The capabilities and limitations of satellite InSAR and terrestrial radar interferometry

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1 Abstract

There are numerous challenges associated with monitoring natural terrain and man-made structures. Established geodetic and geotechnical survey techniques require surveyors and engineers to consider issues such as site access, permits, human safety and labour costs. Overcoming these considerations drives the exploration of new and innovative technologies which can provide accurate and reliable measurements from a distance, without the need to interact with the survey target.

The use of commercially available satellite Interferometric Synthetic Aperture Radar (InSAR) techniques, capable of remotely mapping and monitoring millimetric to metric levels of movement associated with e.g. landslides and buildings, has increased in line with technological advances in satellite sensors and platforms. Recently launched high resolution Synthetic Aperture Radar (SAR) satellites now make it possible to acquire higher spatial resolution imagery, more frequently, and at relatively low cost.

Despite the capabilities of satellite InSAR techniques, a major limitation is their inability to monitor natural terrain and man-made structures on-demand and in near real-time. Terrestrial radar interferometry approaches overcomes this constraint.

This paper describes the capabilities and limitations of satellite InSAR and terrestrial radar interferometry techniques and illustrates their use through a number of example applications.

2 Introduction to satellite InSAR and terrestrial radar interferometry

Radar instruments emit pulses of electromagnetic radiation in the radio and microwave part of the electromagnetic spectrum and detect the reflection of the pulses from objects in its line of sight. A radar signal can be imagined as a sine wave, which contains both amplitude and phase information (Figures 1 & 2). The amplitude is the strength of the radar response. The phase is the fraction of a complete sine wave cycle. When the sine wave starts to repeat itself, one phase cycle has occurred.

