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Subject: November 2016 West Hackberry Subsidence Report

Executive Summary

Subsidence monitoring is a critical component to understanding the cavern integrity of salt storage caverns. This report looks at historical and recent data from two of the three West Hackberry dome cavern operators. DOE SPR and LA Storage are coordinating subsidence surveys to create a comprehensive understanding of ground movement above the dome. Data from annual level and rod surveys, GPS, and tiltmeter data show the sites are experiencing typical ground movement. The highest subsidence rate is seen in the middle of the DOE SPR site at just under one inch per year with less ground movement around the edge of the site. A GPS and tiltmeter instrument in the northeast areas of the DOE SPR site has not seen any trend change since the devices were installed in 2013. Comparison between recent ground movement data and historical trends suggest that there is no reason to believe that any DOE SPR or LA Storage caverns have been structurally compromised.

Introduction

This year's subsidence survey was completed in coordination with two of the three West Hackberry cavern operators. Both DOE SPR and LA Storage sites were surveyed in November 2016 and the data have been analyzed by Sandia National Laboratories. In accordance with the subsidence monitoring requirements set forth by the Louisiana Department of Natural Resources this report discusses the subsidence monitoring plan and presents interpretation of the current results.

Elevation surveys on the SPR section of the West Hackberry dome began in 1986 and there have been 35 surveys since. The surveys are conducted to monitor ground movement and, through interpretation, cavern integrity. Several instances of collapsed caverns from around the world have shown to subside at an accelerated rate before their eventual collapse (Ege, 1979). Therefore, ground movement is a primary indicator of cavern integrity. The surface elevations from the surveys also aid in determining flooding potential at the site and help to validate salt creep models of the cavern system. Along with annual subsidence surveys there is also a tiltmeter and GPS instrument in the northeast area of the SPR site that records data hourly over a cavern that has recently been emptied of oil. The instruments are programmed to alert the operator of any sudden changes in elevation or tilt of the instrument.

The data from the annual survey, GPS, and tiltmeter are then analyzed to determine cavern integrity under the site. This year's data indicates the site is experiencing typical ground movement rates and there are no areas of acute subsidence.

Historical Subsidence at the West Hackberry SPR Site

The Department of Energy acquired the West Hackberry site for crude oil storage in 1977. The site is located near the middle of the dome and is currently adjacent to two additional cavern operators: LA Storage and Targa. The LA Storage facility abuts the western edge of the DOE site while Targa operates storage caverns southeast of the site. Figure 1 shows the orientation of the sites in relation to the dome footprint. The footprint shown in Figure 1 was taken at a depth of 5000 ft. below mean sea level. Figure 2 presents a close up of the information in Figure 1 to show the orientation of wells and survey locations within the sites.

