APPENDIX A:
ADDITIONAL TECHNICAL INFORMATION REGARDING THE DINSAR AND STACKING METHODS.

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More In-Depth Description of the DInSAR Method as Used in This Study

DInSAR as utilized in this study is a satellite, airborne, radar-based system that generates high-resolution remote sensing imagery. The onboard signal processing system uses the magnitude and phase of the received signals over successive pulses from elements of a 'synthetic aperture' to create an image consisting of pixels containing both the phase and amplitude information. The distance the SAR device travels over a target in the time taken for the radar pulses to return to the antenna creates the large "synthetic" antenna aperture (the "size" of the antenna). Typically, the larger the aperture, the higher the image resolution will be, regardless of whether the aperture is physical (a large antenna) or 'synthetic' (a moving antenna). This allows SAR to create high-resolution images with the comparatively small antennas that fit onboard a satellite or aircraft.

The phase information of each image pixel represents the complex vector sum of the radar echoes from all scattering elements within a corresponding resolution cell on the ground, covering an area of approximately 20 x 5 meters for the ERS-1, -2 and Envisat satellites. Other satellites may have different resolution cell sizes, but the final pixel size is usually resampled to a square shape of 20 to 50 meters regardless of the size of the original cells.

The return phase of the signal from each scattering center has its phase determined by the two-way range to the satellite and this will typically vary by several hundred wavelengths (ERS-1, -2, Envisat, Sentinel-1A and 1B etc. 56.66 mm) across a typical resolution cell. The phase of an image pixel by itself is thus a random and not very meaningful parameter. There is, however, a correlation between the phase information in corresponding pixels in scenes covering the same area, and any movements that have occurred between the acquisitions of the scenes will be represented by a phase shift. For this assumption to be valid the satellite needs to be located very precisely over the target area and any difference in the repeat orbits will introduce phase shifts that need to be removed mathematically.

Depending on the intended use of the interferograms, detecting ground movements or generating Digital Elevation Models (DEMs), the maximum allowable offsets in the orbits differ. For DEM generation, a maximum value of the perpendicular offset (offset between orbits) is around 1100 m, whereas values of less than 250 m are needed to measure surface deformation. A high degree of control over the orbits of the satellites is also imperative if the SAR images are to be used for interferometric purposes. In addition to problems with phase shift introduced by offsets in the orbits, other problems will also occur. Examples are loss of coherence caused by differences in the viewing geometry, and ambiguities caused by the relief giving false signals in the interferogram. There are also other factors that may reduce or even totally compromise the quality of the DInSAR results. The most important one is related to temporal decorrelation phenomena caused by the variation of the electromagnetic properties of the radar targets. If the phase reflectivity value of a certain image pixel changes with time, the generation of an interferogram, i.e. the computation of the difference between the phase values of two SAR images; cannot highlight the displacement values. The impact of temporal decorrelation phenomena increases as the temporal baseline of the interferogram (i.e. the time lag between the two SAR acquisitions) increases. Apart from phase decorrelation, propagation effects in both the troposphere and the ionosphere can differ significantly during the first and the second acquisition, thus creating phase disturbances that at best will hinder the interpretation of SAR interferograms, or at worst, completely prevent the processing of the satellite data. Given all these potential issues, only a small number of the available archived scenes are suitable for the generation of interferograms. In general, it can also be said that the availability varies between the ages of the different satellite systems, with more modern systems having greater reliability. This is mostly the result of better control of the orbits of the satellites, but also because of developments that have given the onboard signal processing systems and computers better capabilities.

The interference pattern is a function of the geometries of the orbits as well as the topography of the target area. By analyzing the interference patterns, and knowing the precise orbits, the topography can be calculated and, if the topography also is known, any changes in the topography can be calculated from the interferogram by removing the topographic effects utilizing an existing DEM. The difference in phase between the SAR images is usually represented by color bands in such a way that a movement corresponding to half the wavelength of the radar is shown as a complete color cycle in a color band.

