Ice Thickness Study on Gangju La Glacier

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Executive Summary

The knowledge on thickness of the glacier is important for understanding the total volume of ice, which can help to quantify the reserve of fresh water in form of ice. With rising unprecedented risk, hazard and water scarcity due to climate change, the focus on studying glaciers, glacial lakes and its behavior has picked up the hot topic of discussion.

The recently procured Ice Penetrating Radar (IPR) under National Center for Hydrology and Meteorology was successfully tested on Thana glacier. The reliable result from the Thana glacier IPR survey conducted in September 2018 revealed the maximum depth 228.86 m. The thickness of the given glacier provides general overview of the variation and spatial distribution the ice. It could be used as main parameter for estimating the total volume of the glacier using direct method or fine tune the existing empirical algorithm of the model used for calculating the total ice volume.

As a planned activity under Cryosphere Services Division, NCHM for the year 2019-20, the Division conducted IPR survey on Gangju La glacier using the same equipment tested on Thana glacier in the past. Total seven transects were done using turnkey IPR equipped with 10 MHz frequency on Gangju La glacier. The maximum ice thickness measured was 96.44 m at upper approach (Geo-location: 27°56'21.94"N, 89°56'50.20"E, 5133m.a.s.l) of the glacier, which is facing northeast towards the Pho Chhu sub-basin. This report presents the analyzed technical finding of each transacts and results generated using interpretation tools from the specification thickness of the ice.

1. Introduction

The visible evidence of climate change impacts on glaciers has manifested in the form of Glacial Lake Outburst Flood (GLOF), which is lately identified as the main climate change challenge worldwide. Scientific studies in other parts of the world have shown that the glaciers and ice masses have been shrinking, which is an excellent and physically visible climate change indicator (WGMS, 2008). The glaciers in Bhutan Himalaya have been experiencing the effect of recent global climate change and has been losing their masses as well (Dorji & Statistics, 2016) leading to the formation of numerous glacial lakes and posing unprecedented risks downstream. However, studies and related researches conducted so far on Bhutanese glaciers and glacial lakes are relatively less, which calls for extensive and long term monitoring to understand the impacts of climate change and associated risks.

Cryosphere Services Division (CSD) under the National Center for Hydrology and Meteorology (NCHM), Royal Government of Bhutan is mandated to study snow, glacier and glacial lakes to understand climate change impacts on Cryospheric domain. Field observation on Gangju La glacier observation was initiated since in 2003 by Department of Geology and Mines MOEA in collaboration with foreign institute like Nagoya University, Japan and University of Vienna, Austria. Considering the feasibility factors such as accessibility to the glacier site and a favorable season (September – October), the glacier has been monitored on an annual basis. Besides regular annual mass balance activities, the Division undertook ice thickness on Gangju La glacier. Debris-free (clean-ice) glaciers have been a hot topic of research mainly because in comparison to debris-covered glaciers, clean-ice could more simply be related to the local climate contributing to the studies on the growth of glaciers in the region (Naito, Nozomu & Ageta, others 2006). The ice thickness distribution of a glacier is a fundamental parameter for many glaciological applications. It determines the total volume of the ice body, which is crucial to quantify water availability or sea-level change, and provides the link between surface and subglacial topography, which is a prerequisite for ice flow modelling studies (Tshering, Tashi & Kong, F, 2009).

2. Objective

- Measure glacier ice thickness using Ice Penetrating Radar (IPR)

3. Study Area

Gangju La Glacier is the area of interest for this study. The glacier is located in the Northern frontier of Bhutan at 27. 94°N, 89. 95°E in the headwaters of Pho Chhu, Punatsang chhu basin (*Figure 1.*) with an approximate area of 0.215 km^2. The Gangju La glacier is one of the land-terminating glaciers in Bhutan and such glaciers are very important features as the mass-balance of land-terminating glacier are directly related to prevailing local climate. This clean ice glacier extends from an elevation of 4900 to 5200 m.a.s.l., referred to as "Pho_gr16" in the inventory published by Mool and others (Mool et al., 2001). Gangju La glacier observation was initiated in 2003 by Department of Geology and Mines MOEA in collaboration with foreign institutes like Nagoya University, Japan and University of Vienna, Austria. The Gangju La Glacier is currently being monitored by the Cryosphere Services Division under the RGOB funding and is being monitored annually as a benchmark glacier.

