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GPR and GPS data integration: examples of application in Antarctica

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Abstract
Ground Penetrating Radar (GPR) and Global Positioning System (GPS) techniques were employed in snow accumulation studies during the Italian leg of the International Trans-Antarctic Scientific Expedition (ITASE). The acquired data were useful both for glaciological and climatological studies. This paper presents some results obtained by GPR and GPS data integration employed to determine accumulation/ablation processes along the profile of the traverse that show how the snow-sublayer thickness can vary quickly in just a few kilometres. Some examples of data integration employed in detection and characterisation of buried crevasses are also presented .

Key words *GPR – GPS – geophysics – geodesy – Antarctica*

1. Introduction

The International Scientific Community working on Antarctica has planned a scientific program named ITASE (International Trans Antarctic Scientific Expedition) in order to increase the knowledge of the contribution of the Antarctic continent to the Global Change problem. This program is based on a planned number of traverses carried out on the Antarctic plateau where scientists have to collect data useful for a better understanding of the above mentioned problems. During austral summer 1998/1999, a scientific traverse from Terra Nova Bay (Lat. 74°41′S, Long. 164°06′E) to Dome C (Lat. 75°09′S, Long. 123°06′E) (fig. 1) was carried out by the Italian research group. Global Change is strictly connected to climate change and an untouched memory of this is recorded in the ice of the Antarctic continent. Ice core analysis shows the stratigraphy of snow accumulation year by year marked by the environmental conditions. However, spatial variations of snow accumulation detected by drillings constitute localised information which is not always sufficiently representative of the area around it. The possibility of linking ice core information was addressed by the GPR technique, while data topographic corrections and positioning were performed by means of GPS.

Antarctica mainly consists of a fairly flat plateau located at about 2500 m a.s.l. and only the coastal area is characterised by mountains and outlet glaciers. This Trans-Antarctic Expedition was performed by heavy tractors such as Caterpillars and snow-cats pulling sledges containing fuel and all the needs for the survey and the people for about three months on the Antarctic plateau. The starting point of the Italian traverse was located along the coast, which means that to reach the plateau it is necessary cross one of these glaciers (Reeves Glacier) where the presence of many crevasses was de-

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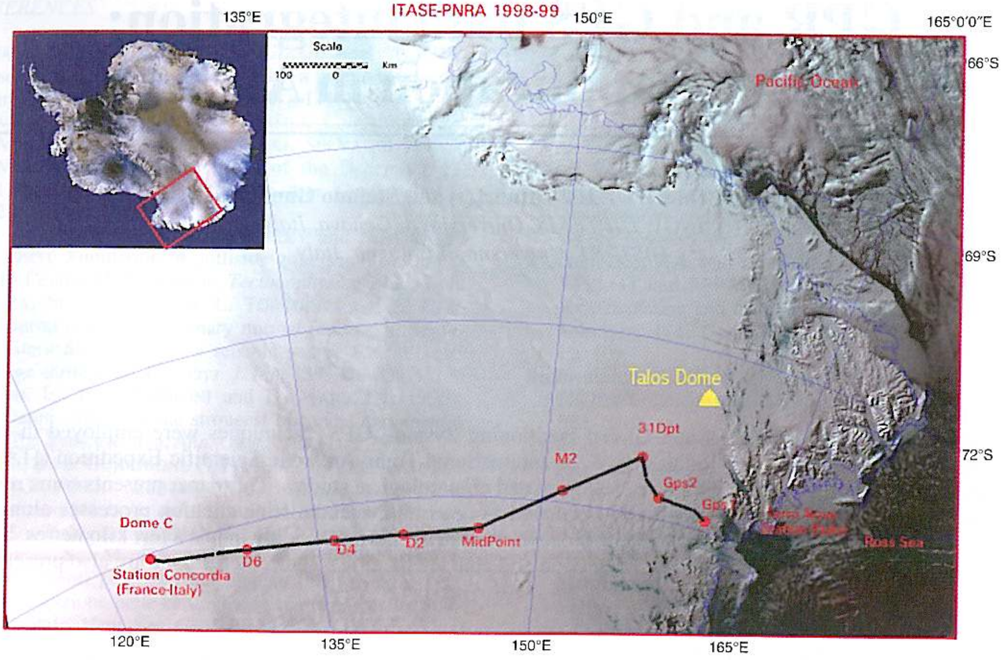

Fig. 1. Map showing the ITASE – Italian branch performed in 1998/1999.

tected. In other words, the traverse had to pass over about 300 km of dangerous terrain where it was necessary to scout the route in order to guarantee safety.

2. GPR method

The GPR method is based on the reflection, due to one or more discontinuities in the media dielectric properties, of the electromagnetic waves generated by an antenna. The main physical factor that can generate a reflected radar wave is the dielectric contrast between different media.

In glaciological employment, there are various physical and chemical parameters, such as liquid water content, snow density, crystal geometry and fabric, conductivity, concentration and composition of ions and microparticles, that can affect the dielectric constant of snow and firn layers, providing a possible and resolvable target for the GPR method (Glen and Paren, 1975). Several of these parameters have a seasonal variation, which constitutes the basis for stratigraphic studies. There are many studies available regarding the different density of polar firn layers (Alley, 1988; West *et al.*, 1996) and their relations to electromagnetic wave reflection inside them (Harrison, 1973; Paren and Robin, 1975; Clough, 1977; Fujita and Mae, 1994). Today the GPR method is widely employed in studies of ice thickness, bedrock topography and thermal properties of ice (Holmlund, 1996; Lozej and Tabacco, 1993), but also in the detection and characterisation of buried crevasses where ice fractures and the air between them represent an ideal target for this technique.

The presence of characteristic layers which have high acidity due to volcanic activity can be considered as a significant marker for a correct translation from 2D (time and distance) electromagnetics to core stratigraphy (Gudmandsen, 1975; Hammer, 1980; Millar, 1981; Delmas *et al.*, 1985). In this study variations in snow accumulation will be shown, mapped by electromagnetic stratigraphy in the upper 15-20 m of the snow pack and the appearance of buried crevasses on the radar data in the same investigation range.

Data acquisition was performed with a GSSI Sir10B (fig. 2) unit equipped with one monostatic antenna with central frequency of 400 MHz in both application examples. Different investigation targets means that a different installation and setting of the instrument was necessary for each one.

Theoretical vertical resolution obtained from the 400 MHz antenna was calculated between 10-20 cm ($V \approx 0.2$ m/ns). Different kinds of GPR data representations are available such as wiggle traces, amplitude colour line scale or using both signal amplitude and phase content (Richardson *et al.*, 1997) but for the first approach an amplitude colour line scale was used.

