Geodetic Astronomy at NGS: Past and Present

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NGS Webinar Series

Outline

Geodetic astronomy uses the stars and other celestial bodies to orient local terrestrial reference frames

- Fundamentals
- Historical practice
- Recent efforts at NGS, including TSACS

Elevation Angles

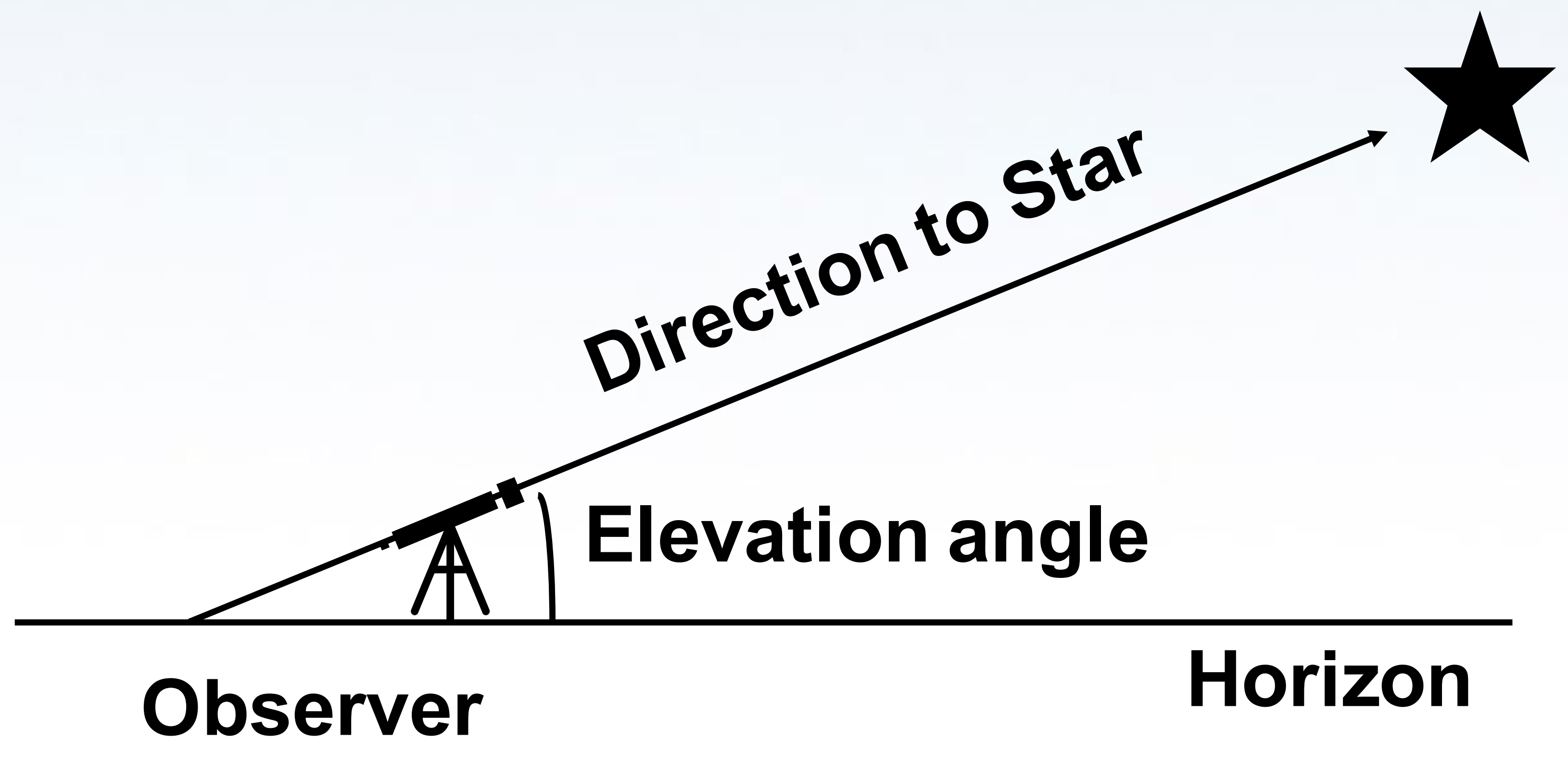
- A fundamental measurement is the elevation angle, or the angle between a celestial body and the plane of the horizon

- Requires three components:

1. A vertical reference (e.g., pendulum, fluid, or natural ocean horizon)

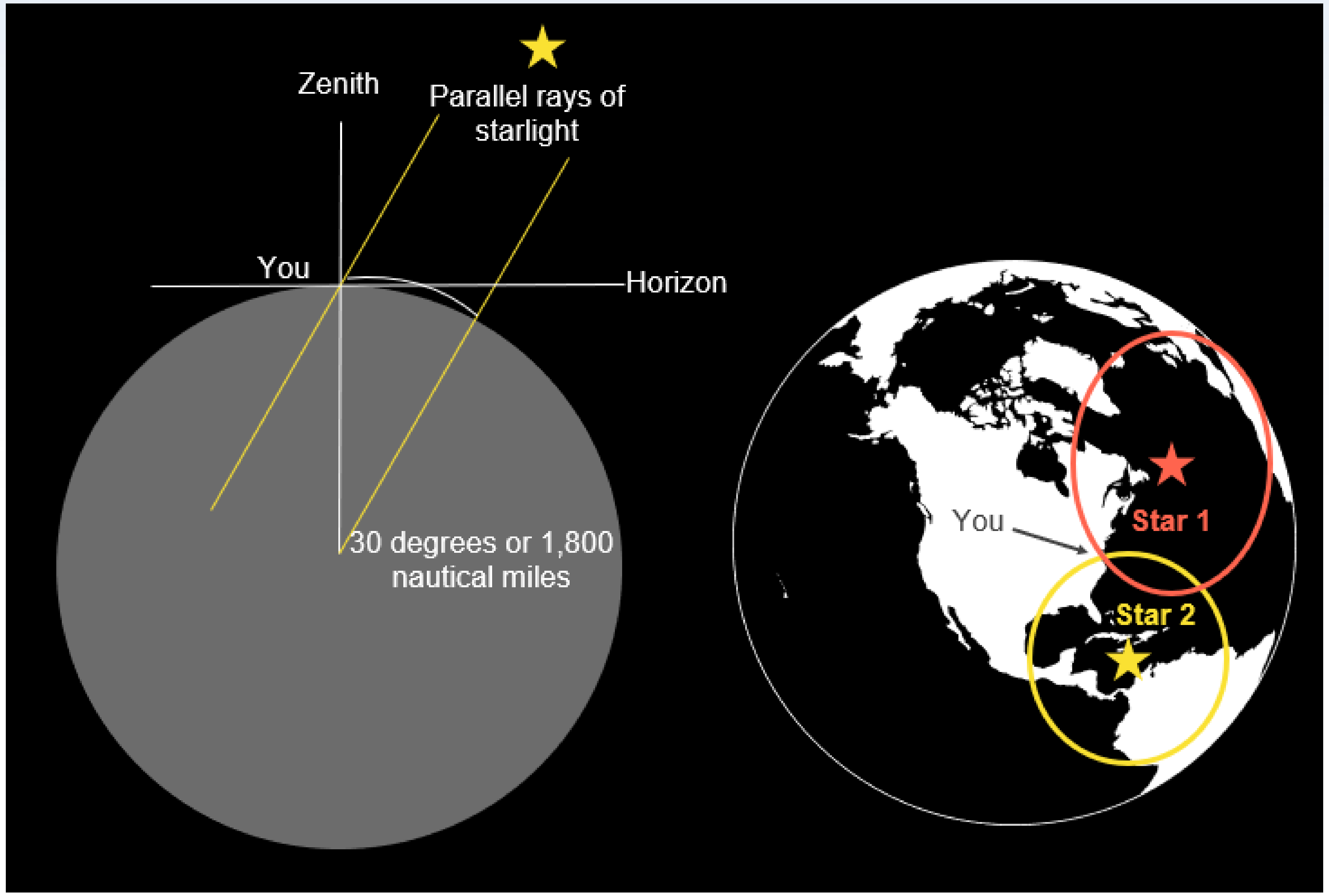
2. A means of measuring angles (e.g., a telescope, graduated circle, or camera)

