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Accumulated movement data and the amplitude dispersion index: a collation alarm

S Coetsee *Reutech Mining, South Africa*

N Greyling *Reutech Mining, South Africa*

P Narshai *Reutech Mining, South Africa*

Abstract

When the return (amplitude and phase) of the electromagnetic signal transmitted and received by the radar antenna for a specific scatterer for the selected resolution is deemed poor quality, a number of processes are set in motion to inform the user that the data for that point or points have lost integrity in the form of bad flags.

This may be due to the fact that the scatterer properties have changed sufficiently enough to not be able to provide a strong and stable enough return. The scatterer may have moved significantly in three-dimensional space, or the speed at which the scatterer is moving has met and exceeded the phase limit between consecutive scans. The phase limit is determined by the frequency or wavelength utilised by the system, onsite atmospherics, the scan time and the speed at which the pit slope is deforming.

If scatterer points on the pit slope cannot be measured consistently during instability, the ability for the system to alarm, based on user selected movement or velocity thresholds, is compromised. These measurement values are dependent on the correct derivation of the true movement from the full phase shift between consecutive scans.

This paper discusses the concept of scatterer identification, tracking and the qualification of the consistency of the phase return for movement data accumulation, in collation with the amplitude dispersion index (ADI) for pit slope monitoring purposes.

The collation alarm is a representation of both the accumulated movement up until the point whereby the integrity of the scatterer is flagged, and the ADI for a selected area threshold is compromised. This alarm informs the user that the slope is either deforming considerably from a dimensional perspective, or that the pit slope is in an ambiguous state of movement.

Keywords: *scatterer, resolution, ADI, phase limit, slope monitoring*

1 Introduction

Any radar sensor has a maximum value for which the true movement of a pit slope can be measured between consecutive scans. Phase ambiguity is the maximum phase shift limit between consecutive scans for a specified frequency and wavelength (Sharon & Eberhardt 2020). This is dependent on the frequency used by the sensor. Once the phase change limit has been reached, data integrity is compromised (Sharon 2020). This is called phase ambiguity; a phenomenon whereby the sensor does not know whether the phase vector rotated in a clockwise or anti-clockwise direction to reach the received position or has done multiple revolutions (2*pi*k, where k is an integer number and is the number of revolutions of 360° that the phase completed). This means it is uncertain if the target moved away from or closer to the sensor and the measurement therefore is ambiguous (+-2*pi*k) (bear in mind different sensors have different negative and positive movement direction conventions).

Phase ambiguity can be caused by two scenarios:

1. Genuine movement of the slope due to instability which results in either dimensional changes of the measured points or targets on the pit slope or targets exceeding the detection capability of the sensor (a function of frequency and scan time).
2. When the atmospheric contribution cannot be resolved and is added to the true movement data, therefore the movement data is recorded as more than it should be.

These two factors require complex and diverse resolving methodologies in order to ensure that phase ambiguity does not occur. In this scenario, the pit slope is deforming, true movement needs to be accumulated and the atmospheric effects need to be removed. Here lies the greatest challenge: the accurate removal of atmospherics effects on the measured phase shift of the received signal.

Whilst the phase is affected by atmospherics, the amplitude dispersion index (ADI) is not, thus the ADI is used in the determination of dominant scatterers per range bin, which is a fixed measurement interval at the face of the pit slope (Kingsley & Quegan 1999). A valid target or scatterer is a strong reflection point on the pit slope for which measurement is taken in the form of point data. This point data is part of a larger three-dimensional (azimuth, elevation, and range) synthetic map which illustrates line of sight movement (negative and positive) over the scanned area of a pit slope in the direction of the radar. When a scatterer reflection is of poor quality compared to previous scans, it is flagged (bad flag) in order to inform the user that the data from that specific point on the pit slope may be compromised. Bad flags, in conjunction with other movement measurement concepts such as relative range (the total accumulated movement between the scan at the reference time or beginning of the database and the last scan), average velocity, velocity delta, inverse velocity, and coherence can be utilised in order to identify potential instability and to track progression thereof.

An example of an instability is provided in Figures 1, 2 and 3 which illustrate three specific time periods. The images on the left show the points with bad flags in red where no more movement can be accumulated as long as the ‘bad flag’ condition persists. The synthetic maps (images on the right) provide the relative range movement data and are representative of the time period indicated on the trend plot.

Figure 1 shows the instability as it starts to develop, Figure 2 indicates an acceleration of the instability and Figure 3 is right at the point whereby the physical movement has exceeded the maximum measurement capabilities of the sensor.

The movement data is compromised and is not accumulated anymore, however, the instability has not yet collapsed. It is at this point that the user needs to be informed that the ability of the system to alarm based on user selected movement or velocity thresholds is compromised. Thus, the collation alarm was developed and the theory behind its formulation is discussed.

