THE INFLUENCE OF BUILDINGS ON SNOW ACCUMULATION AT TARFALA RESEARCH STATION, SWEDEN

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Haiku

Snow drifting in wind,
falling, blowing in cold air.
One piece: earth and sky.

EU GlacioEuroLab No.2 Field Report

Objectives

One of the aims of the Tarfala field course (EU GlacioEuroLab No.2) was to make participants familiar with radar sounding techniques applied to glaciology and hence enable them to operate a Ground Penetrating Radar (GPR) to study glaciers. The study presented in this report originated from the impossibility of transporting the radar equipment up to Storglaciären (primary area of investigation) due to adverse snow conditions. Nevertheless, an alternative back up plan made it possible for three radar surveys to be performed in the research station area. The results of one survey are displayed and an interpretation of the data collected is provided.

Background

In early April, Tarfala research station (~ 67°55'N, 18°36'E) resembles an oasis surrounded by a white desert. In this case the desert is ephemeral and cold and it is made of a special type of sand, snow. Snow cannot be compared to sand, they are two extremely different natural materials, however if we confine the comparison to dry snow only then it is not too wrong to consider it partially similar to sand. Suppose now that a Tuareg, travelling through Lapland, arrives in Tarfala more or less at the same time of the year. Surprisingly, on arrival the Tuareg will find himself surrounded by a familiar landscape. The Berber traveller would quickly note many dune-like features around the station and surely enjoy the beauty of the undulations on the snowy surface oriented at right angles to the direction of the wind, just like ripples on the surface of a sandy dune!

Introduction to the technique

Radar methods are one of the major tools used by glaciologists to investigate glaciers. Radar investigations need special equipment, unfortunately, easily subjected to technical failure (see Tari Oksanen and Sue Adir reports from Tarfala field course 2000). Moreover, the grasp of some basic physics is required in order to operate the radar and to understand how it works. To grasp how electromagnetic signals propagate through ice it is essential to know some of the physical properties of the signal and also some physicochemical properties of the ice. Follows a short introduction to the physical basis of echo sounding by pulsed radio waves.

A short electromagnetic pulse is emitted by an antenna mounted on a platform moving over the surface of the glacier, the pulse penetrates the glacier and it is reflected by inhomogeneities in the ice[§] and by the bedrock so it returns to the antenna (*echo*). Analysis of the pulse delay time enables the determination of the depths of the reflecting interfaces (snow, firn and ice thickness can be obtained), but also makes it possible for glacier temperatures and velocities to be assessed.

[§] *Glacial ice is an inhomogeneous medium due to variation in the ice structure, rock intrusions (moraines), cavities (filled with liquid water or air), fractures (crevasses). Inhomogeneities in density and structure, inclusions and other features create internal reflections and have different impedance contrast and therefore can be distinguished by radar techniques.*

Glacier ice is a *polarisable* non conducting medium (*dielectric*), its electrical properties can be specified by its *impedance*. Impedance is a function of other two parameters: *permittivity* and *conductivity*. Permittivity[§] depends on the characteristics of both the medium (i.e. density) and the electromagnetic wave (i.e. frequency of the oscillation). Conductivity mainly depends on temperature and on the effects of impurities[†].

The variations of electrical parameters between different layers are the most important features for radar sounding of glaciers. The largest changes are caused by changes in ice density, temperature and content of liquid water. Note also that ice absorbs electromagnetic energy, so, as it travels through the ice the electromagnetic wave loses energy and the returning echo is smaller than the original signal (*attenuation decay*).

The choice of operating frequency for a particular purpose is determined by the conditions of wave propagation in the medium and by the limitation of the system used. A decrease in operating frequency, increase in power, results in an increase of the sounding depth, however, it makes the resolution worse and the antenna larger so more difficult to carry. Fortunately, radar sounding of glaciers can be performed from a moving surface vehicle or from an aircraft.

