Urban tunneling and the advantages of using InSAR SPN satellite technology to detect and monitor surface deformation effects

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ABSTRACT

New technologies are increasingly being accepted and used for monitoring urban ground motion before, during and after tunnel construction. These technologies reinforce the measurements obtained with more conventional technologies and/or complement them.

Within the industry of Earth Observation, radar satellite imagery thorough InSAR (**In**terferometric **S**ynthetic **A**perture **R**adar) technology allows to detect and monitor surface movements covering very large areas (several thousand km^2) with millimetric precision. ERS and Envisat satellites have been operating and acquiring data since 1992 providing historical studies covering very large areas (100x100km/frame) over a very long period of time particularly applicable to linear infrastructures. In 2007, the launch of very high resolution satellite constellations, TerraSAR-X (2 satellites) and CosmoSkyMed (4 satellites) marked a new era. These satellites are an important step forward for the detection of surface ground movement as a result of a higher spatial resolution (up to 1m resolution) and more frequent updates as their number of image acquisitions notably increases.

There are many examples of the application of InSAR SPN technology, such as the tunnel constructed in Bilbao city (Spain) to improve the access of a motorway to the city and the effects on the surface caused by the construction of Metro Lines 9 and 5 in Barcelona (Spain). These results show the detection and evolution of movements detected before and during tunnel construction.

1 INTRODUCTION

The construction of tunnels and underground infrastructures in cities has dramatically increased in the last few years. The reasons vary according to different necessities: Due to rapid growth and geographical limitations(e.g. being surrounded by mountains or protected areas) some cities tend to grow vertically in order to assimilate increasing populations, as is the case in Barcelona and Hong-Kong. This increase in population is normally followed by an improvement of the city's capacity to transport its population. Due to this lack of space, the solution is often to build underground transport infrastructures. In other cases, large metropolises that have expanded need to improve or expand their public transportation systems in order to cover the whole territory. These new infrastructures must often be built underground due to the density of buildings and infrastructures on the surface, as is the case in London. The development of underground infrastructures is thus an ever increasing practice to respond to the demand for better transportation in cities around the world.

The construction of underground infrastructures and the resulting settlements may affect the existing structures on the surface. The theoretical calculations of settlement made prior to construction may not always correspond in location and range with the surface deformations that occur during construction, furthermore, some movements continue after the construction of the tunnel. There is a clear necessity to monitor these movements.

By using radar satellite imagery, InSAR SPN technology can detect and measure both surface ground movements caused by geological-hydrogeological phenomena before construction and movements caused by excavation works during the construction of underground infrastructures. This remote sensing technology is particularity effective in studying cities, buildings and infrastructures serve as almost perfect reflectors to the radar signal.

2 INSAR TECHNOLOGY

The InSAR SPN technique is able to detect ground movements on the Earth's surface with millimetric precision by using radar satellite images that cover very large areas. The range of movement that can be measured using this technique depends on the satellite and number of images used for the period of the study.

InSAR is an English acronym meaning *"Interferometric Synthetic Aperture Radar"*. Synthetic Aperture Radars are high resolution radar satellite systems and "Interferometric" refers to the superimposition of radar waves to detect differences through time.

SPN means "Stable Point Network" and refers to a system of points that reflect the radar signal from the satellite continuously through the time.

The principle of interferometry is based on comparing the distance between the satellite and the ground in consecutive satellite passes over the same area or point on the Earth's surface. Radar satellites images record, with very high precision, the distance travelled by the radar signal that is emitted by the satellite is registered. When the distance between the satellite and a certain point is compared through time, InSAR technology can provide highly accurate ground deformation measurements.

