Abstract: Synthetic aperture radar interferometry, InSAR, is a new remote sensing technique that can be used to measure earth surface deformations. It is capable to provide information about the deformation of a large area of land, economically and efficiently in a short time. Therefore, InSAR is a promising technology for monitoring the earth surface deformations related to some natural hazardous events such as earthquakes, volcanic eruptions, landslides, mudslides, and monitoring of land surfaces where is performed underground construction (mine workings, underground tunnels, etc.). However, some critical issues must be addressed before this technology becomes reliable and accurate monitoring. In this paper are presented the basic principles and concepts of InSAR and analyzed the critical issues for the future development of this technology.

Key-Words: Synthetic Aperture Radar (SAR), InSAR, deformation, remote sensing.

1 Introduction

To work effectively, any warning system has a monitoring component that is essential. In order to monitoring the deformation of the earth's surface can be used geotechnical tools, systems based on GPS and many other available surveying techniques. However, most these based on the characteristic points of measurement determined by these techniques and are too expensive for the area which should be monitored is very large. Recently, a promising alternative technique - InSAR - has been explored by researchers, which makes it possible to measure dense points in the study area precisely, depending on the terrain, convenient and efficient in economic terms [8],[15],[2].

InSAR is abbreviation of interferometry synthetic aperture radar (SAR), which derives information using interferograms, which are formed by phase differences between two complex SAR images of the same area, but obtained at slightly different positions with the same sensor or two similar sensors. InSAR can be used to detect the terrain variations [20] and / or deformations [5], under favorable conditions, can be achieved accuracy of the order of centimeters to measure deformations, which is good enough for many monitoring purposes. However, some problems associated with the main processing procedures need to be addressed before it can become a practically viable measurement technique for deformation monitoring, especially when the rate of change is significant.

This paper examines some aspects of the earth's surface deformation monitoring with InSAR technology, describing in briefly the principles of information taking and analyzing critical aspects of this technology.

2 Principles and concepts

InSAR is based on the use of synthetic aperture radar (SAR), more precisely, it derives information using the interferograms which are formed by phase differences between two high resolution complex SAR images, for the same area, obtained at slightly different positions. SAR is microwave imaging radar, developed in 1960, with improved resolution based on the principle of Doppler frequency shift.
2.1 Principle of the real aperture radar

Imaging radar is an active sensor - providing its own illumination in the form of microwaves. It receives and records the echo reflected from the target, and then generates a map of intensity of echo into gray scale to form an image. Unlike optical and infrared imaging sensors, such imaging radar is able to take clear images day and night under all weather conditions.

Figure 1 shows the geometry of the imaging radar commonly used for earth observation. The radar is onboard a flying platform such as a satellite, which sends microwave continuously with a side - look angle θ in the direction perpendicular to the flying track (azimuth direction). Each time, the energy sent by the imaging radar forms a radar footprint on the ground, which is made up of many small cells.

The echo backscattered from each ground cell within the footprint is received and recorded as a pixel in the image plane, according to the slant range between the antenna and ground cells (as shown in Figure 2). During the flying missions, the swept by the radar footprint forms a swath of the ground, thus a radar image of the swath is obtained.

The minimum distance between two distinct objects is called resolution of the radar images, which is the most important measure of radar image quality. Apparently, the higher this value is smaller, the resolution is better. The resolution of a radar image for earth observation is defined by the azimuth resolution in the flying direction (ΔX) and the slant range resolution in the slant range direction (ΔR) or the ground range resolution in the cross track direction (ΔY), as shown in figure 3.

According to the electromagnetic (EM) waves theory, the azimuth resolution is determined by:

\[ \Delta X = \frac{R \lambda}{D} \]  

where, \( R \) is the slant range, \( \lambda \) is the wavelength of the microwaves and \( D \) is the length of the aperture of the radar antenna. Here \( \Delta X \) is actually footprint width as shown in Figure 1. The slant range and ground range resolutions are:

\[ \Delta R = \frac{c \tau_p}{2} \]  
\[ \Delta Y = \frac{c \tau_p}{2 \sin \theta} \]

where, \( c \) is the speed of light, \( \tau_p \) is the pulse duration and \( \theta \) is the look angle.
Equations (1), (2) and (3) show that the slant range resolution (or ground range resolution) is characterized only by the property microwave and the look angle. They do not have any relationship with the position and size of the antenna. On the other hand, the azimuth resolution (\( \Delta X \)) is dependent on the position and size of the antenna.

