Abstract
We discuss measurements of the precursory and post-formation ground displacement in the vicinity of the Bayou Corne, Louisiana, sinkhole made using interferometric synthetic aperture radar (InSAR) and data from the L-band UAVSAR instrument. Large precursory movement was observed at the sinkhole site and shown to be predominantly horizontal in direction, in contrast to sinkhole precursors previously detected with InSAR, all of which indicated vertical deformation. Here we discuss how two opposing imaging directions were used to determine the precursory horizontal movement, and use the same technique to look at the progression of post-formation ground displacement around the expanding sinkhole during the interval 2012-2014. We find that the Bayou Corne sinkhole has expanded asymmetrically about the initial location, and show that expansion has tracked ground movement observed with InSAR along the margins of the water-filled central subsided area. This work shows that InSAR applied to images acquired from multiple directions can be used to image incipient sinkhole formation over large areas and to track the expected direction of expansion. We discuss how geologists can best use the InSAR technique to quantitatively monitor ground movement associated with sinkholes, particularly in areas where radar rapidly decorrelates, e.g., in Florida or Louisiana. These results demonstrate that InSAR could be used in sinkhole warning systems across a much broader geographical area than previously demonstrated, and for identifying both precursory and post-formation surface movement.

Introduction
The Bayou Corne sinkhole, located 50 miles south of Baton Rouge, Louisiana, formed catastrophically sometime between the late evening of 2 August 2012 and early morning of 3 August 2012, as a result of sidewall failure of a brine cavern mined near the western edge of the Napoleonville salt dome. Figure 1 shows radar images of the area both before and after sinkhole development. The Bayou Corne sinkhole formation was unusual in two ways: Firstly, the collapse occurred in the side wall of a solution-mined cavern that was located deep below the surface; the cavern extended from 1.0 km to 1.7 km depth below the surface (LDNR, 2013). Collapse of the thin side wall between the edge of the dome and the cavern interior enabled outside material to move into the empty volume of the cavern, and breached the sheath around the dome, bringing the normally isolated halite within the dome in contact with external materials, including water. This is the first reported sidewall failure within a salt dome, and because it occurred far below the surface, material in lower strata began to fill the cavern without initially causing observable movement at the surface. The second unusual feature of the Bayou Corne sinkhole is that its sudden formation, likely some months after the breach occurred, was preceded by horizontal movement at the surface (Jones and Blom, 2014), indicating that material at the surface flowed towards a chimney-like feature leading down the side of the salt dome to the breach location. The abrupt change that occurred on 2 August 2012 must have been initiated by unblocking of the path to the cavern, consistent with the change in observed quake activity at that time (Nayak and Dreger, 2014; Ellsworth et al., 2012). The Bayou Corne site is located in the Atchafalaya Basin of the Southern Mississippi River Alluvium Major Land Resource Area (MLRA) of Louisiana (Weindorf, 2008), an area with Holocene deposits. The soils in the backswamps are clayey alluvium with poor to very poor drainage and very slow permeability (Weindorf, 2008). The fact that the surface soil is largely mud is likely the reason why the direction of precursory movement did not resemble the vertical deformation reported by sinkhole researchers working in much drier locations (Paine et al., 2012; Conway and Cook, 2013; Nof et al., 2013; Rucker et al., 2013).

Previously, we reported use of InSAR performed on data acquired with the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) to determine that the catastrophic collapse was preceded by precursory ground
movement of up to 26 cm extending across an area of radius ~250 m about the center of the initial sinkhole (Jones and Blom, 2014). The precursory movement was observed in interferograms formed from images acquired on 23 June 2011 and 2 July 2012, indicating that the ground started moving at least one month before catastrophic collapse occurred. The ground movement was evident in two different UAVSAR flight lines that imaged the Bayou Corne area from opposite directions. With two interferograms from different look directions, we could determine the 2-dimensional vector deformation of the surface, as explained in more detail below.

The two interferograms were used to resolve horizontal and vertical precursory movement, showing that the precursory movement was predominantly horizontal. Clays deform easily when wet, and can flow either horizontally or vertically. At the Bayou Corne sinkhole site, the horizontal flow was observed over a much larger area than the initial sinkhole (Figure 2), so vertical surface change almost certainly occurred but was below the level detectible with our instrument.