Apart from phase information, the quality of the correlation, (the ‘coherence') between two SAR images can also be determined. Such coherence values are related to the nature of the ground surface. Any chaotic movements of the scatterers in the target area between the acquisitions will cause the coherence to be low. Open water and active agricultural areas are usually totally decorrelated, whereas urban areas and areas free of vegetation are more likely to have a high coherence over extended periods of time. Low coherence makes it impossible to calculate the phase shift, and thus a high degree of coherence is imperative in the areas of interest. Processing the raw SAR data to create interferograms is a multi-step operation involving Fourier transforms to extract the radar echoes, and other complex mathematics. The technical details of these procedures are beyond the scope of this report, but are described in detail in Lanari et al. (2004), and Hu et al., (2016).

Although several InSAR processing packages are available, we chose GMTSAR, which was developed by the Scripps Institution of Oceanography and the University of Hawaii. There are two reasons for choosing GMTSAR over other available software packages. First, the software is in the public domain and free to use by anyone without restrictions, as it is currently released as open source under the GNU General Public License. Second, when the European Space Agency opened their archives of ERS satellite data for general use in early April 2017, we found that they had changed the data format and virtually no other commercially available software was capable to read the new format. The open nature of GMTSAR allowed us to write a new pre-processor for the new file format, allowing us to process the data successfully.

The software can be divided into three parts:

a. A *pre-processor* responsible for importing and converting satellite data (ERS-1/2, ENVISAT, ALOS-1, TerraSAR-X, COSMOS-SkyMed, Radarsat-2, Sentinel-1A/B, and ALOS-2) to the internal native format used by GMTSAR.
b. *The InSAR processor*, which focuses and aligns stacks of images, maps topography into phase, and forms the complex interferograms.
c. The *post-processor*, which filters the interferograms and constructs interferometric products of phase, coherence, phase gradient, and line-of sight displacement in both radar and geographic coordinates.
d. The Short Baseline Subset (SBAS) processor which stacks the interferograms, removes atmospheric interference and calculates displacement rates (mm/year) using the least-squares method for linear regression.

As described above, the interferograms produced by subtracting phase data from separate radar images result in an image where every pixel describes the displacement that has occurred between the acquisitions of the images. However, the detected displacement will also contain an error of unknown magnitude due to atmospheric interference, which means that any deformation along line-of-sight only can be taken as an approximation for a single interferogram. The SBAS algorithm uses a number of interferograms (>3) and applies a least squares curve fitting on every corresponding pixel in the included interferograms to create an image where the pixels represent the velocity in millimeters per year that best fits any displacement that occurs over time. In addition, the software also outputs "synthetic" interferograms with the cumulative displacement that has occurred between the acquisitions of the radar images. It is also creating maps showing the residuals between the expected and measured displacements. A small residual means that there is a good fit between the model for the displacement and the interferometrically detected displacement of the same pixel.

References

Hu, J., Ding, X.L., Lia, Z.W., Zhang, L., Zhu, J.J., Sun, Q., and Gao, G.J., 2016, Vertical and horizontal displacements of Los Angeles from InSAR and GPS time series analysis: Resolving tectonic and anthropogenic motions: *Journal of Geodynamics*, Vol. 99, Sept 2016, pp. 27-38.

Lanari R., Lundgren P., Mariarosaria M., and Casu, F., 2004, Satellite radar interferometry time-series analysis of surface deformation for Los Angeles, California: *Geophysical Research Letters,* Vol. 31, No. 23, 16 Dec., 2004, 5p.

APPENDIX B:
Listing of Analyzed Radar Images.

Full listing of the downloaded Sentinel-1 SAR data files

The following 172 data files were downloaded from the Alaska Satellite Facility (ASF) for processing. Due to the target being located on the border between two satellite images, two neighboring images located along track had to be downloaded and merged for every acquisition date, resulting in 86 images that were processed with GMTSAR.

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