A REVIEW OF INSAR TECHNOLOGY FOR DETERMINATION OF SURFACE DEFORMATION

Tome Gegovski
MSc, assistant
Ss. Cyril and Methodius University
Faculty of Civil Engineering – Skopje
email: gegovski@gf.ukim.edu.mk

Zlatko Bogdanovski
PhD, Associate professor
Ss. Cyril and Methodius University
Faculty of Civil Engineering – Skopje
email: bogdanovski@gf.ukim.edu.mk

Filip Kasapovski
PhD, assistant
Ss. Cyril and Methodius University
Faculty of Civil Engineering – Skopje
email: kasapovski@gf.ukim.edu.mk

InSAR (Synthetic Aperture Radar Interferometry) is a modern technology in the field of remote sensing that allows determination of deformations of the Earth's crust for large areas with relatively high accuracy.

In this work are presented basic characteristics of InSAR technology and advance InSAR techniques: Differential InSAR (DInSAR) and Permanent Scatterer (PSInSAR).

Keywords: SAR Interferometry, DInSAR, PSInSAR, vertical deformation, geodynamics

1. INTRODUCTION

The Earth's surface is constantly under the influence of seismic processes that cause deformations. The determination of this phenomenon is in the domain of geodetic science, in the field of geodynamics.

The use of classical geodetic methods give excellent results in terms of accuracy. But these methods cannot be used for monitoring deformations on large areas.

The development of satellite technology has great significance for geodetic science because it enables measurements over great distances. The result of this is the development of satellite geodesy and remote sensing.

In the field of remote sensing, the invention of SAR sensors is particularly important, which enable the broadcast of numerous radar signals that are covering large areas of the Earth. These satellite images are the basis for SAR interferometry which allows the determination of deformations, while this technology primarily refers to the obtain of vertical displacement. In the last two decades, several methodologies have been developed for the processing of SAR images, including: DInSAR and PSInSAR, which provide accuracy of few millimeters in determining vertical deformations.

2. BASICS OF SYNTHETIC APERTYRE RADAR (SAR)

SAR sensors are designed to permanently emit and receive radar signals, which register the amplitude and phase of the surface's reflected signals. These sensors are used as an integral part of specially launched satellites that orbit at a distance of about 500 to 800 km. Satellites moving around the Earth constantly broadcast a large number of signals, day and night, 365 days a year. Part of the reflected signals are returned to the SAR sensor of the satellite, and a registered in the form of a SAR image with data containing the amplitude and phase of the signal in each pixel of the SAR image. The angle (θ) between true north-south and the satellite orbit varies slightly, depending on the satellite. Generally, is in the range of 20 to 50 degrees, depending of the satellite. (Fig. 1) [14]

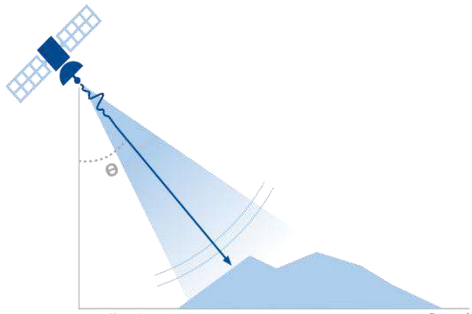

Fig.1 SAR image acquisition (*https://site.tre-altamira.com/insar/*)

Depending on the structural elements of the SAR sensor, several types of signals are used that have a characteristic frequency and wavelength. (Fig. 2) The most commonly used signals for InSAR purposes are: X-band, C-band and L-band. [5]

The SAR image is a matrix of pixels, where each pixel contain data on the amplitude and phase of the reflected signal from the Earth's surface. The amplitude is related to the energy of the backscattered signal. It means solid objects (natural or artificial) have a strong reflexivity and the amplitude of the reflected signal is high. The phrase is used in estimating displacement in interferometric application.

