Playa del Rey, California

InSAR Ground Deformation Monitoring

Interim Report A

Ref.: RV-14524

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GEOSPATIAL SERVICES

SUBMITTED TO:

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EXECUTIVE SUMMARY

This report, Interim Report A, describes the results and methodology used to monitor as well as quantify potential ground deformation at the Southern California Gas Company (SoCalGas) Playa del Rey Gas Storage Field and surrounding areas in California using InSAR satellite radar interferometry for the December 2008 to June 2009 monitoring time period.

The RADARSAT-2 satellite passes over SoCalGas' Area of Interest (AOI) every 24 days at an elevation of approximately 500 miles. The acquired RADARSAT-2 imagery is being used for the generation of deformation maps over the AOI, two (2) of which are delivered to SoCalGas every 6 months. The accuracy of each deformation map is estimated to be in the order of 0.02 ft.

For this deliverable, Milestone 2, two (2) deformation products are produced from scheduled RADASAT-2 Ultra-Fine ascending radar imagery. The current deformation data produced from December 5, 2008 to June 15, 2009 time period are reviewed as part of this Milestone.

The following summarizes key features for this deliverable:

- Satellite radar data were scheduled for acquisition from December 2008 through to June 2009. For this deliverable, eight (8) ascending RADARSAT-2 Ultra-Fine ascending radar data were collected and analyzed.
- All available data are evaluated and the highest quality deformation maps are generated. The time periods are from December 5, 2008 to March 11, 2009 (Pair A) and March 11, 2009 to June 15, 2009 (Pair B).
- The delivered products are geo-referenced with a horizontal accuracy better than 65 ft. Areas of insufficient quality are masked out in the final products. The measurements in the AOI are of good quality.
- Observed deformation and uplift can be attributed to surface moisture in the area of interest. During the time period from December 2008 to March 2009, rainfall accumulation contributed to natural terrain expansion, hence uplift. Less rainfall occurred during the March 2009 to June 2009 time period, resulting in a

decrease in natural terrain moisture and consequently some deformation.

- The estimated precision for the Pair A vertical deformation product is 0.01 ft with a 95% confidence interval, while the estimated precision for Pair B vertical change product is 0.02 ft with a 95% confidence interval.
- Two (2) summation products are included showing the progressive change as imaged by the satellite over six (6) and twelve (12) months. The first, Pair C, is for the six (6) month time period from December 5, 2008 to June 15, 2009. For this period, masked areas are interpolated and common mask areas between the two (2) individual vertical deformation products are extracted and applied to the final summation product.
- The second summation product includes approximately one (1) year of monitoring from May 27, 2008 to June 15, 2009 (Pair D). This was derived by combining the previous and current time period summation products. Mask areas for this overall summation is an accumulation of all the previous masks.

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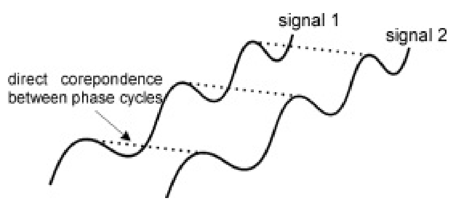
SYMBOLS, ACRONYMS AND DEFINITIONS

γ	**Coherence** Is the degree of similarity of the backscatter response, as measured by the SAR sensor, between corresponding ground cells in both SAR images of an InSAR pair.
ϕ	**Phase** When the sine wave starts to repeat itself (phase angle > 360 degrees), one cycle of phase has occurred. If we collect two separate images from exactly the same satellite position (same range), but at different times with nothing in the target area changing, one would expect the two sine waves from each image to be the same and in phase with each other (they would appear as one if at right-angles to the plane of the signal).  The phase difference is sensitive to both the viewing geometry and the height of the point above the reference surface
λ	**Wavelength** Electromagnetic radiation consists of an electrical field (E) which varies in magnitude in a direction perpendicular to the direction in which the radiation is traveling, and a magnetic field (M) oriented at right angles to the electrical field. Both these fields travel at the speed of light (c). Two characteristics of electromagnetic radiation are particularly important for understanding remote sensing. These are the wavelength and frequency. The wavelength is the length of one wave cycle, which can be measured as the distance between successive wave crests.

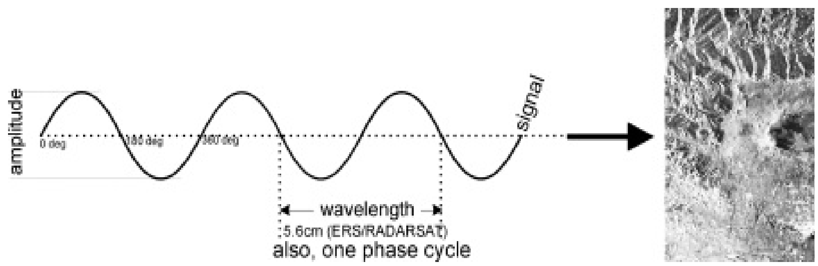
Wavelength and frequency are related by the following formula:

$$c = \lambda \nu$$

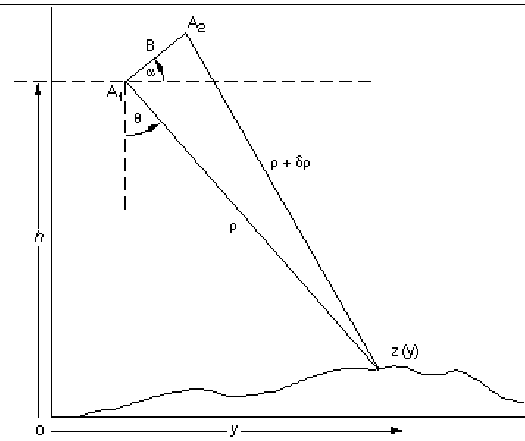
where:

λ = wavelength (m)
ν = frequency (cycles per second, Hz)
c = speed of light (3×10^8 m/s)

Therefore, the two are inversely related to each other. The shorter the wavelength, the higher the frequency. The longer the wavelength, the lower the frequency.



B	**Baseline** The perpendicular baseline (Bperp, or across-track separation between the two satellite positions) is the difference between the position of the satellite in pass 1 and the position of the satellite in pass 2 of an interferometric pair.
ρ	**Range** Consider two radar antennas, A1 and A2, simultaneously viewing the same surface and separated by a baseline vector B with length B and angle α with respect to horizontal. A1 is located at height h above some reference surface. The distance between A1 and the point on the ground being imaged is the range ρ, while $\rho+\delta\rho$ is the distance between A2 and the same point.



AOI	**Area of Interest**
DEM	**Digital Elevation Model** A digital elevation model is a digital representation of ground surface topography or terrain. Digital elevation models are gray scale images wherein the pixel values are actually elevation numbers. The pixels are also coordinated to world space (longitude and latitude), and each pixel represents some variable amount of that space (foot, meter, mile, etc.) depending on the purpose of the model and land area involved.
GSI	**MacDonald Dettwiler and Associates Geospatial Services Inc.**
InSAR	**Interferometric Synthetic Aperture Radar** SAR interferometry makes use of the phase information by subtracting the phase value in one image from that of the other, for the same point on the ground. This is, in effect, generating the interference between the two phase signals and is the basis of interferometry.
LOS	**Line-of-Sight** Line-of-sight between sensor and observed pixel in the terrain.
MDA	**MacDonald, Dettwiler and Associates Ltd.**
RADAR	**Radio Detection and Ranging** RADAR is the acronym for **RA**dio **D**etection **A**nd **R**anging, which essentially characterizes the function and operation of

	a radar sensor. It is the most common form of imaging active microwave sensors is RADAR. The sensor transmits a microwave (radio) signal towards the target and detects the backscattered portion of the signal. The strength of the backscattered signal is measured to discriminate between different targets and the time delay between the transmitted and reflected signals determines the distance (or range) to the target.
SAR	**Synthetic Aperture Radar** The Radar sends out a pulse of radio waves which bounces off the object to be depicted. The scattered pulses then return to the radar, where they are captured by the receiving antenna. The antenna is the radar's aperture, or its opening on the world. SAR antennas are a type of radar antenna designed to take advantage of their satellite's movement, thus creating a "synthetic" aperture or opening.
SRTM	**Shuttle Radar Topography Mission**
	Georeferencing Georeferencing is the process of assigning pixels within an image (raster), with ground co-ordinates, e.g., latitude and longitude. A georeferenced image may then be transformed to match a particular map projection system where each pixel represents a specific location and distance on the ground. Before georeferencing, SAR images consist of arrays of pixels fixed into a geometry corresponding to the acquisition parameters of the satellite–the image is said to be in slant range. The act of georeferencing and transforming into a map projection puts the image into ground range.
	Phase Noise Differential phase noise is caused by changes in microwave reflective properties over time. They result in a reduced ability to use the differential phase for accurate measurements of changes in line of sight.
	Temporal Decorrelation Changes in the Earth’s surface that make it difficult to compare “before” and “after” images. The problem of low coherence regions can be exacerbated as the time of separation is increased between two scenes of an InSAR pair.

1 INTERIM REPORT A OBJECTIVE

The objective of this report, Interim Report A, is to provide SoCalGas with measurements of the deformation that occurred within the project's AOI using Conventional InSAR monitoring from December 2008 to June 2009. Eight (8) RADARSAT-2 Ultra-Fine ascending satellite data, acquired for this time period were examined. For this Milestone, two (2) conventional InSAR deformation maps quantifying movement are generated.

This deliverable pertains to the second deliverable, Milestone 2, of a five (5) year InSAR Monitoring Program, as described in Section 2.1 Table 1 Milestone Deliverables of the Master Document.

1.1 REPORT ORGANIZATION

This report is organized as follows:

- Section 1 provides the introduction and report organization. This section also describes the AOI and the available data for the current monitoring time period.
- Section 2 describes the results for the two (2) deformation maps as well as the two (2) summation products.
- Section 3 provides a summary and conclusions.
- Appendix A lists the deliverables.

1.2 STUDY AREA

The Playa del Rey Gas Storage Field AOI and surrounding area, in Los Angeles, California, is outlined by the red polygon as seen in **Error! Reference source not found.**. The corner coordinates for the polygon are approximately given by a rectangle with coordinates 34º 01' 58"N 118º 28' 5"W and 33º 56' 56"N 118º 20' 4"W.

Figure 1: Playa del Rey AOI and surrounding area in Los Angeles, as outlined by red polygon (radar amplitude image).

