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

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SUBMITTED TO:

Southern California Gas Company
555 W. Fifth Street (Mail Location 23E2)
Los Angeles, CA, USA
90013-1041

ATTN: Mr. Rick Gailing

SUBMITTED BY:

MDA Geospatial Services
57 Auriga Drive, Suite 201
Ottawa, Ontario K2E 8B2
CANADA

Tel: +1-613-727-1087
Fax: +1-613-727-5853

Prepared By:	____________________ Mary Anne McParland Remote Sensing Analyst	July 15, 2010
Reviewed By:	____________________ Michael Henschel Sr. SAR Specialist	July 15, 2010

Executive Summary

This report, Interim Report C, 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 2009 to June 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.

For this deliverable, Milestone 4, two (2) deformation products are produced from scheduled RADASAT-2 Ultra-Fine ascending radar imagery. The current deformation data produced from December 24, 2009 to June 10, 2010 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 2009 through to June 2010. For this deliverable, seven (7) 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 24, 2009 to March 6, 2010 (Pair A) and March 6, 2010 to June 10, 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.
- Deformation and uplift can be attributed to surface moisture in the area of interest. During the time period from December 2009 to March 2010 rainfall accumulation contributed to natural terrain expansion, hence uplift. Subsequently, minimal rainfall occurred from period March 2010 to June 2010 resulting in a decrease in natural terrain moisture.
- The estimated precision for the pair December 24, 2009 to March 6, 2010 vertical deformation product is 0.0183 ft with a 95% confidence interval; while the estimated precision for pair March 6, 2010 to June 10, 2010 vertical change product is 0.0195 ft with a 95% confidence interval.

- Two (2) summation products are generated. The first is for the six (6) month time period from December 24, 2009 to June 10, 2010 (Pair C). For this period, masked areas are interpolated and common mask areas between the two individual vertical deformation products are extracted and applied to the final summation product.

- The second summation product includes approximately two (2) years of monitoring from May 27, 2008 to June 10, 2010 (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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1 Interim Report C Objective

The objective of this report, Interim Report C, is to provide SoCalGas with measurements of the deformation that occurred within the project's AOI using conventional InSAR monitoring from December 2009 to June 2010. Seven (7) 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 fourth deliverable, Milestone 4, 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.
- 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 December 2009 to June 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	Comments
1	December 24, 2009	10583	Acquired
2	January 17, 2010	10926	Acquired
3	February 10, 2010	11269	Acquired
4	March 6, 2010	11612	Acquired
5	March 30, 2010	11955	Acquired
6	May 17, 2010	12641	Acquired
7	June 10, 2010	12984	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 6, 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 (1-4)	Dec-24-09	Mar-6-10	-126
B (4-7)	Mar-6-10	Jun-10-10	83

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 24, 2009 to March 6, 2010 and March 6, 2010 to June 10, 2010. Pair D is the summation from May 27, 2008 to June 10, 2010. For this product, the summation products delivered in the previous deliverables are added to the summation product of the current deliverable (Pair C). Masked areas for the overall summation are an accumulation of each of the previous masks.

2 Results - Interim Report C

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 24, 2009 to March 6, 2010 (72 days)
- Pair B for the time period between March 6, 2010 to June 10, 2010 (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-24-09 to Mar-6-10	72 days	0.0092	0.0183

Table 4: Summary of Pair B

Date	**Time Span**	**Noise Level standard deviation [ft]**	**95% Confidence interval [ft]**
Mar-6-10 to Jun-10-10	96 days	0.0097	0.0195

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 24, 2009 to March 6, 2010

The vertical deformation in the Playa del Rey Gas Storage Field is observed for the time period between December 2009 to March 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 threshholding 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 3. During the time period from December 2009 to March 2010 rainfall accumulation contributed to natural terrain expansion, hence uplift (see Table 5, historical weather data for the Los Angeles airport). A color representation is shown in Figure 4 and Figure 2 of the final product after masking areas that contain noise. The estimated precision for Pair A is within $\pm$0.0183 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	Trace

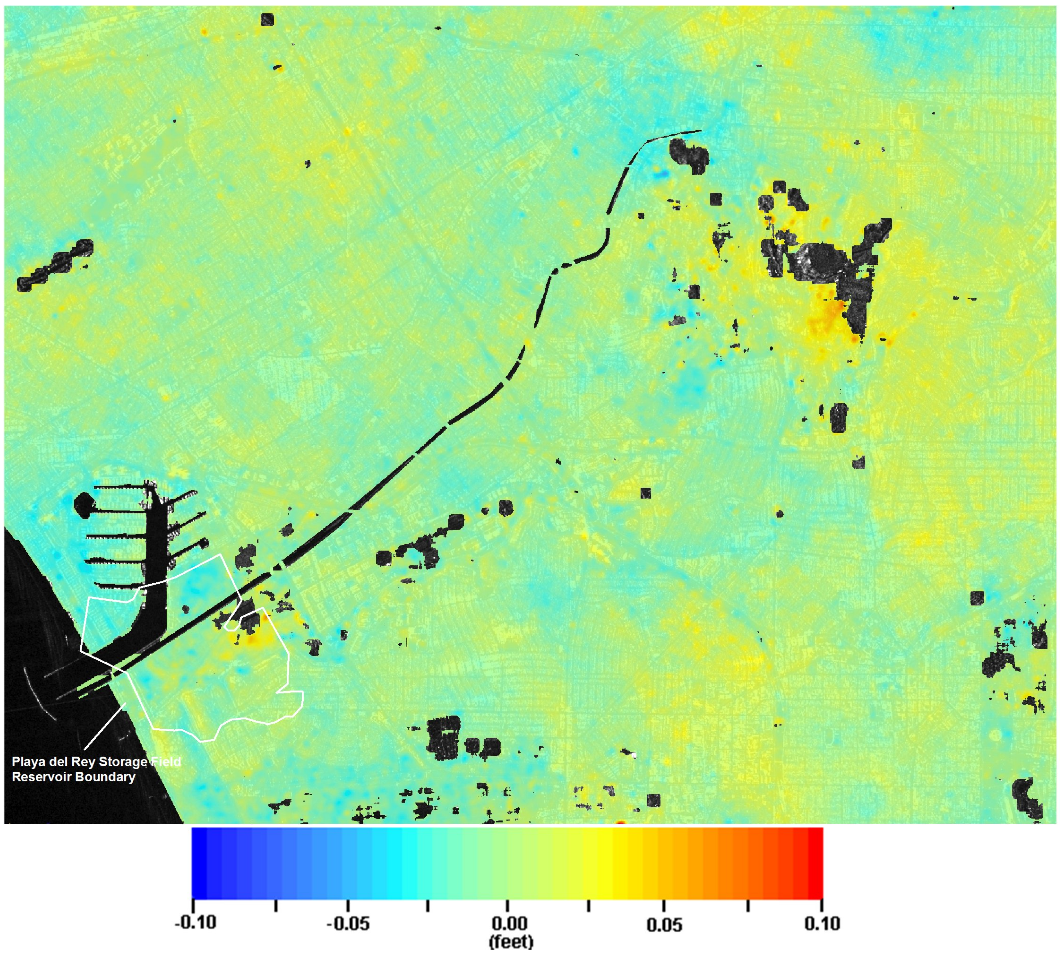

Figure 2: Zoom-in of Playa del Rey AOI. Colour representation of the vertical deformation product from December 24, 2009 to March 6, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

