Almost everything you need to know about...

Applying satellite SAR data in the construction sector

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INTRODUCTION

CONSTRUCTION INDUSTRY CHALLENGES

- Health & safety
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"The rate of musculoskeletal disorders is higher in the construction sector than across all industries."
Health & Safety Executive (2021).

Construction is one of the world economy's largest sectors, accounting for 13% of global GDP. Construction operations are undertaken on infrastructure, property and industrial facilities. It has a sorry reputation for the slow adoption of new technology and hanging on to traditional practices but, thankfully, that is changing. Nevertheless, the sector still faces major challenges.

Health & safety

Construction safety has improved significantly over recent generations thanks to a complete change in culture – just search for some archive construction footage to see how! However, accident rates are still higher than all-industry averages and contractors have set themselves zero-harm targets to help drive down the rates even further. Technology, such as improved digital training content, wearable technology and offsite construction are already helping.

Recent years have seen an increased focus on occupational health. 3.4% of construction workers suffered work-related ill-health between 2018 and 2021 according to the UK Health and Safety Executive (HSE), with most cases being musculoskeletal disorders or mental health problems such as stress, depression or anxiety. This has led to industry-wide initiatives such as the international Health in Construction Leadership Group.

Figure 1. A healthy workforce is a happier and more productive one.

"The built environment and construction sector accounts for 38% of global carbon emissions." COP26 (2021).

"Urgent action is required to decarbonise construction if the sector is to play its role in meeting the 2050 net zero target." Royal Academy of Engineering (2021).

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Decarbonisation

The pledges from the COP26 climate summit need to turn into action for them to have any impact at all. Thankfully, many construction stakeholders, both large and small, have set themselves ambitious net-zero carbon targets and the work has started already. Key is to invest in innovation and technology and to challenge the traditional solutions and methodologies. The huge proportion of global carbon emissions from the construction sector means that if we fail, everybody loses.

Figure 2. Hurricane Katrina recovery, New Orleans, 2005.

Productivity

The construction industry has long faced the day-to-day challenges of tight deadlines, cost overruns, a competitive market and squeezed profit margins. All these can be addressed by improved productivity, but it has grown by just 1% in the last 20 years compared with 2.8% in the total world economy. For too long the construction sector has not prioritised innovation and held on to traditional processes. Technology that provides real-time data for informed decision-making needs to be embraced to overcome the productivity hurdle.

"Productivity growth in construction has averaged only 1% a year over the past two decades." McKinsey and Co. (2017).

Figure 3. Technology providing real-time data improves productivity.

Labour shortage

"Workforce shortages are severe and having a significant impact on construction firms." AGC (2021).

According to the Associated General Contractors (AGC) of America, 88% of firms were experiencing project delays in 2021 and the second highest cited reason was labour shortage. About nine out of ten experienced difficulties filling both craft and salaried professional positions which is back to pre-COVID19 levels. The situation is unlikely to improve on its own with the median age of people working in construction in 2020 at 42.9, compared with just 36 in 1985, according to the US Bureau of Labor Statistics. If a sufficiently large new generation cannot be attracted to the construction industry to meet the shortfall, technology must be embraced to enable more to be done with fewer people.

SATELLITE BASICS

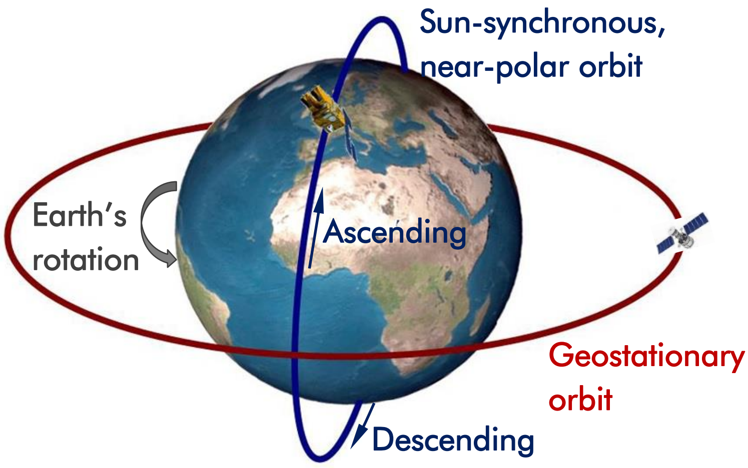


Figure 4: Satellite orbits

Satellite orbits

Most people know the geostationary orbit (at about 35,800 km altitude) that keeps a satellite over the same point on the Earth's surface by taking 24 hours to complete each orbit. Most SAR satellites, however, are in a lower (600-800 km altitude), near-polar orbit which takes 96-100 minutes to complete (Figure 4). They are called sun-synchronous because as the Earth rotates below, the satellite passes over each latitude at the same time of day. This helps to reduce variability between successive images that might otherwise occur if they were taken at different times of the day. When the satellite is travelling north-south it is said to be in a **descending** orbit and when it is travelling south-north it is said to be in an **ascending** orbit. Both ascending and descending SAR images are taken at most locations on the Earth's surface.

Satellite views

Satellites view the Earth's surface either directly down (nadir view) or at an angle from the vertical (off-nadir or side-looking) as shown in Figure 5. All SAR satellites are side-looking and tend to point to the right of their direction of travel. This means that ascending and descending images of the same area are taken from the west and east respectively (Figure 6), but not at the same time. Some satellites are even pointable, so they view the Earth at a range of angles which allows them to be tasked to record images of an area at more regular intervals.