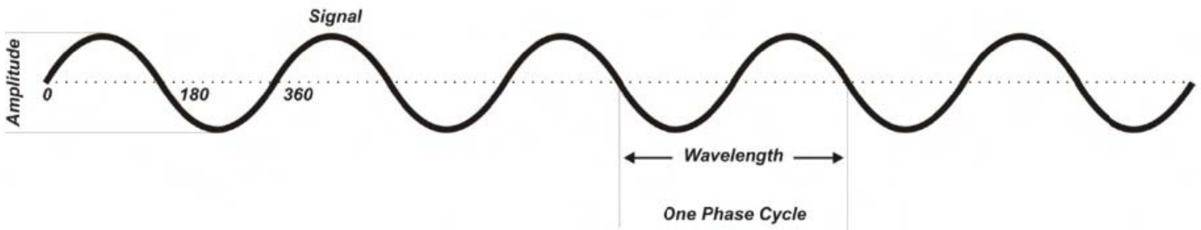

Figure 1: Radar signal - amplitude and phase

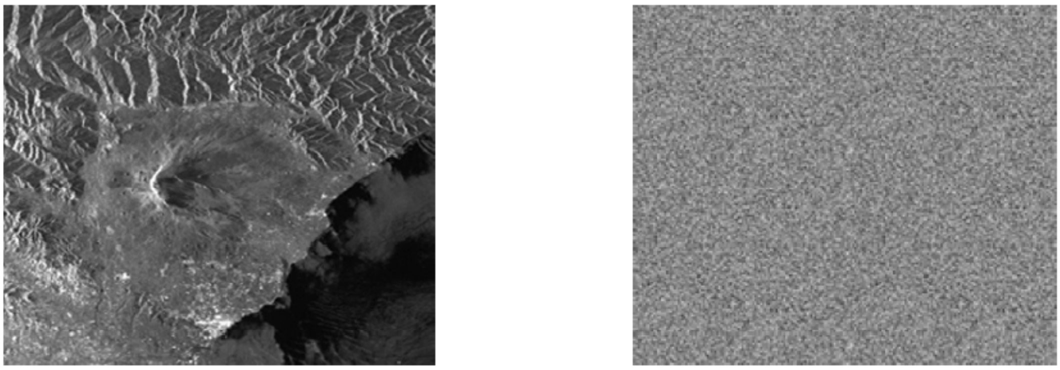

Figure 2: Left - amplitude image, Right - phase image

Synthetic Aperture Radar (SAR) is a type of imaging radar which is usually satellite-based, but can also be used on airborne or terrestrial platforms. SAR uses the relative movement between the radar and imaging target to synthesize the antenna aperture. As the radar travels through space, pulses are transmitted and the movement causes the return echoes to be Doppler-shifted. Comparing the Doppler-shifted frequencies to a reference frequency allows multiple return echoes to be focused on a single point. This creates the same effect as having a much larger physical aperture and allows satellites orbiting hundreds of kilometres in space to have spatial resolutions ranging from 100s m down to 1 m.

SAR satellites cycle in near-polar orbits and image the Earth from an ascending (south to north) or descending (north to south) pass. The SAR sensor is right-looking with respect to the flight direction of the satellite. Figure 3 shows the geometry of a SAR acquisition.

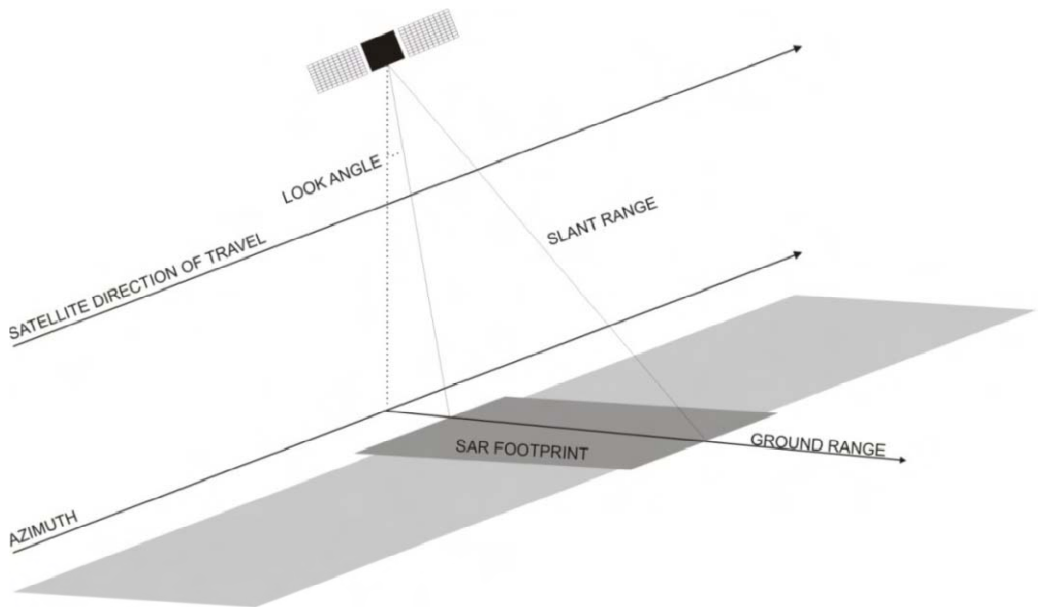

Figure 3: Satellite SAR imaging geometry

Radar can be transmitted at a number of different wavelengths. The most common SAR satellites transmit C-band radar (5.6 cm), but X-band (3.1 cm) and L-band (23.6 cm) SAR instruments are also available. The wavelength and active nature of the system means that SAR imagery can be acquired day and night, and in all weather conditions.

Since the outgoing radar wave is produced by the instrument, the signal phase is known, and can be compared to the phase of the return signal. The phase of the return depends on the distance to the ground (or objects upon it), as the length to the ground and back will consist of a number of whole wavelengths plus a fraction of a wavelength. This is observable as a phase difference in the returning wave. The total distance to the instrument (i.e. the number of whole wavelengths) is not known, but the extra fraction of a wavelength (the phase) can be measured precisely.

If we collect two separate images of a point on the ground from exactly the same position in space, with nothing on or around the point changing, the two signals would be expected to have the same radar amplitude and phase values. In practice, the position of the satellite between two image acquisitions is never identical, and the corresponding difference in the path (distance between the satellite and the ground) results in a phase shift between the two signals. The difference in position of the satellite between image acquisitions is known as the perpendicular baseline.