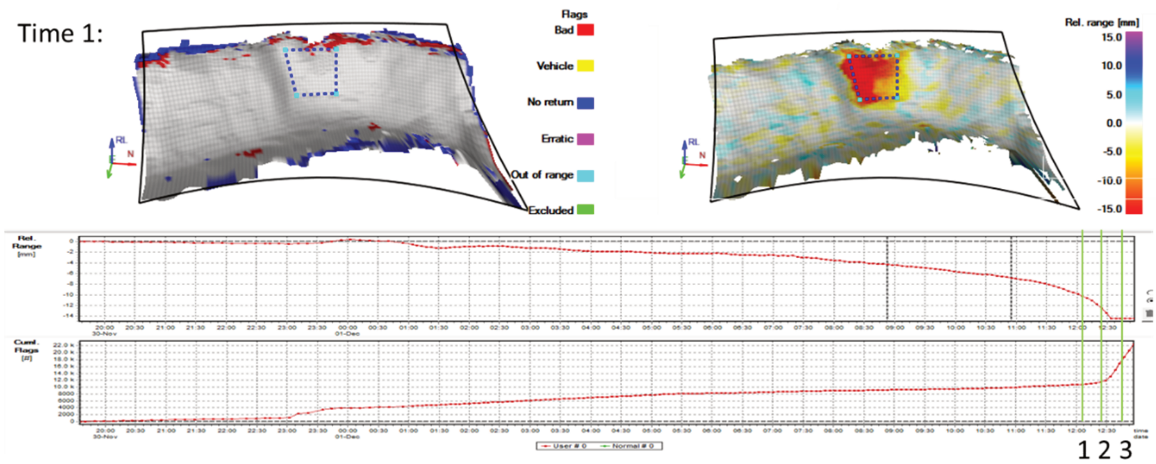


Figure 1 Example of an instability, bad flags, and relative range for Time 1

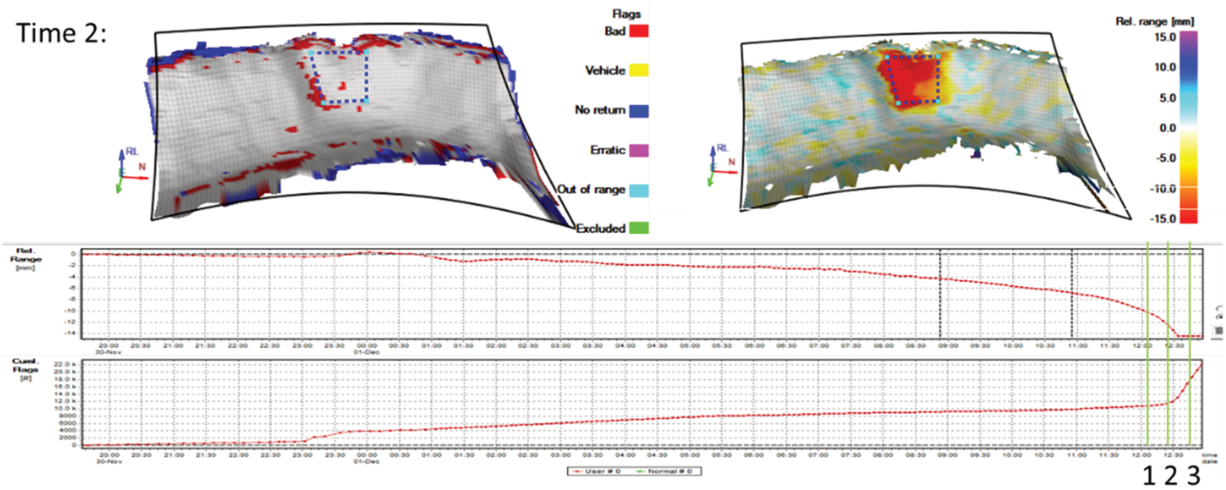


Figure 2 Example of an instability, bad flags, and relative range for Time 2

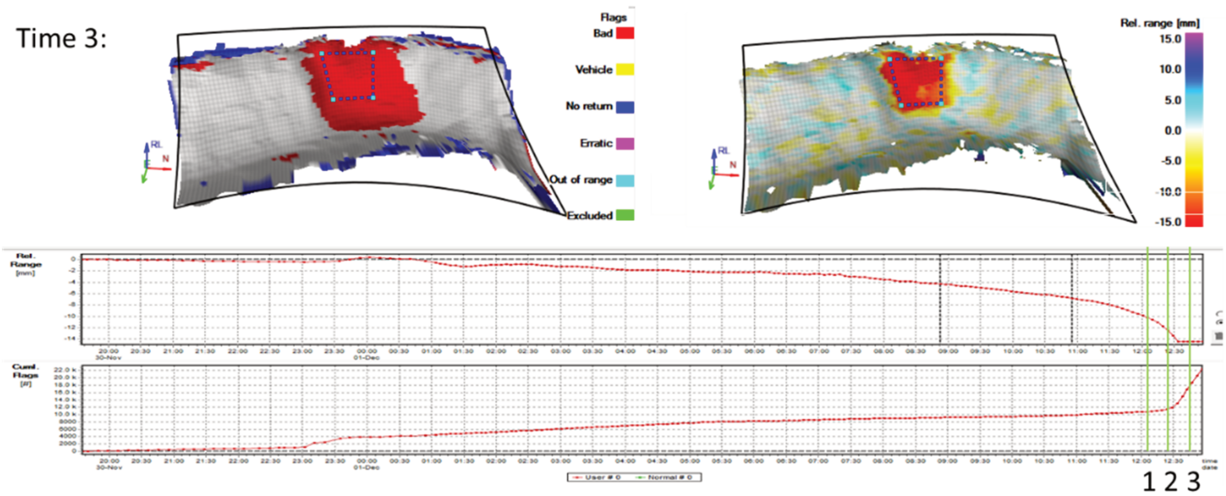


Figure 3 Example of an instability, bad flags, and relative range for Time 3

2 Scatterer selection and amplitude dispersion index

A valid target or scatterer selection requires a number of procedures in order to ascertain if the measurement data being collected for that point on the pit slope is valid or not.

A scatterer is a point that is displayed to the user as an artificial pixel or can be thought of as the actual resolution of the radar sensor which is selected at the time of the compilation of the database for that specific scan area.

All radars use different criteria to determine if a scan point is a valid return or not, however, the principal remains fairly consistent between sensors. If the scatterer stays consistent, the radar will identify that area or representative point as a good scatterer. If there is a return and it is not consistent, it is classified as 'bad' and is flagged (bad flag). A scatterer can intermittently be classified as good or bad.

If the scatterer identification technique is too stringent, true pit slope movement can be classified as false movement and will not be included in movement trend plots. This might lead to slope instability being unidentified or misrepresented in that the true movement component is not illustrated as it may be undercompensated as too many of the points in the area of the instability are flagged and not utilised.

If the scatterer identification technique is not stringent enough, false movement is included in the accumulated movement trend plots such as relative range, which leads to false alarms which also apply to the average velocity, velocity delta, and inverse velocity as they are derivatives of relative range.

Multiple targets can be tracked in a single beam by the radar, at fixed distance intervals called range bins. An easy way to think of a radar is thinking in terms of a ruler (Figure 4); the centimetre markings are the range bins. Within each of these centimetre markings or range bins, the radar can track a single scatterer. Scatterers in the range bin do not contribute to the range resolution; they are there to track if an object is moving. On the image, the green arrows indicate what is called a dominant scatterer for that particular range bin. This is the scatterer with the highest quality return and therefore represents the point being tracked for that range bin (or a combination of scatterers in the range bin).