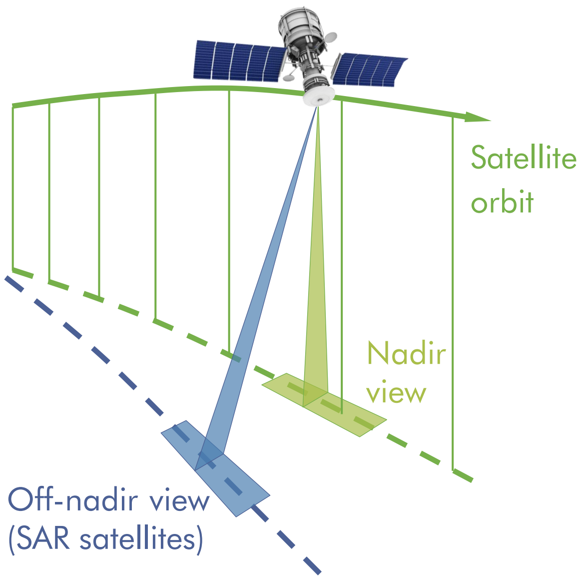


Figure 5. Satellite views

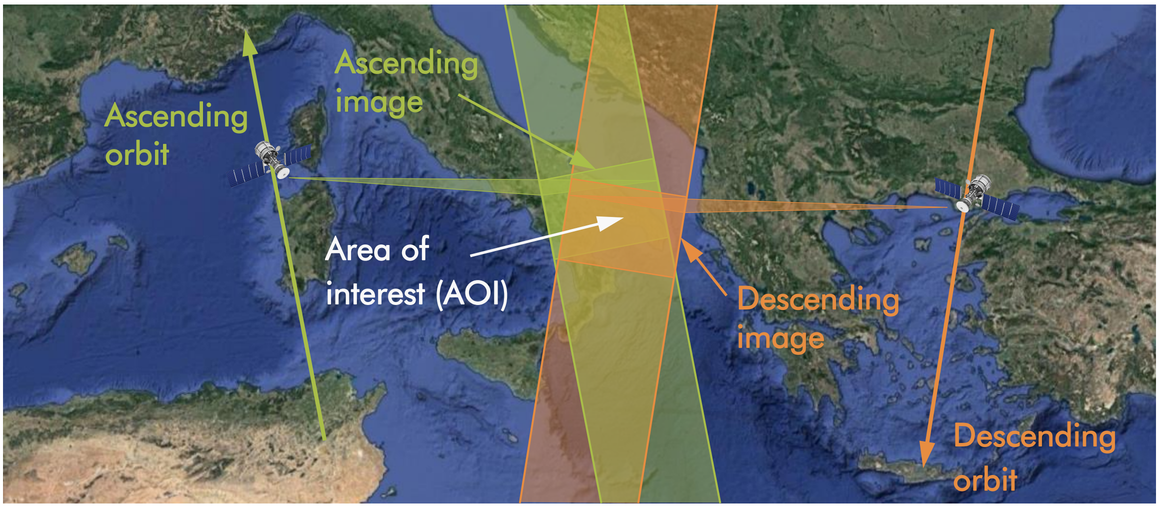


Figure 6. Acquiring ascending and descending SAR images of the same area of interest

SAR

SAR stands for Synthetic Aperture Radar. "Radar" because it transmits electromagnetic waves and receives reflections from objects to determine their distance or range (Figure 7). "Aperture" is another term for the antenna that transmits and receives the electromagnetic energy – the bigger it is the better the spatial resolution. The aperture size on satellites is restricted by practical considerations so in order to achieve sufficiently useful spatial resolutions, a "synthetic" aperture is employed meaning that a sequence of acquisitions from a shorter antenna as the satellite moves through space is used to simulate a larger antenna to improve the spatial resolution.

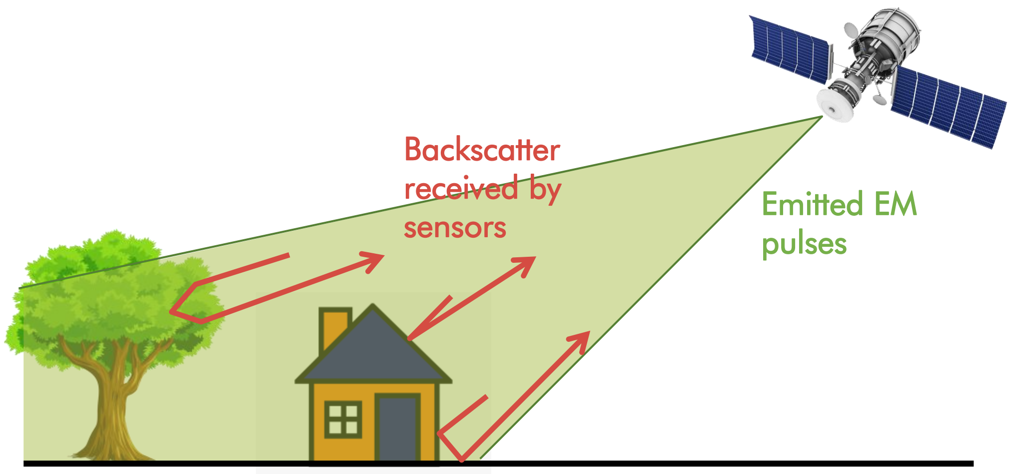


Figure 7. The all-important "radar" part of SAR

Wavelengths

Earth observation satellites have either passive sensors that detect reflected solar and infra-red energy from the Earth's surface or active sensors that emit their own electromagnetic energy and detect what is reflected back (backscatter – as shown in Figure 7).

Passive sensors operate in the ultra-violet, visible and infra-red portions of the electromagnetic spectrum. Active sensors (including SAR) operate at longer wavelengths in the microwave portion which allows them to operate in all weather conditions (including cloud cover), day and night.

What satellite SAR can do…

- Measure ground surface and structure displacements for a high density of points over large areas.
- Measure changes in soil moisture for a high density of locations over large areas.
- Determine historical values of displacement and soil moisture from archived satellite images going as far back as 1991.
- Do all this at reliable time intervals, no matter what the weather, day and night.
- Assess infrastructure asset condition across entire networks quickly, regularly, consistently.

What satellite SAR cannot do…

- Measure displacement and soil moisture of objects hidden from the line of sight of the satellite (e.g. deep below the ground surface or under a dense forest canopy).
- Measure displacement at specific, predetermined locations (unless corner reflectors are installed).
- Measure displacement and soil moisture accurately while surface textures are changing (e.g. during earthworks, snow cover or planting new vegetation).
- Measure displacement and soil moisture continuously (typical intervals are 1 to 6 days).

COMPARE APPROACHES

In this chapter the three main approaches to measuring displacement and other physical parameters for construction projects are compared. These approaches may be applied both to the monitoring of construction activity (e.g. the settlement of an embankment being constructed on soft ground) or in site investigation. Each method is rarely used in isolation since their attributes complement each other. For example, satellite SAR data provides quick, broad coverage of the ground surface while sensors may be installed at specific locations of interest to obtain more detailed information, including below the ground surface.

This chapter includes a brief description of each approach and a comparison is summarised in the table on the following page.

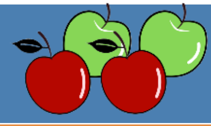
Conventional survey and sensors (visit-based and continuous)

Conventional surveys involve measuring the position of points or targets visible to the instrument (usually a total station) relative to each other and to a reference point. Subsequent measurements are used to detect displacement relative to the initial reading. The subsequent measurements may be taken periodically by repeat visits to the site with a total station or more frequently by a robotic station installed permanently throughout the monitoring period.

To measure displacement at locations not in the line of sight (LOS) of an instrument, including beneath the surface, instruments or sensors may be installed. Examples include tiltmeters and strain gauges, while sensors also exist for a range of other physical properties including humidity, temperature and pressure. Readings from these may be taken either periodically by repeat visits to the site or an a near-continuous basis by recording data to a local datalogger or via mobile networks to a cloud server. For example, lateral displacement of an inclinometer tube installed in the ground may be recorded by a portable probe brought periodically to the site or continuously by vibrating wire tilt sensors installed permanently within the tube.

A visit-based monitoring regime has relatively low cost for short durations because the measuring equipment can be used on multiple sites or rented. It becomes expensive for long durations and more frequent visits, particularly in remote locations, due to the demand on labour, for which a continuous monitoring regime may be more economical. Permanent installations need to be well protected from adverse weather, construction activities, vandalism and theft.

COMPARE APPROACHES



	Visit-based survey and sensors	Continuous survey and sensors	Ground-based LiDAR	Mobile or Airborne LiDAR	Satellite SAR
Description	Monitoring of key parameters by total stations and sensors taken to the site on each visit.	Robotic total stations and sensors installed at the site for continuous monitoring for a defined period.	Obtain 3D surface model. Measure displacements on successive surveys.	Obtain 3D surface model. Measure displacements on successive surveys.	Measurement of displacement and soil moisture across ground surface at regular intervals.
Detect historical trends	No	No	No	No	Yes
Spatial resolution	Single point at each target or sensor	Single point at each target or sensor	Very high, up to about 600 points per m^2.	Very high, up to about 600 points per m^2.	Low
Displacement accuracy	High. Depends on method.	High. Depends on method.	~3cm	~5cm	~2-4mm (time-series), ~3cm (interferogram)
Access	Regular site visits.	Installation and maintenance only.	Regular site visits.	Regular site visits.	No visits.
Equipment	Portable measuring equipment.	Installed sensors.	Portable measuring equipment.	Vehicle-mounted measuring equipment.	None.
Measurement frequency	Low	Continuous	Low	Low	Medium
Vulnerable to vandalism, theft	Possibly	Yes	No	No	No
Data costs	Per visit.	Installation and maintenance.	Per visit.	Per visit.	Free or varies (commercial data).