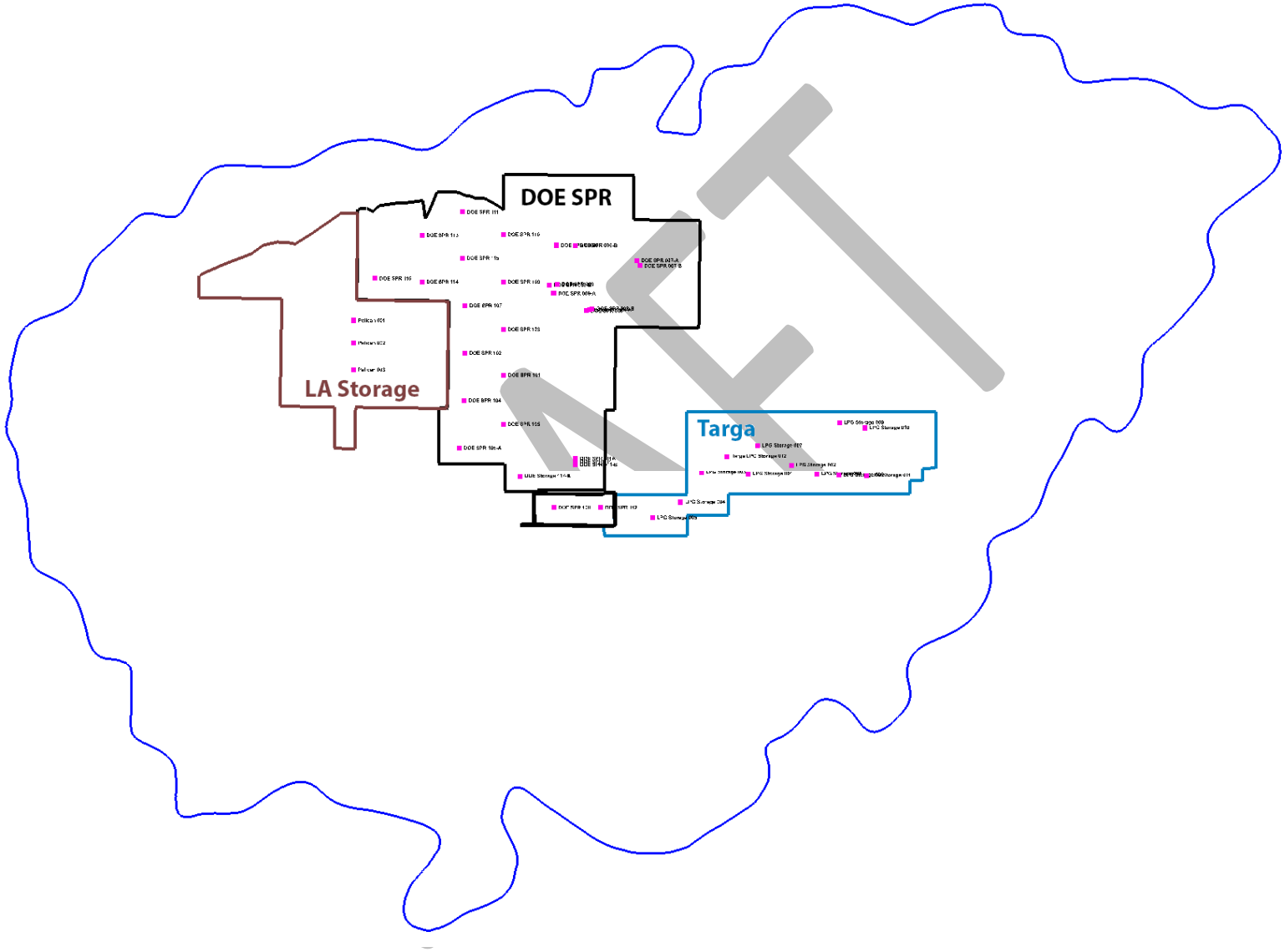


Figure 1 – The current cavern operator boundaries in relation to the dome footprint. The dome footprint was taken at a depth of 5000 ft. below mean sea level.

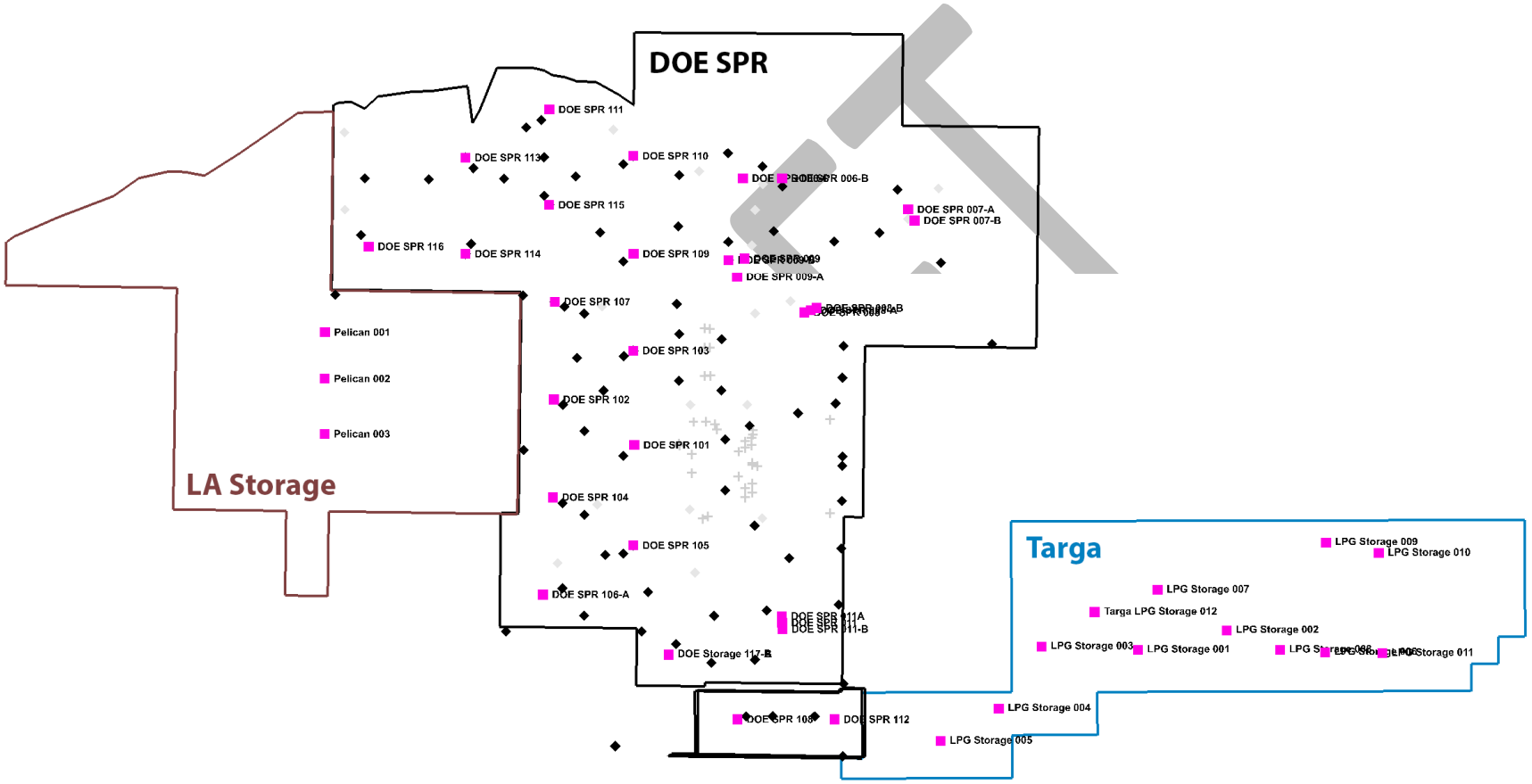


Figure 2 - Close up figure of 1 showing the orientation of the wells (pink squares) and survey locations within the sites. Diamonds and crosses represent survey monuments and markers, respectively. Grey survey monuments/markers indicate locations that are no longer surveyed.

