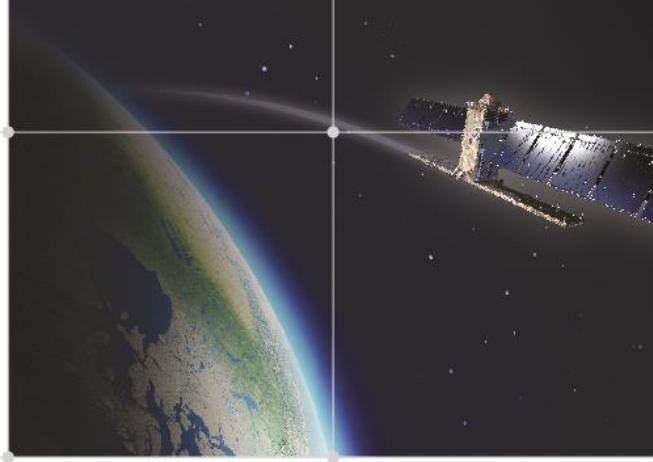




Historical SqueeSAR ground deformation analysis over Livermore and Pleasanton, (CA) using ERS, ENVISAT and Sentinel satellites

Report



TRE
ALTAMIRA
A CLS Group Company

Report specifications

Client:

Tom Rooze

Zone 7 Water Agency

100 N. Canyons Parkway

Livermore, CA 94551-9486

Reference:**Title:**

Historical SqueeSAR ground deformation analysis
over Livermore and Pleasanton, (CA) using ERS,
ENVISAT and Sentinel satellites

TRE ALTAMIRA Job Order:

JO16-3034

Prepared by:

TRE ALTAMIRA

Authors:

Jean Pascal Iannacone
Geoscientist

Approved by:

Giacomo Falorni
Operations Manager

Date:

29 November 2016

Version:

3.0

Executive Summary

An InSAR analysis spanning 24 years (1992 to 2016) was performed using radar data from three different satellites to measure surface deformation in the areas of Livermore and Pleasanton, with the objective of evaluating ground movement. The following points describe the main findings:

- Both seasonal and long term deformation trends were identified and quantified
- Average deformation rates ranged from -0.52 in/y to +0.33 in/y for 1992-2000 (ERS), -1.31 in/y to +0.58 in/y for 2003 – 2010 (Envisat), and from -2.01 in/y to +1.38 in/y for 2015 – 2016 (Sentinel). Standard deviation values, which characterize the measurement precision, ranged from ± 0.01 in/y (ERS, ENVISAT) to ± 0.06 in/y (Sentinel)
- Good correlation was found between the SqueeSAR measurements and the topographic surveys
- The largest seasonal movements were measured over Livermore, in particular over the Mocho II subbasin. Seasonal movements were also identified over Pleasanton (Bernal and Amador subbasins)
- The amplitude of seasonal deformation reached up to +0.56", with an average standard deviation of ± 0.07 "
- An identified deformation boundary correlates well with the local fault map. A second sharp deformation boundary over Mocho II might correspond to an unmapped discontinuity
- Three west-east cross-sections were created to study the deformation over the AOI (seasonal and long term trend)
- Two cumulative deformation change maps were created for the periods 1992 to 1996 (ERS) and 2015 to 2016 (Sentinel)
- Point densities ranged from 415 MP/sq.mi. (ERS) to 1,202 MP/sq.mi. (ENVISAT)

Table of Contents

Executive Summary	2
Acronyms and abbreviations.....	4
1. Introduction.....	5
2. Radar data	6
3. Results.....	8
3.1. Displacement Rate.....	10
3.1.1. 1992 – 2000 (ERS)	11
3.1.3. 2003 – 2010 (ENV)	13
3.1.4. 2015 – 2016 (SNT).....	14
3.2. Seasonal Amplitude	17
3.2.1. 1992 – 2000 (ERS)	17
3.2.3. 2003 – 2010 (ENV)	19
3.2.4. 2015 – 2016 (SNT).....	20
4. Observations.....	23
4.1. Comparison with topographic data – Pleasanton	23
4.2. Surface Cross-sections.....	28
4.3. Interpolated Deformation Maps	30
5. List of deliverables	32
6. Discussion & recommendations.....	35

Acronyms and abbreviations

ALS	ALOS satellite
AR (CR)	Artificial Reflector (Corner reflector)
ATS	Average Time Series
CS	Cross-section
CSK	COSMO-SkyMed satellite
DEM	Digital Elevation Model
DInSAR	Differential InSAR
DS	Distributed Scatterer
ENV	ENVISAT satellite
ERS	ERS satellite
ESA	European Space Agency
InSAR	Interferometric Synthetic Aperture Radar
LOS	Line of Sight
MP	Measurement Point
PS	Permanent Scatterer
PSInSAR	Permanent Scatterer Interferometry
RMT	Rapid Motion Tracking
SAR	Synthetic Aperture Radar
SNT	Sentinel satellite
TS	Time Series

1. Introduction

TRE ALTAMIRA Inc. (TRE) has been contracted by Zone 7 Water Agency (Zone 7) to perform a SqueeSAR analysis of historical ground deformation over the Livermore and Pleasanton area. Three radar satellite data sets (ERS, ENVISAT and Sentinel) covering the period 1992 to 2016 were used for this purpose. The AOI comprises urban and very dry, sparsely vegetated areas and covers approximately 100 square miles. The terrain is flat with some moderate hills and presents conditions suitable for the application of InSAR. Figure 1 shows the AOI with ground water subbasins, faults, topographic benchmarks and wells.

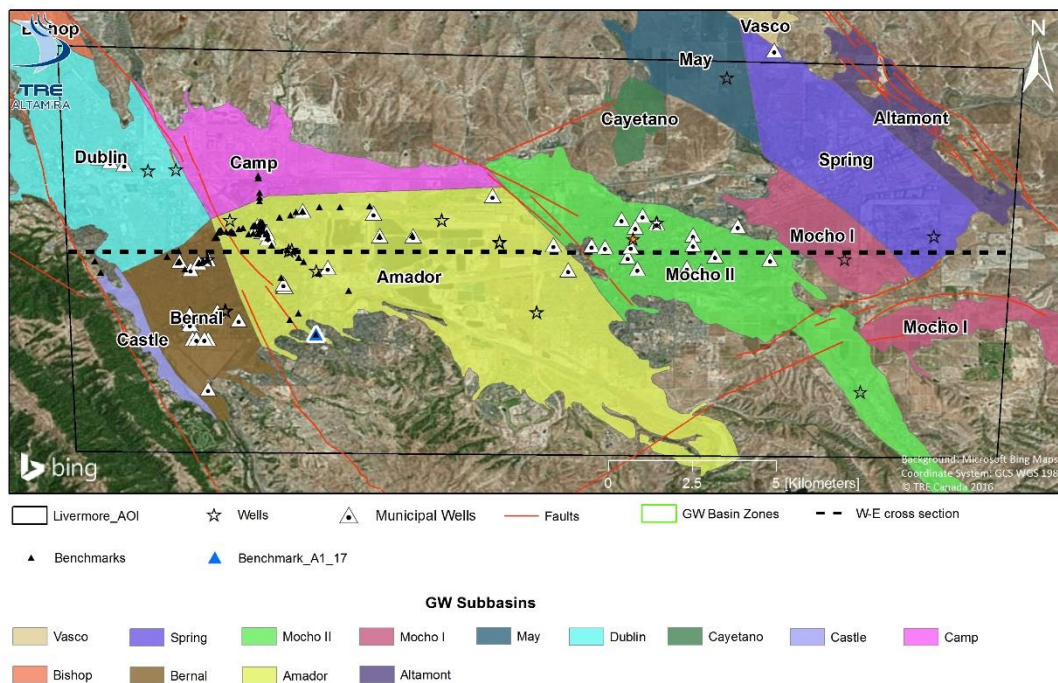


Figure 1: Livermore and Pleasanton AOI with indication of ground water subbasins, faults, topographic benchmarks and wells.

2. Radar data

About 120 SAR images were processed to analyze the deformation over the last two decades at Livermore and Pleasanton. In particular, 47 ERS images were processed from 1992 to 2000 with a nominal image acquisition frequency of 35 days, although a two-year gap is present (688 days from June 1993 to May 1995). Fifty-one images were acquired from ENVISAT (ENV) during a seven-year period spanning from 2003 to 2010 with the same nominal 35-day acquisition frequency. Smaller gaps are present in the ENV data set, such as the one from April 2004 to April 2005. Twenty-nine Sentinel (SNT) images were processed to measure the deformation over 17 months (Jan. 2014 to Jun. 2016). SNT has a nominal 12-day acquisition frequency. All three data sets were acquired from a descending orbit.

Figure 2 shows the ERS, ENV and SNT distribution and coverage over the last two decades. Table 1 summarized the relevant information for each data set while Table 2 lists all the images processed for the present study.

Satellite	Geometry	Line of sight angle (°)	# Images	Acquisition period
ERS	Descending	22.38	47	06/05/1992 – 09/12/2000
ENV	Descending	22.38	51	18/01/2003 – 18/09/2010
SNT	Descending	42.52	29	31/12/2014 – 11/06/2016

Table 1: Satellite data set information

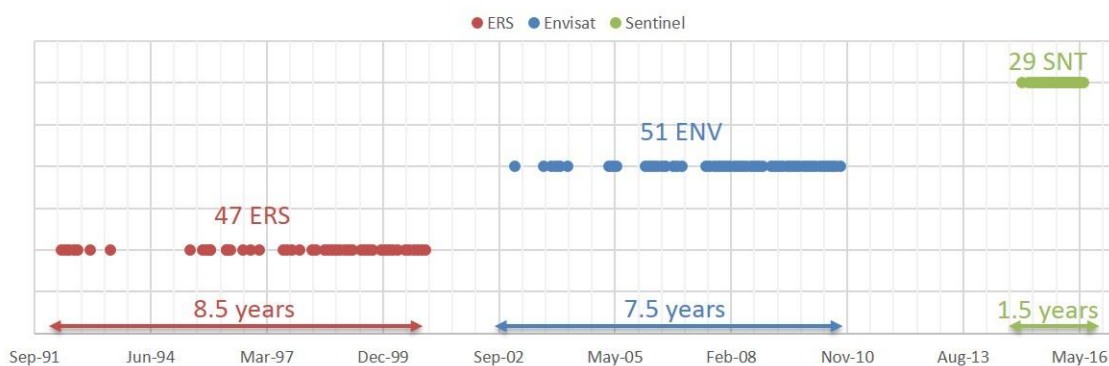


Figure 2: Temporal distribution of the data sets.

ERS		ENVISAT		SENTINEL
06/05/1992	03/07/1999	18/01/2003	05/07/2008	31/12/2014
10/06/1992	07/08/1999	20/09/2003	09/08/2008	01/03/2015
15/07/1992	11/09/1999	29/11/2003	13/09/2008	25/03/2015
19/08/1992	20/11/1999	03/01/2004	18/10/2008	18/04/2015
23/09/1992	25/12/1999	07/02/2004	22/11/2008	12/05/2015
06/01/1993	29/01/2000	17/04/2004	31/01/2009	05/06/2015
30/06/1993	04/03/2000	02/04/2005	07/03/2009	29/06/2015
19/05/1995	08/04/2000	07/05/2005	11/04/2009	23/07/2015
01/09/1995	17/06/2000	11/06/2005	16/05/2009	16/08/2015
07/10/1995	22/07/2000	11/02/2006	20/06/2009	09/09/2015
10/11/1995	26/08/2000	18/03/2006	25/07/2009	03/10/2015
11/11/1995	30/09/2000	22/04/2006	29/08/2009	27/10/2015
29/03/1996	04/11/2000	27/05/2006	03/10/2009	20/11/2015
30/03/1996	09/12/2000	01/07/2006	07/11/2009	02/12/2015
04/05/1996		05/08/2006	12/12/2009	14/12/2015
17/08/1996		14/10/2006	16/01/2010	26/12/2015
26/10/1996		18/11/2006	20/02/2010	07/01/2016
04/01/1997		23/12/2006	27/03/2010	19/01/2016
02/08/1997		21/07/2007	01/05/2010	31/01/2016
06/09/1997		25/08/2007	05/06/2010	12/02/2016
11/10/1997		29/09/2007	10/07/2010	24/02/2016
20/12/1997		03/11/2007	14/08/2010	07/03/2016
04/04/1998		08/12/2007	18/09/2010	19/03/2016
09/05/1998		12/01/2008		31/03/2016
18/07/1998		16/02/2008		12/04/2016
22/08/1998		22/03/2008		06/05/2016
26/09/1998		26/04/2008		18/05/2016
31/10/1998		31/05/2008		30/05/2016
05/12/1998				11/06/2016
09/01/1999				
13/02/1999				
20/03/1999				
29/05/1999				

Table 2: List of SAR images processed in the present study.

