

SNT Satellite Update
InSAR Subsidence
October 16, 2023

Lonquist comment:

The SNT satellite (12-day revisit) passed by Sulphur on Monday October 16. We received the dataset Wednesday and verified that none of the datapoint areas around the dome and caverns near the western flank are showing deviation from their respective trends. The attached evaluation report has been prepared for reference.

We have also received the dataset from the TSX/PAZ constellation (4 & 7-day revisit) which passed by Sulphur on Sunday October 15. This dataset was processed using the new baseline that TREA has developed from their reprocessing of the full image stack from January to September. The point locations and counts have changed as well as the calculated trends for the AOIs. Generally we are seeing less off-trend behavior and nothing of urgent note in the data.



SNT Satellite Update

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

Sulphur Mines Salt Dome

Prepared for:
Westlake Chemical

Prepared by:
Lonquist & Co., LLC
8591 United Plaza Blvd., Suite 280
Baton Rouge, LA 70809

Dataset
Satellite Source
Sentinel-1 (SNT)
Most Recent Image Date
Monday, October 16, 2023

Analysis Report Date:
October 20, 2023

Dataset Information

Satellite Source	Sentinel-1 (SNT)
Revisit Frequency	12 days
Most Recent Image Date	Monday, October 16, 2023
Dataset Image Count	189
Dataset Time Range	October 4, 2016 - October 16, 2023
Dataset Length	7.03 Years
Satellite Line-of-Sight (LOS)	43° West of Vertical (Viewing site from the West)

Analysis Methodology

Time Series Charts

Trend lines were calculated for the averaged displacement values within each AOI. Quadratic regression was used to determine Velocity and Acceleration of LOS displacement. Trends calculated for the AOI point groups are depicted for each AOI in the Time Series section of this report.

Contour Maps

A quadratic trend was also calculated for each individual measurement point across the analysis region. Trend values for each point were used to generate Velocity and Acceleration contour maps to depict the spatial distribution of the movement trends. Negative velocity values indicate subsidence. Negative acceleration values indicate increasing rates of subsidence and positive acceleration values indicate slowing rates of subsidence.

Recent vs. Historical Data

The multi-year SNT dataset timeframe allows for Recent data to be evaluated separately from Historical data and for trends from the two timeframes to be compared. The change in the velocities and accelerations from the two timeframes are provided in the Time Series and Contour Map sections. Velocity values are calculated for the final date in either the Recent or Historical datasets.

Observations

To-date there has been no material deviation from established subsidence trends in the areas investigated.

The comparison of Recent to Historical trends in the SNT data does imply a minor increase in the negative velocity and negative acceleration of LOS displacement in AOI 1, AOI 2, AOI 3, AOI 7 (PPG 7), AOI 8 (PPG 22), and AOI 9 (SMS A1). This suggests that marginal increases in subsidence rates may be occurring in these areas in recent years with the greatest increase occurring in AOI 8.

In the mapped contours of the change in recent vs. historical subsidence rates, the greatest change is seen to be occurring in the northern portion of AOI 8 (PPG 22), the southern portion of AOI 9 (SMS A1), and the central portion of AOI 3, which supports the higher trend change values for those AOIs presented in the AOI Analysis Summary.



Date Signed: October 20, 2023
Austin, Texas

Nathaniel L. Byars, P.E.
Principal Engineer
Louisiana License No. 40697

InSAR Data Sources

InSAR Data

Interferometric Synthetic Aperture Radar (InSAR) is the most well established method to continually evaluate small, normally undetectable, ground movement over a large area. Radar 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. InSAR analysis identifies the change in distance between the satellite and each measurement point over time relative to a stable reference point within the imaged area.

Satellite Sources

Two InSAR datasets are being used to evaluate subsidence over the Sulphur Mines Salt Dome. These datasets provide Line-of-Sight (LOS) displacement measurements from 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.

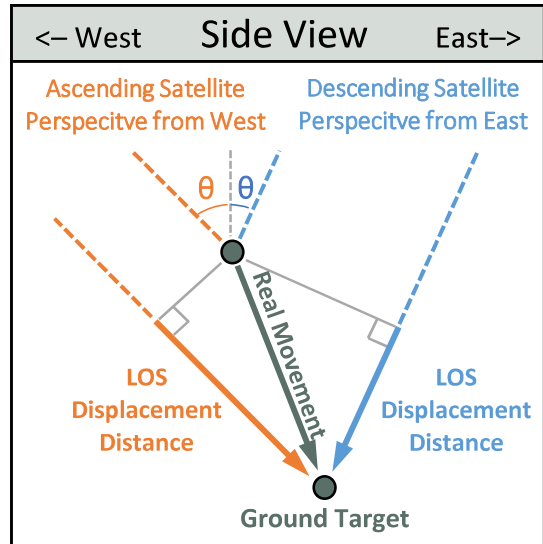
The first dataset comes from a low-resolution Sentinel-1 (SNT) satellite on an ascending orbit that captures data from the west of the site on a 12-day frequency. The second comes from a pair of high resolution satellites that share the same descending orbit and capture data from east of the site. These are a TSX satellite and the PAZ satellite (TSX/PAZ constellation), 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. Prior to May 2023, data was captured from a different high-resolution TerraSAR-X (TSX) satellite on a descending orbit that captured data from the east of the site on an 11-day frequency. The transition was made for the increased data frequency that resulted from a 4 and 7-day revisit period. The image below depicts the orbital paths of the satellites in relation to the Sulphur Mines Salt Dome.

Satellite Orbital Diagram



InSAR Line-of-Site (LOS) Data

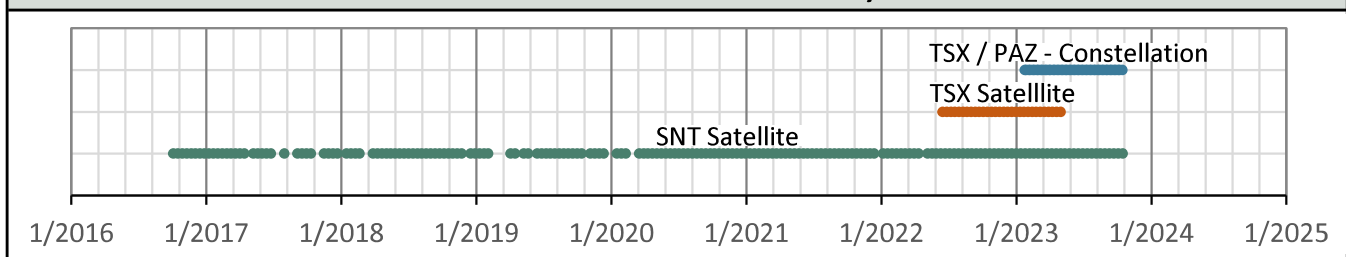
LOS displacement measurements refer to a change in distance between the satellite sensor and the ground target. Measurement positions on the west side of the Sulphur Dome are known to be experiencing some eastward movement toward the dome center due to the geometry of the subsidence basin. The InSAR satellites view the site from eastward and westward positions so LOS measurements are understood to convey a movement distance that is not purely vertical. The diagram to the right illustrates the geometric relationship between the theoretical Real movement of a ground target and LOS displacement measurements from two different satellite viewing directions.



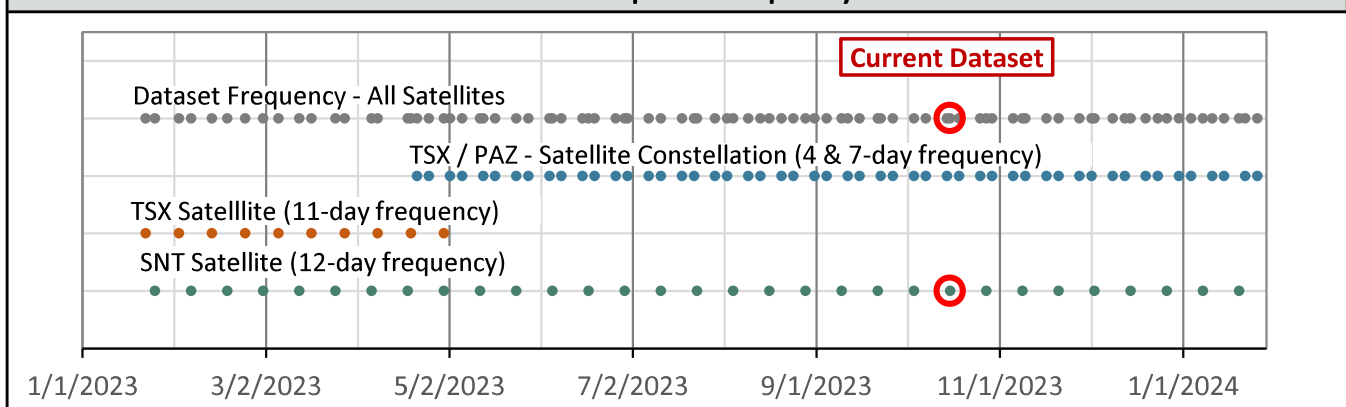
Satellite Properties & Image Frequency

Satellite and Data Properties	SNT	TSX	TSX/PAZ Constellation
Band (Wavelength)	C-band (2.20 in)	X-band (1.22 in)	X-band (1.22 in)
Track	T136	T29	T67 & T120
Pixel resolution	65 x 16 ft	3 x 3 ft	3 x 3 ft
Revisit frequency	12 days	11 days	4 & 7 days
Orbit (LOS Angle, θ)	Ascending (43°)	Descending (17°)	Descending (37°)
Data Start Date	10/4/2016	6/16/2022	1/24/2023
Measurement error range	± 0.20 in	± 0.03 in	± 0.03 in