The first elevation survey was conducted in 1983 with 33 subsidence markers and 43 subsidence monuments. Over time the number of subsidence markers have been reduced in favor of installing additional subsidence monuments. Subsidence monuments are locations established at depth. They can be a brass dish attached to metal rods driven into the ground until refusal or certain locations on current wells. This is in contrast to survey markers which are simply locations identified on surface infrastructure and are more susceptible to human disturbance or the near surface effects of ground water (Moriarty, 2016). Beginning with the July 1990 survey, most of the site was covered with subsidence monuments.

The total subsidence at the West Hackberry SPR site since July 1990 is shown in Figure 3. This was calculated using information from the July 1990 and November 2016 and covers approximately 26.3 yrs. It is clear the highest ground movement is in the center of the site. In the 26.3 year period the middle of the site has subsided just over 2.25 ft. which suggests that area of the site is experiencing an average subsidence rate of 0.088 ft./yr. (1.1 in./yr.). Ground movement away from the center of the site becomes gradually less. This phenomenon is common as subsidence rates will be higher in the beginning and will eventually stabilize near zero (Budhu, 2010).

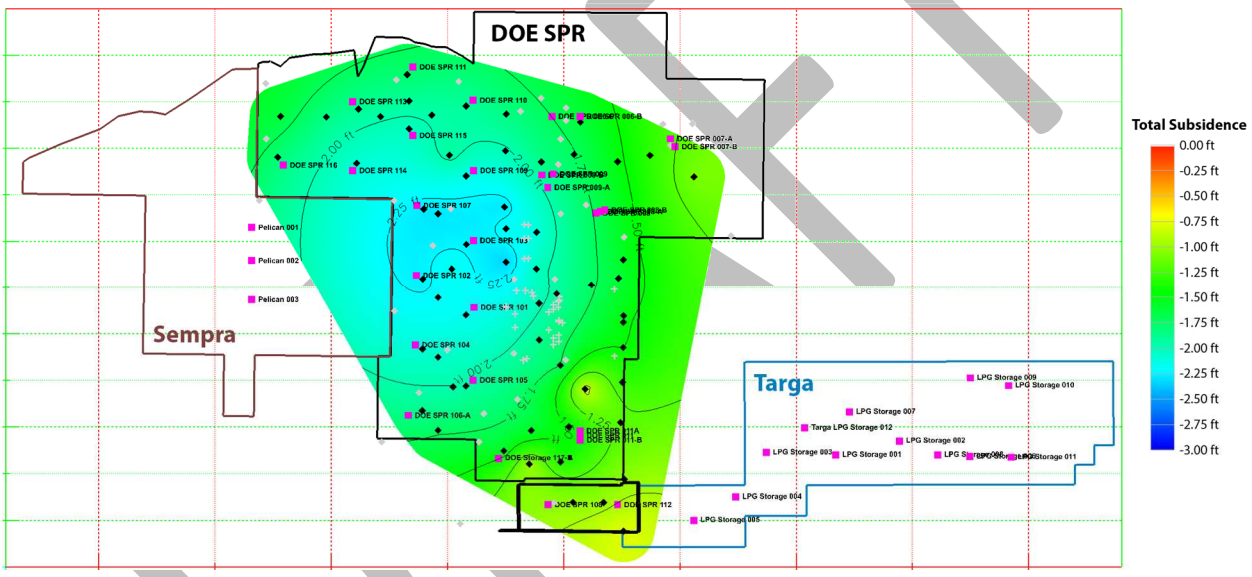
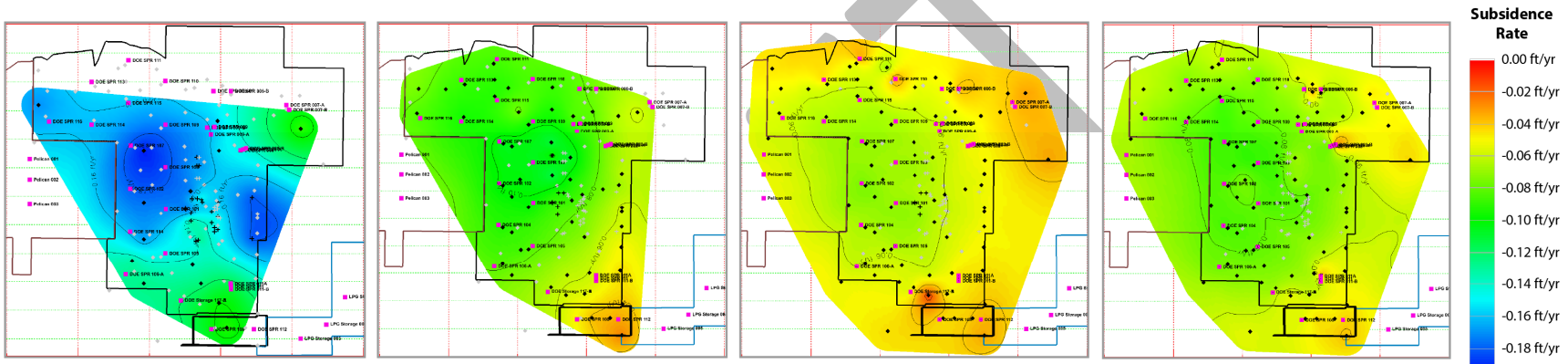