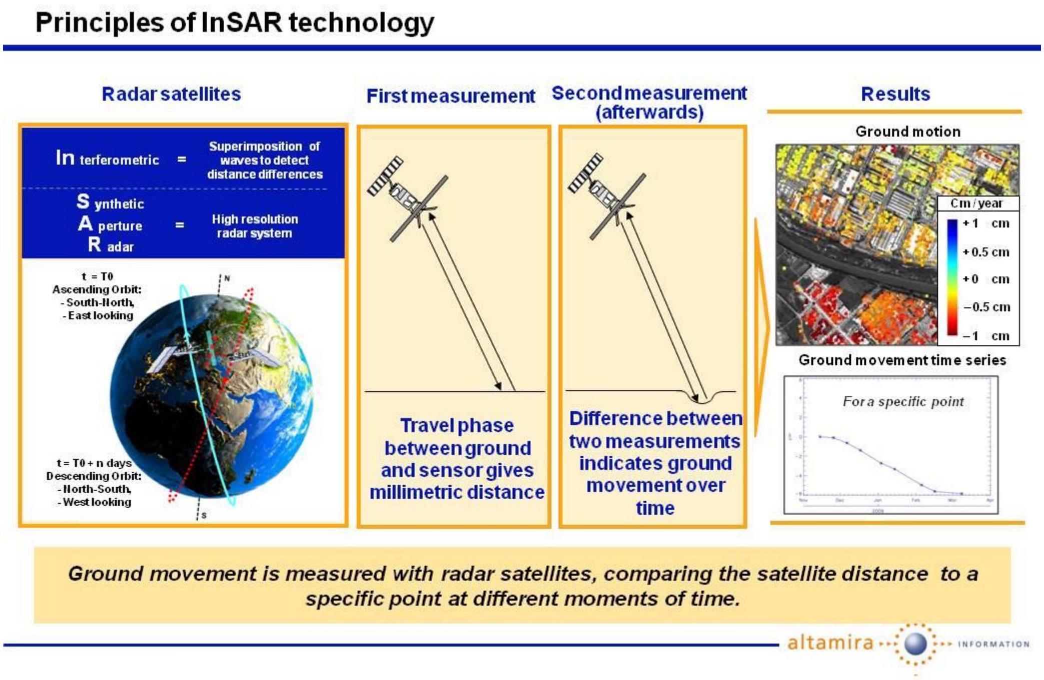

Figure 1 Basic principles of radar interferometry.

Radar signals are electromagnetic waves within the microwave area in the electromagnetic spectrum. The wavelength determines the distance range that can be measured by each satellite. There are radar satellites that work in X Band (λ= 2.8cm) such us TerraSAR-X and CosmoSkyMed, others in C Band (λ=5.6 cm), such as ERS and Envisat, and others with L Band (λ=23cm), such us ALOS PALSAR. The following table (Table 1) shows the technical characteristics of each satellite.

Table 1 Main Characteristics of Radar Satellites

	TS-X	RADARSAT-2	ALOS	ERS/ENVISAT	COSMOSKYMED
Band	X	C	L	C	X
Periodicity [days]	11	24	46	35	8
Resolution [mxm]	3x3	5x5	10x10	20x4	3x3
Measurement precision [mm]	2 (SPN)	3 (SPN)	7 (A-DInSAR)	3 (SPN)	2 (SPN)
InSAR technique	SPN	SPN	A-DInSAR	SPN	SPN
Mission	2007- today	2007- today	2006-2011	1991-2010	2007 - today
Advantages	High spatial resolution up to 1m/pixel	Detection of higher range movements than X band	Detection of higher range movements (cm-dm) More effective with vegetation	Very large archive	Best temporal resolution, up to 4 days

3 CIVIL ENGINEERING APPLICATIONS

InSAR SPN technology has been applied in the civil engineering sector in recent years. It is particularly important to highlight that there are already archives of radar images, including data from 1992-onward. The temporal coverage of these archives is very consistent in some areas of the world, making it possible to perform historical studies of ground deformation for long periods and covering very large areas thanks to the large dimensions of these images.

Therefore, given the stability of natural reflectors detected in cities, the civil engineering sector can benefit from ground deformation data for approximately the last 20 years. Taking into account that the smallest radar image 40x40km wide, if the reflectivity of the area is high for the radar signal, as is the case in urban areas, InSAR technology can provide ground deformation data for wide areas with very high precision (+/- 3 mm per measurement) without having to measure in situ.

On the other hand, the technology can also provide deformation measurement updates of the reflexion points on the ground as the satellites can be programmed for future acquisitions. The temporal resolution, together with the wavelength of either X, C and L bands of the radar signal, determine the characteristics and precision of ground movement surveillance of the satellites. See Table 1.

4 UNDERGROUND INFRASTRUCTURE APPLICATIONS

The main applications of InSAR SPN technology in urban tunnelling are as follows:

- Ground deformation detection prior to the construction of the underground infrastructure, very important for decision making about the final route or location of the infrastructure. InSAR can also help to detect pathologies in buildings and infrastructures prior to construction, valuable information for liability issues during and after construction.
- Detection and surveillance of settlements during construction. The measurements obtained can be used to complement those obtained by in situ techniques and for validation purposes.