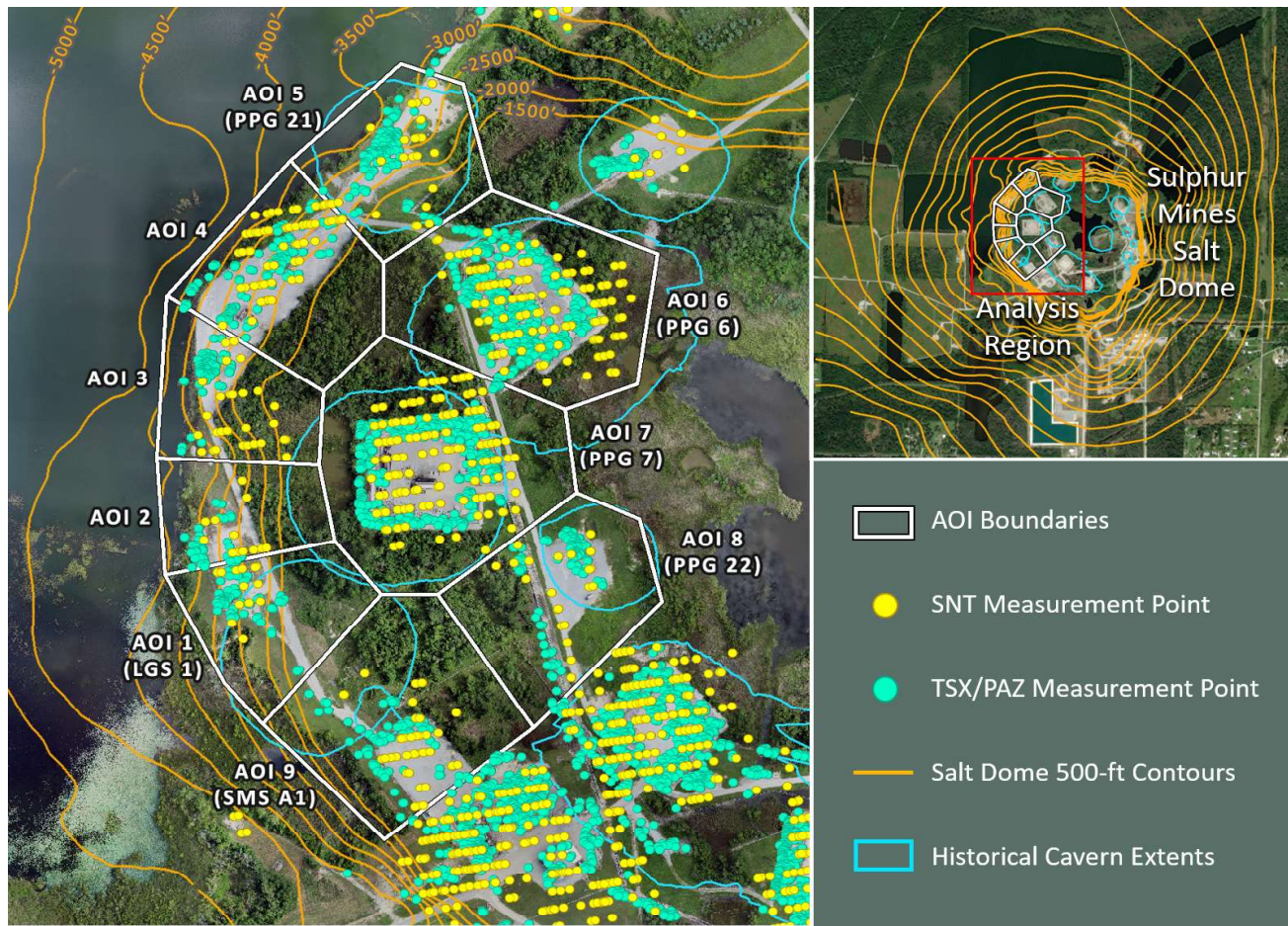
Dataset Measurement History



Dataset Update Frequency



AOI Boundaries & InSAR Measurement Points

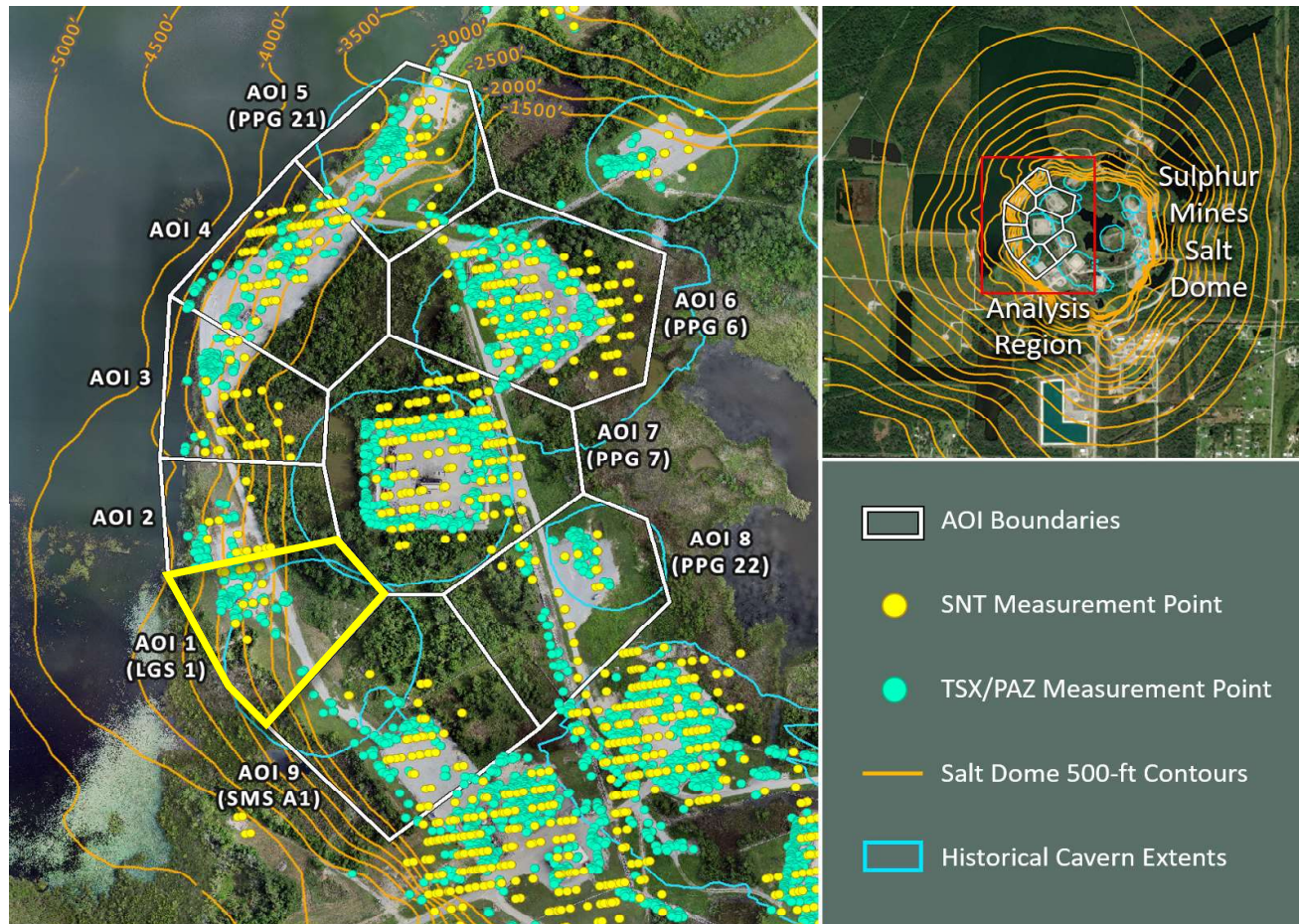


Subsidence Monitoring Areas of Interest (AOIs)

To visually convey and evaluate trend consistency for the displacement time series of each ground target, measurement points were grouped and their displacement values were averaged. The point groups are referred to as Areas of Interest (AOIs) in this analysis and their boundaries are depicted on the above map. The below table lists the trend values calculated in each AOI for the dataset evaluated in this report.

