Chapter 2
InSAR Satellite Surveys: Key Considerations for Monitoring Infrastructure

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2.1 Fundamental Concepts

This section defines InSAR and provides key concepts, necessary for evaluating a site's suitability for InSAR.

What Is InSAR?

Interferometric Synthetic Aperture Radar (InSAR) is a technique for monitoring millimetre to centimetre-level displacement of the Earth's surface through repeated imaging of an area over time (Hanssen 2001). During each pass, a radar satellite transmits microwaves towards the Earth's surface, and records the returned echoes as a radar image. Each pixel in the image contains amplitude (target brightness, typically expressed as intensity, which is the square of the amplitude) and more importantly phase. The phase value for a pixel is expressed as an angle, and proportional to the distance to the ground. Figure 2.1 shows how phase measurements over time relate to ground displacement. Note that the satellite acquires from a side-looking perspective, this is an important aspect of SAR, discussed in SAR Geometry on page 9.

When phase data from the first image is subtracted from another, an interferogram is formed, which contains the phase difference for each pixel.

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V. Singhroy (ed.), *Advances in Remote Sensing for Infrastructure Monitoring*,
Springer Remote Sensing/Photogrammetry,
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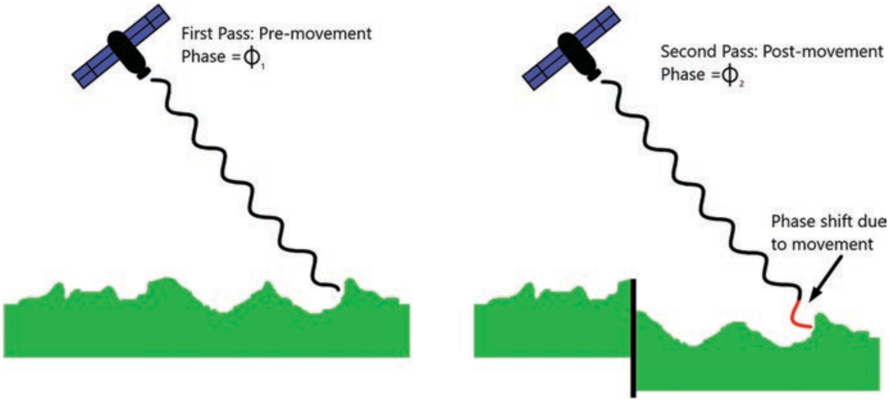

Fig. 2.1 Left: The SAR acquires an image of the ground, which contains phase information. Right: The ground has displaced prior to a subsequent image being acquired, and the phase measurement is consequently longer

Because phase is related to the ground distance, the difference in phase is therefore related to the change in ground distance that has occurred in the time between the two image acquisitions. Unfortunately phase differences also contain other unwanted contributions, relating to topography, atmospheric conditions, and noise. The goal of InSAR processing is usually to correctly separate displacement from other unwanted effects that also influence the phase (Woodhouse 2006).

This is most effectively performed when a series of 15 or more repeated radar images is considered. Common approaches utilise the spatio-temporal statistics of the data to derive displacement from an interconnected network of interferograms that overlap in time (Ferretti et al. 2001; Berardino et al. 2002; Mora et al. 2003; Hooper 2008). Despite best efforts, some areas will not yield useful results, discussed further in Coherence on page 7.

End products typically map displacement over time for areas up to thousands of square kilometres on the ground, which often equates to millions of measurable targets. InSAR, therefore, is essentially a simultaneous satellite survey of millions of targets on the ground, repeated every few days or weeks. Figure 2.2 shows InSAR displacement results over Seattle.

InSAR can be a difficult technology to apply for a few reasons:

- During each acquisition, microwaves are emitted by the radar and travel to the Earth and back. Along the way, these signals encounter the ionosphere, the troposphere, topography, pressure and temperature changes, displacement, and even soil moisture and snow (Hanssen 2001). These effects vary from pixel to pixel and over time, and, therefore, manifest in the data as such.
- Phase values for each pixel are bounded between 0° and 360°. They must be integrated spatially in order to recover higher levels of displacement.
- Each pixel over time has varying amounts of information. Some are fully information bearing, some contain partial information, and others are complete noise.

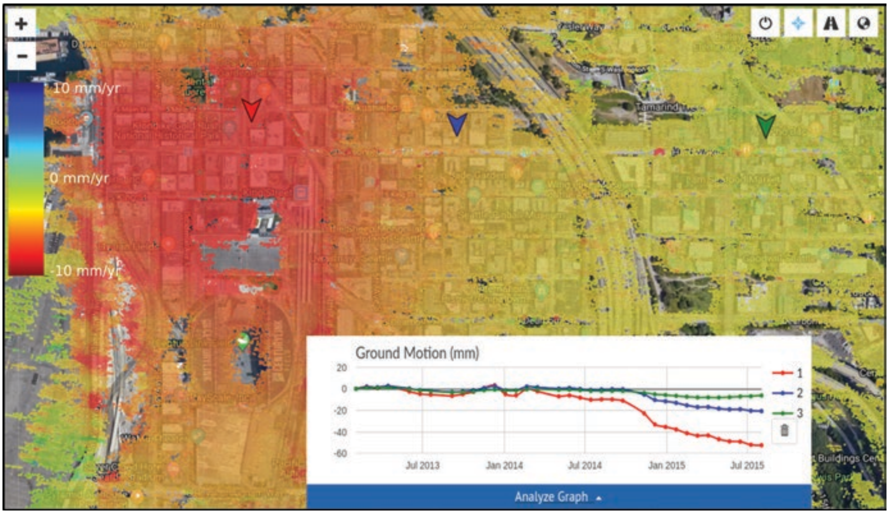

Fig. 2.2 A sample web map of InSAR displacement data generated over Seattle. Tens of millions of targets were tracked over a 3-year time period to map tunnelling-related subsidence. Optical image credit: Google Earth, Landsat/Copernicus

Figure 2.3 shows a single interferogram on the left; the per-pixel phase difference between two radar images, represented by a blue-pink-yellow colour map. The phase values vary across the image for several reasons. The right image shows displacement results, following a complex processing chain to remove unwanted signals, noise, and in this case, non-moving areas.

Targets

The measurable pixels in an InSAR analysis are often referred to as *targets*. InSAR tracks repeatable targets over time. Man-made infrastructure, exposed rocks, and bare ground are examples of targets that are repeatable from one image acquisition to the next. Water, snow, leaves, and crops are not trackable because they change too much between images. Targets that do not change for the duration of a *stack* of images are called *Permanent Targets* (Ferretti et al. 2001), such as built infrastructure or dry deserts. Displacement may or may not be occurring, but the target itself has the same structure. Targets that stay unchanged only for some portion of images, or are only available for monitoring during specific seasons (e.g. due to snow) are called *Temporary Targets* (Hooper et al. 2012).