LiDAR (ground-based, mobile and airborne)

Light detection and ranging (LiDAR) or 3D laser scanning emits pulses of near-infrared laser light to measure ranges to surfaces such as the ground surface, vegetation and buildings. The short wavelengths generate high resolution point clouds with 3D coordinates that are post-processed into 3D models of surfaces. Only points in the line-of-sight (LOS) of the instrument can be captured so multiple scans from different locations are needed to record all features. It can operate day or night but dust, smoke and precipitation affect its accuracy. It can penetrate through gaps in vegetation cover and careful post-processing can strip out such surface features to reveal the terrain.

LiDAR is particularly suited to establishing the detailed 3D geometry of a construction site in the form of a digital surface model (DSM) or, with vegetation and building features removed, a digital terrain model (DTM). It covers large areas quickly at a fraction of the cost of manual surveys but does need good weather windows for maximum data quality.

It is less suited to precise displacement measurement because of the difficulty of following the same flight path on successive visits, maintaining the same point density and accounting for changes in vegetation. Typically, about 4 to 5 cm accuracy can be obtained.

LiDAR instruments can be ground-based, mobile (mounted on road or rail vehicles to survey linear infrastructure) or airborne (on unmanned aerial vehicles (UAV) or drones, helicopters or fixed-wing aircraft.

Satellite SAR data

Satellite SAR data, which is described more fully in the next chapter, is the only technique that does not require any visit to the asset, giving it the distinct advantages of being the safest technique with the lowest carbon footprint. It provides regular data in all weathers across large areas of all the ground surface and built environment that is visible to the satellite. Therefore, it does not provide data at locations well below the surface (e.g. tunnels) and may not provide data at locations obscured by dense vegetation.

Another key advantage of satellite SAR data is its ability to perform retrospective measurement because satellite images are being recorded all the time. This is particularly useful for site investigation where trends can be detected without needing to wait repeated on-site surveys to accumulate sufficient data, as illustrated in the following case study.

CASE STUDY 1

City of Dreams, Limassol

An integrated resort (IR) comprises a hotel and casino combined with other facilities for conventions, retail and dining. The City of Dreams Mediterranean in Limassol will become the largest IR in Europe when it opens its doors in Summer 2022. It includes vast areas of swimming pools and landscaping and it was these parts of the development that needed a special blend of satellite analysis and engineering expertise to identify the right engineering solution.

Trial pit showing the clay and water table

THE CHALLENGE

- The ground conditions comprised a high plasticity clay and the groundwater level was shallow and fluctuated due to nearby extraction for irrigation. All ideal conditions for damaging heave and subsidence of the ground surface.
- To avoid damage to the proposed swimming pools and landscaped areas on shallow foundations, the plan was to excavate several metres of the clay and replace with granular fill across the whole site – costing around €300k.

THE SOLUTION

- Additional site investigation to determine the clay's swelling potential across the site more precisely.
- Retrospective InSAR analysis to measure actual heave/subsidence in recent years.
- Engineering reappraisal of the risk posed by the ground conditions, negating the need for the costly ground improvement.

THE BENEFITS

- Significant reductions in construction cost (€300k), time and carbon footprint associated with the original dig out and replace option.

MEET YOUR FRIEND SAR

Let's learn some more about how satellite SAR data is used in infrastructure asset management, see some common applications and address the frequently asked questions.

Displacement measurement

The movement of objects and the ground surface between successive satellite passes is measured by calculating the phase difference between successive images as illustrated in Figure 8. Rather than direct displacement, the output is fractions of the phase. If all displacements are less than half a wavelength (a few centimetres) then they are easy to determine but if they are greater than half a wavelength this leads to ambiguity. The phase difference between two SAR images is shown in an interferogram, such as the one in Figure 9 obtained from two SAR images, one taken before and one after the magnitude 6.7 earthquake in Bam, Iran. The coloured fringes indicate that ground surface displacements caused by the earthquake increased to several times the wavelength (2.8cm in this case) used to produce the images.

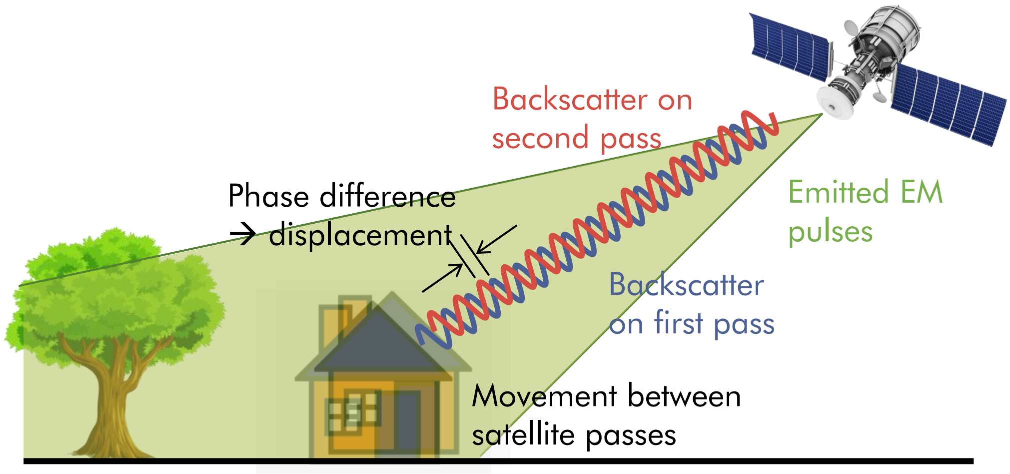


Figure 8. Displacement measurement by satellite SAR

Displacement output is obtained by correcting for topography using a digital elevation model (DEM) in a process called differential interferometric SAR (DInSAR). Further processing to remove residual topographical errors, orbital errors, atmospheric effects and data noise produces a displacement map with centimetric precision. The displacements are in the line-of-sight (LOS) direction between the object and the satellite sensor which will be at some inclination to the vertical.