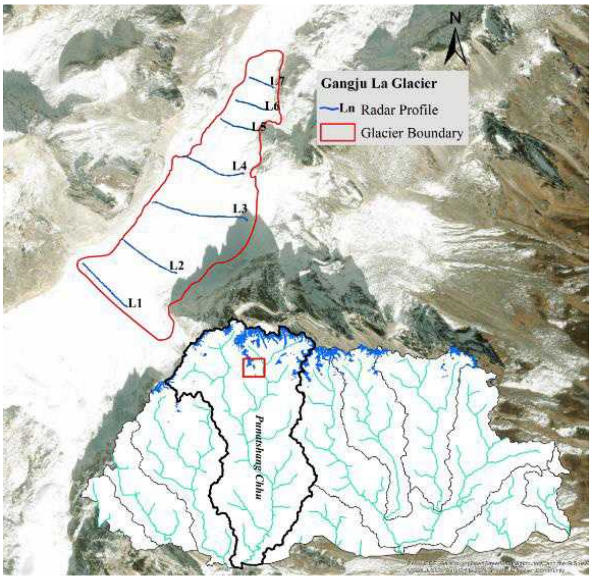

Figure 1: Study Area of Interest

4. Methodology

Generally, Ice Penetrating Radar (IPR) is used to define the bottom topography of ice, estimating the ice flux and basal conditions, determination of internal glacier structures and crevasses, determination of thickness and snow stratigraphy. Electromagnetic wave echo sounding system, built in transmitter and receiver (dipole) integrated with ranging frequency has been used and proven success in glacier ice studies (V. V. Bogorodsky, C. R. Bentley, and P. E. Gudmandsen. Reidel, 1986). The glacier bed geometry is one of the essential information for understanding the quantity of ice in third dimension. So far, glacier studies have been done using Remote sensing techniques to determine the glacier surface area changes, glacier flow velocity and its thickness using empirical formulae. IPR with following (*Table:1*) scientific specification was used during the survey.

Instrument	Frequency	Antenna Spacing	Antenna type	GPS
IceRadar Turnkey system	10MHz	15m	Dipole in single center series set-up	Garmin 18x OEM in built

Table 1: General Specification of IPR

The system used for the survey was is intended for applications in both cold and poly-thermal glaciers (Mingo L and others, et al., 2020). A signal is transmitted from the Transmitter (T_x) unit through an antenna, it propagates outward, it bounces off an object, and it bounces back to antenna set-up to receiver (R_x) unit. Which has a basic requirement for this type of radar sensor is that it be designed for good penetration in the ice and/ or snow. Particular interest is the velocity and attenuation of radio waves propagating through the medium. The most important electrical property influencing the propagation characteristics of a medium is the relative permittivity: a velocity of propagation in freshwater and glacier ice of ~1. 7x 10^8m/s

((V. V. Bogorodsky, C. R. Bentley, and P. E. Gudmandsen. Reidel, 1986), a value which could be considered to be independent of frequency. The during the recent survey, the velocity of propagation of air and ice medium were 3.0x 108 m/s and 1.68×10^8 m/s respectively. Those could be predefined on display screen using IceRadar portable software. Total seven profiles, traversing the glacier from left to right (*Figure 1.*) were taken. Radar data and surface elevation are automatically acquired and logged continuously with 256 stacks for every 2 seconds. The acquired radar data could be viewed live on display screen while taking profile.

5. Equipment and Data Acquisition

Ice Radar Turnkey system integrated with 10 MHz dipole frequency developed at Blue System Integration (BIS), Canada is used for survey. The complete IceRadar comprises a radar-receiving unit, transmitting unit, one antenna set, rigging components and binding system to ski-based sled system, collapsible antenna protective tubing and strain-reliefs (*Figure 2: a*). The EPU (Embedded Processing Unit) is equipped with the acquisition electronics, IceRadar portable software, Global Positioning System (GPS) and touchscreen embedded computer. The portable software logs radar data every 2 seconds along with surface positioning and save in defined directory of EPU memory. Later, the saved data could be exported using Universal Serial Bus (USB) flash drive for further processing.