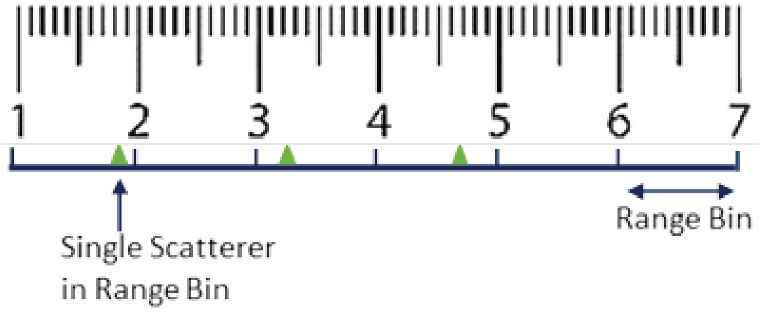


Figure 4 Example of range bins and scatterer selection

The dominant scatterer per range bin is tracked using the ADI as well as the phase delta using the interferometry method (Kingsley & Quegan 1999). The concern with phase is that there can be atmospheric interference, however, the atmosphere cannot influence the ADI (except in very extreme conditions such as ultra-heavy rain or snow fall). If there is not a lot of deviation of the ADI and it remains constant over a specific rolling time window, it can be classified as a good return; the opposite if there is significant deviation or variability.

Figure 5 illustrates a schematic pit slope for which a light green circle shows the beam of the radar antenna on the slope and the black dot represents the strongest scatterer for that specific range bin. Figure 6 shows the same slope with the radar antenna illuminating the same part of the slope but post-instability. The light green circle is in the same range bin as the previous image and the dark green circle will be in another range bin. In the light green circle is a black dot that represents the strongest return post-movement. The strongest return has moved up and left in comparison from where it previously was. Also notice in the dark green circle is a blue dot indicating the strongest return being tracked for that beam.

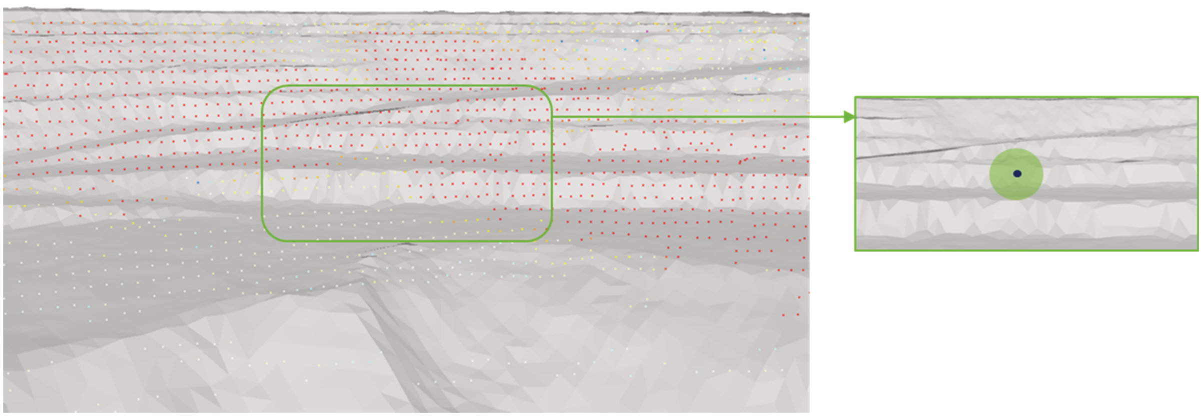


Figure 5 Example of a pit slope, the range resolution, and a dominant scatterer prior to instability

Where there is an instability and an existing scatterer at a specific antenna position disappears, the new scatterer becomes the dominant scatterer. The dominant scatterer at the new position (light green circle) causes complications for continuously tracking movement over time. Although the new scatterer is in the same range bin, the phase can be different resulting in false movement accumulation. The scatter may therefore have moved considerably in three-dimensional space as the instability is progressing.

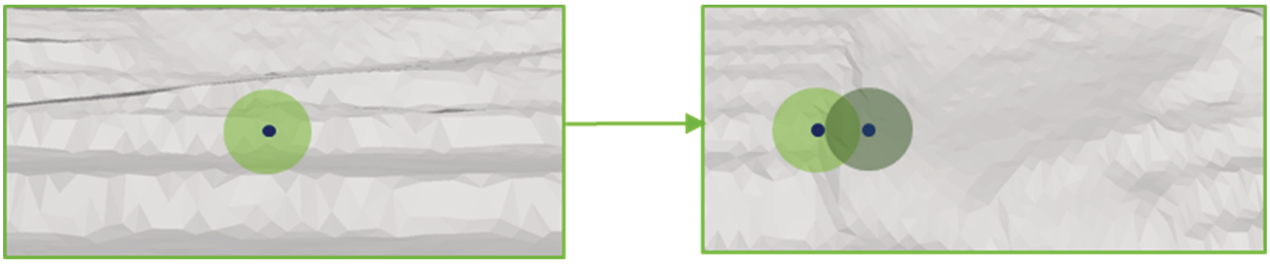


Figure 6 Example of a pit slope, the range resolution, and a dominant scatterer post instability

Another scenario is where scatterer detection might be a problem, such as when an instability is occurring faster than what a radar can reliably track (Figure 7). It cannot be tracked by the sensor as the maximum phase delta measurable between consecutive scans has been exceeded, and phase ambiguity is likely.

It is from this point of departure that the sensor can no longer track the movement of the pit slope effectively and that additional alarming criteria are required in order to inform the user of ominous movement.