3. Time, or a measure of Earth's rotation state (a clock or a fast-moving celestial body like the Moon)



Celestial Navigation

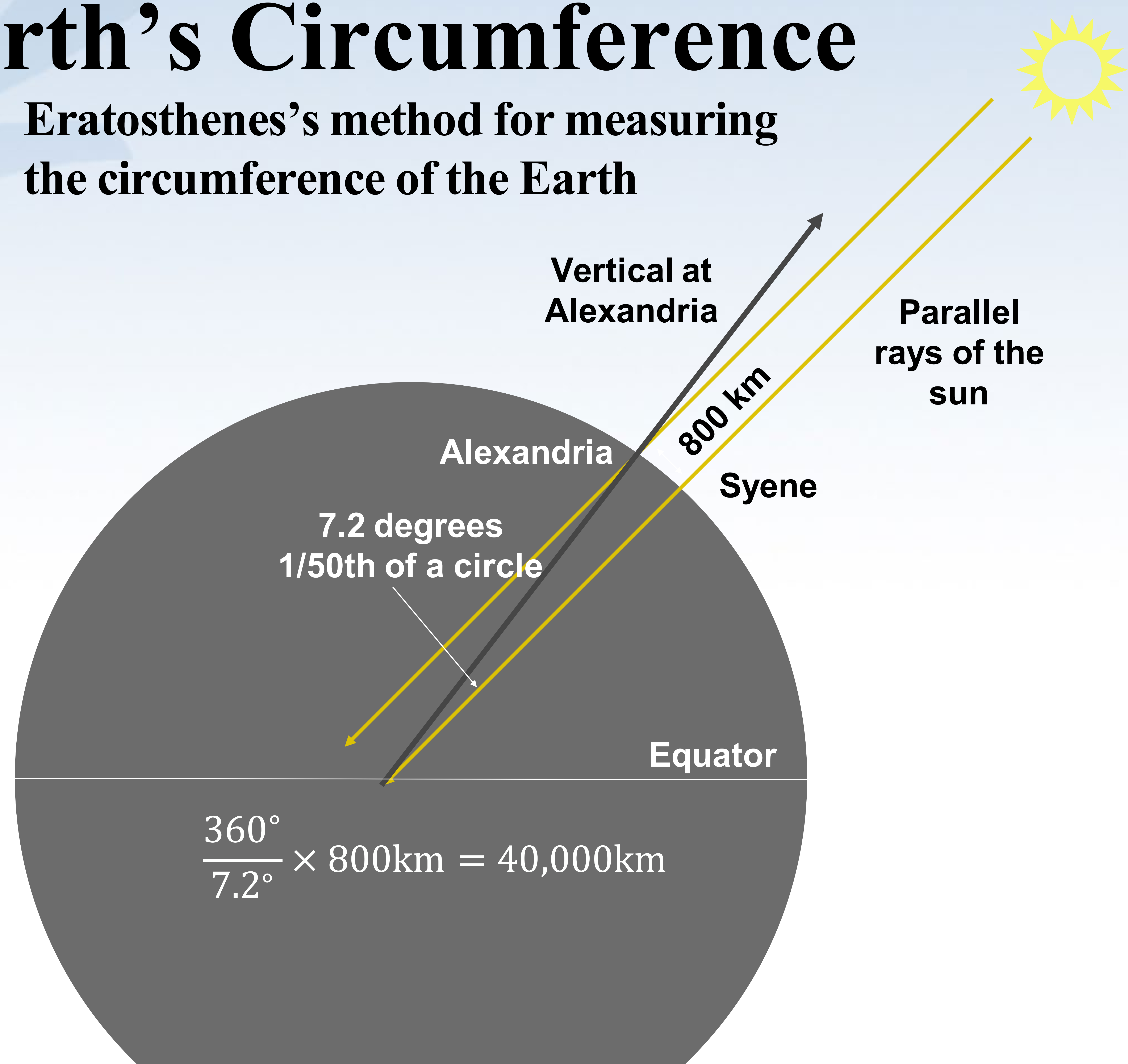
- For any given instant, there will always be a point where a star will be directly overhead
- If you move away from this point, the elevation angle of this star will decrease
- Measuring elevation angle at that instant therefore allows you to determine how far you are from this point
- Measuring the elevation angles of multiple stars makes it possible to determine your position on a sphere