1.3 DATA SELECTION

The RADARSAT-2 Ultra-Fine data used to generate the deliverables for the December 2008 to June 2009 time period are listed in Table 1 below.

Table 1: RADARSAT-2 Ultra-Fine data acquired over Playa del Rey Gas Storage Field

Acquisition #	Acquisition Date	Orbit Number	Comments
1	Dec-5-08	5095	Acquired
2	Dec-29-08	5438	Acquired
3	Jan-22-09	5781	Acquired
4	Mar-11-09	6467	Acquired
5	Apr-4-09	6810	Acquired
6	Apr-28-09	7153	Acquired
7	May-22-09	7496	Acquired
8	Jun-15-09	7839	Acquired

The two (2) InSAR deformation maps that were created are listed in Table 2. On these dates the SAR data were of best quality with suitable baselines. These two (2) maps are generated using the March 11, 2009 acquisition as the shared data, which allows for a comparison between them

Table 2: Selected RADARSAT-2 data for the InSAR analysis. (The pairing numbers refer to the acquisition number from Table 1)

Interferogram Pair	Acquisition Date Master	Slave	Perpendicular Baseline (meters)
A (1-4)	Dec-5-08	Mar-11-09	93
B (4-8)	Mar-11-09	Jun-15-09	126

In addition, two (2) summation maps are generated. These provide an improvement in precision by summing the results of the two maps. Pair C is the summation from December 5, 2008 to March 11, 2009 and from March 11, 2009 to June 15, 2009. Pair D is summation from May 27, 2008 to June 15, 2009. For this product, the summation product delivered in the first deliverable is added to the summation product of the current deliverable (Pair C). Masked areas, for this product, are the summation of the two periods.

2 RESULTS – INTERIM REPORT A

Following the analysis of all available data, by evaluating all sequential combinations, two (2) interferometric Pairs are selected for the generation of deformation products:

- Pair A for the time period between December 5, 2008 to March 11, 2009 (96 days)
- Pair B for the time period between March 11, 2009 to June 15, 2009 (96 days)

These data are selected because the generated interferograms are the best at these dates and are least affected by noise and the DEM error. A mask is applied in incoherent areas. The root-mean-square of the observed values in the deformation map is indicative of the precision of the deformation map. To obtain a 95% confidence interval a factor of two is used. Table 3 and Table 4 show the summary of the estimation of noise level for Pairs A and B, respectively.

Table 3: Summary of Pair A

Date	Time Span	Noise Level standard deviation [ft]	95% Confidence interval [ft]
Dec-5-08 to Mar-11-09	96 days	0.0064	0.0128

Table 4: Summary of Pair B

Date	Time Span	Noise Level standard deviation [ft]	95% Confidence interval [ft]
Mar-11-09 to Jun-15-09	96 days	0.0096	0.0192

The following sections present the results for both Pairs A and B.

Additionally, summation products, Pair C and Pair D, have been created and are presented in this report.

2.1 PAIR A – DECEMBER 5, 2008 TO MARCH 11, 2009

The vertical deformation in the Playa del Rey Gas Storage Field is observed for the time period between December 5, 2008 and March 11, 2009.

In order to extract reliable information from the generated deformation products, a low coherence mask is generated and applied to the deformation map. This mask is created by threshholding the coherence image. Coherence (γ) values, $\gamma < 0.15$, are considered areas of low coherence and are masked out with values set to -999 (NODATA).

Uplift is observed in the Playa del Rey Gas Storage Field AOI, as can be seen from the vertical deformation product shown in Figure 2. This uplift could be attributed to surface moisture due to rainfall. As shown in Table 5, historical weather data for the Los Angeles airport, rainfall amounts from December to March could be attributed to uplift in the Playa del Rey Gas Storage Field. A color representation is shown in Figure 3 and Figure
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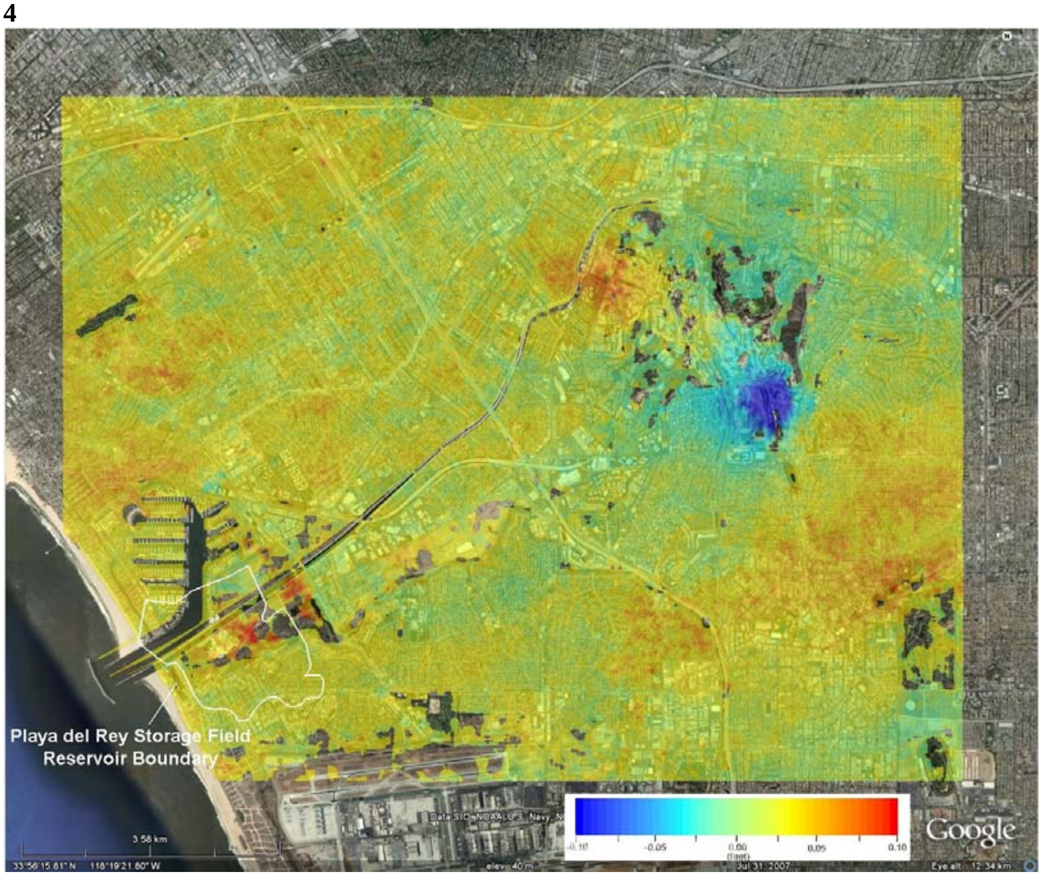

Figure 4, of the final product after masking areas that contain noise. The estimated precision for Pair A is within ±0.01 ft with a 95% confidence interval.

Table 5: Rainfall accumulation per month at the Los Angeles Airport (LAX). Source: National Weather Service

Month	Monthly Precipitation [inches]
December 2008	2.51
January 2009	0.51
February 2009	3.41
March 2009	0.05
April 2009	Trace
May 2009	Trace
June 2009	0.15

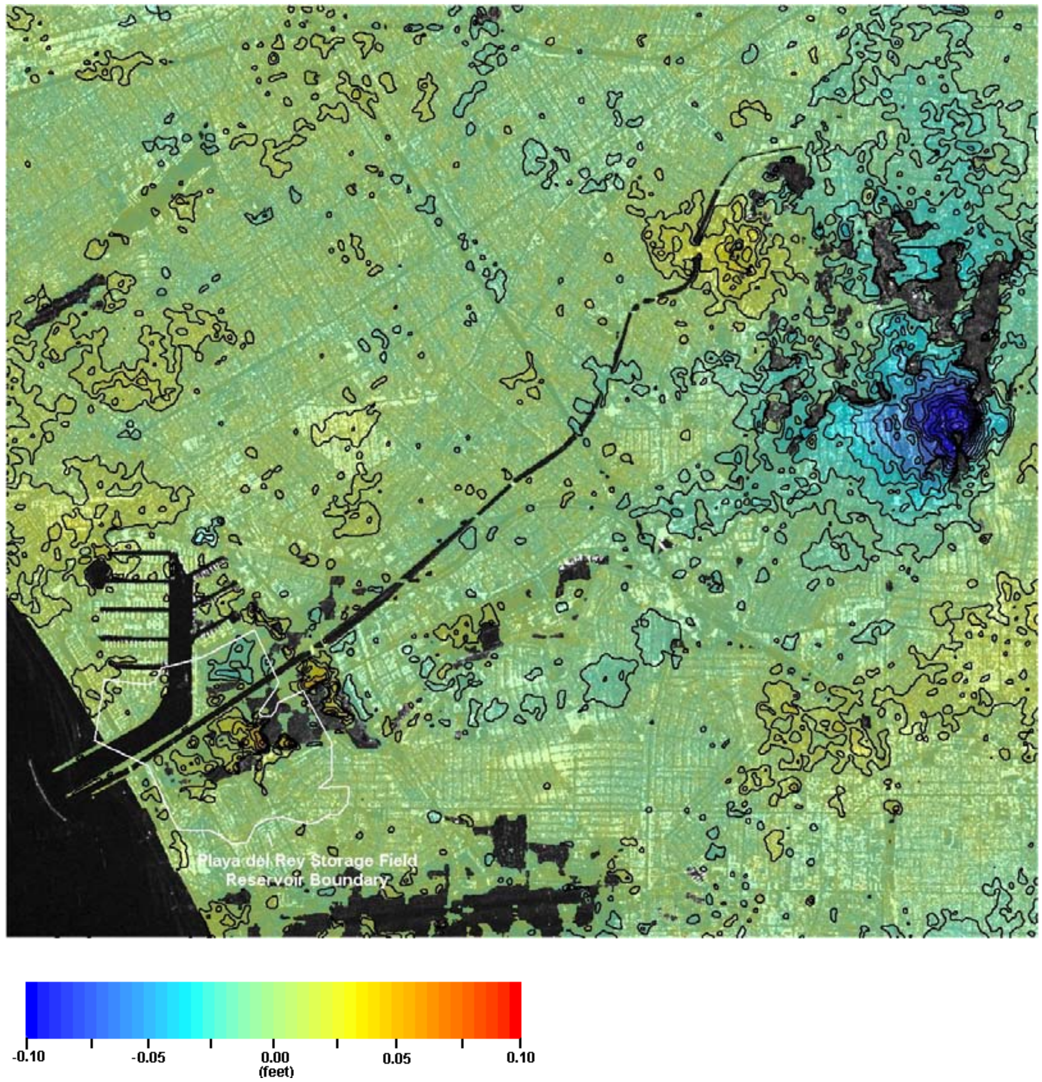

Figure 2: Zoom-in of AOI vertical deformation product for time period December 5, 2008 to March 11, 2009 with 0.01 ft contours.

