13th FIG Symposium on Deformation Measurement and Analysis
4th IAG Symposium on Geodesy for Geotechnical and Structural Engineering

LNEC, LISBON 2008 May 12-15

DEFORMATION MONITORING THROUGH MULTI-PLATFORM INTEGRATION

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Abstract: GPS, Tilt and InSAR measurement technologies all have shortcomings that limit their application in deformation monitoring projects. Proper integration of all three measurement types allows many of these shortcomings to be mitigated and provides stable, high accuracy and high precision measurements of ground surface and structure motion.

The performance regime of each technology is well established. GPS is ideal where absolute measurements are needed, where all three axes of motion are of interest, and when long term accuracy of results is a key requirement. InSAR is especially applicable where large areas need to be covered, ground instrumentation is prohibitively expensive, and deformation rates fall within its lower, yet respectable, resolution limits. Tilt is the only technology capable of both medium and very high precision measurements of the earth surface or structures.

Each of these technologies has several weaknesses that must be addressed for their successful and accurate deployment. For example, GPS sites are relatively expensive and require open sky. Tilt becomes impractical for monitoring areas larger than several square kilometers and loses its precision advantage over long periods of time. Since tilt measures the gradient of the deformation, instrument layout requires special attention and may compromise results if not implemented correctly. InSAR provides line of sight measurements rather than the full motion vector and is often limited in accuracy by variable atmospheric and ground conditions.

Integrating the different technologies, by using data from one set of tools to constrain the analysis of another, takes advantages of their respective strengths while partially cancelling the weaknesses. The result is a more robust and accurate monitoring system that can meet design goals previously unattainable or attainable only at very high cost. The paper outlines the integration methods and provides examples of these systems using real data. Finally, an automated system is introduced that performs data quality control and presents the results in an easy to understand format.

1. SURFACE DEFORMATION MONITORING

Surface deformation monitoring has become an important tool for observation of underground fluid flow. Examples of industry participants that use the technique include: oil and gas producers who monitor steam or water injection and hydrocarbon production, carbon sequestration managers who seek to verify storage site integrity, waste injection managers who require hard data on the extent of disposal domains, and volcanologists who monitor magma movements. Monitoring surface deformation has a few distinct advantages over most other techniques that seek to monitor the same phenomena:

- No requirement for downhole instrumentation
- Ability in many cases to determine the actual extent of fluid volume distribution, using subsurface strain as a proxy for local volumetric changes caused by fluid inflow or egress (Du 2005).
- Surface deformation is highly sensitive to the depth of fluid movement. Surface motion monitoring excels at determining whether even relatively small amounts of an injected fluid are approaching the surface. Compared to borehole techniques, surface monitoring is relative insensitive to the location within a monitored area the fluid migration occurs.

The three most common techniques for monitoring surface deformation are tiltmeters, GPS and InSAR. The premise of each technology is described below followed by a discussion of integration approaches that seek to take advantage of the strengths of each while mitigating the weaknesses.

2. TILTMETER MONITORING

Tiltmeters provide by a wide margin the most sensitive measurement of surface deformation. Most tiltmeters use either an electrolytic sensor similar to those found in a carpenter's level, or a pendulum device. Several organizations have installed long base tiltmeters (Bonaccorso 2004), but the requirement for a long trench relegates these instruments to special applications only. Electrolytic based tiltmeters are available with sensitivity as good as one nanoradian (Wright 1998), equivalent to sensing a one millimetre motion at the opposite end of a 1000 km long rigid beam. The instruments are typically installed in shallow boreholes to isolate them from thermal motions and other near-surface generated noise.

Tiltmeters measure the deformation gradient rather than the deformation itself. In order to calculate the actual deformation, the gradient needs to be integrated. There are an infinite number of surfaces that can be fit to any given set of gradient measurements, so some other constraint is needed in the calculation. Typically, that constraint is to find the smoothest surface that fits all of the measured results (Davis 2001). In order for the smoothest surface to be an accurate reflection of the true ground motion, the density of measurements needs to be high enough to capture all the changes in the deformation gradient. This can be an onerous requirement, but the burden is significantly reduced if one can determine a minimum depth at which ground strain fields should be detected. A model, such as that from Okada (1985) or Palmer (1990) can be used to determine what instrument spacing will accurately capture the deformation associated with strain sourced at a specific depth. Material properties have only minimal effects on the pattern of a propagating strain field, and generally do not need to be considered in this calculation which is, of course, of significant practical advantage.