3. Results

SqueeSAR results provided a good density of points considering the land cover and the medium resolution of the satellites used. The total number of measurement points ranged from ~41,000 (ERS) to over 120,000 (ENV). Results are summarized in Table 3.

AOI	Sq. mi	~ 100
ERS	N. points	41,518
	Density (MP/sq. mi)	415
ENVISAT	N. points	120,205
	Density (MP/sq. mi)	1,202
SENTINEL	N. points	51,443
	Density (MP/sq. mi)	514

Table 3: Summary statistics of measurement points number and density for the ERS, ENV and SNT.

Each measurement point (MP) contains a time series of deformation containing numerous attributes, which include, cumulative displacement, the average deformation rate, acceleration and seasonal amplitude. The average deformation rate is evaluated from the linear regression of the displacement time series and is typically used to identify areas of movement. When movement is non-linear, additional parameters such as acceleration and seasonal amplitude, can be used to better characterize the deformation.

As SqueeSAR is a differential technique it requires reference points, which are assumed to be motionless. The reference points were selected based on their radar characteristics and proximity to the topographic reference benchmark (A1_17), to allow comparison with the topographic survey data. The ERS reference point was about 2,300 feet from A1_17, while ENV and SNT were 950 and 6,230 feet away from A1_17 respectively.

The ERS, ENV and SNT time series in the area surrounding benchmark A1_17 were analyzed in order to identify any existing deformation offsets between the SqueeSAR reference points and the topographic benchmark. Figure 3 shows that A1_17 is stable in the SqueeSAR data sets. Therefore, the topographic survey and the SqueeSAR measurements are comparable.

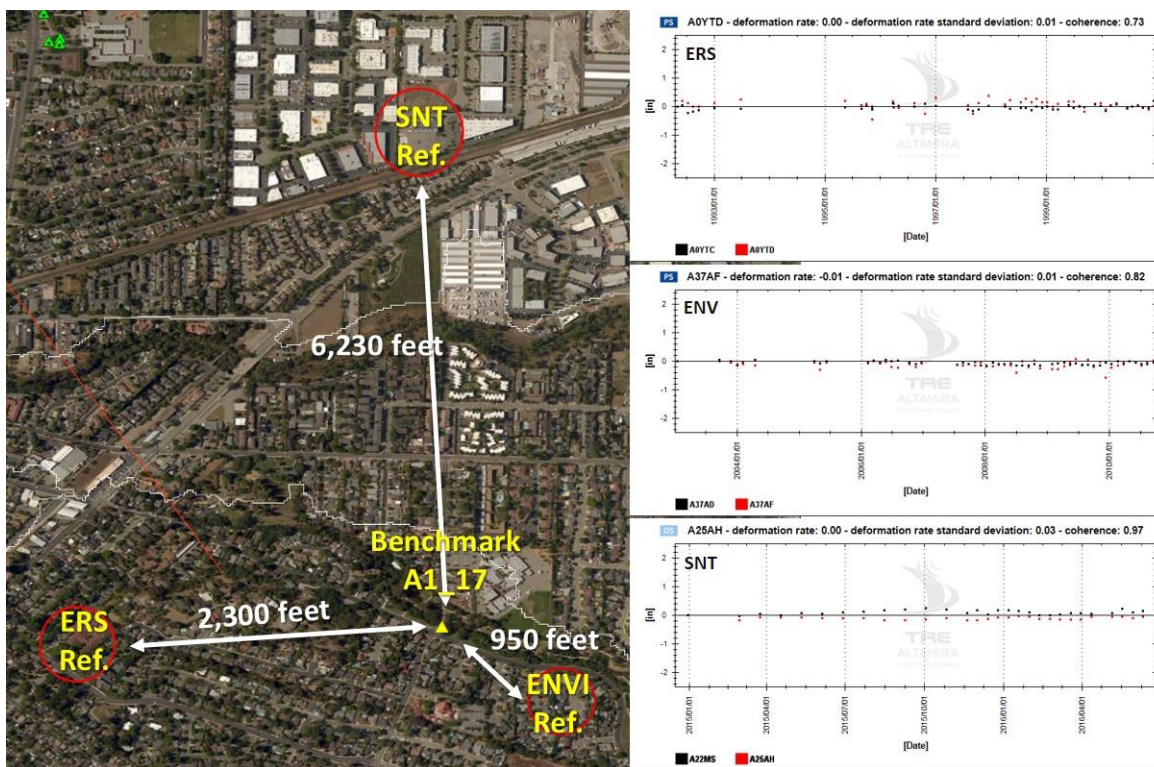


Figure 3: Comparison between the SqueeSAR reference points and benchmark A1_17.

3.1. Displacement Rate

The line-of-sight (LOS) displacement rate is expressed in inches per year (in/year or mm/year, Figure 4). Each point corresponds to a Permanent Scatterer (PS) or a Distributed Scatterer (DS), and is color-coded according to its annual rate of movement. Average displacement values are calculated from a linear regression of the ground movement over the entire period covered by the satellite images. Detailed information on ground motion is provided by means of displacement time series, which are shown for each measurement point. Figure 4 to Figure 8 show the deformation rate map for the ERS, ENV, and SNT data sets, respectively. Negative values (red) indicate movement away from the satellite while positive values (blue) represent movements towards the satellite. The displacement rate error is characterized by the displacement rate standard deviation. The displacement rate for a given point should be read in the form of Displacement Rate $\pm$ Standard Deviation. Standard deviation values tend to increase with distance from the reference point. Higher values indicate a greater variability in the displacement and are often associated with areas of rapid and/or irregular ground movements.

3.1.1. 1992 – 2000 (ERS)

The average deformation rate from 1992 to 2000 ranged from -0.52 in/y to +0.33 in/y. Positive deformation was measured over the western portion of the Bernal subbasin and the central portion of the Mocho II subbasin. Mild negative deformation was also measured over the western portion of Mocho II (Figure 4). The average deformation rate standard deviation was ± 0.01 in/y.

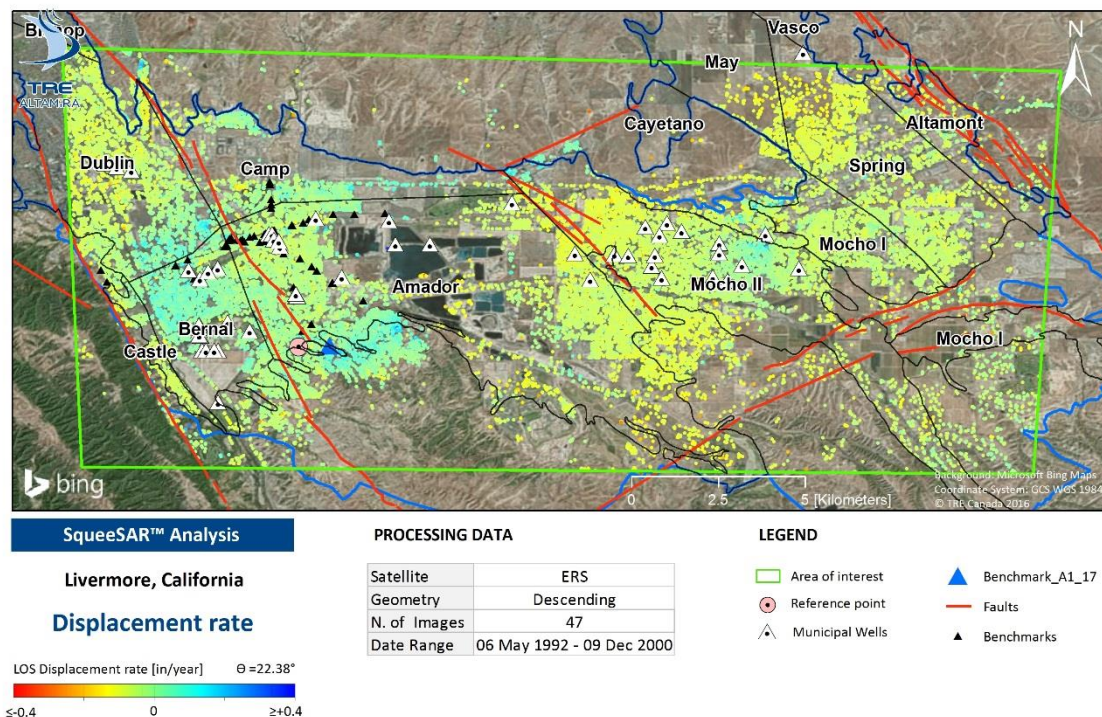


Figure 4: ERS average displacement rate

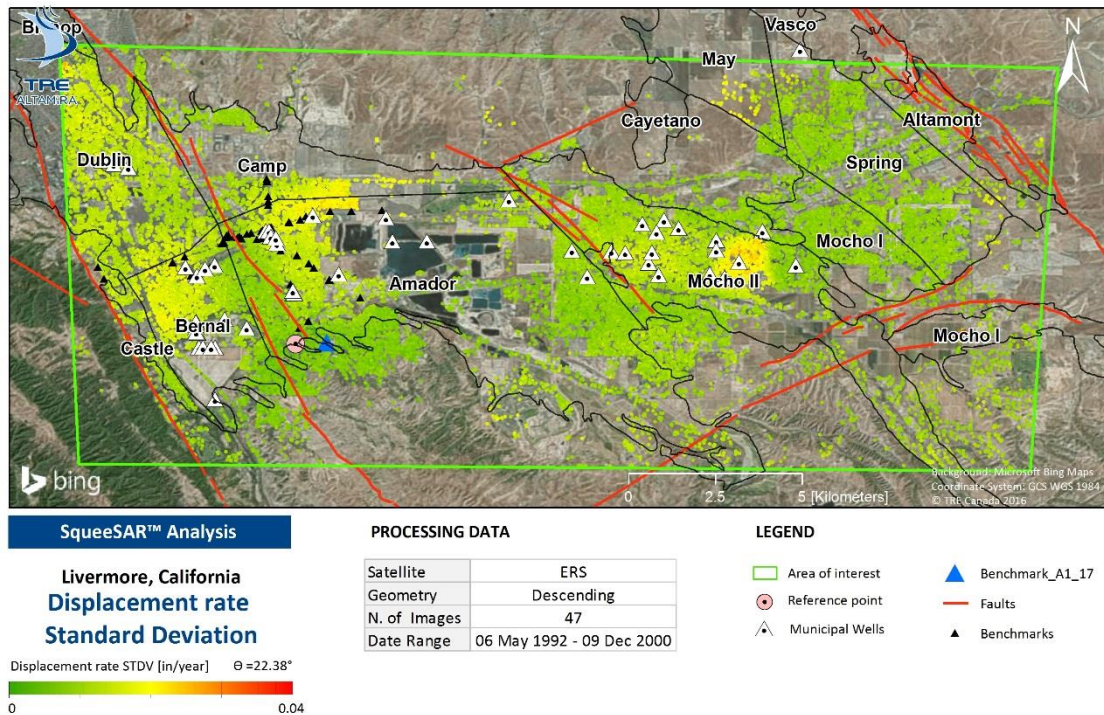


Figure 5: ERS displacement rate standard deviation

3.1.3. 2003 – 2010 (ENV)

The average deformation rate from 2003 to 2010 ranged from -1.31 in/y to $+0.58$ in/y. Positive deformation was measured over the western sector of the Bernal subbasin and the central portion of the Amador subbasin. Negative deformation was measured over Mocho II (Figure 6). The average deformation rate standard deviation was ± 0.01 in/y.