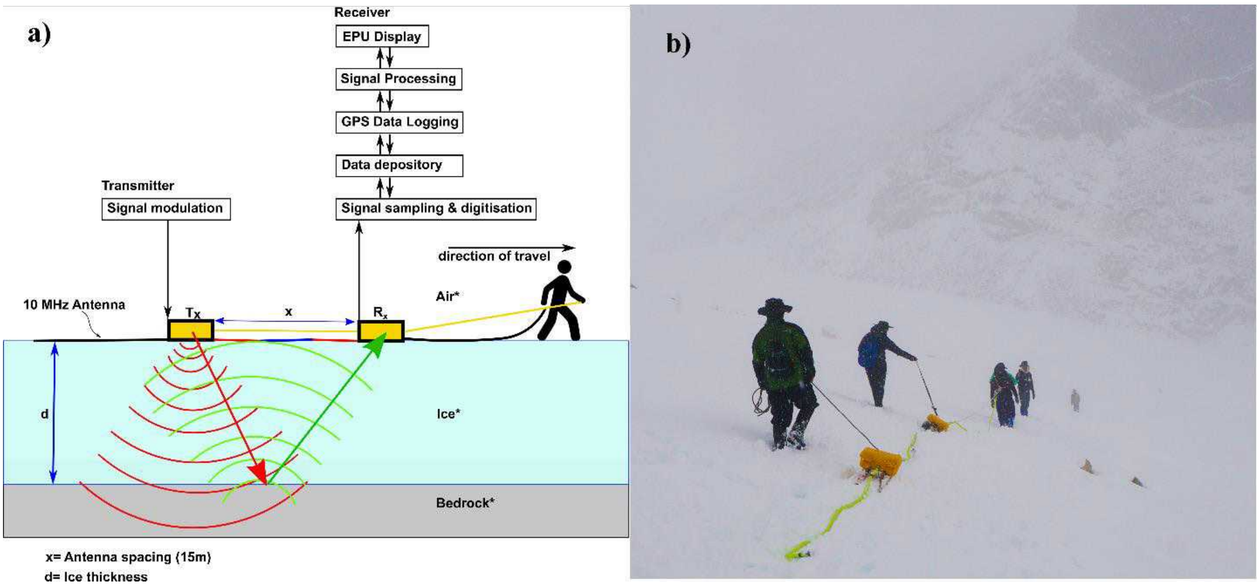

Figure 2: a) Schematic sketch of IPR system, and b) Surveying Gangju La glacier using IPR

The electromagnetic radiation (EMR) frequency used in this IPR is 10 MHz with antenna spacing of 15 m (*Figure 2: a*) to study prominent bottom topography of the ice having an approximate depth of 100 m thickness. The EMR wave speed of the medium to be studied is set at 1.68x10^8 m/s by default, which is directly linked to the permittivity of the ice medium. The survey profiles were taken laterally and longitudinally, sliding the system on the surface of the glacier using sled. However, the longitudinal profile was constraint due to deep gorge features in subsurface resulting in analyzing complex off-nadir reflection. The 2-D migration limits the correction of ice-thickness errors caused by off-nadir resulted due to profiling close and parallel to steep lateral slopes (LAPAZARAN, J., OTERO, J., MARTÍN-ESPAÑOL, A., & NAVARRO, F. (2016)). Hence, the discussion of longitudinal profile was not included in this report.

6. Data post processing

The general principle of IPR or Ground Penetrating Radar (GPR) is to disperse an electromagnetic signal by receiver (T_x) into the object (ground or ice) and to record the reflected signal by receiver (R_x). The depth of targeted object could be calculated from the two-way- travel time (TWT). The IPR data from the current field was post processed using the IceRadarAnalyzer 4.2.5™ produced by the Blue System Integration Limited (system manufacturer). The processing includes quick data viewing, analysis, picking depth points and data export. The EPU fetches raw data in *hdf5* file format. Other programs such as Matlab and Python can access it (http://www.bluesystem.ca/).