Tilt measurements have a few distinct advantages in the measurement of surface deformation:

- No other widely available instrument can measure ground deformation with even close to the precision of tilt.
- Data is continuous, allowing near real time feedback and enabling deformation events to be correlated with the activities that may have caused them.

- Although sites need to be constructed to allow the instruments to be placed below grade, the equipment costs are generally lower than for a high precision GPS installation.

Balancing these advantages are a few weaknesses of tilt measurements:

- Array design needs to be undertaken carefully to make sure the integrated elevation change solution represents the actual surface motion.
- If very shallow fluid flow (or other events) are occurring over a broad area, a lot of instruments are required to adequately monitor the movement.
- Some types of tilt sensors suffer from drift – tilt that is not real which generates error that accumulates over time. When analyzing motion over long time periods, the precision of a tilt-only derived elevation solution can be lower than is available from other technologies.

3. PRECISION GPS

The precision achievable with GPS is far lower than is achievable with tilt, but is nonetheless remarkable. One technique for obtaining high precision GPS measurements is to use a triple differencing algorithm (Remondi 2000) which uses satellite phase data from a relatively stable nearby (<1 km) reference station to differentially correct carrier phase data collected at remote GPS stations. The triple difference approach allows for eliminating or nearly eliminating corrections for the tropospheric delay, ionospheric delay, clock errors in the receiver and satellite, both general and special relativity effects, solid earth tides, and bias in both receiver and satellite.

The noise that remains in the measurements is primarily associated with the length of the baseline between the reference and remote stations, plus site specific multipath effects. A Kalman filtering technique is employed to reduce this inherent noise and obtain the required accuracy. Kalman filtering is typically used to produce the optimal real time estimate, but double differencing algorithms and shaped-averaging techniques may also be used to generate high-accuracy measurement when continuous, near-real time results are not required.

The advantages of GPS monitoring are:

- GPS measures the absolute difference in position between the base and rover. The solution is not subject to errors that increase over time and is robust to outages. If an outage occurs, it will return to a solution that accounts for motion during the outage.
- GPS measures motion in three dimensions. On many geotechnical monitoring projects, the horizontal motions are considerable and cannot be assumed zero.
- High precision GPS is capable of determining motion with accuracy of 1-2 mm.
- Like tilt, GPS can provide continuous data that is available in near real time and can be correlated with events in the field.

Some of the weaknesses of GPS monitoring are:

- GPS provides a motion solution at a single point. It is often not practical to place enough units in the field to provide adequate monitoring based only on GPS.

- GPS requires viewable sky, which can limit applications in construction sites or other areas with dense activity or geographic obstructions.
- High precision GPS equipment costs more than the equivalent in tiltmeter stations.

4. INSAR

Earth orbiting synthetic aperture radar (SAR) satellites project a beam of microwave energy at the Earth surface and receive the portion of this beam that reflects from solid features, such as rock, soil or buildings. InSAR is the technique of looking at how the phase of the reflected energy changes between satellite passes. If the distance between the satellite and a specific point on the Earth surface never changes, then the phase of the reflected microwave should always be the same. Should this distance change, however, either through the motions of the satellite or the deformation of the Earth surface, the phase of the reflected wave will change by an amount equal to the change in distance modulo the wavelength of the microwave signal. If one has sufficient knowledge of the position of the satellite in its orbit, then the amount a point on the Earth surface moves in a given period of time may be calculated by measuring the shift in the phase of the microwave signal reflected from that point. Based on this principle, measurements of the phase change at thousands of points on the Earth surface are used to produce an InSAR image, or differential interferogram. InSAR has a lower sensitivity than GPS that is on the order of several millimeters to 10 or more millimeters depending on the application, yet has the tremendous advantage of covering large swaths of real estate with little or even no ground instrumentation. If vegetation, snow, or water fail to reflect back meaningful phase information, inexpensive reflectors, typically about 1m on a side, can be installed to obtain the needed data.

The example in Figure 1 shows an oil field in Oman. In this image, a subsidence bowl can be seen where cycles of the colors that represent the phase difference in the interferogram form a distinct ‘bowl’ pattern. Each side of this image is over 50 km.

