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

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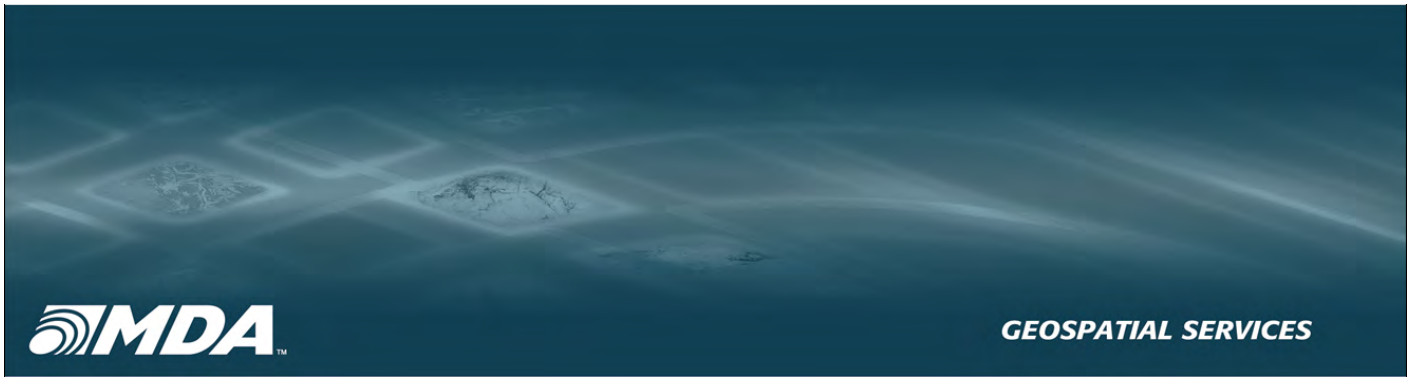

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Executive Summary

This report, Interim Report H, 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 using interferometric synthetic aperture radar (InSAR) satellite for the June 2012 to December 2012 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 used for the generation of deformation maps over the AOI, two of which are delivered to SoCalGas every 6 months.

The following summarizes key features for this deliverable:

- RADARSAT-2 Ultra-fine ascending satellite radar data were scheduled, acquired and analyzed from June 2012 to December 2012.
- The highest quality deformation maps are generated. The time periods are from June 2012 to September 2012 (Pair A) and September 2012 to December 2012 (Pair B).
- The delivered products are geo-referenced with a horizontal accuracy better than 20 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 pair June 2012 to September 2012 vertical deformation product is 0.012 ft with a 95% confidence interval; while the estimated precision for pair September 2012 to December 2012 vertical change product is 0.012 ft with a 95% confidence interval.
- The variation in the reported InSAR ground surface movement is likely related to soil moisture changes. The majority of this variance is within the reported measurement of 0.02 ft, the noise level.

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AOI area of interest

InSAR interferometric synthetic aperture radar

1 Interim Report H Objective

The objective of this report, Interim Report H, is to provide SoCalGas with measurements of the ground deformation that occurred within the project's area of interest (AOI) using conventional interferometric synthetic aperture radar (InSAR) monitoring from June 2012 to December 2012. For this Milestone, two conventional InSAR deformation maps quantifying ground movement are generated.

This deliverable pertains to the ninth deliverable, Milestone 9, of a five 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 deformation maps as well as the cumulative vertical deformation products.
- Section 3 provides a summary and conclusions.
- 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 shown in figure 1. The coordinates for the AOI interest are 34°01'58"N 118°28' 5"W and 33°56' 56"N 118°20'4"W.