SAR interferometry (InSAR) makes use of phase information by subtracting the phase value in one SAR image from that of the other, for the same point on the ground. The resulting phase difference is directly related to the topography and any movement of the ground in the direction of the satellite, but is also affected by atmospheric effects present in the SAR images, errors in estimating the position of the satellite in space and system noise. The phase values combine to form fringes across the image. The interferometric fringes can be thought of as a collection of contours, with each fringe corresponding to a phase difference of 0 to 360° (0 - 2π). The resulting image is called an interferogram.

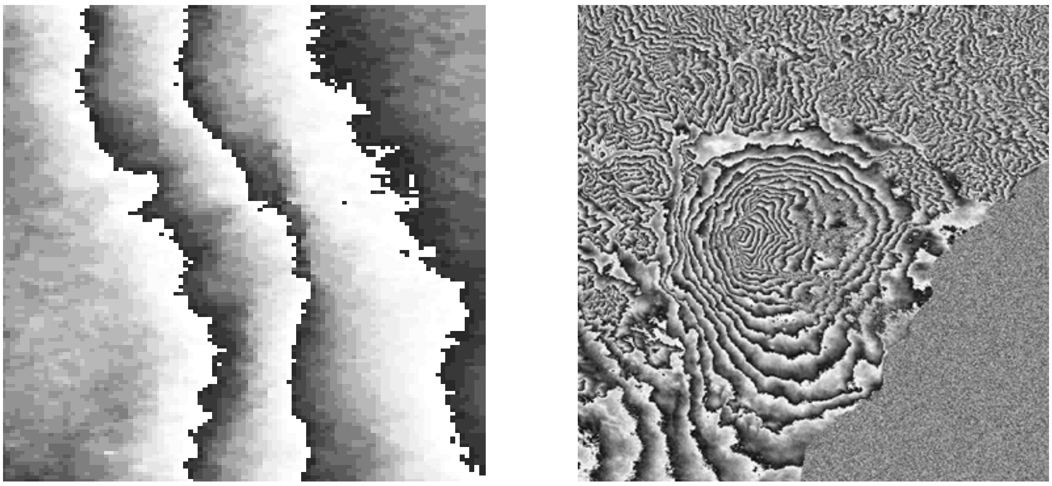

Figure 4: Left - interferogram with interferometric fringes across relatively flat area. Right - interferogram with interferometric fringes tightly spaced fringes in a mountainous region.

InSAR generally involves extracting the topography or deformation while removing or minimising the errors and uncertainties.

Terrestrial radar interferometry can be used to map and monitor near real-time ground and structure to a sub-millimetric level of accuracy. Terrestrial radar interferometry systems can be either real aperture or synthetic aperture.

Each terrestrial radar interferometry acquisition is captured as a complex image; made up of both amplitude and phase information. Using two (or more) acquisitions, it is possible to create a map of phase difference, which, like the satellite systems, has components related to topography, deformation, atmosphere and system noise.

Unlike satellite SAR, where orbital information needs to be calculated and the resulting models may be subject to error, the re-positioning of a terrestrial radar system is negligible, and therefore the topographic component of the phase difference may be ignored. This means that the main sources of error when using terrestrial radar come from atmospheric effects causing changes in the signal path delay, and system noise. Over short periods of time, when the atmosphere may be assumed to be relatively stable, it is possible to obtain results at a sub-millimetric level of accuracy, although errors related to atmosphere become more apparent when imaging over greater distances.