The power of InSAR mapping lies in its ability to generate a fine resolution image over a very broad area with little or even no ground instrumentation. InSAR satellite images typically have a ground resolution of 10 to 20 meters per pixel (newer satellites will bring this down to <5 meters per pixel), with one satellite image covers an area up to 100 km^2. Some of the drawbacks and complications in obtaining this image include image decorrelation, tropospheric interference and satellite look angle limitations. These complications are discussed below.

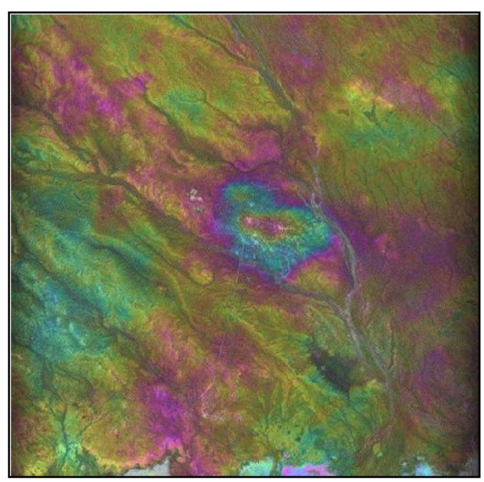

Figure 1 - Deformation mapped by InSAR at an oil field in Oman.

Decorrelation

For each image pixel, the microwave phase information is extracted from the largest returning signal. Local conditions like dense vegetation, moving water, or swampy ground can cause a confused return signal that cannot be reduced to a single phase value. These situations may render large portions of a region of interest (ROI) immeasurable, a condition known as decorrelation. If decorrelation affects a large enough portion of a scene it may even interfere with the ability to get useful results from portions that provide a good radar return, since one can lose the ability to count the interference fringes from a reference point.

Tropospheric Interference

Across a full SAR image (up to 100 km^2) there may be significant differences in signal delay through the troposphere. Without any type of correction, these changes look identical to changes in the earth elevation. Permanent scatter techniques seek to mitigate this delay through modelling, yet require a stack of SAR images (typically 10-15) in order to yield robust results. This delayed start-up time is often of negative consequence for operators and project managers who want results more quickly.

Look Angle

The SAR measurement is taken on the line-of-sight from the satellite to the ground. As a result, the vector components of motion in the three principle axes are undefined unless certain assumptions about the motion are made. In practice, though, ground movements often have very significant horizontal components that will result in computation of an incorrect vertical deformation if they are ignored. In some cases this shortcoming can be addressed by combining the readings from two or even three separate passes of the satellite where the satellite images the same area from different locations in space. If two passes are used, the problem is reduced but not eliminated since any earth movement perpendicular to the plane formed by the two look angles will not be measured. The use of three look angles is rarely possible, and still suffers from assumptions that need to be made about the ground motion between passes since the measurements will not be simultaneous.

Some advantages of InSAR monitoring are:

- A single satellite pass covers an enormous area (~100 km x 100 km)
- Fine pixel resolution provides results every 10 – 20m
- Little or no ground instrumentation is required, so monitoring costs can be quite low.

Weaknesses of InSAR monitoring are:

- InSAR is a periodic measurement that cannot provide real time results
- Resolution is marginal for some projects
- InSAR measures the component of motion in the direction from the ground to the satellite. Motion in the other axes may be important, but is unmeasured.

5. INTEGRATION OF TILT AND GPS

A review of the strengths and weaknesses of tilt and GPS reveals some compelling complementary advantages. Tilt based measurements increase in uncertainty over time, while GPS based measurements do not. Tilt has higher precision and lower cost than GPS. Tilt provides gradient measurements requiring numerical integration, GPS provides absolute elevation changes between reference points. Can a system use both technologies to achieve high precision over both short and long term at reasonable cost?

