Planetary surface characterization by modeling radar scattering

Anne Virkki

ACADEMIC DISSERTATION

Department of Physics
Faculty of Science
University of Helsinki
Helsinki, Finland

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Cover picture: The William E. Gordon telescope of the Arecibo Observatory.
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Abstract

Planetary radar can be considered humankind’s strongest instrument for post-discovery characterization and orbital refinement of near-Earth objects. After decades of radar observations, extensive literature describing the radar properties of various objects of the Solar System is currently available. Simultaneously, there is a shortage of work on what the observations imply about the physical properties of the planetary surfaces. The goal of my thesis is to fill part of this gap.

Radar scattering as a term refers to alterations experienced by electromagnetic radiation in the backscattering direction when interacting with a target particle. In the thesis, I investigate by numerical modeling what role different physical properties of planetary surfaces, such as the electric permittivity, size of scatterers, or their number density, play in radar scattering. In addition, I discuss how radar observations can be interpreted based on modeling.

Because all codes have their own limitations, it is crucial to compare results obtained with different methods. I use Multiple Sphere T-matrix method (MSTM) for clusters of spherical particles to understand scattering by closely-packed regolith particles. I use the discrete-dipole approximation code ADDA to comprehend single-scattering properties of inhomogeneous or irregular regolith particles in wavelength-scale. And finally, I use a ray-optics algorithm with radiative transfer, SIRIS, to simulate radar scattering by large irregular particles that mimic planetary bodies.

The simulations for clusters of spherical particles reveal polarization enhancement at certain bands of sizes and refractive indices in the backscattering direction. The results from computations using MSTM and ADDA imply that the electric permittivity plays a strong part in terms of circular polarization. From the results of ray-optics computations for large, irregular particles, I derive a novel semi-analytic form for the radar scattering laws. And, by including diffuse scattering using wavelength-scale particles with laboratory-characterized geometries, we are able to simulate the effect of numerous physical properties of a realistic planetary surface on radar scattering.

Our model using SIRIS is among the most quantitative models for radar scat-
tering by planetary surfaces. The results support and improve the current understanding of the effects of the surface geometry, the electric permittivity, and the coherent-backscattering mechanism and can be used to interpret radar observations. Furthermore, I underscore that the roles of the absorption and the scatterer geometry must not be underestimated, albeit determining realistic values for the variables can be challenging.
Preface

The subject of this thesis was originally decided based on my bachelor’s thesis, in which I reviewed the current knowledge of the internal structure of asteroids. I wished to continue to study asteroids under the surface, and my supervisor professor Karri Muinonen suggested research of radar scattering, because microwave radiation is able to penetrate deeper into the planetary surfaces than light at optical wavelengths. Consequently, the research for this thesis initially began in 2011 in the form of my master’s thesis. After one year, the master’s thesis was finalized, but a large number of related research problems were only beginning to formulate, so research was continued to a peer-reviewed scientific journal publication after another, and eventually into this thesis.

I am deeply grateful for Karri for all the advice, inspiring discussions, and suggestions for improving the research since I began writing my bachelor’s thesis. Most of all, I am grateful for his continuous support for networking opportunities, which greatly enriched the time as a graduate student and without which the future after defending would have seemed substantially more insecure. Two of these opportunities require special highlighting: First, the two-month research visit at the Arecibo Observatory in 2013, and second, acting as the vice-chair of the local organizing committee of the Asteroids, comets, meteors 2014 -meeting in Helsinki. To say the least, both of these experiences exceeded all the expectations and have given me more than words can describe.

I also wish to thank my other advisors: Antti Penttilä for his help with the algorithms and valuable comments on the papers and Mikael Granvik for moral support. In addition, I wish to acknowledge Johannes, Jani, and Jouni for their co-authorship, and all unique members of the planetary system research group for discussions and the cakes that were shared (with extra acknowledgement for Karri for joking about publication cakes when my first paper was published). Especially, I thank Olli for all the IT support, commenting my texts, but also all the everyday moments we shared.

From the international planetary science community, I wish to acknowledge Dr. Michael Nolan and Dr. Ellen Howell for their support with arranging the research visit and hospitality during the two months in Puerto Rico. In addition, I thank Sondy, Dr. Patrick Taylor, Dr. Lance Benner, and the whole team radar for valuable conversations and making me part of the team.

I am grateful for the pre-examiners of the thesis, Dr. Gorden Videen and Dr. Tuomo Rossi, for the positive and constructive comments concerning the thesis. I acknowledge the Finnish graduate school in astronomy and space physics funded by the ministry of education for funding the main part of the thesis work, CSC – IT Center for Science Ltd. for the computation resources, and the employees of the Department of physics for all the help given with various smaller but yet important tasks.

Finally, I thank my family and friends for continuous support and all the shared joy.

In Helsinki, December 2015,

Anne Virkki
Publications


These articles will be referred to in the text by their Roman numbers. The articles are reprinted with permission of the original journals.
Abbreviations used in the text

au Astronomical unit
DDA Discrete-dipole approximation
GRS Gaussian random sphere
MBO Main-belt object
MSTM Multiple sphere $T$-matrix method
NEO Near-Earth object
OC Opposite circular
SC Same circular
SMASS Small Main-Belt Asteroid Spectroscopic Survey
Symbols and units

\( a \)
Mean radius of a particle

\( \alpha \)
Orientation of a scatterer

\( \mathbf{B} \)
Magnetic field

\( C_{\text{abs}}, C_{\text{ext}}, C_{\text{sca}} \)
Absorption, extinction, and scattering cross section

\( C_{\text{back}} \)
Radar cross section or backscattering cross section

\( C_G \)
Geometric cross section or projected area

\( \chi \)
Electric susceptibility

\( \mathbf{E}, E_\parallel, E_\perp \)
Electric field (\( E_\parallel \) parallel, \( E_\perp \) perpendicular to a scattering plane)

\( \epsilon, \epsilon_0, \epsilon_m, \epsilon_r \)
Complex electric permittivity (\( \epsilon_0 \): of free space, \( \epsilon_m \): of an arbitrary medium, \( \epsilon_r \): relative, \( \epsilon_r, \Re \): real part, \( \epsilon_r, \Im \): imaginary part)

\( f \)
Frequency

\( \mathbf{F} \)
Scattering matrix

\( g, G \)
Gain factors

\( \mathbf{I} \)
Stokes vector

\( k \)
Wave number

\( k_0 \)
Scalar extinction coefficient

\( \kappa_s \)
Projected surface density

\( \lambda \)
Wavelength

\( m \)
Complex refractive index (\( m_\Re \): real part, \( m_\Im \): imaginary part)

\( \mu, \mu_0, \mu_r \)
Magnetic permeability (\( \mu_0 \): of free space, \( \mu_r \): relative)

\( \mu_C \)
Circular-polarization ratio

\( \mu_L \)
Linear-polarization ratio

\( n_0, v_0 \)
Number and volume density of a diffuse medium

\( N \)
Order of scattering

\( \nu \)
Power-law index for shape characterization (GRS particles)

\( \omega \)
Single-scattering albedo

\( \mathbf{P} \)
Scattering phase matrix

\( P_T, P_R \)
Transmitted power, received power

\( q_{\text{abs}}, q_{\text{ext}}, q_{\text{sca}} \)
Absorption, extinction, and scattering efficiency

\( r \)
Distance between the scatterer and the observer

\( R_F \)
Fresnel reflectivity

\( \rho \)
Powder density

\( \rho_F \)
Total charge density

\( \mathbf{S} \)
Amplitude scattering matrix

\( s \)
Layer depth of a diffuse external medium

\( \sigma \)
Conductivity

\( \sigma_r \)
Standard deviation of radius (GRS particles)

\( \hat{\sigma}_{\text{OC}} \)
Radar albedo in the opposite-circular polarization

\( \hat{\sigma}_{\text{SC}} \)
Radar albedo in the same-circular polarization

\( \hat{\sigma}_T \)
Total radar albedo or the backscattering efficiency

\( \theta \)
Scattering angle

\( x \)
Size parameter
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1 Background

1.1 Planetary surfaces

The Solar System formed 4.568 billion years ago from a collapsing molecular cloud of dust and gas [Bouvier and Wadhwa, 2010]. According to a recent study by Boss and Keiser [2015], a supernova relatively close to the cloud initiated the rotation of the cloud and, eventually, enabled the formation of the Sun and planetary bodies as we know them this day.

The planetary bodies can be divided into four categories: planets, moons, minor planets or asteroids (including dwarf planets and meteoroids), and comets. At times, the categories can overlap: a centaur asteroid can resemble both asteroids and comets, or an asteroid that is gravitationally captured by a planet becomes a moon. According to the Minor Planet Center of the International Astronomical Union, by the end of November 2015, the number of discovered minor planets had exceeded 698,400 and the number of discovered comets 3,850.

The moons have as much variation in terms of composition as the planets. Especially, the moons of Jupiter and Saturn host a wide range of geologic features from vast glaciers of ice to volcanoes and lava flows, or even an atmosphere, such as on the Saturn’s moon Titan. In addition, liquid oceans are speculated to exist deep under the surfaces of Titan and the Galilean moons Europa, and possibly Ganymede and Callisto.

Asteroids can be classified based on their physical or dynamical properties. Let us begin with the dynamical populations. The main belt between the orbits of Mars and Jupiter includes the major part of known asteroids (see Fig. 1.1). The majority of the main-belt objects (MBOs) orbit the Sun on an average distance (semimajor axis) of 1.8 to 4.5 astronomical units (au). They are assumed to be primarily remnants of the protoplanetary material that gravitational perturbations by Jupiter prevented to accrete into a planet-size object.

The main belt is also the major source of the near-Earth objects (NEOs), for which the perihelion, i.e., the closest approach to the Sun, is less than 1.3 au. For
1.1. Planetary surfaces

Figure 1.1: On the left: The orbits of Mercury, Venus, Earth, Mars, and Jupiter with the main belt and the trojan asteroids (source: NASA). On the right: The orbits of Jupiter, Saturn, Uranus, Neptune, and Pluto (respectively) with the Kuiper belt (artwork by Don Dixon).

comparison, the semimajor axis of the Earth is equal to 1 au. The NEOs, which can cross the orbit of the Earth, pose a threat of impacts, but also potential opportunities of exploration due to their low velocities relative to the Earth.

The trojan asteroids are a population captured by the gravity of Jupiter on its orbit (at about 5.2 au). They are locked in one of the two Lagrangian points of gravitational stability $60^\circ$ behind and ahead of the planet, as shown in Fig. 1.1.

The most distant asteroids are called transneptunian objects, for which the semimajor axis is greater than that of the Neptune at 30 au. They can be divided into two larger groups based on distance: the Kuiper-belt objects (the semimajor axis less than or equal to 55 au) and the scattered-disk objects (the semimajor axis greater than 55 au).

The distribution of asteroids based on the physical properties refers usually to the taxonomic classification systems, which are based on spectroscopic and photometric measurements at optical (from 0.45 to 0.75 µm) and near-infrared wavelengths (from 0.75 to 2.45 µm). The first, widely used classification was created by Tholen [1989]. The most extensive one of the 21st century is the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) classification covering a few thousands of asteroids.
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(Bus and Binzel [2002], see Table 1.1). Also, the Bus-DeMeo classification (DeMeo et al. [2009]) is noted, as it extends the spectral measurements to the near-infrared wavelengths, up to 2.45 µm. In the Bus-DeMeo classification, nearly all the classes of SMASS classification are preserved with one new (Sv) introduced.

<table>
<thead>
<tr>
<th>Complex</th>
<th>Tholen</th>
<th>SMASS/Bus-DeMeo</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-complex</td>
<td>C, B, F, G</td>
<td>B, C, Cb, Cg, Cgh, Ch</td>
</tr>
<tr>
<td>S-complex</td>
<td>S</td>
<td>S, Sa, Sq, Sr, Sv, A, Q, K, L, R</td>
</tr>
<tr>
<td>X-complex</td>
<td>M, X, E, P</td>
<td>X, Xc, Xe, Xk</td>
</tr>
<tr>
<td>Small types</td>
<td>A, D, T, Q, R, V</td>
<td>D, Ld, O, T, V</td>
</tr>
</tbody>
</table>

Table 1.1: The complexes and types of Tholen and SMASS/Bus-DeMeo taxonomic classifications. Note that X was originally included in the Tholen taxonomy to assign the objects, for which no albedo information was available, Sv is only included in the Bus-DeMeo taxonomy, and Ld only in the SMASS taxonomy. Sources: Tholen [1989], Bus and Binzel [2002], DeMeo et al. [2009].

