COMPARATIVE ANALYSES OF MULTI-FREQUENCY PSI GROUND DEFORMATION MEASUREMENTS

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ABSTRACT

In recent years many new developments have been made in the field of SAR image analysis. The wider diversity of available SAR imagery gives the possibility of covering wide ranges of applications in the domain of ground motion monitoring for risk management and damage assessment.

The work proposed is based on the evaluation of differences in ground deformation measurements derived from multi-frequency PSI analyses. The objectives of the project are the derivation of rules and the definition of criteria for the selection of the appropriate SAR sensor for a particular type of region of interest. Key selection factors are the satellite characteristics (operating frequency, spatial resolution, and revisit time), the geographic localization of AOI, the land cover type and the extension of the monitoring period.

All presented InSAR analyses have been performed using the Stable Point Network (SPN) PSI software developed by Altamira Information [1].

Keywords: InSAR, Persistent Scatterer interferometry, multi-sensor analyses, ground deformation measurements.

1. INTRODUCTION

Available SAR imagery is constantly increasing thanks to the growing number of missions in operation. The existence of these missions (some completed, others still active) offers the possibility to image wide regions of the globe using different operating frequencies.

Selecting the best data stack for a Persistent Scatterer SAR Interferometry (PSI) analysis is therefore possible in some cases. This selection is based on many factors such as availability of SAR acquisitions, land cover of the AOI, type of expected ground deformation and the required precision.

It is also worth highlighting that performing independent PSI studies at different wavelengths and considering the same area gives the possibility to obtain complementary results for a better characterization of the site of interest. For instance, C and X-band data allow for the detection of millimetric displacement rates while L-band data is more suitable for stronger deformation (centimetric) for which X and C-band may be beyond the authorized aliasing limit [2].

To define appropriate selection criteria, comparative PSI multi-frequency (at X-, C- and L-band) studies have been carried out over urban and rural areas. This assisted in determining the performance of the different wavelengths considering different land covers. Considered performance factors are sensor sensitivity to ground motion, impact of temporal decorrelation and spatial resolution.

The capacity to detect motion at each frequency band is first investigated in the Chapter 2. The impacts of the temporal decorrelation and of changes that occur during the monitoring period are evaluated in the Chapter 3.

The results of multi-band PSI analyses conducted at C- (ENVISAT, RADARSAT-2), L- (ALOS PALSAR) and X-band (TerraSAR-X, COSMO-SkyMed) in urban and rural areas are presented in the Chapter 4. Table 1 gives the characteristics of the missions considered. The main purpose is to estimate the noise level for each frequency band over a known stable area, therefore providing knowledge on the precision for ground deformation measurements; the density of measurement points retrieved with different resolutions and at different wavelengths is also evaluated.

Sensors	Imaging mode	Spatial resolution (az [m] x sl rg [m])
ALOS PALSAR	Fine Beam modes	4.5 x 4.5
ENVISAT ASAR	Image Mode	4 x 8
RADARSAT-2	Multilook Fine	3 x 3
TerraSAR-X	StripMap	3 x 1.2
COSMO-SkyMed	Super SpotLight	0.7 x 0.3

Table 1: Imaging mode and spatial resolution considered for each mission

Conclusions and perspectives are discussed in the last chapter.

2. CAPACITY TO DETECT GROUND MOTION

The current availability of multi-frequency SAR data has contributed to the study and to the better understanding of the performance of the different wavelengths for InSAR processing. This knowledge is essential for PSI analysis. The selection of the appropriate imagery influences not only the final result but also the processing steps to be implemented. Equally important is to perform an assessment of the

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area to be studied, since the characteristics of the land cover will have a prominent impact on the performance of the resulting backscatter.

A parameter that is essential to consider for ground movement monitoring is the capacity of measuring motion without ambiguities (caused by the fact that the phase related to the displacement of an interferogram pair is wrapped between - π and π) [3]. The maximum gradient of ground motion between two neighboring points that can be detected without ambiguities is defined by the repeat pass interval δt and the wavelength λ, and is given as by (1):

$$\nu_{max} = \frac{\lambda}{4 \cdot \delta t} \quad (1)$$

Table 2 summarizes the maximum detectable deformation gradient between two neighboring points and the theoretical precision given for a network of PSs using data stacks of different sensors. It is assumed that δt is uniform and given by the nominal revisit time of each mission (same acquisition geometry). Moreover a phase noise level of 0.25 radians [4], which can represent the theoretical maximum phase noise level encountered in a set of PSs, is considered.