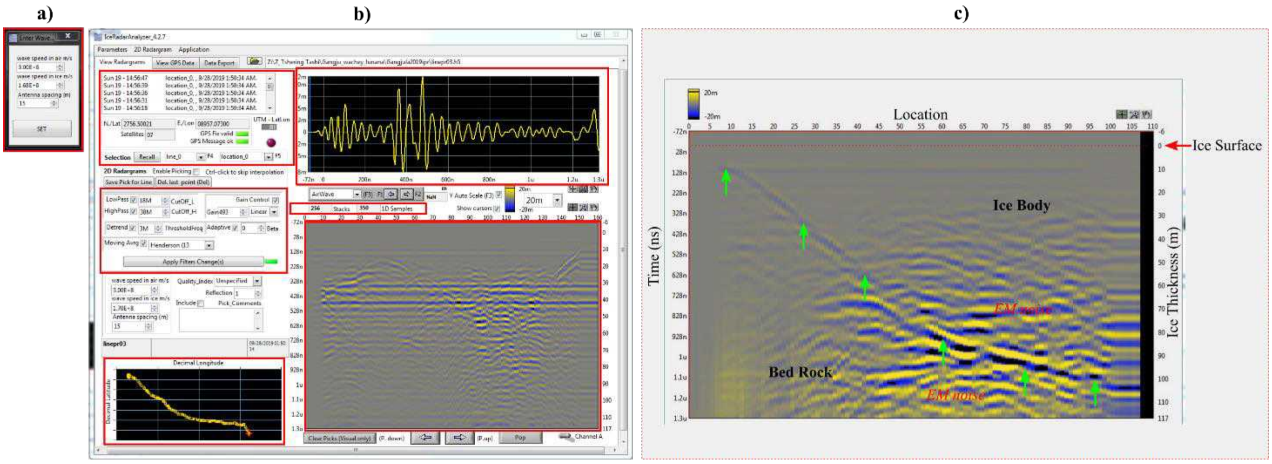

Figure 3: a) Setting of wave speed, b)Adjustment of static filters, and c) 2D visualization of IPR.

Static corrections such as band-pass filtering, gain control, detrend or dewow, threshold frequency and adaptive could be adjusted using the IceRadarAnalyzer 4.2.5™ software as shown in *Figure 3: b.* The glacier bed reflections were traced visually and picked depth variation using the same software, as shown in *Figure 3: c.* User can fix the surface at zero level while picking the corresponding ice depth (*Figure 3: c*). The output data comes in *.pik* (equivalent to *.csv*) format tied with geo-locations that could be arranged in Microsoft Excel™. Unreliable values are filtered out while arranging. The data was further visualized interpreted using ArcMap 10.4.1 and Grapher 11™ for this report.

7. Result and Discussion

7.1. Earlier Result using the same IPR system on Thana Glacier

This IPR system was successfully tested on Thana glacier in September 2018 for the first time as a pilot study after procuring. The measurement profiles were taken along or close to the earlier survey profiles for validation. During the post processing of data set, two profiles were analyzed using the IceRadarAnalyzer software. The measurements along the profiles are given below.

a) A to A′: The highest depth was 175.74 m at location: 28.011°N 90.613°E, 5237 m a.s.l indicating bed elevation at 5061 m a.s.l. whereas earlier survey revealed the maximum depth of 154.74 m (2017 team).

b) C to mid-point of A to A′ (Longitudinal Profile, Fig. 9): The highest depth was 228.86 m at location: 28.022°N 90.611°E, 5305.9m a.s.l indicating bed elevation at 5077.04m a.s.l. Whereas earlier survey revealed the maximum depth of 204.89 m (2017 team)

7.2. Result and Discussion on Gangju La Glacier 2019

Figure 4 shows the processed depth variation graphs from all seven profiles taken laterally on the glacier. The processed radargram represent only the depth variations of the glacier along the profiles using 10 MHz, which is required to for the determination of radar reflection from fluctuations in conductivity without revealing the internal structure of the ice (Matsuoka, K., Maeno, H., Uratsuka, S., Shuji Fujita, Furukawa, T., & Watanabe, O. 2002). 5m interval contour and colour ramp interpolated DEM was generated using QGIS (*kriging*) from processed radargram so see overall ice thickness variation with respect to elevation. The interpolated ice thickness is shown in *Figure 4*.

The maximum depth or thickness of 96.44m was observed at 27°56'21.94"N, 89°56'50.20"E, 5133m.a.s.l (surface), which is at approximately highest surface elevation on the glacier(see figure xx profile A to A′). The highest depth with elevation band is shown in table below (*Table 2*).

Profile	Maximum Ice Depth (m)	Location		Surface Elevation (m.a.s.l)	Bottom Elevation (m.a.s.l)
		Latitude (dd.mm.ss)	Longitude (dd.mm.ss)		
A to A′	96.44	27°56'21.94"	89°56'50.20"	5133	5037
B to B′	77.67	27°56' 26.95"	89°56' 52.35"	5103	5025
C to C′	57.48	27°56' 31.13"	89°56' 56.95"	5061	5003
D to D′	58.17	27°56' 34.74"	89°57' 1.24"	5026	4968
E to E′	49.59	27°56' 39.39"	89°57' 3.62"	4992	4943
F to F′	39.24	27°56' 41.22"	89° 57' 6.03"	4970	4931
G to G′	32.64	27°56' 43.61"	89° 57' 6.76"	4945	4912

