nature

BRIEF COMMUNICATIONS

Subsidence and flooding in New Orleans

A subsidence map of the city offers insight into the failure of the levees during Hurricane Katrina.

It has long been recognized that New Orleans is subsiding and is therefore susceptible to catastrophic flooding. Here we present a new subsidence map for the city, generated from space-based synthetic-aperture radar measurements, which reveals that parts of New Orleans underwent rapid subsidence in the three years before Hurricane Katrina struck in August 2005. One such area is next to the Mississippi River–Gulf Outlet (MRGO) canal, where levees failed during the peak storm surge: the map indicates that this weakness could be explained by subsidence of a metre or more since their construction.

To make the subsidence map, we used 33 scenes recorded from Canada's RADARSAT satellite. The technique involves interferometric phase comparison of 33 synthetic-aperture radar images taken at different times along the same nominal orbit, and exploits points on the ground that strongly reflect radar, termed 'permanent scatterers' (for details of the analyses, see supplementary information).

Figure 1 shows the average distance (range) changes of the permanent scatterers along the direction of radar illumination over the three years (2002–05) during which data were collected. It indicates that subsidence was widespread during this period. All results presented here are range changes in the direction of radar illumination, but it is reasonable to assume that the principal motion was vertical. The mean and standard deviation in rate of range change for all the point targets was -5.6 ± 2.5 mm yr^{-1} (negative rates indicate subsidence). The maximum rate observed was -29 mm yr^{-1}. If surface motion was purely vertical, the corresponding mean and maximum subsidence rates were 6.4 and 33 mm yr^{-1}, respectively. As global sea level is rising at an average rate of about 2 mm yr^{-1} (ref. 1), most of New Orleans is subsiding relative to the global mean sea level at an average rate of about 8 mm yr^{-1}.

Our data have exceptional spatial resolution, allowing assessment of the motion of individual buildings and other structures. Comparison with high-resolution aerial photographs shows that many of the scatterers are located at the intersection of a road and the wall of a building, where the road is roughly parallel to the satellite flight path (perpendicular to the radar look direction), or on building roofs (see supplementary information). The mean elevation of scatterers is therefore considerably higher than the mean ground elevation (Fig. 2). Parks and other areas of vegetation have few or no permanent scatterers.

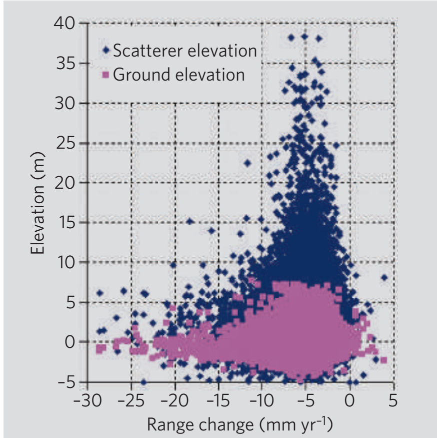

Figure 2 | Relation between range change of permanent scatterers and elevation. Negative range change indicates subsidence. The elevation of many permanent scatterers is several metres to several tens of metres above the land surface because many permanent scatterers are on the roofs of buildings.

Our subsidence rates represent a three-year average. Although subsidence may vary with time, the average range-change rate we obtain is very similar to recent estimates of subsidence from ground-based levelling[2–4], and we believe our estimates reflect rates over a longer term. The geography of subsidence also shows high rates in the areas of Lakeview (south shore of Lake Pontchartrain) and Kenner (near Louis Armstrong New Orleans International Airport), in east New Orleans and in regions bordering St Bernard Parish.

Lakeview is augmented with engineered fill, whereas the other areas are former wetlands, now drained and urbanized. The wetlands have highly organic soils; their subsidence results from drainage projects that promote soil desiccation, oxidation and compaction. In east New Orleans, subsidence rates have historically been the highest in south Louisiana, producing the lowest topography (3 to 5 m below sea level) and deepest flooding — the flooding after Hurricane Katrina caused a significant number of deaths. Subsidence here may also be increased by motion on the active Michoud fault[2].

Parts of St Bernard and Orleans Parishes west of Lake Borgne are experiencing subsidence rates of more than 20 mm yr^{-1}, including the levee system along the MRGO canal (Fig. 1, insets). Parts of this levee system were breached

