Geoid Validation with Astronomical Leveling along the Mississippi River

G33B-3377

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Introduction

In April 2024, a joint effort between NOAA's National Geodetic Survey, Louisiana State University, Oregon State University, and Swisstopo gathered four astrogeodetic camera systems (TSACS, VESTA, QDaedalus, and CODIAC) to conduct colocated astronomical observations on 31 marks on the Mississippi River between New Orleans and Baton Rouge. The goal was to compare the performance of these systems and generate geopotential profiles. *See the companion study G33B-3376*.

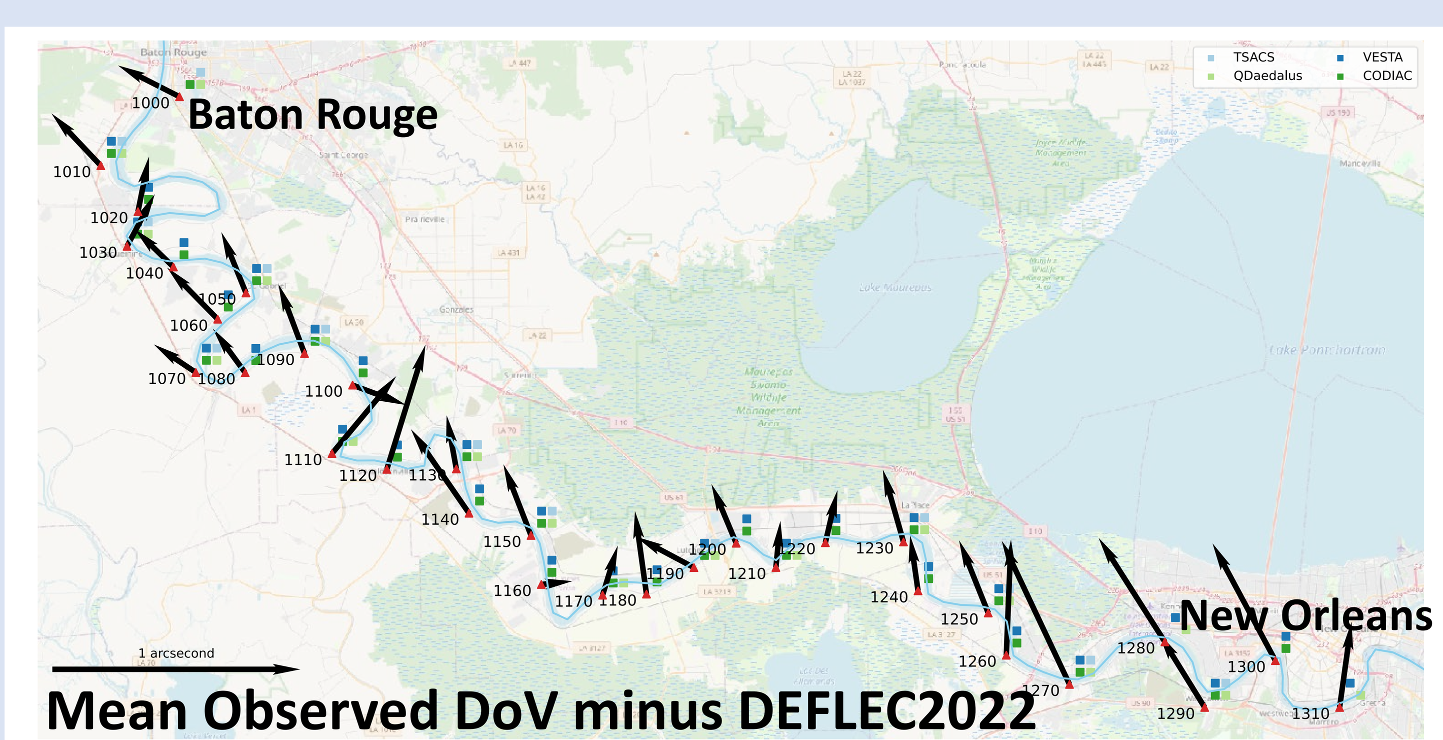
The Mississippi River was selected for this campaign because:

1. The Mississippi River has an especially urgent need for accurate orthometric heights
   - **Navigation**: High volume of shipping along this corridor
   - **Natural hazards:** Levees and evacuation routes protect millions of people vulnerable to floods
2. There is **a low density of terrestrial gravity data** informing geoid determination on the Gulf Coast
3. **GPS/leveling is unreliable** as a method of geoid validation in this region due to **subsidence**

The **geoid** is an equipotential surface formed by gravity that best approximates mean sea level. It is a natural basis for heights because it **predicts which way water flows**. Geodetic astronomy measures the slope of the geoid by estimating the direction of gravity (the **deflection of the vertical,** DoV) using observations of stars. Closely spaced measurements of the deflection of the vertical may be integrated to directly profile the geoid, a practice called **astronomical leveling** or **astrogeodetic leveling.**

NGS will soon release a geoid-based height system built around a model called **GEOID2022**. The goal of this work is to validate GEOID2022 with the data from this survey.