The process of integrating tilt and GPS into a single deformation solution is detailed in Davis (2001). A Delaunay triangulation is set up among all the tilt and GPS sites. A tilt measurement is needed at each GPS site, and is interpolated from the nearby sites if a tilt site has not been co-located with the GPS. Starting with a random Delaunay line that has an elevation measurement on at least one end, the elevation of points along the line are computed using a minimum order spline (up to third order). Another random line is chosen that has an elevation measurement on at least one end, and the process continues until all Delaunay lines have been processed. This results in one possible solution, with elevation calculated at all tiltmeter and GPS sites, plus along the Delaunay lines connecting them. The solution is guaranteed to match the elevation change at each of the GPS sites plus the tilt measurement at each of the tiltmeter sites. However, this may not be the best solution. The entire process is repeated to calculate a new solution. Ideally, one would exhaustively test all possible solutions and select the one with the smoothest surface, determined by tracking the sum of the curvature of each of the Delaunay lines, but this is generally not practical because the number of possible paths through the calculation process grows only slightly slower than the factorial of the number of measurement sites. Instead, the process runs until the statistics indicate a minimum has been approached, as indicated by the standard deviation of the curvatures from all runs. In practice, the best match to survey data has been obtained by averaging the surfaces from a number of ‘best’ solutions. This process mutes any deviant calculations from a single run.

The implication of the integration is that in the neighbourhood of the GPS sites, the solution always has the same elevation uncertainty as the GPS – roughly 1 to 2 mm in the vertical direction. The deployment strategy is to intersperse a few GPS sites within a larger tiltmeter array, with the objective of minimizing the maximum distance from any given tiltmeter to the closest GPS. Using this strategy, the sensitivity of the array comes from the tiltmeters – if the tiltmeters detect a coherent pattern indicative of subsidence or uplift, that pattern will be preserved through the processing. If too many GPS sites are present and their noise level is much higher than the deformation signal, the pattern detected by the tiltmeters may be excessively distorted by the GPS and no longer recognizable. Over the longer term, the GPS stations force the solution to remain stable, so drift in the tilt measurements do not cause miscalculation of elevation change. The drift in elevation becomes a function of the distance to the closest GPS station, hence the strategy of minimizing this distance.

The example in Figures 2 and 3 shows an array of 44 tiltmeter sites and 4 GPS sites spread over approximately 250,000 m^2. The array primarily exists to detect steam migrating towards surface in the short term. To that end, data from the array is collected daily by a computer system and analyzed on an hour by hour basis. A video of the daily surface deformation is published to a web site so the client can immediately attend to any issues, and the results are analyzed to determine the depth of any near surface events. Over the long term, the array is used to determine the balance of injection and withdrawal with the goal of keeping wellbore casing strain below damaging levels. Figure 2 shows the analysis results over a full year without considering the GPS data. In these results, the South and West edges of the field appear to be sinking by several tens of millimetres, which is unlikely (and confirmed incorrect by optical survey) because there are few wells and little production from these areas. In contrast, Figure 3 shows the analysis results when the GPS data is integrated into the analysis. The overall shape of the deformation is largely unchanged, but the additional data indicates that (1) the tiltmeter only solution somewhat underestimated the total deformation and (2) the entire surface shifted so that the actual deformation along the South and West edges of the array is quite close to zero. Result #1 is understandable because, as discussed, the tiltmeter solution searches for the lowest curvature solution. In the GPS + Tilt result, one can see that there are areas of significant gradient change that between tiltmeter sites, so this result could likely have been avoided by using more tiltmeters. Result #2 is partially due to the drift of the tilt data over long periods and partially due to the choice of reference point (the 'star' tiltmeter site just by the lower left corner of the legend) which is assumed to have zero motion. The integrated analysis shows that this location, in fact, rose by roughly 20mm over the year.

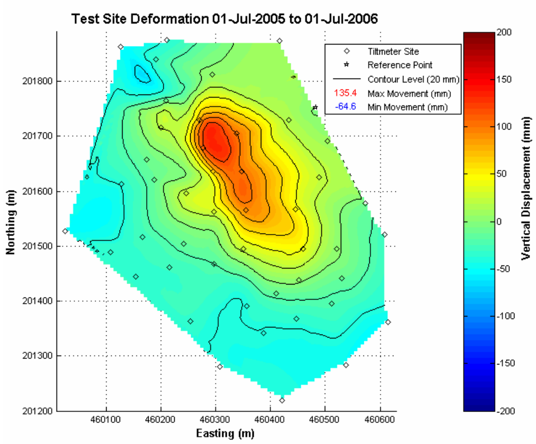

Figure 2 - Deformation calculation over one year from a tiltmeter array. GPS data was not used in the deformation calculations.

