The Southern Louisiana Astrogeodetic Survey: Assessing the Performance of GEOID2022 along the Mississippi River

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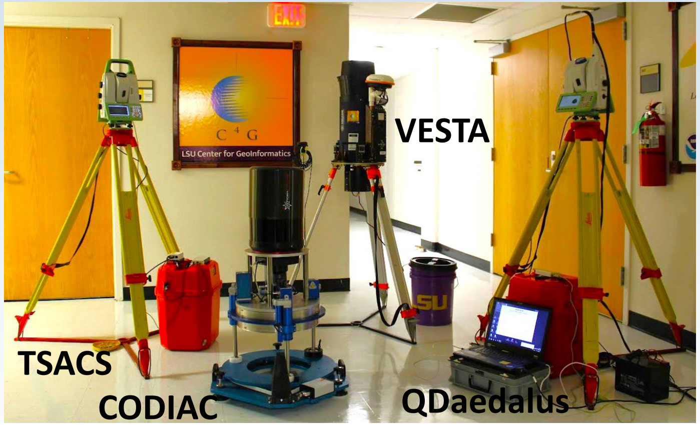
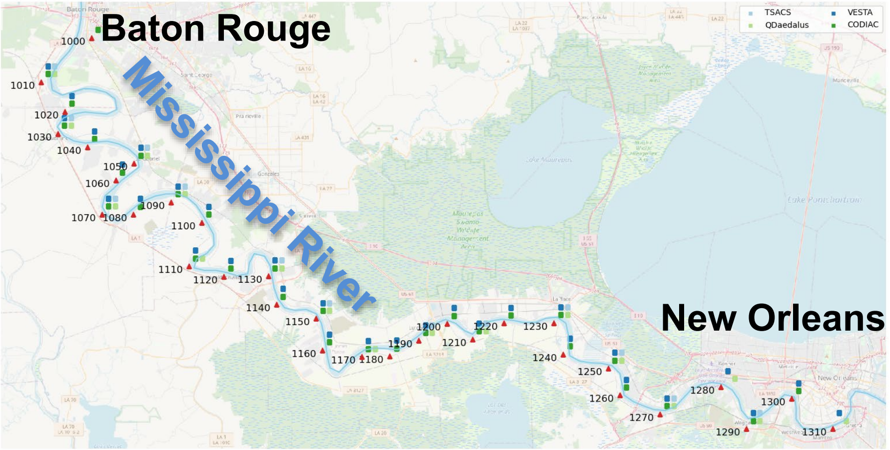
NGS Webinar

Key Points

- In April 2024, NGS joined three other institutions in a survey of the Mississippi River between Baton Rouge and New Orleans using four different astrogeodetic instruments
- The survey used astronomical, gravity, and GNSS observations to validate GEOID2022 in this region
- This region was selected because of the importance of accurate orthometric heights in a critical commercial corridor
- The survey found an apparent slope error in GEOID2022, but affirmed its absolute accuracy





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swisstopo and HEIG-VD

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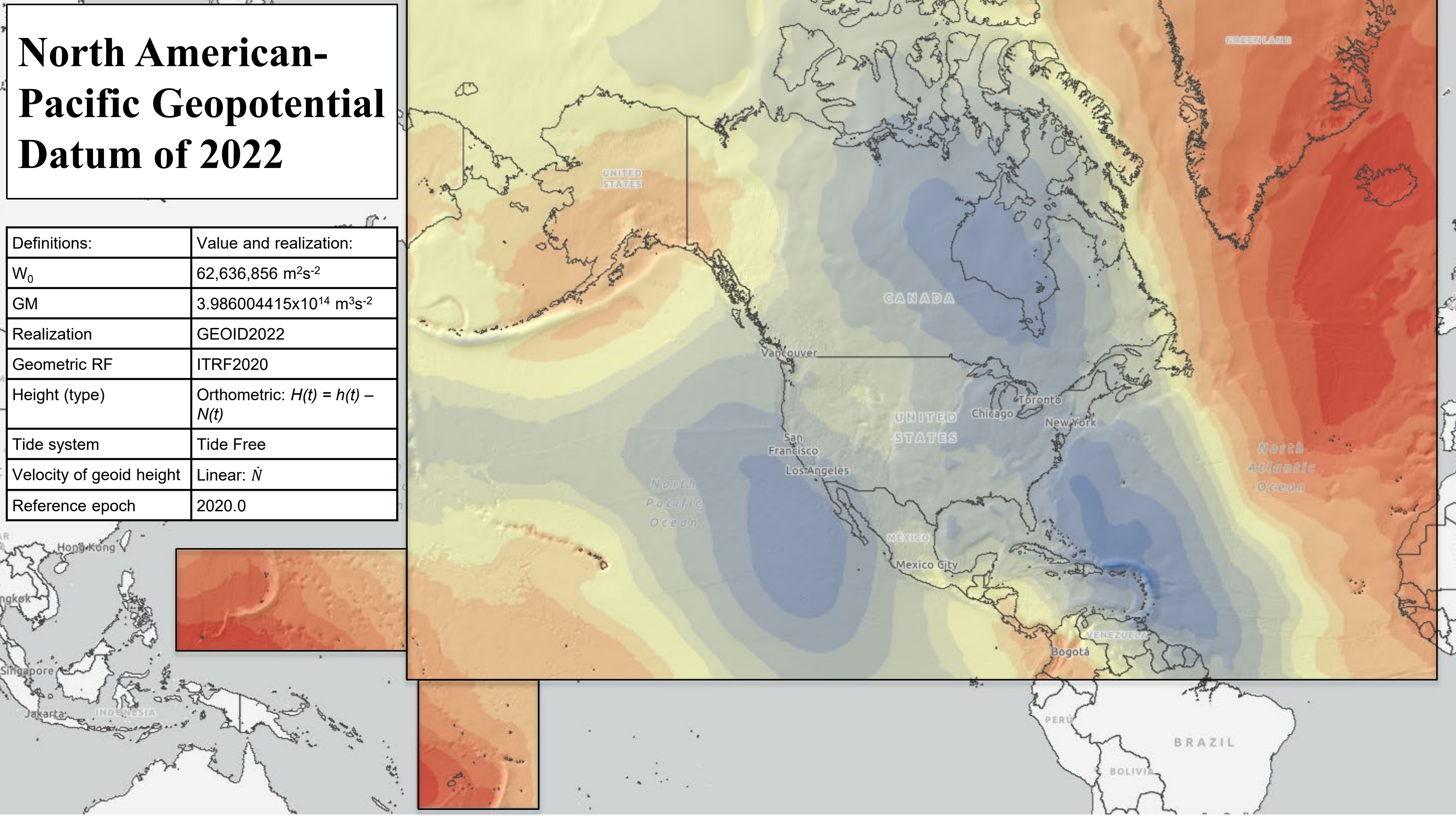
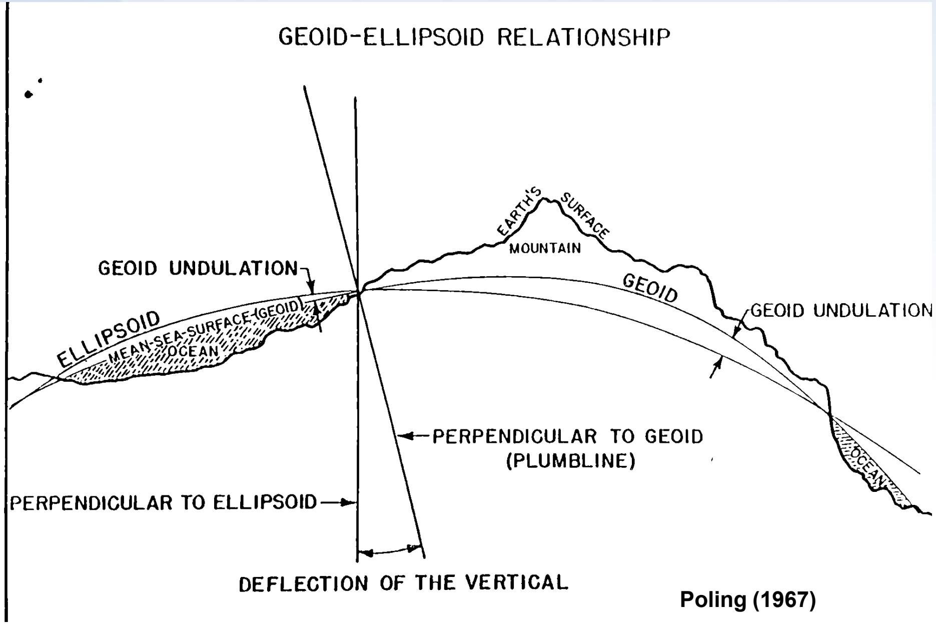
North American-Pacific Geopotential Datum of 2022

