1 **Monitoring of Subsidence with UAVSAR on Sherman Island in California's**
2 **Sacramento-San Joaquin Delta**

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ABSTRACT

Sherman Island, the westernmost island in the Sacramento-San Joaquin Delta in California, plays a crucial role in maintaining the water flux between saline ocean water from the San Francisco Bay to its west and the rest of the Delta to its east. Land elevation below mean sea level and continuous subsidence over the past century has made this island a high priority area for investigations of subsidence and restoration in the Delta. This study reports the results of successful application of Interferometric Synthetic Aperture Radar (InSAR) data and technique to measure subsidence in the Delta, which is a coherence-challenged non-urban area. We carried out a time-series interferometric analysis of Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) L-band (23.8 cm) data, collected from July 2009-August 2014, to assess both the spatial and temporal variation of subsidence on Sherman Island. We report both large-scale (island-wide) subsidence trends and small-scale (levee/farm scale) subsidence features in Sherman Island. Assuming the subsidence is linear during the five years of UAVSAR data acquisition, subsidence rates across the island range from 0-5 cm/yr, with an average of 1.3 ± 0.2 cm/yr. We estimate our systematic uncertainty to be 0.3 cm/yr. Overall, the central region in the island has subsided at a faster rate than the rest of the island. We find our results to be consistent with previous measurements of subsidence rates at electric transmission line towers scattered throughout the island. The results of this study provide insights into several factors influencing subsidence, including soil type, water table depth, land use, land elevation and the location and time of levee repairs. Subsidence monitoring on Sherman Island is essential for maintaining a reliable water supply for the state of California and for protecting the Delta ecosystem.

Keywords: Deltas; subsidence; synthetic aperture radar; interferometry; InSAR; land use; UAVSAR

1. Introduction

The Sacramento-San Joaquin Delta (from here on referred to as the ‘Delta’) is located east of San Francisco Bay, at the confluence of two of the largest rivers in the state of California: Sacramento River which joins the Delta from the north and San Joaquin River which joins from the south. The Delta itself occupies ~39 km east to west and ~77 km north to south (Figure 1) (Lund, 2010). It is bordered by the cities of Sacramento on the northeast, Antioch on the west, Tracy on the south-west and Manteca (near Stockton) on the southeast. The tidal marshland and reclaimed land that make up the Delta are distributed among ~70 major islands and tracts surrounded by about 1700 km of levees or embankments. The Delta plays a critical hydrological role as the main freshwater supply for California and collects runoff from almost 40% of the state’s land area. It is a hub of various state, federal and local water systems and provides water to about two-thirds of California’s residents (Burton and Cutter, 2008; Suddeth et al., 2010; Delta Science Plan, 2013). Moreover, it is also a complex estuary ecosystem and a biodiversity hotspot that provides home to nearly 750 animal and plant species, some of which are threatened or endangered (United States Environmental Protection Agency [USEPA], 2011).

Figure 1. The Sacramento and San Joaquin Rivers join east of the San Francisco Bay in northern California, forming the Delta. The westernmost island in the Delta, Sherman Island, is the focus of this study (outlined in red). Cities forming the boundaries of the Delta are cited in the text and their locations are depicted in this figure.

In the late 1800s and early 1900s, the tidal marshlands that constituted the Delta were reclaimed and converted into farmland (Mount and Twiss, 2005). ‘Reclamation’ refers to the drainage of existing tidal marshlands and construction of levees/embankments, channel networks and drainage ditches to assist in making the region suitable for agriculture. The conversion of tidal marshlands into farmland initiated the process of subsidence in the Delta. As a result of this ongoing subsidence over the past century, current mean island elevations throughout the Delta are below mean sea level, with some islands being as low as eight meters below sea level (Figure 2) (Mount and Twiss, 2005; Deverel and Rojstaczer, 1996; California Department of Water Resources [CA DWR], 2007b).

Figure 2. Land elevation across the Delta derived from LiDAR topographic survey conducted by the California Department of Water Resources (CA DWR) in 2007-08.

96

97 The factors causing subsidence of the Delta land surface have changed over the years. In
98 the early 1900s, controlled firing/burning of the surface soil was a common practice in the
99 preparation of potato fields and led to lowering of surface levels (Cosby, 1941). Later, this factor
100 was superseded by conversion of larger tracts of land into farms, accompanied by drainage of the
101 organic-rich soils in order to lower water tables for growing crops. These drained organic soils
102 were more susceptible to oxidation and consolidation/compaction, which are currently the
103 dominant causes of subsidence in this area (Deverel and Rojstaczer, 1996; Deverel and Leighton,
104 2010). Oxidation refers to the microbial oxidation of organic matter in the soil that constitutes
105 the Delta. The rate of oxidation depends on the content of organic matter in the soil. Other
106 factors that can also contribute to subsidence include shrinkage, anaerobic decomposition, wind
107 erosion, resource withdrawal, dissolution of soil organic matter and direct harvest of soils.
108 Organic matter content and farming practices/water resources management directly contribute to
109 the variation in subsidence throughout the Delta.

110

111 Sherman Island is the westernmost island in the Sacramento-San Joaquin Delta and its
112 geographic location makes it critical for controlling the flux of seawater into the Delta (Figure 1)
113 (Fisher et al., 2011). This island was one of the first in the Delta to be reclaimed during the
114 period 1868-1879 (URS, 2009). This island is primarily used as pasture area, although
115 agricultural farming, primarily of corn, grains, and alfalfa, is also carried out in the central and
116 northeastern parts of the island (Figure 3C) (CA DWR, 2007a; National Resources Conservation
117 Service Soils [NRCSS], 1985). Land surface elevations measured with LiDAR across Sherman
118 island vary from 1 m to -5 m relative to the sea level (levee elevations are higher than the field

elevations listed here) (CA DWR, 2007b) (Figure 3A). This island has been identified as a high priority island in the Delta due to its geographic location, which directly influences Delta water salinity and quality. Any possible damage to this island's levees can lead to serious economic consequences by potentially impacting Delta exports. The island's susceptibility to seismically-induced liquefaction and levee collapse also make it an important region for studies of subsidence (Mount and Twiss, 2005; Torres et al., 2000). Levee breaches have led to inundation of portions of Sherman Island five times since 1900, with the most recent levee breach occurring in 1969 (URS, 2009). The expected annual probability of flooding in Sherman Island has been estimated as >7% annually (or >84% probability of failure over a 25-year period), from the combined risk of earthquakes, high water and dry-weather levee failures, and is amongst the highest reported for all the islands in the Delta (CA DWR, 2009; Bates & Lund, 2013). Therefore, there is an immediate need for accurate monitoring of subsidence rates in Sherman Island, which is essential for project planning, subsidence management and mitigation, flood disaster response, and levee failure impact assessment (Service, 2007; Burton and Cutter, 2008).

