

# Automatic multi-stage slow movement analysis for early warning monitoring systems for surface mining

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## Abstract

*The development of processing techniques for radar monitoring data has significantly aided geotechnical practitioners in managing slope stability risks, especially when the radar system operates in real-time. Notable improvements have been made to address weather conditions and understand velocity behaviour to predict slope failure once the velocity measured on the slope becomes evident, using a real-time radar-based system.*

*Real-time radar monitoring using interferometry principles has limitations regarding measurable velocities. The maximum measurable velocity is typically constrained by phase ambiguity, mainly due to the radar frequency and the minimum time between scans. In the lower band, the minimum measurable velocity is limited by the instrument's precision.*

*This work aims to establish a system that enables geotechnical practitioners to monitor the behaviour of low-velocity ranges using different calculation periods for slow movement analysis, in a practical and automatic manner. This approach detects potential slope failures with minimal displacement rates, enhancing control effectiveness and operational continuity. Geotechnical engineers can inform potential slope stability issues significantly earlier compared to real-time systems for ground-based radars.*

*The new approach, called automatic multi-stage slow movement analysis, captures different ranges of lower band velocities. It automates data visualisation in parallel with real-time monitoring to detect displacement from natural slope deconfinement processes to initial indications of potential failures. This work details the pilot, methodology, and testing – using actual cases within BHP operations – highlighting the benefits of understanding initial slope deformations that are typically undetectable using real-time settings.*

**Keywords:** *monitoring automation, geotechnical monitoring system, slow movement analysis, slope performance, geotechnical monitoring, monitoring integration, ground-based radar, thresholds, interferometry*

## 1 Introduction

In recent years, the application of slow movement analysis (SMA) has emerged as a critical enhancement to conventional real-time slope monitoring systems in open pit mining in addition to the known and well established real-time monitoring systems (Shilov & Tovey 2025; Tovey et al. 2023). SMA enables the detection of low-velocity ground deformations – often in the range of millimetres per month – that typically fall below the sensitivity threshold of real-time ground-based radar systems. These subtle movements, while not immediately hazardous, can serve as early indicators of progressive slope failure, offering valuable lead time for risk mitigation and operational planning (Crouse & Wines 2016; Yang et al. 2011; Lowry et al. 2013).

Despite its proven value, the current implementation of SMA remains largely manual and retrospective. As demonstrated in multiple case studies (e.g. Peryoga et al. 2023; Calderon & Barnes 2025; Michelini et al.

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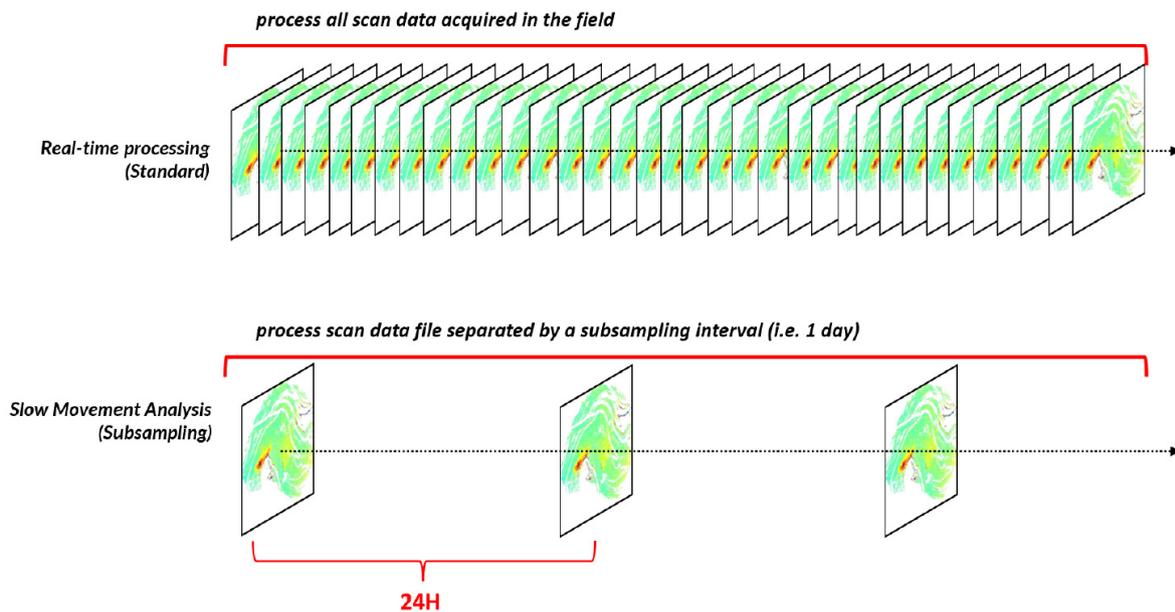
2015), SMA requires the post-processing of radar data using extended time intervals, often in parallel to real-time systems. This process is time-consuming, resource-intensive, and impractical to scale across multiple monitoring areas or operations. Consequently, SMA is often underutilised or only applied reactively after signs of instability have already emerged.