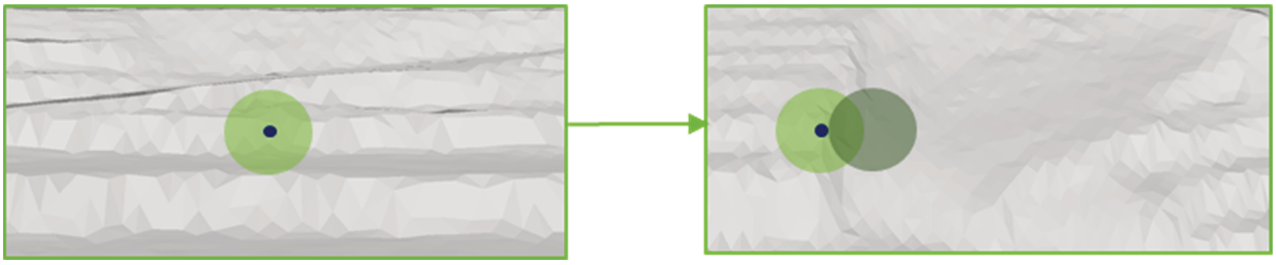


Figure 7 Example of a pit slope, the range resolution, and a dominant scatterer that has not been assigned

3 The concept of area threshold

The resolution of the beam width on the pit slope is defined by the user whilst setting up the scan database attributes. The degree step of the antenna is selected for both the azimuth and elevation. The resolution is therefore a function of the degree step and the distance between the sensor and the pit slope. The further the distance, the larger the beam footprint and aerial coverage of a resolution cell.

The area threshold can represent the smallest instability size, which is typically one bench in height, however, this should be decided in relation with the geotechnical conditions on site and the anticipated mode of failure.

When the area threshold is enabled, an alarm will be triggered when any area threshold configuration within a normal or height threat region exceeds the movement threshold, on average for the relative range, average velocity, and velocity delta alarms. The collation alarm is dependent on the percentage value selected for the bad flag and movement component (refer to Section 4).

Table 1 provides an example of the resolution for different spacing options at various distances to the pit slope.

Figures 8 and 9 show two different databases, each with their own unique attributes and distance to the pit slope. The worked examples illustrate the relationship between the distance, the degree step and then the resolution of the point spacing for the azimuth and elevation.

As the degree step values are adjusted between the examples, the resolution of the points is different in width and height which affects the combination of points used to calculate an area threshold. This is an important factor to take into consideration as the sensitivity of all alarms is based on the number of points and the physical area on the face.

Using a large area threshold means a larger area must move, before the alarm is triggered. However, if only a small area is moving, it will have to move significantly more than the alarm thresholds before the average of the whole area will trigger the alarm, so the alarm may be delayed. Using a smaller area provides an alarm that is more sensitive to small areas moving, but it can also result in more false alarms.

Table 1 Degree step and resultant resolution for various distances to the pit slope from the sensor

Degree step: azimuth	Metres from the pit slope (m)		Degree step: elevation	Metres from the pit slope (m)	
	100	1,200		100	1,200
0.25°	0.4	5.2	0.0250°	0.1	0.5
0.33°	0.6	6.9	0.0375°	0.1	0.8
0.50°	0.9	10.5	0.0500°	0.1	1
0.75°	1.3	15.7	0.0750°	0.1	1.6
1.00°	1.7	20.9	0.2500°	0.4	5.2
2.50°	4.4	52.4	0.7500°	1.3	15.7

