Tectonic and Anthropogenic Deformation at the Cerro Prieto Geothermal Step-over Revealed by Sentinel-1 InSAR

Xiaohua Xu¹, David T. Sandwell¹, Ekaterina Tymofyeyeva¹, Alejandro González-Ortega² and Xiaopeng Tong³

¹Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA
²Centro de Investigacion Cientifica y de Educacion, Ensenada, BC, MX
³Department of Earth and Space Science, University of Washington, Seattle, WA, USA

Revised for: IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING
April 20, 2017

Abstract
The Cerro Prieto Geothermal Field (CPGF) lies at the step-over between the Imperial and the Cerro Prieto Faults in northern Baja California, Mexico. While tectonically this is the most active section of the southern San Andreas Fault system, the spatial and temporal deformation in the area is poorly resolved by the sparse Global Positioning System (GPS) network coverage. Moreover, interferograms from satellite observations spanning more than a few months are de-correlated due to the extensive agricultural activity in this region. Here we investigate the use of frequent, short temporal baseline interferograms offered by the new Sentinel-1A satellite to recover two components of deformation time series across these faults. Following previous studies, we developed a purely geometric approach for image alignment that achieves better than 1/200 pixel alignment needed for accurate phase recovery. We construct InSAR time series using a coherence-based SBAS method with atmospheric corrections by means of common-point stacking. We did not apply Enhanced Spectral Diversity (ESD) because the burst discontinuities are generally small (< 1.4 mm). They can be effectively captured and removed during the atmospheric corrections. With these algorithms, the subsidence at CPGF is clearly resolved. The maximum subsidence rate of 160 mm/yr, due to extraction of geothermal fluids and heat,
dominates the ~40 mm/yr deformation across the proximal ends of the Imperial and the Cerro Prieto Faults.

1. Introduction

The Cerro Prieto Geothermal Field (CPGF) is the second largest geothermal field in the world with an average annual net fluid extraction over 10 million tons. As a consequence, the surface subsides at an extraordinary rate despite the fact that the reservoir is deep and isolated from groundwater [Vasco et al. 2002]. Surrounding the CPGF, the fault system is complex. The northeast end of the CPGF connects to the Imperial fault while the southwest end reaches the Cerro Prieto fault. The Indiviso fault, where the 2010 El Mayor Cucapah earthquake rupture took place, is only 15 km to the west [Gonzalez-Ortega et al. 2014]. Previous estimates of the subsidence rate at CPGF are up to 120-140 mm per year [Sarychikhina et al., 2015, Trugman et al 2014, Sarychikhina et al 2011, Glowacka et al. 2010, Hansen, 2001, pages 175-189], and the expected horizontal deformation across the Imperial fault and the Cerro Prieto fault is around 40 mm per year [Bennett et al. 1996]. Tectonically, this is the most active zone of the southern San Andreas Fault system, but the spatial and temporal deformation for this area is poorly resolved. Part of the reason is the lack of Global Positioning System (GPS) data coverage, and the fact that observations from Interferometric Synthetic Aperture Radar (InSAR) are often biased due to the de-correlation introduced by extensive agricultural activity.

To overcome these challenges, we use SAR data from the C-band Sentinel-1A satellite operated by the European Space Agency (ESA). Sentinel-1A was launched on April 3rd, 2014, and has been in routine operation for about 2 years. The satellite is capable of revisiting a prioritized area (like CPGF) with every 12 days, primarily with a burst radar acquisition mode called Terrain Observations with Progressive Scans (TOPS). For other areas, the revisit time is usually 24 days. While the short revisit time is achieved by using TOPS mode, this new type of acquisition mode brings challenges to data processing. Following previous studies [Prats-Iraola et al., 2012, Gonzalez et al. 2015], we developed a geometric alignment approach using post-processed precise orbits of
Sentinel-1A (~50 mm along-track and ~20-30 mm cross-track Fernandez et al., 2015). We performed a systematic analysis to test the capabilities of this dataset, and used coherence-based SBAS [Tong and Schmidt, 2016] and atmospheric correction with common-point stacking [Tyroffyeveva and Fialko, 2015] to calculate the deformation time series around CPGF.