Definitions:	Value and realization:
W_0	62,636,856 m^2s^{-2}
GM	3.986004415x10^{14} m^3s^{-2}
Realization	GEOID2022
Geometric RF	ITRF2020
Height (type)	Orthometric: $H(t) = h(t) - N(t)$
Tide system	Tide Free
Velocity of geoid height	Linear: $\dot{N}$
Reference epoch	2020.0



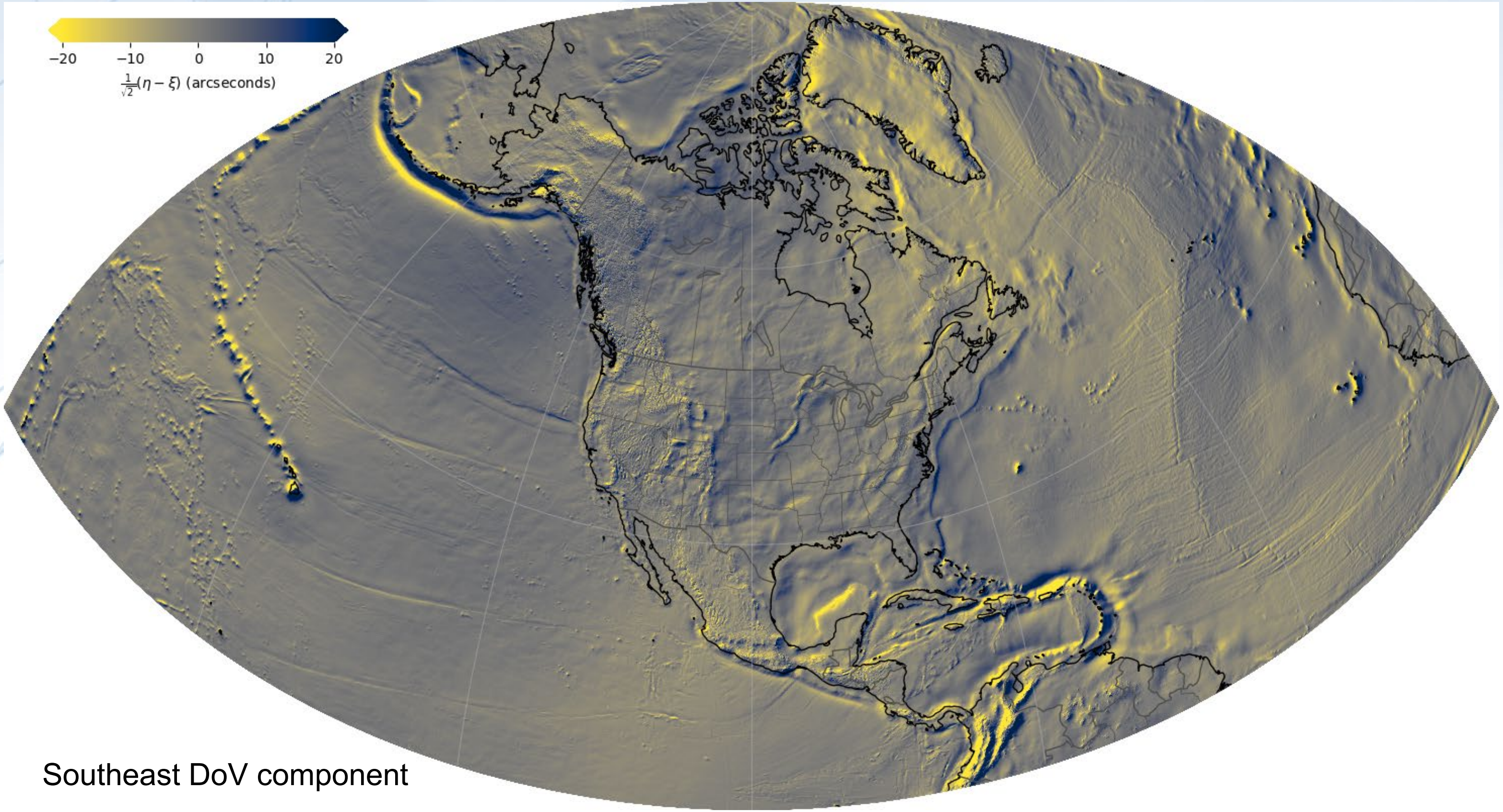
Deflection of the Vertical

- The **deflection of the vertical (DoV)** defines "up" in NAPGD2022 and is realized by the **DEFLEC2022** model
- More precisely, the deflection of the vertical quantifies how much the direction of gravity differs from the ellipsoid normal at Earth's surface. It is related to the geoid slope.
- The deflection of the vertical is used to convert locally oriented survey and navigation data to a global geometric frame
- DoV may be observed using **geodetic astronomy** by comparing the direction of the plumb line to star observations at well-positioned locations



Poling (1967)

