Use of radar for landslide hazard monitoring

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ABSTRACT: Large uncontrolled avalanches pose a hazard to both people and infrastructure. Timely warning of potential avalanches can save lives and reduce damage to the infrastructure. However, access to the potential landslide area can be difficult and electronic monitoring equipment installed at the site may fail. This paper presents a system for remote monitoring using interferometric radar. The radar can be installed several kilometres away from the potential landslide area and movements in the landslide can be monitored with an accuracy better than 1 mm. The data can be presented remotely in real time and a warning can be issued automatically to the relevant authorities if movements are registered. The paper presents the probable technical solution for remote monitoring at Tafjorden and Åkerneset.

1 INTRODUCTION

In the Norwegian fjord Tafjorden, two potentially unstable mountain blocks in Hegguraksla pose a possible hazard to people living close to the fjord. The first site is a block estimated to be approximately 40 m wide, 120 m long and have a height of 200 to 300 m, i.e. approximately 0.8 – 1.5 mill m^3. The second site north of the block also shows sign of instability. This block is approximately 40 m wide, 160-180 m long and the height is approximately 300 m, i.e. the volume is approximately 1.5-2.5 mill. m^3, Blikra (2001). In order to assess the situation, it has been decided that the blocks shall be monitored to determine whether there are movements and if this is the situation, what is the size of the movement.

Because the potentially unstable blocks are remote and not easily accessible, especially during winter time, it has been decided that the blocks shall be remotely monitored. The proposed solution is a dual antenna differential interferometric radar that monitors the two sites in real-time. The paper presents some of the experimental measurements results and the proposed solution.

2 BACKGROUND

Interferometric radar measurements take advantage of the phase of the electromagnetic wave, where the phase φ is varying as a function of range (R) and electromagnetic wavelength (λ) :

$$\varphi = \frac{4\pi \cdot R}{\lambda} \tag{1}$$

where

$$R = \frac{T \cdot C_0}{2 \cdot n(\vec{r}, t)} \tag{2}$$

C_0 = velocity of light in vacuum, T = travel time of the electromagnetic wave from the radar to a reflector on the unstable site and $n(\vec{r},t)$ = spatial and temporal index of refraction. For radar frequencies the index of refraction can be estimated using the semiempirical expression

$$n = 1.0 + \left(\frac{77.6}{T}\left(p + \frac{4810 \cdot e}{T}\right)\right) \cdot 10^{-6} \tag{3}$$

where p = air-pressure (mbar), T = temperature (ºK) and e = partial water vapour pressure (mbar), Bean (1968). Indirectly the index of refraction is also a function of the wind velocity and wind turbulence. The index of refraction is thus varying as a function of time and space. An example of a measurement of a single reflector using a frequency of 9.5 GHz is presented in Figure 1. As the measurement shows, the range to the reflector varies.

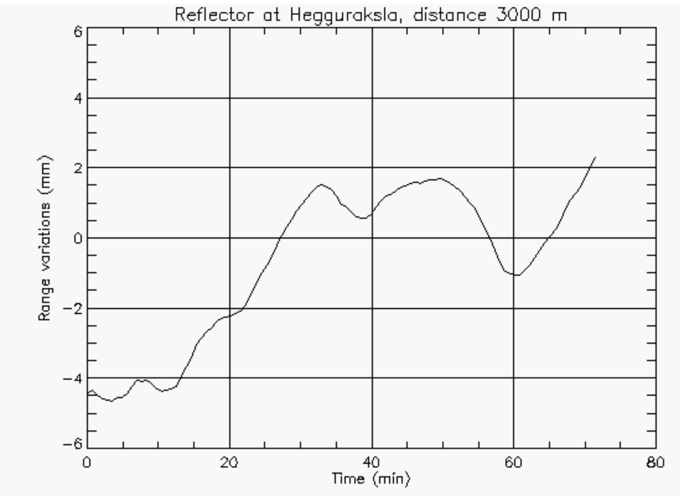

Figure 1. Range measurements showing the variation in range due to the variation in the index of refraction. Range 3000 m.

Due to the variation of the index of refraction, high accuracy instantaneous phase measurements are not possible unless the measurements are averaged over a relatively long time span.

The solution is to introduce a second reflector, reflector 2, and measure the differential phase ($\Delta\varphi$) between the two reflectors, thus reducing the spatial variation of the index of refraction to the space between the two reflectors. The measurement setup is presented in Figure 2.