The most common is the C-complex including about 75% of all known asteroids. Asteroids in the C-complex, most of which are C-type, are the dominating population especially in the outer parts of the asteroid belt. They are extremely dark and carbon-rich. Also, hydrated minerals are present. The spectra (see Fig. 1.2) are very similar to those of carbonaceous chondrite meteorites. Due to the darkness and abundance in the outer parts of the asteroid belt, the C-complex is likely to host a major part of the undiscovered asteroids.

The second most common complex is the S type or the corresponding types in the SMASS classification. Of all known asteroids, about 17% are S type. In the inner asteroid belt, this is the dominating type. The S-complex asteroids are slightly brighter than the C-complex asteroids. Typical minerals are silicates, especially magnesium silicates.

For the X-complex, the brightness at optical wavelengths is comparable to that of the S-complex asteroids. For the M-type asteroids, nickel-iron is a typical mineral, for E (or Xe) type, enstatite is more common [Zellner et al., 1977]. The mineralogy among the X-complex asteroids is likely to vary more than in the S- and C-complexes.

Many of the small types in the Tholen classification only include from one to a few tens of discovered objects, and were moved under the S-complex in the SMASS classification. The most significant of the small types by the number of discovered objects is the V type (6% of the MBOs), the members of which originate primarily from (4) Vesta. V-type asteroids are quite similar to the S-type objects in chemical
composition and brightness, but contain more pyroxene.

Comets, which have been formed at a further distance from the Sun than the asteroids, are distinguished in appearance with the coma, and in their chemical composition by the abundance of ice. However, ice on the surface of a comet nucleus may not be as common as previously thought. Recent spectral measurements by the Rosetta spacecraft of the comet 67P/Churyumov-Gerasimenko suggest crustal composition of polyaromatic organic solids mixed with sulfides and iron-nickel alloys. No ice-rich patches were observed [Capaccioni et al., 2015].

As for the structure, the surfaces of atmosphereless planetary bodies are typically composed of regolith. Regolith is, by definition, a layer of loose, heterogeneous material including dust, broken rock, and other related materials covering solid rock. It can be physically characterized by the particle size and morphology, the surface porosity and roughness of the layer, as well as by the electric permittivity and the magnetic permeability of the material.

The size distribution has been investigated for regolith particles of the Moon and (25143) Itokawa. According to the studies by Shoemaker and Morris [1968] and Tatsuhiro Michikami et al. [2008], a good estimate is a power-law size distribution \( n(a) \propto a^{-3} \), where \( a \) is the mean radius of a particle. However, the size distribution

---

Figure 1.2: The taxonomy key for the DeMeo taxonomy. The spectrum of wavelengths extends from 0.45 to 2.45 \( \mu \text{m} \). Source: DeMeo et al. [2009].
can have substantial local variations, not to mention differences between objects. As we see in Fig. 1.3, which shows surface details from two S-type asteroids – (433) Eros and (25143) Itokawa – the surface can be covered with craters or boulders up to meter-scale size, or lack any evident large rocks.

1.2 Planetary radar

Radar, or radio detecting and ranging, operates by transmitting radio or microwaves and detecting the echo. Based on the time elapsed and the Doppler shift of the echo, the distance and the radial velocity of the target can be determined.

Planetary radar observations have been carried out systematically since the 1950s, first for the Moon, and by 1963, also for Mercury, Venus, and Mars [Thomson, 1963, Pettengill and Dyce, 1965]. The first radar observation of an asteroid, (1566) Icarus, took place in 1968 [Pettengill et al., 1969], and that of a comet, 2P/Encke, in 1980 [Kamoun et al., 1981]. By this day, the number of studied targets has increased to approximately 700.

Compared to other astronomical observation instruments on optical, ultraviolet, or infrared wavelengths, which use the sunlight to observe planetary targets, a
planetary radar transmits coded microwaves and observes the echo. The distance
and radial velocity can be measured with an incomparable accuracy relative to other
ground-based observation techniques: the distance can be estimated down to a few
tens of meters, and the radial velocity down to a few millimeters per second. In-
dications of the rotation state of the target can be obtained, including the pole
orientation and the rotation rate, and possible multibody systems can also be easily
distinguished from single ones.

Despite the strength of the planetary radar as a technique for characterizing
planetary targets in various ways, it is very sensitive to the distance of the target.
The received power of the echo is theoretically described by the radar equation as
follows:

\[ P_R = \frac{P_T G_A^2 \lambda^2 C_{\text{back}}}{(4\pi)^3 r^4}, \]

where \( P_T \) and \( P_R \) are the transmitted and received power, respectively, the wave-
length is denoted using \( \lambda \), \( C_{\text{back}} \) is the radar cross section (defined in Section 2.4) and
\( r \) is the Earth-object distance. The antenna gain, \( G_A \), is equal to \( 4\pi/\lambda^2 \) times the
effective aperture of the antenna. As the radar equation shows, the received power
decreases to 1/16 when the distance to the target doubles. This is why the current
ground-based planetary radars are most effective for NEOs, reasonably efficient for
large MBOs, and useless for transneptunian objects.

The area of the receiving antenna is crucial for the echo power. In practice, only
the largest radio telescopes in the world can be used to observe asteroids, and only
a few of the radio telescopes have transmitters powerful enough to transmit and
receive. The most powerful of these is the 305-meter William E. Gordon telescope of
the Arecibo Observatory. The second largest contribution in terms of the planetary
radar observations has been made by the antennas of the deep space network of the
Goldstone Observatory, the largest of which is 70 meters in diameter. In addition,
the 100-meter Robert C. Byrd Green Bank telescope is notable for being the world’s
largest steerable radio telescope. It does not include a transmitter that would be
strong enough for systematic, independent planetary radar observing but due to the
steerability and large antenna, it is useful for a technique called bistatic radar. In
bistatic radar observations, one telescope transmits the signal, and another telescope
observes the echo.

In modern radar observations, the transmitted signal is usually fully circularly
polarized and has a frequency of 2380 MHz (S band, wavelength \( \lambda = 12.6 \text{ cm} \)) or
8560 MHz (X band, \( \lambda = 3.5 \text{ cm} \)). Also, 430 MHz (P band, \( \lambda = 70 \text{ cm} \)) can be
used but the S and X bands offer better resolution. The echo is received in the same
circular polarization as transmitted (the SC sense) and simultaneously in the opposite
circular polarization (the OC sense). By interpreting the intensity and polarization of the echo, the planetary radar measurements can provide us with information on the physical properties of the near-surface of the target [Ostro, 1993].

For example, a simple reflection in a normal incidence to an interface between two half-spaces of different materials whose size and radius of curvature greatly exceed the wavelength of the incident radiation, fully turns the handedness of the circular polarization. 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].

Figure 1.4 illustrates observational data for 120 asteroids, for which both the circular-polarization ratio and the (OC) radar albedo have been published [Ostro et al., 1983, 1985, 1989, 1991, de Pater et al., 1994, Mitchell et al., 1995, 1996, Zaitsev et al., 1997, Spence et al., 1997, Ostro et al., 1999, Magri et al., 1999, Benner et al., 1999, Hudson et al., 2000, Koyama et al., 2001, Ostro et al., 2001, Benner et al., 2002, Hudson et al., 2003, Ostro et al., 2004, 2005, Busch et al., 2006, Magri et al., 2007a,b, Shepard et al., 2008a,b, Brozovic et al., 2009, Shepard et al., 2010, 2015, Harmon et al., 1989, Nolan et al., 2005].

As Fig. 1.4 demonstrates, in some cases the circular-polarization ratio depends on the spectral taxonomy type of the asteroid, which has been measured at optical and infrared wavelengths. The mean circular-polarization ratio of the NEOs is higher than that of the MBOs as shown by, e.g., Benner et al. [2008], although the fact is not evident in Fig. 1.4. 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 the formation or the collisional evolution of the asteroid [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., 2009, 2010], which also implies that the variation is caused in large part by geometric characteristics, i.e., the surface roughness.

As for the radar albedo, the density of the scattering medium is shown to play a significant part. The effect of the near-surface density, which has been discussed in several papers [Ostro et al., 1985, Garvin et al., 1985, Magri et al., 2001, Shepard et al., 2008a, 2010] is thus related to the electromagnetic properties, as the real part of the electric permittivity has a positive correlation with density. The wide range of values of radar albedos and circular-polarization ratios of X-complex asteroids, and also in specific M- and X-type asteroids, is suggested to be a result of exaggeration of
1.2. Planetary radar

Figure 1.4: The radar properties of asteroids of different spectral complexes. 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 the circular-polarization ratio from 0.1 to 0.6.
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the irregularities in the shape by the strong radar reflectivity [Shepard et al., 2010].

The reader should be aware that there is no question that the circular-polarization ratio could not vary only due to electric permittivity as is shown in Paper I. However, there has been no robust evidence 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 investigation of the effect of the electric permittivity on radar scattering plays a significant part in this thesis.

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 [Hapke, 1990, Peters, 1992, Mishchenko, 1992, Black et al., 2001, Muinonen, 2004]. The CBM will be treated in this thesis as well (the definition of CBM is reviewed in Section 2.5).

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?

1.3 Outline

In the thesis, I investigate, how different physical properties of a target affect the radar echo and how radar observations can be interpreted based on the models. The core of the thesis are simulations of electromagnetic scattering with the primary focus in the backscattering direction.

In Chapter 2, I review the main points of the scattering theory behind the algorithms. In Chapter 3, I describe the algorithms that I have used for the modeling. Chapter 4 presents some of the results of the thesis in terms of how different geometries affect radar scattering. In Chapter 5, I discuss the relevance and applications of the results in terms of radar observations and review how the research carried out has advanced the field. In Chapter 6, I list the papers included in the thesis and briefly review each one in content as well as my contribution to the papers. And finally, in Chapter 7, I summarize the most important findings of the paper, and also, consider future prospects in the field.
2 Electromagnetic scattering

The Maxwell equations, introduced by James Clerk Maxwell in 1860s, establish the foundations for electromagnetic theory. One part of it is formed by the treatment of absorption and scattering of electromagnetic radiation. In SI units, the Maxwell equations are

\begin{align}
\text{Gauss’ law for electricity:} \quad \nabla \cdot \mathbf{D} &= \rho_F, \\
\text{Faraday’s law:} \quad \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t}, \\
\text{Gauss’ law for magnetism:} \quad \nabla \cdot \mathbf{B} &= 0, \\
\text{Ampere-Maxwell law:} \quad \nabla \times \mathbf{H} &= \sigma \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t},
\end{align}

(2.1)

Here, \( \mathbf{D} \) is the electric displacement, \( \mathbf{E} \) is the electric field, \( \mathbf{B} \) is the magnetic induction, \( \mathbf{H} \) is the magnetic field, \( \rho_F \) is the total charge density, and \( \sigma \) is the conductivity. The electric displacement in terms of electric field is \( \mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P} \), where \( \epsilon_0 \) is the electric permittivity of free space, \( \chi \) is the electric susceptibility, and \( \mathbf{P} \) is the electric polarization (average electric dipole moment per unit volume), which is also related to the electric field by the electric susceptibility \( \chi \) so that \( \mathbf{P} = \epsilon_0 \chi \mathbf{E} \). The magnetic field is related to the magnetic induction so that \( \mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M}) \), where \( \mu_0 \) is the magnetic permeability of free space, and \( \mathbf{M} \) is the magnetization (average magnetic dipole moment per unit volume) [Bohren and Huffman, 1983].

2.1 Stokes parameters

Any electromagnetic radiation can be described using the Stokes parameters, introduced by George Gabriel Stokes in 1852 as a mathematically convenient alternative for the description of incoherent or partially polarized radiation in terms of its total intensity, degree of polarization, and the shape parameters of the polarization ellipse. The Stokes parameters can be collectively presented in the form of the Stokes vector, \( \mathbf{I} = [I, Q, U, V]^T \), where \( I \) is the intensity, \( Q \) and \( U \) denote the linear polarization, and \( V \) denotes the circular orientation. The superscript \( T \) denotes the matrix transpose.
Chapter 2. Electromagnetic scattering

Scattering of electromagnetic radiation in terms of the electric fields parallel (∥) or perpendicular (⊥) to the plane of scattering can be described by the four amplitude functions, $S_1(\theta)$, $S_2(\theta)$, $S_3(\theta)$, and $S_4(\theta)$, so that

$$
\begin{pmatrix}
E_\parallel \\
E_\perp
\end{pmatrix}
= e^{ik(r-z)}
\begin{pmatrix}
S_2(\theta) & S_3(\theta) \\
S_4(\theta) & S_1(\theta)
\end{pmatrix}
\begin{pmatrix}
E_{\parallel,\text{inc}} \\
E_{\perp,\text{inc}}
\end{pmatrix}.
$$

(2.2)

The scattering angle, $\theta$, is the angle between the incident and scattered wave vectors. These vectors also define the scattering plane. The distance between the observer and the scatterer is denoted using $r$, $z$ is the $z$-axis coordinate of the observer in a Cartesian coordinate system where the target is at $z = 0$ and the incident radiation is parallel to the $z$ axis, and $k$ is the wave number $2\pi/\lambda$. The subscript "inc" denotes the incident radiation. Using the electric field components, the Stokes parameters are defined (for radiation in general, i.e., elliptical, polarization) as [Bohren and Huffman, 1983]

$$
\begin{align*}
I &= E_\parallel E_\parallel^* + E_\perp E_\perp^* \\
Q &= E_\parallel E_\perp^* - E_\perp E_\parallel^* \\
U &= E_\parallel E_\perp^* + E_\perp E_\parallel^* \\
V &= i(E_\parallel E_\perp^* - E_\perp E_\parallel^*).
\end{align*}
$$

(2.3)

Here, the asterisk (*) denotes the complex conjugate.