The quality of targets also varies spatially, with some exhibiting point-like behaviour with low noise, termed *Point Targets*. Here, the phase response from solid objects such as buildings or boulders dominates over all other objects in the pixel. Point Targets tend to provide excellent InSAR measurements. Pixels containing no

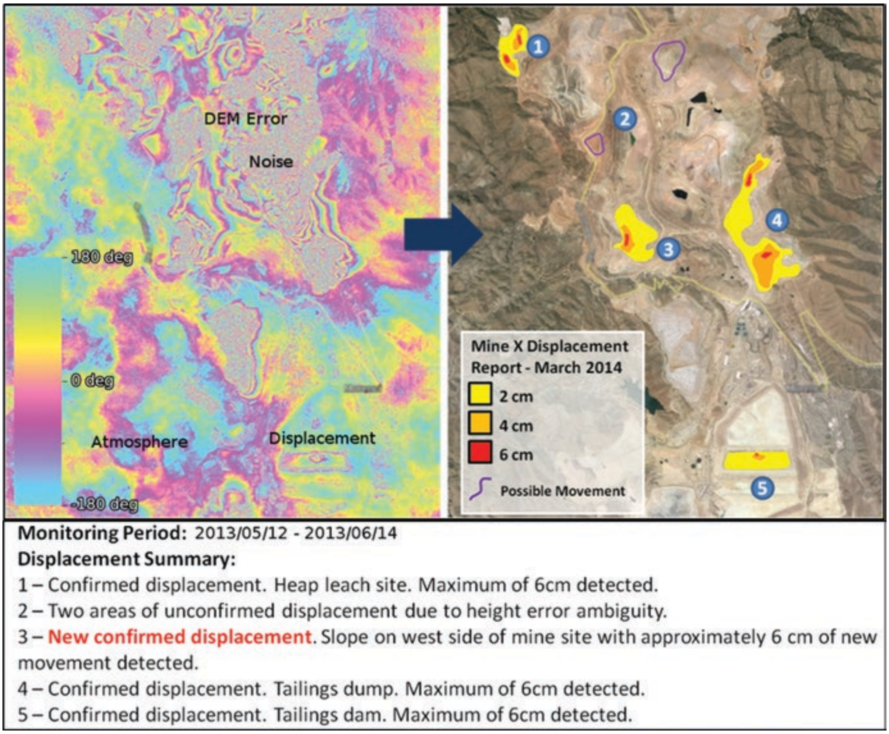

Fig. 2.3 Differencing two radar images produces an "interferogram" (left) containing mixed signals and noise. A derived product (right) indicates when, where, and how much displacement has occurred. Additional context is provided to aid interpretation (bottom). Optical image credit: Google Earth, Landsat/Copernicus

solid dominant object are referred to as *Distributed Targets;* these might contain bare ground or a complex structure. Figure 2.4 shows the various types of targets, with permanent point targets offering the highest quality measurements, and distributed temporary the lowest.

Coherence

For any given pixel, a successful InSAR measurement between a pair of images relies on the target maintaining some continuity over time. If the target is disturbed between acquisitions, then that interferometric measurement is lost. This characteristic of target quality in an interferogram is quantified by the metric of *coherence* (Cattabeni et al. 1994). The coherence of a target may come and go over time (see Temporary Targets discussed in the section above), but continuously changing areas such as water produce very low coherence and cannot be monitored using InSAR.

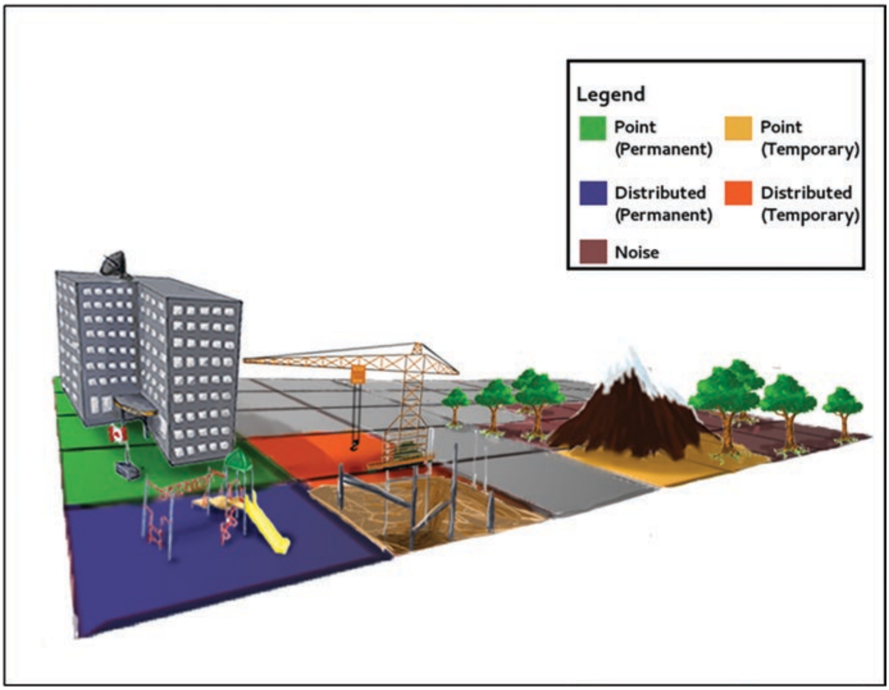

Fig. 2.4 Measurable pixels in InSAR are often referred to as targets. Their quality can vary based on ground cover (point vs. distributed) and whether they persist over time (permanent vs. temporary)

InSAR coherence captures measurement quality, and without it there is no means of discerning information from noise. A target's coherence is expressed as a continuum between zero (no coherence) and one (perfect coherence). Many InSAR processes employ coherence estimates, such as target identification, as weights for algorithms, and for masking out low quality data.

Figure 2.5 left shows an optical image of an oil pumping site bordering a town; vegetation dominates elsewhere. One coherence image can be generated for each interferogram, and Fig. 2.5 right shows an example of this. Here, coherence is being measured spatially; targets are attributed high coherence if they are similar to their neighbours. Processing plants and nearby urban infrastructure provide many permanent point targets with high coherence (closer to 1), whereas vegetated areas are less coherent (closer to 0).

Coherence over time is also important. Figure 2.6 shows coherence images from successive interferograms over a tailings area. Sporadic activity, the lack of hard targets, and changing ground conditions provide targets that are neither point like, nor permanent. Temporary and Distributed Targets must be considered if all the available displacement information is to be extracted.

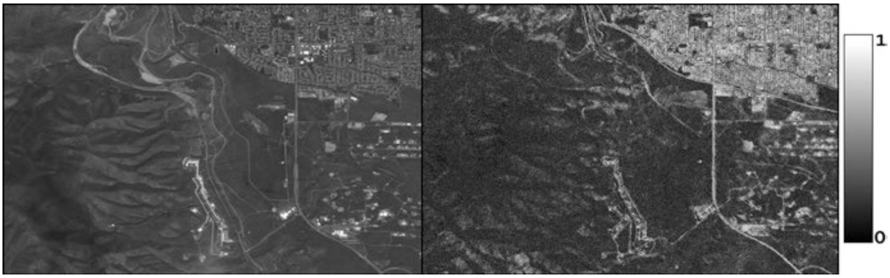

Fig. 2.5 Left: A residential area (north east), an area of natural ground with some vegetation (west and industrial infrastructure all lie close to one another). Right: A corresponding coherence image indicating many bright areas with potential targets, as well as noise in vegetated areas. A useful coherence image such as this successfully attributes measurement potential, and is a key metric for many stages of InSAR analyses. Optical image credit: Google Earth, Landsat/Copernicus

