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Ground Penetrating Radar Survey for Detection of Shelf Ice Depth and Its Spatial Variation in Central Dronning Maud Land, East Antarctica

K. K. Singh, H. S. Gusain, V. D. Mishra and R. P. Shukla
Snow and Avalanche Study Establishment, Chandigarh

ABSTRACT

Ice shelves are a permanent feature of Antarctica; these not only bind but also shape the continental ice sheet. However shelf ice is fluctuating in nature, due to direct contact with the sea. Changes in extent of shelf ice with varying climatic conditions can be interpreted using various remote sensing satellites; but these satellites do not yet have the capability to retrieve depth information. Radio-echo sounding provides an efficient tool to measure ice depth.

Ground Penetrating Radar (GPR) survey has been carried out for detection of shelf ice thickness and to analyze its spatial variation near Princess Astrid Coast during 27th Indian Antarctic Expedition to Antarctica. Thickness information of shelf ice has vital importance for the expedition, as tons of load of cargo items has to be placed over shelf ice.

GPR (Mala Geoscience) of frequency 50 MHz (Unshielded, Bistatic antenna) was used to determine the ice thickness. Longitudinal and transverse GPR profiles were carried out to cover the survey area, along with GPS for geographic information. GPR data were collected in reflection mode and the time window was decided on the basis of the required depth of penetration; however long time windows were used for receiving echoes from deeper shelf ice. Data are stored in 16-bit integer raw data format and for post processing Ground Vision software has been used. Dark current and time gain filters were further used to enhance the quality of radar signal.

The survey results show that the shelf ice thickness varies between 20 to 60 m. 3-D map of the surveyed area was prepared using the latitude and longitude information from the GPS and the depth information from the GPR. After combining various GPR profiles, it is observed that the shelf ice thickness decreases while moving towards the sea in north direction and it increases away from the sea edge towards the south. Sharp reflections of radio waves from two different levels (depth) were observed at few locations in radargram, although these reflections are from very limited area but their interpretation is a further area of research.

Keywords: Antarctica, Dronning Maud Land, GPR, Ice Shelf.

1.0 INTRODUCTION

Antarctica the southernmost continent comprises the area of the earth south of 60^0 and having area around 10% of the land surface of the earth. The Antarctic ice sheet consists of three distinct morphological zones as east (Great), west and the Antarctic Peninsula. The largest is East Antarctica which covers around 10.35×10^6 km^2 and is dominated by the high Antarctic plateaus. Antarctica has 98% of its total area covered with ice. The Antarctic ice sheet, whose average thickness is 2.45 km, has the maximum thickness of approximately 4.8 km at some places (Rasal et al, 1999). It contains around 68% of world's fresh water.

Ice shelves are a permanent feature of certain parts of the Antarctica and are extension of the continental ice, which floats over the sea after crossing the main land. There is a constantly changing balance between processes— ice flow from the continent, snow fall, bottom freezing, bottom melting, the calving of ice bergs; which adds or melts the ice. The stability of ice shelf rests on maintaining this equilibrium (Asthana, 2002). The edges of ice shelves make up 44% of the coastline of the continent, with the remainder consisting of grounded ice walls (36%), ice streams and outlet glaciers (13%) and rock (5%) (Drewry, 1983). Most ice shelves are 100-500 m thick, although thicker areas do occur, such as near the seawards edge of the Filchner-Ronne ice shelf. The thickness of the Filchner-Ronne ice shelf varies from 300 m at the seawards edge up to 1600m at the grounding line (Jenkins and Doake, 1991).