Figure 3. [A] LiDAR elevations across Sherman Island from the topographic survey conducted by CA DWR in 2007; UTM Zone 10, NAD 83, vertical datum NAVD88 (CA DWR, 2007b), [B]

Soil type classification (NRCSS, 1985) and [C] land use classification (CA DWR, 2007a) across Sherman Island. It is important to point out that land use classification varies from year to year and thus this survey from 2007 might not accurately depict the current land use status in the island. Similarly, the soil type map is only intended to provide an island-wide distribution of common soil types and should be used with caution for understanding the effect of soil organic matter content on subsidence.

Historically, moderate subsidence rates (1-3 cm/yr) have been recorded in this island compared to the other islands in the Delta (Deverel and Leighton, 2010). Past studies of subsidence in the Delta have focused on measurement of subsidence from field transect surveys (Broadbent, 1960; Prokopovich, 1985; Weir, 1950); ground-based instruments like extensometers (Deverel and Rojstaczer, 1996; Rojstaczer and Deverel, 1993); LiDAR surveys (CA DWR, 2007b; Glennie et al., 2013); soil loss measured against electrical transmission towers (Rojstaczer and Deverel, 1995); or some combination of these methods (Deverel and Leighton, 2010; Rojstaczer et al., 1991). However, all of these methods have focused on individual measurements made at a particular time and/or at disparate locations.

Given the variation of soil organic content, water table depth, farming, and water management practices on Sherman Island, all factors affecting subsidence, it is important to monitor elevation changes at high spatial resolution and with sufficient temporal duration and resolution to distinguish long term subsidence trends from seasonal or episodic variation. This study reports regularly acquired, spatially comprehensive measurements of subsidence across the entire Sherman Island and has sufficient duration of measurements to extract linear subsidence

rates with sub-centimeter accuracy over much of the area. The results outlined in this manuscript allow us to investigate large-scale (few kilometers; across the extent of the island) and small-scale (20-30 meters; at the scale of the levees) spatial and temporal trends of subsidence on the island. Although studies in the past have attempted to use satellite C-band (ERS-1 and ERS-2) radar data for investigating Delta subsidence, rapid decorrelation in the non-urban landscape of the Delta proved to be a limiting factor in comprehensively characterizing subsidence within the Delta's interior (Cohen et al., 1998; Brooks et al., 2012a). The relatively longer L-band (23.8 cm) wavelength of the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) imagery used in this study, combined with regular acquisitions, high spatial resolution and data processing techniques developed for low coherence regions, have allowed for the application of radar interferometry to monitor subsidence in a coherence-challenged area like the Delta.

2. Instruments and datasets

Data acquired by NASA JPL's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) were utilized for this study. UAVSAR is a pod-based radar system instrumented with a quad-polarization, L-band (23.8 cm) synthetic aperture radar (SAR) with a bandwidth of 80 MHz, which is flown on a NASA G-III aircraft (Hensley et al., 2008; 2009). The G-III aircraft that carries the UAVSAR flies at an altitude of 12.5 km. Figure 4 shows the UAVSAR coverage of Sherman Island by two lines (UAVSAR line IDs SDelta_15502 and SDelta_23518), which image the island from near perpendicular directions (flight track heading is 155° for line 15502 and 235° for line 23518). The incidence angle for the two lines varies from 19.5° in the near-range to 65.4° in the far-range (for the cropped sections of the lines used for this study, the incidence angle range is 39.8°-60.9° for 15502 and 45.9°-58.6° for 23518). The UAVSAR has

185 been flown over Sherman Island regularly since July 2009, yielding 47 and 50 acquisitions for
 186 line 15502 and 23518, respectively, as of August 2014. The time between sequential acquisitions
 187 ranges from 26 to 105 days. Table 1 lists all the UAVSAR data acquisitions utilized for this
 188 study. The single-look complex data (SLC) have a pixel spacing of 0.6 m x 1.6 m. (Hensley et
 189 al., 2009). For this study, we have used HH polarization interferometric products from the
 190 UAVSAR that are multi-looked by a factor of 3 (12) in the slant-range (along-track) direction,
 191 which reduces the speckle noise in the images while maintaining a sufficiently high resolution to
 192 well resolve the levees. The UAVSAR is the ideal instrument for conducting this analysis
 193 because it has fine spatial resolution (7 m multi-look), sufficiently wide imaging swath (22 km),
 194 and the longer wavelength (L-band, 23.8 cm) required to maintain phase coherence between
 195 repeat collections in the Delta (Jones et al., 2011; 2012; 2016).

197
 198 **Figure 4.** Two UAVSAR lines cover the Sherman Island in the Delta from different look
 199 directions. The inset shows the NASA Gulfstream G-III aircraft that carries the UAVSAR.

201 **Table 1.** Inventory of UAVSAR acquisitions used in this study.

Line ID	Flight ID	Date of acquisition (yyyy-mm-dd)	Temporal Baseline (Days)
15502/23518	09048	2009-07-18	-
15502/23518	09068	2009-09-08	53
15502/23518	09080	2009-10-03	26
15502/23518	09086	2009-11-02	31
15502/23518	09093	2009-12-03	32
15502/23518	10007	2010-01-14	43
15502/23518	10025	2010-03-04	50
15502/23518	10026	2010-04-09	37
15502/23518	10036	2010-05-10	32
15502/23518	10051	2010-06-17	39
15502/23518	10059 (1)	2010-07-12	26
15502/23518	10059 (2)	2010-07-12	
15502/23518	10060	2010-07-12	
15502/23518	10068	2010-08-10	30
15502/23518	10070	2010-09-25	47
15502/23518	10075	2010-10-25	31
15502/23518	10083	2010-12-01	38
15502/23518	11003	2011-01-10	41
15502/23518	11006	2011-03-30	80
15502/23518	11027	2011-05-12	44
15502/23518	11036 (1)	2011-06-16	36
23518	11036 (2)	2011-06-16	36
15502/23518	11051	2011-07-20	35
15502/23518	11061 (1)	2011-08-29	41
23518	11061 (2)	2011-08-29	41
23518	11062	2011-08-29	41
15502/23518	11065	2011-10-03	36
15502/23518	11070	2011-11-02	31
15502/23518	11079	2011-12-07	36
15502/23518	12001	2012-01-05	30
15502/23518	12011	2012-02-13	40
15502/23518	12012	2012-03-22	39
15502/23518	12020	2012-04-24	34
15502/23518	12031	2012-05-30	37
15502/23518	12063	2012-07-18	50
15502/23518	12070	2012-08-16	30
15502/23518	12082	2012-09-24	40
15502/23518	13002	2013-01-03	102
15502/23518	13014	2013-01-29	27
15502/23518	13069	2013-04-23	85