DEFLEC2022



Southeast DoV component

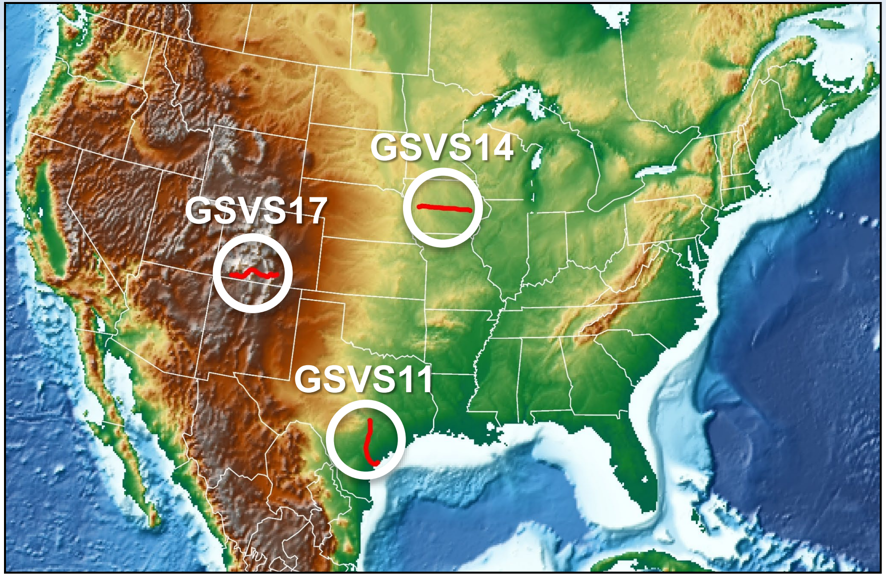
Geoid Computation and Validation

	Stokes Integral	GNSS/Leveling	Astrogeodetic Leveling
	The geoid is a radially weighted integral of gravity anomalies.	The geoid is the difference between ellipsoidal height and orthometric height.	The geoid is the integral of accumulated deflections of the vertical along a path.
Inputs	Gravity anomalies Satellite gravity models	GNSS ellipsoidal heights Orthometric heights from leveling	Deflections of the vertical GNSS geodetic coordinates
Advantages	• Gravity observations are easy to obtain and abundant • Combines all available sources	The most precise validation method available for short distances	• Cost-effective because of relaxed mark spacing and positioning requirement • Not sensitive to height errors, more suited for rough topography • Well suited for linear corridors
Disadvantages	• Requires gravity *everywhere* • Sensitive to errors in heights and biases between datasets • Combination of datasets and tuning of the integral is a high-skill task	• Painstaking. Observations must be conducted every 10-30 meters and GNSS occupations must be lengthy (> 24 h) • Sensitive to height errors, including changes in height between measurements and leveling adjustment errors	• Limited by weather and strict site visibility requirements • Not as precise as the other two methods

$$\mathrm{N} = \frac{R}{4\pi\gamma}\int_{\Omega} \Delta g S(\psi) d\Omega \qquad \mathrm{N} = h - H \qquad N_B - N_A = \int_A^B \varepsilon ds$$

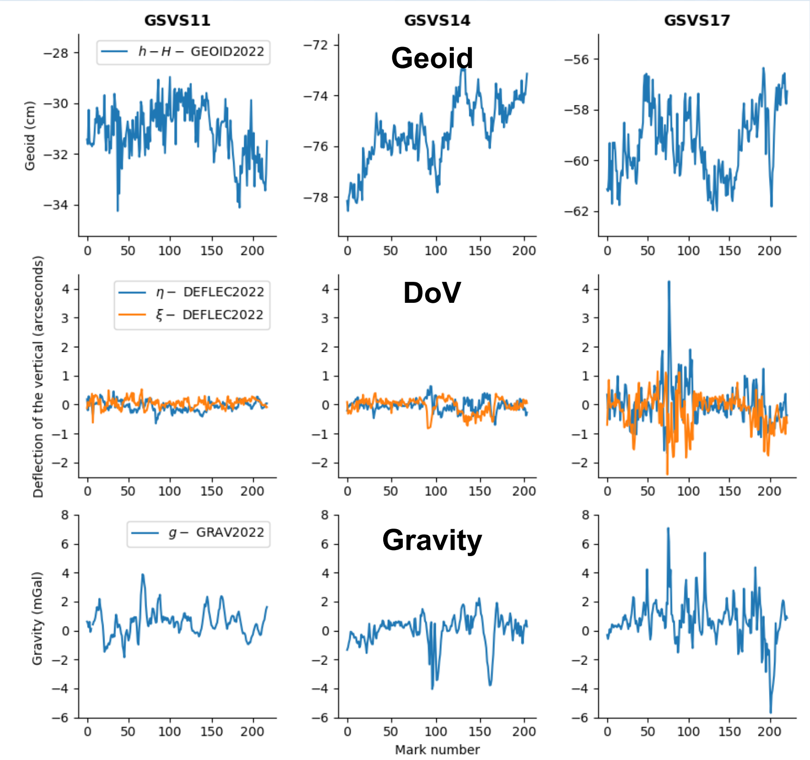
Geoid Slope Validation Surveys

- NGS has used both GNSS/leveling and astrogeodetic techniques to validate the geoid in the *Geoid Slope Validation Surveys*
  - Texas (2011)
  - Iowa (2014)
  - Colorado (2017)
- Each survey established monuments every 1.6 km across ~300 km and required several months to complete



Geoid Slope Validation Surveys

- NAPGD2022 precision based on GSVS
  - **Geoid**: 1 cm
  - **DoV**: 0.2 arcseconds in smooth terrain, 0.6 arcseconds in more rugged terrain
  - **Gravity**: 1-2 mGal
- GSVS required a state-of-the-art zenith camera and new leveling
- Can these validations be performed with less time and labor?



Observed minus predicted NAPGD2022 quantities

Geodetic Astronomy at NGS

- The GSVS projects required borrowing Swiss zenith cameras, which while extremely precise, weighed hundreds of pounds
- In 2020, NGS developed the Total Station Astrogeodetic Control System (TSACS), a hardware kit that enables a robotic total station to perform astronomical observations and estimate deflections of the vertical
- TSACS can estimate deflections of the vertical with ~0.2 arcsecond accuracy after 15 minutes of observing. It may be transported and assembled by single person.
- TSACS has been deployed on NGS's Geoid Monitoring Service Validation Survey in Alaska and is used to adjust IERS site surveys in the US

TSACS at work at the Koke'e Park Observatory in Hawaii

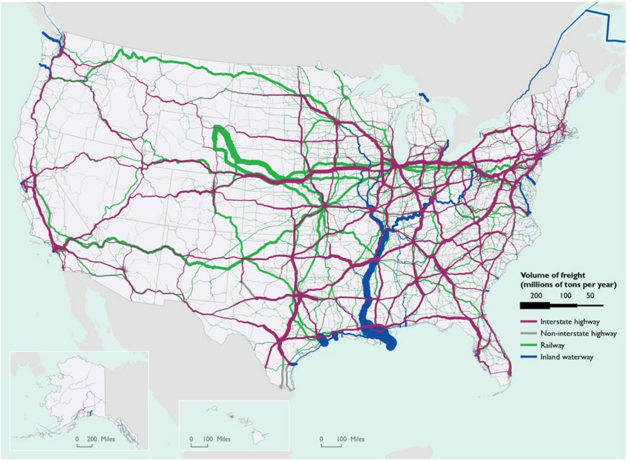
Simplifying Geoid Slope Surveys

- **Eliminate leveling**
- **Wider mark spacing**
  - 5-10 km instead of 1-2 km
  - Take advantage of the smoothness of the geoid
  - Use DEMs to remove gravity signals between the sites
- **Fast GNSS occupation**
  - Geodetic astronomy only requires decimeter positioning accuracy and is insensitive to height errors
- **Relative gravity**
  - Needed for reductions and sanity checks
- **Temporary monumentation**
  - Use PK Nails and temporary marks
  - Mark stability is less important because of relaxed positioning constraints
  - No need to spend time pouring concrete or bushwhacking for existing marks

Why the Mississippi River?