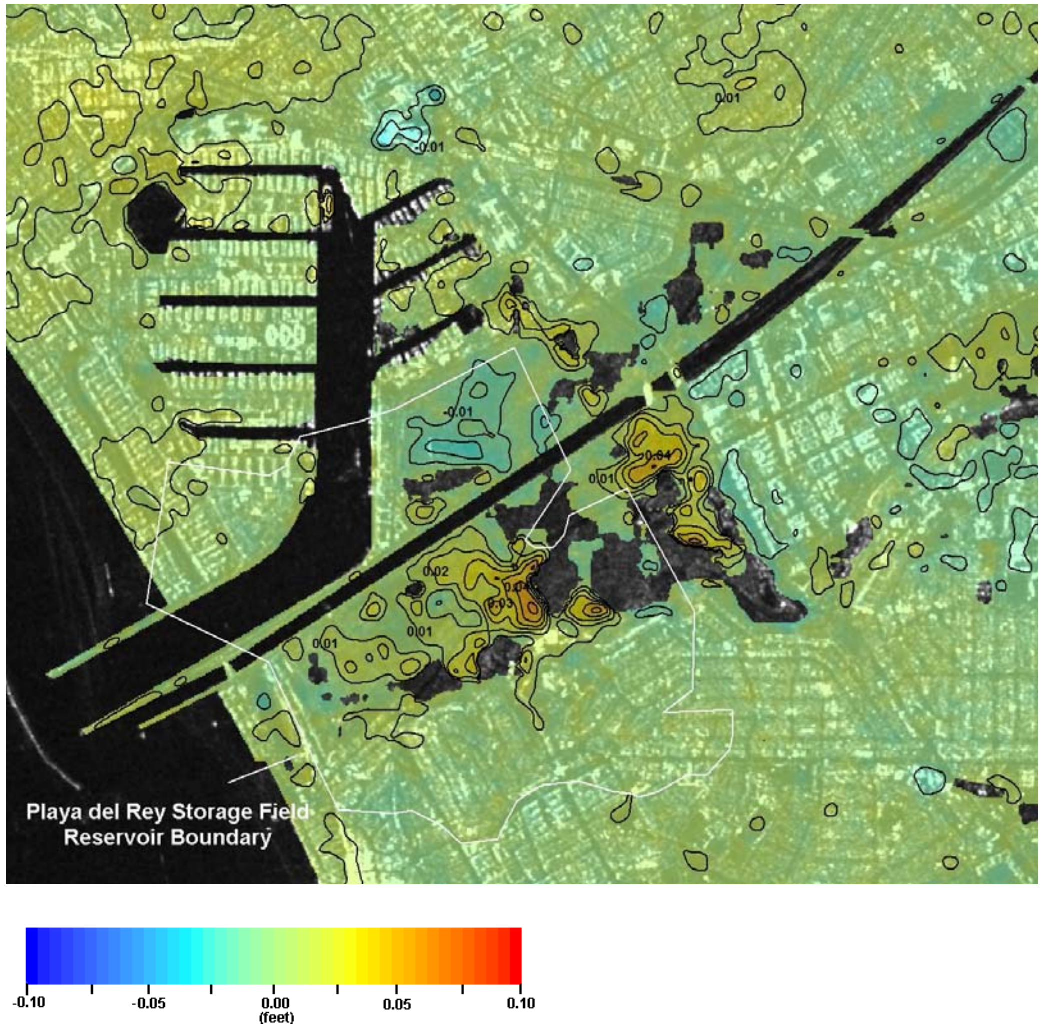

Figure 3: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the vertical deformation product from December 5, 2008 to March 11, 2009, superimposed onto SAR image with 0.01 ft contours.

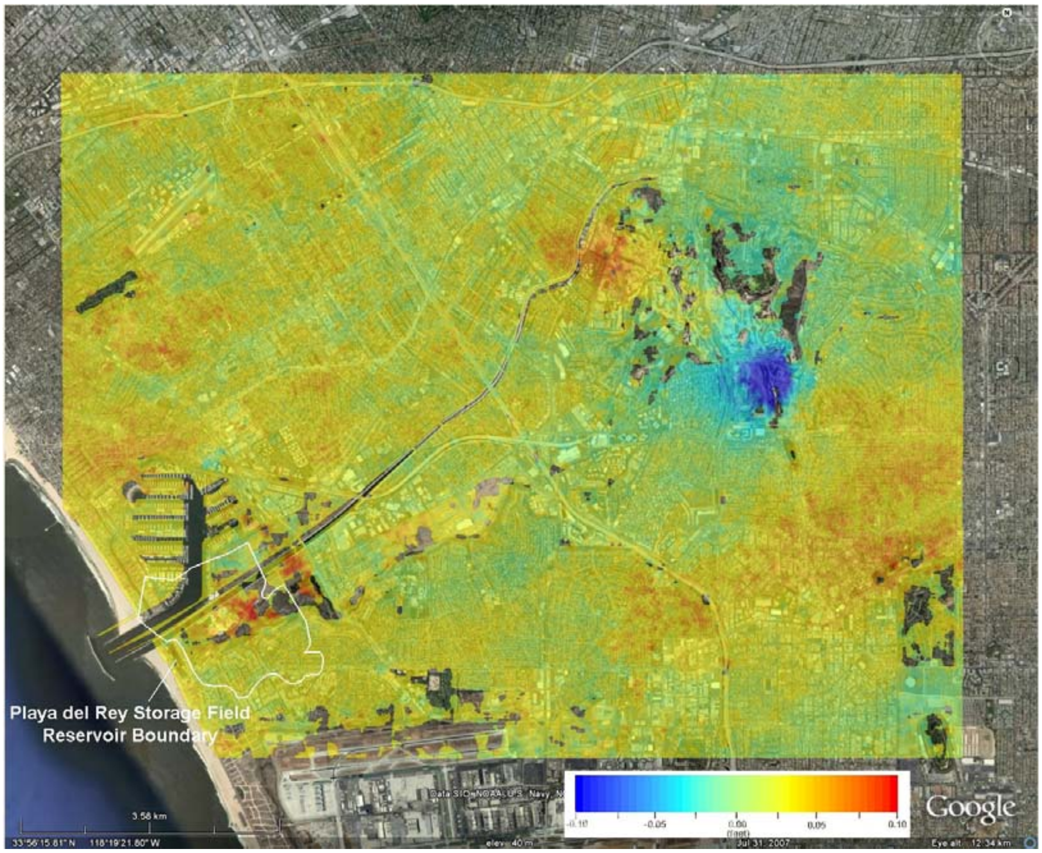

Figure 4: Colour representation of the vertical deformation product from December 5, 2008 to March 11, 2009 superimposed onto Google Earth without contours.

2.2 PAIR B – MARCH 11, 2009 TO JUNE 15, 3009

The deformation in the Playa del Rey Gas Storage Field is observed for the time period between March 11, 2009 and June 15, 2009.

In order to extract reliable information from the generated deformation products, a low coherence mask is generated and applied to the deformation map. This mask is created by threshholding the coherence image. Coherence (γ) values, $\gamma < 0.15$, are considered areas of low coherence and are masked out with values set to -999 (NODATA).

Deformation is observed in the Playa del Rey Gas Storage Field AOI, as can be seen from the vertical deformation product shown in Figure 5**.** This subsidence can be attributed to lack of rainfall during the period from March to June, as shown in Table 5, historical weather data for the Los Angeles airport. Figure 6 and Figure 7 present a color representation of the final product after masking areas that contain noise. The estimated precision for Pair B is within ±0.02 ft with a 95% confidence interval.

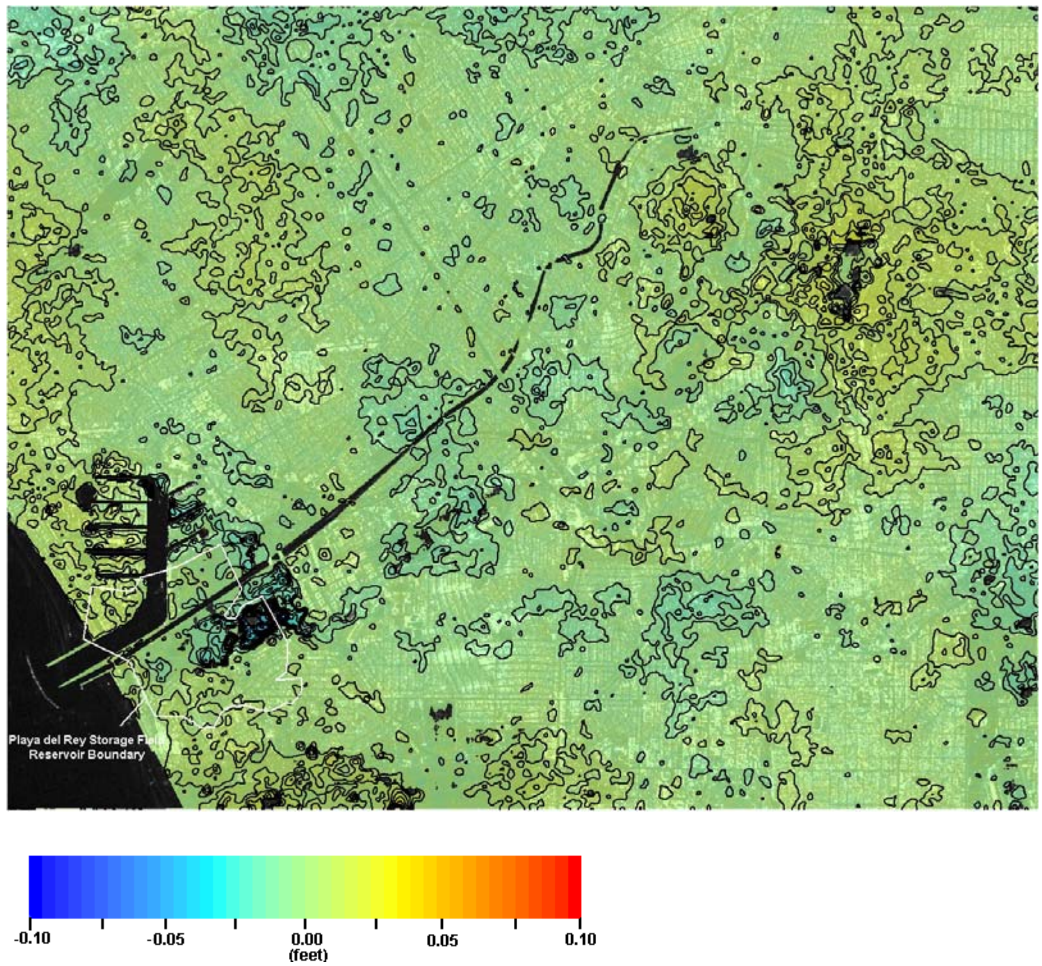

Figure 5: Zoom-in of AOI vertical deformation product for time period March 11, 2009 to June 15, 2009 with 0.01 ft contours.