2.2 Principle of the Synthetic Aperture Radar (SAR)

To improve the resolution of radar images was developed synthetic aperture radar (SAR) based on the principle of Doppler frequency variations caused by the relative motion between the antenna and the target [7]. Figure 4 shows the imaging geometry of synthetic aperture radar while it is being used to take side-looking image of the ground.

Assuming a real aperture imaging radar with aperture length \( D \) moves from 'a' to 'b', then 'c' sloping distances (range) from the antenna to any point, for example a point target, ranging from \( R_a \) to \( R_b \), and \( R_c \). It is obvious that \( R_a > R_b \), and \( R_b < R_c \), which means that at first the antenna is flying nearer and nearer to the point object until the inclined beam (slant range) becomes the shortest \( R_b \), then it go farther away. The variation of slant range \( R \) will cause the frequency shift of the received echo backscattered from point target O, varying from increase to decrease. Precisely measuring the phase delay of the received echoes, tracing its frequency shift and then synthesizing the corresponding echoes, the azimuth resolution can be improved to the intersection of the three footprints, as seen in Figure 4.

![Antenna positions](image)

Compared with azimuth resolution of the full footprint width described in the above chapter, the azimuth resolution (\( \Delta X \)) for synthetic aperture radar (SAR) can be greatly improved. Ideally,

\[
\Delta X = \frac{D}{2}
\]

(4)

Indeed, this means that the azimuth resolution (\( \Delta X \)) of a SAR is only determined by the length of the real aperture of an antenna. It becomes independent of the slant range \( R \) and the wavelength \( \lambda \). As a result, it is now possible to obtain images with 10m azimuth resolution by a SAR. It should be noted here that there is a difference between the traditional real aperture radar and SAR. However, microwaves sent by a SAR must be coherent, in order to measure the Doppler phase shift. The SAR images should record phase delays and echo intensity. Therefore, the SAR image generally is a complex image containing amplitude component and phase component.

2.3 Basic Principle of Interferometric Synthetic Aperture Radar (InSAR)

SAR images (amplitude image) have been widely used to recognize and environmental monitoring. In such cases, the phase component recorded simultaneously by the SAR has been overlooked, indeed for a long period of time. In 1974 Graham reported for the first time that a pair of SAR images of the same area taken at slightly different positions can be used to form an interferogram and the phase differences recorded in the interferogram can be used to generate a topographic map of the earth surface [10]. Such a technology is called interferometry SAR (InSAR).

InSAR, at present time, is a signal processing technique rather than an instrument. It derives information by using the interferogram, \( \varphi(X, R) \), which records the phase differences between two complex radar images of the same area taken respectively by the same SAR or by two similar SARs from slightly different positions as shown in Figure 6. Either \( S_1(X, R) \) be the complex images taken at position \( A_1 \) with its phase component \( \varphi_1(X, R) \) and \( S_2(X, R) \) at position \( A_2 \) with its phase component \( \varphi_2(X, R) \). According to the wave propagation theory, the phase delay measured with an antenna is directly proportional to the slant range from the antenna to the target point.

![Fig. 4](image)
By subtracting $\varphi_1(X, R)$ form $\varphi_2(X, R)$, the differences form an interferogram $\varphi(X, R)$.

$$\varphi = \Delta \varphi = \varphi_2 - \varphi_1 = \frac{2\pi Q \Delta R}{\lambda}$$ \hspace{1cm} (5)

where, $Q=1$, when the two antennas are mounted on the same flying platform, one transmitting wave but both receiving echoes simultaneously to form one-pass interferometry like [21, [22], otherwise $Q=2$.

To measure the earth's surface deformation of an interesting site within a special interval, it is necessary to take the images of the site with the same SAR or two similar SARs at the starting moment and the end moment of the interval to form 'repeat-pass InSAR' thus, $Q = 2$. Parallel flying paths are expected to form 'repeat-pass InSAR'.

For $\varphi(X, R)$, the slant range difference ($\Delta R$) between $R_1$ (the distance from target point $O$ to $A_1$) and $R_2$ (the distance from $O$ to $A_2$) can be calculated using the formula:

$$\Delta R = \frac{\varphi}{4\pi \lambda}$$ \hspace{1cm} (7)

where, $\lambda$ is the wavelength. As $\lambda$ is in the centimeter order, the slant range difference may be measured in the centimeter order.

If there is no surface change during the interval from $A_1$ to $A_2$, the height $Z$ of the point $O$ can be derived from the following equations:

$$\sin(\theta - \alpha) = \frac{R^2 + B^2 - (R + \Delta R)^2}{2RB}$$ \hspace{1cm} (8)

$$Z = H - R \cos \theta$$ \hspace{1cm} (9)

where, $\theta$ is the look angle, $B$ is the length of baseline $A_1$-$A_2$, $\alpha$ is the angle of the baseline with respect to the horizontal line.

