Analysis of Subsidence Data

Review of Subsidence Rates Calculated From Level Survey & InSAR Data

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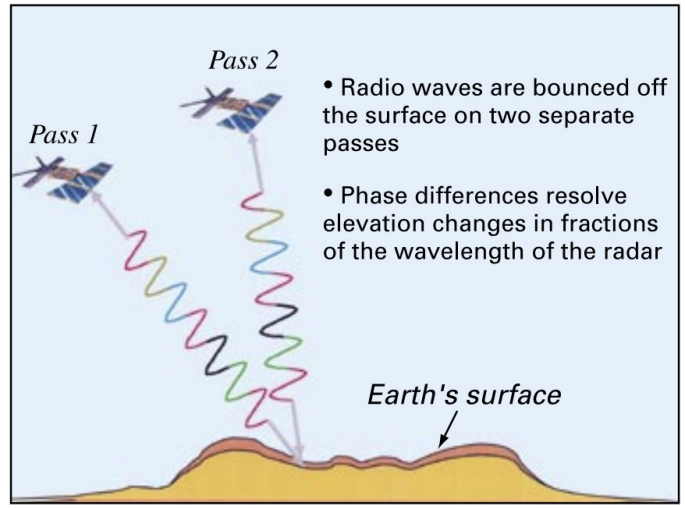
Presentation Outline

- **Part I**: Comparison of BHF Elevations
  - Top vs Bottom
  - InSAR not considered here
- **Part II**: Comparison of InSAR to Level Survey Data
- **Considerations**



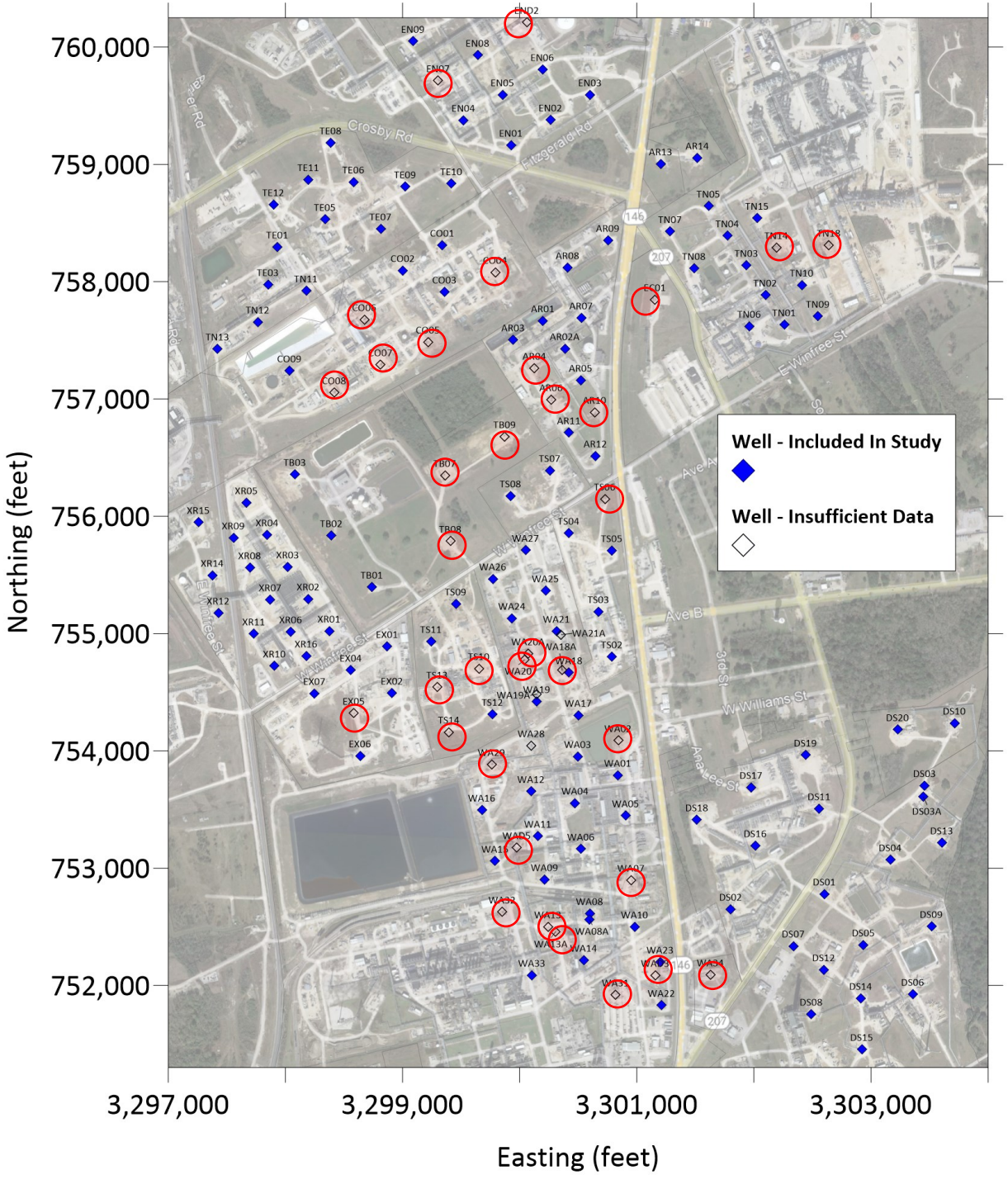
Criteria for Consideration

Required Both 1 and 2 (not used◯)

1. Consecutive level surveys: 4
   - 2016 – 2019
2. InSAR Reflectors: at least 1
   - Within 150 ft

Wellheads Included in Study: 125

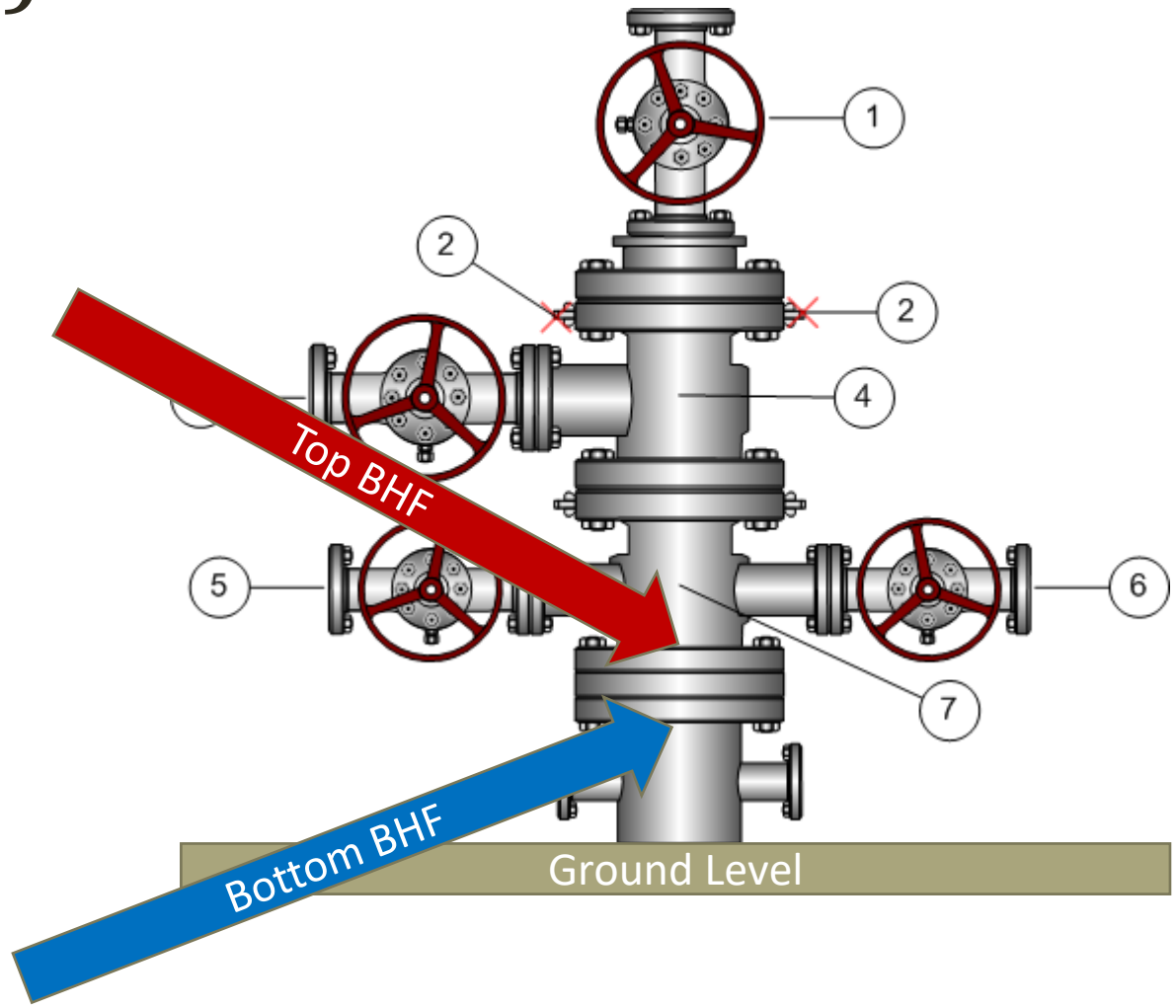
- All wellheads today ~163



Scope of Work (Part I)

Compare Bradenhead Flange (BHF) Elevations

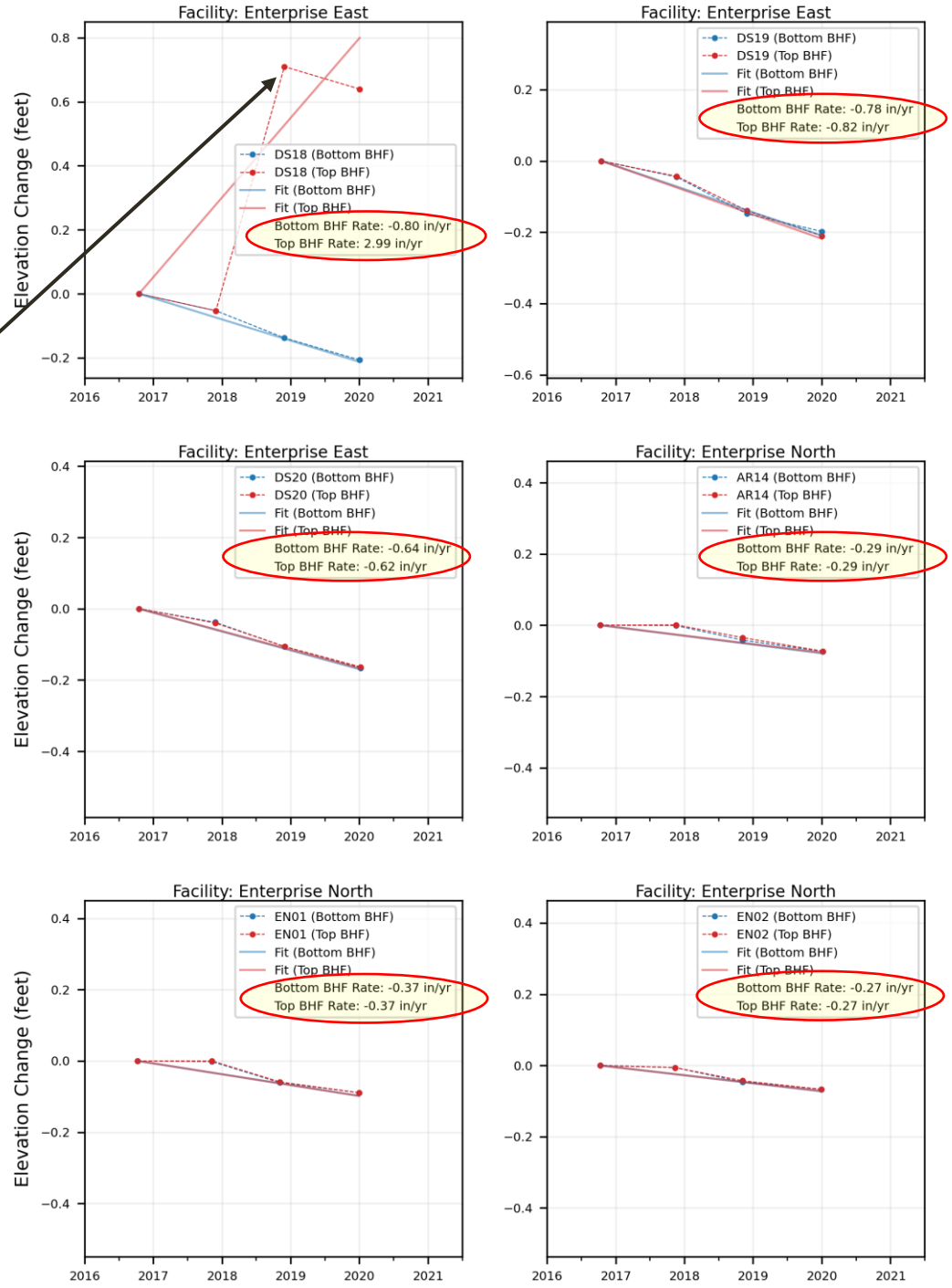
- Tables of the *calipered* offsets between the top and bottom sides of the BHFs on cavern wellheads with time,
- Contoured maps illustrating the subsidence rates based on both the top-side and under-side BHF elevations
- Plots of calipered offset-distances with time for all wellheads
- Results of the analysis of the differences between the two measurements



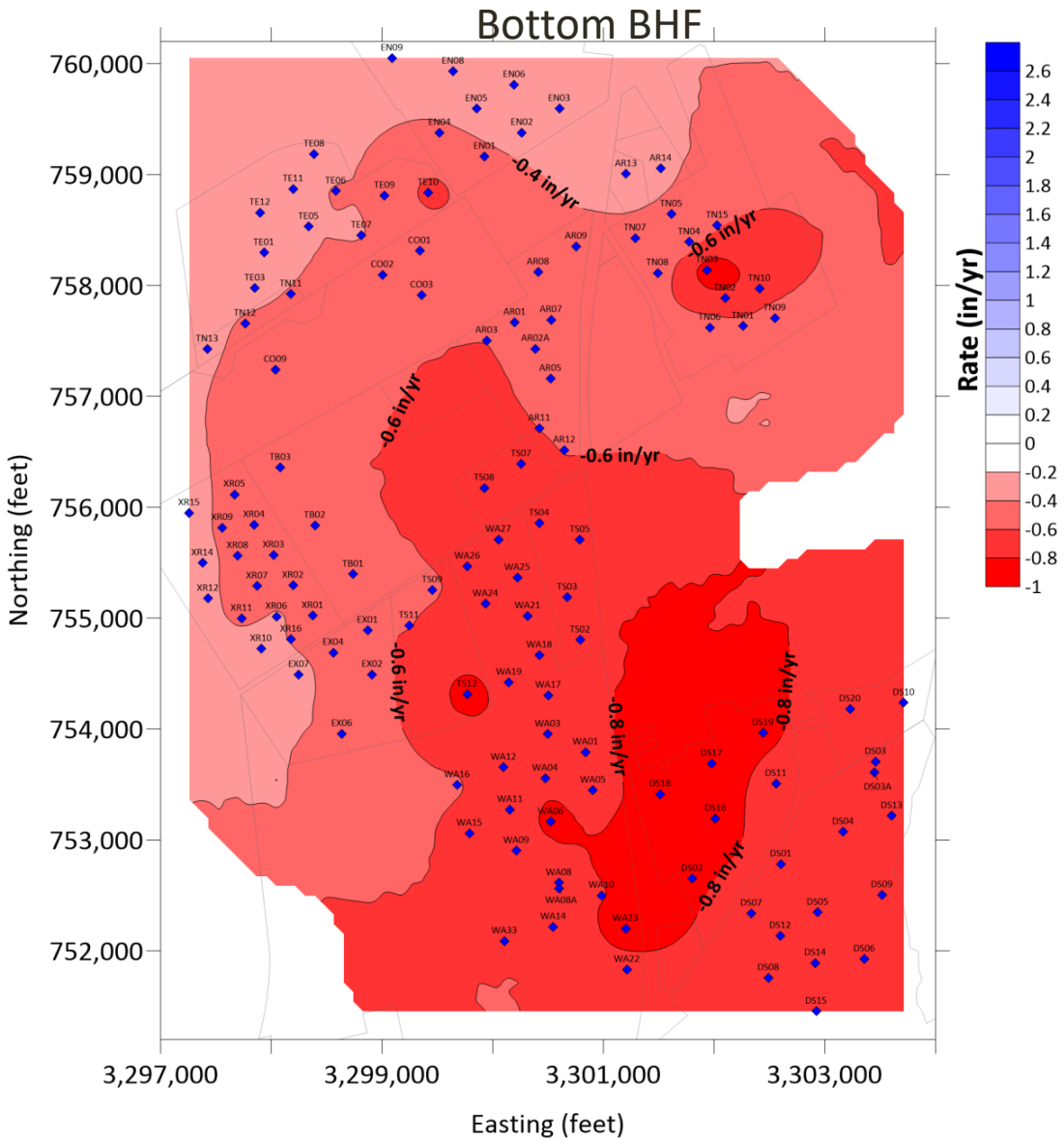
Example:
Bottom vs Top BHF

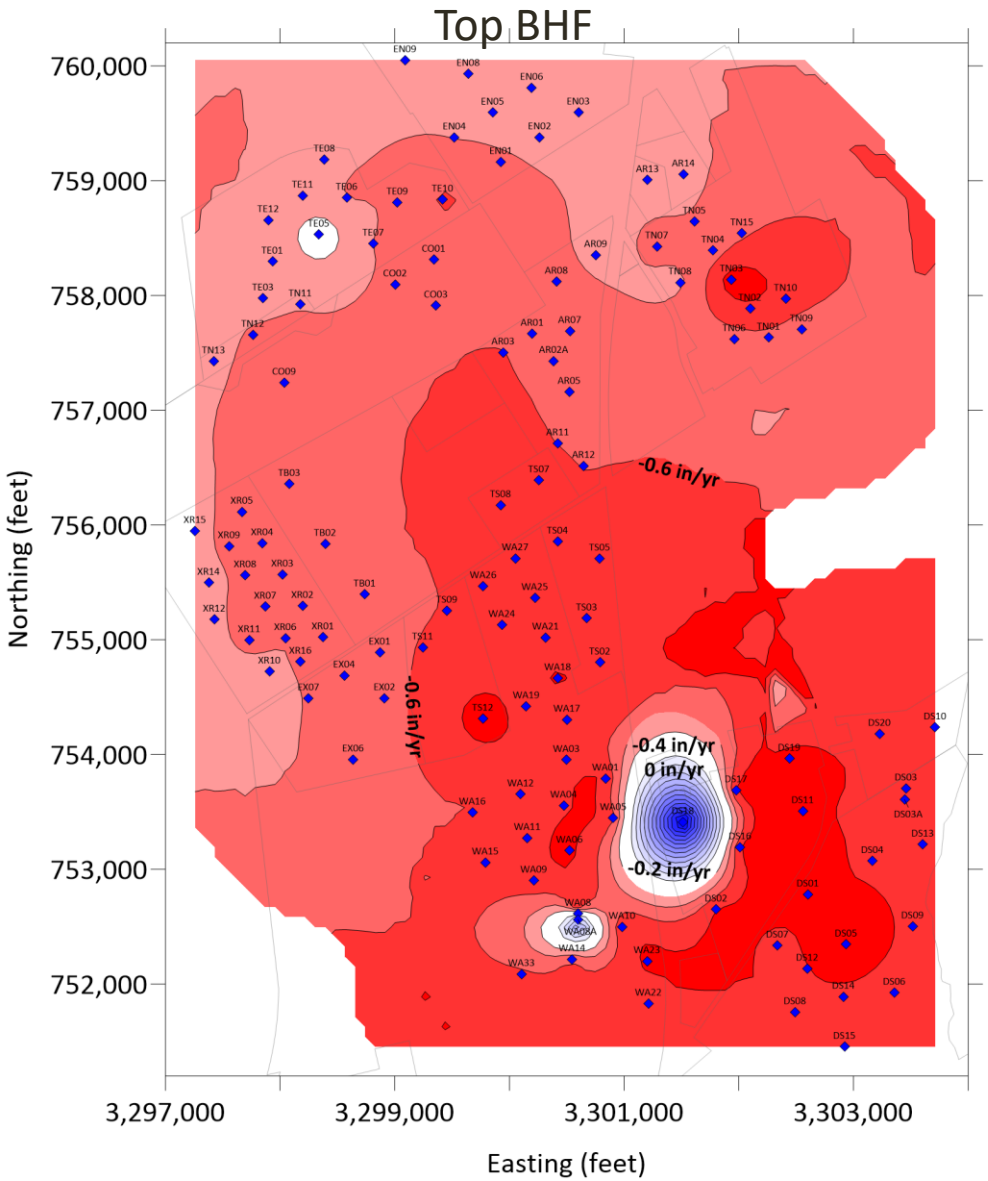
- Based on Level Survey Data

- DS18 (Enterprise East)
  - New location shot on WH in 2018
  - Calipered correction needed
  - Similar to
    - ✓ WA08