In a geotechnical context, InSAR SPN historical and monitoring studies provide deformation data related with **subsidence phenomena** caused by either ground compaction due to water extraction, dissolution of carbonates or salt formations (karst processes).

The technique also detects processes related with **uplift phenomena** due to aquifer natural or artificial recovery, processes related with the presence of shrink and swell clays (e.g.: gypsum-anhydrite transformations). Landslides activated or accelerated by underground construction of infrastructures can also be detected.

Tunnel construction monitoring requires a **historical analysis** to study surface ground behaviour before underground tunnelling takes place, and also, to visualise the density of measurement points provided by the surface to be monitored. A historical analysis can detect and measure deformations on the surface in the past and analyse its evolution during the period of study.

Following a historical study, and depending on the future theoretical settlements predicted for the construction period, the optimum satellite is selected in order to proceed with monitoring during the underground works.

For each satellite, in terms of measurable movement rate, the detection limit is half of the wavelength of the radar signal between consecutive images. If the movement goes over this value between two acquisition dates the surveillance of this point could be lost. On the other hand, the measurement can be recovered if the point is surrounded by a very high density of measurement points. For this reason it is important to know the settlement estimations calculated before tunnel construction.

Surface deformation monitoring with radar satellites for tunnel construction in urban areas has the following technical possibilities:

- X Band (TerraSAR-X and CosmoSkyMed) satellites: allow high spatial resolution studies to be performed and obtaining a very high density of measurement points due to their spatial resolution (3 – 1 m) and the optimum reflection properties in urban areas. On the other hand, X band wavelength does not allow to detect movements greater than 1,4 cm between consecutive images and neighbouring measuring points therefore it is recommended to use all the possible acquisitions, every 11 days in the case of TerraSAR-X and in some cases every 4 days with the satellite CosmoSkyMed.
- C Band (ERS, Envisat and Radarsat-2): allow to monitor movements with broader spatial resolution, 20m in the case of Envisat and 5m for Radarsat-2. The measurement precision is approximately the same than X band but movement rate measureable between consecuative images and neighbouring points is double since the wavelength is double.
- L Band: is recommended when the theoretical settlement estimations shows the possibility of high rate movements: few centimetres and decimetres between consecutive image acquisitions. Measurement precision is not as fine as satellites operating in X and C band but on the other hand motions up to 11 cm between consecutive images can be measured. It is important to highlight that this satellite started its mission in 2007 and finished in March 2011 and is the best to use in vegetated areas.

5 DISCUSSION: ADVANTAGE OF INSAR TECHNOLGY FOR URBAN TUNNEL CONSTRUCTION

Current practice for monitoring during underground infrastructure construction is effective, precise and uses a varitety of techniques with and near real time readings of ground displacement. Also, this can be quite costly and tends to be provide montoring on buildings and other surface structures to the route of the tunnel. InSAR SPN allows to extend these surface monitoring of buildings and structures near the route to a wider area and also to deliver a very high density of measurement points.

On the other hand, InSAR SPN allows to understand the effects of the excavation on the materials that are present further away from the densely monitored route area though the impact on the surface displacement.

Historical o retro studies could be used to discriminate between new motion areas, motions accelerating during tunnel construction and motions occurring before construction and unrelated to the excavation.

As an example demonstrating the advantages of the application of InSAR technique, a project with the objective to monitor displacements affecting buildings in a neighbourhood built on a slope before and during construction, has shown movements occurring during 17 years of study 1993-2009 performed with ERS and ENVISAT images. On the other hand, the latest historical study with the high resolution satellite TerraSAR-X (2009-2010) shows the beginning of new movements when the tunnel works began.

Monitoring updates are taking place every 6 months showing an increase and spread of the deformation on the surface. Also, a deformation gradient can be visualised from a maximum subsidence near the tunnel route to stability up to 100m away from the tunnel. These results provided very useful surface deformation data in areas out of the reach of in situ monitoring methods. Periodic motion updates are continuing in the project and these show that the deformation is not increasing extension or motion range.