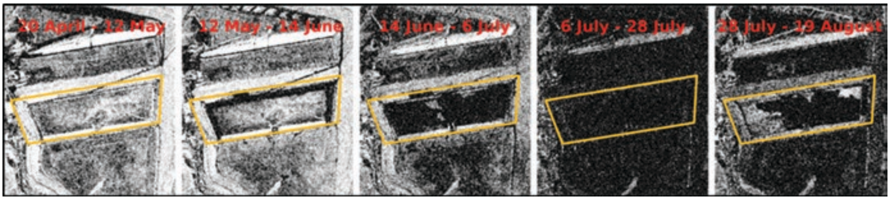

Fig. 2.6 Dynamic areas such as mine tailings have variable coherence over time; temporary target analysis is necessary to monitor such areas. The colour legend shown in Fig. 2.5 applies here also

SAR Geometry

SAR satellites are necessarily side-looking sensors. Microwave pulses emitted and received by the radar are ordered in the image by range. Their range is based on their travel time; pulses that take longer to return are assumed to be further away. A radar pointing straight down would result in many pulses returning simultaneously, which would be superimposed in the image. A side-looking arrangement, as shown in Fig. 2.1, therefore, provides greater opportunity for targets to be separated in range, resulting in greater detail in the image. This is always true for flat areas, but the presence of topography affects measurement coverage and measurement sensitivity (Woodhouse 2006). Effects due to topography can be summarised as follows:

- *Foreshortening*. Moderate slopes facing towards the satellite return pulses that arrive at similar times, and this section of the image is, therefore, compressed providing little opportunity for target measurements (*foreshortening*). Sensitivity to downslope displacement is also poor for these slopes, as displacement is occurring nearly perpendicular to the line of sight (LOS). No target measurements occur on slopes perpendicular to the satellite look direction, as all pulses return simultaneously and are superimposed (maximum foreshortening).
- *Layover*. If the top of the slope is closer to the radar than the base (*layover*), the feature appears reversed in the image as pulses are ordered in reverse. This is

expected for buildings, and with the correct approach, useful displacement information can still be extracted from the data.
- *Ideal Slopes*. Moderate slopes facing away from the satellite provide the best opportunity for targets and good sensitivity to downslope displacement. Coherence can be adversely affected on these slopes because more pulses are reflected away (*specular reflection*), but as long as reasonable surface roughness is present, this tends not to be an issue.
- *Shadow*. Slopes facing away that are steeper than the look angle (angle between nadir and the look direction) are completely obscured to the satellite (*shadow*).

Figure 2.7 illustrates the effects of foreshortening, layover, and shadow in a radar intensity image.

Such geometric effects are easy to simulate using an accurate Digital Elevation Model (DEM). These are available as open source or proprietary data products. Prior to an InSAR monitoring project, a DEM can be used to model all available satellite passes to evaluate which provide the best coverage. A coverage and downslope displacement sensitivity map can be provided to the client.

InSAR Geometry

In addition to the side-looking geometry of single SAR passes, the relative geometry between passes is also important for InSAR. Recall that interferograms are the per-pixel phase difference between two radar images and constitute the fundamental observable for InSAR analyses (Bamler and Hartl 1998). The satellite position can

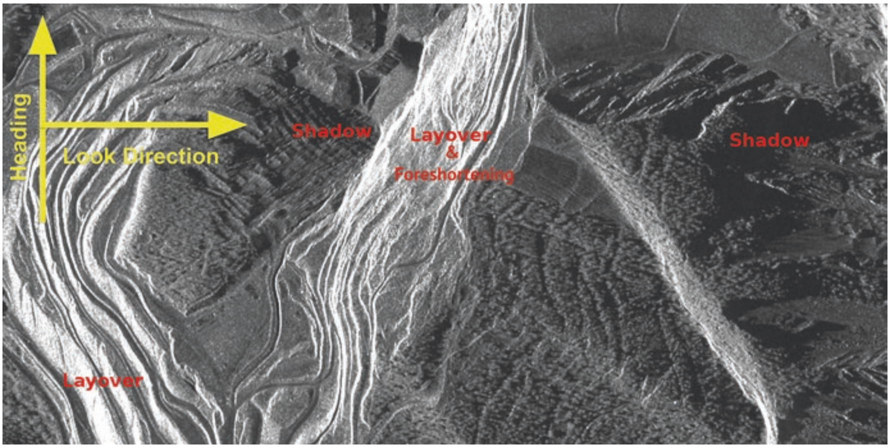

Fig. 2.7 Regions of foreshortening, layover, and shadow manifest in areas with topography as bright areas. They are bright because of simultaneous signal returns and more pulses returning to the sensor. Dark areas facing away produce fewer returns or no returns if the slope is steep enough to be occluded from view

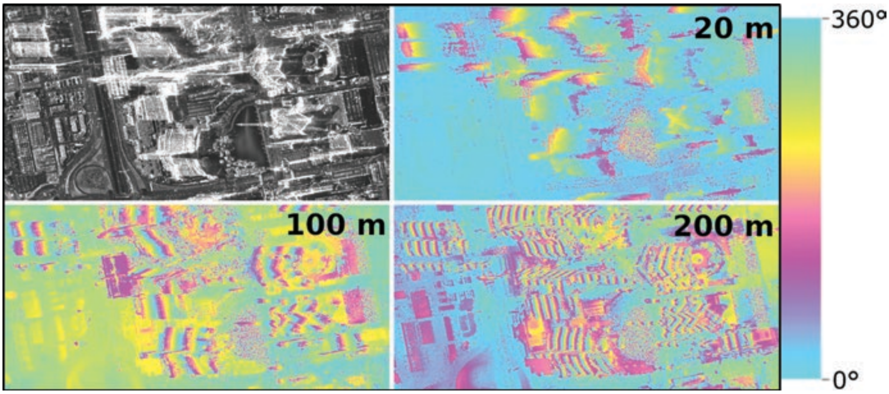

Fig. 2.8 Skyscrapers along the Las Vegas Boulevard appear as bright structures in a radar intensity image (top left). As these buildings are not represented in the DEM, they generate a response in interferograms seen as phase cycles termed *fringes*. The number of fringes present is proportional to the interferometric baseline. Three examples are shown with baselines of 20 m, 100 m, and 200 m

change by hundreds of metres between satellite passes. Surface topography (defined here to include buildings or structures) manifests in interferograms as spatial phase changes, and by an amount proportional to the distance between the two sensor positions at acquisition time (the interferometric baseline). Figure 2.8 shows how larger baselines are more sensitive to topographic effects. The main purpose of the DEM in InSAR is to model and remove this unwanted effect in each interferogram. DEMs are never perfect, and a residual effect typically remains, especially if the DEM is dated or coarser resolution than the SAR data. In the case shown, an excellent correction to the DEM can be estimated because the images are coherent, the topography is unchanging, and the effect is highly systematic; it scales linearly with the size of the baseline.

For any given pixel, if coherence is high and the surface topography is unchanging, a good correction to the DEM is trivial to determine using linear regression, if ten or more images are available. However, surface topography in places like open pit mines not only changes, but the interferograms are less coherent in those areas, because they are changing. Solutions to this problem are more challenging, but data redundancy, rejecting large baseline interferograms, and restricting the timespan of the stack all help.

Atmospheric Effects

Phase differences in interferograms arising from ground displacement are of primary interest, but may be contaminated with phase differences due to atmosphere, ionosphere, snow, and soil moisture. If the displacement signal dominates over sources of error, it can usually be isolated and quantified with high precision. If the displacement is subtle or the contamination is high, isolating displacement becomes more challenging.

Phase changes due to non-homogeneous water vapour in the troposphere are common (Hanssen 2001), but stormy conditions produce more extreme phase turbulence. In these cases, atmosphere can mask the onset of new displacement, and more time is required for the displacement signal to raise above the higher noise levels. Figure 2.9 shows three examples of phase turbulence due to tropospheric water vapour, shown for both C- and X-band interferograms. The X-band data, with its shorter wavelength, is more easily perturbed.

In addition to water vapour in the troposphere (wet or hydrodynamic atmosphere), phase delays also occur due to pressure changes with altitude, known as *hydrostatic atmosphere*, hereafter referred to as dry atmosphere. This is easier to remove as it is highly correlated with height and can be modelled using the DEM (Bekaert et al. 2015).

Other sources of error are now discussed.

- Phase effects due to the ionosphere are typically only seen with longer wavelength sensors in data covering high latitudes (Woodhouse 2006).
- Consistent snow cover between winter images may still provide good coherence if the snow is dry, but the resulting data is biased due to variations in snow density, depth, and ice content. The most common solution is to simply exclude data

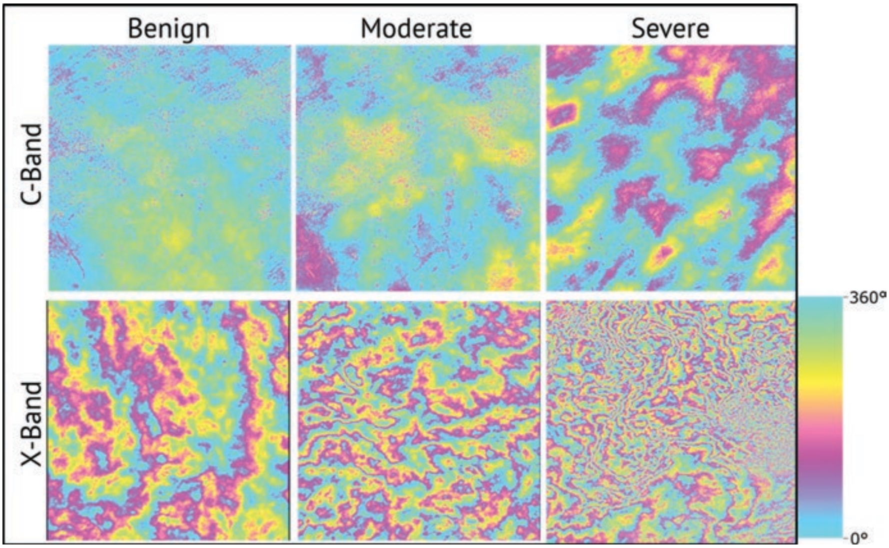

Fig. 2.9 Non-homogeneous atmospheric water vapour manifests as phase variance in interferograms. Phase variance increases as sensor wavelength decreases. As variance increases, the onset of subtle displacement becomes harder to detect

during snow-covered periods. Coherence is very low during snow fall and snow melt due to the absence of repeatable targets.

- Soil moisture signals due to irrigation or water drainage are a nuisance and are most notable in agricultural areas.

Wavelength

SAR satellites operate in the microwave portion of the electromagnetic spectrum; the peak-to-peak length of the wave is known as its wavelength and represents the measuring stick for estimating ground displacement. Wavelengths are grouped into lettered bands for ease of referencing. The most common wavelengths used are 3.1 cm (X-band), 5.6 cm (C-band), and 23.6 cm (L-band). InSAR can capture tiny movements from a thousand kilometres away through the analysis of per-pixel phase values. These phase values can be conceptualised as fractions of a wavelength (see Fig. 2.1), which are subtracted between images to produce an interferogram. Shorter wavelengths are more sensitive to displacement, but also more sensitive to other effects including scattering from vegetation and atmospheric turbulence. Strong displacement over a small area can cause *aliasing*; this is analogous to contours of displacement densifying to the point where they become superimposed. This leads to underestimation in the results, and longer wavelengths may be desirable in these cases.

Areas containing trees cannot be monitored with X-band because returning pulses are randomised by foliage; therefore, the targets are not repeatable. Longer wavelengths are able to penetrate vegetation, reflecting from underlying targets such as tree trunks or bare soil.

Choosing an appropriate wavelength is very important when developing a monitoring plan, but the availability of satellites also affects this choice. Currently, X-band satellites are the most numerous and commercially viable, followed by C-band; there is only one L-band satellite. The number of redundant satellites available affects the risk level and data collection capacity for a project.

Phase Unwrapping

As discussed in What is InSAR, the phase difference values for each pixel are bounded between 0° and 360° degrees. This means that the displacement estimates that result are also inherently bounded; between 0 and 1.5 cm for satellites with X-band wavelengths. Figure 2.10 left shows an X-band interferogram with a displacement zone with an associated colourmap scaled between 0° and 360°. Three clear phase cycles or *fringes* can be seen, with a red transect line passing through the displacement zone. Phase values for pixels along the transect are plotted on the right

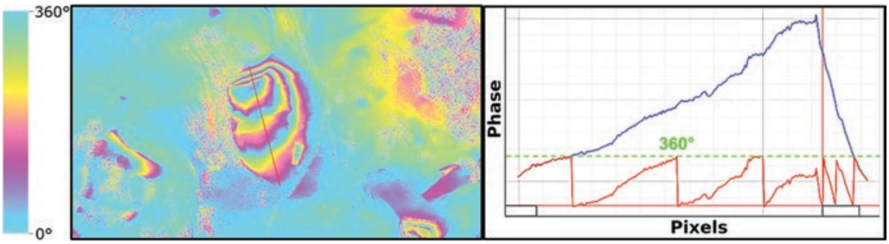

Fig. 2.10 Left: An interferogram with a displacement zone in the centre, and a red transect line passing through it. Right: Phase values along the red transect line produce a sawtooth plot (also red) because the values are natively bounded between 0° and 360°. Successful unwrapping integrates phase values spatially to recover higher magnitude displacement (blue line)

in red; values steadily grow in magnitude, but abruptly return to 0° once they reach 360°. This is termed as *wrapped phase*.

It is trivial here for a human observer to estimate an unbounded displacement maximum, simply by counting the fringes and multiplying by 1.5 cm. To do this algorithmically, for all pixels, given an assumed starting point, is known as *phase unwrapping* (Ghiglia and Pritt 1998). This two-dimensional counting process works to recover the unbounded phase values shown by the blue line in Fig. 2.10 right.

Despite the simplistic example shown, accurate phase unwrapping represents the biggest challenge for InSAR processing. Displacement zones can be complex, with discontinuities or entirely segregated regions due to incoherent areas, and the process must be conducted in two dimensions.

Resolution

For optical imagery, spatial resolution is defined by the smallest resolvable object. For InSAR, however, it is better defined as the minimum distance between adjacent targets. Note that neither of these involves pixel spacing, which could be arbitrarily oversampled, without affecting the level at which objects can be resolved or the actual distance between targets. Pixel spacing is, however, often used synonymously with spatial resolution, and usually their values are close. In reality, spatial resolution for InSAR changes depending on the angle of the terrain (see SAR Geometry) and the distribution of measurable objects within the bounds of each pixel.