Eratosthenes and Earth's Circumference

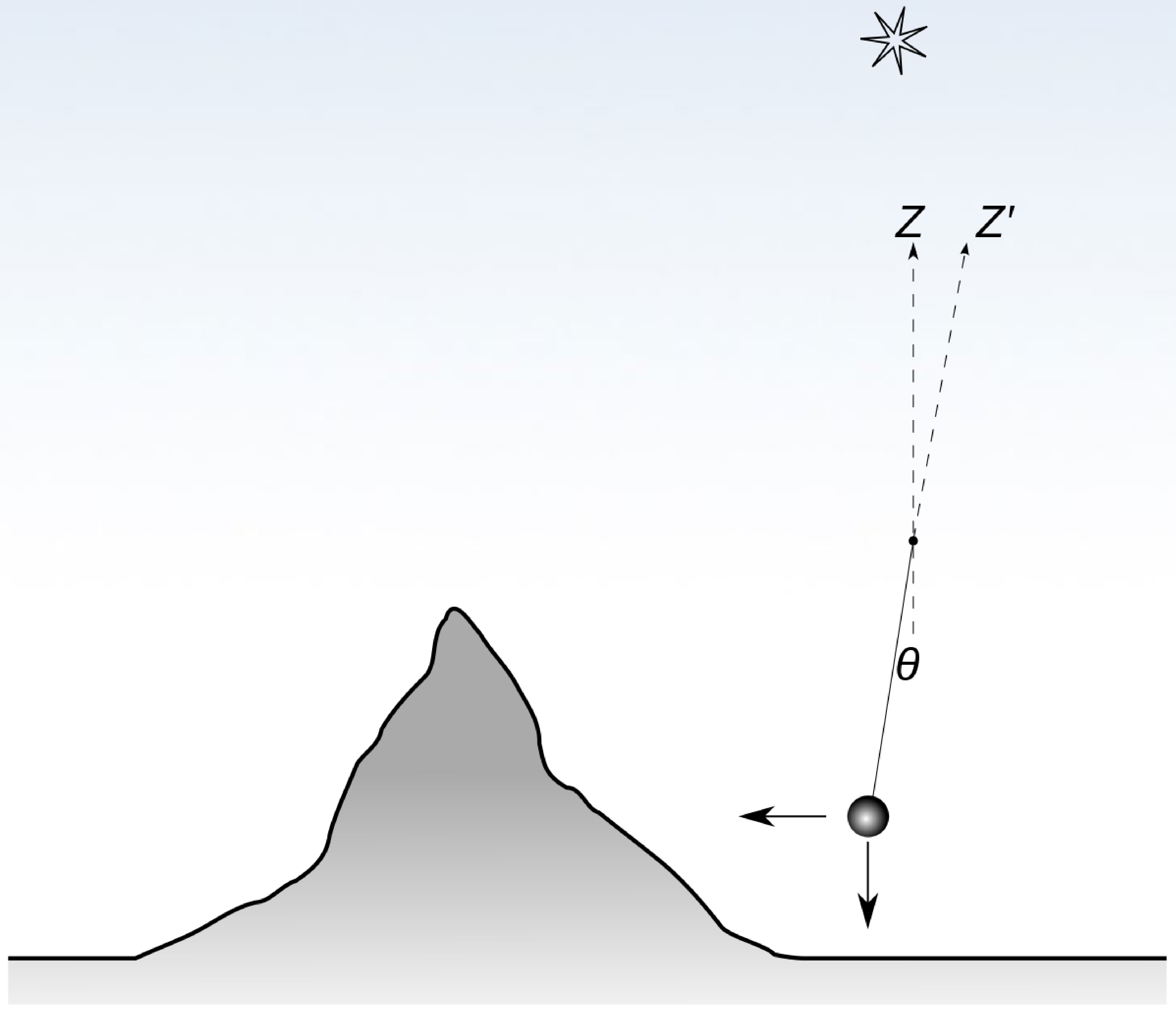
- If you can measure how much elevation angles change over a distance, you can effectively measure the curvature of the Earth
- This is how it was first measured by Eratosthenes, a Greek astronomer, in the 3rd century BC
- Eratosthenes used the difference in the lengths of shadows on the summer solstice and the known distance between two points to determine the circumference of the planet

Eratosthenes's method for measuring the circumference of the Earth



Schiehallion Experiment

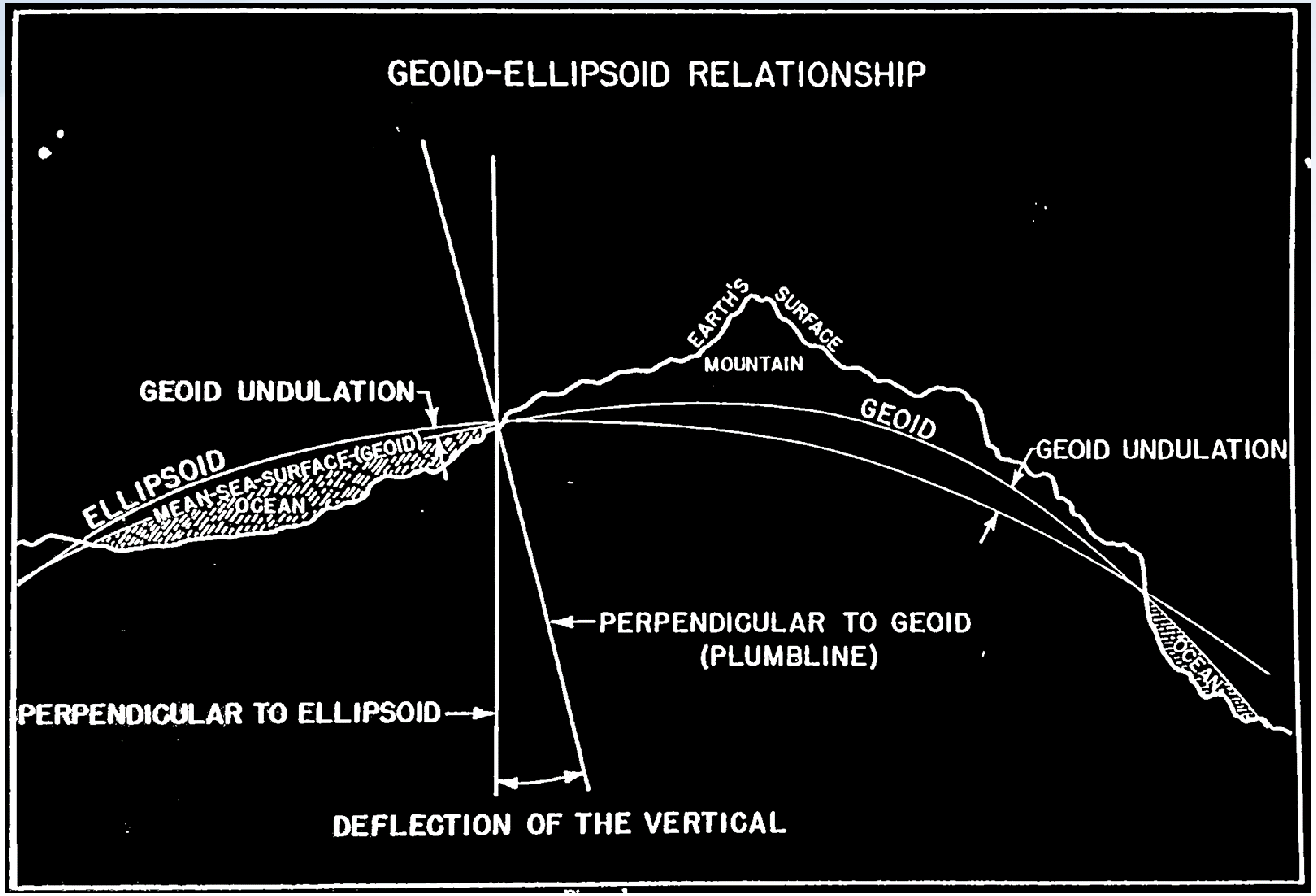
- Whereas Eratosthenes measured Earth's curvature across hundred of kilometers, a team of British astronomers in 1774 first measured minute variations in its curvature across a kilometer
- These astronomers set out to measure how the gravitational attraction of a mountain in Scotland with known volume, shape, and density compared with the attraction of the entire planet, thereby allowing them to estimate Earth's density
- They measured elevation angles on the north and south sides of the mountain and found that the difference in elevation angles between both sides was 11.6 arcseconds larger than predicted from the distance
- This arguably was the first measurement of the deflection of the vertical