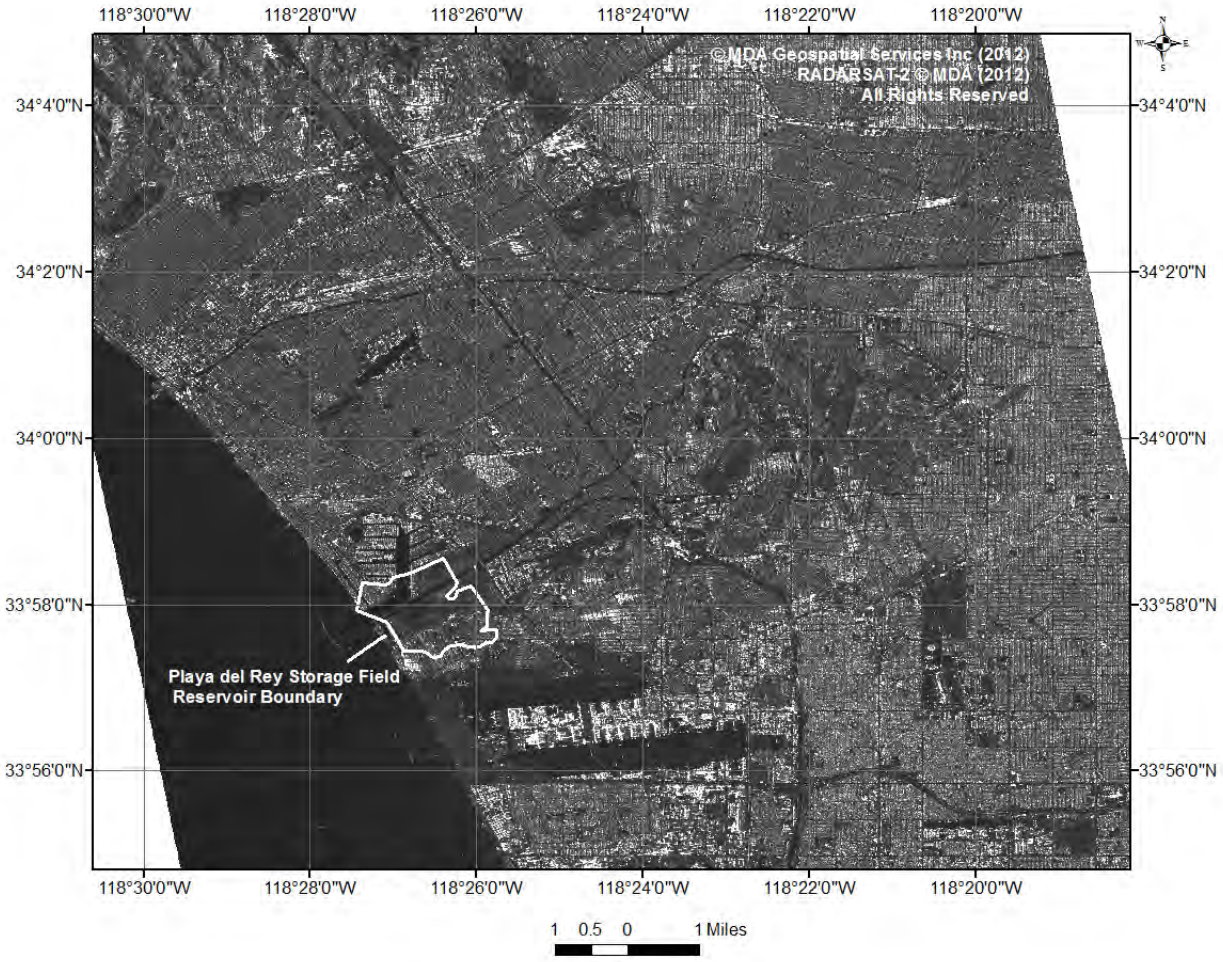

Figure 1: Playa del Rey AOI and surrounding area in Los Angeles.

1.3 Data Selection

The RADARSAT-2 Ultra-Fine data used to generate the deliverables for the June 2012 to December 2012 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
1	June 23, 2012
2	July 17, 2012
3	August 10, 2012
4	September 3, 2012
5	September 27, 2012
6	October 21, 2012
7	November 14, 2012
8	December 8, 2012

The InSAR deformation maps created are listed in table 2.

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
A (1-4)	Jun-23-12	Sept-3-12
B (4-8)	Sept-3-12	Dec-8-12

2 Results - Interim Report H

An analysis of the available data is carried out by evaluating all possible interferometric combinations. Two InSAR pairs are selected for the generation of deformation products:

- Pair A for the time period between June 23, 2012 to September 3, 2012 (72 days)
- Pair B for the time period between September 3, 2012 to December 8, 2012 (96 days)

The root-mean-square of the observed values in the non-deformation area 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 for Pair A

Date	Time Span	Noise Level standard deviation [ft]	95% Confidence interval [ft]
Jun-23-12 to Sept-3-12	72 days	0.006	0.012

Table 4: Summary for Pair B

Date	Time Span	Noise Level standard deviation [ft]	95% Confidence interval [ft]
Sept-3-12 to Dec-8-12	96 days	0.006	0.012

Additional products, the cumulative vertical deformation, are presented in this report:

- Pair C for the time period between June 23, 2012 to December 8, 2012 (360 days)
- Pair D for the time period between May 27, 2008 to December 8, 2012 (1656 days)

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

2.1 Pair A - June 23, 2012 to September 3, 2012

The vertical ground deformation in the Playa del Rey Gas Storage Field is observed for the time period between June 23, 2012 to September 3, 2012, as shown in figure 2.

The color representation of the vertical deformation product are shown in figure 3 and figure 4 after masking areas that contain noise. The estimated precision for Pair A is within $\pm$0.012 ft with a 95% confidence interval.

No significant uplift is seen in the Playa del Rey Gas Storage field from June 2012 to September 2012.

Table 5: Rainfall accumulation per month at LAX. Source: National Weather Service.

Month	Monthly Precipitation [inches]	Month	Monthly Precipitation [inches]
June 2009	0.15	January 2012	1.19
July 2009	0.00	February 2012	0.12
August 2009	0.00	March 2012	1.78
September 2009	Trace	April 2012	1.51
October 2009	1.31	May 2012	0.01
November 2009	0.00	June 2012	0.00
December 2009	2.05	July 2012	Trace
January 2010	6.01	August 2012	Trace
February 2010	4.55	September 2012	Trace
March 2010	0.21	October 2012	0.12
April 2010	1.25	November 2012	0.77
May 2010	0.00	December 2012	1.91
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		
January 2011	0.81		
February 2011	1.47		
March 2011	4.04		
April 2011	Trace		
May 2011	0.53		
June 2011	0.02		
June 2011	0.02		
July 2011	Trace		
August 2011	0.00		
September 2011	0.01		
October 2011	0.63		
November 2011	1.69		
December 2011	0.67		