1. The Mississippi River has an especially urgent need for accurate orthometric heights
   - **Navigation**: Hundreds of millions of tons of shipping in this corridor annually supported by federal infrastructure
   - **Natural hazards**: Levees and evacuation routes protect millions of people from flooding
2. There is a low density of terrestrial gravity data informing geoid determination on the Gulf Coast
3. Geoid validation using GNSS/leveling (GPS on Benchmarks) in this region is unreliable due to subsidence

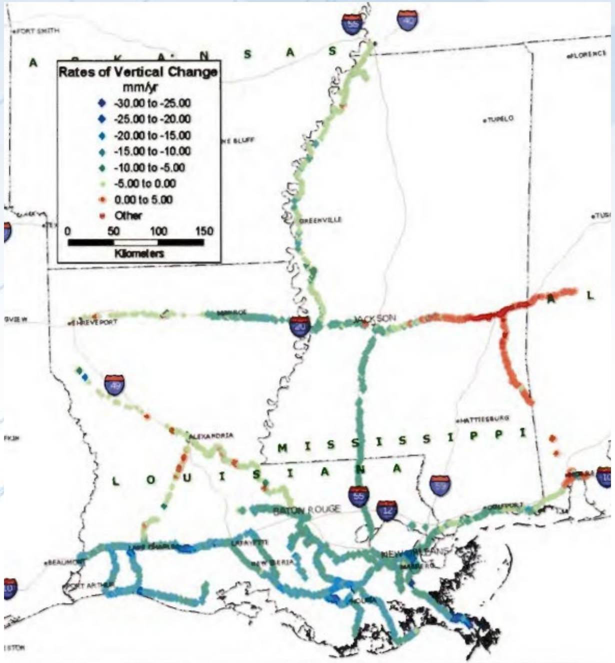
Freight Flows by Highway, Railway, and Waterway: 2018



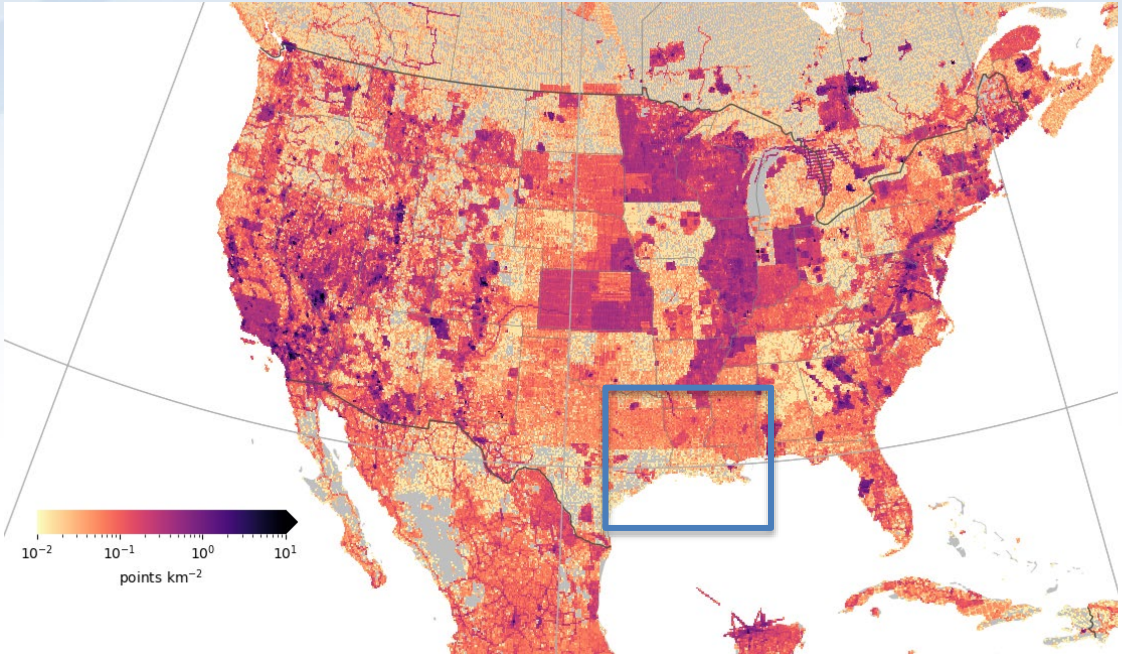
NOTE: Highway flows depicted in this map are based on the Freight Analysis Framework (FAF) data for 2015—the latest year for which the FAF network flow data is available.
SOURCES: Highway—U.S. Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework, version 4.3.1, 2015. Rail—Based on Surface Transportation Board, Annual Carload Waybill Sample and rail freight flow assignment done by Oakridge National Laboratory, 2018. Inland Waterways—U.S. Army Corps of Engineers, Institute of Water Resources, Annual Vessel Operating Activity and Lock Performance Monitoring System data, 2018.

Bureau of Transportation Statistics

Why the Mississippi River?