Deflection of the vertical from the attraction of Schiehallion
Wikimedia Commons

Astronomy and Physical Geodesy

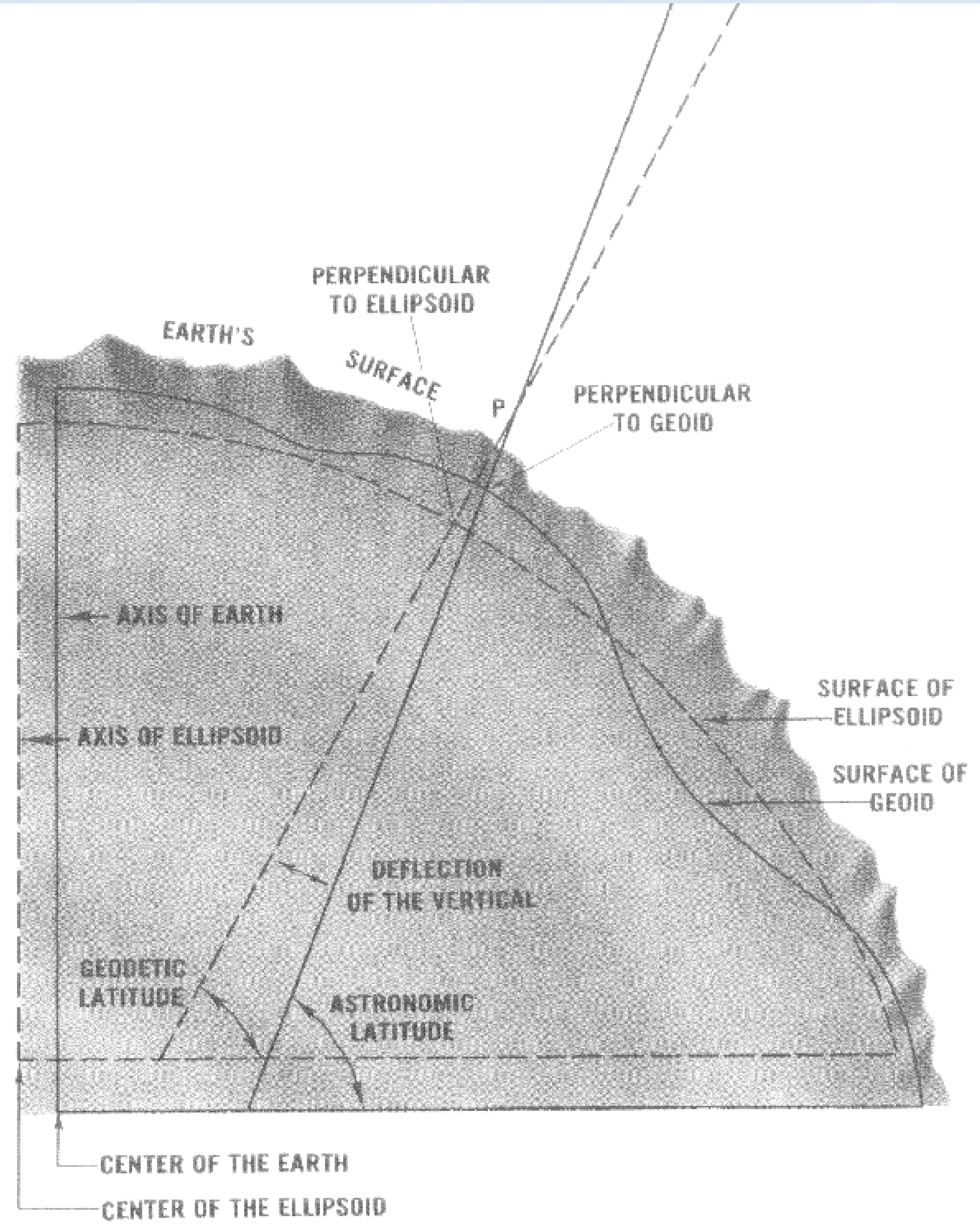
- Important terms
  - Plumb line
  - Geoid
  - Ellipsoid
  - Deflection of the vertical



Poling (1967)

Coordinates

- Astronomic or "natural" coordinates
  - Astronomic latitude and longitude: Which way is up?
  - Orthometric height: How far have I traveled up or down from the geoid?
- Geodetic coordinates
  - Geodetic or ellipsoidal latitude, longitude, and height: Where am I in three-dimensional space?
- The deflection of the vertical gives the difference between astronomic and geodetic latitude and longitudes
- The difference between orthometric and ellipsoidal heights is the geoid undulation



1984, Geodesy for the Layman

Coast & Geodetic Survey Astronomy

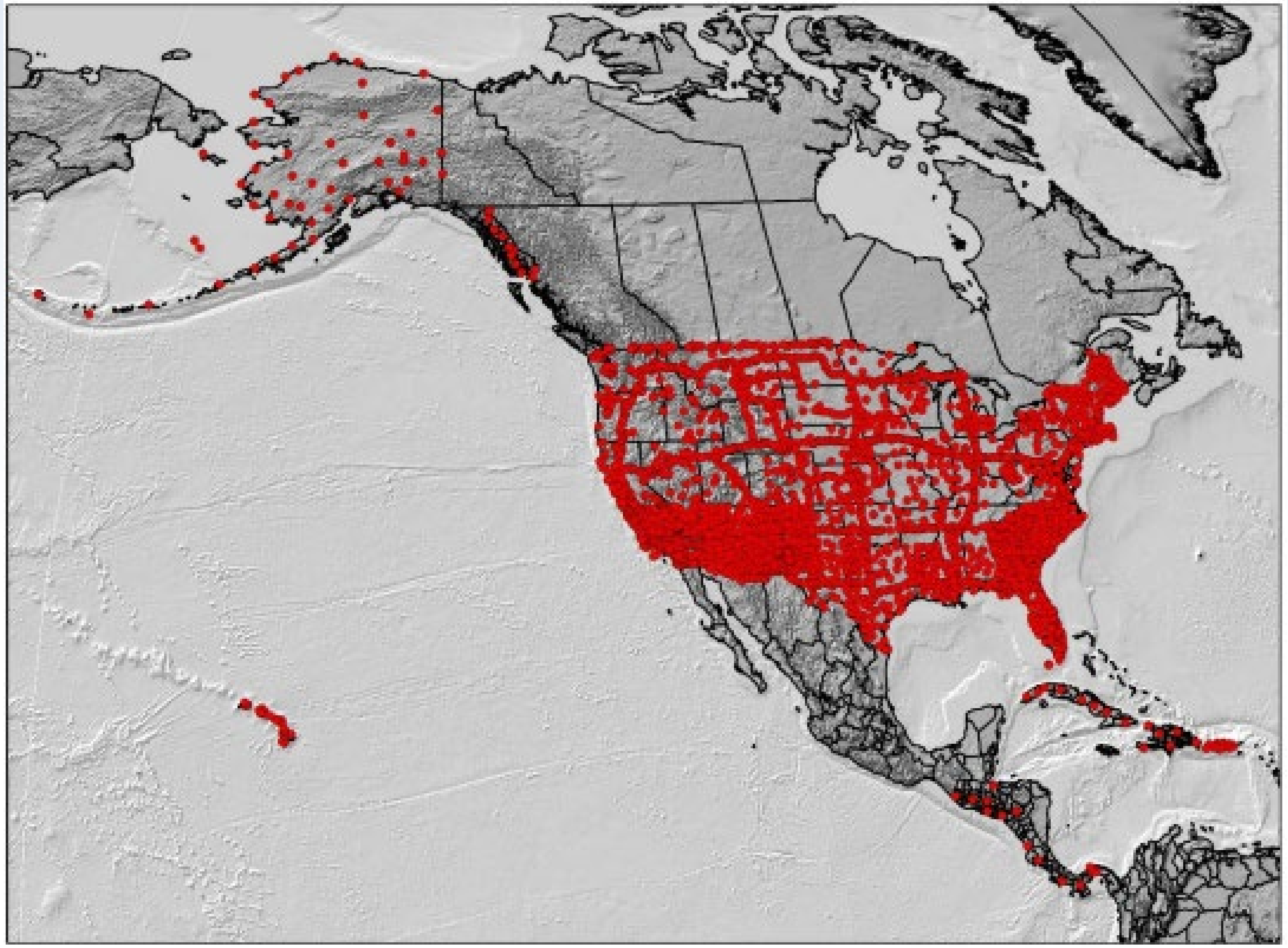
- Starting in 1846, the Coast & Geodetic survey measured 4,000+ astronomic latitudes and longitudes