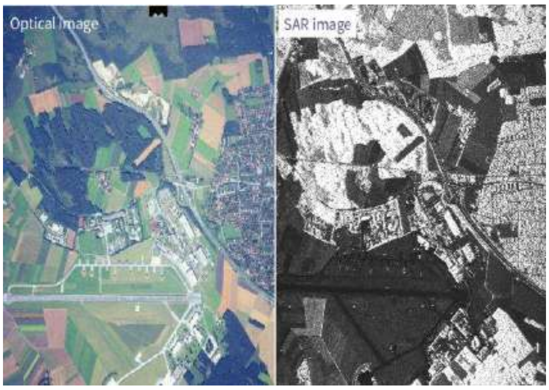

Fig.3 Optical image vs SAR image [2]

The reference frame of a SAR image is defined by the SAR coordinates: range and azimuth. (Fig. 4) Since the radar is not orthogonal to the ground, terrain elevation will result in geometric distortions in the SAR image. In fact, even the variation in the projection of the reference surface (ellipsoid) in range direction, causes geometric distortions, due to the varying incidence angle. [9]

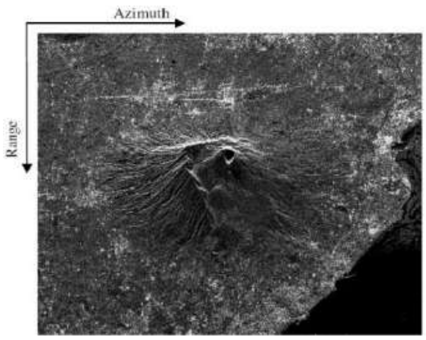

Fig.4 SAR coordinates (*https://site.tre-altamira.com/insar/*)

Band	Frequency	Wavelength	Typical Application
Ka	27–40 GHz	1.1–0.8 cm	Rarely used for SAR (airport surveillance)
K	18–27 GHz	1.7–1.1 cm	rarely used (H2O absorption)
Ku	12–18 GHz	2.4–1.7 cm	rarely used for SAR (satellite altimetry)
X	8–12 GHz	3.8–2.4 cm	High resolution SAR (urban monitoring,; ice and snow, little penetration into vegetation cover; fast coherence decay in vegetated areas)
C	4–8 GHz	7.5–3.8 cm	SAR Workhorse (global mapping; change detection; monitoring of areas with low to moderate penetration; higher coherence); ice, ocean maritime navigation
S	2–4 GHz	15–7.5 cm	Little but increasing use for SAR-based Earth observation; agriculture monitoring (NISAR will carry an S-band channel; expends C-band applications to higher vegetation density)
L	1–2 GHz	30–15 cm	Medium resolution SAR (geophysical monitoring; biomass and vegetation mapping; high penetration, InSAR)
P	0.3–1 GHz	100–30 cm	Biomass. First p-band spaceborne SAR will be launched ~2020; vegetation mapping and assessment. Experimental SAR.

Fig.2 SAR signals (*https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar*)

3. BASICS OF SAR INTERFEROMETRY

InSAR (SAR Interferometry) is a process of determining the phase differences for each pixel from a pair of SAR images acquired at different time periods, on the same surface of the Earth from the same satellite in the identical orbit.

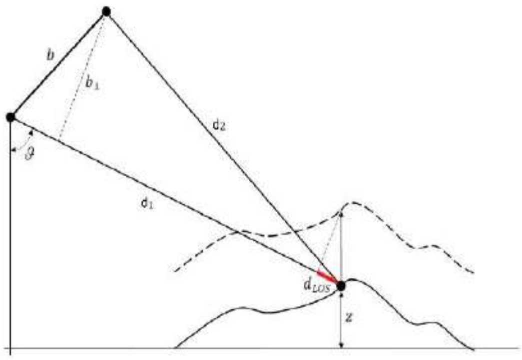

Fig.5 Sketch of the geometry interferometric SAR acquisition (*https://www.mdpi.com/2072-4292/13/23/4756)*

For every SAR pixel of the scene, the mathematically expressions for the returning of complex value signal related to the two SAR images are:

$$i_1 = \gamma_1\, exp\left[-j\frac{4\pi}{\lambda}d_1\right]$$

$$i_2 = \gamma_2\, exp\left[-j\frac{4\pi}{\lambda}d_2\right]$$

Where, γ_1 и γ_2 are reflective function values, d_1 и d_2 are distances from the SAR sensor to the object in both acquisitions, λ is the wavelength. The phase difference (Δφ) can be expressed by the following mathematical expression: [1]

$$\Delta\varphi = \frac{4\pi}{\lambda}\frac{b_\perp}{r_1 \sin\vartheta}z + \frac{4\pi}{\lambda}d_{LOS} + \Delta\varphi_{atm.} + n$$