Level Survey – Bottom vs. Top of BHF



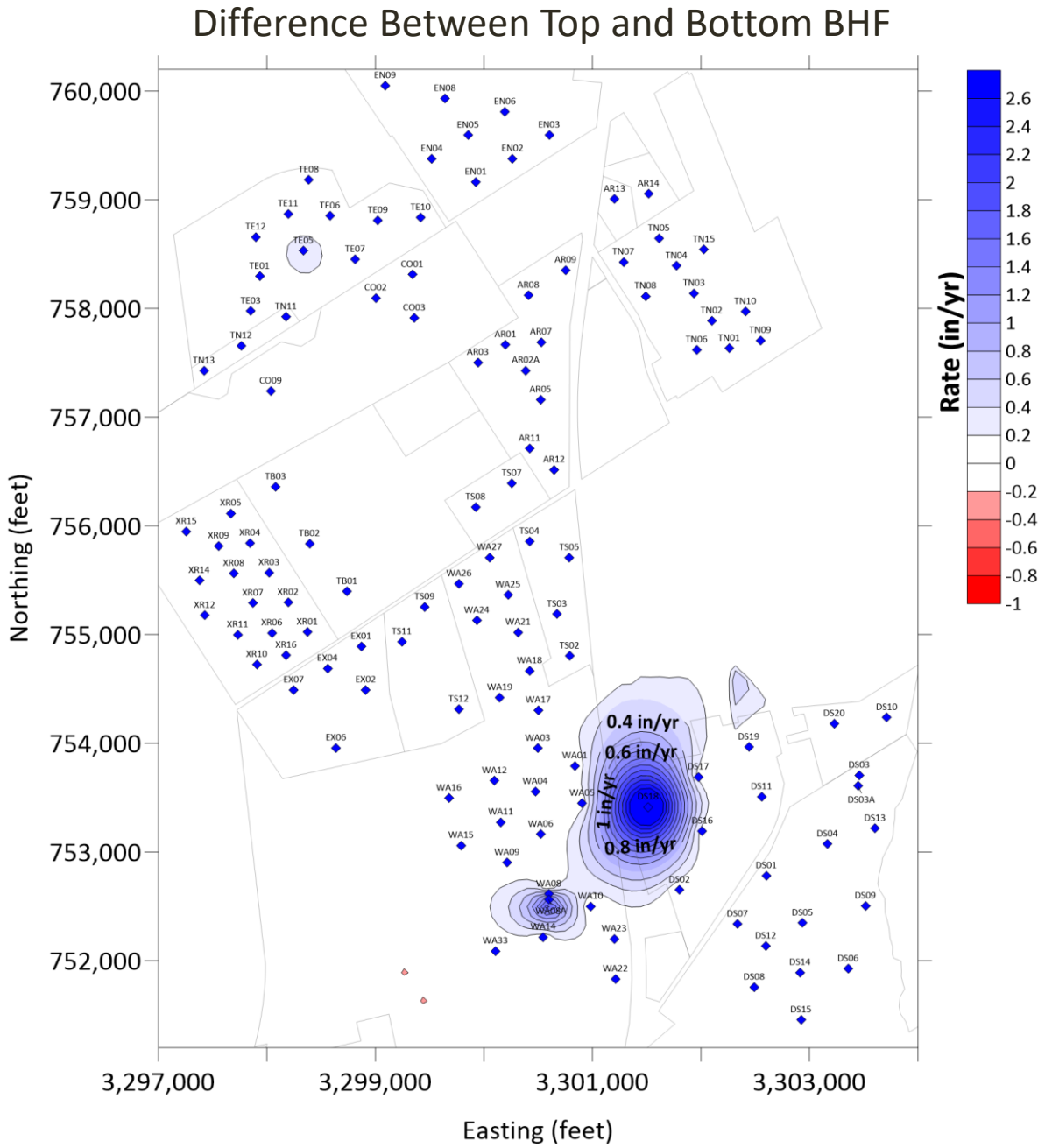


Part 1: Summary

Top & Bottom BHF Measurements

- Very Good Agreement
- Typical: +/- 0.2 in/yr
- Differences Related To
  - ✓ Change of WH Spool
  - ✓ New WH survey location

- Rate: Top BHF < Bottom BHF

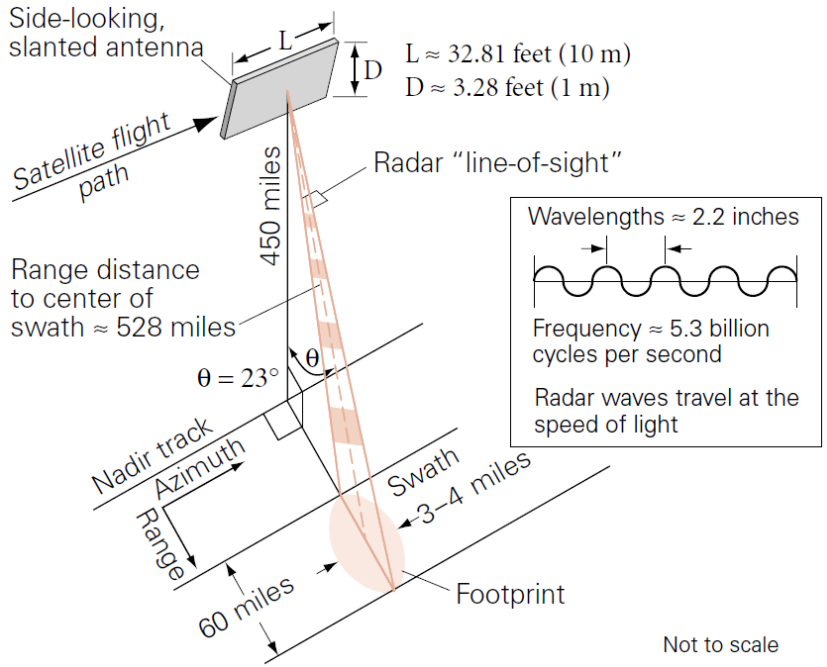


Part II: InSAR & Level Survey

Scope of Work (Part II)

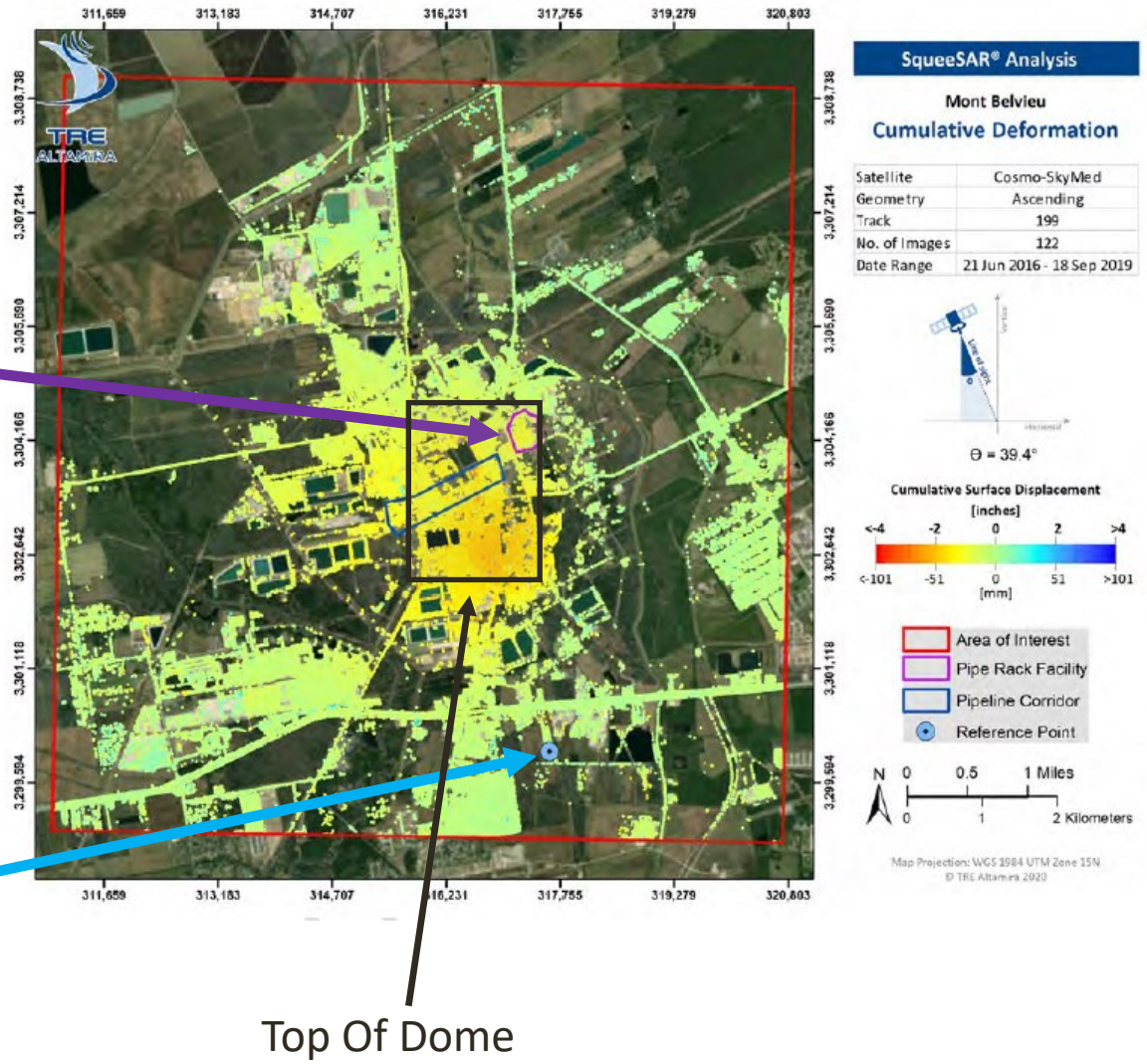
Comparison of InSAR to Level Survey Data

- Comparison of elevation measurements provided by the two methods
- Comparison of calculated subsidence rates resulting from the two methods
- Contour maps illustrating the results and differences of the two methods
- Plots (elevation versus time) comparing level survey data to InSAR data

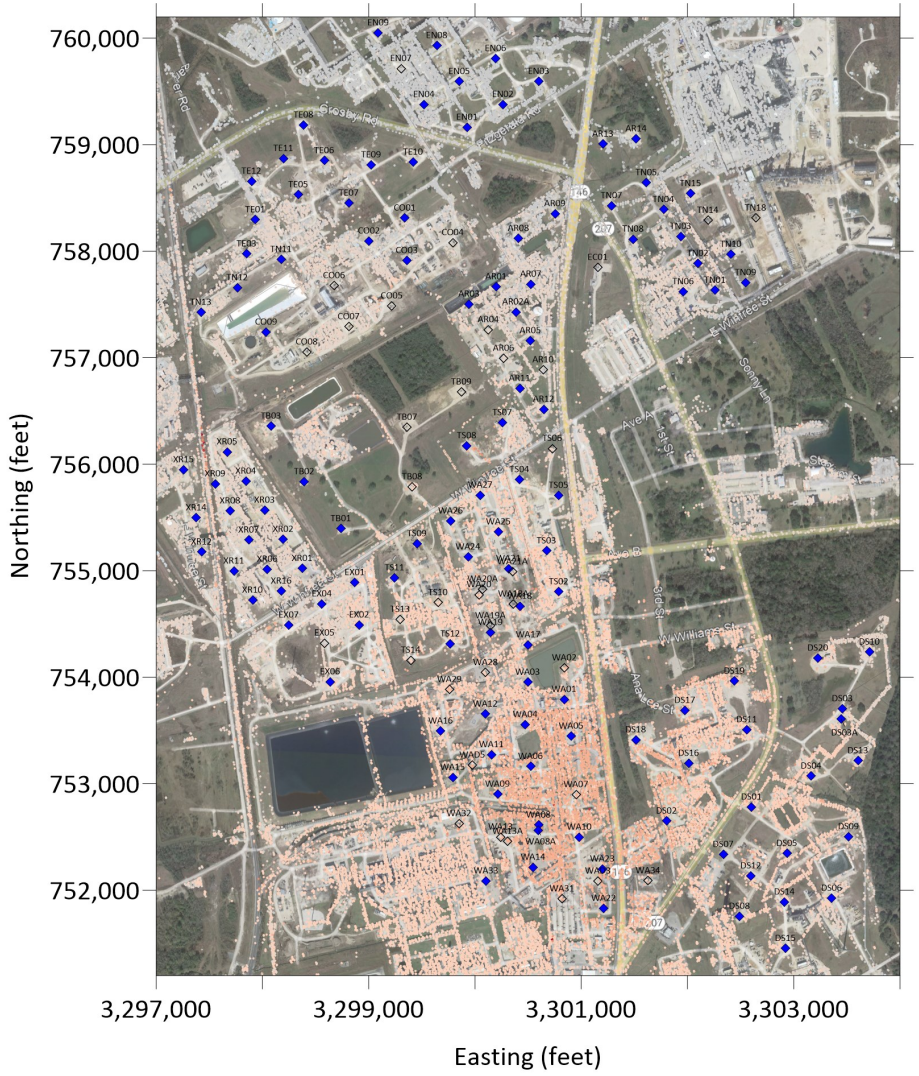


ONEOK InSAR Data

- ONEOK Terminal
- Completed by: Tre Altamira
- Dates:
  - 21-Jun-2016 through 24-Feb-2020
- Rates: -0.97 to +0.29 in/yr
  - Avg: -0.26 in/yr
- Reference Point



InSAR Data – Used Here

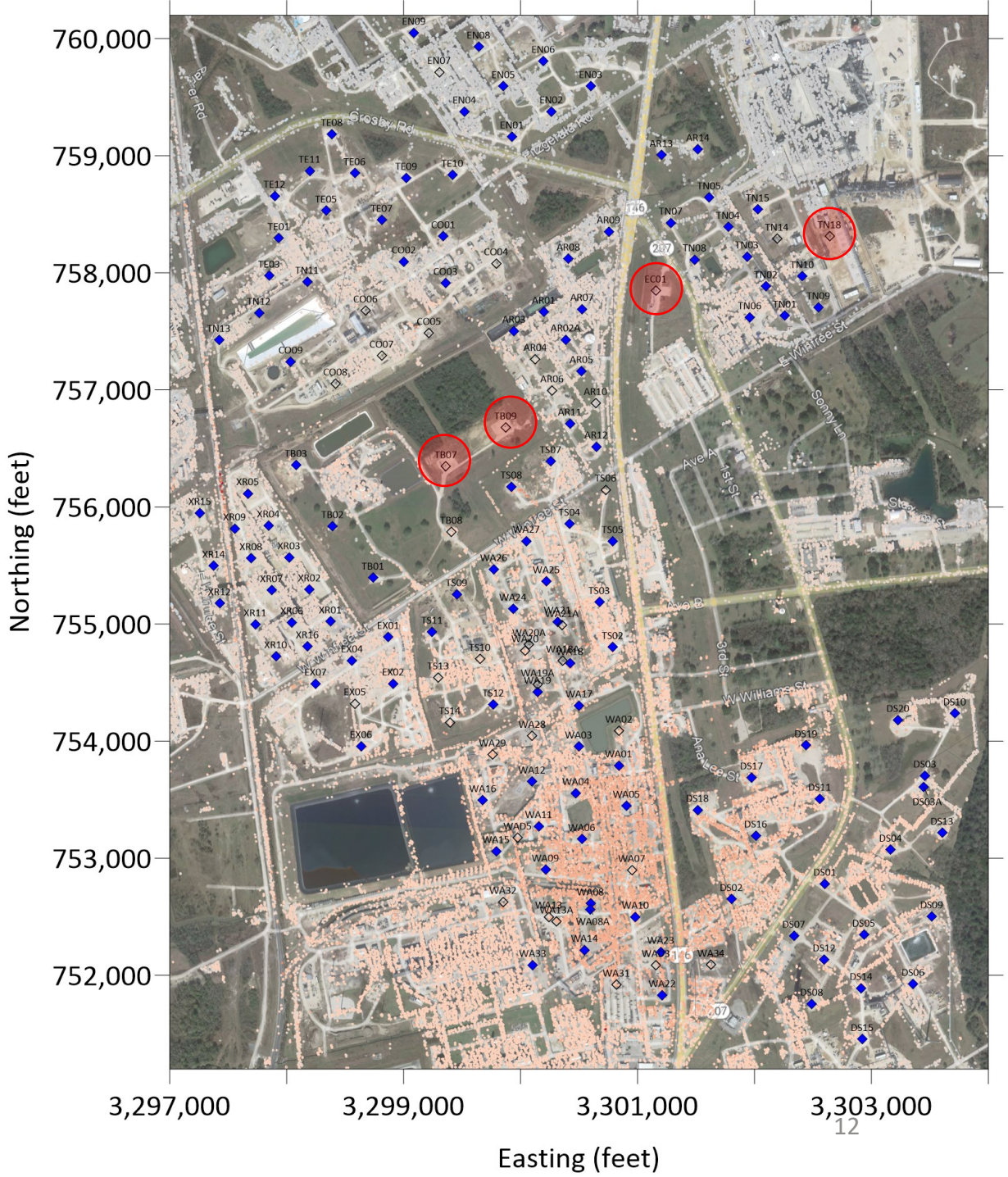


- Unique locations: 97,895
- Measurements in time
  - 131 radar images
  - Frequency: 8 - 16 days (approx.)
  - 21 June 2016 – 24 Feb 2020
- Data points considered: 12,824,245

InSAR Coverage

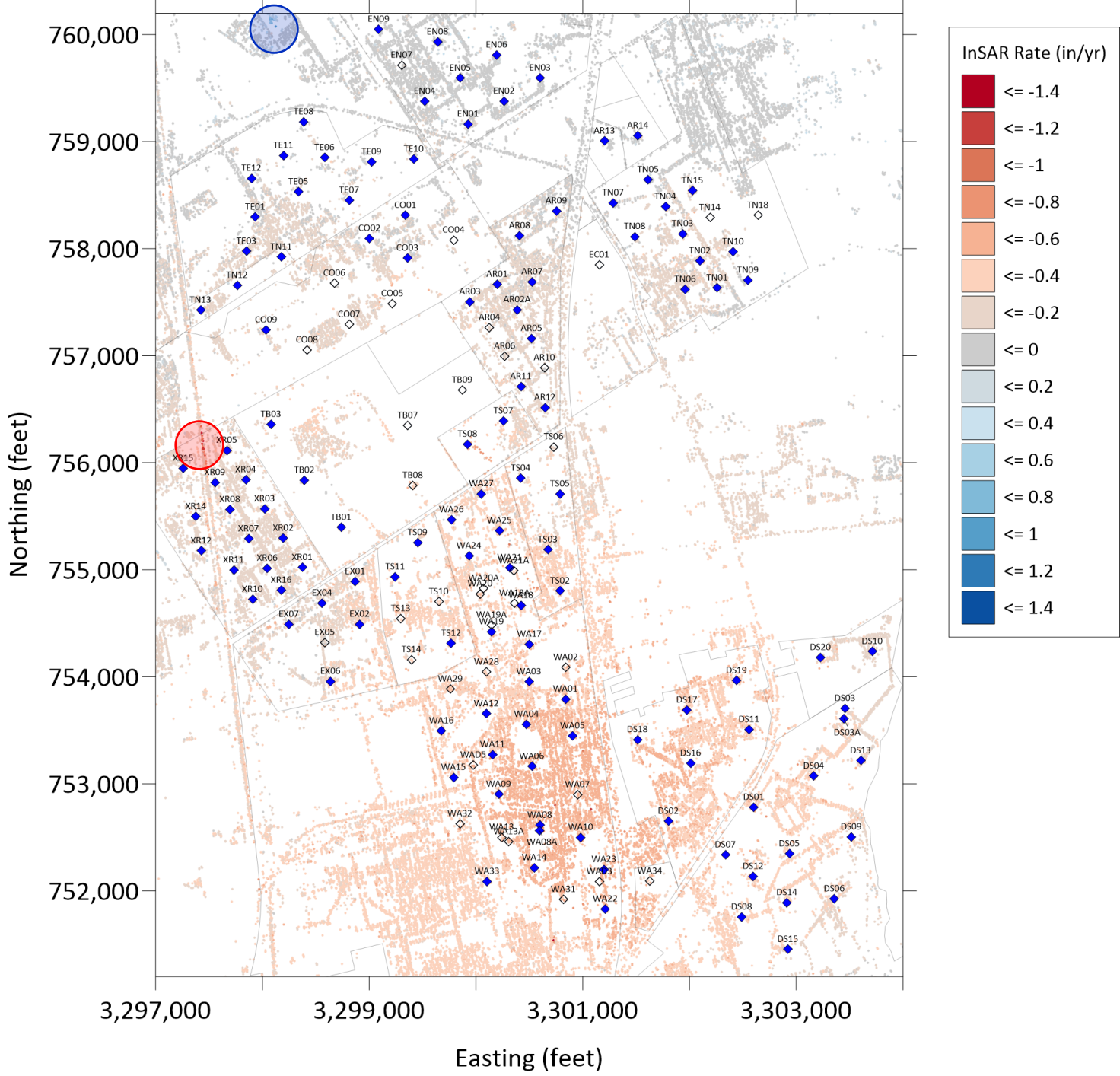
- Good
  - Road (paved, gravel, etc.)
  - Well pad
  - Anything not green