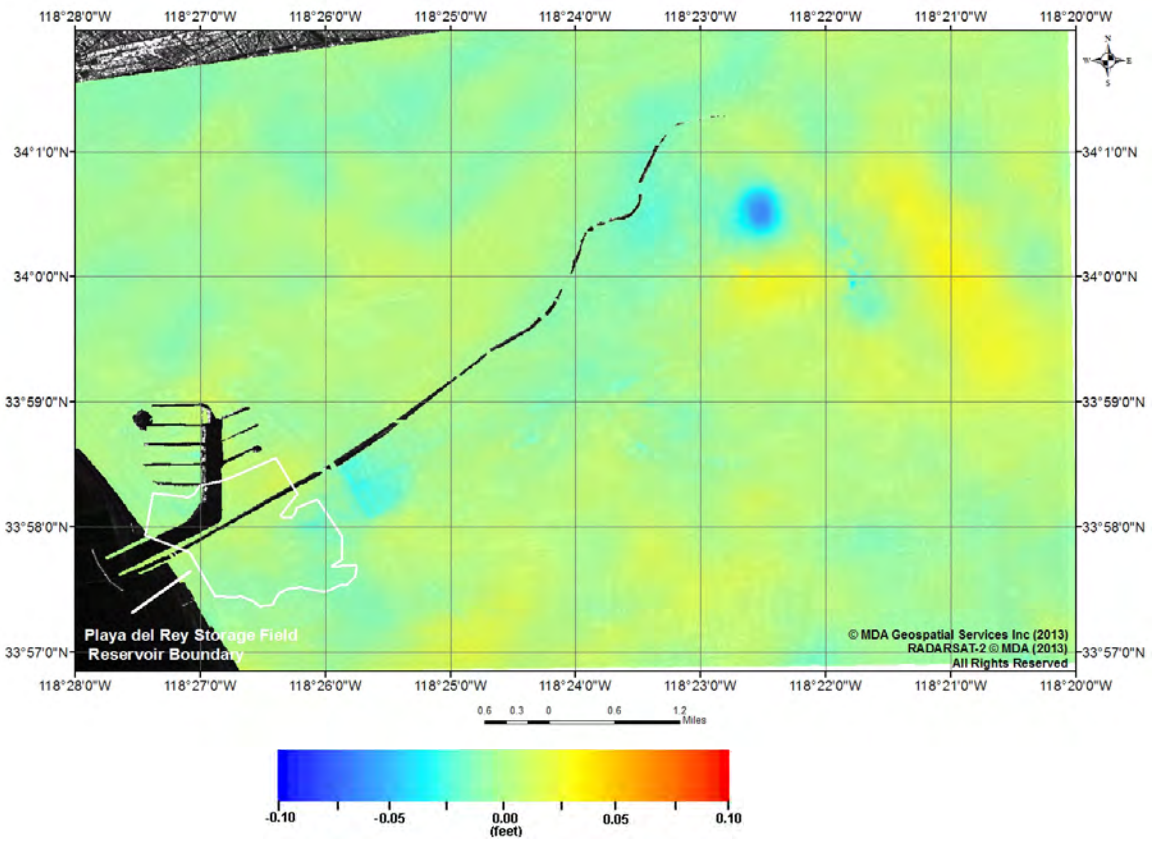

Figure 2: Playa del Rey Gas Storage Field AOI and surrounding area. Color representation of the vertical deformation product from June 23, 2012 to September 3, 2012 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

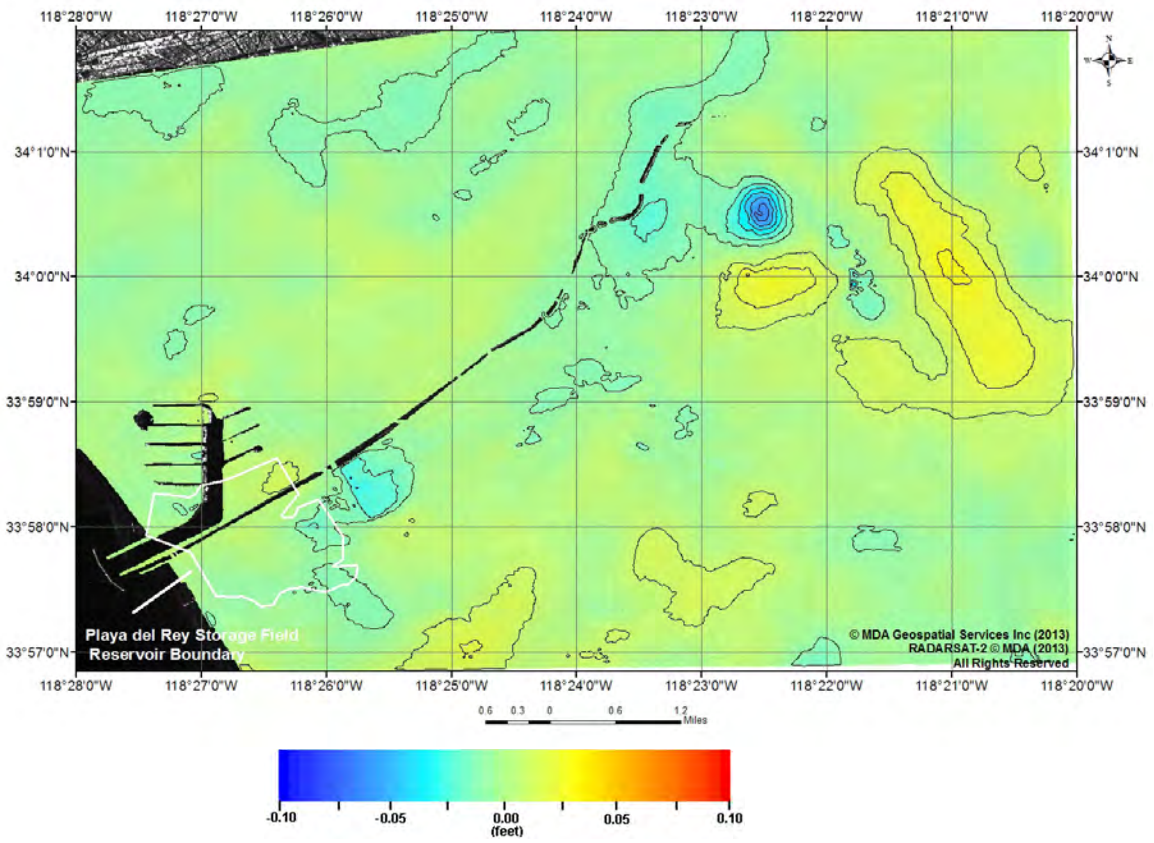

Figure 3: Playa del Rey Gas Storage Field AOI and surrounding area. Color representation of the vertical deformation product from June 23, 2012 to September 3, 2012 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