2. Sentinel-1 TOPS Processing

The Sentinel-1 mission was designed to acquire frequent observations (12 or 24 days) with Interferometric Wide Swath (~250 km) product using TOPS mode [Torres et al., 2012]. Unlike conventional ScanSAR, which illuminates the ground with a series of separated bursts, the TOPS mode SAR system rotates its antenna during the observation of each burst. While this type of observation reduces the along-track amplitude scalloping (signal-to-noise ratio change), it also introduces azimuthally-varying Doppler centroid [Prats-Iraola et al., 2012]. The Doppler centroid variation (~4.5kHz) wraps the satellite Pulse Repetition Frequency (PRF ~486 Hz) 9 times (Figure 1). Due to this feature, the azimuth mis-registration error has to be better than 1/200\textsuperscript{th} of a pixel (i.e. 66 mm) to keep the phase difference at burst boundaries to less than 1.4 mm. Note that standard image cross correlation methods only achieve ~1/10 pixel accuracy, which would result in an unacceptably large phase mismatch of 28 mm at burst boundaries [De Zan, 2014]. Moreover, the extra Doppler centroid goes beyond the Nyquist frequency, so accurate interpolation of the slave image into the master coordinates is not possible without de-ramping the slave, as discussed in Miranda [2015].

Figure 1. Spectrogram of one burst of TOPS-mode data plotted on a log color scale. (a) Original
spectrogram of a single burst of TOPS data wraps around the Nyquist frequency 9 times. (b) Spectrogram after deramping has low power close to the Nyquist, which enables accurate resampling.

We have implemented a robust co-registration method based on the geometric approach and optional enhanced spectral diversity (ESD) described in previous studies [Sansosti et al. 2006; Yague-Martinez et al., 2016]. The code is available as a new pre-processing module in GMTSAR http://gmt.soest.hawaii.edu/projects/gmt5sar. The pre-processing starts with a pixel-wise estimate of range and azimuth offsets using precise orbits and a downsampled (~360 m) Digital Elevation Model (DEM), which covers the region of the Single Look Complex (SLC) satellite images (step 1 in Figure 2). The precise orbit is used to back-project each pixel in the DEM (lon, lat, ellipsoidal height) into the range and azimuth coordinates of the master and slave images \((r,a)\). The algorithm first uses a golden section search method [Press et al., 2007] to quickly find the closest point at the PRF sampling (~14.5 m along-track) between the orbital trajectory and the topography pixel. Then a polynomial refinement algorithm is used to improve the numerical accuracy to better than 10 mm in the azimuth coordinate. The range coordinate is the range between the antenna and the topography pixel evaluated at the corresponding azimuth coordinate. Note that the range-rate or Doppler is zero at this closest point. (A correction for alignment to a non-zero Doppler is discussed in the GMTSAR documentation [Sandwell et al., 2011].) The differences between the range \(\Delta r(r,a)\) and azimuth \(\Delta a(r,a)\) of the slave image with respect to the master image are used to construct a dense look-up map of range and azimuth shifts, using a surfacing technique described in [Smith and Wessel, 1989]. After these maps are generated, the co-registration is done pixel-wise, which accounts for topography variation across the full image.

The second step in the processing is to resample the slave image into the coordinates of the master image (step 2 in Figure 2). Prior to resampling with a 2-D sync function, the slave image is de-ramped and demodulated following the algorithm in Miranda, [2015]. Best results are achieved if the de-ramping and re-ramping are only performed on slave image, leaving the master image unchanged. Using this approach, any possible
inaccuracies in the de-ramping function will introduce no error because each slave is re-
ramped using the conjugate of the original de-ramp function plus an appropriate phase
shift related to the azimuth shift. De-ramping, interpolation, and re-ramping are
performed burst by burst, after which all bursts within one sub-swath are merged to
generate one aligned SLC image.

The third (optional) step in the processing is to use the ESD approach to refine the overall
azimuth shift $\Delta a_{ESD}$. This follows the method described in previous studies [Zan et al.,
2015; Yague-Martinez at al., 2016]. The burst overlap areas are extracted from the
aligned master and slave SLC’s and a double-difference interferogram is formed.
Azimuth filtering is used to estimate phase, after which the coherence and the median of
the phase for all the burst overlaps are used to estimate the phase shift using equation S1.
ESD estimation is available in GMTSAR, so the user can decide when it is needed. The
advantages and disadvantages of using ESD are discussed below.

