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Subsurface radar location of the putative ocean on Ganymede: Numerical simulation of the surface terrain impact

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ABSTRACT

Exploration of subsurface oceans on Jupiter's icy moons is a key issue of the icy moons' geology. Radar is in fact the only sounding technique which is able to penetrate their icy mantles, which can be many kilometers thick.

Surface clutter, i.e. scattering of the radio waves on the rough surface, is known to be one of the most important problems of subsurface radar probing. Adequate numerical modeling of this scattering is required on all stages of subsurface radar experiment, including design of an instrument, operational strategy planning and data interpretation.

In the present paper, a computer simulation technique for numerical simulations of radar sounding of rough surfaces is formulated in general form. Subsurface radar location of the ocean beneath Ganymedian ice with chirp radar signals has been simulated.

1. Introduction

Geological models of Jupiter's icy moons predict oceans of liquid water beneath their icy shells, due to radiogenic and tidal heating (Spohn and Schubert, 2003). At present, there are several evidences of these subsurface oceans, e.g. magnetometric data (Zimmer et al., 2000), grooved terrain (Carr et al., 1998), and so on. Immediate proof of the presence of liquid water beneath the ice would very much extend our current knowledge of the icy moons geology. The radar wave absorption in the icy crust, measured in this experiment, might help us to constrain the physical and chemical composition of the bulk of ice (Chyba et al., 1998; Moore, 2000). Besides, since these oceans are thought to be potentially habitable, such proof would greatly support our hope to find live beings somewhere in our Solar system outside Earth.

However, because these oceans are covered by thick icy layers, they are inaccessible for immediate observation and can be reached only by seismic or electromagnetic waves. While seismic measurements at these depths require powerful sources of waves and landed equipment, a small orbiter carrying the radar onboard can provide deep subsurface sounding with global coverage of the icy moon surface. So far, this approach has been successfully performed in Lunar (Peeples et al., 1978; Oshigami et al., 2009) and Martian (Picardi et al., 2005) research programs.

In this paper we attempt to assess feasibility of such experiment on Ganymede.

Subsurface radar location has now numerous application in geology, geophysics, engineering, and so on. Working principle of this instrument is the transmission of wave packet, which propagates through the medium under investigation and comes back and is then received and analyzed (see Fig. 1). If the coherence of this wave packet is partially lost due to inhomogeneities of the medium, part of this energy is scattered away and does not reach the receiver, and the rest part of the wave packet is distorted. On the other hand, some part of the wave energy emitted by the radar to off nadir directions can be scattered from the rough surface back to the instrument. These are the so-called side clutter echoes, masking useful informative subsurface echo, as it is shown in Fig. 1.

To improve the instrument performance, various signal processing techniques are utilized (focused and unfocused aperture synthesis, migration technique and so on). Accurate theoretical simulation of the experiment includes evaluation of the electromagnetic field, excited in the investigated medium by the transmitter and registered by the receiver, and application of all the data processing procedures implemented in real experiment. Depending on the chosen method of electromagnetic field simulation, this might be really time consuming. Evaluation of mean quantities, such as mean intensity, implies averaging over many realization of the signal. This greatly increases computational costs of the problem.

Presentation of numerical technique for simulation of subsurface radar probing through rough surface with demonstration of some practical applications of it is the basic purpose of this paper.

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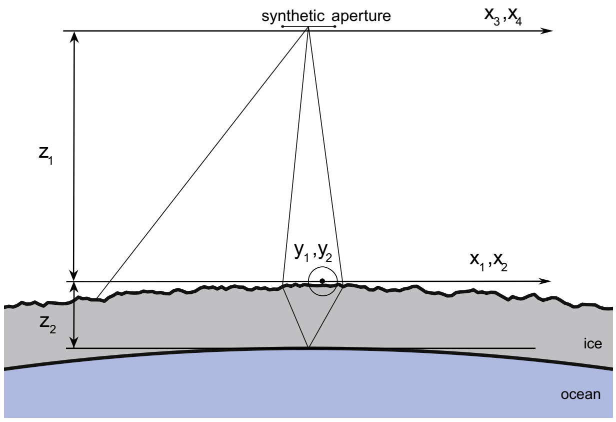

Fig. 1. Spherical surface of Ganymede.

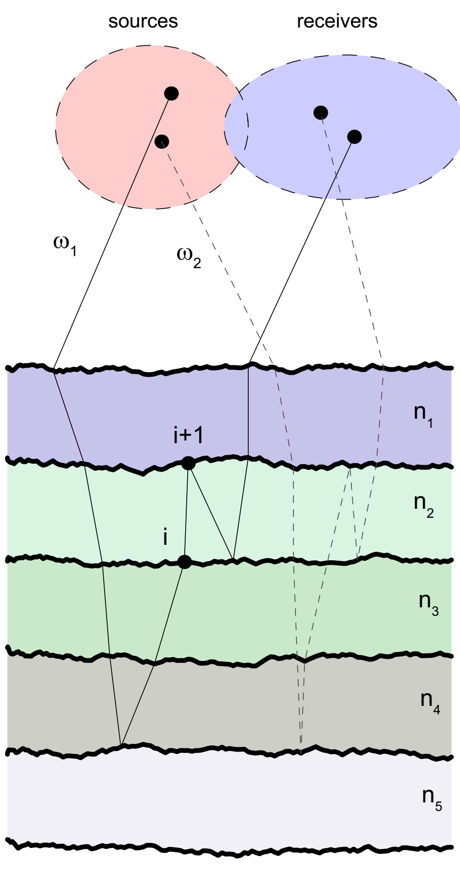

Fig. 2. General scheme of phase screen technique applied for the calculations.