3 Comparison between techniques

Differential interferometry (DifSAR) is used to estimate the ground deformation that has occurred between two SAR image acquisitions. By using a pre-existing Digital Elevation Model (DEM) such as that produced by the Shuttle Radar Topography Mission (SRTM) it is possible to estimate and subtract the interferometric phase contribution caused by topography. Orbital trends are easily removed and system noise is negligible. This means that the phase difference is determined primarily by deformation and atmospheric effects. Water vapour in the atmosphere delays the radar signal and causes a change in the path length of the signal which affects the phase; when the ground moves this also causes a change in the path length of the signal. With only two SAR images it can be difficult to differentiate between the contributions made to the phase by deformation and atmosphere. By using existing information about the location and expected deformation rates it is generally possible to accurately map ground deformation. It is also possible to rely on the fact that often atmosphere is spatially but not temporally correlated while deformation is both spatially and temporally correlated. The maximum phase contribution from atmosphere will be approximately 1-2 cm which causes DifSAR to have an accuracy of 1-2 cm, even though it is sensitive to movements on the millimetric scale.

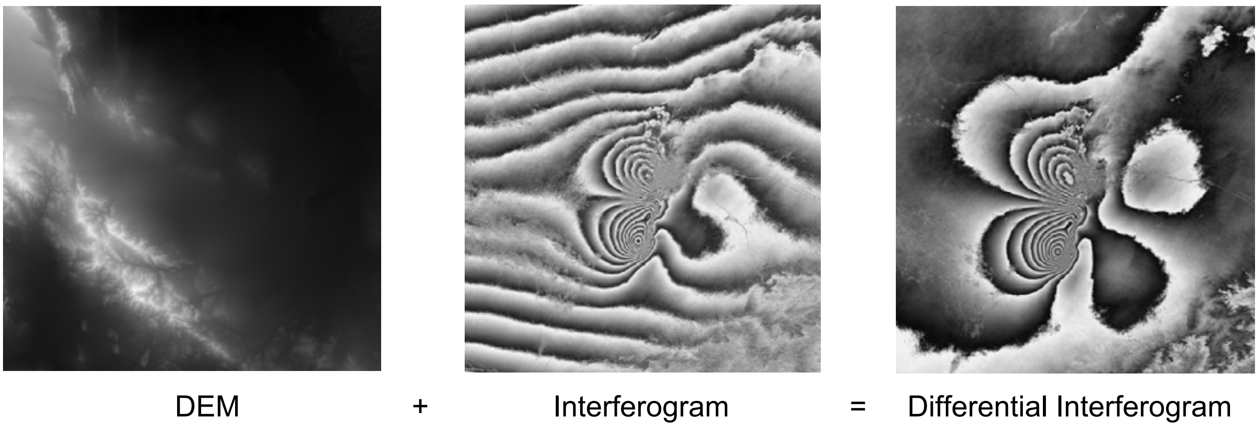

Figure 5: 2-pass differential interferometry where a DEM is used to subtract the topographic component resulting in a differential interferogram with predominantly deformation signals present.

Persistent Scatterer Interferometry (PSI) is an advanced InSAR technique. It requires large stacks of SAR images (typically 20 or more) and works by identifying individual points on the ground which reliably and persistently reflect the radar signal back to the satellite. These points are known as Persistent Scatterers and the phase value at each of these points is analysed rather than the value of the pixel as in DifSAR. Persistent scatterers generally correspond to man-made infrastructure such as buildings and bridges making this technique ideal for monitoring urban areas, larger man-made structures or installations, as well as rocky outcrops.

The topographic and orbital contributions are removed first from the overall phase data. Using a linear least-squares regression the linear deformation and errors in topography are calculated, and then iteratively improved. The remaining phase data is composed of non-linear deformation, atmospheric effects and noise. As discussed above, non-linear deformation is both spatially and temporally correlated, whereas atmospheric effects are spatially correlated but not temporally correlated, so filtering is applied to extract the non-linear deformation and estimate the atmospheric effects. The linear and non-linear deformations are combined to give the result. The output for each persistent scatterer is an average annual motion with an accuracy of 1-2 mm/yr and a time series of displacements with an accuracy of 4-6 mm.