Figure 2. Processing chain for TOPS data using precise orbits and point-by-point geometric co-
registration. The ESD algorithm is implemented in GMTSAR but not used in this study.

The final step is to use any pair of aligned slave images to form an interferogram. We de-
burst the SLC’s by removing $\frac{1}{2}$ of the lines along the lower overlap zone of the first burst
and $\frac{1}{2}$ of the lines along the upper overlap zone of the second burst, and abut the lines to
form continuous SLC files. The full resolution DEM, mapped into the range and azimuth
coordinates of the reference image, is used to form a full-resolution interferogram with
the topographic contribution removed. At this point, the user can decide on the type of
spatial filter used to estimate phase, coherence, and amplitude. In the examples below,
we use a Gaussian filter with a 0.5 gain at a wavelength of 300 m in azimuth and ground
range. The interferometric products are sampled at ¼ of the filter wavelength or smaller
(<75 m). Each subswath is processed independently and then stitched in radar
coordinates. Phase unwrapping is performed in radar coordinates. The results presented
below were geocoded at 4 arcsecond resolution.

The only significant differences between this approach and the approach described in
Yague-Martinez et al., [2016] are that we do not perform common-band filtering in range
or azimuth, and we use geometric alignment instead of patch cross correlation in range.
We have tested both range alignment approaches and find that they work equally well.
One potential advantage of the geometric range alignment approach is that it provides a
pixel-wise topographically-dependent range shift, but that is only needed when the
baseline approaches a large fraction of the critical baseline, which does not happen for
Sentinel-1.

There are two important advantages to this pure geometric co-registration approach. The
first is that it does not require any phase coherence between the master and slave images.
This will become increasingly important as the time separation between the master and
the newly-acquired slaves increases beyond several years. The second advantage is that
after each slave is aligned to the same single master image, interferograms can be
constructed from any two images in the set without needing further co-registration. This
is confirmed below and in the supplementary material (Figure S3), where we show that
the sum of the phase of interferograms in closed circuits is zero to within the phase noise
of the radar. This enables the construction of long deformation time series from short
timespan interferograms. Moreover, this greatly improves the efficiency in data
processing since all images need only be aligned once to a single master.

After point-by-point geometric co-registration, the typical discontinuity between bursts is
1/400th of pixel (Table S1). Larger burst discontinuities are occasionally visible but they are not a constant azimuth shift at all the burst boundaries as expected [Scheiber et al., 2015; De Zan et al., 2014]. These burst discontinuities are potentially due to spatial variations in the ionosphere or clock error on certain bursts [Fattahi et al., 2016; Gomba et al., 2016].

To illustrate the accuracy of the geometric alignment as well as the subswath-to-subswath fidelity of the Sentinel-1 radar, we show a typical TOPS-mode interferogram (i.e., 3 sub-swaths) combined in geo-coordinates, which covers a very large area (~250 km cross-track, ~750 km along-track), from the Sierra Nevada Mountains across the Central Valley to the beach at Santa Barbara (Figure 3). The acquisitions come from relative orbit number (track) 144 on date 07/06/2015 and 07/30/2015. The interferogram was processed with pure geometric alignment/co-registration and no extra adjustment from enhanced spectral diversity (ESD – [Prats-Iraola et al. 2012]). Within this large area, the phase is visually continuous across burst and sub-swath boundaries. When observed at such a large scale, it is clear that the interferogram contains a significant amount of atmospheric noise, some of which is strongly correlated with topography. Also, even though the time-span of the interferogram is only 24 days, there is already some de-correlation around the farms in the Central Valley.
Figure 3. An interferogram combining 3 sub-swaths (109 bursts) from track 144 of Sentinel-1A data, processed with GMTSAR with geometric alignment/coregistration. No enhanced spectral diversity or swath-boundary adjustments were applied.