2.2 Size parameter

Electromagnetic scattering depends on the geometry, size, and electric properties of the scattering particles or medium. In scattering theory, the size of the scattering particle is commonly described using the size of the scatterer relative to the wavelength, i.e., the size parameter:

$$
x = ka = \frac{2\pi a}{\lambda}.
$$

(2.4)

For spheres, $a$ is simply the radius of the sphere, but for irregular scatterers, different conventions exist. The radius, or the size parameter, can refer to that of a sphere with an equal volume or projected area, or that of a circumscribing sphere.

Depending on the size parameter, scattering can be divided roughly into three regimes: the Rayleigh-scattering regime for particles with $x << 1$, the resonance regime for particles with $x \approx k\lambda$, and the ray- or geometric-optics regime for particles much larger than the wavelength ($x >> 1$).
2.3 Scattering matrix

The $4 \times 4$ scattering matrix $F(\theta)$\textsuperscript{1}, which is referred to from here on as the unnormalized scattering matrix, relates the scattered and incident radiation:

$$I = \frac{1}{k^2 r^2} F(\theta) \cdot I_{\text{inc}},$$ \hspace{1cm} (2.5)

following the notations by Bohren and Huffman [1983].

The scattering matrix can also be treated as a normalized scattering phase matrix (used in Paper V), in which case it is defined as

$$I_{\text{sca}} = \frac{C_{\text{sca}}}{4\pi r^2} P(\theta) \cdot I_{\text{inc}}, \hspace{0.5cm} \int \frac{d\Omega}{4\pi} P_{11} = 1,$$

where $C_{\text{sca}}$ 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 $C_{\text{sca}}$ [van de Hulst, 1957]. The relation of the scattering phase matrix to the unnormalized scattering matrix is thus

$$P = \frac{4\pi}{k^2 C_{\text{sca}}} F.$$

(2.6)

Similar to $C_{\text{sca}}$, we can define the absorption cross section as the power incident on the area $C_{\text{abs}}$ that is equal to the power absorbed by a particle, and the extinction cross section as the power incident on the area $C_{\text{ext}}$ that is equal to the power removed from the original beam by both scattering and absorption, i.e., $C_{\text{sca}} + C_{\text{abs}}$. For a spherical particle with an arbitrary radius of $a$ [Bohren and Huffman, 1983]

$$C_{\text{ext}} = \frac{4\pi}{k^2} \text{Re}[S_1(0)],$$

$$q_{\text{ext}} = \frac{4}{(ka)^2} \text{Re}[S_1(0)].$$

(2.7)

The extinction, scattering, and absorption cross sections divided by the projected area, $A$, give the extinction, scattering, and absorption efficiencies ($q_{\text{ext}}$, $q_{\text{sca}}$, and $q_{\text{abs}}$), respectively. The ratio of the scattering efficiency to the extinction efficiency is called the single-scattering albedo ($\omega$), which describes the total power loss at each scattering:

$$\omega = \frac{q_{\text{sca}}}{q_{\text{ext}}},$$ \hspace{1cm} (2.8)

\textsuperscript{1}In Papers II-IV, we use $S$, but here $F(\theta)$ is used in order to distinguish the scattering-matrix elements from the amplitude functions.
In terms of the amplitude functions, the elements of the unnormalized scattering matrix are [Bohren and Huffman, 1983]:

\[
\begin{align*}
F_{11} &= \frac{1}{2}(|S_1|^2 + |S_2|^2 + |S_3|^2 + |S_4|^2), \\
F_{12} &= \frac{1}{2}(|S_2|^2 - |S_1|^2 + |S_4|^2 - |S_3|^2), \\
F_{13} &= \text{Re}(S_2S_3^* + S_1S_4^*), \\
F_{14} &= \text{Im}(S_2S_3^* - S_1S_4^*), \\
F_{21} &= \frac{1}{2}(|S_2|^2 + |S_3|^2 - |S_1|^2 - |S_4|^2), \\
F_{22} &= \frac{1}{2}(|S_1|^2 - |S_3|^2 - |S_4|^2 + |S_2|^2), \\
F_{23} &= \text{Re}(S_2S_3^* - S_1S_4^*), \\
F_{24} &= \text{Im}(S_2S_3^* + S_1S_4^*), \\
F_{31} &= \text{Re}(S_2S_4^* + S_1S_3^*), \\
F_{32} &= \text{Re}(S_2S_4^* - S_1S_3^*), \\
F_{33} &= \text{Re}(S_1S_2^* + S_3S_4^*), \\
F_{34} &= \text{Im}(S_2S_4^* - S_1S_3^*), \\
F_{41} &= \text{Im}(S_4S_2^* + S_1S_3^*), \\
F_{42} &= \text{Im}(S_4S_2^* - S_1S_3^*), \\
F_{43} &= \text{Im}(S_1S_2^* - S_3S_4^*), \\
F_{44} &= \text{Re}(S_1S_2^* - S_3S_4^*).
\end{align*}
\]

(2.9)

The number of independent elements depends on symmetry factors, for example, due to the geometry of the scatterer or ensemble-averaging of particles and their mirror particles in random orientations.

### 2.4 Radar scattering

Considering the radar geometry, electromagnetic simulations are most relevant at exact backscattering ($\theta = 180^\circ$). Using radar, the integrated echo power is described using the radar cross section, $C_{\text{back}}$. The radar cross section is $4\pi$ times the backscattered power per steradian divided by the power incident on a unit area [van de Hulst, 1957]. The radar cross section is measured in a specific polarization state, in the same circular-polarization state as the transmitted signal ($C_{\text{SC}}$) or the opposite circular-polarization state ($C_{\text{OC}}$). Thus, $C_{\text{back}} = C_{\text{SC}} + C_{\text{OC}}$.

If the total radar cross section is divided by the projected area of the target, the total radar albedo is obtained (i.e., $C_{\text{back}}/C_G = \tilde{\sigma}_T$). The total radar albedo is 4 times the geometric albedo\(^2\). Similar to the radar cross section, the radar albedo

\(^2\)The ratio of the backscattering flux from the object to the flux from an equal-sized Lambertian disk at normal incidence.
2.4. Radar scattering

can be indicated using a specific polarization state, $\hat{\sigma}_{OC}$ or $\hat{\sigma}_{SC}$. In the observation reports, usually only $\hat{\sigma}_{OC}$ is reported.

![Figure 2.1](image.png)

**Figure 2.1**: The OC radar albedo as a function of the size parameter and the refractive index for spherical particles in wavelength-scale.

For wavelength-scale particles, $\hat{\sigma}_{OC}$ as a function of the size parameter and the refractive index (see Section 2.6) for a spherical particle can be seen in Fig. 2.1. For large, absorbing particles, which have a radius of curvature at any point on the surface much larger than the wavelength, the radar albedo approaches the Fresnel reflectivity, which can be written as [Bohren and Huffman, 1983]

$$R_F = \left| \frac{m-1}{m+1} \right|^2.$$  (2.10)
Using this fact, Ostro et al. [1985] has deduced a relationship \( \hat{\sigma}_{OC} = gR_F \), where \( g \) is the gain factor that depends on the geometry of the scattering surface. For a large, isotropic, and absorbing sphere, \( g = 1 \). This also applies to a plane interface between two homogeneous, semi-infinite media with a normal incidence. Furthermore, using this relationship, equations for \( \hat{\sigma}_{OC} \) as a function of density have been deduced [Ostro et al., 1985, Garvin et al., 1985, Shepard et al., 2010]. Of these, the study by Shepard et al. [2010] connects the other two:

\[
\hat{\sigma} = \begin{cases} 
1.2 \tanh^2 \left( \frac{\rho}{6.4 \text{ g/cm}^3} \right) & \text{for } \rho \leq 1.57 \text{ g/cm}^3 \\
0.144\rho - 0.156 & \text{for } \rho > 1.57 \text{ g/cm}^3.
\end{cases} \tag{2.11}
\]

The circular-polarization ratio, in terms of the radar cross section or the radar albedos, is defined as

\[
\mu_C = \frac{C_{SC}}{C_{OC}} = \frac{\hat{\sigma}_{SC}}{\hat{\sigma}_{OC}}. \tag{2.12}
\]

Occasionally, the linear polarization is used in the observations. The circular polarization is a more secure choice, because charged atmospheric particles can have a rotating effect on a linearly polarized signal. Theoretically, the linear-polarization ratio \( \mu_L \) is related to the circular-polarization ratio if an average over wide enough range of features can be assumed. For randomly oriented particles and their mirror particles, \( \mu_C = 2\mu_L/(1 - \mu_L) \).

In terms of the scattering matrix, the radar cross section, SC and OC radar albedos, and the circular and linear polarization ratios (at \( \theta = 180^\circ \), for an ensemble of particles and their mirror particles) are defined as follows:

\[
C_{\text{back}} = \frac{4\pi F_{11}}{k^2} = C_{\text{sca}}P_{11}, \tag{2.13}
\]
\[
\hat{\sigma}_T = \frac{4F_{11}}{x^2} = q_{\text{sca}}P_{11}, \tag{2.14}
\]
\[
\hat{\sigma}_{SC} = \frac{\hat{\sigma}_T}{2} \left( 1 + \frac{F_{44}}{F_{11}} \right), \tag{2.15}
\]
\[
\hat{\sigma}_{OC} = \frac{\hat{\sigma}_T}{2} \left( 1 - \frac{F_{44}}{F_{11}} \right), \tag{2.16}
\]
\[
\mu_C = \frac{F_{11} + F_{44}}{F_{11} - F_{44}}, \tag{2.17}
\]
\[
\mu_L = \frac{F_{11} - F_{22}}{F_{11} + F_{22}}. \tag{2.18}
\]
Multiple scattering by a medium with numerous scatterers is the sum of two parts: the incoherent and coherent scattering. The incoherent part refers to the diffuse radiation from the first-order scattering and the so-called ladder terms of the Bethe-Salpeter equation [Tsang et al., 1985]. The coherent part refers to the interference of conjugate pairs of waves scattered along two reversed trajectories (see Fig. 2.2). In the exact backscattering direction, the interference is always constructive, which causes a backscattering peak. Therefore, the enhancement mechanism is called the coherent-backscattering mechanism (CBM). The coherent part is the sum of the cyclical terms of the Bethe-Salpeter equation. The CBM is more relevant for wavelength-scale scatterers than for scatterers in the geometric-optics regime.

The theory that the radar scattering could be affected by diffuse and coherent backscattering was first proposed by Hapke [1990] followed by support from Peters [1992] and Mishchenko [1992], and since, has been considered one of the most significant factors to increase the circular-polarization ratio.

The coherent backscattering term, or the cyclical component at backscattering (superscript C), can be theoretically derived from the ladder components (superscript L) Mishchenko [1996]:

\[ \alpha = 180^\circ - \theta \]

The numbers 1, 2, ..., N depict the order of scattering.