If the target point $O$ has moved to position $O_1$ before the antenna moves to position $A_3$, the slant range $R_3$ (denoted by dot line) becomes

$$R_3^1 = R_3 + \Delta R_2$$

, the phase difference ($\phi_1^1$) between the phases $\phi_1$ and $\phi_3$ (measured position $A_3$) is

$$\phi_{13}^1 = \phi_3 - \phi_1 = \frac{4\pi}{\lambda} (R_3^1 - R_1) =$$

$$= \frac{4\pi}{\lambda} [(R_3 - R - 1) + \Delta R_2] = \frac{4\pi}{\lambda} \Delta R_1 + \frac{4\pi}{\lambda} \Delta R_2 =$$

$$= \phi_{13} + \frac{4\pi}{\lambda} \Delta R_2$$ \hspace{1cm} (10)

The first term $\phi_{13} = \frac{4\pi}{\lambda} \Delta R_1$ is the topography effect, the second term $\frac{4\pi}{\lambda} \Delta R_2$ is the component induced by surface deformation. Given the topography effect, the slant difference $\Delta R_2$ just induced by deformation is

$$\Delta R_2 = \frac{\lambda}{4\pi} (\phi_{13}^1 - \phi_{13}) = \frac{\lambda}{4\pi} \Delta \phi_{13}$$ \hspace{1cm} (11)

This equation shows that $\Delta \phi_{13}$ is the difference between two phase difference interferograms. As a result, this technique (to determine the surface deformation) is sometimes called Differential InSAR (DInSAR).

After the deformation component in the slant range direction ($\Delta R_2$) is obtained from the above equation, $\Delta Z$, the height deformation can be calculated easily as follows:

$$\Delta Z = Z_1 - Z = - \Delta R_2 \cos \theta$$ \hspace{1cm} (12)
3 Some critical problems for determination InSAR technology

InSAR (Interferometry Synthetic Aperture Radar) consists in processing two radar images of the same area, in which each pixel contains amplitude and phase information. After recording two images of space, an interferogram is obtained by computing the phase difference for each pixel. When the two images were taken at the same date, the phase difference is affected by ground displacement projected on the slant range direction or LOS (line of sight), which is close to the vertical direction than radar. This is the principle of differential interferometry, denoted DInSAR.

This technique was proposed at the end of the eighties [8] and its potential was to determine the amplitude of deformations between few millimeters and 10 cm, at least in favorable cases, depending on the soil nature and its geometry, the deformation characteristics, the parameters satellite sensor and the availability of suitable SAR data. Although a ground displacement could be derived from the absolute phase difference, the phase difference given by the interferogram is known modulo $2\pi$. This requires a so-called phase-unwrapping process, which is enhanced if we have a short basic and long wavelength.

However, the phase difference contain other contributions, such as the topography and the atmospheric delay, which must be estimated and removed, and it is affected by several sources of noise, mainly the temporal decorrelation due to the spatial redistribution of micro-reflectors within a pixel like on forest or water. When the InSAR technique is applied in a differential way for ground deformation monitoring, the ground deformation measurement is affected by an atmospheric error (signal to noise) [23], [24].

In recent years, advanced signal processing techniques have been proposed to reduce these limitations. This approach is aimed at the isolation of pure signal from the ground to the other phase contributions and the operation based on multiple images covering a long time period. This improvements reduces the atmospheric effects, but these effects may remain too important if small
amplitude phenomena are monitored (typically 1 cm/year).

Additional adjustments may be considered, using standard atmospheric models [19], [1], with optical data taken by satellite or using signal processing refinements.

Another approach consists is deriving the atmospheric corrections from GPS data.

In addition to phase noise and other possible components of errors, the steps accuracy of processing depends on the accuracy of the satellite status vectors its used to shape trajectory. Lack of precise orbital information can be compensated by the availability of Ground Control Points (GCP) of known coordinates, although their identification is a step of processing operator-dependent.

Precise data on the orbits are essential elements in the processing of the InSAR data [3], [18], [14]. Uncertainties about orbits influence not only in DEM (DEM representing Digital Elevation Model) reconstruction and data geocoding (the geographic coordinates of each scatterer depends on the acquisition geometry), but also in differential applications (DInSAR) for monitoring and detection of small surface displacements. In fact, compensation for the topographic phase contribution can not be carried out correctly using low quality ephemerides (satellite position and velocity vectors), and false fringes can be misinterpreted as surface displacements, especially when the local topography presents considerable height variations.