Where, z is altitude, d_{LOS} projection of the 3D deformation vector of the line of side (LOS) between two acquisitions, $b_\perp$ is perpendicular baseline, ϑ is the angle of inclination of the SAR sensor and $\Delta\varphi_{atm.}$ is the phase shift predicted depending the different atmospheric conditions during the acquisition period of the two SAR images.

A very important prerequisite is that the acquisition of the pair of SAR images should be registered from a similar position (ideally, the satellite would be at an identical position in the orbit during both acquisitions).

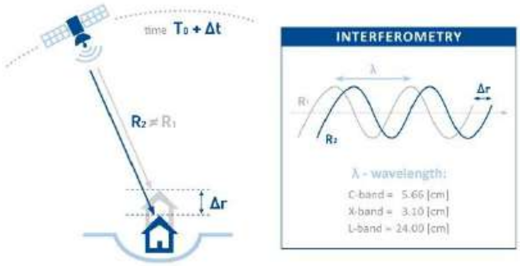

Fig.6 SAR Interferometry (*https://site.tre-altamira.com/company/)*

The result of InSAR processing is the interferogram, which is matrix of pixels with known differential interferometric phase (Δφ) given in values from -π to +π, express through the so-called color fringes. One fringe is equal on one cycle of the spectrum colors from purple to red, which equals the displacement that corresponds to half of the wavelength. If the color sequence is from purple to red, then ground moved away from the satellite and its show that we have ground subsidence. If the color sequence is from red to purple, then ground has moved towards the satellite and it shows that we have ground uplift. [15]

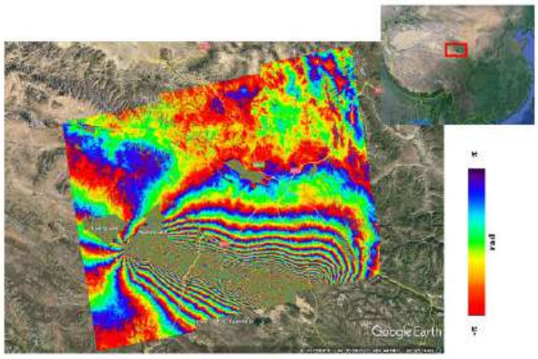

Fig.7 SAR Interferogram (*https://www.mdpi.com/2072-4292/13/23/4756/htm)*

Interferometric fringes can only be observed where scene has a big coherence. The coherence in InSAR means when area on the ground appears to have surface characterization in all SAR images analyzed in all pixels. The coherence is expressed for all pixels separately in range of 0 to 1, 0 means no coherence in pixel and 1 means absolute coherence. In general, for successful determination of displacements the average coherence should be higher than 0.5. [13]

If the coherence satisfies the suggested values, the total displacement can be expressed:

$$total\ displacement\ \ (d_{LOS}) =$$
$$number\ of\ fringers\ \times\ half\ wavelength$$

However, the acquisition of SAR images is done on the surface of the Earth in different weather conditions. It causes phase difference in the interferogram which is not equal to the intensity of the displacement, but is a combination of several additional factors, represented in the following mathematical expression:

$$\Delta\varphi = \Delta\varphi_{disp.} + \Delta\varphi_{flat} + \Delta\varphi_{elev.} + \Delta\varphi_{atm.} + \Delta\varphi_{n.}$$

where, $\Delta\varphi_{flat}$ is Earth's flat phase due to Earth's curvature, $\Delta\varphi_{elev.}$ is topographic correction, $\Delta\varphi_{atm.}$ is atmospheric correction such as: different humidity, temperature, pressure between two acquisitions and $\Delta\varphi_{n.}$ is noise which causes temporal change of scatterers, different capture angles etc. [15]

The need to remove these phase disturbances is the need for the appearance of several InSAR techniques, among which are DinSAR and PSInSAR.

