ANNALS OF GEOPHYSICS, 60, 2, 2017, G0226 dos: 104401/ag-7122.

Airborne Radio Echo Sounding (RES) measures on Alpine Glaciers to evaluate ice thickness and bedrock geometry: preliminary results from pilot tests performed in the Ortles-Cevedale Group (Italian Alps)

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Article history
Received July 26, 2016; accepted February 24, 2017.
Subject classification:
Scintillations, Solar-terrestrial interaction, Space weather, Solar variability and solar wind, Magnetic storms.

ABSTRACT

Radar exploration supports glaciological studies playing several roles in ice exploration such as determining ice thickness and volume, describing ice and snow internal layering and characterizing crevassed areas. The method, widely used with full success on Polar areas, encounters more difficulties when applied to survey mountain glaciers like the Alpine and Himalayan ones. Among them, these difficulties can be addressed to the different physical characteristics of temperate ice and to logistic difficulties related to performing field operations at high elevations on areas where crevasses, seracs and ice-falls are present, making more complicate and complex the glacier surface.

In the framework of the SHARE-PAPRIKA and the SHARE-STELVIO Projects, we performed some preliminary measurements on Careser, Sforzellina and Forni glaciers (Ortles-Cevedale Group, Italy), to evaluate efficiency and applicability of a Radio Echo Sounding (RES) instrument specifically designed, developed and modified by the INGV (Istituto Nazionale di Geofisica e Vulcanologia) laboratories. This paper reports the results we obtained investigating each glacier, the hampering factors and the cost to benefit ratio introduced by the airborne survey.

1. Introduction and study aims

In the recent past, glaciers have begun melting at rates that cannot be explained only by natural climate variability [Dyurgerov M.B. and Meier M.F., 2000]. Glacier shrinkage is particularly severe upon the Alps, and it is likely driven by the important changes occurring in mid-tropospheric conditions, such as the widely acknowledged rapid increase in temperature during the last few decades [IPCC, 2013]. Between 1850 and 1980, glaciers in the European Alps lost approximately one third of their area and one-half of their mass, and since 1980 another 20 to 30% of the ice has melted [European Environment Agency, 2004]. The terminus fluctuation data (since the end of the 19th century in the Alps) show a general retreating trend, with length reduction ranging from a few kilometers (in the case of larger glaciers) to several hundreds of meters [in the case of smaller ones; Hoelzle M. et al., 2003; Citterio M. et al., 2007a]. The mass balance records (long over the last six decades in the Alps) indicate strong ice losses, which seem to be accelerated in these last years [from 1985 to the present, see Zemp M. et al., 2008].

To develop robust and reliable glaciological models to describe glacier behavior and evolution under climate change scenarios, mass balance data are needed with information on glacier geometry (ice thicknesses and volume, bedrock geometry, etc.). In several cases geometry information are only estimated from surface data (i.e.: slope, elevation range, surface topography) and they suffer of a certain degree of uncertainty [Haeberli W. and Hoelzle M., 1995 and Hoelzle M. et al., 2003].

Geophysical exploration can represent a suitable tool for obtaining data on glacier depth and bedrock geometry. Unfortunately, the remoteness of some mountain glaciers and their uneasy accessibility constitute actual restrictions to operate geophysical surveys and can drive the production of irregularly spaced and sparse datasets.

During last decades, the electromagnetic radar methods, such as Ground Penetrating Radar (GPR), Radio Echo Sounding , or Frequency-Modulated Continuous Wave (FMCW) proved their suitability for glaciological purposes [e.g., Goodman R.H., 1975; Bogorodsky V. et al., 1985; Plewes L.A. and Hubbard B., 2001; Dowdeswell J.A. and Evans S., 2004; Hubbard B. and Glasser N., 2005; Navarro F.J. and Eisen O., 2009; Bell R.E. et al., 2014; Urbini S. and Baskaradas J.A., 2010]. Besides, the progress in digital electronics led to more efficient and transportable instruments allowing their use also in Alpine glaciers environment [e.g. Ryser C. et al., 2013; Eisen O. et al., 2009; Binder D. et al., 2009; Hamran S. et al., 1996]. Among them, RES system works transmitting, at a given carrier frequency, a powerful long pulse (usually of user selectable length) and this technique represents one of the main prospecting tool used in Antarctica ice sheet exploration where the ice column can exceed the depth of 4 thousands meters.

In this paper, we report the results obtained from a preliminary test of an airborne RES system manufactured by the INGV (Istituto Nazionale di Geofisica e Vulcanologia) laboratories for Alpine/Himalayan glacier environment exploration in the framework of SHARE-PAPRIKA and the SHARE-STELVIO Projects. The idea was to create a system that could work on local mountain glaciers and, overall (in a further development), on Himalayan ones which are located at higher elevations, with thicknesses greater than 1000 m, imbedded between steep nesting mountain walls with reduced glacier width (compared to the glacier length). In July 2012, our preliminary tests were carried out on a selection of glaciers located in the central Italian Alps: Careser, Sforzellina and Forni glaciers. The main goal of this first test campaign was to verify the effectiveness of the airborne RES system, trying to collect information on ice thickness and bedrock assessment of the investigated glaciers.