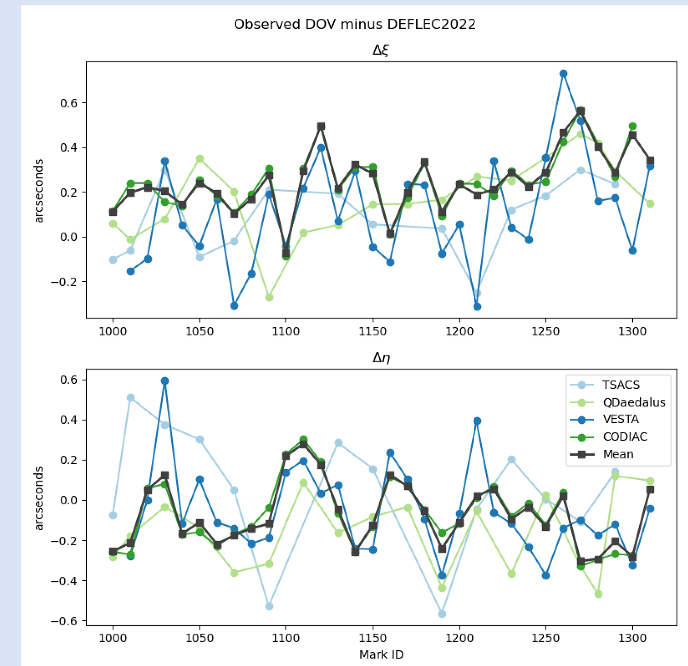
Data



Mean Observed DoV minus DEFLEC2022

The campaign gathered DoV observations on 31 temporary and permanent marks along 170 km of the Mississippi River with 5 km spacing. Geodetic positions for these marks were measured using real-time network GNSS with the C4G XYZ network. LSRC also gathered relative gravity observations to complete the gravity vectors.

Performance of DEFLEC2022



DEFLEC2022 is NGS's model of the deflection of the vertical at the topographic surface. It was derived from the horizontal gradients of GEOID2022 with corrections for surface topography. Evaluating DEFLEC2022 at the observation locations reveals a consistent long-wavelength bias in the model along the profile relative to all four camera systems.

Observed DoV minus DEFLEC2022

Unit: arcseconds	η bias	η std. dev.	ξ bias	ξ std. dev.
TSACS	+0.05	0.31	+0.08	0.17
QDaedalus	-0.16	0.19	+0.17	0.18
VESTA	-0.06	0.22	+0.11	0.24
CODIAC	-0.07	0.16	+0.24	0.14