Rural areas used for agriculture or forest typically do not contain persistent scatterers. Where few natural persistent scatterers exist in the area of interest, corner reflectors can be installed to provide artificial radar scatterers for use in PSI analyses. Corner reflectors are usually trihedral and vary in size depending upon the radar wavelength they are designed for. In addition to increasing persistent scatterer density, they can be deployed in individual monitoring networks. When they are deployed over small areas, atmospheric effects may be assumed as uniform or linear and may therefore be modelled giving millimetric accuracy results without using a large stack of data.

Figure 6: Trihedral corner reflector

Terrestrial radar differential interferometry uses the same technique used in conventional satellite differential interferometry, however as mentioned in the introduction; the baseline component of the total phase difference is negligible as the repositioning of the system is accurate to less than 1 mm. The main difference between the two techniques is the measurement frequency, where currently the shortest re-visit time for satellite interferometry is approximately 3 days; terrestrial radar has a measurement frequency of less than 1 minute. This rapid measurement frequency lends itself to the monitoring of rapidly deforming ground and structures.

4 Capabilities

There are many considerations, capabilities and limitations associated with satellite InSAR and terrestrial radar interferometry. Every project is unique, and requires a subtly different approach.

Satellite SAR image footprints vary in size and extent and when compared with ground based surveying the wide area coverage is unrivalled. One of the most common image footprint sizes is 100 x 100 km allowing vast areas to be monitored with relative ease. Higher spatial resolution images (down to 1 m) typically have smaller footprint sizes.

Satellite InSAR allows remote monitoring which can be extremely useful and cost-effective when the area of interest is difficult for human access, whether this is due to climate, location or perceived health and safety risk.

Different techniques can be used to deliver different levels of accuracy depending upon project requirements. Satellite InSAR is capable of centimetric to millimetric levels of accuracy while terrestrial radar interferometry is capable of sub-millimetric accuracy.

Ground deformation is measured in the line of sight of the satellite. Although this is sufficient for many applications there are instances when the need to distinguish between vertical and horizontal deformation is required. By utilising SAR images from both ascending and descending orbits and different imaging modes, multiple look angles are obtained which makes it possible to resolve the vertical and horizontal components of deformation.

SAR data archives exist back to 1992, making it possible to retrospectively map ground deformation. This can prove invaluable in establishing environmental baselines and for validating and enhancing risk models.

Terrestrial radar interferometry systems are capable of monitoring objects up to 8 km away. This allows the user to set up the system at a safe distance and monitor multiple areas from one location.

The accuracy of terrestrial radar systems can be further improved by the installation of local reference points (e.g. corner reflectors), near to the area of interest, which will mitigate the atmospheric influence experienced between the terrestrial radar system and the area being monitored.

Terrestrial radar interferometry can provide real-time mapping of movement and displacements of a specific structure or over large areas (several square kilometres) in one dimension. Using two or more systems it is possible to derive measurements in two or three dimensions.

5 Limitations

Coherence is a measure of similarity of the ground cover radar response between two SAR or terrestrial radar images. In desert or urban areas there are very few changes and this results in high levels of coherence. Conversely, the growing of crops in agricultural areas, vegetation in rural areas, snowfall, destruction of infrastructure during natural disasters and other variables that cause the ground cover to change significantly will result in low coherence between images. Areas of low coherence will provide unreliable measurements and will generally be excluded from a final result. Coherence naturally degrades over time so acquiring data with a short temporal spacing is the best way to mitigate this issue.

Phase values are measured on a repeating scale from 0 - 360 degrees (0 - 2π radians) as it is only the fraction of a complete wavelength (phase cycle) that is known. Each phase value therefore needs to have the correct multiple of 2π added to it to go from the "wrapped" state where the phase values can only be 0 to 2π to the "unwrapped" state where the phase values can take any value from 0 to $\Phi + n2\pi$, where Φ is the phase value and n is an integer. This process is known as "unwrapping" and is the most important aspect of InSAR and terrestrial radar processing. Errors in the unwrapping mean that the unwrapped phase value is incorrect and therefore the deformation result will also be incorrect.