Figure 2.2: The interference effect of the coherent-backscattering mechanism. The phase angle \( \alpha = 180^\circ - \theta \).
Chapter 2. Electromagnetic scattering

\[ P_{11}^C = \frac{C_{\text{sca}}^L}{2C_{\text{sca}}^C} (P_{11}^L + P_{22}^L - P_{33}^L + P_{44}^L), \]
\[ P_{22}^C = \frac{C_{\text{sca}}^L}{2C_{\text{sca}}^C} (P_{11}^L + P_{22}^L + P_{33}^L - P_{44}^L), \]
\[ P_{33}^C = \frac{C_{\text{sca}}^L}{2C_{\text{sca}}^C} (-P_{11}^L + P_{22}^L + P_{33}^L + P_{44}^L), \]
\[ P_{44}^C = \frac{C_{\text{sca}}^L}{2C_{\text{sca}}^C} (P_{11}^L - P_{22}^L + P_{33}^L + P_{44}^L). \]

If only the incoherent (radiative transfer, superscript "RT") part, and the first-order-scattering (superscript "(1)") part are available, the ladder part is computed so that

\[ C_{\text{sca}}^L P^L = C_{\text{sca}}^{\text{RT}} P^{\text{RT}} - C_{\text{sca}}^{(1)} P^{(1)} \] (2.19)

Using these equations, \( \hat{\sigma}_{\text{SC}} \) and \( \hat{\sigma}_{\text{OC}} \) including both the radiative-transfer and the cyclical parts are therefore

\[ \hat{\sigma}_{\text{SC}} = \frac{q_{\text{sca}}^{\text{RT}}}{2} (P_{11}^{\text{RT}} + R_{11} + P_{44}^{\text{RT}} + R_{44}), \]
\[ \hat{\sigma}_{\text{OC}} = \frac{q_{\text{sca}}^{\text{RT}}}{2} (P_{11}^{\text{RT}} + R_{11} - P_{44}^{\text{RT}} - R_{44}), \]
\[ R_{11} = \frac{1}{2} \left[ P_{11}^{\text{RT}} + P_{22}^{\text{RT}} - P_{33}^{\text{RT}} + P_{44}^{\text{RT}} - \left( P_{11}^{(1)} + P_{22}^{(1)} - P_{33}^{(1)} + P_{44}^{(1)} \right) \frac{\sigma_{s}^{(1)}}{\sigma_{R}^{(1)}} \right], \]
\[ R_{44} = \frac{1}{2} \left[ P_{11}^{\text{RT}} - P_{22}^{\text{RT}} + P_{33}^{\text{RT}} + P_{44}^{\text{RT}} - \left( P_{11}^{(1)} - P_{22}^{(1)} + P_{33}^{(1)} + P_{44}^{(1)} \right) \frac{\sigma_{s}^{(1)}}{\sigma_{R}^{(1)}} \right]. \] (2.20)

2.6 Electromagnetic properties of planetary surfaces

The electromagnetic properties of a material include the electric permittivity, magnetic permeability, and the conductivity (\( \epsilon, \mu, \) and \( \sigma, \) respectively) [Bohren and Huffman, 1983]. Using these parameters, the complex refractive index, \( m, \) a dimensionless number that describes how radiation propagates through a medium, can be derived so that

\[ m = m_R + im_\Im = \sqrt{\mu_r \epsilon_r}, \] (2.21)
2.6. Electromagnetic properties of planetary surfaces

where \( \epsilon_r = \epsilon/\epsilon_0 = \epsilon_{r,\Re} + i\epsilon_{r,\Im} \) and \( \epsilon_{r,\Im} = \sigma/(2\pi f) \), where \( f \) is the frequency of the incident radiation. The real part of the refractive index, \( m_\Re \), is the ratio of the speed of light in vacuum and the phase velocity of the radiation in the medium. The imaginary part, \( m_\Im \), is related to the absorption of the medium: If \( m_\Im = 0 \), the scattering particle or medium is non-absorbing. Note that all the parameters are relative to the host environment, e.g., \( \epsilon_r = \epsilon/\epsilon_m \), where \( \epsilon \) is the permittivity of the scatterer and \( \epsilon_m \) that of the host medium, and that we will assume the material non-magnetic (\( \mu_r = \mu/\mu_0 = 1 \)).

The real and imaginary parts of the relative refractive index and the relative electric permittivity are related as follows:

\[
\begin{align*}
\epsilon_{r,\Re} &= m_\Re^2 - m_\Im^2, \\
\epsilon_{r,\Im} &= 2m_\Re m_\Im, \\
m_\Re &= \sqrt{|\epsilon_r| + \epsilon_{r,\Re}/2}, \\
m_\Im &= \sqrt{|\epsilon_r| - \epsilon_{r,\Re}/2},
\end{align*}
\]

where \( |\epsilon_r| = \sqrt{\epsilon_{r,\Re}^2 + \epsilon_{r,\Im}^2} \) [Bohren and Huffman, 1983].

The electric permittivity and the magnetic permeability depend on the frequency. In Papers III and V, we have selected values of electric permittivity using those measured by Campbell and Ulrichs [1969] at microwave wavelengths of 430 MHz and 35 GHz as guidelines. For example, for olivine and anorthosite, refractive indices of \( 2.49 + 0.01i \) and \( 2.61 + 0.01i \), respectively, can be deduced from the reported electric permittivities. For basalts, the measured refractive indices vary from \( 2.37 + 0.012i \) to \( 3.10 + 0.145i \). For meteorites with very high proportions of metallic iron, \( m_\Re > 4 \) and \( m_\Im > 1 \).

Table 2.1 lists some example materials that were studied in Papers III and V as well as their estimated electric permittivity and refractive index. The first section includes ice and three types of rocky material. The first type of rock ("rock 1") is fractured or porous, weathered siliceous rock or anorthosite with a negligible content of metal. The second type ("rock 2") is solid siliceous rock with low metal content. The third type of rock is basalt or siliceous rock with a high metal content.

The electric properties of ice depend on its purity. If ice is not completely pure water ice but is assumed to include microscale impurities such as dust or other non-volatiles, the real and imaginary parts of the refractive index increase slightly (here, from \( m = 1.76 + 0i \) to \( m = 1.78 + 0.001i \)).

The second section lists electric properties of meteorites at 100 MHz (E. Heggy, personal communication). The frequency that is used differs from the preferred
frequency by a magnitude of about 20, but the measured materials are better analogs to asteroids. In meteorite classification, LL refers to very low metal abundance, L to relatively low, and H to relatively high metal abundance. Mesosiderites have a very high metal abundance. This shows how the abundance of metal affects the electric properties.

Table 2.1: Example electric permittivities and refractive indices at microwave frequencies of some materials that can be found in planetary environments. In the first section, the values have been estimated using measurements from regular rocks as guidelines. In the second section, the electric properties have been characterized using meteorites.

<table>
<thead>
<tr>
<th>Material</th>
<th>Electric permittivity</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure water ice (Ice 1)</td>
<td>$3.10 + 0.0i$</td>
<td>$1.76 + 0.0i$</td>
</tr>
<tr>
<td>Impure ice (Ice 2)</td>
<td>$3.17 + 0.004i$</td>
<td>$1.78 + 0.001i$</td>
</tr>
<tr>
<td>Rock 1</td>
<td>$4.67 + 0.022i$</td>
<td>$2.16 + 0.005i$</td>
</tr>
<tr>
<td>Rock 2</td>
<td>$6.45 + 0.051i$</td>
<td>$2.54 + 0.01i$</td>
</tr>
<tr>
<td>Basalt or stony iron</td>
<td>$8.53 + 0.18i$</td>
<td>$2.92 + 0.03i$</td>
</tr>
<tr>
<td>LL5-meteorite</td>
<td>$4.7 + 0.016i$</td>
<td>$2.17 + 0.004i$</td>
</tr>
<tr>
<td>L5-meteorite</td>
<td>$5.6 + 0.027i$</td>
<td>$2.37 + 0.006i$</td>
</tr>
<tr>
<td>H5-meteorite</td>
<td>$5.8 + 0.021i$</td>
<td>$2.41 + 0.004i$</td>
</tr>
<tr>
<td>Mesosiderite</td>
<td>$8.0 + 0.090i$</td>
<td>$2.83 + 0.016i$</td>
</tr>
</tbody>
</table>

Figure 2.3 shows the OC radar albedo plotted as a function of the refractive index when only specular scattering is considered (computed with Eq. 2.10). This provides us with implications on a possible refractive index based on known $\hat{\sigma}_{OC}$ (see Fig. 1.4). Measured refractive indices of certain meteorite classes (Table 2.1) can be used to evaluate the credibility of these estimates: LL5-meteorites with a very low content of metal are likely the best analogies to C- and S-type asteroids; whereas mesosiderites with a high content of metal are likely better analogies to M-type asteroids.

Determining the refractive index is important not only with regard to modeling, but can help to evaluate the chemical (e.g., the content of metal) and structural composition (e.g., the density or the porosity) of the surface, which are related to the refractive index. Consequently, implications of the formation of the planetary body can be acquired.

For example, the mean OC radar albedo for the C-complex asteroids is $\hat{\sigma}_{OC} \approx 0.10 \pm 0.05$. This constrains the refractive indices to the range 1.6-2.3. For S-type asteroids, the range is moderately wider, from 1.9 to 2.8, and also the absorption is possibly slightly higher. By computing the refractive indices from the average
2.6. Electromagnetic properties of planetary surfaces

Figure 2.3: The OC radar albedo as a function of the refractive index using $\hat{\sigma}_{OC} = gR_F$ with $g = 1$, i.e., a large, absorbing particle that has a radius of curvature much larger than the wavelength at any point on the surface (the black solid line). For asteroids (horizontal dashed lines), the OC radar albedo is known, and for the meteorites (vertical dashed lines), the effective refractive index has been measured. The relation can be used to estimate the refractive indices of different taxonomic types. "Mes." refers to mesosiderites.

For asteroids, the observed values of $\hat{\sigma}_{OC}$ using Equation 2.10, $m = 2.16 + 0.005i$ would fit best for the refractive index of C-complex asteroids, and $m = 2.54 + 0.01i$ for that of S-complex.

In terms of comets, the observed OC radar albedos are relatively low, which suggests low refractive indices ($|m| < 2$) as well. However, considering the surface as solid ice is likely unrealistic. As I stated in Section 1.1, spectral measurements by the Rosetta spacecraft of the comet 67P/Churyumov-Gerasimenko suggest crustal composition of polyaromatic organic solids mixed with sulfides and iron-nickel alloys instead of water ice [Capaccioni et al., 2015].

For X-complex asteroids with high metal content, $m = 2.8 + 0.02i$ or higher values for both the real and the imaginary parts could be realistic based on the measurements for mesosiderites. For M-type asteroid (216) Kleopatra, the radar observations show $\hat{\sigma}_{OC} \approx 0.52$ (with $\mu_C = 0$), which would imply $|m| = 6.2$. Note
that if the iron content is high, also the magnetic permeability can exceed 1, and thus, affect the refractive index, as given by Equation 2.21. However, as is evident in Figure 1.4, the X-complex has the widest range of values in $\tilde{\sigma}_{OC}$, implying a wide spread of compositions. As is well known, all X-complex asteroids are not rich in metal content although their spectra measured at optical and infrared wavelengths may be similar.
3 Computational methods

Electromagnetic scattering can be simulated with a vast number of computational methods. Each code has its own advantages and constraints; some codes are optimized in accuracy, some codes are fast, and some codes are both accurate and fast but can only be utilized for very specific, simplified geometries or sizes.

The Mie theory was developed by Gustav Mie in 1908 to theoretically describe the scattering by an isotropic spherical particle with size comparable to the wavelength of incident radiation. In addition to the theoretical formulation of the Mie theory, Bohren and Huffman [1983] present the theory with a numerical algorithm. This is an example of a fast and rigorous algorithm, which can be used only for spherical particles, and is utilized for the purpose in this thesis as well. For less symmetric geometries, other algorithms are required.

3.1 Multiple sphere T-matrix method

The $T$-matrix method is a method for computing electromagnetic scattering by spherical as well as non-spherical particles, published by Waterman [1965]. Also the names null-field method and extended boundary condition method are sometimes used. The solution is turned into a single $T$-matrix representation that transforms vector spherical-harmonics coefficients of the incident field to the coefficients of the scattered field, and needs to be computed only once for a given particle.

The multiple-sphere $T$-matrix method (MSTM, Mackowski and Mishchenko [2011]) used in the present work is an approach involving a superposition solution to the Maxwell equations for the multiple spherical boundary domain. It is a rigorous method that simulates the electromagnetic radiation for an arbitrary number of spheres. Using MSTM, electromagnetic scattering by inhomogeneous bodies may also be simulated, but only using spherical inhomogeneities.
3.2 Discrete-dipole approximation

The Discrete-Dipole Approximation (DDA) [Purcell and Pennypacker, 1973, Draine and Flatau, 1994] is a method, in which the scatterer is divided into a discrete set of dipoles on a cubic lattice. The dipoles form a group of linear equations for the total electric field, and consequently, the scattering matrices as well as the extinction, scattering, and absorption cross sections.

