An overview of RAR application for pit slope monitoring: with a focus on spatial and temporal resolution

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ABSTRACT: An overview of Real Aperture Radar (RAR) for pit slope stability monitoring is provided, with a specific focus on spatial and temporal resolution based on the physics utilised by the system. For the purpose of this paper, the RAR system discussed is the Reutech Mining Modular Movement and Surveying Radar (MSR). The system is deployed at a position whereby it is mechanically steered to conduct sequential interferometric measurements to delineate deformation data from the pit slope. The area that may be scanned is definable, and comprises 186° in azimuth and129° in elevation. The sample acquisition time (temporal resolution) is dependent on the scan rate. The spatial point resolution is defined by user selected options. The radar is georeferenced in order to allow for 3D identification of synthetic map points and therefore the interrogation of data from potential areas of concern, which may indicate instability of the pit slope.

Keywords: Real Aperture Radar (RAR), spatial and temporal resolution, monitoring, deformation, instability.

1 INTRODUCTION

The Reutech Mining MSR is a radar that employs single transmit and receive channel (transceiver) in order to capture pit slope movement or deformation through phase shift or offset. The 'MSR Modular' is Reutech Mining's third generation of movement and surveying radars. The system is developed specifically for accuracy and precision through the repeatability of interferometric measurement. The user definable spatial point resolution, scan rate and scan line spacing determine the spatial and temporal resolution for that database configuration. The azimuth and elevation values are set based on the area of interest of the pit slope that the user would like to collect monitoring data. The system also caters for atmospheric reduction to the total phase measured, through the removal of the effects of temperature, humidity and air pressure, which is referred to in combination as the refractive index, *n*. There are a variety of radar sensors utilised for pit slope monitoring, this paper describes the applicability of RAR to the mining environment with respect to the importance of: spatial resolution in terms of the density of data points which have movement data assigned to them and temporal resolution which is the frequency in time in which the points are measured.

2 FUNDAMENTALS OF KEY RADAR CONCEPTS

This section provides an overview of key radar concepts for RAR applications in pit slope monitoring.

2.1 How radar works

Sharon & Eberhardt (2020) provide a detailed overview of how ground based radar works with regards to the basic components, displacement interferometry and phase measurement, as well as some information pertaining to measurement limitations and corrections. These topics, whilst referred to in these works, are considered beyond the scope of this paper.

In essence, the radar system, via the feed horn and parabolic antenna transmits and then receives sinusoidal waveforms of a specific frequency via a transceiver of the pit slope. Using interferometry (the direct comparison of two consecutive acquisitions), the phase shift of the wavelength is calculated for each data point. These data points, georeferenced in three-dimensional space, then have displacement data assigned to them, which in turn, forms what is called the synthetic map. The synthetic map is a point cloud, which represents all of the points scanned within the designated azimuth and elevation (referred to as a scan region).

Relative range is the total accumulated movement between the scan at the reference time or beginning of the database and the last scan. Relative range may also be known as deformation or displacement. Relative range is not time windowed as it is an accumulated measurement of pit slope movement, this may be reported in mm, cm or inches. Average velocity is calculated by dividing the total accumulated movement since the reference time or the beginning of the database by the allocated time window. This is a sliding scale and may be reported in mm/hr, cm/day and in/hr. Velocity delta is effectively a measure of acceleration or deceleration over the specified time window; it is reported in mm/hr, cm/day and in/hr.

2.2 Frequency selection

Kingsley & Quegan (1999) describe that radars utilise radio waves in the electromagnetic spectrum for which there is a discernible frequency applied. The relationship between the frequency f and the wavelength is λ is:

$$c = f\lambda \ [\mathrm{ms^{-1}}] \tag{1}$$

Where c is the velocity of light (approximately 3 x 10^8 $\mathrm{ms^{-1}}$) in air or space, f is the frequency (Hz = $\mathrm{s^{-1}}$) of an electromagnetic wave which is related to λ the wavelength. In the case of the MSR Modular system, the formula parameters are: f which has the selected frequency of between 9.5 and 10.0 GHz and the resultant wavelength λ, which is approximately 30 mm. When the wavelength is less than 1 cm, the term 'millimetric radar' is sometimes used to describe these systems.

2.3 Antenna gain and transmit power

The antenna gain (diameter or size) of a parabolic reflector antenna can be approximated by the proceeding formula:

$$G = 10\log_{10} k\left(\frac{\pi D}{\lambda}\right)^2 \tag{2}$$

G is the gain over an isotropic source in dB. k is the efficiency factor which is generally around 50% to 60%, i.e. 0.5 to 0.6. D is the diameter of the parabolic reflector in metres. λ is the wavelength of the signal in metres (www.electronics-notes.com).