In the sections that follow we discuss the data and methods used for pre-event and post-formation sinkhole monitoring at the Bayou Corne site, explain why the observed precursory displacement was interpreted as being horizontal in direction, compare the post-formation interferograms to ground survey sinkhole plan measurements available through the Louisiana Dept. of Natural Resources (LDNR), and discuss the most recent InSAR results which cover the period after the April 2014 ground survey.

**Method**

Deformation measurements using InSAR require two or more synthetic aperture radar images acquired at different times. Image pairs can be analyzed via interferometry to determine the difference in the signal phase between the two acquisitions, which relates to the amount of surface deformation that occurred if stringent observational criteria are met and if the surface did not undergo significant decorrelation during the interval between image acquisitions.

Interferometry can measure changes in distance between the platform and surface at cm to mm scales, thus measuring elevation changes. For side-looking SAR instruments the measured displacement can be a combination of horizontal and vertical motion. Principal advantages of InSAR over point techniques such as GPS are geographically complete regional coverage and ability to measure small changes in elevation over time using a time series of images. Principal disadvantages include data availability and processing issues, and loss of ability...
to create interferograms due to surface changes in roughness or water content between observations (temporal decorrelation). Longer wavelength radars, like the L-band UAVSAR (23.8 cm), experience less impact from decorrelation than shorter wavelength SAR instruments.

The UAVSAR data used in the work reported here was acquired over the Bayou Corne area in eight deployments dating from June 2011 to October 2014. Interferograms formed from sequential acquisitions of two UAVSAR flight lines (IDs 14013 (looking to the NE) and 32018 (looking to the SW)) were used in this analysis. The specific dates of acquisition are given in Table 1. The earliest data used was acquired on 23 June 2011, over a year before the sinkhole formed; second set was acquired on 2 July 2012, one month before surface collapse; and the subsequent collections occurred 2-3 times per year through 2014.

Figure 1 shows the UAVSAR radar intensity images of the Bayou Corne area around the sinkhole site on 2 July 2012, a month before the sinkhole formed and at the time when large precursory movement was evident, and on 28 October 2014, the date of the last acquisition reported here. The location of the failed cavern is indicated in this figure and the sinkhole lies to the northwest, just beyond the edge of the Napoleonville salt dome. In the earlier acquisition, the site where the sinkhole formed (approximately centered on the water filled area in the later image) is not distinguishable from the background area. In July 2012, the backscattered intensity from the surface in that area is consistent with scattering from soil, not still water, which would be radar dark as in the October 2014 image.

Application of InSAR techniques in agricultural areas and other areas with highly variable vegetation and soil moisture is notoriously difficult. Certainly, on the face of it, the Bayou Corne site seems a poor candidate for InSAR. However, we were able to successfully form interferograms in large part because we used L-band radar, which has a longer wavelength (24 cm) than the contemporaneously operating satellite SARs, which at X- and C-band (3.3 cm and 5.5 cm, respectively) could not obtain coherent images over the Bayou Corne site. In addition, the ground movement at the sinkhole site was very large, and hence was visible over the instrument and speckle noise and the phase variance caused by temporal decorrelation. Furthermore, we consider it likely that double bounce scattering from ground-to-tree-to-antenna, with the trees being stable scattering surfaces, contributed to our unexpected success in obtaining coherent InSAR phase across many months.
Results

Sinkhole Precursory Movement

We used two 375-day temporal baseline (23 June 2011 – 2 July 2012) interferograms that imaged the area at an incident angle of 60 degrees but from opposite directions to look for precursory surface movement. Figure 2 shows a photograph of the area acquired during that time interval (on 16 Nov 2011) prior to the sinkhole formation indicating the location of the well head attached to the cavern that failed, and one of the interferograms showing precursory deformation covering the same area. The interferogram was multilooked by a factor of 3 x 12 during UA VSAR processing, georeferenced to 6 m pixel spacing, then smoothed with a 3 x 3 boxcar filter. Precursory deformation is seen extending across an area ~500 m across. The deformation shows a distinctive 2-lobe pattern, which indicates movement of the surface away from the radar in the nearer lobe and towards the radar in the further lobe. Because InSAR only measures a change in distance in the line-of-sight direction, we cannot resolve horizontal and vertical motion from a single interferogram.