15502/23518	13100	2013-05-29	37
15502/23518	13129	2013-07-19	52
15502	13155	2013-10-24	98
23518	13165	2013-10-31	105
15502/23518	13185	2013-11-25	33 (15502) / 26 (23518)
15502/23518	14005	2014-01-17	54
15502/23518	14019	2014-02-12	27
15502/23518	14033	2014-04-02	50
15502/23518	14062	2014-05-15	44
15502/23518	14086	2014-06-16	33
15502/23518	14112	2014-08-14	60

3. Methodology

The technique of InSAR is based on coherent processing of radar signals collected over the same scene at two different times to derive surface deformation from the change in the relative phase of the two returns (Figure 5) (Balmer and Hartl, 1998; Rosen et al., 2000; European Space Agency, 2007; Richards, 2007). In this way, deformation along the line-of-sight direction on the scale of a fraction of the radar wavelength can be resolved as long as the phase coherence between the signals is maintained (Zebker and Goldstein, 1986; Gabriel et al., 1989). As part of the InSAR data processing, interferograms showing the difference in interferometric phase between two acquisitions over the same area are generated. Another important parameter calculated during InSAR processing is the interferometric coherence, which is a measure of correlation between different acquisitions.

Figure 5. The basic principle of InSAR is demonstrated in this figure. When the radar instrument is flown over a patch of ground the first time (first pass), it transmits microwave pulses towards the surface of the Earth and receives the reflected echo of the radar signal. The incident and reflected signal can be compared in terms of change in amplitude and phase. During the second pass, the radar instrument flies again over the same region to measure new reflection and change of range (distance between instrument and land surface) along line-of-sight direction through the relative change in the phase of the returned signal. (Image credit: Paul A. Rosen)

We generate stacks of co-registered single-look complex data (SLCs) with the standard UAVSAR processor. While selecting SLCs to be used for our analysis, we take into account standard data quality metrics to evaluate potential acquisition errors associated with airborne InSAR data, including positional accuracy of the flight track (aircraft motion), nadir return in images and image decorrelation. We do not include any SLCs for which more than 20% of the flight track is outside with respect to the reference tube (the percentage of flight track outside the

tube for the SLCs used in this analysis ranged from 0% to 8.9%, with an average value of 0.5%). In addition, we apply network deramping (described later in the manuscript) to further correct for aircraft motion. Furthermore, we use a low coherence threshold mask (also described later in the manuscript) to exclude areas with excessive image decorrelation. Finally, we use these selected SLCs to form interferograms (containing magnitude and wrapped phase information) in radar coordinates (slant-range/azimuth).

Figure 6 provides an overview of the methodology used for processing the UAVSAR data for this study. The single-look interferograms are down-sampled (multi-looked) by a factor of 3×12 (range $\times$ azimuth). Analysis was done to determine the best down-sampling factor to get a combination of reduced noise and reasonable high spatial resolution. It was found that because of the noise reduction, down-sampling by a factor of 3 (slant range) $\times$ 12 (azimuth) best resolved the higher coherence finer scale features and gave good interferometric phase signals. The interferometric coherence (statistical estimate of change between different acquisitions) is calculated as the normalized magnitude (zero to one) of the complex correlation image following the spatial averaging to reduce noise. Figure 7 shows the pairs of acquisitions used for forming interferograms for both lines. As a general rule, data from flights spaced 1 to 4 months apart were used for generating the interferograms in order to reduce the effect of temporal decorrelation, in addition to annual summer-to-summer interferograms. Each acquisition is used for forming a minimum of 5 interferograms.

Figure 6. Overview of processing methodology

Figure 7. Pairs of acquisitions used for forming interferograms for both lines (15502 and 23518) are shown in this figure. 47 data acquisitions taken by the UAVSAR were utilized to generate 168 interferograms for line 15502, and 50 acquisitions were used to generate 198 interferograms for line 23518. Each acquisition is used for forming a minimum of five interferograms.

The next major step in the data processing is phase unwrapping. We further down-sample the 3×12 interferograms by an additional 3×3 to obtain spatially filtered interferograms. We use these interferograms to create low resolution unwrapped phase masks, which are then used to determine the correct wrap for the 3×3 pixels in the full resolution interferograms. We carry out two-dimensional phase unwrapping on the 9×36 multi-looked interferograms using the SNAPHU algorithm (Statistical-cost, Network-flow Algorithm for Phase Unwrapping) (Chen and Zebker, 2001), modified as follows for low-coherence data. In order to deal with the large amount of low coherence regions in the images, which would otherwise lead to many disconnected regions and incorrect unwrapping, we make the assumption that the deformation in low coherence areas is sufficiently slow that more than one phase wrap does not occur between the low coherence pixel and its nearest high coherence neighbor. With UAVSAR's wavelength of 23.8 cm and the short repeat interval providing greater coherence as compared to shorter wavelength radar platforms, this is valid in an area with slow subsidence like our study area. Based on this, before using SNAPHU to phase unwrap the scene, we replace the phase values in low coherence areas by the phase of the nearest high coherence neighboring point. Thresholds defining "low" and "high" were determined experimentally, with 0.40 and 0.45 generating consistent, low error, results for all scenes. Following phase unwrapping with SNAPHU, the original phase + $N \times 2\pi$ of the low coherence pixel is restored, with the 2π multiple selected to put the phase on the same wrap as the nearest high coherence neighbor.

We utilize the Small Baseline Subset (SBAS) (Berardino et al., 2002) time-series interferometric method implemented in the Generic InSAR Analysis Toolbox (GIAntT) (Agram et al., 2012, 2013) to calculate ground surface deformation from unwrapped phase. Before

