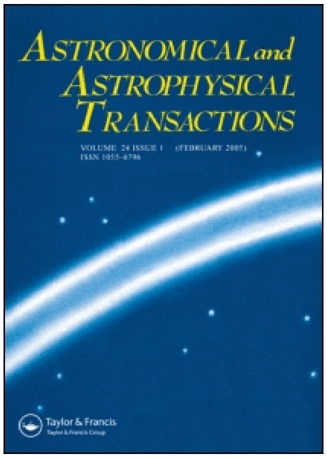

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GROUND-BASED RADAR EXPERIMENTS FOR THE STUDY OF RADIATION SCATTERING BY ATMOSPHERELESS CELESTIAL BODIES

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The radar observations of atmosphereless bodies are active physical experiments. Therefore they permit us to study not only physical properties of these objects, but also the radiation scattering itself. Two kinds of such experiments are suggested: (1) the study of coherent backscattering from regolithic surfaces and (2) tbe measurement of their scattering matrix. What information about the cosmic bodies and the scattering process can be obtained from these experiments is considered.

KEY WORDS Radar, radar astronomy, regolith, backscattering, scattering matrix

Unlike optical observations, radar experiments provide us with the unique possibility of performing active radiation scattering experiments. They can be used not only in the usual manner for obtaining some astrometric information, the shape of objects and parameters of its rotation, but also for obtaining information about the physical properties of the surface of the body and about the radiation scattering process itself. We could obtain more information if we measured more characteristics of scattered radiowaves. There are two possibilities of achieving this: (1) to change the phase angle; and (2) to introduce a polarization modulation of the transmitted signals for obtaining different elements of the scattering matrix of the body. These two kinds of the experiments are considered below.

1 THE NON-ZERO PHASE ANGLE EXPERIMENT

This experiment needs at least two distant antennas: transmitter and receiver(s). It can be performed only for nearby objects, such as near-Earth asteroids and the Moon. Certainly, the region of phase angles α available for radar experiments is very small: tbe widest region is possible for the Moon with $\alpha = 0.–1.8°$, whereas the largest value of phase angle for near-Earth asteroids available for observations in the near future (November, 1996) is expected for Toutatis for which $\alpha = 0.14°$ (Yeomans *et al.*, 1992). Nevertheless, we can study the nearly-opposite region, which is very important not only for understanding properties of the scattering surface, but also for understanding the physics of the radiation scattering process itself.

In the case of optical observations of atmosphereless solar-system bodies two interesting phenomena are known for small phase angles: (I) the sharp, nonlinear increase of brightness as the phase increase angle decreases, called "the opposition effect" and the reversal of the sign of linear polarization, called "the negative polarization". Both phenomena are observed in two types. The first type is rather wide with a small-amplitude with the width of the opposition peak being about 7° with an amplitude ≤ 0.3 magn., while the width of the negative polarization branch is $\approx 22°$, with an amplitude about 1–1.5%; (II) the second is characterized by the very narrow region of phase angles where α is observed to be about 1–2° along with a large amplitude: ≈ 2 for brightness and $\approx 5\%$ for polariation. These phenomena are different in nature. The wide, low peak of brightness and polarization can be explained by the simple geometric-optical theory of multiple scattering taking into account shadow effects (Wolff, 1975). The sharp, narrow peaks are explained in terms of coherent backscattering, arising from the physical phenomen on called "the weak localization of photons". All near-opposition phenomena are very sensitive to the size of regolithic grains, their packing and composition. Therefore by studying the amplitude and angular characteristics of scattered radiation at small phase angles one can obtain information about the properties of a scattering surface.

For example, the halfwidth at half-maximum α_{HM} for both photometric and polarimetric coherent backscattering effects (Mishchenko, 1993) is given by

$$\alpha_{\mathrm{HM}} = 0.56/(kl), \tag{1}$$

where k is the wavenumber, $k = 2\pi/\lambda$ (λ is the wavelength), and l is the scattering mean free path given by $l = 1/(nC_{\mathrm{sca}})$. Here n is the number density of the grains and C_{sca} is their scattering cross-section. Thus n depends on particle packing and C_{sca} depends on grain properties e.g. size, shape and composition, defined by dielectric permittivity and loss. Therefore these properties of surface regolithic grains can be evaluated, if values of albedo or polarization at several small phase angles $\alpha \leq 2\alpha_{\mathrm{HM}}$ can be measured.