3. Estimation of InSAR Time Series at the CPGF

To investigate the evolution of the subsidence at CPGF, and the spatial and temporal deformation across the nearby faults, we processed interferometric synthetic aperture radar data from the Sentinel 1-A satellite spanning the period from October 2014 to July 2016. The satellite collected 42 acquisitions on descending track 173 and 36 acquisitions on ascending track 166. We constructed 201 interferograms from the descending scenes
and 183 from the ascending scenes, with a 90-day temporal threshold and a 200-meter perpendicular baseline threshold (Figure 4, Figure S2). We did not use the ESD method [Prats-Iraola et al. 2012], because the phase discontinuities at burst boundaries were much smaller than the atmospheric phase contributions (Table A1, Figures S3 and S4), and could be effectively removed along with the atmospheric signals as described below. To confirm that ESD is not needed, we also performed the analysis using ESD and compared the results (see Supporting Material). The differences in average velocity are generally less than 1 mm/yr.

C-band data from synthetic aperture radar (SAR) observations are strongly decorrelated by agricultural activity or existence of vegetation over this region [Wei and Sandwell 2010]. The short 90-day temporal threshold was set in order to mitigate this effect, and also resolve seasonal changes in time series.

Figure 4. Perpendicular baseline vs. time plot for track 173 over CPGF. The dots represent acquisition dates and the grey lines denote interferometric pairs selected with a 200-meter baseline threshold and 90-day temporal threshold. The colors of the dots indicate the atmospheric noise coefficient (ANC) [Tymofyeyeva and Fialko, 2015], with a larger value representing a stronger atmospheric noise contribution on that date. The red and blue dashed lines correspond to the interferograms used in the circuit test.
3.1. Circuit Test

To further illustrate the accuracy of the geometric alignment, as well as the accuracy of the calculation of the interferometric baselines, we performed a circuit test for track 173 by summing up interferograms along the dashed lines shown in Figure 4. The circuit had two segments. The time-increasing segment was the sum of 21 interferograms from 10/29/2014 to 07/26/2016, as shown with dashed blue lines in Figure 4. The time-decreasing segment spanned the same time interval, and is shown by the dashed red lines in Figure 4. Theoretically, the sum around this circuit should be zero except for possible phase noise due to decorrelation. The results are shown in Figure 5, where the phase and coherence of the direct 2-year interferogram are compared with the sum of 21 interferograms over the same time span. While the phase from a direct interferogram and the summed interferograms share similar features, the coherences are very different. The average coherence of the 21 interferograms is significantly higher than the coherence of the direct 2-year interferogram. This provides improved phase recovery of the summed interferogram with respect to the direct interferogram. The closure test (Figure 5f, Figure S6) produces a very small phase residual (median of 0.013 mm, median absolute deviation of 0.97 mm), considering that we are summing up 42 interferograms spanning 4 years. This indicates the error introduced from data processing is small for deformation signals greater than ~1 mm/4yrs.
Figure 5. Circuit test for the CPGF area on track 173. a) is an interferogram connecting 10/29/2014 and 07/26/2016 with d) being its coherence. b) is the interferogram generated by adding up 21 interferograms following the red dashed line in Figure 4, with e) being their average coherence. c) is the interferogram generated by adding up 21 interferograms following the blue dashed line in Figure 4. f) is the phase residual when adding up 42 interferograms along the dashed line circuit (median of 0.013 mm, median absolute deviation of 0.97 mm). The black lines are the nearby faults from USGS (http://earthquake.usgs.gov/hazards/qfaults/) and CICESE.

3.2. Atmospheric Correction and SBAS

The main objective of this analysis is to compute displacement time series for each of the ascending and descending stacks of SAR images to an accuracy of a few mm/yr, in order to better constrain the interseismic deformation of the region. Because atmospheric and ionospheric phase delays, as well as orbital and clock errors, are sometimes much greater than the ground deformation signal, we use the high redundancy of the interferograms to estimate and remove these errors. This is done in combination with SBAS time series estimation using an iterative approach described in [Tymofyeyeva and Fialko, 2015]. They note that the phase of each interferogram $\Delta \phi$ can be decomposed into the following terms,
where $\Delta \tau$ is the deformation signal, $\alpha$ is the phase error in each SAR image, and $\epsilon$ represents other errors, such as an inaccurate DEM or antenna noise. These $\alpha$-related errors can be estimated and removed by means of common-point stacking, assuming they are randomly distributed in time. One important advantage of this stacking method is that it will capture the miss-registration errors at the same time, as they are also random in time. Together with this error correction, we applied a coherence-based small baseline subset (SBAS) method to compute time series for the CPGF region [González and Fernandez, 2011; Marotti et al., 2012; Tong and Schmidt, 2016]. Instead of omitting low coherence pixels, this algorithm solves for the time series at every pixel while taking in coherence as weights [Rosen et al. 2000] for the least squares problem. The short revisit times of the Sentinel-1A satellite, combined with the coherence-based SBAS, help mitigate strong de-correlation in this area.