2. Study sites

The glaciers we have chosen for our study (Careser, Sforzellina and Forni) are located in the Ortles-Cevedale Group (Central Italian Alps, Figure 1) and show different size, aspect and type.

Ortles-Cevedale represents one of the most important glacierized sector of Italian Alps hosting 129 glaciers, shared among Lombardy, Trentino and South Tyrol and covering an area of about 72 km^2 [Smiraglia C. et al. 2015, D'Agata C. et al., 2014]. The highest elevation peaks are Ortles and Cevedale (3905 and 3769 m a.s.l., respectively).

Over the years, these glaciers were also monitored by the glaciological campaigns performed by the Comitato Glaciologico Italiano [CGI, 1914-1977].

Figure 1. Flight path and investigated glaciers (base layer from Google Earth ©).

2.1 The Careser Glacier

Careser Glacier (Figure 1) is a mountain glacier derived from a much wider glacier which, since the Little Ice Age (LIA) up to the beginning of the last century, exhibited a well-developed valley tongue, completely melted away. It is set in a wide, south facing cirque surrounded by peaks ranging from 3162 m a.s.l. (Cima Lagolungo) to 3386 m a.s.l. (Cima Venezia). Its gentle sloping surface of 2.83 km^2 extends from a minimum altitude of 2860 m a.s.l. to a maximum elevation of 3310 m a.s.l. It is now split in five ice bodies covering a total area of about 1,6 km^2 [Carturan L. et al., 2013]. During the 1999, seismic and GPR measurements pointed out a maximum thickness value of 70 m [Forieri A. et al., 1999]. They also reported for this glacier surface velocities small in magnitude (maximum of 2 m yr−1 between 1968 and 1970). Carturan L. et al. [2013] performed GPR profiles in the eastern part of the Careser Glacier in 2007 and in 2008 and found a maximum thickness of 88 m, averaging 27.5 m.

The meltwater has been artificially dammed at 2600 m a.s.l. since the 1920's for hydropower production and since then the glacier has been intensely investigated. On Careser Glacier, mass balance measurements have been carried out since 1967 and the data series, the longest one for the Italian Alps, extends until present without interruptions [Giada M. & Zanon G., 1991; 1996; 2001; Zanon G., 1970; 1992, Carturan L. & Seppi R., 2007; Carturan L. et al., 2016]. Careser is part of the reference glaciers network taken into account by the World Glacier Monitoring Service on a global scale and the mass balance data are regularly published in the Glacier Mass Balance Bulletin and Fluctuations of Glaciers [IUGG (CCS)-UNEP-UNESCO- WMO, 2013].

2.2 The Sforzellina Glacier

The Sforzellina Glacier (Figure 1) is a northwest-facing cirque glacier [about 0.3 km^2 of surface area, see Cannone et al., 2008] extending from 2850 to 3100 m a.s.l. and located in Valfurva (Upper Valtellina). Sforzellina Glacier has one of the older and more continuous records of terminus fluctuations (from 1925 up to now) and mass balance (from 1987 up to now) [CGI, 1914-1977, 1978-2015; Catasta G. and Smiraglia C., 1993; Cannone N. et al., 2008]. It is also one of the few Italian glaciers of which we have information about ice thickness and bed geometry. Its flow speed was found ranging from 5 and 10 m/y. On Sforzellina Glacier, different geophysical surveys were applied in order to evaluate ice thickness and bedrock morphology. Geoelectrical, through Vertical Electrical Soundings [VES; Resnati C. and Smiraglia C., 1989; Guglielmin M. et al., 1995], and seismic reflection methods [Merlanti F. et al., 2001] gave a maximum ice thickness of 42 and 60 m, respectively. In 1999, a GPR survey was performed

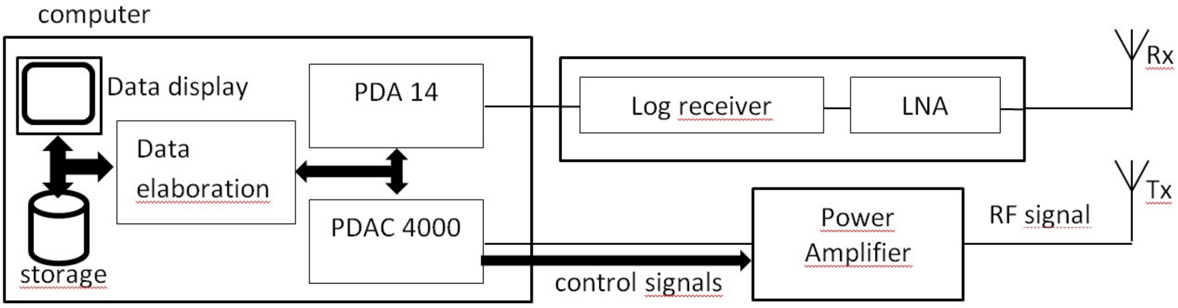

Figure 2. Sketch of the 40 MHz RES system.

Figure 3. RES system and antenna arrangements for helicopter survey.

to obtain high-resolution bedrock topography [Pavan M. et al., 2000]. The maximum ice thickness calculated was of 60 m in the central area of the glacier. In addition, geomorphological surveys were also performed to map the glacial landforms related to past glacial evolution [Rossi S. et al., 2003]; more recently, since the twenties of the past century, the glacier extention was reconstructed, mapped and analyzed with respect to vegetation occurrence and growth to look for climate change impacts on the alpine environment [Cannone N. et al., 2008].