This research addresses the critical need for a more efficient and scalable approach by proposing the development and implementation of an automated SMA system. The proposed system integrates multiple time intervals for sub-sampling and enables live visualisation alongside real-time radar data. By automating the detection of low displacement rates and embedding SMA outputs directly into operational monitoring workflows, this approach aims to eliminate the need for parallel manual processing.

The ultimate goal is to empower geotechnical practitioners with a predictive monitoring tool that enhances early warning capabilities without increasing operational complexity. By bridging the gap between real-time monitoring and long-term deformation analysis, the automated SMA system offers a practical and proactive solution for improving slope failure predictability – potentially providing weeks to months of additional lead time, as evidenced in prior studies.

### 1.1 What is slow movement analysis?

SMA is a post-processing method that calculates cumulative displacement from radar scans over user-defined intervals – typically 24 hours, 72 hours, or longer. By increasing the duration between analysed scans, SMA allows for minor displacements (e.g. in the order of 0.1 mm) to accumulate and exceed detection thresholds, thereby becoming visible within the monitoring system (Figure 1). This method complements real-time monitoring by capturing low-velocity slope deformations indicative of deeper or broader geomechanical trends.



**Figure 1 Sub-sampling process in ground-based radars (IDS slow movement analysis training course [IDS Georadar 2018])**

### 1.2 Benefits of slow movement analysis

The implementation of SMA provides several critical advantages in slope monitoring:

- Early detection of subtle movements: SMA enables the identification of slow, progressive displacements that may be precursors to larger-scale failures.

- Enhanced risk management: by detecting movements earlier, SMA supports the implementation of preventive measures before displacements reach critical thresholds.
- Holistic monitoring: SMA contributes to a more complete deformation profile by supplementing high-temporal-resolution data from real-time analysis with low-velocity movement trends.

## 2 Methodology

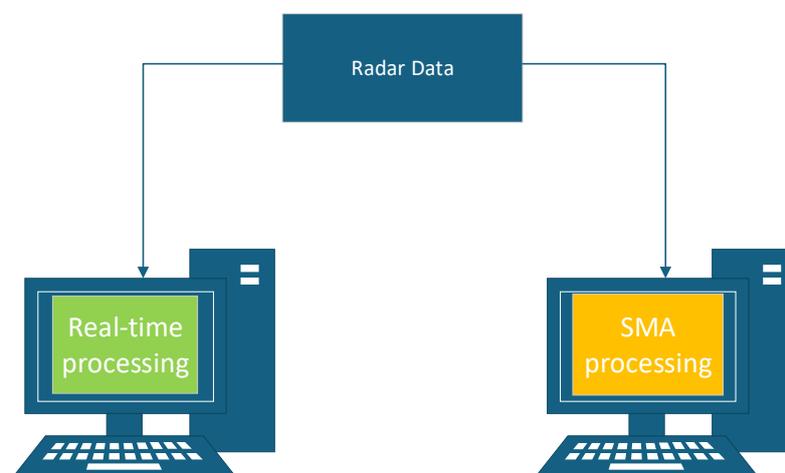
The implementation of an automated SMA system represents a pivotal advancement in geotechnical monitoring, aiming to bridge the gap between real-time radar surveillance and long-term deformation trend analysis. This methodology outlines the development of a fully integrated SMA framework capable of executing simultaneous real-time and multi-scale processing, without the need for additional infrastructure such as external PCs or virtual machines. By leveraging recent advancements in radar software architecture, the system enables the automated generation of SMA outputs across 3 discrete temporal resolutions – 24 hours, 3 days, and 5 days – selected based on optimal interval studies conducted by Calderon & Barnes (2025) using historical datasets from WAIO operations. This approach not only reduces manual intervention and processing time but also ensures a consistent and interpretable output format. Centralised data access and enhanced visualisation tools further streamline the user experience, allowing geotechnical practitioners to access both real-time and SMA insights through a unified interface. The following sections detail the system architecture, time interval selection rationale, and the integration strategy for live SMA visualisation alongside conventional monitoring workflows.