There are limits to the magnitude and spatial extent of deformation features that InSAR can detect. This depends upon temporal and spatial resolution of the data and the magnitude and extent of the deformation. Phase gradients from pixel to pixel should be as small as possible. A subsidence bowl that is only tens of metres across would cause extremely high gradients from pixel to pixel and when this gradient becomes greater than π it is impossible to determine the correct multiples of 2π to add to the phase value, causing unwrapping errors and an incorrect deformation estimate. Data with a high spatial resolution results in more pixels covering the same phase gradient making the gradient between the pixels smaller and unwrapping easier. Small subsidence areas of subsidence that deform quickly with high magnitudes of motion will have steep phase gradients resulting in unwrapping errors. By having short temporal separations between images the magnitude of deformation is smaller, which in turn makes the phase gradients smaller, increasing the chances of phase unwrapping. The ideal situation is to have high temporal and spatial resolution data as this keeps phase gradients as low as possible.

The near-polar nature of the satellite orbits means this line of sight images the ground from the east or west, capturing any deformation occurring in these directions. However any component of ground deformation oriented north-south will not result in motion towards or away from the satellite and InSAR will be insensitive to this motion.

Terrestrial radar interferometry is also only capable of measuring the deformation occurring in the line of sight of the system. As the system is located on the ground, it is least sensitive to motion perpendicular to the look direction of the system.

SAR data archives vary depending on the satellite and location on Earth. Some satellites such as ERS-1 and ERS-2 have built up substantial SAR archives that are suitable for PSI. Other satellites only acquire data to order, meaning there are limited quantities of data which makes PSI less feasible. Descending data stacks are much more common than ascending data stacks because the satellite is often in darkness on the ascending pass so the solar panels are not generating power. While on the descending pass the satellite is in sunlight so there is enough power to acquire more data. This means that only certain locations have had enough ascending and descending data acquired to allow the successful analysis of the vertical and horizontal components of deformation.

Satellite InSAR is not an ideal technology for real-time measurements. Although it’s technically possible to generate an interferogram a few hours after image acquisition there are a number of logistical hurdles that make this extremely difficult.

Significant variations in topographic height can cause distortions in SAR images because of the oblique viewing geometry of the SAR instrument. Hill or ridge slopes facing the SAR satellite can be subject to distortions, known as foreshortening and layover that are expressed as a compression or "thinning" of slopes facing the SAR satellite. The same hills and ridges can also act to obscure areas from view when they are facing away from the satellite, known as shadowing.

The resolution in azimuth of a terrestrial radar system decreases with range. For real aperture systems the resolution, for Ku-band (1.76 cm) radar, is 7m at 1km and for synthetic aperture systems it is 3.5m at 1km, provided the length of the synthesised aperture for one system is the same as the real aperture for the other.

Other limitations of terrestrial radar interferometry include increased noise due to vegetation, line of sight obstruction and un-resolvable atmospheric artefacts.

6 Typical Applications

InSAR's wide area capabilities make it ideal for monitoring large areas. Fugro NPA's *motionmapNL* product is a PSI result covering the whole of the Netherlands. It was produced by combining 8 stacks of SAR data and contains over 2.5 million persistent scatterers. Ground settlement corresponding to gas fields and salt mining are visible, as well as the effects of ground water recharge into disused mine sites, resulting in ground heave.

Figure 7 shows PSI data for central London spanning 1992 - 2001. Two linear subsidence features are visible. One corresponds to tunnelling for the extension to the Jubilee Line for London Underground, and the other results from cable tunnelling. Open spaces such as Hyde Park, Regents Park and Richmond Park may be identified by their lack of persistent scatterer coverage.