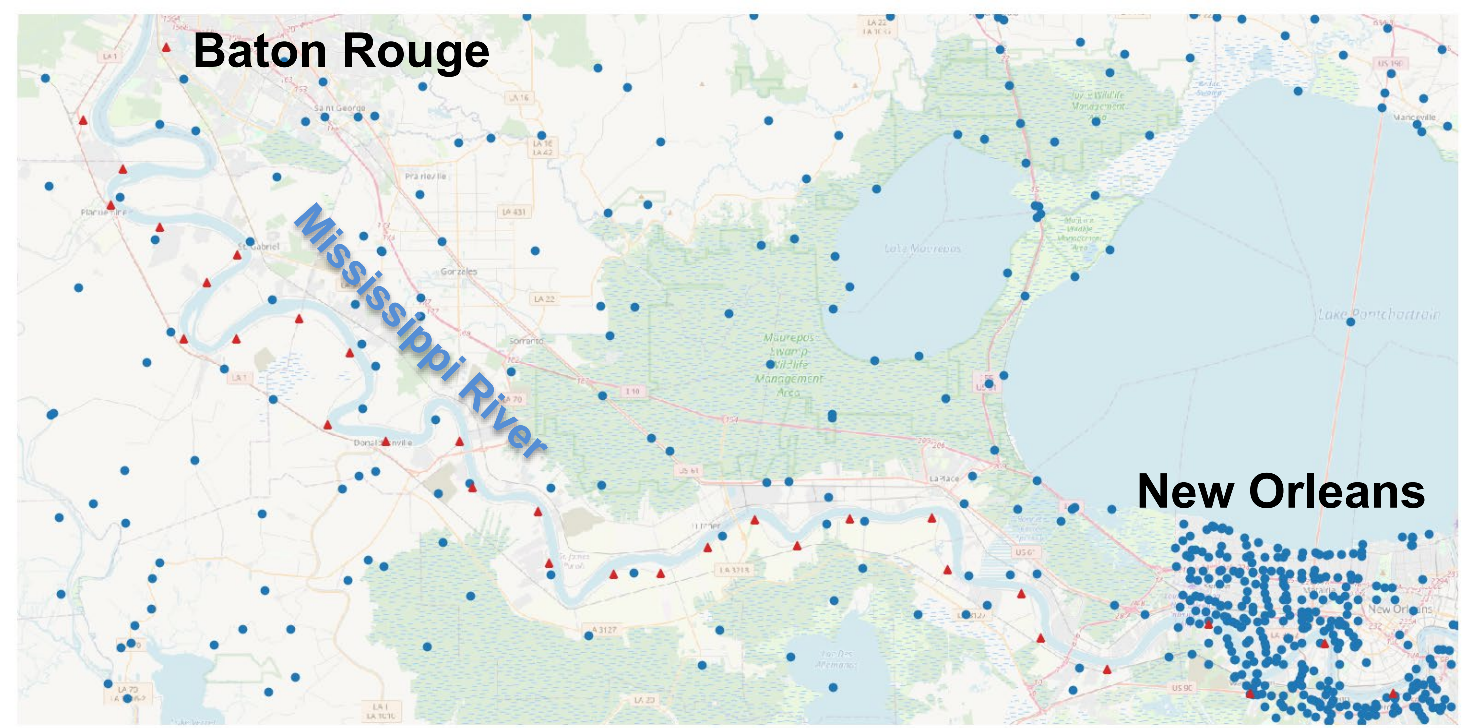


Rates of subsidence inferred by repeat leveling with rates of more than 1 cm/yr (NOAA TR NOS NGS 50, 2004)



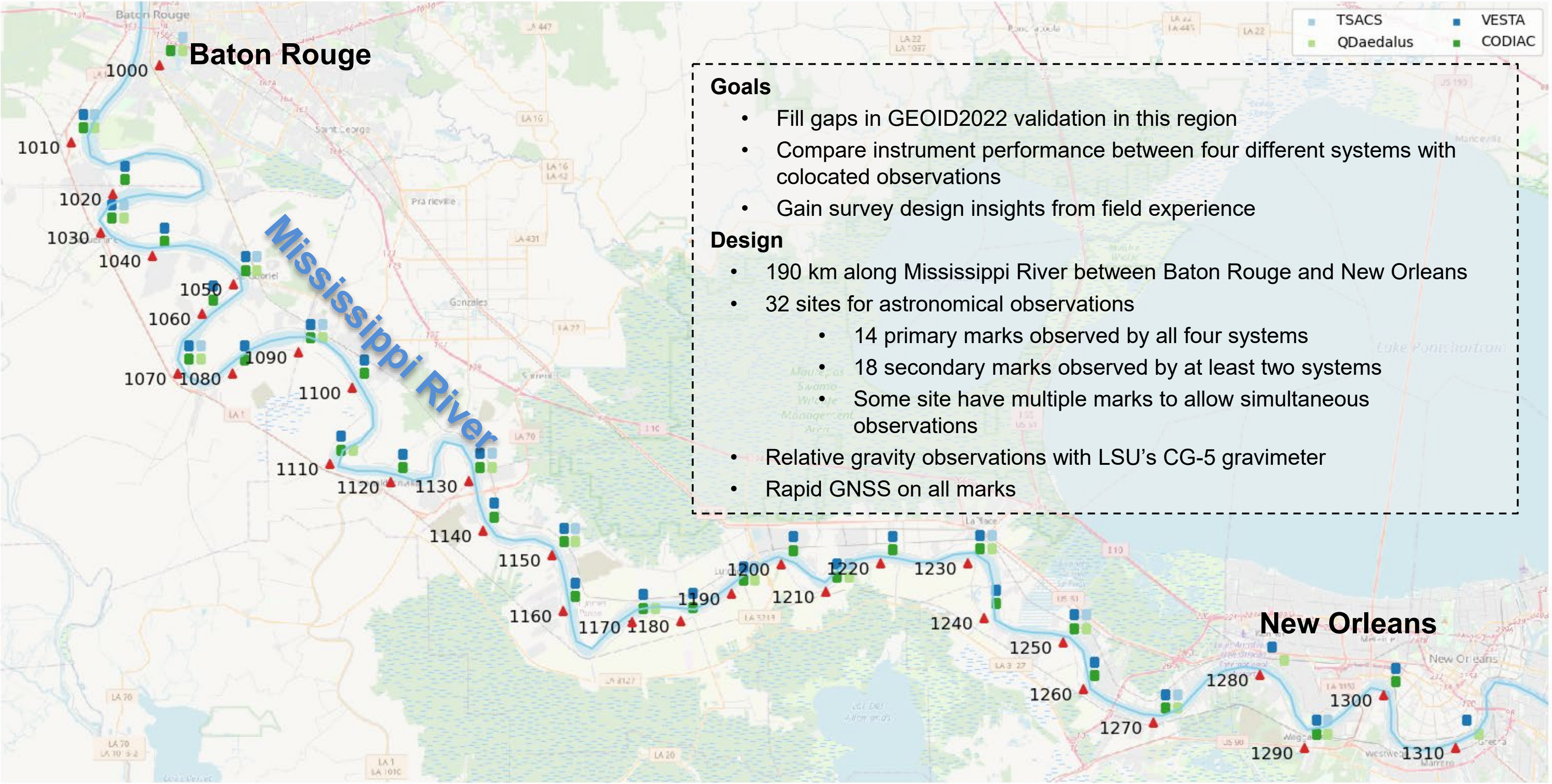
Density of point gravity measurements used in GEOID2022, showing low density of measurements in southern Louisiana.

Why the Mississippi River?