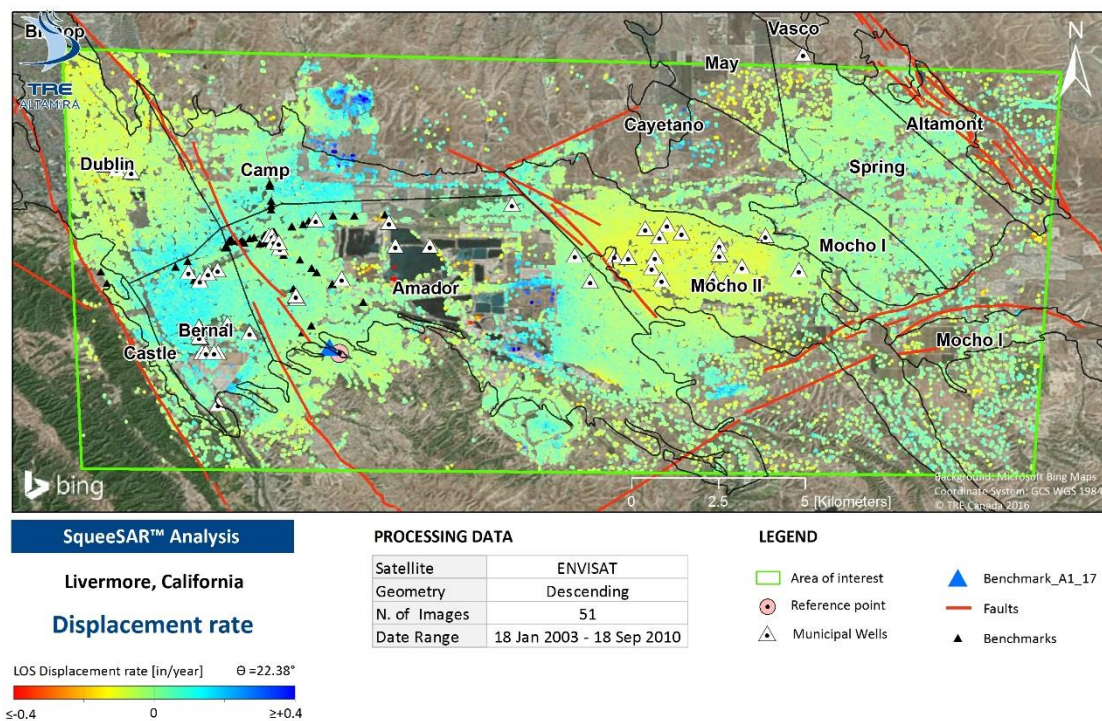


Figure 6: ENV average displacement rate

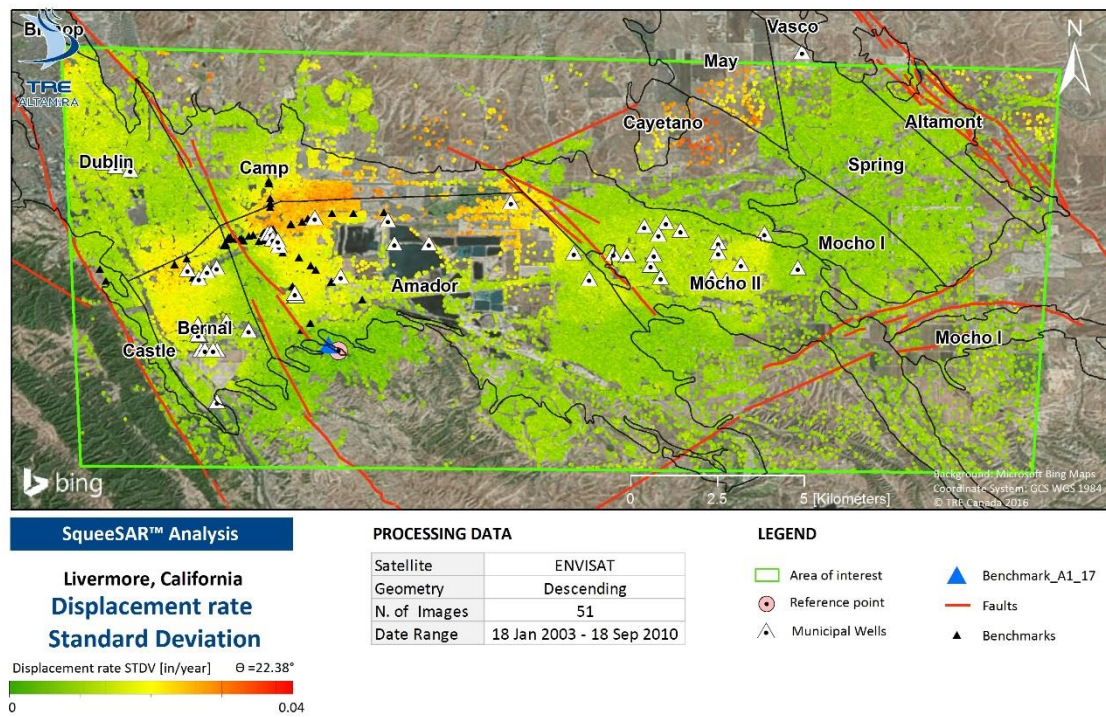


Figure 7: ENV displacement rate standard deviation

3.1.4. 2015 – 2016 (SNT)

The average displacement rate from 2015 to Jun 2016 ranged from -2.01 in/y to ± 1.38 in/y. Positive deformation values were measured over the entire Bernal subbasin and most of the Amador subbasin. Mild deformation was measured over Mocho II while negative values were measured near the Mocho II/Amador contact, to the West of a mapped fault. The deformation rate map shows a sharp boundary along the fault. The average deformation rate standard deviation was ± 0.06 in/y.

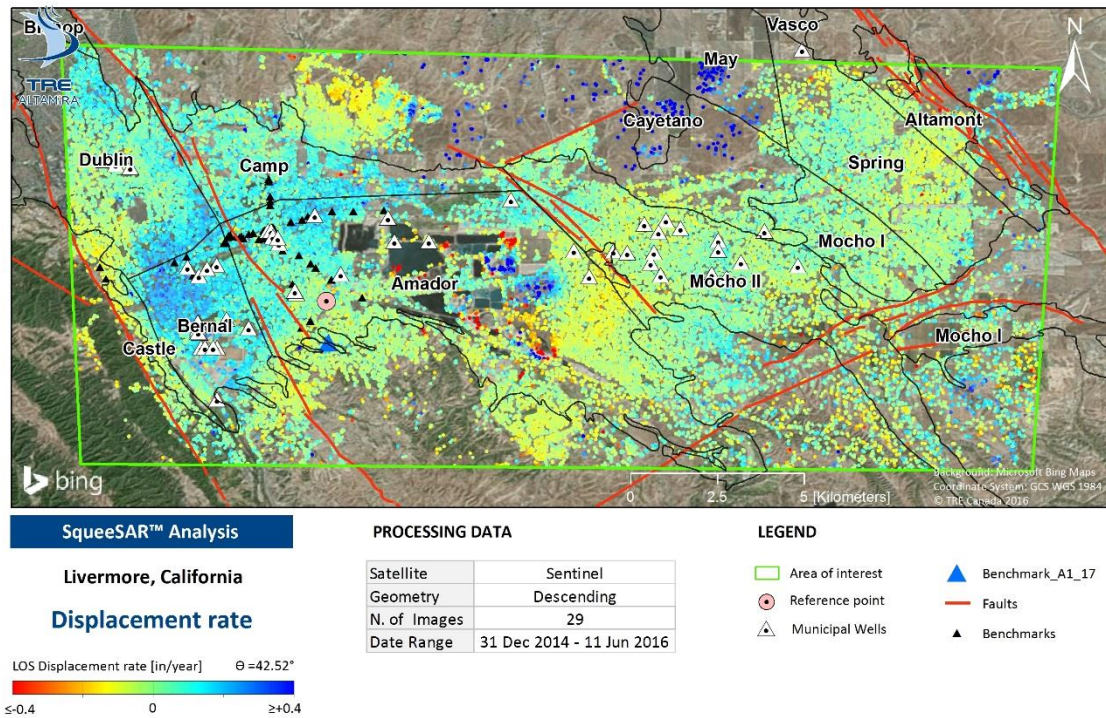


Figure 8: SNT average displacement rate

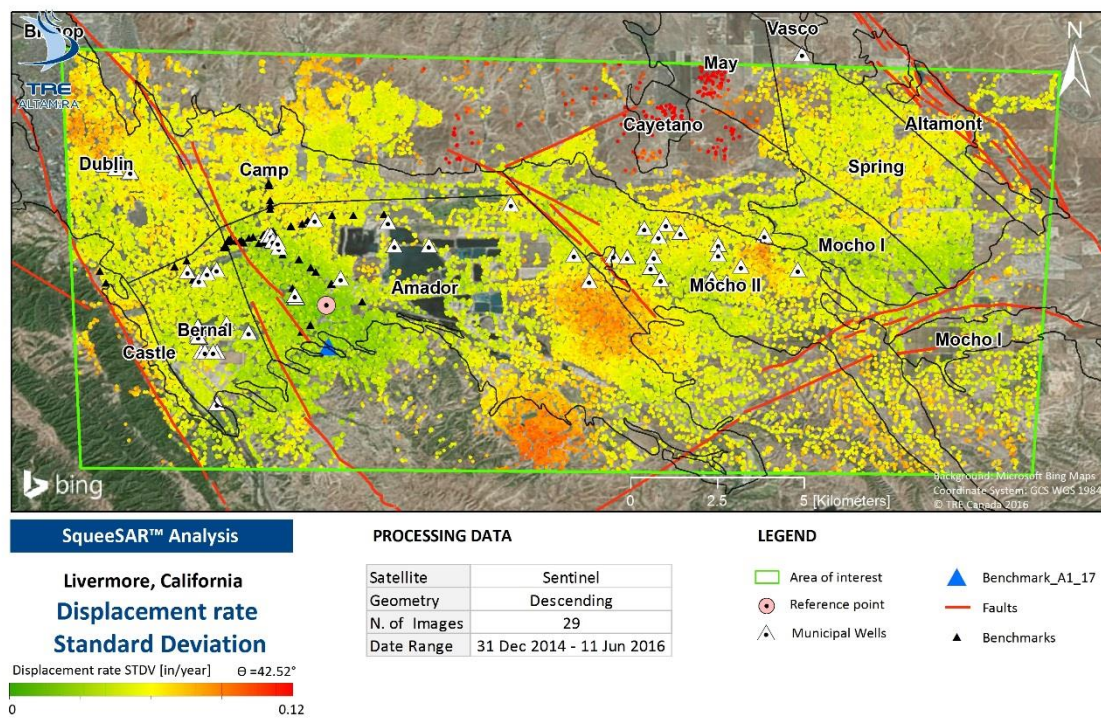


Figure 9: SNT displacement rate standard deviation

3.2. Seasonal Amplitude

Seasonal amplitude values characterize cyclical (seasonal) trends that are present in the deformation time series. Deformation measurements are fitted to a sinusoidal model to determine the range of displacement values measured at each point over the course of one year. The seasonal amplitude value represents the excursion of movement associated with seasonal changes. Values close to zero (green) show little seasonal deformation. Positive values (red) correspond to areas with larger seasonal deformation. Seasonal amplitude standard deviation values characterize the error of the cyclical movements in the deformation time series. The seasonal amplitude for a given point should be read in the form of Seasonal Amplitude $\pm$ Standard Deviation.