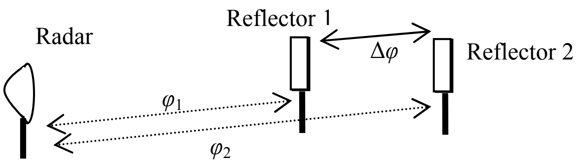

Figure 2. General arrangement for differential interferometric radar measurements

The differential movement (Δr) between the two reflectors, where one is on stable ground, can then be calculated as

$$\Delta r = \frac{\lambda \cdot \Delta\varphi}{4\pi} \tag{4}$$

The differential interferometric radar is a well proven technique, demonstrated for the first time in 1974, Graham (1974), and later in a number of different applications either regionally using air- or space-borne radar for ice sheet movement detection, Goldstein (1993), digital elevation models (DEM) Zebker (1986), monitoring of volcanoes, Massonnet (1995) and detection of unstable slopes, Strozzi (2002) or locally as a ground based fixed installation for e.g. monitoring of volcanoes with or without reflectors, Malassingne (2001), Antonello (2003).

The advantage of the ground based differential interferometric radar is the high temporal sampling-rate combined with inexpensive spatial sampling using relatively cheap corner-reflectors as compared to other electronic equipment e.g. GPS and extensiometers. Depending on the transmitted frequency, the radar can also be used under any weather conditions at large distances.

3 EXPERIMENTAL MEASUREMENT RESULTS

In order to prepare for the installation and assess different radar configurations, i.e. different polarisations, bandwidths and pulse waveforms, an experimental measurement setup using two radar reflectors were installed on the mountain at Hegguraksla, Tafjorden, see Figure 3, at a distance of approximately 3000 m. The height relative to the radar was approximately 630 for reflector 1 and 650 m for reflector 2.

Figure 3. The reflectors at Hegguraksla, Tafjorden. View from Fjøra.

One measurement over approximately one hour is presented in Figure 4 using 9.5 GHz and horizontal polarisation. The measurements presented in figure 4 were made during relatively stable weather conditions and are hence marginally influenced by local variations of the weather, e.g. rain or mist in the vicinity of the reflectors that can change the index of refraction.

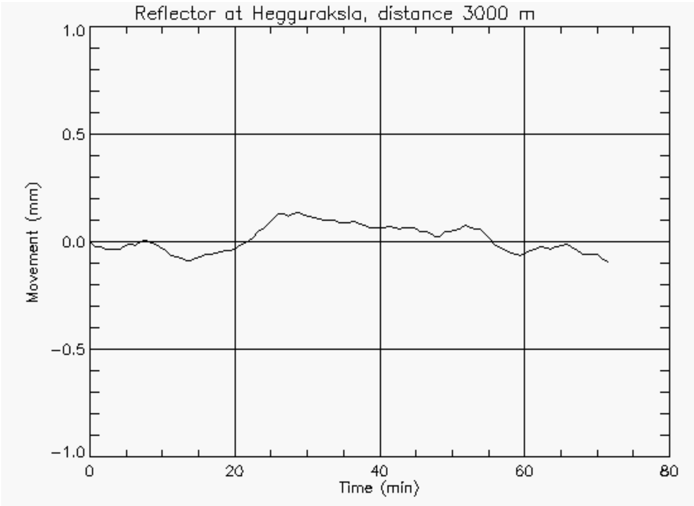

Figure 4. Results from the measurements of reflectors on Hegguraksla during relatively stable weather conditions. The data presented corresponds to approximately 5 minutes average.

The statistics of the measurement are presented in Table 1.

	Value (mm)
Mean	0.013
Median	-0.003
Standard deviation	0.064

Table 1. Statistics of the measurement presented in figure 4.

As the statistics of the measurements indicates, the proposed solution achieves very good results.

A subset of a longer measurement set, approximately 8.20 hours, and during more varying local weather conditions, is presented in Figure 5.