We have computed values of C_{sca} for silicate particles of spherical shape from Mie theory and for spheroids with axis ratio $a/b = 5$ from the T-matrix code (Mishchenko, 1992). In Table 1 we give the expected values of phase angles for the coherent backscattering α_{HM} under the following considerations

(1) wavelengths of radar observations are 3.5 cm (Goldstone) and 0.86 cm (intended for the European Asteroid Radar project (Zaitsev, 1995));

(2) the mean size of particles corresponds to the values known for lunar regolith (40 μm (McKay *et al.*, 1974)) and for large main-belt asteroids 100 μm (Dollfus, 1989);

Table 1. The halfwidth at half-maximum of coherent backscattering for Lunar and asteroidal silicate particles

Size, μm	α_{HM}, deg.				
		Spheres		Spheroids	
	λ (cm) =	3.5	0.86	3.5	0.86
40		1.7×10^{-6}	2.6×10^{-5}	7.1×10^{-7}	2.6×10^{-4}
100		6.1×10^{-6}	4.0×10^{-4}	2.8×10^{-5}	3.0×10^{-4}

(3) the permittivity for silicates was considered;

(4) the closest packing of grains was suggested.

Although the values of α_{HM} are very small, it does not mean that the effect can not be observed. For radar observations of near-Earth asteroids the accuracy of determination of the distance and position is very high. For example, during the recent radar observations of the asteroid 1991 JX, the angular position of the asteroid was determined with uncertainties of a few hundredths of an arcsec and the parameters of its movement were known with an accuracy of about 30 m for the distance, and 0.3 mm s^{-1} for its radial velocity (Ostro *et al.*, 1995). Such extreme accuracy makes it possible to obtain several echo signals within the phase angle region indicated in Table 1, using several ground-based distant antennas. Moreover the small values of phase angles permit the study of backscattering for many near-Earth objects, about 10 per year (Yeomans *et al.*, 1992).

Let us look at the problem from another aspect, namely what should be the size of grains to exhibit coherent backscattering peak at radar observations at phase angles of 0.14° (Toutatis) and 1.8° (the Moon). The results are presented in Table 2.

The values of regolithic grain size obtained for Toutatis are quite realistic for near-Earth asteroids, because is expected that the smaller asteroids cover the coarser regolith (Dollfus, 1989): the smaller the body, the larger the particles which can be retained by its gravitation. In the case of the Moon, finding the radar coherent

Table 2. The size of the Lunar and Toutatis particles showing the coherent backscettering at radar observations

α_{HM}, deg.	Size, μm				
		Spheres		Spheroids	
	λ (cm) =	3.5	0.86	3.5	0.86
0.07		1200	250	250	200
0.9		2500	1200	400	220

opposition peak will show the importance of the above-mentioned scale of size for this body.

We analysed tbe coherent backscattering in terms of intensity and polarization, but this description is suitable for quantities measured at radar observations, namely $\mu_l = I_s/I_0$ for the linearly polarized signal or $\mu_c = I_0/I_s$ for circularly polarized, where I_s is the component of the radiance scattered with its polarization in the same direction as that of the transmitted signal and I_0, the component with the opposite polarization. Laboratory experiments on light scattering and simulating radar observations (Hapke and Biewett, 1991; Hapke *et al.*, 1993) found the coherent backscatteriag peak for quantities μ_l and μ_c as well. Moreover, its halfwidth at half-amplitude is equal to obtained for the intensity and polarization.

The usual "shadow" opposite effect can also be studied at radar observations. For example, for the Moon precisely this effect can be observed at available phase angles. It gives information about surface roughness of size more than the wavelength. From radar measurements one can then study structure and composition of the surface at a scale size of about dozens of centimeters according to the theory (Wolff, 1975; Kolokolova, 1990; Wolff and Dollfus, 1991), developed for optical observations.

2 EXPERIMENTS ON MEASUREMENTS OF THE SCATTERING MATRIX OF AN ATMOSPHERELESS BODY SURFACE

We can determine the values of the elements of the scattering matrix, transmitting successive signal with right/left circular polarization, and also linear polarization with different positions of polarization plane and by measuring the echo signals with facilities sensitive to different polarizations. Below we show which elements of the scattering matrix can be obtained and what information about surface properties can be obtained from them.

According to the theory of radiation scattering, the usual measurements of I_s (the signal with the same direction of polarization as the source signal) and I_0 (the signal with the opposite direction) which determine μ_l and μ_c are not very informative. It appears, their wide use is explained by the simplified conception that radiation with unchanged direction of circular polarization or changed plane of linear polarization suffers specular reflection and the other one suffers diffuse reflection. In general, this is not correct even from the assumption about plain specular reflections of light on the surface: radiation changes the direction of linear polarization after an odd number of reflections and does not change it after an even number. For circular polarization the situation is the opposite. But besides the specular reflections many other processes take place at the scattering of radiowaves from surfaces: diffraction (Bass and Fuks, 1979), total-internal reflection (Goldstein and Green, 1980), mode-coupled reflection (Hagfors *et al.*, 1985), etc. All these processes are capable of producing a change from linear polarization to circular and vice versa, and also to depolarize the radiation. If one could identify all these changes in the echo signal much more information about a scattering surface would be obtained.

