Playa del Rey, California
InSAR Ground Deformation Monitoring
Interim Report D

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Executive Summary

This report, Interim Report D, 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 Los Angeles using InSAR satellite radar interferometry for the June 2010 to December 2010 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.

The following summarizes key features for this deliverable:

- Satellite radar data were scheduled for acquisition from June 10, 2010 through to December 19, 2010. For this deliverable, RADARSAT-2 Ultra-Fine ascending radar data were collected and analyzed.
- The highest quality deformation maps are generated. The time periods are from June 10, 2010 to September 14, 2010 (Pair A) and September 14, 2010 to December 19, 2010 (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.
- The estimated precision for the vertical deformation product Pair A, June 10, 2010 to September 14, 2010 is 0.0276 ft with a 95% confidence interval. The estimated precision for Pair B, September 14, 2010 to December 19, 2010 is 0.027 ft with a 95% confidence interval.
- The area of interest has large variations in precipitation from the winter to summer. The current monitoring period includes information from early summer to late fall. The rainfall amount varies significantly in this time period. Some variation in the reported ground surface is likely to be due to soil moisture changes. It is anticipated that the majority of this variance is within the reported measurement of 0.03 ft.
- For this report, a new approach was selected to better represent the cumulative product from May 2008 to December 2010 over SoCalGas' AOI. To account for the decorrelation in incoherent areas, additional data was acquired to provide a consistent time series.

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1 Interim Report D Objective

The objective of this report, Interim Report D, is to provide SoCalGas with measurements of the deformation that occurred within the project's AOI using conventional InSAR monitoring from June 2010 to December 2010. For this Milestone, 2 conventional InSAR deformation maps quantifying movement were generated.

This deliverable pertains to the fifth deliverable, Milestone 5, 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 presents the results for the 2 deformation maps and cumulative vertical deformation.
- Section 3 provides a summary of the results.
- Appendix A lists the deliverables.
- Appendix B provides a list of definitions for commonly used terms.

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 Figure 1. The corner coordinates for the polygon are approximately given by a rectangle with coordinates 34°01'58"N 118°28'5"W and 33°56'56"N 118°20'4"W.

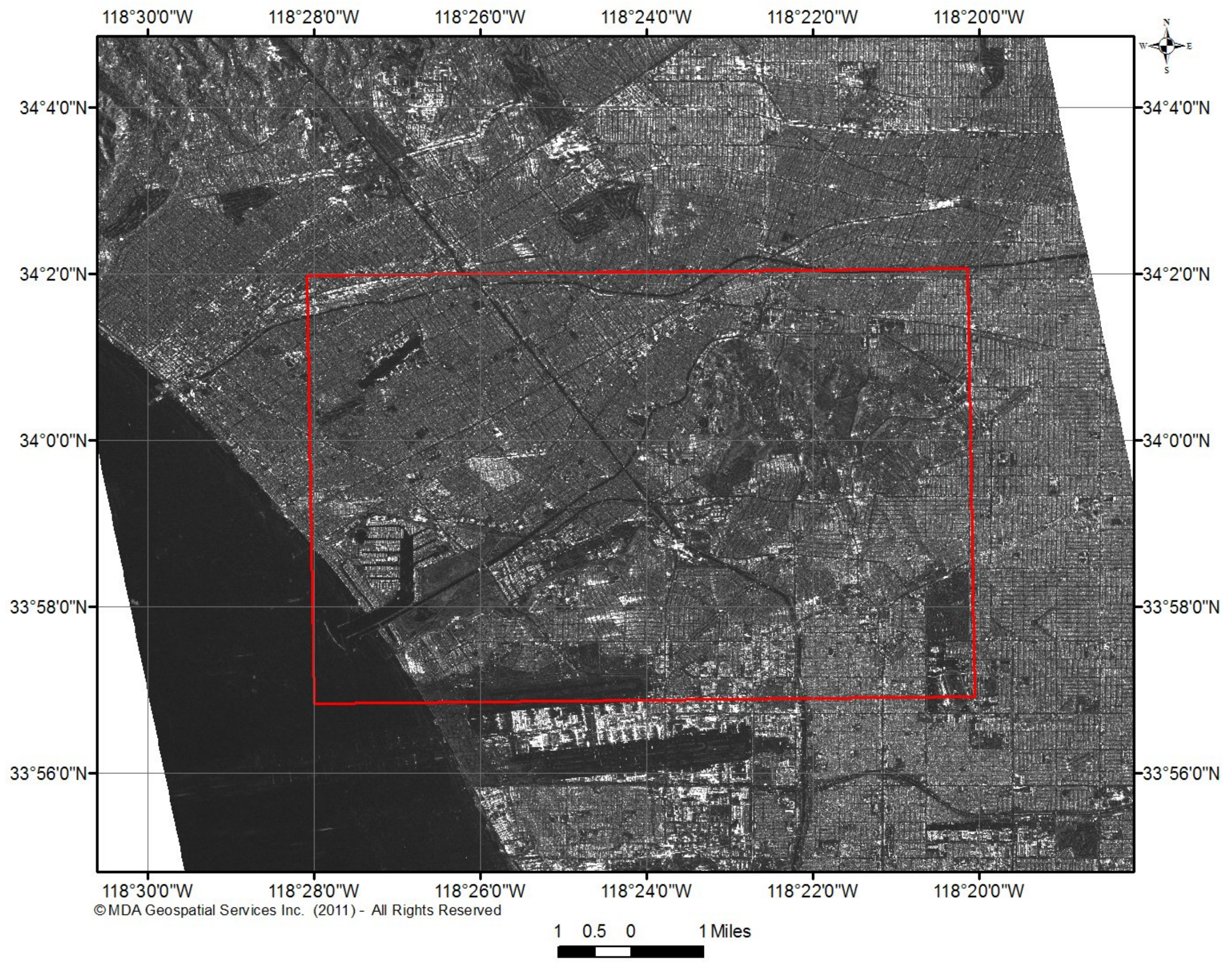

Figure 1: Playa del Rey AOI and surrounding area in Los Angeles, as outlined by red polygon (radar amplitude image).