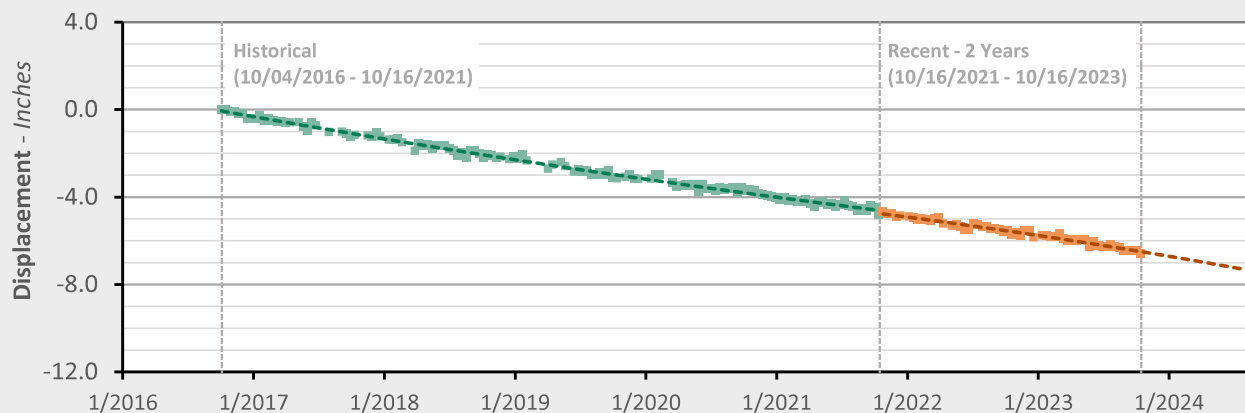
AOI Name	SNT (10/16/2023)	LOS Velocity (<i>in/yr</i>)			LOS Acceleration (<i>in/yr²</i>)		
	Point Count	Historical	Recent	Change	Historical	Recent	Change
AOI 1 (<i>LGS 1</i>)	13	-0.74	-0.98	-0.24	+0.06	-0.11	-0.18
AOI 2	15	-0.75	-1.07	-0.32	+0.08	-0.09	-0.17
AOI 3	29	-0.65	-0.90	-0.25	+0.04	-0.21	-0.25
AOI 4	63	-0.73	-0.62	+0.11	+0.01	+0.08	+0.06
AOI 5 (<i>PPG 21</i>)	24	-0.68	-0.53	+0.15	+0.01	+0.09	+0.08
AOI 6 (<i>PPG 6</i>)	134	-0.88	-0.95	-0.07	+0.06	-0.02	-0.08
AOI 7 (<i>PPG 7</i>)	140	-1.00	-1.25	-0.25	+0.09	-0.13	-0.22
AOI 8 (<i>PPG 22</i>)	21	-1.06	-1.47	-0.40	+0.13	-0.21	-0.34
AOI 9 (<i>SMS A1</i>)	39	-0.79	-1.02	-0.23	+0.11	-0.13	-0.23

AOI 1 (LGS 1) - Location Map



AOI 1 (LGS 1) - Displacement Time Series

SNT (10/16/2023) Point Count: 13



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.74 in/yr	-0.98 in/yr	-0.24 in/yr
Acceleration:	+0.06 in/yr ²	-0.11 in/yr ²	-0.18 in/yr ²

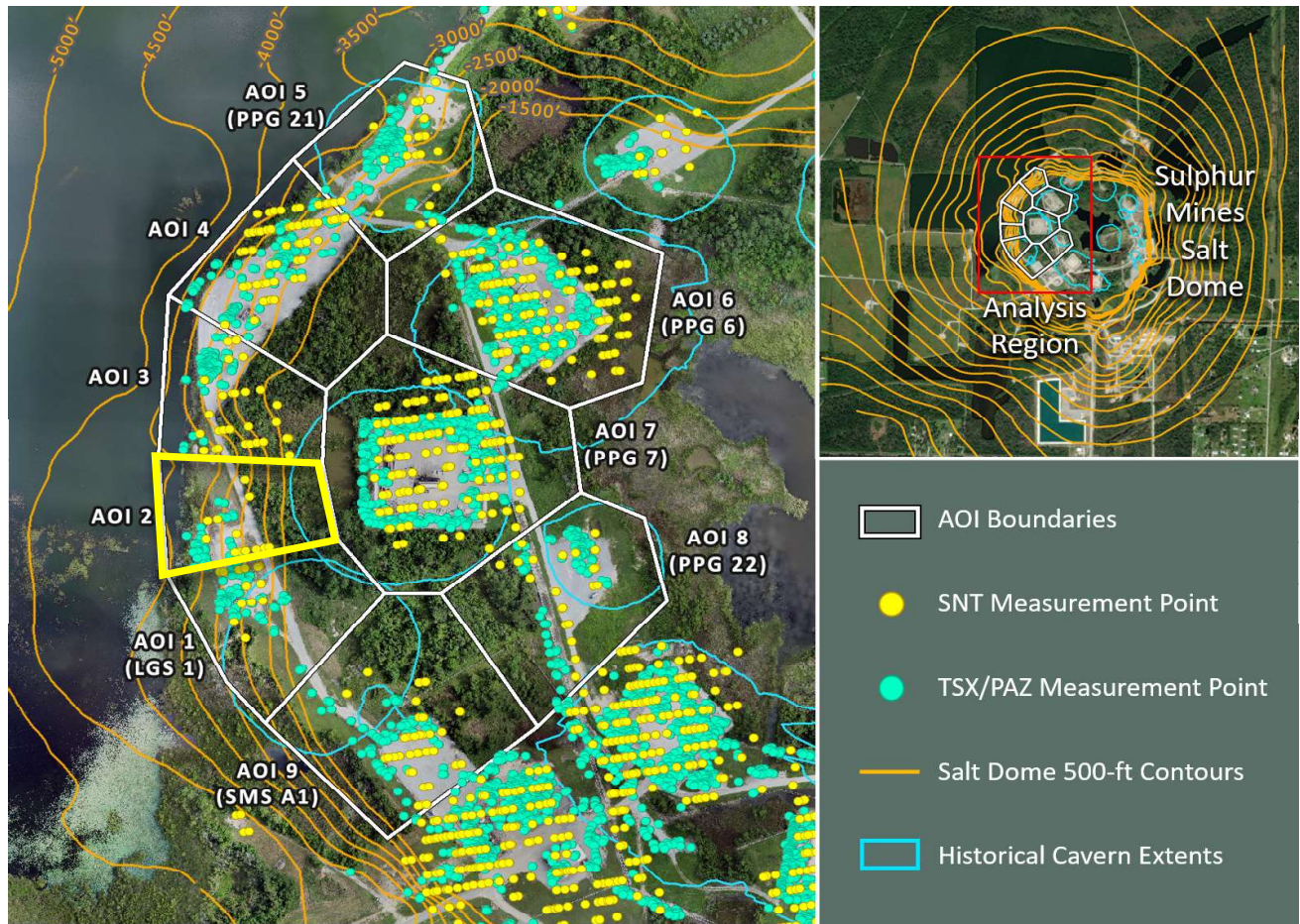
■ Historical LOS Displacement Measurement

--- Historical Trend Line (Quadratic Regression)