The discrete-dipole algorithm used in the thesis is the Amsterdam Discrete-Dipole Approximation (ADDA) [Yurkin et al., 2007]. Briefly, the DDA formulations for the electric field implemented in ADDA utilize the dipole polarizations $\mathbf{P}_i$:

$$\alpha_i \mathbf{P}_i - \sum_{j=1,j\neq i}^N G_{ij} \mathbf{P}_j = \mathbf{E}_{\text{inc}}^i, \quad i, j = 1, 2, 3, \ldots, N. \quad (3.1)$$

Here, $\mathbf{E}_{\text{inc}}^i$ is the incident electric field, $\alpha_i$ is the dipole polarizability (the bar depicting a tensor), $G_{ij}$ is the interaction term, and indices $i$ and $j$ enumerate the dipoles. The dipole polarization is also

$$\mathbf{P}_i = \alpha_i \mathbf{E}_{\text{exc}}^i = V \chi \mathbf{E}_{\text{tot}}^i, \quad (3.2)$$

where $\mathbf{E}_{\text{exc}}^i$ is the exciting field, the sum of the incident field and the field due to all dipoles excluding the dipole $i$ itself. $V$ is the volume of a dipole, $\chi$ the electric susceptibility of the dipole, and finally, $\mathbf{E}_{\text{tot}}^i$ is the total scattered electric field. For more details, see, for instance, a recent paper by Yurkin and Hoekstra [2011].

3.3 Siris

For the modeling of Gaussian-random-sphere (GRS) particles (see detailed theory in Section 4.3), we use a code developed by Muinonen et al. [2009] for simulating electromagnetic scattering by GRS particles in the geometric-optics regime, i.e., irregular particles that are large compared to the wavelength of the incident waves. The propagation of the electromagnetic radiation can be described using rays that travel in straight lines refracting and reflecting at interfaces between different media.

In the code, the geometry, size, and material of the particles are user-definable. It is also possible to include diffuse internal or external scattering in the computations by using the scattering phase matrix to describe the redistribution of energy on each scattering. This can also be understood as the probability with which the ray scatters to a certain direction.
3.3. Siris

The number density of the scatterers or the mean distance between two consecutive scattering events is described using the optical thickness ($\tau_s$) for diffuse external scatterers, and the mean free path ($l$) for the diffuse internal scatterers. In addition, the single-scattering albedo is defined to describe the energy loss due to absorption. Extinction is assumed to be exponential.

The scalar extinction coefficient, $k_0$, can be used for describing both $\tau_s$ and $l$:

$$\tau_s = \int_0^s k_0 ds = k_0 s = s/l, \quad l = \frac{1}{k_0},$$

where, using the number and volume densities $n_0$ and $v_0$, respectively,

$$k_0 = n_0 q_{\text{ext}} \pi a^2 = \frac{3v_0 q_{\text{ext}}}{4a}, \quad n_0 = \frac{3v_0}{4\pi a^3}. \quad (3.4)$$

The values of $l$ and $\tau_s$ that we study in Paper V are listed in Table 3.1. The geometric, projected surface density of the layer of diffuse external medium is

$$\kappa_s = (1 - e^{-\tau_s}) \times 100\% \quad (3.5)$$

<table>
<thead>
<tr>
<th>$l$ (m)</th>
<th>0.13</th>
<th>0.38</th>
<th>0.63</th>
<th>1.26</th>
<th>2.52</th>
<th>5.04</th>
<th>10.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$ ((\lambda))</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>10</td>
<td>20</td>
<td>40</td>
<td>80</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>3.08</td>
<td>1.05</td>
<td>0.63</td>
<td>0.32</td>
<td>0.16</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>$\kappa_s$ (%)</td>
<td>95</td>
<td>65</td>
<td>47</td>
<td>27</td>
<td>15</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 3.1: The corresponding values of mean free path ($l$) and optical thickness ($\tau_s$) for $\lambda = 12.6$ cm. The optical thickness corresponds to the mean free paths with a mean layer thickness of 40 cm. The bottom line lists the geometric, projected surface density of the layer of diffuse external medium for each optical thickness.

As a Monte Carlo ray-tracing method, the output always includes numerical noise. Therefore, we optimize the CPU time by using enough (6-10 million) rays to reach an acceptable accuracy for the scattering matrix, and carry out a smoothing spline fit [Hastie and Tibshirani, 1990] to the required scattering-matrix elements before computing the CBM corrections and the radar parameters.

For example, if we model the scattering-matrix elements by the relation $Y_i = \eta(\theta_i)$, where $\theta_i$ is one scattering angle between 90° and 180° with a resolution of 1°, the smoothing spline estimate $\hat{\eta}$ of the function $\eta$ is defined to be the minimizer of

$$f(\hat{\eta}, \hat{\beta}, \theta) = \sum_{i=1}^{91} (Y_i - \hat{\eta}(\theta_i))^2 + \hat{\beta} \int_{90^\circ}^{180^\circ} \hat{\eta}''(\theta)^2 d\theta. \quad (3.6)$$

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Above, $\hat{\beta}$ is a smoothing parameter that controls the fidelity between the data and roughness of the function estimate. Here, $\hat{\beta} = 0.1$ has been selected. The values have been chosen empirically so that the fit does not excessively try to follow the noise (too small value) nor to smooth down the possible curvature (too high value).
4 Geometry defines radar scattering

In the thesis, I have studied radar scattering by isotropic clusters of spherical particles (Section 4.1, Papers I and IV) and inhomogeneous single and clusters of spherical particles in the resonance regime (Section 4.2, Paper II). Also, radar scattering by Gaussian-random-sphere (GRS) particles in the geometric-optics regime (Section 4.3, Paper III) has been investigated. These computations are focused on the roles that specific geometries, sizes, and materials play in radar scattering.

In Paper V, we first compute the scattering properties of small (resonance regime) irregular particles, which are then utilized as diffuse internal or external scatterers inside or on the surface of large GRS particles. In the same paper, we also investigate further the effect of the scatterer geometry in terms of both single and multiple scattering (Sect. 4.4).

As for other research carried out on the subject, two of the mechanisms of how multiple scattering increases the observed polarization ratio (circular or linear) are examined by Campbell [2012]. The first one is dihedral scattering, which assumes locally wide and smooth facets in wavelength-scale oriented in right-angle pairs, allowing two mirror-like reflections for backscattering. The second one is scattering from dipole elements, i.e., subwavelength-scale cracks or rock edges in the scattering medium are considered as dipole-like elements. The scattering from dipole elements is more realistic in terms of planetary surfaces, but also more complicated to simulate.

The scattering by dipole elements is related to the coherent-backscattering mechanism, which causes enhancement of intensity at backscattering by large number of wavelength-scale scatterers illuminated with coherent radiation [Akkermans et al., 1986, Muinonen, 2004]. Nelson et al. [2000] have shown the enhancement effect also for circular polarization ratio, and, for example, Hapke [1990] and Black et al. [2001] have explained the high circular polarization ratios of the Galilean moons with the coherent-backscattering mechanism.

Other geometries, for which radar scattering properties have been studied on the resonance regime are, for example, prolate and oblate spheroids by Mishchenko and Hovenier [1995], spheroids, cylinders, and Chebyshev particles by Mishchenko
and Sassen [1998], and various non-spherical single scatterers (broken agglomerated particles, GRS particles etc.) in the resonance-regime by Zubko [2012].

### 4.1 Isotropic spherical particles

A sphere is an easy choice of geometry in terms of modeling. It is convenient for constructing various other shapes and the scattering by spherical particles is numerically well-founded both for single and multiple particles.

For spherical scatterers, the scattered radiation follows from the vector spherical harmonics coefficients of the Lorenz-Mie theory [Bohren and Huffman, 1983]:

\[
\begin{align*}
A_l &= \frac{m\psi_l(mx)\psi'_l(x) - \psi_l(x)\psi'_l(mx)}{m\psi_l(mx)\xi'_l(x) - \xi_l(x)\psi'_l(mx)}, \\
B_l &= \frac{\psi_l(mx)\psi'_l(x) - m\psi_l(x)\psi'_l(mx)}{\psi_l(mx)\xi'_l(x) - m\xi_l(x)\psi'_l(mx)}. \tag{4.1}
\end{align*}
\]

Here, \(\psi_l\) and \(\xi_l\) are Riccati-Bessel functions and strictly related to the spherical Bessel and Hankel functions \(j_l\) and \(h_l^{(1)}\) so that

\[
\psi_l(x) = x j_l(x), \quad \xi_l(x) = x h_l^{(1)}(x). \tag{4.2}
\]

At backscattering, for example, the amplitude function

\[
S_1(180^\circ) = S_2(180^\circ) = \sum_{l=0}^{\infty} (-1)^l (l + \frac{1}{2})(a_l - b_l). \tag{4.3}
\]

As a result, \(F_{11} = F_{22} = -F_{44}\); therefore, for a single sphere \(\mu_C = \mu_L = 0\).

In terms of radar scattering, spherical particles can be somewhat problematic in terms of polarization properties. Due to the symmetries in the geometry, scattering phenomena such as strong constructive or destructive interferences, only applicable to clusters of monodisperse spherical particles can emerge (see Fig. 4.1). Albeit finding perfectly spherical scatterers in nature can be unlikely, we can learn something about the physical properties of scatterers that affect the SC and OC radar albedos.

Figure 4.1 shows \(\hat{\sigma}_{\text{SC}}, \hat{\sigma}_{\text{OC}},\) and their ratio \(\mu_C\) in the \(m-x\) space using bispherical particles. The pattern in \(\mu_C(m, x)\) has been shown to be reproduced by clusters of spherical particles in Paper I. In each panel, two sets of bands can be distinguished: the first, primary band, becomes asymptotically vertical on smaller size parameter values and asymptotically horizontal on larger size parameter values. The numerous secondary bands are more vertical relative to the primary band. For \(\hat{\sigma}_{\text{OC}},\) several primary bands are distinct; whereas for \(\hat{\sigma}_{\text{SC}},\) only one can be distinguished. Note also that, for a single spherical particle, \(\hat{\sigma}_{\text{OC}}(m, x)\) appears similar but \(\hat{\sigma}_{\text{SC}} = 0.\)
4.1. ISOTROPIC SPHERICAL PARTICLES

Figure 4.1: From left to right: The SC radar albedo ($\hat{\sigma}_{SC}$), the OC radar albedo ($\hat{\sigma}_{OC}$), and the circular-polarization ratio ($\mu_{C}$), each as a function of the refractive index ($m$) and the sphere size parameter ($x$) computed in the orientation-averaging setup for a bispherical particle.

The primary band of $\mu_{C}(m, x)$ is a result of enhancement by the primary band of $\hat{\sigma}_{SC}$ and, at higher values of $m$ and $x$, attenuation by the (first) primary band of $\hat{\sigma}_{OC}$. Subsequent primary bands of lower amplitude exist as a result of the multiple primary bands of $\hat{\sigma}_{OC}$, but here, we concentrate on the most distinct band.

Also, the extinction efficiency by a single spherical particle can produce a pattern constituting of similar features as the primary and secondary bands, i.e., interference and ripple structure, respectively (see, e.g., Ch. 10 of van de Hulst [1957] or Sec. 4.4.2 and Ch. 11 of Bohren and Huffman [1983]). The maxima of the interference and ripple structure of the more systematic extinction efficiency do not mainly coincide with the presented bands at backscattering, so it is reasonable to keep the terminology separated. In addition, the amplitude of the secondary bands greatly exceeds that of the ripple structure. The ripple structure includes the even finer-structured morphology-dependent resonances (MDRs, Hill and Benner [1988]), which also should not be confused with the pattern.

However, it is plausible that the features have similar roots. The interference can be stronger in different directions on different values of $m$ and $x$. This implies that the primary band is an enhancement effect by a general scattering capability of a particle at certain values of $m$ and $x$.

Figure 4.2 illustrates $\hat{\sigma}_{SC}$ and $\hat{\sigma}_{OC}$ as functions of $x$ using clusters with different numbers of particles. As for the material, we use here the refractive index of water ice at microwave frequencies, i.e., $m = 1.78 + 0i$ [Warren, 2008]. As Fig. 4.2 shows, there is relatively little difference between 1, 2, 10, and 50 spheres in terms of the structure...
Chapter 4. Geometry defines radar scattering

Figure 4.2: The comparison of $\hat{\sigma}_{OC}(x)$ (black) and $\hat{\sigma}_{SC}(x)$ (gray) between 1, 2, 10, or 50 spherical particles in a cluster. Here, $m = 1.78 + 0i$. For one particle, $\hat{\sigma}_{SC} = 0$.

of the functions. Therefore, it is a valid approximation to study the backscattering by multiple spheres using bispheres.

Different orientations contribute to different peaks as shown in Fig. 4.3. However, as long as the scattering by a cluster is orientation-averaged and the near-field enhancement is comparable, the pattern with distinct primary and secondary bands emerges.

The effect of the distance ($d$ in units of size parameters) on $\hat{\sigma}_{SC}$, $\hat{\sigma}_{OC}$, and $\mu_C$ is illustrated in Fig. 4.4. When the spherical particles are brought further apart, $\hat{\sigma}_{SC}$ attenuates proportional to $d^{-2}$ (i.e., energy received by the second particle); whereas $\hat{\sigma}_{OC}$ oscillates. This implies that $\hat{\sigma}_{OC}$ is sensitive to the far-field interference effects and $\hat{\sigma}_{SC}$ to the near-field effects, but not vice versa. For multiple spherical particles in close proximity, the waves can set on trajectories, on which the polarization helicity does not convert as sharply.