1.3 Data Selection

The RADARSAT-2 Ultra-Fine data used to generate the deliverables for the June 2010 to December 2010 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
1	July 4, 2010	13327
2	July 28, 2010	13670
3	August 21, 2010	14013
4	September 14, 2010	14356
5	October 8, 2010	14699
6	November 1, 2010	15042
7	November 25, 2010	15385
8	December 19, 2010	15728

The InSAR deformation maps created are listed in Table 2. On these dates the SAR data were of best quality with suitable baselines. These 2 maps are generated using the September 14, 2010 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 numbers from Table 1.

Interferogram Pair	Acquisition Date Master	Acquisition Date Slave	Perpendicular Baseline (meters)
A (7-11)	Jun-10-10	Sept-14-10	214
B (11-15)	Sept-14-10	Dec-19-10	-93

2 Results - Interim Report D

An analysis of the available data is carried out by evaluating all sequential combinations. Based on this, 2 intereferometric pairs are selected for the generation of the deformation products.

- Pair A for the time period between June 10, 2010 to September 14, 2010 (96 days)
- Pair B for the time period between September 14, 2010 to December 19, 2010 (96 days)

These data are selected because the generated interferograms are of best quality at these dates and are least affected by noise and the DEM error. A mask is applied to the 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]**
Jun-10-10 to Sept-14-10	96 days	0.0138	0.0276

Table 4: Summary of Pair B

Date	**Time Span**	**Noise Level standard deviation [ft]**	**95% Confidence interval [ft]**
Sept-14-10 to Dec-19-10	96 days	0.0135	0.027

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

2.1 Pair A - June 10, 2010 to September 14, 2010

The vertical deformation in the Playa del Rey Gas Storage Field is observed for the time period between June to September 2010.

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 thresholding the coherence image. Coherence (γ) values, $\gamma < 0.16$, are considered areas of low coherence and are masked out with values set to -999.

Deformation 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 deformation could be attributed to lack of rainfall. As shown in Table 5, historical weather data for the Los Angeles airport, rainfall amounts from June to September could be attributed to subsidence in the Playa del Rey Gas Storage Field. In the south easterly limits of the Playa del Rey Storage Field Reservoir Boundary, (center co-ordinate 33°58'4"'N 118°26'4"W) deformation values range from 0.07 to 0.08 ft subsidence, as seen in Figure 2.

A color representation of the vertical deformation product are shown in Figure 3 and Figure 4 of the final product after masking areas that contain noise. The estimated precision for Pair A is within $\pm$0.0276 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]
June 2009	0.15
July 2009	0.00
August 2009	0.00
September 2009	Trace
October 2009	1.31
November 2009	0.00
December 2009	2.05
January 2010	6.01
February 2010	4.55
March 2010	0.21
April 2010	1.25
May 2010	0.00
June 2010	0.00
July 2010	Trace
August 2010	0.00
September 2010	Trace
October 2010	1.56
November 2010	0.59
December 2010	8.83

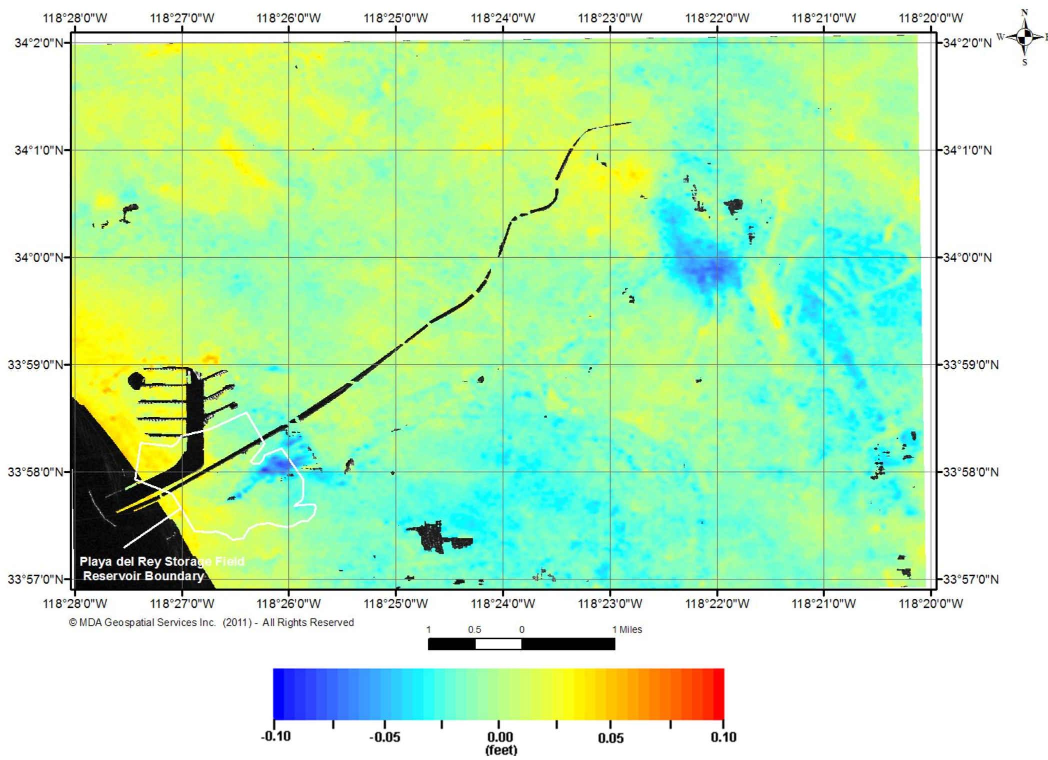

Figure 2: Playa del Rey Gas Storage Field AOI and surrounding area. Colour representation of the vertical deformation product from June 10, 2010 to September 14, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