### 3.3. Velocity and Displacement Time Series

The mean line-of-sight (LOS) velocity acquired for each track is shown in Figure 6. Since there is no good quality GPS model for the region [Sandwell et al., 2016] to provide large spatial scale control on the InSAR data, we selected a point far from faults on the North America plate and set its displacement to zero for every interferogram; this provides a reference point for all other pixels. Note that this does not violate the closure test that is the preset rule for error estimation by common-point stacking. The displacement time series and atmospheric corrections for each epoch are provided in the supplementary material (Figure S3 and Figure S4). The maximum observed LOS velocity of the subsiding region is -178 mm/yr for track 173 and -157 mm/yr for track 166. The boundaries of the subsidence are well defined in LOS velocity map and the overall subsidence rate increases toward the east from the Cerro Prieto fault to the Imperial fault. More interestingly, the eastern margin of the subsidence terminates at the southern end of the Imperial fault, which may indicate that the fault acts as a barrier to subsurface fluid flow.
Figure 6. Velocity map derived from analyzing 42 scenes, 201 interferograms (Figure 4) from descending track 173, and 34 scenes 183 interferograms (Figure S2) from ascending track 166. a) is the line-of-sight (LOS) velocity map for track 173. b) is the LOS velocity map for track 166. c) and d) are the decomposed vertical velocity and fault parallel velocity following [Lindsey et al., 2014], assuming the average fault azimuth to be N36.5°W. A 0.15 coherence threshold was used to mask the data projected. The black lines are the faults and black arrows are GPS survey mode data in North America fixed reference frame with circles denoting the uncertainty. The black circle in a) is the location of the Heber geothermal field and the black square in d) is the location we pinned down to zero in the SBAS processing.

We decomposed the two LOS velocity maps into fault-parallel horizontal velocity and vertical velocity, by assuming the average fault azimuth to be N36.5°W [Lindsey et al., 2014]. The estimated maximum vertical subsidence is 163 mm/yr and the horizontal motion from east to west (over the mapped area) is roughly 40 mm/yr, in agreement with the overall change in velocity across these fault systems [Bennett et al., 1996]. The large vertical deformation in the region of the CPGF is caused by removal of geothermal fluids [Glowacka et al., 2010]. If the CPGF were modeled by deflating Mogi source(s) one
would expect significant horizontal motions in a direction pointing to the region of maximum subsidence [e.g., Segall, 2010]. Therefore our fault-parallel decomposition is not valid in this region and the original LOS data should be used for inverting for the Mogi sources [Trugman et al., 2015]. In addition to the subsidence of the CPGF, we also observe significant subsidence at Heber geothermal field (black circle in Figure 6a), although the maximum LOS velocity here is smaller, only around -60 mm/yr.

Figure 7. Error reduction by common point stacking. The plot on the left is the uncorrected displacement in radar coordinates on 04/27/2015 with respect to the first acquisition on 10/29/2014, estimated with coherence based SBAS for descending track 173. The middle plot is the error estimated by the common point stacking method [Tymofyeyeva and Fialko, 2015]. The plot on the right is the displacement acquired with coherence based SBAS after removing the estimated error from every interferograms.