Sensor	**δt (days)**	**ν_{max} (mm/year)**	**Precision assuming a phase noise of 0.25 rad (mm)**
COSMO-SkyMed	8	353.6	0.6
TerraSAR-X	11	257.1	0.6
RADARSAT	24	213.0	1.1
ENVISAT	35	146.2	1.1
ALOS	46	468.1	4.7

Table 2 : Maximum detectable deformation gradient between two points and precision in function of the operating frequency.

The selection of the optimum wavelength must account for the magnitude of the ground motion and the precision required for the measurement. Table 2 shows that ALOS is the most suitable [2] to detect movement of fast magnitude although the precision is clearly degraded. It can moreover be inferred that COSMO-SkyMed, with its revisit time of 8 days (using two satellites on a 16 day orbit), also allows monitoring fast movements with a great precision.

3. IMPACT OF THE TEMPORAL DECORRELATION

The ground motion monitoring efficiency depends on the capability to retrieve measurement points over the site. The type of land cover has a direct impact on the quality and number of measurement points.

Urban areas present an optimal performance in obtaining persistent scatterers, since manmade structures are usually stable and have a high backscattering. On the other hand, field and highly vegetated areas are affected by constant changes of structure that modify their backscattering.

- Urban areas give in general a good level of backscattering and allow obtaining a considerable number of measurement points whatever the considered wavelength. In that case the most important factor to consider is the sensor resolution in order to maximize the final density of PSs (section 4). In such an environment, SAR interferometry allows detecting surface ground motions with high precision.
- Over vegetated areas, depending on the wavelength, penetration through the foliage may or not be achieved. This becomes a concerning matter when InSAR is applied over rural areas that include forest, agricultural crops and mixed vegetation. As shown in [5], the shorter wavelengths are backscattered on the tops of the trees. At C-band for example (ENVISAT or RADARSAT satellites), the penetration depth is within a few meters of the crown. The radar wave interacts with the upper part of the canopy, mainly with leaves and twigs. Longer wavelengths (or lower frequency) penetrate through the vegetation and can reach the ground. For this reason, at L-band, the penetration is deeper.

Furthermore, any activity that induces changes in the terrain backscattering affects the PSI study. Such changes could be agricultural activity or construction works. They prevent the measurements and make difficult the PS detection over the site.

Figure 1 and Figure 2 illustrate the impact of the temporal decorrelation in the monitoring of agricultural area.

The interferometric coherence and phase are compared at L- (ALOS) and C-bands, considering a short (Figure 1) and a large (Figure 2) temporal baselines. Similar spatial resolutions are considered for the study, as well as a short perpendicular baseline, in order to avoid geometric decorrelation.

The interferometric coherence gives a measure of the phase correlation between the master and slave images of the interferometric pair. As it is influenced by the degree of similarity of the surface between two dates, it can be used as quality factor of the measurement point in field areas. The coherence varies between 0 and 1. High interferometric coherence indicates zones with high quality of measurements.

Figure 1 shows that L-band preserves the phase over the short time interferogram (46 days for ALOS, 35 days for ENVISAT); while at C-band the coherence is much lower. This is mainly due to its longer wavelength which is less sensitive to the small changes of the single scatterers contained within each resolution cell. A field is highlighted by the white circles; the important decrease of the C-band coherence can be noticed.

On the contrary, Figure 2 shows that due to the seasonal agricultural activities the coherence is considerably decreased almost everywhere, also at L-band. As expected, crop fields are one of the land cover for which InSAR analysis is worsen whatever the resolution or wavelength. Nevertheless, it should be stressed that the temporal decorrelation could somehow be limited by reducing the observation period. TerraSAR-X and COSMO-SkyMed (and future ESA's SAR mission Sentinel-1) offer data with a repeat cycle of the order of a week. PSI analyses are then possible over few months with a good number of images. This allows for instance, to measure between snow seasons in mountainous areas, maximizing the density of measurement points in short periods of time; this is illustrated in section 4.