2. Phase screen technique for simulation of wave propagation

One of the widely used approaches to the numerical simulation of wave propagation in inhomogeneous media is the phase screen technique (Ilyushin, 2009a; van de Kamp et al., 2009). The geometry of general model of multi-layered medium is shown in Fig. 2. Rough boundary surfaces, which separate the layers, are approximately modeled by random phase screens

$$\phi_i = -2kh(x_i, y_i) \tag{1}$$

and

$$\phi_i = 2\Delta k h(x_i, y_i) = 2\frac{\omega}{c}\Delta n h(x_i, y_i), \tag{2}$$

for transiting and reflected waves, respectively. Here Δk is the difference of wave numbers in two media, separated by the ith surface.

Between the boundaries all the media are homogeneous, i.e. volume scattering is neglected. For nearly vertical wave propagation, in the paraxial approximation the complex amplitude of the transiting or reflected wave can be expressed in the form

$$E(x,y) = \int A_i \exp(i\phi_i) E(\vec{r}\,') G(\vec{r}\,', \vec{r})\, dx'\, dy', \tag{3}$$

where $\vec{r} = (x,y,z)$ is an arbitrary point within the medium, $\vec{r}\,' = (x', y', z')$ is an integration point on the phase screen plane, A_i is the Fresnel amplitude reflection or transmission coefficient, respectively, ϕ_i is the random phase shift (1) or (2), introduced by the phase screen. The Green function of the Helmholtz equation in the paraxial approximation equals to

$$G_{ij} = \frac{k}{2\pi i|z-z'|} \exp\left(ik|z-z'| + ik\frac{(x-x')^2}{2|z-z'|} + ik\frac{(y-y')^2}{2|z-z'|} \right). \tag{4}$$

In the point (x_0, y_0, z_0) a concentrated (point) source of the sounding radiation $E_0 \delta(\vec{r} - \vec{r}_0)$ is located. Within the paraxial approximation, adopted in this study, the field generated by the source in the medium is

$$E(\vec{r}) = E_0 \int \delta(\vec{r}\,' - \vec{r}_0) G(\vec{r}\,', \vec{r})\, d^3\vec{r}\,' = E_0 G(\vec{r}_0, \vec{r}). \tag{5}$$

Thus, complex amplitude of the wave field of frequency ω in the point $\vec{r}_{N+1}$ in the medium after N reflections from and transmissions through the rough boundary surfaces equals to

$$E_\omega(\vec{r}_{N+1}) = E_0 \int \cdots \int \prod_{i=1}^{N} A_i \exp(i\phi_i) G_{i,i+1}\, dx_i\, dy_i, \tag{6}$$

where $G_{i,i+1} \equiv G(\vec{r}_i, \vec{r}_{i+1})$. Taking an average of two fields (6) at different frequencies $\langle E_{\omega_1} E^*_{\omega_2} \rangle$, we obtain the two frequency correlation function of the field (Ishimaru, 1978)

$$\Gamma_{\omega_1\omega_2}(\vec{r}_{N+1}, \vec{r}_{2N+2}) = \langle E_{\omega_1} E^*_{\omega_2} \rangle = E_0 E_0^* \int \cdots$$

$$\int M\{\phi\} \prod_{i=1}^{N} A_i \exp(i\phi_i) G_{i,i+1} \prod_{i=N+2}^{2N} A_i^* G^*_{i,i+1}\, dx_i\, dy_i, \tag{7}$$

where

$$M\{\phi\} = \left\langle \exp\left(\sum_{i=1}^{N} i\phi_i(x_i, y_i) - \sum_{i=N+2}^{2N} i\phi_i(x_i, y_i) \right) \right\rangle \tag{8}$$

is the characteristic function of the joint distribution of all the random phases. In the case of multi-variable normal distribution of the phases, the characteristic function is (Davenport and Root, 1958)

$$M\{\phi\} = \langle \exp(\textstyle\sum i\phi_i) \rangle = \exp\left(-\frac{1}{2} \sum_{i,j} \beta_{ij}(x_i, y_i, x_j, y_j) \right), \tag{9}$$

where β_{ij} are the random phase covariations $\phi_i(x_i, y_i)\phi_j(x_j, y_j)$, accounting their signs in the formula (8). If aperture synthesis of some other averaging procedure is applied to the observed fields, the expressions (6) and (7) should be integrated over corresponding variables with proper weighting (aperture) functions. Similarly, higher order field correlation functions can be evaluated.

After matched filtration, we get the temporal profile of the mean signal intensity

$$\langle |E(t)^2| \rangle \propto \frac{1}{(2\pi)^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} H(\omega_1) H(\omega_2) \Gamma(\omega_1, \omega_2) \exp(i(\omega_1 - \omega_2)t)\, d\omega_1\, d\omega_2. \tag{10}$$

An expression for the characteristic function $M\{\phi\}$ (9), which appears in formula (7) for the two-frequency correlation function,