Technical enrichment study: Wind-induced tilting and rotations of South Florida's coastal high-rises

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Executive Summary

In our recently published study, we used Interferometric Synthetic Aperture Radar (InSAR) technology to demonstrate that many new and older high-rises on Miami's barrier islands are subsiding at rates of up to 1.3 cm (0.5 inch) per year (Aziz Zanjani et al., 2024; https://doi.org/10.1029/2024EA003852). In some cases, the ongoing settlement is persisting more than 20 years after construction. These observations are certainly concerning for the long-term safety and stability of tall coastal structures. The study identified 35 structures including some prominent high-rises along the South-east Florida coastline (Fig.1) and received wide-scale media attention both regionally and Nationally.

The findings of the subsidence study were based on data from ascending, east-looking satellite orbits, and, with only one look direction available, we initially assumed that all observed displacements reflected vertical subsidence. We have since analyzed data from descending, west-looking orbits, which reveal that the ongoing displacement pattern is more complex. In addition to the vertical motion, several high-rises are found to be *tilting* and *rotating* at rates of up to 1 cm per year (Fig. 2), which is quite unexpected. We attribute these lateral and angular motions to persistent easterly winds, potentially amplified by hurricane events, acting on the superstructure and interacting with subsurface foundation elements (shear and moment. From an engineering perspective, these preliminary observations of *tilt* and *rotations* of tall structures are certainly concerning and require a more robust characterization of displacements in the three-dimensional space. We therefore propose to systematically monitor, quantify and document these tilts and rotations and reconcile with our earlier vertical subsidence study, for a comprehensive determination of displacements in tall coastal buildings. A secondary goal is to identify any pattern such as building orientation, layout, type and geometry of structural foundations affecting the mode and magnitude of displacements. The findings of this technical enrichment study will be disseminated broadly through workshops or TAC meetings involving experts from FBC, policymakers and the engineering community so that FBC can make informed decisions on potential future revisions of building codes relevant to the design and construction of high-rise coastal structures.

Preliminary evidence for tilt and rotations

Tilt: InSAR data from the TerraSAR-X satellite provide clear evidence of complex structural motion in some high-rises, likely driven by wind loading. Fig. 3 illustrates this for the Porsche Design Tower, where TerraSAR-X observations show a 12 cm increase in line-of-sight distance for a radar scatterer near the rooftop. In contrast, Sentinel-1 data show only a 2–3 cm change (Fig.1). With TerraSAR-X being west-looking and Sentinel-1 east-looking, this discrepancy indicates a combination of approximately 8 cm of vertical subsidence and 7 cm of westward displacement, consistent with westward tilting of the structure.

Rotation: The Acqualina Resort in Sunny Isles Beach provides evidence of possible structural rotation. InSAR data show that the distance to the satellite is decreasing over the southern portion of the building (yellow colors, approximately +0.25 cm/yr), while simultaneously increasing over the northern portion (blue colors, approximately -0.75 cm/yr) (Fig. 4b). This displacement pattern is consistent with an counter-clockwise rotation of the structure combined with vertical subsidence. In contrast, the nearby Trump Royale, located just a few hundred meters to the north, exhibits uniform displacement (blue colors), indicative of consistent vertical settlement without rotation.

Project Tasks

Task 1: *Characterize tilt and rotations of structures using InSAR*

The first task is to acquire and process consistent InSAR data covering mid- and high-rise buildings along Miami's beaches and bayfront. We will utilize data from the high-resolution TerraSAR-X satellite, which offers a spatial resolution of 3×3 meters — providing approximately an order of magnitude greater measurement point density than the Sentinel-1 data used in our previous work. While west-looking (descending) TerraSAR-X data are available dating back to 2017, east-looking (ascending) acquisitions have been available since 2023. By combining these datasets, we can reliably resolve both vertical and horizontal displacements, as illustrated in Figure 2.

Task 2: *Investigate implications for Florida Building Code and hurricane resistance*

For all major high-rise structures along the coast and bayfront, we will obtain foundation design plans from local building departments and examine them for factors that may explain why certain buildings exhibit tilting or rotation while others remain stable. Figure 4 offers an example: the Trump Royale, which shows uniform settlement, is oriented east–west, while the Acqualina, which appears to be rotating, is oriented north–south. The Trump Royale's orientation likely results in a greater number of foundation piles aligned in the east–west direction, providing additional resistance to lateral forces from persistent easterly winds.