Other advantages where also experienced in a project to monitor the surface of Barcelona city during construction of Metro Line 5 (Figure 2 and 3). Due to the large size of the radar satellite images (50x30km) a long track of the metro line could be studied with ease. The results show several areas of subsidence coinciding in time and space with the construction timing and areas tunnelled for the metro. Two satellites where used, TerraSAR-X for the period 2007-2009 and Radarsat-2 for 2010.

The TerraSAR-X study shows a correspondence between the areas of subsidence labelled as A, B, C, D and the metro track as can be seen in figure 2. It is important to highlight the maximum subsidence was detected in 2008, of up to 1,5 cm/year. In some areas motion gradient towards localised subsidence troughs can be seen, such as that shown in figure 2 in Plaza de las Habaneras.

A further study was carried out later with the Radarsat-2 satellite with data from 2010. This shows the same regions of movement with evidence that the settlements have continued in 2010. Also shown is that in some areas there is an increase and extension of the movement in 2010 such as in Vall d´Hebron, Taixonera-Coll and Carmel (Figure 3) although the gradient of surface deformation in Plaza de las Habaneras seem to have decreased.

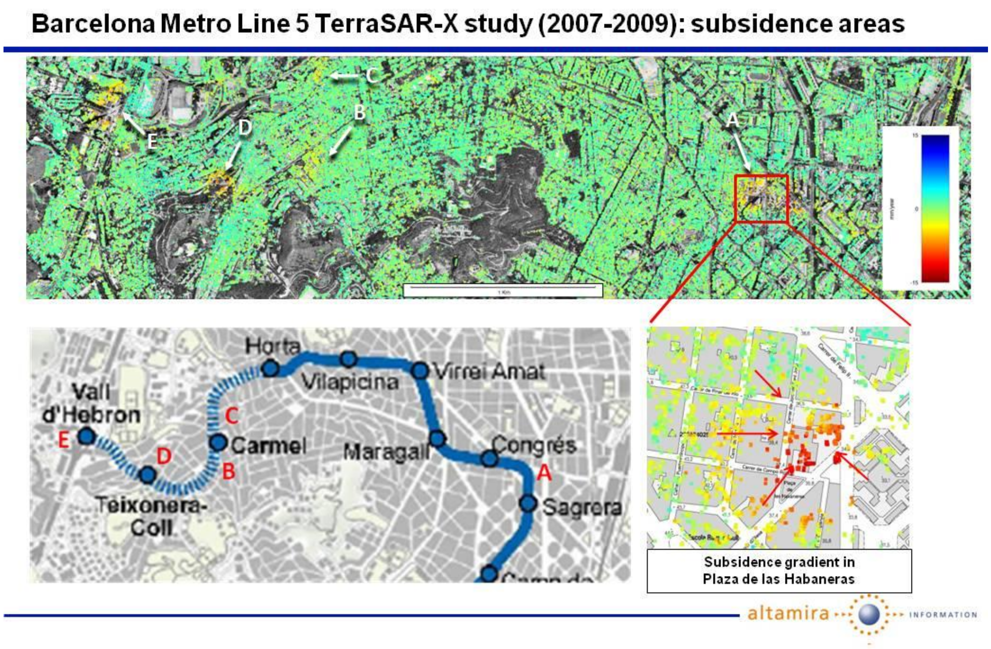

Figure 2 Movement evolution in Barcelona city because of Metro construction (2007-2009)