The radar sounding is one of the techniques, which has been used successfully in Antarctica for snow accumulation studies (Richardson et al., 1997 and Sinisalo et al., 2003). According to their study this radar-based method is found more suitable for estimating the accumulation rate, than using the stakes for measurements. Most of the materials attenuate or scatter the radio waves; however the cold ice is relatively transparent to radar waves and in glaciology deep penetrating radar have been used since 1950s to map the bedrock beneath glaciers and ice sheets (Bogorodsky et al., 1985). GPR has been used to determine the accumulation rates in Antarctic firn (Forster et al., 1991). The 50 MHz Mala antennas clearly detected bedrock return from glaciers up to depth about 300m in Scandinavian Arctic region, where the ice was close to 0^0C (Maijala et al). GPR is found suitable for ice depth measurement for glaciers because of the difference in dielectric permittivity of water in liquid and crystalline form (Bjoernson et al. 1996). Higher frequencies radar waves are commonly used to detect internal structures of the glaciers due to their higher resolution, while lower frequencies are more suitable to penetrate the ice to view the bottom topography. Crevasse-prone area was surveyed using 400 MHz GPR antenna to detect and draw real time assessment of the width of the cavities at the route between the Norwegian research station and the cargo unloading area in Dronning Maud Land, Antarctica (Taurisano et al, 2006).

In GPR, interaction of radio waves with matter depends on the dielectric constant of the material and the velocity of the radar wave, which is used for the depth estimation of any medium; it varies with its dielectric permittivity (Davis and Annan 1989). Sub-glacial topography between the southern Antarctic Mountains and the South Pole has also been investigated by using radar reflections (Jiracek and Bentley, 1965).

During the 27^{th} Indian Antarctic Expedition, GPR profiling was performed to estimate the thickness of shelf ice near the *India Bay* region. The study has its importance as most of the important materials (fuel, food etc) are offloaded at the shelf and are later carried to the Indian station. The objective of this study was to find the bed topography of the shelf ice using radio waves.

2.0 STUDY AREA

The observation site lies in Princess Astrid Coast, which covers the area between meridian of 5^0 E and 20^0 E. This area experiences winds from NE and SE direction. Snowstorms of very high intensity are generally observed. The maximum temperature of this region is ~3^0C and minimum temperature is ~ -48^0C. Precipitation is mainly in the form of snow, with very few occasions of rain/drizzle.

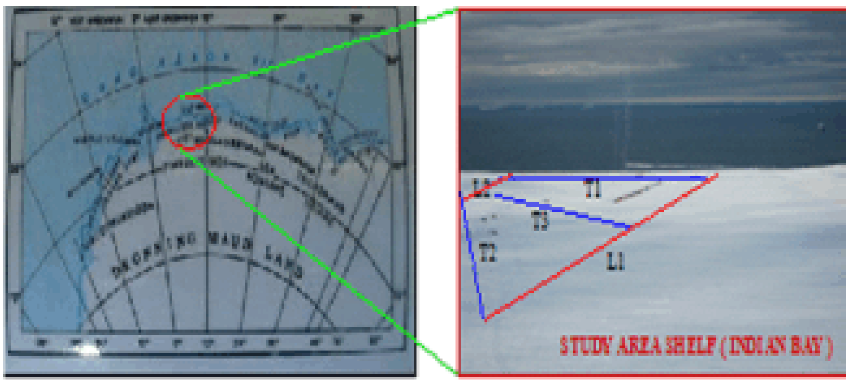

Fig. 1: Survey area in Princess Astrid Coast

The GPR profiles were conducted in longitudinal and transverse directions. The profiles L1(70^{0}05'36" S, 12^{0}23'46" E to 70^{0}04'51" S, 12^{0}24'20" E) and L2 (70^{0}05'24" S, 12^{0}23'20" E to 70^{0}04'53" S, 12^{0}23'41" E) are the longitudinal profiles and T1(70^{0}04'55" S, 12^{0}23'42" E to 70^{0}04'54" S, 12^{0}24'49" E), T3(70^{0}05'12" S, 12^{0}23'21" E to 70^{0}05'12" S, 12^{0}24'07" E), T2 (70^{0}05'24" S, 12^{0}23'08" E to 70^{0}05'27" S, 12^{0}24'19" E) are the transverse profiles in the survey area **(Fig. 1).**

3.0 INSTRUMENT USED AND METHODOLOGY

In the present study, Ramac GPR (*Mala Geoscience*) with 50 MHz centre frequency antenna, which is Unshielded (Bistatic) in nature, was used to obtain profiles. We did obtain some profiles with 500 MHz antennas but the penetration was only 5-6 m. The lower frequency as 50 MHz permits the deeper penetration required to reach the desired depths. The transmitter and receiver of the antenna were fixed 2 m apart from each other, which were pulled (lifted) manually **(Fig. 2).** In this antenna, the wheel attachment facility is not available; hence data is collected by pressing the keyboard at fixed distances.