284 starting the time-series analysis, we generate a mask to eliminate very low coherence areas and
285 water bodies in the region based on three inputs that are calculated for each pixel in the image: a
286 minimum average coherence threshold, where the average is calculated over all the
287 interferograms; a minimum threshold for the coherence that must be satisfied for at least a
288 specified percentage of the interferograms; and a water mask generated using water body GIS
289 shapefiles (vector outlines) from the USGS National Hydrography Dataset (Simley and Carswell,
290 2009). The minimum average coherence threshold (0.3) is selected based on the average
291 coherence of the water in the scene. The percentage criteria for the coherence of individual
292 interferograms (coherence > 0.35 for at least 40% of the interferograms) is selected to eliminate
293 areas that are not coherent frequently enough to obtain good results over the five year interval of
294 our study. This eliminates saturated and frequently flooded land areas. Next, we select regions
295 with minimal phase change and high coherence as the phase reference. To identify appropriate
296 potential reference regions, we generate maps of minimum, maximum and average coherence for
297 the entire scene and extract pixels with consistently high minimum coherence (> 0.5). We avoid
298 selecting areas with known time-varying elevations, particularly geologic historic fault lines and
299 man-made structures like electrical transmission lines, which can expand/contract with changing
300 temperatures. We evaluated multiple reference regions for this study and selected the concrete
301 base of one of the electric transmission line towers ($\sim 38.07^\circ\text{N}$, 121.71°W) as a reference. The
302 average coherence at this location was 0.88. Figure 8 shows the phase reference and locations of
303 electrical transmission towers used in previous subsidence measurements and an extensometer in
304 operation during our study and used as validation for our UAVSAR measurements, as described
305 later in this manuscript. The scene is then cropped to the geographic boundaries of Sherman
306 Island only. Figure 9 shows a typical example of an interferogram with magnitude and phase

307 information, the associated interferometric coherence and the mask for one of the lines covering
308 Sherman Island (15502).

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Figure 8. [A] Location of the reference point used for this study in Google Earth® optical imagery. The reference region is at the base of one of the electric transmission line towers

(~38.07 °N, 121.71 °W) located within Sherman Island. The locations of electrical transmission power lines used for comparison with previous studies are also indicated in panel A. The transmission line built in 1910 cuts across Sherman Island from west to east, and the transmission line built in 1952 cuts across from north to south. Location of the extensometer that is used for providing ground-truth for UAVSAR measurements is also shown. Close-up views of the reference region location at increasing resolutions are shown in the bottom left [B] and bottom right [C] panels.

Figure 9. Example of an interferogram with magnitude (upper left) and phase (upper right) information, coherence (lower left) and water mask (lower right) for line 15502. Each of the sub-figures is shown in radar (range/azimuth) coordinates. Line ID: 15502, Dates of acquisition: 2010-09-25 and 2010-10-25, Temporal baseline: 31 days.

We utilize atmospheric data from NOAA's NARR (North American Regional Reanalysis, National Oceanographic and Atmospheric Administration) weather model for North America (Mesinger et al., 2006), to correct for effects of tropospheric delay. This atmospheric model provide estimates of air temperature, atmospheric pressure and humidity as a function of elevation at a spatial resolution of 30 km and temporal resolution of 3 hours. This three-dimensional distribution of atmospheric variables is used to determine the atmospheric phase delay correlated with topography for each pixel of each interferogram (Doin et al., 2009; Jolivet et al., 2011; Jolivet and Agram, 2012).

Next, we use GIANt's network de-ramping algorithm for estimating flight path variation effects on interferograms, which evaluates a scene tilt in a network sense, independently on each interferogram using a least-squares scheme (Biggs et al., 2007; Cavalie et al., 2007, 2008; Lin et al., 2010; Agram et al., 2012; Jolivet et al., 2012). This tilt is induced by small errors in the measured aircraft flight position. The tilt is expressed as a two-dimensional plane, $ax+by+c$, where a , b and c are the fit parameters and x and y are fractional sample and line location in the interferograms. Then, the SBAS algorithm, modified for coherence weighting, is used to calculate time series of cumulative surface deformation along the line-of-sight direction.

The cumulative displacement results are adaptively smoothed based on average coherence, with higher coherence points undergoing lesser averaging and only pixels of similar coherence being averaged together. The smoothed displacements along the line-of-sight are then projected to subsidence/uplift assuming that there is no horizontal displacement component. Although this could introduce minor artifacts in areas with steep fringe gradients (Bawden et al,

2001), that is not a problem in our study area. The six closest GPS stations from the Plate Boundary Observatory (PBO) network, which are distributed around the edge of the Delta, all measure average horizontal velocity of 1.3-1.4 cm/yr, indicating the Delta to be moving northwest with respect to stable North America (reference frame NAD08) with near-uniform velocity. By choosing a phase reference within Sherman Island, we remove most of the effect of horizontal tectonic motion. Thus, the assumption that the interferograms measure predominantly the vertical component of the displacement field is reasonable. Exceptions would be in areas with topographic relief, and might occur on the slopes of the levees as discussed later.

Uncertainties in the calculated subsidence are estimated by performing a Jackknife test (Efron and Stein, 1981), a variation of the bootstrap resampling technique, using subsets generated on the basis of SAR acquisitions. These uncertainty estimates are used to weight the cumulative subsidence values at each time step for calculating rates of subsidence. We calculate rates of subsidence from the projected subsidence measurements by estimating a least-squares linear fit to the time-varying subsidence measurements between July 2009 and August 2014 for each pixel. We then georeference (convert data from radar coordinates to geographic coordinates) the results obtained from the two UAVSAR lines covering Sherman Island and calculate the linear subsidence rate across Sherman Island and the uncertainty (random error) in the calculated rate. Finally, we calculate the average of the subsidence and subsidence rates for the two lines. For pixels that are masked in one line but not the other, the value used is the subsidence/subsidence rate for the unmasked pixel.

In radar interferometric time-series analysis, random errors related to data acquisition and processing can lead to decorrelation, and systematic errors resulting from effective path length variations over the scene can result in biases (Hanssen, 2001; Reeves et al., 2014). Data acquisition and processing errors include baseline decorrelation, doppler centroid decorrelation, volume scattering decorrelation, thermal or system noise, temporal terrain decorrelation and processing induced decorrelation (from co-registration and interpolation). The effect of all of these errors is contained in the coherence parameter and we account for them through various techniques. We only include those pixels in our analysis for which coherence averaged across all interferograms is greater than 0.3 and overall coherence is greater than 0.35 in at least 40% of the interferograms. This is used as a threshold for identifying water bodies, flooded areas, and areas with too much disturbance to yield reliable subsidence measurements with InSAR. We modify the SNAPHU phase unwrapping algorithm for low-coherence data. We also perform coherence weighting on the cumulative displacements generated by the SBAS calculation. We undertake coherence-based smoothing of the cumulative displacements and use the uncertainties in subsidence as weights while calculating rates of subsidence. All of these measures minimize the effect of any random errors that would lead to decorrelation. Microwave path length variations can occur as a result of aircraft motion effects or tropospheric delay effects. We account for these errors by including network de-ramping and atmospheric correction in our calculations, as described earlier in this section.

To estimate the systematic error in our analysis, we modified the mask that is used for cropping out low coherence areas and water bodies to use a different minimum average coherence threshold (0.285 compared to the previously used 0.3) and no requirement on the

percentage of interferograms exceeding a minimum coherence threshold. We compared the average subsidence rate calculated using the two masks for the whole island, and estimated the systematic uncertainty as the Root-Mean-Square-Error (RMSE) of the difference. Using this procedure we determined our systematic uncertainty to be 0.3 cm/yr.