■ Recent LOS Displacement Measurement

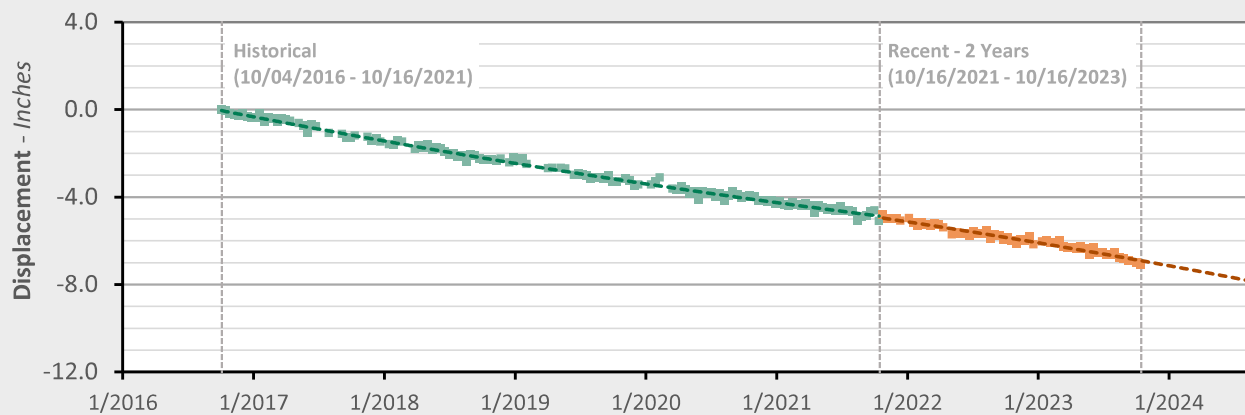
--- Historical Trend Line (Quadratic Regression)

AOI 2 - Location Map



AOI 2 - Displacement Time Series

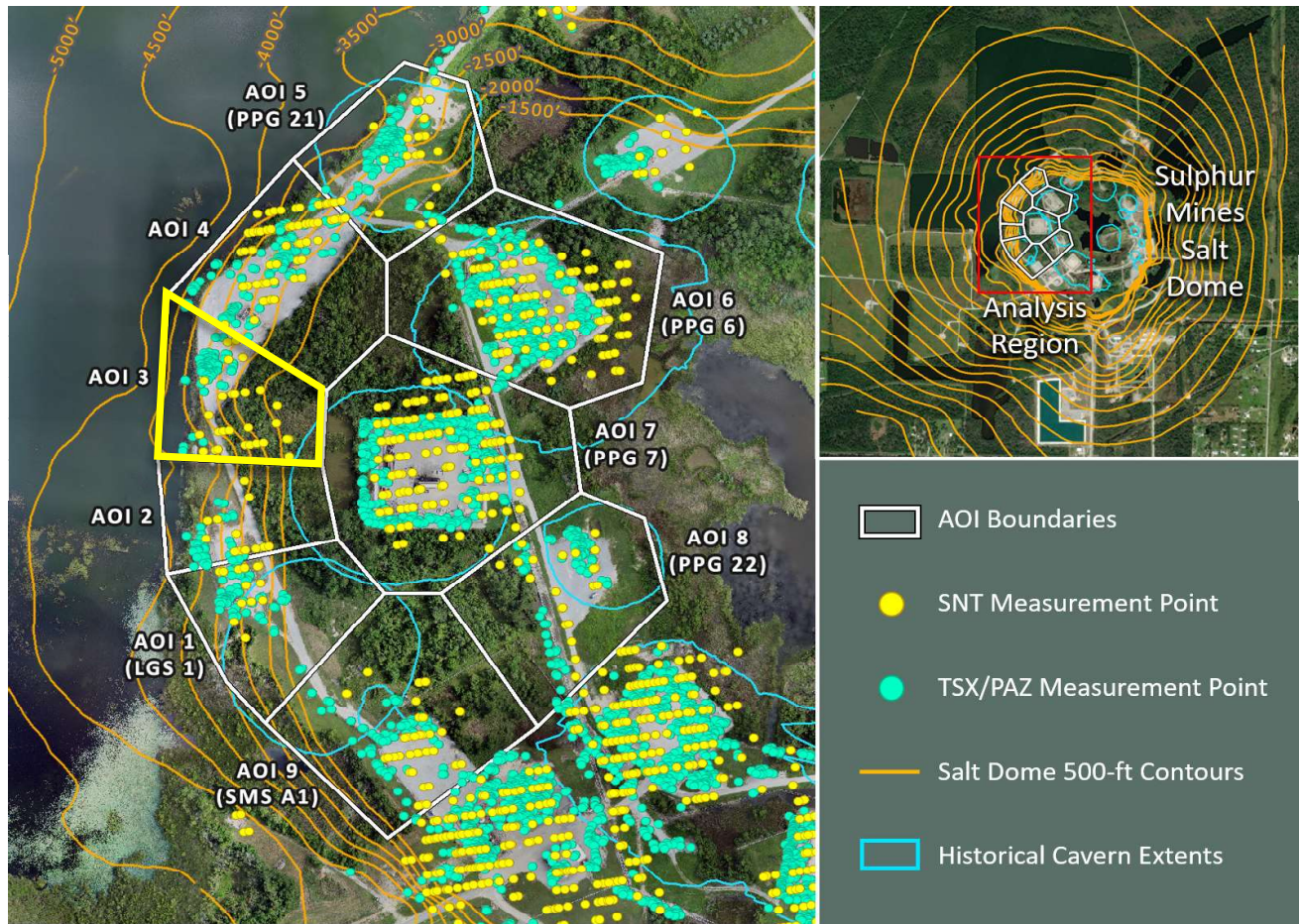
SNT (10/16/2023) Point Count: 15



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.75 in/yr	-1.07 in/yr	-0.32 in/yr
Acceleration:	+0.08 in/yr ²	-0.09 in/yr ²	-0.17 in/yr ²

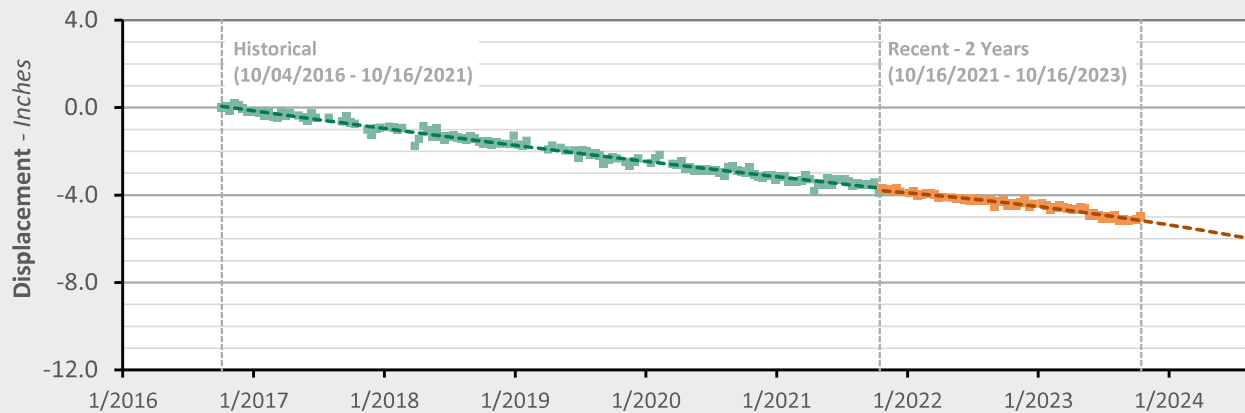
■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