Aeolian effects on snow accumulation (snow drift related processes)

A series of processes starting from snow formation in the atmosphere and ending with its deposition are responsible for the accumulation of snow on a glacier. After *precipitation*, *transport*[‡] can have significant effects on snow accumulation patterns.
Snow drift is the ability of the wind to lift snow particles from the surface, it depends on the wind strength and on the history of the snowpack. Wet, dry, old or fresh snow have a different *threshold friction velocity*[‡‡]. Moreover, snow drift is a manifestation of a two phase flow with constantly changing particle size distribution, snow particles become smaller through sublimation, as opposed for instance to drifting sand particles in sandstorms. Therefore, snow drift physics are extremely complex. A brief description of the basic drifting processes is given below.

Once a snow particle is lifted, it may fall down again immediately and upon impact with the surface eject another particle. These processes are typical for the *saltation layer*, in which a significant part of the snow drift takes place. If the wind is strong enough the particles may be lifted above the saltation layer and become suspended (*blowing snow*). Blowing snow occurs up to several tens or hundreds of meters height

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§ *Note that the speed of the electromagnetic wave propagating in ice is inversely proportional to the square root of its permittivity.*

† *Note that impurities are of great importance for radioglaciology since some of the electrical properties of ice depend strongly on the degree of impurities.*

‡ *Snow moves as a particulate flux as it is relocated by the wind.*

‡‡ *Threshold friction velocity is a variable that depends on wind speed, surface roughness, grade of metamorphism and wetness of the snow.*

above the surface and severely limits near surface visibility as experienced in Tarfala (Figure 1).

Therefore changing wind conditions and availability of snow from the surface are main factors affecting drifting snow related processes (i.e. erosion and deposition). Such processes are thought to be important as in the formation of blue ice areas in Antarctica (Figure 2).

Snow radar measurements

GPR allows measurement of continuous profiles and it is best used in combination with indipendent data obtained at some reference points. Snow density pits and core drillings, are used to obtain a more significant set of data. Furthermore, by running radar in conjunction with regular snow probing, the point measurements provided with the manual probing can be checked against the continuous radar profiles. This greatly improves the accuracy of the measurements (see section on calibration). After calibration of the radar system, radar measurements, geolocated with Global Positioning System (GPS) data, can replace manual probing enabling information to be obtained more rapidly and continuously.

In radar studies the different physical and chemical properties of subsurface layers produce different reflections intensities due to variations of the *dielectric constant*[§]. The dielectric constant in snow is affected by various physical and chemical parameters such as liquid water content, snow density[†], crystal fabric, conductivity, concentration and composition of ions and microparticles.

Electromagnetic wave speed through snow is described by: $\mathbf{V=c/\sqrt{\varepsilon}}$ where $\mathbf{V}$ is the speed of electromagnetic waves in snow, $\mathbf{c}$ is the speed of electromagnetic waves in a vacuum (~$3\mathrm{x}10^8$ m/s), and $\boldsymbol{\varepsilon}$ is the complex dielectric constant of snow expressed by: $\boldsymbol{\varepsilon=\varepsilon' - i\varepsilon''}$ where $\boldsymbol{\varepsilon'}$and $\boldsymbol{\varepsilon''}$ are the real and imaginary part respectively. A complete description of the dielectric constant of snow involves the dielectric properties of its constituents: air, ice and liquid water. However, in the absence of liquid water $\boldsymbol{i\varepsilon'' \ll \varepsilon'}$ and thus the imaginary part of the dielectric constant is negligible. Therefore, if we consider the snow to be dry (no melting) then: $\mathbf{V=c/\sqrt{\varepsilon'}}$. The real part of the dielectric constant is almost solely dependent on the snow density (obtainable from the density profiles data). The relationship between the dielectric constant of snow and snow density is given by the empirical equation $\boldsymbol{\varepsilon'=(1+ 0.845\ \rho)^2}$ where $\boldsymbol{\rho}$ represents the specific gravity (i.e. the density relative to the density of water). Generally density increases with increasing depth hence density-depth profile will influence the wave speed/depth profile for propagation of electromagnetic waves. Furthermore, snow density may vary between different regions due to local meteorological conditions (air temperature wind activity and solar radiation). Therefore it is crucial to acquire snow density data from different locations in the area under investigation.