- Poor
  - Green (trees, grass)
  - Brine pond (water)
  - No InSAR Data:
    - ✓ Enterprise Central (EC01)
    - ✓ Pure Salt (7 & 9)
    - ✓ ONEOK (18)

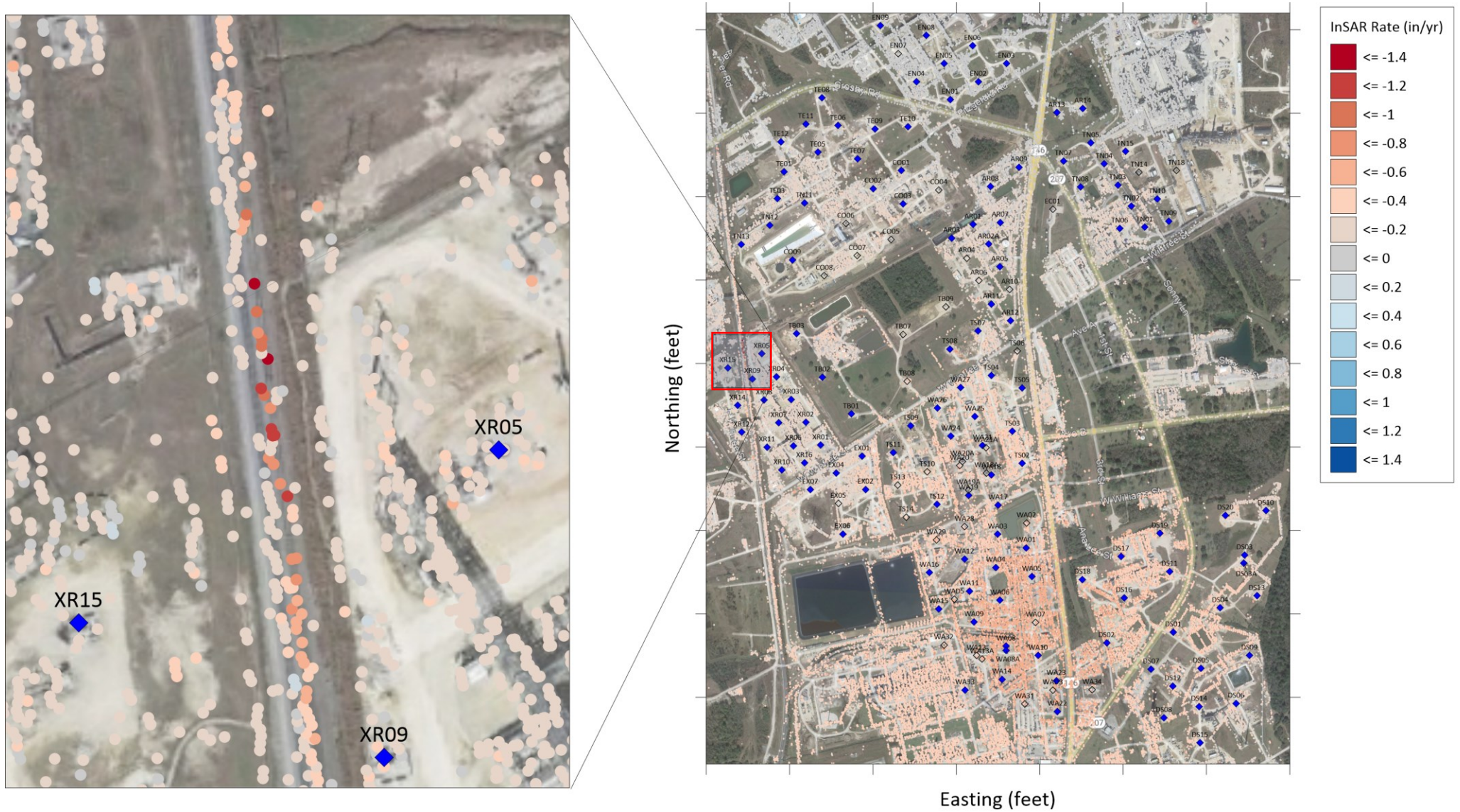


InSAR Rate

- Range
  - -1.4 in/yr (max)
  - +1.4 in/yr (min)
- North: lower
  - Enterprise North
  - Energy Transfer North
- South-Central: higher
  - Targa
  - Enterprise East



Example: InSAR Variability



Overview of InSAR Data

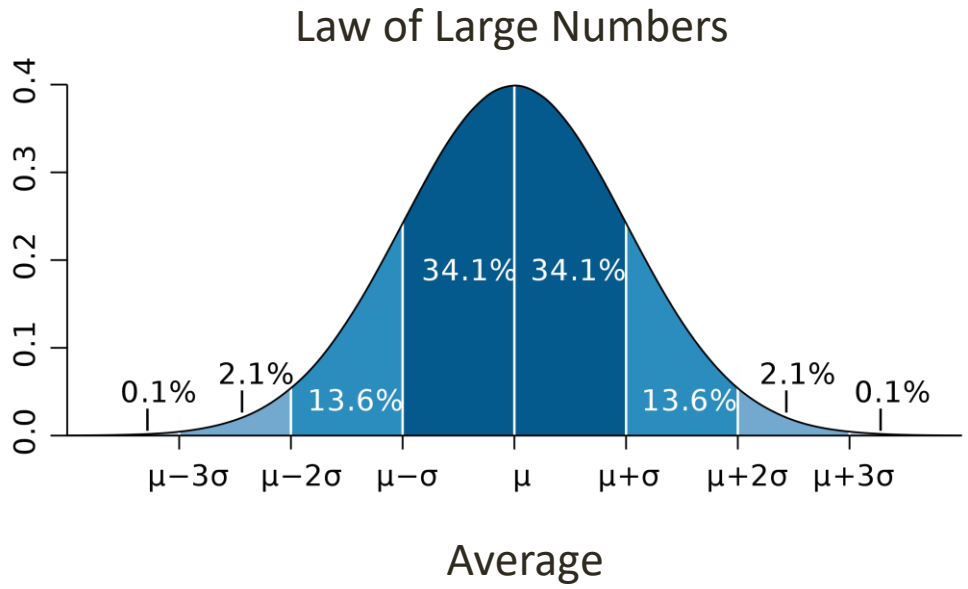
- Little Confidence in Single Reflector
- Accurate Analysis Needs Large Data Set

Fundamental Assumptions

- **Average** Value Approaches **Actual**
- **Error is normally distributed about mean**

InSAR Quantifies **Change** in Elevation

- Subsidence is summation of change



Part II (A) – InSAR Group

InSAR Group

Group = Area Around WH

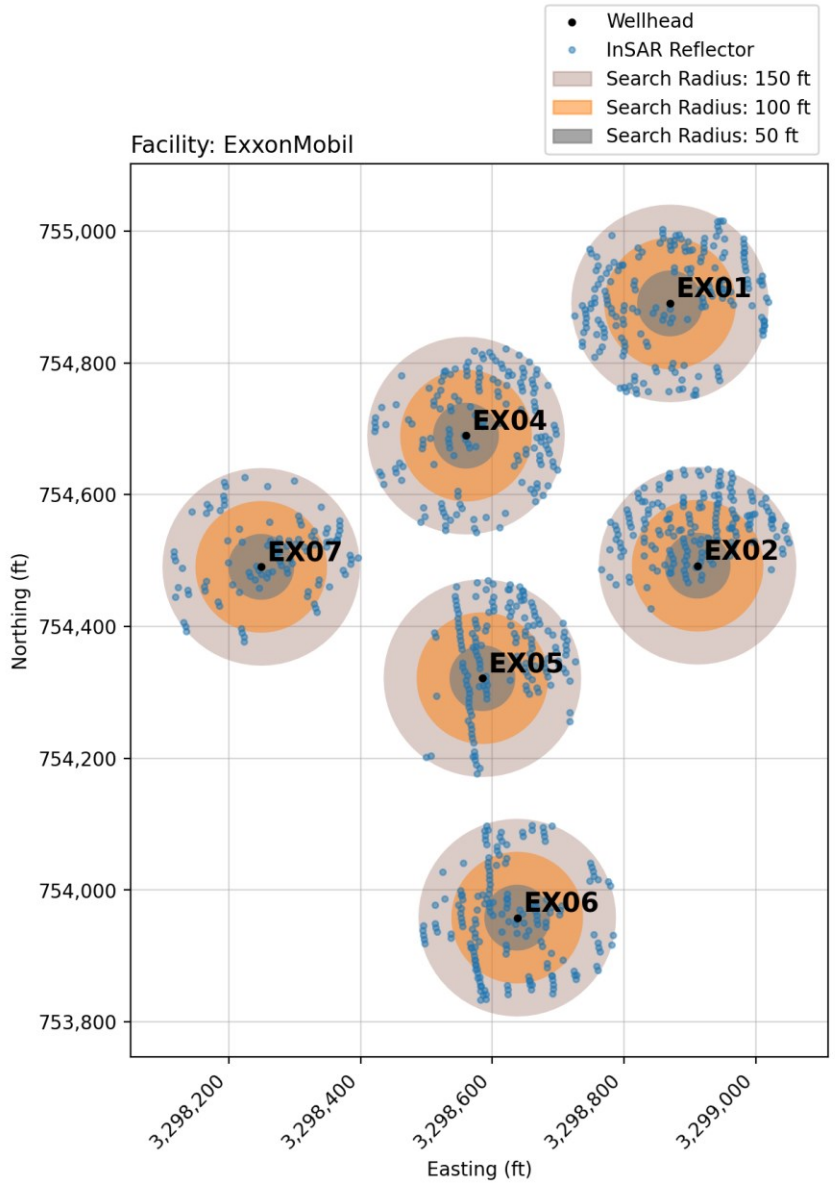
- Use average group value

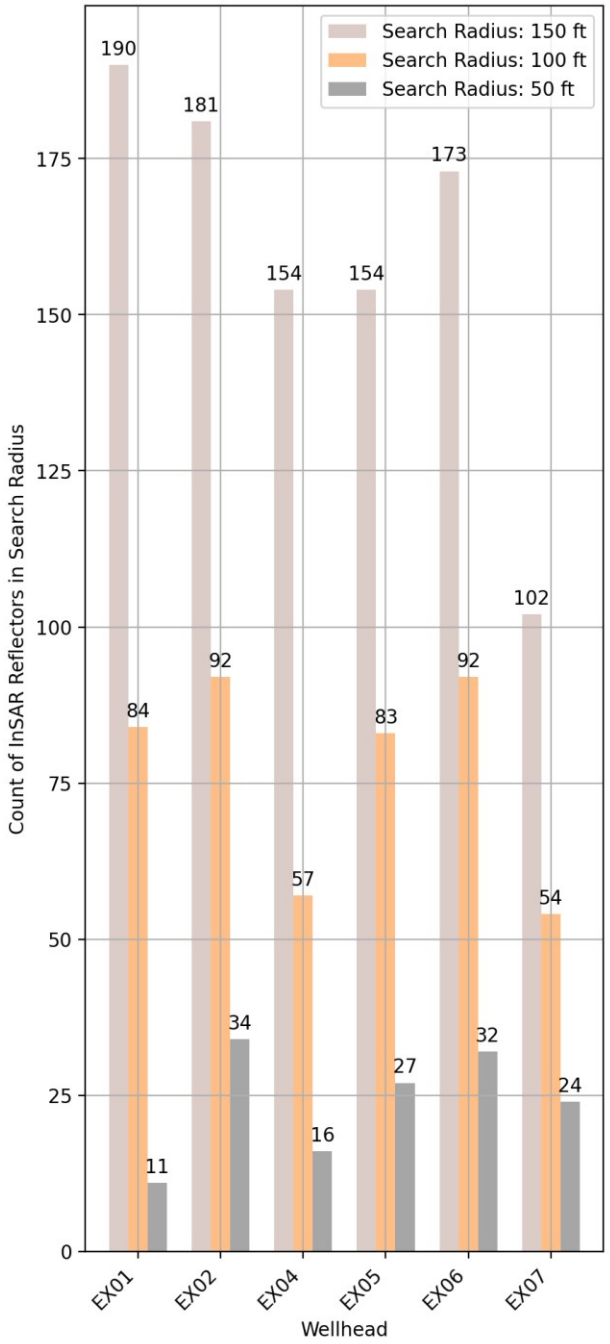
Key Point:

One rate for each WH

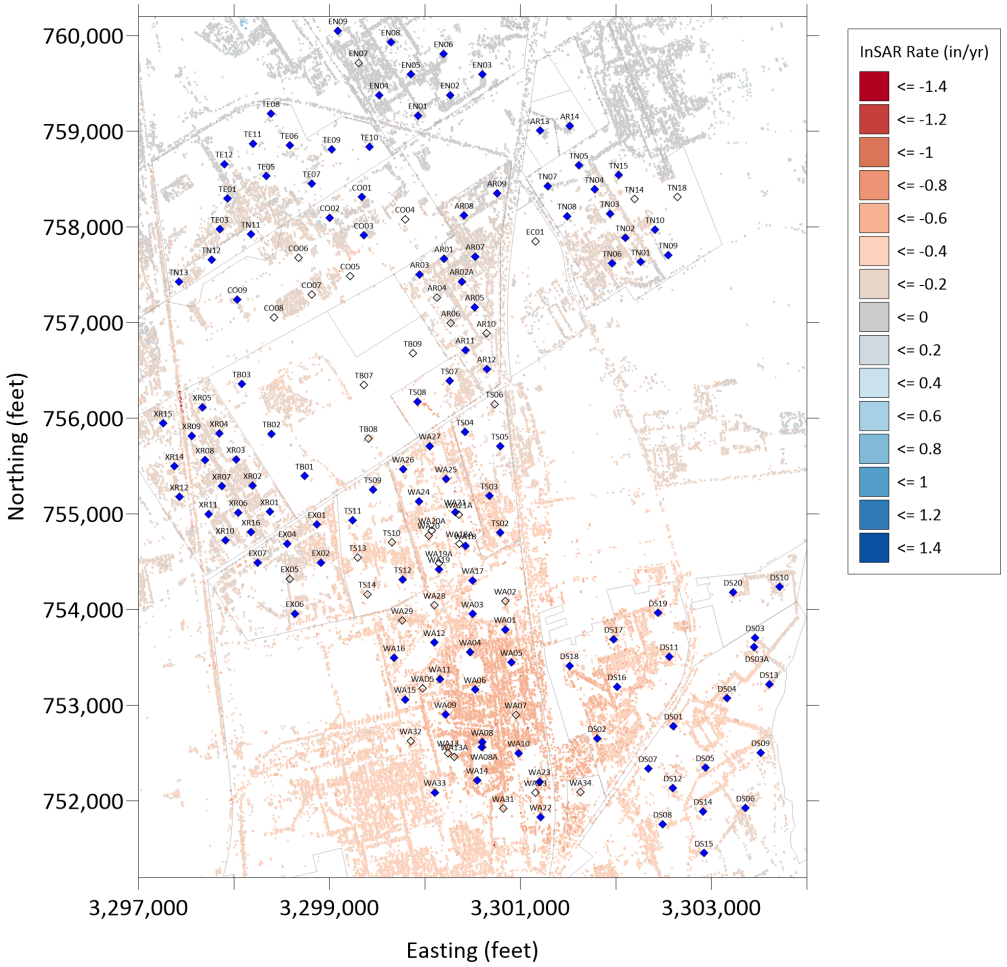
Group Search Radius (Buffer)

- 50 ft
- 100 ft
- 150 ft

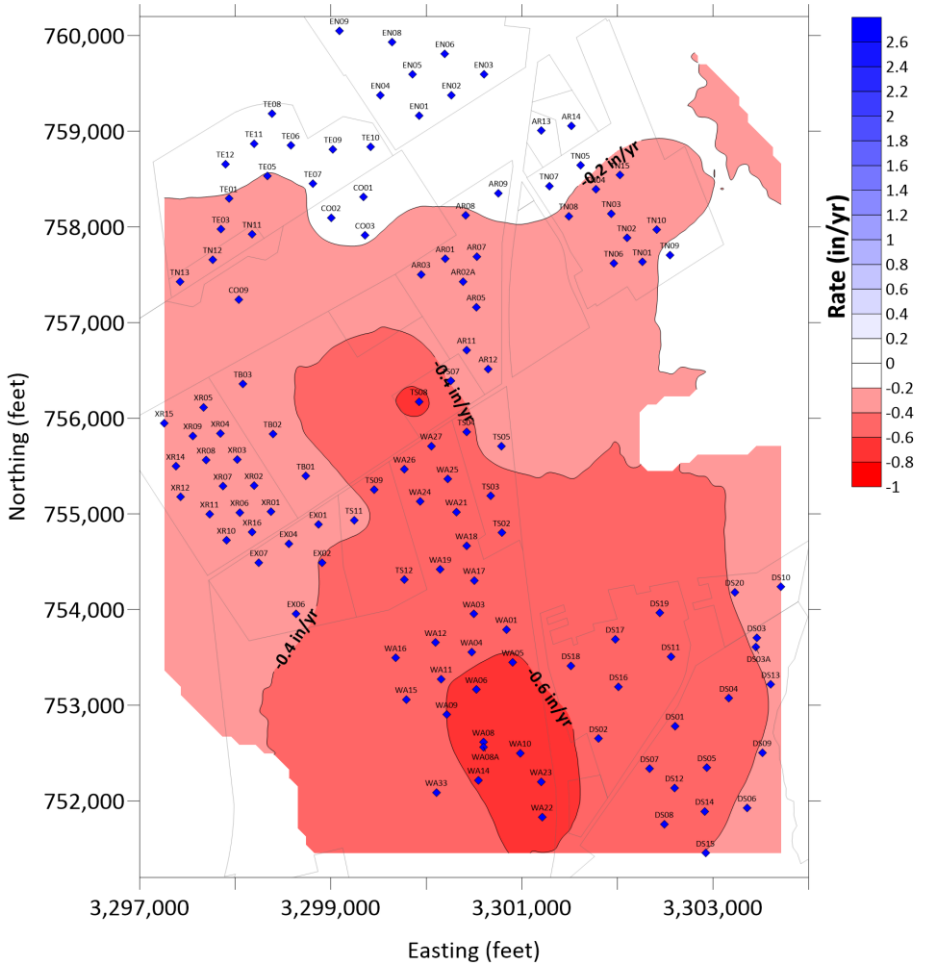




InSAR Rate: Point vs Group



Point Data

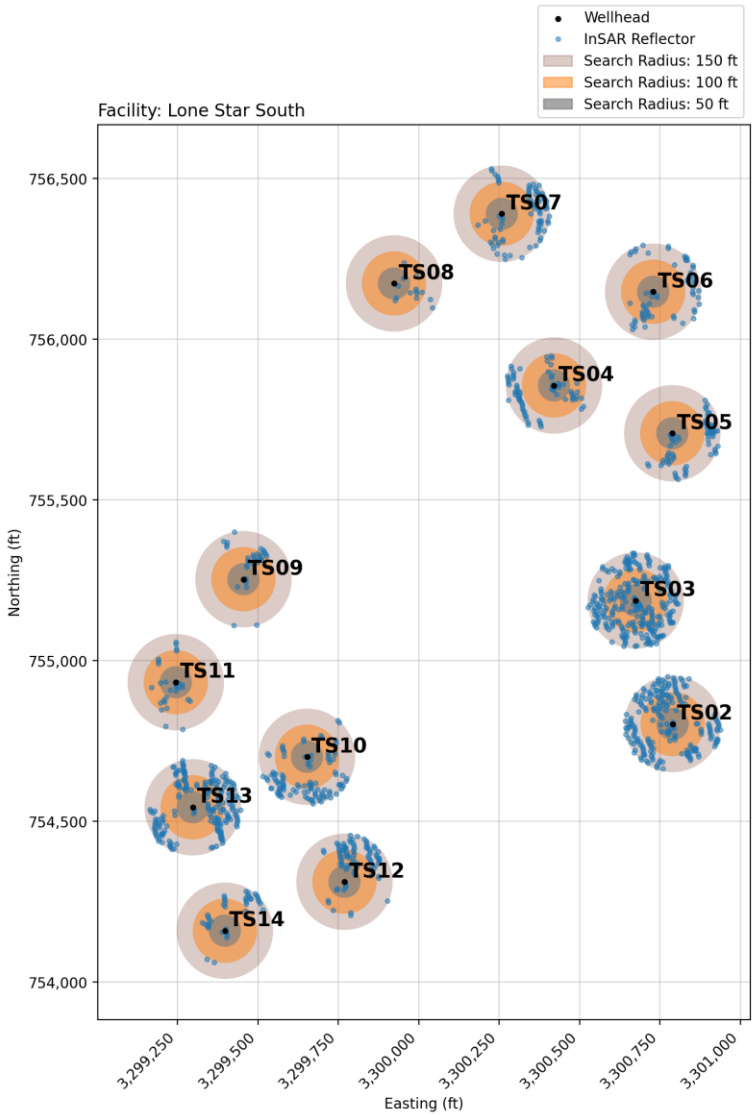


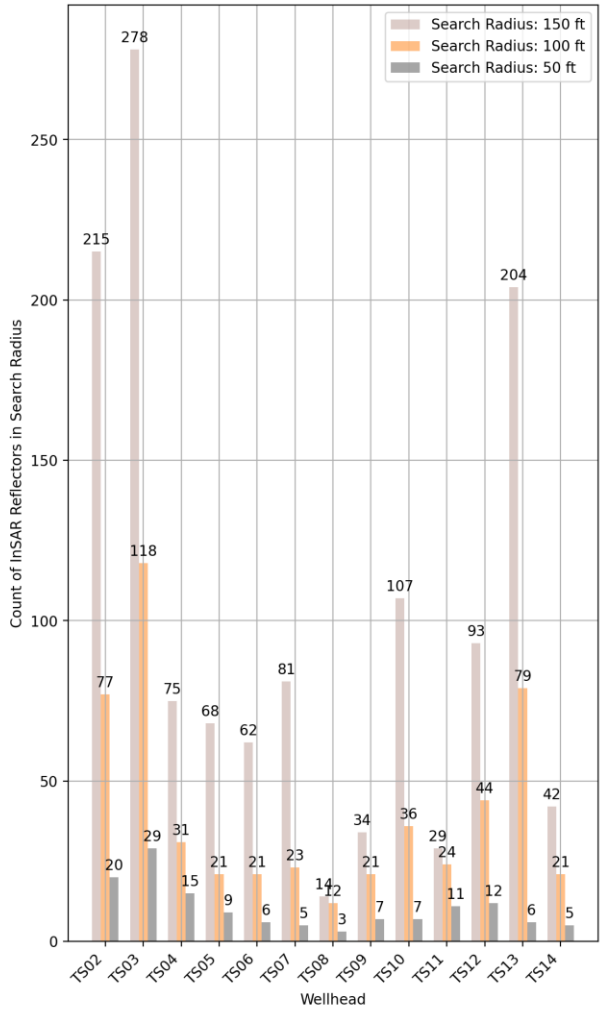
Group Data (150 ft Search Radius)

