Remote Sensing by Low-frequency Radar

Workshop Naples, Italy -20/21 September 2001

Helicopter-borne GPR systems for geological application, a comparison between pulse radar and stepped frequency radar

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Abstract

Ground-penetrating radar (GPR) has become a useful tool in solving different geophysical tasks in environmental geology, glaciology, archaeology, mineral exploration and the detection of near-surface objects.

The large variety of handheld GPR devices, even for rugged field conditions, are effective tools for surveying small areas. GPR-equipped fixed-wing aircraft are used mainly for surveying large areas or inaccessible regions, for example, dessert areas, permafrost areas or high mountain ranges. A GPR system installed in a helicopter is an effective way to survey large areas with high data density. Large areas, even in inaccessible regions, may be surveyed within a short time and even limited logistic demands. The high agility of a helicopter allow to increase the data density in areas of special interest.

Using ground penetration radar for geological applications a high resolution of near-surface structures is necessary. Stepped frequency radar technology offers an attractive alternative to the classical pulse radar systems.

A helicopter-borne GPR system for measuring ice thickness up to 3.000 m in Antarctica has been developed by the BGR in cooperation with the Technical University of Hamburg-Harburg. The system is a pulse radar system and consists of the following components: transmitter–receiver unit, antenna, data acquisition and a GPS navigation unit. The antenna is a corner reflector with two dipoles in a distance of λ/4 apart. The dipoles are installed in such a manner that an optimum bundling is achieved. The antenna is mounted to the helicopter via a 15 m towing rope and a coaxial cable. The system can operate as well as monostatically and bistatically. The normal operating frequency is 150 MHz, but can be varied between 70 and 150 MHz.

This system was modified for near-surface applications in 1999-2000. These modifications were firstly tested during a survey at the Careser glacier in the Italian Alps in October 2000. The results clearly show the base of this glacier in a depth range of 10 to 80 m.

The RST Group, a Swiss-German company for costumer-designed radar developments, designed a stepped frequency GPR able to operate from a helicopter. The frequency range is programmable between 20 MHz and 2 GHz The system antenna was mounted on a non-conducting frame connected to the helicopter as a sling load. All electronic parts were installed in the helicopter.

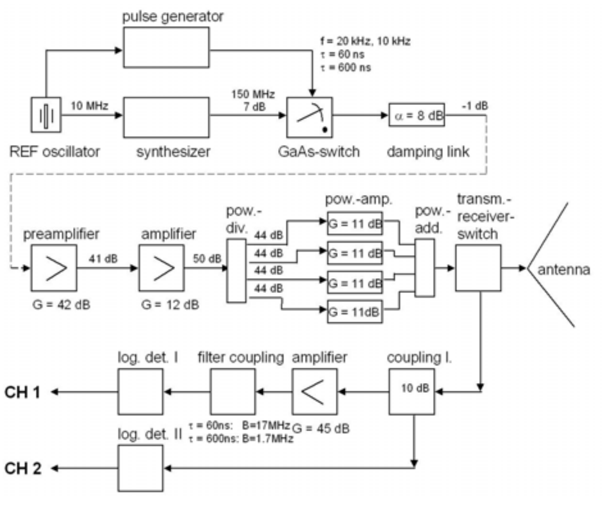
This alternative GPR was flown about along the same flight tracks at the Careser glacier to compare the performance of the SF-radar and pulse radar systems.

The system parameters of both systems and field data acquired during the test survey are discussed.

Characteristics of the used „Pulse Radar System“ (PRS)

The pulse radar system has a long history. Their concept offers degree of a maturity which is also reflected by the successful application as a ground penetrating radar. The airborne. PRS of BGR is dedicated, in particular, to ice sheet thickness measurements.

The concept and the main features are summarised as follow:



Center Frequency :	150 MHz	Peak Power:	1,5 KW
Pulse width:	12/60/600 nsec	Quantisation:	8 Bit
Puls rep. Frequency:	20 kHz	Antenna Gain	14 dB

Helicopter with the antenna rig

Ortler mountains with the Careser Glacier

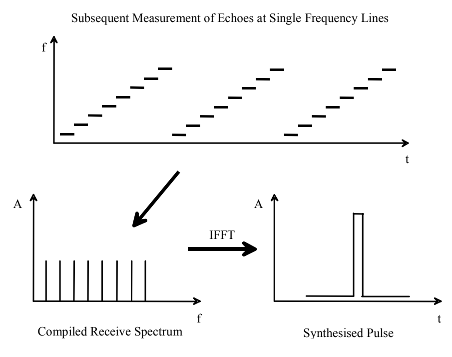


Fig.1. Basic operation scheme of a SFR

Characteristics of the used „Stepped Frequency Radar“ (SFR)