Figure 2.11 illustrates spatial resolution by comparing InSAR results derived from 3 m and 20 m SAR data; optical imagery is shown for reference.

Spatial resolution has progressively improved over time; typical resolution was over 20 m in the 1990s, 8 m in the 2000s, and 3 m currently. Metre and sub-metre resolutions are also available on current satellites, but coverage decreases with increasing resolution (similar to a zoom lens on an optical camera).

Resolution is also used in a temporal context; the temporal resolution of a SAR satellite, also known as its revisit period, indicates how long before the satellite can

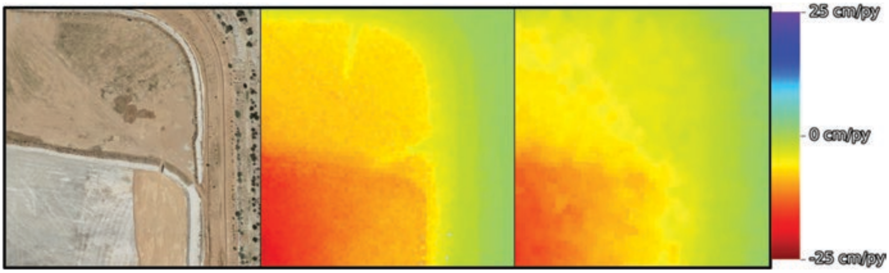

Fig. 2.11 Left: optical imagery of a tailings storage facility. Centre: a displacement heat map from 3 m TerraSAR-X data. Right: the same result for the same period using 20 m Sentinel-1 data. Whilst magnitudes are similar, some smaller features are lost in the Sentinel-1 results. Optical image credit: Google Earth, Landsat/Copernicus

collect data over the same position on the ground. Revisit has also improved over the decades, starting from 35-day revisit in the 1990s, to 24-day in the 2000s, down to 4-day currently. Many modern satellite missions (TSX, Cosmo, Sentinel, RCM) operate in constellations of identical sensors that are interchangeable and can, therefore, revisit more frequently. For example, the Cosmo constellation from the Italian Space Agency comprises 4 satellites with 1-, 3-, 4-, and 8-day revisit, for an average revisit of 4 days. Higher temporal resolution provides opportunities to maintain coherence over dynamic land cover, and also better supports operations at active sites by providing higher quality and more timely monitoring data.

Displacement Sensitivity

InSAR is inherently one dimensional; displacement is measured in the line of sight of the satellite. Displacement for a target moving down a slope that happens to exactly coincide with the look direction, can be fully captured. In general, however, this will rarely be the case, and InSAR will underestimate the real displacement (Pepe and Calò 2017). This is not particular to InSAR, but true for any dimensionally restricted technology, such as levelling or Electronic Distance Measurement (EDM). Figure 2.12 illustrates the issue with a simplified sliding block scenario. Despite usual underestimation, slopes that face away from the look direction provide good opportunities for InSAR monitoring, slopes that face the radar, on the other hand, do not (see SAR Geometry on page 9).

The best workaround for capturing better displacement estimates, as well as providing better coverage, is to image an area of interest from two directions, one looking east (usually ascending passes) and one looking west (usually descending passes). From these two independent LOS measurements, a direction of displacement can be solved in the east-west-up-down plane. The ascending and descending displacement vectors can then be co-projected along the solved vector, not only providing directional information, but also increasing the displacement magnitude

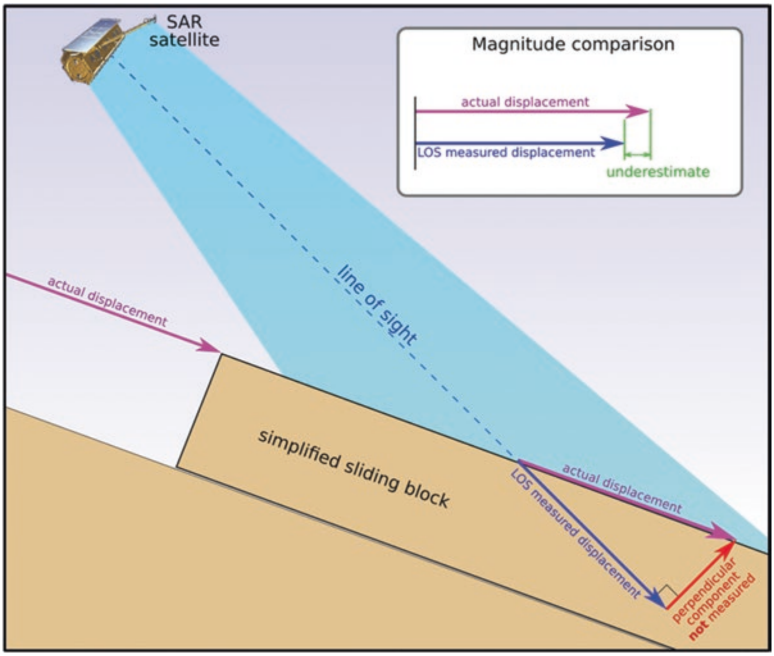

Fig. 2.12 A simplified sliding block displacement scenario. InSAR underestimates the actual displacement, because it only captures the component that is along the LOS

appropriately. Note that the north-south direction is not considered because this is nearly the flight path of the satellite and there is no displacement sensitivity along this axis.

Satellite Options

InSAR monitoring programs are typically conducted in two stages, a historical archive analysis to check site suitability and establish a baseline, followed by ongoing monitoring to highlight emerging risks. Spaceborne SAR satellites have existed since the 1990s; many satellites had good default data collection worldwide, enabling historical analysis for very little cost as older data are generally free. Figure 2.13 shows all of the SAR satellites that are currently viable for operational monitoring. The planned lifetime of a SAR satellite is generally 7 years, and actual lifetimes vary around this number. The data from a given satellite is self-contained due to variations in wavelength and look direction between satellites. Exceptions to this exist when satellites are specifically cloned from one another and launched along the same orbit track (e.g. TSX and PAZ). Results from different sensors *can* be combined, but issues can occur if the resolutions differ significantly.

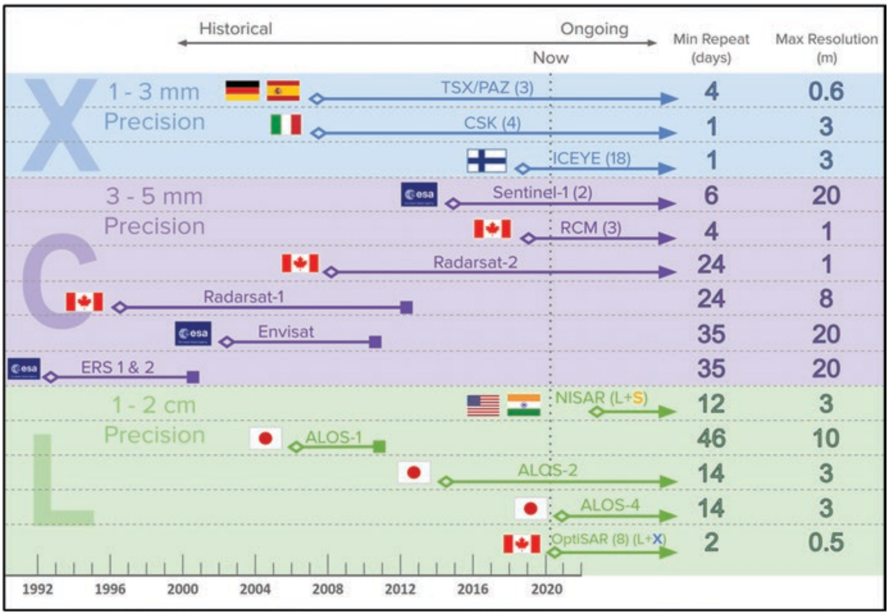

Fig. 2.13 Key specifications of historic and currently operational satellites. Lower precision satellites in L-band wavelengths are the only option for densely vegetated areas. Higher precision satellites in C- and X-band wavelengths can achieve good results over open ground and urban areas

2.2 Case Studies

This section draws on the InSAR characteristics already presented to show how they can influence site evaluation. A number of case studies are discussed, starting with an overview of the project, followed by a site evaluation. Key results are illustrated at the end of each case study.