Reflection arrival times are converted in depth, knowing the media transmit velocity function that is also a function of the dielectric constant contrast between snow layers. Electromagnetic wave propagation in a media is described by

$$c = c_0/\sqrt{\varepsilon_r}$$

where c is the speed of electromagnetic waves in the media, c_0 is the speed of electromagnetic waves in a vacuum (0.3 m/ns) and ε_r is the complex media relative dielectric constant. This parameter is described by

$$\varepsilon_r = \varepsilon' - i\varepsilon''$$

where ε' is the real part, and $i\varepsilon''$ is the imaginary part of the relative dielectric constant. Dielectric properties in snow are dependent on three principal factors: air, ice and liquid water (espe-

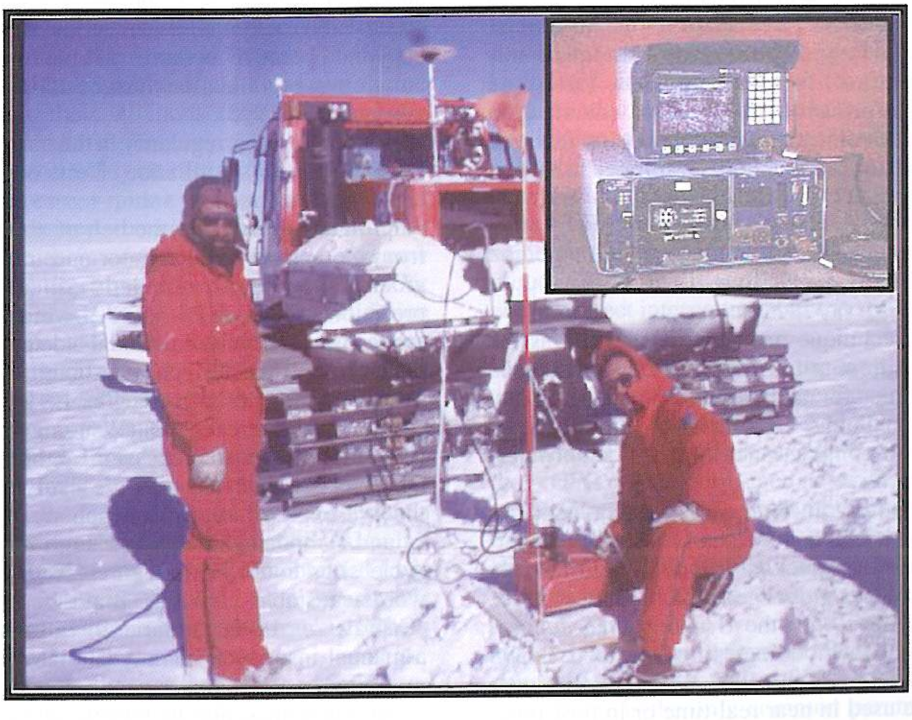

Fig. 2. Picture of the GSSI Sir10B unit equipped with one monostatic antenna with central frequency of 400 MHz.

cially in temperate glaciers). The presence of liquid water principally affects the imaginary part of the dielectric constant so in the particular case of the Antarctic plateau, assumed to be dry, this part should be considered negligible. Thus, it is possible to also write

$$\varepsilon_r = \varepsilon'$$

and then

$$c = c_0/\sqrt{\varepsilon'}. \qquad (2.1)$$

There are several studies concerning the dielectric properties of snow (Sihvola *et al.*, 1985) and interactions with electromagnetic waves (Mazler, 1987). Some *in situ* experiments were also carried out (Kovacs *et al.*, 1995) to determine the relationship between dielectric properties and polar firn density, giving the following empirical equation:

$$\varepsilon' = (1 + 0.845 \cdot \rho)^2 \qquad (2.2)$$

where ρ is the specific density. This equation is valid for snow, firn and ice. Thus, local core density information was used to calculate an initial electromagnetic wave velocity function for converting reflection arrival times to meters of depth.

3. GPS data acquisition

GPS technique has to be considered as the main positioning tool to be efficiently adopted in Antarctica for navigation, geodynamics monitoring, mapping, GPS-assisted photogrammetry, and in conjunction with many geophysical surveys.

Particularly in remote areas, the advantages provided by GPS are remarkable, since it performs surveys quickly, accurately and directly connected to a global geodetic reference frame. In this paper only the dynamic GPS relative positioning methodologies are described (DGPS and continuous kinematic). Both the techniques could be used in near real-time or in post-processed mode, but in the first case the receivers (rover and fixed) must be interconnected by a radio modem-link. DGPS makes it possible to reach an accuracy of 1-5 m using the modulated codes as the principal observable GPS. This differential technique could be used over a few hundred kilometres between the rover and the fixed station. If the GPS carrier phases are also measured, they could be used to smooth the solution (DGPS code smoothed).

The continuous kinematic approach is based mainly on the GPS carrier phase observation, and makes it possible to reach an accuracy of a few centimetres in relative positioning. The application range is usually restricted to ten or so kilometres depending on whether a real-time (RTK) or a post processed application is undertaken.

The use of double frequency, dual code GPS receivers can guarantee a rapid initialisation of the kinematic survey even during the motion (*On-The-Fly*) (Euler and Landau, 1992), but the reliability of the computed track depends on different factors (*i.e.* distance between master and rover stations, atmospheric conditions, geometry of the acquired constellation, multi-path, etc.) and operative methods suitable for the kinematic survey validation must be adopted (Cannon and Shi, 1995).

Moreover, the irregularity in the ionosphere's structure causes scintillation effects on the GPS signal characterised by a short-term variation in amplitude and phase in the belt of about ± 30° from the geomagnetic equator and in polar regions. This effect is particularly critical for high precision relative GPS surveys which require the recovery of cycle slips and the determination of the integer carrier phase ambiguities (initial integer number of wavelengths between each satellite and the receivers) (Wanninger, 1993).

Sometimes post processing algorithms for the detection of cycle slips are likely to fail in the presence of strong ionospheric noise on L_1 and L_2 and in Antarctica a high number of cycle slips could be left unresolved. In other words, unstable solutions could be produced (Capra *et al.*, 1995; Vittuari, 1994). In this case, a manual inspection of raw data is required to mark high noise signals.

In Antarctica, due to logistic and morphologic constraints, the application range of the kinematic method often exceeds the limit of ten or so kilometres in the distance between the reference stations and the rover antenna. Of course, the accuracy achievable on long distances in an environment is strongly affected by ionospheric disturbances and it is very easily subject to deterioration, particularly as regards the height component.

The satellite coverage in Antarctica is characterised by a high number of in-view satellites (6-10), with a GDOP (a parameter related to the satellite geometry) usually lower than 4, at maximum elevation lower than 65°. Though the Antarctic coverage is not optimal, the availability of a high number of in-view satellites is useful for kinematic applications, as it enforces the robustness of the method and helps the ambiguities search for algorithms.