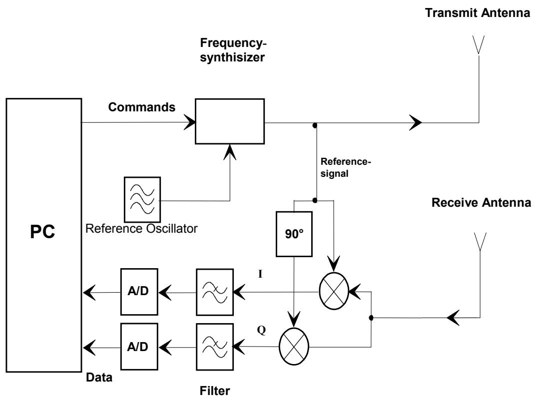
Two instruments from RST, a company mainly involved in space-related radar projects, have been used during the campaign, SUSI (Stepped Frequency Ultra Wideband Subsurface Imaging Radar) and DEEPER. Both instruments are very versatile programmable radars that are not explicitly dedicated to airborne applications. They have been developed in order to evaluate the optimum radar parameters for a variety of applications. They are forerunners of a generation of more dedicated instruments. In particular, the antennas that were available during the campaign were not well-suited for airborne applications.

The most spectacular missions of the RST instruments were preparatory investigations of anti-personnel mine detection, GPR measurements in the Himalayans and water search experiments in the United Arab Emirats.

Main characteristics of **SUSI**:	
Frequency range:	5 MHz .. 8 GHz, programmable
Number of frequency lines:	up to 2048, programmable
Dwell time per frequency line:	min. 1 msec, programmable
Output power:	5 mW
Quantisation:	16 Bit
Antenna gain:	2 dB

Main characteristics of **DEEPER**:	
Frequency range:	2 .. 55 MHz, programmable
Number of frequency lines:	up to 4096, programmable
Dwell time per frequency line:	min. 1 msec, programmable
Output power:	5 mW
Quantisation:	16 Bit
Antenna gain:	-12 dB

The employed antennas are modified dipoles. In the case of DEEPER they are resistively loaded.



In contrast to classical pulse radar systems, SFR systems operate with amplitude-continuous radar signals. The signal bandwidth being required for the desired radar resolution is generated sequentially instead of providing the instantaneous complete spectrum of the pulse radar case. Figure 1 illustrates the basic SFR modulation scheme. The radar transmitter sequentially provides signals stepping through the desired frequency range. Depending on the application this could be done, for instance, in linear steps as depicted in the figure. In the receiver section both, phase and amplitude measurement of the echo signals is performed. The results are fed into a data processing, the well-known IFFT (Inverse Fast Fourier Transform), for example. The output is a pulse that can be compared to that of a pulse radar. It contains the range information of the target, while its pulse width, the radar range resolution, is related to the bandwidth of the applied radar spectrum.

The advantages of the SFR can briefly be summarized as follows: low instantaneous bandwidth, high sensitivity, high penetration depth, low sensitivity to RF-interferences, low power consumption, high resolution w.r.t. measurement frequency, low output data rate (saves memory, allows for high dynamic range AD-converters), reduced wideband antenna problems. Most of the advantages are directly related to the continuous wave operation and the low instantaneous bandwidth of the SFR. The second key factor resulting from the sequential operation principle, is the unique possibility for powerful instrument calibration in both, the frequency as well as in the time domain. The influence of the overall calibration is finally reflected by the achieved radar range resolution performance that is close to theory.

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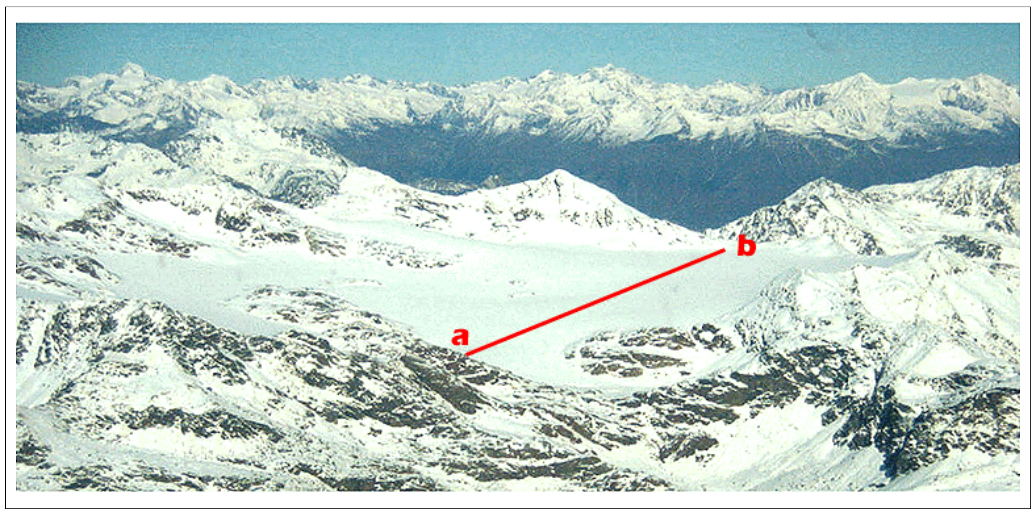

