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Ground motion measurement in infrastructure and transport projects using InSAR technology

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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 (Interferometric Synthetic Aperture Radar) technology allows to detect and monitor surface movements covering very large areas (several thousand km2) with millimetric precision. ERS and Envisat satellites have been operating and acquiring data since 1992, offering the possibility to perform 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 COSMO SkyMed (4 satellites) marked a new era. These satellites allow 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.

Keywords-Monitoring; InSAR; infrastructures

I. 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 of Barcelona. 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. 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.

There are many examples of the application of InSAR SPN technology, the article reports the results of the monitoring of the Metro Lines 9 and 5 in Barcelona (Spain). Those show the detection and evolution of movements detected before and during tunnel construction.

II. InSAR Technology

The InSAR SPN technique is able to detect ground movements on the Earth's surface with millimetric precision over very large areas by using radar satellite images. 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.

Radar signals are electromagnetic waves within the microwave area in the electromagnetic spectrum. The wavelength (λ) 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 COSMO SkyMed, others in C Band (λ=5.6 cm), such as ERS and Envisat, and others with L Band (λ=23cm), such as ALOS PALSAR. Tab. 1 and Tab. 2 show the technical characteristics of each satellite and their specificities for ground deformation measurement using InSAR SPN technology.

TABLE I. MAIN CHARACTERISTICS OF THE ESA C-BAND AND JAXA L-BAND RADAR SATELLITES

	ERS/ENVISAT	ALOS
Mission	1991-2010	2006-2011
Band	C	L
Repeat pass [days]	35	46
Resolution [mxm]	20x4	10x10
Measurement precision [mm]	3	7
Advantages	Very large archive	Detection of higher movement ranges (cm-dm) - Effective also in vegetated areas

TABLE II. MAIN CHARACTERISTICS OF THE NEW GENERATION C-AND X-BAND RADAR SATELLITES

	RDSAT-2	TS-X	CSK
Mission	2007- today	2007- today	2007 - today
Band	C	X	X
Periodicity [days]	24	11	8
Resolution [mxm]	5x5	3x3	3x3
Measurement precision [mm]	3	2	2
Advantages	Detection of higher range movements than X band	High spatial resolution up to 1m/pixel	Best temporal resolution, up to 4 days

III. UNDERGROUND INFRASTRUCTURE APPLICATIONS

A. Advantages of the InSAR technology

InSAR SPN technology has been applied in underground infrastructure construction monitoring 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, it is possible to benefit from information on ground deformation data for approximately the last 20 years. In urban areas where the number of detected measurement points is important, InSAR technology can provide data for wide areas with very high precision (+/- 3 mm per measurement) without having to measure in situ.

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.

B. Selection of the suitable imagery

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 COSMO SkyMed) 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 COSMO SkyMed.
- 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 consecutive images and neighbouring points is double since the wavelength is double.
- L Band: is recommended when the theoretical settlement estimations show 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

It is finally also important to highlight that the InSAR 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 (Tab.1 and 2).

IV. Monitoring of the construction of the Barcelona metro lines

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

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

Those advantages were experienced in a project to monitor the surface of Barcelona city during construction of Metro Line 5 based on TerraSAR-X and Radarsat-2 radar satellite (Tab. 2) for the period 2007-2009 and 2010, respectively. 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.

The TerraSAR-X study results, displayed in Fig. 1, show 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 (Fig. 2) although the gradient of surface deformation in Plaza de las Habaneras seem to have decreased.

Fig. 3 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.

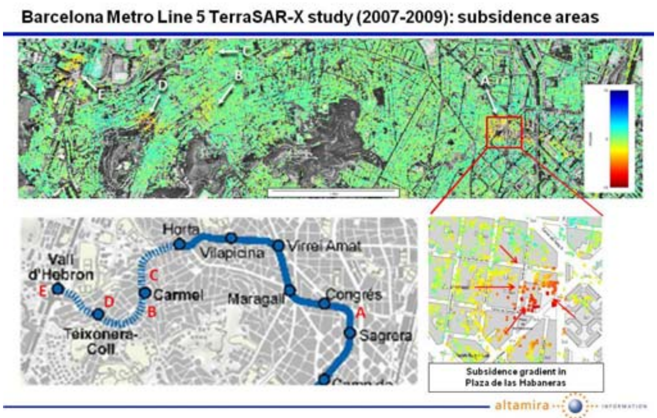

Figure 1. Movement evolution in Barcelona city because of Metro construction (2007-2009)

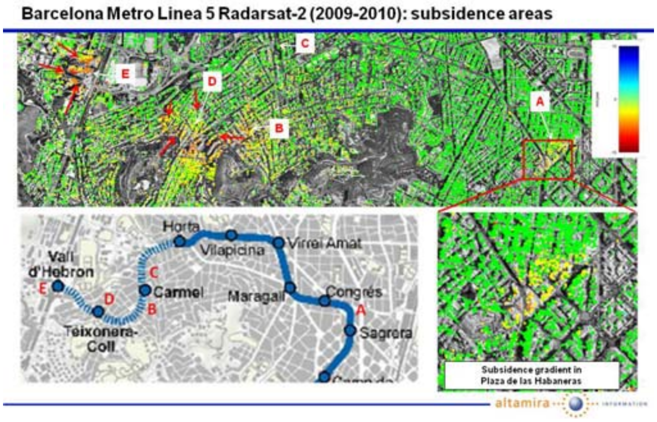

Figure 2. Movement evolution in Barcelona city because of Metro construction (2009-2010)

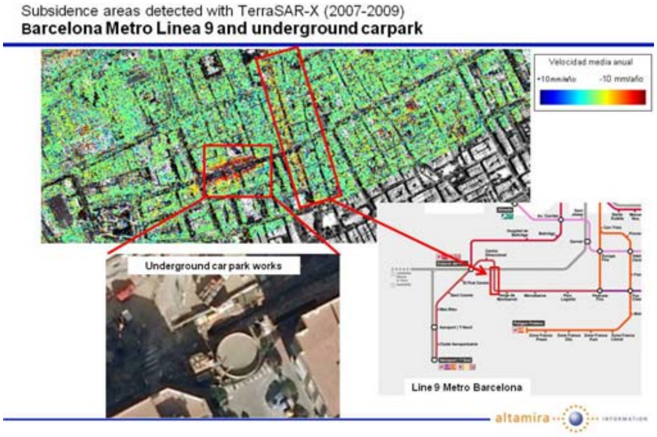

Figure 3: Surface movement due to the construction of a car park and Metro Line 9 (Barcelona)

V. CONCLUSIONS

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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