2.3 The Forni Glacier

The Forni Glacier (Figure 1) is the largest Italian valley glacier (ca. 11 km^2 of area). It lies on the northern slopes below Mt. S. Matteo, at an elevation range between 3670 m and 2600 m a.s.l. From 2005, it hosts the first supraglacial Automatic Weather Station (AWS) of the Italian Alps [Citterio M. et al., 2007b; Senese A. et al. 2012a; 2012b; 2014], thereby increasing the scientific value of the glacier. This AWS was already included in several international projects such as the meteorological network SHARE (Stations at High Altitude for Research on the Environment) developed by EvK2CNR Association and the CEOP network (Coordinated Energy and Water Cycle Observation Project), promoted by WCRP (World Climate Research Programme). It is also the only Italian site inserted in the SPICE (Solid Precipitation Intercomparison Experiment) and the Cryonet projects managed and promoted by WMO (World Meteorological Organization). The records for length variations in the Forni Glacier are among the longest standing in the Italian Alps, making it a benchmark glacier of primary importance. Fluctuation data for the glacier terminus show a basic retreating trend from 1895 to present with a tongue retire assessed of about 2 km. Moreover, from historic maps and aerial photos, its area coverage has been calculated for the last 150 years. The results show that the Forni Glacier has also experienced a marked decrease in area: from 17.80 km^2 at the end of the LIA (~1860) to 11.34 km^2 in 2007 (-36.3%) [Diolaiuti G. and Smiraglia C., 2010; D'Agata C. et al., 2014].

During last decades, several different geophysical surveys were carried out on the Forni Glacier in order to evaluate ice thickness and bedrock morphology. Among them, VES survey [Guglielmin M. et al., 1995] and seismic reflection [Merlanti F. et al., 1995] gave a maximum ice thickness of the glacier tongue at the base of the central ice fall (at about 2950 m asl) of 100 and 120 m, respectively.

Peak power	4 kW
Carrier frequency	40 MHz
Pulse lenght	25-500 ns
ADC resolution	14 bit
Sampling frequency	100 MHz
Vertical resolution	1.1-20 m
Samples per trace	2048
Maximum depth (in ice)	1.7 km

Table 1. INGV RES radar characteristics.

The glacier flow was evaluated ranging from 40-45 m/y in the upper sectors to 10-15 m/y at the snout [Garavaglia R. et al., 2014].

The availability of meteorological and geometry data by an AWS and radar surveys, respectively, are crucial for developing and applying flow models on Forni Glacier. In this way once the past glacier evolution is well reproduced, the future scenarios could be investigated. In fact, without very important input data as thickness and slope at each grid point, a flow model could not be developed.

3. The RES System

Based on our past experience in airborne RES measurements [Tabacco I.E. et al., 1999; Tabacco I.E.

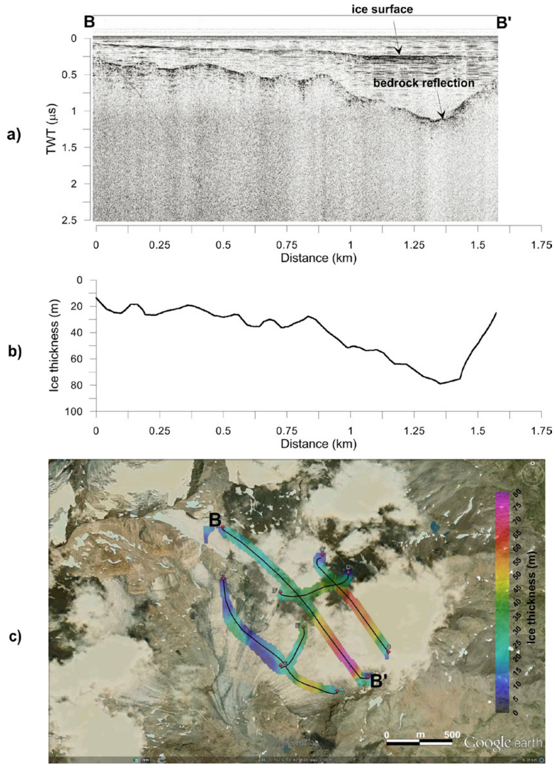

Figure 4. Example of profile recorded on the Careser Glacier: a) radargram; b) ice thickness along the profile; c) interpolated ice thickness dataset on Google Earth © map.