3.1. DINSAR

The process of interferometric analysis of the displacements of single pair SAR images excluded from the influences of the Earth's curvature and terrain topography is called DInSAR. This technique uses a Digital Elevation Model (DTM) of the area of interest. The word "differential" refers to the removal of the topographic phrase correction from the interferogram.

After implementation of the DTM, the above expression is transformed with the removal of the influence of $\Delta\varphi_{flat}$ and $\Delta\varphi_{elev.}$ and has the following form: [13]

$$\Delta\varphi_{interf.} = \Delta\varphi_{disp.} + \Delta\varphi_{atm.} + \Delta\varphi_{noise} + \varepsilon$$

where ε is the sum of possible errors in the DTM.

These processings are done exclusively using software algorithms, that do an individual calculation for each pixel in a single pair of SAR images.

The scheme of DInSAR processing in the SNAP software (Sentinel-1 Toolbox) developed by European Space Agency (ESA), with using the SLC data from Sentinel - 1 satellite is given in Fig.8 [10]

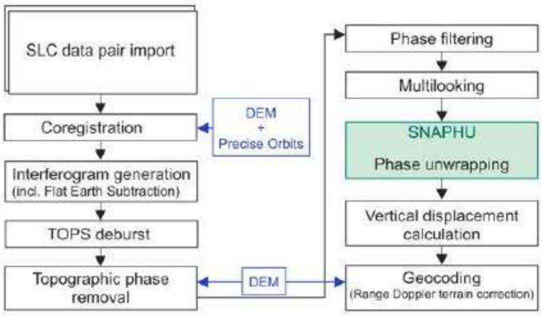

Fig.8 DInSAR scheme processing [7]

However, the vertical deformations determined by the DInSAR technique are filed with errors from atmospheric influences which can significantly affect the accuracy. This technique is usually used to review vertical displacements of significant intensity and serves as a basis for using some of the advanced techniques (such as PSInSAR), which use time series to remove atmospheric influences and obtain vertical deformations with millimeter accuracy.

3.2. PSINSAR

PSInSAR (Persistent Scatterer Interferometry) is advance technique for surface displacement determination. The first PSInSAR algorithm appeared in 1999, in the PS Technique by Politecnico di Milano (Polimi). [3]

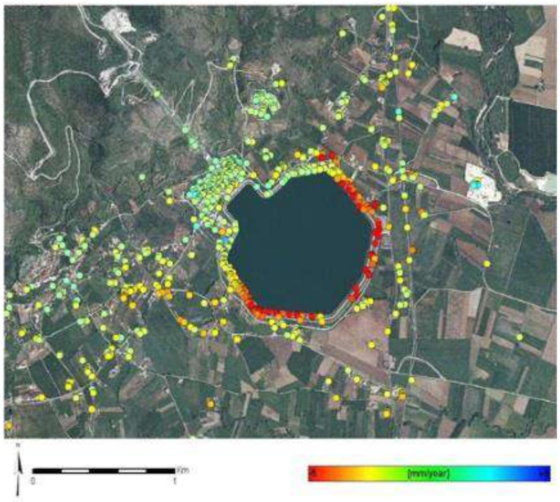

Fig.9 Permanent Scatterer (PS) and Distribute Scatterer (DS) [3]

PSI technologies are advanced forms of DInSAR, where the fundamental difference is that PSI technologies develop multiple interferograms from a stack of radar images. As a minimum of 15 SAR image are usually required for PSI algorithm. In fact, PSI represent a specific class of DInSAR with appropriate data processing and analysis procedures to separate $\Delta\varphi_{disp.}$ of the other components represented in final equation of the DInSAR.