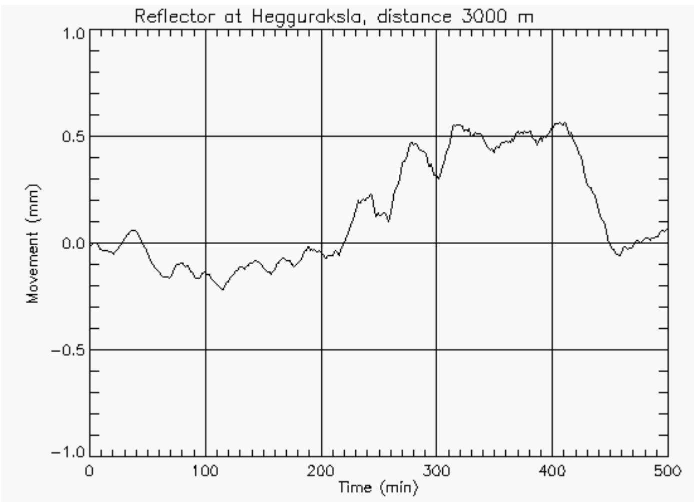

Figure 5. Results from the measurements of reflectors on Hegguraksla during more unstable weather conditions. The data presented corresponds to approximately 7 minutes average.

According to the meteorological data for the period, the changes seen during approximately 2.5 hours in the latter part of the measurements are probably due to local rain or fog/clouds in the mountain area that influences the index of refraction between the two reflectors. The statistics of the measurement is presented in Table 2.

	Value (mm)
Mean	0.058
Median	0.001
Standard deviation	0.250

Table 2. Statistics of the measurement presented in figure 5

Note that even if the index of refraction is varying due to unstable weather, the changes are small and continuous, while a physical movement will appear as a discontinuous large movement. The fluctuations due to the variations in the index of refraction will also over time vary around zero movement while a physical movement will be biasing the data. Filtering the measurement data by a moving window, e.g. equal to 2 samples pr. day will improve the accuracy of the data even further.

A similar measurement campaign will be conducted at another site, Åkerneset, in the neighbouring fjord, Sunnylvsfjorden, in order to optimize the radar configuration, i.e. frequency, polarisation, bandwidth and reflector size, for the monitoring of a larger potentially unstable rock slide area.

4 SYSTEM OVERVIEW

In order to put the radar in an operative context, the proposed solution for the surveillance of Hegguraksla in Tafjorden is presented in Figure 6.

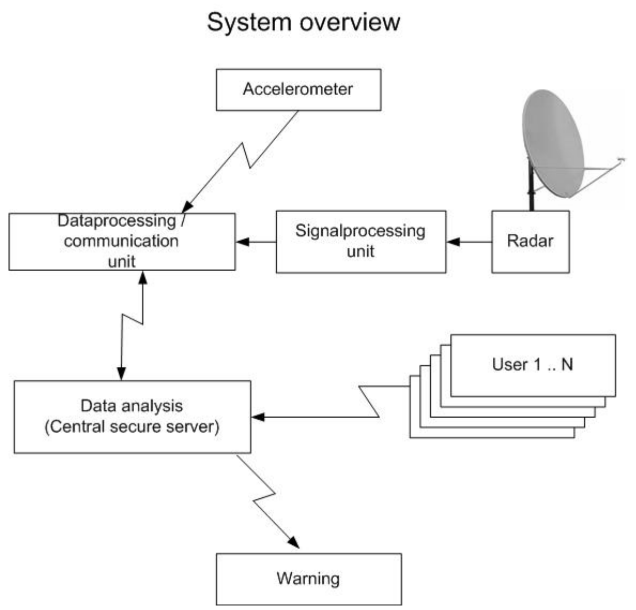

Figure 6. Proposed system solution for the surveillance of Hegguraksla, Tafjorden

The measurements of the reflectors are processed on site and the resulting data is sent to a remote, secure and supervised server for analysis and generation of graphs. The data on the server can be accessed through internet by different users through a password protected logon interface. As a backup, a SMS alert message will be sent to registered users in case of movements or velocities triggers a preset threshold.

In addition to the radar with both signal and data processing, an accelerometer is proposed. The data from the accelerometer will be correlated with the radar data as part of the initial long term testing of the radar. Thus movements registered by the radar will be checked against the accelerometer in order to verify/ test whether the movement was due to an actual physical movement of the mountain block.

5 CONCLUSION

A number of experimental measurements have been done in order to optimize the interferometric radar configuration for the real-time monitoring of two blocks in Hegguraksla, Tafjorden. The experimental measurement results show that a very high accuracy in measured physical movements of the reflectors can be achieved using differential interferometric radar with a frequency of 9.5 GHz and horizontal polarisation. Measurements during relatively stable weather conditions indicated an accuracy of about 0.01 mm with a standard deviation of 0.06 mm at a range of approximately 3000 m.

The real-time monitoring will be presented to approved users that can view and assess the data using internet.

The proposed radar configuration will be installed at Fjøra, Tafjorden during 2005.

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