Altimetric profile determination is one of the ambitious and problematic aspects of geodetic activities along the traverse.

Using the standard approach to perform the double difference post-processed kinematics profile, it is necessary to use at least one fixed GPS as a reference point. After the initialisation of the survey, the estimated values of integer carrier phase ambiguities are propagated throughout the continuous acquisition, and if a signal loss of lock occurs a new set of integer carrier phase ambiguities must be re-estimated.

If the carrier phase ambiguities set is not well determined, the kinematic-derived profile shows a bias in correspondence with the new ambiguity determination (Capra *et al.*, 1996; Helliot *et al.*, 1991; Vittuari, 1994). Validation of results could be carried out for example using two rover receivers (R1, R2), and two reference stations (ST1, ST2). The stability of the reciprocal distance between the two roving GPS antennae located at a fixed distance on the vehicle, as computed from simultaneous independent solutions (*i.e.* distance calculated for rover antenna R1 from reference station ST1 and the simultaneous rover antenna R2 position obtained from reference station ST2), could be used as a test value to validate the computed track (Hothem *et al.*, 1994).

Support of other activities is one of the most important aspects for the geodetic contribution during field work in Antarctica (especially for a Traverse). The Antarctic plateau is characterised by the total absence of natural reference points so any sample, any experiment and any operation needs accurate positioning to be complete. For this reason all activities were supported by GPS positioning. However, support of a GPR survey cannot be a simple support but a complete integration of two methodologies. In the next paragraph the potential of this «integration» will be shown in detail.

4. GPS and GPR integration for glaciological purposes

The GPR and GPS methods are two of the geophysical techniques have been greatly improved by current technological know how. Designed for extremely different kinds of targets, in the last 10 years they have been used as references in their own fields. The GPR technique is one of the most important non-destructive sounding methods and today is successfully applied in many different conditions, such as detection of buried objects, archaeological prospections, voids detection, stratigraphic studies, hydrology, concrete and floor conditions, etc.

It is also needless to describe how many applications are suitable for geodetic techniques using GPS instrumentation, such as high precision positioning, landslide movement detection, cartography, navigation, etc. However, there are some particular conditions in which both techniques give only a part of the information needed for correct interpretation of the studied problem.

For these reasons, one of the most important aspects of this work was the integration between the two methods.

Using the GPS result as a reference, layers from GPR can be positioned not with respect to the surface (as usual) but with respect to the height (ellipsoidal height or quasi-orthometric height if geoidal undulation is available). In order to couple the two results (GPS and GPR), synchronising of the two acquisitions on a time scale is necessary. Figure 3 shows a logical approach used to combine GPS and GPR solutions. Time is the only common parameter between the data sets collected by the two techniques so it was chosen for coupling the data.

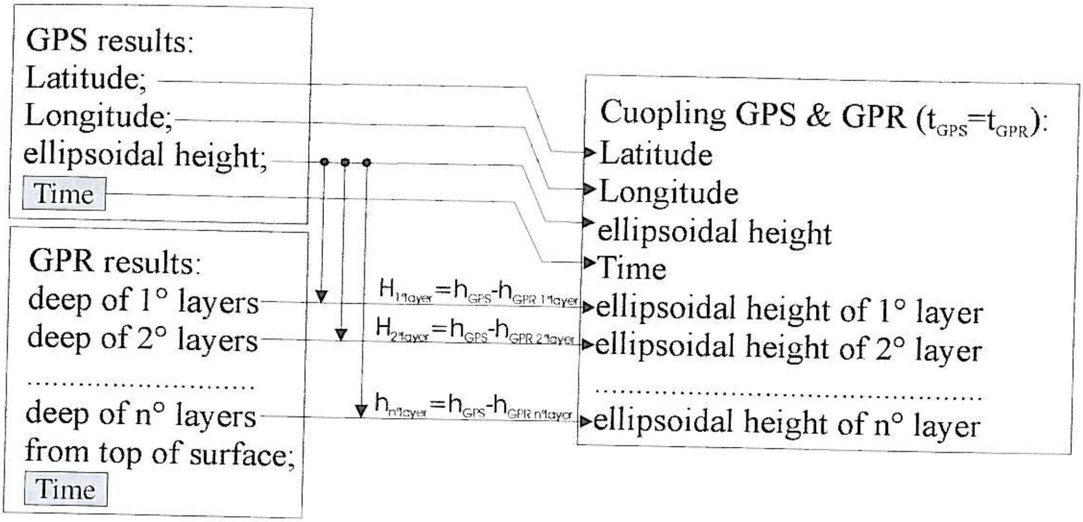

Fig. 3. Scheme of methodology used for GPR/GPS data integration.

Firstly, GPR data acquisition was marked directly by GPS time and the GPR acquisition rate was calculated as an integer minute fraction. Finally, processed data from both techniques were integrated together obtaining a new GPR section where electromagnetic stratigraphy was positioned according to both ellipsoidal height and surface coordinates.

4.1. *Examples of GPR and GPS data integration for snow stratigraphy detection*

Based on the experience of the first Italian traverse, carried out from Terra Nova Bay to Talos Dome (Frezzotti *et al.*, 1998), the mainframe unit was mounted inside the snow cat (Pisten Bully 330D) cabin together with a GPS instrument, while the antenna was pulled on a small wooden sledge (fig. 2). The main acquisition parameters were 200 ns for vertical investigation range and from 1 to 5 scan/s for the acquisition rate and these parameters were checked daily trying to get the best performance from the instrument. The Pisten Bully and thus the antenna speed varied from about 8 to 12 km/h which means, with the defined acquisition rate, about one scan every 1-3 m. During the ITASE traverse from Terra Nova Bay to Dome C (about 1200 km completely investigated with GPR) some stops (nine) were planned which represent the sites for the main drilling operations. The GPR method was employed both to determine the layering situation along the traverse route and the choice of perforation sites.

In this case, profiles were carried out on a triangular shaped route with each leg about 5 km and one vertex positioned on the main drilling site. Concerning data enhancement, each section was treated with horizontal high pass, vertical low and vertical high pass filters (FIR type) and a gains optimisation along the profiles was also performed.

Accurate wave speed information is necessary for a good correspondence between electromagnetic layers and reference layers recognised by firn core chemical-physical analysis.