AOI 3 - Location Map



AOI 3 - Displacement Time Series

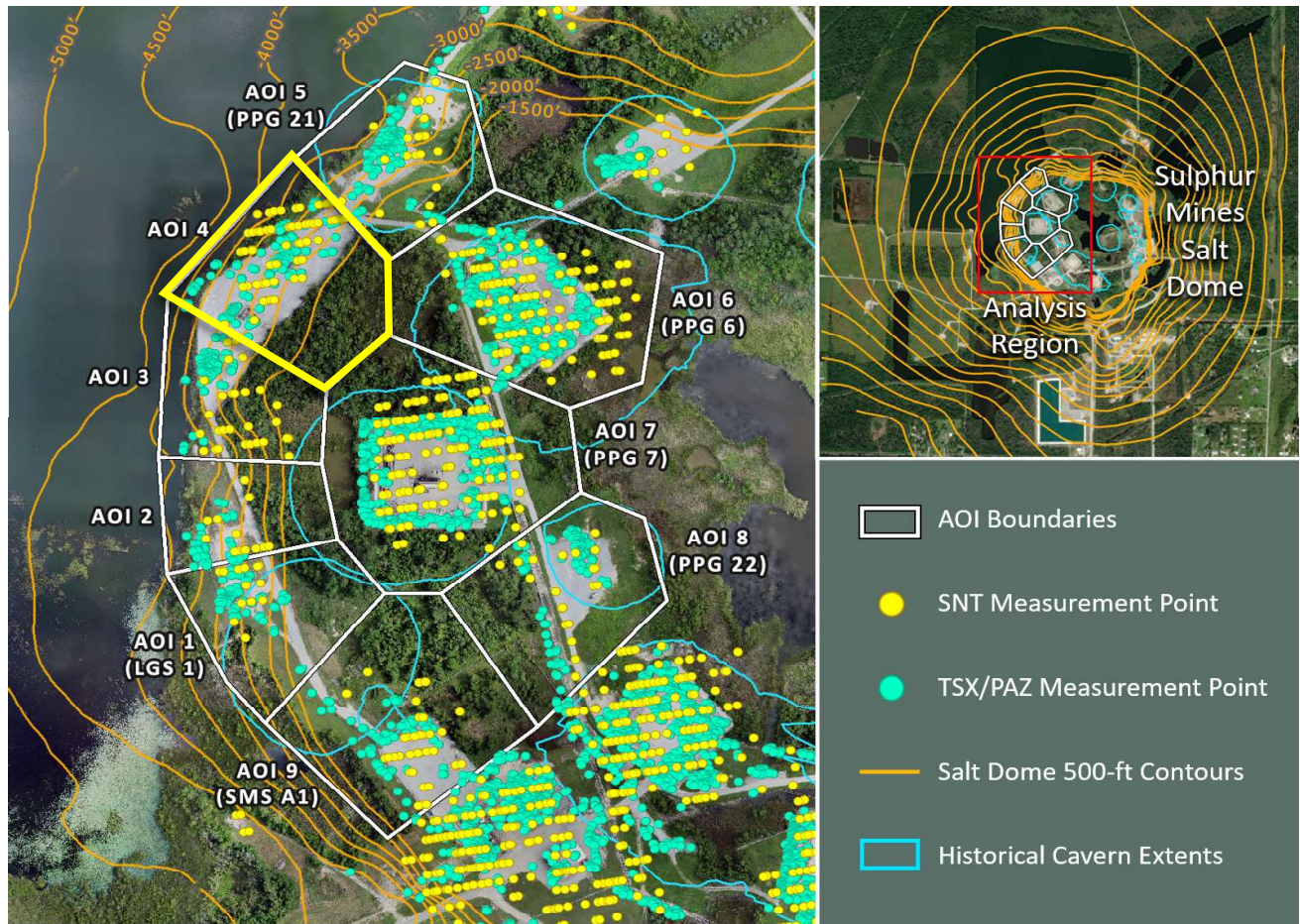
SNT (10/16/2023) Point Count: 29



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.65 in/yr	-0.90 in/yr	-0.25 in/yr
Acceleration:	+0.04 in/yr ²	-0.21 in/yr ²	-0.25 in/yr ²

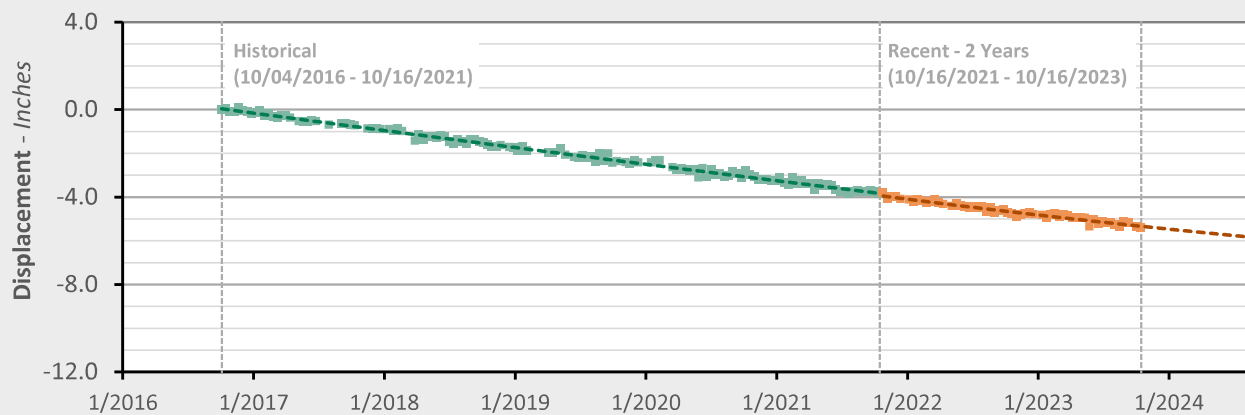
■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

AOI 4 - Location Map



AOI 4 - Displacement Time Series

SNT (10/16/2023) Point Count: 63



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.73 in/yr	-0.62 in/yr	+0.11 in/yr
Acceleration:	+0.01 in/yr ²	+0.08 in/yr ²	+0.06 in/yr ²

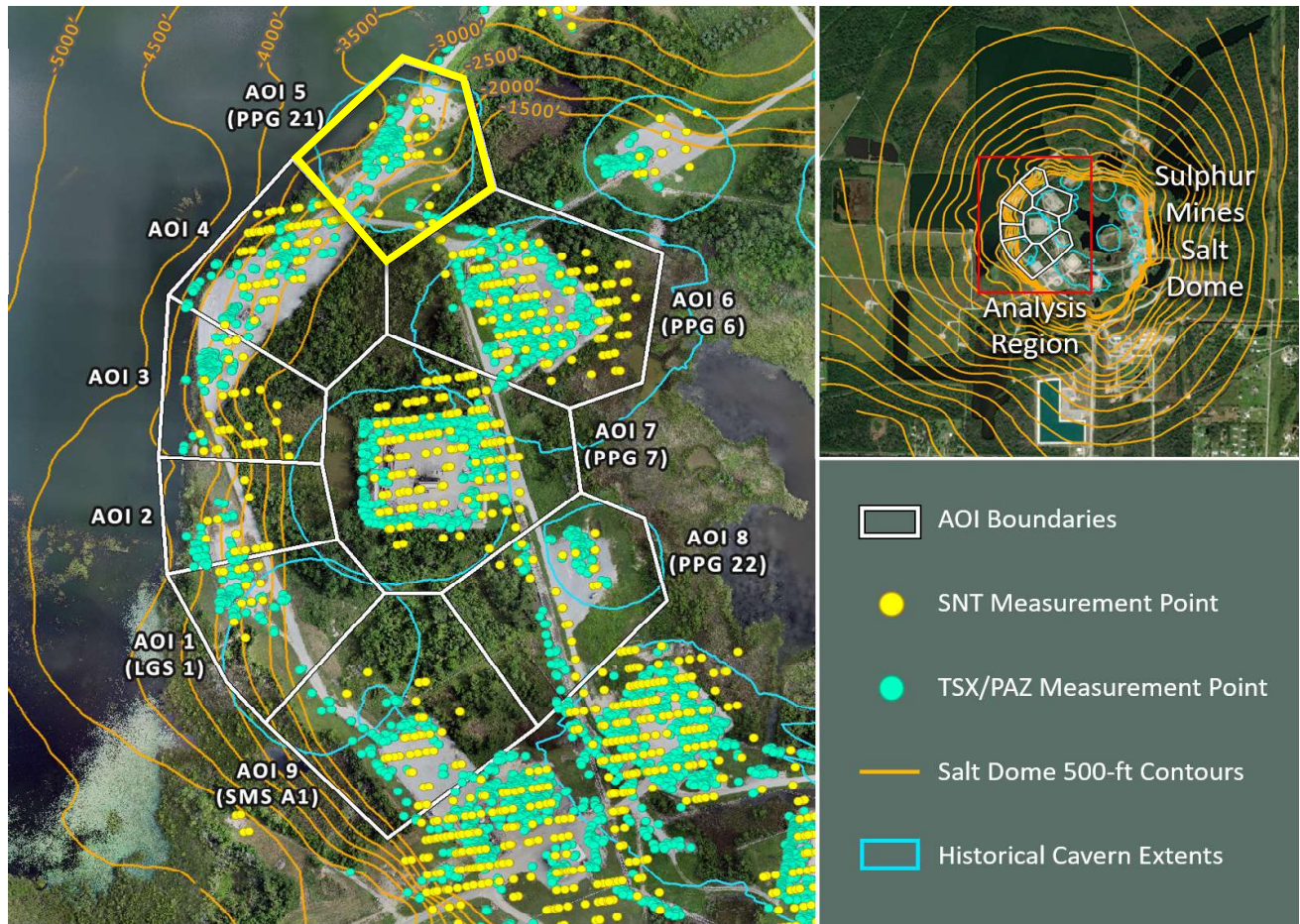
■ Historical LOS Displacement Measurement

--- Historical Trend Line (Quadratic Regression)