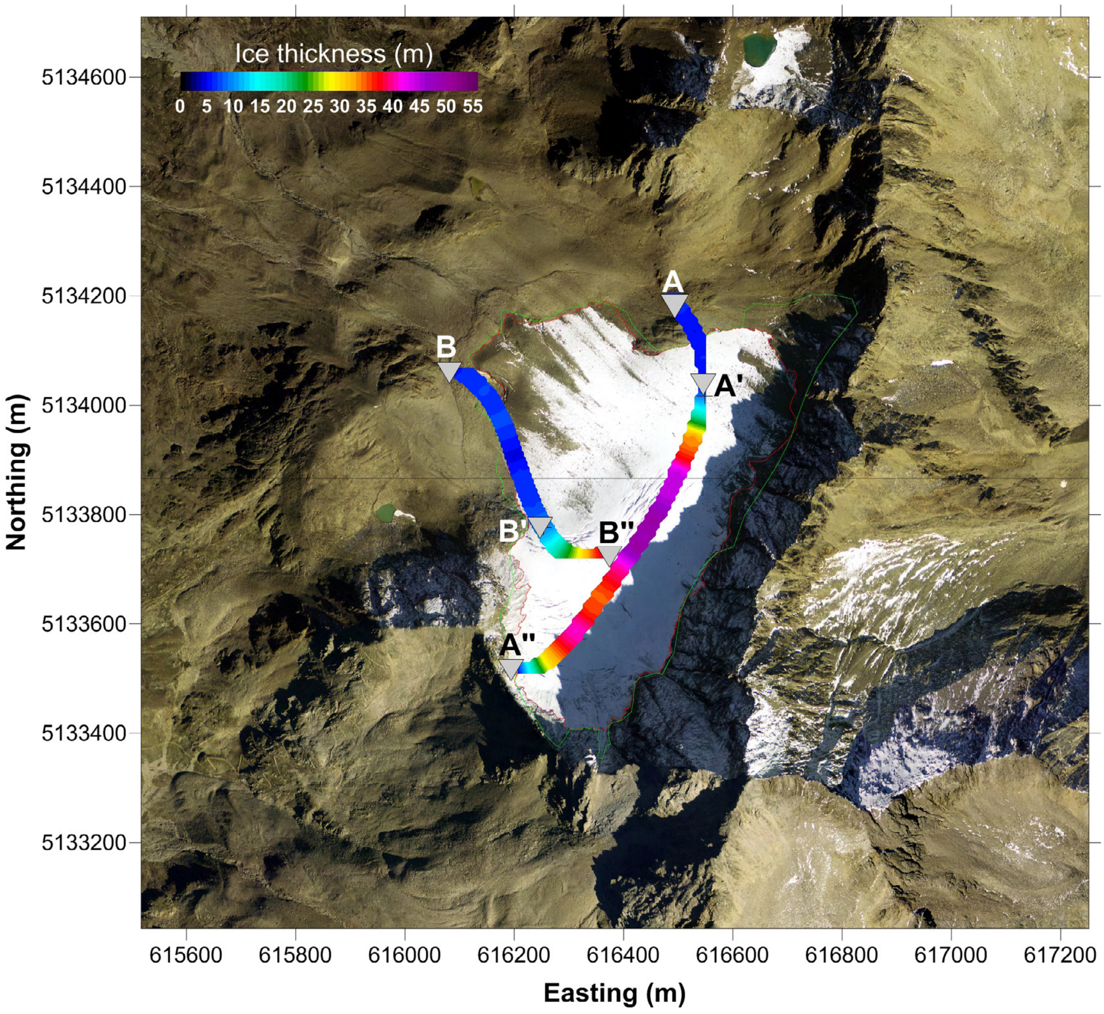

Figure 5. Map of interpolated ice thickness along the RES profiles carried out on Sforzellina glacier.

et al., 2008 Zirizzotti A. et al., 2008], we develop a 24 V.d.c. system operating at 40 MHz (4 kW maximum peak power) with an envelope pulse width variable between 25 ns (1 cycle) and 500 ns (20 cycles). A simple sketch of the RES system is shown in Figure 2. The main parts of the radar are two Signatec PCI boards: the PDA 14 Analog-to-Digital acquisition Card (ADC) with 14 bit of resolution and the PDAC4000 waveform generator running at 4 mega samples per seconds. These two cards are used to generate and control the radar waveform, and to record the demodulated signal from the logarithmic envelope receiver. The receiver is composed of a low noise amplifier (LNA) followed by an envelope logarithmic detector. The minimum detectable signal is -110 dBm limited by the thermal noise at the receiver input. The ADC frequency sample clock is 100 MHz recording 2048 samples for each trace. As a consequence the maximum recording window is 20.48 μs that means an ice thickness of about 1.7 km. Using a pulse length varying from 25 ns to 500 ns, the theoretical vertical resolution ranges between 1.1 and 20 m.

The horizontal sampling rate varies from 10 to 100 traces/s allowing multiple signal stacking options depending on the ground speed. Flight heights above glacier surface ranged between 20-100 m while ground speed varied between 55 to 75 km/h resulting in an averaged ground sampling of 0.15-2.1 m/scan.

Antennas were placed on a wooden bird (Bygol-1) suspended at 18 m below the helicopter's fuselage by means of a barycentric rope while the system occupied a rear seat place (Figure 3).

The location of the radar traces was obtained by coupling a geodetic GPS (Global Positioning System) receiver synchronized to the radar acquisition (1 position/s). The differential correction was applied in post processing using a GPS Base station.

To convert reflection travel times to depth for all recorded data, we assumed a wave speed of 168 m μs^{-1} for solid ice.

Recorded datasets were post processed by Vertical and Horizontal bandpass filtering, deconvolution, gain equalizing and migration. Then, bedrock data were interpolated along the line by kriging method and

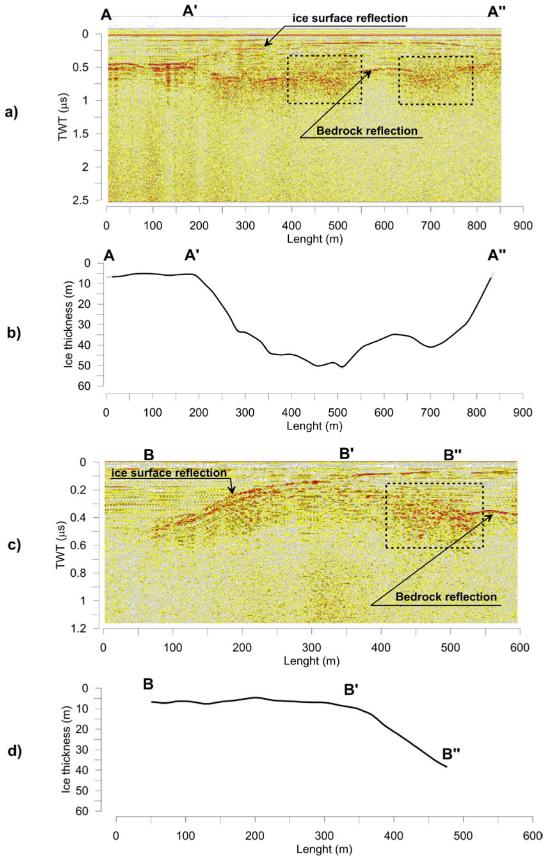

Figure 6. Sforzellina Glacier: radargram collected on AA'A'' profile (a) and its conversion in ice thickness (b); radargram relative to the BB'B'' profile (c) and its conversion in ice thickness (d).

plotted as thematic layers on Google Earth (GE) maps. A commercial GSSI SIR 3000 GPR system was used as reference during the first phase of the test survey.

4. Results

4.1 Careser Glacier

The Careser Glacier survey consists in approximately 5 km of profiles (Figure 4c) covering the main parts of the glacier. All the flow lines we investigated returned very clear bedrock reflections and practically no sign of backscattered energy areas (Figure 4a). Figures 4b and 4c represent, respectively, the ice thickness of BB' profile (that includes the maximum recorded depth of about 80 m) and the interpolation of all the along-the-line ice thickness data overlapped on a Google Earth image of the glacier.

It is useful to note, for the following discussion, the energy of the signals reflected from both the interfaces (ice surface and bedrock) and its continuity. The ice thickness increases along the flow line ranging from 10 m at the glacier terminus to 80 m in the upper glacier sector, resulting in agreement with findings reported by Forieri A. et al. [1999] and Carturan L. et al. [2013].

4.2 Sforzellina Glacier

The Sforzellina Glacier survey was conducted through two perpendicular lines (Figure 5) in order to get information on both the glacier basin morphology (AA'A'') and along the small ice tongue (BB'B''). The Figure 6 reports more in detail the obtained results on both the RES lines.

Comparing the radargrams in Figures 4a and 6a, the Sforzellina ice-bedrock reflections showed lower amplitude than ones recorded on Careser Glacier survey. The bedrock echoes partially disappear from 420 to 500 m and from 675 to 750 m, along the profile where also backscattered energy appears (see black dot boxes in Figures 6a and 6c). Despite this, it was possible to define the bedrock morphology along the whole track. Being a little cirque glacier, the thickness trend results completely different from the previous glacier. In fact, it is characterized by a quite symmetrical profile (i.e. an increase followed by a decrease) reaching a maximum depth of 50 m in the middle part according with the results by Resnati C. and Smiraglia C. [1989], Guglielmin M. et al. [1995] and Pavan M. et al. [2000]. Finally, we also recorded shallow reflections between AA' and BB' profiles (featuring also multiple effects) even though the presence of a debris coverage on the glacier surface which in some zones is thicker than 40 cm .

4.3 Forni Glacier

The Forni Glacier is composed by three accumulation basins which merge into the main glacier tongue, with the presence of crevasses and debris coverage areas [i.e. medial moraines, see Smiraglia C., 1989]. It was the widest of the studied glaciers and we carried out 7 transects for a cumulative length of about 20 km. Figure 7a shows the radargram corresponding to the flow line along the central ice stream raising from an altitude of 2563 to 3217 m a.s.l. (AA' in Figure 7c).

The section AA' remarks the massive presence of the energy backscattering phenomena that does not permit to identify effective bedrock reflections along most of the profile. Bedrock echoes are well identifiable only at the beginning and at the end of the profile and partially in small spots in the central part (red boxes in Figure 7a). Nevertheless, the maximum ice thickness points (about 120 m) were recorded on the glacier tongue at the base of the central ice fall and in the upper accumulation basin of the left branch of the Forni Glacier, at the end of C-C'' profile. These results are also in agreement with those obtained by other authors [Guglielmin M. et al., 1995; Merlanti F. et al., 1995]. The occurrence of deeply crevassed areas, as the