A Permanent Scatterer (PS) is defined as a radar target, within a resolution cell, that displays stable amplitude properties and coherent signal phase, throughout all of the images within a data stack. Objects that make good PS are varied and can be natural or artificial. Natural PS forms usually are: rock outcrops, un-vegetated earth surface, boulders etc., among the artificial object: buildings, street lights, bridge parapets, above-ground pipelines, appurtenances on dams and roof structures, and any rectilinear structure that can create a dihedral signal reflection back to the satellite. [13]

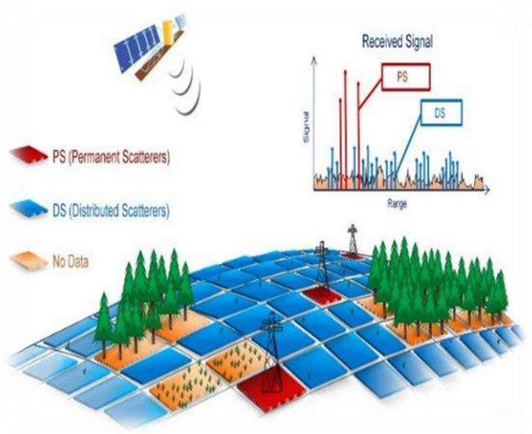

Fig.10 Permanent Scatterer (PS) and Distribute Scatterer (DS) [3]

In the paper “Analysis of Permanent Scatterers in SAR interferometry” the authors presented statistical analysis of the PS density in urban areas as a function of the standard deviation of the phrase differences where in urban areas about 100 PS/km^2 can be identified and exploited for terrain deformation monitoring with millimetric accuracy. [8]

The last evolution of PSInSAR technology is SqueeSAR developed by Tele - Rilevamento Europa in collaboration with Politecnico of Milano. SqueeSAR technique searches for targets in the radar image set that consistently reflect radar signals throughout the entire dataset of images, exploiting both permanently scattering ground targets: PS like buildings, pipelines, linear structures, open outcrops etc. and homogenous distributed scatterers (DS), for e.g., homogeneous ground or scattered outcrops, uncultivated areas, debris covered areas. (Fig. 10) [3]

These two Insar techniques are very important and used for the determination of surface deformations, but in the last two decades more InSAR techniques have appeared chronologically systematized in Fig. 11.

Another approach of PS InSAR is the small baseline distances between either the satellite positions of different acquisition times, which is used to reduce the geometric and temporal decorrelation. This method also has time-series analysis approach and is called the small baseline subset. [11]

The major restriction of this approach is that it is limited to the scatterers that have sufficiently high coherence, even at large baselines, which typically leads to low PS density in nonurban areas. [4]

For first time this technique is developed and published in paper of Berardino et al (2002).

PSI method reference	Baseline configuration	Pixel selection criterion	Deformation model
Ferretti et al. (2000, 2001)	Single master	Amplitude dispersion	Linear deformation in time
Berardino et al. (2002)	Small baselines	Coherence	Spatial smoothness
Mora et al. (2003)	Small baselines	Coherence	Linear deformation in time
Schmidt and Bürgmann (2003)	Small baselines	Coherence	Spatial and temporal smoothness
Werner et al. (2003)	Single master	Amplitude dispersion & Spectral phase diversity	Linear deformation in time
Duro et al. (2003) and Crosetto et al. (2008)	Small baselines	Amplitude dispersion, coherence, spectral coherence	Linear deformation in time
Kampes (2006)	Single master	Amplitude dispersion & Signal to clutter ratio	Different types of deformation models
Hooper et al. (2004)	Single master	Amplitude and phase criterion	Spatial smoothness
Crosetto et al. (2005)	Small baselines	Coherence	Stepwise linear function in time
Costantini et al. (2008)	Single master	Amplitude dispersion	Linear deformation in time
López-Quiroz et al. (2009)	Small baselines	Coherence	Spatial smoothness
Ferretti et al. (2011)	Single master after triangulation	Statistical homogeneity test	Deformation model in time
Perissin and Wang (2012)	Target-dependent interferogram subset	Quasi-PS approach	Linear deformation in time
Hetland et al. (2012)	Small baselines	Coherence	Different types of deformation models
van Leijen (2014)	Single master	Amplitude dispersion	Different types of deformation models
Goel and Adam (2014)	Small baselines	Statistical homogeneity test	Linear deformation in time
Lv et al. (2014)	Single master	Statistical homogeneity test	Linear deformation in time
Devanthéry et al. (2014)	Small baselines	Amplitude dispersion & Cousin PS	Spatial smoothness

Fig.11 Characteristics of the main PSI approaches. [4]

