Pointing a Total Station at the Stars with NGS's Total Station Astrogeodetic Control System

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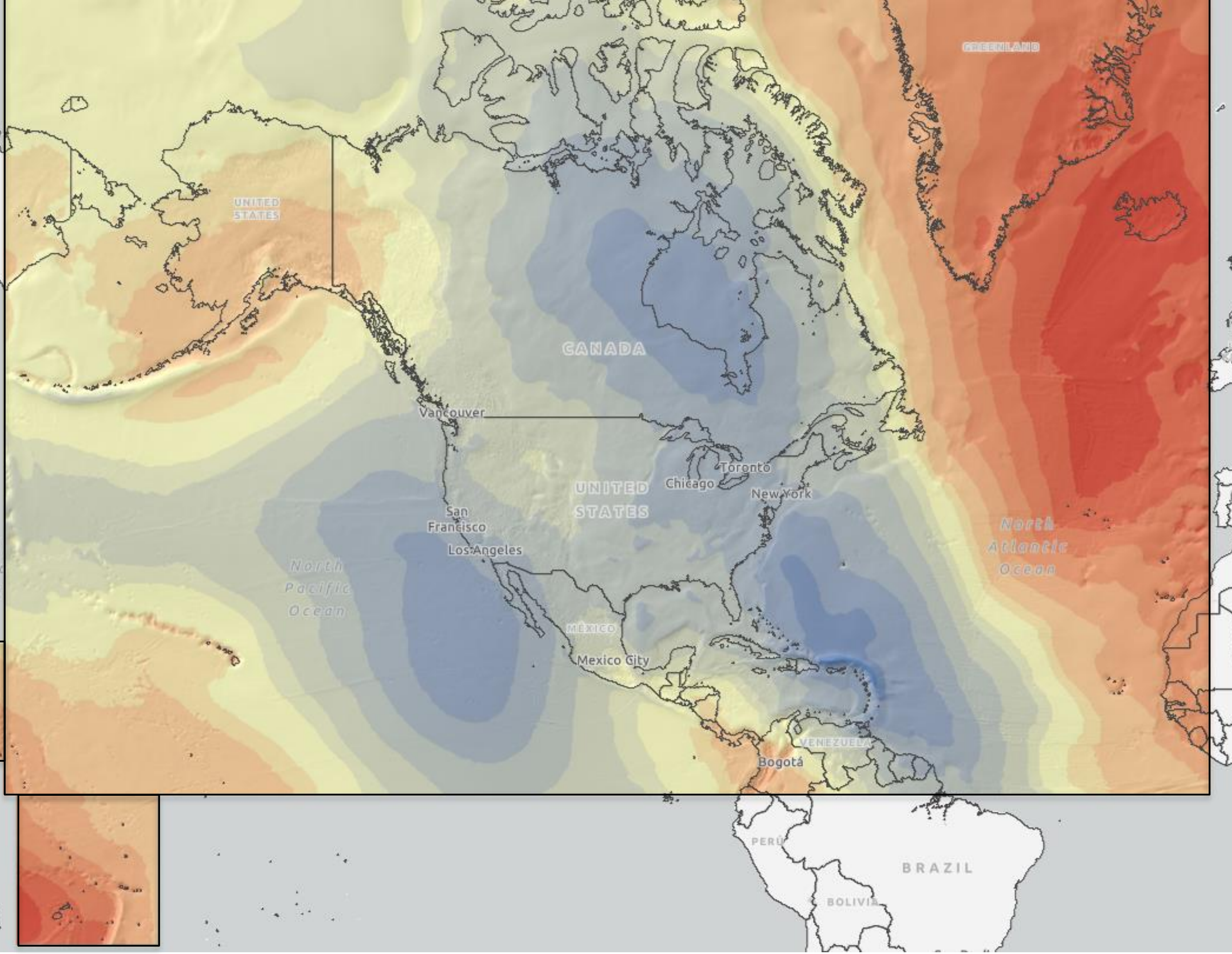
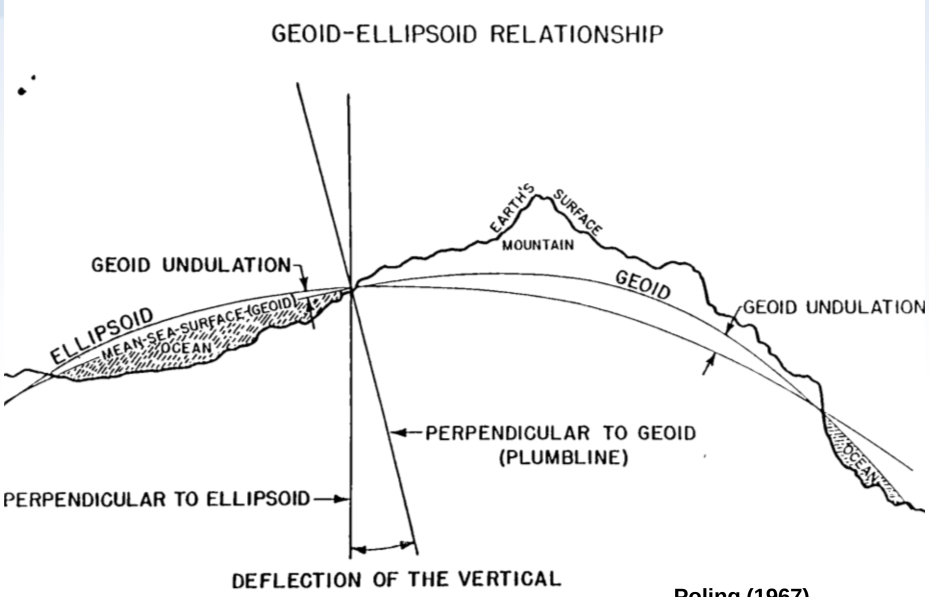
Definitions:	Value and realization:
W_0	62,636,856 m^2s^{-2}
GM	3.986004415x10^{14} m^3s^{-2}
Realization	GEOID2022
Geometric RF	ITRF2020
Height (type)	Orthometric: $H(t) = h(t) - N(t)$
Tide system	Tide Free
Velocity of geoid height	Linear: $\dot{N}$
Reference epoch	2020.0