This implies that the antenna gain for a 1.2 m diameter MSR antenna, at X-Band frequencies, is approximately 40 dB. This means that the energy going in the direction of the area of interest is approximately 10 000 times more than it would have been with an isotropic antenna. In addition, because the same antenna is used for receiving, the receiver is effectively 10 000 times more sensitive than an equivalent receiver utilising an isotropic antenna.

Figure 1 illustrates the MSR pencil beam radar showing the transmit and receive beam for an antenna with a parabolic reflector. The practical implication is that the same movement accuracy (which is dependent on the received signal to noise power ratio) can be achieved with much less transmit power than what a wide-beam antenna would require. This antenna gain can be achieved with a relatively small dish, as the wavelength is relatively shorter at the chosen X-Band frequency of operation. The parabolic antenna for the MSR system is responsible for first focusing, and then radiating and receiving the electromagnetic energy in the form of a pencil beam (refer to Figure 1). The beam width may be calculated based on the size of the antenna using this formula:

$$\text{Beamwidth } \Psi = \frac{70\lambda}{D} \tag{3}$$

D is the diameter of the parabolic reflector and λ is the wavelength of the signal (https://www.electronics-notes.com). The antenna gain (the diameter or size) of the MSR unit is 1.2 m, and has a beam width of 2°.

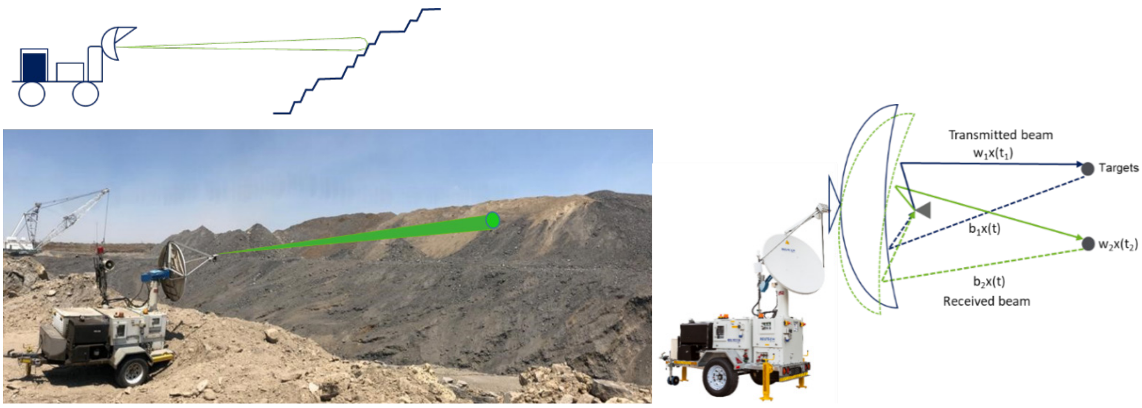

Figure 1. Illustration of the MSR pencil beam radar (left) showing the transmit and receive beam for an antenna with a parabolic reflector (right).

Practical considerations for the purpose of monitoring in a mining environment include: the size (gain) of the antenna, from a mounting perspective on the trailer (weight and stabilisation), the motors utilised for mechanically steering (size, wearability) and the effect of inclement weather (destabilisation of scan path due to wind speed etc.).

2.4 The concept of phase return

The echo from the target has a time-delay directly proportional to the distance from the radar. This time-delay is measured as a phase shift between transmitted and received signals.

In simple terms, if a reflective target is stable, then the phase registered by the radar for the reflected signal will be the same between two consecutive measurements. If a phase change is registered, then a movement of the target has occurred between the two acquisitions (not considering *n*), the magnitude of which can be calculated based on the phase delta, as illustrated in Figure 2.