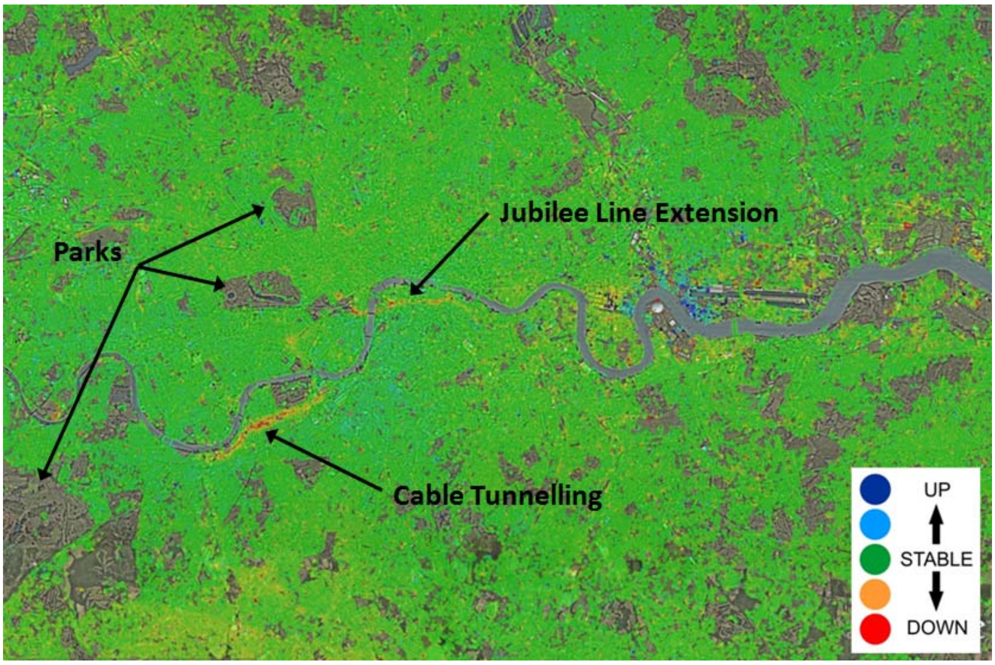

Figure 7: PSI result for London, England from 1992-2001. The result has been spatially interpolated and styled according to the average annual motion. Data © Fugro NPA 2011, Background image © Bluesky, TeleAtlas, Google 2011

Figure 8 shows a zoom-in of the London data shown in Figure 7. The image shows buildings are persistently and reliably reflecting the radar signal back to the satellite so the locations of persistent scatterer points generally correspond to the buildings where as the open areas (e.g. parks) contain few or no persistent scatterer points.

Figure 8: Zoomed in section of the London PSI result showing a linear settlement feature and the individual persistent scatterer points which are styled according to their average annual motion. Data © Fugro NPA 2011, Background image © Bluesky, TeleAtlas, Google 2011

Fugro NPA have used PSI data to help assess the impact of climate change induced sea level rise and land subsidence. The Thames Estuary 2100: *"Absolute Fixing of Tide Gauge Benchmarks and Land Levels: Measuring Changes in Land and Sea Levels around the coast of Great Britain and along the Thames Estuary and River Thames using GPS, Absolute Gravimetry, Persistent Scatterer Interferometry and Tide Gauges"* project (Bingley et al., 2007), helped to improve flood risk models for the Thames Gateway region by accounting for PSI-derived subsidence measurements (high vertical accuracy), combined with GPS measurements (high horizontal accuracy); sea level rise of 1 mm/year was adjusted to account for ground subsidence of ~2 mm/year, the result being an average, net sea level rise of ~3 mm/year across the region.

The terrestrial radar interferometry data in Figure 9 show the response back to the radar at a sand quarry, with the far side of the quarry located at a distance of 500m. Using terrestrial radar it is possible to create a DEM by introducing a baseline offset into the measurements, Figure 9 shows the resulting fringes relating to topography. The last image in Figure 9 shows a deformation field (wrapped between $-\pi$ and $+\pi$) created using two acquisitions with a temporal offset of 9 minutes.