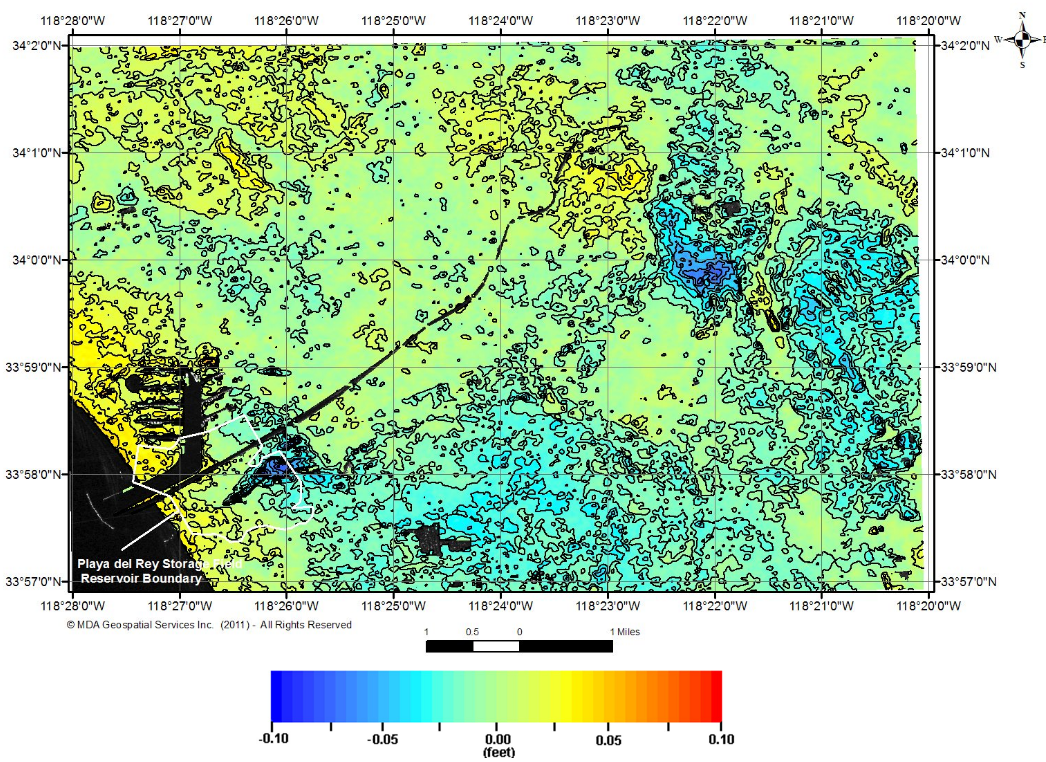

Figure 3: Playa del Rey Gas Storage Field AOI and surrounding area. Colour representation of the vertical deformation product from June 10, 2010 to September 14, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