The different orders of scattering can be separated as illustrated in Fig. 4.5 to demonstrate the effect of different trajectories. Figure 4.6 shows $\hat{\sigma}_{SC}$ and $\hat{\sigma}_{OC}$ as

\footnote{Note that here the orientation-average refers only to a few tens of orientations seen in the top-row panels of Fig. 4.4, not orientation average over hundreds or thousands of orientations, as the term is commonly understood.}
4.1. Isotropic spherical particles

Figure 4.3: On the left: The effect of orientation on $\hat{\sigma}_T$ (on the top) and $\mu_C$ (on the bottom) as a function of the orientation, $\alpha$, and the size parameter, $x$. On the right: $\mu_C + 1$ (solid lines) and $\hat{\sigma}_T/10$ (dashed lines) as a function of $\alpha$ for a few specific values of $x$. The circles above the lines illustrate the size and orientation of the bispherical particles that cause the peak below each one.

well as $\mu_C$ for orientation-averaged bispherical particles computed up to the first, second, or third order of scattering using a volume-integral-equation method JVIE by Markkanen et al. [2012]. In order to demonstrate the effect of the near-field (non-propagating part), the electromagnetic coupling between the spheres is separated into the propagating and non-propagating parts in a sense of Weyl expansion\(^2\).

Here, we see that for $\hat{\sigma}_{OC}$, already the first-order scattering (i.e., the backscattering by a single sphere) is a good approximation and, therefore, can be theoretically approximated using the Mie theory. As for $\hat{\sigma}_{SC}$, the second-order scattering of bispherical particles is required for a relatively good approximation, and the third order for a very good. For $\hat{\sigma}_{SC}$, also the near-field enhancement is required. The peaks of $\mu_C$, i.e., the coincidence points of the primary and secondary bands, are thus a result of interference change in $\hat{\sigma}_{OC}$, but also the second-order scattering that increases the SC component.

As presented in Paper I, the positions of the secondary bands in the $m$-$x$ space are strictly tied to the size and material of the spheres. Compared to a larger number of spherical particles, in a closely-packed cluster of uniform size distribution, the

\(^2\)The Weyl expansion is a half-space representation containing both evanescent and homogeneous plane waves for the scalar spherical wave that is related to the electromagnetic field propagator.
Chapter 4. Geometry defines radar scattering

Figure 4.4: The effect of the distance (unit 1 size parameter) between two spheres on $\hat{\sigma}_{SC}$ (left), $\hat{\sigma}_{OC}$ (middle), and on $\mu_C$ (right), when $x = 2.2$. On the top, the orientation is fixed, and on the bottom, the orientation average is depicted (solid lines). The dashed line in the left bottom panel shows the decrease of $\hat{\sigma}_{SC}$ proportional to $d^{-2}$, here $0.4(d/x)^{-2}$.

Figure 4.5: The first, second, and third order of scattering, respectively.
4.2 Inhomogeneous spherical particles

If the spherical particle under investigation is not homogeneous, scattering can become less predictable, but also more interesting. Because the depolarization properties by a homogeneous spherical particle are well-known ($\mu_C = \mu_L = 0$), comparing the backscattering properties with those of an inhomogeneous spherical particle should provide implications of the effect of the material on the depolarization. After we have an estimate of how inhomogeneous spherical particles compare to isotropic spherical particles, geometric complexity can be increased to see if similar differences can be observed.

For inhomogeneous single spherical particles, the magnitude of $\mu_C$ is directly proportional to the effective refractive index of the particle. Using large values of refractive index (effective refractive index from $m = 2.587 + 0.0157i$ to $m = 2.663 + 0.0182i$), the phase shift can increase $\mu_C$ up to magnitudes from 0.01 to 0.1. Using smaller values of refractive index (effective refractive index from $m = 1.821 + 0.0081i$ to $m = 1.853 + 0.0076i$), the values of $\mu_C$ are at least one order of magnitude less (0.005 or less).

For clusters of spheres, the inhomogeneity has little effect on the radar observables (Fig. 4.7). As expected, the depolarization arises from the the most prominent secondary bands remain in place, although the local values may vary slightly due to variations in the near-field enhancement.

Figure 4.6: From the left to right: $\hat{\sigma}_{SC}$, $\hat{\sigma}_{OC}$, and $\mu_C$ for orientation-averaged bi-spherical particles summed up to the first (dark gray), second (mid-gray), or third order of scattering (light gray), when the near-field is included (circles) or excluded (diamonds). The solid black line depicts the exact solution.
Figure 4.7: The comparison of the MSTM computations (solid lines) to the ADDA computations for $\mu_C$ (on the left) and $\hat{\sigma}_T$ (on the right) as a function of the equal-volume-sphere size parameter. The black solid line represents aggregates of spherical particles with $m = 2.49 + 0.0124i$ (45 % of the mass density) and $m = 2.68 + 0.0188i$ (55 %), and the grey solid line represents those with $m = 1.78 + 0.0089i$ (45 %) and $m = 1.86 + 0.0074i$ (55 %). The diamond markers with corresponding colors depict the ADDA computations using the same aggregates as for the MSTM; whereas the circles and triangles depict aggregates with a different inhomogenization (see Paper II) with mass density ratios of 48% and 37% instead of 45%, respectively.
irregularities. Therefore, if inhomogeneity is the only factor of asymmetry in the
scatterer, it can have a depolarizing effect, and the electric permittivity plays a
primary part. If the particle is irregular, the geometry of the scatterer dominates the
effect of the permittivity variations inside the particles. The particles, for which also
$\mu_C$ produces peaks, are the most sensitive to the variations in the electric permittivity.

### 4.3 Large Gaussian-random-sphere particles

For mimicking large boulders on planetary surfaces, we utilized irregular Gaussian-
random-sphere (GRS) particles (see Fig. 4.8).

![Figure 4.8: The upper row: Gaussian-random-sphere (GRS) particles with the stan-
dard deviation of the radius $\sigma_r = 0.05, 0.1, \text{ and } 0.2$ (respectively from
the left to the right) and $\nu = 4$. The lower row: The standard deviations as above,
but here $\nu = 3$. The particles have been generated using the same random-number
sequences.](image)

The Gaussian-random-sphere particle $r = r(\vartheta, \varphi)e_r$ is described in spherical co-
dinates $(\vartheta, \varphi)$ by the spherical-harmonics series for the logarithmic radial distance
s = s(\vartheta, \varphi) [Muinonen et al., 1996, Peltoniemi et al., 1989]:

\[ r(\vartheta, \varphi) e_r = \frac{a \exp [s(\vartheta, \varphi)]}{\sqrt{1 + \sigma_r^2}} e_r, \]

\[ s(\vartheta, \varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} s_{lm} Y_{lm}(\vartheta, \varphi), \tag{4.4} \]

\[ s_{l,-m} = (-1)^m s_{lm}^*, \]

where \( a \) and \( \sigma_r \) are the mean and relative standard deviation for the radial distance, \( Y_{lm}s \) are the orthonormal spherical harmonics, and \( s_{lm}s \) are Gaussian random variables with zero means. The sufficient and necessary set of independent variables consists of Re(\( s_{lm} \)) with \( m \geq 0 \) and Im(\( s_{lm} \)) with \( m > 0 \) (\( \text{Im}(s_{l0}) = 0 \)).

The standard deviations of Re(\( s_{lm} \)) and Im(\( s_{lm} \)) follow from the covariance function \( \Sigma_s \) for the random variable \( s \). \( \Sigma_s \) describes the auto-covariance of the random variables \( s(\vartheta_1, \varphi_1) \) and \( s(\vartheta_2, \varphi_2) \), an angular distance \( \gamma \) apart, and is given by a series of Legendre polynomials \( P_l \):

\[ \Sigma_s(\gamma) = \sum_{l=0}^{\infty} C_l P_l(\cos \gamma), \quad \sum_{l=0}^{\infty} C_l = \log_e(1 + \sigma_r^2), \tag{4.5} \]

where the coefficients \( C_l \geq 0 \) (\( l = 0, \ldots, \infty \)). In practice, the series representations in Eqs. (4.4) and (4.5) are truncated at a maximum degree \( l_{\text{max}} \). In detail, the random variables \( s_{lm} \) are

\[ s_{lm} = \sqrt{\frac{2\pi C_l}{2l+1}} \left( x_G \sqrt{1 + \delta_{m0}} + iy_G \sqrt{1 - \delta_{m0}} \right), \quad l = 0, 1, \ldots, \infty, \quad m = 0, 1, \ldots, l, \tag{4.6} \]

where \( x_G \) and \( y_G \) are Gaussian random variables with zero means and standard deviations equal to unity.

The GRS is parameterized by \( a \) and \( C_l \) (\( l = 0, \ldots, \infty \)). We choose the power-law covariance function and thus further parameterize \( C_l \) by

\[ C_0 = C_1 = 0, \]

\[ C_l = \frac{\tilde{C}}{l^\nu}, \quad l = 2, 3, \ldots, l_{\text{max}}, \]

\[ \tilde{C} \sum_{l=2}^{l_{\text{max}}} \frac{1}{l^\nu} = \log_e(1 + \sigma_r^2) \Rightarrow \tilde{C} = \log_e(1 + \sigma_r^2) \left[ \sum_{l=2}^{l_{\text{max}}} \frac{1}{l^\nu} \right]^{-1}, \tag{4.7} \]
where the power-law index $\nu$ and the standard deviation $\sigma_r$ are the two statistical shape parameters and $\tilde{C}$ is a normalization constant.

In the numerical methods, the GRS sample particles are described using a triangular mesh. The mesh is obtained by dividing the full solid angle into octants, and dividing each octant into $N_r$ rows containing $1, 3, 5, \ldots, 2N_r - 1$ triangles from the poles toward the equator on a uniform mesh in the polar angle. Depending on the number of rows, there are thus altogether $8N_r^2$ triangles representing the shape, and altogether $4N_r^2 + 2$ nodes defining triangle corners. For the current computations, using $N_r = 30$, the number of triangles totals 7200.

Figure 4.9 illustrates the effect of the particle size and geometric irregularity on radar scattering ($\mu_C$ and $\hat{\sigma}_{OC}$) by GRS particles computed using Siris. Here, I visualize the fact that the OC radar albedo approaches pure Fresnel reflection (Eq. 2.10) as all internal refractions and reflections cease to affect the backscattering.

When the absorption is either negligible or very strong (i.e., $m_\infty \geq 0.01$), the effect of the size becomes insignificant in the geometric-optics regime. The explanation is simple: For non-absorbing particles, the internally scattered waves contribute equally regardless of the size of the particles. When the absorption increases, the contribution of the internally scattered waves decreases due to the size of the particle, i.e., the distance travelled inside it, or because the absorption is higher to begin with.

As a result, we can derive a semi-empirical model for the radar albedo of GRS particles (in the geometric-optics regime) so that

$$\hat{\sigma}_{OC} = G_{OC}(\sigma_r, \nu, m, ...) \exp\left(\frac{-4\pi m_\infty \lambda d}{\lambda}\right) + R_F, \quad (4.8)$$

$$\hat{\sigma}_{SC} = G_{SC}(\sigma_r, \nu, m, ...) \exp\left(\frac{-4\pi m_\infty \lambda d}{\lambda}\right). \quad (4.9)$$

Here, $R_F$ is the Fresnel reflectivity (cf. Eq. 2.10), and $d$ is the mean distance that the wave travels inside a sample particle with a mean radius $a$. The value of $d$ depends on the shape and the refractive properties of the scatterer. Theoretically, it should be approximately 4 (i.e., one internal reflection along the diameter of the particle). The parameters $G_{OC}$ and $G_{SC}$ are the positive gain factors that depend on the geometry and, possibly in some cases, the material of the target. For the particles in this study, the effect of the refractive index on the gain factors is in all cases small, and in most cases negligible.

The structure of the equations that follow the shape parameters $G$ can be deduced from well-known principles of electromagnetic scattering. As a wave propagates in a medium for a path length $z$, the attenuation of irradiance $I$ (energy per unit area and time) is such that $I = I_0 \exp(-4\pi m_\infty z/\lambda)$ (see, e.g., Bohren and Huffman [1983], p.
Chapter 4. Geometry defines radar scattering

Figure 4.9: The OC radar albedo and the circular-polarization ratio of different materials as a function of the mean radius. Here, water ice is compared with siliceous rock and basalt or metal-rich rock (the shade of gray darkening as the refractive index increases as given in the first section of Table 2.1). On the top, the standard deviation of the radius ($\sigma_r$) equals 0.05, in the middle, $\sigma_r = 0.1$, and on the bottom, $\sigma_r = 0.2$. Notice the different scale of the OC radar albedo in the top panel, and that here $\lambda = 12.6$ cm.
29). For particles that are large enough to absorb all internal waves, $\sigma_T$ approaches $R_F$ as shown in, e.g., Bohren and Huffman [1983], p. 123.