Fig. 2: Use of 50 MHz unshielded GPR antenna for ice depth estimation at Shelf ice

In order to interpret the results of radio-echo sounding, velocity of propagation of radio waves in ice **(Table 1)** is essential. A technique is proposed by Robin et al 1975 to relate different ice parameters (density, ice fabric and temperature) to the velocity of radio waves in ice. Estimated velocity reported is ~167.7±0.3 m/μs at -20^0 C. Same range of velocity of radio waves in ice is also observed by Jiracek and Bentley (1971).

	ε (rel)	σ (ms/m)	V (m/ns)	α (db/m)
Air	1	0	0.3	0
Fresh Water	80	0.5	0.033	0.1
Sea Water	80	30000	0.01	1000
Snow	2-3.5	0.00001	0.2	0.01-0.1
Ice	03-Apr	0.01	0.16	0.01

The Long time windows (1133 ns to 1433 ns) with sampling frequencies of 322 to 407 MHz was used for receiving echoes from shelf ice several tens of meters in depth. Data is stored in 16-bit integer raw data format and is further transferred from control unit to Laptop, using standard parallel port. Post processing of the data was done in the Ground Vision software. First, to amplify the dynamical range of the data display, a top mute of first arrivals corresponding to the direct wave was performed. To remove the Dark current, which is the constant offset in the amplitude of the registered trace, the DC filter is used and time gain filter is used to compensate the loss in data due to spreading and attenuation.

4.0 RESULTS AND DISCUSSION

Cold ice, such as of Antarctica, does not usually contain liquid water in cavities or in channels; and the amount of water at the grain boundaries remains less than in temperate ice (Himalayan Glaciers) and decreases with decreasing temperature. The depth to which a radar pulse will penetrate is dependent upon the power and performance of the system, the frequency of the pulse, the number and strength of the reflecting interfaces and the attenuation properties of the subsurface materials (Gruber & Ludwig, 1996).

Figure 3 shows the longitudinal profile of Shelf ice using 50 MHz GPR antenna. The trace window shows a single trace which is the received signal at a point. The radargram is formed by combining all the traces. The horizontal axis displays the antenna position or the distance traveled, while the vertical axis represents a time scale for the radar signal delay time after signal position and also the depth of the medium (Annan & Davis 1976).