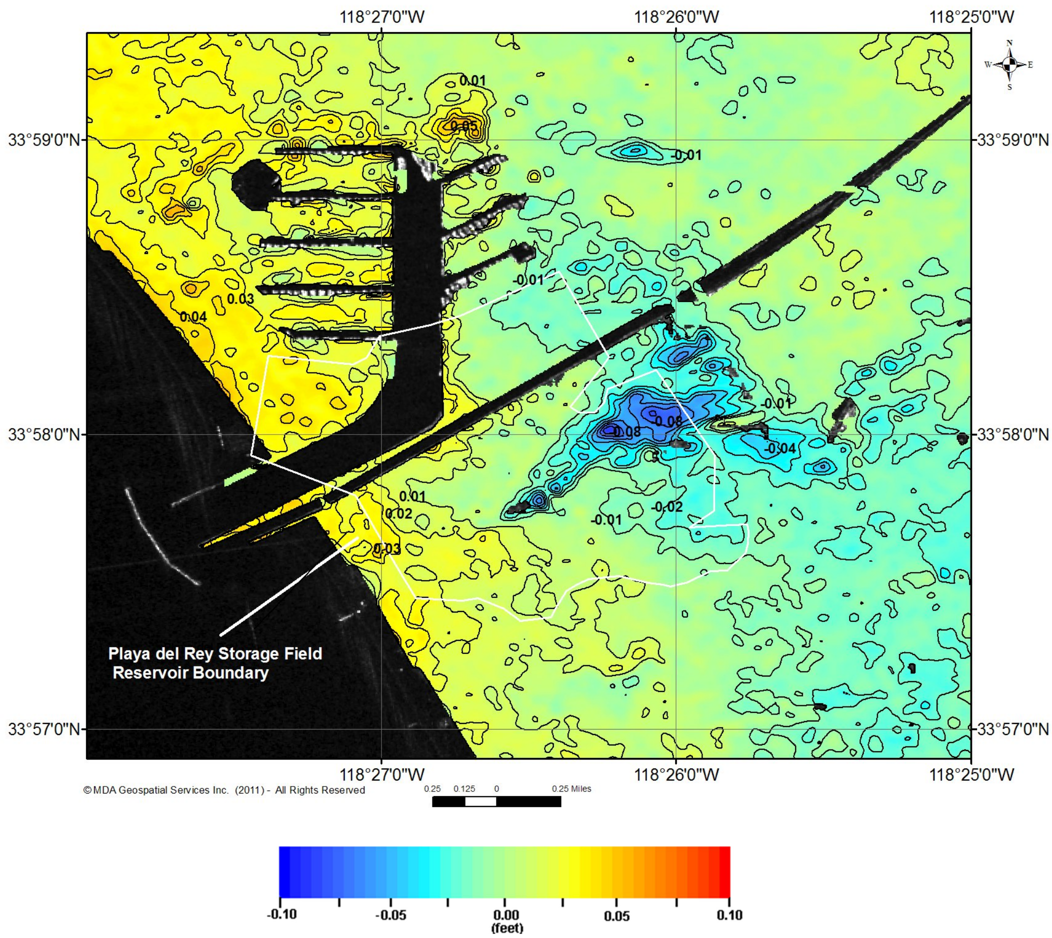

Figure 4: Zoom-in of Playa del Rey Gas Storage Field AOI. Colour representation of the vertical deformation product from June 10, 2010 to September 14, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.2 Pair B - September 14, 2010 to December 19, 2010

The deformation in the Playa del Rey Gas Storage Field is observed for the time period between September to December 2010.

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 thresholding the coherence image. Coherence (γ) values, $\gamma < 0.16$, are considered areas of low coherence and are masked out with values set to -999.

The coherence is low in the overall image and is likely due to heavy rain conditions in the region, as a result, a significant portion of the Playa del Rey Gas Storage Field AOI has been masked out. Uplift is observed in a small area of the Playa del Rey Storage Field Reservoir Boundary, (center co-ordinate 33°58'19"'N 118°26'27"W) deformation values range from 0.03 to 0.05 ft uplift, as can be seen from the vertical deformation product shown in Figure 5. This uplift can be attributed to surface moisture due to rainfall for the time from September to December, 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 $\pm$0.027 ft with a 95% confidence interval.

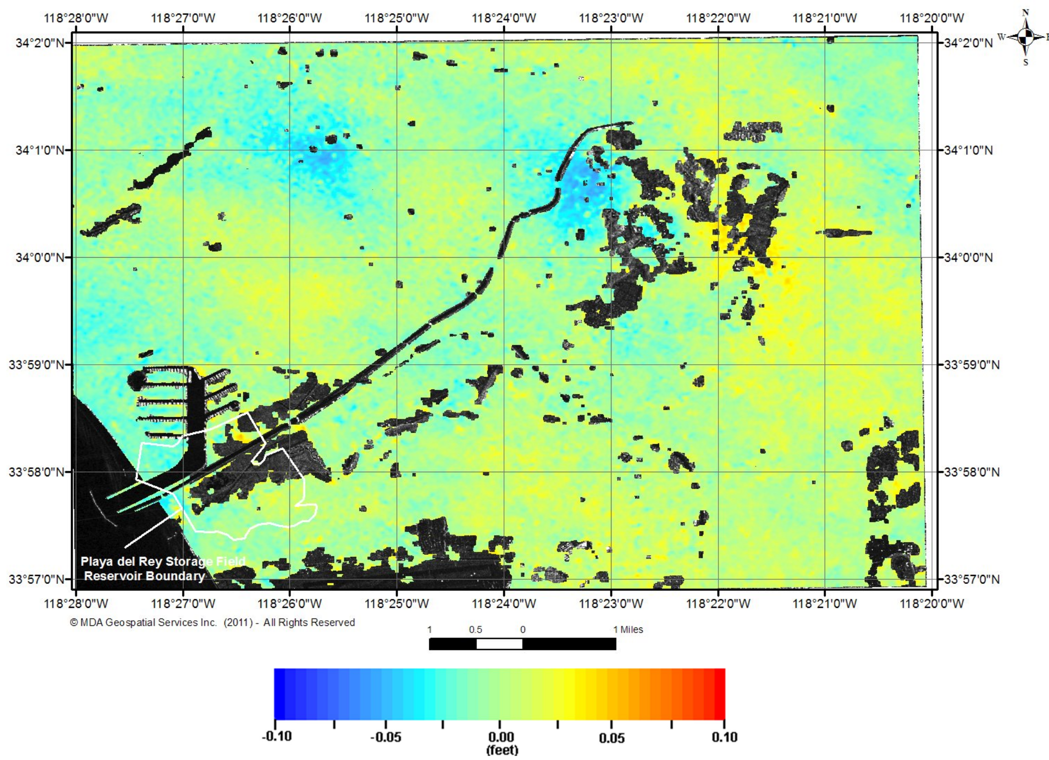

Figure 5: Playa del Rey Gas Storage Field AOI and surrounding area. Colour representation of the vertical deformation product from September 14, 2010 to December 19, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