Part II (B) – InSAR vs Level Survey

Considerations

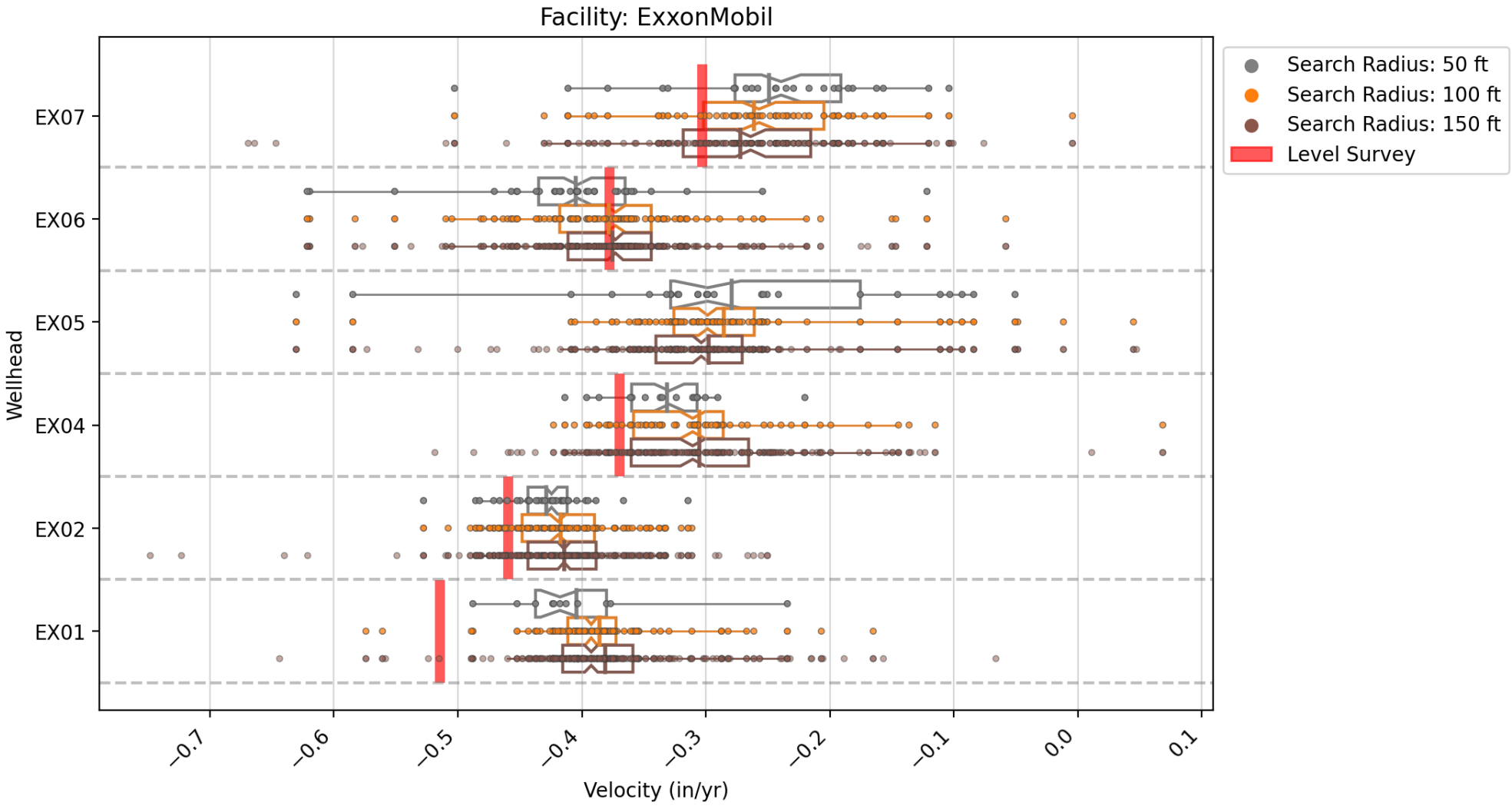
- Comparison
  - InSAR Reflectors
  - Wellheads (Bottom of BHF)
- Search Radius: 150 ft
- Level Survey Data
  - 2016 – 2019
  - 3.5 years of data



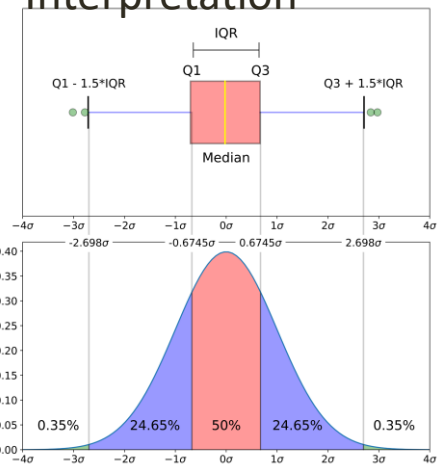


Example: Lone Star South

Example - InSAR vs Level Survey: ExxonMobil



Interpretation



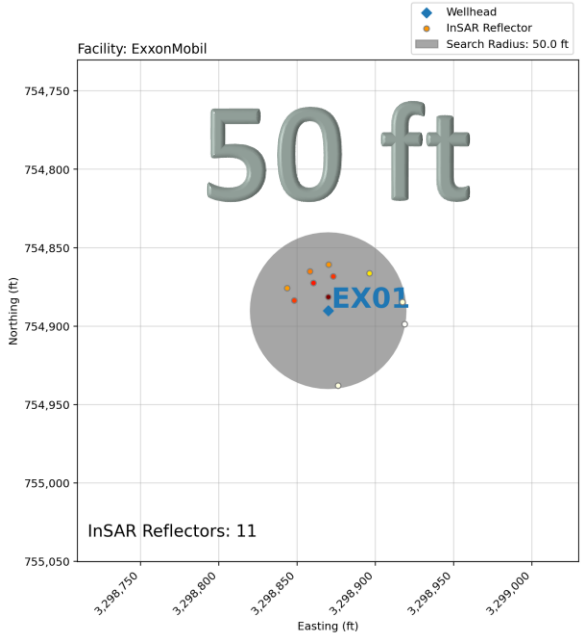
Search Radius

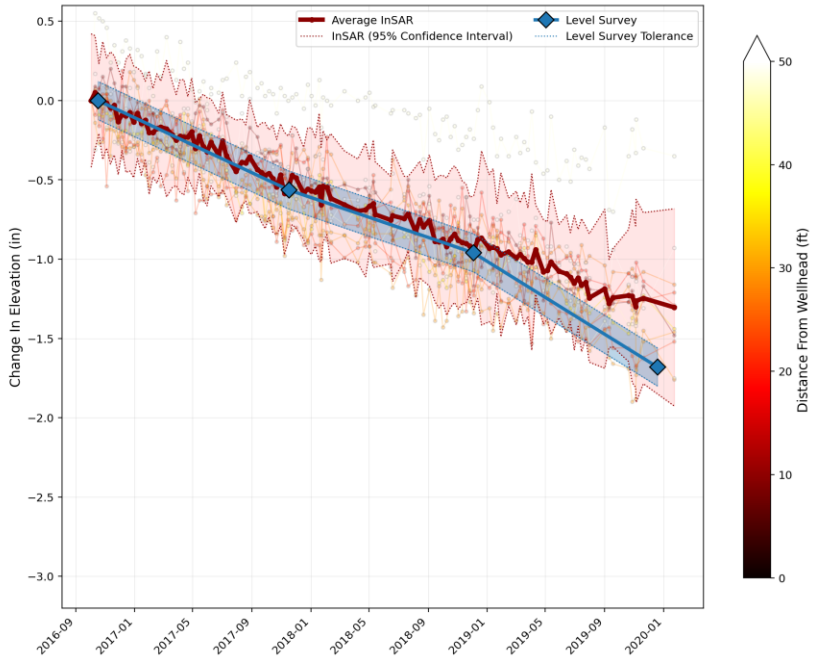
Example: ExxonMobil #1

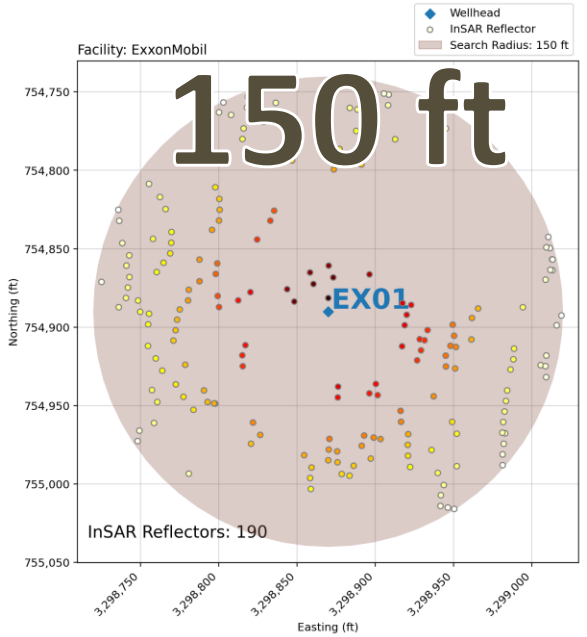
Reflectors: 11 vs 190

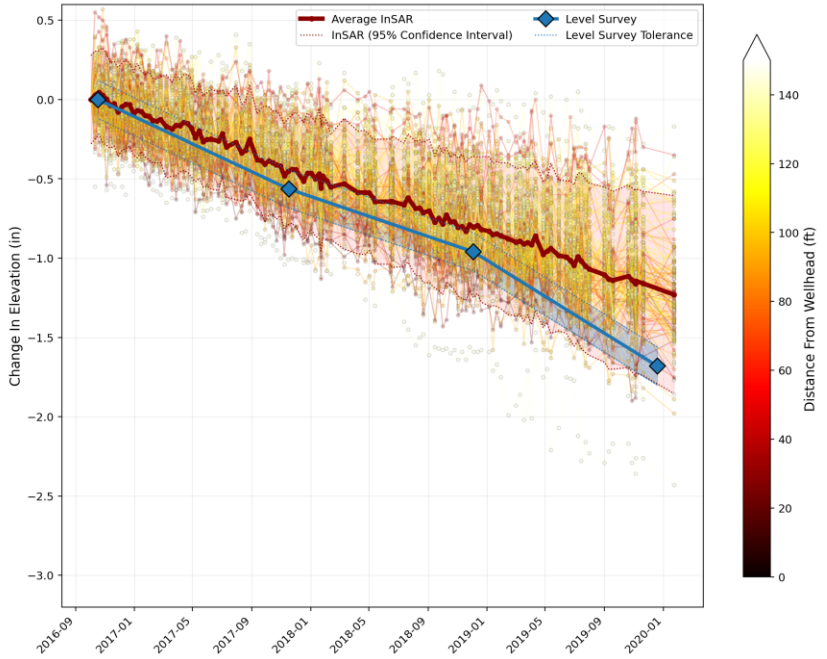
- Red: InSAR Average
- Blue: Level Survey

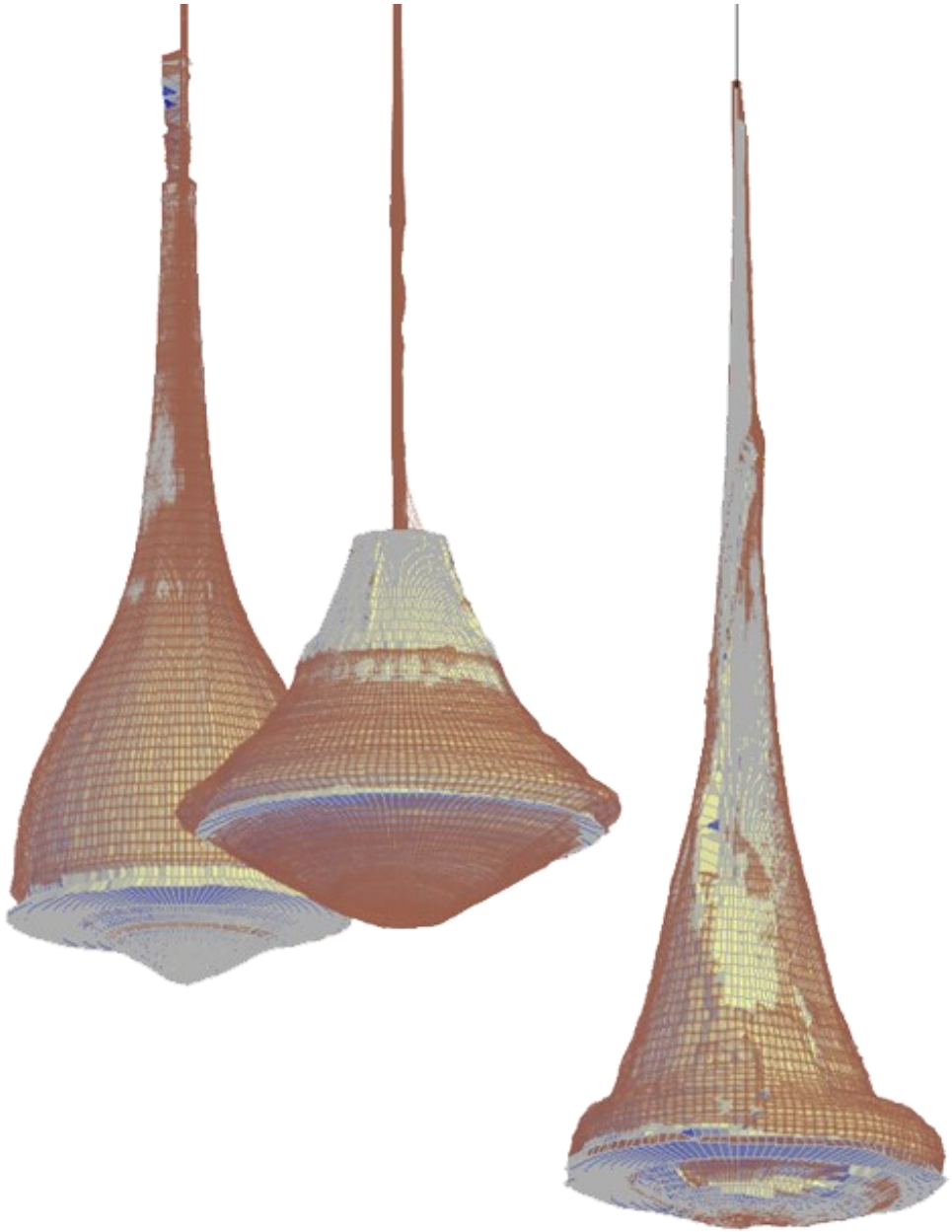
- Provided Plot of each WH











Part II (C) – Contours

Contour Maps – General Comments

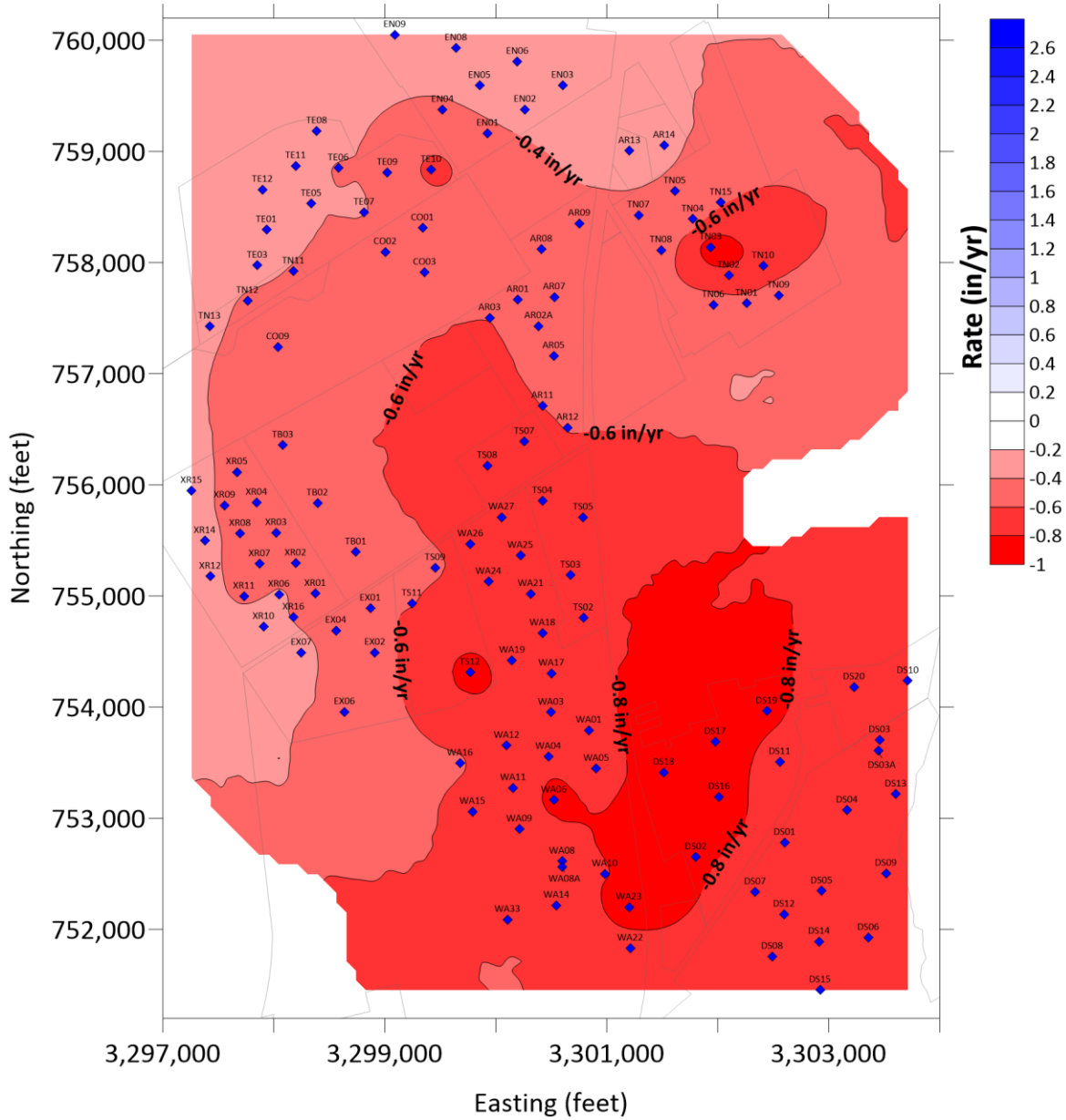
- Goal – Compare InSAR to Level Survey (not quantify subsidence)