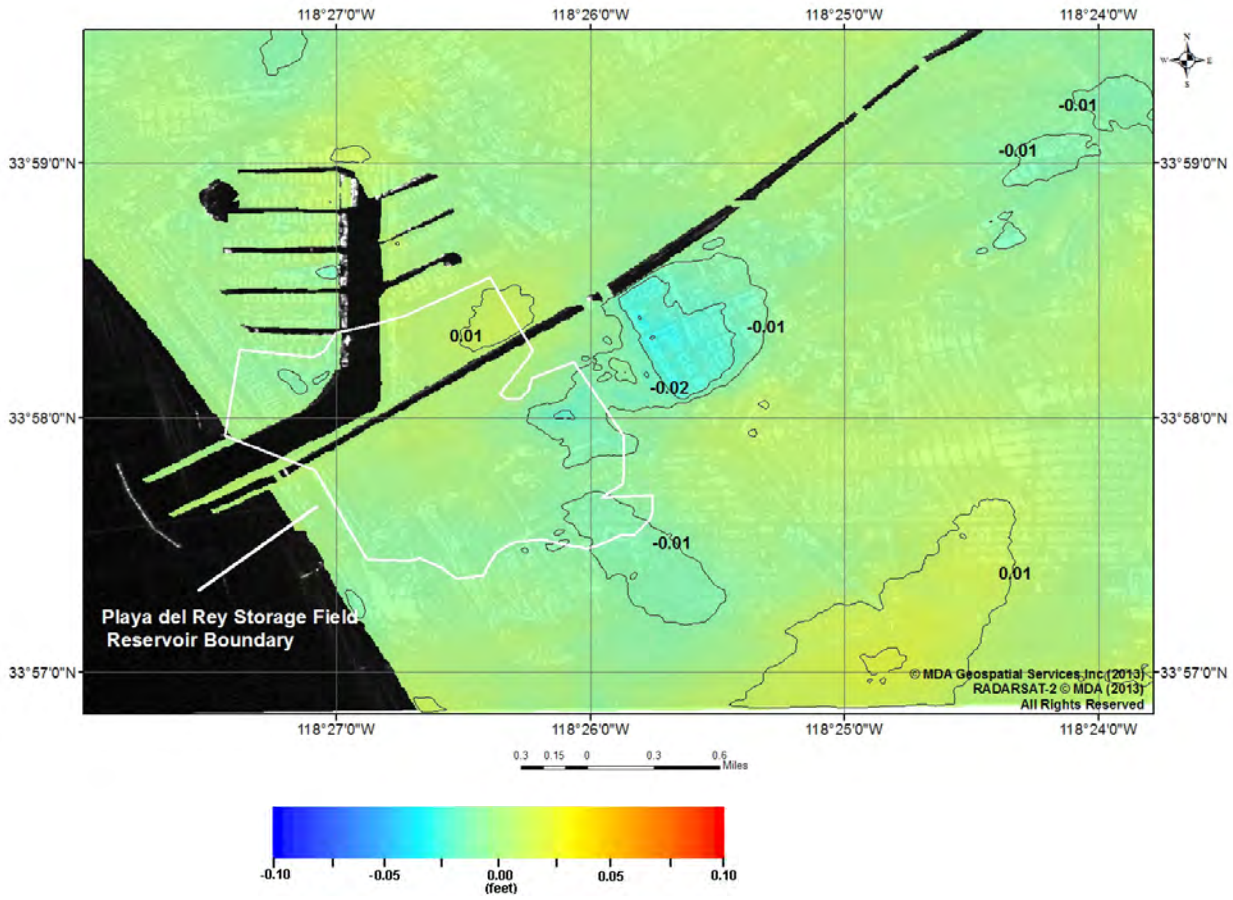

Figure 4: Zoom-in of Playa del Rey Gas Storage Field AOI. Color representation of the vertical deformation product from June 23, 2012 to September 3, 2012 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.2 Pair B - September 3, 2012 to December 8, 2012

The vertical ground deformation in the Playa del Rey Gas Storage Field is observed for the time period between September 3, 2012 to December 8, 2012, as shown in figure 5.

Figure 6 and figure 7 present a color representation of the final product. The estimated precision for Pair B is within $\pm$0.012 ft with a 95% confidence interval.

A localized area of deformation is observed in the AOI, in the easterly limits of the Playa del Rey Storage Field Reservoir Boundary, (center co-ordinate 33°58'18"'N 118°25'57"W). Subtle deformation values range from 0.005 to 0.01 ft uplift, as shown in figure 7.

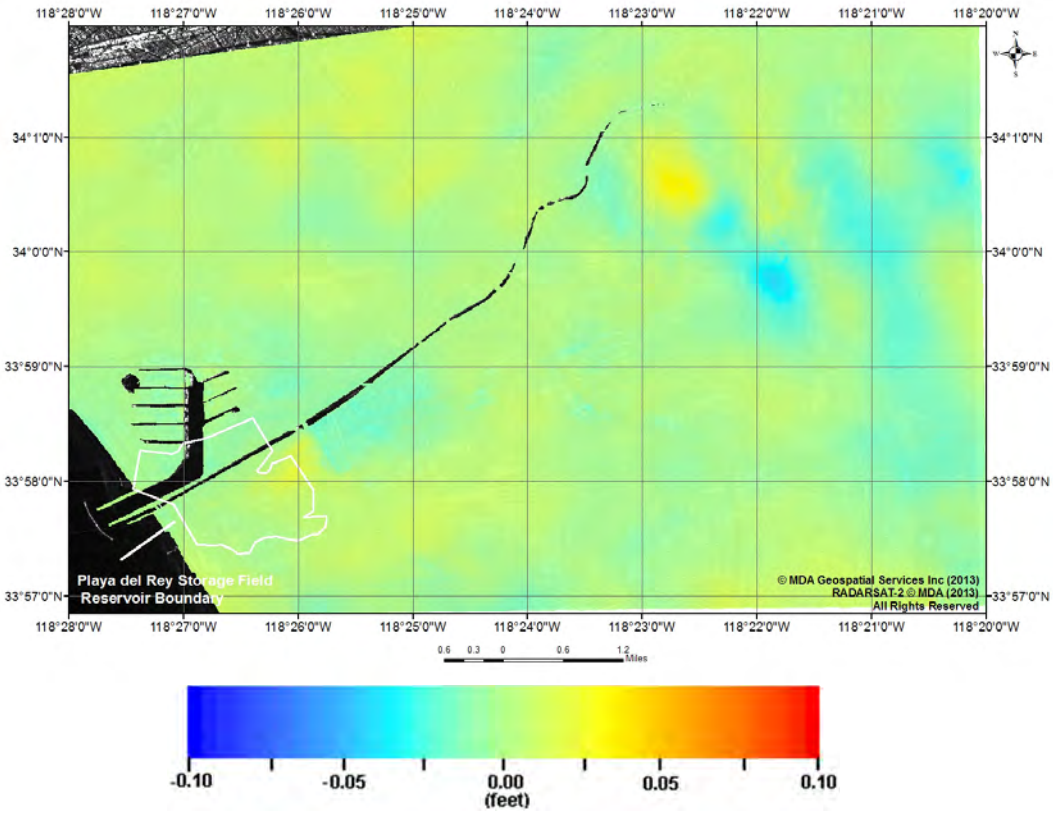

Figure 5: Playa del Rey Gas Storage Field AOI and surrounding area. Color representation of the vertical deformation product from September 3, 2012 to December 8, 2012 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