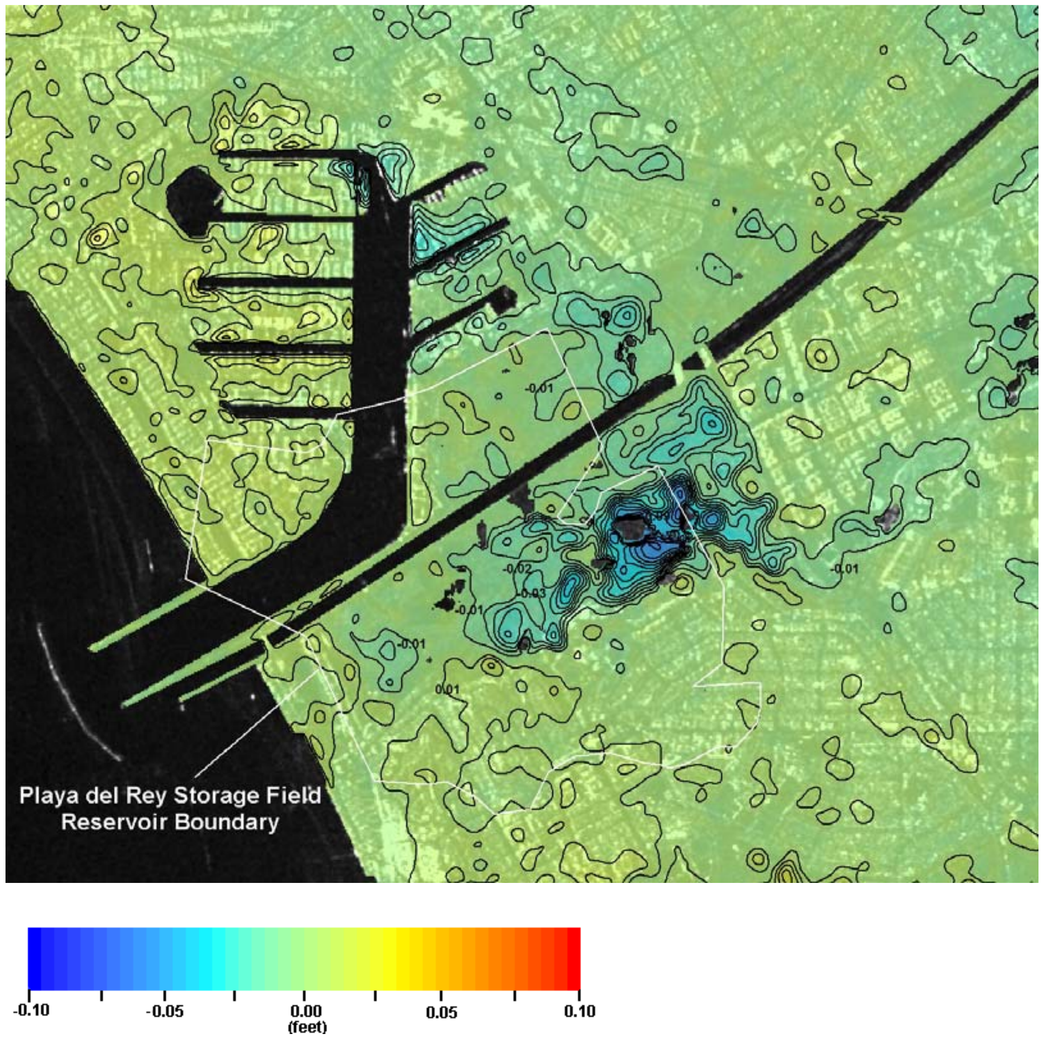

Figure 6: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the vertical deformation product from March 11, 2009 to June 15, 2009 superimposed onto SAR image with 0.01 ft contours.

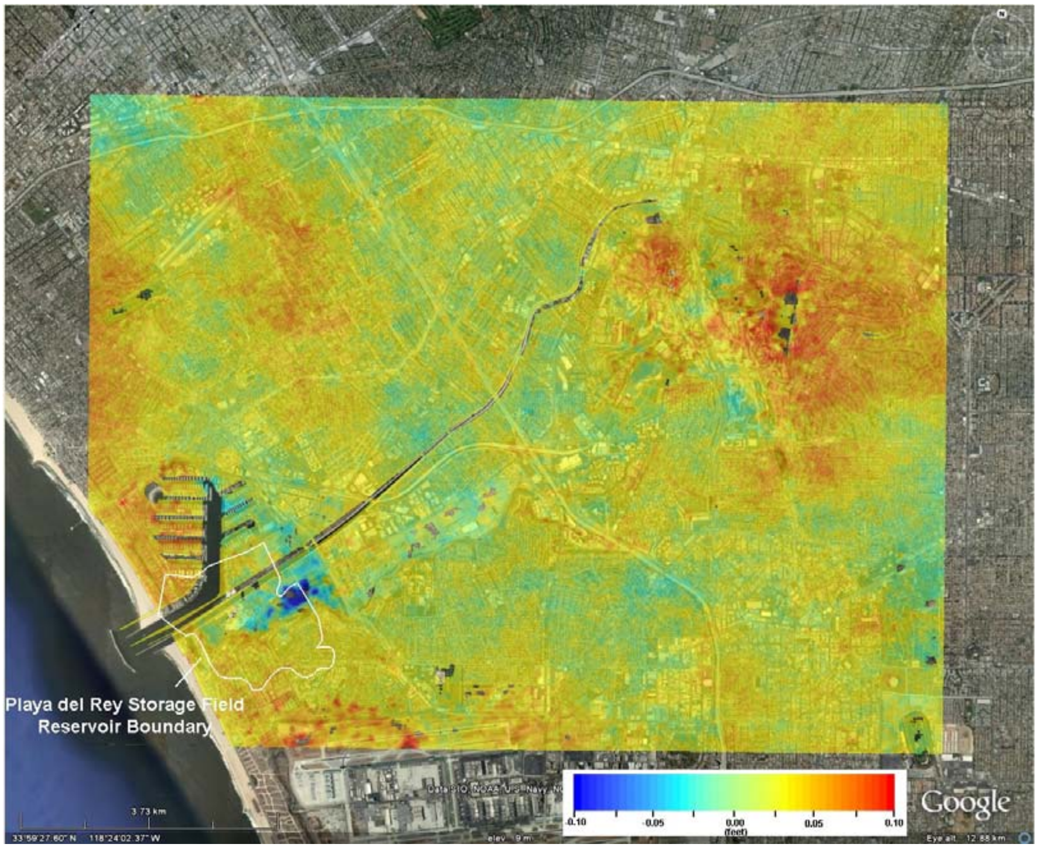

Figure 7: Colour representation of the vertical deformation product from March 11, 2009 to June 15, 2009 superimposed onto Google Earth without contours.

2.3 PAIR C – SUMMATION DECEMBER 5, 2008 TO JUNE 15, 2009

Figure 8 shows the summation of the individually estimated deformation results during the two (2) time periods (December 2008 to March 2009 and March 2009 to June 2009). This is a better estimate of the actual deformation that occurred in this time frame because independent noise in the two individual deformation maps is summed.

In particular, atmospheric effects that contribute to noise are independent in the two maps and minimized by taking the average. From Figure 8, Figure 9 and Figure 10, the averaged colour representation of the maps, there is a relatively small amount of deformation occurring in the Playa del Rey Gas Storage Field AOI, which could be attributed to natural terrain expansion, i.e. moisture in the ground.

Subsidence is observed however over an area situated between Windsor Hills and Ladera Heights, center coordinate 33º 59' 46"N 118º 21' 45"W. Subsidence in this area is in the order of 0.07 – 0.12 ft as shown in Figure 11 to Figure 13.