Seattle Tunnelling

An engineering construction project in Seattle, WA, USA, involved extensive tunnelling through the downtown area using the largest tunnel boring machine (TBM) in the world, named Bertha (nicknamed Big Bertha by the media). The TBM stalled in December 2013 after hitting a steel pipe and InSAR results captured up to 60 mm of displacement. This radiated outward for more than a kilometre, characteristic of displacement caused by groundwater pumping, which was necessary to repair Bertha. The widespread displacement affected local terrestrial benchmarks used as reference stations to monitor subsidence, which resulted in an underestimate from terrestrial survey results. Table 2.1 provides an overview of the case study.

Table 2.1 Overview of the Seattle tunnelling case study

Characteristic	Comment
Targets	The Seattle metropolitan area has dense urban infrastructure such as houses and roads, and superstructures such as skyscrapers and bridges. Urban infrastructure provides excellent permanent targets for InSAR monitoring over years and decades. Snow is rare, making uninterrupted monitoring the norm
Topography	The area has very little topographic relief, but dense skyscrapers in the downtown core cause blind spots due to layover and shadow. The topography is static, thus errors in the DEM (e.g. over infrastructure) can be readily corrected once 15–20 images have been collected
Sources of error	• Dry atmosphere is a non-issue due to flat terrain. Wet atmosphere is not expected to be overly turbulent, consistent with coastal mid-latitude areas • Soil moisture effects are not expected (no agriculture/drainage) • Seattle experiences little to no snow, thus year-round monitoring is expected
Wavelength	Urban infrastructure provides excellent targets for any radar wavelength; C-band and X-band are the best choices for higher precision. Smaller wavelength data will generate noisy measurements over parks and golf courses, and no measurements over areas with trees
Resolution	High spatial resolution (3 m or better) is necessary in order to generate distinct returns from densely packed infrastructure. Weekly imaging is desirable to detect the onset of accelerations due to groundwater extraction, and also to amass the data required to mitigate atmospheric and DEM errors
Known displacement	Information regarding previous displacement is not available
Satellite options	• ALOS-2 (L-band) is unsuitable for detecting subtle displacement • Sentinel resolution is too coarse for monitoring infrastructure • TSX, CSK, and Radarsat-2 are good choices for monitoring infrastructure, but provide no coverage over vegetation. Radarsat-2 has a long revisit (24 days) which may not suffice during the most dynamic time periods

Historical high-resolution Radarsat-2 data was available prior to and during the tunnelling activities, which was ideal for establishing a baseline and characterising the impact of tunnelling and associated groundwater extraction. 35 images were available between February 2013 and August 2015 and results are shown in Fig. 2.14.

Aqueducts and Aquifers

The California Aqueduct transports water over 640 km and is the backbone of the California State Water Project. The aqueduct crosses through the Tulare Lake Basin, in which water is pumped from underground aquifers. Government agencies regulate aquifer pumping as well as monitoring the condition of the aqueduct. Table 2.2 provides an overview of the case study.

TSX was chosen due to the availability of pre-existing archive data. Forty images covering two 1500 km^2 areas during 2015 and 2016 were analysed to produce a

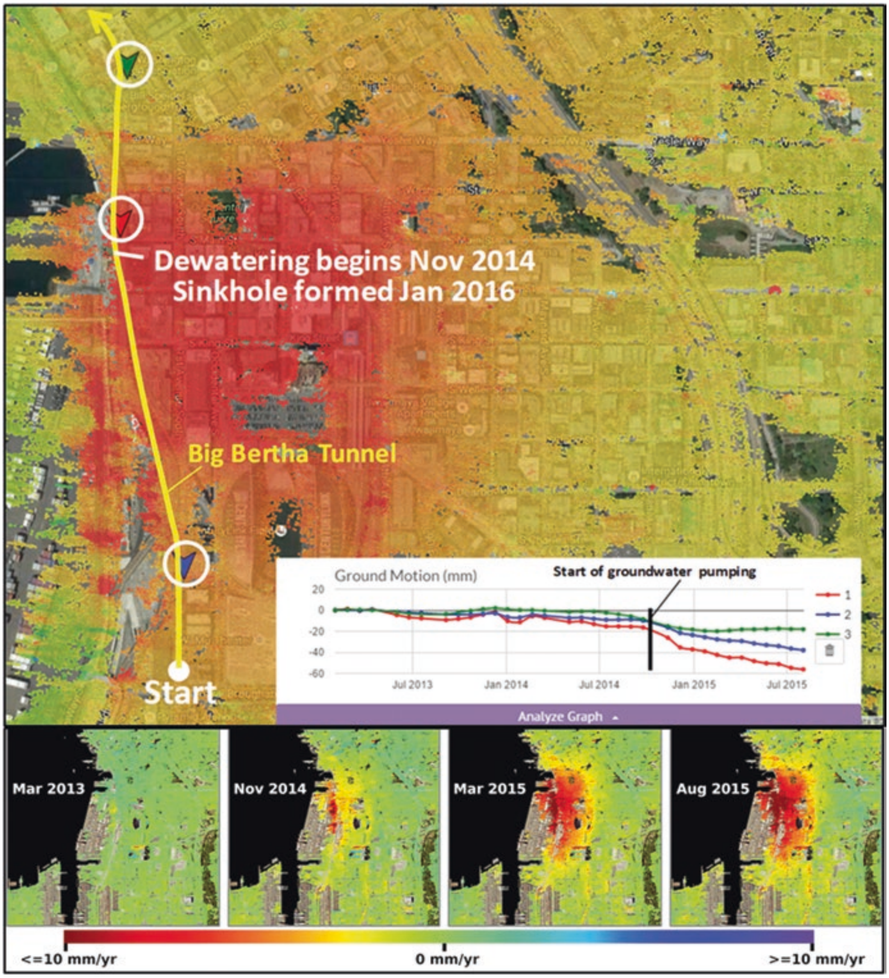

Fig. 2.14 Top: InSAR results over Seattle indicate the onset of displacement coinciding with groundwater pumping following the stall of the Bertha TBM. Bottom: From December 2013 to October 2014, the ground displaced 10–20 mm along the route of the TBM. In November 2014, the ground suddenly began sinking significantly, with up to 60 mm of line-of-sight displacement occurring over the next 9 months. Optical image credit: Google Earth, Landsat/Copernicus

high-resolution (3 m) displacement map over 85 km of the California Aqueduct. A low-resolution map was also produced at 30-m resolution to reveal large-scale displacement across the entire 3000 km^2 area. Five large displacement zones were identified, each with displacement rates exceeding 5 cm/year and a combined area greater than 500 km^2. Results for an example displacement zone are shown in Fig. 2.15. Almost 20 km of the California Aqueduct is within these large