As mentioned in Section 2, there is usually a small phase offset (< 1.4 mm) between bursts. We do not correct for this offset because it has the same temporal characteristics as the atmospheric delay, in that it is common in interferograms that share an acquisition date and random in time. Therefore, we use the common-point stacking approach [Tymofyeyeva and Fialko, 2015] to magnify, estimate, and remove the burst offsets together with the atmospheric noise. Figure 7 shows the estimated error on 04/24/2015 from the time series calculated for descending track 173. The uncorrected deformation map (Figure 7, left) is contaminated by an atmospheric delay having the characteristic pattern as a lee-wave [Vachon et al., 1994]. Also, there are small burst discontinuities around azimuth line 2700 and 4100. These features are absorbed into the estimated error.
After applying the correction, the deformation time series are considerably flatter (Figure 7, right). A full comparison for track 173 can be found in Movie S1, where the uncorrected time series is more turbulent in time and the corrected is much cleaner. It also brought our attention that, during this study, the assumption that the atmosphere is equally strong across the full scene is occasionally biased by topographical barriers. When different sources of atmospheric signal come in to the same scene, the stronger one will potentially dominate the atmospheric correction sequence, thus a prioritized area (usually your area of interest) needs to be selected ahead to avoid such situation. Figure 8 shows the corrected and uncorrected LOS displacement time series at the CPGF. The corrected time series are very clean, while the uncorrected time series are quite noisy, even though they were computed with the same smoothness parameter using coherence based SBAS [Tong and Schmidt, 2016].

Figure 8. LOS displacement time series at CPFG. Top plot is the subsidence revealed by descending track 173, and the bottom plot is ascending track 166. The magenta dashed lines are the time series without the error correction from [Tymofyeyeva and Fialko, 2015], and the blue lines are the corrected time series. Both results used coherence based SBAS [Tong and Schmidt, 2016] with the same smoothing parameter.
3.4. Comparison with GPS Data

Over the past six years, we have deployed two linear GPS arrays across the Imperial and Cerro Prieto faults to better characterize their velocity gradient. The monuments consist of stainless steel couplers cemented into massive concrete structures. The GPS antennas are screwed directly into the couplers for accurate and rapid deployment. To obtain the GPS position estimates we used GAMIT/GLOBK software [Herring et al., 2008] in ITRF2008 reference frame [Altamimi et al., 2011]. Site velocities were computed by least squares linear fitting to time variation of coordinates for each station and then rotated with respect to Stable North America Reference Frame (SNARF) [Blewitt et al., 2005]. Velocity uncertainties are estimated within 1-sigma confidence level [Herring, 2003]. We extracted fault-parallel velocity along two traces to compare with InSAR data. The extracted InSAR velocity is the mean value over 10x10-pixel (~180m x 260m) boxes along A-A’ and B-B’ traces shown in Figure 6d, taking the standard deviation as the measurement uncertainty. The InSAR velocity is shifted to match the GPS, because during InSAR data processing, the point pinned to zero is not essentially zero if measured with GPS under North America fixed reference frame. The A-A’ trace is not extracted exactly along the GPS locations because these areas are not well correlated. However, the comparison shows good agreement across the Imperial Fault with an overall ~30 mm/yr deformation across the fault (Figure 9a). The fast increase toward the western end suggests there is a hidden fault, as pointed out by [Lindsey et al., 2016], or possibly this sharp curve is biased by the subsidence signal from the nearby Heber geothermal field. The comparison also shows good agreement across the western side of the Cerro Prieto fault but poorer agreement on the eastern side. The InSAR measurements in this eastern area were extracted slightly south of the GPS line in the Colorado River valley where the correlation is the best. The InSAR to GPS differences in this region may be may be due to seasonal hydrologic signals, which would contaminate the frequent InSAR acquisitions, but would not be resolved by the less frequent GPS measurements. If we combine the GPS and InSAR data, the estimated deformation from east to west along B-B’ is close to 40 mm/yr, with a larger portion going across the Indiviso fault than the Cerro Prieto fault. The higher deformation rate over Indiviso fault may reflect continued post-seismic deformation following the 2010 El-Mayor Cucapah earthquake [Gonzalez-
Figure 9. Comparison between InSAR fault-parallel velocity map and GPS. InSAR velocity are extracted along the two magenta trace in Figure 6d. GPS data are projected to the fault parallel direction.