### 2.1 Historical approach to slow movement analysis

Historically, SMA was a manual and resource-intensive process. Operators first processed real-time radar data and then duplicated and reprocessed it manually to extract slow movement trends. This method had several limitations:

- time-consuming operations
- requirement for dedicated hardware or virtual machines (VMs)
- need for additional software licenses
- complex workflows that limited frequency and consistency of SMA analysis.

A diagram of the historical SMA approach is shown in Figure 2



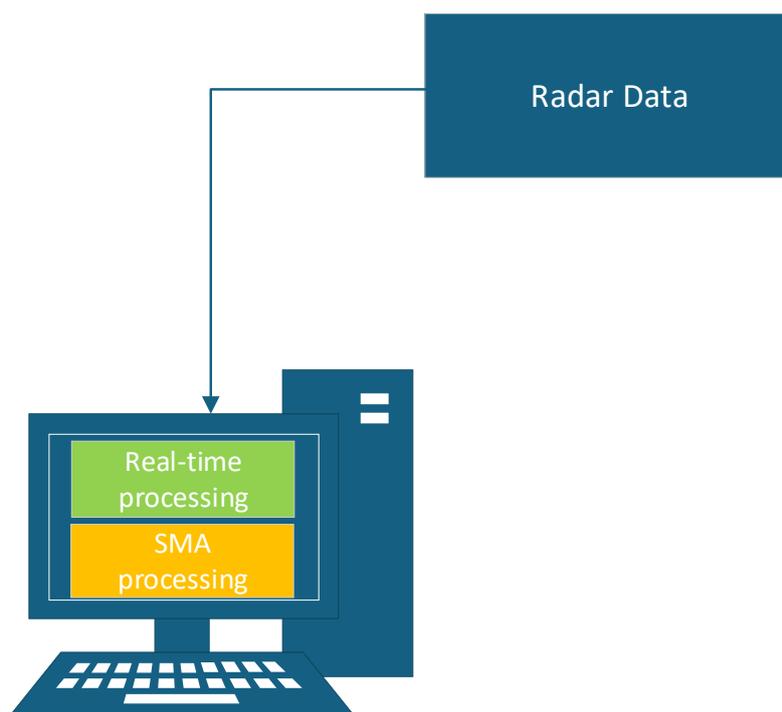
**Figure 2** Diagram of the historical approach of slow movement analysis

## 2.2 Current approach

With advancements in radar monitoring software, SMA can now be executed through dedicated modules or applications designed to operate in parallel with real-time data streams. This evolution has introduced several efficiencies:

- integrated data processing with real-time analysis
- reduction in processing time and manual intervention
- uniform scale for SMA data output
- improved user interface and visualisation tools.

This transition has enabled more frequent and reliable SMA outputs, supporting continuous monitoring strategies without duplicating datasets or increasing operational overhead. A diagram of the current approach of SMA is shown in Figure 3.