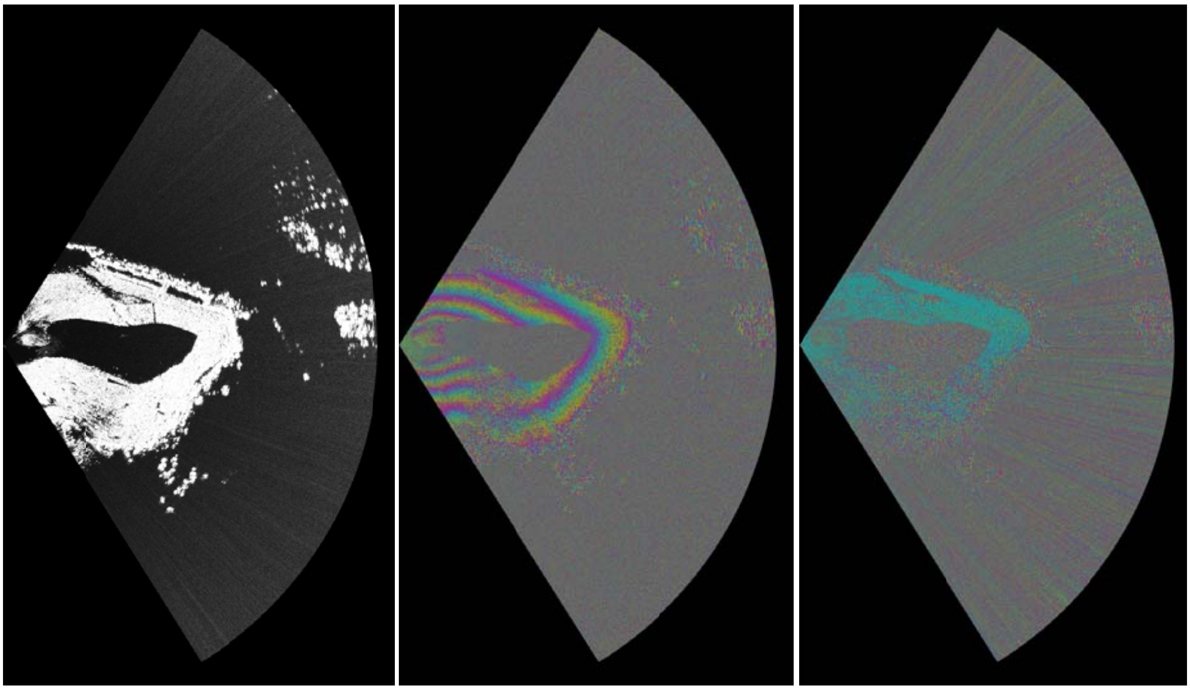

Figure 9: Radar amplitude image (left), topographic map (middle) and an interferogram (right), of a sand quarry imaged using a terrestrial radar system.

7 Future satellites

Sentinel 1 will consist of a constellation of two C-band radar satellites operated by the European Space Agency. The first satellite is planned to be launched in 2013 followed by the second a few years later. It will have a similar resolution to the Envisat ASAR instrument (~30 m) but with wider swath coverage allowing routine SAR acquisition initially every twelve days, increased to every six days once both satellites are in orbit. It is also anticipated that Sentinel-1 data will have an open access policy further adding to the cost-effectiveness of InSAR.

The L-band ALOS-2 and the Argentine SAOCOM radar satellites are currently at the planning stage and are expected to become available over the coming years. Continuity of X-band SAR data has been confirmed until 2020.

8 Summary

Satellite InSAR and terrestrial radar interferometry are two innovative technologies that have a wide range of applications, although like all technologies, they have their inherent capabilities and limitations.

The ability to remotely, accurately and cost-effectively monitor small deformations across thousands of square kilometres is unique to satellite InSAR.

Terrestrial radar interferometry provides a highly accurate and on-demand monitoring capability that can balance out some of the limitations of satellite InSAR.

Each and every project is different, and a clear understanding of the limitations, especially unwrapping and coherence, is essential in providing reliable results.

The techniques continue to improve, with new terrestrial radar systems being developed, and several new InSAR satellites scheduled for launch.

R. Bingley *et al*.; Absolute Fixing of Tide Gauge Benchmarks and Land Levels: Measuring Changes in Land and Sea Levels around the coast of Great Britain and along the Thames Estuary and River Thames using GPS, Absolute Gravimetry, Persistent Scatterer Interferometry and Tide Gauges, April 2007*, Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme.*

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