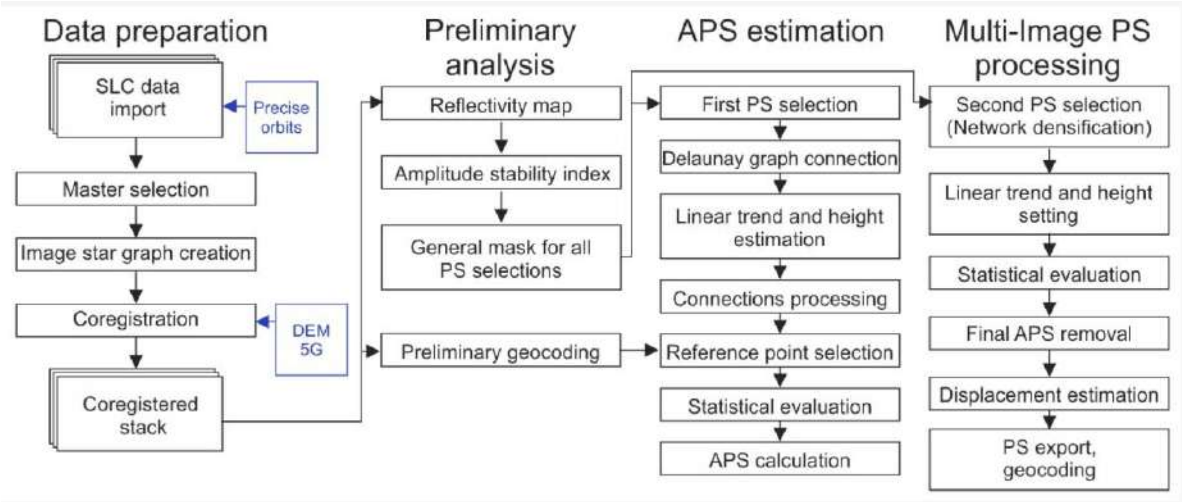

Fig.12 Simplified workflow of PSI Processing in SARPROZ [7]

PSinSAR processing is a very complex procedure that requires high knowledge and requires the use of several scientific software packages.

In the paper [7] is presented simplified workflow of PSI processing in software SARPROZ. (Fig. 11) The authors emphasized that a critical part is the coregistration of the SAR images into a single master SAR image before deriving interferograms. It is very important to choose a proper master scene which must have the following specifications:

- It must be acquired under good weather conditions (no rain) and
- That has a suitable position (approximately in the middle) in the image star graph considering the perpendicular and temporal baseline.

In the paper [12], the author used several scientific software packages, developed on different universities. Their first step in the data processing was focusing the radar image to obtain the single look complex images (SLC). For that they planned to use the scientific package ROI-PAC (Repeat Orbit Interferometry Package) developed at the Jet Propulsion Laboratory (JPL) on the Caltech (California Institute of Technology) university, but in the processing that step was skipped, because they used directly SLC radar data downloaded from ESA (European Space Agency) web side. The interferogram which they processed is generated in DORIS (Delft object-oriented radar interferometric software) developed at the TU Delft, Netherland. The phase unwrapping process, they did in SNAPHU software developed by Stanford. And the phrase processing they did in scientific software StaMPS/MTI (Stanford method for persistent Scatterer/Multi Temporal InSAR) developed at the Stanford University.

The complete processing procedure is shown in Fig. 13.