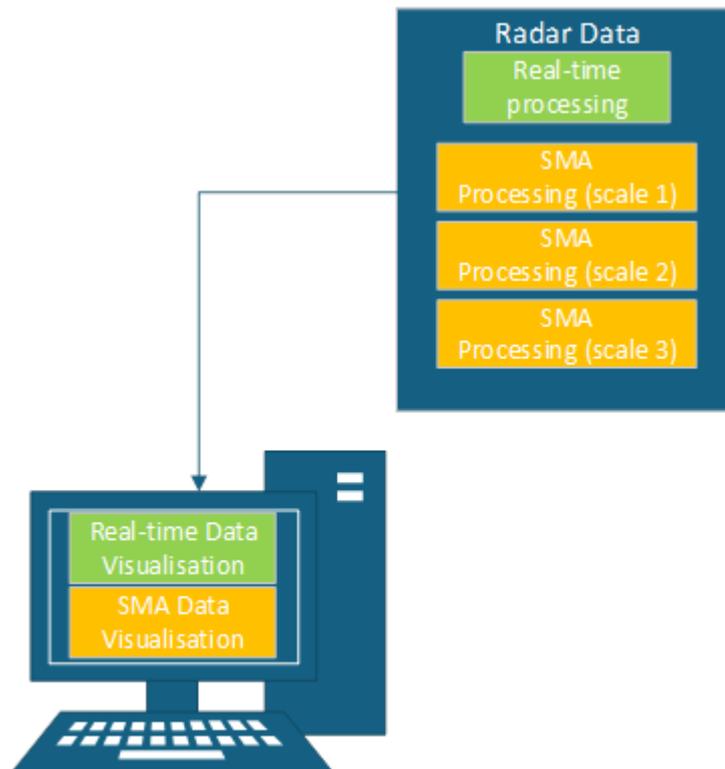
**Figure 3** Diagram of the current approach of slow movement analysis

## 2.3 Future approach

The future of SMA lies in further automation and deeper integration with real-time systems. Key features of the envisioned approach include:

- simultaneous real-time and multi-scale SMA processing
- automated generation of three discrete SMA scales (e.g. 24 hrs, 3 days, 5 days)
- elimination of additional infrastructure requirements such as PCs or VMs
- seamless user experience with centralised data access and analysis tools.

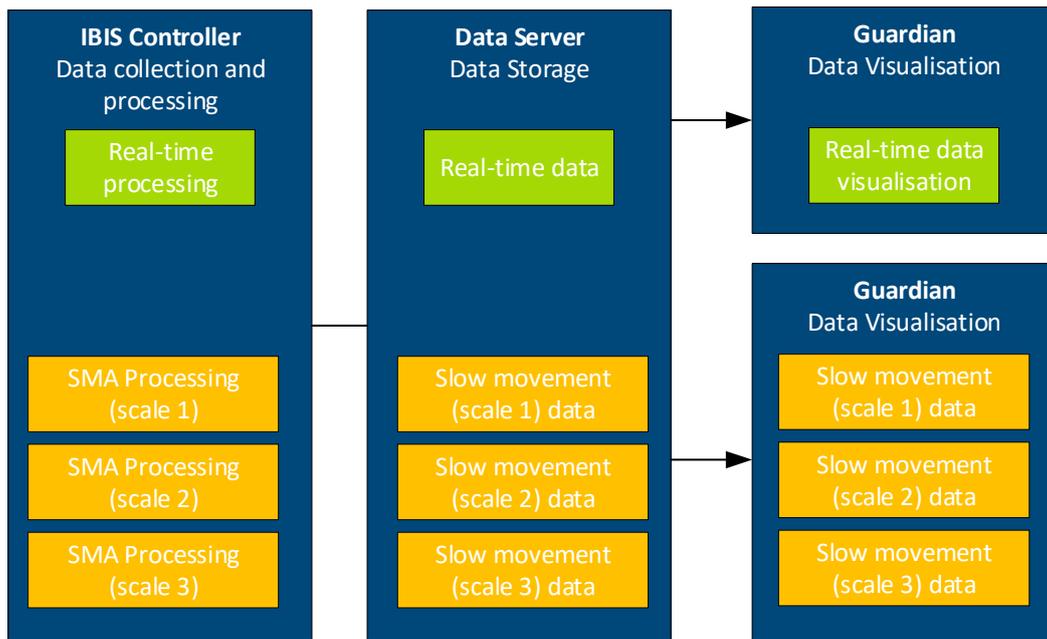
This progression will not only streamline workflows but also improve the consistency and interpretability of ground deformation data across varying temporal resolutions. A diagram of the future approach of SMA is shown in Figure 4.



**Figure 4 Diagram of the future approach of slow movement analysis**

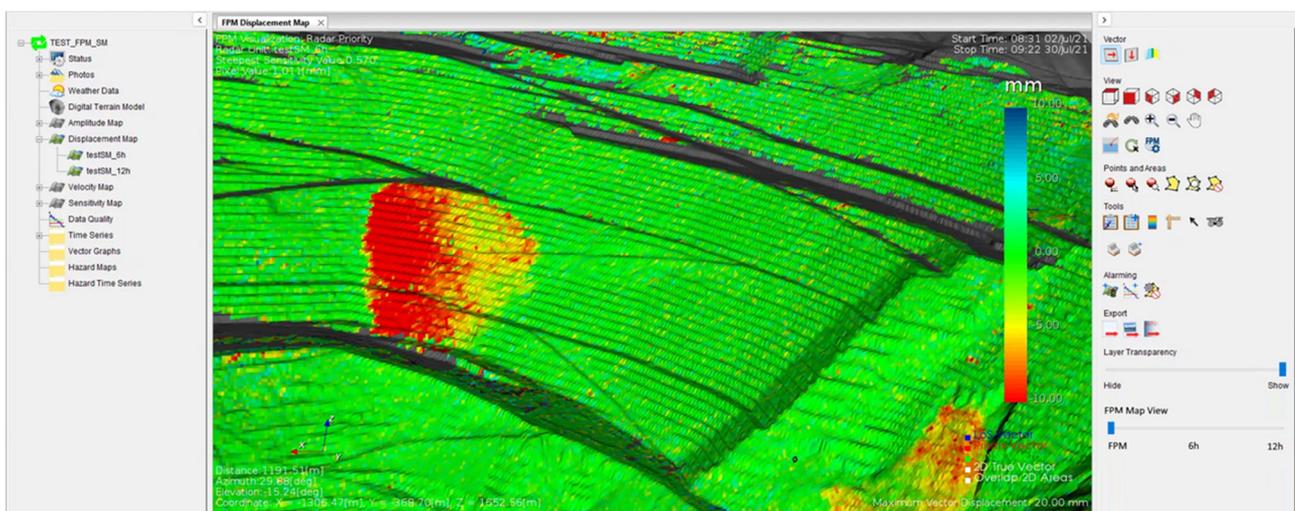
The future-state of the monitoring system introduces a more advanced and integrated architecture, where the Guardian full pit monitoring (FPM) software for real-time monitoring is seamlessly connected with Guardian Slow Movement (SM) FPM for automated SMA across 3 predefined temporal scales. This integration is enabled through the deployment of Controller 5.X within IBIS radar units, allowing for parallel processing of real-time and SMA data streams directly at the sensor level. As a result, users gain access to live, multi-scale SMA visualisations within the same operational interface, eliminating the need for external processing infrastructure or manual data handling. This streamlined configuration not only enhances the interpretability of displacement trends across different time resolutions but also supports a more proactive and predictive geotechnical monitoring strategy. The future-state diagram illustrates this architecture, highlighting the unified data flow and centralised visualisation capabilities that underpin this next-generation monitoring approach.

Figure 5 illustrates the architecture of the new IBIS controller and its downstream applications, enabling automatic processing of SM data. Both real-time and subsampled data are processed in parallel on the radar itself, eliminating the need for manual sub-setting at the client end. As a result, SMA data can be accessed directly in Guardian SM (or its future equivalent) without manual extraction, displaying detectable displacement across three time scales within the same pit. This streamlined process significantly reduces data handling time, allowing SMA to theoretically be integrated into routine operations and existing real-time monitoring workflows.

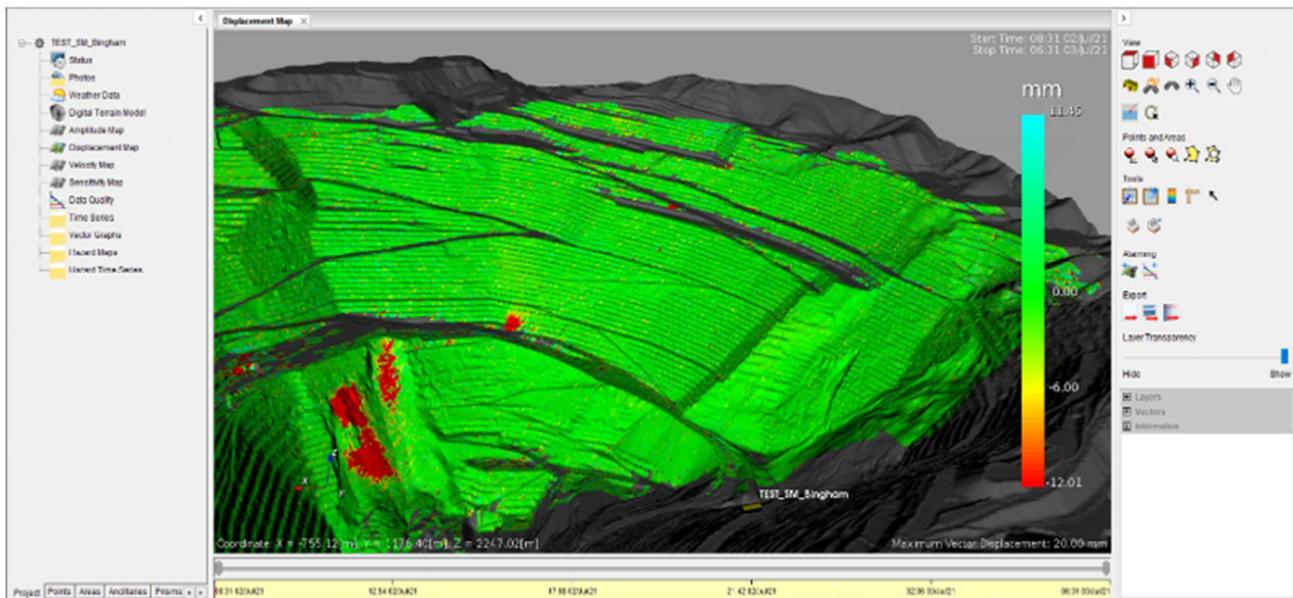


**Figure 5** IBIS Controller 5.X architecture

Figure 6 illustrates a practical example of 2 SMA time intervals operating concurrently and in real-time (Figure 7) alongside the standard real-time monitoring system. This side-by-side visualisation highlights how different temporal resolutions can reveal varying spatial patterns and magnitudes of displacement. Areas of potential concern may appear more prominently or exclusively at certain SMA scales, depending on the cumulative displacement captured over the selected interval. Importantly, each SMA scale is expected to utilise a velocity or displacement colour legend calibrated to its specific detection range. As a result, a ‘red’ zone in a real-time view – typically indicating rapid movement – may not correspond to a ‘red’ zone in a 3-day or 5-day SMA view, where slower but persistent movements are emphasised. This differentiation is critical for accurate interpretation; depending on the actual displacement rates, each time interval (T) may highlight different zones of concern, offering a more nuanced understanding of slope behaviour over time.



**Figure 6** Example of visualisation guardian full pit monitoring using slow movement analysis with 2 scales (time intervals)