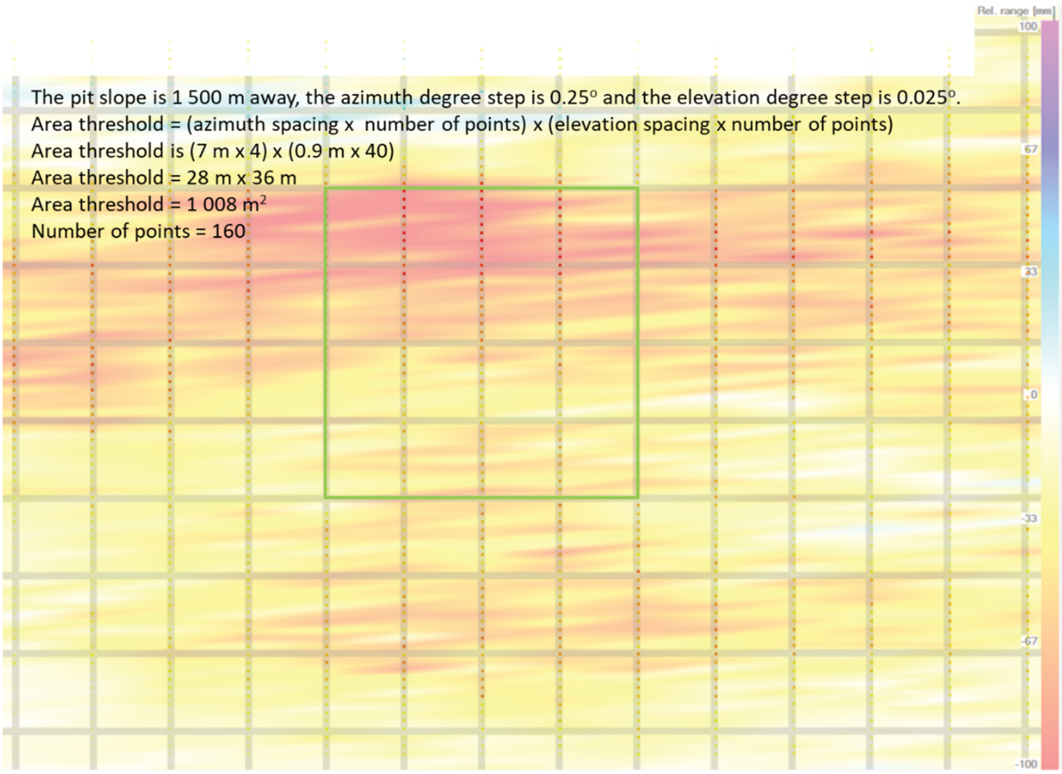


Figure 8 Example of the area threshold for an instability

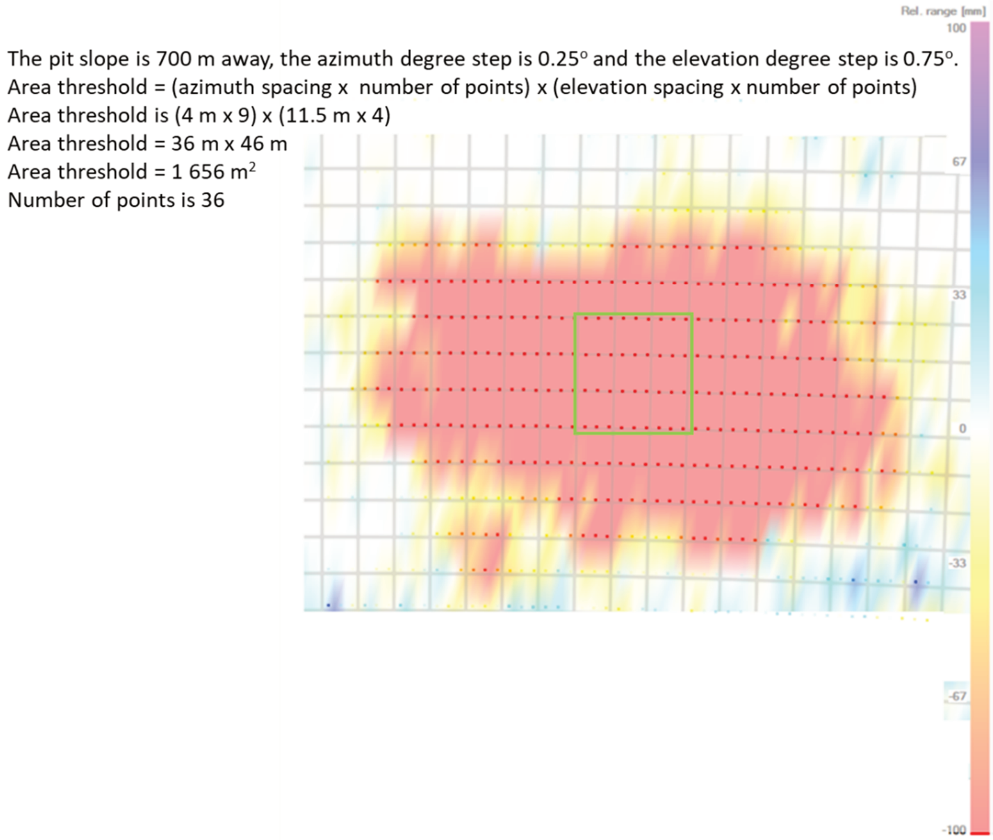


Figure 9 Example of the area threshold for an instability

4 The collation alarm

The collation alarm is a representation of both the accumulated movement up until the point whereby the integrity of the scatterer is flagged, and the ADI for a selected area threshold is compromised. This alarm informs the user that the slope is deforming considerably from a dimensional perspective (from defined bad flags) and that phase information cannot reliably be used to track movement, but movement is likely to continue and the user should pay particular attention to the data being collected.

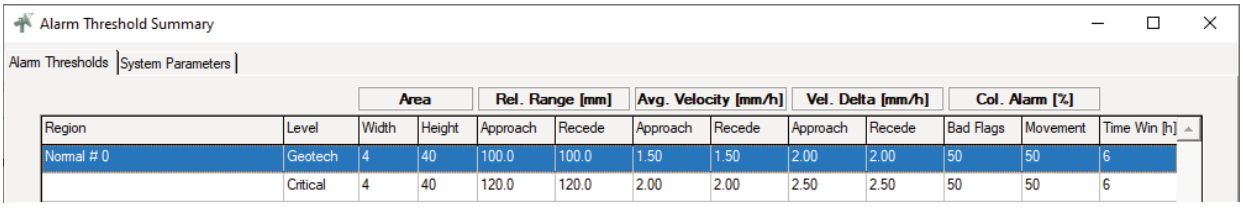
The collation alarm notifies the user that the maximum measurement capabilities of the sensor have been reached and that operational controls are required.

An example of the alarm threshold page and the collation alarm settings are presented in Figure 10. An example is provided:

- If all of the predefined parameters are exceeded, an alarm will be triggered and communicated to the user.
- Before a collation alarm is triggered, both the bad flags area threshold percentage and the percentage of movement needs to be met and exceeded as part of the procedure to meet the collation alarm criteria.
- The bad flags are scan points for which the sensor has deemed unreliable due to inconsistent returns caused by slope deformation.
- The movement threshold is based on relative range, average velocity, and velocity delta settings.
- In this example, the area threshold* of four scan points in azimuth and 40 in elevation is set, which is an alarming area with 160 scan points in total.

- Remember, the area threshold is a function of the resolution selected for the database and the distance between the sensor and the pit slope.
- The % bad flags parameter was set at 50%, thus, 50% of the 160 (80) scan points within the area threshold need to be demarcated as bad in order for the criteria to be met.
- The % movement parameter was set at 50%, thus, 50% of the 160 (80) scan points within the area threshold need to have met and exceeded the movement criteria.
- The % movement is set to 50% of the relative range geotechnical alarm which is applied at 100 mm. Multiplying the relative range by 50% implies 50 mm of total movement for the alarming area which has to be achieved in order for a collation alarm to trigger.
- In summary, if 50 mm of relative range movement is achieved and half of the alarming area is allocated as bad flags, a collation alarm will trigger.
- The same theory would apply to the average velocity and velocity delta alarms.
- The collation alarm will trigger on the relative range, average velocity or velocity delta thresholds in the order in which they are exceeded.

*The area threshold is a selected number of azimuth and elevation points which represent the height and width in metres measured on the synthetic map. The area threshold is a function of the degree step selected for the specific database in use and the distance between the sensor and the pit slope. The algorithms check every possible overlay combination of the area threshold. It is not a stationary side-by-side set area.


Alarm Threshold Summary

Alarm Thresholds | System Parameters

		Area		Rel. Range [mm]		Avg. Velocity [mm/h]		Vel. Delta [mm/h]		Col. Alarm [%]		
Region	Level	Width	Height	Approach	Recede	Approach	Recede	Approach	Recede	Bad Flags	Movement	Time Win [h]
Normal # 0	Geotech	4	40	100.0	100.0	1.50	1.50	2.00	2.00	50	50	6
	Critical	4	40	120.0	120.0	2.00	2.00	2.50	2.50	50	50	6

Figure 10 Example of the alarm threshold page and the collation alarm settings

The amplitude of the full scan area and the area of concern is provided. Figures 11, 12, 13 and 14 detail the amplitude, bad flags and the relative range, average velocity and the velocity delta synthetic maps respectively. The collation alarm is indicated over the portion of the instability which has met and exceeded the collation alarm percentage values enabled by the user.

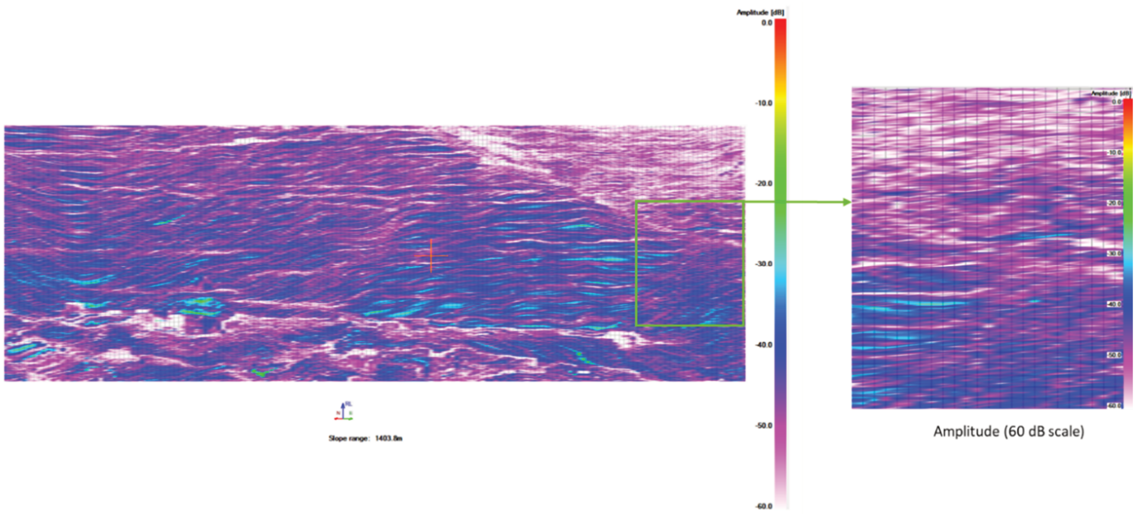


Figure 11 The amplitude for the scan area and the area of concern highlighted on the right

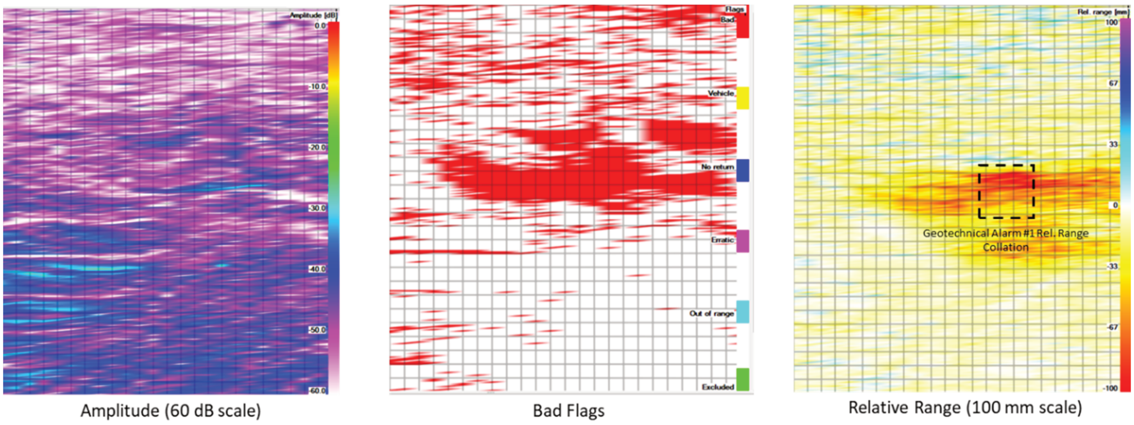


Figure 12 **Illustrative example of the amplitude, bad flags, and relative range synthetic map which illustrates a relative range collation alarm over the portion of the most accumulated movement and bad flag combination for the percentage set enabled by the user**

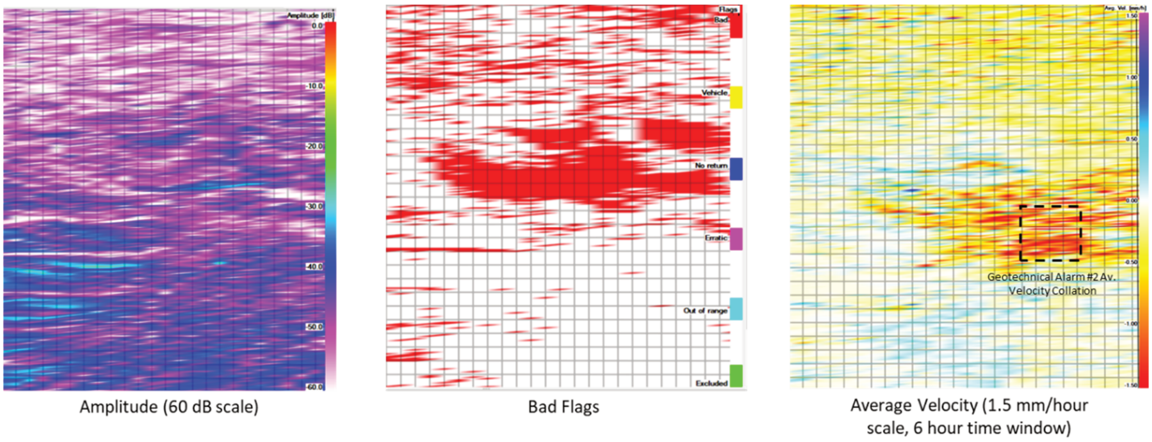


Figure 13 **Illustrative example of the amplitude, bad flags, and average velocity synthetic map which illustrates a relative range collation alarm over the portion of the highest velocity (negative, towards the sensor) and bad flag combination for the percentage set enabled by the user**