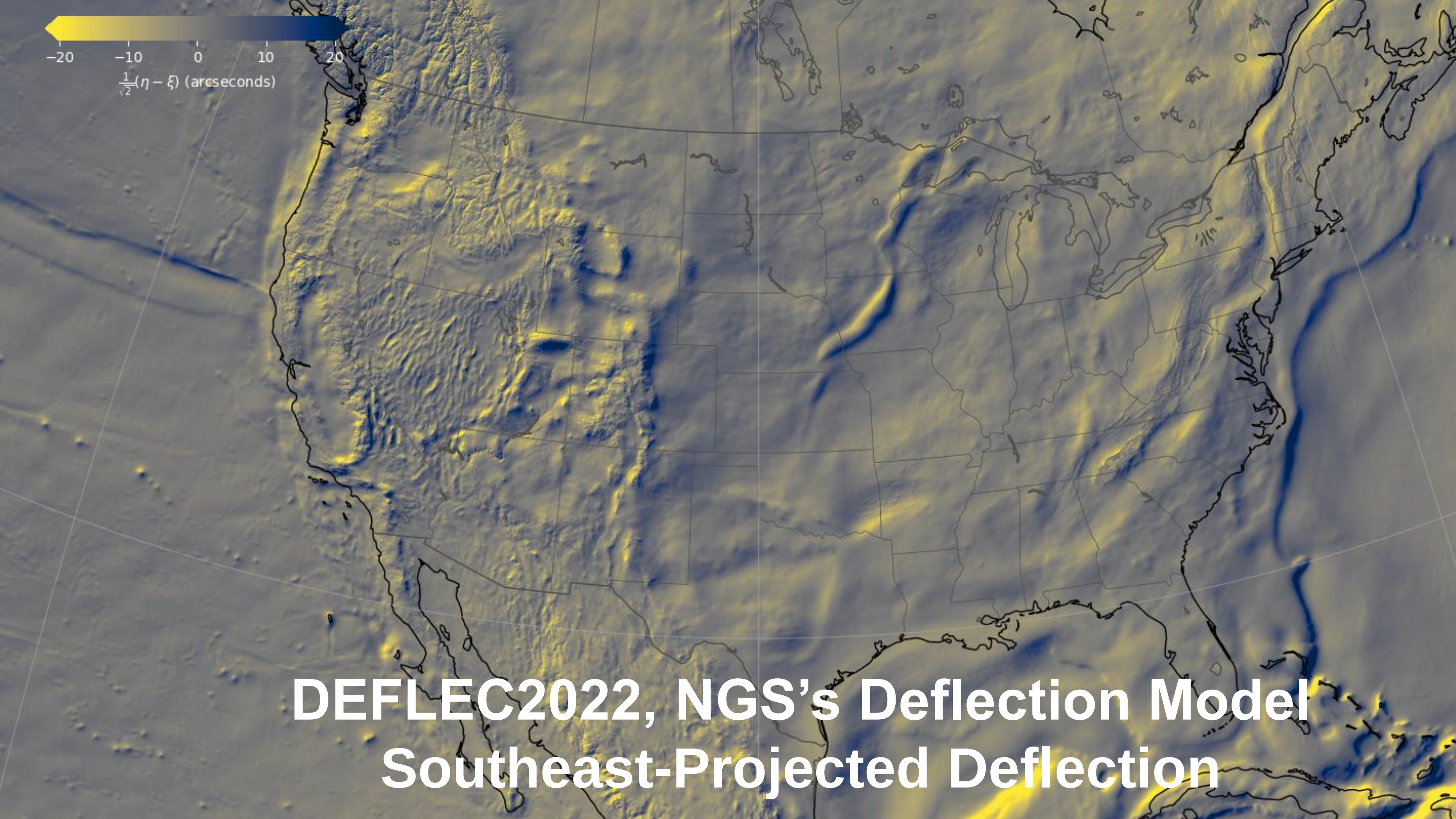


Deflection of the Vertical

- 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)

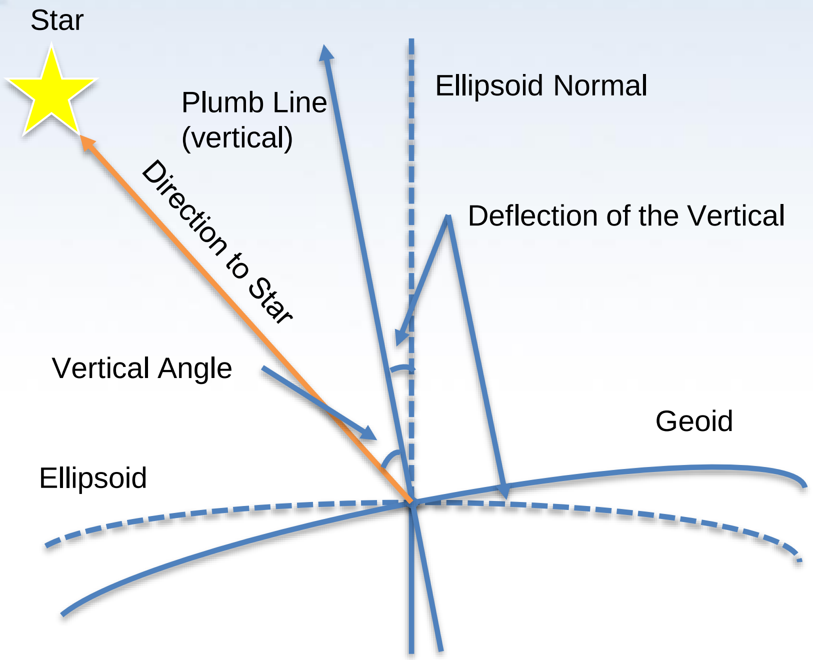


DEFLEC2022, NGS's Deflection Model
Southeast-Projected Deflection

Measuring Deflection of the Vertical

Measuring deflection of the vertical requires four key components:

1. A **vertical reference** (e.g., pendulum, fluid, or natural ocean horizon)
2. A means of measuring the angles between **stars** and the vertical reference (e.g., a camera or vertical circle)