- Geodetic astronomy provided

  - **Orientations**: Azimuths, datum definitions

  - **Positioning**: Astronomic latitudes and longitudes were repeatable within meters across continents. They helped correct drift in triangulation networks and define sate and national borders.

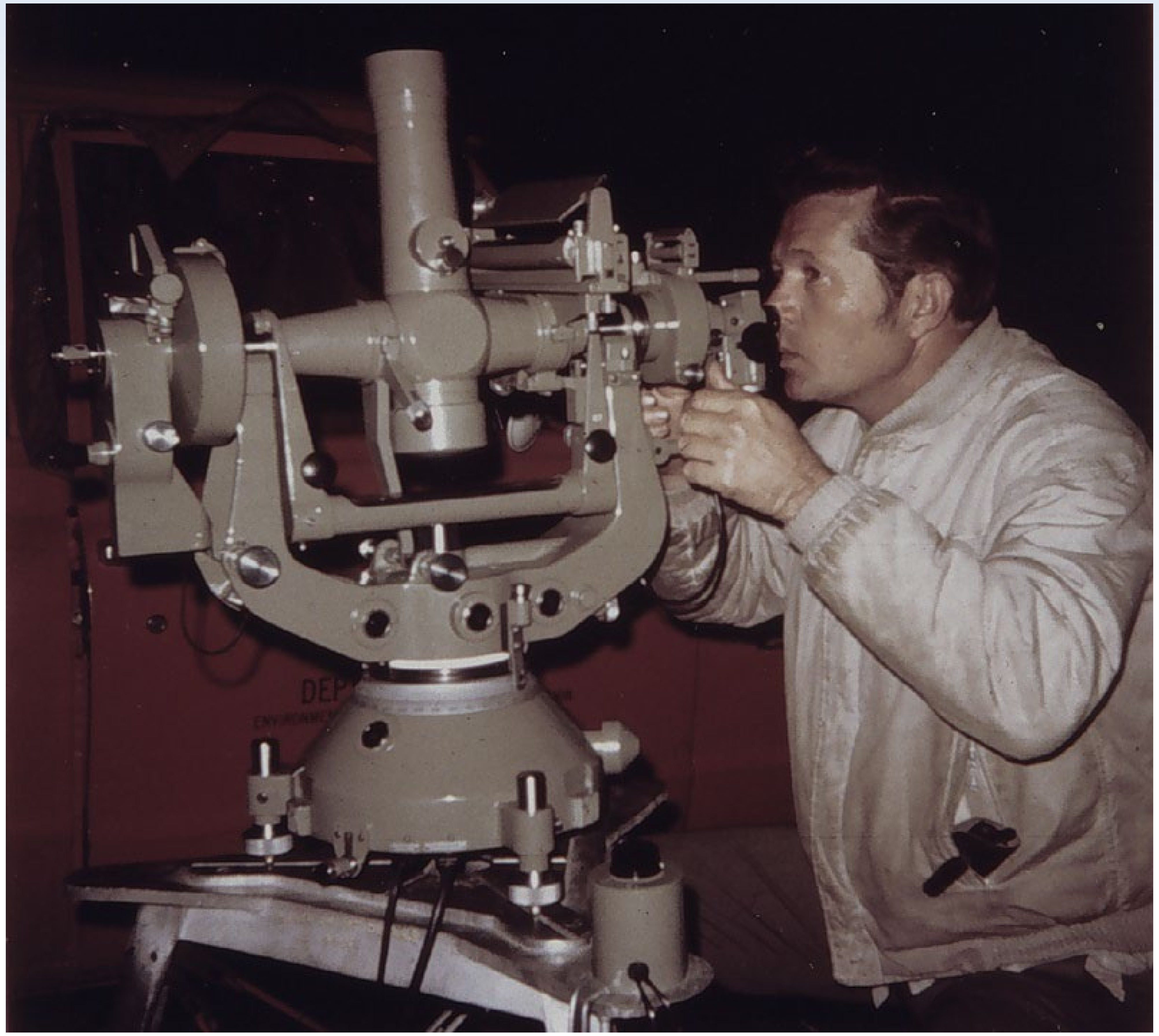
  - **Physical geodesy:** Deflections of the vertical helped with early geoid studies