Fig. 2 Careser Glacier with the survey line

Theoretical Performance Comparison

Penetration Depth

The penetration depth performance of a radar system can be described by the so-called "radar equation". For a given target radar cross-section σ in the distance R the signal-to-noise ratio (S/N) at the receiver output is given by:

$$\frac{S}{N} = \frac{P_t G_t G_r \lambda^2 \sigma e^{-2\alpha R}}{(4\P)^3 R^4 k T_{sys} B_n} \qquad (1)$$

P_t represents the transmit power, G_t and G_r the gains of transmit and receive antenna, λ the radar wavelength, B_n the noise bandwidth of the radar receiver, T_{sys} its noise temperature, and k the Boltzmann constant. The term $e^{-2\alpha R}$ takes into account the two-way attenuation of the radar signals in the soil.

For the pulsed radar, B_n is matched to the pulse length τ in an optimum case: $B_n=1/\tau$. Now (1) can be rewritten:

$$\frac{S}{N} = \frac{P_t \tau G_t G_r}{k T_{sys}} \bullet \frac{\lambda^2 \sigma e^{-2\alpha R}}{(4\P)^3 R^4} \qquad (2)$$

In this notation, the first term comprises the instrument parameters. In the literature it is frequently called "dynamic range", DR:

$$DR = \frac{P_t \tau G_t G_r}{k T_{sys}} \qquad (3)$$

This figure represents a measure for the theoretical range performance of a radar system. If we introduce the parameters of the pulsed system (incl. T_{sys}=400 K, τ=60 nsec), we obtain DR=190 dB. Coherent averaging by a factor of 8 gives another 9 dB.

In the SFR case (τ=2 msec, programmed) we obtain 157 dB for SUSI and 129 dB for DEEPER. This estimate means that the SFR principle will be able to compensate only for a part of significantly higher transmit power and antenna gains of the pulsed system. Thus, a much better image quality in terms of penetration of the pulsed system has to be expected. Apart from the numbers calculated, DEEPER is expected to benefit from reduced material losses at lower radar frequencies.

Vertical Resolution

The theoretical radar resolution ΔR in the vertical direction is given by:

$$\Delta R = \frac{\upsilon}{2B} \qquad (4)$$

where B represents the radar bandwidth and v the velocity of propagation in the material. In the SFR case, B is given by the frequency spectrum applied, in case of the pulsed system by the pulse length as stated above.

The applied radar parameters lead to a theoretical radar resolution of 4.5 m (60 nsec) / 0.9 m (12 nsec) for the pulse radar, 3 m for DEEPER (12.5 .. 37.5 MHz) and 0.375 m (100 .. 300 MHz) for SUSI. The dielectric constant has been assumed to 4. Of course, the practically achieved resolution also depends on antenna issues.

Radar Campaign

Although approximately 2 weeks have been allocated for the measurement campaign, the team had bad luck. Almost the entire time period suffered from bad weather conditions. Rain and fog in the high mountains just allowed for short test flights in the valley and for only two flights, one for each radar system, over the glacier. This has to be considered a real pity since no optimisation of radar parameter settings, in particular with regard to the comparability of the measurement results, could be performed. Fig. 2 gives an impression of the Careser Glacier, located at app. 3000 m altitude. The line a-b show us the aproximatily the track of survey with the PSR and SFR systems.

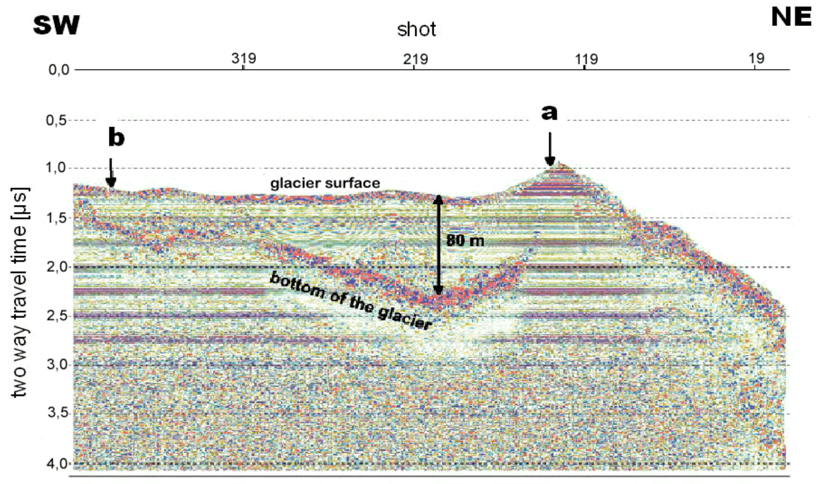

Fig.3 Careser Glacier profile measured by PRS

Field data after processing (1 µs two way travel time correspond 84 m ice thicness)