3.2.1. 1992 – 2000 (ERS)

The average seasonal amplitude for the ERS data was up to $+0.55''$. with average standard deviation of ± 0.06 in. The highest seasonal values were measured at Mocho II. The seasonal deformation forms a sharp North-South boundary that likely corresponds to a discontinuity (e.g. unmapped fault, geological contact, etc.)

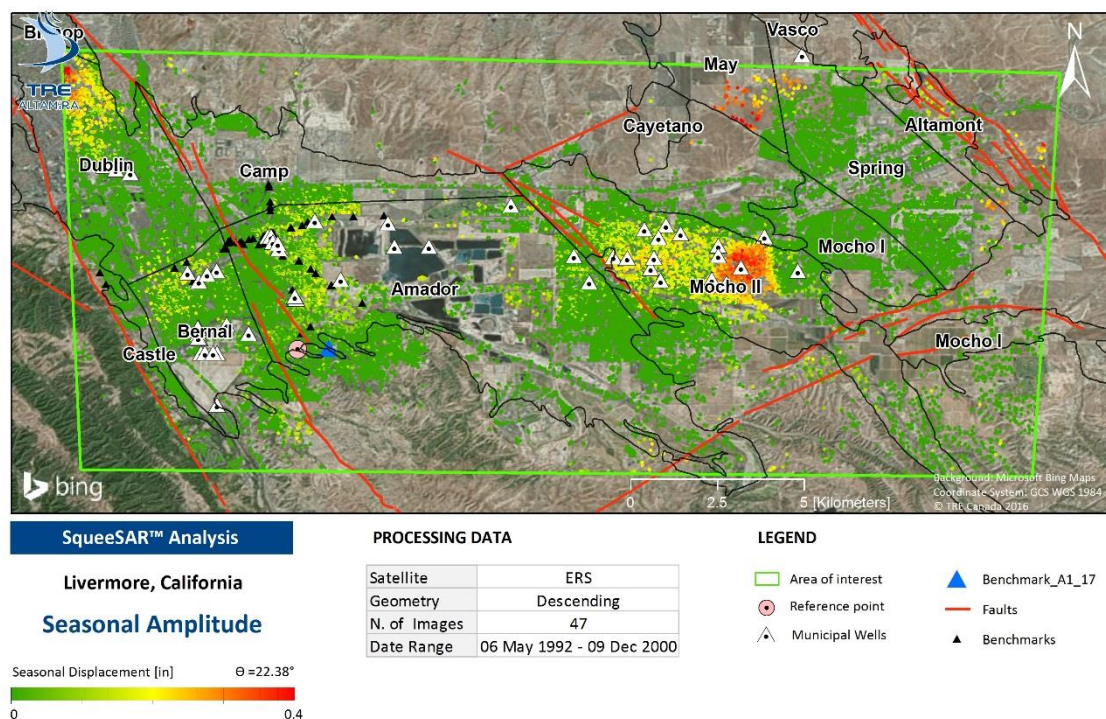


Figure 10: ERS seasonal deformation

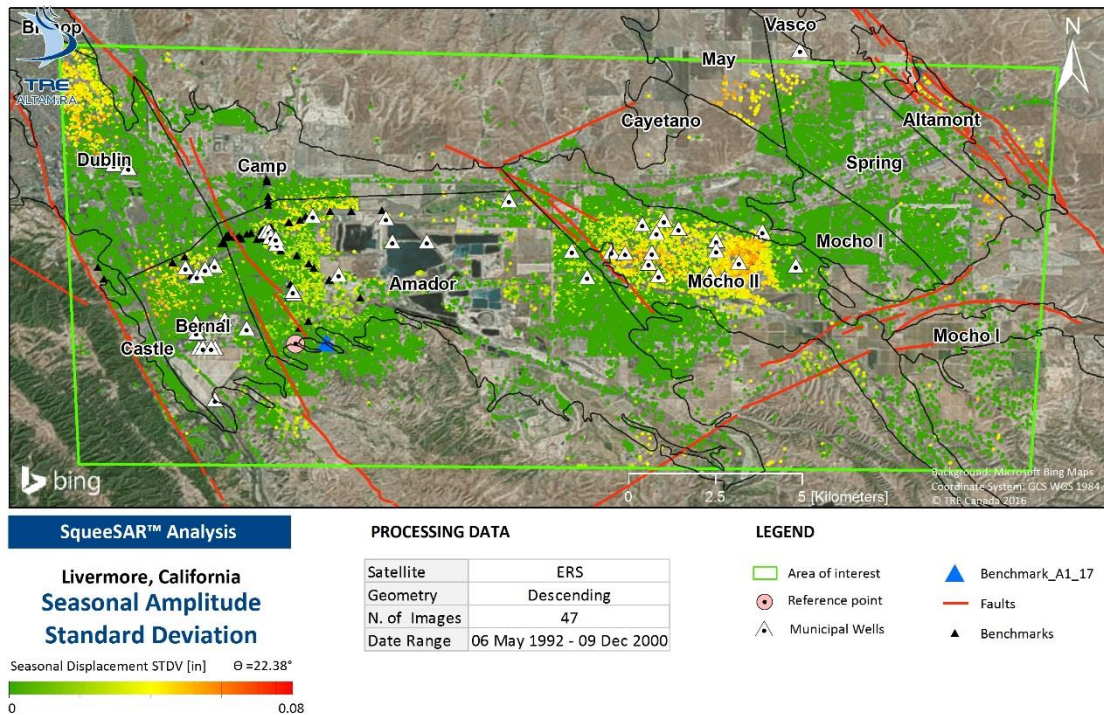


Figure 11: ERS Seasonal Amplitude standard deviation

3.2.3. 2003 – 2010 (ENV)

The average seasonal amplitude for the ENV reached a maximum of $+0.56''$ with an average standard deviation of $\pm 0.07''$. Seasonal fluctuations were measured at Mocho II, Bernal, West portion of Amador and Dublin, with the highest seasonal values measured at May and Cayetano. The two deformation discontinuities (mapped and unmapped) were measured over Mocho II.

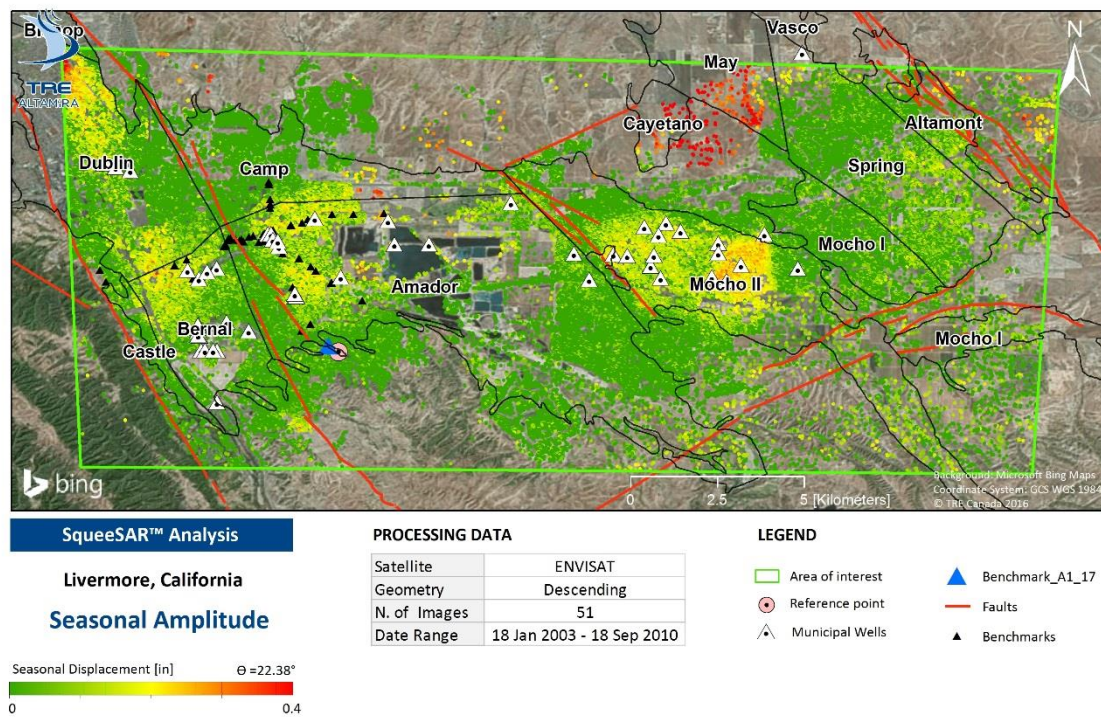


Figure 12: ENV seasonal deformation

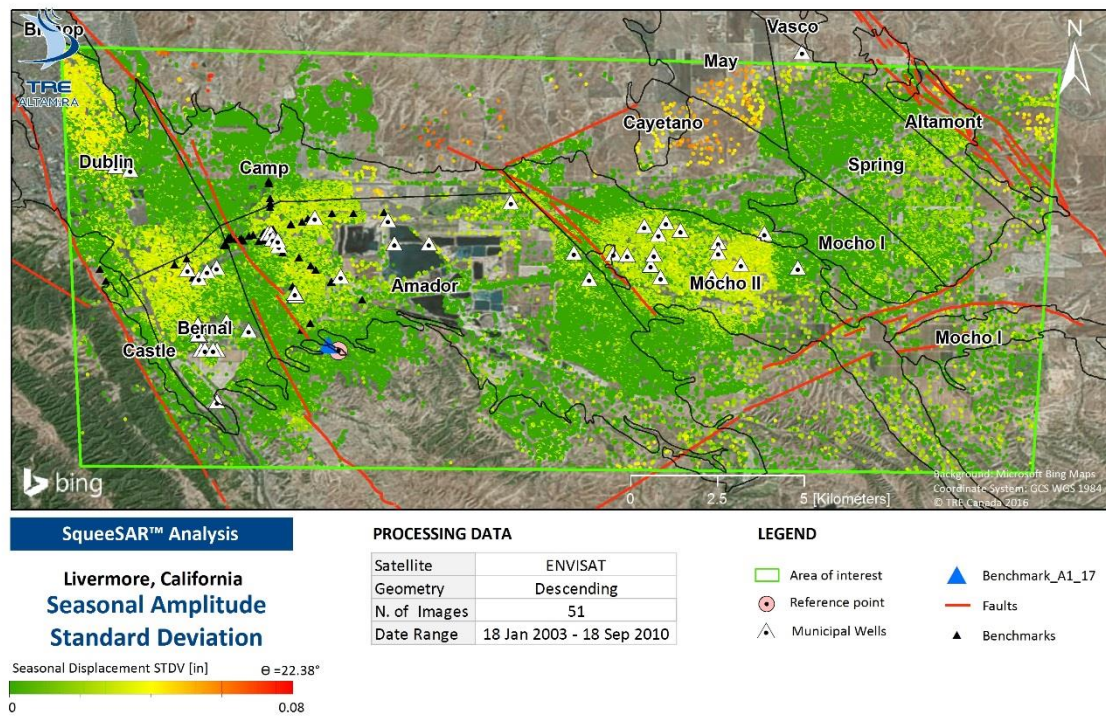


Figure 13: ENV Seasonal Amplitude standard deviation

3.2.4. 2015 – 2016 (SNT)

Typically, the characterization of seasonal movements requires data spanning at least two years, while the SNT data in this study covered a period of approximately 18 months. The average seasonal amplitude reached a maximum of +0.57'' in. with an average standard deviation of $\pm 0.09''$ in. The highest seasonal movements were measured over Cayetano and May subbasins. Seasonal movements were also measured over Mocho II and Amador.