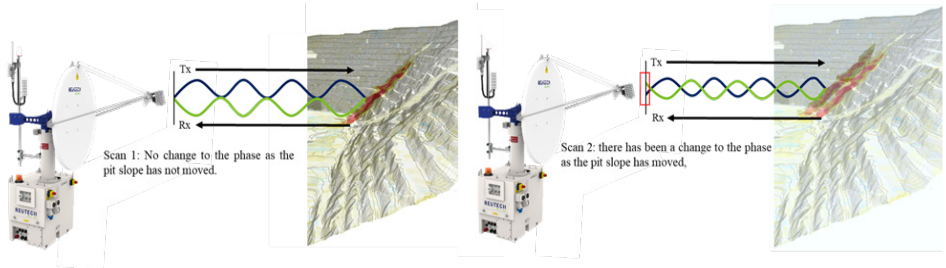

Figure 2. The transmitted (TX) and received (RX) signal is shown for two consecutive measurements, where there is no change (Scan 1 left), however, Scan 2 (right) illustrates a phase delta (outlined in red) which indicates change.

2.5 *The search pattern and formation of the synthetic map*

The parabolic antenna is mechanically steered in a predefined search pattern in order to generate the synthetic map. There is a number of key parameters that are required in order to collect the data to illustrate, deformation of the pit slope.

The radar works in spherical coordinates. The angular position is read from the rotary encoder of the mechanical system as the beam scans over the search area. An example of a search area, with information pertaining to the scan rate, scan line spacing and point data is provided in Figure 3.

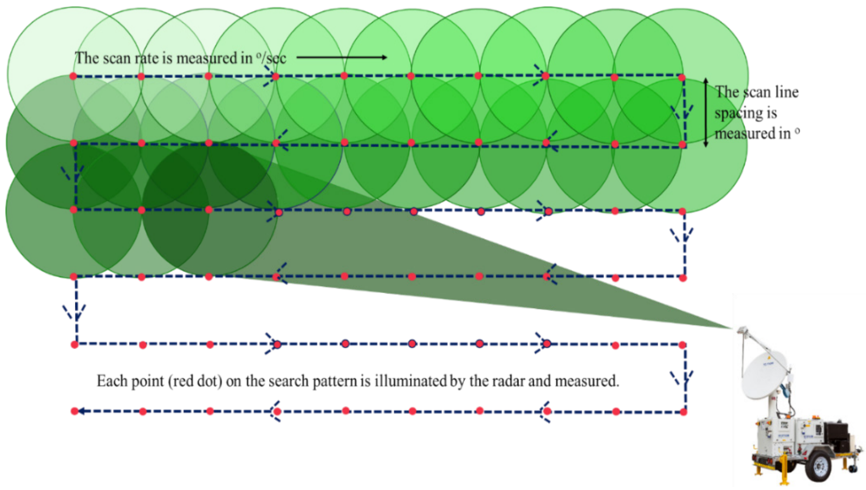

Figure 3. An example of a search pattern on a synthetic map for identifying a pit slope instability.

2.5.1 *Scan rate and scan line spacing*

The scan rate is measured by the number of degrees per second (°/sec) and describes the angular speed of the antenna as it collects point data on the azimuth plane of the search pattern (Figure 3). The assignment of the scan rate has a direct effect on the scan time or temporal resolution. The default value is utilised is 40°/sec.

The scan line spacing is measured in degrees (°) and describes the offset between the azimuth planes of the search pattern. Either 0.75° or 1.00° may be selected for the database upon deployment by the user (Figure 3). Tighter scan lines mean that the spatial resolution within the vertical or elevation direction is increased. This parameter can make the scan time faster (1.00°) or slightly slower (0.75°).

2.5.2 *Spatial resolution: point spacing*

As mentioned, a fixed point is illuminated and measured on the pit slope for successive interferometric measurement. Having an antenna design that is highly directional in azimuth and elevation is beneficial as it can resolve a targets position in three-dimensional space. The resolution is restricted to the antenna beam width on the pit slope, which is 2°. This is a constant and does not change. The user defines the azimuth and elevation degree step and therefore the apparent spatial resolution of the synthetic map. A larger degree step for both parameters results in a larger resolution, therefore a larger distance offset between measured points. The greater the distance between the radar and the pit slope (target), the greater the point spacing. This is due to the fact that the beam footprint becomes larger, the further away the slope.

2.5.3 Temporal resolution

Temporal resolution is defined as the amount of time required for the radar to sample and resample the phase offset being collected from the pit slope from the exact same location for interferometric measurement (Théau, 2008).

