Measurement of slow uniform surface displacement with mm/year accuracy

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Abstract – Interferogram stacking, a technique to improve the relative accuracy of SAR interferometric surface displacement mapping based on a combination of multiple interferograms, is presented. Its potential and usefulness is demonstrated with the land subsidence cases of Bologna and the Euganean Geothermal Basin (Italy). For one of the investigated cases the potential to map slow uniform surface displacements at mm/year accuracy is confirmed by the validation with levelling data.

INTRODUCTION

With repeat-pass differential SAR interferometry changes in the altitude of the Earth's surface with a theoretical resolution of better than one millimeter can be detected. However, the mapping accuracy is limited by path delay inhomogeneities, usually called "atmospheric distortions". While these errors can be larger than 2π for extreme cases, typical error values are significantly smaller than π. But an error of π/2, for example, still results in a displacement error of an eighth of a wavelength. In order to obtain reliable displacement values, the surface displacement signal has to dominate over the estimation error. In the case of slow uniform surface displacements this is achieved through the stacking of multiple long-time interferograms. In fact, under the assumption of statistical independence between the atmospheric distortions of independent interferograms, the displacement terms add up linearly whereas the error term increases only with the square root of the number of pairs considered. Therefore, interferogram stacking consents to reduce the relative estimation error.

THE INTERFEROGRAM STACKING TECHNIQUE

Phase distortions caused by spatially heterogeneous atmospheric (in particular water vapor) and ionospheric conditions limit the accuracy of differential SAR interferometry. Large atmospheric distortions can be often identified by their specific shape, by cross-comparison of interferograms, or possibly based on meteorological data. It is not clear, though, how to best integrate such tests in an operational processing chain.

The goal of our analysis is to achieve an operational and robust technique. For this reason we take a conservative assumption on the atmospheric distortions in the single interferograms used for the stacking. As a typical atmospheric distortion we consider a relative high phase-error of π/2, which corresponds for the ERS SAR configurations to an error of approximately 0.7 cm in the estimation of the displacement. In order to obtain reliable displacement estimates, the displacement signal should dominate over the error term. In order to keep the expected error in the order of 5%, the displacement phase term has to be 20 times the assumed atmospheric distortion, i.e. 10π or 5 fringes, corresponding to around 14 cm of displacement for the ERS SAR configurations. Since the displacement increases with increasing acquisition time interval, interferometric pairs with long acquisition time intervals are preferred to reduce the effect of the atmospheric distortions. For instance, we preferably select an interferogram with three or more years acquisition time interval to map the displacement of an area with velocities up to 5 cm/year. In order to map faster displacement velocities, shorter intervals are preferred to study the temporal dynamic of the displacement. For slower displacement velocities even longer intervals would be required. The time interval cannot be much extended above few years because of data availability and because the use of very long time intervals introduces excessive temporal decorrelation that precludes interpretation of the data. A welcome approach to improve the ratio between the displacement signal and the atmospheric phase errors is the stacking of interferograms. Under the assumption of a stationary process (i.e. assuming that the displacement velocity is constant in time) the displacement terms add up linearly, whereas the atmospheric errors (for which we can assume statistical independence for independent interferograms) increase only with the square root of the number of pairs considered.

The mathematical framework of the stacking technique is simple. Let us consider n independent interferograms with different acquisition time intervals t_j and unwrapped phase ϕ_j. The sum of all t_j results in a total acquisition time interval t_{cum} and the sum of all ϕ_j results in a cumulative unwrapped phase ϕ_{cum}. The average displacement velocity along the look direction v_{disp} is computed as

$$v_{disp} = \frac{\lambda \cdot \phi_{cum}}{4\pi \cdot t_{cum}} \tag{1}$$

and the displacement velocity estimation error as

$$\Delta v_{disp} = \frac{\lambda \cdot \sqrt{n} \cdot E}{4\pi \cdot t_{cum}}\,. \tag{2}$$

Here E is the assumed phase error of a single interferograms (e.g. $\pi/2$) and λ is the wavelength. Equation (1) and (2) can be used to determine the cumulative time t_{cum} required to map a certain displacement velocity v_{disp} with a predefined expected relative estimation error. The potential of the stacking technique is demonstrated by the fact that the stacking of more than 10 independent interferograms with atmospheric distortions up to π/2 allowing to reach a cumulative time interval of more than 20 years results in an expected displacement velocity estimation error of around 1 mm/year. Such interferogram stacking is made possible by the immense ERS SAR data archive.