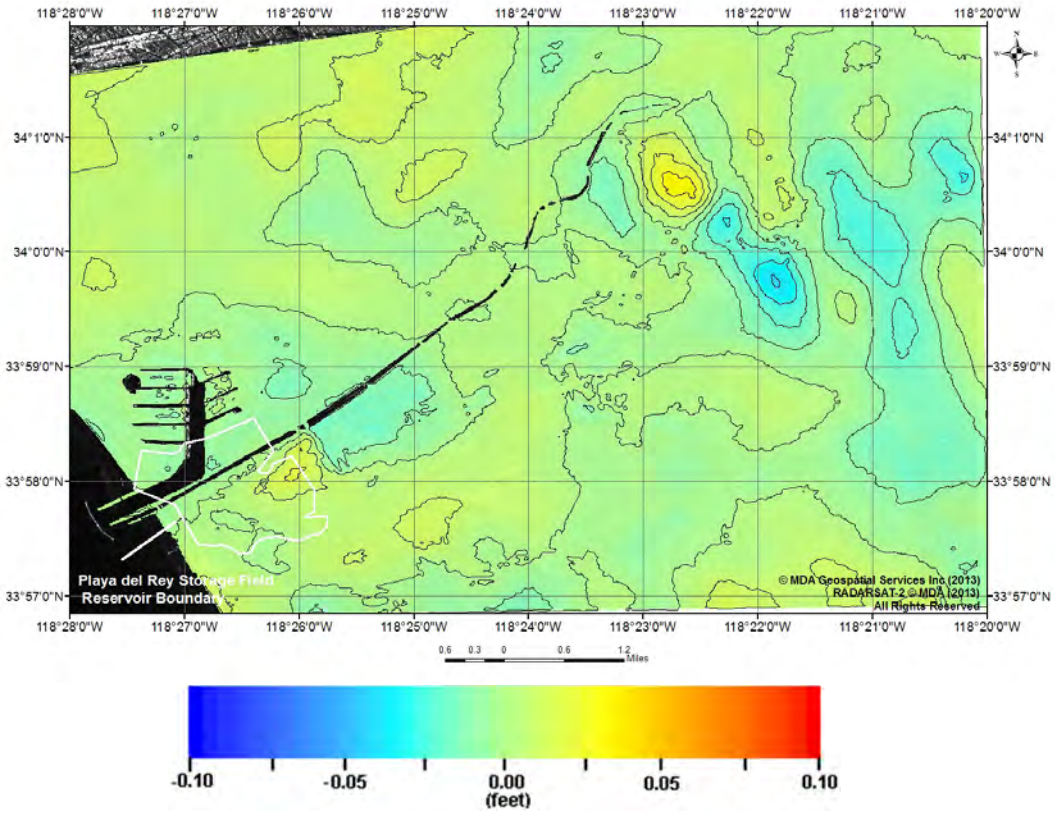

Figure 6: Playa del Rey Gas Storage Field AOI and surrounding area. Color representation of the vertical deformation product from September 3, 2012 to December 8, 2012 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

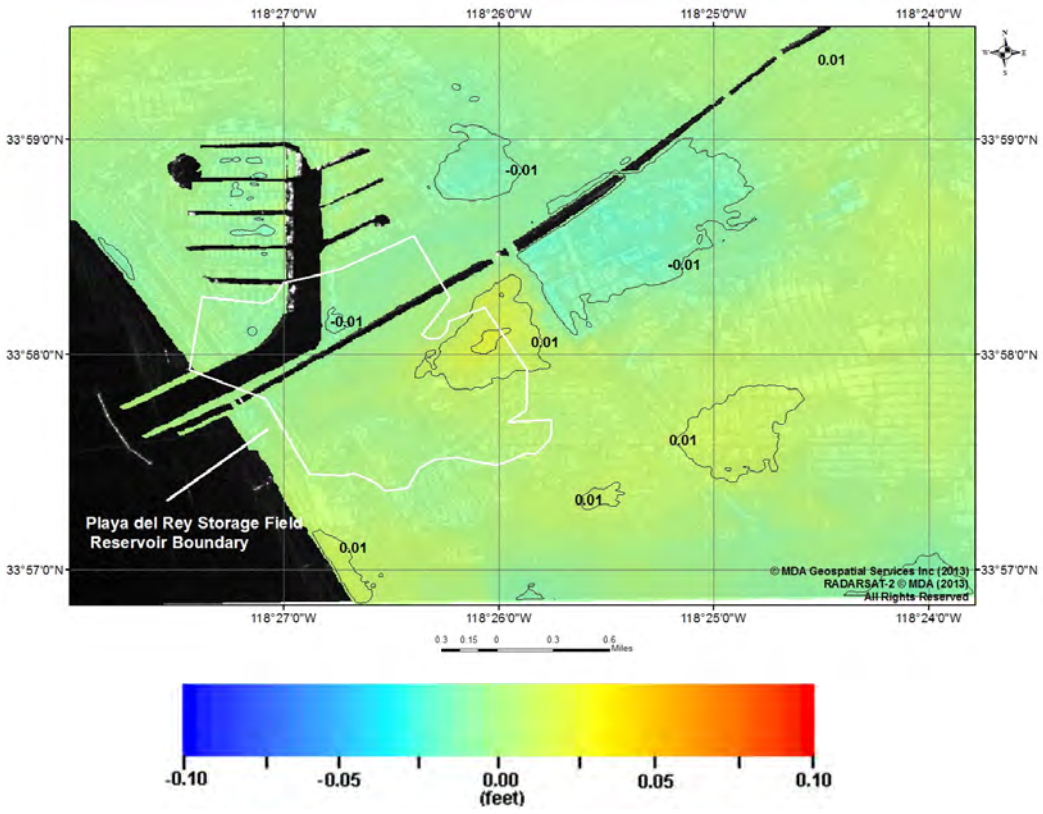

Figure 7: Zoom-in of Playa del Rey Gas Storage Field AOI and surrounding area. Cumulative vertical deformation from September 3, 2012 to December 8, 2012, with 0.01 ft contours.

2.3 Pair C - Cumulative Vertical Deformation June 23, 2012 to December 8, 2012

Pair C represents the cumulative vertical deformation results over the AOI and surrounding areas in Los Angeles from June 2012 to December 2012 (figure 8).

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 movement in the Playa del Rey Gas Storage Field is negligible and related to phase noise (figure 9).