Table 2: Maximum depth measured along the profiles

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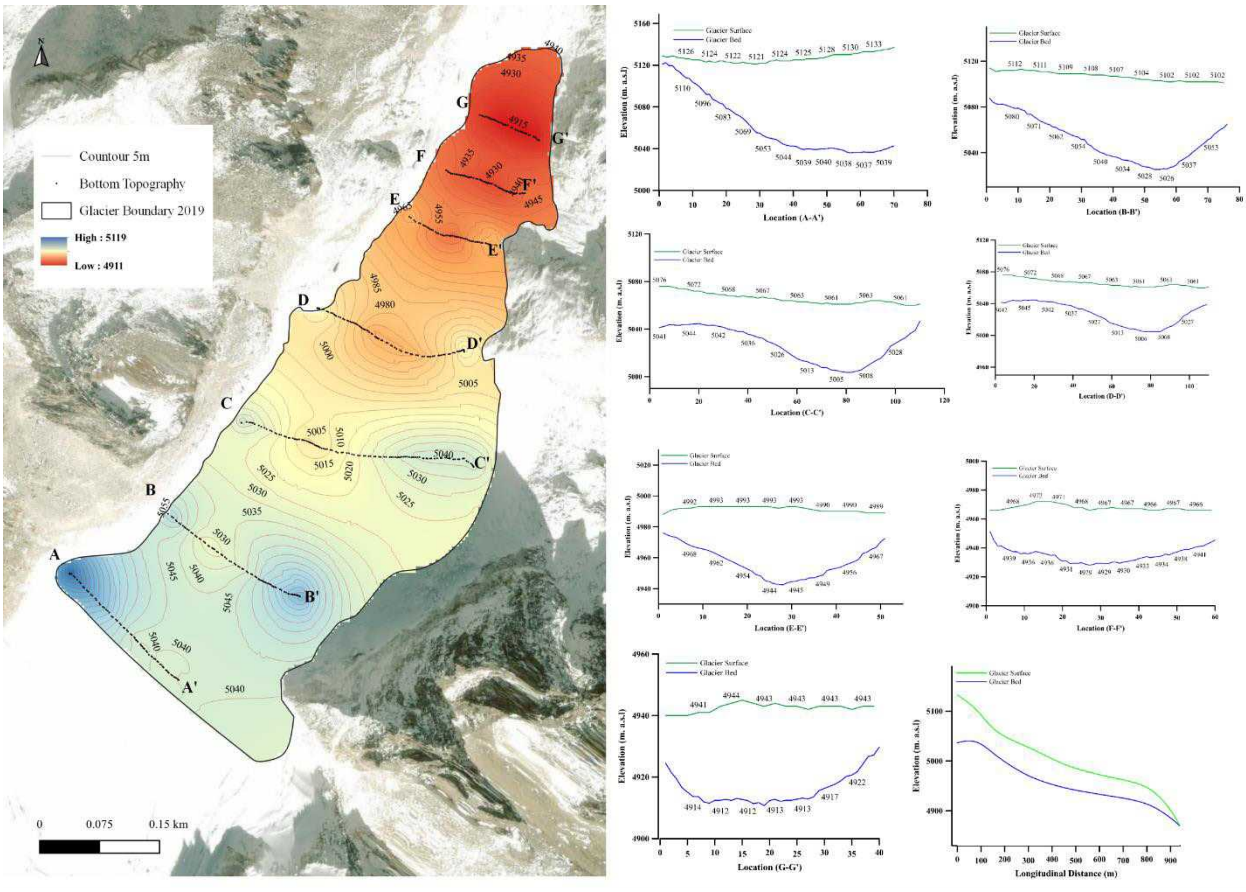

Figure 4: Interpolated radargram on Esri satellite Basemap and 2D visualization of surface and bed elevations of Profiles.

8. Conclusion

The Ice radar survey was done using single frequency i.e. 10 MHz with spacing of 15m. Output of radar survey were analyzed using IceRadarAnalyzer 4.2.5™ software achieving reliable geo-tagged results. More lateral cross sections rather than horizontal profile are recommended mainly to avoid off-nadir error reflected from close and parallel to steep lateral slopes. The fixed 10 MHz antenna IPR reveals consistent depth topography of that glacier having maximum approximate thickness of 90 to 100 m. The radargram of such antenna type reveals bed reflections masking other stratigraphy within the glacier mass. Application of multi-frequency (e.g. 30 to 100 MHz) can contribute to better understanding the sub-surface of the glacier especially clean ice with shallow depth glacier like Gangju La. The results picked from the radar survey revealed ice thickness only taking consideration of EM wave reflected from the bedrock using 10MHz antenna. There is possibility of considerable uncertainties mainly due to the presence of surface meltwater (Bohleber, Pascal & Sold, & others 2017) and internal reflections depending on nature of the terrain. The information and data will contribute in bridging the gap from surface balance to understanding the overall volume fluctuation of the ice mass of Gangju La glacier in future.

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