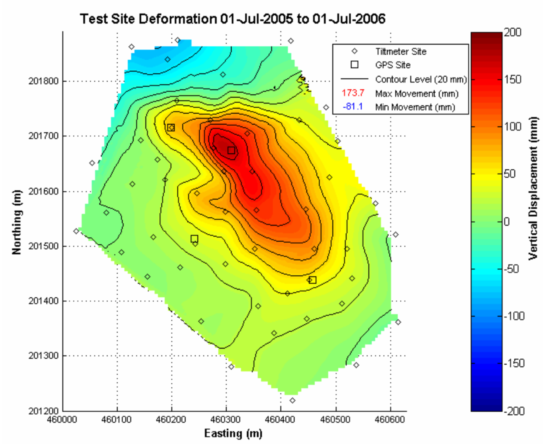

Figure 3 - Deformation calculation over one year from an integrated tiltmeter and GPS array.

6. INTEGRATION OF INSAR AND GPS

The precise point measurements taken by GPS offer the opportunity to significantly improve the accuracy of a broad InSAR image. There are three specific ways GPS can be used to aid the generation of an InSAR image.

The first step in the integration is to match the deformation at the GPS measurement points. The measured GPS deformation over the time period of the InSAR data is calculated, then the component of that motion in the direction of the satellite is compared with the InSAR measurement. It is often necessary to filter the InSAR results before correcting the image to match the GPS. If the InSAR image is not smooth, the value of the correction might vary drastically depending on which particular pixel a given GPS site is in. The extent and value of the filter can be determined by two criteria. First, there is a characteristic aerial extent associated with the source depth of any deformation process (Okada 1985), and that extent is nearly independent of the mechanical properties of the material. For example, if there is a shallowest depth that can be chosen for the monitoring, one can choose a filter that removes only deformation that would be associated with sources shallower than the target depth. Second, the filter should be set so that the variation in the GPS correction image due to a small change in the easting or northing location of any GPS site is small compared to the correction itself. If this criterion is met, one can be confident that pixel to pixel variations in the InSAR image due to noise are not affecting the correction process.

In order to estimate the correction at other points in the InSAR image, one can interpolate between GPS stations. Outside of the area monitored by GPS, however, extrapolation may produce unreasonable and undesirable results. Instead, we apply the criteria that the average ground motion at the perimeter of the monitored area must be zero. The perimeter is user defined and fortunately can be quite distant from the ROI thanks to the large spatial cover of an InSAR image. Note that this does not mean zero motion at every point on the perimeter. Only the mean is zero. Physically, the assumption is that there is no large scale motion outside of the monitored area, or if there is, it can be safely subtracted from the image without affecting the results for the area under investigation.

With the constraints in place that provide a correction to the perimeter of the image and at the specific GPS points, a reasonable estimate of the correction at any point within the image can be made by interpolation. Note that this correction must be performed individually for each series of InSAR images that have a common line of sight before those series can be combined into one longer term image.

Next, the image needs to be converted from line of sight to true vertical deformation. This requires an estimate of the easting and northing motion at every point in the InSAR image. One relatively simple approach is to run through essentially a repeat of the line of sight correction process. The easting and northing deformation is measured at each GPS site, and we have already made the assumption that the mean ground motion around the perimeter of the monitored area is zero. Similar to the process of estimating a line of sight correction, one could now estimate the easting and northing motion by interpolating between the GPS locations and the assumed correction value at the image perimeter. In this case, since there is no other information, the motion at the perimeter would be assumed identically zero.

There is a refinement to this process that we hope provides a better estimate of the motion. Easting and northing ground motion often correlates well with the gradient of the deformation. On landslides, for instance, the ground generally moves in the downhill direction. (This may not be true at the bottom of a slide, where as the ground slumps it may move aerially in the uphill direction). We make use of this correlation by looking at how well the easting and northing motion at the GPS sites correlates with the magnitude and direction of InSAR gradient at those locations. A correlation constant is developed that describes how well the InSAR gradient can be used to predict the easting and northing motion at the GPS sites. The final estimated easting and northing motion at any point in the InSAR image is the combined results from the simple interpolation method and gradient correlation method, weighted by the correlation constant.

Finally, with a corrected deformation in the line of sight direction to the satellite, and estimated easting and northing motion for every point in the image, and knowledge of the direction to the satellite, one can quickly calculate the best estimated true vertical motion.