For this purpose and in a first approximation, the density information obtained from analyses carried out on the 31st Deposit site cores was used for electromagnetic wave speed calculations. According to the method described by Richardson and Holmlund (1999) the two way

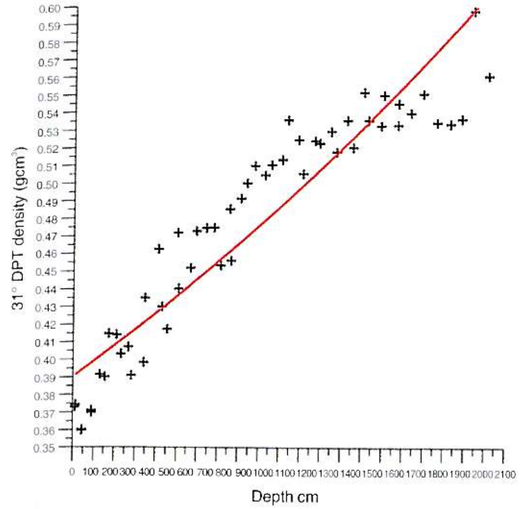

Fig. 4a. «31° Deposit» site (along the traverse) core densities plot and exponential function data fitting.

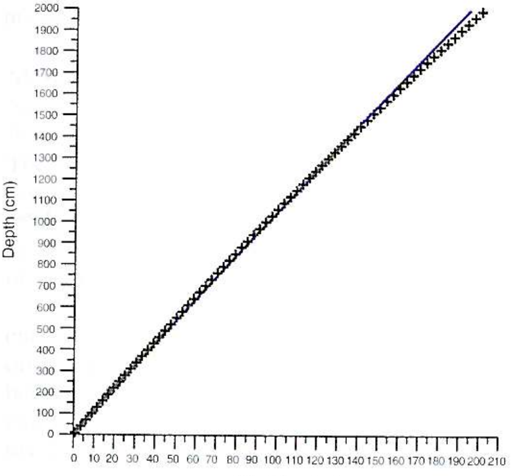

Fig. 4b. Depth-two way travel time function calculated by eq. (4.2).

travel times picked out from radar data were converted to meters of depth using depth-density, depth-wave speed and depth-travel time relations which were fitted by both exponential and power functions.

The equation used for data fitting (fig. 4a) was

$$y_{(x)} = a \cdot e^{bx}$$

and the depth-density relation result

$$\rho_{(z)}[\mathrm{g/cm^3}] = a \cdot e^{bz[\mathrm{cm}]} = 0.39024 \cdot e^{(0.0002203 * z)} \qquad (4.1)$$

$$r^2 = 0.87$$

where «z» is the depth below the surface expressed in centimetres, constants a and b derived from data fitting calculations and where r^2 is the correlation coefficient.

Values were substituted in eqs. (2.1) and (2.2) and then a power fitting equation was used to convert the two-way-travel time raypath to depth directly (fig. 4b)

$$d_{(twt)}[\mathrm{m}] = a \cdot T^{b}[\mathrm{ns}] = 12.2203 \cdot T^{(0.966795)} \qquad (4.2)$$

$$r^2 = 1$$

where $d_{(twt)}$ is the depth below the surface expressed in meters and T is the two way travel time expressed in nanoseconds. Thus the picked arrival time of each layer detected on GPR data was converted to meters of depth by this function. Finally, from converted and processed data the depths of some of the strongest reflections were picked out and assumed as reference layers that represent a specific event or short time period and time horizontal variations provide information on snow accumulation. Figure 5 shows an example of how much the snow stratigraphy changes in about 11 km of continuous profile. Picking out some strong horizons (fig. 6) it is clear that the snow accumulation rate is much higher in the second part and in the first part of profile while in the central part and also in the final part the snow stratigraphies close up to become erased or so thin that they are undetected by the system.

Considering only data from a GPR survey it is possible have an idea of the layering conditions but sometimes it could be difficult to make a correct interpretation of the formation dynamics.

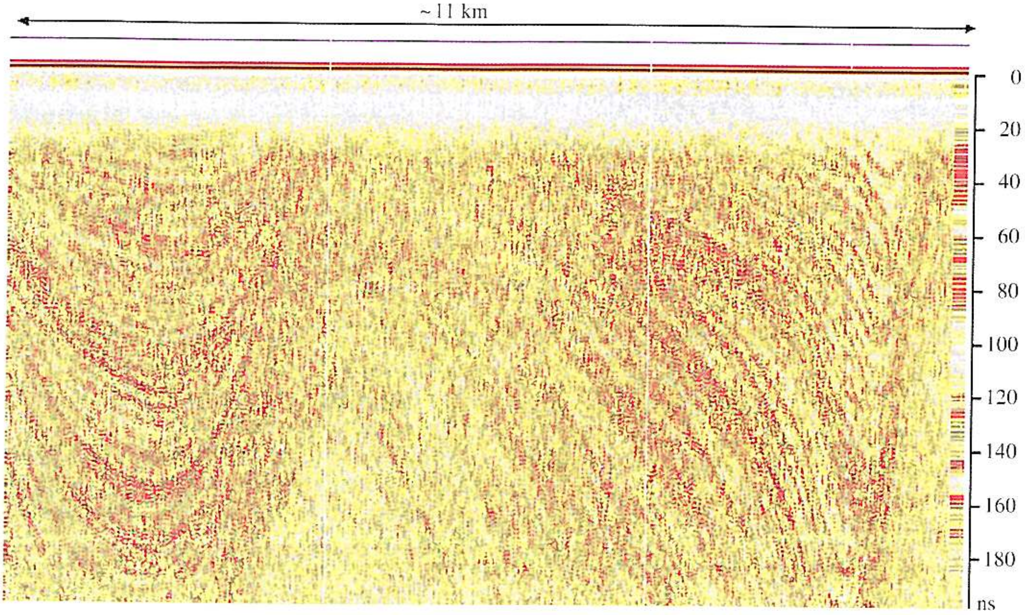

Fig. 5. Example of GPR layout in an area close to «31° Deposit» (lat. 74°1.52′S; long. 155°57.6′E; 2065 m ellipsoidal height).