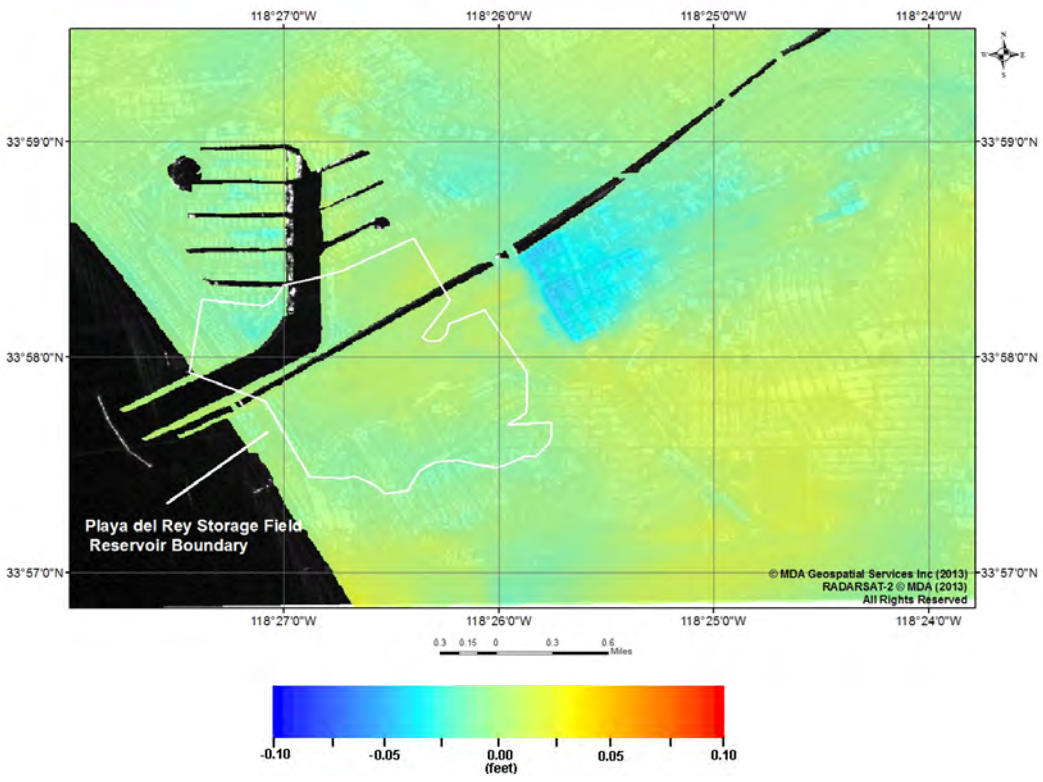

Figure 8: Playa del Rey Gas Storage Field AOI and surrounding area. Color representation of the cumulative vertical deformation from June 23, 2012 to December 8, 2012 superimposed onto SAR image.

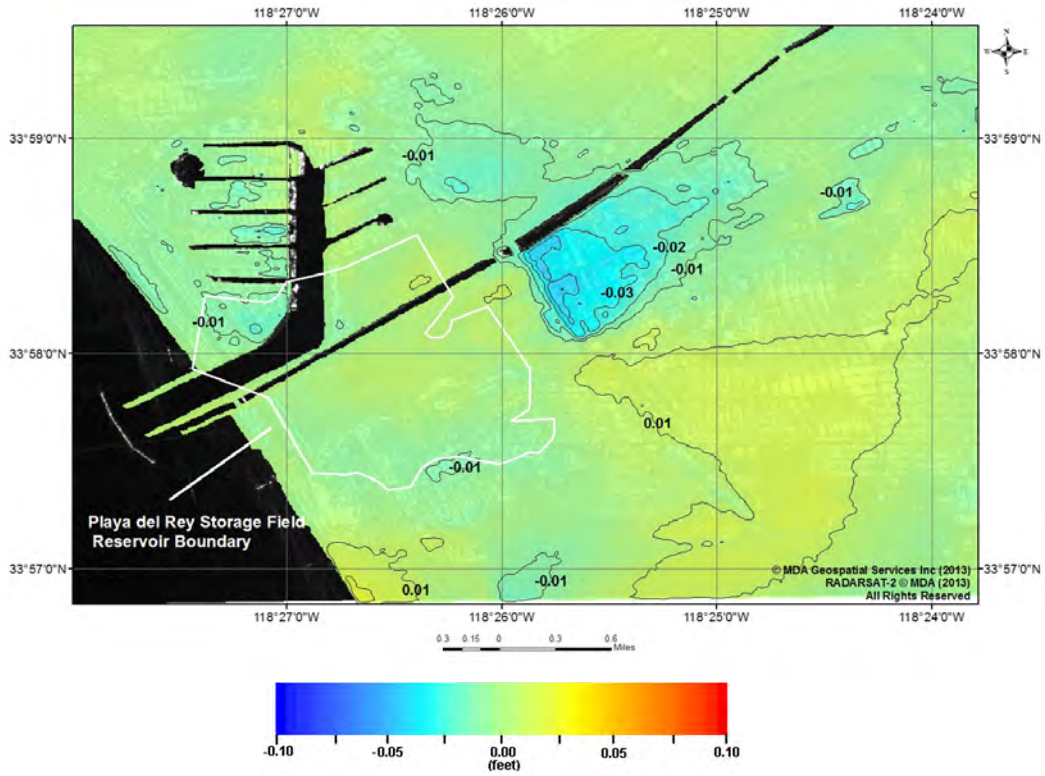

Figure 9: Zoom-in of Playa del Rey Gas Storage Field. Color representation of the summation of the vertical deformation products from June 23, 2012 to December 8, 2012 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.4 Pair D - Cumulative Vertical Deformation May 27, 2008 to December 8, 2012

Pair D represents the cumulative vertical deformation results over the AOI from the start of the monitoring period, May 27, 2008 to the current period analyzed, December 8, 2012 as is shown in figure 10 and 11.

Minimal ground surface movement is observed in the Playa del Rey Gas Storage Field AOI over the 4 year time period. This result is attributed to natural terrain expansion and contraction during the time periods where surface moisture has fluctuated. These measurements are within the phase noise.