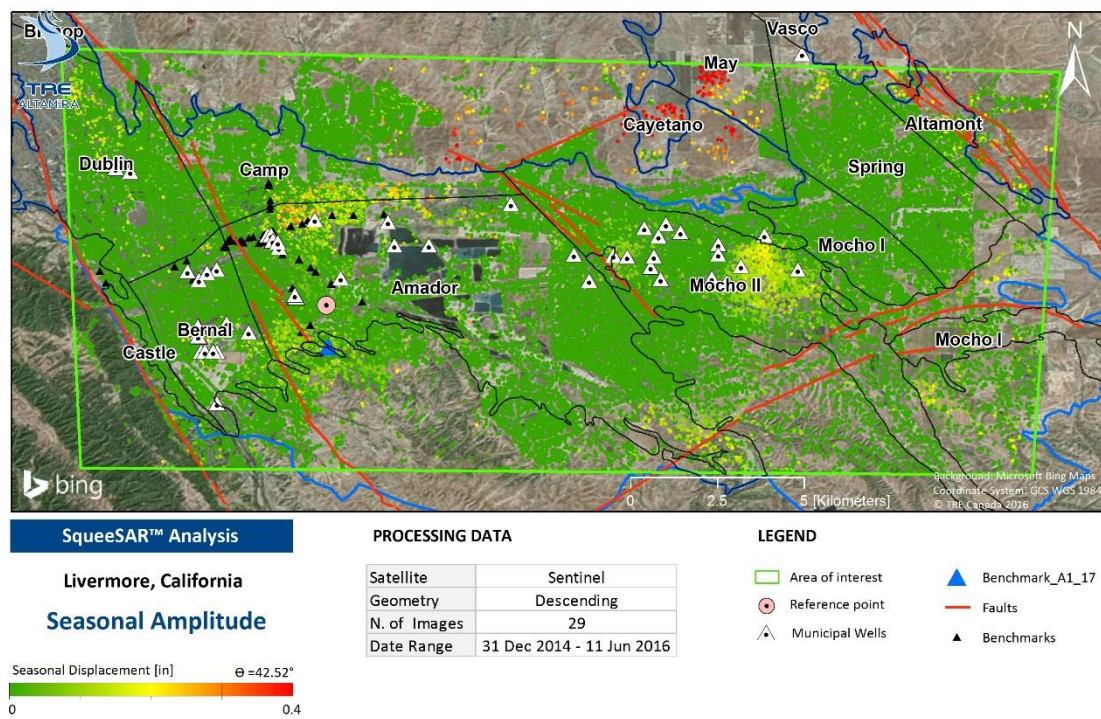


Figure 14: SNT seasonal deformation

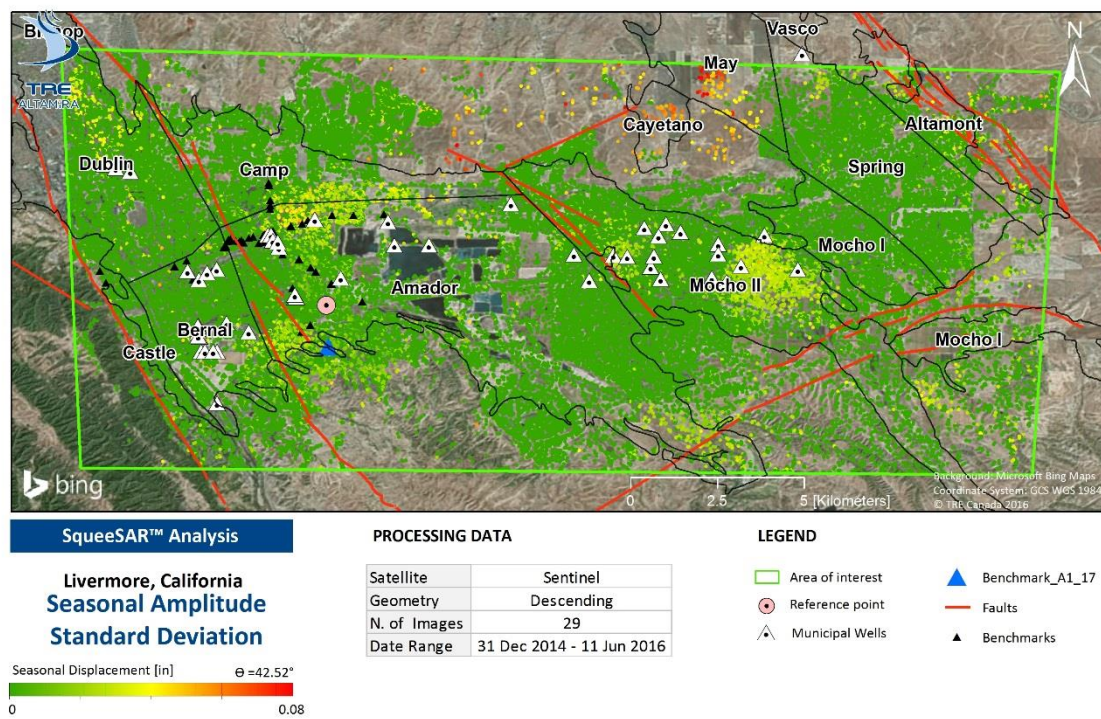


Figure 15: SNT Seasonal Amplitude standard deviation

4. Observations

The results presented in this section highlight features of interest in the data by comparing the ground deformation with ancillary data provided by Zone 7, such as topographic measurements. To facilitate comparisons, the results are described in the same units (feet) of the ancillary data.

4.1. Comparison with topographic data – Pleasanton

The SqueeSAR results were compared with the topographic survey data over Pleasanton. The survey data overlaps in time with parts of the ENV and SNT data sets, to which it was compared. Figure 16 and Figure 18 show the ENV and SNT average deformation rates over Pleasanton, the locations of the topographic benchmarks and the municipal wells. Figure 17 and Figure 19 show the corresponding seasonal deformation.

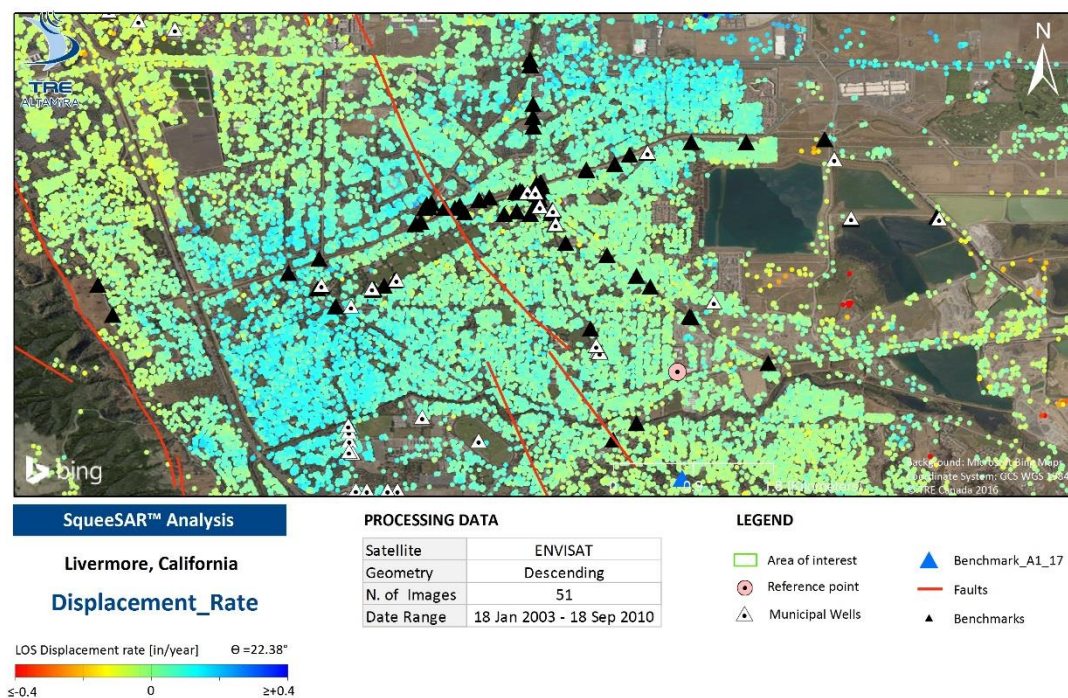


Figure 16: Average displacement rate over Pleasanton from 18 Jan 2003 to 18 Sep 2010.

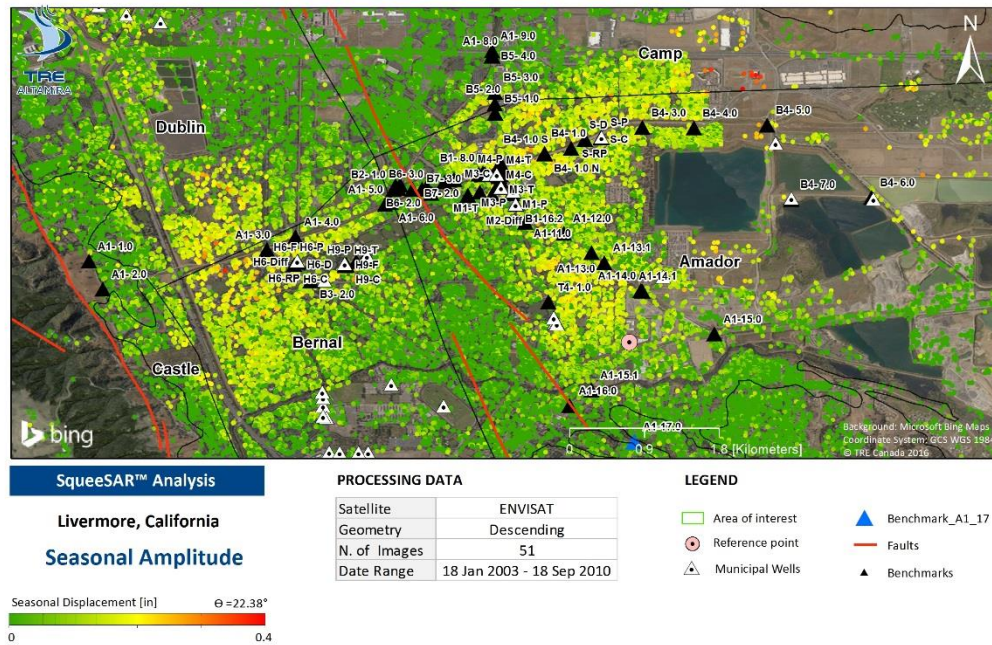


Figure 17: Average seasonal movements over Pleasanton from 18 Jan 2003 to 18 Sep 2010.