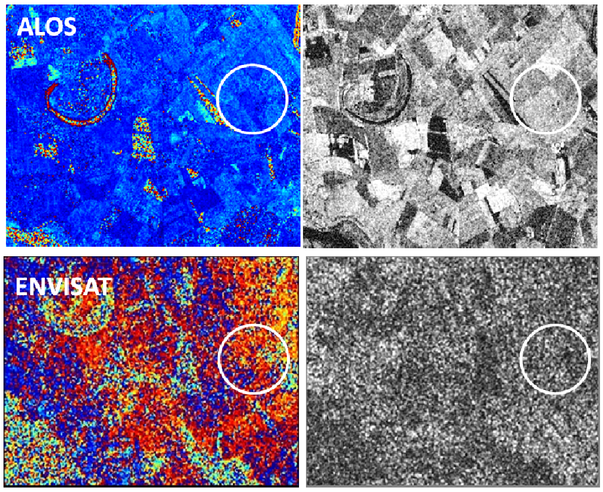


Figure 1: Effect of temporal decorrelation for a short temporal baseline interferometric pair (46 days for ALOS and 35 days for ENVISAT). The ALOS and ENVISAT interferometric phase and coherence are displayed

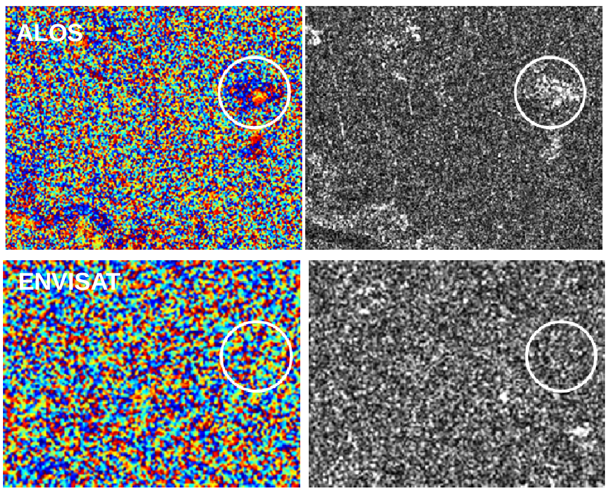


Figure 2: Effect of temporal decorrelation for a one-year temporal baseline interferometric pair. The ALOS and ENVISAT interferometric phase and coherence are displayed

4. INFLUENCE OF THE SPATIAL RESOLUTION

The density of detected measurement points is also directly linked to the spatial resolution of the images.

It is clear that the higher the spatial resolution, the higher the density of measurement points that can be obtained from a given area. Higher spatial resolution implies more samples of the ground surface. In consequence, these samples are smaller and less sensitive to changes caused by temporal or geometric decorrelation. The stability constraints for each resolution cell are relaxed since the area required to be stable is smaller and therefore small areas of stability can be retrieved. This in consequence increases the chance to have measurement points.

To illustrate this statement, Figure 3 presents an example of comparison of the PS density obtained with two different data stacks at C-band but with very different spatial resolution. In particular, PSI results derived from the analysis of ENVISAT and RADARSAT2 data over an urban area are analyzed. Both sensors operate at C-band, but the Canadian satellite offers a slant-range resolution of 3 meters (Multi-look Fine Mode), against the 8 meters (Image mode) provided by ENVISAT (Table 1). This difference is reflected over the final point stable density obtained which is 10649 PS/Km^2 for RADARSAT2 and 1793 PS/Km^2 for ENVISAT, as illustrated by Figure 3.

The higher spatial resolution reached with the fine mode of RADARSAT-2 allows increasing the measurement point density in the streets and around the buildings with a ratio higher than the ratio of resolutions (5.9 more points using data 2.7 times better in terms of spatial resolution).

Figure 3: PS location maps for comparison of the PS density achieved at C-band and over the same time period with the Image Mode of ENVISAT and the Multi-Look Fine Mode of RADARSAT-2

4.1 PSI analysis in urban area

The objective is to analyze the performance of the ground detection capabilities using PSI processing with different wavelengths in urban area (land cover of good backscatter not affected by temporal decorrelation). The analysis considers the evaluation of the noise level and the density of measurement points in function of the wavelength and the sensor's resolution.

An urban area known as stable during the observation period was considered. In order determine the noise level of the different bands, the mean annual displacement measured for each processing is compared. The used data stacks were composed of 27 TerraSAR-X, 12 COSMO-SkyMed, 20 RADARSAT-2, 42 ENVISAT and 15 ALOS images. The achieved density and the estimated ground motion precision of the measurement points for each data stack is reported in Figure 4 and Table 3.