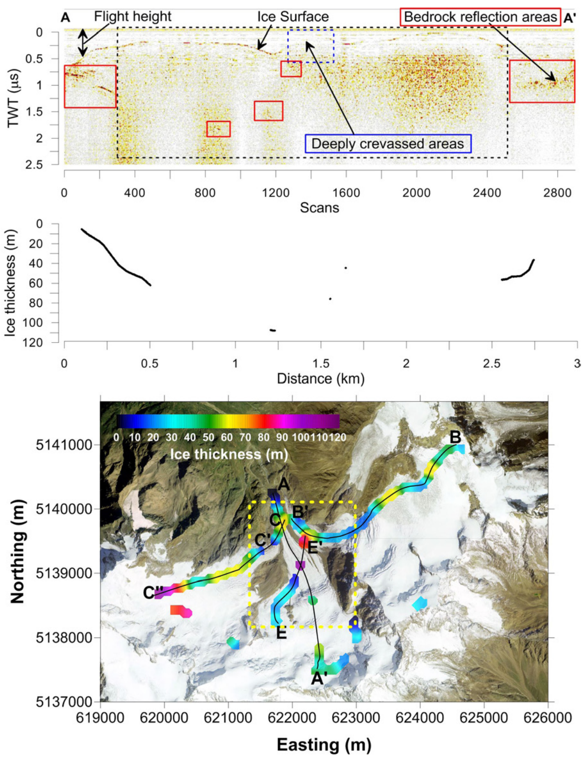

Figure 7. Example of profile recorded on the Forni Glacier: a) AA' radargram (X axis scale reports the scan numbers and not the distance due to high helicopter's speed variations); b) ice thickness along the profile; c) interpolated ice thickness along all the recorded profiles.

one located in the middle part of the main flow line, avoids recording any bedrock echoes even disturbing the continuity of the ice surface reflection (blue dots, box in Figure 7a). The waves backscatter phenomena affects large parts of the glacier but we were able to collect coherent spots of bedrock reflections in lateral ice sectors of the glacier (Figures 8a, 8b and 8c).

5. Discussion

The effectiveness of our RES airborne system and the record of bedrock echoes were the core of this first test performed on Alpine glaciers and we obtained enough good results. In fact, we found similar glacier thickness values compared to the results coming from previous studies [Resnati C. and Smiraglia C., 1989; Guglielmin M. et al., 1995; Forieri A. et al., 1999; Pavan M. et al., 2000; Merlanti F. et al., 2001, Cannone N. et al., 2008; Carturan L. et al., 2013], even if not all bedrock echoes were recorded.

The RES waves scattering in glaciers survey is a well-known phenomena. Smith B.M.E. and Evans S. [1972] showed that bedrock echoes could be obscured by scattering waves probably due to the presence of water-filled voids in the ice. In 1976, Watts R.D. and England A.W. found that the masking of bottom-echo returns occurred preferentially in glacier accumulation areas where ice lenses and water inclusions were more numerous in firn and ice at its melting point. Even more recently, several authors [Ryser C. et al., 2013; Eisen O. et al., 2009; Binder D. et al., 2009] debated on the role of water inclusions in radar signals scattering. In addition, internal reflectors could also result from the presence of impurities (such as debris or ash layers and chemical precipitates), fluctuations in ice density, bubble content, geometry and crystal axis orientation, the presence of brine, or changes in water content and temperature with depth [Dowdeswell J.A. et al., 1984].

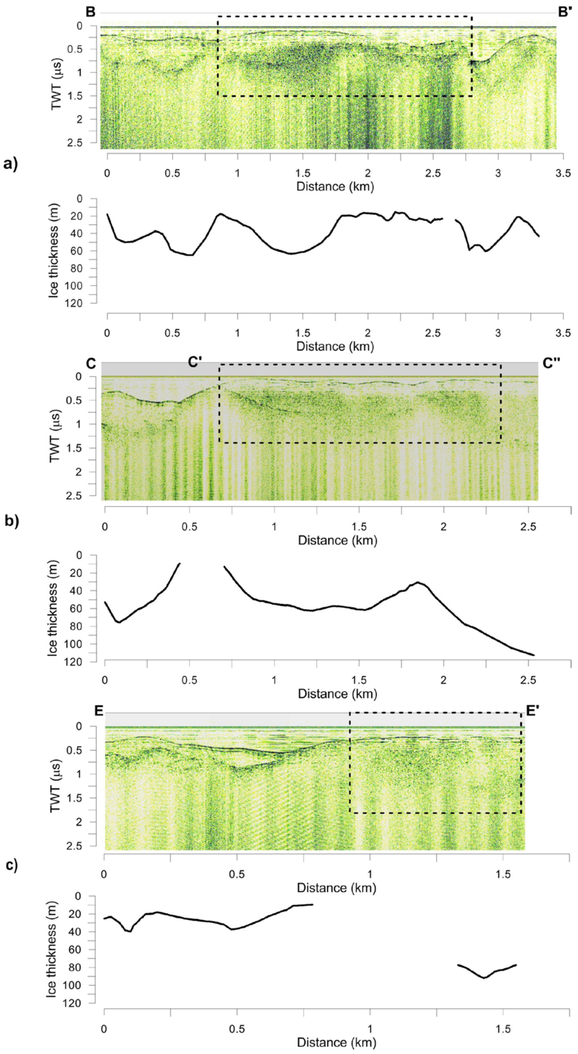

Figure 8. RES profiles and ice thickness values recorded on the lateral branches of Forni Glacier; refer to Figure 7c for their positions on map.