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

Measuring Latitude

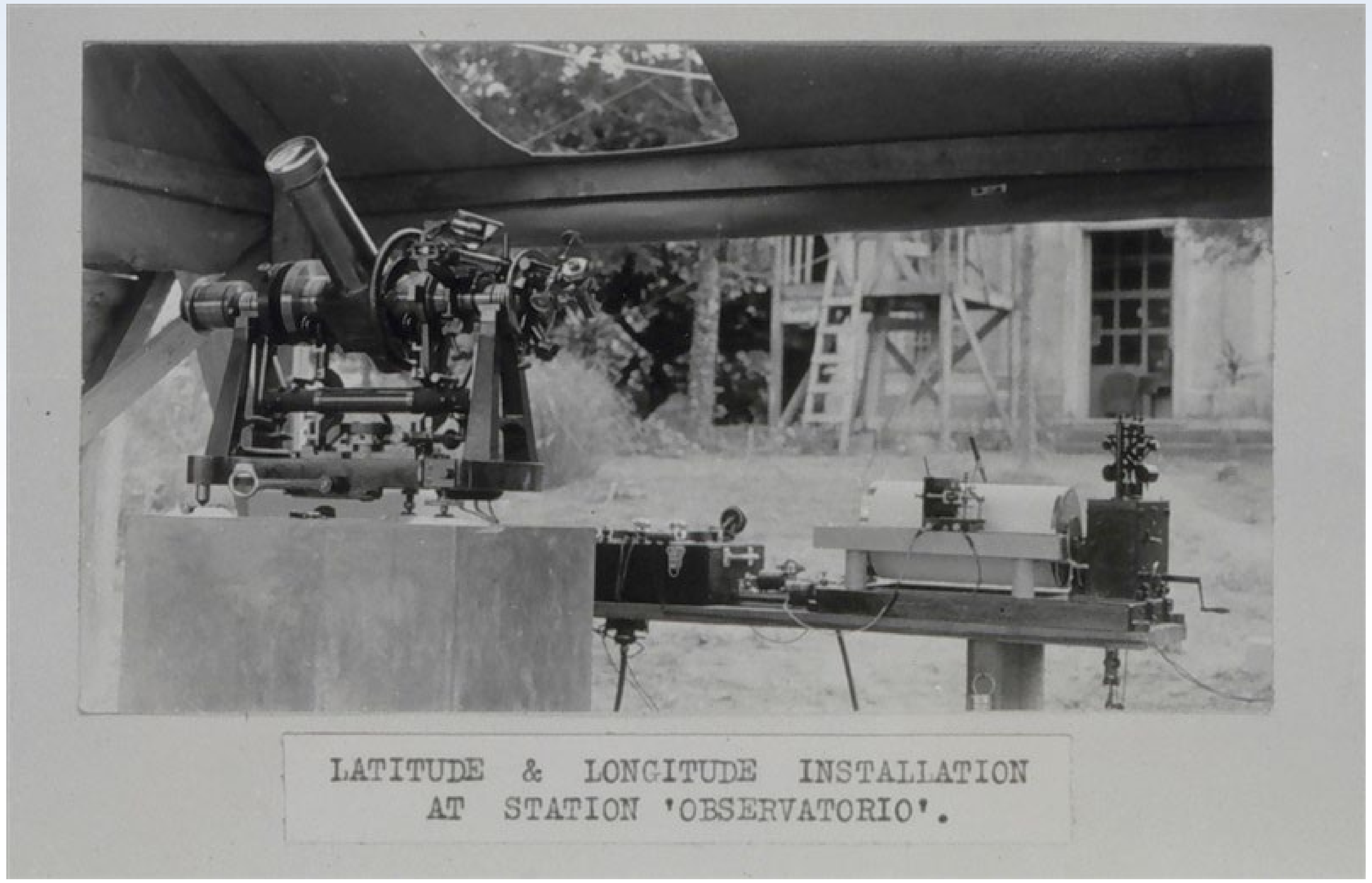
- Latitudes are most easily measured when a star transits, or reaches its highest or lowest point in the sky.
- The Coast & Geodetic Survey used the Horrebow-Talcott method, which involved measuring the transits of pairs of stars at similar elevation angles, but opposite sides of the sky.
- This method could reliably recover latitudes with 0.3 arcsecond precision after observing 16 pairs of stars.
- This method was slow and could take an entire night to obtain all pairs.



Wild T-4 Theodolite in action (1970, NOAA Photo Library)

Measuring Longitude

- Longitude requires measuring the precise time of passage of a star, usually at transit
- The Coast & Geodetic Survey used telegraphic methods to synchronize clocks in the different cities up to the 1930s
- Surveyors in the mid-20th century used shortwave time broadcasts for time synchronization
- Longitude observations were sensitive to observer reaction times, which had to be precisely calibrated.



Bamberg Transit, radio, and chronograph drum for longitude (1935, NOAA Photo Library)

Measuring Azimuth

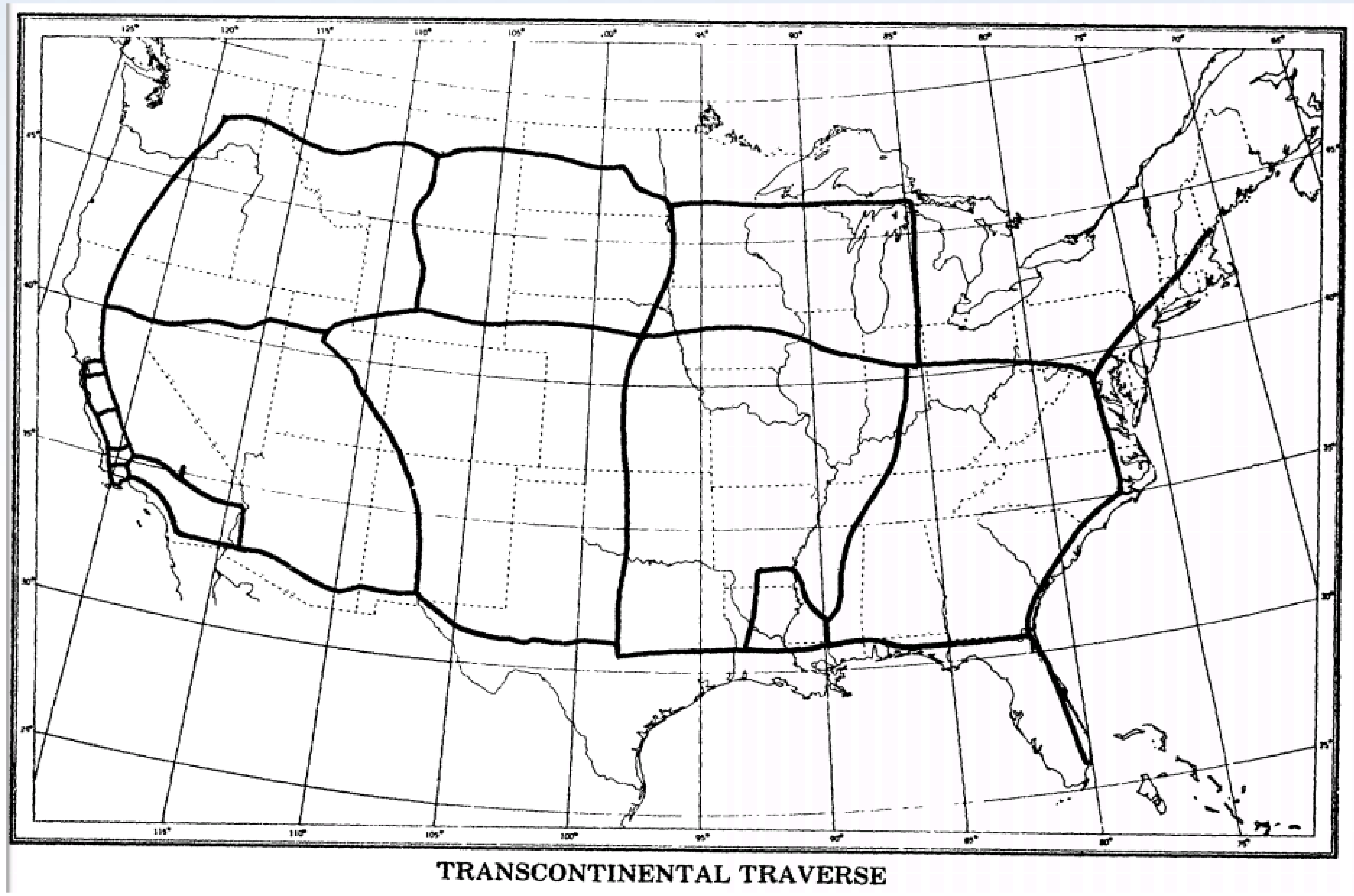
- Astronomic azimuths were performed with lighter, more portable equipment, like the Wild T-3 (late 20th century) or Parkhurst theodolite (mid-20th century)
- An azimuth observation consisted of alternating observations of Polaris (or another circumpolar star) and a lighted target several kilometers away
- Typical accuracy was on the order of 1.5 arcseconds after 16 sets of observations of Polaris and the terrestrial target

Lighted Wild azimuth target (photo by author)