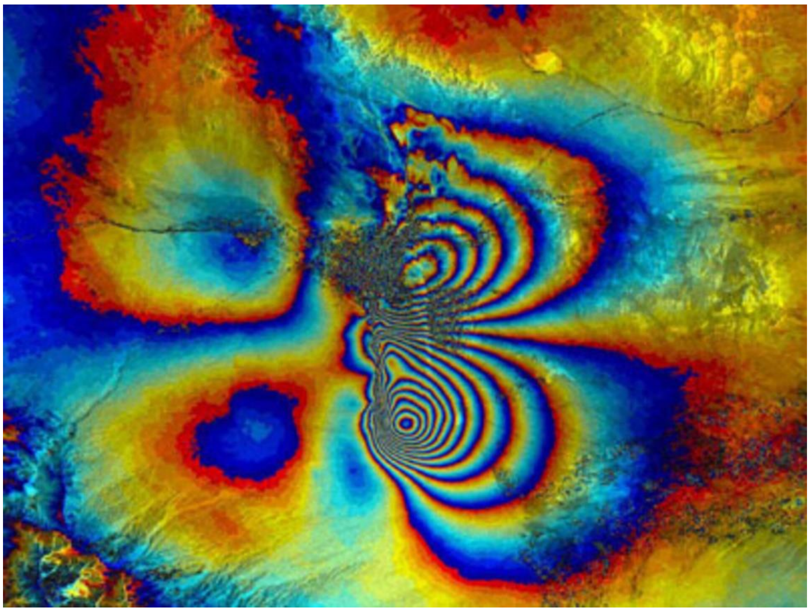


Figure 9. Interferogram of ground motion associated with the Dec 2003 earthquake at Bam, Iran ©ESA.

Displacement: getting millimetric precision

Analysing a time series stack of images – usually a minimum of 20 – enhances displacement precision by improving corrections for errors such as atmospheric effects and residual topographical errors. There are several algorithms to do this which are suited to different conditions, but they all enable the spatiotemporal analysis of the radar phase across multiple images to produce displacement data with millimetric precision and about 2-4mm accuracy depending on the frequency band.

Either average velocity or displacement over different time periods can be calculated and the data presented as coloured dots or pixels overlaid on maps or optical satellite images to indicate their location, such as that shown in Figure 10.

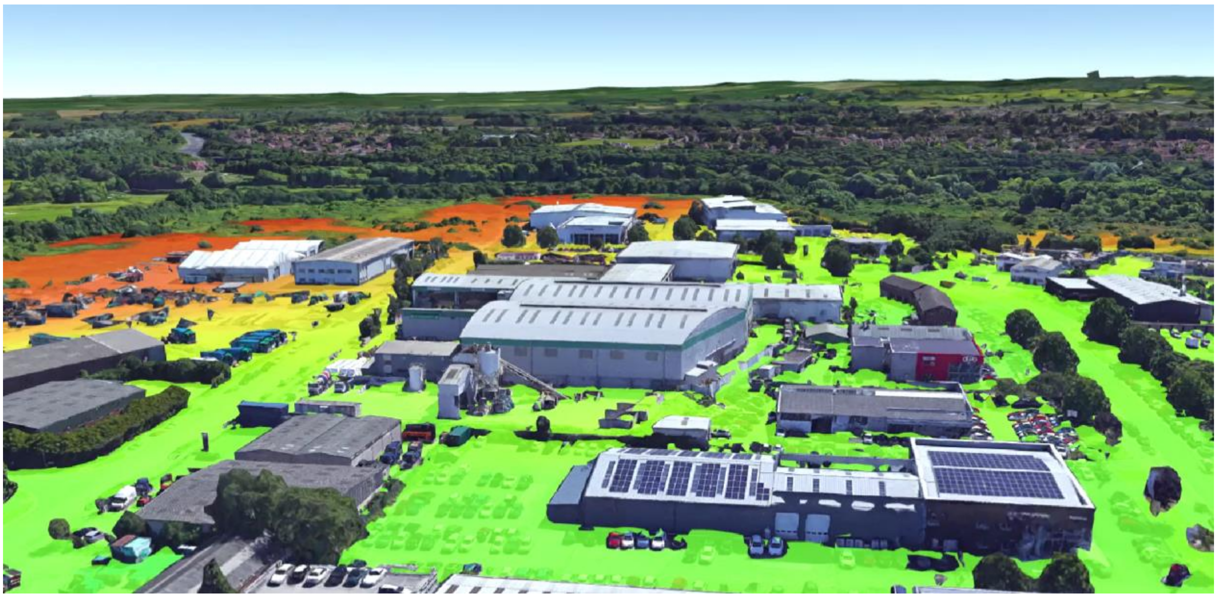


Figure 10. Ground surface vertical velocity (mm/year) presented as coloured pixels on a 3D surface model

Vertical and horizontal displacement

The displacements obtained from InSAR, whether from one pair of images or a time series, are in the line-of-sight (LOS) direction, i.e. along a straight line from the satellite antenna to the object on the Earth's surface. The ascending and descending orbits have different LOS directions on opposite sides of the vertical axis at known incidence angles as illustrated in Figure 11. Displacement data is derived independently from ascending or descending images. Positive values denote movement towards the satellite and negative values movement away from the satellite.

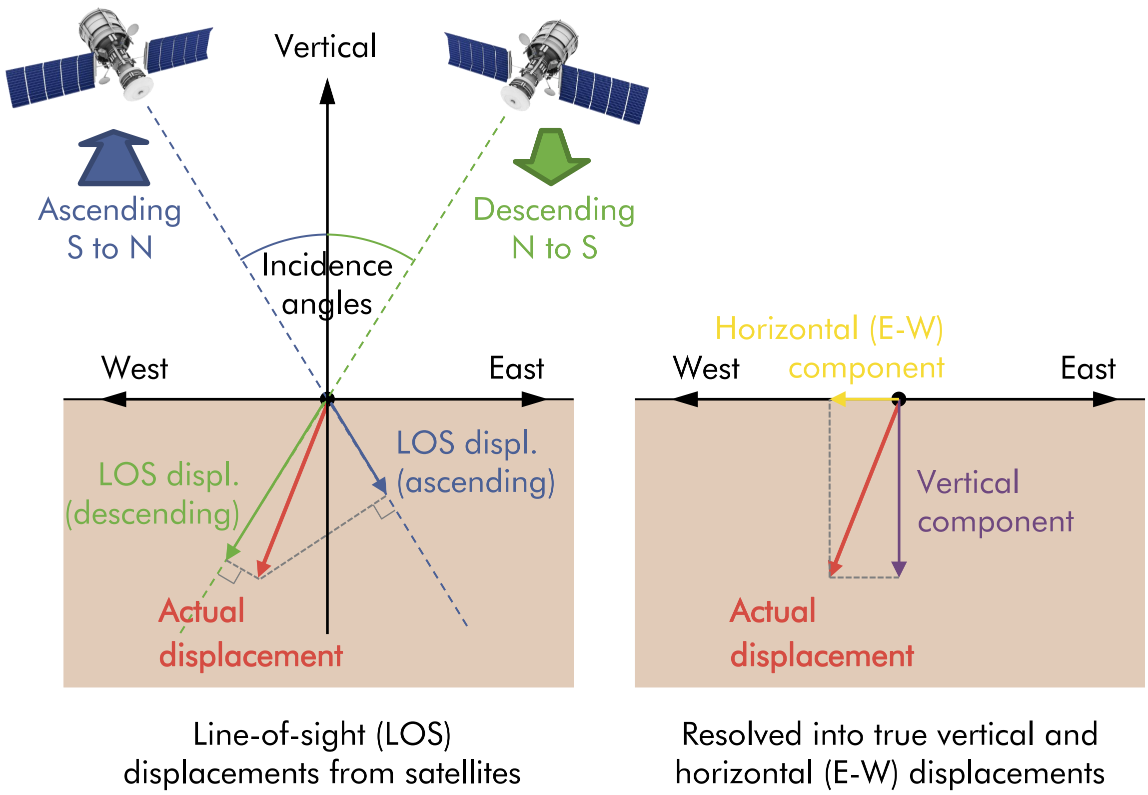


Figure 11. Converting displacement data from LOS to true vertical and horizontal (E-W)

On its own, LOS displacement data provides an indication of patterns of movement. If it is known that movements are predominately vertical (e.g. heave and subsidence of a horizontal ground surface), then vertical displacements can be deduced straightforwardly. If the prevailing direction of displacement is unknown (e.g. on sloping ground), then one set of LOS displacements may be insufficient to deduce the true pattern of movement.

