Icarus 269 (2016) 38–49

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Radar scattering by planetary surfaces modeled with laboratory-characterized particles

A. Virkki[a,*], K. Muinonen[a,b]

[a] Department of Physics, University of Helsinki, P.O. Box 64, FI-00014, Finland
[b] Finnish Geospatial Research Institute, Geodeetinrinne 2, Masala FI-02431, Finland

ARTICLE INFO

Article history:
Received 28 September 2015
Revised 28 December 2015
Accepted 8 January 2016
Available online 14 January 2016

Keywords:
Asteroids
Composition
Surfaces
Radar observations
Radiative transfer

ABSTRACT

We model radar scattering by planetary surfaces using a ray-optics algorithm that includes Fresnelian reflection and refraction, diffuse scattering, and coherent backscattering. We enhance the realism of the ray-optics algorithm by using scattering particles that are geometrically representative of the surfaces and interiors of planetary bodies. The shapes as well as the dielectric properties of the scattering particles have been characterized in laboratory. The results demonstrate the effects of various physical parameters on radar scattering with an emphasis on asteroids. We present the effects of number density, size distribution, and dielectric and geometric properties of scattering particles on the radar reflectivity and circular-polarization ratio of planetary surfaces. We also briefly discuss applications to the Galilean Moon Europa and comets.

1. Introduction

During the last few decades, a vast literature describing the radar scattering properties of various Solar System objects has accumulated. Simultaneously, there is a shortage of work on what the observations imply about the physical properties of the diverse planetary surfaces. We simulate radar scattering using an algorithm of ray optics and diffuse scattering. We enhance the realism by using scattering particles that are geometrically representative of the surfaces and interiors of planetary bodies. Thus, we can simulate multiple scattering in planetary surfaces, including dust, boulders, or broken rock or ice more accurately than has been done before.

In the modern radar observations, the most common setup for the transmitted signal is a fully circular polarization with a frequency of 2380 MHz (S band, the wavelength $\lambda = 12.6$ cm) or 8560 MHz (X band, $\lambda = 3.5$ cm). The echo can be received simultaneously in the same (SC) and opposite circular (OC) polarization states as compared to the state of the echo originally transmitted.

The echo power in the SC sense depends substantially on the physical properties of the target. For example, in a simple reflection at normal incidence on an interface between two isotropic, dielectric media that is either planar or has a radius that greatly exceeds the wavelength of the incident radiation, the handedness of the circular polarization turns fully. Craters, boulders, or any wavelength-scale irregularities, on the other hand, cause part of the radiation to remain in the original helicity. Therefore, the ratio of the echo power in the SC sense to that in the OC sense, i.e., the circular-polarization ratio, has traditionally been used as a measure of the target's near-surface, wavelength-scale geometric complexity, or "roughness" (Ostro et al., 2002).

Currently, data for about 700 asteroids have been obtained using planetary radar. Fig. 1 illustrates observational data for 120 asteroids, for which both the circular polarization ratio and the (OC) radar albedo have been published.

As Fig. 1 demonstrates, in some cases the circular-polarization ratio depends on the spectral taxonomy type of the asteroid, which has been measured on optical and infrared wavelengths. As well, the mean circular-polarization ratio of the near-Earth asteroids (NEAs) is higher than that of the main-belt asteroids (MBAs), as shown by, e.g., Benner et al. (2008). The variation of the circular-polarization ratios between the different spectral or population types are explained by the dependence of the surface roughness on the type, which is related to how the asteroid has formed (Benner et al., 2008; Shepard et al., 2008b). As well, the circular-polarization ratio can vary substantially even locally, within some specific asteroids (Virkki et al., 2014) and inside and near craters (Campbell et al., 2010; 2009), which also implies that the variation is caused in large part by geometric characteristics, i.e., the surface roughness.

The circular-polarization ratio can vary only due to electric permittivity (Mishchenko and Hovenier, 1995; Virkki et al., 2013).

* Corresponding author. Tel.: +358 503185480.
E-mail address: anne.virkki@helsinki.fi (A. Virkki).

http://dx.doi.org/10.1016/j.icarus.2016.01.011
0019-1035/

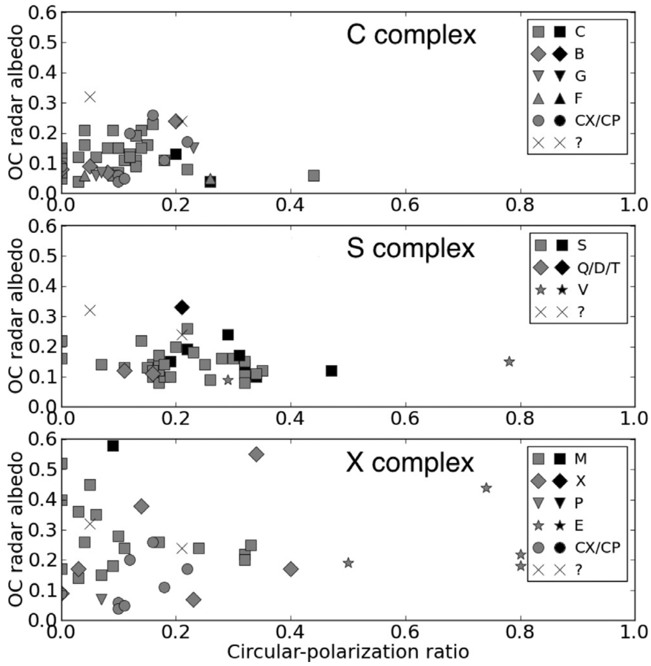

Fig. 1. The radar properties of asteroids of different spectral groups. The gray markers depict main-belt asteroids and the black markers near-Earth asteroids. The Q, D, and T types, with only one representative asteroid in each, and two V types are included with the S type. The types of two asteroids were unknown. For comets, the OC radar albedo is typically less than 0.1 and circular-polarization ratio 0.1–0.6 (Benner et al., 1999; 2002; Brozovic et al., 2009; Busch et al., 2006; de Pater et al., 1994; Harmon et al., 1989; Hudson et al., 2000; 2003; Koyama et al., 2001; Magri et al., 2007a; 1999; 2007b; Mitchell et al., 1996; 1995; Nolan et al., 2005; Ostro et al., 2005; 2004; 1983; 1985; 1999; 2001; 1991; 1989; Shepard et al., 2008a; 2008b; 2010; 2015; Spence et al., 1997; Zaitsev et al., 1997).