4. InSAR-derived subsidence across Sherman Island

The time-series interferometric approach described above enabled us to calculate cumulative subsidence and uncertainty estimates across Sherman Island, as measured on August 14, 2014 with respect to the first acquisition on July 18, 2009. Results from both UAVSAR flight lines (15502 & 23518) indicate subsidence of 0-25 cm over the five years of data acquisition, with 5.8 ± 1.4 cm being the average subsidence observed across the island in the areas that were not masked.

Overall, we calculate an average subsidence rate of 1.3 ± 0.2 cm/yr (with 0.3 cm/yr systematic uncertainty), ranging between 0-5 cm/yr across the island, as observed in Figure 10A, which shows subsidence rates derived from a linear fit to the subsidence vs. time. We observe a large-scale trend of greater subsidence rates in the central portion of the island, and along the levees on the western shoreline. This observation could be attributed to land use (Figure 3C) and associated water management practices. Most of Sherman Island is used as pasture area, except for the agricultural fields in the central regions of the island, which are used for growing crops. Variable depth to groundwater resultant from variations in drainage depth could be responsible for the observed island-wide spatial variation of subsidence. This association between water table depth (and hence the depth of the unsaturated zone) and subsidence has been suggested by

other researchers also (Stephens et al., 1984; Deverel and Leighton, 2010). Oxidative subsidence is inversely correlated with depth to groundwater (Stephens et al., 1984). The depth of the unsaturated zone influences the extent of oxidation. The greater the depth of the unsaturated zone, the larger is the subsidence rate. We find soil type (and hence percentage of organic matter content) to be a factor affecting large-scale subsidence across Sherman Island. Areas dominated by soils with higher organic content (like Rindge mucky silt loam, Gazwell mucky clay) exhibit generally higher subsidence rates compared to areas with lower organic content soils (like Sailboat silt loam, Columbia fine sandy loam) (Figure 11A). We also observe a trend of higher subsidence rates for lower elevations (Fig. 11B). For most soils (except Sailboat, Sailboat Variant and Egbert), soil type and land elevation are found to be correlated. Higher organic content soils are observed to be generally associated with lower elevations, which could indicate ongoing subsidence over a relatively longer time period (Fig. 11C). Greater subsidence along the western shoreline levees may be associated with multiple repairs involving addition of fill material that have been carried out over the past few years.

Also plotted is the estimate of uncertainty (random error) in the subsidence rate (Figure 10B). Difference between the subsidence rates derived from the two lines is largest in some areas along the levees and in southern Sherman Island (Figure 10C). In areas along the levees, this could indicate a breakdown in the assumption that there is no horizontal component to the line-of-sight movement, particularly on levee slopes. For example, in the area shown in Figure 12a marked by the yellow star, there are slanted telephone poles. In inland areas, where the two lines differ more than the average, temporal change of scatterers could be responsible for the observed difference between the two lines. Also, it is possible that the three hour temporal resolution of the atmospheric model used does not differentiate between atmospheric conditions during

442 acquisitions for the two lines made on the same day within an hour or so, and this could be a
443 contributing factor. Therefore, we consider our subsidence results in such regions to be poorly
444 constrained.

445

Figure 10. [A] Subsidence rates on Sherman Island derived from a weighted linear fit to the cumulative subsidence vs. time, from July 18, 2009 to August 14, 2014. **[B]** Uncertainty in subsidence rate (cm/yr). **[C]** Standard deviation in the subsidence rates calculated from the two UAVSAR lines, 15502 and 23518. Black pixels in this image indicate the ones for which subsidence was calculated from one line only.

Figure 11. [A] Variation of average subsidence rates with soil type (organic matter content) across the whole island is shown. Greater organic matter content in soils is generally associated with higher average subsidence rates. **[B]** Higher subsidence rates are observed for lower elevations. **[C]** Correlation is observed between soil organic content and elevation, with higher organic content soils being generally associated with lower elevations (exceptions include Sailboat, Sailboat Variant and Egbert soil types). Land elevations reported in Figs. 11B and 11C have been measured with respect to vertical datum NAVD88 (CA DWR, 2007b).

On smaller scales, we observe multiple high subsidence features on Sherman Island (Figure 12). The first feature is located in southwestern Sherman Island and has experienced almost 25 cm of subsidence in the five years since UAVSAR began acquiring data over the island (indicated by a yellow star in Figure 12a). Optical imagery over the feature shows a scour pond that had formed after the levee breach of 1969 and a dredge disposal site (used for

466 providing source material for repairing/maintaining levees). The section of the levee in this area
467 has been repaired multiple times and the observed subsidence is presumably related to repair-
468 induced loading on the previously-unloaded organic soils in the new setback levee section due to
469 the addition of fill material during repair work. For contrast, we show in Figure 12a subsidence
470 vs. time at a nearby site (indicated by the red star) that is roughly the same distance inland from
471 the levee. Here we see modest subsidence combined with seasonal oscillations. This example
472 demonstrates how changes in land elevation from one season to the next can be significant
473 enough to make the timing of the elevation measurement important. The UAVSAR data
474 analyzed for this study cover the time period from July 2009-August 2014, thus minimizing the
475 effect of seasonal oscillations in land elevation, in calculating the rate of subsidence. In Figure
476 12b, we show a high subsidence feature in the central portion of the island, for which the
477 temporal trend of subsidence consists of a mixture of seasonal oscillations overlain with an
478 overall decrease in elevation. This subsidence feature overlaps with a mix of cultivated and
479 fallow land, as observed in the corresponding visual imagery. In this case, the variation of soil
480 moisture and water table depth between land used for agriculture and land left bare could have a
481 direct impact on the location of the subsidence feature. Figure 12c shows a feature in the
482 northeastern section of the island, for which there is some indication of correlation between the
483 shape of the feature and the variation of soil type and organic matter content, although the
484 feature shape does not exactly follow the soil type variation, which could be in part due to the
485 coarse resolution of the soil type map available. Finally, the northeastern ‘tail’ section of the
486 island shows greater subsidence in the central portion compared to the edges of the section, close
487 to the water channels and the remnant natural levees of the island. As shown in Figure 12d, a

488 combination of soil type and topography variation is likely contributing to the variation of
489 subsidence observed here.