4. Discussion and Conclusions

We demonstrate a pure geometric algorithm for InSAR processing of TOPS data from the Sentinel-1A satellite. The accurate orbits and software result in phase differences at burst boundaries of generally less than 1.4 mm. Since this error is far smaller than the atmospheric phase delays and could be associated with azimuthal misalignment, ionospheric variations, or true ground motion, we propose that the enhanced spectral diversity method for tuning the azimuth alignment is not needed. Moreover, there are three significant advantages to pure geometric alignment with no ESD. First by aligning all repeat images to a single reference, circuit closure is guaranteed. This closure is required for common point stacking and long timespan SBAS time series. Second, long time series can be processed incrementally, so that when a new SAR image is added it can be geometrically aligned to the master image and interferograms can be constructed from any of the other images. Third, interseismic motion can produce a significant along-
track shift that can be corrected using an accurate plate tectonic model rather than estimated with ESD. For example, consider a long time span interferogram of a stable plate interior that is moving at 40 mm/yr in the satellite azimuth direction with respect to the International Terrestrial Reference Frame. The satellite orbit is computed in this fixed reference frame so after a decade of plate motion the azimuth shift of 0.4 m will cause a large burst mismatch of 8 mm. The coherence between the reference and repeat images may not be sufficient for accurate ESD, but since the tectonic motion is well known, an accurate azimuth shift can be applied during the processing. The main disadvantage to not performing ESD is that the small residual mismatch can lower the coherence at the burst boundaries [Shirzaei et al., 2017].

We demonstrate the combined accuracy of the Sentinel-1 radar and orbits as well as the GMTSAR software by performing a circuit sum of 42 interferograms. The circuit closes to less than 1 mm, which is much smaller than the atmospheric error. This accurate closure ensures that long time-span interferograms can be accurately constructed from SBAS analyses of redundant short time-span interferograms. This approach provides a means to extract interseismic motion in agricultural areas where 1- and 2-year interferograms are largely decorrelated.

We applied the method of pure geometric alignment, common-point stacking for error estimation, and coherence based SBAS to ascending (42) and descending (34) acquisitions in the region surrounding the CPGF. The error estimation technique works well due to the small baselines, short time-span, and regular cadence of Sentinel-1A satellite. The improved coverage facilitates the combination ascending and descending LOS mean velocity grids into vertical and fault-parallel grids. The fault-parallel estimates show adequate agreement with two dense GPS profiles across the Imperial and Cerro Prieto faults. This new analysis provides refined estimates of three important crustal deformation signals in the region. 1) We produce the first complete map of the area of high subsidence rate at the step-over between the Imperial and Cerro Prieto faults. The estimated subsidence rate is higher now (~160 mm/yr) than in the past (120-140 mm/yr). Considering that the CPGF is currently only 11 m above sea level, the region
will be at sea level in just 65 years if the current rate continues. 2) We show that the Imperial fault does not accommodate the full 40 mm/yr of strike slip motion across the region and there is significant deformation across unmapped faults in the western Mexicali valley and further to the west. 3) We observe that currently the Cerro Prieto fault accommodates less than half of the full plate motion. Our analysis shows significant motion across the Indiviso fault and faults further to the west. This could be continued near-field postseismic deformation following the 2010 El-Mayor Cucapah earthquake. These three crustal deformation signals will be more fully resolved in the next few years as the Sentinel-1B begins its systematic coverage of the region to complement the critical measurements from Sentinel-1A.

Acknowledgements

The authors want to thank the three anonymous reviewers for their valuable suggestions. The authors also want to thank ESA for the extraordinary data open policy on the Sentinel-1 mission and want to thank ASF and UNAVCO for archiving the data and the precise orbital products. The fault traces were provided by CICESE. This study was funded by the NASA Earth Surface and Interior Program (NNX16AK93G), the NSF Geoinformatics Program (EAR-1347204) and the Southern California Earthquake Center (SCEC). SCEC is funded by the NSF cooperative Agreement EAR-1033462 and USGS Cooperative Agreement G12AC20038.

References


Transactions on, 48(2), 759-769.


Shirzaei, M., R. Burgmann, and E. Fielding, Applicability of Sentinel-1 TOPS multitemporal interferometry for monitoring slow ground motions in the San Francisco Bay Area, Geophysical Research Letters, in press, March, 2017