Figure 3 - Total ground movement at the West Hackberry SPR site between July 1990 and November 2016 (26.3 yrs.) in relation to the current cavern operator boundaries. The cooler colors indicate greater subsidence while the warmer colors represent less subsidence. The pink squares represent well locations while the diamonds and crosses represent survey monuments and markers, respectively. Grey survey monuments/markers indicate that survey location was unavailable for at least one of the two surveys used to create the map.

While the site indicates the highest subsidence rate is just over an inch a year, the actual subsidence rate at the SPR site has changed over time. Figure 4 shows the SPR site and the calculated subsidence rates for particular time periods. The first time period (September 1986 – July 1990) experiences the highest subsidence rates. During this time the central and east central areas of the SPR site experience more than 0.18 ft./yr. (2.16 in./yr.) of vertical ground movement. The next two time periods show less subsidence across the site, however, the central area of the site still experiences the greatest subsidence. The last time period between 2010 and 2016 shows the subsidence rates increase slightly across the site. The highest area of subsidence is still in the center of the site.



September 1986 -July 1990
(3.8 years)

Average Rate
-0.150 ft/yr (-1.80 in/yr)

July 1990 - September 2000
(10.2 years)

Average Rate
-0.079 ft/yr (-0.95 in/yr)

September 2000 - July 2010
(9.8 years)

Average Rate
-0.056 ft/yr (-0.67 in/yr)

July 2010 - November 2016
(6.3 years)

Average Rate
-0.069 ft/yr (-0.83 in/yr)

Figure 4 – West Hackberry subsidence rates over time. The cooler colors indicate greater subsidence while the warmer colors represent less subsidence. The SPR well locations are labeled with pink squares. Survey monuments are depicted as diamonds and survey markers used are shown as crosses. Grey survey monument/marker indicate that the survey location was unavailable for at least one of the two surveys used to create the map.

Historical subsidence trends for the SPR site are also apparent in site wide statistics. Figure 5 shows the calculated subsidence rates through time in feet per year. The black line represents the site wide median while the dark grey areas shows the extents of the 25th and 75th percentiles. The lighter grey area shows the extents of the 10th and 90th percentiles. It is also clear from this figure that the subsidence rates have decreased over time. Statistics from the most recent surveys, however, have begun to increase slightly. While it is possible that subsidence is increasing, it is also possible there could be errors in the most current surveys.

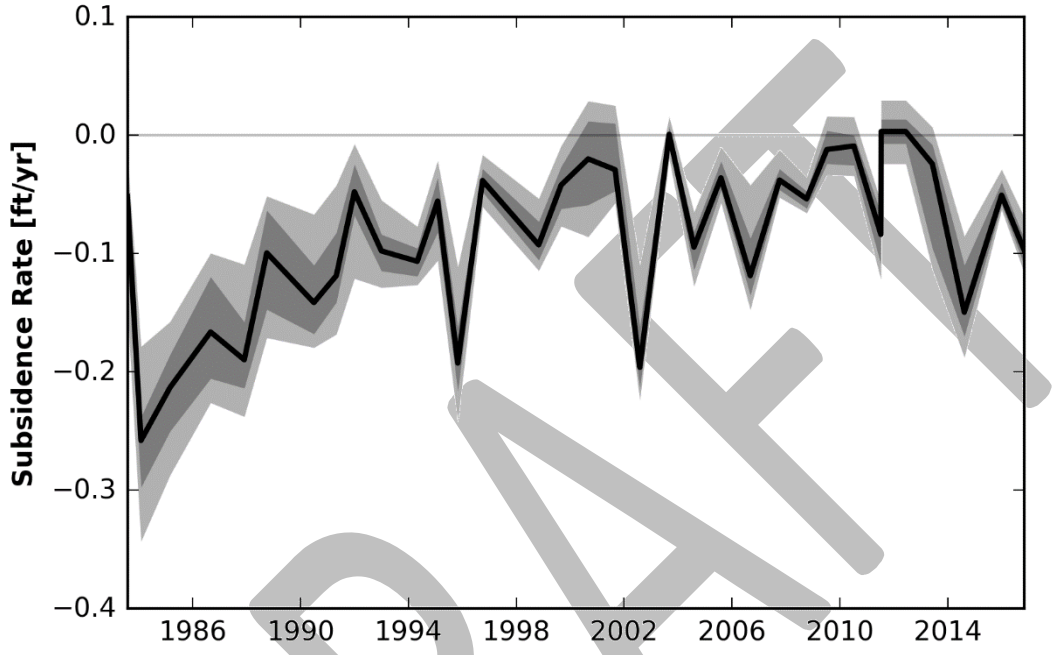


Figure 5 - Subsidence rates over time for West Hackberry with the black line indicating the median subsidence rate and the darker grey area representing the upper 75th and lower 25th percentiles. Lighter grey region shows the extents of the 10th and 90th percentiles.