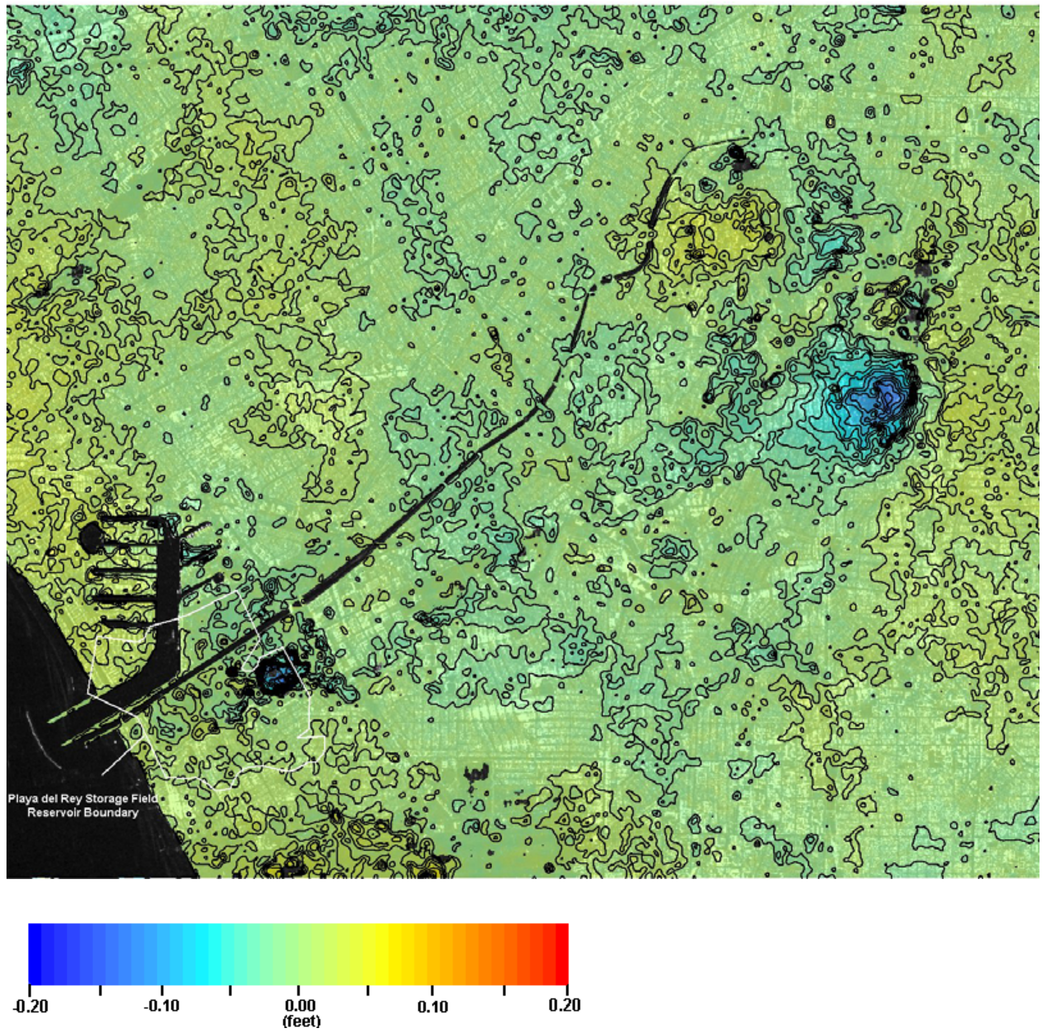

Figure 8: Zoom-in of the Playa del Rey Gas Storage Field AOI. Summation of the vertical deformation products from December 5, 2008 to June 15, 2009 with 0.01 ft contours superimposed on SAR image.

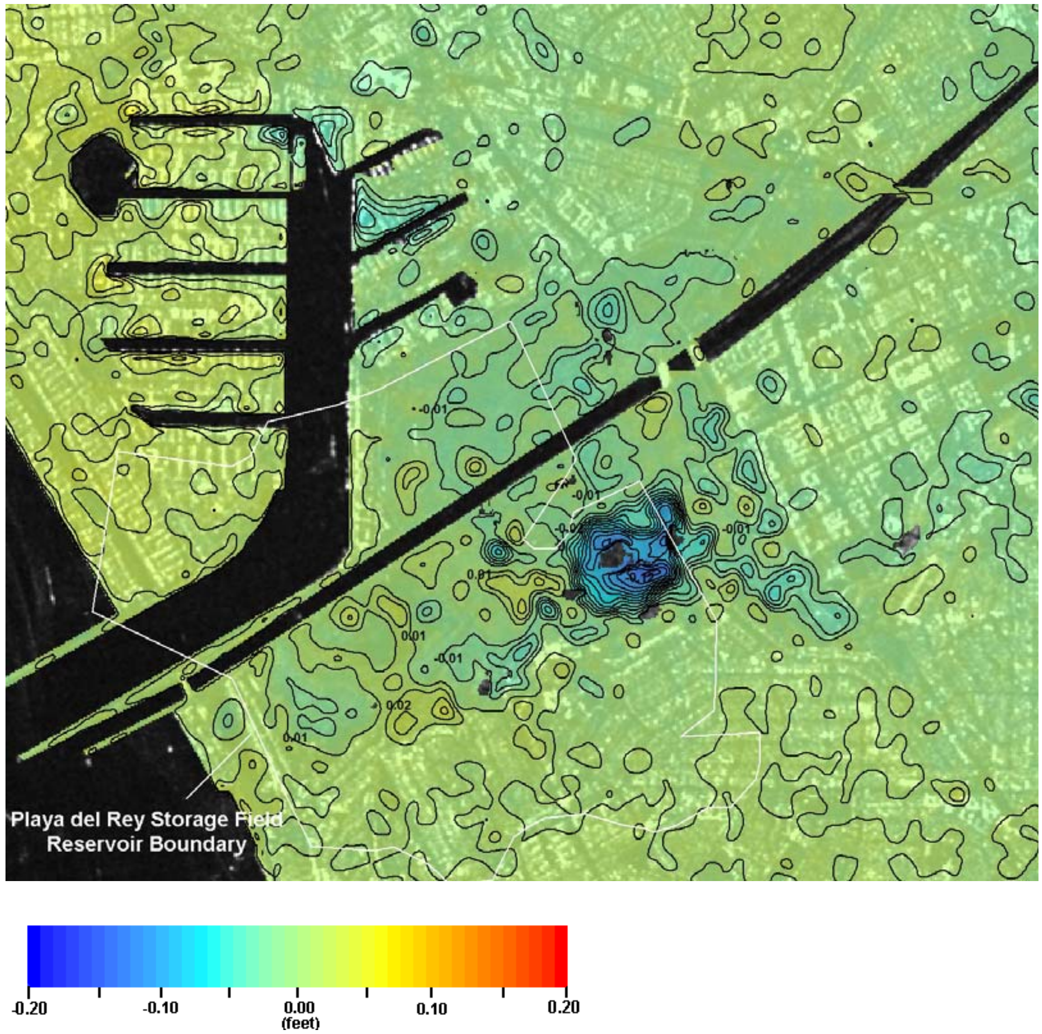

Figure 9: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the summation of vertical deformation products from December 5, 2008 to June 15, 2009 superimposed onto SAR image with 0.01 ft contours.

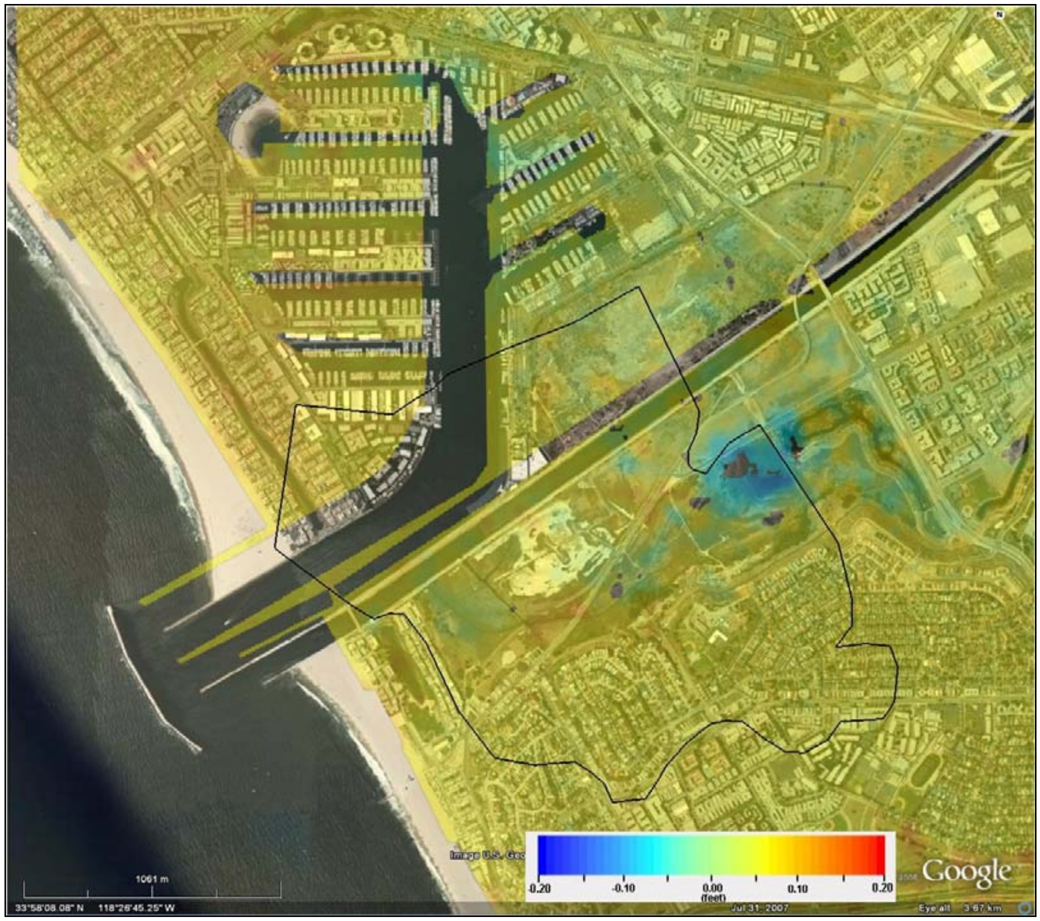

Figure 10: Zoom-in of the summation vertical deformation products from December 5, 2008 to June 15, 2009 superimposed onto Google Earth without contours.

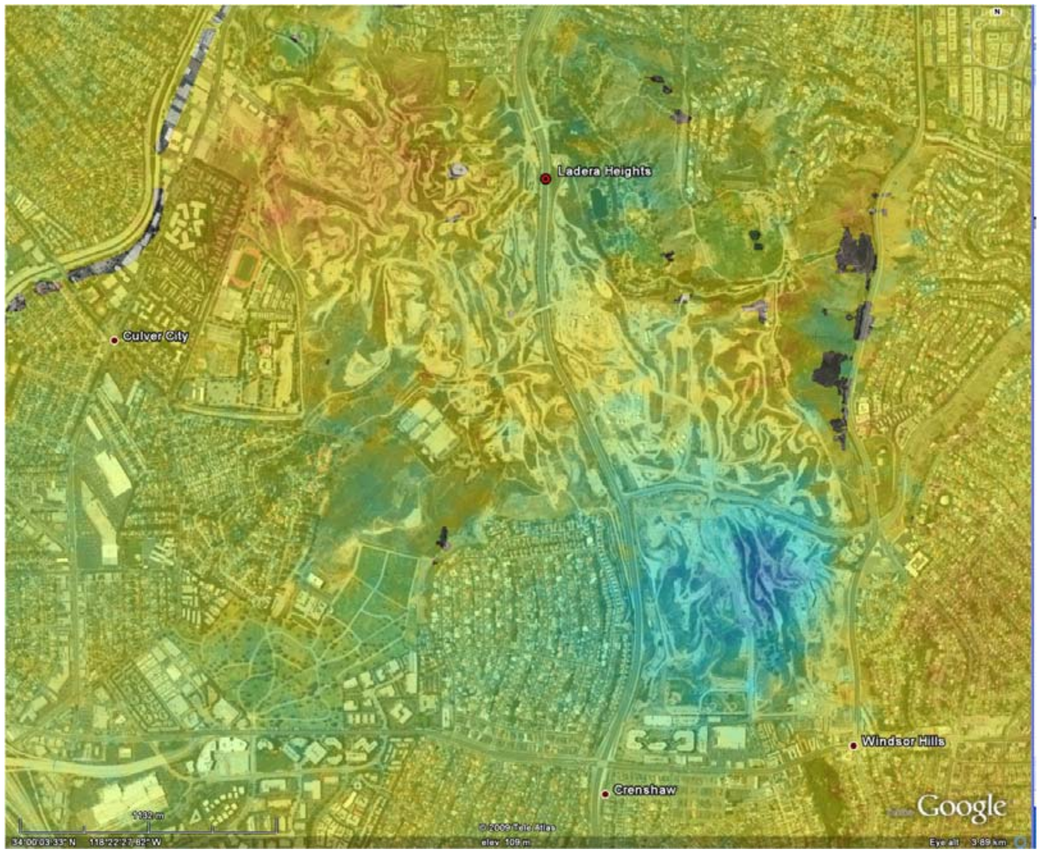

Figure 11: Zoom-in view showing vertical deformation from December 5, 2008 to June 15, 2009 of area between Culver City, Ladera Heights and Windsor Hills without contours.