As compared to the gain factor, $g$, in Ostro’s model for the radar albedo, which is defined to be unity for a sphere, the factors $G_{OC}$ and $G_{SC}$ are equal to zero for a homogeneous, smooth surface or large, absorbing spheres with no contribution from diffuse or internal scattering. Note that also Ostro’s gain factor of unity only applies to large, absorbing spheres, although it is not explicitly stated in the original paper [Ostro et al., 1985].

![Figure 4.10](image.png)

Figure 4.10: The SC and OC radar albedos for the data of the first case in Fig. 4.9 ($\sigma_r = 0.05$, circles) with the radar scattering laws (Eqs. 4.9) fitted (solid lines). Here, we use $G_{SC} = 1.17$, $G_{OC} = 4.26$, and $d = 4$ for all cases.

Figure 4.10 visualizes the scattering laws using the data computed for GRS particles with $\sigma_r = 0.05$. For the GRS particles, the gain factor $G_{SC}$ is here in most cases approximately one fourth of $G_{OC}$, but as shown in Paper III, this should not be considered as a general rule.

### 4.4 Irregular wavelength-scale particles

The polarization at backscattering is sensitive to the scatterer geometry, especially in the resonance regime. Therefore, using only spherical particles as scatterers can lead to errors in terms of the circular-polarization ratio. Also, using only large GRS particles would be unrealistic, as the most effectively scattering particles are wavelength-scale particles, as can be seen in Fig. 4.11, which demonstrates the effect of different-sized particles on scattering using different refractive indices. The
function is derived from the size distribution $n(x) \propto x^{-3}$ and the scattering cross section and used as the weighting factor ($w$) in the ensemble-averaging of scattering matrices (see Paper V):

$$w = \sum_{x=0.5}^{\text{max}(x)} n(x)C_{\text{sca}}(x)$$

From Fig. 4.11 we can deduce that when $m_{\Re} > 1.5$, the most effective mean scatterer diameter in terms of the S-band radar ($\lambda = 12.6$ cm) is only 5-8 cm. When $m_{\Re} < 1.5$, the particles with a mean diameter of 16 cm are the most effective contributors.

![Figure 4.11: The normalized weight as a function of size demonstrates the effect of different-sized particles to scattering using different refractive indices. Using $\lambda = 12.6$ cm, the mean radius of a scatterer $a \approx 2x$ cm.](image)

For the irregular, wavelength-scale particles, we utilize laboratory-characterized geometries that have been originally derived to simulate light scattering by atmospheric dust particles [Lindqvist et al., 2014]. Briefly, the surface topography was determined from a stereo pair of scanning-electron-microscope (SEM) images acquired from different tilt angles. As we can see in Fig. 4.12, which shows the three geometries that we use, although the shape characterization was carried out for micrometer-scale dust particles, the shapes of decimeter-to-meter-scale boulders
4.4. Irregular wavelength-scale particles

collected on the Moon during the Apollo program resemble those of the dust particles.

Figure 4.12: On the left, the scanning-electron-microscope images and, in the middle, the shape models of the three micrometer-scale dust particles illustrated in two different orientations [Lindqvist et al., 2014]. In the text, the geometries of the dust particles are referred to as particle A (on the top), B (in the middle), and C (on the bottom). On the right, boulders of rock collected from the Moon (photo credit: NASA).

For each of the three particles, an ensemble-averaged scattering phase matrix is computed using the discrete-dipole approximation algorithm ADDA [Draine and Flatau, 1994, Yurkin and Hoekstra, 2011]. Figures 4.13 and 4.14 illustrate the scattering-phase-matrix elements of the irregular scatterers compared to those of spherical scatterers. Here, the sensitivity of the polarization near the backscattering direction can be seen clearly, especially for the polarization elements $P_{22}$ and $P_{44}$. 
Figure 4.13: From the top: $P_{11}$, $-P_{12}/P_{11}$, $1 - P_{22}/P_{11}$, and $P_{44}/P_{11}$ as a function of the scattering angle when the scatterers are void inclusions in ice (the first column), solid rock (2) in ice (the second column), and solid rock (2) in powdered rock (the third column). The dashed, dotted, and dash-dotted lines depict the three different stereogrammetric geometries and the black line the average of the three. The light gray solid line depicts spheres with the same size distribution.
4.4. Irregular wavelength-scale particles

Figure 4.14: From the top: $P_{11}$, $-P_{12}/P_{11}$, $1 - P_{22}/P_{11}$, and $P_{44}/P_{11}$ as a function of the scattering angle when the scatterers are composed of ice (the first column), rock 1 (the second column), or rock 2 (the third column). The dashed, dotted, and dash-dotted lines depict the three stereogrammetric geometries (see Fig. 4.12) and the black line the average of the three. The light gray solid line depicts spheres with the same size distribution.
5 Applications to radar observations

5.1 From single scattering to multiple scattering

Considering planetary surfaces, a large part of the electromagnetic scattering is multiple scattering. Nevertheless, comprehensive understanding of single scattering is a mandatory step before proceeding to multiple scattering. As is shown in Paper V, the single-scattering features are present in the multiple-scattering curves. This is supported by Paper IV, which shows that the first-order scattering plays a major part in $\hat{\sigma}_\text{OC}$.

In Papers I, II, and IV, we simulate radar scattering by spherical particles, both single and clustered. A sphere is a simple choice of geometry in terms of well-known scattering properties that can be used to reproduce more complex geometries. It has been recently shown [Muinonen et al., 2012] that the radiative-transfer coherent-backscattering model using spherical particles is capable of reproducing exact electromagnetic results for loosely packed finite systems of scatterers. This speaks for the relevance of the present modeling of diffusely scattering external and internal media.

In Paper III and V, we study radar scattering by GRS particles (Section 4.3) and laboratory-characterized geometries (Section 4.4). These choices of geometry require more computational resources than spherical scatterers, but as we show in Paper V, are a crucial step for realistic modeling of radar scattering by planetary surfaces. The ray-optics computations for GRS particles are applicable to meter-scale or larger boulders on the planetary surfaces and could be used directly to mimic mini-moons [Granvik et al., 2012].

In Paper V, we also show that, for void inclusions in ice ($m = 0.56 + 0i$), the shape of the scatterers plays a secondary role with regard to the scattering-matrix elements, i.e., the scattering-matrix elements for spherical particles are similar to those of irregular particles using an ensemble-average for a wide range of size parameters (see Paper V for details). For particles with a greater relative refractive index ($m_\text{R} > 1.5$), the geometry plays a more significant role (see Fig. 5.1).
5.1. From single scattering to multiple scattering

![Graphs showing SC and OC radar albedo and circular-polarization ratio as functions of mean free path and optical thickness.](image)

Figure 5.1: On the top: The SC and OC radar albedo and the circular-polarization ratio as a function of the mean free path for a diffuse internal medium that is composed of irregular (solid lines) or spherical (dashed lines) void (gray) or rock (black) inclusions in ice are compared. On the bottom: The SC and OC radar albedo and the circular-polarization ratio as a function of the optical thickness for a diffuse external medium that is composed of irregular (solid lines) or spherical particles (dashed lines) of ice (gray) or rock (black). See Section 3.3 for the definitions of the optical depth and the mean free path and Section 2.6 for definitions of the materials. Both examples include the CBM. Rock refers to rock 2 and ice to impure ice in Table 2.1.
Chapter 5. Applications to radar observations

Figure 5.1 illustrates the radar observables (including the CBM correction) as a function of the number density of the scatterers (as explained in detail in Section 3). The computations carried out using spherical particles compared to irregular particles of ice and rock (impure ice and rock 2 in Table 2.1) reveal a remarkable difference. Indeed, while the values of $\mu_C$ and $\hat{\sigma}_{OC}$ computed using rock can double when using spherical scatterers instead of irregular ones, for ice, they can triple. As for $\hat{\sigma}_{SC}$, the geometry as well as the electric permittivity play a smaller role. In the case of internal scatterers (Fig. 5.1), the specific shape plays a secondary role for the OC radar albedo as well.

What causes the dramatic difference between the geometries in the external scatterers’ case, and between the external and internal scatterers’ cases? As we show in Paper IV, a major part of $\hat{\sigma}_{OC}$ arises from the first-order backscattering independent of the geometry of the scatterers (see Fig. 4.6). Therefore, what we see in the single-scattering features is reflected in the multiple scattering features: a backscattering peak of a spherical scatterer causes extra enhancement compared to an irregular scatterer. As for $\hat{\sigma}_{SC}$, already the first-order backscattering may contribute, but only if the scatterers are irregular. In the case of spherical scatterers, $\hat{\sigma}_{SC}$ arises only from the second and higher orders of scattering.

In addition to the geometry, the path of the radiation and the material affect the echo (Fig. 5.2). As Figs. 4.14 and 4.13 show, the radiation tends to scatter more forward than backward. As for the external scatterers, the forward-scattered radiation in the first-order scattering is likely to be absorbed into the host particle. The most likely contribution to the echo after the first-order backscattering is thus two scatterings in angles of approximately $90^\circ$, commonly known as double bounce. In between the scatterings, a reflection from the surface of the host particle is also possible. As for the internal scatterers, more forward-scattering takes place, but the signal is also more sensitive to the absorption of the material. Therefore, e.g., void inclusions enhance $\hat{\sigma}_{SC}$ more than the rock inclusions in ice. In addition, small part of the signal power is reduced on each pass of the surface of the host particle in Fresnel reflections and refractions.

5.2 Variations in the surface properties

Figure 5.3 illustrates the radar scattering by diffuse external and internal scatterers. The results have been thoroughly analyzed in Paper V. Therefore, the results are only summarized here with an emphasis on the applications in radar scattering by planetary surfaces. If the diffuse scatterers are in the wavelength-scale, the radar
5.2. Variations in the surface properties

reflectivity systematically increases as a function of the number density of the diffuse surface scatterers, or the surface roughness. This applies to both $\hat{\sigma}_{\text{SC}}$ and $\hat{\sigma}_{\text{OC}}$. The rate of increase depends slightly on the electric properties of the surface, and can therefore be affected by the metal content as well as the near-surface packing density.

Also, the CBM enhances the radar observables. The enhancement depends on the number density of scatterers, and it is more substantial for $\hat{\sigma}_{\text{SC}}$ than for $\hat{\sigma}_{\text{OC}}$, which is why it also increases $\mu_C$. The radar observables emerging from internal scatterers are found to be less dependent of the effect of geometry and material than those emerging from external scatterers, i.e., surface roughness.

For super-wavelength-scale scatterers, a slight decrease of $\hat{\sigma}_{\text{OC}}$ as a function of the optical thickness is seen, possibly due to a reduced area that reflects the echo at normal incidence. In large scatterers with high absorption (imaginary part of the refractive index), larger part of the signal is absorbed instead of enhancing the signal. The CBM enhancement by large scatterers is questionable, as was stated in Section 2.5, which also, in part, affects the decrease of $\hat{\sigma}_{\text{OC}}$ as a function of optical thickness.

What can we say about the radar scattering in terms of, e.g., asteroid taxonomy (discussed in Sections 1.1 and 1.2) based on the simulations? Figure 5.4 depicts the
Figure 5.3: The SC and OC radar albedo and the circular-polarization ratio as a function of the optical thickness for the diffuse external medium (wavelength-scale scatterers in the first row and larger scatterers in the second row) and as a function of the mean free path for the diffuse internal medium (wavelength-scale scatterers, on the bottom). The thin gray lines depict the values computed using Siris, and the thick black lines with corresponding line style depict the CBM-corrected values. In the lower middle panel, the horizontal dash-dotted lines at 0.02 (fine-grained regolith or porous ice, dark gray) and 0.08 (solid ice, light gray) computed using Equation 2.10 depict the OC radar albedo without diffuse scattering. See Section 3.3 for the definitions of the optical thickness and the mean free path and Section 2.6 for definitions of the materials.
modeled radar observables in the $\hat{\sigma}_{OC} - \mu_C$ space, which enables easy comparison with the observed data in Fig. 1.4. The different materials are depicted with different colors, and the geometric characteristics with different markers. Increasing the number density of scatterers moves the position of the marker diagonally from lower left to upper right.

Figure 5.4: The OC radar albedos and the circular-polarization ratio modeled using irregular wavelength-scale scatterers as diffuse external (DEM) or internal media (DIM) or meter-scale GRS particles as DEM. The markers from left to right depict: rock 2, rock 1, and ice (squares and circles), rock 2, rock 1, absorbing ice, and non-absorbing ice (diamonds), and voids in solid ice, ice grains in porous ice, rock 2 in solid ice or external rock 1, and rock 2 in fine-grained regolith (triangles).