However, no robust evidence has been published to explain the variation of the circular-polarization ratio between the different taxonomic types of asteroids, comets, or the local variations in terms of electric permittivity. Therefore, the effect of the electric permittivity on radar scattering plays a significant role in this paper.

The radar albedo is shown to depend on the density of the scattering medium. The near-surface density, which has been discussed in several papers (Garvin et al., 1985; Magri et al., 2001; Ostro et al., 1985; Shepard et al., 2008a; 2010) is thus related to the electromagnetic properties, as the dielectric constant has a positive correlation with density (Rayleigh, 1892). Shepard et al. (2010) suggest that the large range of the values of radar albedo as well as circular-polarization ratio among the M and X type asteroids, and also within specific asteroids, is a result of exaggeration of the irregularities in the shape by the radar reflectivity. Note also that the E- and P-type asteroids may differ in terms of composition substantially compared to the M- and X-type asteroids.

For the icy Galilean Moons Europa, Ganymede, and Callisto, the OC radar albedos are 1.0, 0.6, and 0.3, and the circular-polarization ratios 1.5, 1.4, and 1.2, respectively (Campbell et al., 1978; Ostro et al., 1992). These peculiarly high values have been explained with the coherent-backscattering mechanism (CBM), which can enhance the circular-polarization ratio at backscattering (Black et al., 2001; Hapke, 1990; Mishchenko, 1992; Peters, 1992). The CBM will be treated in this paper as well (the definition of CBM is reviewed in Section 2.4).

Questions, which the current knowledge on radar scattering do not comprehensively answer, are, e.g., what role do different electric permittivities and geometries of the planetary surfaces play in the radar reflectivity and polarization? Is the CBM the only explanation for the high circular-polarization ratios and radar albedos for the icy Galilean Moons? In which cases is the CBM relevant for the radar scattering by asteroid or comet surfaces?

To outline the paper, we give a brief overview of the relevant scattering theory in Section 2. We present the model particles and the selected values for the materials and sizes of the particles in Section 3. We illustrate and discuss the differences in the radar scattering due to different physical parameters in Section 4. And, finally, we summarize and draw conclusions based on the essential results in Section 5.

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 for the linear polarization, and V for the circular polarization. The ensemble-averaged 4×4 scattering phase matrix $\mathbf{P}(\theta)$ relates the incident and scattered Stokes vectors $\mathbf{I}_{\rm inc}$ and $\mathbf{I}_{\rm sca}$:

$$\mathbf{I}_{\rm sca} = \frac{\sigma_s}{4\pi R^2}\mathbf{P}(\theta)\cdot\mathbf{I}_{\rm inc}, \qquad \int_{4\pi}\frac{d\Omega}{4\pi}P_{11} = 1. \tag{1}$$

Here, 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 σ_s is the ensemble-averaged scattering cross section, which describes the total power scattered by a particle in terms of incident power falling on the area σ_s (van de Hulst, 1981).

Similar to σ_s, we can define the absorption cross section as the power incident on the area σ_a that is equal to the power absorbed by a particle, and the extinction cross section as the power incident on the area σ_e that is equal to the power removed from the original beam by scattering and absorption, i.e., $\sigma_s + \sigma_a$. The extinction, scattering, or absorption cross section divided by the projected area, A, gives the extinction, scattering, or absorption efficiencies (q_e, q_s, or q_a), respectively. The ratio of the scattering efficiency to the extinction efficiency is called the single-scattering albedo (ω), which describes the remaining power at each scattering.

2.2. Radar properties

Considering simulations of radar scattering, mainly the backscattering direction ($\theta = 180^\circ$) is relevant. Using radar, the integrated echo power is described using the radar cross section, $\sigma_{\rm back}$. The radar cross section is 4π times the backscattered power per steradian divided by the power incident on a unit area (Bohren and Huffman, 1983).

If the radar cross section is divided by the projected area of the target, the total radar albedo is obtained (i.e., $\sigma_{\rm back}/A = \hat{\sigma}_T$). As well as the radar cross section, the radar albedo can be indicated using a specific polarization state, $\hat{\sigma}_{\rm OC}$ or $\hat{\sigma}_{\rm SC}$. In terms of the scattering-matrix elements, we can define:

$$\begin{aligned}
\sigma_{\rm back} &= \sigma_s P_{11}(180^\circ),\\
\hat{\sigma}_T &= q_s P_{11}(180^\circ),\\
\hat{\sigma}_{\rm SC} &= \frac{\hat{\sigma}_T}{2}\left(1 + \frac{P_{44}(180^\circ)}{P_{11}(180^\circ)}\right),\\
\hat{\sigma}_{\rm OC} &= \frac{\hat{\sigma}_T}{2}\left(1 - \frac{P_{44}(180^\circ)}{P_{11}(180^\circ)}\right),
\end{aligned} \tag{2}$$

The relationship between the OC radar albedo and Fresnel reflectivity R_F is given by Ostro (Ostro et al., 1985) as $\hat{\sigma}_{\rm OC} = gR_F$, where the 'gain factor' g depends on the target's angular scattering