Current Survey Information

The most recent subsidence survey was completed in November 2016 by John T. Jakubik & Associates, LLC, a licensed surveyor in Louisiana. The report was submitted to DOE on December 19, 2016 and subsequently given to Sandia National Labs on January 20, 2017 for analysis. There were three benchmarks used to confirm the survey results and 113 monitoring stations measured across the DOE and LA Storage sites. Three new wells located on the LA Storage site were added to this year's survey (Pelican 001-003). The subsidence rates were taken by comparing elevations from two different surveys. Since this is the first year the Pelican wells were included, there was no subsidence rates calculated for those locations.

Benchmark Monument Information

There were three benchmarks used in the survey. The primary benchmark was a U.S. Coast and Geodetic Survey monument (12V20, PID: AV0581) located on the north headwall of a culvert 100 ft. west of the Hackberry Cemetery on Hwy 390 approximately 1.4 mi SE from the middle of West Hackberry. The two

additional benchmarks are U.S. Coast and Geodetic survey monuments labelled H-211 (PID: AV0332), and J-211 (PID: AV0333) and are located 3.2 mi. E and 2.3 mi. ESE of the site, respectively.

Monitoring Stations

113 survey monuments were measured during this year's annual subsidence survey. Of those 113, there were three new stations. The new monuments, identified as Pelican 001-003, are located on wells owned and operated by LA Storage, LLC. There were also three survey locations omitted from the analysis due to survey error. Well 6B, WH-68, and WH-71 experienced unrealistic ground movement that was uncorroborated by surrounding monuments. Both WH-68 and WH-71 are partially underwater on the northern edge of the site while Well 6B is close to three other monuments that indicated normal subsidence rates. Site engineers saw no indication of abnormal ground movement and abnormal elevations from these locations are thought to be due to rodman error.

Data Analysis

The data analysis is performed in several steps. First, the elevation, GPS, and tiltmeter data are stored in Microsoft Excel spreadsheets and analyzed using python scripts. Subsidence rates are calculated by comparing elevation differences over a given amount of time, typically the time between surveys. The maps of subsidence rates are created in Mining Visualization Studio.

Results

The subsidence results for the two most current surveys are presented in Figure 6. The site shows the same overall subsidence trend with the highest subsidence occurring in the center of the site, however, the subsidence rates are higher than in previous years. The average subsidence rate across the site is 0.099 ft./yr. (1.19 in./yr.). The cause for this subsidence is currently unknown but could be linked to multiple factors. First, the sites could actually be experiencing an increase in subsidence. This is unlikely as the GPS and tiltmeter (discussed later) have not experienced any significant change in subsidence or tilt rate. Since the subsidence profile is consistent with previous years' surveys, it seems there may be a systematic error in one or both of the surveys used to generate Figure 6.