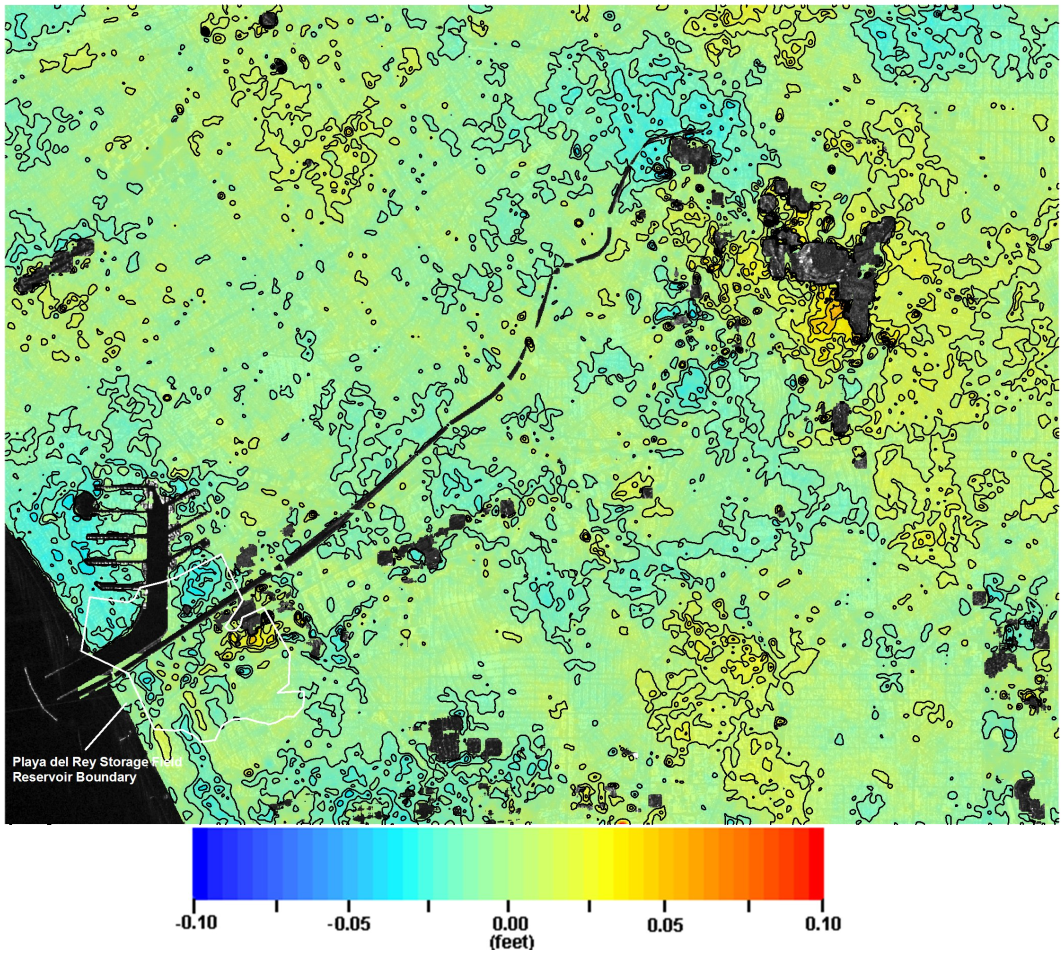

Figure 3: Zoom-in of Playa del Rey AOI. Colour representation of the vertical deformation product from December 24, 2009 to March 6, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

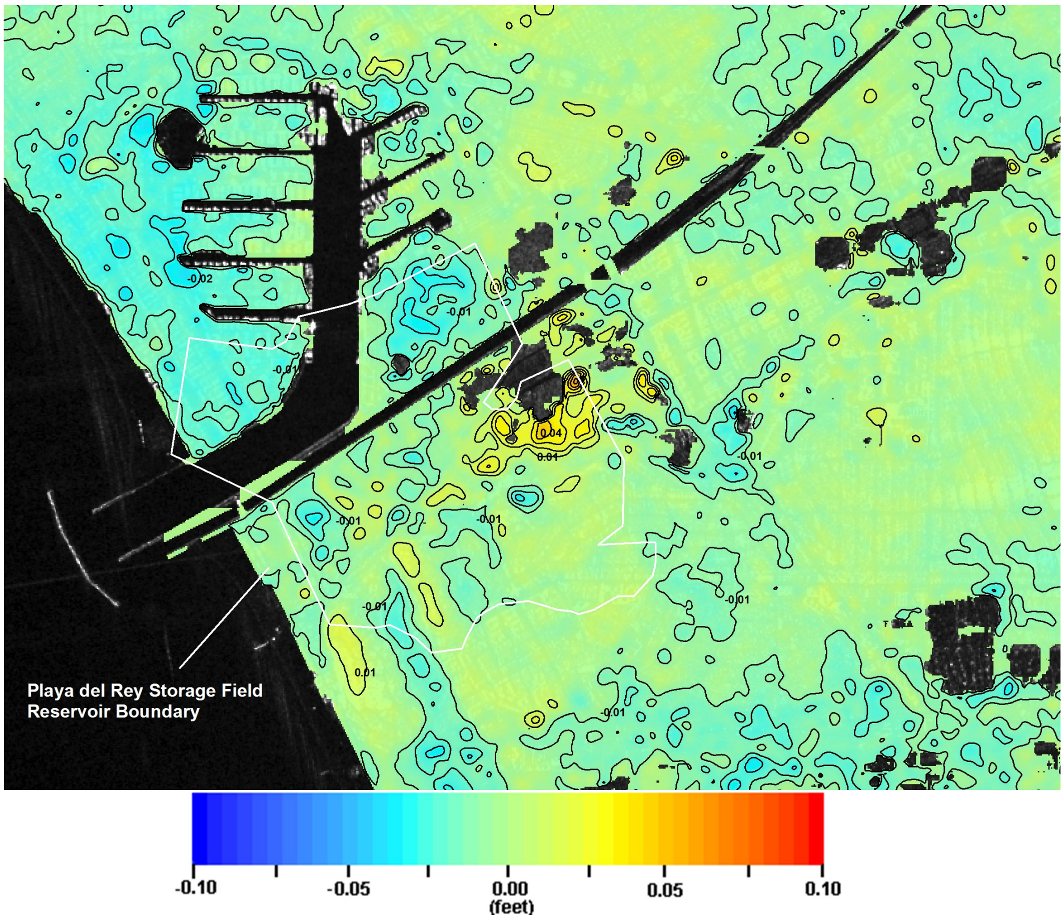

Figure 4: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the vertical deformation product from December 24, 2009 to March 6, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.2 Pair B - March 6, 2010 to June 10, 2010

The deformation in the Playa del Rey Gas Storage Field is observed for the time period between March to June, 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 threshholding the coherence image. Coherence (γ) values, $\gamma < 0.16$, are considered areas of low coherence and these are coherence and are masked out with values set to -999.

As shown in Table 5, historical weather data for the Los Angeles airport, minimal rainfall occurred from period March 2010 to June 2010 resulting in a decrease in natural terrain moisture.

Figure 7 and Figure 5 present a color representation of the final product after masking areas that contain noise. The estimated precision for Pair B is within $\pm$0.0195 ft with a 95% confidence interval.

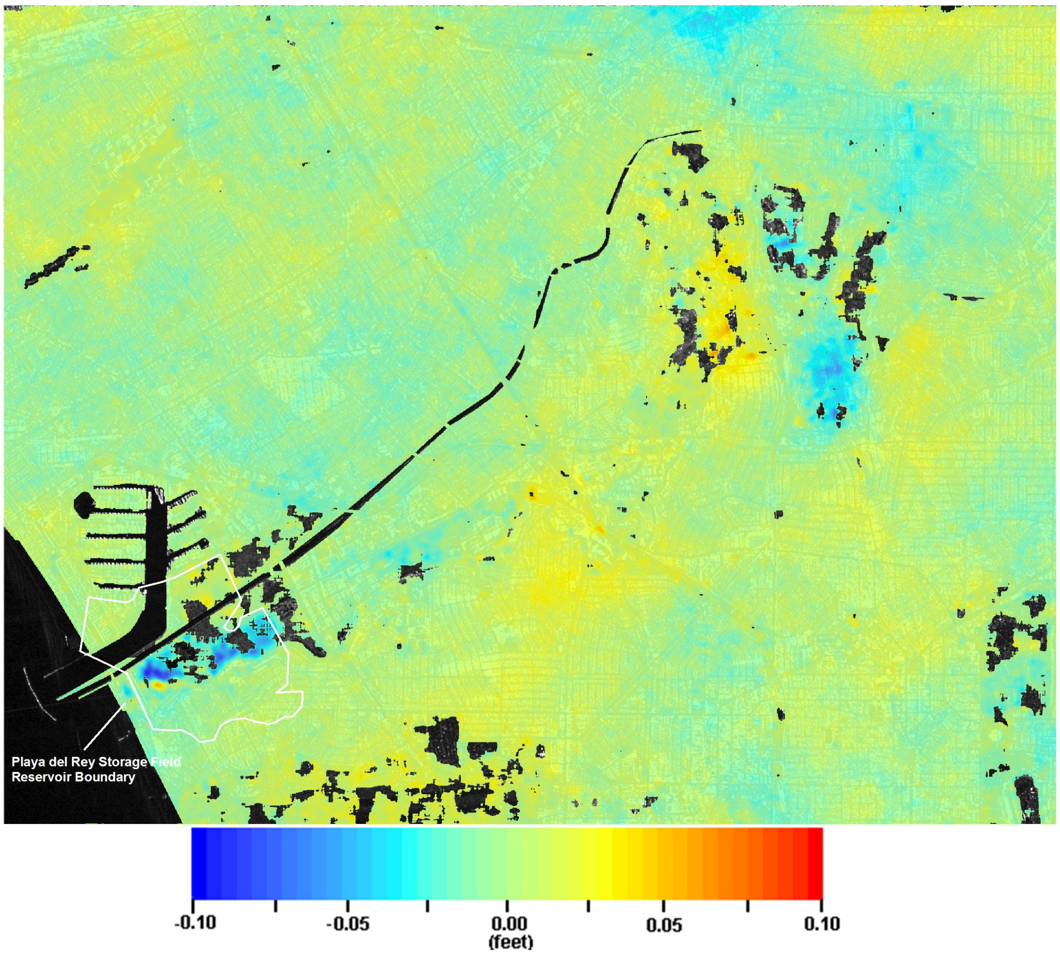

Figure 5: Zoom-in of Playa del Rey AOI. Colour representation of the vertical deformation product from March 6, 2010 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

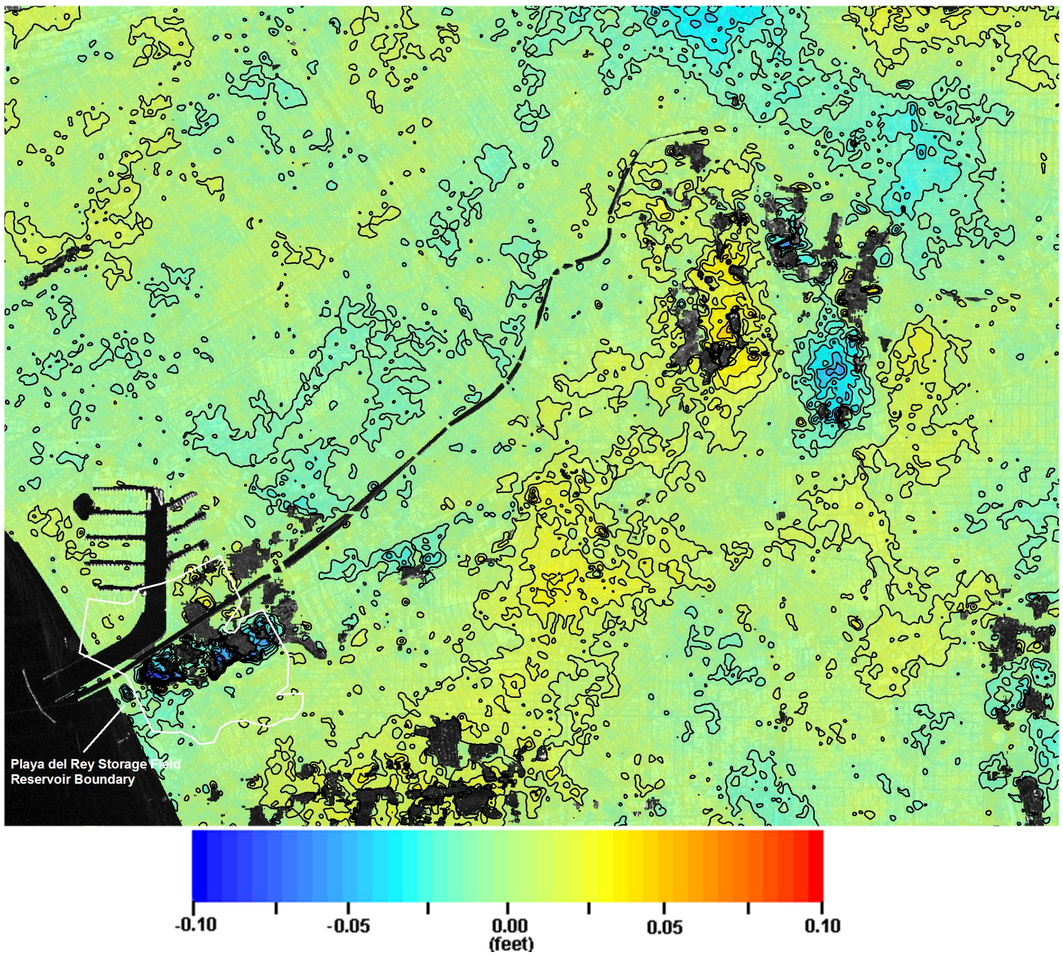

Figure 6: Zoom-in of Playa del Rey AOI. Colour representation of the vertical deformation product from March 6, 2010 to June 10, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

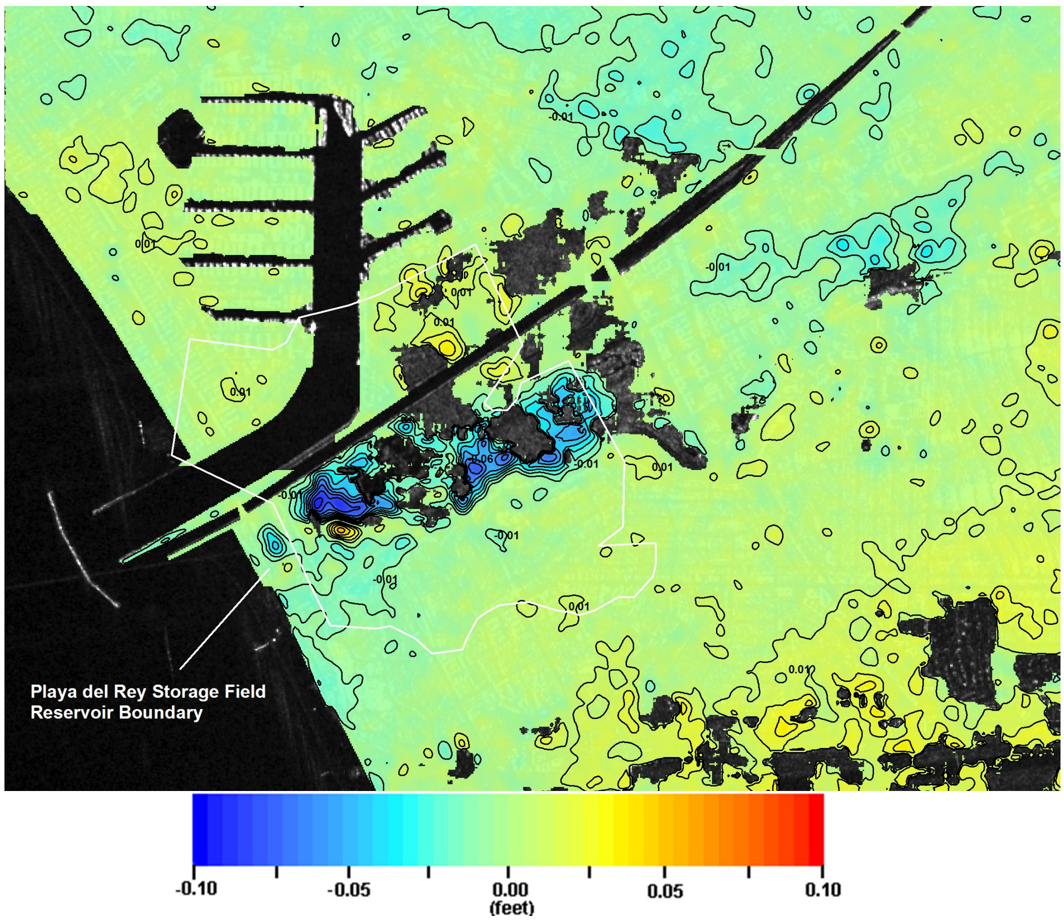

Figure 7: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the vertical deformation product from March 6, 2010 to June 10, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.3 Pair C - Summation December 24, 2009 to June 10, 2010

Figure 8 shows the summation of the individually estimated deformation results during the two (2) time periods (December 2009 to March 2010 and March 2010 to June 2010). 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 33°59’ 42"N 118°21’42"W. Subsidence in this area is in the order of 0.03 - 0.05 ft as shown in Figure 11 to Figure 12. West of the subsidence is an area of uplift, center coordinate 34°00’ 18"N 118°22’ 35"W. Uplift in this area is in the order of 0.04 - 0.09 ft as shown in Figure 11 to Figure 12.

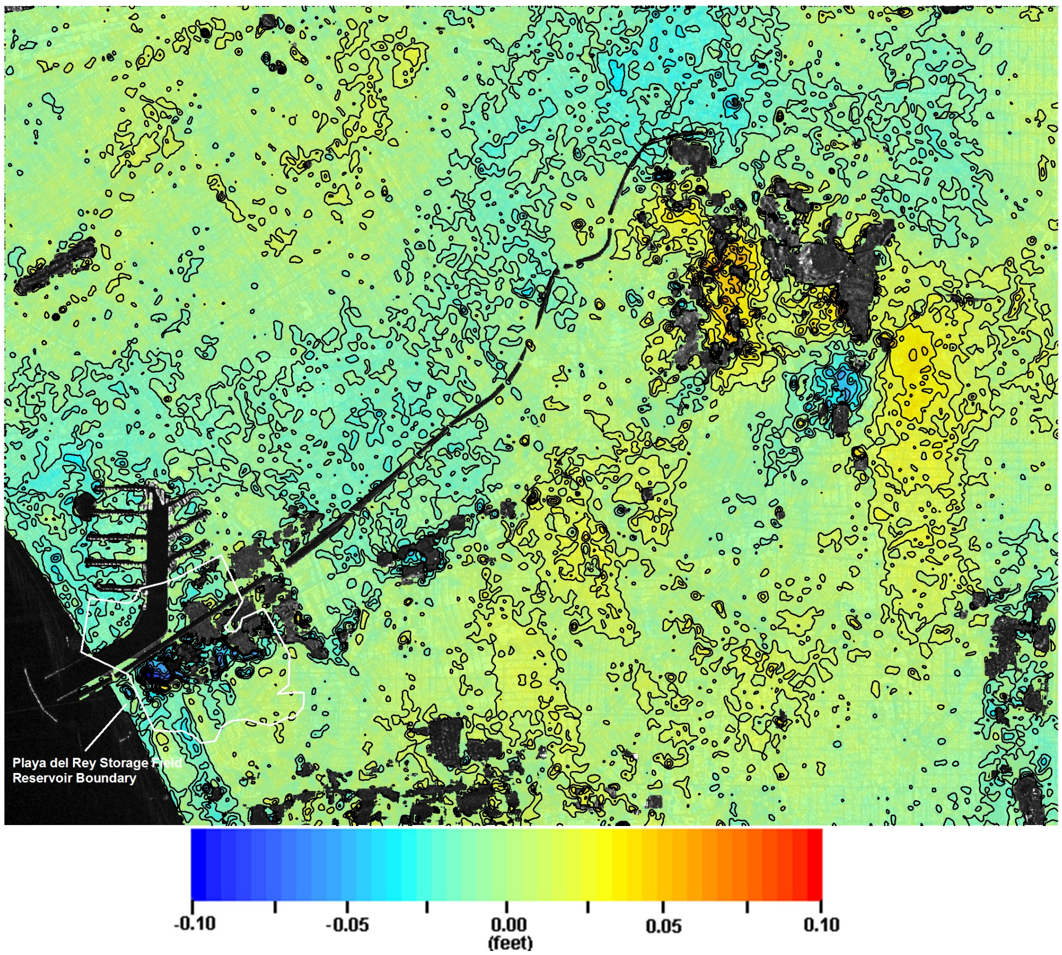

Figure 8: Zoom-in of Playa del Rey AOI. Colour representation of the summation of the vertical deformation products from December 24, 2009 to June 10, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

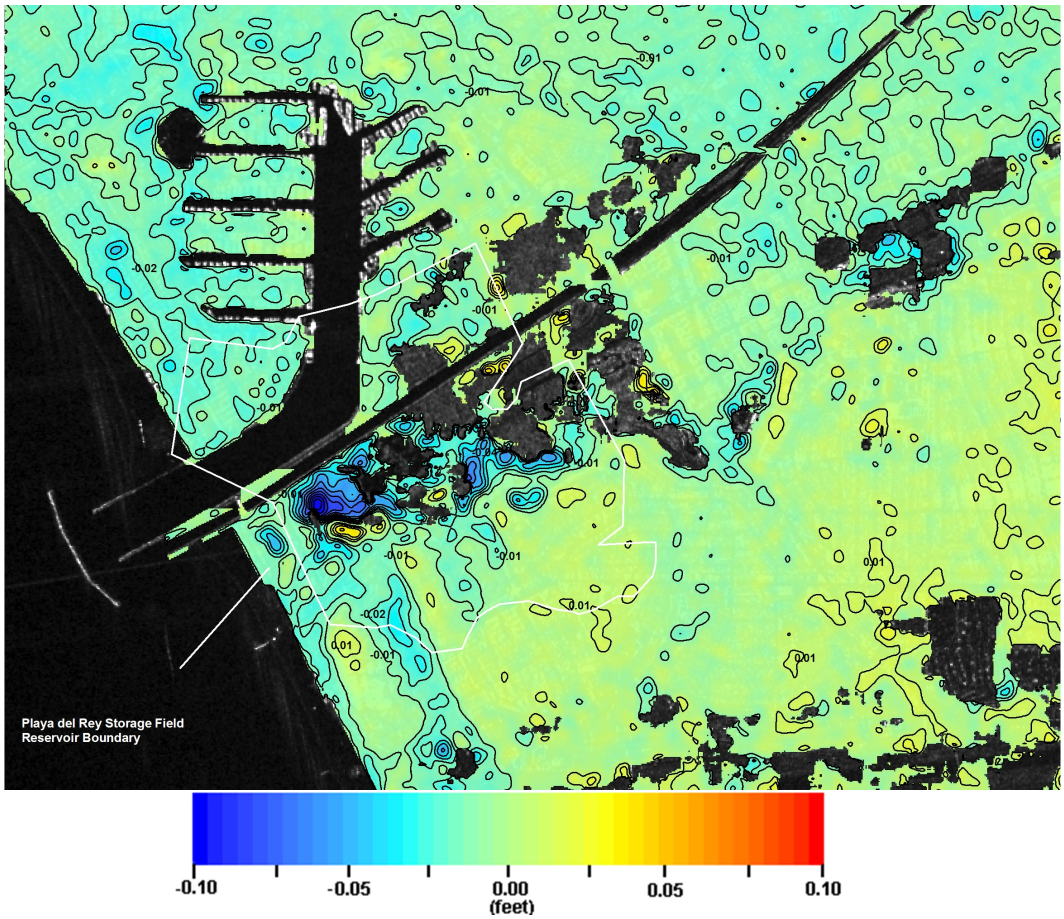

Figure 9: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the summation of the vertical deformation products from December 24, 2009 to June 10, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

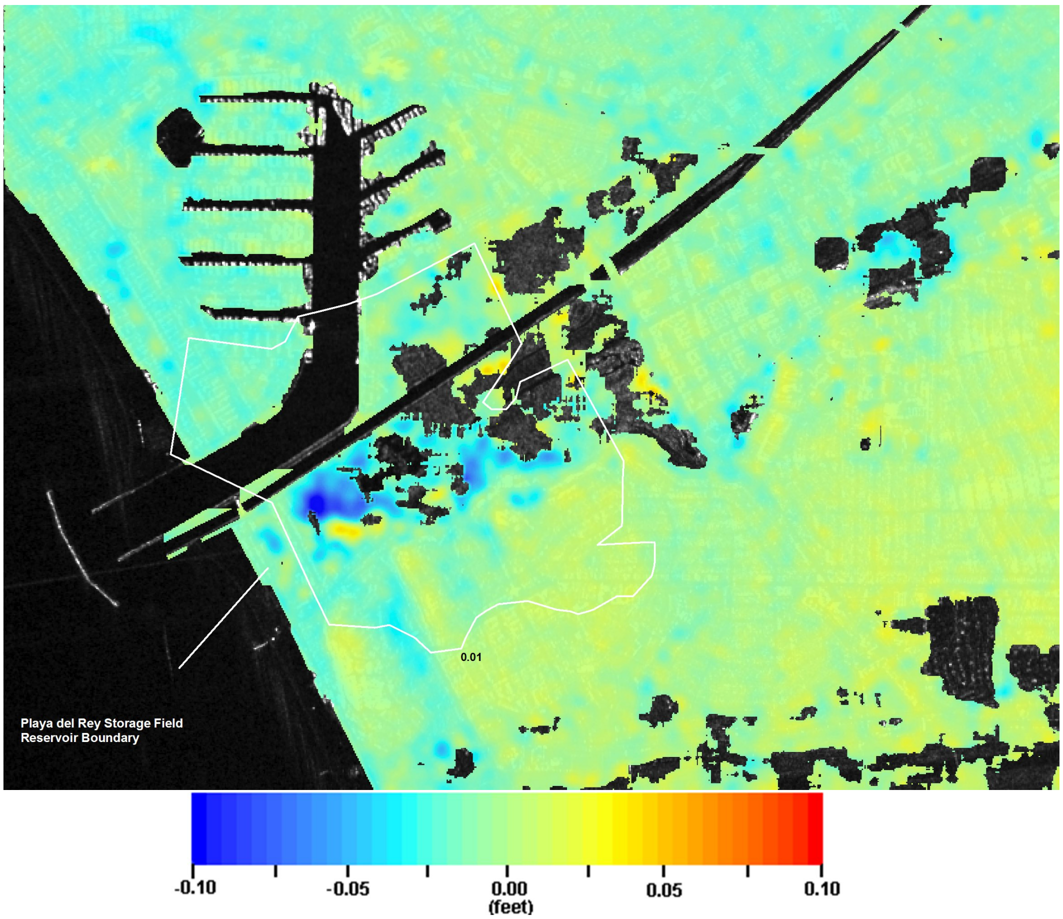

Figure 10: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the summation of the vertical deformation products from December 24, 2009 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

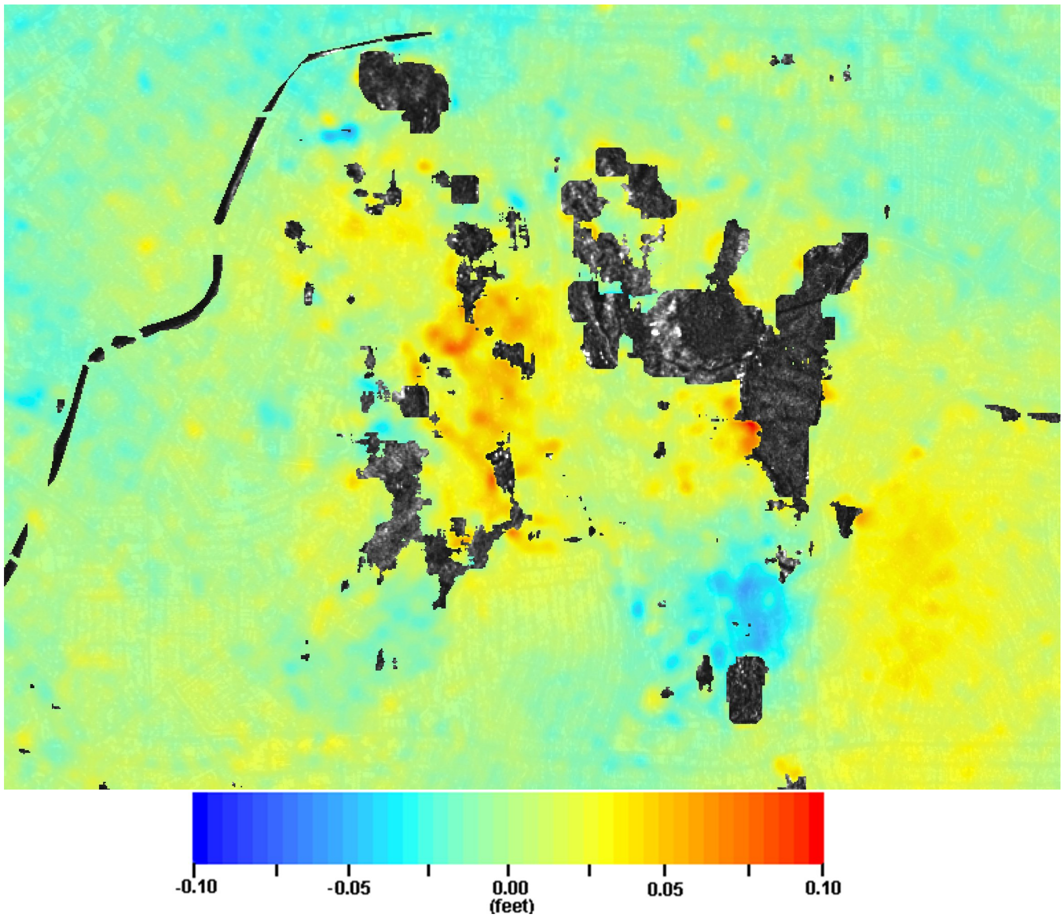

Figure 11: Zoom-in of area between Culver City, Ladera Heights and Windsor Hills. Colour representation of the summation of the vertical deformation products from December 24, 2009 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

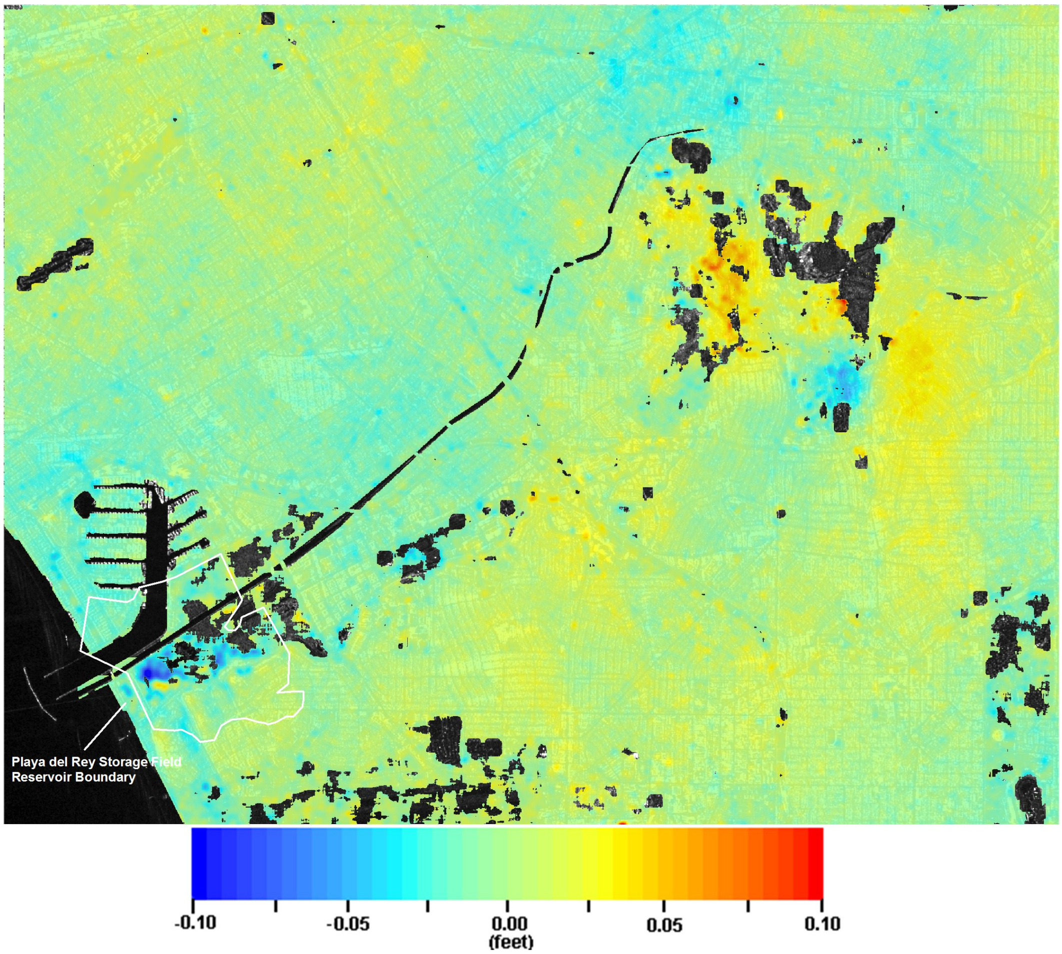

Figure 12: Zoom-in of Playa del Rey AOI. Colour representation of the summation of the vertical deformation products from December 24, 2009 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

2.4 Pair D - Summation May 27, 2008 to June 10, 2010

Figure 13 shows the summation of the individually estimated deformation results starting May 27, 2008 (May 2008 to August 2008, August 2008 to December 2008, December 2008 to March 2009, March 2009 to June 2009, June 2009 to September 2009, September 2009 to December 2009, December 2009 to March 2010, March 2010 to June 2010). From Figure 13, Figure 14 and Figure 15, 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 related to the relatively high precipitation during this time period (December 2009 to March 2010).

Subsidence is observed over an area situated between Ladera Heights and Windsor Hills, center coordinate 33°59' 44"N 118°21' 47"W. Subsidence in this area is in the order of 0.05 - 0.17 ft as shown in Figure 16 and Figure 18. Uplift is observed over an area situated between Ladera Heights and Culver City, center coordinate 34°0' 39"N 118°23' 01"W. Uplift in this area is in the order of 0.05 - 0.14 ft as shown in Figure 16 and Figure 18.