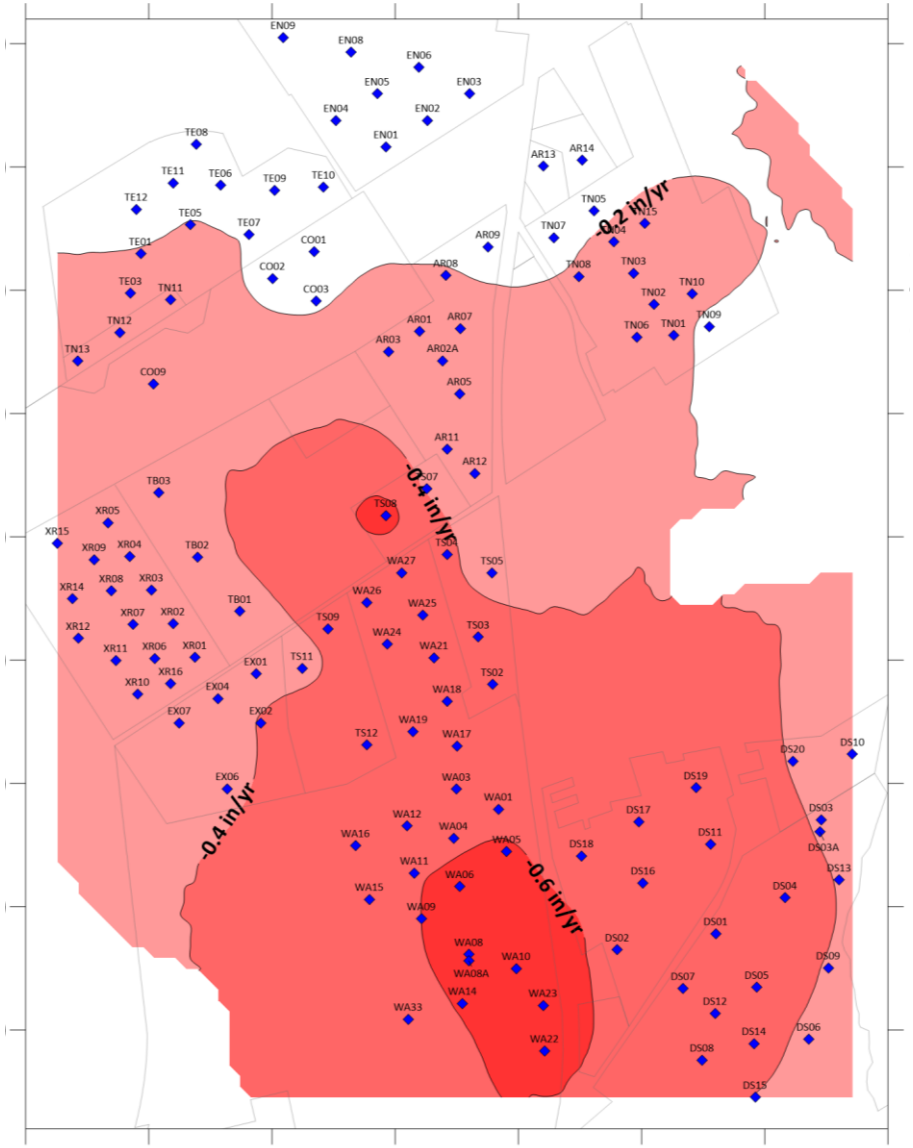
- Data was “cropped” such that it could be compared
  - “apples to apples”
  - InSAR: Grouped to 150 ft

- Level Survey:
  - Wellheads that were measured all four years
  - October 2016 – January 2020
  - Accounted for absolute rate (i.e., off-dome GPS: -0.071 inch/yr)
  - Surface monuments/benchmarks not evaluated

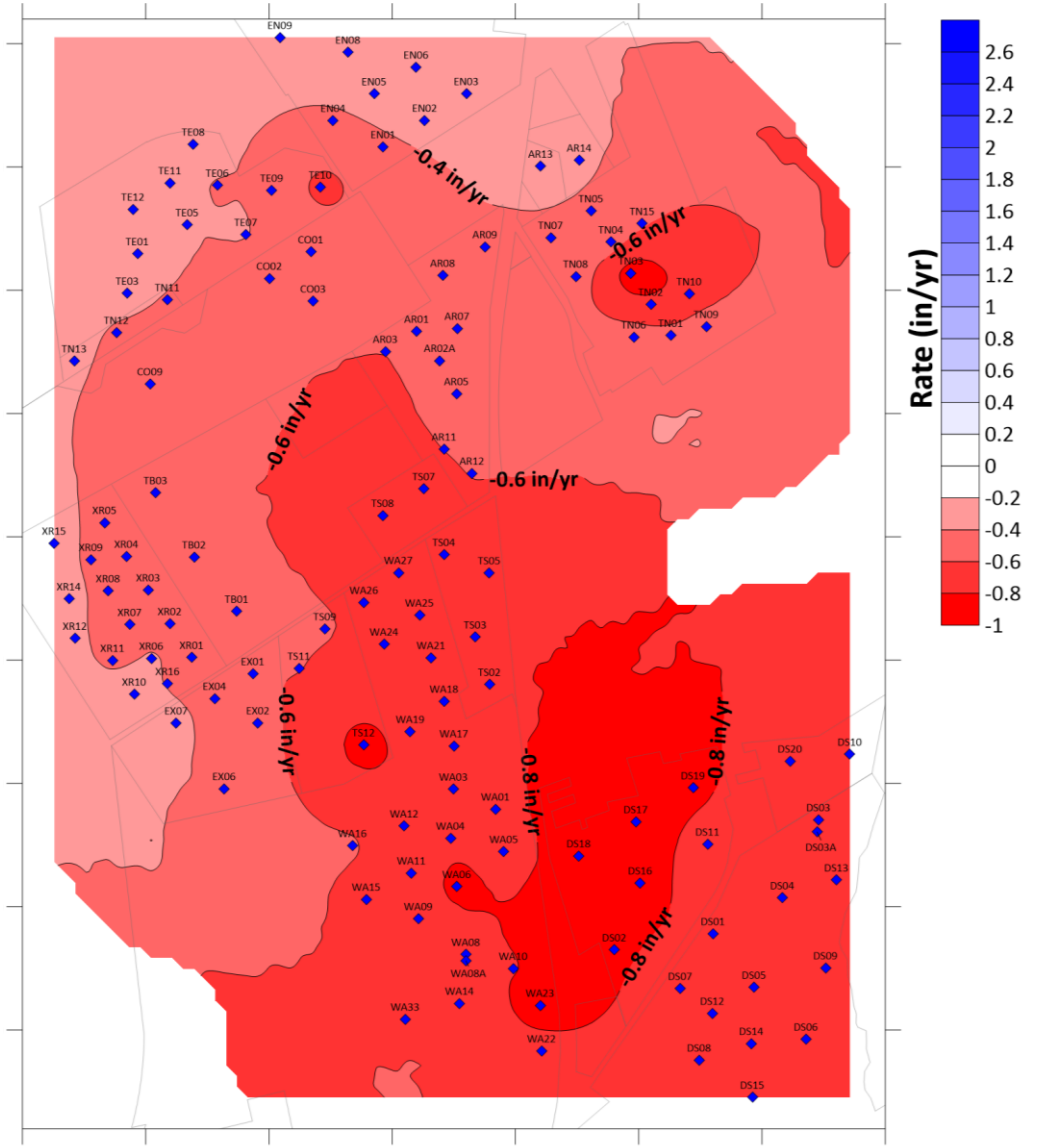
Contour - Level Survey

- Highest Rates
  - South (Ent. East & Targa)
  - ONEOK (TN03)
- Lowest Rates
  - North (Ent. North, LS North)
  - West (Ent. West, ExxonMobil





InSAR



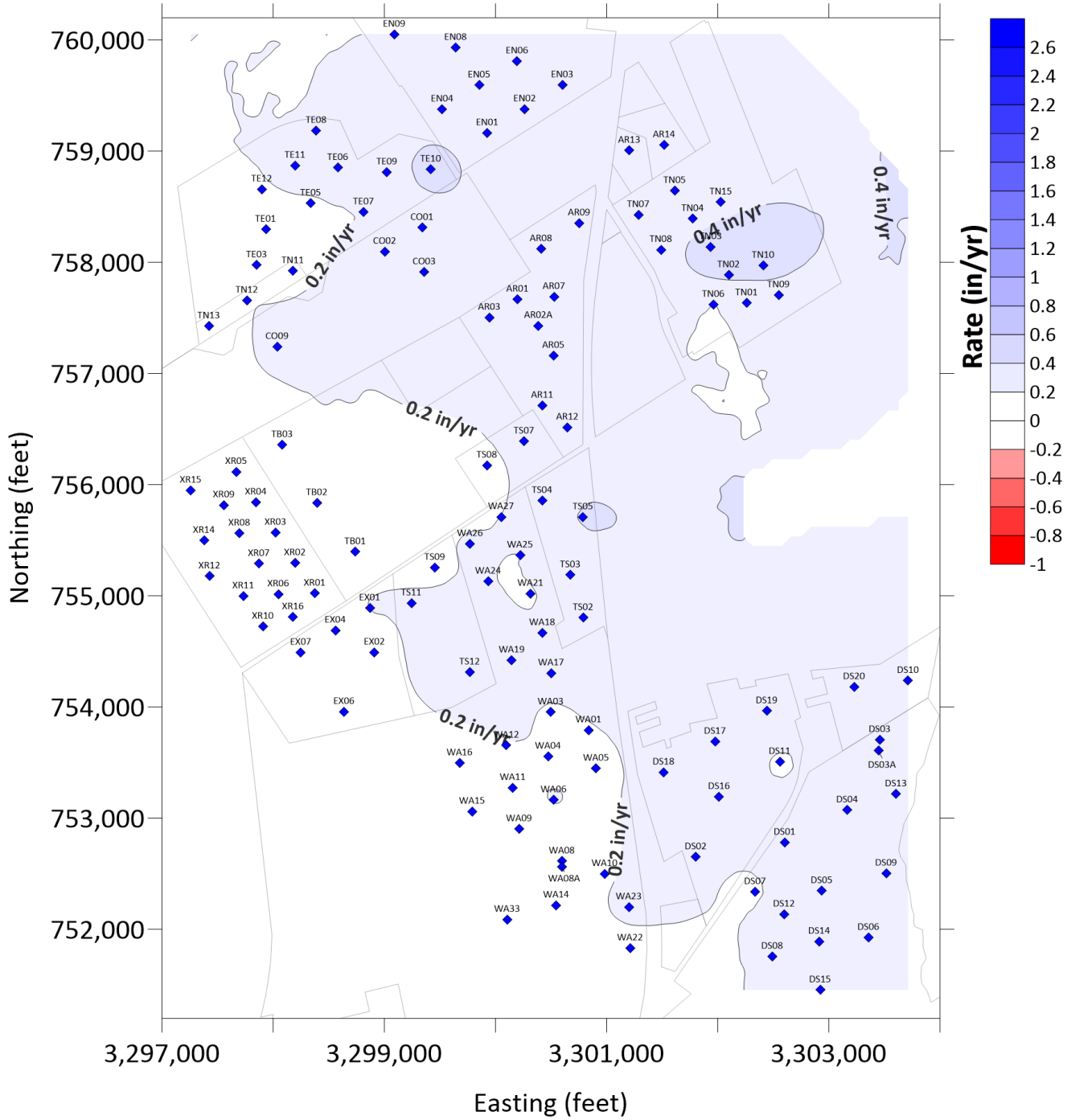
Level Survey

Diffrence: Subsidence Rate (InSAR – Level Survey)

- Blue -> Level Survey is Greater
  - Units: Inch/year

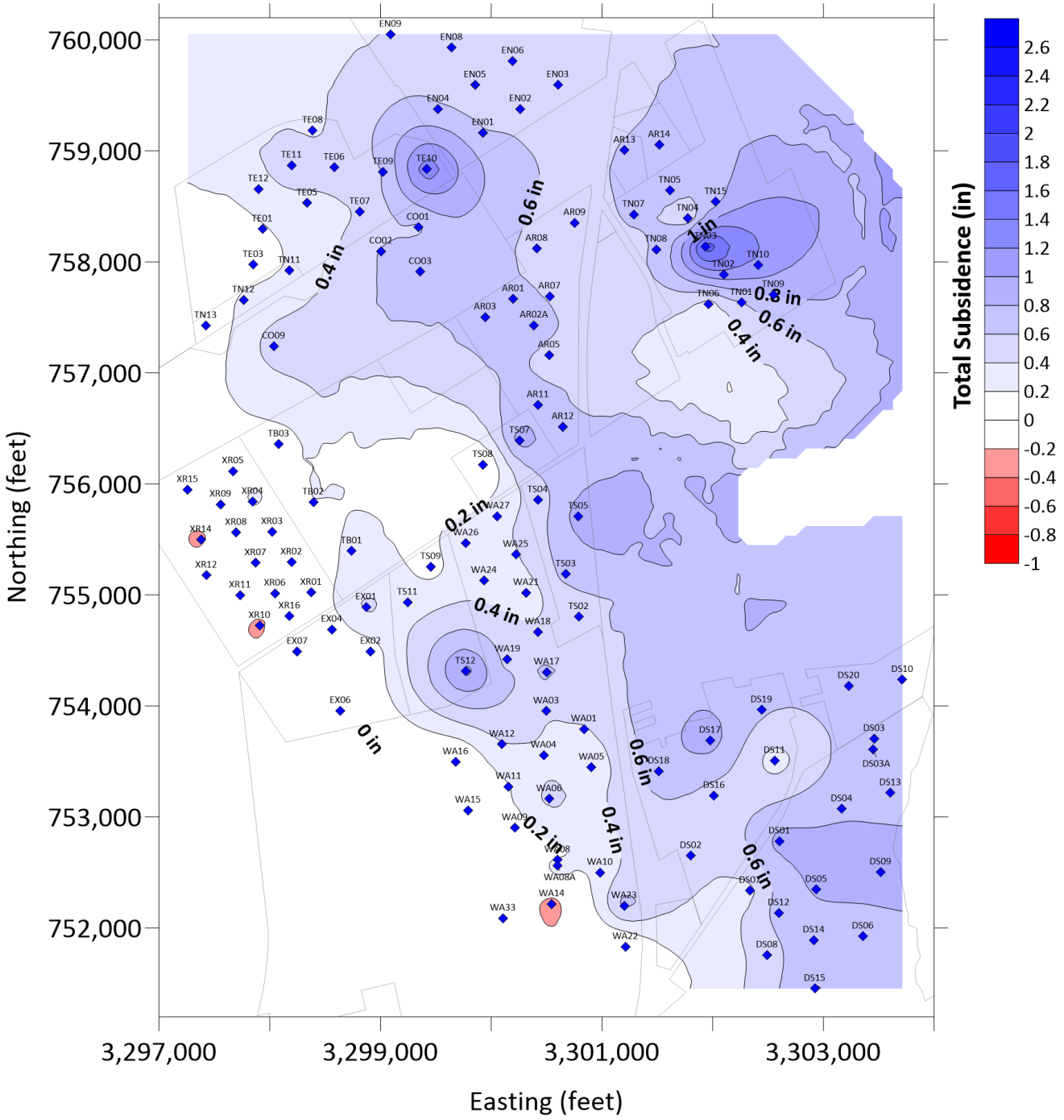
- Smaller Differences
  - South & West
  - Exxon, Targa

- Larger Differences
  - East
  - ONEOK



Difference: Total Subsidence (InSAR – Level Survey)

- Cumulative Subsidence
  - Units: Inch
- Blue -> Level Survey is Greater
- Red -> InSAR is Greater
- Smaller Difference
  - South & West
  - Exxon, Targa
- Larger Difference
  - ONEOK, Enterprise East



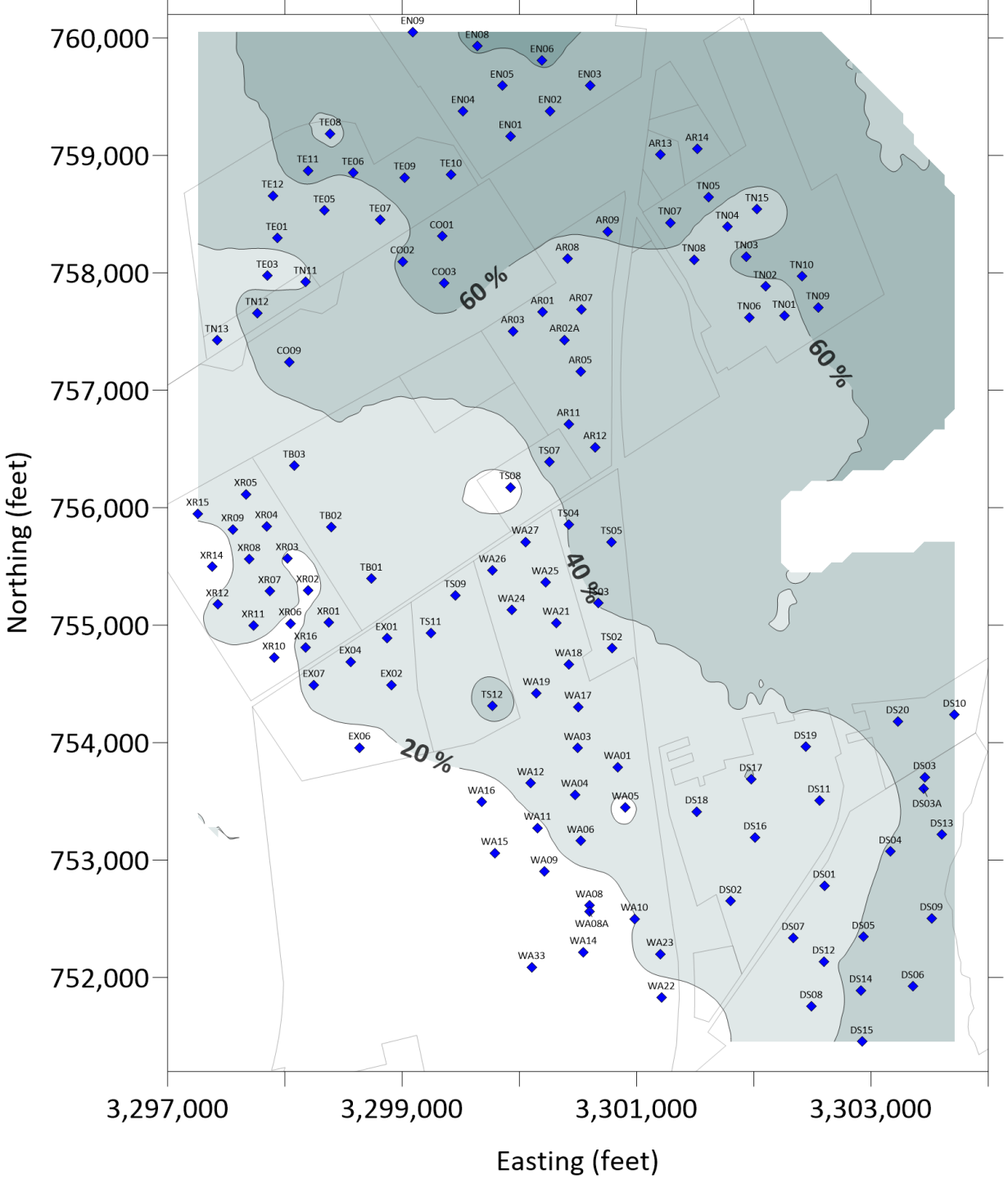
Percent Difference (normalized)