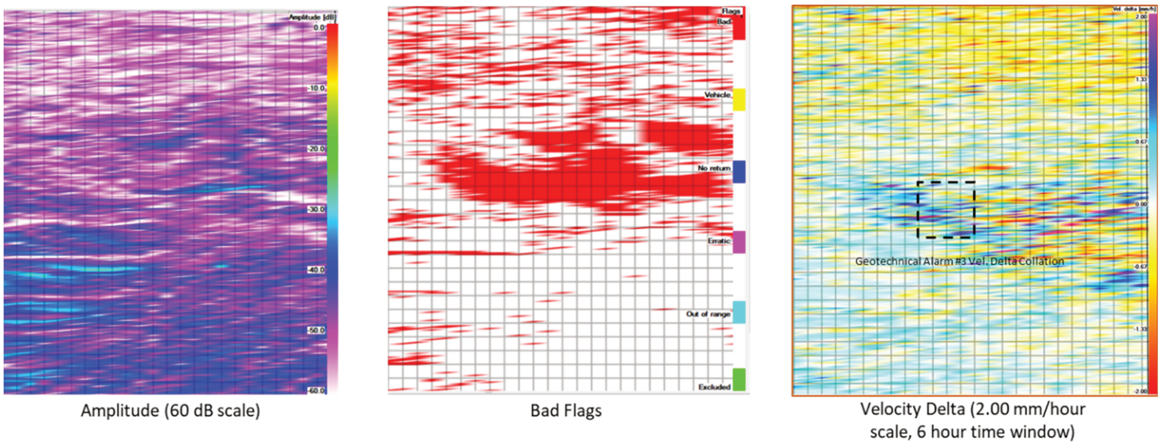


Figure 14 **Illustrative example of the amplitude, bad flags, and velocity delta synthetic map which illustrates a relative range collation alarm over the portion of the highest velocity (positive, away from the sensor) and bad flag combination for the percentage set enabled by the user**

The relative range, average velocity and velocity delta trend plots are shown in Figure 12 for the instability example utilised. The relative range shows a linear or slightly bi-linear movement pattern (Sullivan 2007).

The average velocity and velocity delta trend plots display acceleration and deceleration cycles which are specific to the encapsulated unstable area. In this case, there was no collapse, only linear movement until later stabilisation which is not illustrated in these trends.

The temperature and refractivity plots display the diurnal fluctuations of the atmosphere measured at the sensor. It is possible to see that the refractivity, measured in parts per million (ppm), does not exceed more than 1 ppm for the 2 minute 17 second scan time for the whole scan region (4,290,000 m^2, refer to Figure 11).

The trend plot in Figure 15 shows a linear to bi-linear relative range trend plot to a scale of 250 mm of negative movement (towards the sensor) for the unstable portion of the slope. Figure 16 displays the variability of the scale of deformation taking place over the area of instability for three selected points. The trend plots in Figure 17 represents much more detailed movement patterns, as the points represent the single dominant scatterer for that range bin for that beam resolution on the pit slope. It can be seen that the relative range trend plot illustrates linear (P#1), bi-linear (P#2), as well as some potential stick-slip patterns (P#3). It is important to note that the instability is not moving in a homogenous fashion, rather, parts of the face are moving at differential accumulated movement and therefore at varied speed and acceleration and deceleration profiles. It is this information that becomes paramount to detecting and understanding the type of displacement occurring which may in turn indicate the failure mode, as well as if key blocks are becoming unstable prior to the full mass of the sliding area collapses.

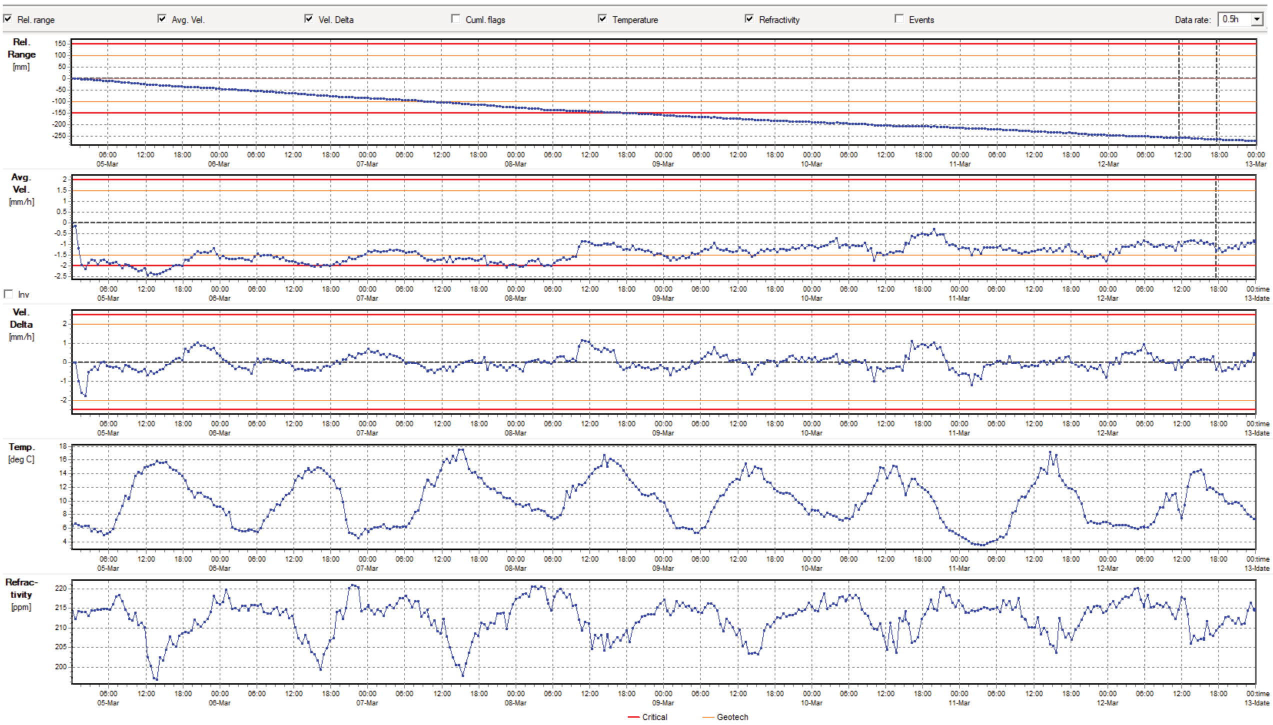


Figure 15 Relative range, average velocity, and velocity delta trend plots along with the temperature and refractivity plots are illustrated for the instability example utilised