When both ascending and descending orbit LOS displacement data at known incidence angles have been obtained, then displacements can be resolved into true vertical and horizontal (east-to-west) directions, or in other directions such as in the direction of east-west sloping ground. Some temporal interpolation is required because the ascending and descending images are not acquired at the same time and some spatial interpolation is required because the measurement points may be distributed differently between the ascending and descending images.

Horizontal displacements can be determined currently only in the east-west direction due to the near-polar orbit of the satellites and the east-west inclination of the satellite views. Data analysis techniques to decompose displacements into the horizontal north-south direction are under development and will be available soon. Also, new satellites with mid-inclination orbits, such as at 45° to the polar orbit, offer the possibility of detecting north-south horizontal displacements more easily in the near future.

Soil moisture

The amplitude of reflected SAR signals depends on a number of factors, in particular surface roughness, slope angle and the dielectric constant of the ground. Soil moisture influences the dielectric constant so, with all other factors constant, changes in the amplitude of received signals between successive images indicate changes in soil moisture. With some in situ measurements to determine absolute values of moisture content and to calibrate their variation with SAR amplitude, useful maps of soil moisture, such as that shown in Figure 12, can be produced. This a very useful application of SAR data in geotechnical engineering because geohazards such as landslides and swelling clays are heavily influenced by changes in soil moisture.

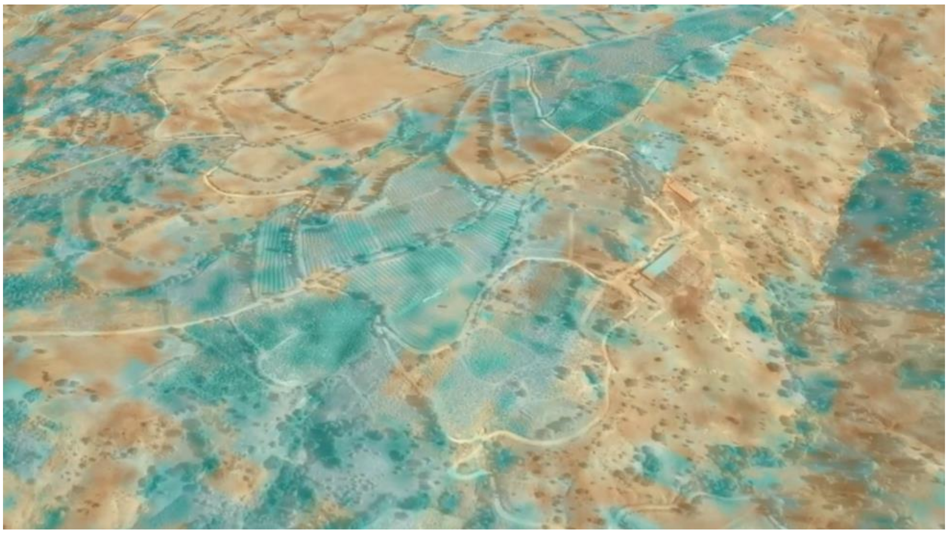


Figure 12: Calibrated satellite SAR soil moisture output

GIS

Large data files of displacement, soil moisture and other data associated with their geolocation are created. These are best uploaded to a web-based geographical information system (GIS) for viewing the data overlaid on maps, optical satellite images or 3D surface models. GIS also allows the plotting of temporal graphs and profiles, setting warning trigger levels and downloading specific data sets of interest.

FAQs

What's the spatial resolution of data?	This depends on the satellite. Freely available Sentinel-1 data has a resolution of about 5m in the range (E-W) direction and about 20m in the azimuth (N-S) direction. Some commercial satellites have much better spatial resolution and planned missions have sub-metre values.
How accurate is the displacement data?	The displacement accuracy is about 2-4mm on accumulated displacement and 1mm/year on velocities. But note that displacements may be the average of various reflecting objects within a pixel (20m x 5m in the case of Sentinel-1 images) or from one particularly strong reflecting object, so the uncertainty is greater on the spatial distribution of displacement within each pixel than the averaged displacement value itself.
How often is data recorded?	Freely available Sentinel-1 data alternates between ascending and descending image captures every 3 or 6 days for most land-based locations. Commercial data may be available more frequently and some satellites can even be tasked to capture data from a location as often as daily. Note that time-series InSAR analysis for millimetric displacement precision must be repeated each time a new image is acquired.
Have these techniques been validated?	The ESA-funded Terrafirma project in 2009 validated SAR data from rural and urban sites in The Netherlands. They found standard deviations of differences between time-series InSAR and ground truth of only 1.0 to 1.8mm/year (search "Terrafirma validation" on internet). There are also countless other examples of InSAR data complemented by and co-validated with in situ surveys.
How accurate is the location of each data point?	While displacements are measured with millimetric accuracy, the location of a data point associated with a displacement value can be up to about 10m out in the horizontal and vertical direction. Higher spatial resolution tends to mean higher geolocation accuracy, so the error may drop to about 1-3m for high resolution commercial satellites.

Do the techniques still work in vegetated areas?	While the built environment reflects SAR signals very well, the natural landscape and vegetation reflect SAR signals in a more irregular and unpredictable way. Vegetation also changes and grows with time. These all mean that fewer or no measurement points may be obtained as vegetation density increases. There are InSAR analysis techniques to help overcome this in many cases. Alternatively, using longer wavelength SAR increases the penetration through vegetation at the expense of spatial resolution.
Can you guarantee that data for a particular object will be obtained?	It is possible to estimate the density of measurement points that will be obtained and the higher the density the higher the probability of obtaining data near a particular point of interest. Note that geolocation uncertainty also means that you can never be sure that a specific point in space to, say, the nearest 50cm is being measured. The only way to do this is to install a corner reflector (see below).
How far back can historical data go?	Freely available Sentinel-1 SAR data exists for most of the Earth's land surface from 2014 onwards. Earlier SAR satellite data exists from 1991 to 2012 with less complete coverage. Other commercial satellite data is likely to exist for major cities and some other areas of interest and archives can be searched.
Do the techniques work in cloud cover?	Yes, SAR operates in microwave and radio wave parts of the electromagnetic spectrum which means they go straight through clouds and operate in any weather conditions, day and night.

CORNER REFLECTOR

Where insufficient measurement points are obtained or to guarantee displacement data at a specific location, a metallic trihedral corner reflector can be installed. It needs to be designed to be the correct size (typically about 1m across) and to point in the right direction towards the ascending or descending orbit of the chosen satellite. It will not provide historical data prior to its installation.

THE BUSINESS CASE

Here we look at how site investigation and monitoring using satellite SAR data helps to address the biggest challenges facing the construction industry today, making a compelling business case for wider adoption of this technology.

Fewer boots on site.

Health and safety

In common with the trend for increased offsite construction to reduce the number of staff working on hazardous construction sites, using satellite SAR data further reduces the number of "boots on site". While some of the complementary survey and monitoring methods require on-site working, satellite SAR data collection and processing requires no staff on site at all.