Wild T-3 theodolite (1977, NOAA Photo Library)

Transcontinental Traverse

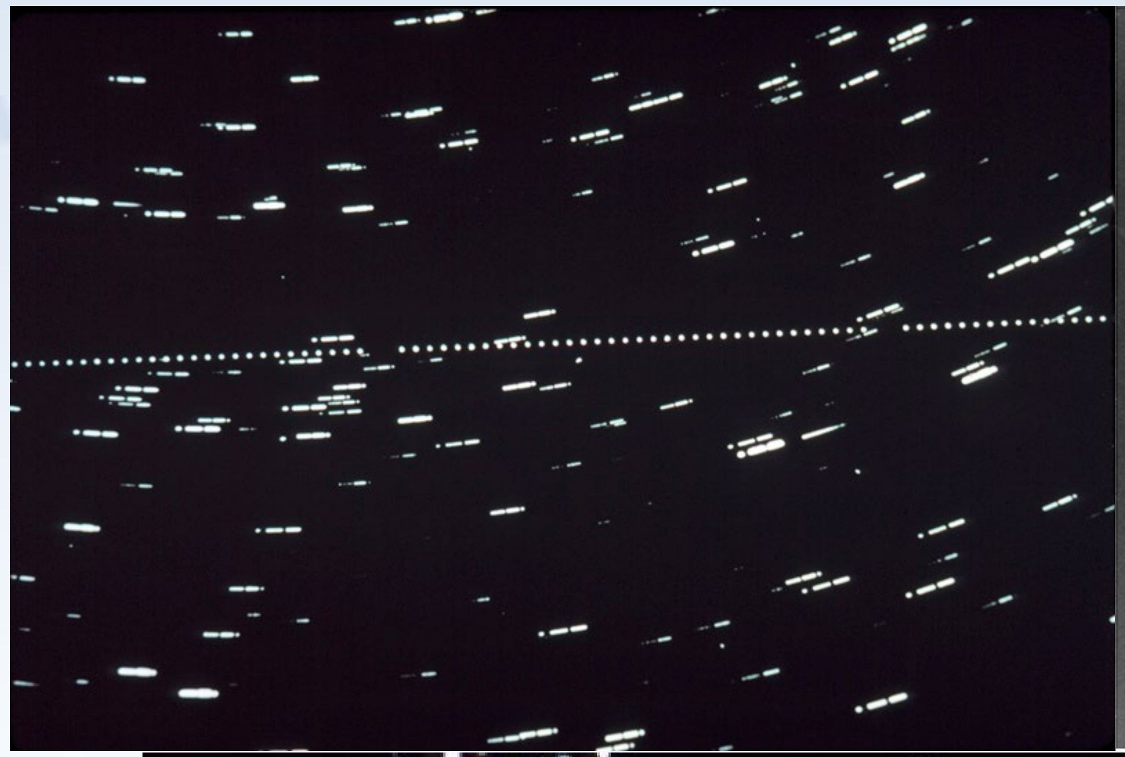
- Between 1961 and 1976, the Coast & Geodetic Survey (later NGS) conducted more than 2,700 astronomic latitude, longitude, and azimuth observations as part of the *High-Precision Transcontinental Traverse*
- This program used high-precision distance and angle measurements to connect stations that observed satellites and geodetic framework for the contiguous United States
- Dense deflection-of-the-vertical profiles of were used to study the geoid