490

Figure 12. Examples of small-scale subsidence features observed across Sherman Island with UAVSAR are shown in this figure. The top panel shows locations of these features outlined in black rectangles. (a) The yellow star shows an area adjacent to the levee in southwestern Sherman Island that experienced ~25 cm of subsidence over the five years of our study. Optical imagery of the feature shows a scour pond and a dredge disposal site. The red star shows subsidence vs. time for a nearby point that does not exhibit rapid subsidence, but instead slow subsidence with much larger seasonal oscillations in land elevation. (b) Subsidence feature in central Sherman Island that shows a mix of subsidence and seasonal oscillation in its elevation trend. (c) Subsidence feature in northeastern Sherman Island that is partially correlated with

variation of soil type. (d) The ‘tail’ section in northeastern Sherman Island shows subsidence variation that generally follows the variation of topography and soil type.

We compare our results for subsidence rates during the period 2009-2014 to previous subsidence measurements on Sherman Island. Multiple past studies have measured soil loss against concrete bases of electrical transmission towers to estimate subsidence at a few locations across Sherman Island. Rojstaczer et al. (1991) and Rojstaczer and Deverel (1995) reported subsidence rates of 2.3 cm/yr and 1.5 cm/yr from 20 and 12 power pole measurements taken from power pole lines crossing Sherman Island from west to east and north to south, respectively. Deverel and Leighton (2010) concluded Sherman Island to be subsiding at an average rate of 1.3 cm/yr, based on measurements from 13 towers from the North-South crossing transmission line across the island. Deverel and Rojstaczer (1996) installed an extensometer in southern Sherman Island, which yielded a subsidence rate of 0.46 cm/yr. Brooks et al. (2012b) and Glennie et al. (2013) developed a customized LiDAR system mounted on a balloon and flew it over a section of the southwestern levee of Sherman Island. By comparing their observations with the LiDAR survey of 2007-08 conducted by the CA DWR, they calculated 10s of centimeters of subsidence across and around the levee. Following the approach of previous studies for calculating subsidence at the base of the electric transmission line towers, we selected four regions within 100 meters of the base of each power pole. We calculated an average of the subsidence rates at these four neighboring regions to estimate the subsidence rate at each power pole. Our results are comparable in magnitude to the power pole, extensometer and LiDAR-based measurements from previous studies. Tables 2 and 3 show a comparison of our results with individual power pole measurements reported by Rojstaczer et al. (1991), Rojstaczer and

Deverel (1995) and Deverel and Leighton (2010). Figure 8 shows the location of the electric transmission line towers used for this comparison.

Table 2. Comparison of UAVSAR-derived subsidence rates at individual electric transmission line towers with previous studies. Individual towers in this table are from electrical transmission line 1910, which cuts across Sherman Island from west to east, as shown in Figure 8. The error bars in the UAVSAR subsidence rates indicate only the random component of the uncertainty.

Latitude	Longitude	Power pole number	Subsidence Rate during 1988-2006 from Deverel & Leighton, 2010 (cm/yr)	Subsidence Rate during 1910-1988 from Rojstaczer et al., 1991 (cm/yr)	UAVSAR Subsidence Rate (cm/yr)
38.088299	-121.704203	274	-1.4	-1.28	-1.4 $\pm$ 0.5
38.082598	-121.709647	278	-0.75	-1.25	-0.8 $\pm$ 0.3
38.081173	-121.711535	279	-1.25	-1.9	-0.3 $\pm$ 0.3
38.079754	-121.713427	280	-0.8	-1.4	-0.8 $\pm$ 0.2
38.078421	-121.715182	281	-2.25	-1.3	-0.8 $\pm$ 0.5
38.076973	-121.717149	282	-0.6	-1.35	-0.6 $\pm$ 0.5
38.075849	-121.718661	283	-1.2	-2.45	-0.9 $\pm$ 0.4
38.071312	-121.724722	287	-2.3	-1.8	-1.6 $\pm$ 0.3
38.067004	-121.730468	291	-1.4	-2.8	-1.6 $\pm$ 0.8
38.064227	-121.73419	292	-1.95	-2.3	-1.8 $\pm$ 0.3
38.062814	-121.736092	293	-1.2	-2.3	-1.3 $\pm$ 0.5
38.055789	-121.745479	298	-1.3	-3	-1.2 $\pm$ 0.6
38.054372	-121.74737	299	-0.6	-3.05	-0.6 $\pm$ 0.4
38.094372	-121.702669	271	-	-1.15	-1.0 $\pm$ 0.2
38.092355	-121.703191	272	-	-1.28	-1.2 $\pm$ 0.3
38.090328	-121.703683	273	-	-2.18	-1.8 $\pm$ 0.3
38.075559	-121.719008	284	-	-2.49	-1.0 $\pm$ 0.4
38.069886	-121.726614	289	-	-2.6	-1.9 $\pm$ 0.4
38.061384	-121.738006	294	-	-2.5	-2.0 $\pm$ 0.2
38.057192	-121.743618	297	-	-2.75	-0.9 $\pm$ 0.7

Table 3. Comparison of UAVSAR-derived subsidence rates at individual electric transmission line towers with previous studies. Individual towers in this table are from electrical transmission line 1952, which cuts across Sherman Island from north to south, as shown in Figure 8. The error bars in the UAVSAR subsidence rates indicate only the random component of the uncertainty.

Latitude	Longitude	Power pole number	Subsidence Rate during 1952-1988 from Rojstaczer et al., 1991 (cm/yr)	UAVSAR Subsidence Rate (cm/yr)
38.064246	-121.701739	10	-0.14	-0.5 ± 0.2
38.06134	-121.705456	11	-0.78	-0.7 ± 0.2
38.060956	-121.705739	12	-2.78	-1.6 ± 0.3
38.067776	-121.704723	13	-1.52	-1.4 ± 0.5
38.063315	-121.709699	14	-1.94	-1.6 ± 0.2
38.06298	-121.709958	15	-2.22	-2.0 ± 0.3
38.070019	-121.709919	16	-0.97	-1.0 ± 0.2
38.064848	-121.714328	18	-1.38	-1.1 ± 0.6
38.072469	-121.71535	19	-3.47	-2.3 ± 0.5
38.068502	-121.722082	20	-1.94	-1.9 ± 0.2
38.068127	-121.722345	21	-1.25	-1.4 ± 0.2
38.074672	-121.72069	22	-0.28	-0.3 ± 0.5

We installed an extensometer in southeastern Sherman Island, located at 38.05 °N, 121.71 °W as shown in Figure 8 (this is the same location as the one for the extensometer used by Deverel and Rojstaczer (1996)). Using this extensometer, we measured change in land surface elevation from September 2010-August 2014 to ground truth our remotely sensed data. The extensometer recorded a subsidence rate of 0.4 cm/yr at the location. We calculated the UAVSAR-derived subsidence in a 3-by-3 pixel area centered at the extensometer location for comparison with the extensometer-derived measurement (Figure 13). The average UAVSAR-measured subsidence rate at the extensometer's location is 0.5 ± 0.1 cm/yr. Both the UAVSAR and the extensometer estimates represent subsidence resultant primarily from oxidation of

shallow organic soils. We note that the InSAR and extensometer measurements have different references: the UAVSAR measurements are relative to the concrete base of one of the electric transmission line towers in central Sherman Island (Figure 8), and the extensometer records elevation changes relative to a depth of ~20 feet (~ 6.1 m) below land surface (the extensometer legs were driven to refusal into the mineral layer below the peat layer, which is at ~20 feet (~ 6.1 m) below the ground). The difference between the extensometer and InSAR measurements is ~0.1 cm/yr, which is within our estimated systematic uncertainty (~0.3 cm/yr).