[§] *Note that relative permittivity it is also called the dielectric constant of the medium.*

[†] *If the medium considered is snow, then the density is very important because it is a mixture of two dielectrics (ice and air).*

Provided that the wavelength is sufficiently larger than the grain of snow, the real part of the dielectric constant of snow, ε', is independent of radar frequency. This condition is satisfied over a large range of frequency (10MHz to 10GHz).

Finally, processing of raw data by Fourier Transformation (FT) analysis enables the conversion of the received amplitude and phase of recorded reflections into 'pictures' and the determination of the travel time record.

Snow radar soundings in combination with manual probing were performed after two days of heavy snowfall and strong winds on April the 7th (see Figure 3). The radar registration, two major buildings (laboratory and mess) and two snow pits, were positioned by GPS registrations. The resulting map is shown in Figure 4.

Equipment

The equipment used was a ground based monopulse RAMAC radar, operating with a centre frequency and bandwidth of 800 MHz. The maximum penetrable depth was of approximately 6m below the snow surface. The radar major components are the *transmitter* and *receiver* electronics (*control unit*) and the *antenna* (800 MHz, *shielded*†). The antenna was housed in a purpose made sledge, pulled by Kai Rasmus and Francesco Senia (Figures 3 and 10). A hip chain device was used for keeping track of the distance. Manual probing was conducted by Yvonne Kramer (Figures 3 and 11). Data were recorded on the hard disk of a Husky portable computer and later processed by FT analysis. The correspondence between the two different sets of data was achieved by placing markers in the data log corresponding to points probed by hand. GPS data were collected by Greet De Keukelaere and Peter Moore (Figure 11).

Calibration

The high level of agreement between the radar data and the manual probing data (Figure 5), resulted in the optimal radar calibration as can be seen in Figure 6. Only a few imperfect measurements can be identified on the manual probing data set, these are likely to originate from irregularity in the underlying bedrock.

The time for the electromagnetic wave to go through an ice/snow layer and back is given by: $\mathbf{t=2h/V}$ where $\mathbf{h}$ is the thickness of the layer and $\mathbf{V}$ is the speed of electromagnetic wave propagation in the medium. Therefore the thickness of the layer is readily obtained ($\mathbf{h= tV/2}$). The same formula is used to work out the value of $\mathbf{V}$ from the calibration graph. The slope of the trend line in Figure 6 is equal to $\mathbf{2/V}$.

Results and discussion

The radar profiles obtained from the radar registration (Figures 7, 8 and 9) revealed that snow accumulation varies over the surface under investigation. The snow layer is

† *Low background noise antenna, gives good resolution for shallow investigations. A lower frequency antenna (200 MHz, unshielded to maximise penetration depth) can be used for higher penetration depths.*

clearly seen in the registration. The part of the profile in between arrows indicates the areas influenced by the proximity of the buildings. The maximum travel time corresponds to a snow depth of about 3 meters.

The measured snow layer thickness shows a large variation over a short distance this is better seen in Figure 5. Higher accumulation corresponds to a thicker layer (two to three meters thick) and is associated with the vicinity of the buildings (marked zones 1-6 and 24-31).

The area around the base is characterised by a relatively flat topography, with the station buildings as the major features above surface, vaguely resembling nunataks above a glacier. Regions of glaciers characterised by nunatak areas are associated with high spatial variability in snow accumulation. In a nunatak area the variability, at least partly, may be explained by lee side accumulation and erosions effects due to wind channeling nearby individual nunataks. Similarly at Tarfala, according to the radar registrations, the spatial pattern of accumulation appears to be affected by the presence of the buildings. Dune-like features (*undulations* and *barchans*) can be observed around the buildings especially early in the morning when the snow surface is still untouched, before the many activities at the busy research station have started. These features might form in the same way as a sand dune is formed. For a snow dune to form a patch of snow must first begin to accumulate. This occurs where the wind speed is reduced by an increase in surface roughness, or by instabilities in the airflow. The buildings greatly reduce wind speed and therefore can be responsible for the interception of snow by causing turbulence in the nearby airflow.

Finally, although the impression gained in the field was that buildings and snow strongly interact with each other, it is difficult to say from observations over such a limited area and time the exact relationship between accumulating snow and the buildings at Tarfala.

