered Stokes vectors $\mathbf{I}_{\text{inc}}$ and $\mathbf{I}_{\text{sca}}$:

$$\mathbf{I}_{\text{sca}} = \frac{1}{k^2R^2}\mathbf{S}(\theta)\cdot\mathbf{I}_{\text{inc}}, \tag{1}$$

where θ is the scattering angle (i.e., the angle between the incident and scattered wave vectors), R is the distance of the scatterer from the observer, and k is the wave number $2\pi/\lambda$, and λ is the wavelength.

2.2. Radar properties

The total radar albedo ($\hat{\sigma}_T$), also known as the backscattering efficiency or the radar reflectivity, is the total echo power divided by the projected area of the target. Using the first element of the scattering matrix $\mathbf{S}$, the total radar albedo is

$$\hat{\sigma}_T = \frac{4S_{11}(180^\circ)}{k^2D_{\text{eff}}^2} \tag{2}$$

where D_{eff} is the effective diameter of the scatterer. The total radar albedo is directly proportional to the geometric albedo (p_r), i.e., $\hat{\sigma}_T = 4p_r$ (Ostro, 1993). For an ideally conducting metal sphere, the total radar albedo is unity.

The observation results often provide us only with the radar albedo in the opposite sense of circular polarization ($\hat{\sigma}_{\text{OC}}$, relative to the transmitted signal), which is usually the stronger of the two orthogonal states. As a function of the scattering-matrix elements, $\hat{\sigma}_{\text{OC}} = \hat{\sigma}_T\,(1 - S_{44}/S_{11})/2$. Correspondingly, $\hat{\sigma}_{\text{SC}} = \hat{\sigma}_T\,(1 + S_{44}/S_{11})/2$.

The relationship between the OC radar albedo and Fresnel reflectivity R_F is given by Ostro et al. (1985) as $\hat{\sigma}_{\text{OC}} = gR$, where the 'gain factor' g depends on the target's angular scattering law, shape, and orientation. For normal incidence, the Fresnel reflection coefficient for flux densities is

$$R_F = \left|\frac{m-1}{m+1}\right|^2, \tag{3}$$

where m is the complex refractive index.

The circular-polarization ratio, μ_C, is the ratio of the echo power in the same circular-polarization state to that in the opposite circular-polarization state. In terms of the scattering-matrix elements (see, e.g., Bohren and Huffman, 1983), for ensembles of particles in random orientation, μ_C can be defined as

$$\mu_C = \frac{S_{11}(180^\circ) + S_{44}(180^\circ)}{S_{11}(180^\circ) - S_{44}(180^\circ)}. \tag{4}$$