

IS IT POSSIBLE TO DETECT MAGNETIC MATERIALS ON VENUS WITH BISTATIC RADAR PROBING? *L. V. Starukhina*¹ and *M. A. Kreslavsky*^{1,2}, ¹Astronomical Institute, Kharkov National University, Kharkov, Ukraine, starukhina@astron.kharkov.ua, ²Dept. Geol. Sci., Brown University, Providence, RI, USA, misha@mare.geo.brown.edu.

Magnetic materials on Venus: As thermodynamic calculations have shown [e.g., 1, 2], under Venus conditions magnetite Fe_3O_4 is an expected weathering product of basaltic minerals. Magnetite is a ferrimagnetic with the Curie point 853 K; below this temperature, that is everywhere on the Venus surface, magnetite has non-negligible magnetic permeability μ . Thus, magnetic properties of surface materials are likely to influence radiophysical measurements [3]. Magnetite is an endmember of several series of substitutional solid solutions with spinel crystal structure and ferrimagnetic behavior, e.g. titanomagnetites $x\text{Fe}_2\text{TiO}_4(1-x)\text{Fe}_3\text{O}_4$, magnomagnetites $\text{Mg}_x\text{Fe}_{1-x}\text{Fe}_2\text{O}_4$, magnetite-spinel series $\text{Mg}_x\text{Fe}_{1-x}\text{Al}_{2y}\text{Fe}_{2(1-y)}\text{O}_4$, etc. The Curie point decreases in these series from the magnetite endmember and reaches the temperature range of the surface for some compositions. Hematite Fe_2O_3 is also an endmember of a series of minerals with peculiar magnetic behavior.

Unfortunately, there are no laboratory measurements of magnetic permeability of minerals at microwave frequencies and high temperatures relevant for radar probing of Venus.

Here we consider how magnetic materials can be detected with radiophysical probing methods, especially with bistatic radar. For this purpose we describe the electromagnetic properties of the surface material by bulk dielectric permittivity ϵ and bulk magnetic permeability μ (both are complex numbers; $\mu = 1$ means absence of magnetic behavior). The relation between bulk ϵ and μ and amount of different minerals composing the surface is not considered here.

Bistatic radar probing: In experiments of this type [4] the spacecraft uplink transmitter is used as a source of probing microwave radiation directed to the "mirror reflection" point of the planet. The probing radiation is linearly polarized at $\sim 45^\circ$ to the incidence plane (an alternative scheme with circularly polarized probing wave is also possible). The radiation reflected by the surface is received on the Earth and its complete polarization state is determined. In this observation scheme the received radiation is specularly reflected from the horizontal facets of the surface; the contribution of diffuse scattering is negligible. The amplitude of the received signal strongly decreases with the increase of roughness (= decrease of the number of horizontal facets), but the polarization state is defined solely by bulk ϵ and μ of the uppermost surface layer. This situation is different from monostatic radar obser-

vations, where for all polarization components the influences of the surface and shallow subsurface interfaces, and of the surface roughness and electromagnetic properties of material are mixed. Radiometric observations are insensitive to subsurface structure, and the influence of roughness is much weaker than for monostatic radar probing, but still is much higher than for bistatic experiments.

The specular reflection of the electromagnetic waves from the surface is completely described by two complex Fresnel coefficients for horizontally and vertically polarized incidence wave amplitudes:

$$F_{\perp} = \frac{\mu \cos \theta - \sqrt{\mu \epsilon - \sin^2 \theta}}{\mu \cos \theta + \sqrt{\mu \epsilon - \sin^2 \theta}}, \quad F_{\parallel} = \frac{\epsilon \cos \theta - \sqrt{\mu \epsilon - \sin^2 \theta}}{\epsilon \cos \theta + \sqrt{\mu \epsilon - \sin^2 \theta}}$$

where θ is the incidence angle. The polarization state of the reflected wave can be expressed through the complex coefficient $F_{\parallel} / F_{\perp}$. Thus, the bistatic radar experiment gives a reliable estimate of $F_{\parallel} / F_{\perp}$ for the surface material. This is one complex equation for two complex unknowns μ and ϵ . If the absence of magnetic materials is assumed ($\mu = 1$), ϵ can be obtained unambiguously (as it was done for Venus in [4]). Below we consider, how we can deconvolve μ and ϵ with radiophysical data for Venus, if we do not assume $\mu = 1$.

Electromagnetic properties of plains: The Magellan bistatic radar experiment [4] gave $\epsilon \approx 4$ under the assumption of $\mu = 1$ for the plains. The received circular polarization zero within the measurement accuracy, which means $\text{Im } \epsilon = 0$. Admixture of some magnetic material gives $\text{Re } \mu > 1$ and/or $\text{Im } \mu > 0$; it can be compensated by proper increase of $\text{Re } \epsilon$ and/or $\text{Im } \epsilon$ to obtain exactly the same $F_{\parallel} / F_{\perp}$.

A straightforward way to obtain both ϵ and μ is to make use of the dependence of $F_{\parallel} / F_{\perp}$ on θ , that is to measure $F_{\parallel} / F_{\perp}$ in a bistatic radar experiment twice for the same site at different incident angles θ_1 and θ_2 . The absolute value of Jacobean of the pair of $F_{\parallel} / F_{\perp}$ at θ_1 and θ_2 considered as functions of ϵ and μ serves as a generalized measure of sensitivity of the measurements to the variations of ϵ and μ . Fig. 1 shows how this sensitivity depends on angles θ_1 and θ_2 . It is seen that the sensitivity is maximal for $\theta_1 \approx 40^\circ$ and $\theta_2 \approx 72^\circ$. However, more detailed calculations show that even in its maximum the sensitivity is too low to identify small deflection of μ from 1. The minimal values of $|\mu|$ that can be identified with this method are

~ 3 , that is on the order of $|\mu|$ for pure magnetite at room temperature and microwave frequencies.