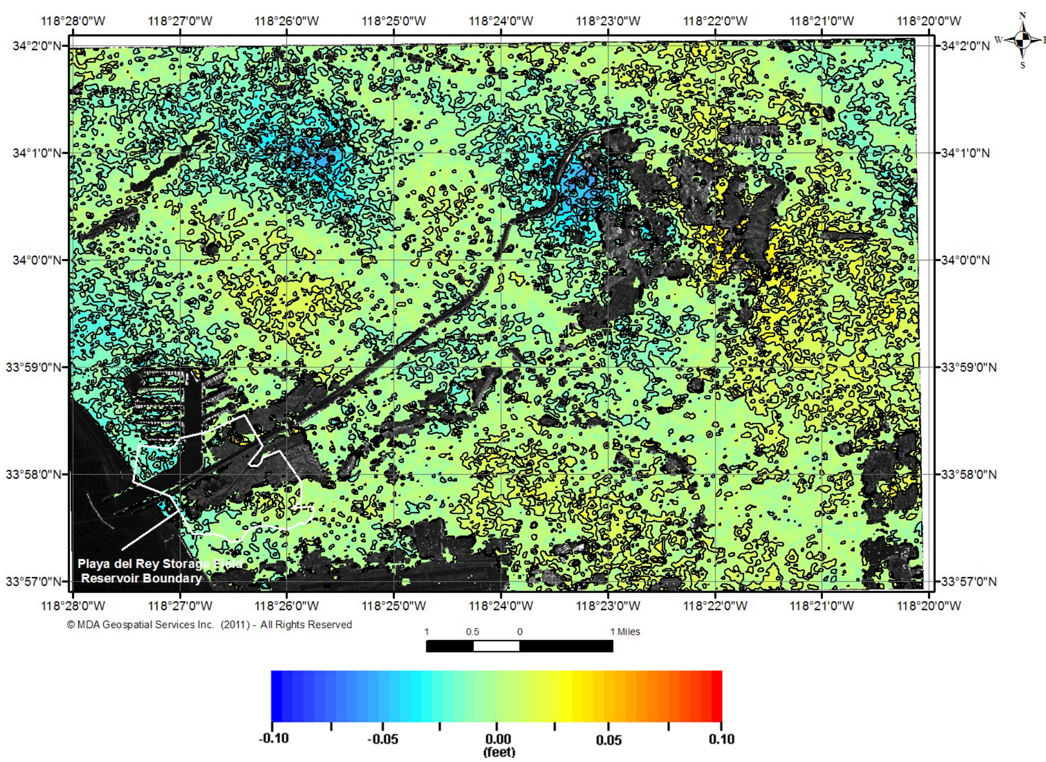

Figure 6: Playa del Rey Gas Storage Field AOI and surrounding area. Colour representation of the vertical deformation product from September 14, 2010 to December 19, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

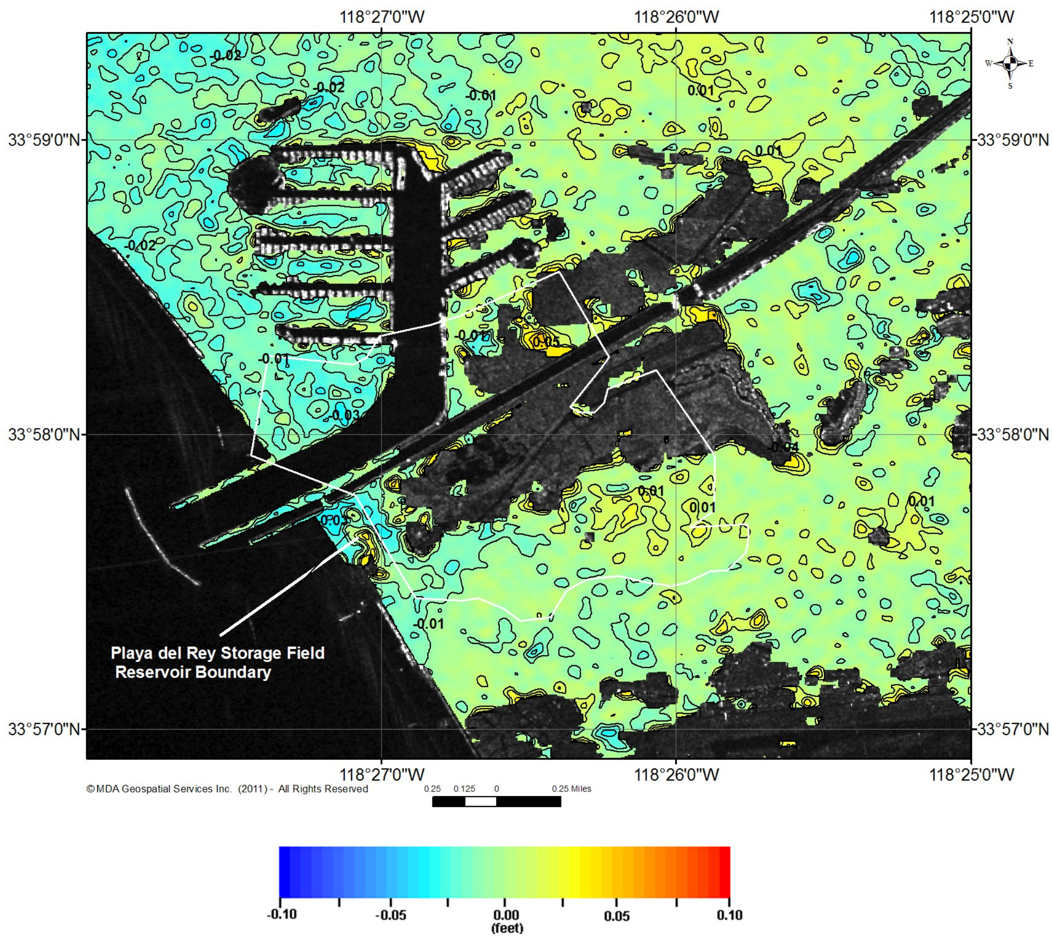

Figure 7: Zoom-in of Playa del Rey Gas Storage Field AOI. Colour representation of the vertical deformation product from September 14, 2010 to December 19, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.3 Pair C - Cumulative Vertical Deformation May 27, 2008 to December 19, 2010

For this report, a new approach was selected to better account for the decorrelation in incoherent areas that have been observed at the Playa del Rey Gas Storage Field. By enhancing the temporal and spatial accuracy, the use of repeated measurements has reduced the atmospheric noise and highlighted the fact that the actual ground change in the AOI is negligible.

Pair C represents the cumulative vertical deformation results over the AOI and surrounding areas in Los Angeles from the start of the monitoring period, May 27, 2008 to the current period analyzed.