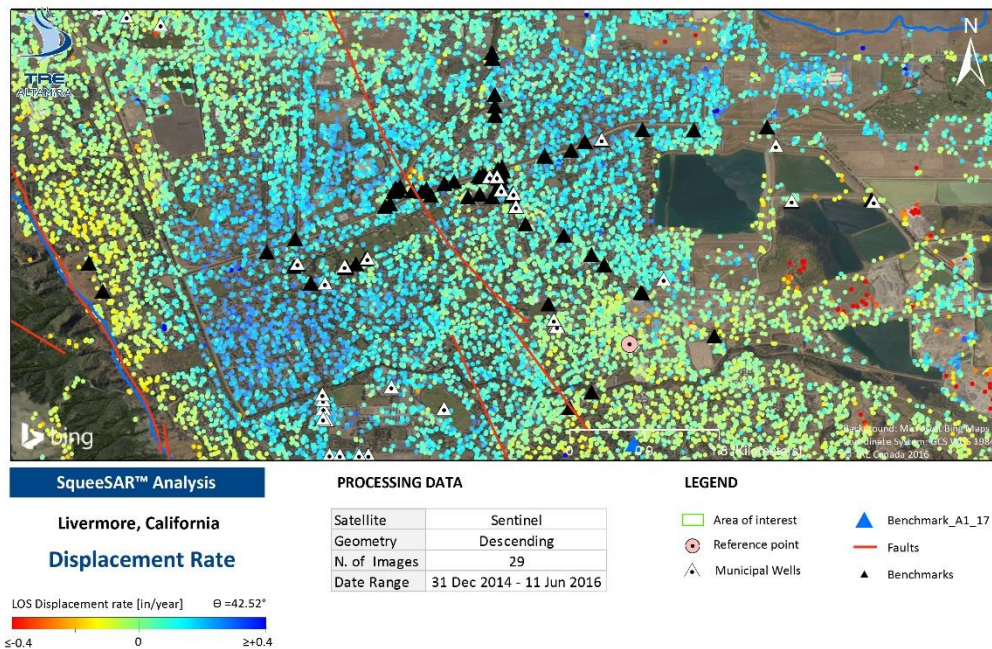


Figure 18: Average displacement rate over Pleasanton from 31 Dec 2014 to 11 Jun 2016.

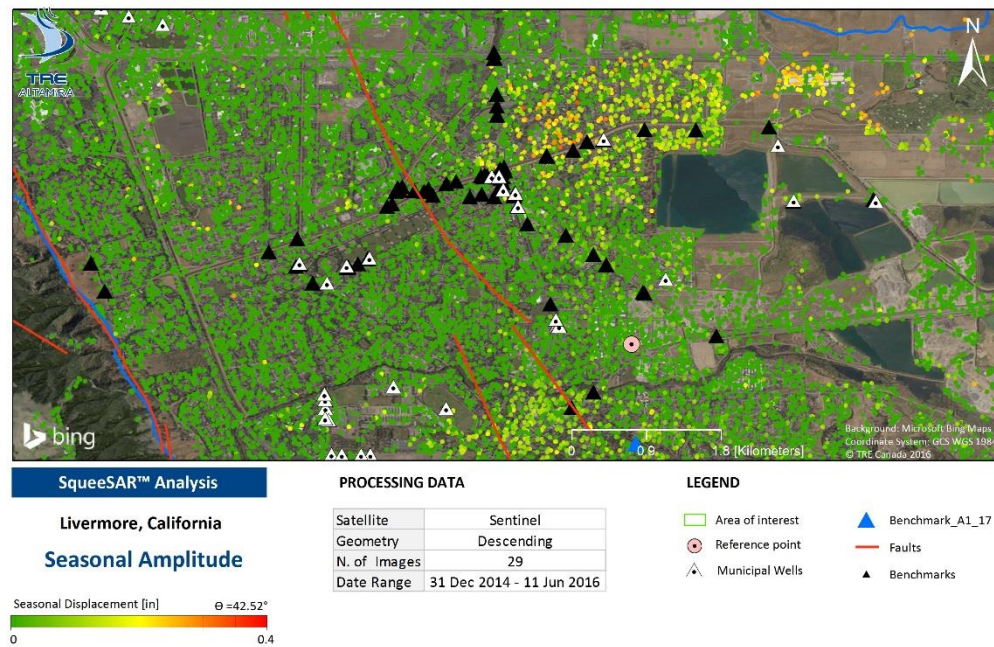
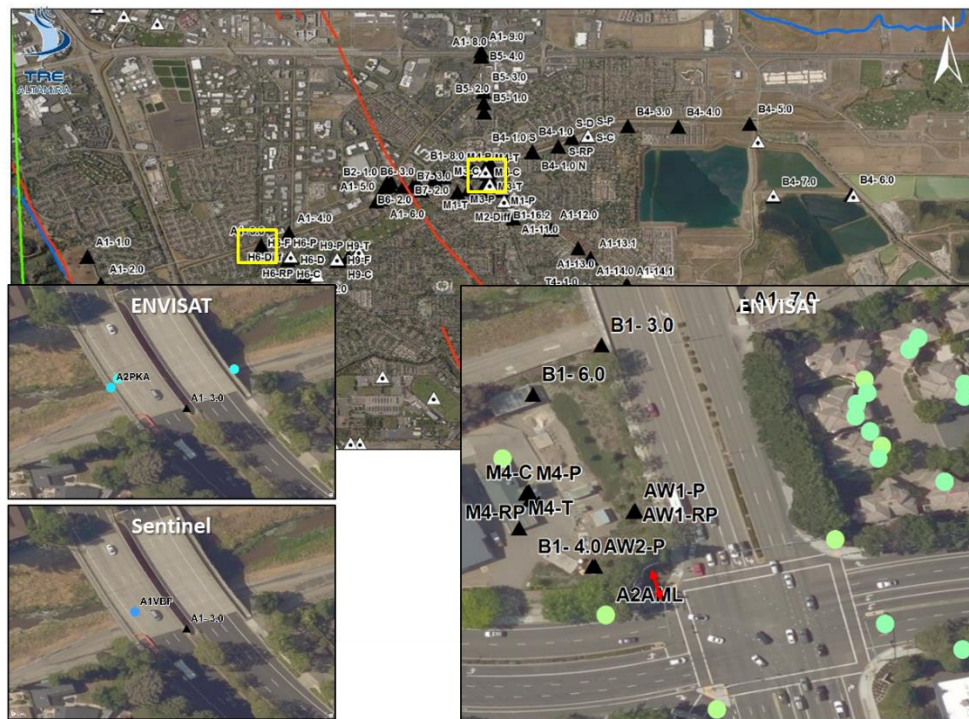


Figure 19: Average seasonal movements over Pleasanton from 31 Dec 2014 to 11 Jun 2016

The ground elevation at benchmarks B1-4.0 and A1-3.0 was compared with the SqueeSAR results for the period of overlapping measurements (Figure 20). To allow a direct comparison the survey measurements were projected to the satellite line-of-sight (LOS).



21

Figure 20: Locations of topographic benchmarks B1-4.0, (right) and A1-3.0 (left) used for the comparison with SqueeSAR.

Figure 21 compares SqueeSAR elevation changes (red points) to topographic elevation changes (black points) for benchmark B1-4.0. The results show that the two techniques provided very similar results, with both indicating over +0.10 feet of cumulative positive deformation from 2003 to 2006/2007 followed by a period of negative deformation that brought the ground surface back to the initial elevation levels (2003).

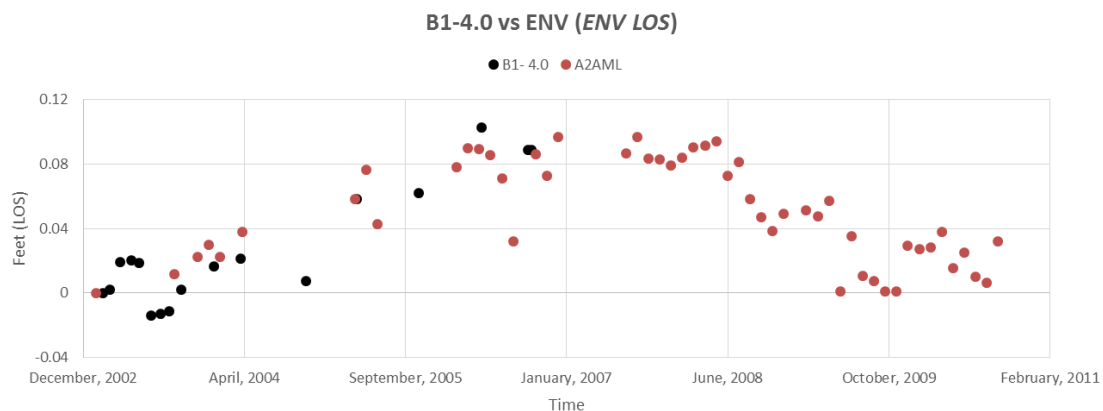


Figure 21: Topographic measurements vs SqueeSAR at benchmark B1-4.0

Topographic measurements are still being collected at Benchmark A1-3.0, which will allow comparisons to continue into the future and with multiple SqueeSAR data sets (Figure 22). The topographic measurements (black points) fit well with both the ENV (red points) and SNT data (green points). Note that in this graph the topographic data was projected to the ENV line of sight, which differs from the SNT line-of-sight. The SNT data were added to the same plot to have a 13-year deformation monitoring overview. The rigorous comparison of the topographic measurements (projected to the SNT line-of-sight) with the SNT data is shown in Figure 23.

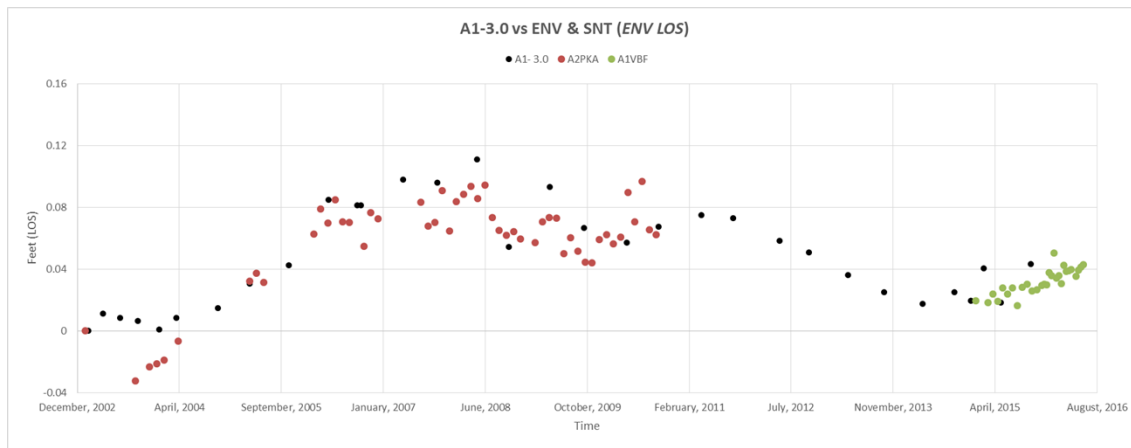


Figure 22: Topographic measurements vs ENV and SNT SqueeSAR at benchmark A1-3.0 (ENV line of sight).

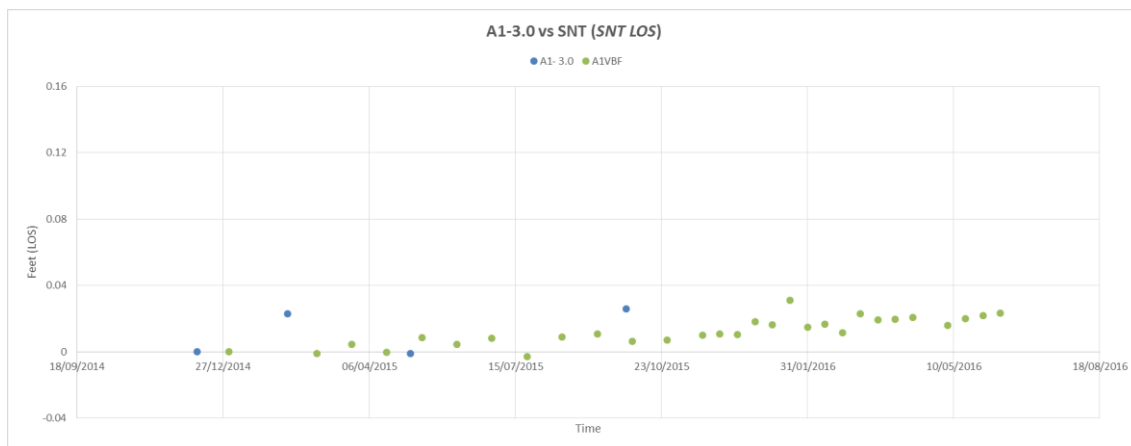


Figure 23: Topographic measurements vs SNT SqueeSAR at benchmark A1-3.0 (SNT line of sight).