Error considerations

Uncertainty in the depth of the snow-cover can originate from various sources. To obtain reliable values from radar soundings accurate calibration is required. Two calibrations were conducted: the first was a complete disaster, mainly due to the bad weather conditions but also to the little effort and poor organisational skills of the teams involved. The second, in contrast was a great achievement of smart team-work supported by sunshine. It is worth noticing that in this study the instrumentation was working extremely well and that the interpretation of the radar registration was facilitated by the high quality and the relatively simple analytical tool, ‘user friendly software’, utilised for processing the data.

Variability in snow density can result in significant errors in the snow depth values, therefore a good knowledge of snow density in the area under investigation is essential. A series of snow pits were dug in the area with this purpose, the results are displayed elsewere[§].

[§] *The complete data sets resulting from all the activity of the course is available from John Moore home page on the World Wide Web at the address: http://www.urova.fi/home/hkunta/jmoore/glacioeurolab2/glacioeurolab2data.html*

Finally irregularity in the underlying bedrock can be responsible for inaccurate interpretations of the data, so, to obtain more precise information about the depth and the pattern of the snow covered ground an examination of the surface topography would be useful to reveal the existence of humps and hollows.

Conclusions

The presence of snow and its accumulation patterns around Tarfala Research Station is ephemeral and mainly governed by local weather and global climate. The local topography and the station buildings, their size and shape, are also important factors. The buildings and the snowpack and the wind interact with one another. The resulting feedback mechanism regulated by the wind turbulence is responsible for the formation of barchans around the buildings. In this way the snow not only affects the life at the station but also it is affected by the presence of the station.

Snow is a very light material, so it can be easily relocated by wind. Hence, drifting snow is responsible for the formation of beautiful wavy surfaces that are best admired under the light of a full moon night.

Acknowledgements

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Glossary

Barchan: a crescent-shaped dune.
Berber: language and people of certain native, nord-arab tribes.
Conductivity: reciprocal of resistivity.
Deflation: removal of loose particles by the wind.
Dielectric: a nonconductor of electric charge in which an applied electric field causes a displacement of charge (*polarisation*) but not a flow of charge.
Dune: accumulation of sand forming a low hill or ridge in hot arid and coastal environments.
Haiku: short Japanese poem**,** a form of poetry with 17 syllables in three unrhymed lines of five, seven, and five syllables, often describing nature or a season. Also called hokku.
Impedance: quantity that measures the opposition of a medium to the passage of a current.
Nunatak: a bedrock knob that rises above the surrounding glaciated area.
Permittivity: in a medium other then the vacuum the potential energy of interaction between two charges is reduced, and the vacuum permittivity must be replaced by the permittivity of the medium. The permittivity is normally expressed in terms of the dimensionless relative permittivity, which is also called the dielectric constant of the medium.
Resistivity: a material's ability to oppose the flow of an electric current.
Ripples: small depositional features consisting of regular wave-like undulations oriented at right angles to the direction of the prevailing wind.
Tuareg: tribal people of the Sahara desert.

Figure 1. A bad day in Tarfala. Drifting snow is intercepted by the station buildings and it is also responsible for the extremely low visibility conditions.

Figure 2. Skating on blue ice, courtesy of K. Rasmus. The interplay between rock, ice, snow and wind is responsible for the formation of Blue Ice Fields in Antarctica.

Figure 3. The snow radar, with the antenna inside the sledge, is pulled along the track and the manual probing is conducted at marked locations.