3. The precise **time** of the observation to account for Earth's rotation
4. Geodetic **position** (from triangulation or GNSS)



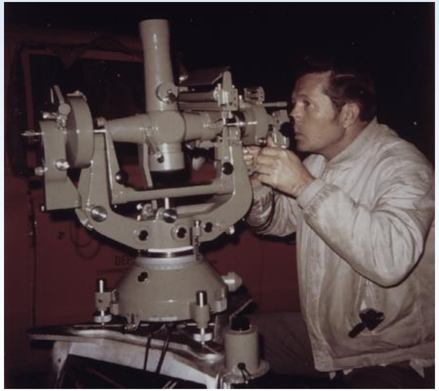
Historical US Geodetic Astronomy

- NGS and its predecessors have performed thousands of DoV observations since the 19th century

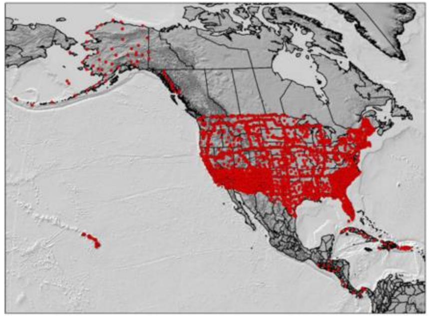
- This method required manual observations that were slow and could take an entire night to observe a single site. This technique was abandoned in the 1980s.