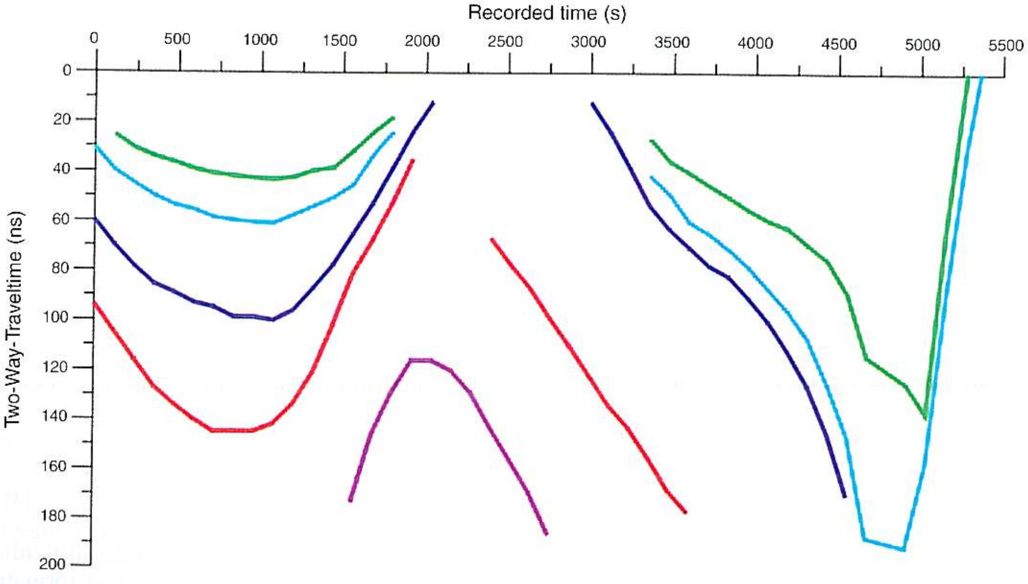

Fig. 6. Interpretation of some sub-layers present in fig. 5.

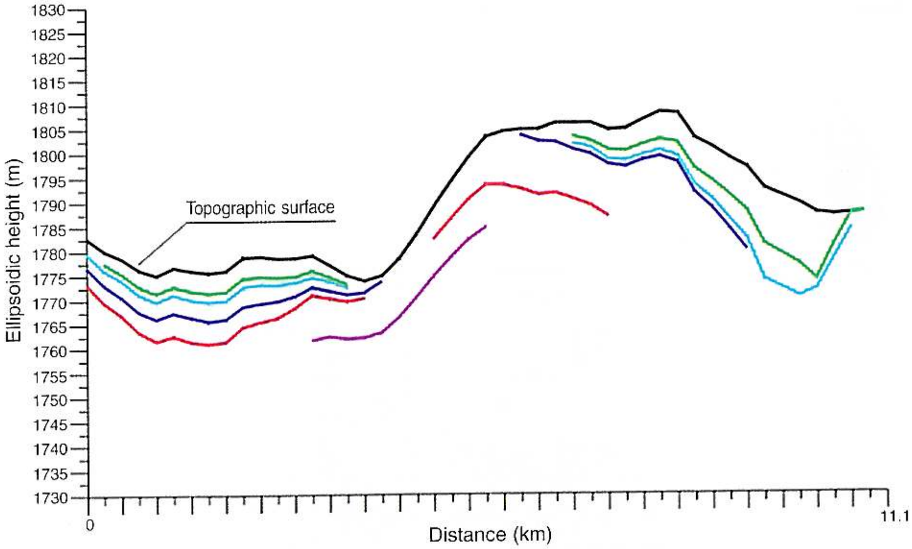

Fig. 7. Integration of the two methodologies.

GPS surveys were performed using two Master Stations located at the beginning (Terra Nova Base Station – TNB1) and at the end of the traverse (Concordia Station – Dome C). These not optimal logistical constraints are imposed by the difficulty of installing other GPS reference stations along the traverse leg between Terra Nova and Dome C. A sampling rate set up of 5 s and 15° of elevation mask were chosen in order to achieve the best result and to have enough memory for a day's work. The precision obtained is strictly connected with the distance between Master and Rover stations and is included in a range from a few centimetres to several decimetres. Geotracer GPS Software was used for data processing.

Considering only data coming from a GPS altimeter profile it is possible to recognise, for example, where some surface undulations occur but without any information on the layering condition.

Figure 7 shows the integration of the GPR and GPS methodologies. The integration of the two methodologies seems to indicate wind as a possible reason for producing ablation downwind of the hill and accumulation upwind of the hill.

4.2. *Examples of GPR and GPS data integration for traverse route scouting*

In order to avoid dangerous risks induced by the presence of crevasses along the route as shown in figs. 8a,b, during the austral summer of 1997/1998 an accurate scouting of the first part of the traverse route was carried out with GPR and GPS linked together with the first aim of detecting and locating buried crevasses along the route and the second aim of finding a safe way to reach the plateau. The survey was conducted both by helicopter (mainly) and directly on the ground by snow-cat (only in critical areas) where a safe way cannot be detected from the air.

The investigation target was buried crevasses inside a range of 15-20 m under the surface and at least 1-2 m wide. A 400 MHz antenna was mounted with a steel arm on the helicopter's left skid while the double frequencies antenna was installed under the helicopter's front top window (fig. 9). For the ground survey the antenna was mounted on a small wooden sledge kept around 7 m behind the snow-cat blade by an aluminium arm (fig. 10), while the GPS an-

Fig. 8a. A problem during Hillary Expedition (1965).

Fig. 8b. A problem with the first Italian traverse realised between Terra Nova Bay and Talos Dome (austral summer 1996/1997).

tenna was installed on top of the Pisten Bully cabin. Concerning the helicopter survey, an investigation range of 200-250 ns (considering a flight height of about 5-10 m) was set and a scan rate of about 100 scans/s guarantee a good horizontal resolution with a helicopter speed of about 25 knots (45 km/h). Electromagnetic wave speed in firn was considered constant (about 0.2 m/ns) because it is not so important for this kind of prospecting where the main two aims are crevasse detection and positioning. The ground survey was conducted in a small area where the confluence between the Browning Pass and the Priestley glacier occurs and a safety route cannot be detected by air due to the presence of many buried crevasses. Instrument settings were different and a range of 150 ns and a 30 scan/s rate (snow-cat speed 10 km/h) were selected. The GPS kinematic survey was carried-out with a sample rate of 1 s (1 Hz), while a GPS time marker was sent to the GPR every minute. Data enhancement was similar for the air and ground surveys, including horizontal high pass, vertical low and vertical high pass filters (FIR type) and gains optimisation along the profiles. Especially in the air survey, an appropriate horizontal high pass filtering was needed because there was noise interference between the helicopter and the GPR antenna.

When a crevasse was detected on the GPR track, the GPS kinematic 3-dimensional positions were obtained at the crevasse edge, by an interpolation between the nearest marked positions. The measurement of the helicopter velocity was obtained by GPS positions and timing between the nearest 1 s GPS acquisitions. Data

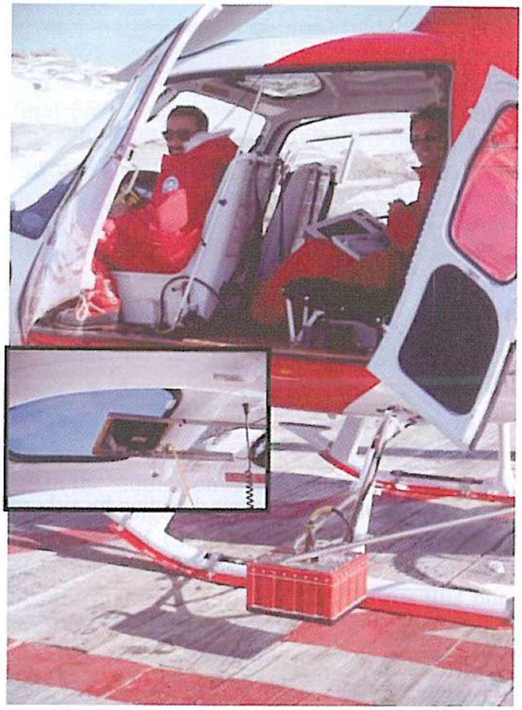

Fig. 9. GPR and GPS helicopter installation for scouting.