No equipment.

Satellite SAR data covers large areas in an instant, so there is no need to carry the heavy equipment from point to point across a large site that is associated with other measurement methods. This reduces the risk of staff developing musculoskeletal disorders that may develop over time from such activities.

Decarbonisation

Taking measurements by satellite SAR data requires no journeys to site and no site equipment or power. Its carbon footprint is virtually zero, so it contributes to decarbonising construction, particularly on large or remote sites.

Labour shortage

No workforce is required on site to perform the elements of site investigation and monitoring that use satellite SAR data. It is all performed by office-based specialists. Apart from gaining some intelligence on ongoing site activities to assist in the interpretation of satellite SAR data, little or no demands are placed on contractor's work time and no support is required while surveys are undertaken.

Productivity

There are several ways that the use of satellite SAR data can significantly improve productivity on construction projects. The first comes in site investigation, that all-important early stage in a project where any geohazards are assessed and important decisions are made on foundation and sub-structure options or whether even to proceed with the project on a particular site at all. If such decisions could be made earlier, that would save money throughout the project.

"$1.6 trillion of additional value-added could be created through higher productivity in construction."
McKinsey and Co. (2017).

One unique quality of satellite SAR data is that it is being recorded and archived for the entire land surface all the time. So, data going back over five years is available for any site immediately. That means trends of site behaviour can be detected immediately without needing to wait months or years with the other methods, as illustrated in Figure 13. Susceptibility to geohazards such as expansive clays, landslides and sinkholes can be assessed right away and problem areas can be pinpointed precisely. This allows site investigations and further in-situ monitoring to be planned and executed in a more informed and efficient manner, saving time and money right away. Important design decisions and cost estimates can be made earlier.

"Leverage proven and emerging tech to make use of limited available resources."
ASCE Report Card 2021.

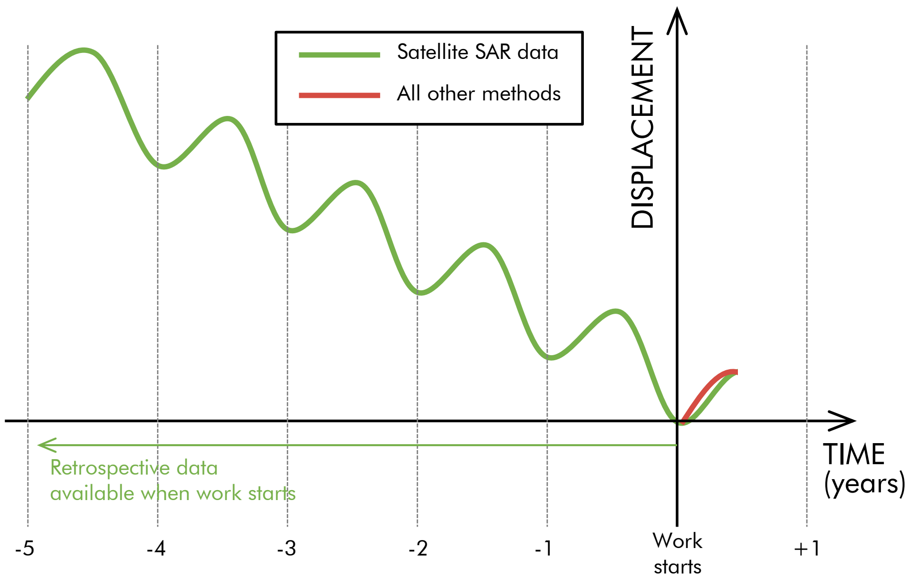


Figure 13: Comparison of typical data trends available 6 months after monitoring starts

There are also more direct productivity improvements that result from using satellite SAR data, particularly on large, remote or hazardous sites. Data for entire sites can be obtained free-of-charge, in an instant, every few days, in all weather conditions. Only the data processing has a cost element and there is no need to mobilise equipment and labour on site.

"Data-driven design, procurement and construction is needed to improve quality and efficiency, and to reduce waste in the infrastructure sector."
ICE State of the Nation Report 2020.

These productivity improvements can be enjoyed both at the site investigation stage, as mentioned earlier, as well as during construction monitoring. When large projects include ground engineering elements such as deep basements, tunnelling or embankments, uncertainties in ground properties necessitate monitoring to manage the risk of excessive ground movement or failure. With conventional monitoring methods, cost and risk must be balanced by choosing certain locations for instrumentation and regular survey without blanketing the site with expensive sensors everywhere. But both cost and risk are reduced with satellite SAR data because complete site coverage is obtained with every image without needing to worry that something critical is being missed until it's too late. This means that the number of in situ sensors can be reduced, or they can be held in reserve and installed in critical areas pinpointed by the satellite SAR data.

The case for satellite SAR data

The benefits of satellite SAR data sources to construction projects are many, as summarised in Figure 14. Some of the benefits are unique to this format and cannot even be obtained with other recent technological approaches.

A key benefit is the value for money offered by this technique. No other data collection method comes close in terms of the total area or linear km's and rate of measurement that can be achieved over a whole year. For example, a manual survey by total station of 100 targets distributed around a built-up area of 1 hectare, every week for one year would cost in the region of $40,000. For less than a quarter of the cost, the whole 1 hectare area could be surveyed by satellite SAR data giving about the same number of measurement points and about the same accuracy at intervals of less than one week. Note, however, that the SAR data would provide average displacements across pixels whereas the manual survey would provide displacements at specific points.

Figure 14. The many benefits of satellite SAR data to the construction sector

Saving for satellite SAR surveys compared with manual total station surveys

That clarification illustrates the way that the different methods complement each other. Consequently, satellite SAR should not replace other monitoring methods but rather support them. The strength of satellite SAR data lies in its regular, whole-site coverage, avoiding the need to survey the whole site by more expensive means so regularly. Instead, the detailed monitoring methods can be focussed on those areas pinpointed by satellite SAR data as areas of concern or those locations that are hidden from satellite lines of sight (e.g. underground or in dense forests).

All the data is immediately stored on a secure, web-based GIS accessible from any device with internet access. So, time is saved by avoiding record-keeping and archiving of monitoring data. Trigger levels can be set so that the pertinent people are informed immediately when any issue has been identified on a project.

CASE STUDY 2

Bishops Cleeve, Glos.

InSAR settlement data for the entire municipal landfill

Landfill sites can be suitable for development but there are potential hazards including land subsidence that need to be addressed. One such site on the edge of an old municipal landfill was being considered for the construction of a hydrogen plant. A combination of satellite analysis and geotechnical expertise was needed to identify a solution.

THE CHALLENGE

- Ongoing landfill settlement that threatened the viability of the site was an unknown quantity and was difficult to predict accurately.
- Measuring the settlement of the site in situ would be expensive and take months to accumulate enough data to detect trends.
- The proposed hydrogen bullet tank was settlement-sensitive so a solution to mitigate differential settlements without disturbing the capping was needed.

THE SOLUTION

- Retrospective InSAR analysis of two years of archived satellite data was used to provide settlement trends across the entire landfill.
- The settlement data and site investigation information were used to help develop a finite element analysis (FEA) model of the edge of the landfill to predict settlements of the proposed hydrogen plant.
- A reinforced soil platform was proposed to mitigate differential settlements and protect the hydrogen tank.