3 EXAMPLE DATABASE PARAMETERS, RESULTANT SYNTHETIC MAPS AND ASSOCIATED TREND PLOTS

Two examples (A and B) are detailed in Table 1 and are illustrated in Figure 4, whereby the horizontal and vertical degree step, scanline spacing, azimuth and elevation (region size) and the distance to the pit slope are varied. This is to show the effect on the resultant spatial and temporal resolution. Increasing the spatial resolution (making the degree step smaller) results in a denser point cloud and synthetic map, which assists in defining the:

- Attributes of the movement mechanics of the pit slope; such as the response to excavation, dewatering or depressurisation activities, active instability and post collapse behavior.
- Categorisation and interpretation of displacement (movement stages and pattern types which are typically inhomogeneous over the unstable area) and the speed of accumulation.
- To determine the size of an instability, the potential volume of the collapse material and possible run-out distance.

Of importance is the temporal resolution over the period of an active instability (summarised and discussed from Shellam & Coggan 2020), in order to ensure that, inter alia:

- The chance of phase ambiguity is reduced (when the phase is wrapped and the true movement direction or magnitude cannot be resolved).
- To accurately capture the full movement profile of the instability (the faster it moves the harder this becomes).
- Shorter acceleration times leading to collapse are captured.
- To allow for a high update rate which in turn ensures alarm thresholds are triggered so that the trigger action response plan (TARP) may be followed.
- To aid with collapse forecasting.
- To assist with operational control and mitigation of the instability, or identified hazardous area/s.

4 CONCLUSIONS

An introduction to some of the concepts pertaining to real aperture radars for the MSR systems are explained. Two examples of how certain parameters may affect the spatial and temporal resolution of the database, the resultant synthetic map and the trend plots utilised for assessment and analysis of the slope condition were provided.

Table 1. Parameter selection for two database setup examples.

Parameter		Example A	Example B
Degree step: horizontal spacing	(°)	0.25	0.50
Degree step: elevation spacing	(°)	0.025	0.75
Scan speed	(°/sec)	40	40
Scanline spacing	(°)	0.75	1.00
Azimuth region size	(°)	120	90
Elevation region size	(°)	60	45
Range to the pit slope	(m)	1 000	3 000
Horizontal point spacing/resultant resolution	(m)	4.4	26.2
Elevation point spacing/resultant resolution	(m)	0.4	39.3
Scan time	(minutes:seconds)	02:51	01:37

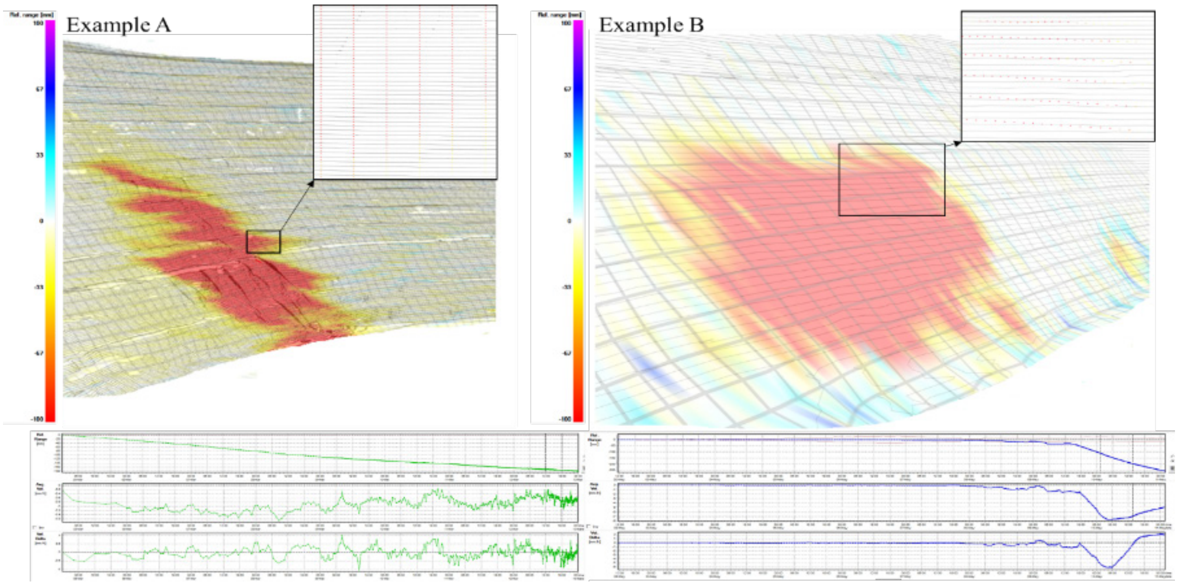

Figure 4. Examples A and B showing instabilities on the pit slope, the resolution (point spacing) selected for the synthetic map and the trend plots for the relative range, average velocity and velocity delta data.

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