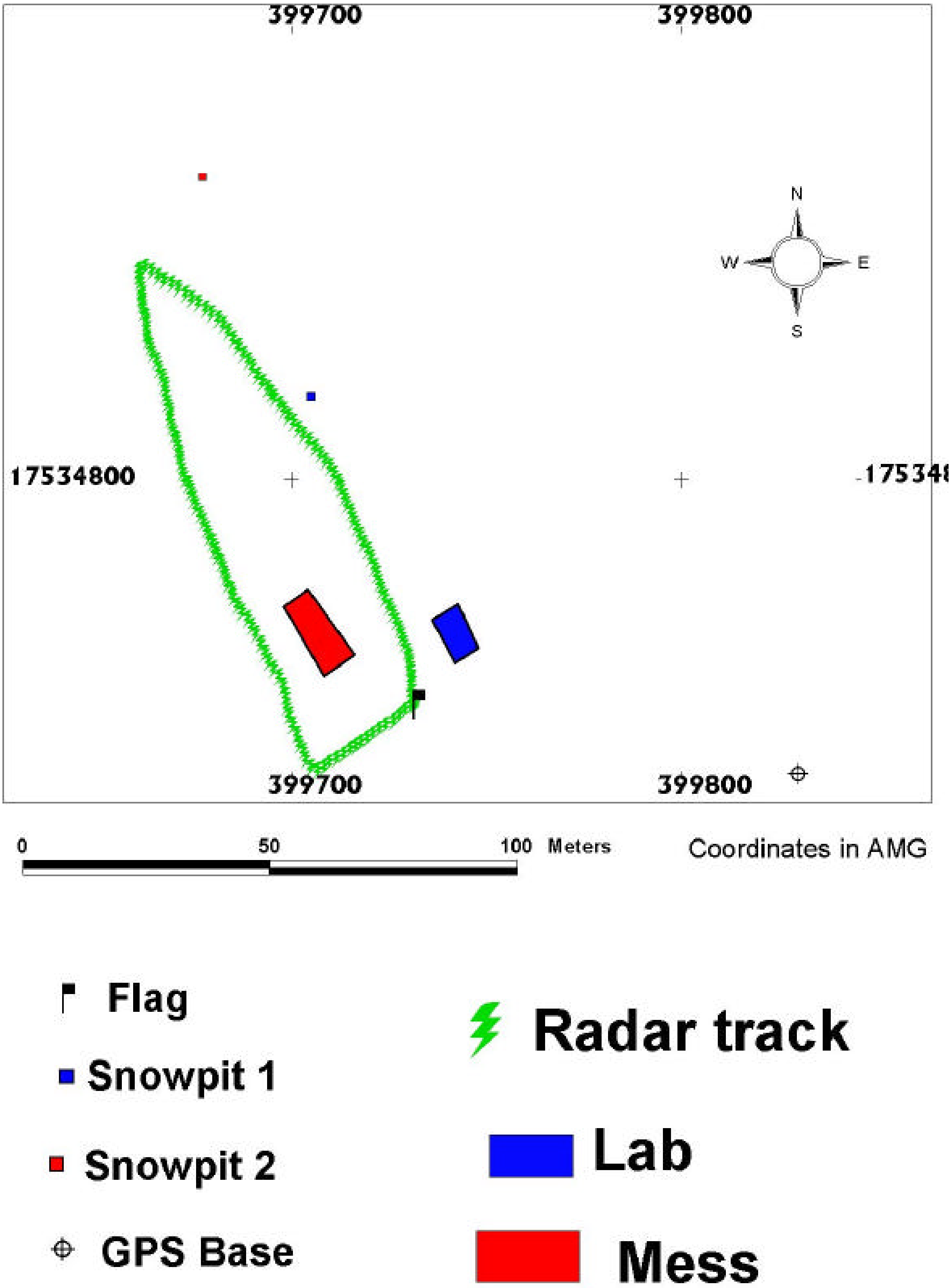

Figure 4. Location map of the study area in Tarfala. Snow radar profile, buildings and snowpit locations are indicated. Trajectory in System AMG (Grid, ZoneZone_34: 18E to 24E).