THE BENEFITS

- Settlement data for the entire landfill over the previous two years was obtained for a more informed consideration of development of the site.
- This data gave confidence in the ongoing settlement predictions.
- An inexpensive solution to mitigate differential settlements was proposed in a concept design.

IMPLEMENTATION

When satellite SAR data is being considered as a site investigation or construction monitoring tool, providers of these services should be approached to discuss suitable solutions. At this initial stage and through all the subsequent stages possibly all the way to purchase and application, it is good to know the right questions to ask so that the service meets everybody's expectations. The purpose of this chapter is to provide outline guidance on some of the issues that need to be raised and agreed upon when procuring satellite SAR data.

Procurement

Ideally at an early stage in the procurement process but certainly prior to signing, it is vitally important that all project stakeholders as well as the provider of the satellite SAR data understand the purpose of the data collection. All need to be clear on what output will be produced following processing and presentation of the data and agree that it is appropriate for the intended purpose. The output should also be obtainable accurately by a well-defined process. All these are important because satellite SAR data involves advanced and continuously developing technology that may be unfamiliar to some stakeholders. A thorough engagement process with potential providers is recommended so that the right data sources and processing techniques are proposed to meet the needs of a project and to help ensure that stakeholders fully appreciate the service being offered.

"A thorough engagement process with potential providers is recommended"

For example, it may not be possible to obtain satellite SAR data for the entire area of a site due to some parts being hidden from the view of the satellite by dense vegetation. It is better to discuss these issues openly and alternative data collection methods arranged beforehand, such as small areas of manual survey or instrumentation, rather than stakeholders learning later that there are gaps in site coverage.

The starting point for internal discussions is to set the goals and objectives of the investigation or monitoring and to decide what information is required. To plan the full regime of monitoring that may include other techniques as well as satellite SAR data. Will an initial pilot study be undertaken if the techniques are being applied for the first time? Is the site visible to satellites at all locations?

The duration of the monitoring is important as is the frequency of output generation. These depend on the length of time that construction activities are expected to cause ground movements (which could extend well beyond the completion of construction) and the speed at which ground movements may develop. If they develop slowly then the frequency of analyses can be reduced. Will the results be reported at set intervals in a formal manner, or the data uploaded to a GIS platform and stakeholders notified of an update? Is the monitoring intended to identify trends or to provide early warning of excessive ground movement to allow contingency measures to be invoked?

Once the goals and objectives of the monitoring have been agreed internally, detailed discussions with potential providers of satellite SAR data should be held to reach a common set of expectations for the information that can be obtained. Providers can confirm which parameters can be obtained for the site, the likelihood of obtaining sufficient measurement points, the accuracy and precision of data, spatial resolution, geolocation accuracy and frequency of measurements. They can propose strategies and options for increasing the amount and quality of information obtained.

An important consideration is for the internal resources and protocols within the relevant stakeholder organisations to be planned and ready for the arrival of the first satellite SAR data. Who will be responsible for viewing and interpreting the data, monitoring trends and acting on alarms? Will the client or data provider be responsible for interpretation and recommendations? Do either the client or provider have sufficient in-house expertise and resources to view and interpret the data? Engineers are needed for interpretation and decision making, in particular to avoid false alarms. Specialist skills are needed for data analysis, communication and storage.

"Who will be responsible for viewing and interpreting data?"

"Engineers are needed for interpretation and decision-making"

All the new information needs to feed into forward work planning and the decision-making process on the timing and nature of mitigation measures.

Standards

The processing of satellite SAR data into high-precision outputs of displacement and soil moisture, for example, uses relatively recent technology that continues to evolve. Consequently, there is not much formal standardisation of the techniques although the techniques are scientifically rigorous, validated and peer reviewed. The growing use of these techniques in infrastructure asset monitoring means that there is a need for a degree of standardisation and standards development is in its early stages (see *Future* chapter).

Nonetheless, there are standards in related fields that should be adopted by providers and specified by clients. These include standards for data formatting (ISO/TR 19121:2000 *Geographic information — Imagery and gridded data*) and metadata formats (ISO 19115 *Geographic information — Metadata* in three parts) to facilitate the transfer of data more easily between databases and platforms. ISO 19650-1:2018 *Organization and digitization of information about buildings and civil engineering works* defines a common data environment (CDE) where the large amount of project and asset information collected these days should reside. PAS 1192-5:2015 *Specification for security-minded building information modelling, digital built environments and smart asset management* provides principles and requirements for managing smart asset management data securely.

Specification

As in all procurement, specifications can range from the very detailed to the quite open. With the processing of satellite SAR data into outputs such as displacement and soil moisture being relatively new technology under continuous development by various providers, open specifications based on performance and outputs are more suitable. Independent advice on specification should be sought at an early stage from potential providers of satellite SAR data.

Satellite SAR monitoring of construction sites creates large volumes of data that need to be accessible but managed securely to protect intellectual property rights and commercial interests and to keep sensitive information from getting into the wrong hands. So, data security is an area where organisations may choose to specify work in a more detailed way. Some of the standards described in the previous section provide specifications for data security.

Data back-up is essential to protect them from corruption, hardware failure and other risks. Greater data protection is gained by using different types of secure storage in different locations, such as locally and on cloud-based servers, while still having sufficiently fast access to the data.

Data visualisation is another area where specification may need to be more detailed, particularly if data needs to be displayed on existing client GIS platforms. Some of the standards described in the previous section provide standard data formats for portability that may be adopted. Overlaying the data on maps or optical satellite images helps in the visualisation of the data and should be a standard requirement. Also, dashboard tools such as the plotting of temporal graphs or isochronous horizontal profiles and the possibility to download data in a transferable format to other data analysis software, e.g. spreadsheets, should come as standard. Warnings when pre-defined trigger levels are reached can also be specified to be managed by the GIS platform. Specific requirements on the security of GIS platforms are also summarised in the box below.

Web-based GIS SaaS minimum requirements

The web-based software-as-a-service (SaaS) is accessed using any of the latest versions of a modern web browser. No installation is required on the user's PC or device.

It should follow industry standard security protocols for web apps. The web app, database and geoserver should be hosted on a cloud server with disk encryption, SSL encryption and web application firewall (WAF). Data should be replicated for backup purposes to a remote location on a cloud server and again encrypted.

A closed registration policy should be adopted, meaning that a user can only gain access by invitation from the system administrator and authentication is needed before accessing any data. A strong password policy should be employed with password expiration and two-factor authentication to increase user login security. Each user is then connected to a specific set of data with no access to other data.

Pricing

The cost of providing processed satellite SAR data for site investigation or construction monitoring depends on a multitude of factors, as summarised in Figure 15. Note that there is not necessarily a linear relationship between certain factors and price. For example, if the study area were doubled in size, the cost of providing the data would not double because some of the tasks are automated and would simply involve some slightly longer computer processing times. So, economies of scale do have a significant effect.