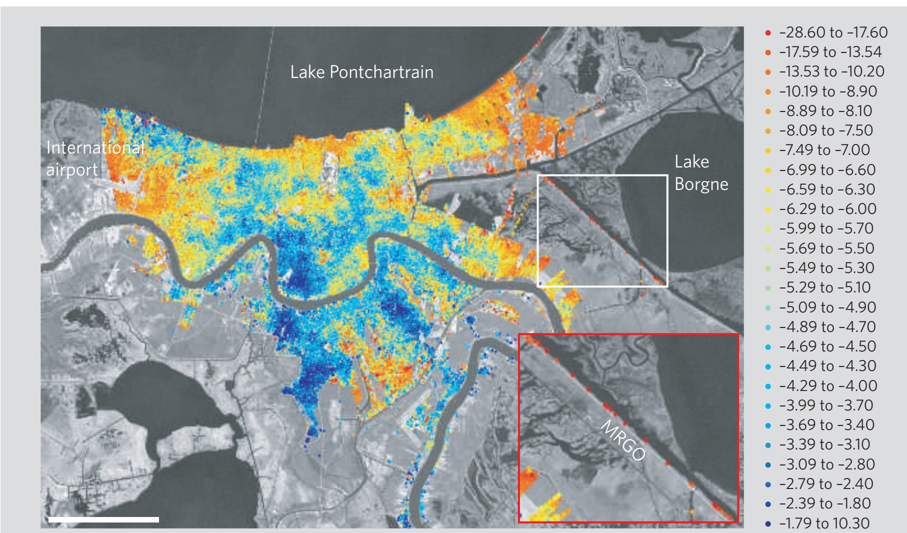

Figure 1 | Map showing rate of subsidence for permanent scatterers in New Orleans and vicinity during 2002–05. Velocity values are given in millimetres per year as range change in the direction of radar illumination. Negative values indicate motion away from the satellite, consistent with subsidence. International airport, Louis Armstrong New Orleans International Airport; MRGO, Mississippi River–Gulf Outlet canal. Insets show location (white frame) and magnified view (red frame) of the region west of Lake Borgne, including eastern St Bernard Parish. Note the high rates of subsidence on the levee bounding the MRGO canal. Large sections of the MRGO levee were breached when Hurricane Katrina struck on 29 August 2005 (see supplementary information). Scale bar, 10 km.

during the flooding associated with Hurricane Katrina, and this could be explained by the correlation we observe between the location of breach points and the high rate of subsidence beneath these levee sections (see supplementary information). Our subsidence estimates are probably minimum values considered over the lifetime of the levees, given that subsidence was most rapid in the first few years after their construction in the 1960s. Levee failure may have resulted from overtopping because the levees were too low — data collected after the storm[5] indicate that water levels exceeded those expected by 0.9–1.7m. Alternatively, the high subsidence rates we observe might reflect active faulting or a weak, easily compacted substrate, promoting failure at or near the levee base.

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SUPERFLUID HELIUM

Visualization of quantized vortices

When liquid helium is cooled to below its phase transition at 2.172 K, vortices appear with cores that are only ångströms in diameter, about which the fluid circulates with quantized angular momentum[1]. Here we generate small particles of solid hydrogen that can be used to image the cores of quantized vortices in their three-dimensional environment of liquid helium. This technique enables the geometry and interactions of these vortices to be observed directly.

Since the discovery of quantized vortices[2], attempts have been made to visualize them. Although the ends of parallel vortices in an array could be located[3], there has been no successful imaging of vortices in arbitrary three-dimensional configurations. Suspended particles can trace fluid motions, and the velocities of frozen particles in superfluid helium have been measured since hydrogen was first condensed for the purpose[4]. These particles usually have diameters larger than 10 µm[5,6], although smaller polymer particles have been used[7].

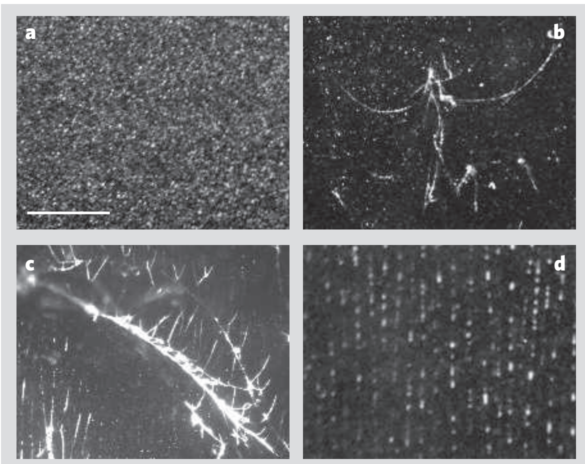

Figure 1 | Quantized vortex cores in liquid helium. a–d, Images of particles (light against dark background) obtained with a camera and 105-mm lens under different conditions: **a,** just above the transition temperature, when they are uniformly dispersed; **b, c,** on branching filaments at tens of millikelvin below the transition temperature; and **d,** regrouping along vertical lines for steady rotation about the vertical axis. In **b** and **c**, the particles on lines are evenly separated in small regions. Scale bar, 1 mm.

Our technique generates smaller hydrogen particles by injecting a premixed gaseous solution of hydrogen, greatly diluted with helium, into liquid helium in its normal phase above the transition temperature (for details of methods, see supplementary information). This procedure yields a mist of randomly distributed hydrogen particles (Fig. 1a) that are smaller than the 2.7-µm resolution of our long-range microscope. The suspension so prepared is then cooled to below the transition temperature.

Images taken with a digital camera focused on a thin laser-illuminated sheet show that not only do the particles trace fluid motions, but a fraction of them also collect on slender filaments, which are often several millimetres long (Fig. 1b, c).

Particles respond in a complicated way to superfluid flows[8] and can be trapped in vortex cores[9]. The following evidence suggests that the observed filaments are particles collected on such cores. First, these filaments appear only below the transition temperature. Second, when the liquid-helium cell is set in steady rotation, the particles arrange themselves along uniformly spaced lines (Fig. 1d). The lines are parallel to the axis of rotation, which is in the image plane. This observation agrees with the expectation that quantized vortices form a rectilinear array aligned with the axis[1]. Third, if we assume that our sheet illuminates a slice of such an array, we find that the number density of lines per unit area normal to the axis of rotation, for a series of rotation rates, is consistent with Feynman's rule[10], which predicts about 2,000Ω lines per cm^2, where Ω is the angular velocity of the container in radians per second.

The filaments are complex: for example, they may give rise to branched networks and to particles evenly spaced along lines. Others have speculated how particles could act as passive tracers of the flow[7,8]; our images indicate that the presence of particles in the superfluid may transform the topology of vortex tangles by stabilizing forks in the vortices. This technique offers a tantalizing glimpse of new phenomena for future investigation.

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