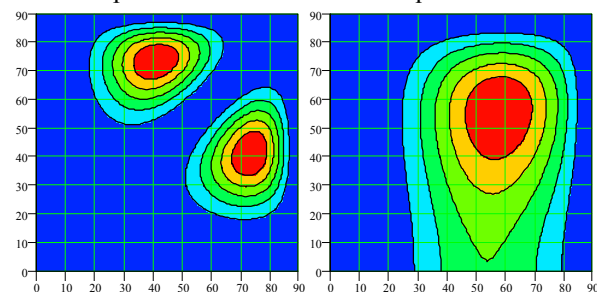


Fig. 1

Fig. 2

Another method is to use the Magellan radiometric measurements as an additional constraint to bistatic radar probing in S band. The emissivity mapped in the Magellan radiometric experiment [5] is approximately equal to $1 - |F_{\perp}|^2$. This adds one real (rather than complex) equation, and does not complete the whole set of equations. However, we found that when $\text{Im } \epsilon$ and $\text{Im } \mu$ are small, the deviation of $\text{Re } \mu$ from 1 can be detected. The sensitivity function for the pair of $|F_{\perp}|$ and $|F_{\parallel}|/|F_{\perp}|$ on ϵ and μ (assuming $\text{Im } \epsilon = \text{Im } \mu = 0$) is shown in Fig 2 as a function of radiometric look angle (vertical axis) and bistatic incidence angle (horizontal axis). Magellan radiometric observations were taken at look angles $< 45^\circ$. It is seen that the best observations are at the largest look angle, that is for the 1st cycle of Magellan survey about 10°N latitude. The best incidence angle for the complementary bistatic radar probing is $50-60^\circ$. The minimal value of $\text{Re } \mu$ that can be identified with this method is ~ 1.3 . This corresponds to 20% of magnetite by volume, if we assume its μ at room temperature. (For the Magellan bistatic experiment the combinations of look and incidence angles were far from the maximum in Fig. 2.)

This method has several complications. Roughness makes emissivity differ from $1 - |F_{\perp}|^2$. Scattering models can be used to make corrections for roughness [e.g., 6, 7]. For plains, the corrections are small and do not depend on the model choice [7]. A more severe problem is the absolute inaccuracy of the Magellan emissivity measurements [5]. Use of emissivity ratios along the same Magellan orbits resolves this problem [7], but then it allows only detection of variations of magnetic properties rather than magnetic properties themselves.

Electromagnetic properties of highlands: The Magellan bistatic radar experiment results [4] gave $\text{Im } \epsilon \sim 100$ (semiconducting material) and $\text{Re } \epsilon$ and $|\mu| \ll \text{Im } \epsilon$ for the high-reflectivity material of Maxwell Montes. Emissivity data do not contradict this conclusion. For the equatorial highlands, the limited data on

emissivity in two polarizations (that give separately $|F_{\parallel}|$ and $|F_{\perp}|$) have been analyzed in [6]. It has been shown that the observations are consistent with $\text{Re } \epsilon \sim 50$ for the high-reflectivity regions in Ovda Tessera. With the same data we found that $|\epsilon| \sim 35-50$ is consistent with the observations, that is semiconductors ($\text{Im } \epsilon \gg 1$) are equally possible as high-dielectric materials ($\text{Re } \epsilon \gg 1$). $|\mu| \gg 1$ is not consistent with these data. The "upper snow line", that is the sharp transition from high to normal reflectivity at the highest part of Ovda Tessera is consistent with both drop of $|\epsilon|$ back to plain values (as discussed in [6]) and sharp increase of $|\mu|$ due to ferrimagnetic phase transition (Curie point). We found that the dual polarization emissivity data are consistent with both possibilities.

Bistatic radar probing of the Ovda Tessera will be able to distinguish between high permittivity and conductivity ($\text{Re } \epsilon \gg 1$ or $\text{Im } \epsilon \gg 1$) for equatorial highlands in the same way as it was done in the Magellan bistatic experiment for Maxwell Montes. The most accurate data can be obtained at incidence angle $\theta \approx 78^\circ$, but a wide range of incidence angles $\theta > 50^\circ$ will work well. Bistatic radar probing of the low-reflectivity area above the "upper snowline" will distinguish between the "normal" $|\epsilon|$ and high $|\mu|$ options. Good incidence angle range for this is $50-70^\circ$. Since all natural magnetic minerals at microwave frequencies have $\text{Im } \mu > 0$, the proper sense of reflected circularly polarized component above the "upper snowline" would mean the presence of magnetic materials. Thus, the identification of $|\mu| > 1$ above the "upper snowline" will not depend on Magellan emissivity measurements.

Conclusions: Bistatic radar measurements of the plains are sensitive to the presence of ferrimagnetic minerals at tens percent level, if analyzed together with Magellan radiometric results. The bistatic radar probing of equatorial highlands can distinguish between high conductivity and permittivity of radar-bright material. It also can test the hypothesis of the ferrimagnetic Curie point as the cause of the "upper snowline".

References: [1] Wood J. A. (1997) In *Venus II*, 637-666. [2] Fegley B. et al. (1997) In *Venus II*, 591. [3] Starukhina L. V. and Kreslavsky M. A. (2002) *LPSC XXXIII* #1559. [4] Pettengill G. H. et al. (1996) *Science*, 272, 1628-1631. [5] Pettengill G.H. et al. (1992) *JGR* 97, 13091-13102. [6] Arvidson R. E. et al. (1994) *Icarus* 112, 171-186. [7] Kreslavsky M. A. et al. (2000) *Solar System Res.* 34, 379.