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Reflecting Sub-Ice Surfaces Observed by Radio Echo Sounding System

C. Bianchi[1], P. De Michelis[1], U. Sciacca[1], E.I. Tabacco[2],
A. Zirizzotti[1] & E. Zuccheretti[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia, Roma - Italy
[2]Università di Milano - Sezione Geofisica, Milano - Italy

**Corresponding author* (bianchi@ingv.it)

INTRODUCTION

The reflection coefficient (R) at the interface of two media provides information on their electromagnetic nature. If the first medium is known, *e.g.* air (or ice, that in a broad interval of physical conditions maintains certain propagative characteristics nearly constant), the electromagnetic properties of the second medium can be determined. Hence, the ice/seawater, ice/water and ice/rock interfaces exhibit different reflection coefficients which can be detected by means of a RES system (Tabacco et al., 1999; Tabacco et al., 2000). The length of the radio wave does not allow the employment of sophisticated antennas, and so folded dipoles are arranged beneath the wings of the aircraft. As a consequence, the transmitted radio wave beam illuminates a relatively large area, and the power of the echo signal greatly depends on the shape of the reflecting surfaces. An electromagnetic analysis shows that, in certain conditions, the variations in amplitude detected by the system are mainly due to focusing or defocusing effects determined by the shape of the reflectors (Bianchi et al., 2001; Tabacco et al., 1999).

ELECTROMAGNETIC ANALYSIS

To determine the nature of the sub-ice surface one must consider the physical properties of the media that affect the reflection of radio waves. The reflection coefficient is given by:

$$R = \frac{\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}}{\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}}$$

where ε_{r1} and ε_{r2} are the complex relative permittivities of the two media and R is the percentage of the amplitude of the return signal. RES techniques are based on the analysis of the power of the signal, and R^2 is the quantity that takes into account the percentage of reflected power. Hence the strength of the return signal depends on the particular interface involved in the wave propagation path. The complex relative permittivity characterising the electromagnetic

Tab. 1 – Electromagnetic properties of the considered media.

Medium	*Real part of relative permittivity ε' (dimensionless)*	*Conductivity σ (S/m)*
air	1.0	0
ice (-20 °C)	3.18	$\approx 1.6 \cdot 10^{-5}$
ice (-50 °C)	3.18	$\approx 1 \cdot 10^{-6}$
seawater	84.4	≈ 3
water	81	$\approx 10^{-3}$
bedrock	10-11	$\approx 10^{-7} - 10^{-3}$
sea ice	3.44	$\approx 10^{-2} - 0$

propagation of radio waves can be written as: $\varepsilon_r = \varepsilon' - i\varepsilon''$, where, ε' is the real part, $\varepsilon'' = \sigma/\varepsilon_0$ is the imaginary part, σ (S/m) is the conductivity, *i* is the imaginary unit, ε_0 (F/m) is the vacuum dielectric permittivity and ω (rad/s) is the angular pulsation of the radio wave. Hence, the real part of the relative permittivity ε' and conductivity s are sufficient to calculate *R*. Table 1 reports the above mentioned quantities at the operating frequency of the RES system and for the indicated media. Table 2 lists the power reflection coefficient R^2 for the described interfaces indicating the percentage of power reflected by the interface.

For ice/rock, ice/water and ice/seawater interfaces, in the ideal case of smooth and flat reflecting surfaces, and neglecting all the others radio propagative parameters (because assumed constant), we would expect the power loss indicated in table 2. The experimental RES return intensity at the various interfaces is different (Bogorodsky et al., 1985; Bentley et al., 1998). In real cases, once other contributions are excluded, the differences in the value of return intensity allow us to distinguish interfaces, especially ice/rock and ice/water interfaces when analysing subglacial lake surfaces. In particular, in the case of continental glaciers ice/ rock and ice/water interfaces are expected, along with some intermediate cases such as ice/wet-ice and ice/wet-rock. The first two interfaces introduce losses of –11 dB and –3.5 dB, as can be seen in the reported analyses. For example, figure 1a shows a profile of a suspected subglacial lake, and its electromagnetic analysis is reported in figure 1b. The flat segment of the reflector determines a return signal power loss of less than 11 dB with respect to the adjacent profile. This fact confirms that the flat reflector is a subglacial lake or a wet, flat surface. Other morphological interpretations such as the extension of the supposed lake-surface reflector in comparison with whole profile contours and the internal layering of the glacier, can further sustain this interpretation.

Tab. 2 – Power reflection coefficient R^2 and approximate power lost at the indicated interfaces.