Subsidence is observed over an area situated between Ladera Heights and Windsor Hills, center coordinate 33°59' 42"N 118°21' 48"W. Subsidence in this area is in the order of 0.05 - 0.13 feet as shown in Figure 8. The uplift is observed over an area situated between Ladera Heights and Culver City, center coordinate 34°0' 5"N 118°21' 33"W. Uplift in this area is in the order of 0.05 - 0.09.

Figure 9 shows the cumulative vertical deformation results from May 27, 2008 to December 19, 2010. Subtle deformation is observed in the Playa del Rey Gas Storage Field AOI. This result is attributed to natural terrain expansion during the September 2010 to December 2010 period when rainfall accumulation in December was high.

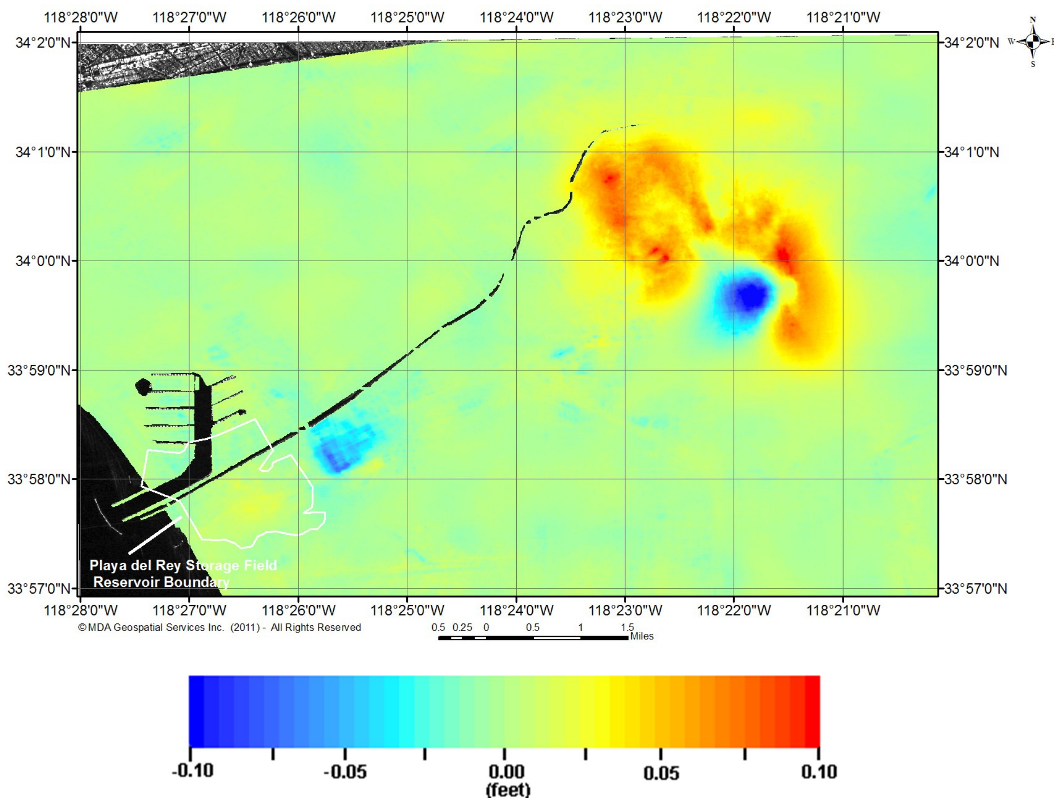

Figure 8: Playa del Rey Gas Storage Field AOI and surrounding area. Colour representation of the cumulative vertical deformation from May 27, 2008 to December 19, 2010 superimposed onto SAR image.