Figure 21 and Figure 22 show that the deformation trend is not linear over time in this area.

4.2. Surface Cross-sections

The surface deformation over Livermore and Pleasanton was analyzed along a West-East profile to identify deformation patterns and characterize the surface elevation changes within the different subbasins (Figure 24)

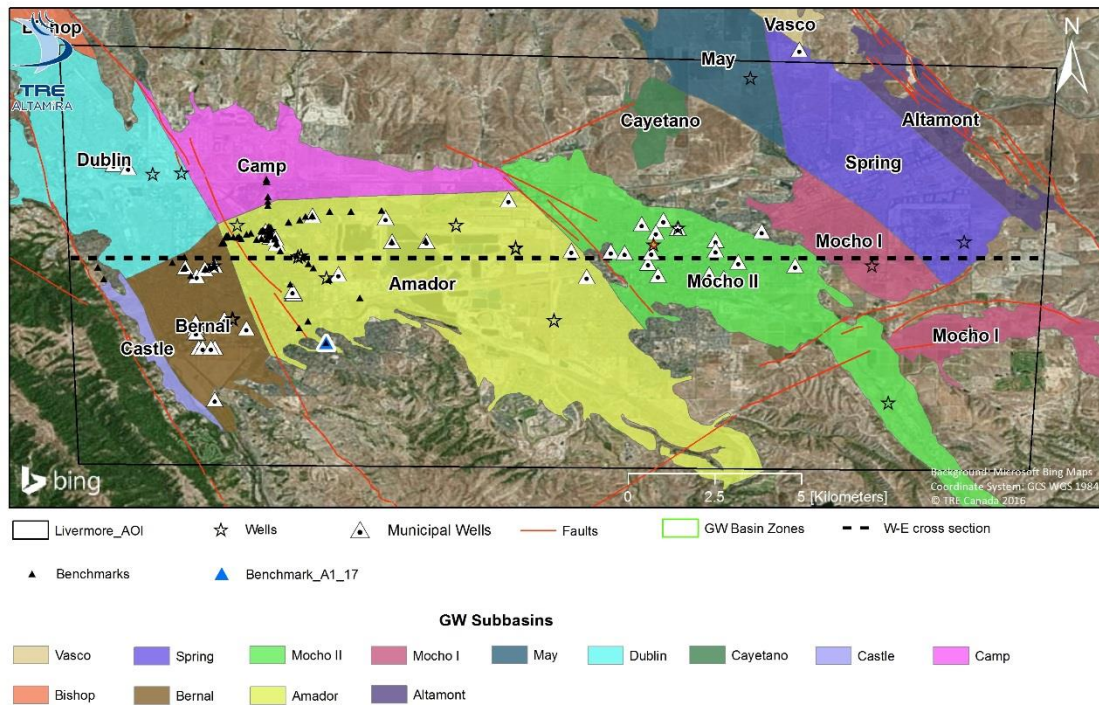


Figure 24: West-east profile used to derive the deformation cross-sections over the subbasins (Figure 25).

Three surface cross-sections were created along the W-E profile highlighted in Figure 24. Figure 25 shows the ERS (top), ENV (middle), and SNT (bottom) results, with both the deformation rate (points) and seasonality (crosses) represented. The colors at the bottom of the chart identify the subbasin. Known faults often correspond to sharp changes in the deformation results, both in seasonal and long term results.

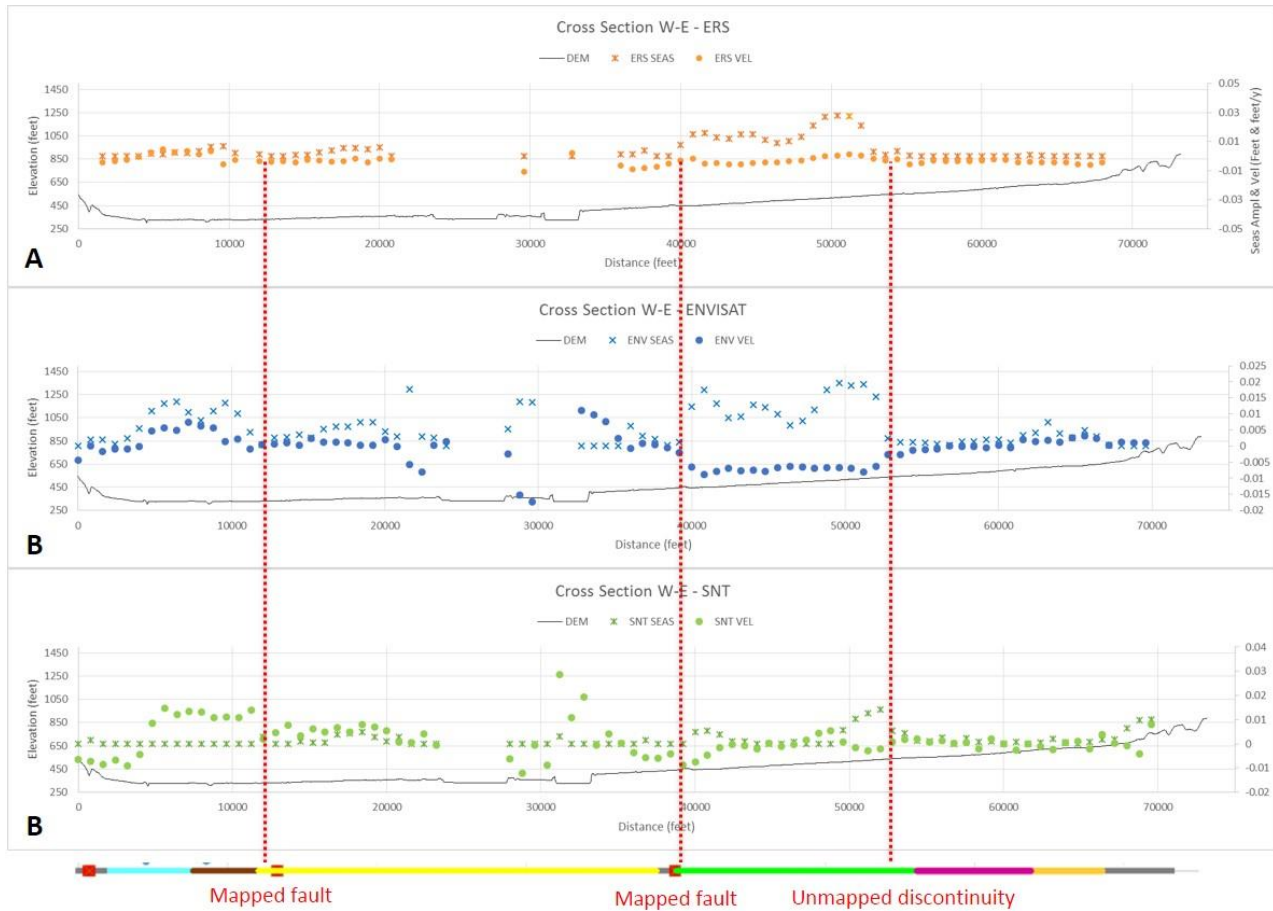


Figure 25: Surface cross-sections along the W-E profile, highlighted in Figure 24. Each graph analyzes the deformation rate (points) and seasonality (crosses) within each SqueeSAR database (ERS on top, ENV in the middle and SNT at the bottom).

The largest seasonal deformation from 1992 to 2000 (ERS) was over Mocho II, with values of up to +0.03 feet (Figure 25). Little long-term and seasonal deformation was observed over Pleasanton from 1992 to 2000. Similar behaviour was observed in the ENV and SNT datasets, except for slightly stronger seasonal deformation from 2003 to 2010 (ENV). The red lines indicate areas of abrupt change in deformation pattern.

4.3. Interpolated Deformation Maps

Figure 26 shows cumulative ground deformation from Dec 2014 to Dec 2015 from the interpolation of the SNT SqueeSAR line-of-sight results. The contour line interval is 0.01 feet. Up to 0.02 feet of positive deformation was observed over Bernal and northern Amador while localized areas of negative deformation occur over Amador as a result of a few subsiding points.

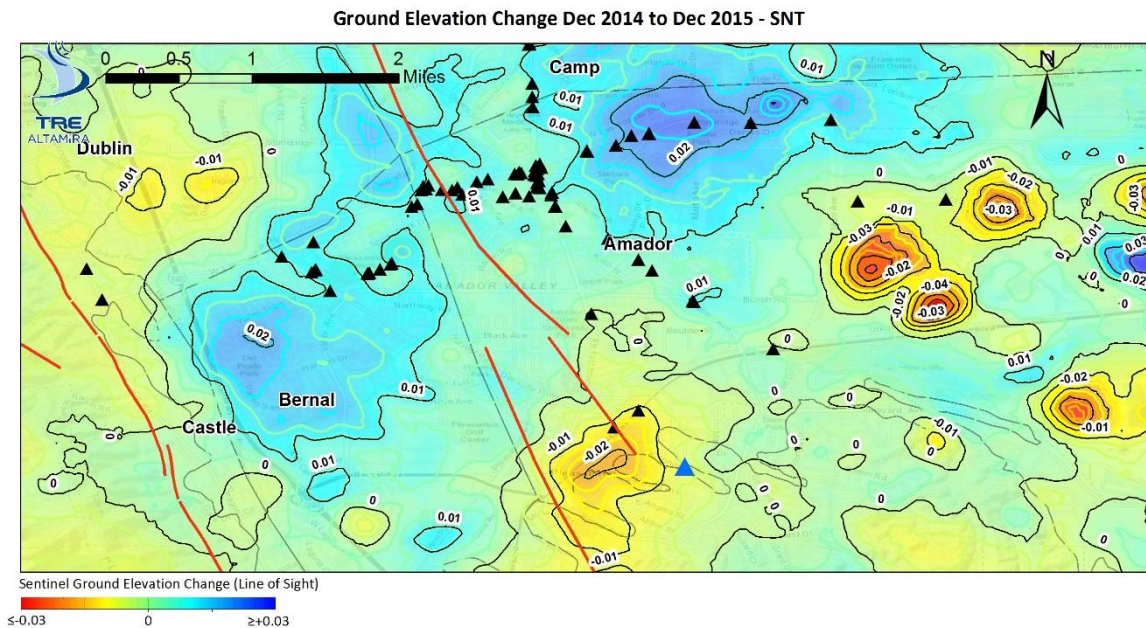


Figure 26: Ground elevation change map interpolated from SNT data (Dec 2014 to Dec 2015).

Figure 27 shows cumulative ground deformation from Aug 1992 to May 1996 resulting from the interpolation of the ERS SqueeSAR data over a portion of the AOI, while Figure 28 shows the same map (1992 to 1996) covering the entire AOI. Note the different colour scale used for the ERS and SNT results.