Interface	Reflected power ratio R^2	Loss in dB
air/ice	0.08	- 11
air/seawater	0.9	- 0.4
ice/seawater	0.83	- 0.8
ice/water	0.446	-3.5
ice/rock	0.088	- 10.5
ice/sea ice	$4 \cdot 10^{-4}$	- 34

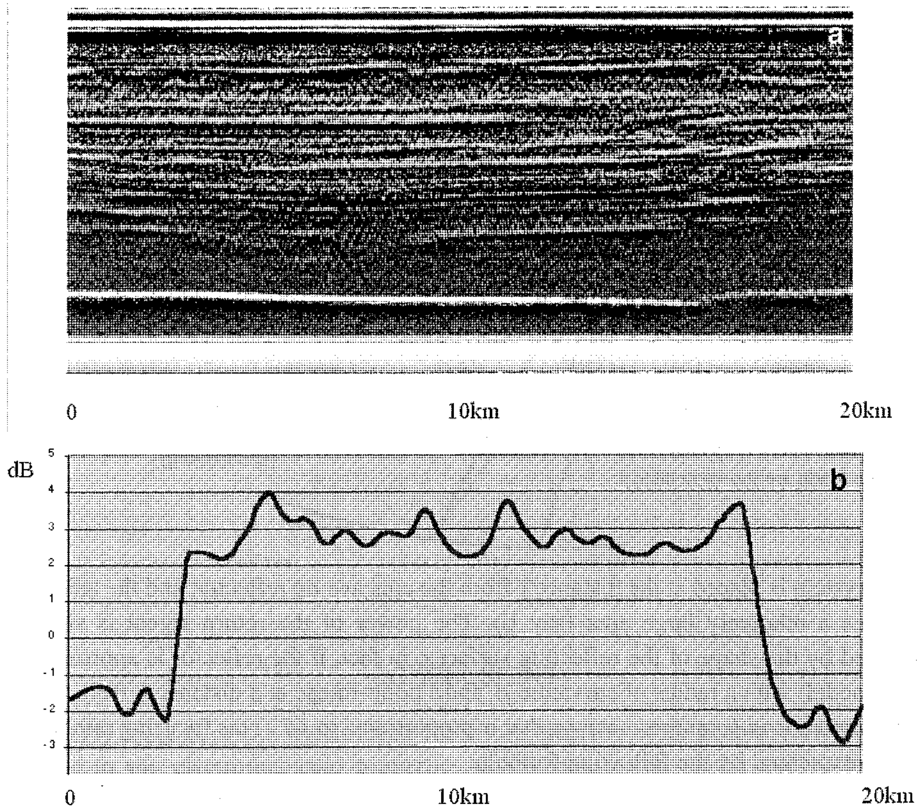


Fig. 1 – A) reports the profile of a subglacial lake B) the variation in the return intensity (dB). In agreement with theoretical calculations, the power of the return signal from the subglacial lake (bottom flat reflector) is 5-7 dB greater than that of the ice/rock interface.

The different interfaces between two media reflect different portions of the incident power which are then detected by the RES system. When the investigated surfaces are concave or convex, the radio signal is respectively focused or defocused producing gain or loss in the received power of the signal (Davies, 1990). Depending on the shape of the surface and other geometrical conditions, the power variation can reach several dB. Variations of ± 8-10 dB were recorded along the profile of floating ice tongues (Bianchi et al., 2001; Tabacco et al., 1999) after excluding other possible contributions. Floating ice tongues are useful for evaluating the electromagnetic property of the transmissive medium because of the constant ice/seawater interface and other peculiar characteristics. A segment of the profile is shown in the upper trace of figure 2, while the lower trace in the same figure shows power variations due to concave and convex reflecting surfaces. Numerical modelling was used to create 2D and 3D representations of the bottom ice surface. These models can explain the variations in amplitude observed during measurements. The bottom reflecting surfaces were divided into different segments corresponding to concave and convex faces, and individual reflectors were studied. The best-fit arc and its radius of curvature were thus identified.

For a convex and concave spherical cap, adopting 2D and 3D models, and exploiting a simple law of the optical geometry, the reflector gain can be determined. Referring to figure 3,