Gravity observations (blue points) used in GEOID2022

The Southern Louisiana Astrogeodetic Survey



Goals

- Fill gaps in GEOID2022 validation in this region
- Compare instrument performance between four different systems with colocated observations
- Gain survey design insights from field experience

Design

- 190 km along Mississippi River between Baton Rouge and New Orleans
- 32 sites for astronomical observations
  - 14 primary marks observed by all four systems
  - 18 secondary marks observed by at least two systems
  - Some site have multiple marks to allow simultaneous observations
- Relative gravity observations with LSU's CG-5 gravimeter
- Rapid GNSS on all marks

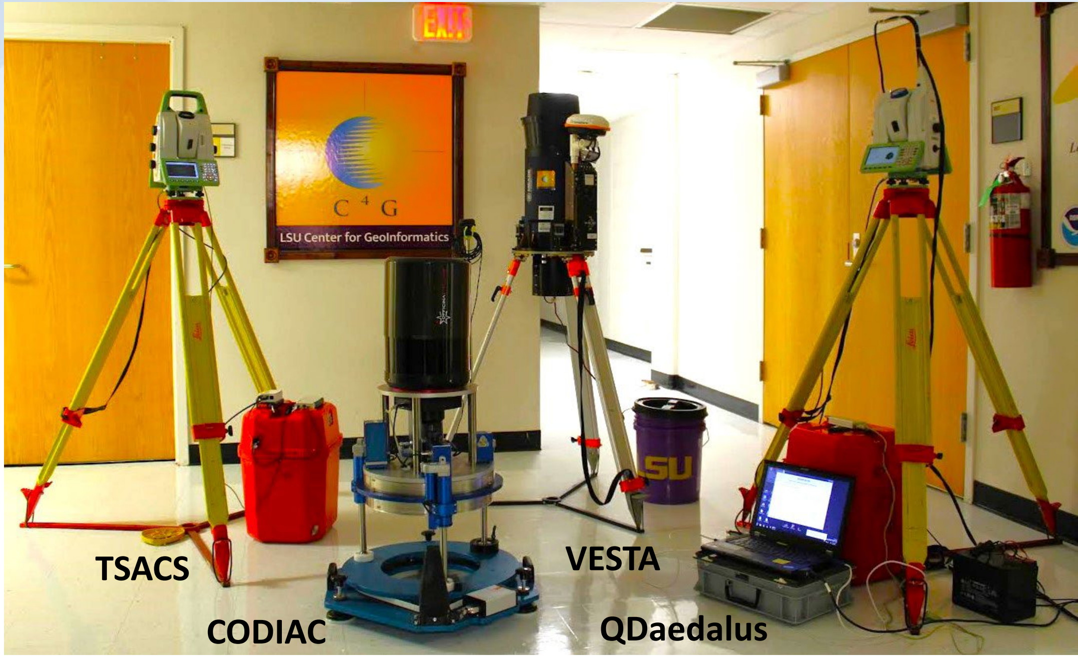
Participating Instruments

Zenith cameras

- CODIAC
  - Owned by swisstopo, 0.05″
- VESTA
  - Owned by Louisiana State University, 0.1″

Total station-based systems

- QDaedalus
  - Owned by Oregon State University, 0.15″
- TSACS
  - Developed by NGS, 0.2″



Reconnaissance and Site Setup

- Visibility suitable for total stations, which look at stars 30 degrees from the zenith
- Suitability for CODIAC (wheel-accessible, no major slope)
- Multiple marks per site to accommodate simultaneous observation (normally within 100 meters of each other)
- Temporary monuments used (PK nails and inscribed crosses)
- RTN GNSS positions of all marks using C4G XYZ network

Photos: Müge Albayrak, Benjamin Fernandez

GRAVITY STATION DESCRIPTION	STATION TYPE: Astrogeodetic Observation Site	STATION DESIGNATION: 1010
COUNTRY: United States	STATE/PROVINCE - COUNTY: LA - WEST BATON ROUGE	CITY: Addis
LATITUDE: 30°21'22.02303" N	LONGITUDE: 91°15'21.43775" W	ELEVATION: 6.85
GRAVITY STATION MARK: NAIL	AGENCY: LSRC - C4G	INSCRIPTION: 1010
POSITION/ELEVATION REFERENCE: NAD83/NAVD88	POSITION/ELEVATION SOURCE: C4GNET RTN	SOURCE DESCRIPTION: CORS REAL-TIME-NETWORK
POSITION/ELEVATION REMARKS: EL HGT = -20.247	GRAVITY VALUE/SOURCE/DATE: g = 9 ± 0.00 mGals (unmeasured)	

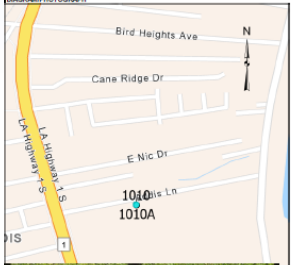
DESCRIPTION/CONTACT

The decimal lat/long for the station a 30.35611751 -91.25595493

The station is located at Rock Zion Church in Addis, Louisiana. The mark is a 60D nail and washer with flagging. The mark is 92.5 feet S the centerline of Addis Ln., 45.5 feet S the SE corner of a fence around a pump station, 27 feet W of the SW corner of the church, and 12 feet N of a sewer manhole cover.

STATION ASSIGNED TO: ALL PID:

DIAGRAM/PHOTOGRAPH



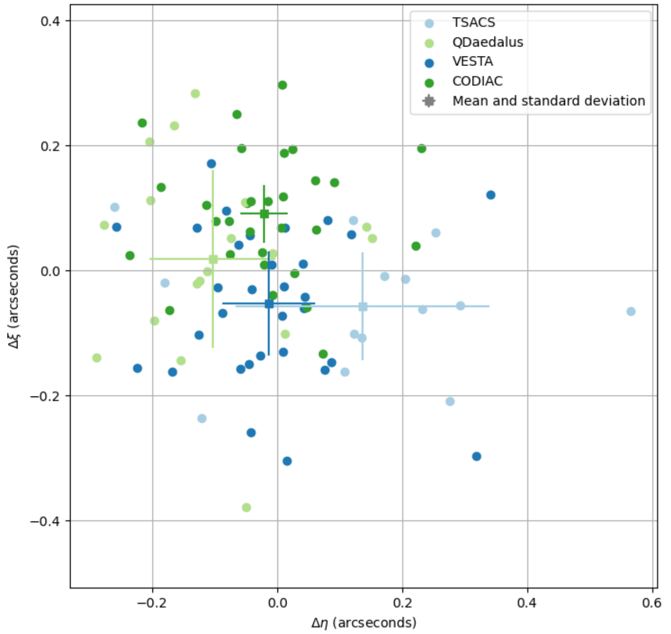
BAF/JTC	LSRC/C4G	APRIL 1 2024

Operations

- QDaedalus and TSACS occupied 15+ sites over 4 nights in two weeks
- CODIAC occupied 31 sites over 6 nights in two weeks
- VESTA occupied 32 sites over 14 nights in April, May and June
- Occupation time was a minimum of 40 minutes, *except with CODIAC*, which required only 20 minutes
- Simultaneous occupations turned out to be rare
- VESTA and CODIAC, which use the same tiltmeter, were found to have vibration issues near oil refineries and passing ships
- CG-5 relative gravity was gathered in the following weeks at all sites