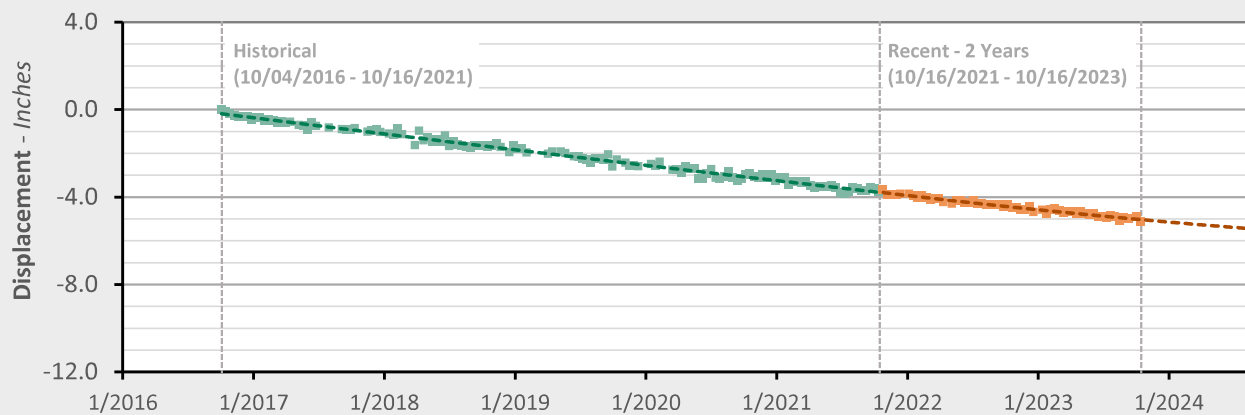
■ Recent LOS Displacement Measurement

--- Historical Trend Line (Quadratic Regression)

AOI 5 (PPG 21) - Location Map



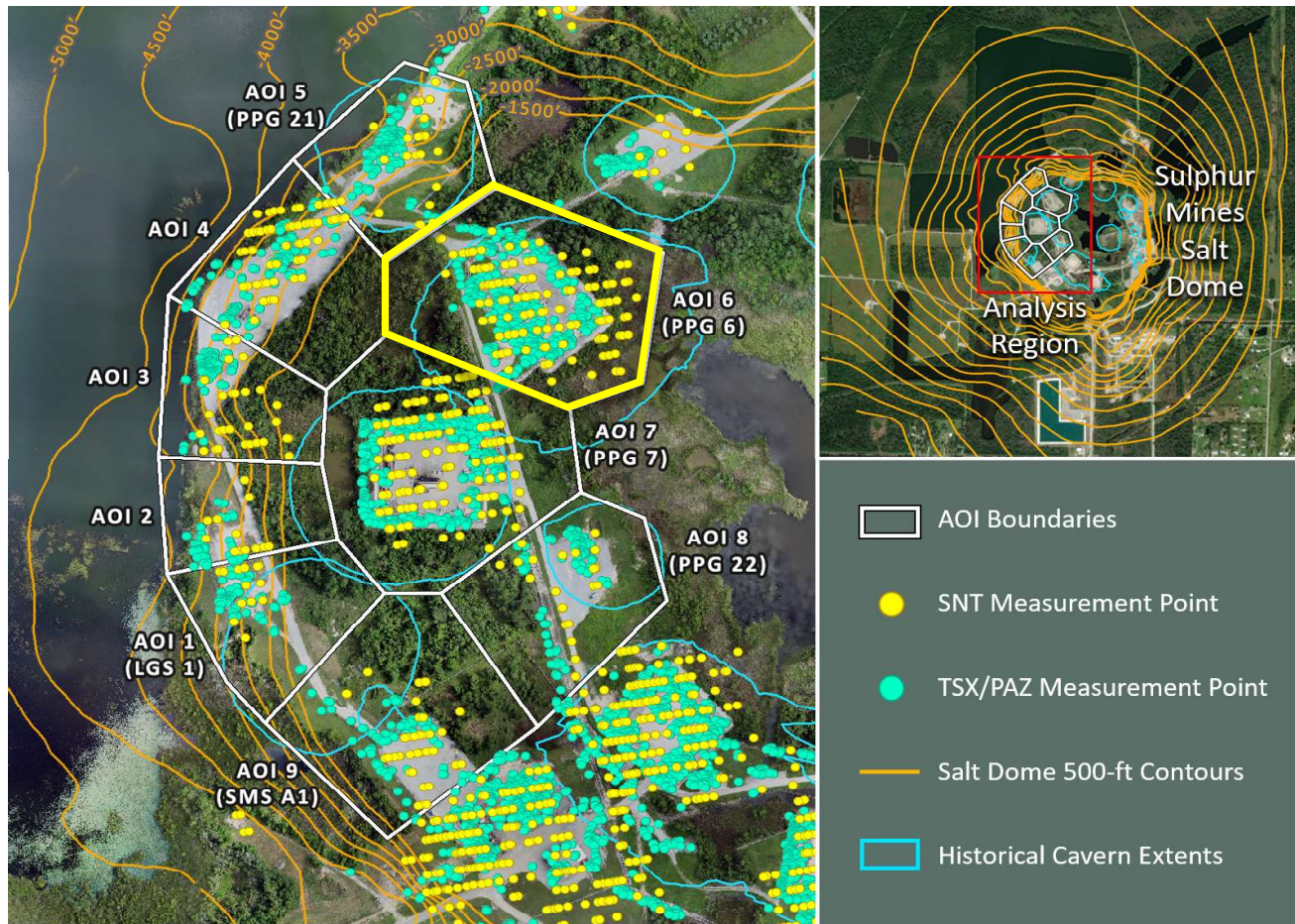
AOI 5 (PPG 21) - Displacement Time Series SNT (10/16/2023) Point Count: 24



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.68 in/yr	-0.53 in/yr	+0.15 in/yr
Acceleration:	+0.01 in/yr ²	+0.09 in/yr ²	+0.08 in/yr ²

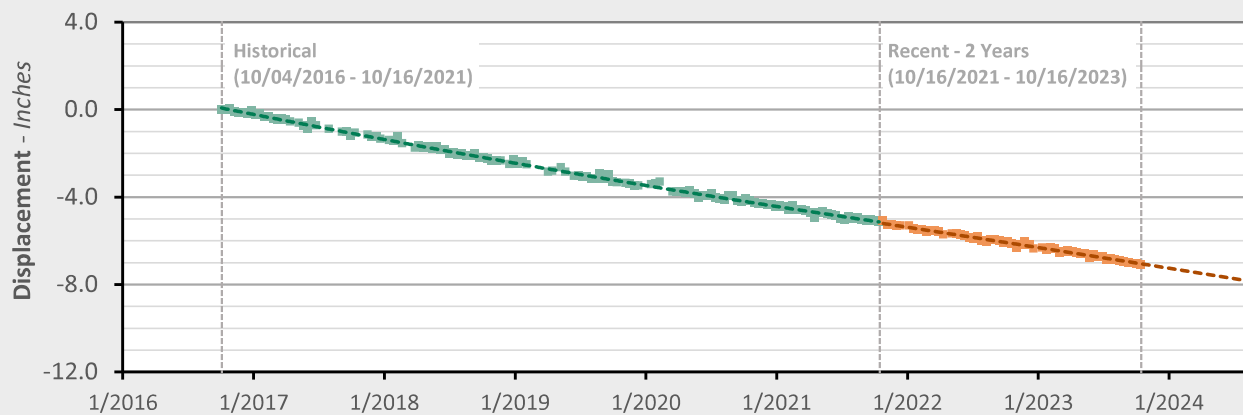
■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