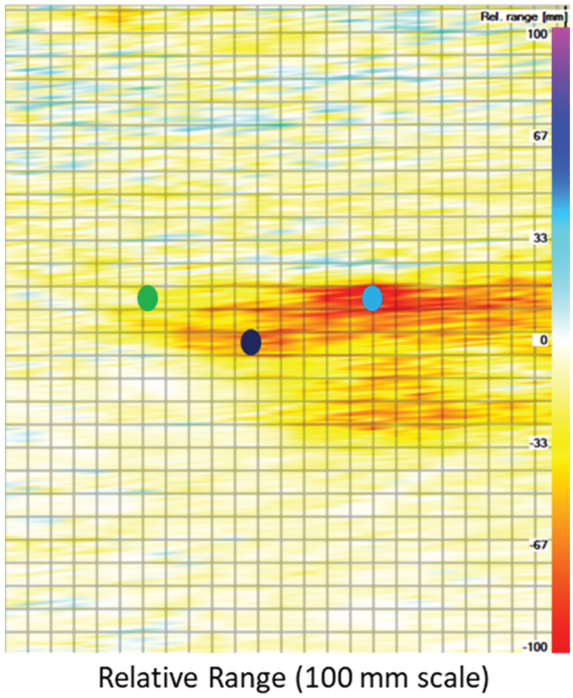


Figure 16 Relative range synthetic map showing differential movement dependent on where on the instability the points were selected (P#1 green, P#2 dark blue and P#3 light blue)

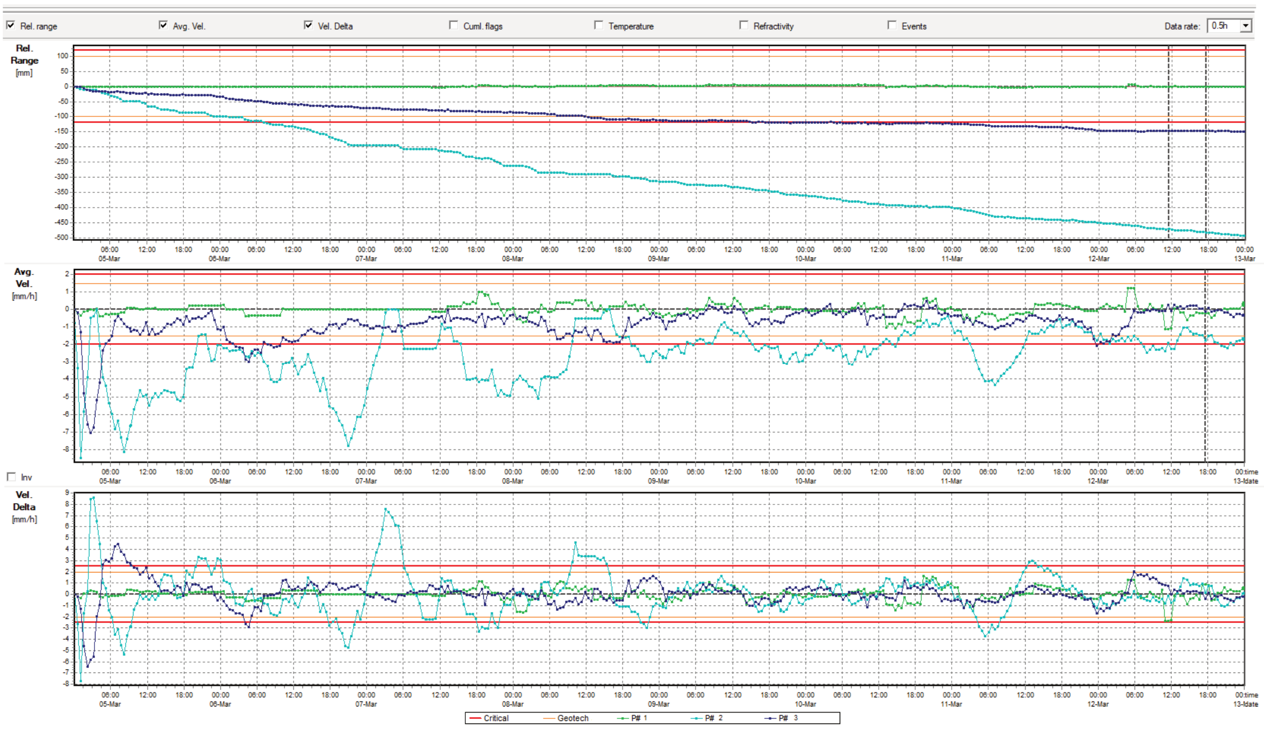


Figure 17 Relative range, average velocity, and velocity delta trend plots which show highly differential movement dependent on where on the instability the points were selected

5 Conclusion

The concepts of scatterer identification, tracking, and the qualification of the consistency of the phase and amplitude return for movement data accumulation, in collation with the ADI for alarm generation, was illustrated by means of a theoretical example.

The collation alarm is a representation of both the accumulated movement up until the point whereby the integrity of the scatterer is flagged, and the ADI points for a selected area threshold are significantly different (which is a function of the distance to the pit slope and the degree step selected which defines the resolution). This alarm informs the user that the slope is either deforming considerably from a dimensional perspective, or that the pit slope is in an ambiguous state of movement.

This allows the user to be informed when there is potential ongoing slope deformation on portions of the pit slope for which the radar data integrity has been compromised due to substantial amounts of movement (phase ambiguity is likely), or when the quality of the dominant scatterer in the range bin has been compromised.

Regardless of the movement stage, restricted access, or evacuation standard operation procedures need to be effected in order to manage the risk at hand, both in terms of the likelihood and consequence of the potential event.

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