Figure 3 shows the line-of-sight movement obtained from the two interferograms, one looking at the sinkhole from the northeast and the other looking from the southwest. Because we had two interferograms we were able to resolve vertical movement from one dimension of the horizontal movement, specifically that in the direction of the projection of the line-of-sight vector on the surface. The striking double-lobe pattern is apparent in both interferograms and the direction of change in the line of sight distance differs in sign with roughly equal magnitude when measured from the two opposite directions. The cartoon at the bottom of Figure 3 shows how this indicates that the movement was primarily horizontal, with inflow towards the center of the pattern. We note that this observed pattern (increasing distance from one observer, with decreasing distance to an observer looking from the opposite direction) precludes the possibility that the observed signal was due to a change in the level of standing water on the surface, which would have had the same sign for both observations. Without another perpendicular imaging geometry, it is not possible to determine through InSAR measurement both dimensions of the horizontal movement. InSAR cannot measure displacement perpendicular to the line-of-sight direction, which is why the horizontal displacement shows the 2-lobe pattern: InSAR cannot capture radial horizontal movement without a 3rd image looking perpendicular to the two that we have. However, radial inflow towards a sink location is likely to have occurred.

Sinkhole Progression

The size of the Bayou Corne sinkhole, where the sinkhole proper is defined as the area with standing water depth > 10 ft (3 m), has been tracked by LDNR since its formation. The sinkhole, initially ~10,000 m² in surface extent, had expanded by 15 April 2014 to ~130,000 m², with >223,000 m² of area with water depth > 2 ft (0.6 m), designated the “sinkhole plus subsided area” in the surveys of the area supplied to the LDNR and posted on their Bayou Corne incident website (http://dnr.louisiana.gov/index.cfm?md=pagebuilder&tmp=home&p id=939).

We used the 15 April 2014 Bayou Corne sinkhole survey (Louisiana Department of Natural Resources, 2014), which showed the full sinkhole extent on several dates between 4 Oct 2012 and 15 April 2014, to determine the direction and timing of expansion of the Bayou Corne sinkhole for comparison to the UAVSAR post-sinkhole-

<table>
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<th>Date</th>
<th>Days to Sinkhole Formation</th>
<th>Image Interval (Temporal Baseline) [days]</th>
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<tr>
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Table 1. UAVSAR Acquisitions– UAVSAR acquisition dates, time between acquisition and sinkhole formation, and the temporal baseline between the SAR images used to form sequential interferograms.
formation interferograms. For the ground surveys, depth measurements were taken with sounding rods to determine the sinkhole depth. No earlier or later surveys were available from the LDNR website, so the ground measurements cover a subset of the time period covered by the UAVSAR data set.

The interferograms formed from sequential acquisitions (dates in Table 1) of the UAVSAR flight line viewing the region from the southwest are shown in Figure 4. These are plotted in radar coordinates (slant range, also known as line-of-sight distance, vs. azimuth, or flight track position) and cover the outlined region in the intensity images of Figure 1. The interferograms are multilooked a factor of 3 x 12 (slant range x azimuth) and have pixel size of 7 m x 7 m. The location of the zero phase reference used is outside of the plotted area and indicated by an ‘X’ in Figure 1. The center of the initial sinkhole that formed on 3 Aug 2012 is indicated on each interferogram.

Once the sinkhole formed, the open water areas have very little radar backscatter (dark on interferogram) and InSAR cannot be performed. In areas surrounding the open water, much of the area experiences too much temporal decorrelation to be used for InSAR (phase changes randomly from pixel to pixel, giving a speckled look to the color figures). This information is useful in delimiting the extent of major surface change between the two acquisitions forming the interferogram. In addition, along the margin in some areas the phase remains coherent and shows fringed pattern indicating coherent surface movement. In the earlier interferograms (1, 2, and 3 in particular) the interferograms show some double-lobed characteristics so it is clear that surface flow towards the sink continued after sinkhole formation, although it was not as clearly dominant as in the precursory ground movement.