Table 2.2 Overview of the Seattle tunnelling case study

Targets	The aqueduct traverses hundreds of kilometres over mostly agricultural fields but some arid land as well. Permanent Targets are expected from arid land as well as isolated lampposts, fences, roads, canal infrastructure (e.g. pumping stations, bridges, canal banks, etc.), and scattered small buildings. Targets over agricultural fields, which are subject to crop cover, resetting by soil turnover and soil moisture. The area does not receive snow
Topography	The agricultural areas are relatively flat and significant geometric effects are not expected. Single look monitoring is, therefore, adequate. The topography is unchanging, hence a recent publicly available DEM suffices
Sources of error	• Significant soil moisture effects are expected over agricultural fields • Dry atmosphere effects should be insignificant, except for the hilly areas. Wet atmosphere has turbulence typical for mid-latitudes • Ionospheric effects can manifest at mid-latitudes; some ionospheric changes may appear if long-wavelength L-band images are used
Wavelength	L-band would achieve the best coverage by penetrating vegetated areas. However, X-band or C-band will be more sensitive to subtler displacement at the expense of some coverage
Resolution	Low resolution is sufficient for aquifer related subsidence, but 3 m or better spatial resolution is needed for monitoring small displacement features on the aqueduct itself. Biweekly images are sufficient as gradual displacement over time is expected (see next)
Known displacement	No site-specific information was available, but displacement magnitudes and gradients are typically low for aquifer applications
Satellite options	• C-band options are not ideal; Sentinel-1 with 20-m spatial resolution is too coarse; Radarsat-2 has high-resolution modes, but its 24-day repeat is limiting • ALOS-2 L-band data would make a good option archive data where already available to build upon • Both CSK and TSX are good options for generating a perforated displacement map with coverage over infrastructure and bare land with high spatial resolution and displacement sensitivity

displacement zones. The high-resolution map revealed two additional small (100 m) localised areas of the aqueduct that were subsiding.

Northern Alberta: Pipelines

Pipelines in Northern Alberta traverse hundreds of kilometres of challenging terrain subject to landslides and seasonal changes. Operators are interested in characterising geohazards throughout the area that threaten pipeline integrity, and planning routes for future pipelines. Sprawling pipeline infrastructure in remote areas is difficult to monitor effectively and efficiently using ground-based techniques. Table 2.3 provides an overview of the case study.

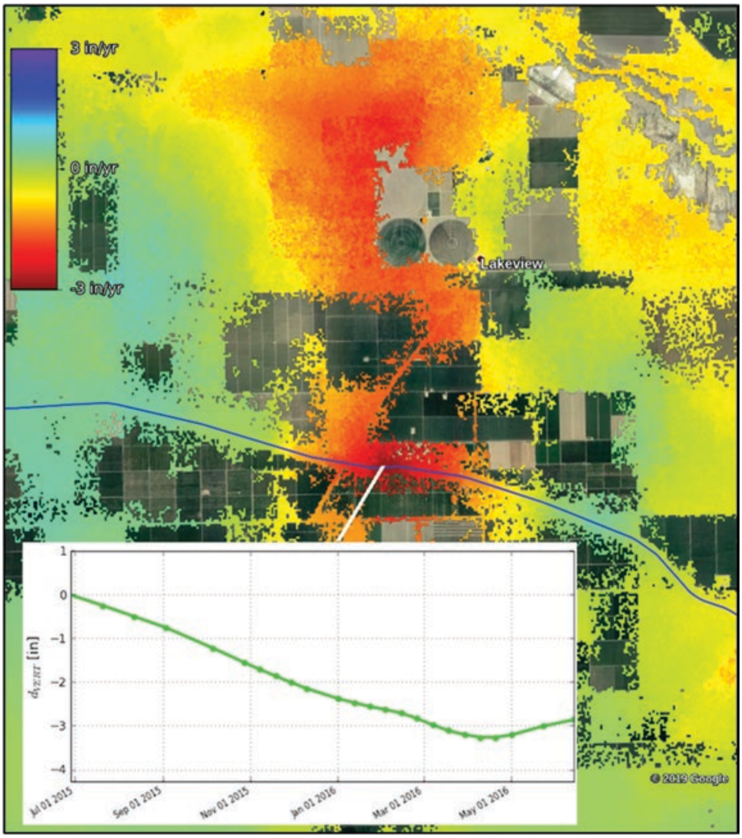

Fig. 2.15 Ground displacement along the California Aqueduct (blue line). Good coverage was achieved over bare ground and man-made infrastructure including the aqueduct itself using TSX data. Agricultural fields exhibited lower coverage due to crop cover and soil turnover, and also higher noise due to soil moisture effects. The results cover an area measuring 3000 sq. km and indicate multiple large displacement regions. Optical image credit: Google Earth, Landsat/ Copernicus

ALOS-2 was not commercially operational at the time of this project. 3vG analysed 17 ALOS-1 images, acquired between February 2007 and March 2011. Despite its lower resolution (15 metres), and its long temporal repeat (46 days minimum), displacement of 2–10 cm/year was evident over pipeline assets and surrounding terrain. Displacement histories for 18 million points were generated.

Seven thousand square kilometres of terrain were almost fully mapped for displacement, identifying numerous geohazards along the pipeline right of way. Excluding water bodies, spatial coverage was near complete. A landslide that had impacted the pipeline was clearly identified in images prior to the event; the known extent of this landslide matched well with InSAR results (see Fig. 2.16). Another

Table 2.3 Overview of the Alberta pipelines case study

Targets	The terrain in the area of interest is highly vegetated and dotted with lakes and swamps. Permanent Targets from processing facilities and other infrastructure are few and far between. The area receives heavy snow annually, limiting the InSAR monitoring period. Ground conditions following snow do not necessarily re-establish, limiting long-term measurements
Topography	The area is mostly flat and geometric effects are, therefore, not expected. The topography is unchanging and hence a recent publicly available DEM is sufficient to remove topographic effects from interferograms
Sources of error	• Dry atmosphere variations should be insignificant as the area is flat. Wet atmosphere can be turbulent if short wavelength sensors (X- or C-band) are used • At these latitudes, significant ionospheric changes may appear if long-wavelength L-band images are used • Significant soil moisture effects due to drainage, lakes, and agriculture are common in such terrain • Snow signals are expected in images with partial or full snow cover
Wavelength	L-band data is the only viable option for monitoring. The longer wavelength penetrates vegetation, possibly even interlinking measurements across the snow season each year. Sub-cm level precision will not be possible as precision is a function of the wavelength (see wavelength section). In agricultural areas, farming activity can reset targets and limit coverage even with L-band imaging
Resolution	High-resolution imaging (3 m or better) is needed as local fast-moving displacement is likely present (see next)
Known displacement	Pipelines in the area have been previously affected by small landslides. Seasonal soil dynamics over water-rich ground were also known to stress the pipeline
Satellite options	• TSX, CSK, Radarsat-2, and Sentinel are not useful due to short wavelengths • ALOS and ALOS-2 are the only options for historical and ongoing monitoring, respectively

landslide that was being monitored with ground-based methods was also accurately mapped. Seasonal freeze/thaw cycles in water-rich areas manifested as uplift/subsidence hotspots in the InSAR data; strong displacement gradients exist at the boundaries of such areas and can stress the pipeline.