**Figure 7** Example of visualisation guardian full pit monitoring using real-time

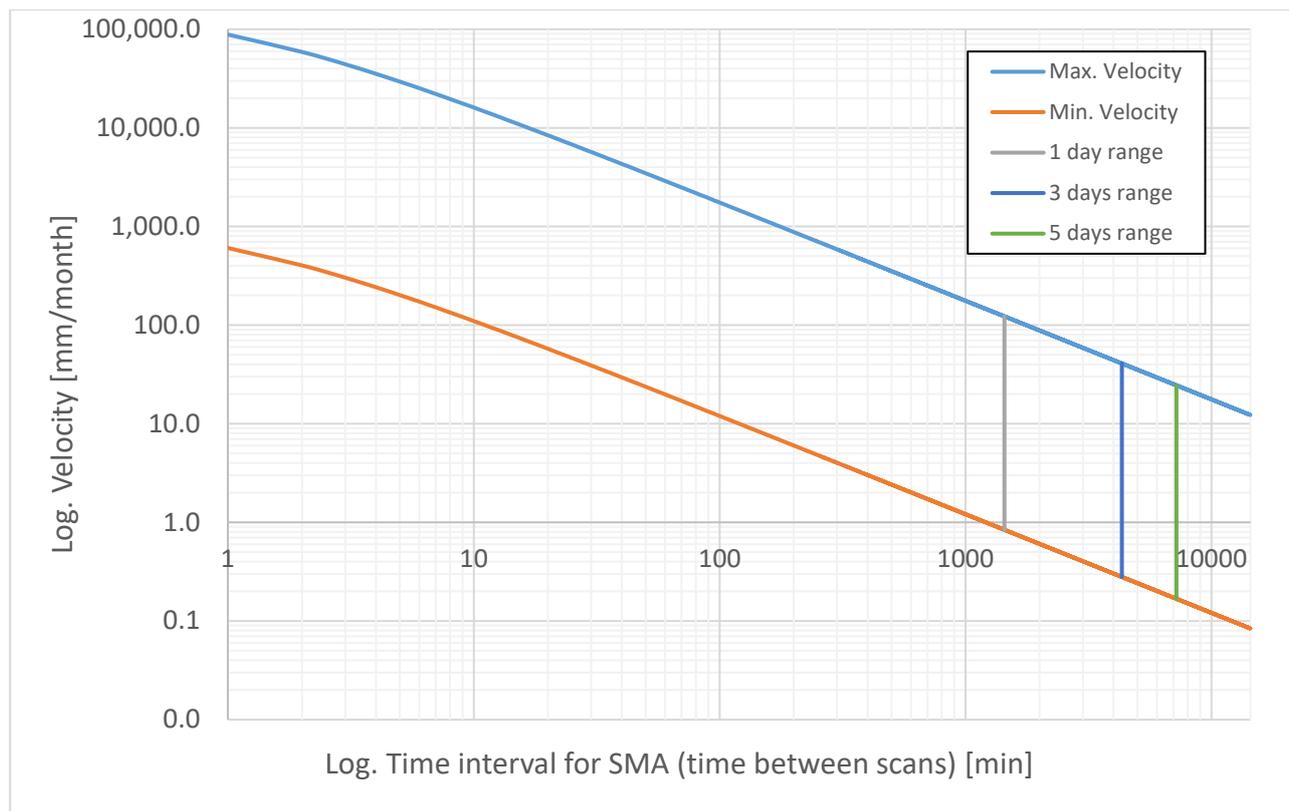
## 2.4 Selection of time intervals for slow movement analysis multi-stage application

As established in the foundational works of Peryoga et al. (2023), Leoni et al. (2015), and Calderon & Barnes (2025), different time intervals ( $T$ ) enable the radar system to capture movements that would otherwise remain undetected in real-time monitoring due to sensitivity limitations. In Guardian SMA, increasing the time interval between scans improves the system's ability to detect lower displacement rates by allowing subtle movements to accumulate beyond the radar's noise threshold. This relationship is quantitatively represented in a log-log chart (Calderon & Barnes 2025), which illustrates the maximum and minimum detectable velocities as a function of the time interval.

The selection of 1-day, 3-day, and 5-day intervals in this research is based on a strategic balance between operational practicality and geotechnical sensitivity.

- The 1-day interval provides partial overlap with real-time monitoring, ensuring continuity and facilitating comparative analysis.
- The 3-day interval serves as an intermediate scale, designed to capture transitional deformation trends that may be missed at shorter intervals due to phase ambiguity or underrepresented at longer intervals. This tiered configuration ensures comprehensive coverage of displacement behaviours, supporting a more predictive and responsive slope monitoring framework.
- The 5-day interval is specifically chosen to meet the lower detection threshold of approximately 0.5 mm/month, a critical benchmark for early warning as demonstrated in previous studies. This interval offers a practical compromise between data density and the ability to detect long-term, low-rate displacements under typical atmospheric conditions.

Figure 8 shows the relationship between the velocity of the pit wall and the time between scans,  $T$  (in a log-log format). The upper and lower bounds (see minimum and maximum velocity lines) for the velocities for each  $T$  value are theoretical in this graph; variations in practice will occur due to instrumentation error and atmospheric changes over time. This graph also highlights how multiple  $T$  values are essential in continuously detecting velocities as failures progress.