All these changes can be controlled with measurements of scattering matrix elements. The scattering matrix is the matrix $M(4\times4)$ which shows transformations of transmitted and scattered radiation are described by their Stokes vectors I and I' and the scattering process is described by

$$\begin{pmatrix} I'_1 \\ I'_2 \\ I'_3 \\ I'_4 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{21} & M_{22} & M_{23} & M_{24} \\ M_{31} & M_{32} & M_{33} & M_{34} \\ M_{41} & M_{42} & M_{43} & M_{44} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix}.$$

The scattering matrix elements for a surface depends on the composition of the material by means of its dielectric permittivity and loss, as well as on surface structure. Thus this contains information about these surface properties. Moreover, it gives us 16 quantities for the determination of these properties, many more than from measurements of the parameters μ_l and μ_c.

To obtain the scattering matrix elements one should measure not left and right polarized components separately, but all the circularly polarized radiation, then all the linearly polarized and finally all the depolarized radiation. To obtain all the scattering matrix elements it is necessary to combine such measurements with the successive transmission of radiation with different states of polarization.

A detailed algorithm of the scattering matrix measurements would take the following form:

First the linearly polarized radiation with any orientation of the plane of polarization (e.g. for non-zero phase angle, coinciding with the scattering plane) is transmitted, that is the signal with the Stokes vector (1,1,0,0). The received signal will have the Stokes vector

$$\begin{pmatrix} M_{11} + M_{12} \\ M_{21} + M_{22} \\ M_{31} + M_{32} \\ M_{41} + M_{42} \end{pmatrix}.$$

Then let us perform the following succession of measurements:

(1) measure all the returned signal, that is the Stokes parameter $I'_1 = M_{11} + M_{12}$,

(2) measure all the linearly polarized component with the plane of polarization coinciding with the plane of polarization of the transmitted signal, that is the Stokes parameter $I'_2 = M_{21} + M_{22}$,

(3) measure all the linearly polarized component with the plane of polarization at the angle 45° to the plane of polarization of the transmitted signal, that is the Stokes parameter $I'_3 = M_{31} + M_{33}$,

(4) measure the circularly polarized component of the returned signal, that is $I'_4 = M_{14} + M_{44}$.

Then transmit the signal with the linear polarization perpendicular to the first one, that is with the Stokes vector (1,–1,0,0). It gives us the returned Stokes vector

$$\begin{pmatrix} M_{11} - M_{12} \\ M_{21} - M_{22} \\ M_{31} - M_{32} \\ M_{41} - M_{42} \end{pmatrix}.$$

Its components can be obtained separately after the repetition of the above described succession of measurements.

After adding and subtracting these vectors the first and second columns of the scattering matrix can be obtained.

Thus, two linearly polarized transmitted signals and four measurements of echo signals allow us to obtain elements of the first and second columns of the scattering matrix.

To obtain the third column of the scattering matrix (M_{13}, M_{23}, M_{33}, M_{43}) one should transmit the signal with the Stokes vector (1,0,1,0) and then (1,0,–1,0), that is with the radiation linearly polarized at the angle 45° to the first of the above described planes of polarization and then to the second one. Note, that at these measurements the first column is obtained again and can be used to get more accurate values of its elements.

Finally, if we repeat the above described transmissions and measurements with a right circularly polarized signal (1,0,0,1) and a left one (1,0,0,–1) the fourth column of the scattering matrix will be obtained, that is M_{14}, M_{24}, M_{34}, M_{44}.

In summary, to obtain all elements of the scattering matrix it is necessary to transmit successively six signals with the different polarization and to make four measurements for each signal (see Figure 1).

These measurements may be reduced in dependence on what matrix elements are necessary and on what kind of symmetry the observed body and its surface have. Then the number of transmissions and measurements decreases (Bohren and Huffman, 1983).

For example a spherical symmetric body or an isotropic surface, located perpendicularly to the direction of transmission and covered by randomly oriented isotropic particles, have a scattering matrix of the form

$$\begin{pmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{12} & M_{11} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & -M_{34} & M_{33} \end{pmatrix}.$$

In this case the scattering matrix is completely defined after measurements of only four of elements. On the other hand if the surface is covered by randomly oriented anisotropic particles (e.g. grains from olivine, yielding a biaxial crystal) two more elements are added and the matrix has the form:

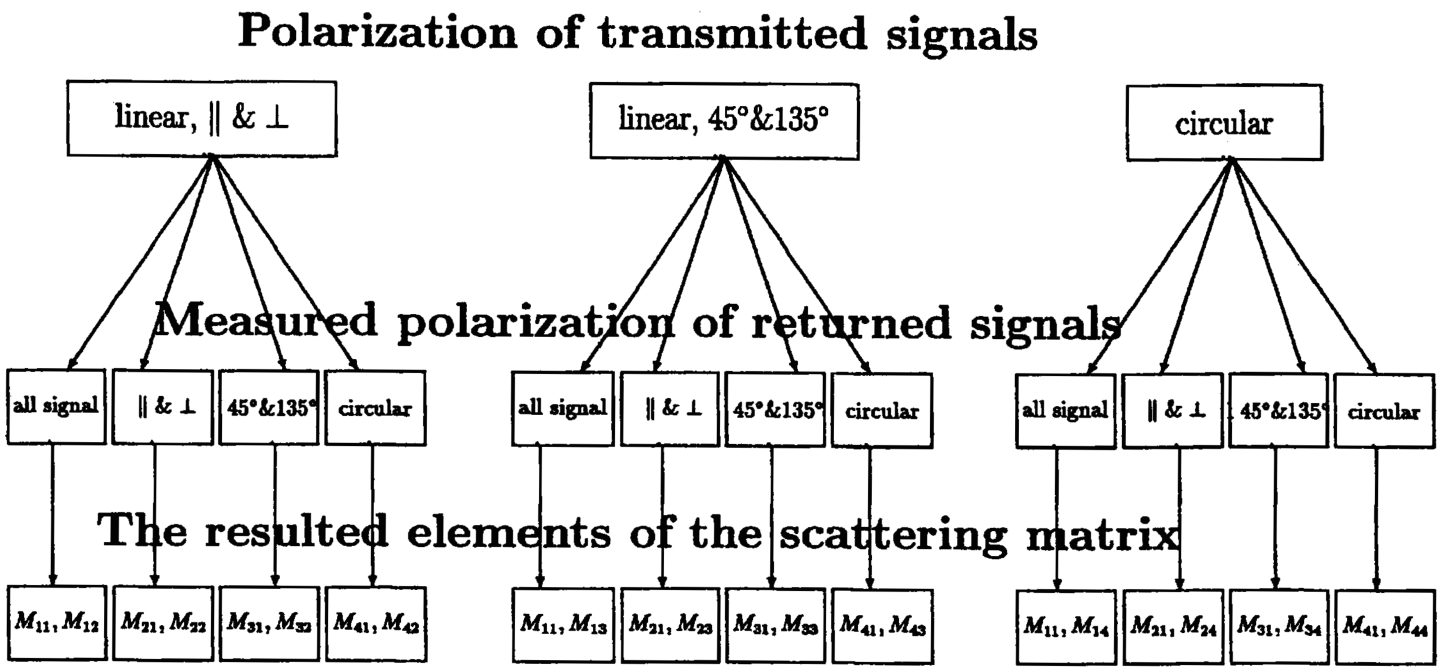

Figure 1 The scheme of the experiment on a measurement of the scattering matrix of a cosmic body.

$$\begin{pmatrix} M_{11} & M_{12} & 0 & 0 \\ M_{12} & M_{22} & 0 & 0 \\ 0 & 0 & M_{33} & M_{34} \\ 0 & 0 & -M_{34} & M_{44} \end{pmatrix}.$$

If the body has a non-spherical shape or has a stuctural or compositional inhomogeneity e.g. a rather large crater or spot, or the observed surface is inclined to the direction of transmission, or anisotropic particles on the surface are oriented, some elements from non-diagonal blocks take non-zero values.

For example a body with an axially symmetric shape covered by anisotropic irregular randomly oriented grains has the following scattering matrix, described by 10 independent parameters

$$\begin{pmatrix} M_{11} & M_{12} & M_{13} & M_{14} \\ M_{12} & M_{22} & M_{23} & M_{24} \\ -M_{13} & -M_{23} & M_{33} & M_{34} \\ M_{14} & M_{24} & -M_{34} & M_{44} \end{pmatrix}.$$

Therefore information about non-zero values of some matrix elements or the equality of some of them allows us to determine both macroscopic (shape of the body) and microscopic (shape or internal anisotropy of the structure of particles) properties of observed body. Moreover, some elements of the scattering matrix are very sensitive to the composition of scattering material, just as others are very sensitive to the structural characteristics of the surface, making it possible to study them with radar measurements.

Note that the matrices shown above are suitable for any phase angle. For backscattering, as is usual for radar observations, the number of independent elements of the scattering matrix decreases (van de Hulst, 1957; Hagfors, 1967) because of the absence of the plane of reference. This plane, at non-zero phase angles, is the scattering plane, that is the plane containing the directions of transmission and observation. Coincidence of these directions at backscattering does not permit the definition of such a plane.

Much information can be obtained as a result of a complex experiment on the study of the phase dependences of scattering matrix elements.

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