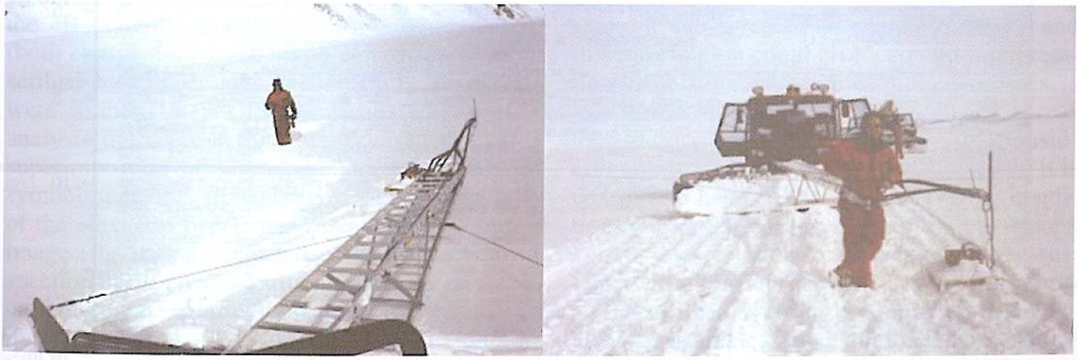

Fig. 10. Device utilised for ground real time scouting during the traverse.

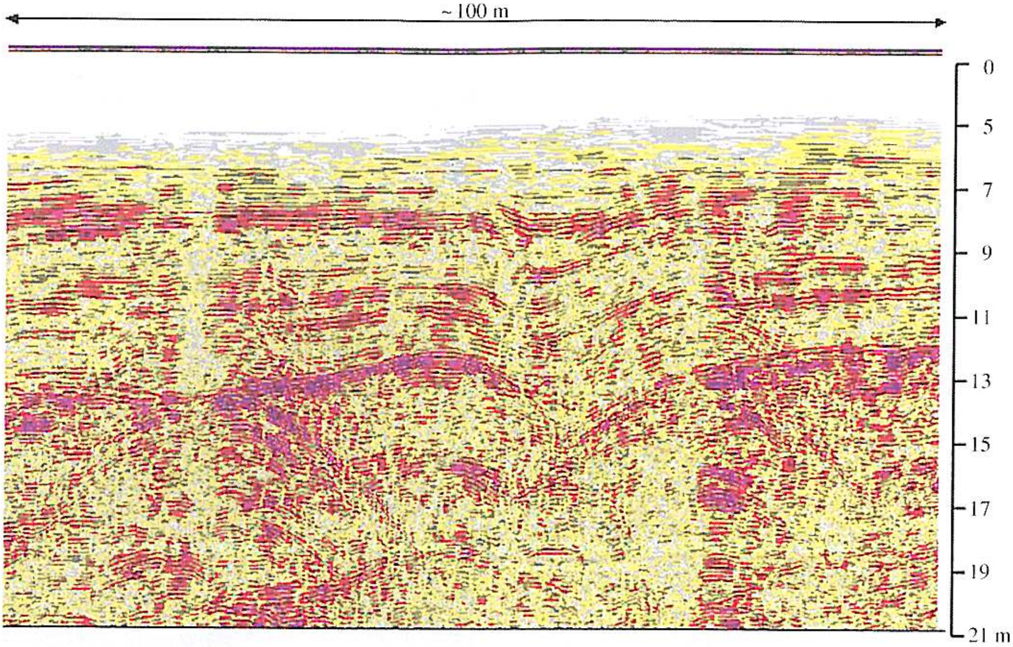

Fig. 11. Example of crevasses detection by airborne survey.

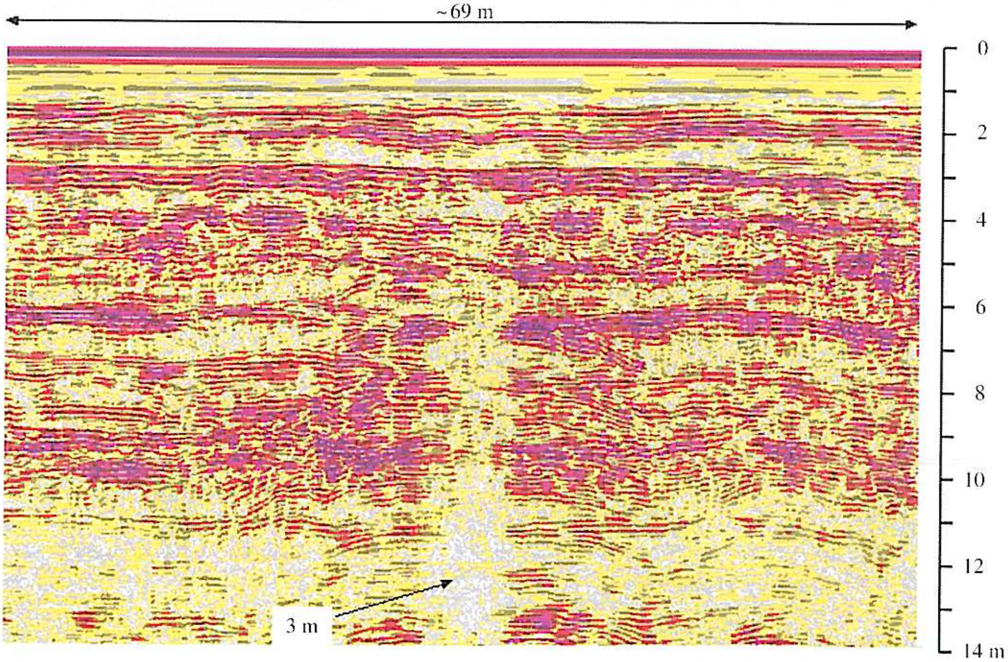

Fig. 12. Example of crevasses detection by ground survey.

analysis showed that the integration of the two methods permits not only the correct detection of crevasses with very good accuracy, but also information on typology, dimensioning, depth under the snow bridge, age and condition of the structures is given. Crevasses usually appear on GPR data as a marked interruption in snow layering at the crevasse wall with sometimes strong signal diffraction from more reflective layers.

