Initial results of the Netlander imaging ground-penetrating radar operated on the Antarctic Ice Shelf

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[1] The objective of the Netlander mission was to land 4 small geophysical stations on the surface of Mars to study the deep interior, subsurface, surface and atmosphere of the planet. Included in the payload was a ground penetrating radar (GPR) designed to retrieve not only the distance but also the direction of the reflectors, thus providing a simplified 3D imaging of the subsurface. In this paper we report initial results obtained during the RANETA campaign on the Antarctic ice shelf. Data from two soundings of the ice-bed rock interface are analyzed, demonstrating the capability of the radar to disentangle echoes from different reflecting facets of the bed rock. Citation: Berthelier, J. J., S. Bonaime, V. Ciarletti, R. Clairquin, F. Dolon, A. Le Gall, D. Nevejans, R. Ney, and A. Reineix (2005), Initial results of the Netlander imaging ground-penetrating radar operated on the Antarctic Ice Shelf, Geophys. Res. Lett., 32, L22305, doi:10.1029/2005GL024203.

1. Description of the Experiment

[2] The Netlander GPR has been described in previous papers [Berthelier et al., 2000; 2003] and the instrument principle will be briefly recalled here. The main objective of the experiment was to achieve long range soundings to possibly access to liquid water reservoirs in the Martian atmosphere of the planet. Included in the payload was a ground penetrating radar (GPR) designed to retrieve not only the distance but also the direction of the reflectors, thus providing a simplified 3D imaging of the subsurface. In this paper we report initial results obtained during the RANETA campaign on the Antarctic ice shelf. Data from two soundings of the ice-bed rock interface are analyzed, demonstrating the capability of the radar to disentangle echoes from different reflecting facets of the bed rock. Citation: Berthelier, J. J., S. Bonaime, V. Ciarletti, R. Clairquin, F. Dolon, A. Le Gall, D. Nevejans, R. Ney, and A. Reineix (2005), Initial results of the Netlander imaging ground-penetrating radar operated on the Antarctic Ice Shelf, Geophys. Res. Lett., 32, L22305, doi:10.1029/2005GL024203.

2. Observations

[3] During the RANETA campaign, 8 soundings were performed in the vicinity of the French-Italian Cap Prudhomme station (139.90 E, 66.68 S) at distances from the coast from ~5 km to ~45 km corresponding to altitudes of ~285 m to ~1100 m above sea level. Gneiss is the dominant material in the bedrock. A sketch of the radar,
2.2. Radar Soundings

[5] Raw waveforms of the 2 electric (upper curves) and 3 magnetic (lower curves) components of reflected waves are presented in Figures 2 (left) and 3 (left) for two soundings performed respectively at ~20 km (January 29, case 1) and ~30 km (February 1st, case 2) from the coast. A 1 μs long, Gaussian shaped pulse with a 4 MHz centre frequency was transmitted through the Ex antenna. In order to improve the S/N ratio of these measurements, in particular of the Hz or Hx magnetic components that were subject to interferences, data were processed through a numerical Wiener filter and filtered data are shown in Figures 2 (right) and 3 (right). In case 1, the Ex waveform distinctly shows two echoes that originate from reflection on the ice-bedrock interface at ~6.1 and ~8.3 μs respectively. Similar echoes are also observed on the Ey antenna signal but with a much weaker level and with a waveform more complex and extended in time. The Ey antenna being orthogonal to the transmitting Ex antenna, the smaller level of the returning signal indicates that the interface is rather smooth at the ~100 m scale of the transmitted wavelengths. The two main echoes observed on Ex are also observed on the magnetic antennas. In case 2, a single signal is observed on the Ex antenna at ~10 μs with no distinct delayed signal. The signal on the Ey antenna is much weaker and extended in time for the same reasons as in case 1. Similarly a single signal is detected on the magnetic antennas although slightly more extended in time than on the Ex antenna.