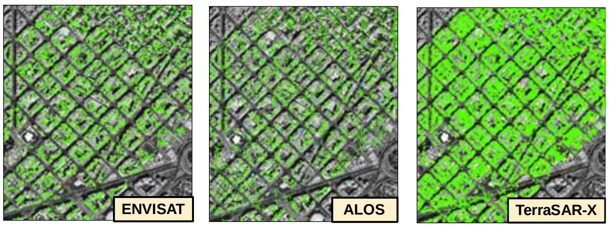


Figure 4 : PSI ground motion results over a stable urban area in the case of analyses with ENVISAT, ALOS and TerraSAR-X.

In the results, the closest to zero average displacement rate (or lower noise floor level) is obtained with the use of X-band data. This is due to the higher sensitivity of the phase to slant-range change of distances given by the use of a short wavelength (as pointed out theoretically in Table 2). Moreover, its higher spatial resolution allows the detection of more measurement points as shown by the PS density values.

As already discussed, Table 3 illustrates that the spatial resolution is directly linked to the density of measurement points. Results obtained with the standard imaging modes of TerraSAR-X and RADARSAT-2 are considerably over the capabilities of the rest of the satellites. However the performances of the Super Spotlight Mode of COSMO-SkyMed which gives the highest PS density are impressive.

Sensors	Mean annual displacement (mm/year)	Standard deviation (mm/year)	PS density (PS/Km^2)
ALOS	0.68	4.46	2.100
TerraSAR-X	0.00	1.00	26.815
RADARSAT-2	0.08	1.10	10.650
COSMO-SkyMed	0.00	0.75	105.424
ENVISAT	0.23	0.58	1.793

Table 3 : Evaluation of the ground motion precision achieved with different data stacks by estimating the mean annual displacement rate in known stable urban area achieved with the PSI analysis at L, X and C-band and at different resolutions

The graphs of Figure 5 and Figure 6 show the evolution of the PS density in function of the spatial resolution and of the wavelength, respectively. They have been derived from the Table 3. The shape of the first curve shows that the PS density increases at a higher rate than the spatial resolution ratio. This should be accounted for when processing large areas using high resolution data. The PSI processing procedures must then be optimized in order to manipulate such great amount of information and overcome memory overflows. No main conclusion can be derived from the Figure 6, due to the high influence of the spatial resolution, the PS density does not show high correlation with respect to the wavelength

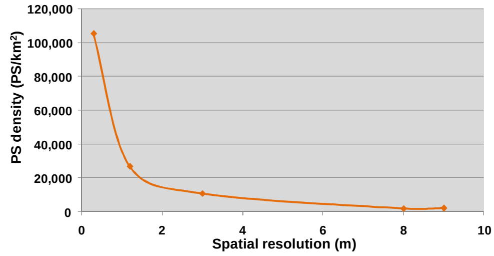


Figure 5: Evolution of the PS density in function of the spatial resolution derived from Table 3

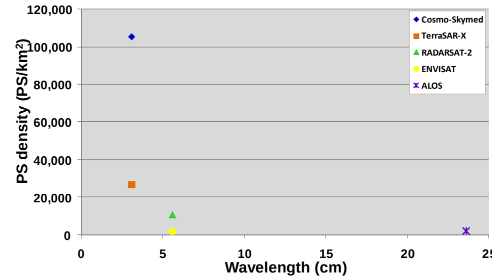


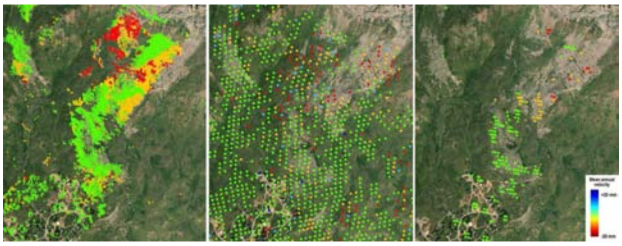
Figure 6 : Evolution of the PS density in function of the wavelength derived from Table 3

4.2 PSI analysis in rural area

The performances in PSI processing for ground detection capabilities in rural areas are now analyzed. Those areas are typically affected by temporal changes. The analysis considers the density of points for the detection of ground motion in a mountainous area affected by known landslides [6].

The used data stacks are composed of 14 TerraSAR-X, 12 ALOS and 88 ENVISAT images with overlapping periods. The TerraSAR-X monitoring period extends over only a year, the ones of ALOS and ENVISAT are of 3 and 4 years respectively. The X-band results are thus less affected by temporal decorrelation; this will influence the achieved PS density obtained.