The separation between low and high backscatter areas, termed as "Radar Transition Surface" (RTS), was related to the presence of a Cold-temperate Transition Surface (CTS) into ice body temperatures [Eisen O. et al., 2009]. Then, due to the different dielectrical properties of ice and water, low-backscatter areas were ascribed to a cold ice body with low or null content of liquid water [Pettersson R. et al., 2003; Navarro F.J. et al., 2005]

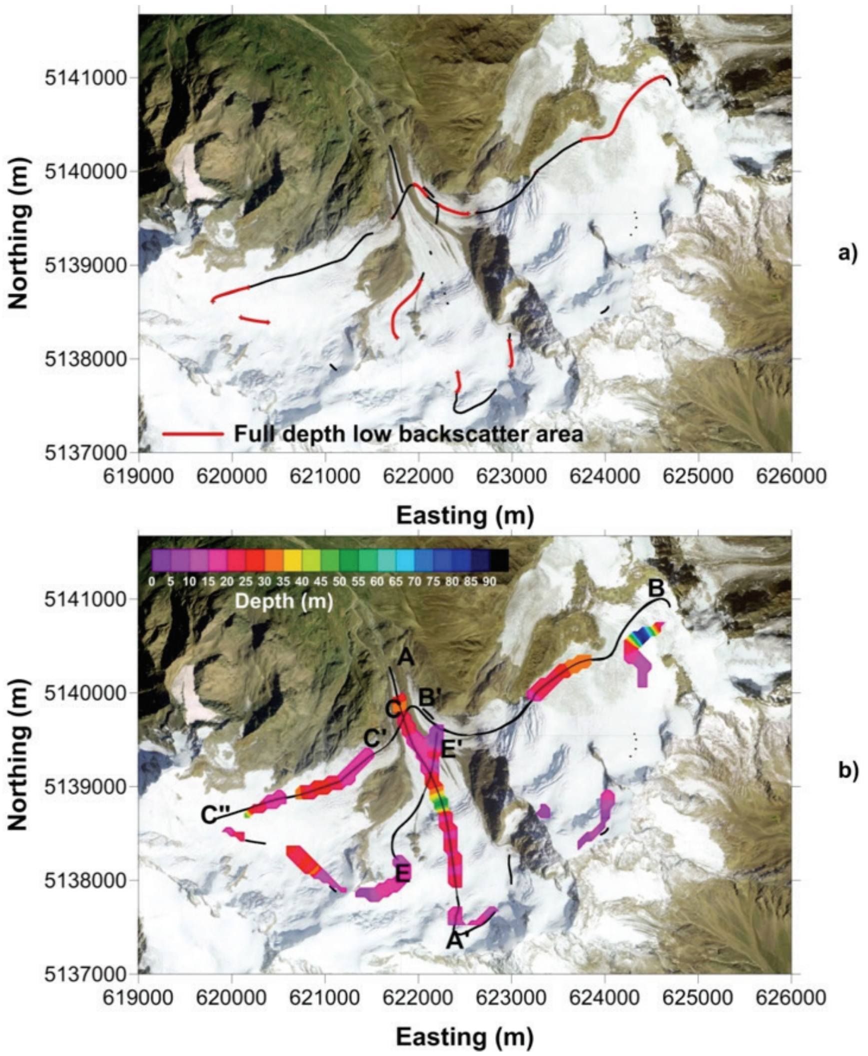

Figure 9. a) Distribution of full-depth low backscatter areas; b) RTS (Radar Transition Surface) depth.

while strong scattering areas were originated by liquid water inclusions in temperate ice [e.g., Bamber J.L., 1988; Tabacco I.E. et al., 1995; Hamran S. et al., 1996; Murray T. et al., 2000]. Finally, another well known factor that limits the RES survey is the presence of steep and crevassed areas, considering that they may occupy large sectors of glaciers [Dowdeswell J.A. et al., 1984; Huss M. et al., 2008].

Considering all the above descripted hampering factors, the choice of the operational frequency of a radar systems could become critical. Signal absorption and wave scattering increase with the frequency, with the ice temperatures and with superficial and internal inhomogeneity of the glaciers. The use of lower frequency could be advantageous in sounding relatively thick ice at or near its melting point, but implied also a lower resolution.

In our test flights, we chose the 40 MHz frequency that offered a good compromise between the antenna dimensions (safe to be flown), the penetration capability (exploiting also the appropriate selection of the pulse length) even if, as negative point, we expected a certain sensitivity to meter-size englacial scatterers.

In order to deal also with the worst possible condition, we planned to perform our test in the month of July, when melting water content of the glaciers was supposed abundant in our study area [e.g. Senese A. et al., 2012a, b].

Summarizing, the Careser Glacier (surface area 2.83 km^2, max depth recorded 80 m, altitude comprised between 2860 and 3310 m a.s.l., ice flow speed v<<5 m/y, south facing cirque) survey has shown very clear bedrock reflections everywhere and practically no sign of backscattered energy areas. According to the above considerations, these results could be interpreted due to the gentle sloping surface and to a reduced presence of water.