- Renewed interest in the geoid in the last 20 years has inspired NGS to borrow state-of-the-art Swiss zenith cameras to measure geoid slopes

- However, NGS's operational needs for geoid validation drove a demand for NGS to have its own system



Astronomical latitude observations with a Wild T-4 theodolite (1970, NOAA Photo Library)



Astronomic latitudes and longitudes in NGS's database (2019, *NOAA Technical Report NOS NGS 69*)

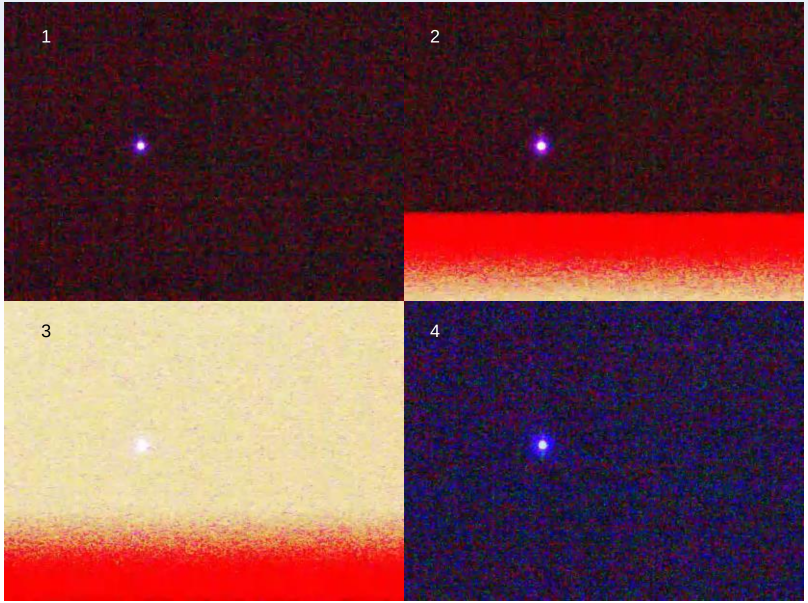
Developing a System for NGS

- NGS has two Leica TS60 imaging robotic total stations that can measure elevation angles with 0.5 arcsecond precision
- These total stations could be programmed to record images of stars and data on their elevation angles
- These elevation angles can be gathered at multiple azimuths and combined into a single solution for DoV