In a real case not all interferograms may be statistically independent because a SAR image may be used for various pairs. In this case, the expected relative error is larger than the one computed with Equation (2). In addition, due to different ground conditions and spatial baselines the coherence of the interferograms may be different resulting in a different coverage with unwrapped-phase information. In our methodology a displacement value is only determined for points with more than a minimum number of valid values. Finally, since interferogram stacking is based on the assumption of stationary displacement velocities, information on the temporal dynamic of the displacement is lost.

RESULTS

The ERS satellites carry SAR instruments suitable for interferometric data analysis. Their 35 days repeat-orbit cycle is appropriate for subsidence monitoring in most of the cases. The large archive of ERS SAR data available since 1991 allow subsidence studies with SAR interferometry in many regions around the world. For the validation of the stacking technique we selected two sites in Italy, Bologna and the Euganean Geothermal Basin. A more detailed description of these studies can be found in [1] and [2].

Bologna

Land subsidence in Bologna is caused by ground-water exploitation for industrial, domestic and agricultural uses [3]. Maximum subsidence velocities of 6 to 8 cm/year were observed with precision levelling surveys between 1987 and 1992. We produced two subsidence maps for the time periods 1992-1993 (Figure 1) and 1997-1998 (Figure 2) using in both cases six ERS SAR data covering a cumulative time interval of 4 years. The expected accuracy computed with Equation (2) assuming atmospheric distortions of π/2 is 0.5 cm/year. The results of differential SAR interferometry are in very good agreement with those derived from levelling surveys (Figure 3). For 215 points distributed over the urban area of Bologna the average difference between the SAR interferometric subsidence results of the time period 1992-1993 and the levelling data of 1987-1992 is 0.4 cm/year with a standard deviation of 0.9 cm/year. The minimum and maximum differences are –3.7 and +2.6 cm/year, respectively. The small standard deviation of 0.9 cm/year between the two data sets indicates a good performance of SAR interferometry. The systematic offset can be explained by the different time period, indicating a decrease of the subsidence velocity as evident also in the comparison of Figures 1 and 2. More recent levelling data acquired in 1999 will be used for an improved validation, once such data become available.

Euganean Geothermal Basin

Land subsidence of the Euganean Geothermal Basin is related to the geothermal groundwater withdrawal [4]. Up to 1991 the maximum rate of land subsidence has been 1 cm/year as observed from precision levelling surveys. After 1991 the subsidence velocity decreased as a consequence of a regulation of the groundwater exploitation. In order to map this low displacement velocity, 10 ERS SAR interferograms in the time span 1992 to 1996 were selected. Interferogram stacking was applied to generate a single map with a cumulative time interval of more than 20 years. The expected accuracy computed with Equation (2) assuming atmospheric distortions of π/2 is 1 mm/year. The resulting interferometric map shown in Figure 5 reveals a clear subsidence signal over Abano Terme with a maximum vertical displacement velocity of 3 mm/year, in agreement with the results of the last levelling surveys performed in 1991 and 1995 (Figure 4). The high correspondence of the two different surveying techniques is confirmed by a direct quantitative comparison along the levelling lines, an example of which is shown in Figure 6. For the 17 points where we have values available from both SAR interferometry and levelling the average difference of the displacement velocity values is 0.2 mm/year with a standard deviation of 1.0 mm/year. The minimum and maximum differences are –1.5 mm/year and +2.2 mm/year, respectively. This result confirms the high accuracy that can be achieved with the interferogram stacking technique.

CONCLUSIONS

Interferogram stacking, a technique to increase the displacement velocity estimation accuracy in differential SAR interferometry by combination of multiple interferograms, was presented. Its potential to map slow uniform surface displacements at mm/year accuracy was demonstrated by theoretical considerations and by the results of Bologna and the Euganean Geothermal Basin. The high accuracy expected with interferogram stacking together with the availability of ERS SAR data can contribute to an extensive use of this remote-sensing application for the monitoring of the subsidence in many regions around the world.