The range of modeled values is mainly comparable to the observed data, excluding the largest optical depths. For wavelength-scale scatterers, the minimum modeled values of $\hat{\sigma}_{OC}$ are obtained using host particles (e.g., asteroids) without diffuse scatterers. The minimum observed values of $\hat{\sigma}_{OC}$ are approximately 0.04, which corresponds to an effective $\text{Re}(m) \approx 1.5$. The maximum values of $\hat{\sigma}_{OC}$, as well as $\mu_C$, are obtained using a large optical thickness, that is, in practice, a large number of surface scatterers.

For the C-complex asteroids, our model suggests either very low number density of wavelength-scale scatterers on the surface and/or mainly large boulders if any.
Chapter 5. Applications to radar observations

For the S-complex asteroids, the model implies slightly more wavelength-scale scatterers than for the C-complex. Comets do not differ significantly from the C and S complexes in terms of $\hat{\sigma}_{\text{OC}}$ and $\mu_C$, so similar interpretations are likely to apply. As mentioned before in Section 1.2, for the NEOs the average $\mu_C$ is greater than for MBOs. The model implies that, therefore, the surface of NEOs is slightly more covered with wavelength-scale scatterers than that of MBOs. This can be a result of different collisional evolutions or possibly space weathering, which is more prominent closer to the Sun.

The X complex is likely to include asteroids with high and low metal content. Those with high metal content, we exclude from the model as explained in Section 2.6. The most interesting type of the X complex is the E type, for which only relatively high values of $\hat{\sigma}_{\text{OC}}$ and $\mu_C$ have been measured, i.e., mean values of 0.26 and 0.74, respectively. In our model, the best fit is in the case of internal scatterers rock 2 in FGR using $l \approx 2$ m, i.e., powdered regolith with inclusions of solid wavelength-scale rock scatterers, possibly with moderate metal content but not specifically high. This conclusion is in good agreement with the hypothesis that the E-type asteroids are rich in the mineral enstatite [Zellner et al., 1977], which has a brittle tenacity [Sinkankas, 1966], and thus, easily fragments into smaller grains. Furthermore, the conclusion is in agreement with the observed sharp opposition effects and polarization surges in the visible regime of light, explained also by the CBM mechanism [Muinonen et al., 2002].

For the Galilean moon Europa, all the radar observables are extraordinarily high. We find that solid ice inclusions in porous/powdered ice reproduce circular-polarization ratios that are comparable to the observed values. Also, we note that rock inclusions inside porous/powdered ice are also capable of reproducing higher values of radar observables as previous studies [Black et al., 2001] suggest. Another open question is the surface of Europa: to what extent can the structural composition of the icy surface be neglected? As we show in Paper V, the geometry is crucial especially for ice because of its low absorption. This implies that extra caution should be taken when modeling or interpreting radar scattering on icy surfaces.

Finally, I will continue the discussion about estimating the refractive indices of the different taxonomic types of asteroids based on $\hat{\sigma}_{\text{OC}}$, which I began in Section 2.6. As Fig. 5.3 illustrates, not only $\mu_C$ but also $\hat{\sigma}_{\text{OC}}$ primarily increases, when the number density of scatterers increases. Therefore, if the observed value of $\mu_C$ is large for a certain target, Equation 2.10 is not likely feasible to estimate the mean refractive index based on $\hat{\sigma}_{\text{OC}}$.

For example, for the E-type asteroids high value of $\mu_C$ suggests that also $\hat{\sigma}_{\text{OC}}$ is enhanced more than average. This implies effective refractive index much smaller
5.2. Variations in the surface properties

than suggested by Equation 2.10, which gives $|m| \approx 3.1$. To conclude, the refractive index and the tendency to fracture to smaller grains suggests that the content of metal of the E-type asteroids is very low. For M-type asteroids the observed values of $\mu_C$ are low, because the material is harder and does not fracture easily.
6 Summary of the publications

The thesis consists of five journal publications:


The papers are summarised below in sections 6.1-6.5. The author’s contributions to the papers are described in section 6.6.
6.1 Paper I

In Paper I, we simulate electromagnetic scattering by clusters of spheres using MSTM in order to see how the radar signal scatters. Also, we study how the refractive index, size of the particles, the number of spheres in the cluster, and their size distribution (uniform versus polydisperse) affect the circular-polarization ratio.

As a result, we discover an interference pattern for the circular-polarization ratio as a function of \( m \) and \( x \) consisting of two sets of bands: a primary band related to the general extinction capability of the scatterers and secondary bands related to the destructive and constructive interference variations. We also find that the number of spheres has relatively little effect on the pattern, and that the peaks of \( \mu_C \) can be reproduced for bispherical particles in specific orientations. Polydisperse size distribution fades the secondary bands but not the primary band.

6.2 Paper II

Although the circular-polarization ratio for an isotropic sphere is zero, for inhomogeneous spherical particles it can increase significantly. We carried out computations using ADDA to study how the refractive indices, size of the particles, and the distribution of the material in the spheres affects the circular-polarization ratio and the radar albedo.

We found that, for inhomogeneous single spherical particles with high values of refractive index, despite the high standard deviation of the resulting values, the circular-polarization ratio is significantly greater than for the particles with smaller values of refractive index. For clusters of spheres, the inhomogeneity has little effect on the radar observables. As expected, the depolarization arises from the most prominent irregularities. Therefore, if the variation of the electric permittivity is the only factor of asymmetry in the scatterer, it can have a depolarizing effect, and the electric permittivity evidently plays a primary part. If the particle is irregular, the geometry of the scatterer dominates the effect of the permittivity variations inside the particles. The particles, for which also \( \mu_C \) produces peaks, are the most sensitive to the variations in the electric permittivity.

6.3 Paper III

In Paper III, we proceeded to model GRS particles. The computations were carried out using Siris. We studied the effect of the refractive index using five different
refractive indices relevant for planetary surfaces, size parameter range from $x = 25$ to $x = 150$, and a few geometry variations ($\sigma = 0.05$, 0.1, and 0.2, see Section 4).

From the computed results, we deduced semi-analytic equations for $\hat{\sigma}_{SC}$ and $\hat{\sigma}_{OC}$ as functions of size parameter and the real and imaginary parts of the refractive index. The crucial effect of material’s absorption on radar scattering was comprehensively discussed.

### 6.4 Paper IV

In Paper IV, we reviewed the emergence of the interference pattern introduced in Paper I in a profound manner. Because the number of spheres in the cluster affects the pattern relatively little, we concentrate on the fundamental case of a bispherical particle. We investigated the effect of the geometry in terms of orientation and distance between the particles. Also, we computed the scattering only to a certain order, first, second, and third, to understand which wave paths contribute to the pattern and how.

We discovered that for $\hat{\sigma}_{OC}$, the first-order backscattering by a single spherical particle is a good approximation and, therefore, can be theoretically approximated using the Mie theory. For $\hat{\sigma}_{SC}$, the second order is required for a relatively good approximation, and the third order for very good. For $\hat{\sigma}_{SC}$, also the non-propagating part of an electric field is required. The peaks of $\mu_C$, i.e., the coincidence points of the primary and secondary bands, are thus a result of interference change in $\hat{\sigma}_{OC}$, but also the second-order scattering that increases the SC component.

### 6.5 Paper V

In Paper V, we increased the realism of the scattering scenario by using laboratory-characterized geometries and therefore more realistic scatterers. We investigated what part the number density, material, or geometry play in radar scattering. First, we computed single scattering by irregular particles, and then utilized the ensemble-averaged scattering matrices to study scattering by a system with diffuse scatterers inside or on the surface of a 252-meter GRS particle, e.g., an asteroid or an icy satellite. Also, the CBM is included, and scattering matrices for meter-scale particles computed in Paper III utilized as a comparison for the centimeter-scale particles.

The results were a demonstration of the effects of various physical parameters on radar scattering. We showed how increasing the number density of the diffuse internal or external scatterers can increase the radar reflectivity and the circular-
polarization ratio of planetary surfaces, with an emphasis on asteroids. As well, the radar observations of the Galilean moon Europa and comets were treated. The effect of the electric permittivity was discussed with an emphasis on the absorption, and the geometry of the scatterers to show its relevance in different radar-scattering scenarios. For example, we showed the crucial effect of the geometry of the surface scatterers on radar scattering. We also gave estimates for electric permittivities of asteroids and comets on microwave frequencies and interpreted the radar observations of asteroids, such as the S and C complexes and E-type asteroids.

6.6 Author’s contribution to the papers

For each one of the publications, the author carried out all or the majority of the computations, analyzed and illustrated the results, and wrote the majority of the text. The details and exceptions are listed below.

In Paper I, the author planned the research and analyzed the results in cooperation with the co-authors. The author implemented the packing algorithm for the clusters of spheres that were used as the scattering geometry, and carried out all the computations using MSTM. A. Penttilä derived the equation for the truncated power-law distribution (Equation 14 in Paper I).

In Paper II, the author independently planned and implemented the inhomogeneous-particle models, and carried out all the computations using ADDA and Mie code. The author translated the Mie code of Bohren and Huffman [1983] from Fortran77 to python.

In Paper III, the author planned the research in cooperation with K. Muinonen, carried out all the computations using Siris, and analyzed the results (e.g., deduced the semi-analytic equations for the radar albedos). K. Muinonen provided the Siris code and Section 3.2 of the paper defining the GRS particles.

In Paper IV, the author coordinated the planning of the research and analyzed the results in cooperation with the rest of the team. The author carried out the majority of the computations using MSTM and Mie code, with the exception that J. Markkanen computed the data for comparison of different orders of scattering and the propagating and non-propagating parts of the electric field.

In Paper V, the author planned and implemented all the computations using ADDA, Siris, and Mie code independently, and analyzed the results in cooperation with K. Muinonen. The shape models were provided by H. Lindqvist but modified to a more effectively computable form by the author.
6.7 Publications not included in the thesis

In addition to the papers listed above, the author has published or participated in the preparation of the following papers:


The first paper listed above was omitted, because the results of the paper, which was made in an early stage of the dissertation process, were later evaluated by the author to not support the final arguments of the dissertation. The paper presents clusters of spherical particles as an applicable geometry to simulate radar scattering in planetary regolith. However, as shown in Paper V for diffuse external media, spherical particles should not be used. For diffuse internal media, spherical particles may be applicable but the model is oversimplified in terms of multiple-scattering effects.

In the second paper listed above, the author was preparing a shape model and a circular-polarization-ratio map for the asteroid 2006 AM4, for which the author discovered variation of circular-polarization ratio as reported in Virkki et al. [2014]. However, due to problems in the dual-polarization radar data, based on which the model was to be derived, adequately accurate shape model was not possible to be obtained in the time given for the publication of the dissertation.
7 Concluding remarks

The key results of the thesis can be divided into two parts: the effect of the structural and chemical composition of scatterers (all papers), and the practical implications on radar scattering (Papers III and V).

The simulations reveal that using spherical particles as scatterers may be an easy choice, but also, may cause undesired outcomes in terms of applications due to, for example, constructive or destructive interference by isotropic spherical particles. We show some scattering phenomena for the first time, such as polarization enhancement in the backscattering direction at certain sizes and refractive indices. In terms of applications, on the one hand, it can seem redundant to study oversimplified scenarios. On the other hand, focusing on as small number of variables as possible can be useful. For example, studying inhomogeneous spherical particles revealed that the electric permittivity defines the phase shift caused by the scatterer, and hence, the depolarizing capability of the scatterer. In Paper V, we show how the single-scattering features reflect to the multiple-scattering features at backscattering.

We enhance the realism of modeling by using scattering particles that are geometrically representative of the surfaces and interiors of planetary bodies. By using large, irregular particles as the scatterers, a systematic effect of the absorption to the radar observables could be seen, which lead to a semi-analytic, novel form of the radar scattering laws. By using small (wavelength-scale) laboratory-characterized particles as diffuse internal or external media inside or on the surface of a very large particle, we were able to model the multiple-scattering aspects of radar scattering quantitatively. We could find that the current understanding of the effects of the chemical and structural composition mainly apply, but we also underscore that the absorption and the scatterer geometry can have a crucial effect on radar scattering that should not be underrated.

To conclude, the results demonstrate the effects of various physical parameters such as number density, size distribution, and dielectric and geometric properties on radar scattering, and thus, help to interpret the radar observations. The greatest challenges include assessing realistic values for some of the free parameters such as
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the size distributions and absorption, which are shown to have major effects on radar scattering. Nevertheless, our model is quantitatively well-established and can help to constrain these free parameters. Yet, the future is open for increasing understanding of radar scattering. Also, applications in other fields, such as geology or geophysics are possible.
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