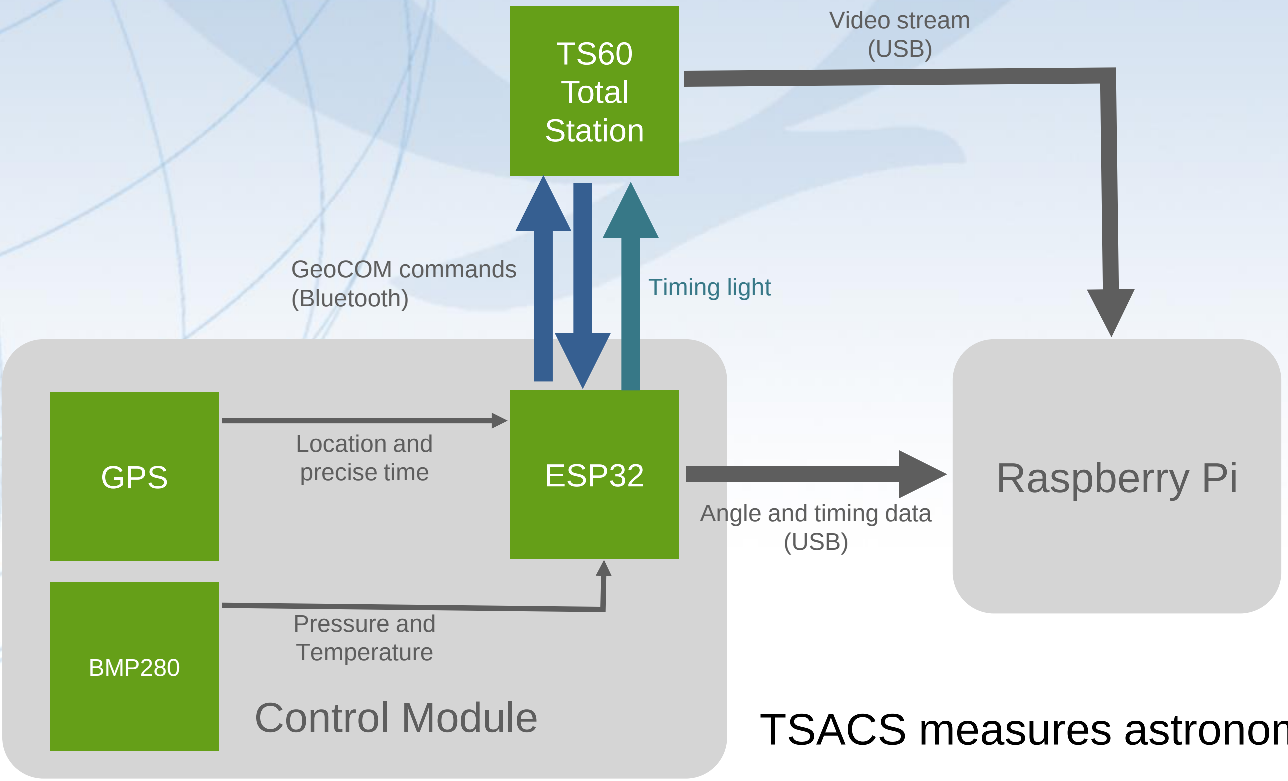
Image: Leica Geosystems

TSACS

- NGS developed the **Total Station Astrogeodetic Control System (TSACS)** in 2020
- TSACS directs a Leica TS60 robotic total station to observe bright stars 60 degrees above the horizon and record video
- The data from the total station may be used to estimate both DoV components simultaneously
- A single observation sequence observes 25 stars in 15 minutes to yield a DoV with a precision of 0.2 arcseconds or better in under an hour
- Contrast with historical techniques that require an entire night



Sequence of video frames recorded using TSACS showing starlight and a timing light flash with rolling-shutter artifact



T otal
S tation
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TSACS measures astronomic latitude and longitude.

TSACS directs the Leica TS60 robotic total station to record video of stars with precise timing.

TSACS Hardware

Timing Light

5V Power Bank

Raspberry Pi

GEV-234 Cable

Control Module

ESP32 Microcontroller

GPS

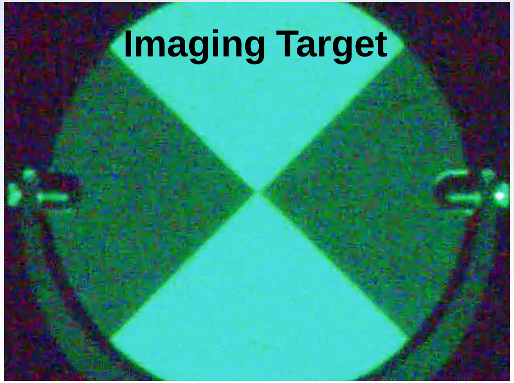
USB C To Power

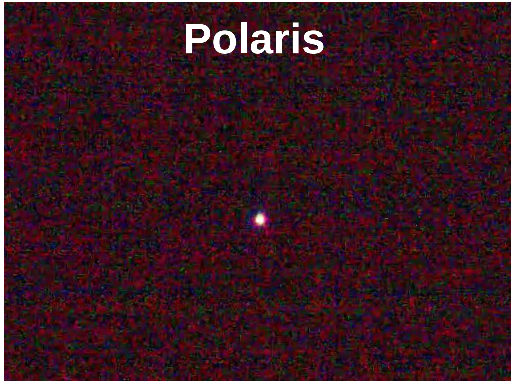
USB to TS60

Timing Light

Azimuths with TSACS

- NGS has experimented with using TSACS to observe terrestrial targets and Polaris simultaneously to establish astronomic azimuths
- Azimuths and deflections of the vertical orient local survey networks in global reference frames
- TSACS can establish azimuths with approximately 0.4 arcsecond accuracy, an order of magnitude better than GNSS
- NGS uses these azimuths for orienting IERS vector tie surveys





TSACS Deployments

- Washington, DC (2020)
  - Testing against historical measurements and models
- Alaska (2021, 2025)
  - Monitoring geoid change
- Columbus, Ohio (2022)
  - Geoid validation and testing
- Austin, Texas
  - Testing and demonstration with NGA and ARL partners
- IERS vector tie surveys
  - Hawaii
  - Greenbelt, MD
- Louisiana (2024)
  - Geoid validation on the Mississippi River

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

Conclusions

- Geodetic astronomy offers precise optical solutions for both geoid validation (heights) and orienting local tie surveys (directions)
- TSACS was developed to fill a need for geodetic astronomy at NGS using commercial survey equipment and inexpensive hobbyist electronics
- NGS is constantly making improvements to TSACS, including using 3D printing to improve hardware components
- TSACS is in a state where anyone at NGS or its trusted partners can be trained make an observation and analyze the data