Plot = (InSAR – Lvl Srvy) / Lvl Srvy

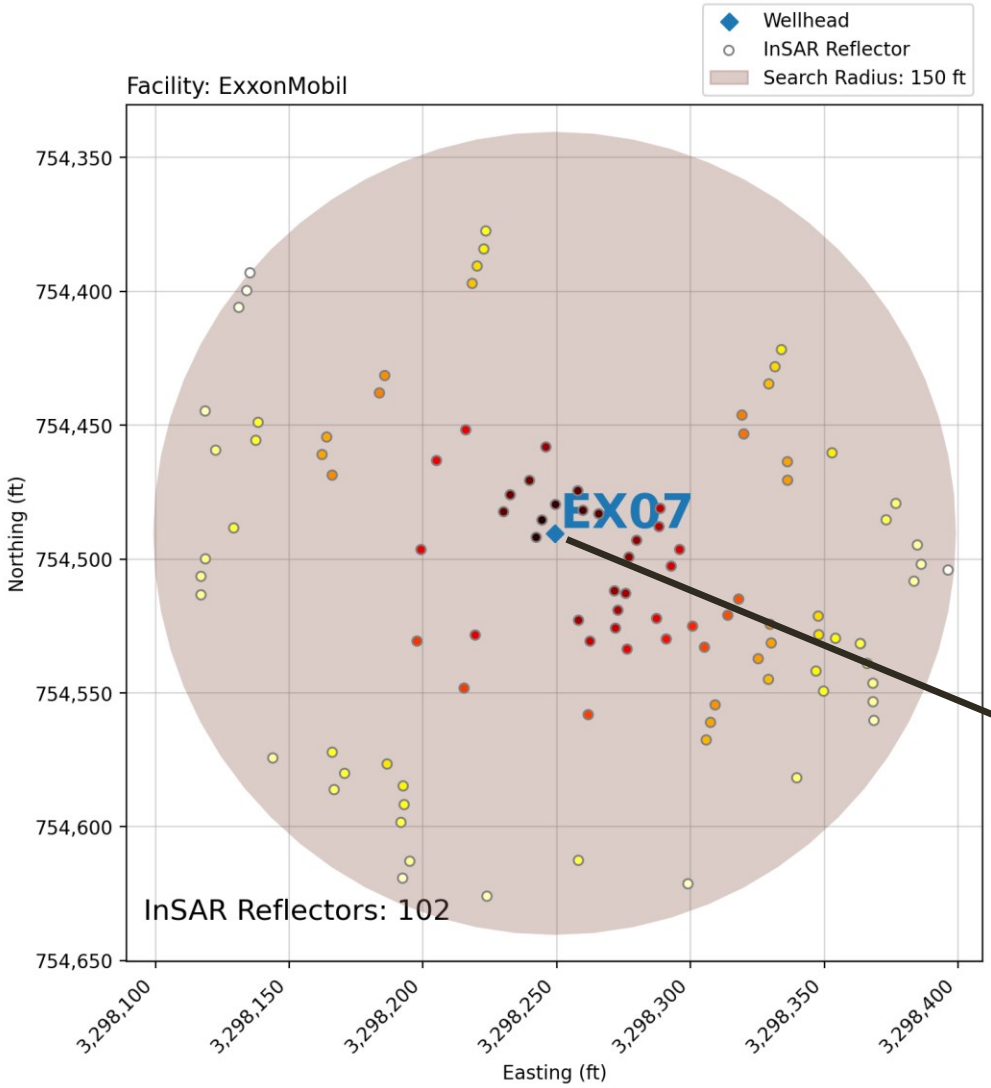
- Darker -> Level Survey is Greater

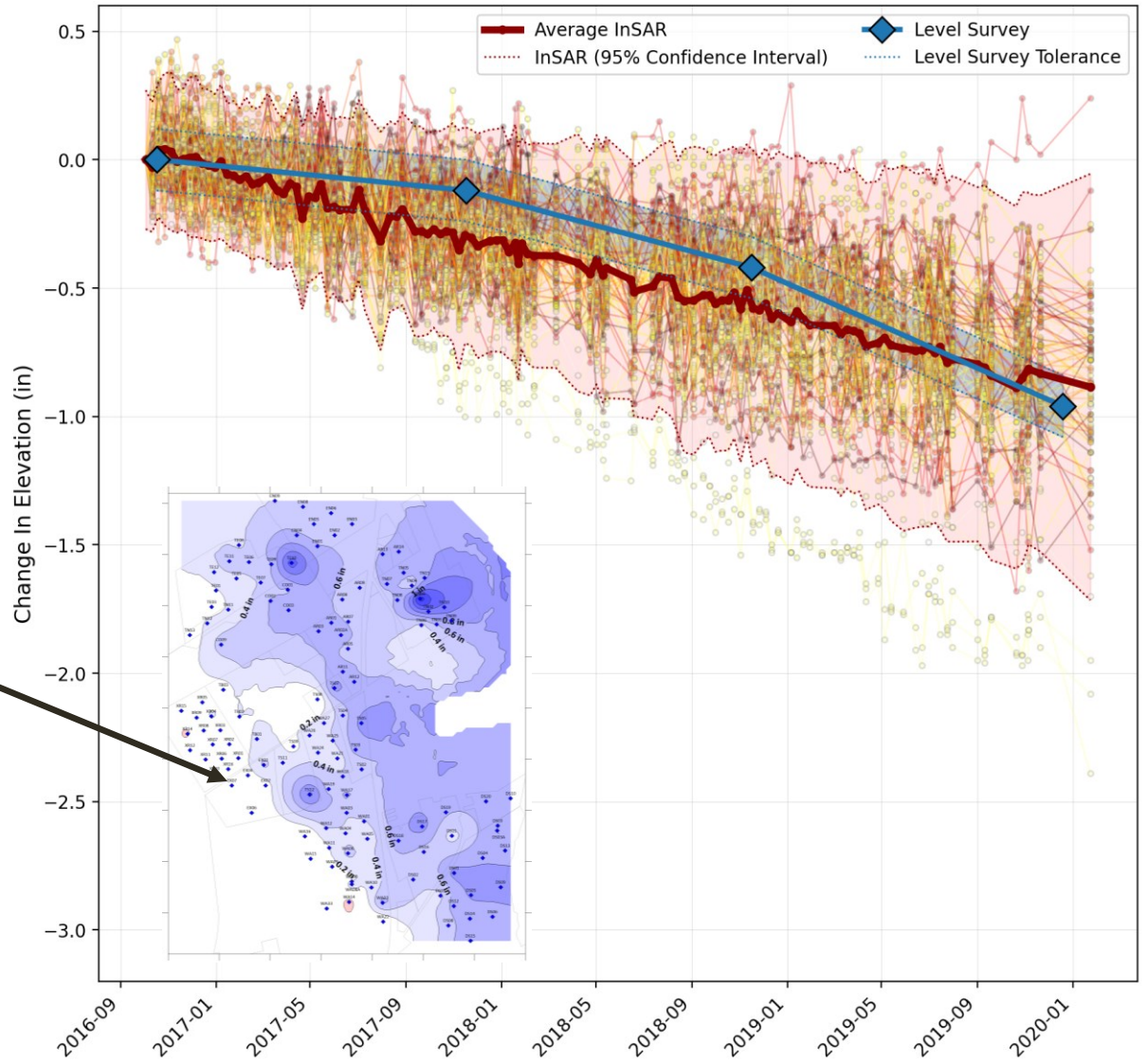
- Smaller Difference
  - South & West
  - Exxon, Targa

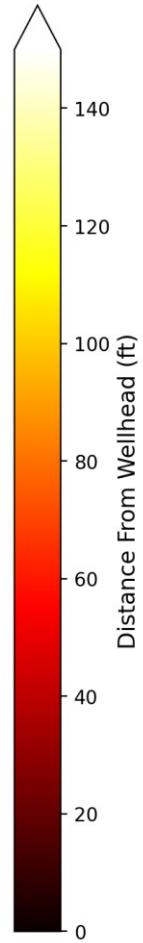
- Larger Difference
  - North & East
  - ONEOK, Enterprise East, ET North



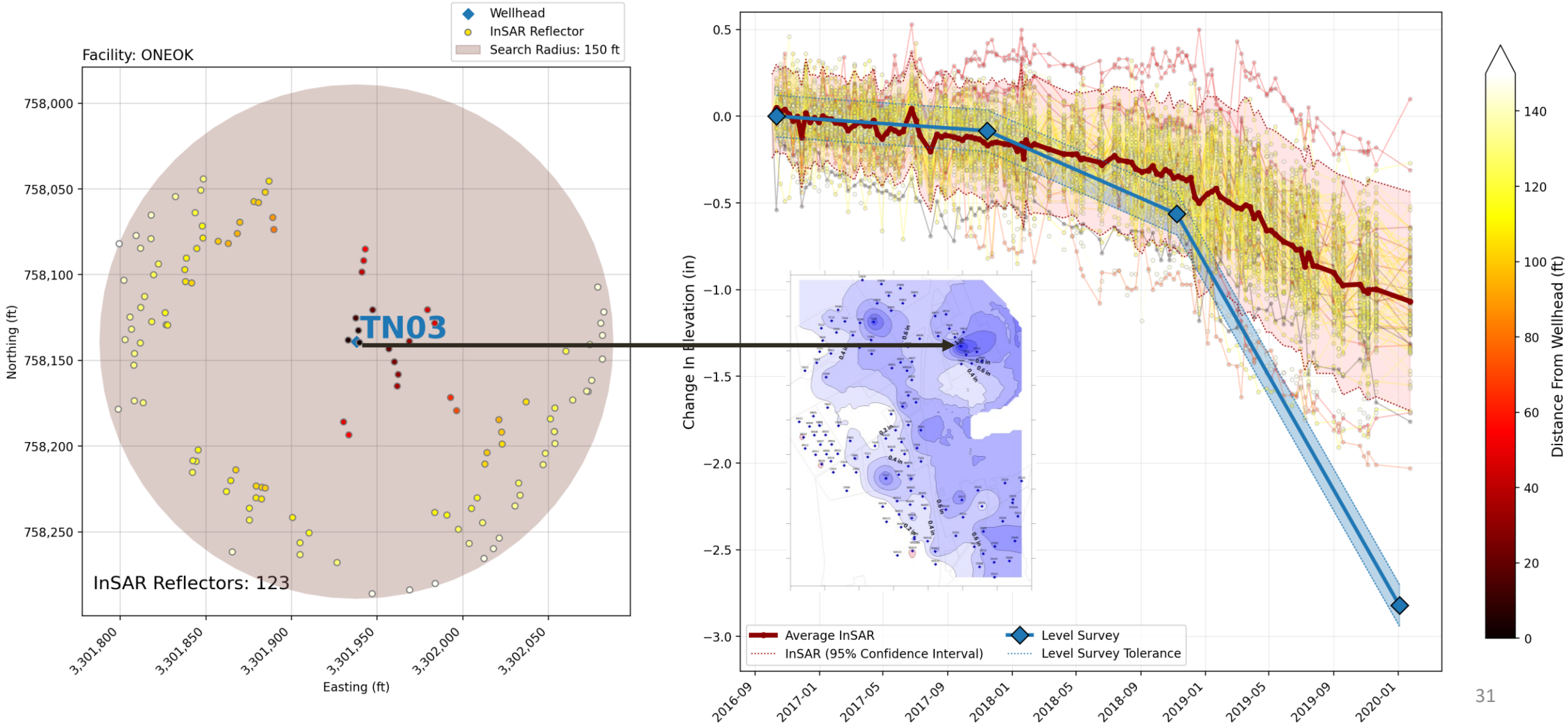
Example: Good Agreement







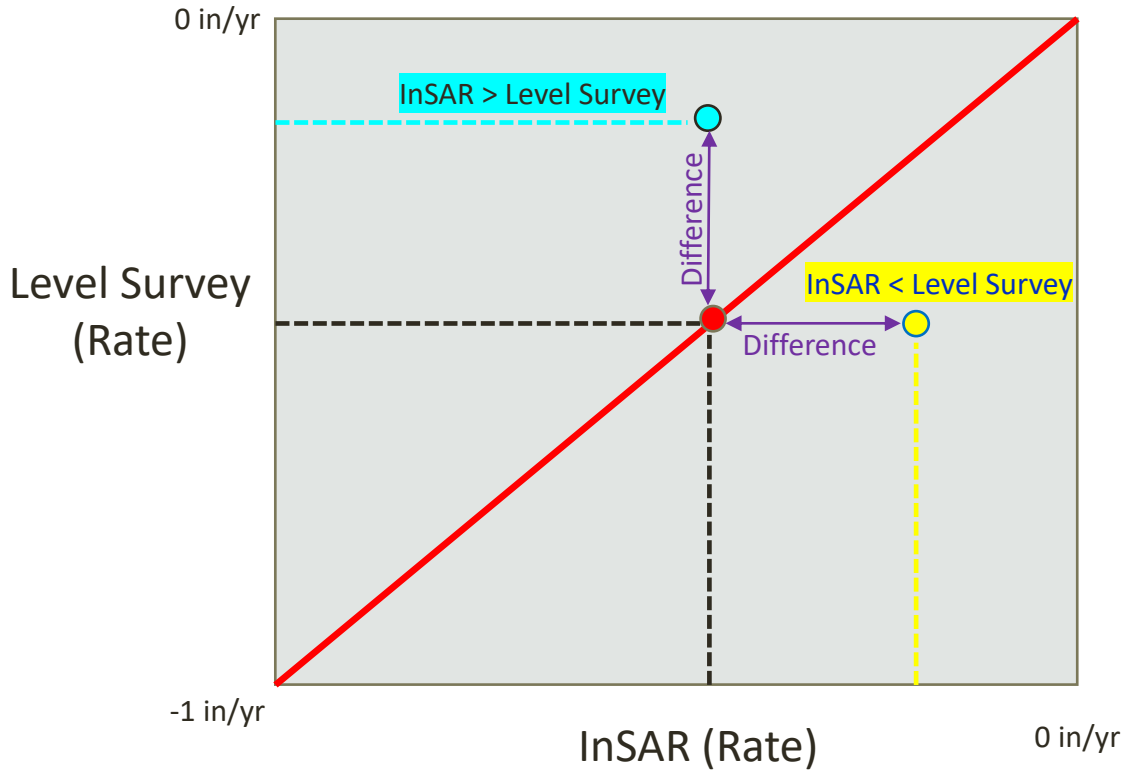
Example: Poor Agreement

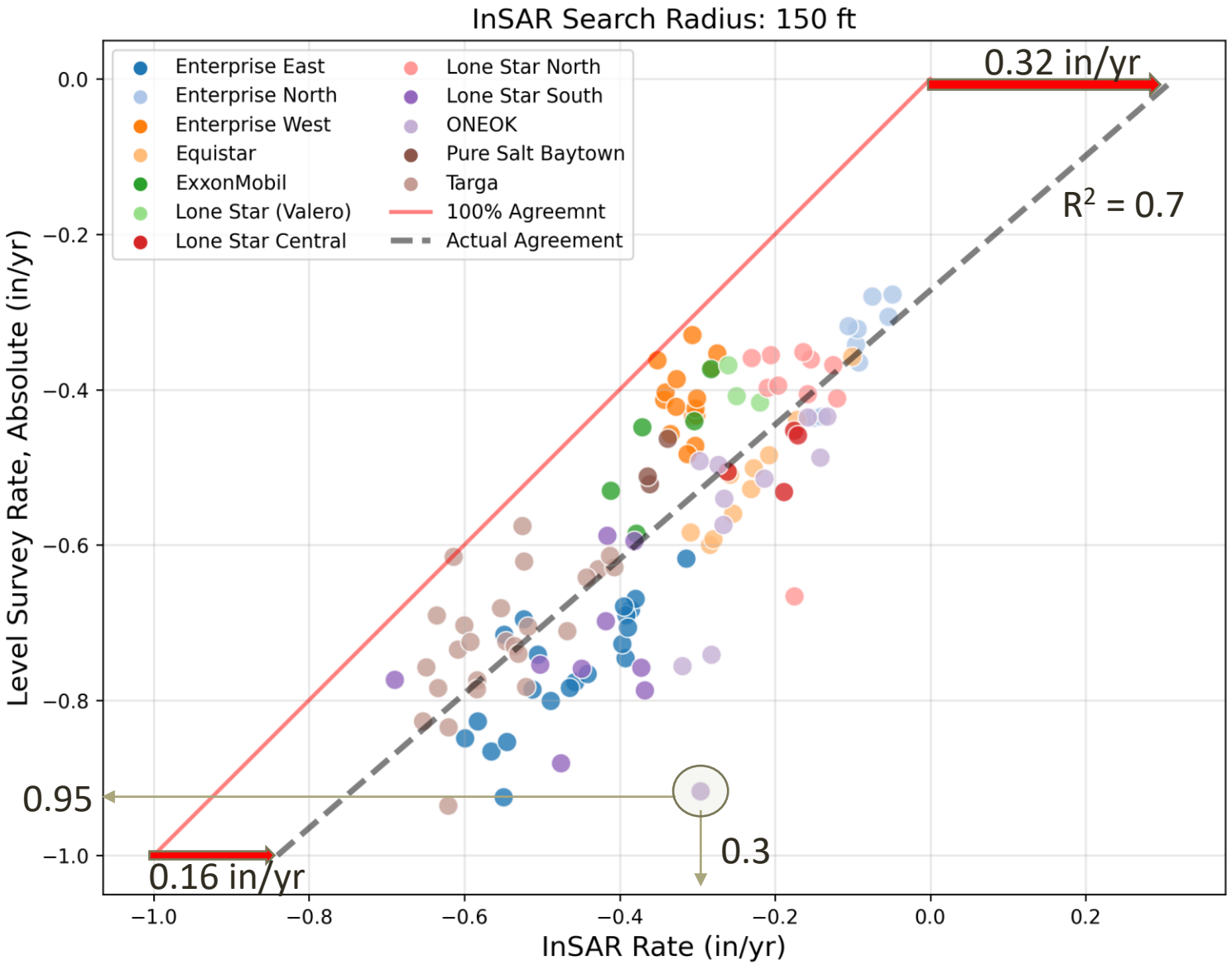


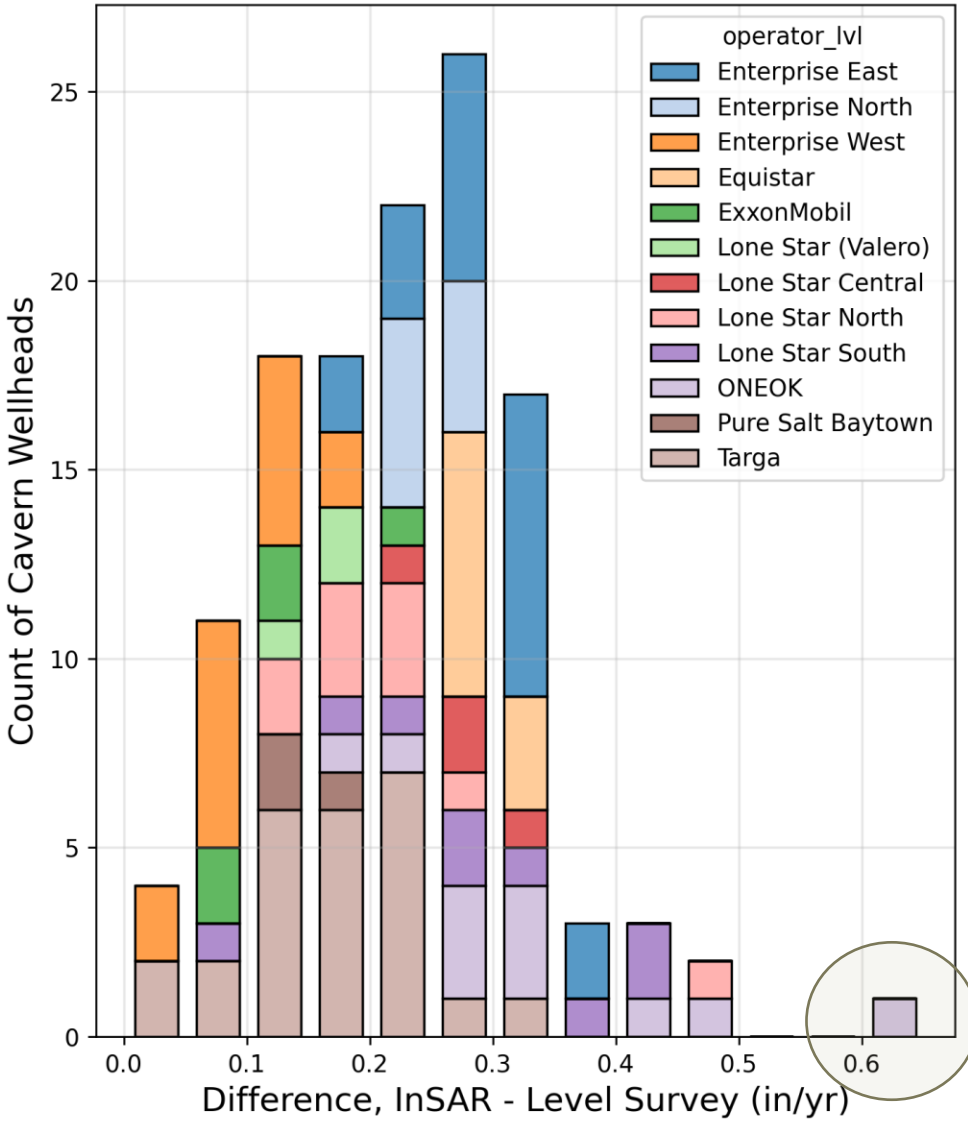
Part II (D): Correlation

Correlation (next slide): How To Interpret

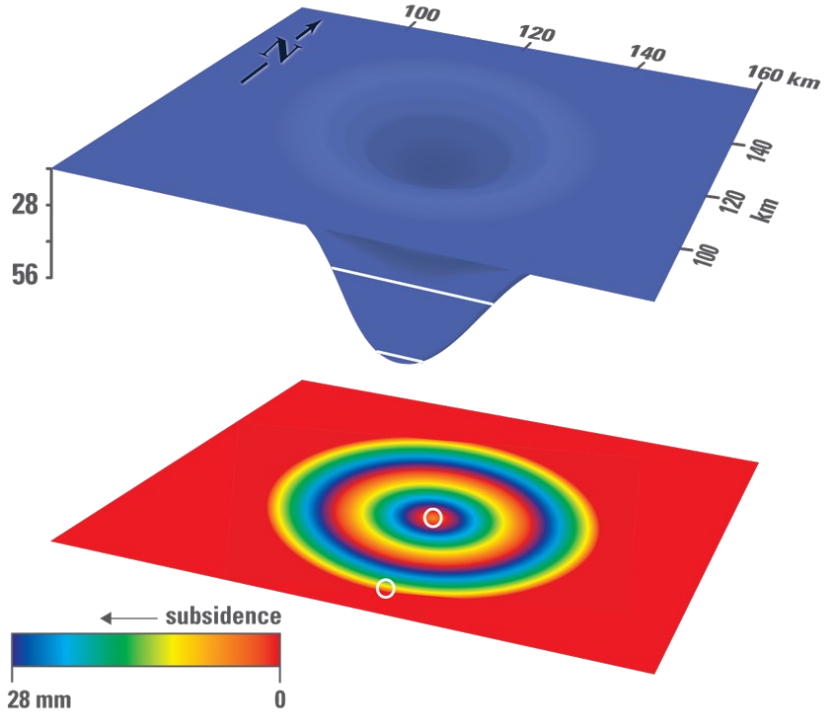
- Level Survey Rate = InSAR Rate
  - Red Line => Perfect Agreement
- InSAR Rate > Level Survey Rate
  - Upper-Left
  - InSAR predicts more subsidence
- InSAR Rate < Level Survey
  - Lower-Right
  - InSAR predicts less subsidence
- Purple: Difference in Rates