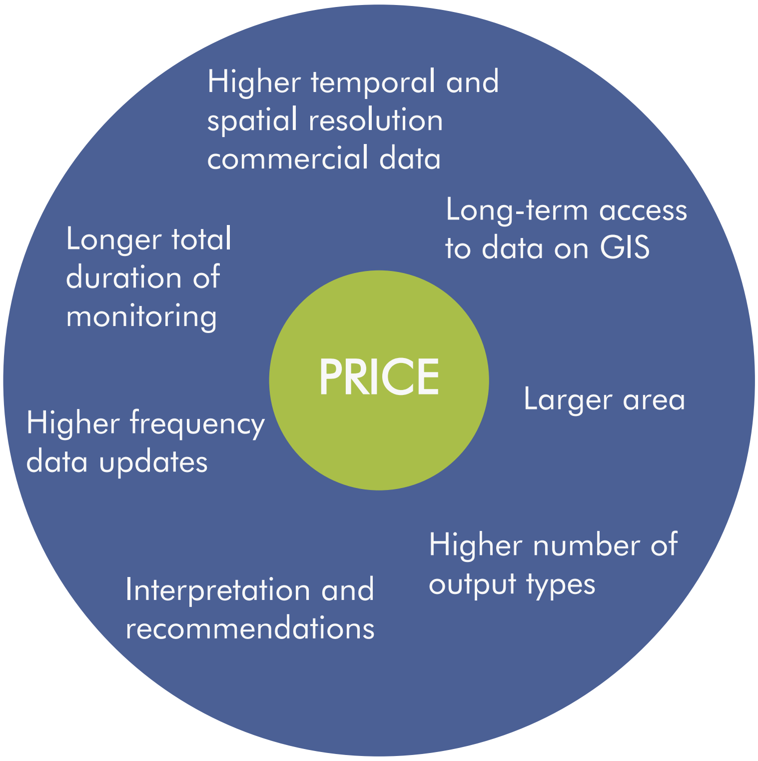


Figure 15. Factors that increase the cost of satellite SAR data

The frequency of satellite data acquisition and frequency of processing and updating output are not quite the same thing. Although data may be acquired every few days, costs can be reduced by processing data and updating output at longer intervals, say on a monthly basis, while still retaining the same temporal resolution of data. This is because time-series InSAR analysis needs to be repeated for the entire sequence each time new data is added, so the workload is much higher if the analysis is repeated every time new satellite data is acquired.

The volume of data and the length of time it needs to be accessible on a web-based GIS platform both have an impact on data storage costs on cloud-based servers.

The satellite data can make the greatest difference to the cost. It can range from cost-free to a significant proportion of project costs for commercial data with higher spatial and temporal resolution where that is required. Satellites can even be tasked to acquire data more regularly from areas of interest at even higher cost. This has a big impact on costs due to the high number of images (at least 20) usually required for analysis. Note that some analysis providers have agreements with certain commercial satellite data companies. While this may reduce the cost of acquiring the data, it means that providers can favour data from certain satellite data companies.

Satellite SAR data Procurement checklist

AGREED BY ALL STAKEHOLDERS

- ☐ Purpose of data collection
- ☐ Information needed
- ☐ Output that will be produced

TECHNICAL REQUIREMENTS

- ☐ Measurement precision & accuracy
- ☐ Site areas to be included
- ☐ Spatial resolution
- ☐ Geolocation accuracy
- ☐ Time interval between data updates
- ☐ Total duration of monitoring

PRACTICAL REQUIREMENTS

- ☐ Formal reporting
- ☐ Platform to access and view data
- ☐ Data update notifications
- ☐ Trigger levels for any warnings
- ☐ Protocols for issuing warnings
- ☐ Strategies for spatial gaps in data
- ☐ Combining other monitoring approaches
- ☐ Pilot study needed?

INTEGRATION

- ☐ Who is responsible to view the output?
- ☐ Who is responsible for interpretation?
- ☐ Who will respond to any alarms?
- ☐ Decision-making on interventions
- ☐ Who has the expertise to interpret data?
- ☐ Integration with forward work planning
- ☐ Integration with maintenance planning

CASE STUDY 3

Robroyston, Glasgow

Robroyston in Glasgow is undergoing significant development with a new railway station providing park and ride from the adjacent M80 motorway into the city, and plans for 1,600 new homes. A key element of the development was the construction of a link road between the existing M80 junction and the new station and car park.

THE CHALLENGE

- Soft peat pockets needed deep ground improvement to support a new road embankment.
- Tensar proposed its much more cost effective Stratum solution but needed a way to predict differential settlement of the embankment.
- In situ monitoring techniques were sometimes damaged during construction or became inoperable over time.

THE SOLUTION

- From R&D work at Tensar, a peer-reviewed method of characterising the Stratum system in FEA was developed.
- Both transverse and longitudinal differential settlement of the road due to the peat pockets was predicted by 3D FEA for a range of geological scenarios.
- Satellite InSAR data was analysed to provide post-construction embankment settlement data along the entire embankment length to complement or substitute for the in situ measurements.

THE BENEFITS

- The Stratum system was up to the job and saved Glasgow City Council £500k of deep ground improvement.
- The settlement predictions allowed Tensar to demonstrate the effectiveness of their proposed ground improvement solution for this specific site.
- Verification of performance of the constructed solution over the entire length without costly in situ surveys.

THE FUTURE

The increasing pressure to improve productivity in the construction sector and, essentially, do more with less point to a growth in the use and value of satellite data. Large areas and years of historical data are available immediately, allowing more informed and more timely decision-making and cost planning.

The safety-driven need to avoid site access where possible, labour shortages and the drive to decarbonise the construction sector all mean that the adoption of remote sensing techniques of asset monitoring – satellite SAR data in particular – will continue to grow.

As more data is collected and as analysis methods are improved by utilising technologies such as artificial intelligence, predicting trends will become more accurate and it will be possible to make important project decisions earlier and with greater confidence.

The new surveying and monitoring techniques will not replace the old (e.g. manual survey) but interfacing between them needs to improve so that they are used in a balanced and effective way to maximise available resources.

The number of satellites, particularly commercial microsatellites, will continue to grow rapidly. This will bring more affordable high-resolution SAR data and higher frequency revisits. There will be greater choice of wavelengths suited to different applications and inclined orbits will permit easier horizontal north-south displacement measurement.

Increased adoption of satellite SAR data for construction monitoring will bring some broad level standardisation while still allowing ample scope for further technological developments. The Geoscience and Remote Sensing Society (GRSS) of the Institute of Electrical and Electronics Engineers (IEEE) has already prepared proposals for standards development including in the field of satellite SAR data. Meanwhile, the *Monitoring in Geotechnical Engineering* working group of the ISO technical committee on Geotechnics is working on a draft document including annexes for new technologies such as satellite SAR data.

"Using AI can help extract maximum information from vast amounts of data about infrastructure assets."
National Infrastructure Commission, UK 2017.

CONCLUSION

The construction industry is facing a daunting combination of both old and new challenges. Workforce accident and illness rates as well as productivity growth all compare unfavourably with other sectors of industry. Decarbonisation of one of the highest carbon-emitting industries is a relatively new but long overdue goal. The industry also needs to address the growing labour shortage.

It has been shown that, when combined with other investigation and monitoring approaches, satellite SAR data provides a cost-effective, safe, reliable and objective means of assessing site geohazards and measuring ground movements and moisture changes. This allows more informed and earlier decision making and cost planning on construction projects. Other surveying and monitoring resources are deployed more efficiently, all without site visits and virtually zero carbon emissions.

The continuing development of artificial intelligence technologies and launches of satellite constellations combined with the increasing need for improved productivity and safer working in the construction sector mean that the use of satellite SAR data is likely to increase exponentially in the coming years.

Find out more about Geofem infrastructure geohazard monitoring services