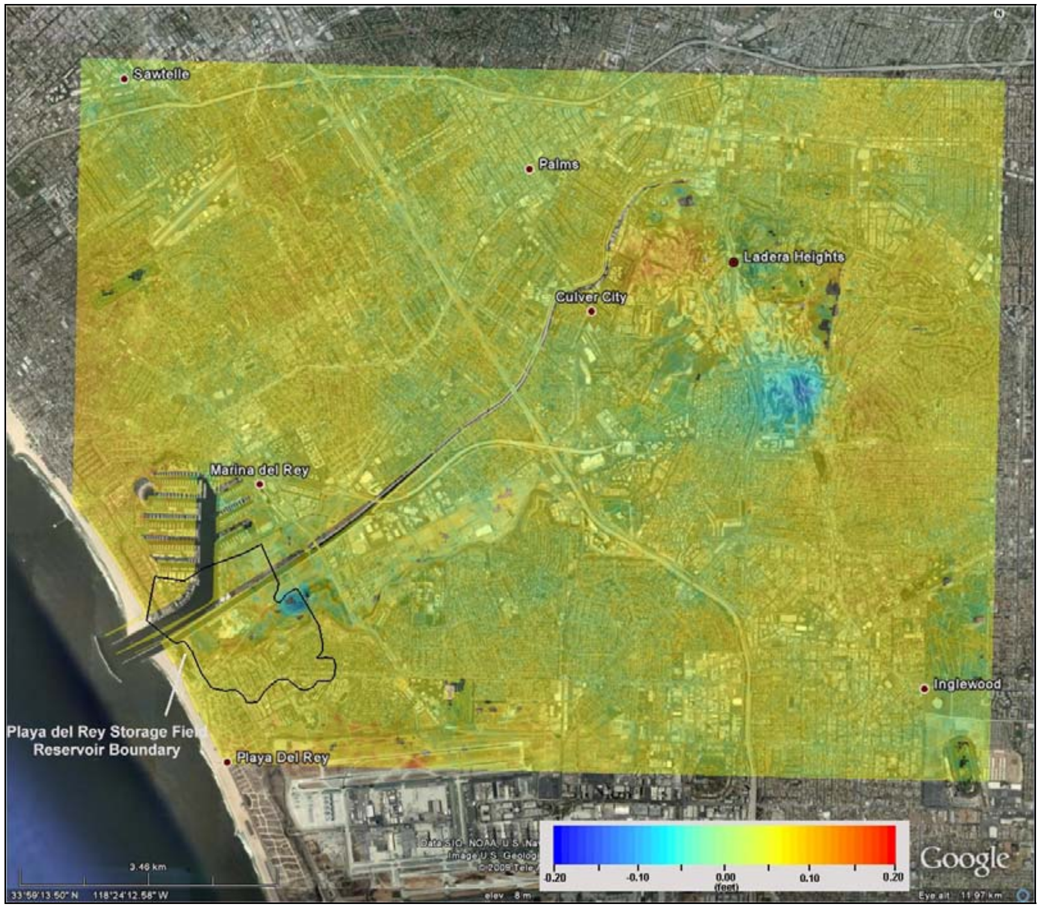

Figure 12: Colour representation of the summation of vertical deformation from December 5, 2008 to June 15, 2009 superimposed onto Google Earth without contours.

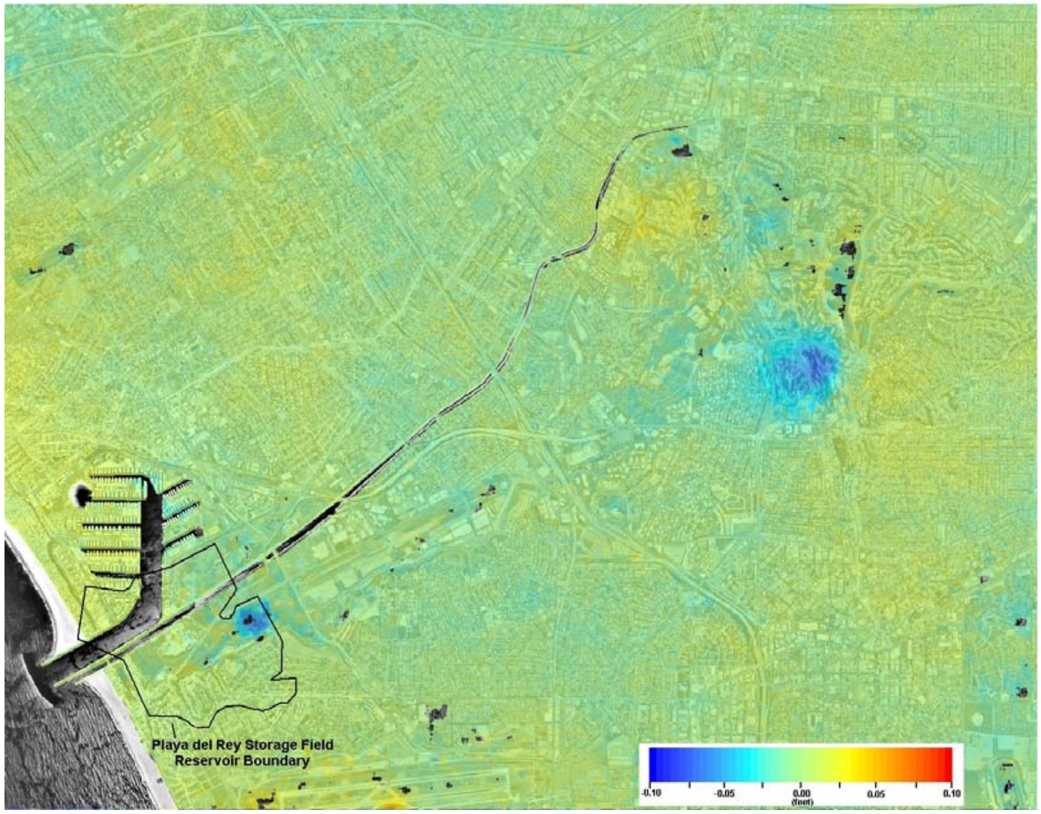

Figure 13: Zoom-in of the summation of vertical deformation products where blue represents subsidence and red represents uplift from December 5, 2008 to June 15 2009 without contours.

2.4 PAIR D – SUMMATION MAY 27, 2008 TO JUNE 15, 2009

Figure 14 shows the summation of the individually estimated deformation results starting May 27, 2008 (May to August 2008, August 2008 to December 2008, December 2008 to March 2009 and March 2009 to June 2009). From Figure 14, Figure 15 and Figure 16, the averaged colour representation of the maps, there is deformation occurring in the Playa del Rey Gas Storage Field AOI. This result could be attributed to natural terrain expansion during the December 2008 to March 2009 period.

Subsidence is observed over an area situated between Ladera Heights and Windsor Hills, center coordinate 33º 59’ 40”N 118º 21’ 48”W. Subsidence in this area is in the order of 0.05 – 0.17 ft as shown in Figure 17 to Figure 19.