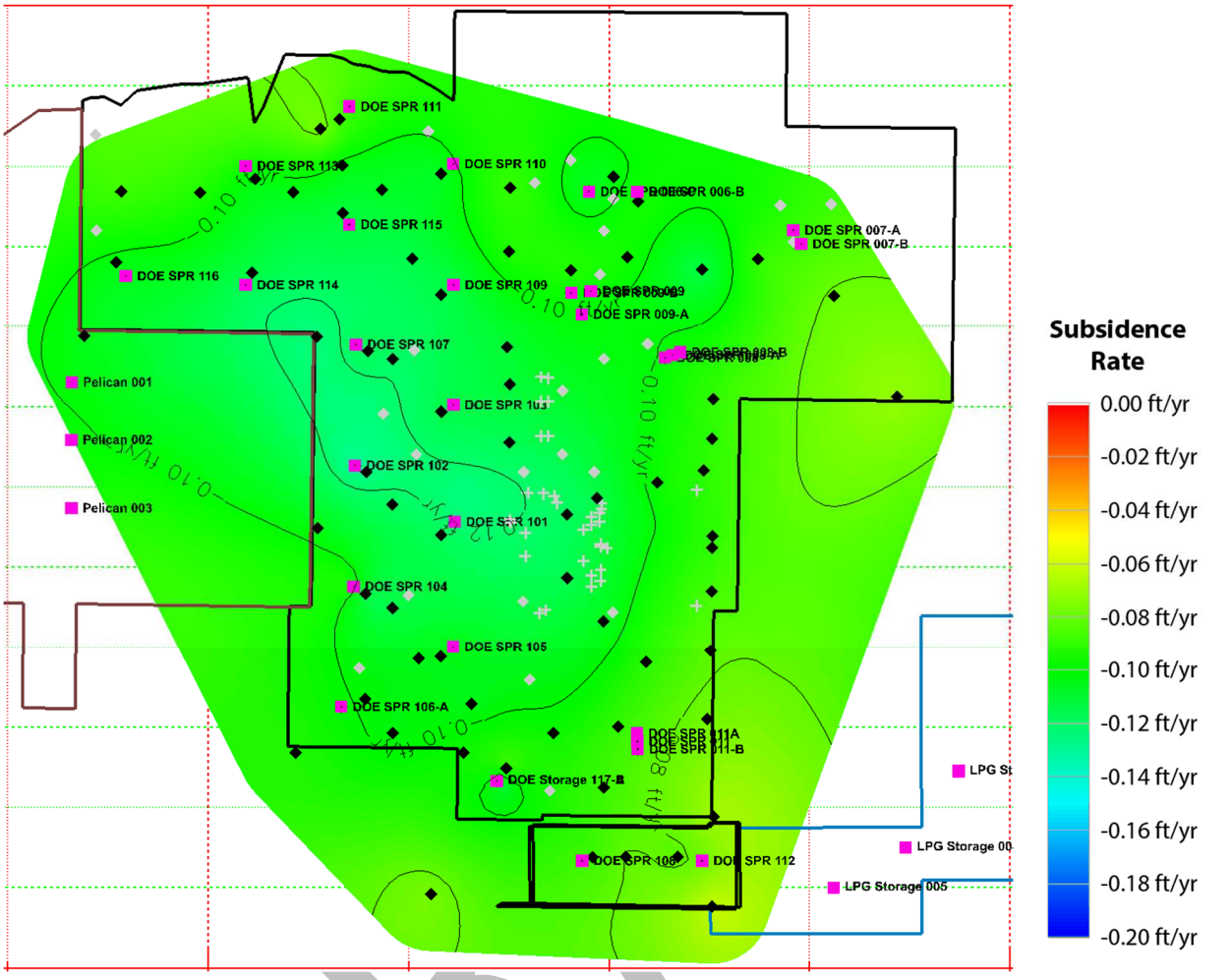


Figure 6 - Calculated subsidence rates between December 2015 and November 2016 with current operator boundaries overlaid on the map. The cooler colors indicate greater subsidence while the warmer colors represent less subsidence. The pink squares represent well locations while the diamonds and crosses represent survey monuments and markers, respectively. Grey survey monuments/markers indicate that survey location was unavailable for at least one of the two surveys used to create the map.

One possibility for the increased subsidence is that the benchmarks have experienced vertical ground movements. During the annual land based surveys, the elevation of the benchmark is not verified and it is assumed that the benchmark elevation does not change over time. If the benchmark experiences uplift, the surveyed elevations at the site would indicate greater subsidence than is actually occuring. Another possible cause of the increased subsidence could be the difference in survey practices between surveyors. The December 2015 subsidence survey was not completed by John T. Jakubik & Associates and could have been conducted using slightly different methods. Another explanation for the increased subsidence could be due to the time between surveys. The two surveys were taken less than a year apart which is shorter than the typical time period between surveys. Since the subsidence rates are calculated by taking the change in elevation divided by time, small amounts of time can exacerbate any small errors in elevation.

To mitigate some of the issues mentioned previously, the most recent survey was also compared with a survey taken in August 2014. This survey was taken by the same contractor and the time between surveys is increased. Figure 7 shows the subsidence rates between August 2014 and November 2016 (2.3 yrs.). The subsidence trends and overall rates are reflective of previous years. The average subsidence rate was

0.067 ft./yr. (0.80 in./ft.) while the highest subsidence rates are just over 0.080 ft./yr. (0.96 in./yr.) in the middle of the site. Regardless, the overall subsidence profile across the site is consistent with previous years and indicates there has been no loss of structural integrity of any DOE SPR caverns.