Results: Instrument Performance

Observed DoV minus site mean values



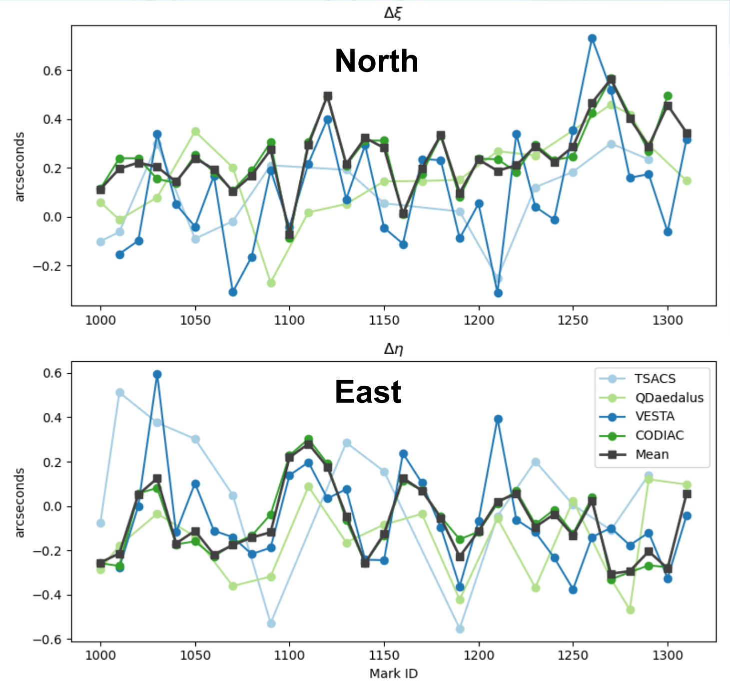
Unit: arcseconds

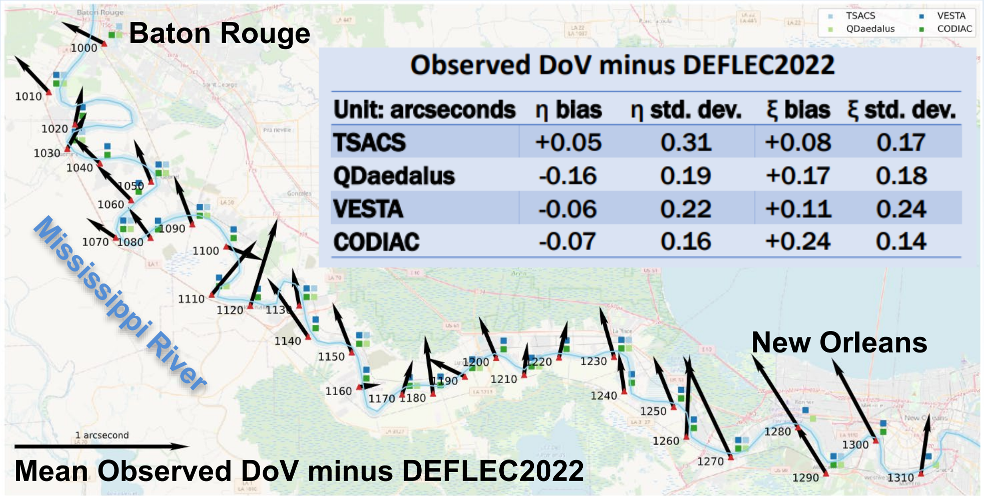
Instrument	# Obs.	North bias	East bias	North Error	East Error
CODIAC	30	+0.091 ± 0.027	-0.021 ± 0.031	0.05	0.04
QDaedalus	18	+0.019 ± 0.032	-0.103 ± 0.036	0.14	0.10
TSACS	14	-0.057 ± 0.035	+0.137 ± 0.039	0.09	0.20
VESTA	31	-0.053 ± 0.027	-0.012 ± 0.031	0.08	0.07

- Instrument biases and uncertainties for typical >40-minute observation sessions were obtained using ANOVA and least squares
- CODIAC has a narrowly significant bias of 0.1 arcseconds to the north relative to the other three instruments
- TSACS has excessive east-west variability and bias
- These results suggest any of these instruments can *otherwise* be used to achieve 0.15 arcsecond accuracy for a typical single occupation.

Results: Geoid Validation

Observed DoV minus DEFLEC2022





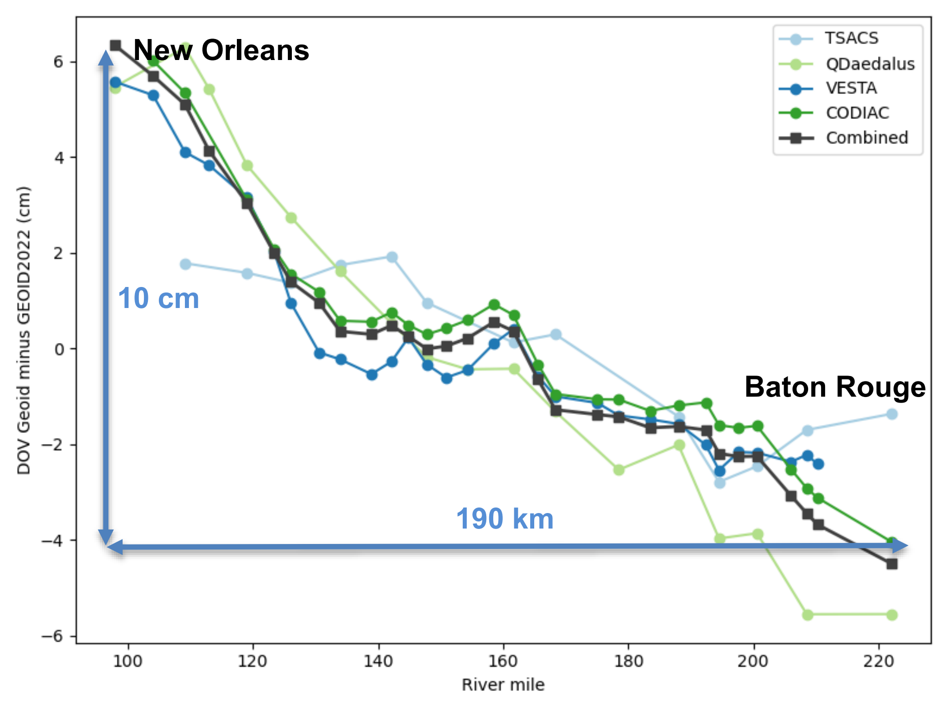
Observed DoV minus DEFLEC2022

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 DEFLEC2022 shows a consistent bias somewhat aligned with the profile, indicating a geoid slope error.