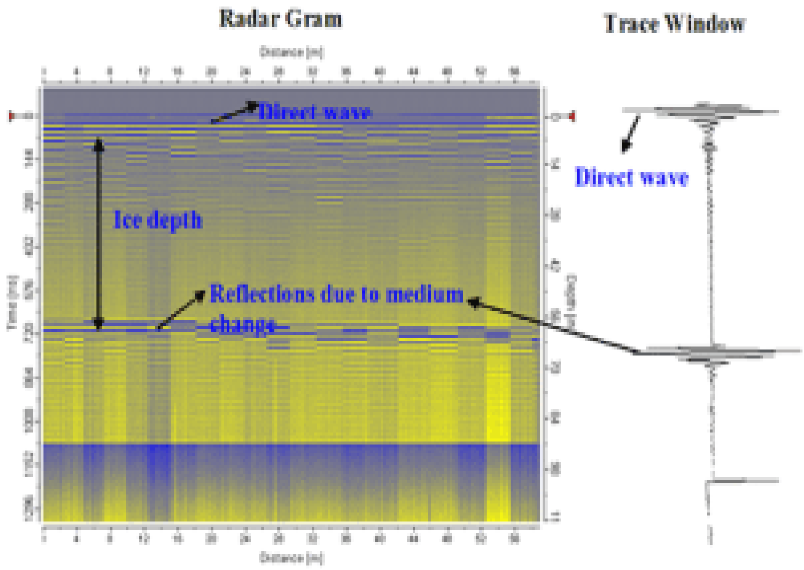

Fig. 3: GPR profile of shelf ice using 50 MHz antenna in distance mode

The signal from the transmitter, which propagates directly through the air to the receiver, is called direct wave and can be seen at the top part of radargram. The radargram shows high reflection of the radar signal at around 56m depth and this reflection varies with the distance traveled. The GPR works on the principle of dielectric contrast, according to which if radio waves meet a boundary of two materials with a different permittivity, a part of their energy is reflected. Hence high reflections in the radargram show the bed topography of the shelf ice. On ice shelves, strong continuous echoes are typical of areas where basal melting predominates and there is a clean boundary between sea and ice. Trace window shows high amplitude for the direct wave and then the amplitude of the signal decreases, until it interacted with a material having different permittivity. In trace window of Fig. 3 further increase in amplitude is observed at depth of around 56m.

3-Dimensional map **(Fig. 4)** of the surveyed area was generated using Surfer software. GPR derived depth information is plotted at different latitude and longitude acquired by using hand held GPS (Garmin). From the 3-D plot, it is observed that the ice depth thickness is high ~ 60m at around 2 km away from the sea edge and the thickness of ice decreases while moving towards the sea. The bottom topography was found very undulating as the ice thickness varies from point to point. At the edge of sea, the ice thickness is around 20 m, hence a dip of 40 m is observed, while moving a distance of 2 km towards sea in the North direction.

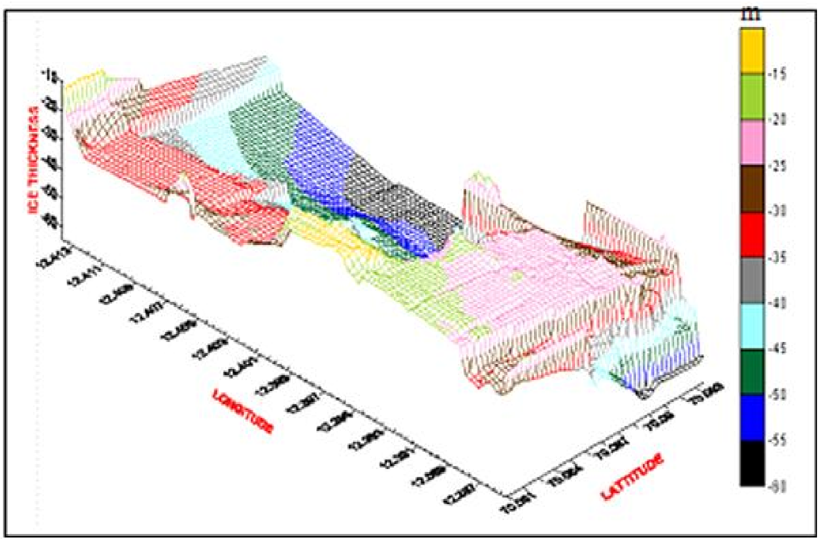

Fig. 4: 3-D map of shelf ice using depth information from GPR

Fig. 5 shows the contour map of the bed topography of the shelf ice. The quantitative information is similar to as shown in 3-D map of Fig. 4.