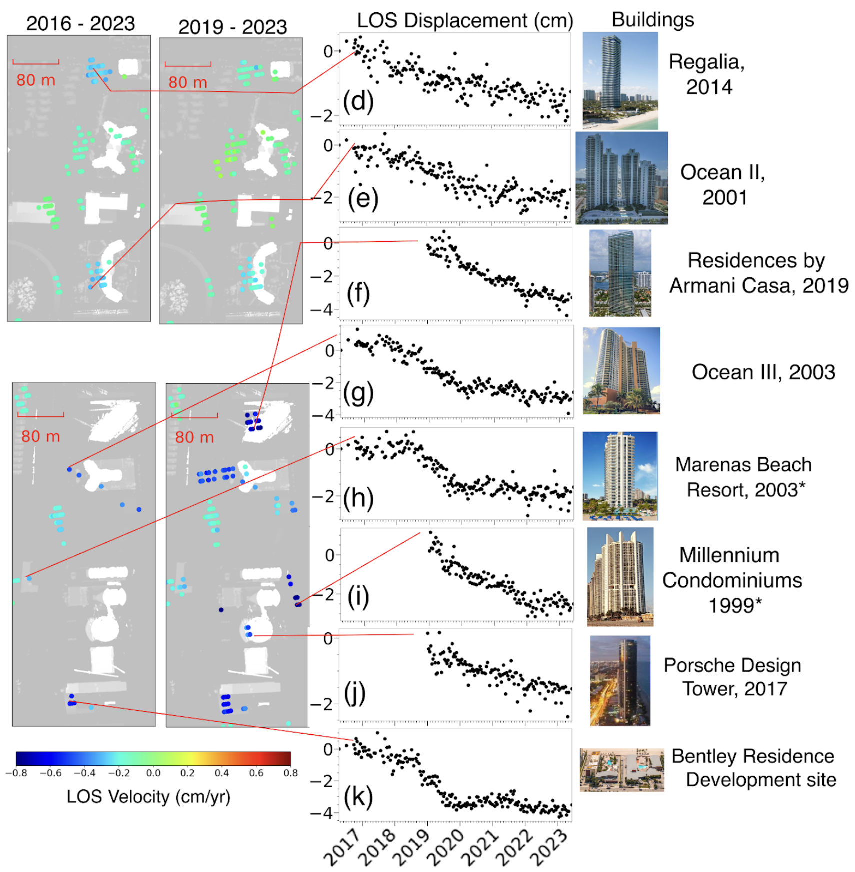

***Figure 1**. Example of displacement time series data for coastal high-rises in northern Sunny Isles Beach, Miami-Dade County, Florida showing 2-4 centimeters displacement in radar line-of-sight (LOS) direction during 2016-2023. Inferred vertical motion is about 35% more.*

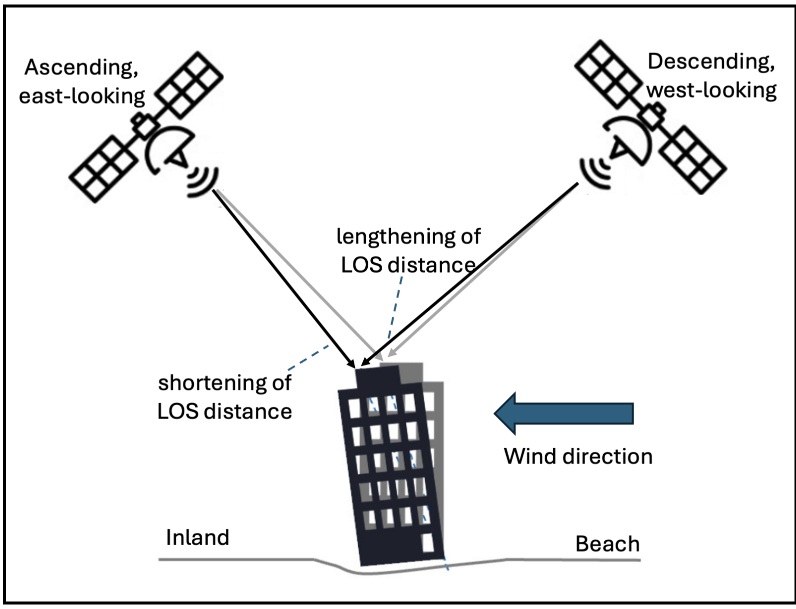

Figure 2. *Principle for detecting tilting and rotation of high-rise buildings with InSAR. Horizontal, westward motion due to subtle tilt or rotation of a high-rise caused by blowing winds result in a shortening of the distance between a scatterer and the satellite for imagery taken from eastwards looking (ascending) satellite orbits, while westwards looking (descending) satellite orbits respectively. LOS: satellite Line-of-Sight direction.*