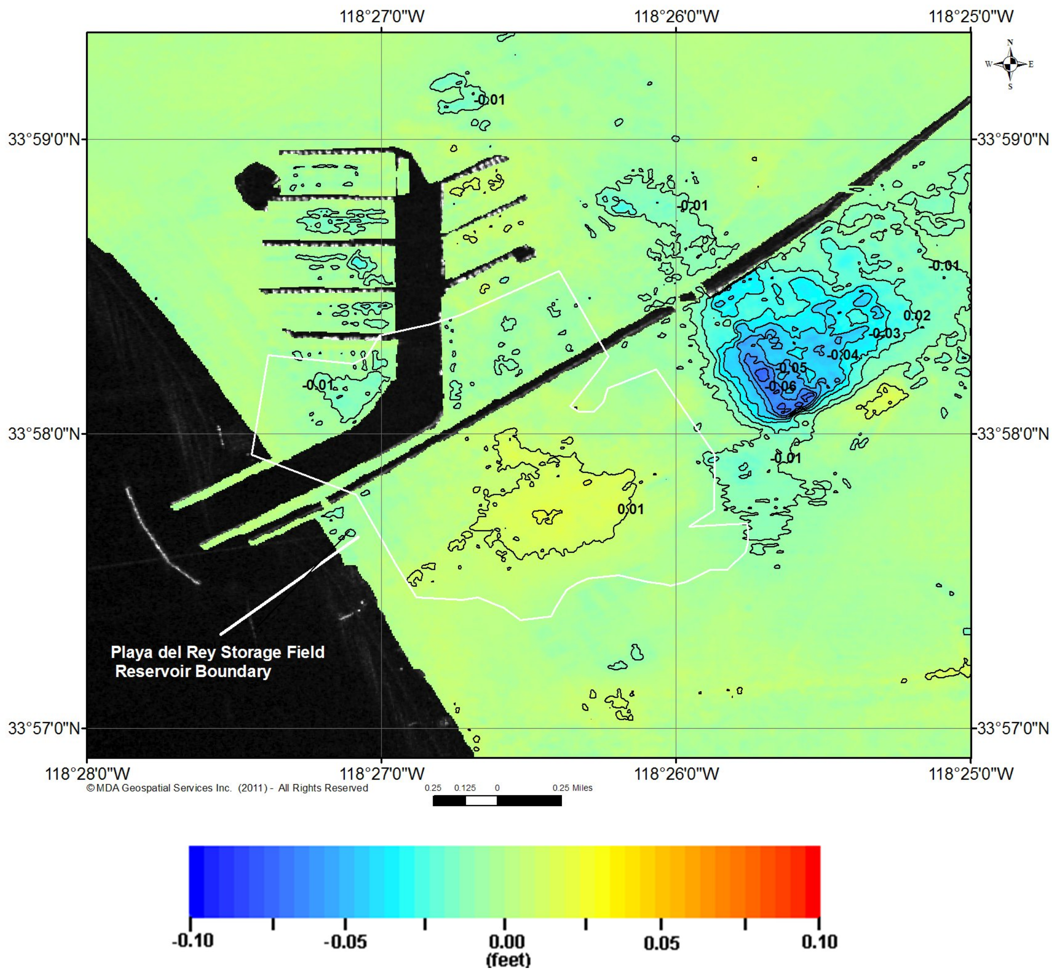

Figure 9: Zoom-in of Playa del Rey Gas Storage Field AOI and surrounding area. Cumulative vertical deformation from May 27, 2008 to December 19, 2010, with 0.01 ft contours.

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 D, pertains to Milestone 5 of the current contract, RV-14524.

The following items describe the main findings of the work performed, for this milestone:

- RADARSAT-2 Ultra-Fine ascending data were scheduled by MDA for acquisition. The acquired data, covering the period of June 2010 to December 2010, were analyzed and utilized as part of the deliverables.
- 2 deformation maps were generated as part of the fifth Milestone of a 5 year monitoring program.
- The estimated precision for the vertical deformation product Pair A, June 10, 2010 to September 14, 2010 is 0.0276 ft with a 95% confidence interval. The estimated precision for Pair B, September 14, 2010 to December 19, 2010 is 0.027 ft with a 95% confidence interval.
- The area of interest has large variations in precipitation from the winter to summer. The current monitoring period includes information from early summer to late fall. The rainfall amount varies significantly in this time period. Some variation in the reported ground surface is likely to be due to soil moisture changes. It is anticipated that the majority of this variance is within the reported measurement of 0.03 ft.
- For this report, a new approach was selected to better represent the cumulative product from May 2008 to December 2010 over SoCalGas' AOI. The resulting analysis indicates that no major deformation is occurring in the Playa del Rey Gas Storage Field.

A Deliverables

The deliverables, which are included on CD-ROM for Milestone 5, are listed in Table 6. 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_InterimReportD_2011.pdf	Interim Report D in PDF format.
Conventional Deformation map	
061010_091410_DEF.xyz 061010_091410_DEF.tif 091410_121910_DEF.xyz 091410_121910_DEF.tif 052708_121910_DEF.xyz 052708_121910_DEF.tif	ASCII files with location and vertical deformation measurements in ft. Coherence (γ) values, $\gamma < 0.17$, are considered areas of low coherence and are masked out with values set to -999.
Projection_Report.pdf	Describes the coordinate projection system of the delivered data.

B Standard Definitions

Amplitude (a) The amplitude of a wave is the distance from the centre of the wave to the peak, see Figure 10.

Ascending Satellite tracks that transit from the south to the north are labeled ascending.

Aspect Angle (α) The aspect angle is the angle at which the local area is observed.

Azimuth Azimuth or track describes the direction of travel of the sensor over the ground.

Baseline (B) The baseline is the vector describing the distance between two radar observations of the same point (see also perpendicular baseline).

Coherence (γ) Coherence, γ, is used as a measure of the degree of similarity between the backscatter (amplitude and phase) response of coregistered SAR returns over time or space.

Coregistration Coregistration is the process of locating subsequent radar images to the same observation space. A set of coregistered images show information from the same point on the ground at the same image coordinate.

Descending Satellite tracks that transit from the north to the south are labeled descending.

Electromagnetic Wave An electromagnetic wave is a self-propagating wave that may exist in a vacuum or in matter. The wave has both electric and magnetic field components that oscillate with perpendicular phase. Electromagnetic radiation exists on a spectrum from gamma-rays to long radio waves. The visible spectrum is narrowly between 400 and 700 nm. Microwaves, the radiation used in SAR observations, are generally between a fraction of a millimetre and a metre in length.

Frequency (f) Frequency describes the number of cycles per second. Frequency is given in Hertz (Hz). For an electromagnetic wave, wavelength, λ, and frequency, f, are related through the speed of light, c, as $c = \lambda f$.

Frequency Band Radar frequencies are often referred to by a band letter. The coding goes back to the research conducted during WWII. C-Band extends from approximately 4-8 GHz. RADARSAT-1 & 2, ENVISAT, and ERS-1 & 2 all operate in C-Band. L-Band at 1-2 GHz was the operating frequency of the original SEASAT satellite in the 1970s, and the ALOS satellite currently operates in that range. The TerraSAR-X satellite operates in X-Band (8-12 GHz). Figure 11 shows the electromagnetic spectrum.