AOI 6 (PPG 6) - Location Map



AOI 6 (PPG 6) - Displacement Time Series

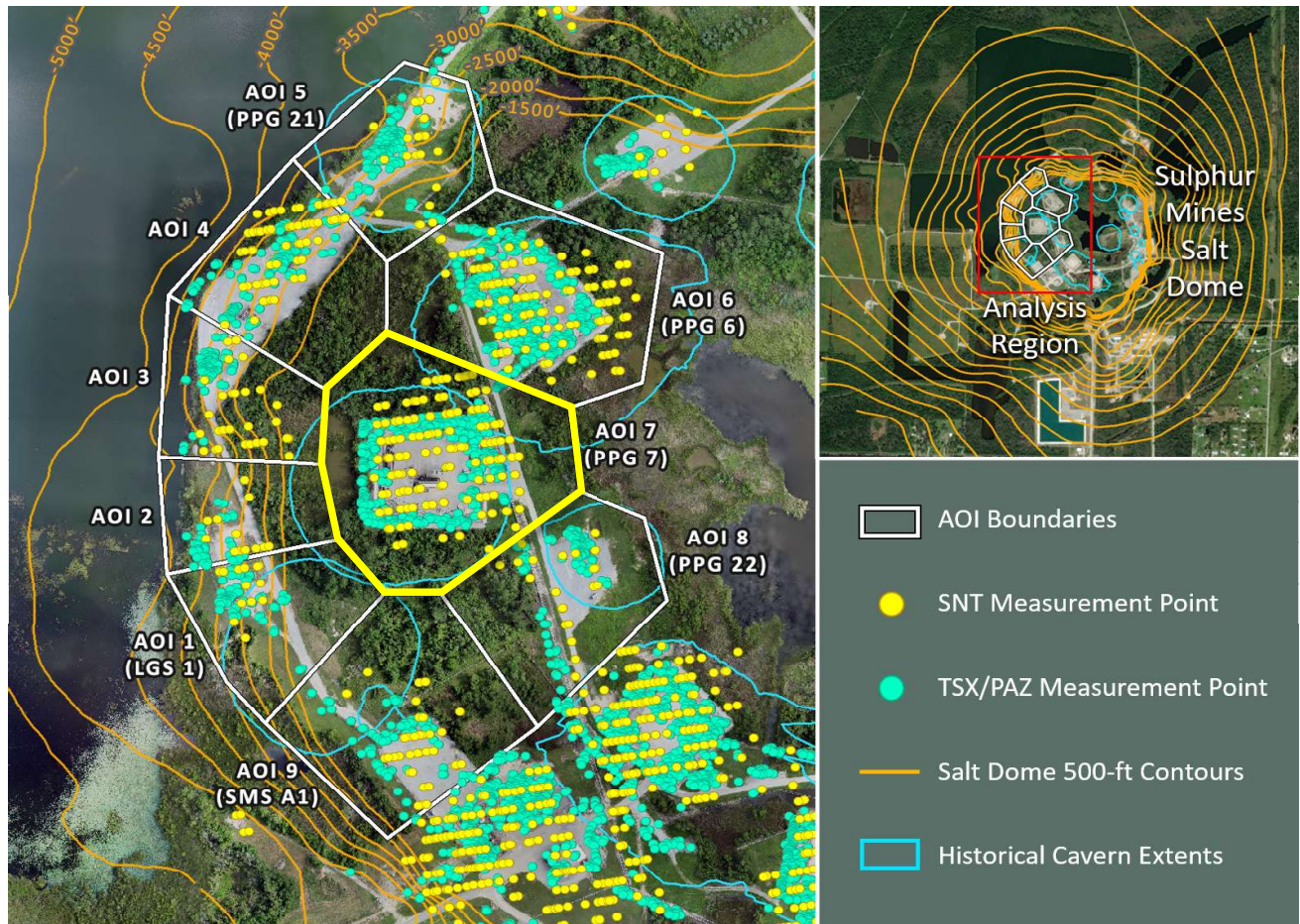
SNT (10/16/2023) Point Count: 134



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.88 in/yr	-0.95 in/yr	-0.07 in/yr
Acceleration:	+0.06 in/yr ²	-0.02 in/yr ²	-0.08 in/yr ²

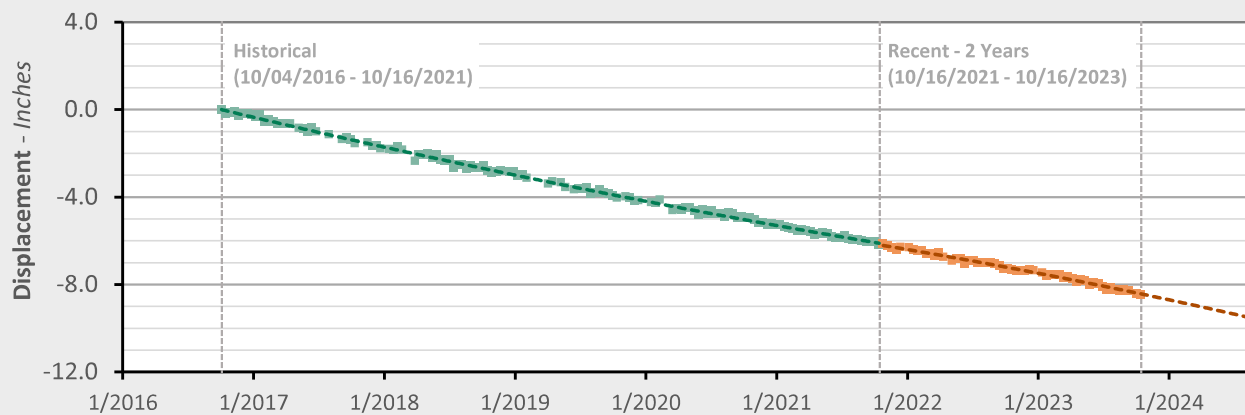
■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