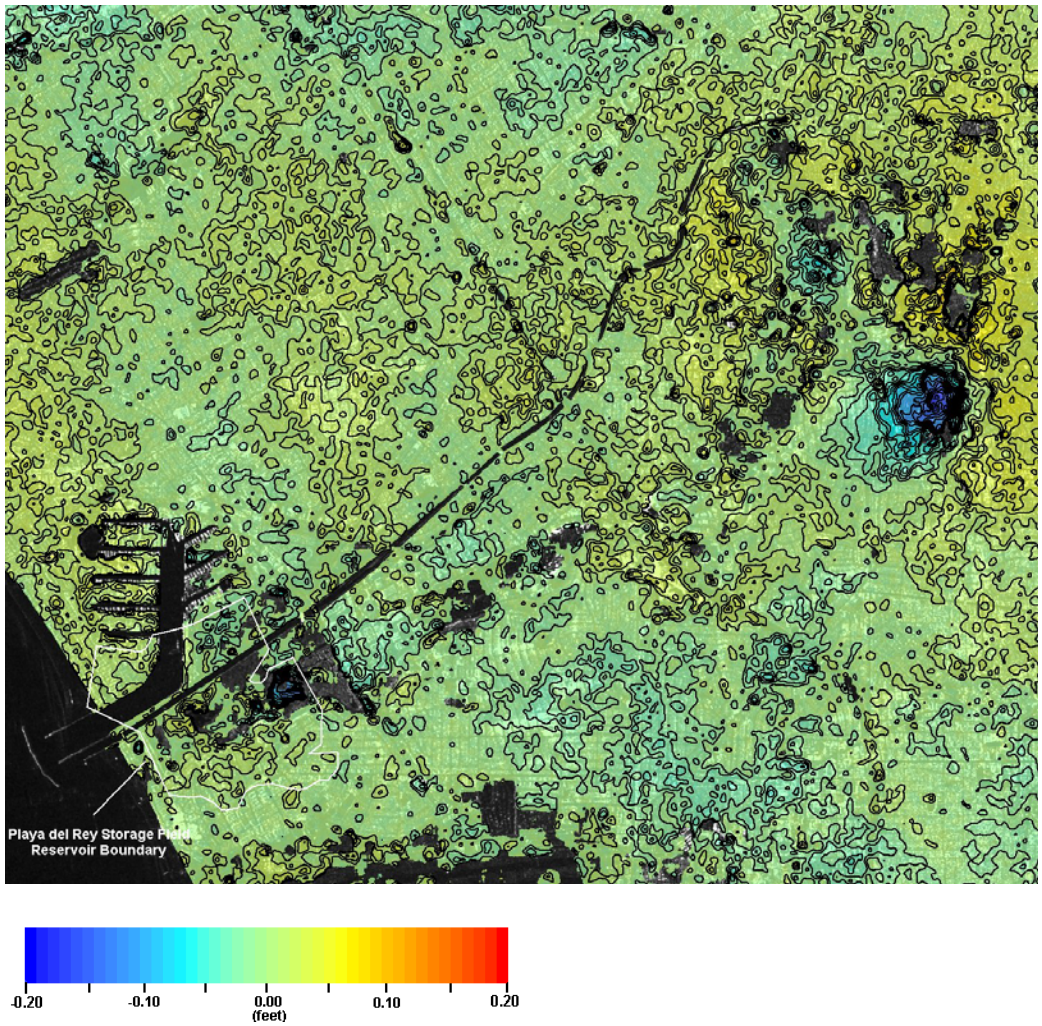

Figure 14: Zoom-in of Playa del Rey Gas Storage Field AOI. Summation of the vertical deformation from May 27, 2008 to June 15, 2009 with 0.01ft contours superimposed on SAR image.

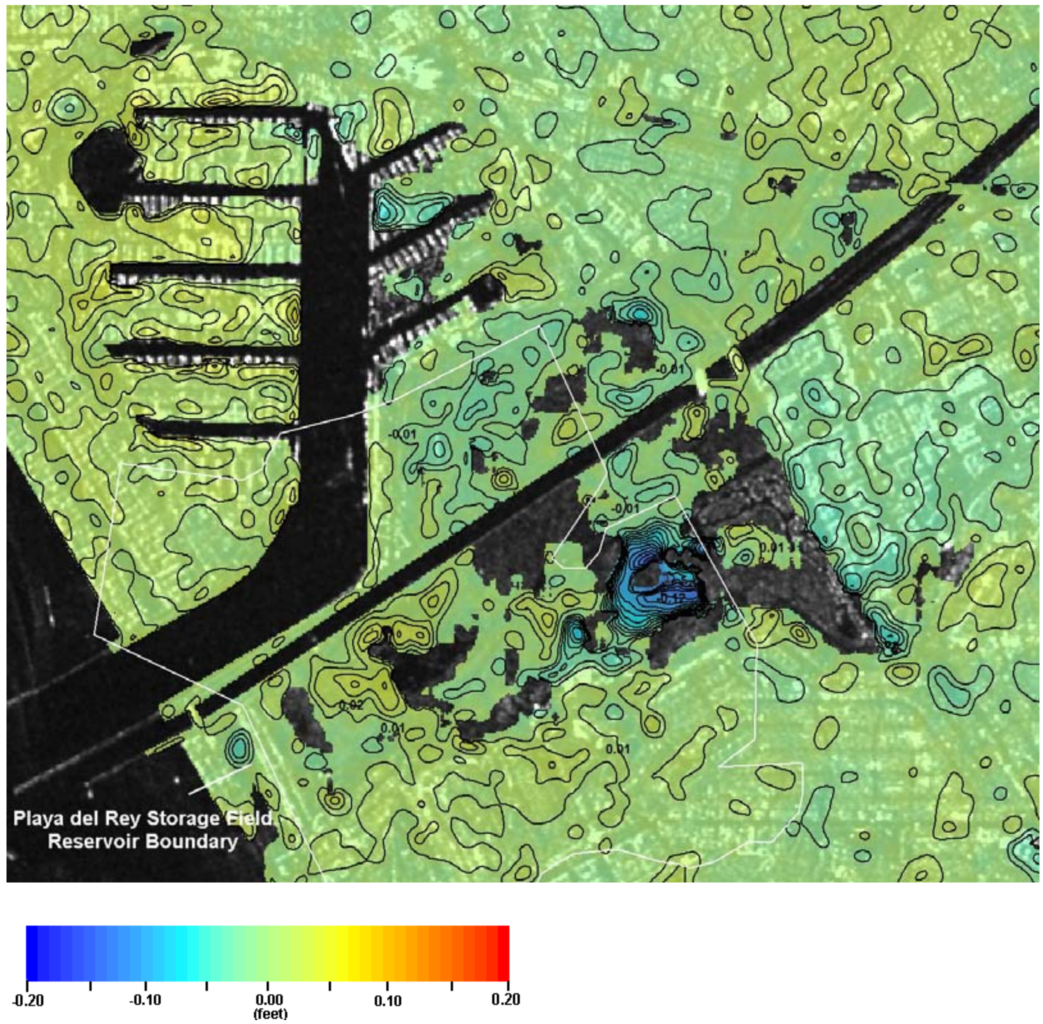

Figure 15: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the summation of vertical deformation from May 27, 2008 to June 15, 2009 superimposed onto SAR image with 0.01ft contours.

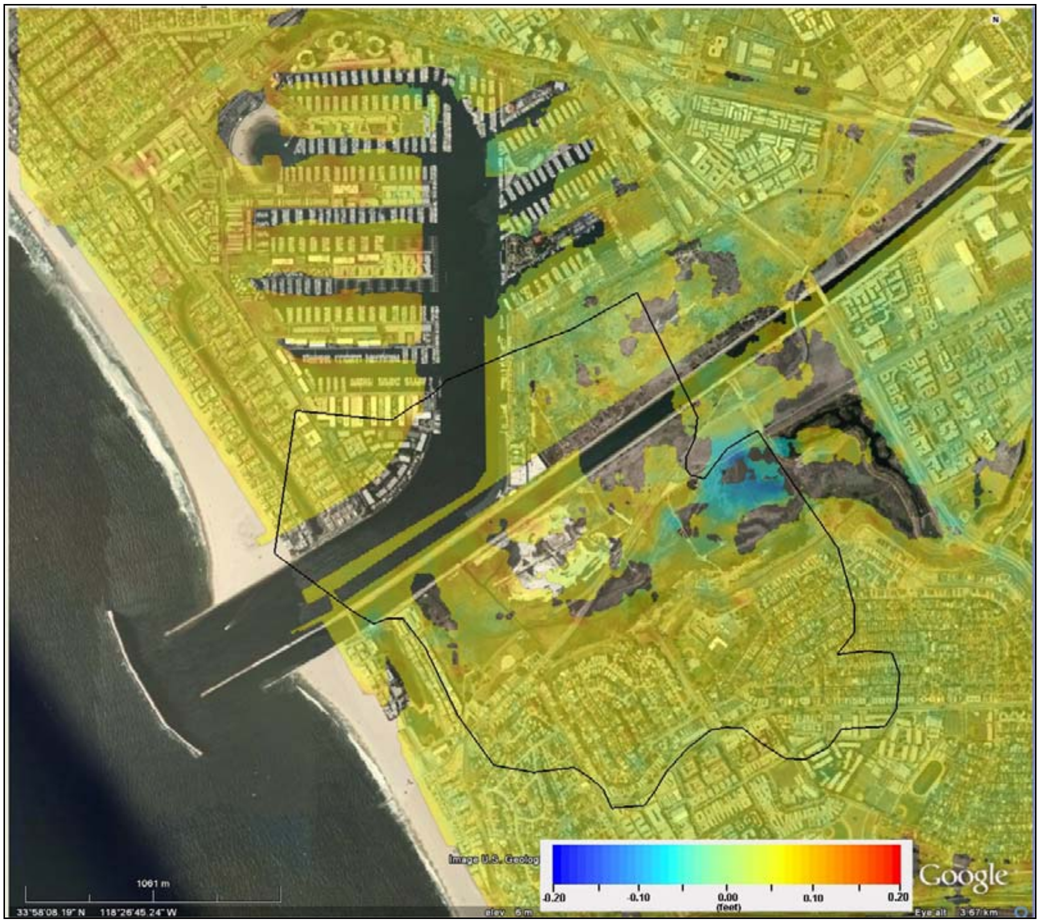

Figure 16: Zoom-in of the summation vertical deformation superimposed onto Google Earth from May 27, 2008 to June 15, 2009 without contours.

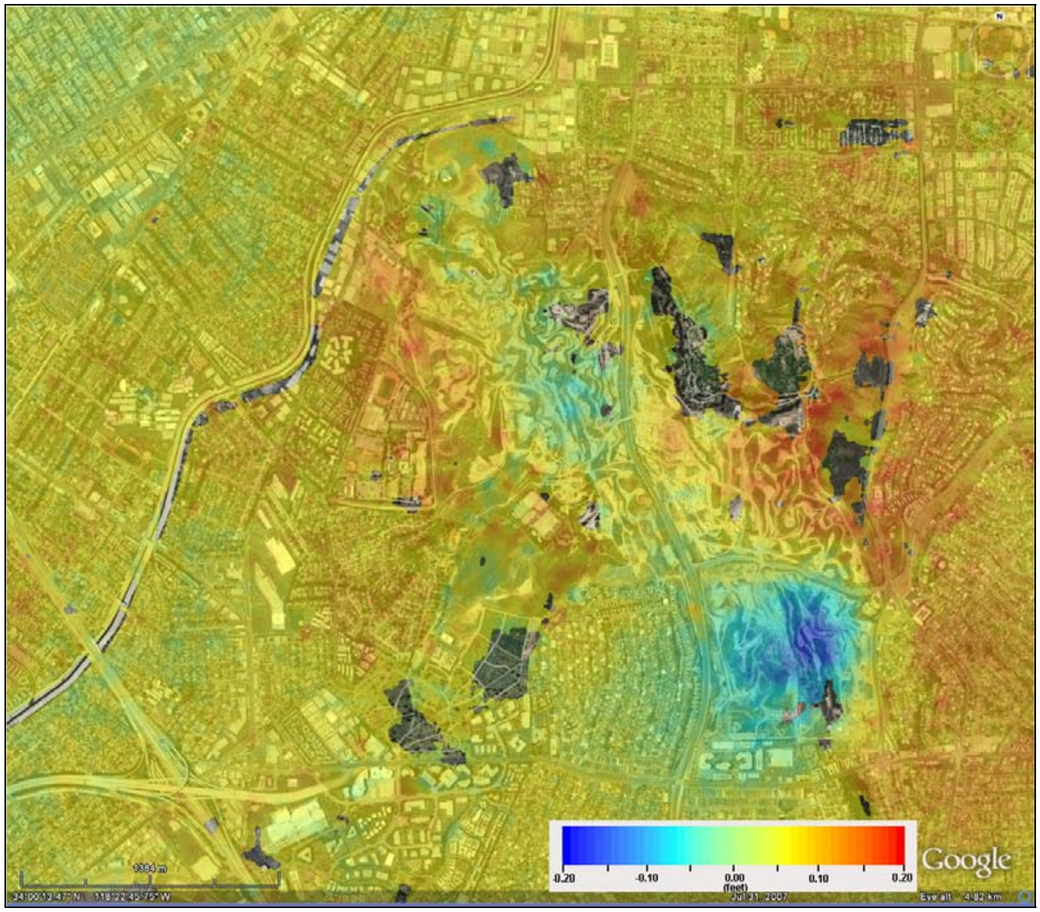

Figure 17: Zoom-in of the colour representation of the summation of the vertical deformation between Culver City, Ladera Heights and Windsor Hills superimposed onto Google Earth from May 27, 2008 to June 15 2009 without contours.