Phase distortion due to atmospheric effects (i.e., changes in refractive index in the propagation medium) has gained more attention [17], [9], [12], [6] because it can seriously compromise InSAR DEM quality. These effects are mainly due to variations in time and space by water vapor in the atmosphere and reducing the power of the energy spectra. The corresponding correlation length extends well beyond the window size used to estimate coherence, so that the final topography can have strong distortions, in spite of high coherence values.

4 Examples of InSAR applications

In the table below, you can see the number of satellites and bands which works, and the period in which they were, are and will be active.

This article is theoretical, so we mention a few projects on this subject, at various moments in time. In the field of seismology and volcanology, starting from 1992-1995, the volcanic Mount Etna was classic monitored, but in the same time the interpretation of some records from satellite ERS-1/2. There were some controversies of scientists were attributed to possible atmospheric effects and less magnetic influences of such volcanic areas.

Recent and comprehensive research, such as those on Mount Okmok, a volcano in Alaska, leading to unpredictable results, finding lifting of approx. 140 cm before the eruption, based on interferograms.

Nisyros volcano from Greece was studied with InSAR technology determining the lifting of 84 mm before the eruption in 1997, and in the region of volcano Lazulfre from Chile were highlighted lifting of around 3 cm / year in the period 2003-2006 based on interferometric data.

Land subsidence and lifting can be monitored using InSAR, an example being the city of Venice in Italy, resulting displacements between +1 and -2 mm / year.

Monitoring of the surface from the mining areas and geological characteristics can be estimated
using InSAR interferograms in areas like Gardanne from south of France, Wilmington and Salt Lake (from California), Santa Fe and Baldwin Hills from USA, laying out displacements of order 3 - 5 cm.

In areas where is performed underground construction (tunnels, subway), even in urban areas, it is useful to monitor the vertical displacement phenomena of the earth's surface and neighboring buildings, as in Germany, for construction of a wastewater tunnel between Bottrop and Dortmund, from Emscher region, where they used interferometric data TerraSAR-X, is generated the deformation model based on the interferograms DInSAR and PSI (Persistent Scaterrer Interferometry), being able to notify deformations of the order of a few mm.

Recently, during the construction of a section of subway in Budapest, Hungary, TerraSAR-X data was analyzed using PSI (Persistent Scaterrer Interferometry) and SBAS (Small Baseline Subset Interferomery) techniques which determine movements of the ground surface with sub-centimeter accuracy. Significant surface displacements of up to approx. 10 mm/year were detected especially in the vicinities of the underground stations. This successful experiment show that radar imagery from space can be an appropriate tool to complement traditional ground surveys.

5 Conclusion

In spite of the complex processing techniques and practical limitations, the repeated data of interferometry SAR can provide a valuable instrument for generating low-cost DEM for large areas of the earth surface.

The data are still affected by temporal decorrelation and atmospheric disturbances, but if possible a multi-basis approach (i.e., can be generated when a sufficient number of interferograms in the area), the final results can be greatly improved.

These problems are mainly due to the fact that the current SAR systems are originally designed to provide rather the high resolution radar images, other than the interferometry.

Efforts are made to improve current InSAR technique, so that more robust and reliable, so future InSAR systems to be equipped with three antennas on the same platform on satellite [4] and binding devices having GPS antenna.

With the time, the constraints of hardware were reduced and the sophisticated algorithms for optimization have become more reliable, in the coming years is expected "standardization" of InSAR DEM data processing, and at the same time, data are available for at least 80% of Earth's surface and can achieve analysis and more accurately updates.

In conclusion, InSAR has recently attracted more and more attention in many fields of monitoring the earth's surface deformation because it has many advantages over the other survey techniques [2] even if InSAR technology is currently not the most accurate measurement, but it is certainly one of the most promising one.

On the other hand, at present, InSAR is the only technology that can be used to monitor the deformation of the earth's surface on large areas with high density of points, accurately, quickly and efficiently, day and night, in all weather conditions, although there are still a lot of improvement to be made.

Synthetic, advantages of radar satellite technology are:

- High precision of measurements – average vertical precision 1 mm and between two measurements is 3 mm;
- Possibility to measure the past – possibility to analyze movement in the past, data available from 1992 until present;
- High frequency of updates – new measurement data every 4 days and possibility to increase frequency if necessary;
- Guaranteed measurement points – reflectors guarantee measurement in any environment, robust and simple solution, requires no maintenance;
- Cost and time efficiency – measurements made from space, eliminating need for on-site work and first movement results available in only few months.
References:


