Sulphur Mines Salt Dome

Calcasieu Parish, LA

Enhanced Subsidence Monitoring Program

Continuous InSAR Monitoring of Ground Displacement Near Western Caverns and Dome Flank

LCO Project F2219.7

Prepared for:

Westlake US 2 LLC

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Louisiana Firm License Number EF-5937

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CERTIFIED BY:
Lonquist & Co., LLC

Louisiana Registration No. EF5937

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Date Signed: March 13, 2023
Baton Rouge, LA

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Introduction

Salt caverns are created through a process called solution salt mining. This is done by drilling into a salt formation and circulating water into the drilled hole to dissolve the salt. This process forms a brine-filled cavern within the salt structure. Salt caverns can then be used to store petroleum, natural gas and various other gases such as hydrogen and ammonia. Salt domes have been known to experience deformation due to gradual closure of the mined spaces within the salt formation or other geological processes related to the salt and overlying caprock. The gradual closure of cavern space is formally known as salt creep and stops only when the cavern has reached a geostatic equilibrium with the surrounding rock. Factors such as cavern depth, temperature, salt properties, regional stresses, overburden density, operating pressures, and the geometry of and proximity to neighboring caverns affect the magnitude of salt creep.

Due to salt creep, the overburden rock structure begins to move downward towards the caverns. This can be seen on the surface as ground subsidence (or ground displacement) vertically and to a lesser extent horizontally toward the center of the subsidence basin. Consequently, it is anticipated that surface subsidence will transpire over all solution-mined caverns in domal and bedded salt to varying extents. The vertical movement over a solution-mined cavern generally ranges from less than ¼ inch annually to several inches per year. Pursuant to the provisions of Statewide Order 29-M (LAC 43: XVII. Subpart 3) and Statewide Order 29-M-3 (LAC 43: XVII. Subpart 5), this subsidence or displacement must be measured annually over all solution-mining and storage caverns.

At Sulphur Mines Salt Dome, recent events have required that an enhanced monitoring effort be implemented on the western side of the dome flank by Westlake 2 US, LLC (“Westlake”). Westlake has contracted Lonquist and Co. LLC (“Lonquist”) to implement the features of this enhanced monitoring plan. This plan is being submitted to comply with Item 2 of the First Supplement to Compliance Order IMD 2022-027.

An annual subsidence monitoring plan for the Sulphur Mines Salt Dome is being prepared under a separate cover. This enhanced monitoring plan is not intended to replace or recreate the analyses conducted in the annual subsidence monitoring surveys submitted by the three cavern operators on the dome. The deliverables from the enhanced plan will be supplementary, with a focus on early detection of trend deviation or changes in displacement acceleration for areas generally on the western side of the dome.

Continuous Subsidence Monitoring Methodology

An investigation of the technologies and methods available for frequent monitoring of ground displacement was performed. Interferometric Synthetic Aperture Radar (InSAR) was identified as the most well established and rapidly deployable method to continually evaluate small, normally undetectable, ground movement over a large area. InSAR is a high-accuracy, remote sensing technology that effectively provides an updated level survey of a target area with each successive pass of an orbiting satellite. Spatial density of the measurement points varies, but in areas of non-vegetated ground cover, a great number of datapoints can be continually gathered. This is the primary feature that sets the technology apart from other surveying methods.

TRE-Altamira ("TREA"), a global leader in InSAR ground displacement monitoring, has been contracted by Lonquist to collect, process, and deliver ground displacement data with each orbital pass from a collection of satellites. TREA utilizes an advanced, proprietary form of InSAR data processing that tracks ground movement by analyzing a stack of radar images collected over time. This technology, termed SqueeSAR, provides a collection of spatially distributed measurement points that each contain a time-series of ground deformation measurements reported to a 0.1 mm (0.004 inch) scale. Appendix A has been prepared by TREA and should be referenced for a detailed description of the InSAR monitoring system and data processing method.

InSAR Data Collection and Monitoring Frequency

Data Properties

Imagery collected via satellites over successive orbital passes is used to identify and define measurement points on the ground. Objects or ground features providing a stable reflection of radar energy such as buildings, roads, and infrastructure produce the highest quality measurement points. Measurement points can be generated in some areas with vegetation, but data quality is affected by changing ground characteristics over time, leading to data gaps in areas with dense vegetation or wetlands. In the absence of stable reflectors, additional datapoints can sometimes be generated in areas with lower but homogenous signal return by averaging groups of readings into a single measurement point.

InSAR uses phase and amplitude in the radar signal images to measure the distance between the satellite sensor and the measurement points on the ground. The data generated from the InSAR technique results in a time-series of displacement values at each measurement point. These displacement values are reported in relation to the original distance measured for each point in the dataset.

When a measurement point on the ground moves, whether that be vertically or laterally, the phase value detected by the sensor on the satellite is impacted due to a change in the distance between the sensor and ground target. Displacement values generated in this way are referred to as 1-D Line-of-sight ("LOS") measurements, referring to the line-of-sight of the satellite to the ground target. Data collected in this manner is understood to convey a movement distance that is not purely vertical. This distinction only affects the assignment of a precise direction to the movement identified. As the primary component of the observed displacement is often vertical, InSAR analyses based on 1-D data are regularly used to identify and monitor the consistency of movement trends related to ground subsidence.

Analysis of an InSAR dataset allows for the identification of displacement velocity in inches/year and acceleration in inches/year^2. Measurement precision is affected by the satellite sensor resolution and the timeframe of the dataset. Average accuracy ranges for individual measurements can vary between ±0.20 inches for a low-resolution satellite and ±0.03 inches for a high-resolution satellite. With time, velocity trends can be measured with high accuracy yielding standard deviations in the range of ±0.01 inches/year.

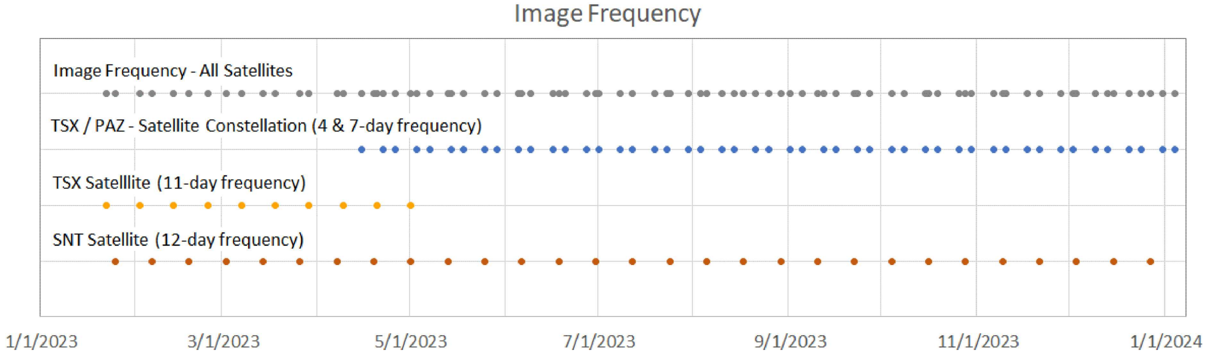
Data Collection Frequency

The two InSAR datasets that will be used to facilitate continuous monitoring of the Sulphur Mines Salt Dome are 1-D readings acquired from InSAR satellites on both ascending and descending orbits. An ascending orbit denotes the satellite's longitudinal course from south to north as it passes over the site, while a descending orbit denotes the satellite is moving from north to south.

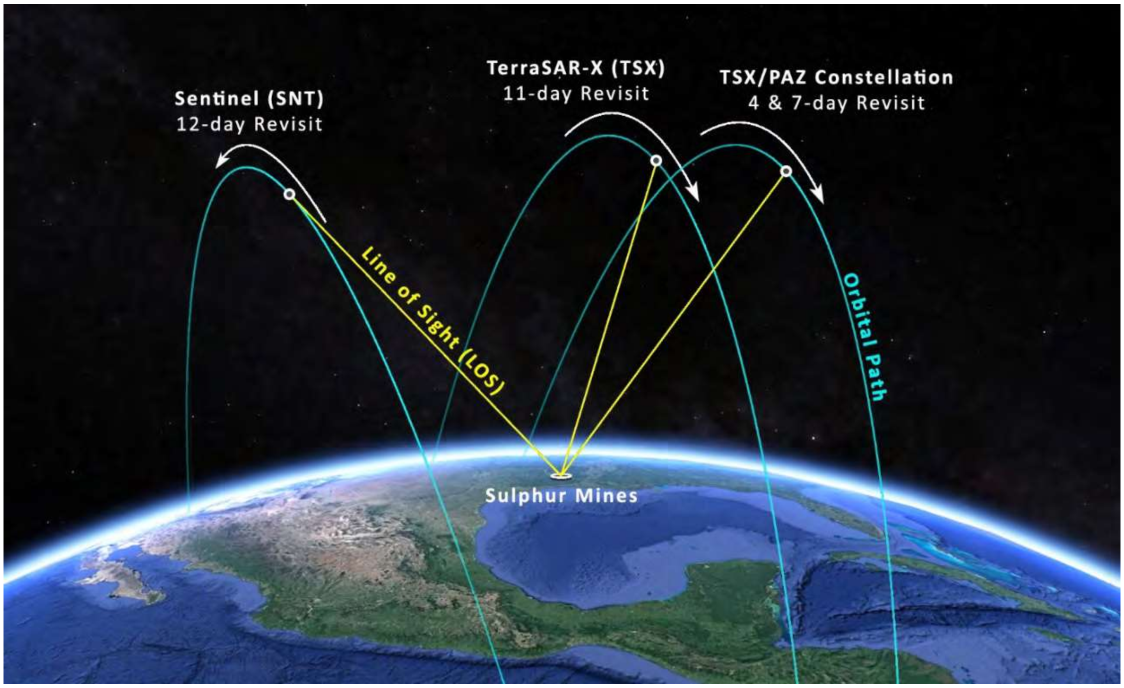
The first dataset is captured from a Sentinel 1 ("SNT") low-resolution satellite on an ascending orbit. The dataset timeframe covers October 4, 2016 to present and new images are captured with each pass on a 12-day revisit frequency. The second dataset is gathered via a TerraSAR-X ("TSX") high-resolution satellite on a descending orbit with an 11-day revisit frequency. The dataset timeframe covers June 16, 2022 to present. As of the date of this report, four (4) SNT datasets and five (5) TSX datasets have been received and evaluated for trend consistency over the western part of the dome as part of this continuous monitoring effort.

Beginning in late-March 2023 the source for the second dataset will transition to a pair of high-resolution satellites that share the same orbit. These are a second TSX satellite and the PAZ satellite, both with an 11-day revisit frequency. Their orbits are offset with the PAZ satellite passing over the site 4 days after the TSX satellite. This pair is referred to as the TSX/PAZ satellite constellation. The reason for the transition to the TSX/PAZ constellation in April is the increased data frequency that will result from a 4 and 7-day revisit period. Data capture for the TSX/PAZ constellation began in late January 2023 and a sufficient image stack for processing is estimated to be available by late-March 2023. Figure 1 below provides additional information on the image timeline, satellite data parameters, and a diagram of the orbital paths in relation to the Sulphur Mines Salt Dome.

Figure 1 – InSAR Image Collection Frequency, Satellite Data Parameters and Orbit Visualization



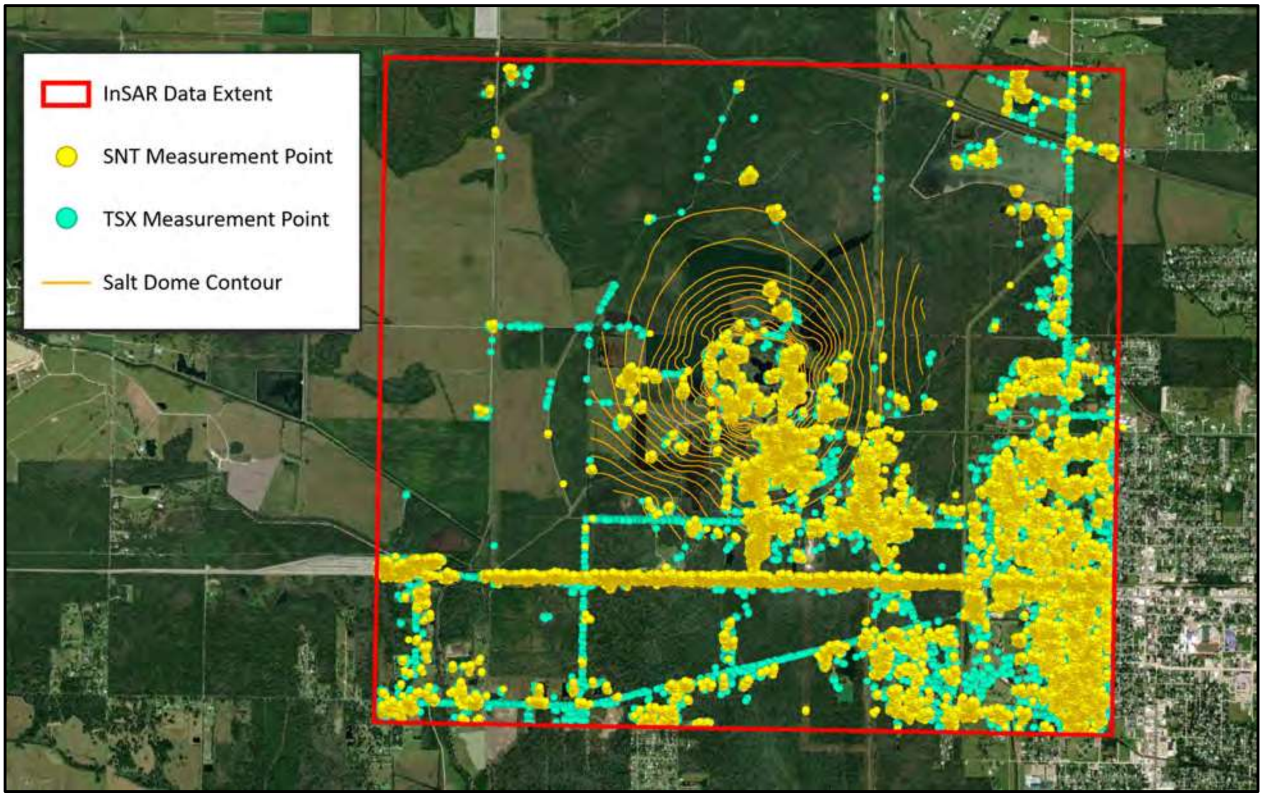
			TSX/PAZ Constellation	
	Sentinel-1	**TerraSAR-X**	**TerraSAR-X**	**PAZ**
Mode / Resolution	16 x 65 ft	Spotlight (3 x 3 ft)	Spotlight (3 x 3 ft)	Spotlight (3 x 3 ft)
Track	T136	T29	T67	T120
Band (wavelength)	C-Band (2.32 in)	X-Band (1.22 in)	X-Band (1.22 in)	X-Band (1.22 in)
Nominal frequency	12- day	11- day	11- day	11- day
Orbit (LOS angle)	Ascending 43°	Descending 17°	Descending 37°	Descending 37°
Date range	04 Oct 2016 – 20 Jan 2024	16 Jun 2022 – 01 May 2023	24 Jan 2023 – 11 Jan 2024	28 Jan 2023 – 15 Jan 2024
Number of images	199	30	34	33



Subsidence Monitoring Areas of Interest (AOIs)

Each of the InSAR datasets cover a 14-square mile area that extends roughly 1.85 miles out from the center of the Sulphur Mines Salt Dome. Figure 2 below depicts the measurement point locations and data extent for the most recent SNT and TSX datasets in relation to the dome structure contours.

Figure 2 – SNT and TSX InSAR Measurement Points

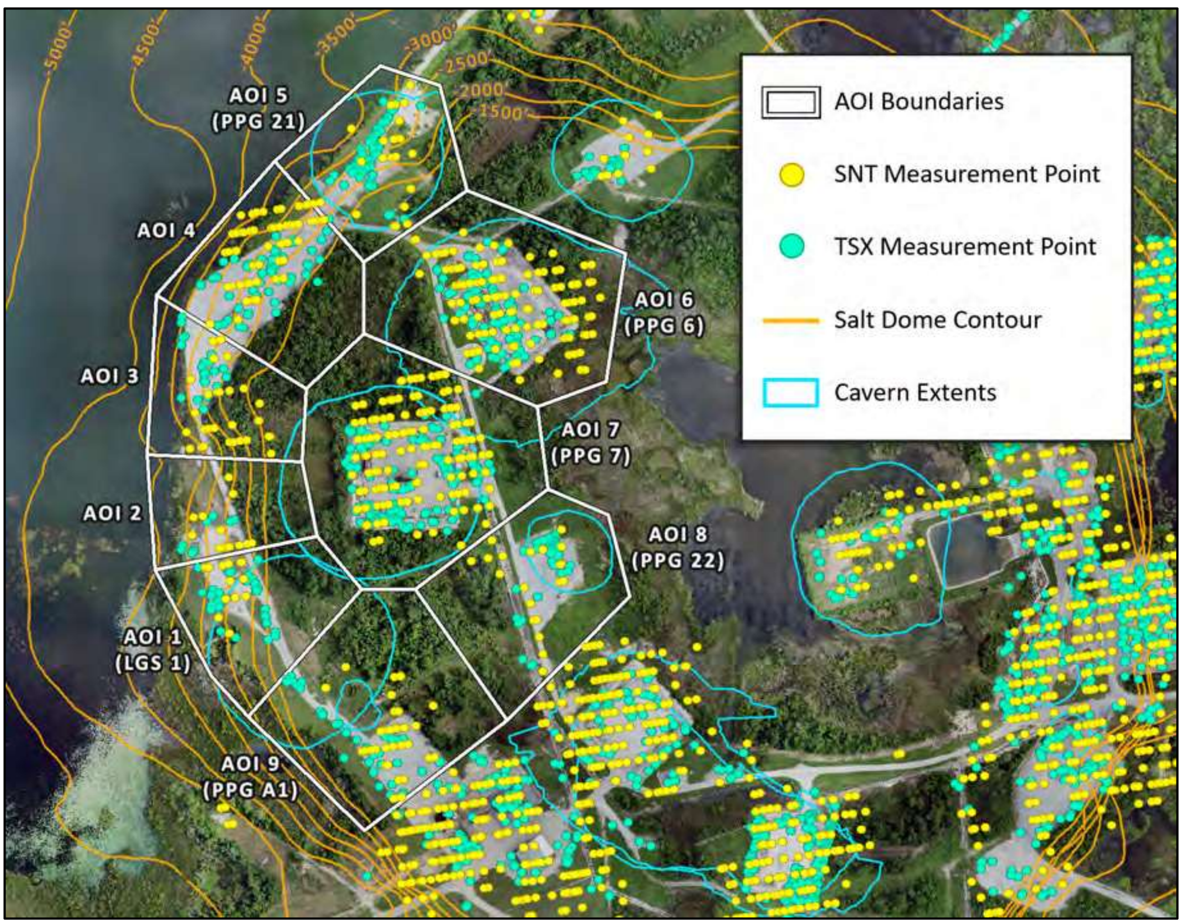


The displacement values associated with each measurement point can be used to generate contour maps of displacement velocity and acceleration, indicating the spatial distribution of subsidence magnitudes. Velocity and acceleration rates are determined via trend analysis of the displacement time-series for each individual measurement point. In total, 1,051 measurement points lie within the analysis extent planned for this continuous monitoring effort. In order to visually convey and evaluate trend consistency in each displacement time-series, it is necessary to group measurement points and generate time-series charts of the averaged displacement values for each group. Averaging of the displacement data within point groups also allows for the reduction of scatter (noise) associated with measurement accuracy in the time-series charts of individual measurement points.

To accomplish this, nine (9) Areas of Interest ("AOIs") have been defined as proposed point groups for calculation and display of average displacement rates and trend behavior. These AOIs are listed below in Figure 3 along with their associated areas and measurement point counts, as identified in the most recent SNT and TSX datasets. The map in Figure 3 depicts the AOI boundaries in relation to the InSAR data, dome contours, and cavern extents.

Figure 3 – InSAR Areas of Interest (AOIs)

Name	Area (Acres)	SNT Count	TSX Count	Total MP Count
AOI 1 *(LGS 1)*	3.86	13	38	51
AOI 2	2.49	15	9	24
AOI 3	2.94	29	22	51
AOI 4	4.28	62	65	127
AOI 5 *(PPG 21)*	3.59	25	66	91
AOI 6 *(PPG 6)*	6.35	134	119	253
AOI 7 *(PPG 7)*	7.20	140	170	310
AOI 8 *(PPG 22)*	4.43	21	43	64
AOI 9 *(PPG A1)*	5.09	39	41	80



Continuous Monitoring and Evaluation Plan

New data gathered with each pass of the InSAR satellites is processed and delivered by TREA within 48 hours of image capture. Once received, Lonquist will perform a same-day, preliminary review of the data and confirm that no material deviations from the established linear subsidence trends have been observed. In the event that a notable deviation is observed, a same-day preliminary report will be issued to Westlake detailing the observed trend deviation.

Following the preliminary review, Lonquist will process and evaluate the data, and issue a standardized report within 24-48 hours which will be provided to Westlake and the DNR. The streamlined system for generating this standardized report is under development, and is planned to be in operation by mid-April 2023. Evaluation of the nine (9) datasets that have been received from TREA since late January 2023 have been performed manually by evaluating trend consistency in the measurement point groups around the caverns and flank on the western side of the dome. To-date there has been no material deviation from the established subsidence trends in the areas investigated.

The standardized reporting method that is being developed will streamline the performance of the reviews that have been carried out to date. Grouping and averaging of the measurement points defined in the nine (9) AOI regions will be used to depict subsidence trends on a time-series plot for each AOI. Both recent and long-term trends will be depicted, and the associated velocity and acceleration values generated by each trend line will be indicated on the plots for comparison.

In addition, both recent and long-term velocity and acceleration rates will be calculated for each individual measurement point and used to produce contour maps over the western side of the dome. An additional pair of maps depicting the difference (subtraction) of the recent and long-term velocity and acceleration will be generated to highlight the intensity and location of trend variation if present. This approach will provide a clearer distinction between locations that may be experiencing slight changes in subsidence behavior in relation to historically consistent motion.

If notable observations are made during these efforts, additional investigation of key regions will be performed and reported, and these regions will remain an area of focus in subsequent datasets. Additional deliverables may be utilized as necessary to convey specific observations such as time-series plots of smaller point groups and their associated trends or cross sections of certain dome regions depicting profiles of displacement magnitude over time.

Appendix A – InSAR Measurement Technique Outline

TRE ALTAMIRA
A CLS Group Company

March 10, 2023

To:

Teresa Rougon
Lonquist & Co. LLC
12912 Hill Country Blvd F-200
Austin, TX, 78738

Subject: InSAR Measurement Technique Outline for Subsidence Monitoring Plans

Hello,

Please find enclosed a summary of the InSAR measurement technique used by Lonquist for their subsidence monitoring plan. The document describes the collection of the radar imagery, how InSAR measurements are obtained, the measurement precision and location accuracy as well as the differences between 1-D and 2-D measurements.

It also includes a section on the Quality Assurance and Quality control procedures followed by TRE Altamira Inc to produce InSAR measurements.

We are available to answer any additional queries you may have on the InSAR technique and on best practices for its use in subsidence monitoring plans.

Best regards

Giacomo Falorni
Technical Director
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Subsidence Monitoring Method

InSAR

InSAR is a technique to process Synthetic Aperture Radar (SAR) satellite imagery to measure displacement of the Earth's surface. The satellites are active systems that are able to acquire images in all weather conditions during both the day and the night. The SAR instrument sends pulse bursts of radar energy to the Earth's surface. Much of the radar signal is scattered or absorbed, but some is reflected back from the ground surface and collected by the receiver on the satellite to form a SAR image, which is a matrix of complex numbers containing both signal amplitude and phase values.

Amplitude values are related to the amount of energy backscattered to the sensor. Generally, metallic and solid objects such as well heads, exposed rocks, and artefacts provide a strong reflected signal and are therefore clearly visible in a radar image (they appear brighter). Vegetated areas typically produce relatively low amplitude values, while water bodies appear as dark and smooth surfaces since the signal is reflected specularly away from the satellite (i.e. no signal is returned to the satellite). Bright areas will typically provide a higher density of measurement points. Amplitude values are also important for assessing the visibility of corner reflectors.

The phase values provide the basis for Interferometric Synthetic Aperture Radar (InSAR), also referred to as SAR Interferometry, which is the measurement of signal phase change over time. When a point on the ground moves, the distance between the sensor and the ground target changes, affecting the phase value recorded by the SAR sensor. Figure 1 shows the relationship between ground movement and the corresponding shift in signal phase between two SAR signals acquired over the same area at different times.

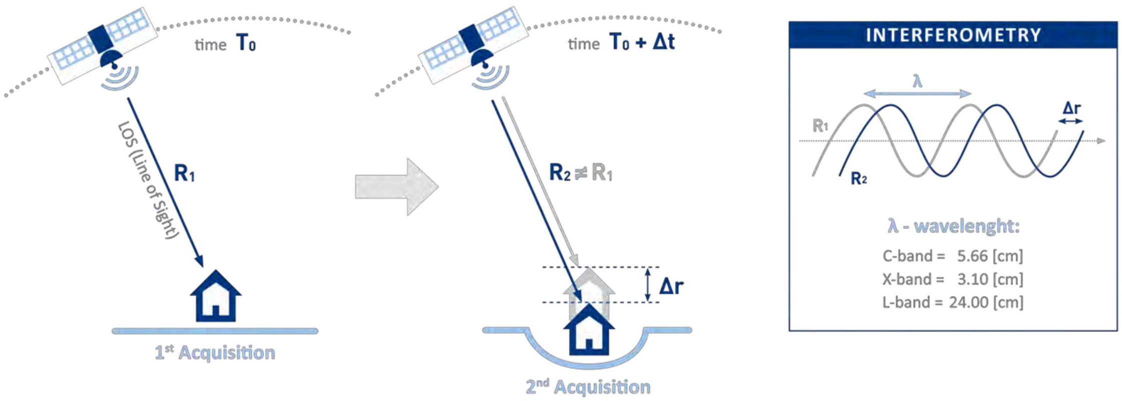

Figure 1: The relationship between ground displacement and signal phase shift.

Any displacement of a radar target is measured along the satellite Line-Of-Sight (LOS) which is the sensor to target direction or angle at which the satellite views the ground. By examining small changes in the reflected radar wavelengths between sequential images it is possible to accurately determine the amount and rate of ground movement. By combining multiple images, a comprehensive history of ground movement can be established (Ferretti, Prati, & Rocca, 2000).

Satellites

SAR satellites have sun-synchronous orbits, which are slightly inclined in comparison with the meridians. They are right looking and can illuminate a land strip (swath) up to 155 mi wide, depending on the satellite. The combination of sun synchronous orbits and the satellite look direction allow areas to be imaged from both the east (descending orbit, with the satellite traveling from north to south and pointed west) and from the west (ascending orbit, with the satellite traveling from south to north and pointed east; Figure 2). Areas of interest can therefore be observed from opposite directions. This characteristic can be used to extract 2-D (vertical and E-W) measurements.

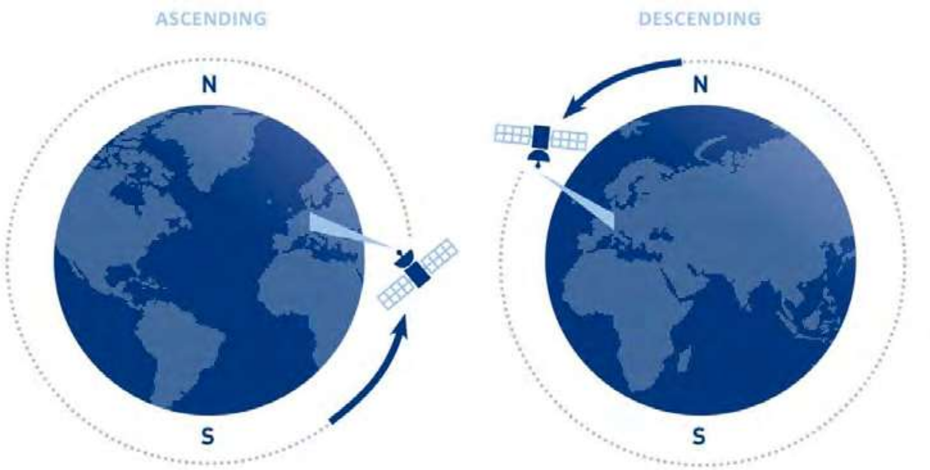

Figure 2: Ascending and descending orbit acquisitions.

SqueeSAR Analysis

SqueeSAR® is an advanced multi-image InSAR algorithm patented by TRE ALTAMIRA that provides high precision measurements of ground displacement in the form of a point cloud. The algorithm identifies measurement points (MPs) from objects on the ground that display a stable return to the satellite in every image of an archive (at least 15 images) and can measure both linear and non-linear ground movement (Ferretti et. al., 2011). The MPs belong to two different classes (Figure 3):

- **Permanent Scatterers (PS)**: point-wise radar targets characterized by a highly stable radar signal return (e.g. buildings, rocky outcrops, linear infrastructures, etc.)
- **Distributed Scatterers (DS)**: patches of ground exhibiting a lower but homogenous radar signal return (e.g. rangeland, debris fields, arid areas, etc.) that can be aggregated. DS therefore refer to small areas covering several pixels rather than to a single target or object on the ground. For clarity of presentation and ease of interpretation, DS are represented as individual points.

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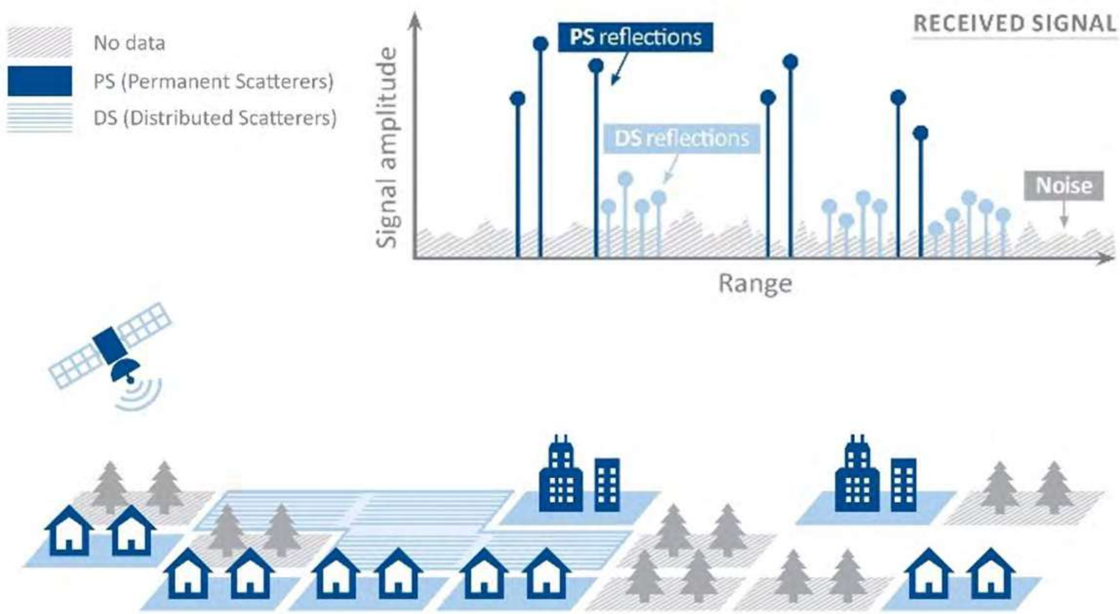

Figure 3: Schematic of PS and DS radar targets.

Each SqueeSAR MP provides the following information:

- Position and elevation estimated with respect to average sea level (ft)
- Displacement time series (TS) representing the evolution of the displacement for each acquisition date (in)
- Average annual displacement rate (in/yr), calculated from a linear regression of the displacement time series over the analysis period.

The density and distribution of the MPs is related to the resolution of the imagery and the surface characteristics of the area. In general, MP density increases with satellite resolution and over areas with man-made structures or bare ground and decreases with the presence of vegetation and over areas with changes to the ground cover over time (e. g. snow, operational activities).

1-D Measurements

In InSAR analyses, measurements are 1-D readings along the sensor's line-of-sight (LOS) where the vector of ground displacement is projected onto the LOS. If a ground movement is purely vertical, it will produce similar readings when viewed from similar angles, even if acquired from different orbits. However, a same ground displacement will produce different readings when viewed from different angles (Figure 4) or if a horizontal movement component is present.

Each measurement point corresponds to a Permanent Scatterer (PS) or a Distributed Scatterer (DS), and is color-coded according to its annual rate of movement and direction. In a 1-D LOS analysis, negative values (red) indicate movement away from the satellite, while positive values (blue) indicate movement towards the satellite.

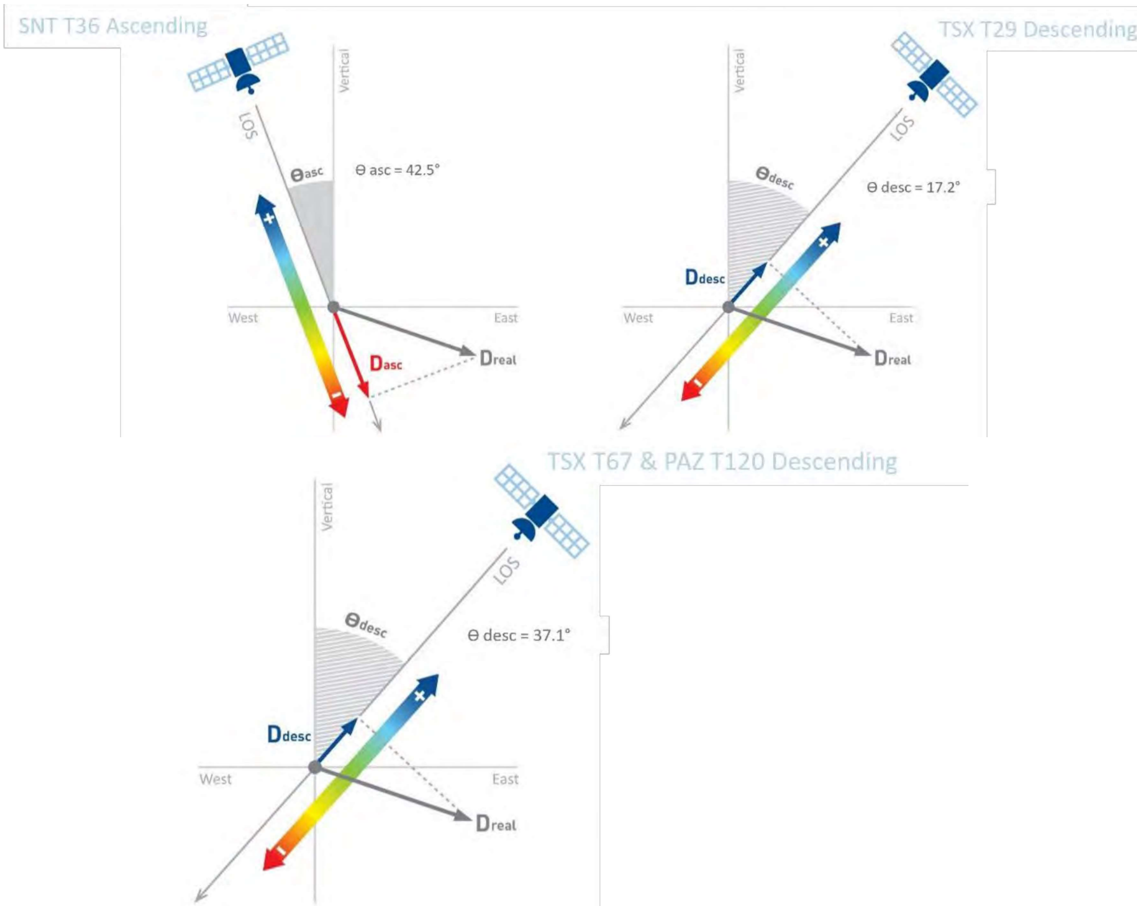

Figure 4: SqueeSAR measures the projection of real movement (Dreal) onto the LOS. The same real movement (Dreal) will produce a different value from a different LOS (different inclination or different orbits). The above figure shows the individual satellites and respective orbits used for the InSAR monitoring. SNT and TSX monitoring is ongoing while TSX and PAZ monitoring will begin in March 2023.

Reference Point

SqueeSAR measurements are differential in space and time. Measurements are spatially related to the local reference point, and temporally to the date of the first available satellite image.

The local reference point is assumed to be motionless and selected for its optimal radar properties and motion behavior. The reference point corresponds to a radar target with a high signal to noise ratio for all images of the archive, and that is not affected by displacement rate variations (non-linear movement or cyclical displacement) in the time period covered. The selection of the reference point is imagery dependent. If the number of images and/or time span varies the reference point may change, to maintain the highest quality of the results and reduce noise in the displacement readings. In any case, in instances where a reference point is changed, it is compared with previous reference points to align the measurement time series and ensure continuity of the measurements in time. Reference points may be affected by linear regional displacement phenomena (e.g. gradual regional subsidence or tectonic movements) but this does not impact the measurement precision nor any differential displacement, as both the reference point and all other points are equally affected by the regional movement.

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Measurement Precision

SqueeSAR measurements contain two precision indices: the displacement rate standard deviation and the time series error bar.

The displacement rate standard deviation characterizes the error associated with the displacement rate with respect to the reference point. Given the standard deviation (σ), and assuming that the errors are normally distributed (Gaussian), 95% of the values tend to be included in a ±2σ range. The displacement rate standard deviation is inversely proportional to the number of processed images and the length of the interval covered by the imagery. This value is evaluated for both the 1-D and the 2-D measurements.

The displacement time series error bar indicates how well an analytical model fits the displacement time series. The model is selected individually for each measurement point with an advanced Model Order Selection technique that also considers the quality of the image archive (number of processed images, time span covered by the archive and possible gaps in the acquisitions). The lower the standard deviation, the lower the average residual with respect to the analytical model (i.e. the smaller the error bar of the time series). This parameter is evaluated only for 1-D measurements.

Table 1 provides a summary of the factors affecting the measurement precision and the geolocation (position in space) precision of the MPs estimated from a 1-D SqueeSAR analysis, as well as typical precision values.

Table 1: Factors affecting the measurement and geolocation precision of SqueeSAR points with typical values at mid-latitudes. Values are referred to a MP less than 0.62 mi from the reference and a dataset of at least 30 radar images covering a 2-year period.

<table>
<tr><th></th><th>Measurement Precision</th><th colspan="2">Geolocation Precision</th></tr>
<tr><td>Factors</td><td>• Period of analysis
• Temporal continuity of acquisitions
• Number of images processed
• Distance from the reference point (REF)
• Measurement point density</td><td colspan="2">• Satellite resolution
• Satellite orbit accuracy (normal baseline)
• Number of radar images (for z values)
• Absolute accuracy of the REF</td></tr>
<tr><td>Typical Values</td><td>Displacement Rate Standard Deviation: <1 mm/yr (< 0.04 in/yr)
Time series Error Bar: ±5 mm (±0.2 in)</td><td>TerraSAR-X / PAZ
x = ±3 ft
y = ±10 ft
z = ±5 ft</td><td>Sentinel-1
x = ±26 ft
y = ±39 ft
z = 26 ft</td></tr>
</table>

Quality Assurance & Quality Control Procedures

TRE Altamira (TREA) has standardized Quality Control (QC) procedures in place and all work is quality controlled through oversight of the reports and statistical analysis of provided databases. TREA production is ISO 9000 certified, guaranteeing that all phase products undergo ISO approved QC controls. TREA implements a full documentation control system and TREA reports are checked and approved by at least one higher level of management.

TREA has successfully managed many similar corporate-wide projects and uses standard industry project management practices. A Project Manager is appointed for the project and a Technical Responsible (TR) is assigned for each site and is the primary lead for all data products over that site. The TR develops a specific knowledge and experience of the site and is then involved in all reporting and training activity over the site. The TR(s) report directly to Project Manager and then up to the Technical Director, who maintains oversight and is engaged in the reporting and delivery phases. The TR's duties include communication with the end-user, managing the reporting and data, and technical support to the end-users. A backup TR is constantly updated and steps in during periods of principal TR unavailability. Change management and change control are implemented via continued communications between the Project Manager and the Technical Director on any aspect of the project. TREA reports are reviewed and approved by the Technical Director.