A further stimulus to the use of differential SAR interferometry for Earth’s surface displacement studies will be provided by the launch of ESA’s ENVISAT spacecraft carrying an Advanced SAR and of NASDA’s ALOS spacecraft with the PALSAR. Keeping in mind that the valuable archive of ERS SAR data useful for the displacement application is the result of the operation of the ERS satellites in the single mode (35-day repeat orbits) for most of the time, it is essential that the SAR's of the ENVISAT and ALOS missions are operated in a single interferometric mode for most of the time.

ACKNOWLEDGMENTS

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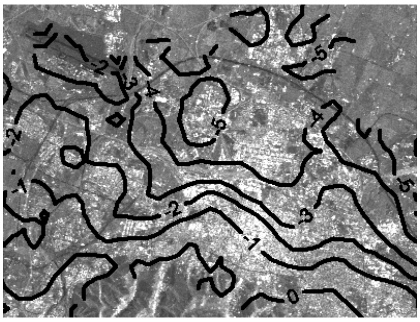

Figure 1. SAR interferometric subsidence map (in cm/year) in Bologna for the time period 1992-93.

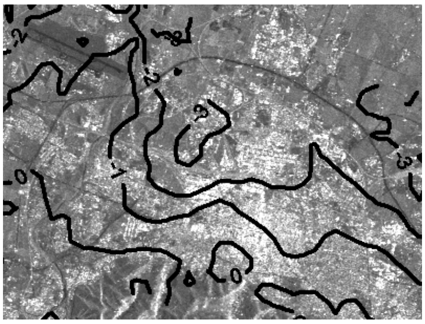

Figure 2. SAR interferometric subsidence map (in cm/year) in Bologna for the time period 1997-98.

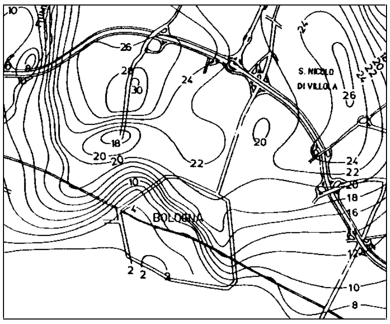

Figure 3. Map of the vertical ground movements from two levelling surveys in 1983 and 1987 in Bologna [3].

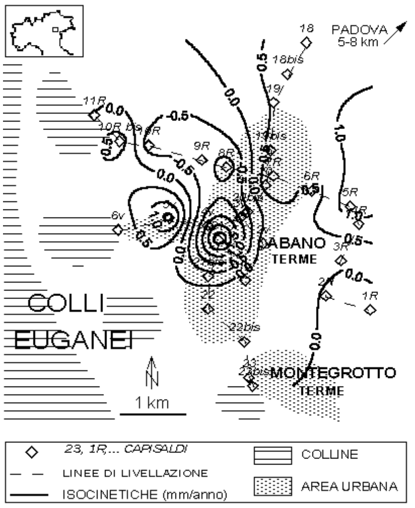

Figure 4. Map of the vertical ground movements (in mm/year) from two levelling surveys in 1991 and 1995 in the Euganean Geothermal Basin (data from Comune di Abano Terme and Regione del Veneto).

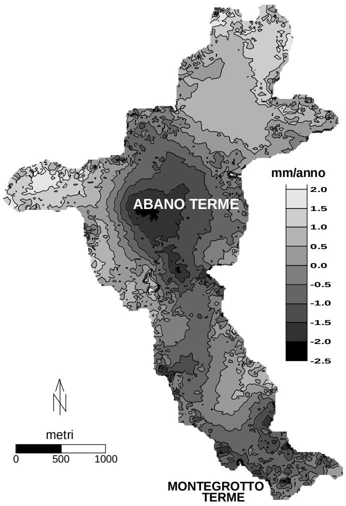

Figure 5. ERS interferometric displacement velocity map (in mm/year) for the time interval 1992 and 1996 in the Euganean Geothermal Basin.

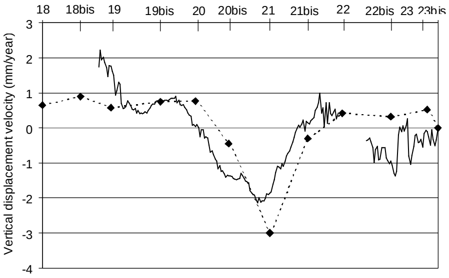

Figure 6. Profiles of the vertical displacement velocity from ERS SAR interferometry (continued line) and levelling surveys (dotted line) along the levelling line Abano Terme – Montegrotto Terme.