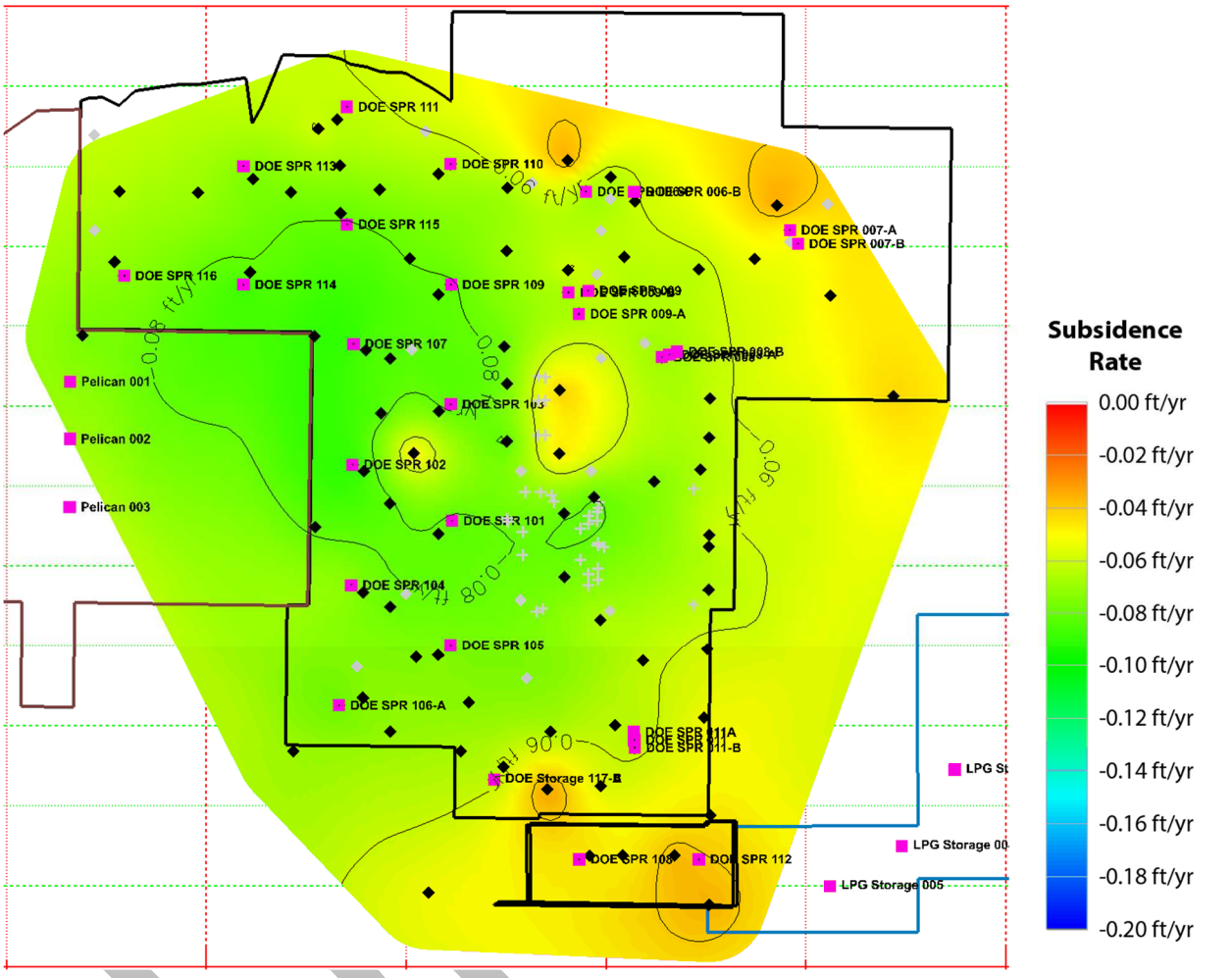


Figure 7 - Calculated subsidence rates between August 2014 and November 2016 with current operator boundaries overlaid on the map. The cooler colors indicate greater subsidence while the warmer colors represent less subsidence. The pink squares represent well locations while the diamonds and crosses represent survey monuments and markers, respectively. Grey survey monuments/markers indicate that survey location was unavailable for at least one of the two surveys used to create the map.

GPS and Tiltmeter

In addition to the annual subsidence survey, there is also a GPS and tiltmeter instrument that was installed at the site in early 2013. The GPS and tiltmeter are affixed to the Cavern 6 wellhead and measurements are recorded hourly. Figure 8 shows the GPS measurements since the GPS was installed. The transparent black circles represent the original hourly GPS measurements and the red line shows the filtered hourly data. The data were filtered using a median filter with a kernel size of 7 days. The grey line is the linear regression, or best fit line, and represents the linear subsidence rate of the GPS. The GPS is showing a slight amount of uplift of approximately 0.02 ft./yr. (0.24 in./yr). This is a small amount of uplift but not reflective of the site which was calculated to be subsiding at approximately 0.06 ft./yr. (0.72 in./yr.). The error could be due to multiple sources and is currently under investigation. One of the most possible causes is subsidence of the reference GPS. If the reference GPS is subsiding at a greater rate than the site

GPS, the site GPS would look as though it were uplifting. It is also possible there is an instrumentation or recording error.

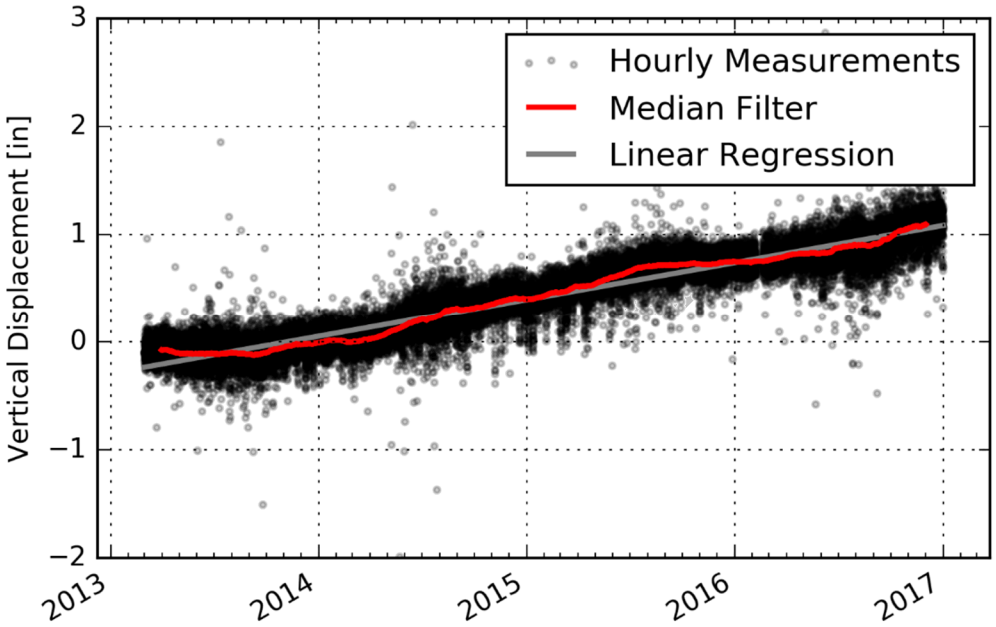


Figure 8 - West Hackberry GPS measurements

Figure 9 shows the tiltmeter data since early 2013. The black and green circles represent the original northing and easting measurements respectively. Like the GPS data, the northing and easting data have been filtered using a median filter with a kernel size of 7 days. The most noticeable feature of the data is a large jump in June 2013. A previous report concluded this disturbance was due to human activity during an oil transfer (Gutierrez, 2013). There is also noise in the tiltmeter measurements during certain seasons. The easting measurements vary more in the fall and winter while the northing measurements vary in the spring and summer. The cause of this is not presently known and is being investigated. Despite this, there is little effect on the median trend.

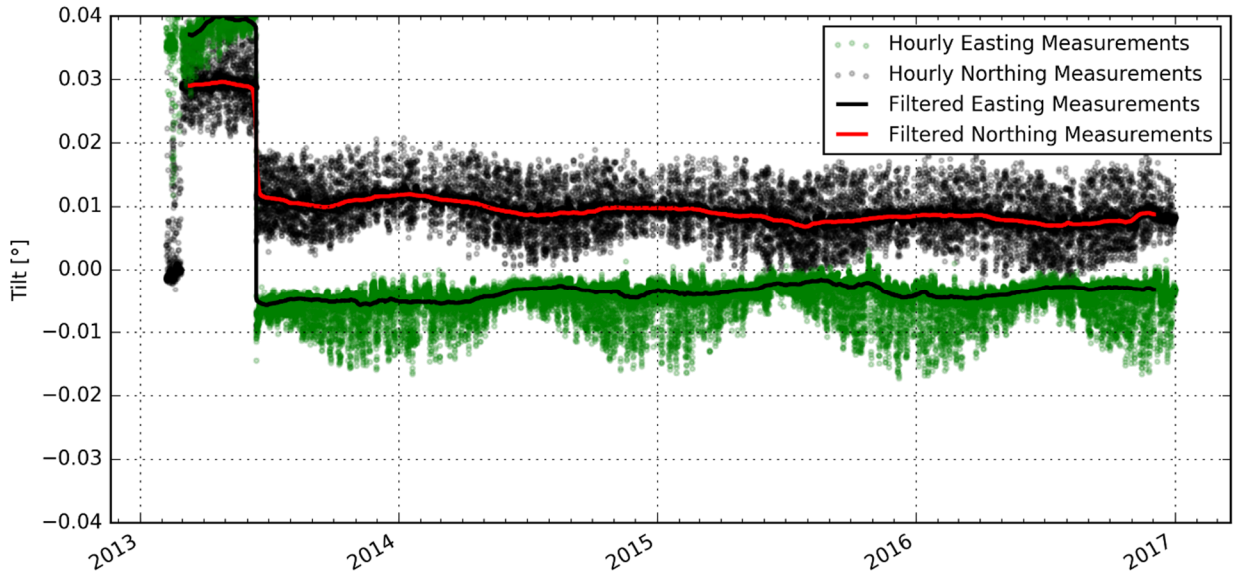


Figure 9 - West Hackberry tiltmeter measurements

Conclusions

Based on the subsidence history of the site and the available data, it can be concluded that ground movements are within typical ranges and do not suggest there is any loss of cavern integrity for any of the DOE SPR or LA storage caverns. The subsidence from the most recent surveys show the site subsiding at a higher than expected rate, however, there is evidence to suggest this is not actually the case. When calculating the subsidence rates with the August 2014 and November 2016 surveys, ground movement is within expected rates. This is likely due to a small, systematic error in one or both of the most recent surveys. Regardless of the overall change in rate, the subsidence profile across the site has not changed. The highest subsidence is seen in the middle of the SPR site with no areas of acute subsidence. This type of subsidence is expected and of little concern. The data from the GPS suggests the instrument is actually uplifting but is unlikely as the surrounding survey monuments show that area has been subsiding. This could be due to a sinking reference GPS, instrumentation error, or recording error. The tiltmeter also suggests there is little tilt near the instrument. There was one instance of human disturbance that affected the tiltmeter but subsequent data has shown little angular movement in the past 3.5 years. Subsidence surveys above the West Hackberry salt dome will continue on an annual basis. With the addition of LA storage's Pelican wells, subsidence rates will be calculated with a larger footprint and provide a more comprehensive understanding of ground movements at the two sites. Moving forward, DOE and LA Storage are planning upcoming discussions with TARGA to have their property included in future dome surveys. If an agreement with TARGA can be made, TARGA survey data will be included in future reports.

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