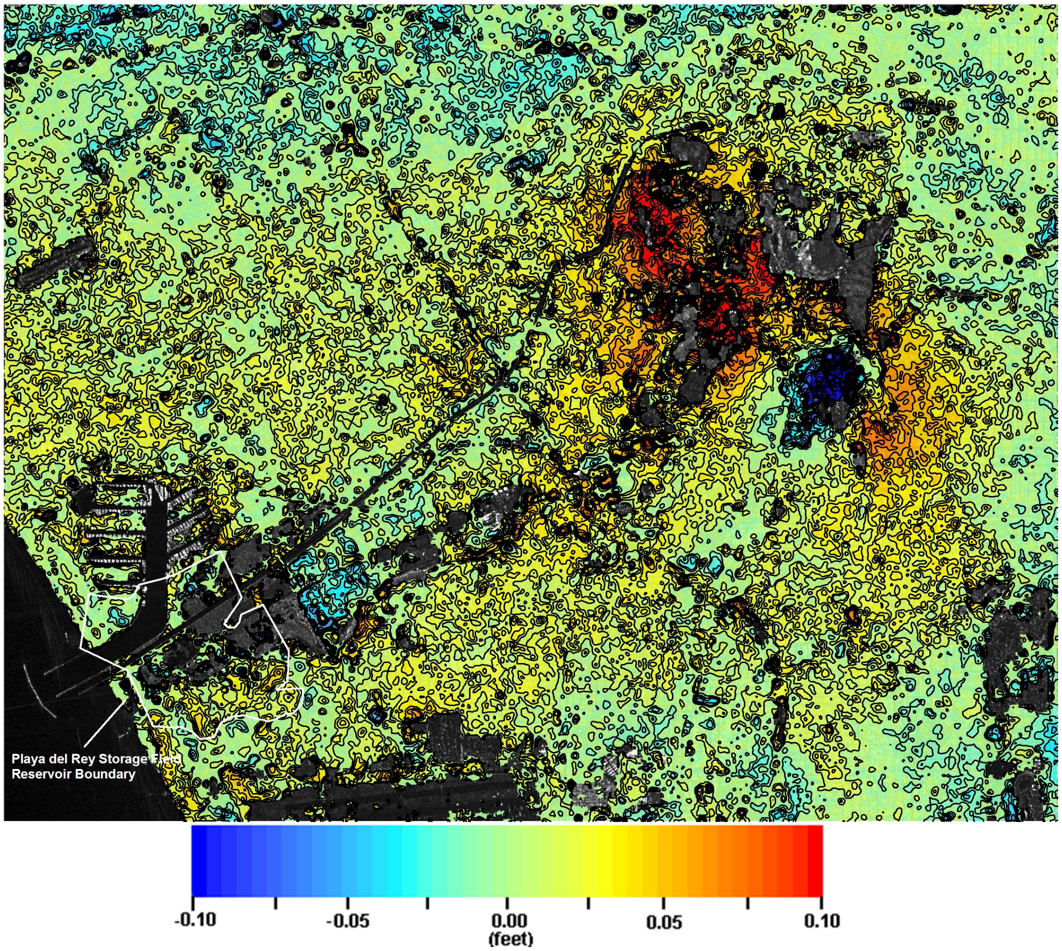

Figure 13: Zoom-in of Playa del Rey AOI. Colour representation of the summation of the vertical deformation products from May 27, 2008 to June 10, 2010 superimposed on SAR image with 0.01 ft contours. In this representation, blue corresponds to subsidence and red indicates uplift.

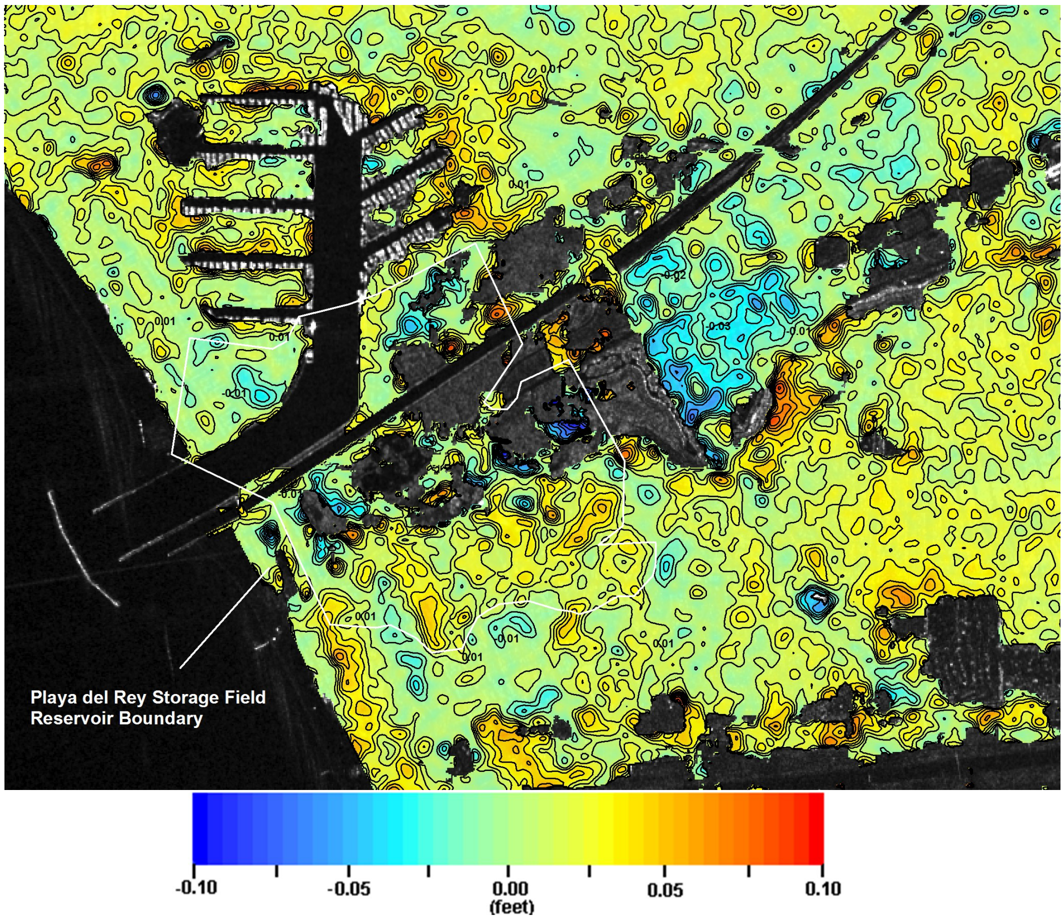

Figure 14: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the summation of the vertical deformation products from May 27, 2008 to June 10, 2010 superimposed on SAR image with 0.01 ft contours In this representation, blue corresponds to subsidence and red indicates uplift..