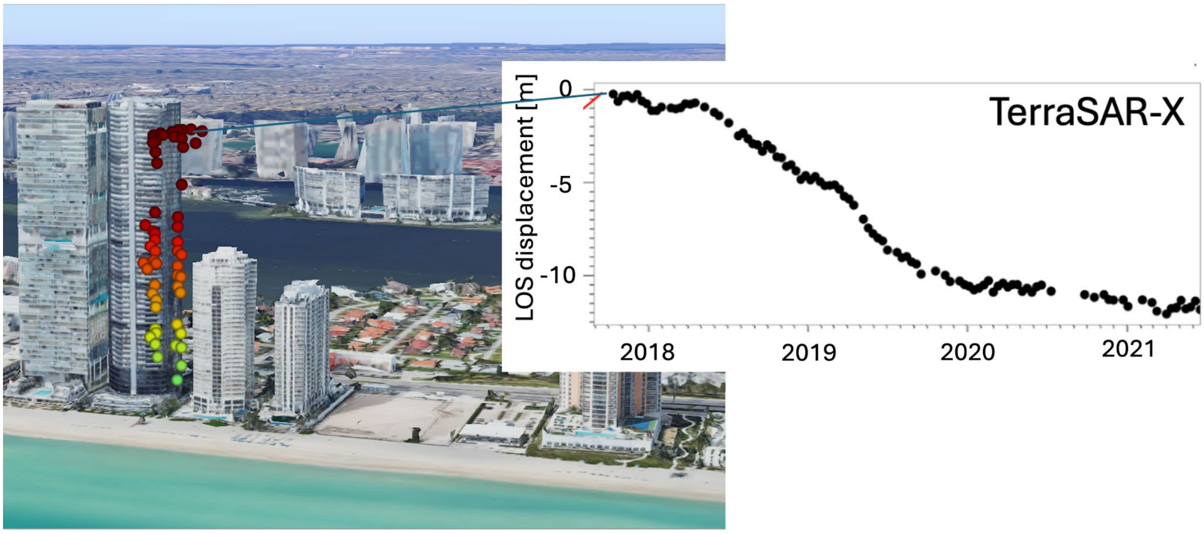

Figure 3. *Displacement time series from the west-ward TerraSAR-X sensor for the Porsche Design Tower, Sunny Isles Beach, showing 12 centimeters increase in line-of-sight (LOS) distance during 2017-2021. The east-ward looking Sentinel-1 sensor recorded only 3 cm LOS displacement during the same period (Fig. 1). This discrepancy can be explained by ~7 cm (3 inches) of westward motion caused by tilt of the structure.*

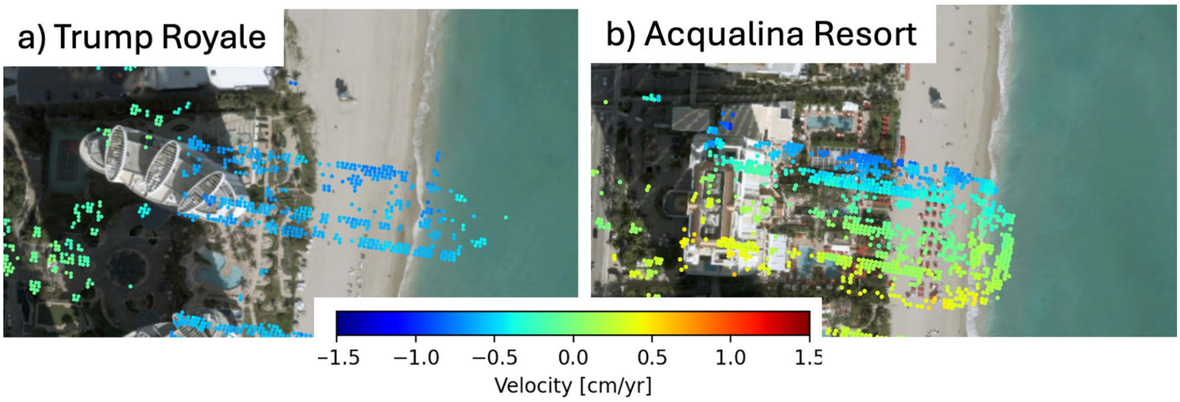

Figure 4. *Line-of-sight velocities for the Trump Royale and Acqualina Resort condos in Sunny Isles Beach from westward looking TerraSAR-X. While the Trump Royale appears to be uniformly sinking, only the northern part of the Acqualina resort records a lengthening of the distance (-0.75 cm/yr), the southern part records a shortening (0.25 cm/yr). These observations can be explained by a combination of anti-clockwise rotation and uniform sinking.*

References

Aziz Zanjani, F., **Amelung, F**., Piter, A., **Sobhan, K**., Tavakkoliestahbanati, A., Eberli, G.P., Haghighi, M.H., Motagh, M., Milillo, P., Mirzaee, S. and Nanni, A., 2024. Insar observations of construction-induced coastal subsidence on Miami's barrier islands, Florida. *Earth and Space Science*, *11*(12), 2024; https://doi.org/10.1029/2024EA003852