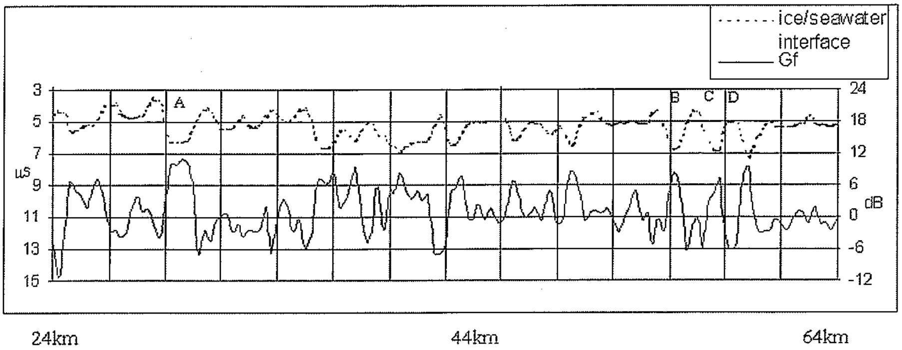


Fig. 2 – Smooth bottom surface profile (distance vs. ice thickness) and relative amplitude variation (dB). The quadratic regression shows that the circular arc approximates concave reflectors when these coincide with the greatest recorded signal amplitude (A-C); it approximates convex reflectors when these coincide with the lowest level of the signal (D). The curvature radii are shown in table 3.

the RES system is placed at the distance r from the concave-up reflector, and the antenna beam illuminates a relatively large area (say L). The power of the return signal is significantly determined by the shape of the reflecting surfaces; in fact, if the reflector is approximately an arc (2D model) with a radius of curvature ρ_l and a point-image at a distance q from the arc, the receiving antenna in l captures a power that is proportional to $1/l$. This focusing effect produces a gain G_f expressed by the following formula:

$$G_f = +\frac{1}{1-\frac{r}{\rho_1}}$$

In the case of a convex-up arc reflector, there is a power loss of the same amount. If spherical reflectors are considered (3D model), the gain is:

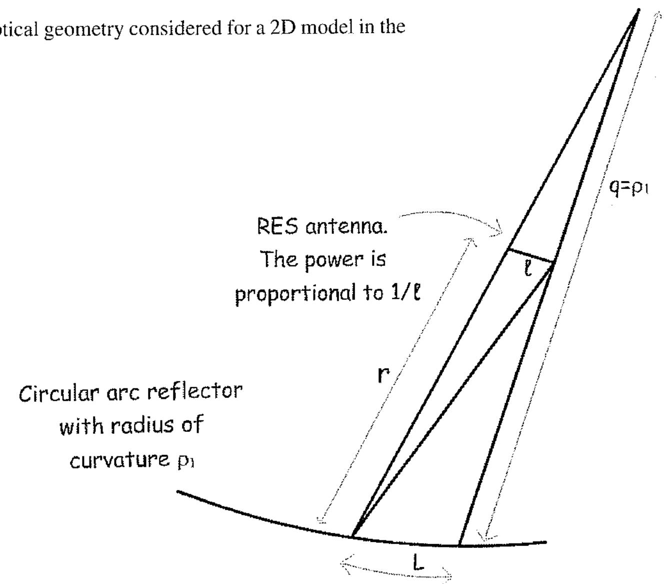
$$G_f = \pm\frac{1}{(1-\frac{r}{\rho_o})^2}$$

where ρ_o is the radius of curvature of the spherical reflector. Four reflectors with their geometrical characteristics and the relative gain/loss are reported in table 3.

Tab. 3 – The selected reflectors in figure 2 and the respective G_f.

Reflector as in figure 2	*Range r (m)*	*Radius of curvature ρ_l or ρ_0 (m)*	*G_f (dB unit) 2D model*	*G_f (dB unit) 2D model*	*Power variation (dB)*
A (494-531)	650	1190	+3.39	+ 6.86	+ 8.79
B (940-968)	732	1200	+ 4.01	+ 8.17	+ 6.67
C (976-994)	720	1300	+ 3.5	+ 7.01	+ 5.47
D (994-1016)	570	1000	-4.05	- 8.09	- 6.61

Fig. 3 – The optical geometry considered for a 2D model in the case of an arc.



CONCLUSIONS

In the RES analysis of sub-ice surfaces, the return intensity of the bottom reflector can vary greatly due to the electromagnetic properties of the interfacing media and to focusing or defocusing effects which depend on the particular shape of the reflector. This paper shows how these effects can be estimated. By means of a simple electromagnetic analysis, it is possible to distinguish the interfaces involved in the reflection phenomenon. In the case of continental glaciers, two possible interfaces (ice/water ad ice/rock) are considered. Considering only the power contribution from the bottom interface, the power of the return signal varied by 8-10 dB. Radio echo sounding along a longitudinal profile of a floating ice tongue were used to develop an electromagnetic analysis that has shown the close link between the shape of the bottom reflecting surface (ice/seawater interface) and the amplitude of the signal. Amplitude variations along the examined profile are, in general, compatible with the two proposed models based on the geometric optics. Power variations are determined by circular arc (2D) or spherical reflectors (3D) that display concave or convex faces towards the sounding apparatus.

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