InSAR Search Radius: 150 ft
Enterprise East
Enterprise North
Enterprise West
Equistar
ExxonMobil
Lone Star (Valero)
Lone Star Central
Lone Star North
Lone Star South
ONEOK
Pure Salt Baytown
Targa
100% Agreemnt
Actual Agreement
0.32 in/yr
R^2 = 0.7
0.95
0.3
0.16 in/yr
Level Survey Rate, Absolute (in/yr)
InSAR Rate (in/yr)


operator_lvl
Enterprise East
Enterprise North
Enterprise West
Equistar
ExxonMobil
Lone Star (Valero)
Lone Star Central
Lone Star North
Lone Star South
ONEOK
Pure Salt Baytown
Targa
Count of Cavern Wellheads
Difference, InSAR - Level Survey (in/yr)

Summary



- Review of InSAR Data
  - Lacking in “green” areas
  - Search Radius: minor influence on rate
  - Total Subsidence:
    - ✓ InSAR: rely on previous data
    - ✓ Level Survey: independent measurements
- InSAR Under-Estimates Subsidence (Relative to Level Survey)
  - Consistently – not random error
- Difference
  - Rate: 0.01 to 0.62 inch/yr
  - Magnitude: -0.32 to 1.75 inch
- Difference increases with decreasing subsidence rate
  - Largest error is in the North

Reported Precision

- Level Survey: +/- 0.12 inch
  - Closure tolerance
- InSAR:
  - Horizontal: +/- 5 inch (1)
  - Vertical: +/- 0.4 inch (2)
  - Reported by Tre Altmira: +/- 0.02 inch
  - Observed Accuracy: +/- 0.5 inch
    (see next slide)

Precision

Source: https://site.tre-altamira.com/insar/

The most important factors impacting on measurement quality are:

- Spatial density of the measurement points (the lower the density, the higher the error bar)
- Quality of the radar targets (signal-to-noise ratio levels)
- Climatic conditions at the time of the acquisitions
- Distance between the measurement point and the reference (REF)
- Number and temporal distribution of acquisitions

For SqueeSAR® measurements, the standard deviation refers to the average displacement rate with respect to the reference point (as in traditional geodetic networks, measurement precision decreases as distance from reference point increases).

Considering a dataset of at least 30 scenes covering a 2-year period, a measurement point (MP) located less than 1 km away from the REF has a typical standard deviation value lower than 1 mm/year. The single displacement value precision is generally within ± 5 mm (see table below).

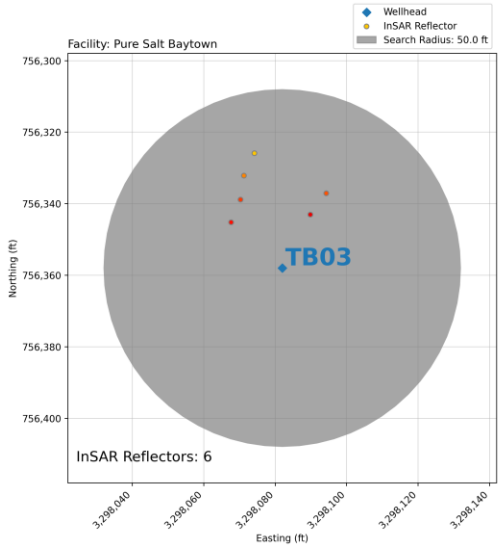
Displacement (LOS)	Average displacement rate	Single measurement
Precision	< 1 mm/year	< 5 mm

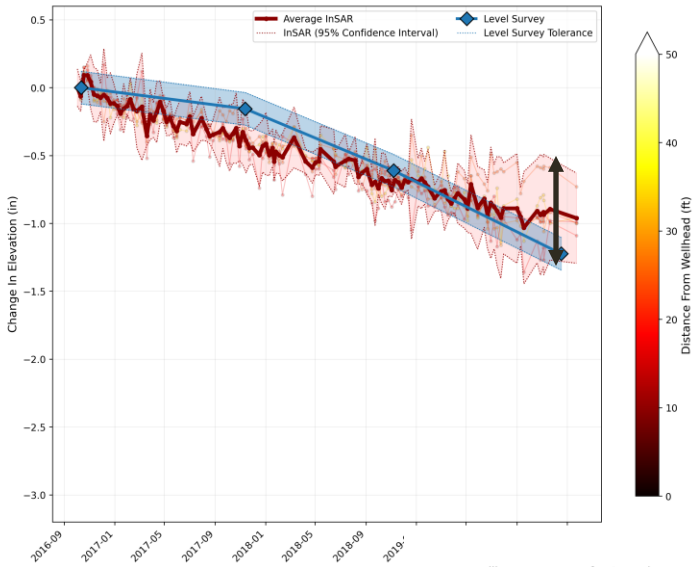
1 mm/year = 0.04 inch/year
5 mm = 0.2 inch

Citation

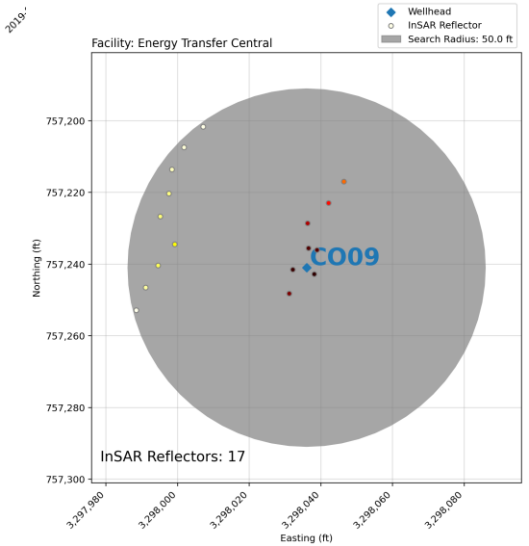
1. Schmidt, K. et al., 2018. Geometric Accuracy of Setninel-1A and 1B Derived form SAR Raw Data with GPS Surveyed Corner Reflector Positions. Remote Sensing, https://doi.org/10.3390/rs10040523
2. https://www.earthdata.nasa.gov/learn/backgrounders/what-is-sar

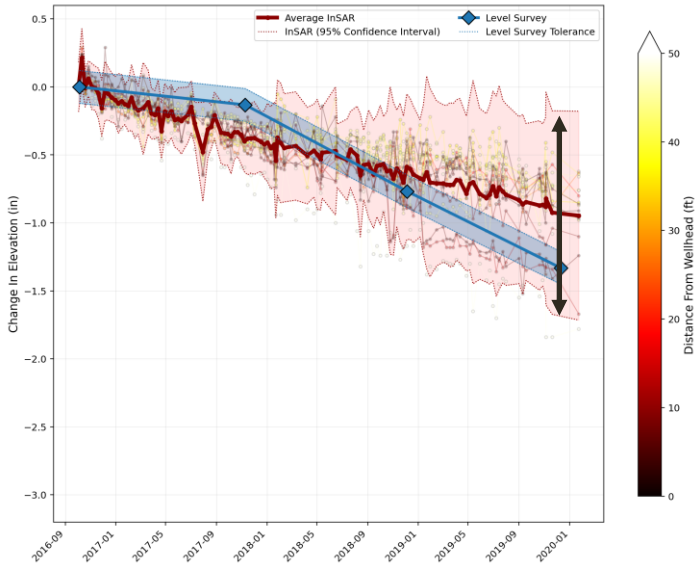
Practical Evaluation of Accuracy





Perceived Accuracy
+/- 0.4 inch





Perceived Accuracy
+/- 0.8 inch

Considerations

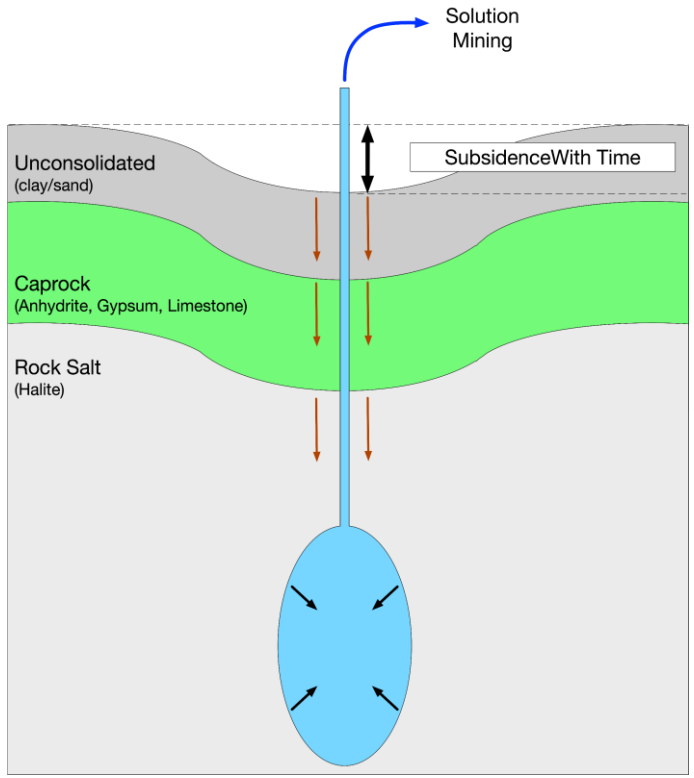
Additional Considerations

Subsidence “should” increase with mining
- Has remained approx. constant with time

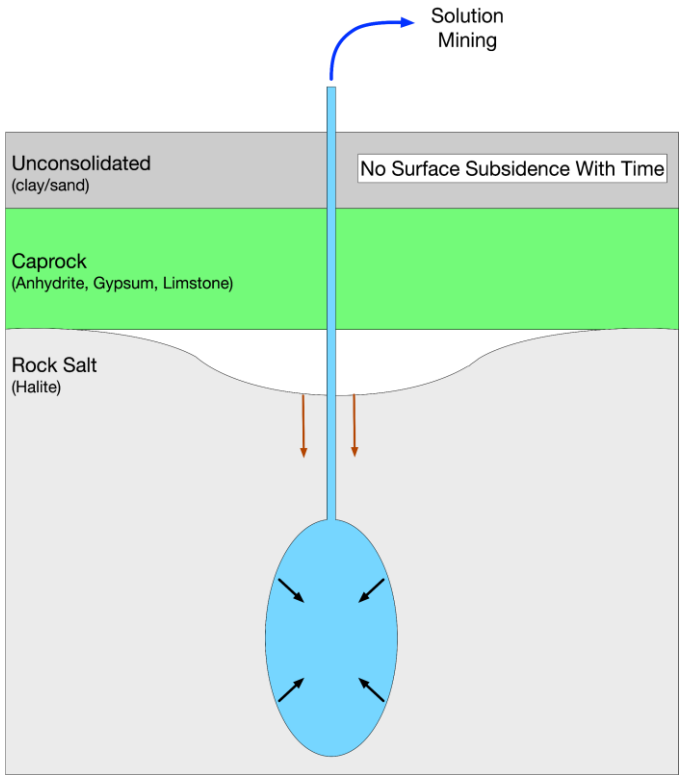
- Concern
  - Continued cavern closure
  - Stress concentration in caprock
  - Sudden deformation (not creep)

- Recommendations
  - Evaluate Cavern Vol. vs Subsidence
  - Monitor casing deformation
  - Measures In-Situ Stress
  - Design/place caverns accordingly

Stable



Unstable



Comments on “Transition”

Recommend: Make Haste Slowly

- Level survey wasn’t always “good”
  - Numerous surveyors tried
  - Data was acquired/evaluated
  - Current method took time
- InSAR may improve
  - Algorithms
  - Installed reflectors
  - Reference point further off dome
- Consider Obtaining Both
  - Possible transition with time
  - During Transition
    - ✓ Level Survey & InSAR
- Surface Monuments
  - Frequently damaged/lost
  - 166 included in survey
  - May be able to exclude in future

InSAR Data Acquisition

Acquired by space agencies

- Not private companies (yet)
- Italy, Germany, Canada, Japan, Korea, Europe, & US

- Algorithms developed by
  - Academia
  - Governments
  - Private companies

Alternative Algorithms

- DARES
- Tre Altamira
- Geo Kinesia
- 3vGeomatics
- SkyGeo

SMRI Request for Proposal

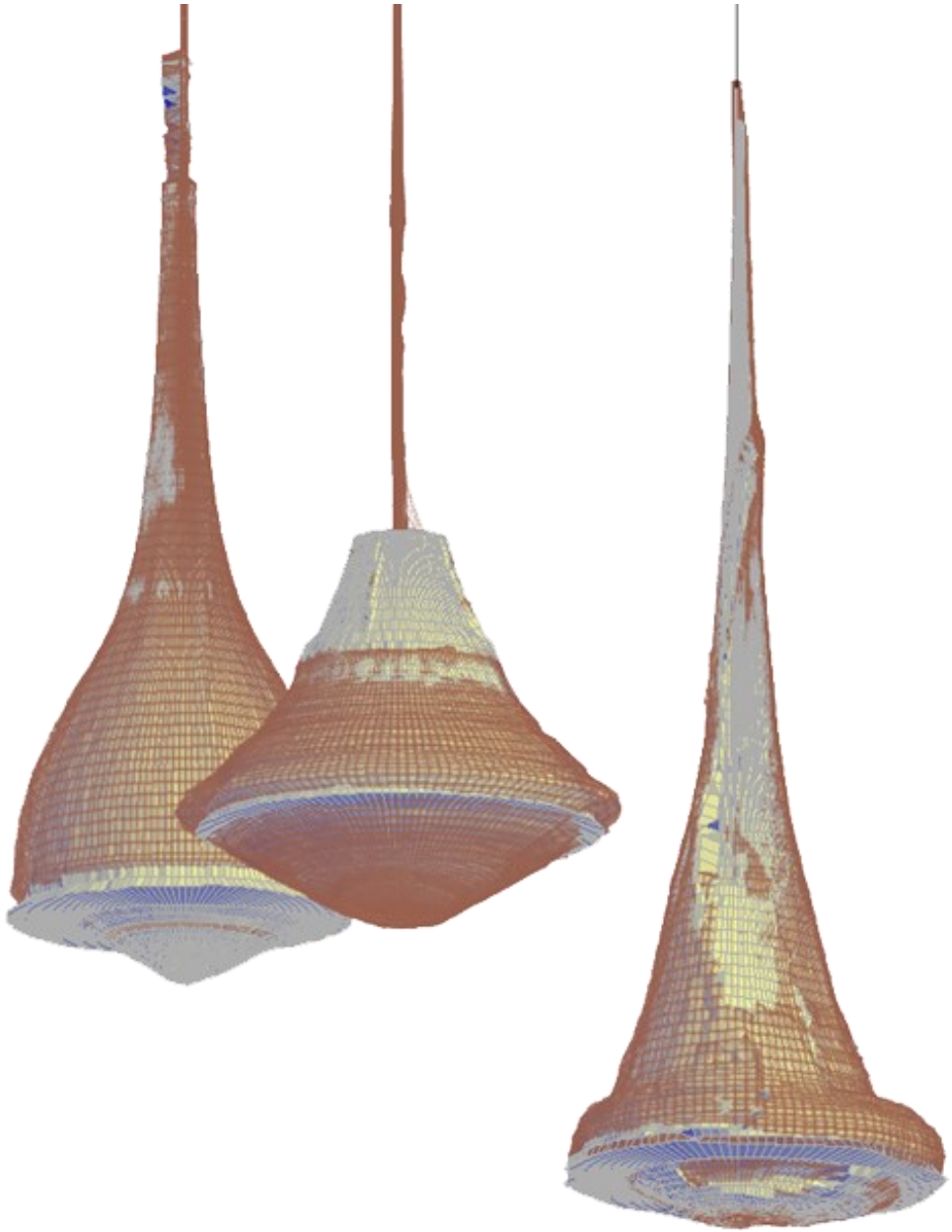
Project Summary

- Costs: at 77% total budget
  - $23K (total: $30,550)
- Deliverables
  - Presentation of Results
  - Data
    - ✓ Tables
    - ✓ Figures (facility & well specific)
  - Memo?
  - Report (more detail and citation)?

Questions?

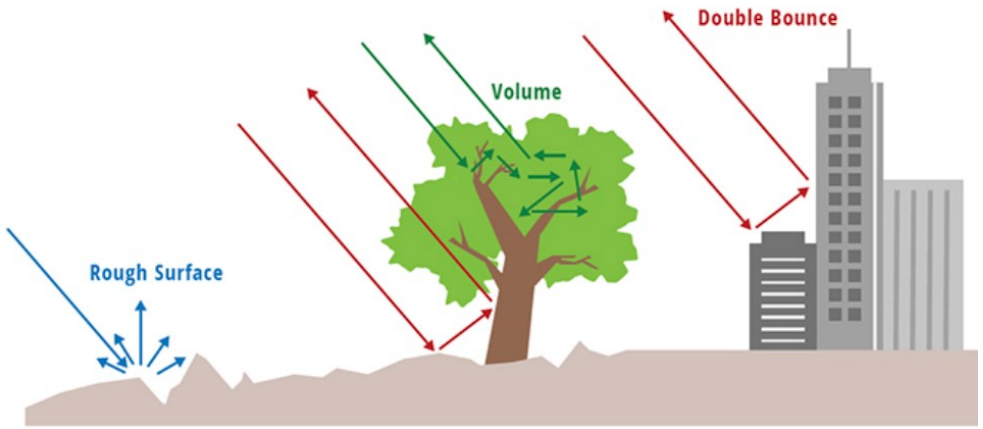
References

- Galloway, D.L., Jones, D.R., and Ingebritsen, S.E.,2000. “Measuring Land Subsidence from Space”. USGS Fact Sheet-051-00.
- Lampe, B.C., 2020. Level Surveys and Subsidence Analysis, Barbers Hill Field, Chambers County, Texas, 2019 Report to the Railroach Commission of Texas.
- Cunningham, E., 2020. SqueeSAR Analysis of Ground Movement over Mont Belvieu. Report by Tre Altamira.
- Schmidt, K. et al., 2018. Geometric Accuracy of Setninel-1A and 1B Derived form SAR Raw Data with GPS Surveyed Corner Reflector Positions. Remote Sensing, https://doi.org/10.3390/rs10040523



Extra Slides

InSAR – Anticipated Results



USGS Fact Sheet-051-00

METHOD	Component displacement	Resolution[1] (millimeters)	Spatial density[2] (samples/survey)	Spatial scale (elements)
Spirit level	vertical	0.1–1	10–100	line-network
Geodimeter	horizontal	1	10–100	line-network
Borehole extensometer	vertical	0.01–0.1	1–3	point
Horizontal extensometer:				
Tape	horizontal	0.3	1–10	line-array
Invar wire	horizontal	0.0001	1	line
Quartz tube	horizontal	0.00001	1	line
GPS	vertical horizontal	20 5	10–100	network
InSAR	range	5–10	100,000–10,000,000	map pixel[3]

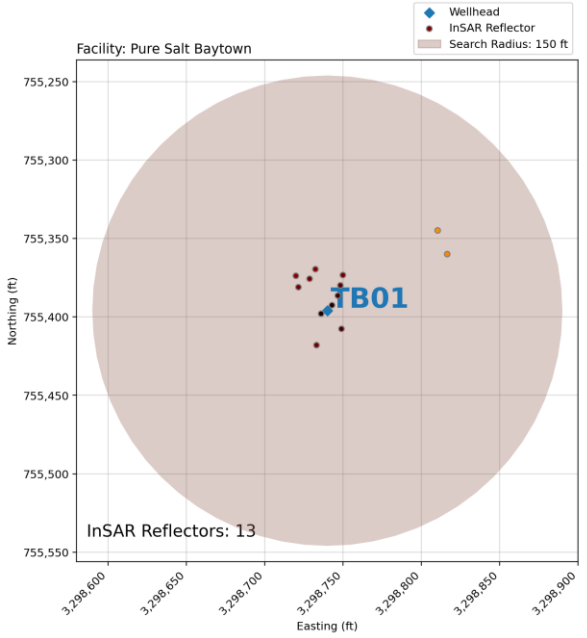
[1]Measurement resolution attainable under optimum conditions. Values are given in metric units to conform with standard geodetic guidelines. (One inch is equal to 25.4 millimeters and 1 foot is equal to 304.8 millimeters.)