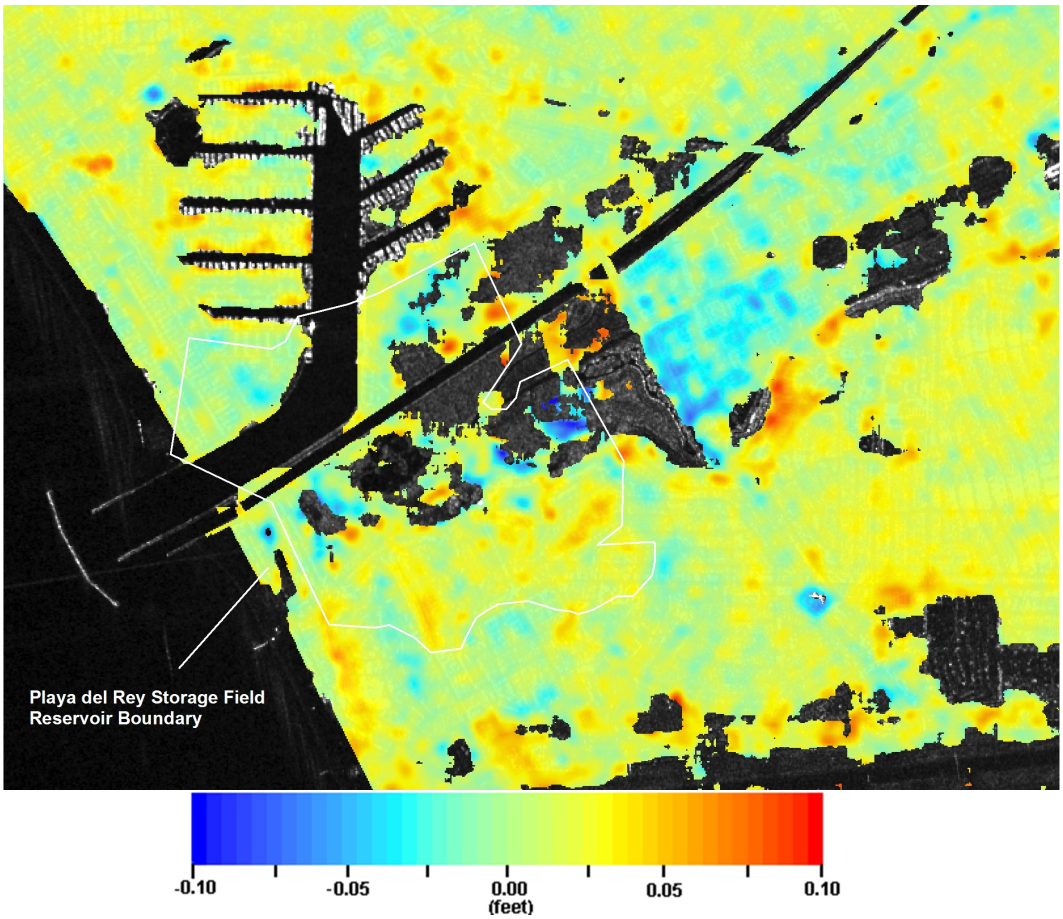

Figure 15: Zoom-in of Playa del Rey Gas Storage Field. Colour representation of the summation of the vertical deformation products from May 27, 2008 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

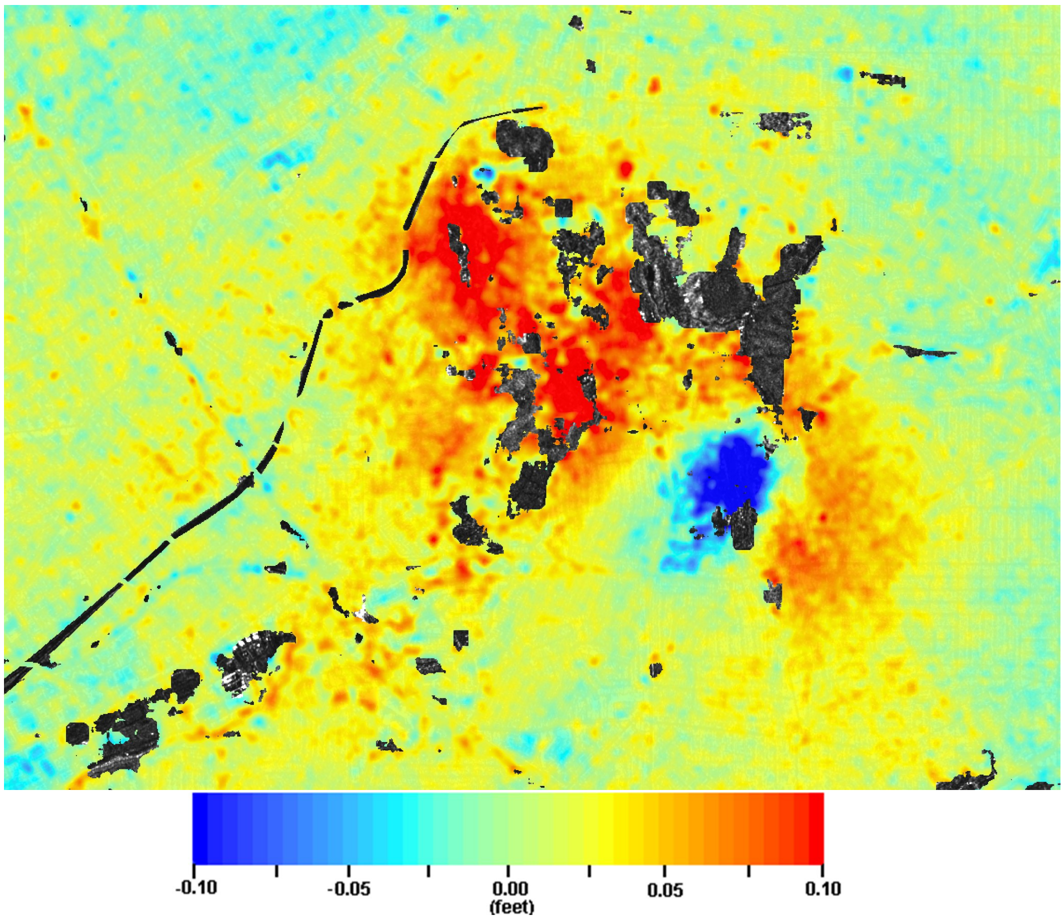

Figure 16: Zoom-in of area between Culver City, Ladera Heights and Windsor Hills. Colour representation of the summation of the vertical deformation products from May 27, 2008 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

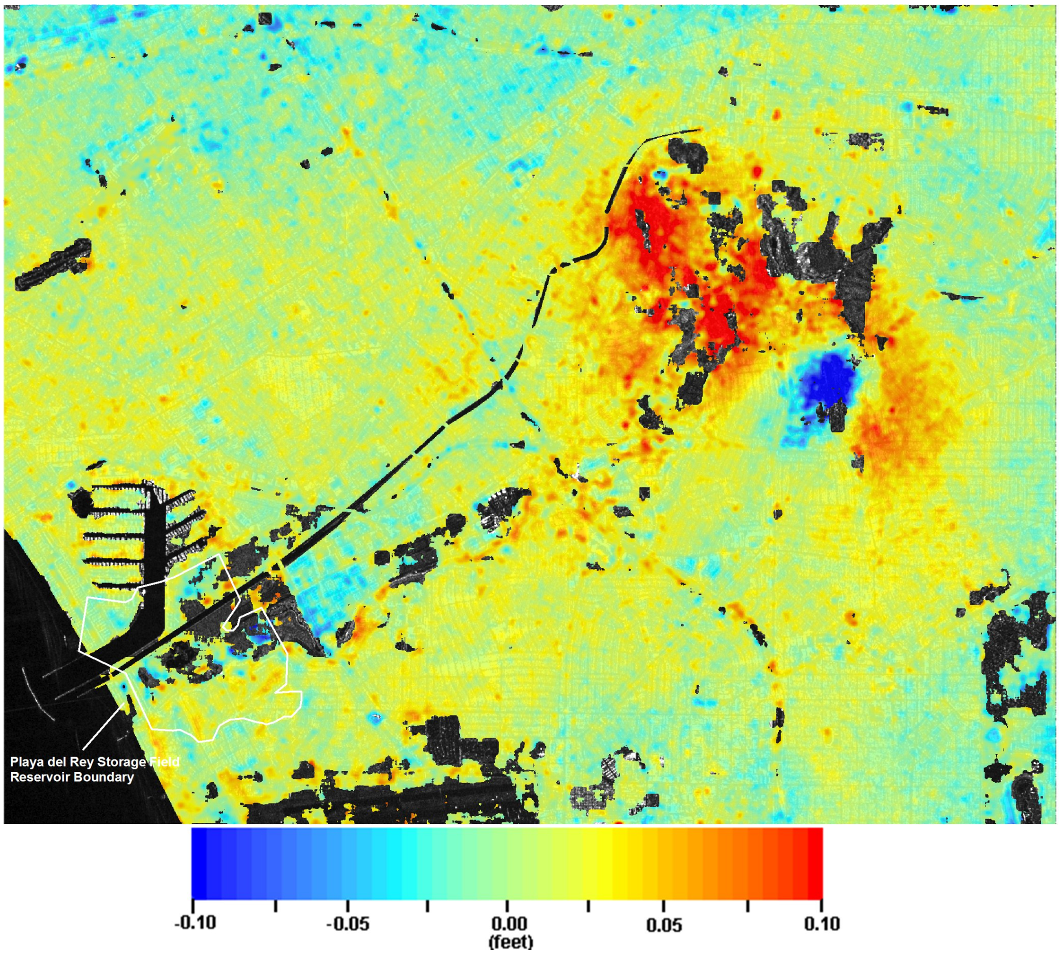

Figure 17: Zoom-in of Playa del Rey AOI. Colour representation of the summation of the vertical deformation products from May 27, 2008 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