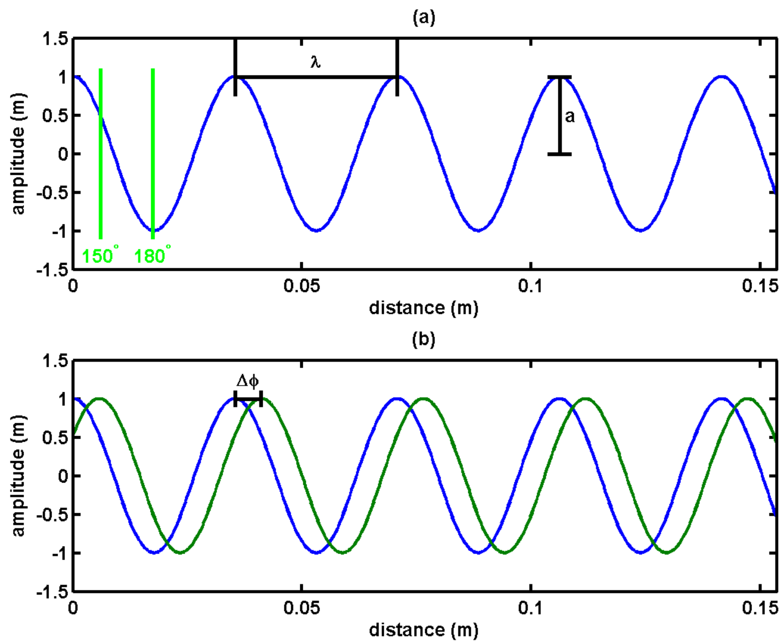

Figure 10: Definition of a 5.6-cm wave. Panel (a) shows the definition of wavelength, λ, and amplitude (a). The green lines show the location on the wave associated with 150° and 180° of phase. Panel (b) demonstrates the phase difference, $\Delta\phi$, between two waves.

Georeferencing Georeferencing is the procedure used to assign individual radar observations to geographic positions. The process involves calculating the geographic position based on the time to target and the observation time of the radar. Georeferencing for RADARSAT-2 has been measured (based only on the state vectors and the imaging geometry) to be better than 20 m on the ground.

Incident Angle (θ_i) The incident angle is the angle the incident radiation makes with respect to the surface normal. In satellite remote sensing, θ_i is often used to describe the angle between the mean surface normal and the incident radiation.

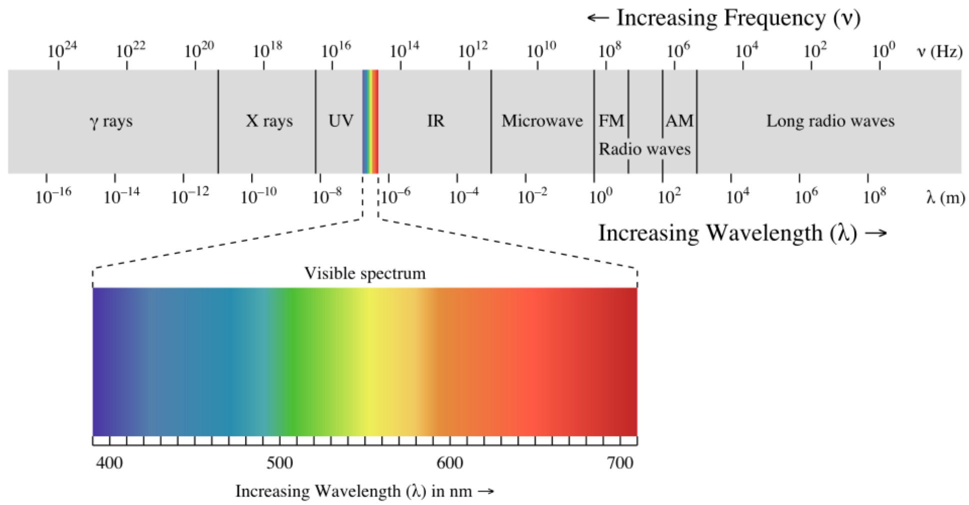

Figure 11: Electromagnetic spectrum showing the wavelength and frequency characteristics of radiation. The microwave portion of the spectrum contains the waves used for RADAR observation.

Line of Sight The line of sight describes travel of a wave from the radar to a point on the ground. Observations are only possible along the line of sight.

Look Direction Look direction refers to the side of the radar track (or azimuth) that the antenna pattern illuminates. That is, a right looking radar sends energy at approximately 90° to the right of the azimuth track.

Pass Pass or pass direction is used to refer to an ascending or descending satellite azimuth.

Perpendicular Baseline (B_{perp} or $B_\perp$) is the separation of two radar observations in the direction perpendicular to the first radar observation.

Phase (ϕ) Phase describes the position on a wave. Figure 10 shows a wave with phase labeled as 150° and 180°. ϕ is often reported in radians from 0 to 2π, which corresponds to degrees from 0 to 360.

Phase Difference ($\Delta\phi$) The phase difference (or phase shift) describes the difference between the position on two waves. Figure 10 shows a phase difference of 60° or $\pi/3$. The accuracy with which the phase difference can be measured is why InSAR is so valuable.

Phase Noise Phase noise refers to artifacts present in the phase measurement that are not due to the signal we want to capture.

Range (ρ or R) Range is used to describe the distance between a radar target on the ground and the sensor.

Slant Range Native SAR observations are recorded by time to target and time of observation. Slant range describes the distance along the radar line of sight.

Slant Range Coordinates The coordinate system of the native radar observations, defined by time of observation (azimuth) and time to target (slant range). Observations are aligned as range and azimuth pixels with constant spacing in slant range and slow time.

Speed of Light (c) The speed of light is 299 792 458 m/s.

Temporal Decorrelation As the time between observations increases, the physical reasons for the similarity of observations may change. In the monitoring of a field, for instance, the growth of grasses over time will cause decorrelation of the backscatter.

Wavelength (λ) Wavelength describes the distance between subsequent points of equal phase in consecutive cycles of a wave.