Southwest USA Copper Mine

This open pit copper mine in southwest USA is very typical for the region, with large copper reserves of medium to low grade. Mining activity such as blasting, excavation, dumping, leeching produce some of the highest levels of displacement for any InSAR application, commonly reaching 100 cm/year or more. Much of the displacement is expected, but surprise events can occur also and geotechnical engineers often use InSAR to warn of concerning displacement before can affect safety or production. Table 2.4 provides an overview of the case study.

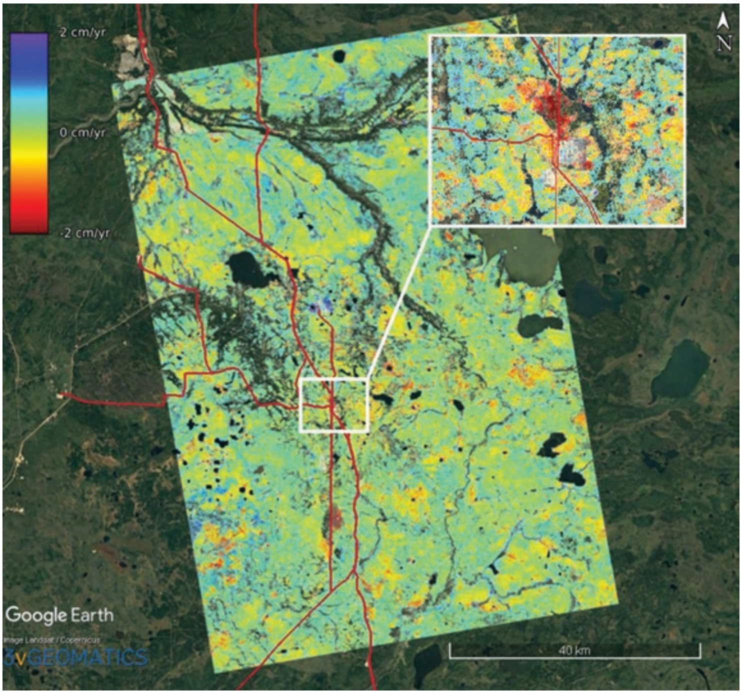

Fig. 2.16 Displacement results along pipeline rights of way in Northern Alberta using archived L-band ALOS-1 SAR data. The results provided a proof of concept for the pipeline operators, and the inset area shown is one example of a known geohazard captured by the InSAR results. Optical image credit: Google Earth, Landsat/Copernicus

TSX was chosen due to the availability of pre-existing archive data. Ninety-two ascending and ninety descending images were available, from July 2016 to April 2019, both data sets were utilised in order to derive displacement direction on slopes. A high-resolution (3 m) displacement map over the mine was produced (Fig. 2.17 left), as well as solved direction estimates for all pixels covered by both directions and with significant displacement (Fig. 2.17 right).

Following this initial baseline report, regular ongoing reports were provided. These were in the form of Rapid Reports, which provide a snapshot of displacement since the previous image, as well as quarterly Comprehensive Reports, providing displacement time series information and directional information as shown.

2.3 Summary

InSAR can be an effective tool for operational monitoring; its biggest advantage lies in mapping vast areas that would be prohibitive to monitor by more traditional means. A careful consideration of factors on the ground, such as the type of cover, the characteristics of the displacement activity, and the topography of the area are

Table 2.4 Overview of the southwest USA copper mine case study

Targets	The mine property covers 100 km^2 over arid terrain with practically no vegetation. Permanent targets are expected from boulders and infrastructure while many other areas will provide high quality distributed targets. Many targets will be temporary, due to mining activity. The area does not receive snow, but a turbulent atmosphere in late summer is likely to leave high residual noise in the data, despite attempts to remove it, and this might bias target selection
Topography	Many slopes exist, some steep enough to provide foreshortening, layover, and shadow effects, especially the pit. Elevation for some areas is expected to change over time, especially on stockpiles, dumps, and the two adjoined pits. The DEM should have resolution comparable with the chosen SAR data and be contemporary with it also. This is often available from the site personnel, but coverage may need to extend with the best open-source DEM data available
Sources of error	• Errors in the DEM are expected to grow significantly over time —Solving errors in the DEM using the InSAR data is straightforward for areas that are coherent over time —For less coherent, DEM updates every 6 months will aid unwrapping and displacement estimation —Processing shorter periods of no more than 3 months at a time will minimise DEM corrections going stale • Soil moisture effects are expected in the rainy summer period • Dry atmosphere effects will be significant, especially in the pits. Wet atmosphere can be highly turbulent in August and September • Ionospheric effects are not expected • The chance of unwrapping errors will increase in proportion to the magnitude displacement for an area
Wavelength	X-band will work well in the arid, vegetation free environment, providing high precision results
Resolution	High-resolution data of 3 m or less is required to capture and help identify small localised displacement areas
Known displacement	Many known areas of displacement exist, and most are displacing at magnitudes where prior knowledge is not required. A critical areas of interest from the site will help focus InSAR analysts when producing reports
Satellite options	• C-band options are not ideal; Sentinel-1 with 20-m spatial resolution is too coarse; Radarsat-2 has high-resolution modes, but its 24-day repeat is limiting • ALOS-2 L-band is not precise enough • Ascending and descending CSK or TSX are good options. Data from both ascending and descending directions is required to improve coverage, displacement sensitivity, and provide displacement direction information • Careful consideration of satellite incidence angles is required to optimise coverage and sensitivity to displacement on slopes

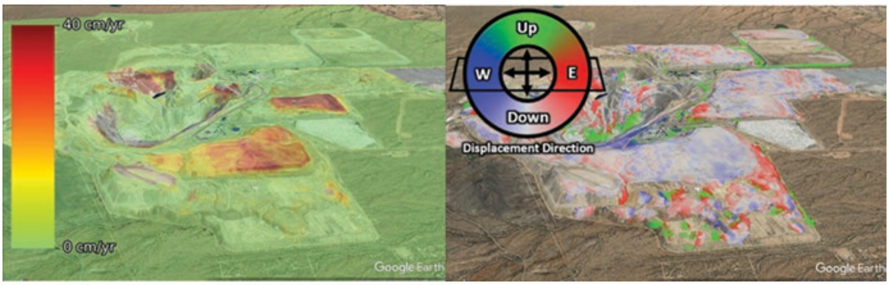

Fig. 2.17 Left: High magnitude displacement over a copper mine. Right: Data from both ascending and descending directions provided information regarding the direction of displacement in the up-down-east-west plane. Optical image credit: Google Earth, Landsat/Copernicus

required for success. These help to narrow down and inform data choices in terms of wavelength, resolution, and satellite look geometry.

These and other ground and satellite characteristics have been discussed to help laypeople to assess the applicability of InSAR for their site. Real-world case studies have been included to show examples of this decision process.

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