Figures 11 and 12 show two examples of crevasse detection by airborne and by ground surveys respectively. In the first one (fig. 11), it is possible to observe two different kinds of crevasses close together. The «A» crevasse opens just below the surface, for a width of 4 m, with a really thin snow-bridge on it and clean walls typical of a young structure. Crevasse bottom reflection can be considered at about 14.5 m below the surface. «B» case shows an older and wide (about 18 m) crevasse characterised by a thick snow-bridge (about 11 m) on it. It was interesting to observe that the snow-bridge just below the surface was not in good condition and the layering structure was starting to collapse into the ice opening, becoming dangerous. This kind of information was important for the route choice where the crevasses had to be passed over. Finally, fig. 12 shows a crevasse recorded during the ground survey that shows characteristics similar to those described for the previous «A» example. Data acquired directly from the ground were of better quality than the airborne data so the post-processing digital enhancement was «lighter».

Finally the majority of the crevasses detected during scouting (300 km) were the «A» type, the «B» type being found only in some areas (both comparable to the «type 2» crevasses described by Glover and Rees, 1992). All data were inserted in a GIS (Terascan) where an analysis of the best route was carried-out by superimposing the GPS kinematic tracks, the symbols and the alphanumeric characteristics of the crevasses over a geo-referenced satellite image (fig. 13). In selected cases a direct inspection of the crevasse structure was necessary on the ground, in order to evaluate the feasibility of cross-over with heavy vehicles or to identify the position of the snow-bridges and mark them on the terrain. In these cases, a GPS Real Time Kinematic (RTK) approach was adopted since maximum accuracy was required and a 9600 baud radio-modem link was used coupled with Geodetic double frequency receivers. This is the most precise modality for Real Time navigation and the accuracy is at sub decimetric level. Finally it was possible to find the best way to pass over the critical area on the computer, and using DGPS it was possible to mark the final pre-planned route on the ground. Double frequency GPS receivers installed on aluminium pipes (3 m long with a diameter of 13 cm driven in the ice for more than 1.5 m) were used as reference stations. The positions of the reference stations were preliminarily obtained by static GPS observations simultaneous with those acquired by selected stations of the Italian Geodetic Network in Terra Nova Bay.

5. Conclusions

In the studies on Antarctica's contribution to Global Change, most investigations are related to the spatial variations of snow accumulation of which little is currently known. A great deal of information has to be collected for this purpose, the main source being the ice cores drilled in Antarctica. Using this methodology only a punctual accumulation pattern is available and the common assumption is that of a fairly flat stratigraphy between drilling points.

The real possibility of «connecting» and providing continuity between drilling points can be achieved by GPR methodology. The integration between GPR and GPS makes it possible to refer the sub-layers to an ellipsoidal height and this information could give a correct interpretation of ablation and accumulation processes.

The data obtained indicate that in some areas the stratigraphy could change quickly. Considering only data coming from a GPR survey, it is possible to have an idea of the layering conditions but sometimes it can be difficult to make a correct interpretation of the dynamic processes. Otherwise, considering only data coming from a GPS altimeter profile it is possible to recognise, for example, where some surface undulations occur but without any information on layering conditions.

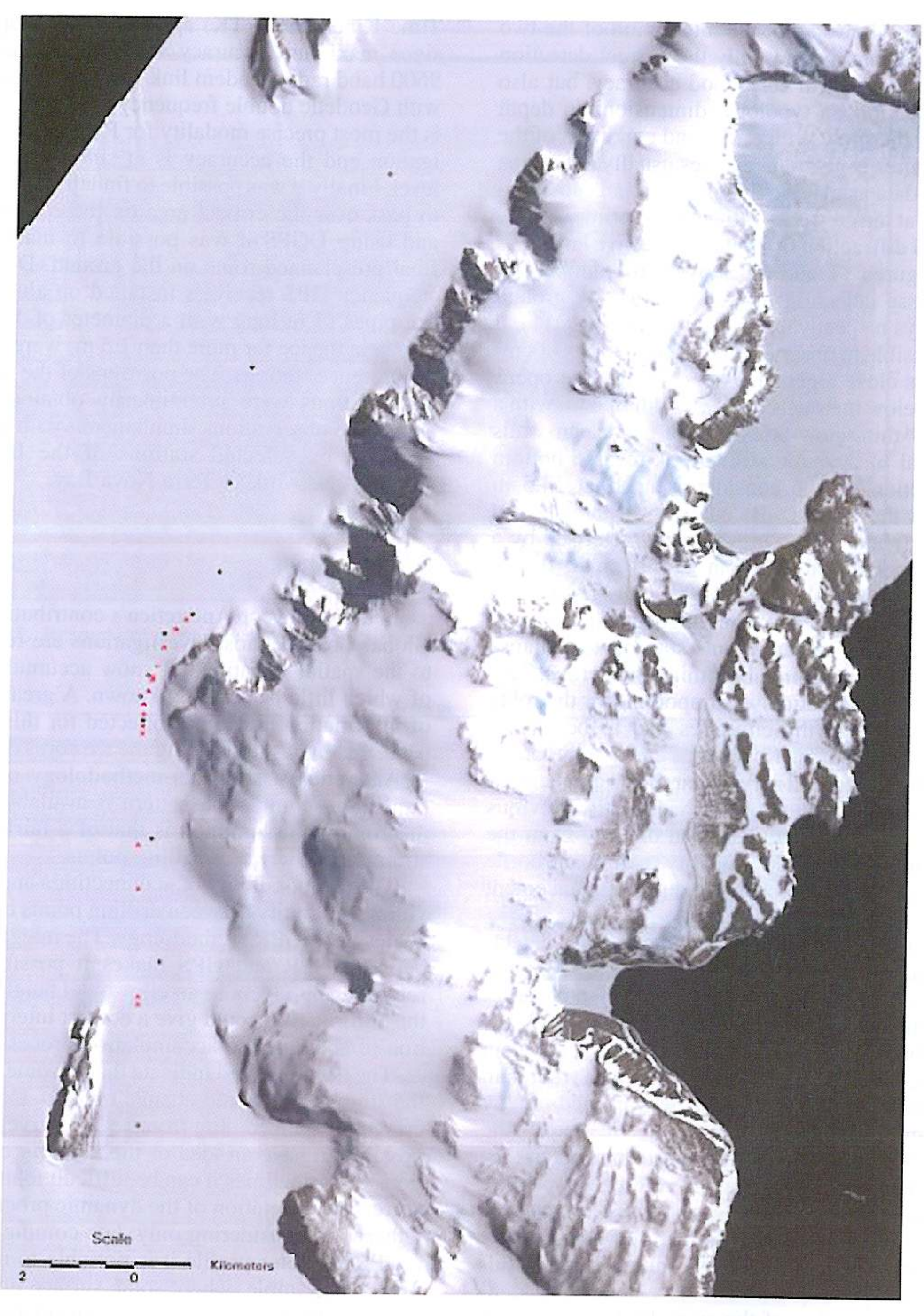

Fig. 13. Location on a geocoded satellite image of crevasses (red points) and the pre-planned way (black points).