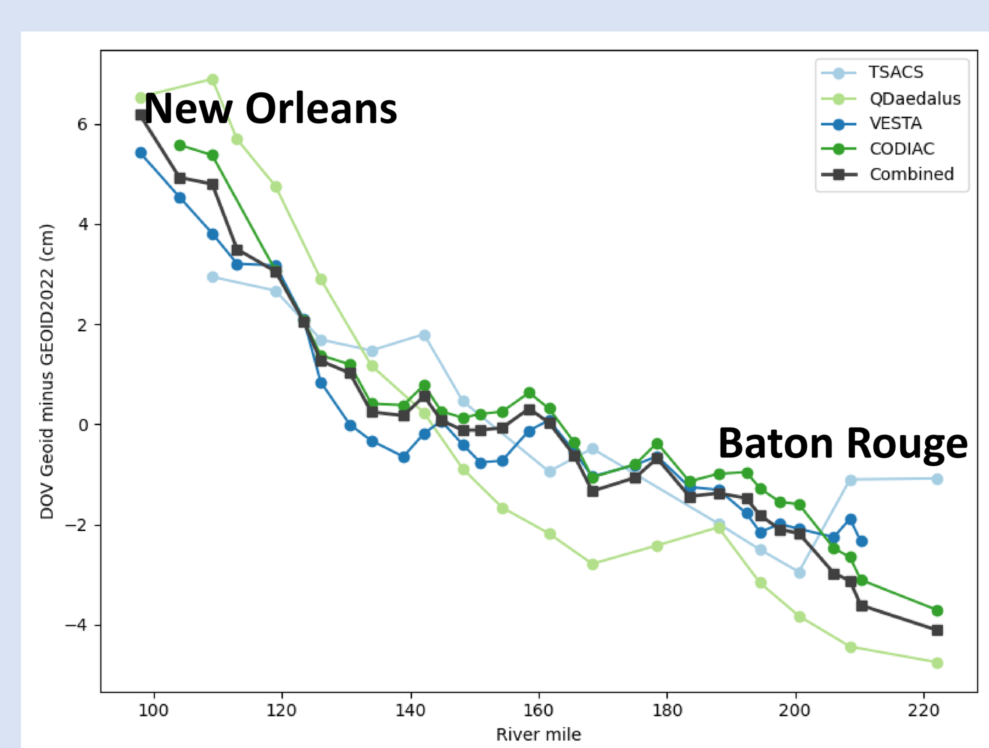
Comparison with GEOID2022

The deflections of the vertical may be integrated from point to point to obtain a geoid profile. Conceptually, this is represented by the following formula:

$$N_B - N_A = -\int_A^B \vec{\varepsilon} \cdot d\vec{s}$$

N is the geoid undulation, $\vec{\varepsilon}$ contains the DoV components η and ξ, and $d\vec{s}$ contains the vector displacement increments between successive marks in the profile. In normal practice, this formula requires higher-order terms for height-dependent corrections to account for non-parallel geopotential surfaces, but the nearness of this entire profile to sea level (<12 m) limits these corrections to the millimeter level.

The deflections were corrected for the attraction of local topography, including the hydrography of the Mississippi River. This smooths out high-frequency variations in the geoid between the sites.



The geoid profile reveals an apparent 2 cm RMS error and 8-10 cm end-to-end slope error in GEOID2022 between New Orleans and Baton Rouge. This is consistent with predicted errors in GEOID2022 in Louisiana, but the end-to-end error is larger than expected.

Discussion

The slope error in DEFLEC2022 and GEOID2022 revealed by this survey is higher than expected, but consistent with the 2 cm RMS error predicted for this region.

We have examined the following error sources as source of this slope error:

- Astronomical reduction biases
- Geodetic coordinate errors
- Terrain correction errors
- Terrestrial gravity errors
- Geoid profile integration method errors
- Systematic errors in the computation of DEFLEC2022 and GEOID2022

Original GNSS/leveling profiles may resolve if there's a systematic error in the astronomical data. The most plausible explanation is a long-wavelength error in the satellite model GOCO06s, which controls the long-wavelength component of GEOID2022. As the great-circle length of the profile is 120 km, a long-wavelength error in the geoid can be attributed to this model. This is also consistent with results from longer Geoid Slope Validation Survey geoid profiles, where residuals are dominated by errors at the 100 km scale. Errors at the 100 km scale, where satellite, airborne, and terrestrial gravity are the least mutually sensitive, remain a primary source of geoid error in CONUS.

If this error is attributable to satellite model errors, then GEOID2022 may be refined with improvements to destriping algorithms and understanding of the spatial and spectral statistics of GRACE, GRACE-FO, and GOCE observations. Ultimately, improvement will come from future satellite gravity missions with a lower inclination and greater sensitivity to east-west geopotential gradients at temperate latitudes.

Conclusions

- This survey provides confirmation that GEOID2022 may be used in this region with the expectation of ~2 cm RMS height error.
- However, long-wavelength errors in the geoid seem to inflate the geoid height error between Baton Rouge and New Orleans to ~10 cm.
- This survey demonstrates how deflections of the vertical may be used along rivers to provide geoid validation and geopotential profiles.
- Rivers are natural candidates for astrogeodetic campaigns because
  - Astrogeodetic profiles are naturally suited for linear profiles with predictable topographic variation
  - Rivers represent the confluence of commerce, navigation, and natural hazards and are thus where accurate heights are most urgently needed
- Future work may include deploying astronomical cameras along key inland waterways, like the Columbia and Hudson Rivers; or extending this work farther along the Mississippi River.

Acknowledgments

This research is supported by the Graduate Women in Science (GWIS) fellowship and NOAA National Geodetic Survey (NGS) Geospatial Modeling Grant NA23NOS4000333, "NSRS Modernization and Geodetic Workforce Development in the Arctic and Pacific Region", and by the Geospatial Center for the Arctic and Pacific (GCAP).