Figure 7 shows the motion map obtained at each frequency. It is first important to notice that the landslide has been correctly detected at each band. In the areas where the TerraSAR-X interferometric coherence is kept, the retrieved density of measurement points is very high, allowing a better sampling of the magnitude and of the spatial extent of the detected ground motion. Nevertheless, the capacity of the L-band data to keep the coherence even in vegetated areas allows a more uniform (but less dense) distribution of the measurements, giving information of measurement almost everywhere. The use of ENVISAT data results in a map characterized by a lack of measurement points; this is mainly due to the important temporal decorrelation and the low resolution of the data.



a) *b)* *c)*

Figure 7 : Landslide detected with the mean annual velocity field of the PSI processing for three different bands. Left image corresponds to TerraSAR-X, the middle image to ALOS and the right image to ENVISAT.

The performance of the processing in terms of achived PS density are summarized in Table 4. As expected, the PS density is considerably lower than in urban area (Table 3).

Sensors	PS density PS/km^2
ALOS PalSAR	553
TerraSAR-X	4644
ENVISAT	182

Table 4: Performance of the multi-band PSI analyses over mountainous area in terms of PS density.

5. CONCLUSIONS

In this study, 466 SAR images have been used to make an assessment and comparison of the PSI processing performances at different wavelengths and at different resolutions. Imagery from ENVISAT, RADARSAT2, ALOS PalSAR, TerraSAR-X and COSMO-SkyMed were processed using the Stable Point Network technique (SPN); PSI software developed by Altamira Information.

The availability of multi frequency SAR data allowed making a qualitative assessment of the performances of each band for PS analysis. A wide range of sites and factors (observation geometry, landcover, temporal decorrelation and deformation behavior) have been considered. Criteria for the selection of appropriate SAR sensor for ground motion monitoring have been derived.

A prerequisite is to have a good knowledge of the landcover and topographic characteristics of the area of study. Fields that undergo seasonal agricultural activity are expected to have a reduced density of measurement points while high density measurement is achieved in urban places.

- Regarding the capability of detecting ground motion, the selection of the optimum wavelength must consider the magnitude of the expected deformation and the required precision. The usage of X-band with a sensor of short revisit time will give the highest precision (lowest noise floor level) and will provide the capability to detect fast motion. This proficiency, for instance, is offered currently by COSMO-SkyMed and TerraSAR-X with a revisit time of 8 and 11 days respectively.
- The relation between PS density and spatial resolution was demonstrated. PS density is increased at a higher rate than the spatial resolution ratio. It is important to consider, especially with large areas, that using high resolution sensors can be detected a huge number of measurement points, in the order of tens of millions. The PSI processing procedures must be optimized to support the handling of such great amount of information in order to overcome memory overflows. It was demonstrated that PS density will rely mainly of the spatial resolution of the images and not in the band frequency.
- The band frequency will influence the PS distribution over areas regarding their landcover. It was shown that L-band is less affected by temporal decorrelation. Especially in rural environments where thanks to the capacity of penetration through the vegetation canopy the final PS map distribution is more uniform. Nevertheless, the temporal decorrelation can be limited by reducing the observation period (with high frequency of acquisitions) of the used data stack. PSI analyses are then possible over few months with a good number of images. This situation can be exploited to increase the interferometric coherence and maximize the number of measurement points.

As a conclusion, in urban areas, the achieved density of measurement is good whatever the wavelength. The use of X-band data allows however getting high precision information over structures of small dimensions. In rural areas and vegetated zones, L-band would obtain best results in term of the detected motion and PS distribution over the site. The impact of temporal decorrelation can anyway be really important and prevent from achieving measurements. In that cases the high resolution and short revisit offered by the current X- band missions could allow overcome this effect and allow retrieving points in some rocky areas between dense vegetation.

The best performance for ground motion monitoring with PSI processing is generally obtained using high resolution and short revisit time data. These two important factors allow reducing temporal decorrelation, increasing PS density, obtaining high precision detection and monitoring fast terrain motions. Those capabilities are currently offered by TerraSAR-X and COSMO-SkyMed in X-band. In the near future, the launch of the SAOCOM constellation mission [7] will include an L-band sensor with these capabilities. This will therefore expand the possibilities for PSI operational monitoring over field areas with L-band data [8].

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