Results: Geoid Validation

- The residual deflections of the vertical may be integrated along the profile to obtain geoid slope error
- Results consistently suggest a ~10 cm geoid slope error between New Orleans and Baton Rouge
- The standard deviation of this error profile is a little more than 2 cm, affirming that GEOID2022 may have 2 cm absolute accuracy in this region
- However, the relative bias of ~0.5 mm/km is concerning



Possible Explanations

Observational blunders

- Unlikely to impact four systems independently

Geodetic coordinate errors

- Coordinates were verified with multiple observations by both NGS and LSU

Tides and other astrogeodetic reduction errors

- Too small (often < 0.01 arcseconds)

Topographic and bathymetric (river) attraction

- Modeled and found not to impact the overall slope

Systematic errors in DEFLEC2022 independent of GEOID2022

- A very similar geoid error can be obtained while ignoring DEFLEC2022 completely

Short-period variations in local gravity

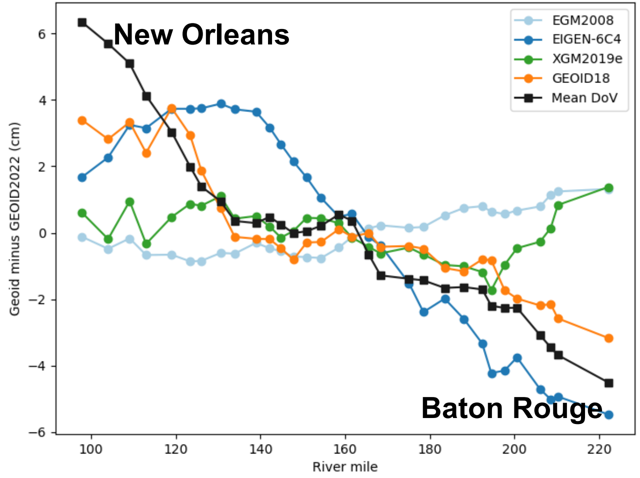
- Likely too small, but need to investigate more

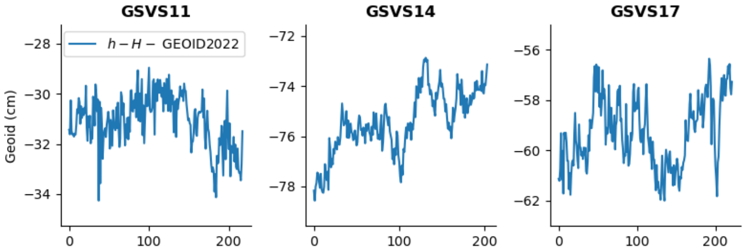
Possible Explanations

Satellite model errors seem to be the most likely candidate explanation

- This trend spans more than 120 km of straight-line distance, a spatial scale controlled by satellite data
- Pre-GOCO06s models like EIGEN-6C4 and GEOID18 (a hybrid geoid with GNSS/leveling) seem to match this trend
- Other models using GOCO06s, such as XGM2019e do not feature this error
- GSVS error characteristics seem to be white noise on top of long-wavelength errors
- *Hypothesis*: If this is a satellite data error, then extending the survey up or down the river will show this trend return to zero
- GEOID2022 may be improved with future satellite gravity models in coming years

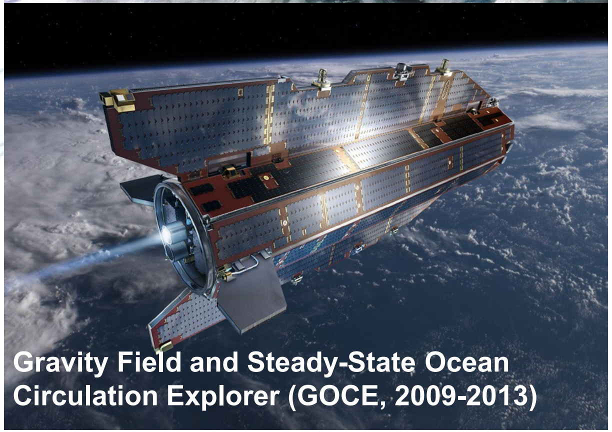
Survey Results Compared with Alternative Models



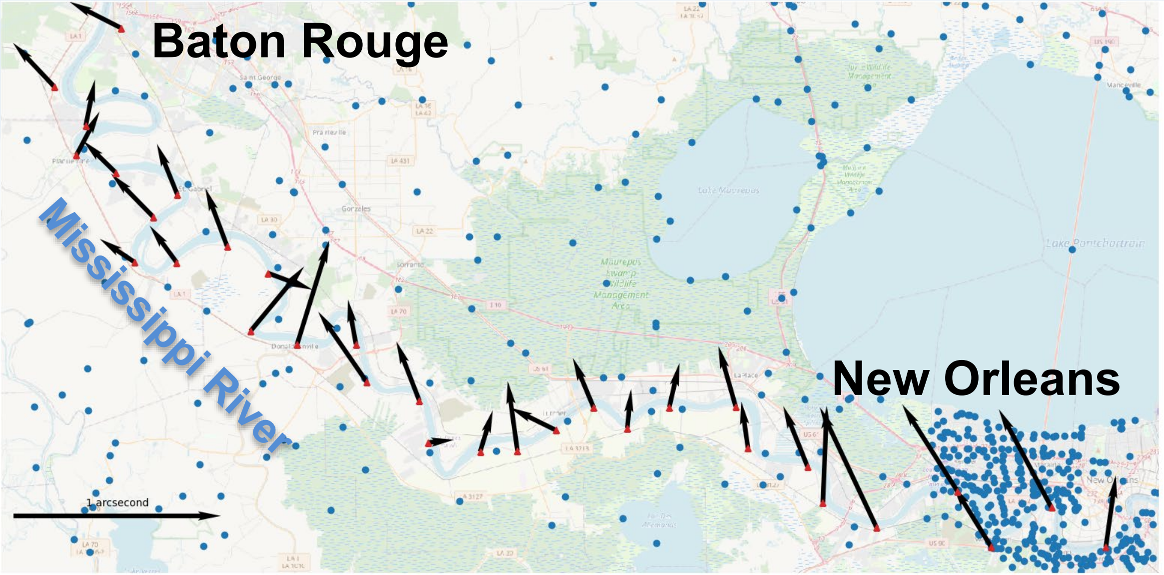


GSVS Geoid Residuals by Mark #

Gravity Recovery and Climate Experiment (GRACE, 2002-2017)



Gravity Field and Steady-State Ocean Circulation Explorer (GOCE, 2009-2013)



Above: Gravity observations (blue points) used in GEOID2022 alongside observed deflections minus DEFLEC2022 (arrows)

Left: Satellite gravity missions used in GEOID2022

Conclusions

GEOID2022 accuracy in southern Louisiana

- Absolute uncertainty of about 2 cm
- Relative uncertainty of about 0.2 arcseconds or 1 mm/km
- Future improvements to GEOID2022 are likely to come from improved satellite gravity modeling and combination

Simplified geoid slope validation

- DoV accuracy with any of these systems is on the order of 0.1-0.2 arcseconds
- A team of 2-4 can carry out a similar survey in about a month
- Other regions of interest
  - Geodetic astronomy is well suited for corridors, including shipping routes, valleys, and rivers
  - Rivers are where water, commerce, and populations drive the need for accurate orthometric heights
  - Techniques will be continued in Alaska in 2025 for GeMS surveys