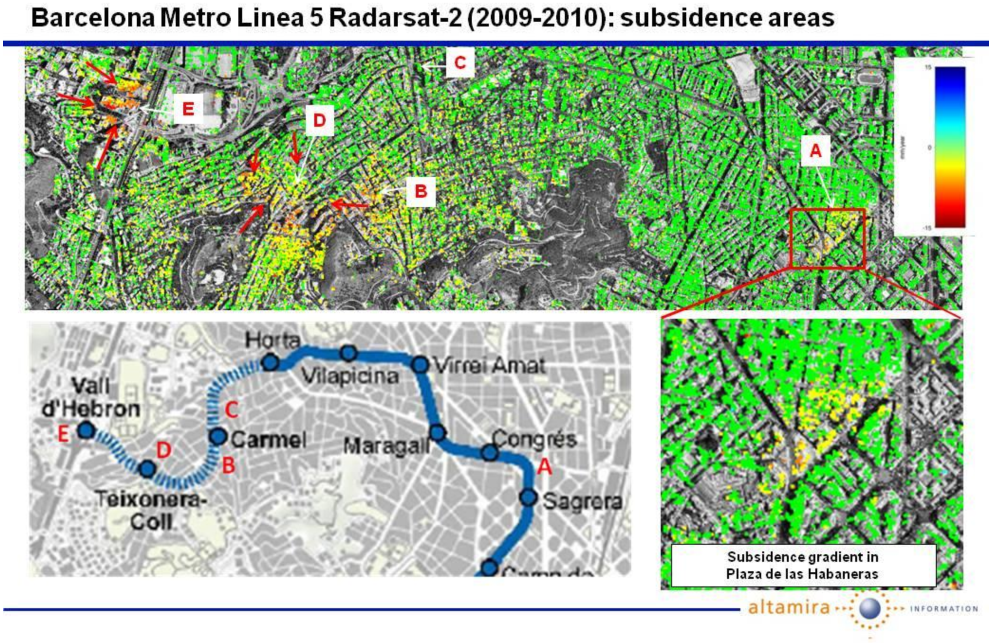

Figure 3 Movement evolution in Barcelona city because of Metro construction (2009-2010)

The following illustration, figure 4, shows the example of surface deformation caused by the construction of Metro Line 9 and an underground car park in Barcelona. The construction of the car park shows that the access shaft of 15 cm of diameter flooded with water. This is an area which geotechnically sensitive due to the delta deposits and the high groundwater level. In this study subsidence gradient away from the area of works is also visible in the displacement dataset.

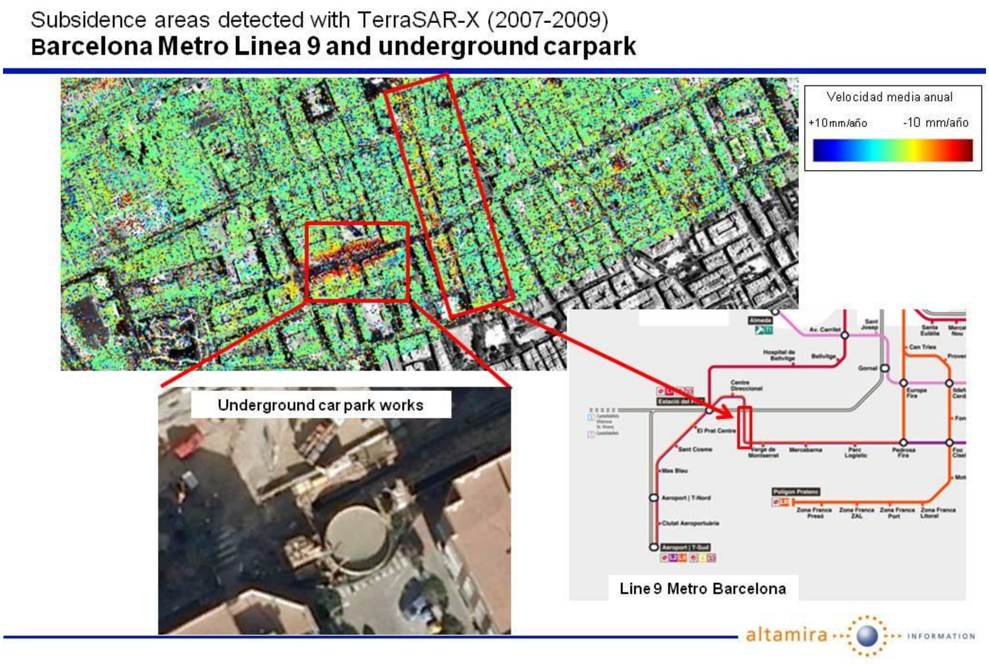

Figure 4 Surface movement due to the construction of a car park and Metro Line 9 (Barcelona)

6 CONCLUSIONS

As a conclusion, the advantages using InSAR SPN technology for underground infrastructures construction explains the increase of use of new and remote monitoring technologies in the last few years. The technique has proven to be complementary to traditional methods and extends the range of measurements by traditional in situ methods during construction. Also the advantage of providing historical deformation data (retro studies) and the capacity to program with new image acquisitions for long periods of time for monitoring purposes makes this technology unique and on occasion irreplaceable.

It is important to highlight its promising future with the launch of new radar satellites improving every time spatial and temporal resolution using different radar wavelengths and incidence angles. This means an enormous improvement in the detection, measuring capabilities and evolution analysis of ground movement with radar satellites.

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