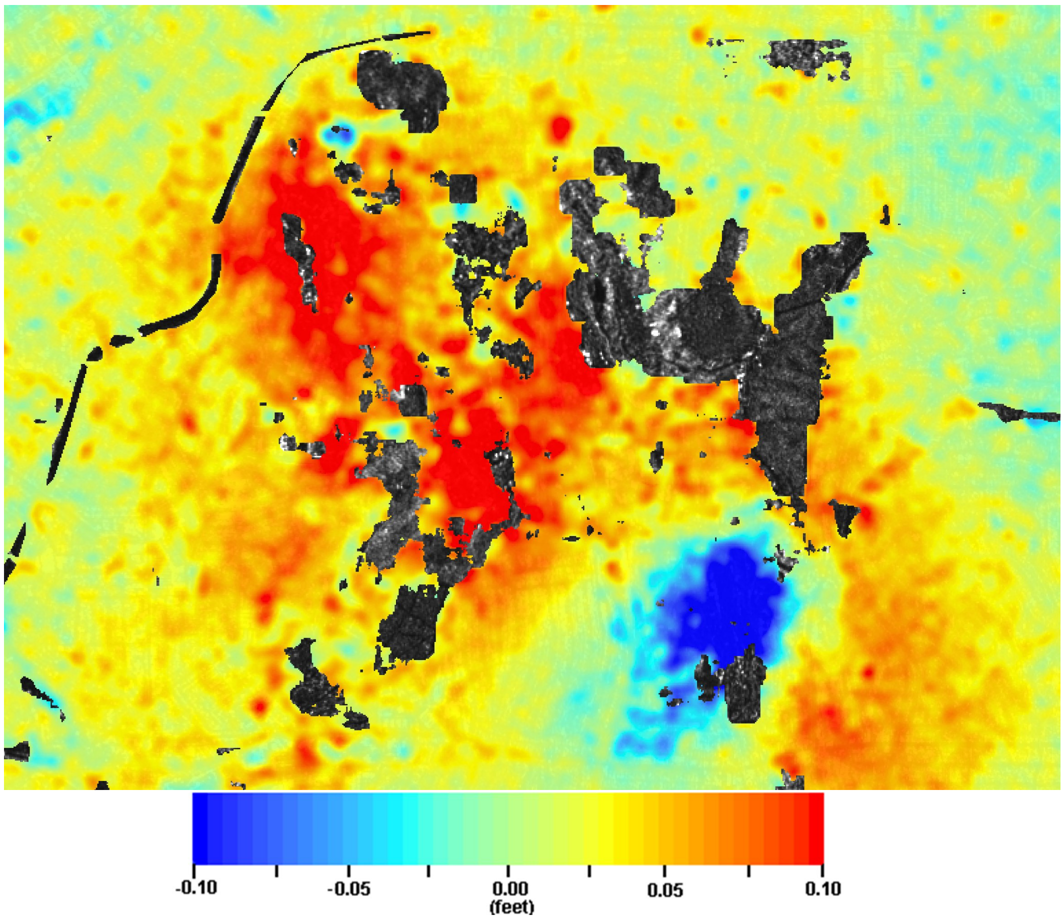

Figure 18: Zoom-in of area between Culver City, Ladera Heights and Windsor Hills. Colour representation of the summation of the vertical deformation products from May 27, 2008 to June 10, 2010 superimposed on SAR image without contours. In this representation, blue corresponds to subsidence and red indicates uplift.

3 Concluding Remarks

Vertical surface deformation measurements are calculated for the Playa del Rey Gas Storage Field and surrounding areas in Los Angeles using conventional radar interferometry (InSAR). This report, referred to as Interim Report C, pertains to Milestone 4 of the current contract.

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

- RADARSAT-2 Ultra-Fine ascending data were scheduled by MDA for acquisition. The acquired data, covering the period of December 2009 to June 2010, were analyzed and utilized as part of the deliverables.
- Two (2) deformation maps were generated as part of the fourth Milestone of a five (5) year monitoring program.
- The estimated precision for the Pair A vertical deformation product is 0.0183 ft with a 95% confidence interval; while the estimated precision for Pair B vertical deformation product is 0.0195 ft with a 95% confidence interval.
- Two (2) summation products are generated. The first is for the six (6) month time period from December 24, 2009 to June 10, 2010 (Pair C). For this period, masked areas are interpolated and common mask areas between the two individual vertical deformation products are extracted and applied to the final summation product.
- The second summation product includes approximately two (2) years of monitoring from May 27, 2008 to June 10, 2010 (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.
- Deformation is present in the outlying areas, as seen in the vertical summation product for Pair D (Figure 17). The subtle deformation seen in the Playa Del Rey Gas Storage field however is due to seasonal moisture change, as discussed in the previous sections. The next 3 years should confirm what the nature of the changes occurring within the SoCalGas AOI are related to.

A Deliverables

The deliverables, which are included on CD-ROM for Milestone 4, 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_InterimReportC_2010.pdf	Interim Report C in PDF format.
Conventional Deformation map	
122409_030610_DEF.xyz 122409_030610_DEF.tif 030610_061010_DEF.xyz 030610_061010_DEF.tif SUM_122409_061010_DEF.xyz SUM_122409_061010_DEF.tif SUM_052708_061010_DEF.xyz SUM_052708_061010_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. Additional format supplied as Geotiff.
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 19.

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 20 shows the electromagnetic spectrum.

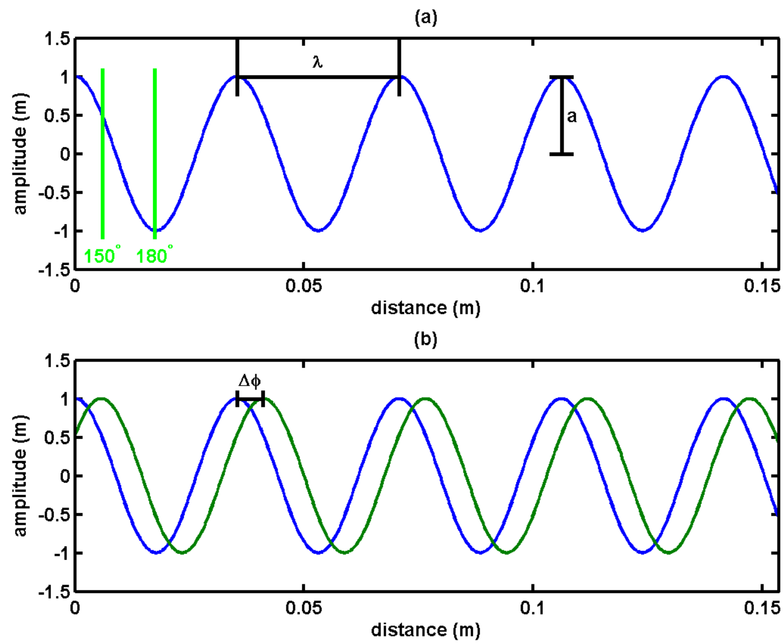

Figure 19: Definition of a 5.6-cm wave. Panel (a) shows the definition of wavelength, λ, and amplitude (a). The green lines show the location on the wave associated with 150° and 180° of phase. Panel (b) demonstrates the phase difference, $\Delta\phi$, between two waves.

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.

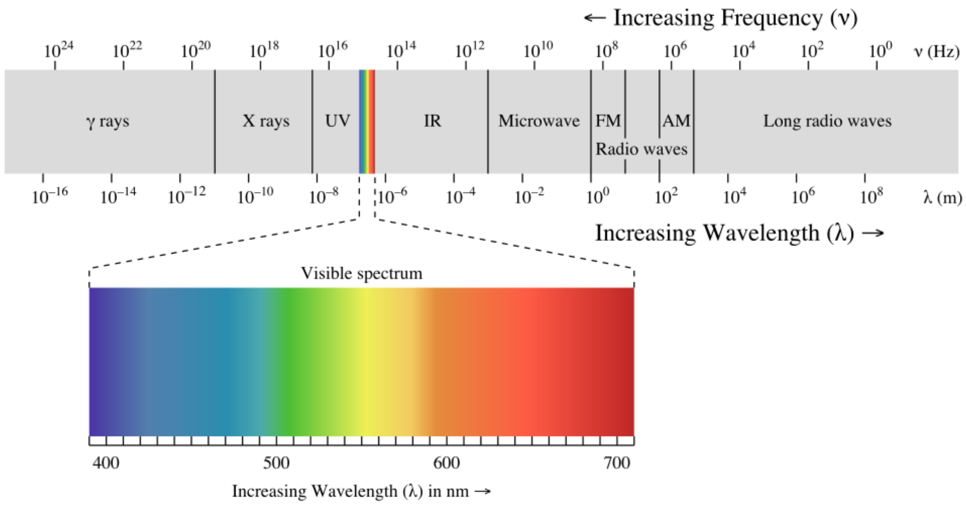

Figure 20: Electromagnetic spectrum showing the wavelength and frequency characteristics of radiation. The microwave portion of the spectrum contains the waves used for RADAR observation.

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 19 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 19 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.