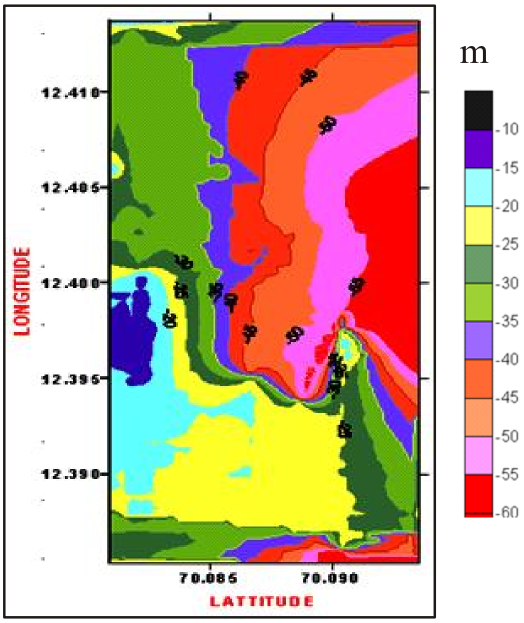

Fig. 5: Contour map (2-D) of shelf ice using depth information from GPR

Sharp reflections of radar waves from two different levels were observed **(Fig. 6)** and these reflections along with the distance traveled during the acquisition of data form the bed topography of different surfaces. From the trace window the changes in the amplitude of the signal are around 42m and 70m depth at a particular point. These amplitude changes are due to change in the dielectric properties of the medium. These two layers in the GPR data are observed for very limited distance in the longitudinal profile L1 in which the data is collected, while moving towards the sea edge, i.e. performing the experiments near the sea.

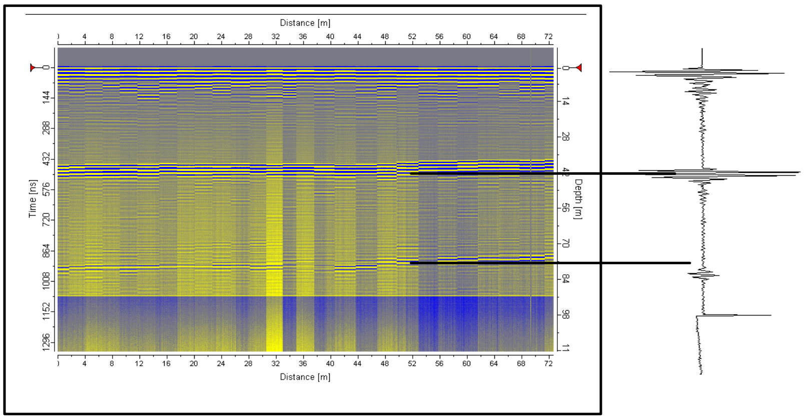

Fig. 6: GPR Signatures showing reflections coming from two different depths

Figure 7 shows the spatial variation of bed topography of the limited area of the shelf ice. Comparison of depth values observed from two different

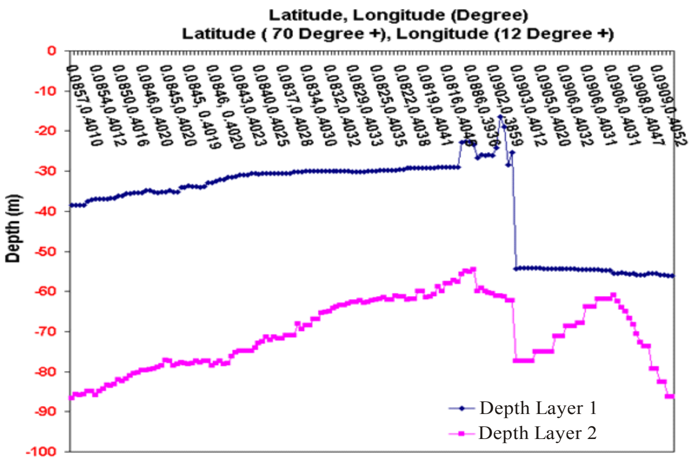

Fig. 7: Spatial variation between two different layers

layers shows the variation of 5 to 50 meters between layer -1 and 2. It is observed that layer-2 has its maximum depth value 86.09m at lat. S 70^{0}05'08" and long. E 12^{0}24'03" and minimum value 54.64m at lat. S 70^{0}05'19" and long. E 12^{0}23'37". Layer -2 represents the bed topography of the ground surface and it slopes towards the sea shore. Near the end portion of the shelf ice the difference in depth between the bed surface of the ice and ground surface is very less and increase in this difference is observed while moving away from the sea shore. These reflections from the ground surface disappear when we moves further inward towards the continental ice.