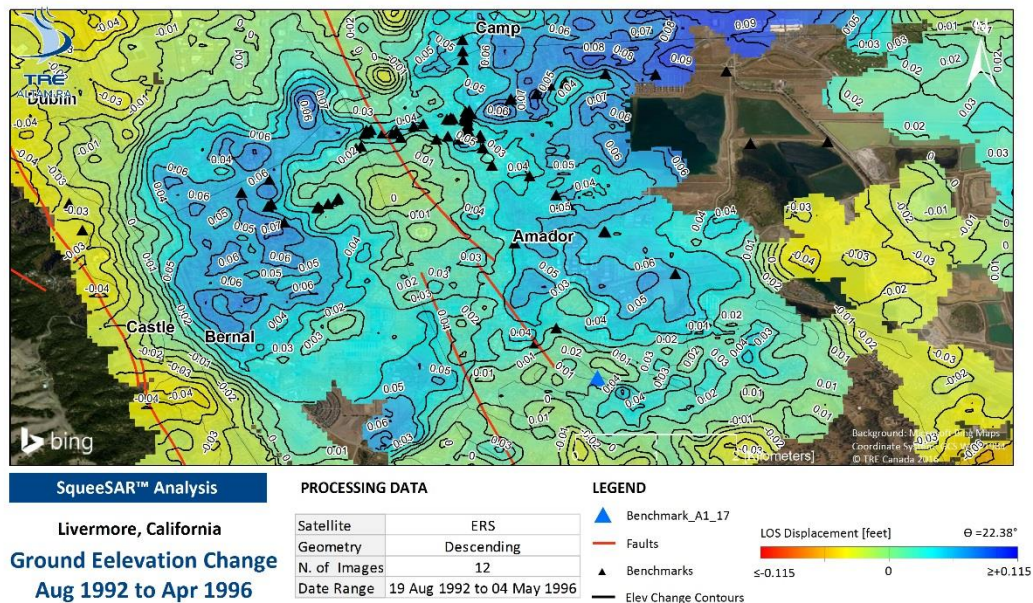


Figure 27: Ground elevation change map interpolated from ERS data (Aug 1992 to May 1996) over Pleasanton.

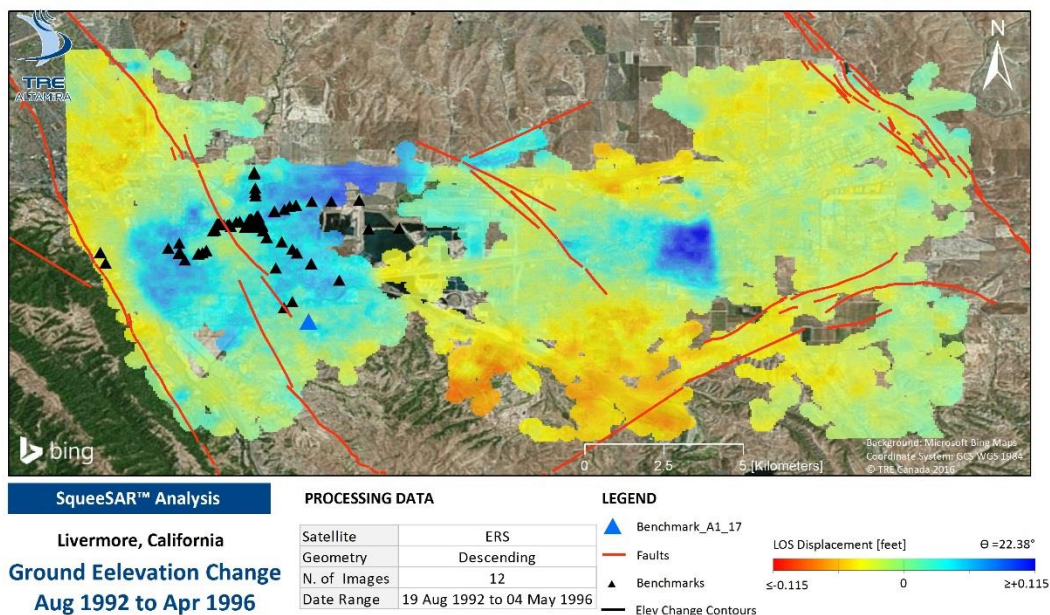


Figure 28: Ground elevation change map interpolated from ERS data (Aug 1992 to May 1996) over the entire AOI.

5. List of deliverables

The SqueeSAR™ data are delivered in shapefile format and “NAD 1983StatePlane California III US feet” coordinates (EPSG code: 2227). The shapefile of each elaboration contains details about the measurement points identified, including displacement rate, elevation, displacement, seasonal amplitude and quality indexes. The information associated within the database files are described in Table 4.

For each shapefile a Metadata file (.xml) and a Processing Report (.pdf) is attached, containing technical specifications of the analysis performed.

TRE-ALTAMIRA provides its Clients with a toolbar for ESRI® ArcGIS 10.X which allows the final users to easily load, visualize and analyze the SqueeSAR™ results. For set-up procedure and functionalities, see the attached manual *TRE_ToolbarSetup_5.0.pdf*.

The complete list of delivered data is reported in Table 5.

Please note that results can be also visualized and downloaded from the TREmaps web-based portal (<https://tremaps.treuropa.com>). SqueeSAR™ results are superimposed onto a Google Maps background and time-series can be loaded on mouse click. The access to the data is through a secure Client login (only authorised users will have access to the SqueeSAR™ results).

For TREmaps functionalities see: <http://treuropa.com/tremaps/getting-started>.

Field	Description
CODE	Measurement Point (MP) identification code
HEIGHT	Topographic Elevation [feet] referred to WGS84 ellipsoid
H_STDEV	Height standard deviation [feet]
VEL	MP displacement rate. Positive values correspond to motion <i>toward the satellite</i> ; negative values correspond to motion <i>away from the satellite</i> [in/year]
V_STDEV	Displacement rate standard deviation [in/year]
COHERENCE	Index varying between 0 and 1, related to the MP phase noise and to the capability of the motion model adopted to cope with the actual MP behaviour.
S_AMP_STD	Average seasonal amplitude standard deviation [in]
SEASON_PHS	Average seasonal phase [day]
EFF_AREA	This parameter represents the effective extension of the area [sq. ft.] covered by Distributed Scatterers (DS). For permanent scatterers (PS), its value is set to 0.
Dyyyymmdd	Series of columns that contain the displacement values of successive acquisitions relative to the first acquisition available. Displacement values are expressed in [in]

Table 4: Description of the fields contained in the database.

Product	File name
SqueeSAR ERS Descending (1992-2000)	LIVERMORE_ERS_T70_D_NAD83_I10283A2S
SqueeSAR ENV Descending (2006-2011)	LIVERMORE_ENVI_T70_D_NAD83_I10283A1S
SqueeSAR SNT Descending (2003-2010)	LIVERMORE_SNT_T42_D_NAD83_I10283A3S
Executive Report	Livermore Historical SqueeSAR_201609.pdf
Power point Presentation	Livermore_InSAR_results_GoTo_201608.pptx
ESRI® ArcGIS 10.1 Toolbar	TRE_Toolbar.esriAddIn
	TRE_Toolbar_Setup_5.0.pdf

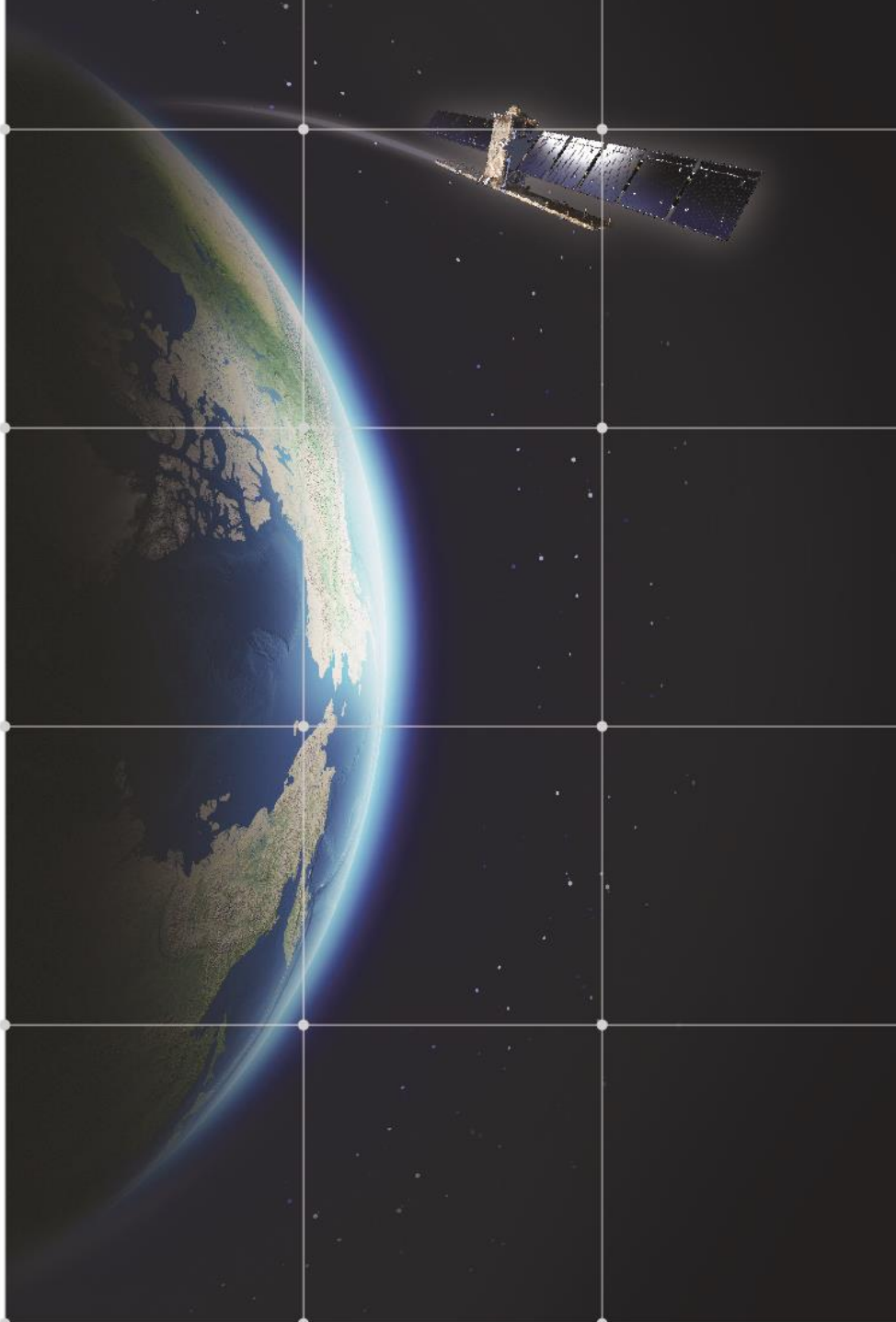
Table 5: Products delivered

6. Discussion & recommendations

Three SqueeSAR processings (ERS, ENV, and SNT) were carried out over the Livermore and Pleasanton area to measure ground deformation over a 24 year period (1992 to 2016). The results correlated well with topographic surface elevation measurements over portions of the same time span.

The precision of the measurements was in the order of ± 0.01 in/y for the deformation rate and $\pm 0.07''$ for seasonal displacement. The high spatial and temporal density of the SAR measurements allowed both long-term and seasonal ground movement to be characterized.

A second SNT satellite is due to become operational in September 2016, which could lead to a further increase in the image acquisition frequency, possibly even to a new image acquired every 6 days, over the Livermore – Pleasanton area. Annual processing of the data set would lead to accurate characterizations of ground movement both in time and space. Costs would be limited to data processing as SNT imagery is publicly available. A final consideration regards the use of imagery acquired from different orbits in space. This approach would allow Line-of-Sight data to be decomposed into vertical and east-west movement, thereby further characterizing ground deformation in the area and potentially allowing any tectonic movement to be accounted for.



**TRE
ALTAMIRA**
A CLS Group Company



MILAN

Ripa di Porta Ticinese, 79
20143 Milano - Italy
Tel. +39.02.4343.121
Fax +39.02.4343.1230

tre-altamira.com

BARCELONA

C/ Corsega, 381-387
E-08037 Barcelona Spain
Tel.: +34 93 183 57 50
Fax: +34 93 183 57 59

VANCOUVER

410 - 475 West Georgia Street
Vancouver, BC V6B 4M9 - Canada
Tel. +1.604.331.2512
Fax +1.604.331.2513