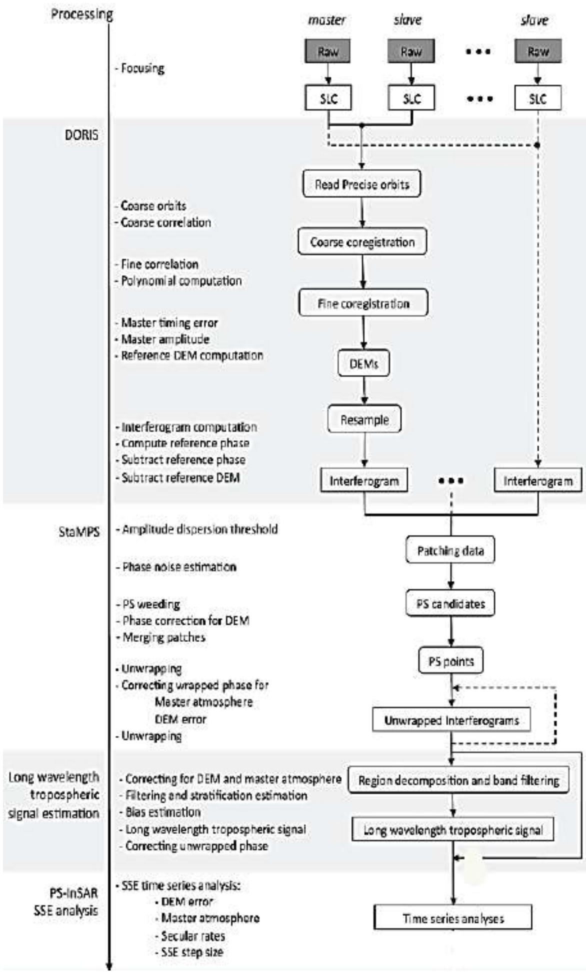

Fig.13 PSInSAR processing with using of many software packages [12]

4. CONCLUSION

InSAR technology is capable of responding to the needs for continuous and massive monitoring of the Earth's surface, through the determination of its deformations. This is proven by numerous works in the last two decades devoted to this particular issue.

In almost all studies and research on this topic, the general conclusion is that this technology offers opportunities for determining vertical deformations within a few millimeters, using the advanced PSInSAR technique. For this purpose, in many papers, comparative analyzes of this technology have been made with the classical methods for deformation analyses. In most of them, the both methodologies give the similar results.

The advantage of this technology compared to other geodetic methods for determining Earth's deformations is the possibility to use it on large areas, in any period from the past when SAR images are available.

The disadvantages of this technology are the impossibility of using it for every surface, especially surfaces with dense vegetation. Also, a disadvantage of this technology can be the complex processing of SAR images.

In general, it is a new technology that is constantly being upgraded and sets a new standard in the determination of vertical deformations.

REFERENCES

[1] Bamler, R., & Hartl, P. (1998). Synthetic aperture radar interferometry. *Inverse Probl.*

[2] D'Hondt, O., & Hellwich, O. (2018). Regularization and Completion of TomoSAR Point Clouds in a Projected Height Map Domain. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 9.

[3] Bellotti, F., Alessandro, F., & Del Conte, S. (2015). Advanced InSAR techniques to support tectonic settings analyses. *Rendiconti Online Societa Geologica Italiana*.

[4] Crosetto, M., Monserrat, O., Cuevas-González, M., & Devanthéry, N. (2016). Persistent Scatterer Interferometry: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*.

[5] EarthData. (2022). *What is Synthetic Aperture Radar*. Retrieved from https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar

[6] ESA. (2021). *TOPS Interferometry Tutorial.*

[7] Fárová, K., Jelének, J., Kopacková-Strnadová, V., & Kycl, P. (2019). Comparing DInSAR and PSI Techniques Employed to Sentinel-1 Data to Monitor Highway Stability. *Remote sensing*.

[8] Ferretti, A., & Rocca, F. (2000). Analysis of Permanent Scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*.

[9] Hanssen, R. F. (2001). *Radar Interferometry.*

[10] Imperatore, P., Pepe, A., & Sansosti, E. (2021). High Performance Computing in Satellite SAR Interferometry:. *Remote sensing*.

[11] Jia, H., & Liu , L. (2016). A technical review on persistent scatterer interferometry. *Journal of Modern Transportation*.

[12] Pribicevic, B., Đapo, A., & Govorcin, M. (2018). Surface Deformation Monitoring in the Republic of Croatia with MT-InSAR.

[13] RiskNET. (2016). *INTERFEROMETRIC SYNTHETIC.* Retrieved from An Introduction for Users of InSAR: http://www.risknet-alcotra.org/rna/allegati/insar-manual.pdf

[14] TRE Altamira. (2022). *TRE Altamira*. Retrieved from InSAR at a glance: https://site.tre-altamira.com/insar/

[15] Valentino, G. (2021, May 3). Introduction to Interferometric SAR - Dr. Gianluca Valentino (theory). Malta.