Based on the ground surveys, between 4 Oct 2012 and 15 Aug 2013 the sinkhole expanded in all directions, with the largest expansion to the SSW and more expansion to the west than to the east or north. Interferograms 2 and 3 most closely cover this time period. The deformation patterns in interferograms 1, 2, and 3 of Figure 4 all show greater extent of the deformation pattern to the SW, with the largest extent in the same direction as measured in the surveys. By 24 July 2013, the end date of interferogram 3, the deformation to the SW had decreased. Between 15 Aug 2013 and 15 April 2014 the ground surveys measured an abrupt slowing of expansion to the SSW and continued expansion to the north and east, with the largest expansion in the NE quadrant and the next largest expansion to the NW. This time pe-

Figure 3. Precursory deformation derived from the two UAVSAR flight lines imaging the Bayou Corne site. The upper (middle) image shows movement in the line-of-sight direction for a look direction pointing to the NE (SW). Positive values (red) indicate an increase in distance, i.e., movement away from the radar. A point on the ground appears to move towards one direction and away from the other. The cartoon at the bottom shows how this pattern of sign change corresponds to inward flow towards the center between the two lobes.
Figure 4. The six post-sinkhole-formation interferograms from UAVSAR line ID 14013 covering the region outlined in white in Figure 1, formed from sequential UAVSAR images of the Bayou Corne area acquired during the period from 2 July 2012 to 28 Oct 2014 (Table 1). The track and look directions are indicated on interferogram 1, which also shows the location of the nearby intact caverns within the salt dome as lying below the white outlined area. The center of the original sinkhole that formed in Aug. 2012 is indicated with a star on all interferograms.


The cavern. During the period 24 July 2013 to 28 October 2014, the size of the incoherent area around the sinkhole steadily decreased. The direction of maximum movement derived from the interferograms generally matches sinkhole expansion measured with sounding rods for the State of Louisiana and posted on the LDNR Bayou Corne incident website. In the last interferogram (Interferogram 6 of Figure 4), documenting change between 9 April 2014 and 28 October 2014, there is little incoherent area around the open water and indications that slow movement is still occurring. There is an extended region around the sinkhole (yellow in image) showing change contained within the borders of a levee built to isolate the sinkhole from the Bayou Corne waterway, the nearby highway, and the outskirts of the town. Without further information, we cannot distinguish whether this signal is water level change or vertical surface movement.

This work shows that sinkhole monitoring with InSAR is possible even in areas with wet soil and significant vegetation. The major sinkhole that formed near Bayou Corne, Louisiana, in August 2012 was the result of mine collapse, unlike the sinkholes that occur in karst. Nonetheless, the methods of identifying and monitoring the Bayou Corne sinkhole have general applicability to all types of sinkholes. For example, the natural environment of Florida has much more in common with Bayou Corne than with Holbrook, AZ, or the Dead Sea in Israel, both arid areas where vertical deformation associated with sinkholes have been observed [Conway and Cook, 2013; Nof et al., 2014]. In areas with similar sediments and soil conditions to the Louisiana site, horizontal movement could precede collapse as an indicator of potential ground failure. Using L-band SAR (i.e., UAVSAR or ALOS-PALSAR), it is possible to detect movement at least in some locations that would not maintain temporal coherence nearly as long if using shorter wavelength SAR instruments, e.g., at X-band (TerraSAR-X, COSMO-Skymed) or C-band (Radarsat, Sentinel). However, even at L-band, the cumulative movement had to be large (several centimeters or greater) to be apparent against the background decorrelation in these InSAR-challenging areas. We had better success using a longer wavelength SAR and longer intervals between acquisitions rather than shorter wavelengths and shorter intervals between acquisitions because there was less movement over the shorter intervals and, for the shorter wavelength SARs, too much temporal decorrelation occurred for the small ground movement to be visible above the phase variance from noise sources.

The InSAR technique can measure surface deformation from satellites or aircraft over time as a series of snapshots. Proper analysis permits detection and monitoring of surface deformation, including that from developing...
sinkholes. Radar image swaths can typically cover hundreds of square kilometers, and thus have the distinct advantage of being able to cover very large areas. InSAR detection of surface deformation due to sinkhole development has now been documented in multiple studies, thus showing promise for incorporation of the method as one part of a sinkhole warning system.

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References