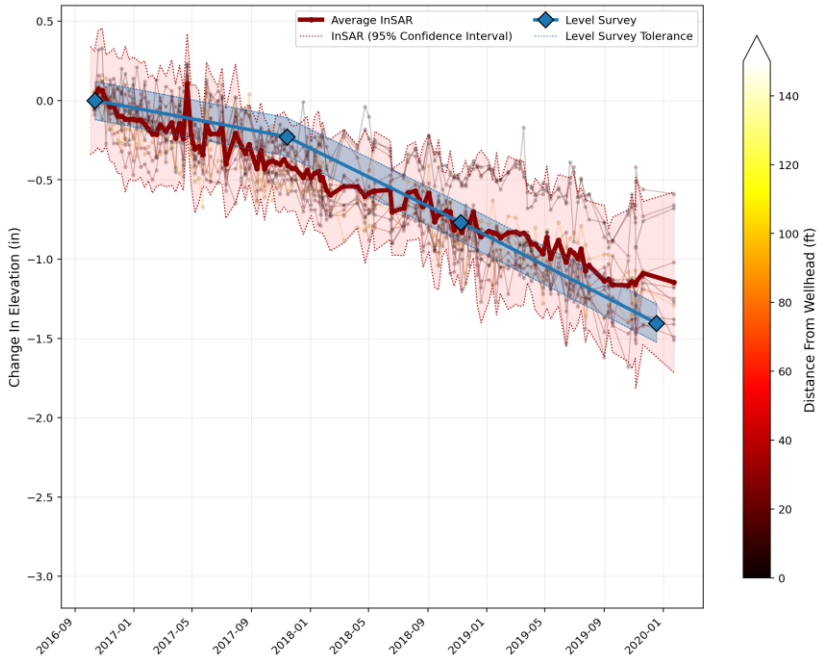
[2]Number of measurements generally attainable under good conditions to define the spatial extent of land subsidence at the scale of the survey.

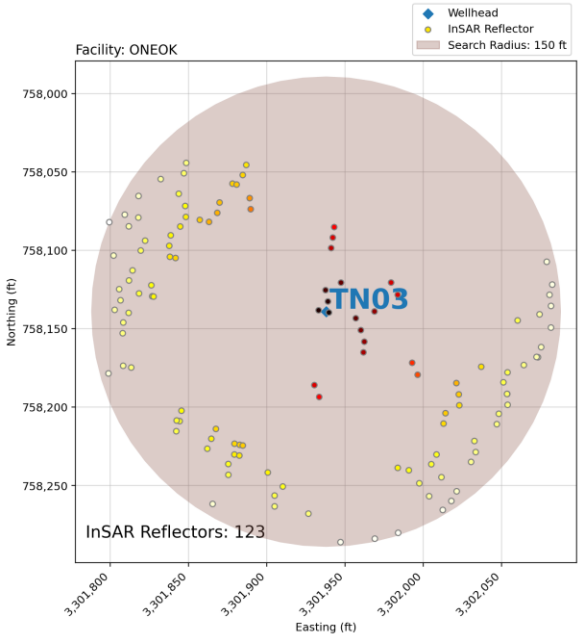
[3]A pixel on an InSAR displacement map is typically 40 to 80 meters square on the ground.

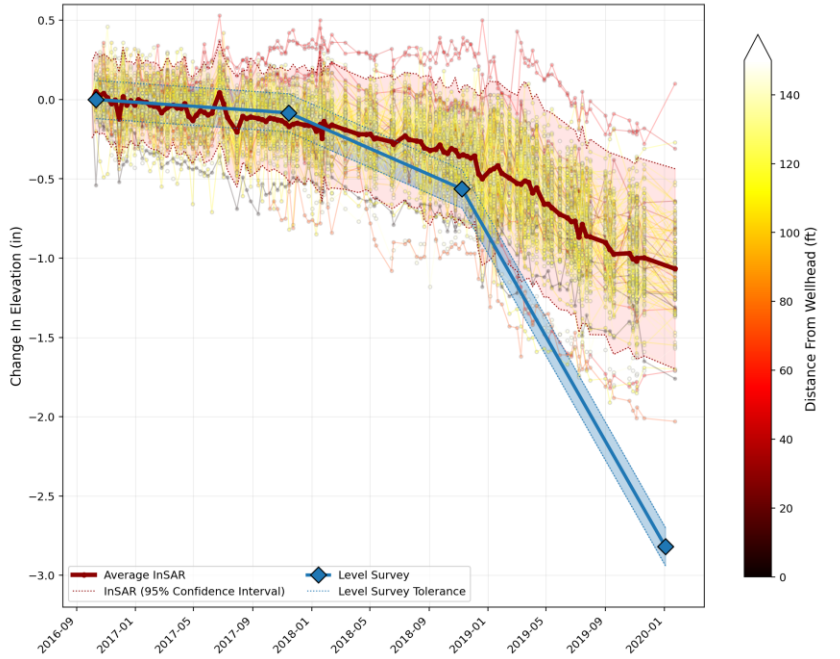
Influence of Reflector Location

- TB01: reflectors near WH
- TN03: most reflectors at edge of search radius



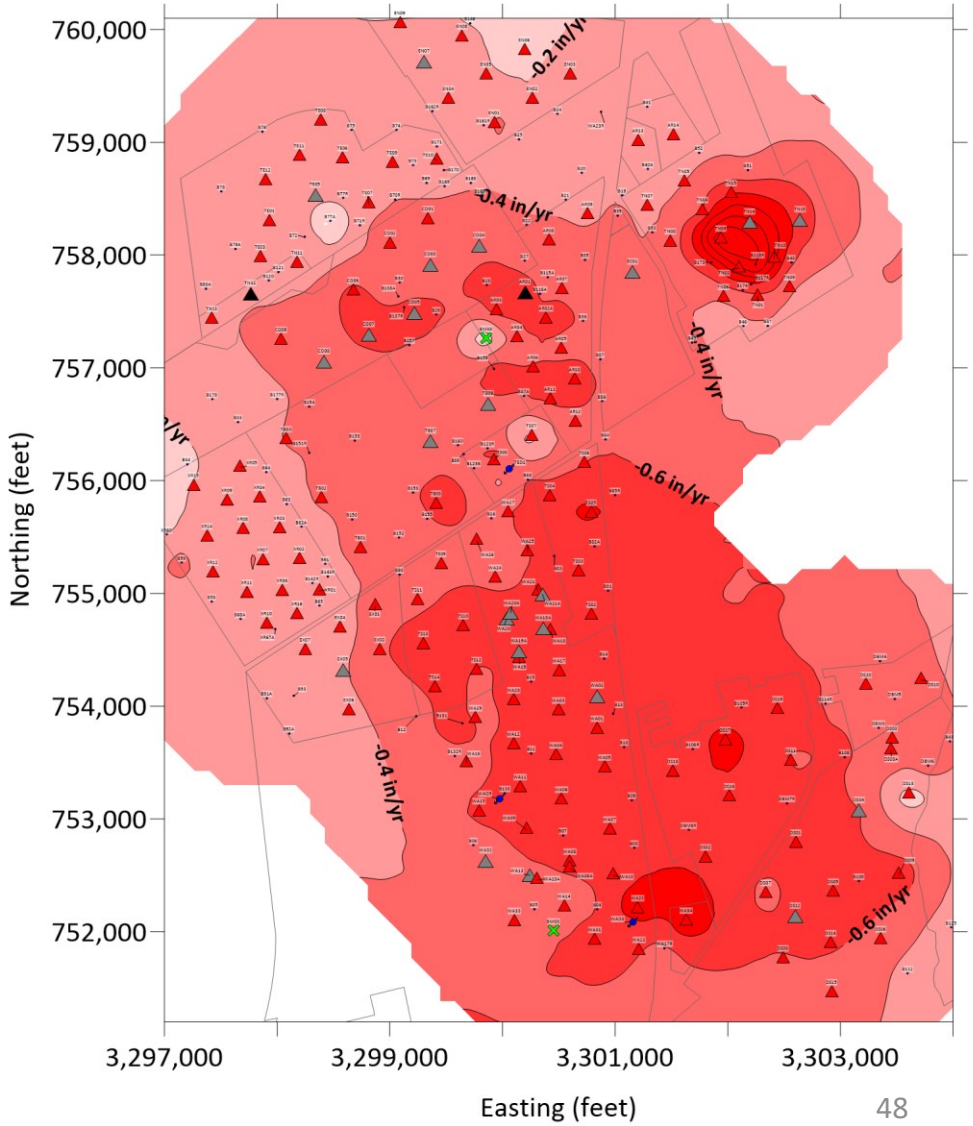




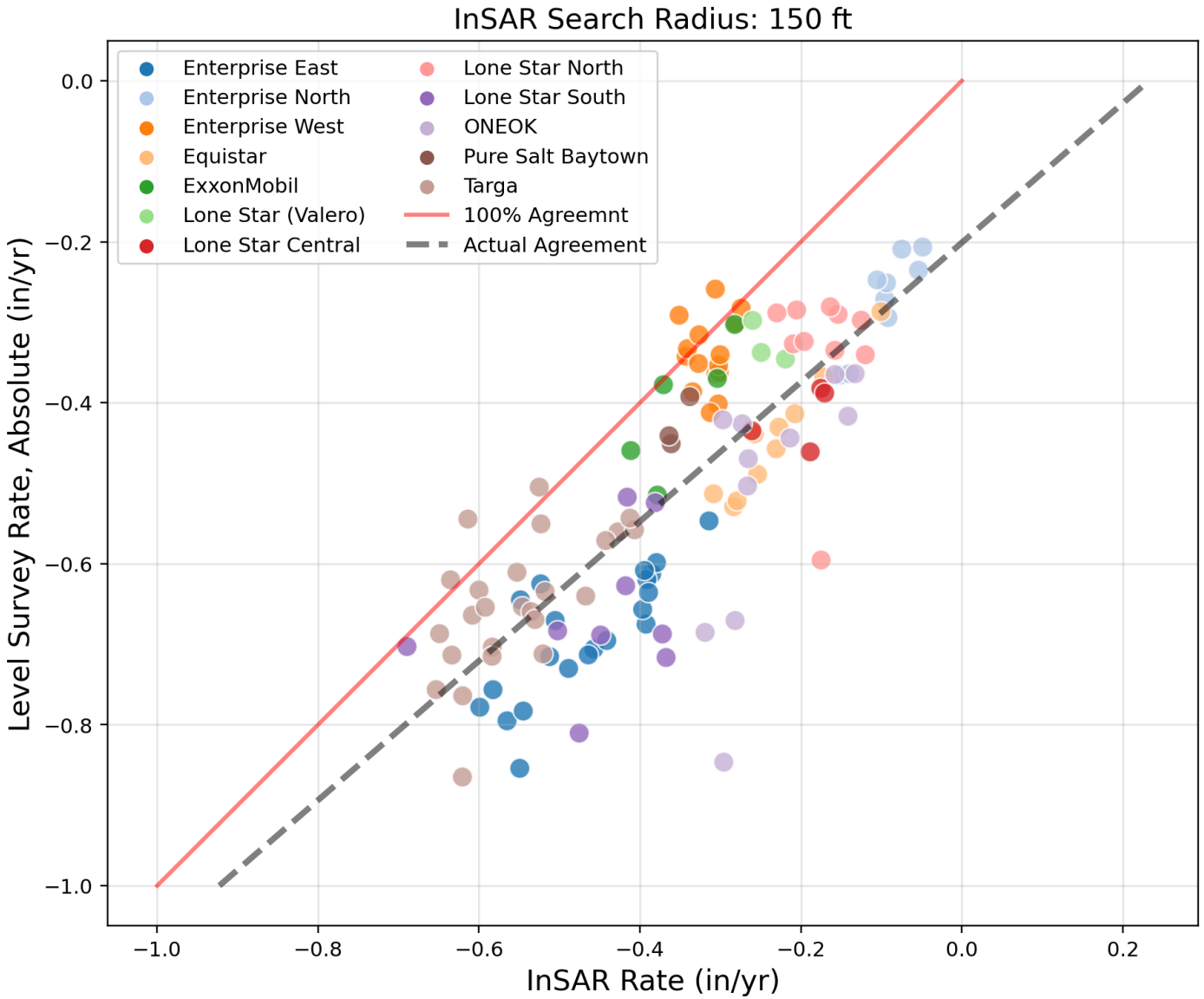


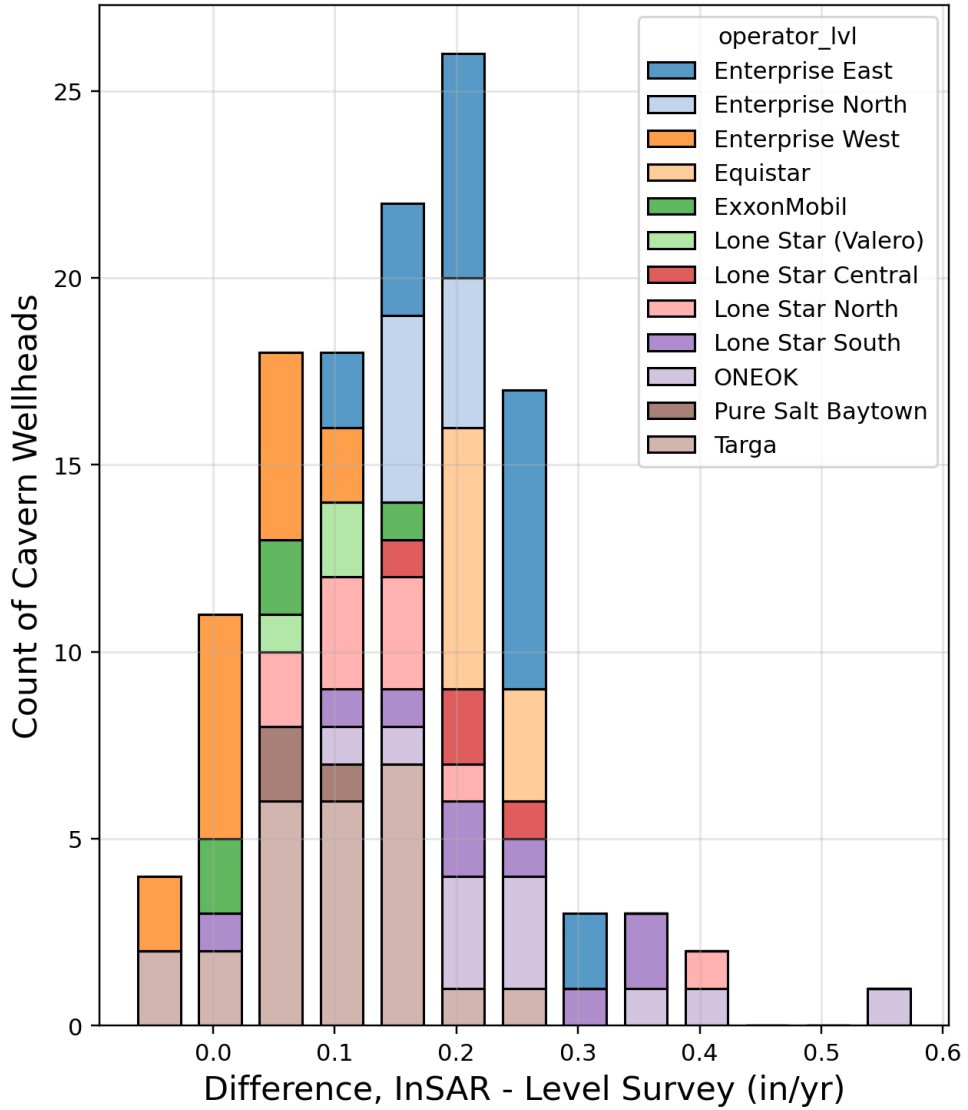
2019 Level Survey Data

- Modification from Report to RRC
  - Assumed quadratic fit
  - Included surface monuments



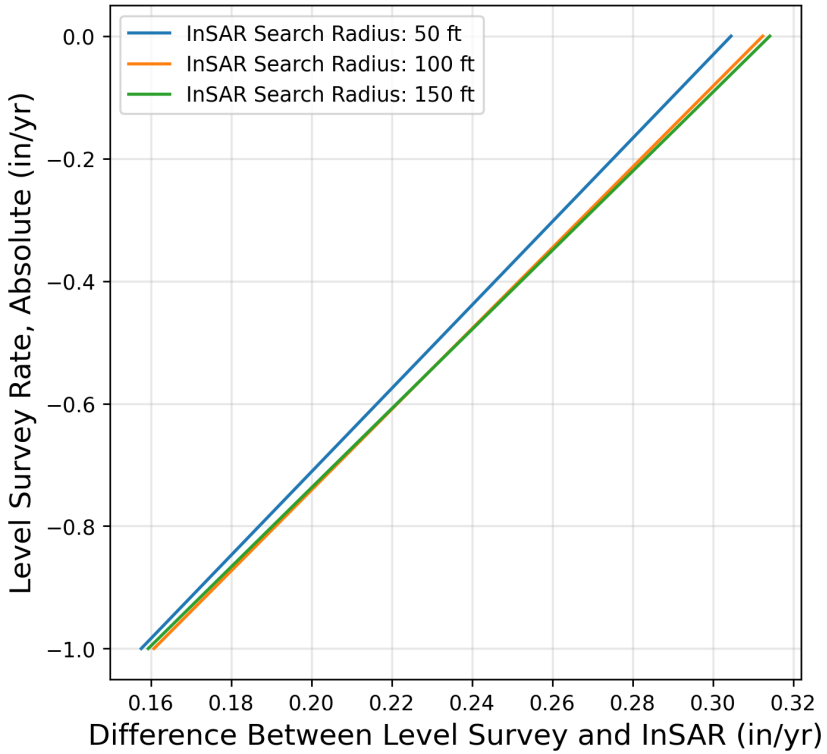
Correlation - Relative (Level Survey Without GPS, -0.071 in/yr)



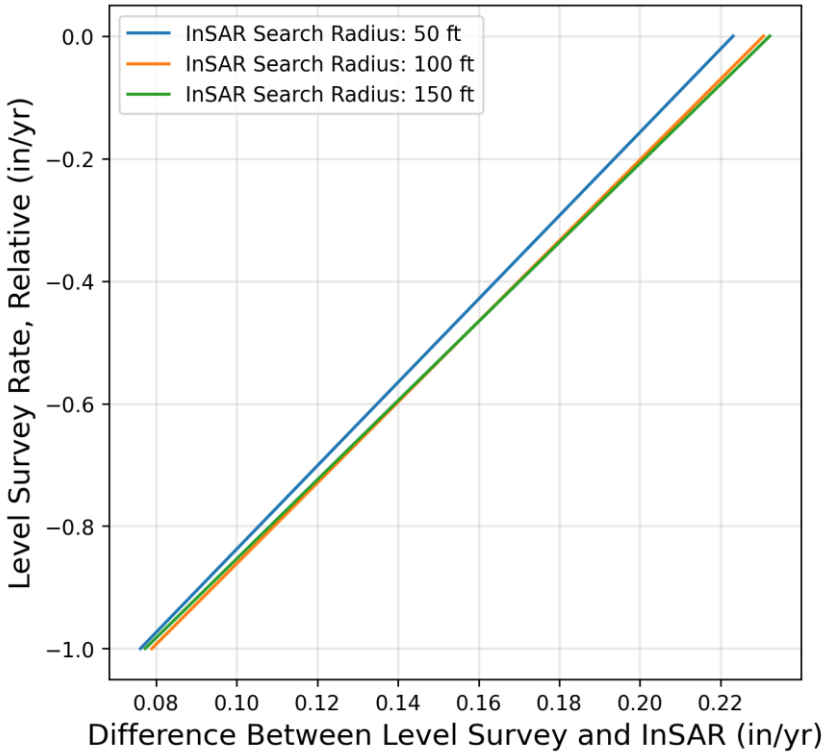


Difference in Subsidence Rate Results

Level Survey Without GPS



Level Survey With GPS



Analysis Summary

- Review of InSAR Data
  - Lacking in “green” areas
  - Search Radius: minor influence on rate
  - Measured elevations rely on previous data
    - ✓ Level surveys are independent measurements

- Comparison
  - InSAR Under-Estimates Subsidence
    (Relative to Level Survey)
  - Difference in Rate: 0.01 to 0.62 inch/yr
  - Difference in Magnitude: -0.32 to 1.75 inch
  - Difference increases with decreasing subsidence