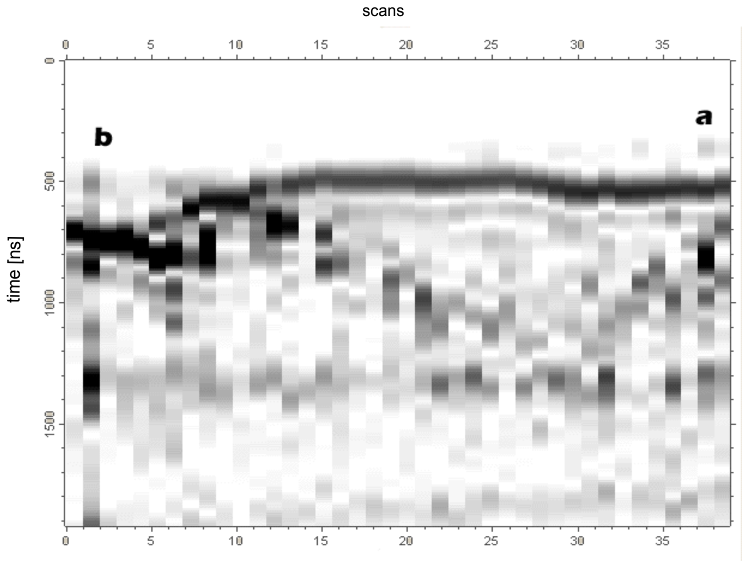

Fig.4 Careser Glacier profile measured by SFR (DEEPER)

Discussion of Results

During the two glacier flights radar data of several profiles have been provided by all three participating instruments. Due to the heavy antenna rig and the high altitude of the Careser Glacier, the helicopter was operated at its performance limits. In addition, the terrain offered a very complicated topography with strongly inclined surfaces. Therefore, it was not possible to fly exactly repeating tracks allowing direct comparison of results provided by the pulsed system and the SFRs.

Thus, the comparison could only be based on the evaluation of the quality of the measured radar cuts. In Fig. 3 a cut measured by the pulsed system is shown. Clearly visible are the surface and the bottom of the glaciers. There are indications for an internal structure of the glacier, more detailed statements would be highly speculative, however.

In Fig. 4 a profile of DEEPER is displayed. Both figures show the surface as well as the bottom of the ice. It is evident, however, that the pulsed system images the structures with higher performance.

The main reasons can be listed as follows:

1) the better power link budget of the pulsed system,
2) the significantly smaller number of measurement points in the SFR case,
3) energy loss due to defocusing of the SFR measurements.

The enormous advantage due to antenna gain and transmitter power of the pulsed system had been expected. The small number of measurement points for the SFR is a consequence of the long sweep time compared to the flight velocity. On one hand, since the helicopter operated at its limits, the flight speed could not be reduced. On the other hand, in order to provide a high compression ratio, the SFRs were operated with 1024 frequency lines leading to a long sweep time. This, in turn, caused a target defocusing in conjunction with echo energy loss within the sweep. Although it is usual practise to correct for the defocusing, we could not apply this technique because we did not have high accuracy flight path recordings synchronised to the radar data.

Unfortunately, the weather did not allow for further flights. Otherwise, as learned from the first flight, we would have operated the SFRs with a reduced number of frequency lines and hence faster sweep time.

Concerning the vertical resolution no features could be identified that would allow a practical verification.

Resume and Conclusions

Two totally different radar concepts have been flown on the measurement campaign. While the pulsed radar system was optimised for airborne applications and the flight characteristics of the helicopter, the SFR had to live with the conditions encountered during one single available flight over the glacier.

As expected, the pulsed system provided images of better performance. Nevertheless, it is amazing what could be achieved with a few milliwatts in the case of the SFRs.

Since we failed to provide a comparison in quantitative terms, it is intended to have a further helicopter-borne GPR campaign in the near future. Here we will try to operate the systems with a variety of radar parameters. Since the SFRs have been modified for considerably higher measurement speed and since, in the case of SUSI, directional antennas are now available to the team, we hope to get a more realistic comparison beween the systems. Maybe we can even test a gated system currently under development at RST. For verification of vertical resolution we will probably deploy artificial radar targets.

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