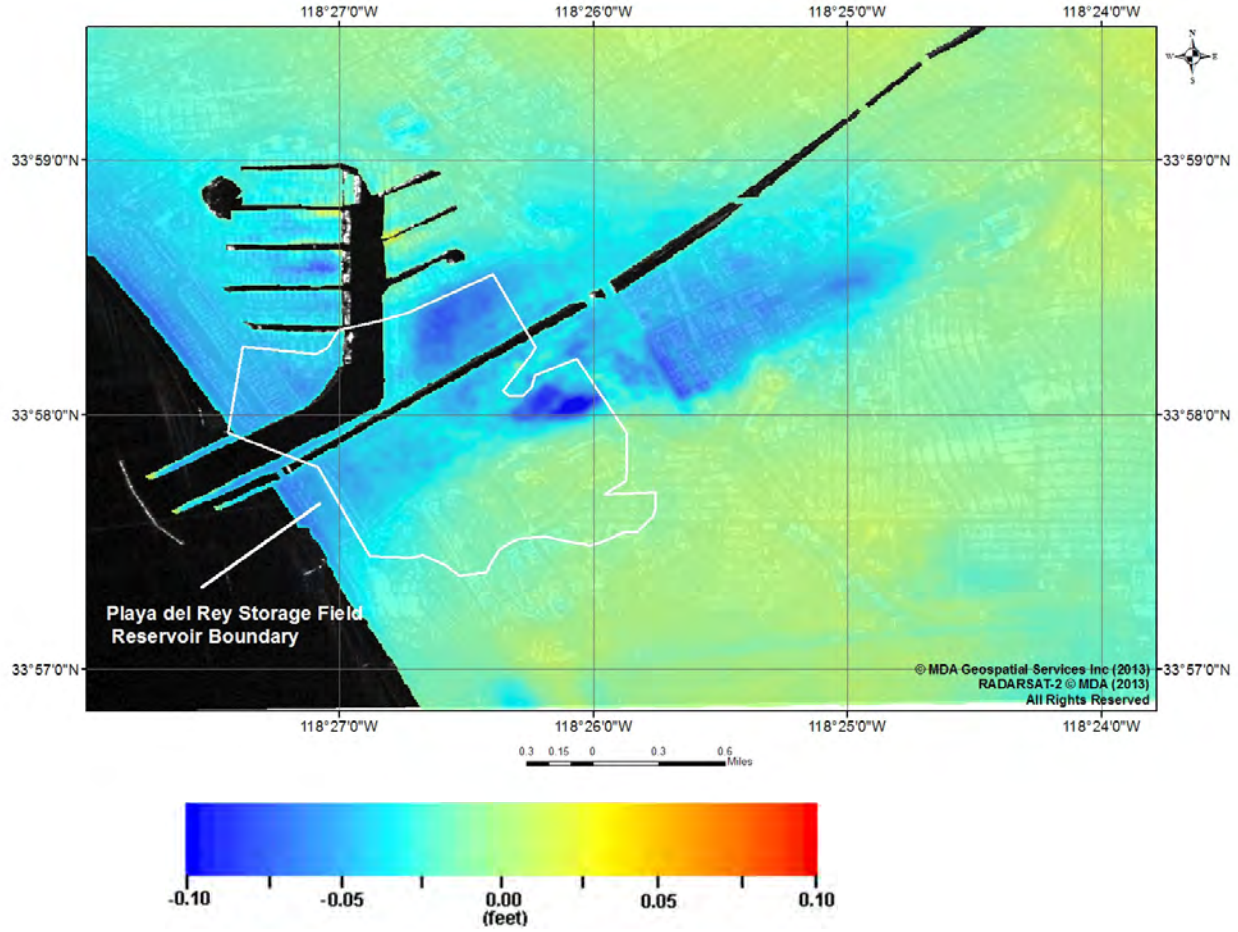

Figure 10: Zoom-in of Playa del Rey Gas Storage Field AOI and surrounding area. Cumulative vertical deformation from May 27, 2008 to December 8, 2012, with 0.01 ft contours.