Figure 13. Comparison of UAVSAR-measured and extensometer-measured subsidence at location within Sherman Island (38.05 °N, 121.71 °W). The extensometer measured a subsidence rate of 0.4 cm/yr, while the UAVSAR measurements yielded an average rate of 0.5 ± 0.1 cm/yr. Location of the extensometer is indicated with a red circle.

Cohen et al. (1998) had previously investigated the feasibility of using InSAR for measuring subsidence in the Sacramento-San Joaquin Delta. Rapid decorrelation in the agricultural landscape of the Delta, at the shorter C-band wavelength (5.66 cm) employed for that study, was found to be a hindrance for calculating accurate subsidence measurements in this region using InSAR. Urban areas located to the west of the Delta were found to maintain reasonable coherence. By applying the Persistent Scatterer (PSInSAR) technique to C-band InSAR data from the ERS-2 satellite, Brooks et al., (2012a) were able to detect individual persistent scatterers within the Delta to be subsiding at a rate of ~3-20 mm/yr. However, the PSInSAR technique did not allow for calculation of subsidence throughout Sherman Island, except at a few persistent scatterer points located mainly on the northeastern boundary of the island. The longer L-band wavelength (23.8 cm) UAVSAR data employed for this study, dedicated regular acquisitions and the SBAS data processing technique adapted for a coherence-challenged area, enabled us to monitor subsidence across Sherman Island at a much finer scale, both spatially and temporally. Table 4 shows a comparison of our average results for the whole island with those of previous studies, both from the extensometer and power pole measurements and with the limited InSAR results available.

582 **Table 4.** Comparison of UAVSAR-derived results with previous studies of subsidence on
583 Sherman Island, California.

Study	Time period covered	Method	Average subsidence rates
Rojstaczer et al., 1991; Rojstaczer and Deverel, 1995	1. 1910-1988 2. 1952-1988	Power pole measurements	1. 2.3 cm/yr 2. 1.5 cm/yr
Deverel and Rojstaczer, 1996	March 1990- May 1992	Extensometer	0.46 cm/yr
Deverel and Leighton, 2010	1988-2006	Power pole measurements	Average: 1.3 cm/yr Range: 0.59-2.24 cm/yr
Brooks et al, 2012a	1995–2000	ERS-2: PSInSAR technique	3-20 mm/yr; very few data points (persistent scatterers) available for Sherman; predominantly along northeastern boundary of Sherman
Brooks et al., 2012b; Glennie et al., 2013	16 and 17 May 2012	Balloon LiDAR	10's of centimeters of subsidence by comparison with 2007-08 CA DWR LiDAR survey
Extensometer results from this study	September 2010- August 2014	Extensometer	Subsidence rate: 0.4 cm/yr at one location
UAVSAR results from this study	July 2009- Aug 2014	UAVSAR: SBAS technique	Average subsidence: 5.8 ± 1.4 cm Range of subsidence: 0-25 cm Average subsidence rate: 1.3 ± 0.2 cm/yr Range of subsidence rate: 0-5 cm/yr

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4. Conclusions

Measuring subsidence in agricultural landscapes in California's Sacramento-San Joaquin Delta with InSAR has been a challenging problem for many years. While the utility of InSAR for monitoring deformation in California's urban and desert areas that maintain phase coherence over long periods of time is well-documented, the use of this technique has been limited in agricultural areas due to rapid decorrelation at the relatively shorter radar wavelengths usually employed for such studies. The novelty of the research described here lies in using longer wavelength (L-band) radar data, acquiring them at relatively short and regular intervals, and using time-series algorithms modified for low-coherence data. This approach minimizes the effects of decorrelation, thus enabling us to calculate deformation and evaluate its spatial and temporal variation across a coherence-challenged area like Sherman Island in the Sacramento-San Joaquin Delta.

The CA DWR LiDAR survey of 2007-08 estimated land elevations as low as 5 meters below sea level in many parts of Sherman Island. UAVSAR-based cumulative subsidence estimates across Sherman Island from 2009-2014 are found to range from 0-25 cm, with the average cumulative subsidence being $\sim 5.8 \pm 1.4$ cm. The average subsidence rate across the island is 1.3 cm/yr (with ± 0.2 cm/yr random uncertainty and ± 0.3 cm/yr systematic uncertainty), and ranges between 0-5 cm/yr depending upon location, with substantial heterogeneity at the field scale and, in some areas, over smaller scales. Our subsidence estimates are comparable to measurements from electric transmission line towers, extensometers and LiDAR surveys, carried out in past studies. Our results are also validated by measurements we

took with an extensometer in Sherman Island, during an overlapping time period with the UAVSAR data acquisition. Rojstaczer and Deverel (1995) had found subsidence rates on Sherman Island to vary with soil organic matter content, and we also find soil type to be one of the important factors affecting measured subsidence, with higher organic matter content contributing to an increase in average subsidence rates. Land use (which affects water table depths in the Delta), elevation and timing/location of levee repair also seem to play a significant role in controlling subsidence.

Sherman Island's location in the western Delta is crucially linked to water supply reliability for the state of California and makes it a prime area of interest for subsidence mitigation studies. This island is a testing ground for evaluating various approaches for subsidence reversal for the Delta. Along with the levee rehabilitation and repair efforts undertaken by the California DWR in Sherman Island over the years, the agency also constructed the Mayberry Farms Subsidence Reversal Project in the island in 2010, focused on the feasibility of creating permanent wetlands for reducing subsidence and sequestering carbon. Other tidal restoration projects are also being examined for their efficiency and sustainability in Sherman Island (Orr et al., 2003; Fischer, 2011; Bates and Lund, 2013; Hatala, 2013; Deverel et al., 2014, 2015). The results of this study will directly feed into these investigations of techniques for subsidence reversal in the Delta.