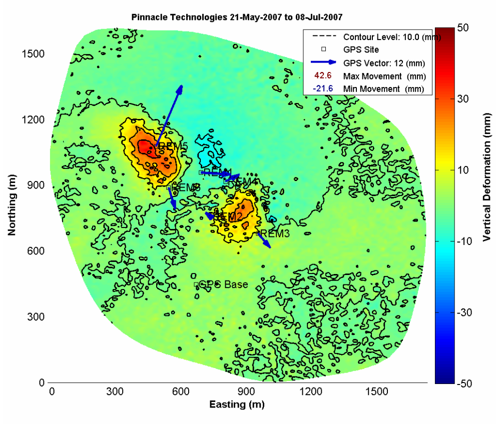

Figure 4 - Uncorrected InSAR deformation measurements from a test area.

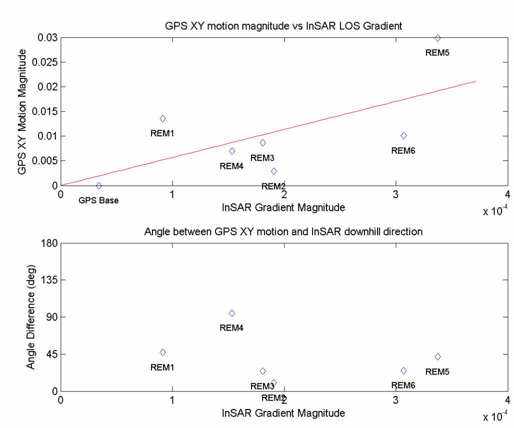

Figure 5 - GPS Easting/Northing motion correlated to InSAR gradient

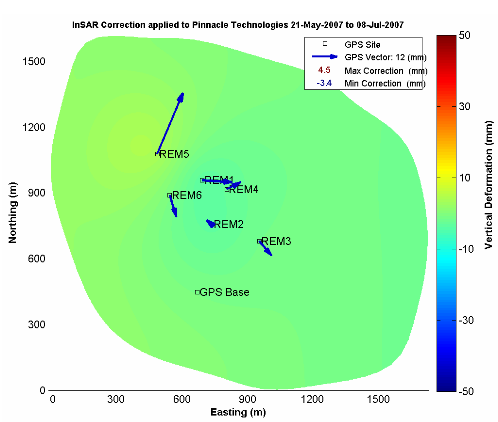

Figure 6 - Correction applied to InSAR image to match GPS in the line of sight

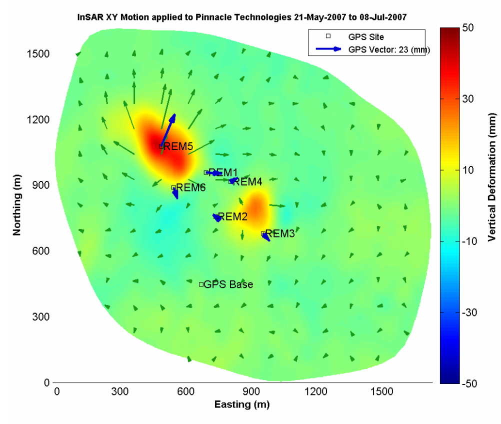

Figure 7 - Estimated Easting/Northing motion vector field

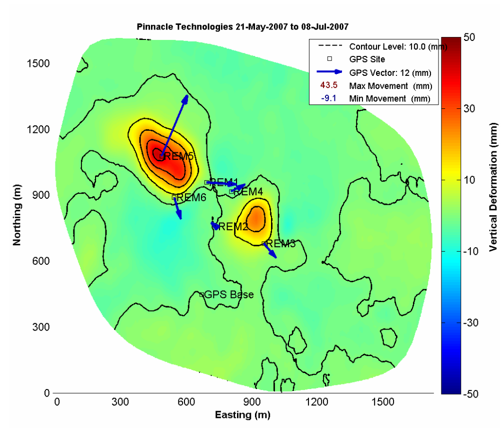

Figure 8 - Final integrated GPS and InSAR results

7. CONCLUSION

Different techniques for surface deformation monitoring have different strengths and weaknesses. Combining the techniques into an integrated analysis can mitigate the weaknesses individual methods, resulting in a more powerful, robust monitoring system. The steps presented here are early efforts. Many other directions remain to be investigated. The ultimate goal is to constrain as much as possible the set of possible events happening underground, and many other technologies can provide crucial pieces to the puzzle.

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