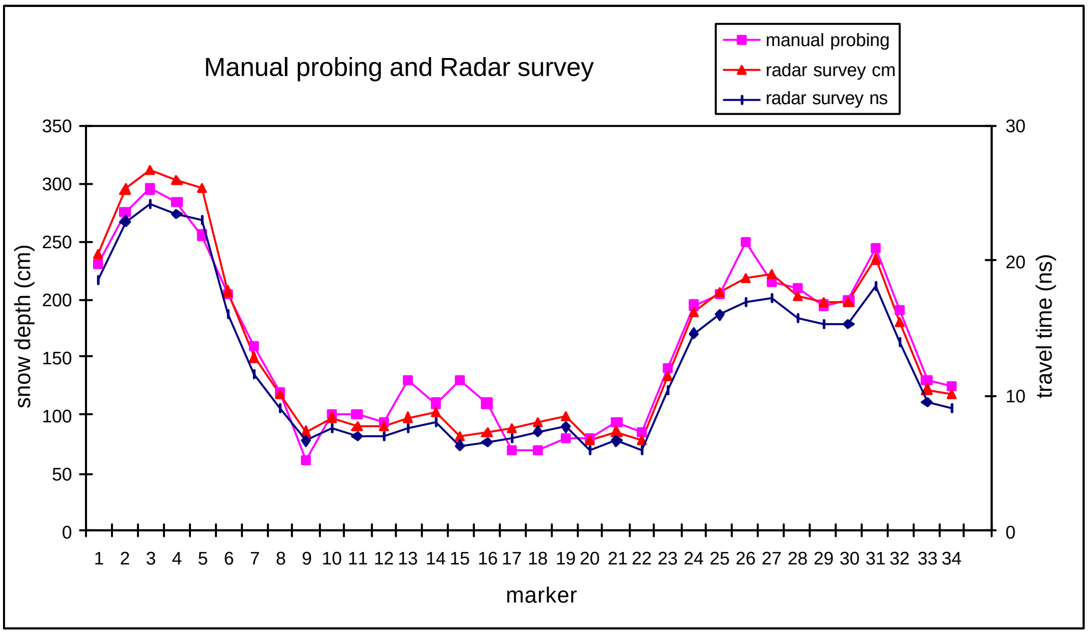

Figure 5. Curves of accumulation from radar and manual probing data. Note the good level of agreement between the curves.

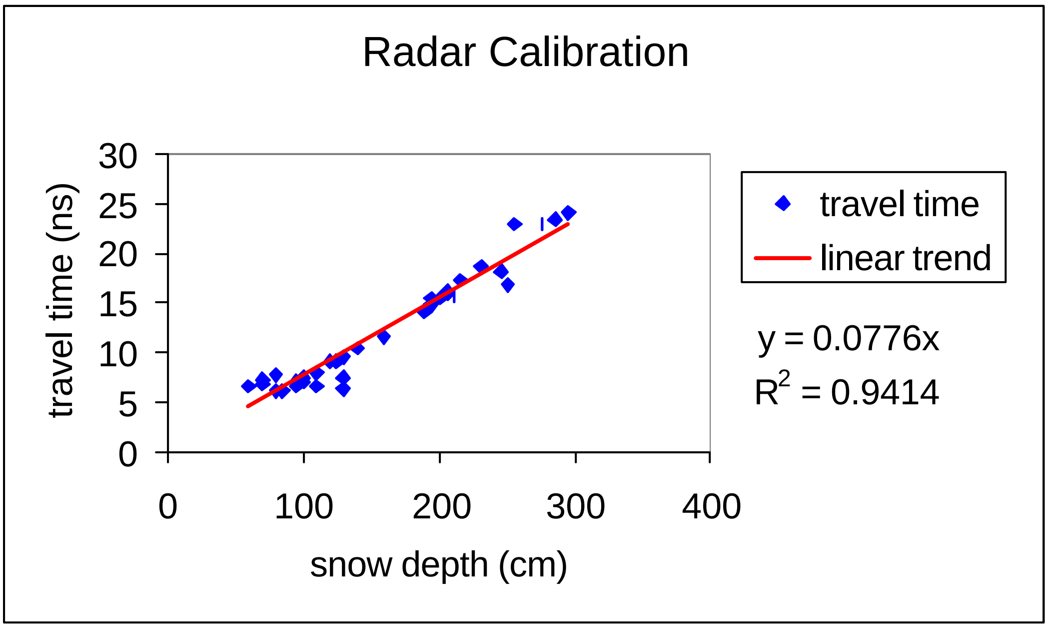

Figure 6. Radar calibration graph. From the slope of the trend line the speed of the electromagnetic wave in the snow is obtained (**V**≈258m/µs).