AOI 7 (PPG 7) - Location Map



AOI 7 (PPG 7) - Displacement Time Series

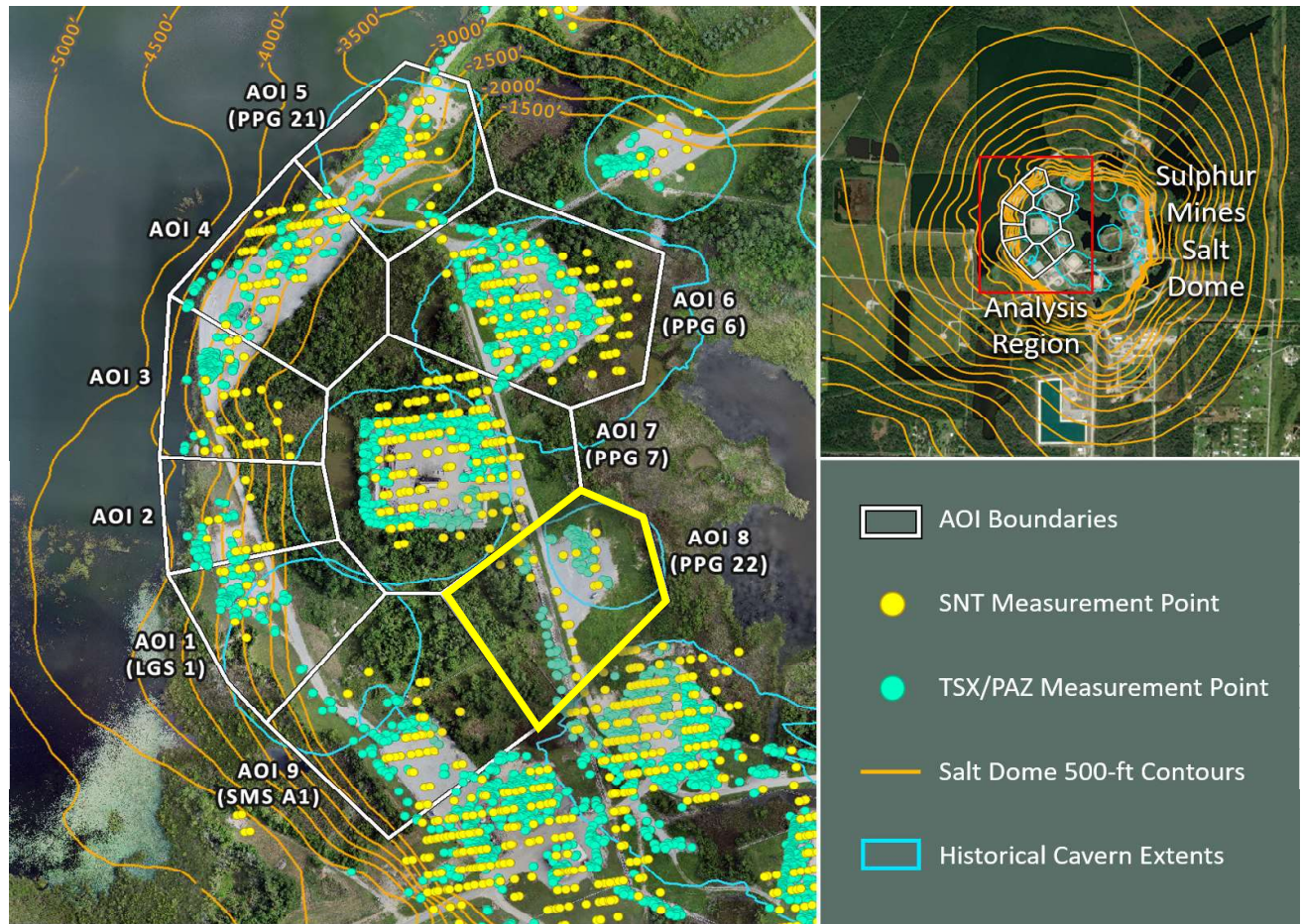
SNT (10/16/2023) Point Count: 140



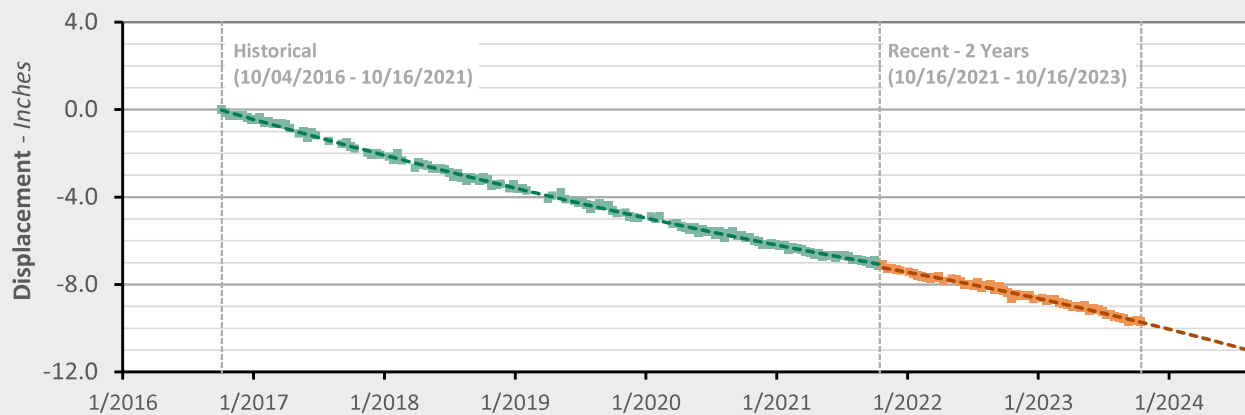
	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-1.00 in/yr	-1.25 in/yr	-0.25 in/yr
Acceleration:	+0.09 in/yr ²	-0.13 in/yr ²	-0.22 in/yr ²

■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

AOI 8 (PPG 22) - Location Map



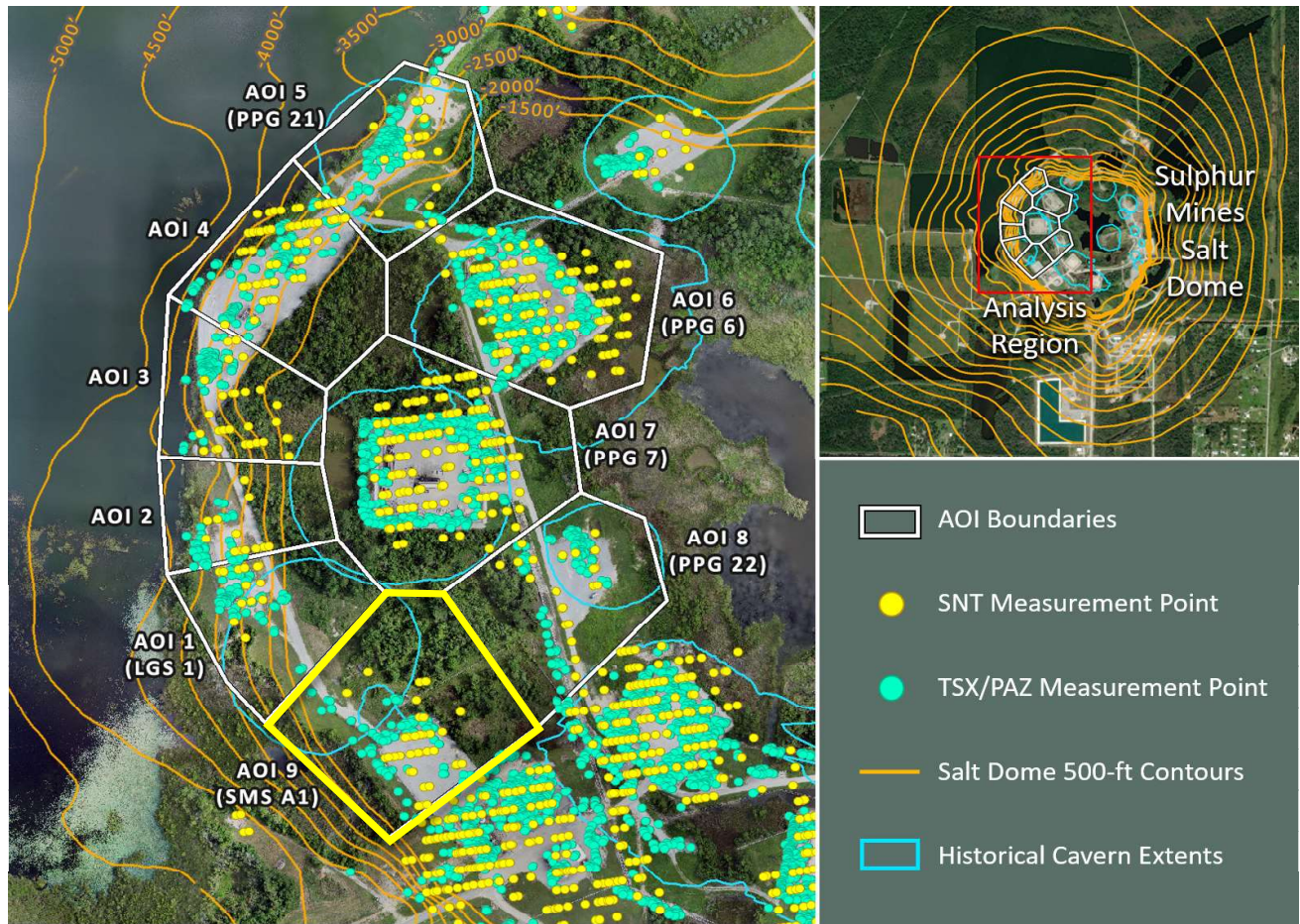
AOI 8 (PPG 22) - Displacement Time Series SNT (10/16/2023) Point Count: 21



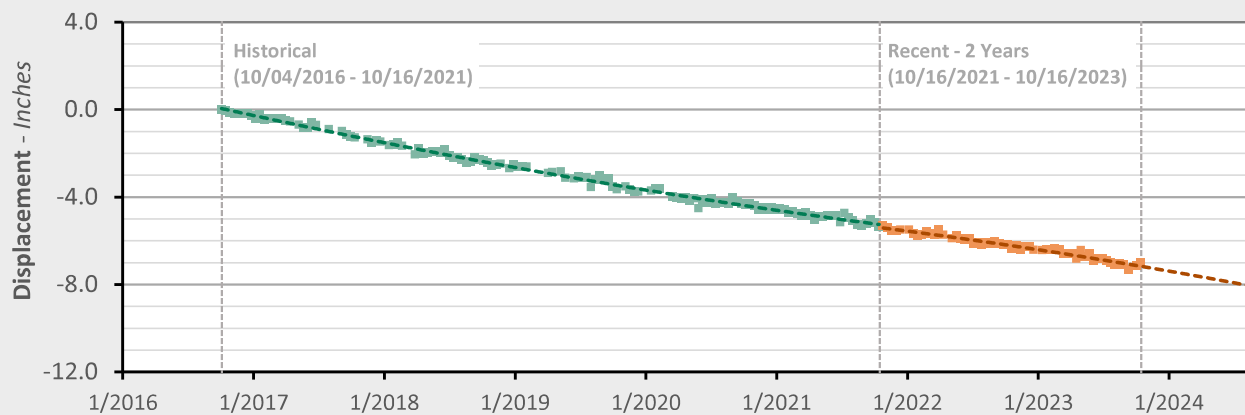
	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-1.06 in/yr	-1.47 in/yr	-0.40 in/yr
Acceleration:	+0.13 in/yr ²	-0.21 in/yr ²	-0.34 in/yr ²

■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

AOI 9 (PPG A1) - Location Map



AOI 9 (SMS A1) - Displacement Time Series SNT (10/16/2023) Point Count: 39



	Historical Trend Values	Recent Trend Values	Trend Change
Velocity:	-0.79 in/yr	-1.02 in/yr	-0.23 in/yr
Acceleration:	+0.11 in/yr ²	-0.13 in/yr ²	-0.23 in/yr ²

■ Historical LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)
 ■ Recent LOS Displacement Measurement
 --- Historical Trend Line (Quadratic Regression)