The Sforzellina Glacier (surface area 0.3 km^2, max depth recorded 60 m, altitude comprised between 2850 to 3100 m a.s.l, and ice flow speed ranging from 5 to 10 m/y, northwest facing cirque) survey has showed also in this case clear bedrock reflections but also scattered waves starting from about 20 m of depth in some limited areas. These areas seem to be located in bedrock depressions (see Figures 6 a, b) where water accumulation could be more probable. Observing the Figure 6a, despite of the occurrence of scattered waves, we recorded very bright ice bottom reflections between the along-the-line interval 250-550 m and weak reflections between 650-770 m. This difference could be interpreted as sign of a substantial difference in liquid water content at ice-bedrock interface in the northern part of the glacier. Along the AA' and BB' profiles (Figures 6a and 6c), shallow reflections were recorded under the debris covered parts of the glacier surface showing also multiple effects (especially in BB' section). The surface reflection shows an evident decrease in amplitude in the debris free part of the glacier and no evidence of backscatter or superficial clutter effects between the two reflections are found. A possible interpretation of this behavior is the presence of shallow ice (up to 5 m thick) covered by a thin layer of fine debris (with a debris thickness minor than the wavelength resolution).

The Forni Glacier (surface area 11 km^2, max recorded depth 120 m, altitude comprised between 2600 and 3700 m a.s.l., ice flow speed ranging from 10 to 45 m/y, north aspect) survey pointed out a more complex geophysical image if compared to the previous two. Large parts of the glaciers returned radargrams heavily affected by waves scattering that in many cases obscured the bedrock reflections, especially in the upper parts of the three basins. Considering all the profiles where this phenomena occured, the RTS showed an averaged depth of about 20-30 m while full-depth low backscatter areas appear in sequence both at high and low altitude (Figure 9).

6. Conclusions

To develop robust and reliable glaciological models to keep running under different climate change scenarios, information on glacier geometry are fundamental and only geophysical exploration can give such information on wide areas and with good accuracy and reliability. Under the umbrella of the SHARE-PARPIKA and SHARE-STELVIO Projects, INGV laboratories developed a Radio Echo Sounding System (RES) specifically designed for airborne measures. The choice of a RES system was substantially driven by the goal to develop a system able to investigate Alpine (ice depth generally ranging from 10 to 200-400 m) and Himalayan (ice thickness also deeper than 1000 m) glaciers.

This paper reports the preliminary results of a test carried out on a selection of glaciers in the Ortles-Cevedale Group, Italy (Careser, Sforzellina and Forni glaciers). We surveyed, in the same day during the ablation season, three different glaciers placed at 10 km distance each other obtaining three different "radar images". Due to their proximity, and within a reasonable tolerance, we could state that they are under the same weather/climate trend. The glaciers have similar altitudes of the main parts, but strong differences in ice mass, ice speed and glacier structures development. The main goals were: i) verifying the RES system reliability; ii) assessing the effectiveness of a power pulse to backscatter phenomena; iii) collecting information on ice thickness and bedrock assessment of the investigated glaciers; and iv) evaluating the effectiveness of airborne measurements .

Even if under the technical point of view, the first point was satisfied, while the second one showed not so encouraging results. In this first test, we were able to collect 100% of good quality data on glaciers featuring the smallest dynamics (Careser and Sforzellina) while, on the third one, we got about the 65% of the expected information.

Comparing the Careser and the Sforzellina Glaciers, they feature similar ice thickness and elevation but different ice flow speed. If electromagnetic waves backscattering could be considered as a marker of water presence, we found that Careser Glacier is completely free from this effect. Instead, as expected, we recorded backscatter in deeper parts of Sforzellina Glacier. Finally, the Forni Glacier showed large part of the profiles affected by high backscatter phenomena that in many cases impeded the identification of the bedrock echoes, especially at higher altitudes.

It is our opinion that the strong differences in waves backscattering showed by these three glaciers could be addressed to the water presence, surface slope and crevasses areas. Moreover, in some cases, the scattered waves are able to pass through the ice, as happens in lateral branches of Forni Glacier, but despite of the power and the pulse lengths, there is a threshold at which the waves penetration at the used frequency is completely impeded.

Finally, if the survey target is to explore wider and not easily reachable parts of a glacier, the airborne measures become indispensable. In fact, our tests prove that, within a 75 minutes flight, we were able to collect good quality datasets on the main parts of three different glaciers 10 km far each other and with a whole glacier area of about 15 km^2.

Acknowledgements. The present work was carried out in fulfillment of the SHARE-PAPRIKA and the SHARE-STELVIO Projects; SHARE-PAPRIKA is funded and managed by the EVK2CNR association, SHARE-STELVIO is funded by The Lombardy Region Government and is managed by FLA (Lombardy Foundation for the Environment) and EvK2CNR association . We hereby acknowledge: the Eliwork company (Morbegno, Italy) for their avionic support (special thanks to G. Petrelli for his precious suggestions and ability in Bygol-1 development); Dr. Claudio Rossi (SGG company, Siena, Italy) for borrowing us one of the antennas used in the test; the Cepina Hotel (Cepina, Italy) that hosted us in a friendly and nice accommodation.

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