5.0 CONCLUSIONS

GPR is a relevant instrument for ice depth estimation as the radio waves are generally transparent for the ice media and penetration is more for cold ice in polar region. GPR of 50 MHz frequency was used for shelf ice thickness measurements and it further aids in investigations of bottom roughness characteristics of shelf ice. Larger time windows were used to get the reflections from the greater depths. The 3-D map of the survey area was generated by plotting the depth information from GPR with the corresponding latitude and longitude values, which show decrease in ice depth while moving towards the sea. Generally the bottom topography of the shelf ice was found very undulating.

For stability assessment of the shelf ice, 3-D map generated of the ice shelf using GPR can be used and the logistic and scientific material of the expedition should be offloaded accordingly at safer places. Apart from this study, some lower frequency antennas should also be used to mark the crevasses of the area, which are very large in number and are a great threat for the stability of the shelf ice. At some places near the sea edge, two layers at different depths were observed, which needs to be explored further.

REFERENCES

Asthana R, Gaur M P and Dharwadkar A 2002.Glaciological studies during the expedition. Eighteenth Indian Expedition to Antarctica, Scientific report. department of ocean development, Technical Publication No. 16, pp 95-109.

Björnsson H, Gjessing Y, Hamran S E, Liestol O, Palsson F and Erlingsson B 1996. The thermal regime of sub-polar glaciers mapped by multi-frequency radio-echo sounding; Journal of Glaciology. 42, 23-32.

Bogorodsky V V, Bentley C R and Gudmandsen P E 1985 Radioglaciology. D. Reidel publishing Co.

Davis J L and Annan A P 1989 Ground penetrating radar for high resolution mapping of soil and rock stratigraphy. Geophysical Prospecting. 37 pp. 531-551.

Drewry D J 1983 Antarctica: Glaciological and geophysical folio. Cambridge, university of Cambridge. Scott Polar Research Institute.

Forster R, Davis C, Rand T and Moore R K 1991 Snow-Stratification investigation on an Antarctic ice stream with an X-band radar system. Journal of Glaciology 37(127) pp 323-326.

Jenkins A and Doake C S M 1991 Ice ocean interaction on the Ronne ice shelf. Journal of Geophysical Research. 96 pp 791-813.

Jiracek G R and Bentley C R 1971 Velocity of electromagnetic waves in Antarctic ice; Antarctic Research Series 16 199-208.

Mala geoscience 1995 RAMAC-GPR-Operating Manual. Mala Geoscience, Skolgatan 11, 93070 Mala, Sweden.

Maijala P and Moore J C . GPR investigation of glaciers and sea ice in the Scandinavian Arctic.

Rasal A S and Mahor D R 1999 Meteorological studies carried out during the 15th Indian scientific expedition to antarctica. Fifteenth Indian expedition to Antarctica, Scientific report, 1999. Department of Ocean Development, Technical publication No. 13, pp 39-62.

Richardson C, Aarholt E, Hamran S E, Holmlund P and lsaksson E 1997 Spatial distribution of snow in Western Dronning Maud Land East Antarctica, mapped by a ground based snow radar. J. Geophys. Res.102(B9), 20343-20353.

Sinisalo A, Grinsted A, Moore J C, Karkas E and Pettersson R 2003 Snow-accumulation studies in Antarctica with ground penetrating radar using 50, 100 and 800 MHz antenna frequencies;penetrating radar; Journal of Glaciology 37 194-198.

Taurisano A, Tronstad S, Brandt O and Kohler J 2006 On the use of ground penetrating radar for detecting and reducing crevasse-hazard in Dronning Maud Land, Antarctica; Cold region Science and Technology 45 166-177.