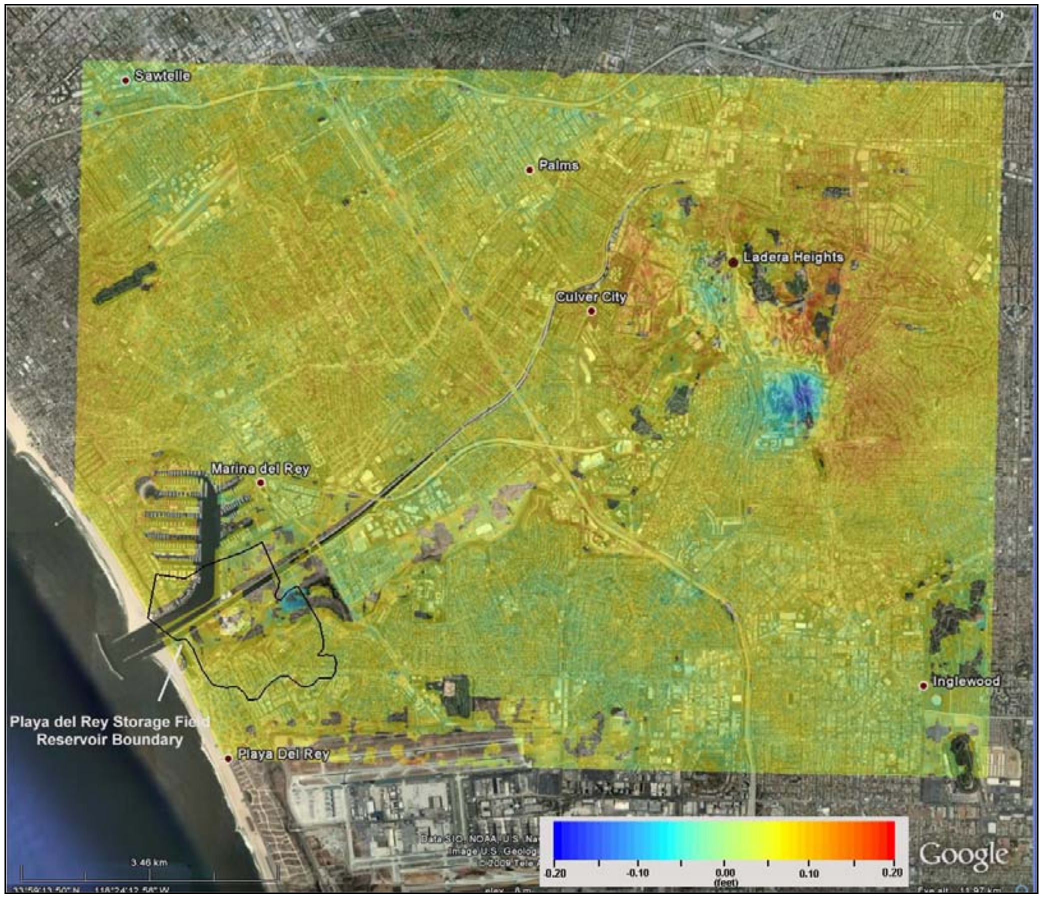

Figure 18: Zoom-in of the colour representation of the summation of vertical deformation from May 27, 2008 to June 15, 2009 superimposed onto Google Earth without contours.

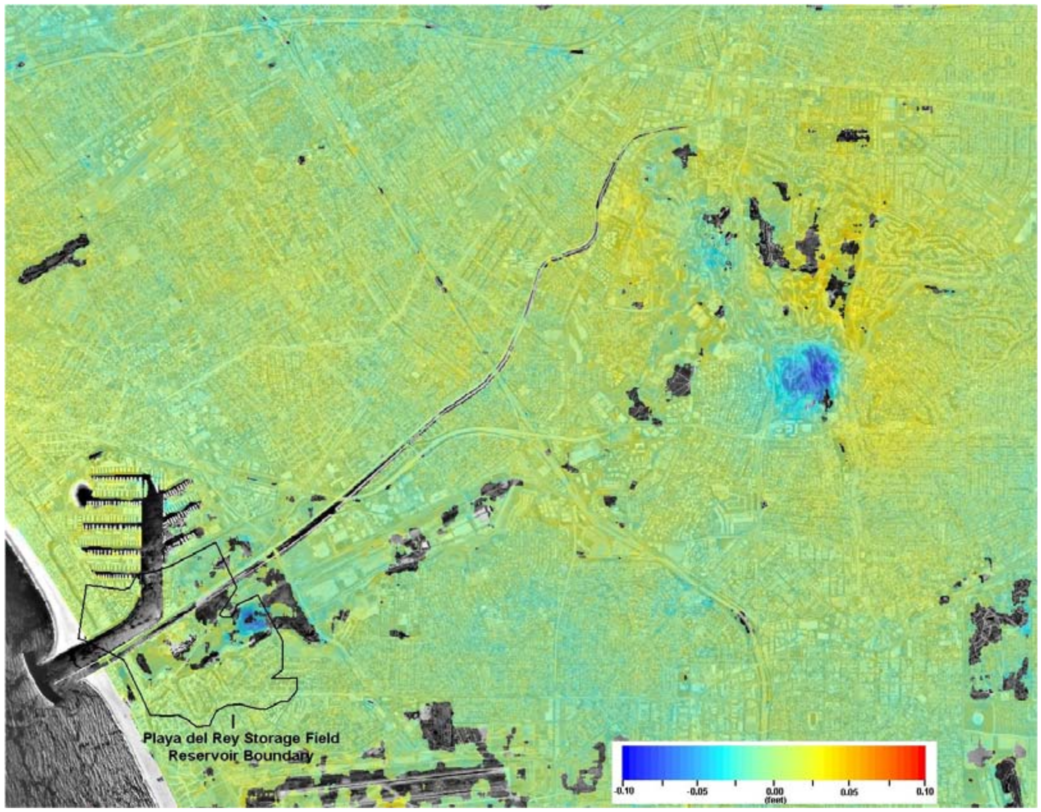

Figure 19: Zoom-in of the summation of vertical deformation where blue represents subsidence and red represents uplift from May 27, 2008 to June 15, 2009 without contours.

3 CONCLUDING REMARKS

Vertical surface deformation measurements are calculated for the Playa del Rey Gas Storage Field and surrounding areas in California using conventional radar interferometry (InSAR). This report, referred to as Interim Report A, pertains to Milestone 2 of the current contract.

The following items describe the main findings, as per Milestone 2:

- RADARSAT-2 Ultra-Fine ascending data were scheduled by MDA for acquisition. The acquired data, covering the period of December 2008 to June 2009, were analyzed and utilized as part of the deliverables.

- Two (2) deformation maps were generated as part of the second Milestone of a five (5) year monitoring program.

- The estimated precision for the Pair A deformation map is 0.01 ft with a 95% confidence interval, while the estimated precision for the Pair B deformation map is 0.02 ft with a 95% confidence interval.

- Uplift is observed in the Playa del Rey Gas Storage Field area during the period from December 2008 to March 2009. This pattern could be attributed to natural terrain expansion due to increased surface moisture during this period.

- Subsidence is observed in the Playa del Rey Gas Storage Field area during the period from March 2009 to June 2009. This pattern could be attributed to lack of natural terrain moisture due to decreased surface moisture during this period.

- For both time periods, subsidence is observed in an area situated between Ladera Heights and Windsor Hills, approximate center coordinate 33º 59’ 42”N 118º 21’ 51”W as shown in the summation product in **Error! Reference source not found.**. Deformation in this area is in the order of 0.05 – 0.17 ft.

- In addition, the summation (Pair C, December 2008 to June 2009) of these maps is computed and is also included as a deliverable with increased precision. For this period, masked areas are interpolated and common mask areas between the two (2) individual deformation products are extracted and applied to the final summation product.

- The second summation product includes approximately one (1) year of monitoring from May 27, 2008 to June 15, 2009 (Pair D). This was derived by combining the previous and current time period summation products. Mask areas for this overall summation is an accumulation of all the previous masks.

A. DELIVERABLES

The deliverables, which are included on CD-ROM for Milestone 2 are listed in Table 6**Error! Reference source not found.**. These delivered data are described in XYZ ASCII files and are in California US State Plane, NAD27, 65.62 ft spacing.

Table 6: Delivered Data

Deliverable file	**Description**
PlayadelRey_SoCalGas_IterimAReport_2009.pdf	Interim Report A in PDF format.
Conventional Deformation map	
120508_031109_DEF.xyz 120508_031109_DEF.tif 031109_061509_DEF.xyz 031109_061509_DEF.tif SUM_120508_061509_DEF.xyz SUM_120508_061509_DEF.tif SUM_052708_061509_DEF.xyz SUM_052708_061509_DEF.tif	ASCII files with location and vertical deformation measurements in feet. Coherence (γ) values, γ < 0.3, are considered areas of low coherence and are subsequently masked out with their values set to -999 (NODATA). Additional format supplied as GeoTiff.
Projection_Report.pdf	Describes the coordinate projection system of the delivered data.