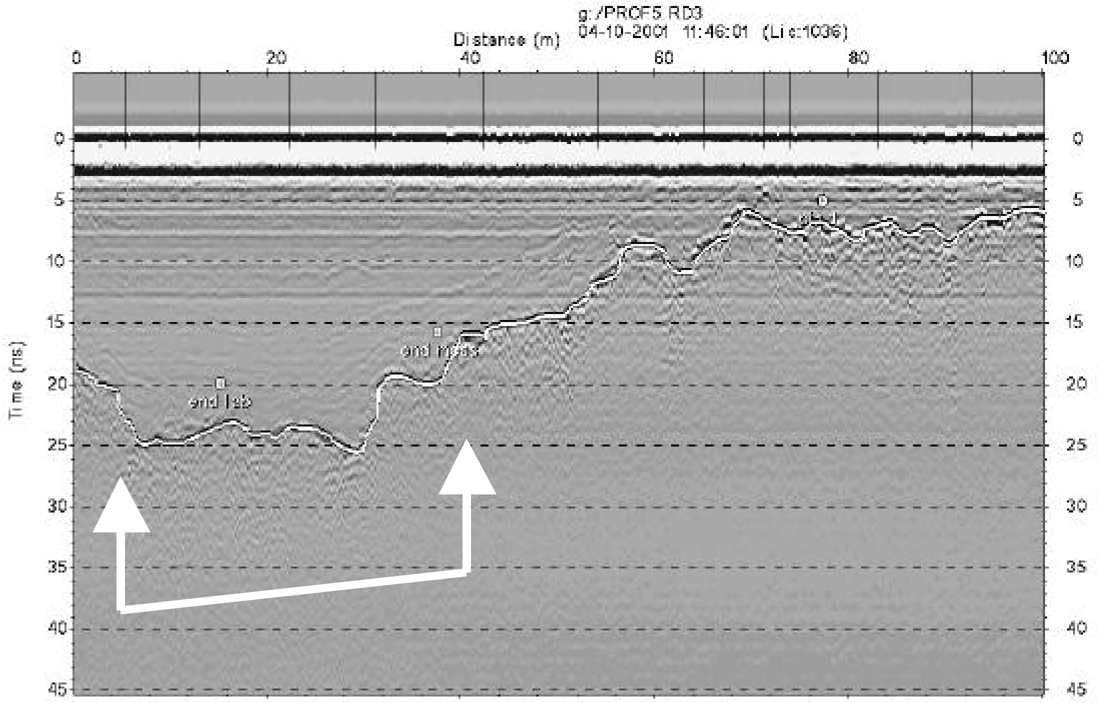

Figure 7. Snow radar registration. The snow layer is clearly seen in the registration. The arrows indicate the area affected by the nearby mess and laboratory buildings. The maximum travel time corresponds to a snow depth of about 3 m.