3. Data Analysis and Results

[6] Before processing the data to retrieve the direction of the propagation vector, magnetic data have to be corrected from two main parasitic effects (i) the existence of a magnetic field induced by the current flowing in the electric antennas when excited by the electric field of the reflected wave, and (ii) the imperfect decoupling of the magnetic antenna with respect to components perpendicular to its axis. The far field limit of the radar being about 150 meters [Berthelier et al., 2000], waves incident on the bedrock can be considered as locally plane waves with electric and magnetic components \( E_i \) and \( H_i \) perpendicular to the propagation direction defined by its unit vector \( k_i \). Since the radar is mono-static and measures reflected waves at the location of the transmitter, the detected waves arise from the reflection of the incident waves on a facet of the bedrock that is perpendicular to \( k_i \). The \( E_r \) and \( H_r \) components of the reflected waves are perpendicular to their propagation direction defined by its unit vector \( k_r \), opposite to \( k_i \), and a straightforward method to retrieve the propagation direction...
Since we are only interested in determining $\theta$ and $\varphi$ and the distance $d$, the attenuation of the reflected waves through geometrical spreading, propagation losses and reflection included in $f(t, H_0/H, d, n_1, n_2)$ is simply taken into account by normalizing the amplitude of the detected signals to the reference waveform at the time of transmission. The function $f$ also includes the shift in time, equal to the propagation time $\tau$ of the reflected wave. $\tau$ is determined by correlating the received electric field waveform (due to its very good S/N ratio) with the reference waveform. To a good approximation, $\tau = d/v_1(\omega)$, where $v_1(\omega) = c/n_1(\omega)$ is the propagation velocity at the centre frequency of the transmitted pulse. Due to the rather good homogeneity of the ice from the surface to the bedrock, we assume that $n_1(\omega)$ is constant along the propagation path and equal to the value deduced from the antenna impedance measurements. From $\tau$, the value of $d$ can therefore be obtained. We are thus left with a set of 3 non linear equations (2), (3), (4) with 3 unknown angles $\theta, \varphi, \alpha$ that is solved using an iteration technique. As mentioned above, one has to take into account the refraction of the wave at the exit from the ice to derive the propagation angles $\theta^*_{\alpha}$ and $\varphi^*$ in the subsurface from the computed values of $\theta$ and $\varphi$.

[7] For the two examples shown in Figures 2 and 3 the results are the following:

- case 1: reflecting facet 1: $\theta^*_1 = 17^\circ, \varphi^*_1 = 155^\circ$ and $d_1 = 509$ m reflecting facet 2: $\theta^*_2 = 39^\circ, \varphi^*_2 = 181^\circ$ and $d_2 = 542$ m
- case 2: reflecting facet: $\theta^*_1 = 29^\circ, \varphi^*_1 = 171^\circ$ and $d_1 = 760$ m

Estimated uncertainties are typically 10° to 15° on $\theta$ and $\varphi$ and ~60 meters on $d$. The main source of errors in the determination of the direction of the reflectors is linked to the parasitic effects on magnetic measurements. An improved correction algorithm is presently being developed which significantly reduces these uncertainties.

[8] The retrieved $\varphi$ angles are close to 180°. This result is in agreement with the observed strong maximum of the received electric signal along the (transmitting) Ex antenna: waves detected by the radar propagate close to the vertical Oxz plane containing the Ex antenna. No detailed topographic information on the bedrock is available over the area where the soundings have been performed but, within 20 to 30 kilometers from the coast it is thought that the average level of the bedrock stays quite close to the sea level. Taking into account the values of $\theta^*$, the retrieved distances compare reasonably well with the altitudes of the two sites, respectively 413 m and 618 m. The main echoes correspond to propagation $\theta^*$ angles of about $25^\circ \pm 5^\circ$ and the second echo in case 1 corresponds to a propagation significantly off vertical. Two reasons can be advocated to explain these observations. First, the radiation pattern of interfacial dipole antennas over a soil with $n \sim 3.3$ shows a secondary maximum around ~20° to 25° off vertical in the vertical plane containing the antenna [Engheta et al., 1982], and the sensitivity of the radar is enhanced in this angular range. In addition, close to the region where the RANETA campaign took place, the topography of the coast and islands is very much irregular and this is probably true also for the bedrock under the ice shelf.
In such conditions, it is not astonishing to observe oblique echoes.

4. Conclusion

[9] We have presented two of the soundings performed with a prototype of the Netlander GPR on the Antarctic ice shelf over an ice thickness from ~500 m to 750 m. In one case, the analysis performed on the measured 3 magnetic components of the reflected waves has shown that these waves were reflected from two distinct facets of the bedrock and the location of these facets were determined. This initial result, in good agreement with previous simulation results, shows that the specific concept of the radar allows one to disentangle echoes from various reflecting facets of an interface. An improved method of analysis is presently being developed to make full use of the imaging capabilities of the radar and obtain a comprehensive description of the bedrock topography and roughness. If the imaging concept is necessary to interpret soundings performed from a single fixed location, such a technique can also significantly improve the performances of ground penetrating radars operated in a standard mode on a network of positions to retrieve the 2D or 3D structure of the underground.

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