We plan to extend this analysis to monitor subsidence at a similar scale on the other islands in the Delta and to explore its effect on the levees in the area. Utilizing this dataset and technique for the entire region can greatly help by modernizing and innovating monitoring in the

Delta, through providing more consistently acquired data over the whole Delta, at a high spatial and temporal resolution. Finally, the analysis described in this manuscript is of direct relevance to the upcoming NASA-ISRO Synthetic Aperture Radar (NISAR) mission to be launched in 2020 (Rosen et al., 2014). The measurements made possible by the frequent (every few weeks) and continuous (for five years) data acquisition for the work described here provide a reference point for the expected results that could be achieved with the NISAR, which will provide global coverage every 12 days, at the same L-band wavelength as the UAVSAR as well as potentially at S-band (12 cm).

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List of figure captions

Figure 1. The Sacramento and San Joaquin Rivers join east of the San Francisco Bay in northern California, forming the Delta. The westernmost island in the Delta, Sherman Island, is the focus of this study (outlined in red). Cities forming the boundaries of the Delta are cited in the text and their locations are depicted in this figure.

Figure 2. Land elevation across the Delta derived from LiDAR topographic survey conducted by the California Department of Water Resources (CA DWR) in 2007-08.

Figure 3. [A] LiDAR elevations across Sherman Island from the topographic survey conducted by CA DWR in 2007; UTM Zone 10, NAD 83, vertical datum NAVD88 (CA DWR, 2007b), **[B]** Soil type classification (NRCSS, 1985) and **[C]** land use classification (CA DWR, 2007a) across Sherman Island. It is important to point out that land use classification varies from year to year and thus this survey from 2007 might not accurately depict the current land use status in the island. Similarly, the soil type map is only intended to provide an island-wide distribution of common soil types and should be used with caution for understanding the effect of soil organic matter content on subsidence.

Figure 4. Two UAVSAR lines cover the Sherman Island in the Delta from different look directions. The inset shows the NASA Gulfstream G-III aircraft that carries the UAVSAR.

Figure 5. The basic principle of InSAR is demonstrated in this figure. When the radar instrument is flown over a patch of ground the first time (first pass), it transmits microwave pulses towards the surface of the Earth and receives the reflected echo of the radar signal. The incident and reflected signal can be compared in terms of change in amplitude and phase. During the second pass, the radar instrument flies again over the same region to measure new reflection and change of range (distance between instrument and land surface) along line-of-sight direction through the relative change in the phase of the returned signal. (Image credit: Paul A. Rosen)

Figure 6. Overview of processing methodology

Figure 7. Pairs of acquisitions used for forming interferograms for both lines (15502 and 23518) are shown in this figure. 47 data acquisitions taken by the UAVSAR were utilized to generate 168 interferograms for line 15502, and 50 acquisitions were used to generate 198 interferograms for line 23518. Each acquisition is used for forming a minimum of five interferograms.

Figure 8. [A] Location of the reference point used for this study in Google Earth® optical imagery. The reference region is at the base of one of the electric transmission line towers (~38.07 °N, 121.71 °W) located within Sherman Island. The locations of electrical transmission power lines used for comparison with previous studies are also indicated in panel A. The transmission line built in 1910 cuts across Sherman Island from west to east, and the transmission line built in 1952 cuts across from north to south. Location of the extensometer that is used for providing ground-truth for UAVSAR measurements is also shown. Close-up views of the reference region location at increasing resolutions are shown in the bottom left **[B]** and bottom right **[C]** panels.

Figure 9. Example of an interferogram with magnitude (upper left) and phase (upper right) information, coherence (lower left) and water mask (lower right) for line 15502. Each of the sub-figures is shown in radar (range/azimuth) coordinates. Line ID: 15502, Dates of acquisition: 2010-09-25 and 2010-10-25, Temporal baseline: 31 days.

Figure 10. [A] Subsidence rates on Sherman Island derived from a weighted linear fit to the cumulative subsidence vs. time, from July 18, 2009 to August 14, 2014. [B] Uncertainty in subsidence rate (cm/yr). [C] Standard deviation in the subsidence rates calculated from the two UAVSAR lines, 15502 and 23518. Black pixels in this image indicate the ones for which subsidence was calculated from one line only.

Figure 11. [A] Variation of average subsidence rates with soil type (organic matter content) across the whole island is shown. Greater organic matter content in soils is generally associated with higher average subsidence rates. [B] Higher subsidence rates are observed for lower elevations. [C] Correlation is observed between soil organic content and elevation, with higher organic content soils being generally associated with lower elevations (exceptions include Sailboat, Sailboat Variant and Egbert soil types). Land elevations reported in Figs. 11B and 11C have been measured with respect to vertical datum NAVD88 (CA DWR, 2007b).

Figure 12. Examples of small-scale subsidence features observed across Sherman Island with UAVSAR are shown in this figure. The top panel shows locations of these features outlined in black rectangles. (a) The yellow star shows an area adjacent to the levee in southwestern Sherman Island that experienced ~25 cm of subsidence over the five years of our study. Optical imagery of the feature shows a scour pond and a dredge disposal site. The red star shows subsidence vs. time for a nearby point that does not exhibit rapid subsidence, but instead slow subsidence with much larger seasonal oscillations in land elevation. (b) Subsidence feature in central Sherman Island that shows a mix of subsidence and seasonal oscillation in its elevation trend. (c) Subsidence feature in northeastern Sherman Island that is partially correlated with

variation of soil type. (d) The ‘tail’ section in northeastern Sherman Island shows subsidence variation that generally follows the variation of topography and soil type.

Figure 13. Comparison of UAVSAR-measured and extensometer-measured subsidence at location within Sherman Island (38.05 °N, 121.71 °W). The extensometer measured a subsidence rate of 0.4 cm/yr, while the UAVSAR measurements yielded an average rate of 0.5 ± 0.1 cm/yr. Location of the extensometer is indicated with a red circle.

List of table captions

Table 1. Inventory of UAVSAR acquisitions used in this study.

Table 2. Comparison of UAVSAR-derived subsidence rates at individual electric transmission line towers with previous studies. Individual towers in this table are from electrical transmission line 1910, which cuts across Sherman Island from west to east, as shown in Figure 8. The error bars in the UAVSAR subsidence rates indicate only the random component of the uncertainty.

Table 3. Comparison of UAVSAR-derived subsidence rates at individual electric transmission line towers with previous studies. Individual towers in this table are from electrical transmission line 1952, which cuts across Sherman Island from north to south, as shown in Figure 8. The error bars in the UAVSAR subsidence rates indicate only the random component of the uncertainty.

995 **Table 4.** Comparison of UAVSAR-derived results with previous studies of subsidence on
996 Sherman Island, California.
997