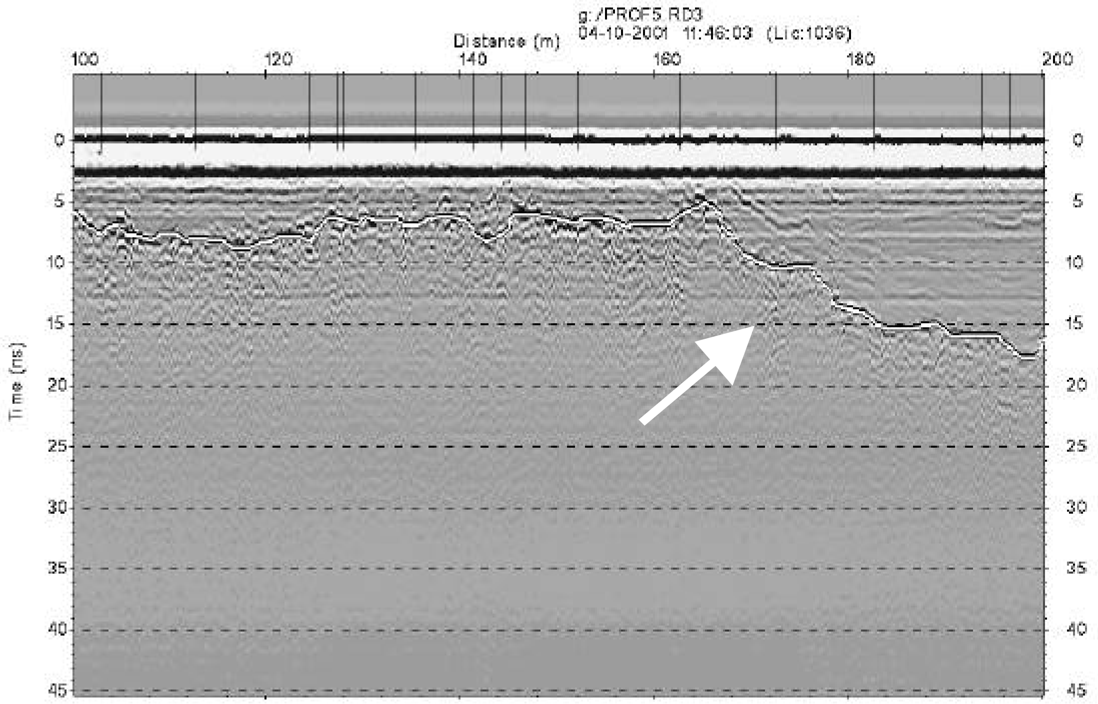

Figure 8. Snow radar registration in the area with no buildings. A thinner snow layer is clearly seen in the registration. The snow layer gets thicker nearer to the station.

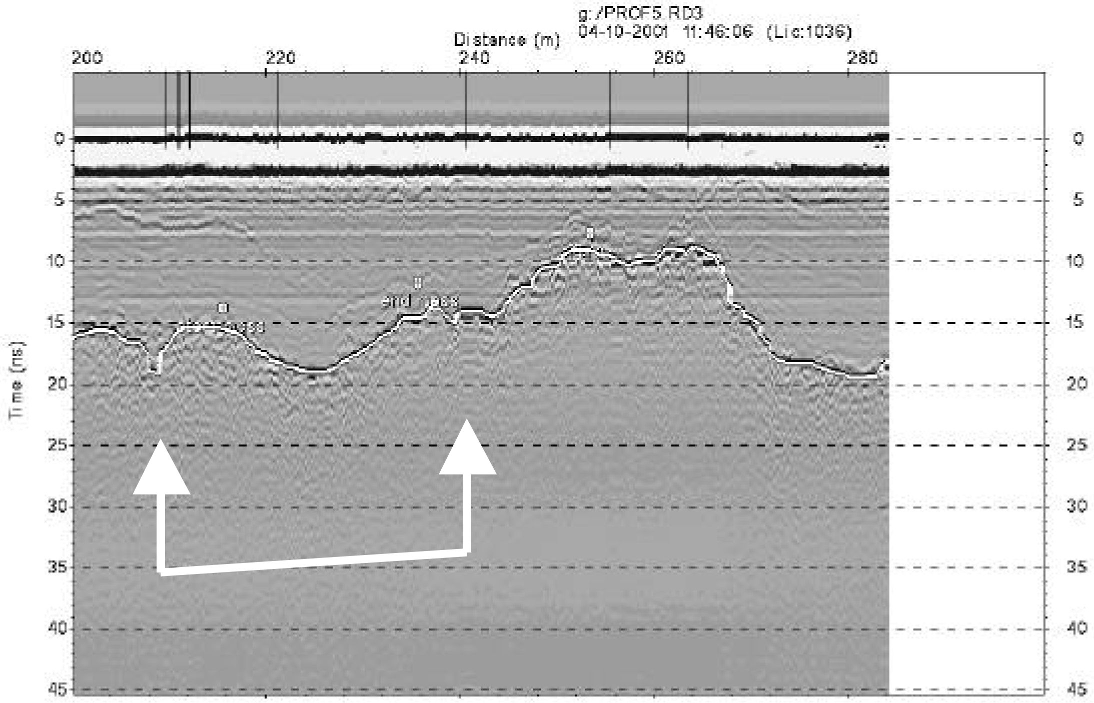

Figure 9. Snow radar registration. The arrows indicate the area affected by the mess building.

Figure 10. Radar operators.

Figure 11. Manual probing.

Figure 12. GPS data collection.