So, in order to carry out drilling for glaciological studies, which must be a sample of the area, it could be better to perform a GPR+GPS survey to localise the most representative drilling site.

Integration of the two methodologies makes it possible to formulate more accurate hypotheses on snow dynamics accumulation and seems to indicate wind as a possible reason for producing ablation downwind of the hill and accumulation upwind of the hill (fig. 7).

The scouting performed close to Terra Nova Bay made it possible to reach the plateau fairly safely, passing over some crevasses of well known dimensions, structures with a metric precision in absolute positioning. All crevasse details (positions and characteristics) were loaded in a GIS (Terascan), consenting safer navigation across the outlet glacier on the way to the Antarctic plateau.

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REFERENCES

ALLEY, R.B. (1988): Concerning the deposition and diagenesis of Strata in Polar Firn, *J. Glaciol.*, **34** (118), 283-290.

CANNON, M.E. and J. SHI (1995): Precise airborne DGPS positioning with a multi-receiver configuration: data processing and accuracy evaluation, *Can. Aeronaut. Space J.*, **41**, 40-48.

CAPRA, A., A. GUBELLINI and L. VITTUARI (1995): Reti GPS per il controllo di deformazioni: analisi dei risultati ottenuti con differenti programmi di elaborazione dati, *Bollettino SIFET*, **4**, 133-144.

CAPRA, A., F. RADICIONI and L. VITTUARI (1996): Kinematic GPS profiles and navigation in Antarctica, in *Proceedings of XVIII ISPRS Congress, Vienna*, **31** (B1), Commission I, 31-35.

CLOUGH, J.W. (1977): Radio-echo sounding: reflections from internal layers in ice sheets, *J. Glaciol.*, **18** (78), 3-14.

DELMAS, R., M. LEGRAND, A.J. ARISTARAIN and F. ZANOLINI (1985): Volcanic deposits in Antarctic snow and ice, *J. Geophys. Res.*, **90** (D7), 12901-12920.

EULER, H.I. and H. LANDAU (1992): Fast GPS ambiguity resolution on the-fly for real time applications, in *Proceedings of the 6th International Geodesy Symposium on Satellite Positioning*, Columbus, Ohio, vol. 2, 650-658.

FREZZOTTI, M., O. FLORA and S. URBINI (1998): The Italian ITASE expedition from Terra Nova Station to Talos Dome, *Terra Antartica Reports*, **2**, 105-108.

FUJITA, S. and S. MAE (1994): Relation between ice sheet internal radio-echo reflections and ice fabrics at Mizuho Station, Antarctica, *Ann. Glaciol.*, **20**, 80-86.

GLEN, J.W. and J.P. PAREN (1975): The electrical properties of snow and ice, *J. Glaciol*, **15** (73), 15-37.

GLOVER, J.M. and H.V. REES (1992): Radar investigations of firn structures and crevasses, *Geol. Surv. Can.*, **90** (4), 75-84.

GUDMANDSEN, P. (1975): Layer echoes in polar ice sheets, *J. Glaciol.*, **15** (73), 95-101.

HAMMER, C.U. (1980): Acidity of polar ice cores in relation to absolute dating, past vulcanism and radio-echoes, *J. Glaciol.*, **25** (93), 359-372.

HARRISON, C.H. (1973): Radio echo soundings of horizontal layers in ice, *J. Glaciol.*, **12** (66), 383-397.

HELLIOT, D.H., W. STRANGE and I.M. WHILLIANS (1991): GPS in Antarctica, *BPRC Technical Report 91.02*, Byrd Polar Research Centre, Columbus.

HOLMLUND, P. (1996): Radar measurements of annual snow accumulation rates, Z. *Gletscherk. Glazialgeol.*, **32**, 193-196.

HOTHEM, L., M. MARSELLA and L. VITTUARI (1994): Airborne GPS dual frequency *P*-code and *P*-codeless data – Experience with recent software advancements, in *Proceedings of International Symposium on Kinematic System in Geodesy*, Geomatics, Banff, Calgary, Canada, 207-217.

KOVACS, A., A.J. GOW and R.M. MOOREY (1995): The *in-situ* dielectric constant of polar firn revisited, *U.S. Army Cold Regions Research and Engineering Laboratory*, **23**, 245-256.

LOZEJ, A. and I. TABACCO (1993): Radio echo sounding on Strandline Glacier, Terra Nova Bay (Antarctica), *Boll. Geofis. Teor. Appl.*, **35** (137-138), 231-244.

MAZLER, C. (1987): Applications of the interaction of microwaves with the natural snow cover, *Rem. Sensing Rev.*, **2**, 259-392

MILLAR, D.H.M. (1981): Radio-echo layering in polar ice sheets and past volcanic activity, *Nature*, **292** (5822), 441-443.

PAREN, J.G. and G. ROBIN (1975): Internal reflections in polar ice sheets, *J. Glaciol.*, **14** (71), 251-259.

RICHARDSON, C., E. AARHOLT., S.E. HAMRAN, P. HOLMLUND and E. ISAKSSON (1997): Spatial snow distribution mapped by radar, *J. Geophys. Res.*, **102** (B9), 20343-20353.

RICHARDSON, C. and P. HOLMLUND (1999): Spatial variability at shallow snow-layer depths in Central Dronning Maud Land, East Antarctica, *Ann. Glaciol.*, **29**, 10-16.

SIHVOLA, A., E. NYFORS and M. TIURI (1985): Mixing formulae and experimetal results for the dielectric constant of snow, *J. Glaciol.*, **31** (108), 163-170.

VITTUARI, L. (1994): Advanced kinematic GPS in Antarctica, in *IV Geodetic Meeting Poland-Italy, 12-13 September 1994, Warsaw, Poland*, edited by J. SLEDZINSKI, Politechniki Waszawskiej, 181-194 (Reports on Geodesy N4(12)).

WANNINGER, L. (1993): Effects of the equatorial ionosphere on GPS, *GPS World*, **4** (7), 48-54.

WEST, R.D., D.P. WINEBRENNER, L. TSANG and H. ROTT (1996): Microwave emission from density-stratified Antarctic firn at 6 cm wavelength, *J. Glaciol.*, **42** (140), 63-76.

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