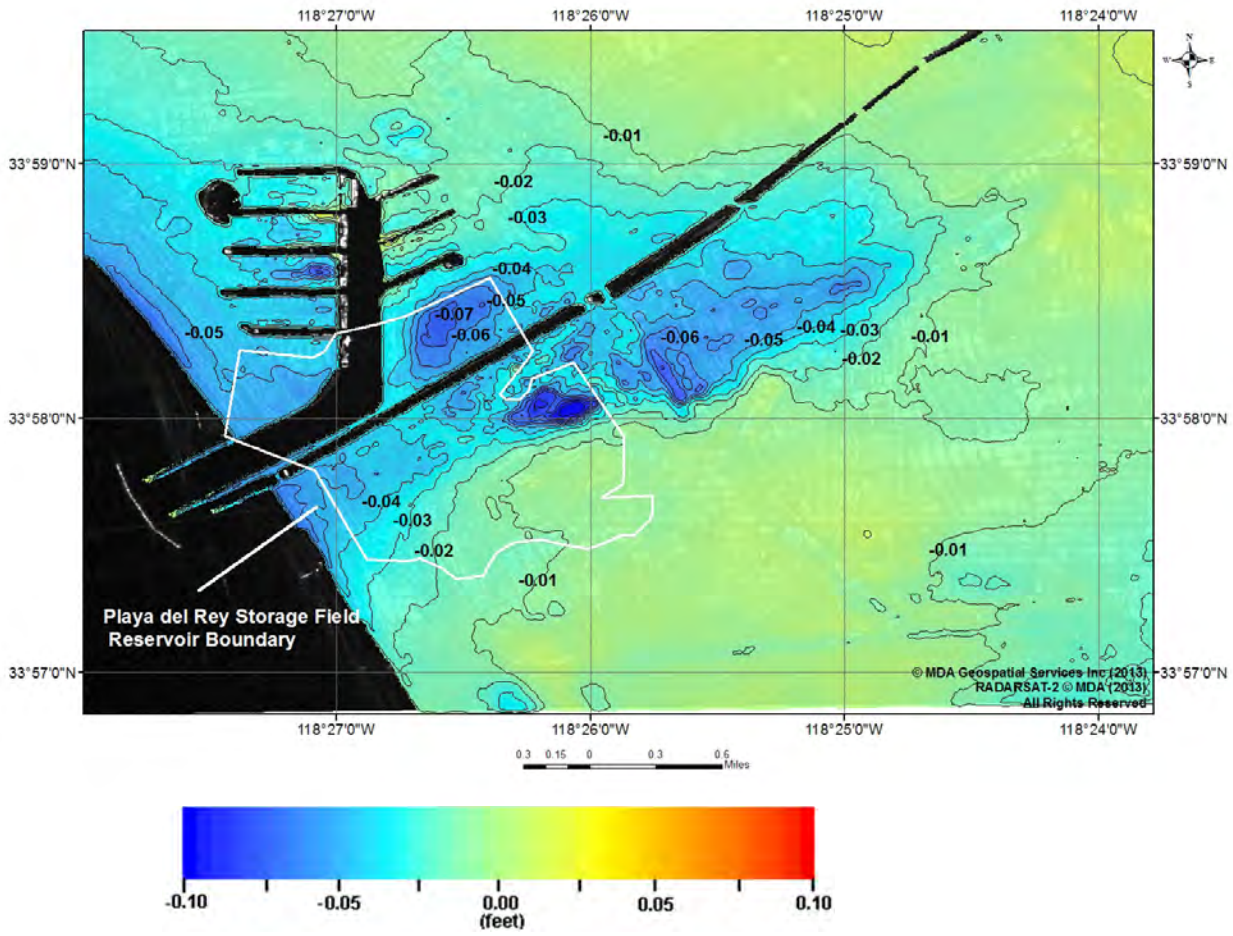

Figure 11: Playa del Rey Gas Storage Field AOI and surrounding area. Color representation of the cumulative vertical deformation from May 27, 2008 to December 14, 2011 superimposed onto SAR image.

3 Concluding Remarks

Vertical surface deformation measurements are derived for the Playa del Rey Gas Storage Field and surrounding areas in Los Angeles using conventional InSAR. This report, referred to as Interim Report H, pertains to Milestone 9 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 2012 to December 2012, were analyzed and utilized as part of the deliverable.
- Two deformation maps were generated. The estimated precision for the vertical deformation product Pair A, June 23, 2012 to September 3, 2012 is 0.012 ft with a 95% confidence interval. The estimated precision for Pair B, September 3, 2012 to December 8, 2012 is 0.012 ft with a 95% confidence interval.
- The variation in the reported InSAR ground surface movement to present is likely related to soil moisture changes. The majority of this variance is within the reported measurement of 0.02 ft, the noise level.
- The resulting analysis from June 2012 to December 2012, indicates that no major deformation pattern is occurring in the Playa del Rey Gas Storage Field.

A Deliverables

The deliverables, which are included on CD-ROM for Milestone 9, are listed in Table 6. These delivered data are described in XYZ ASCII files and are in California US State Plane, NAD27, 20 ft spacing.

Table 6: Delivered Data

Deliverable file	**Description**
PlayadelRey_SoCalGas_InterimReportH_2012.pdf	Interim Report H in PDF format.
Conventional Deformation map	
062312_090312_DEF.xyz 062312_090312_DEF.tif 090312_120812_DEF.xyz 090312_120812_DEF.tif	ASCII files with location and vertical deformation measurements in ft. Areas of low coherence 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 12.

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 13 shows the electromagnetic spectrum.

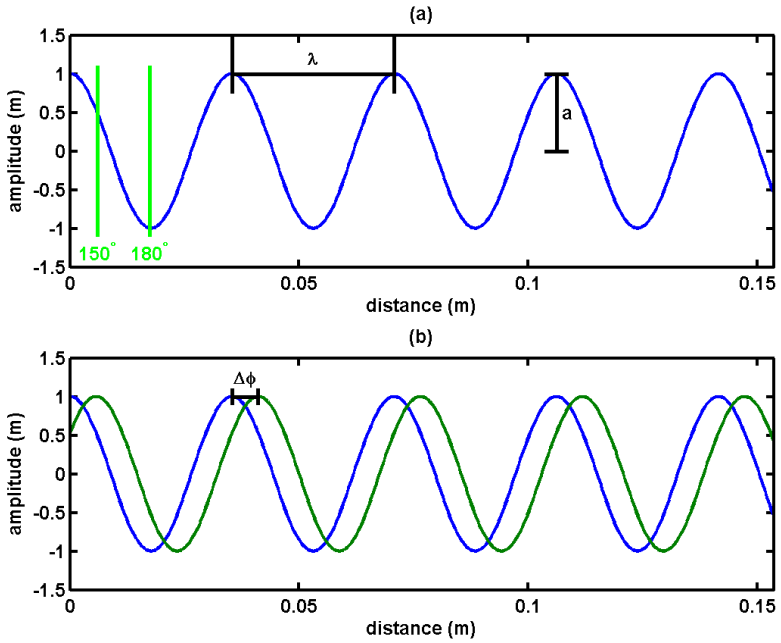

Figure 12: Definition of a 5.6-cm wave. Panel (a) shows the definition of wavelength, λ, and amplitude (a). The green lines show the location on the wave associated with 150° and 180° of phase. Panel (b) demonstrates the phase difference, $\Delta\phi$, between two waves.

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.

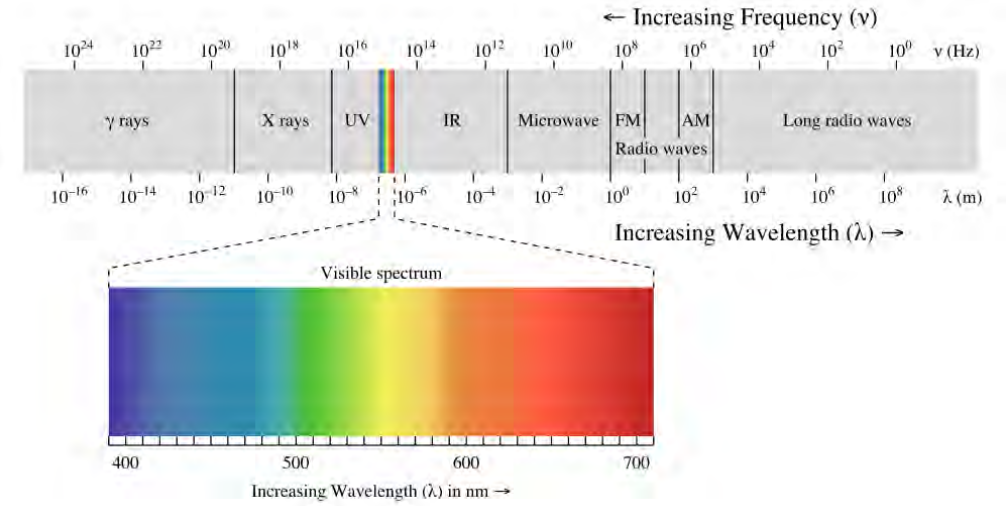

Figure 13: Electromagnetic spectrum showing the wavelength and frequency characteristics of radiation. The microwave portion of the spectrum contains the waves used for RADAR observation.

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 12 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 12 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.