**Figure 8 Detectable displacement rates by time interval from (Calderon & Barnes 2025)**

### 3 Results and discussion

#### 3.1 Pilot implementation and system validation

During the first half of the calendar year 2025 the Automatic Multi-Stage SMA system was piloted at Radar A68 in the Whaleback mine, WAIO, BHP. The primary objective of this pilot was not to evaluate the deformation data itself, but to validate the end-to-end data flow from the newly deployed Controller 5.1 into the Guardian FPM live environment, specifically focusing on the integration of multi-scale SMA outputs. This included the automated generation and visualisation of SMA data across 3 temporal resolutions (1-day, 3-day, and 5-day intervals) in parallel with real-time monitoring.

The pilot successfully demonstrated the system's ability to process and display SMA outputs live on the radar itself, without requiring additional infrastructure or manual intervention. This confirmed the robustness of the data pipeline and the reliability of the SMA module in a production environment.

#### 3.2 Operational deployment and impact

Following the successful pilot, the system was fully deployed at the beginning of the second half of the calendar year 2025. Since then, the geotechnical team has leveraged the multi-scale SMA outputs to enhance long-term slope behaviour interpretation and improve early warning capabilities. The integration of SMA into daily workflows has led to several key operational improvements:

- Trigger action response plans enhancement:
  - SMA outputs have been incorporated into trigger action response plans (TARPs), enabling the identification of slow-moving areas that may not be flagged by real-time systems. This has allowed for dynamic reclassification of radar monitoring zones – from background to critical – based on emerging trends in low-velocity deformation.

- Instrumentation strategy optimisation:
  - The system has informed decisions to deploy additional surface and sub-surface instrumentation (e.g. prisms, extensometers) in areas where SMA indicates potential long-term instability. This targeted approach ensures that instrumentation resources are allocated based on predictive insights rather than reactive responses.
- Improved archiving logic:
  - With SMA data available in real-time, the archiving of radar projects is now guided by a more comprehensive understanding of slope behaviour. Rather than relying solely on real-time velocity thresholds, archiving decisions now consider the presence or absence of slow, progressive movements, ensuring that critical data is retained for future analysis and back-analysis.

## 4 Conclusion

The implementation of the Automatic Multi-Stage SMA system represents a significant advancement in the field of geotechnical monitoring for surface mining. By automating the detection, data collection and visualisation of low-velocity ground movements across multiple time intervals, the system addresses a long-standing gap between real-time monitoring and long-term deformation analysis. The successful pilot at Radar A68 in Whaleback mine during first half of the calendar year 2025 validated the system's technical architecture, particularly the seamless data flow from Controller 5.1 into the Guardian FPM live environment.

Following this validation, the full deployment in second half of the calendar year 2025 has enabled geotechnical teams to proactively identify and respond to early indicators of slope instability. The integration of SMA into operational workflows has led to measurable improvements in risk management, including the refinement of TARPs, more strategic deployment of complementary instrumentation, and a more informed approach to archiving radar projects.

### 4.1 Potential benefits

The system delivers a range of operational and strategic benefits:

- Enhanced predictive capability: early detection of slow, progressive movements improves lead time for intervention.
- Operational efficiency: automation eliminates the need for manual SMA processing, reducing workload and improving consistency.
- Improved decision-making: real-time access to multi-scale data supports more informed geotechnical assessments.
- Risk-based monitoring optimisation: SMA insights enable dynamic reclassification of radar zones and targeted monitoring.
- Data-driven archiving: archiving decisions are now based on actual slope behaviour, not just elapsed time.
- Scalability: the system integrates seamlessly with existing infrastructure, supporting broader deployment across sites.

In conclusion, the Automatic Multi-Stage SMA system not only enhances the technical capabilities of slope monitoring but also transforms how geotechnical data is used to support safety and operational continuity. Its successful implementation at Whaleback sets a precedent for future deployments across BHP and the broader mining industry, paving the way for a more predictive, efficient, and integrated approach to geotechnical risk management.

This work confirms that integrating SMA into live monitoring environments not only enhances early warning capabilities but also supports more informed decision-making in geotechnical risk management. As the system continues to evolve, future enhancements may include adaptive time interval selection, integration with artificial intelligence-based pattern recognition, and broader deployment across other high-risk sites.

## Acknowledgement

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