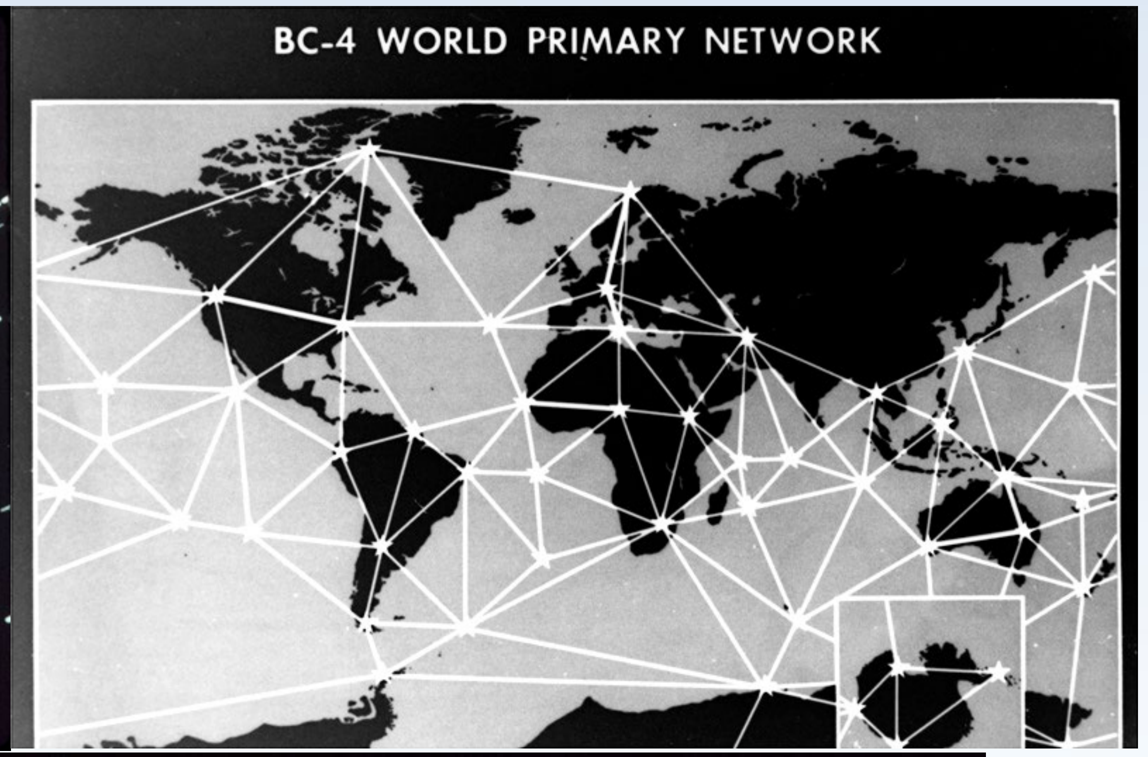


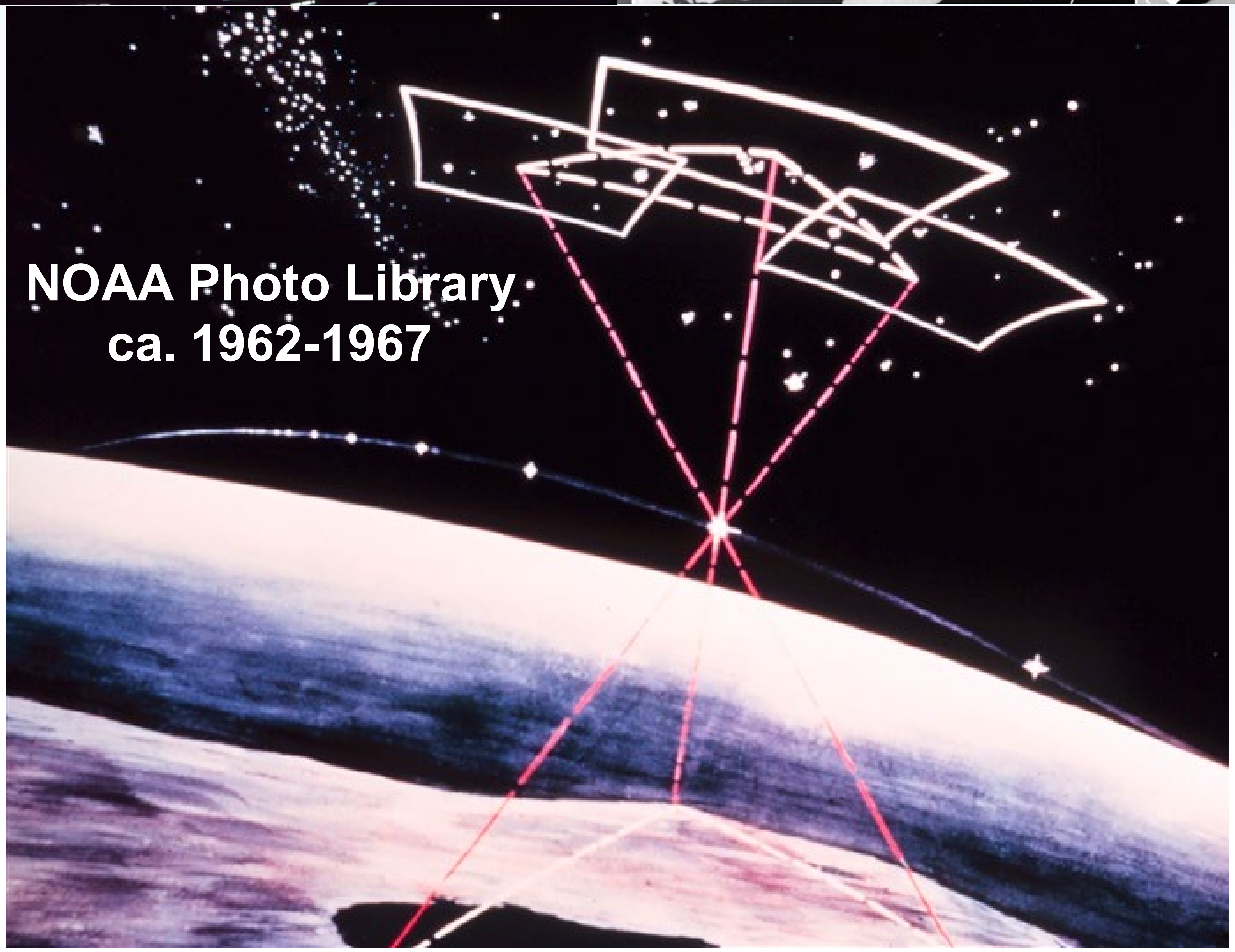
1984, *Geodesy for the Layman*

Satellite Triangulation

- The Coast & Geodetic Survey contributed to early satellite triangulation programs in the 1960s, photographing satellites against a background of stars
- These satellites could be used like triangulation targets, with the stars providing directional reference, to allow the solution of the relative positions of these stations
- The satellite triangulation program contributed to the development of the first global geodetic datums
- These methods were superseded by more precise radio-based techniques that could be used in all weather



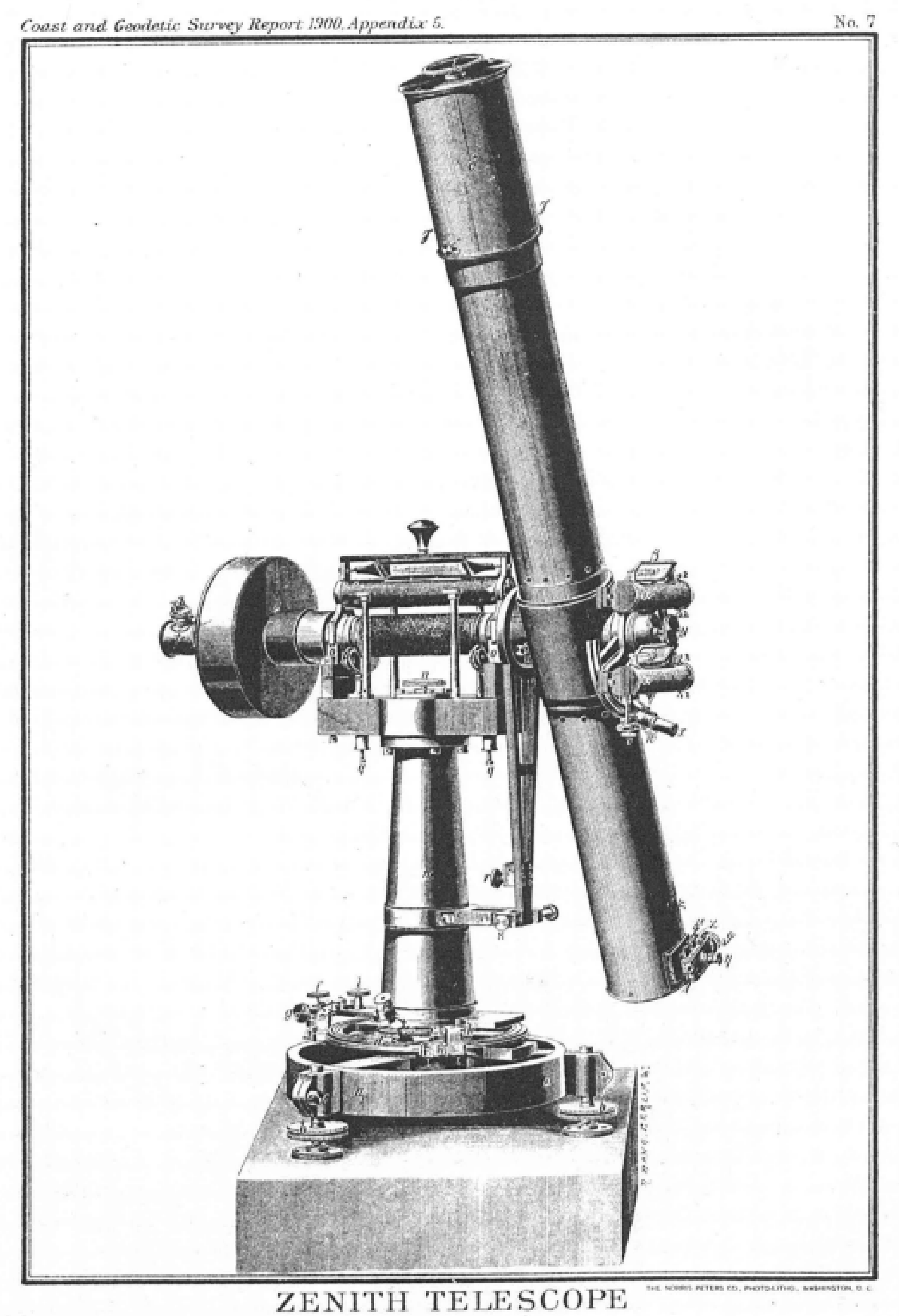




NOAA Photo Library
ca. 1962-1967

Variation of Latitude

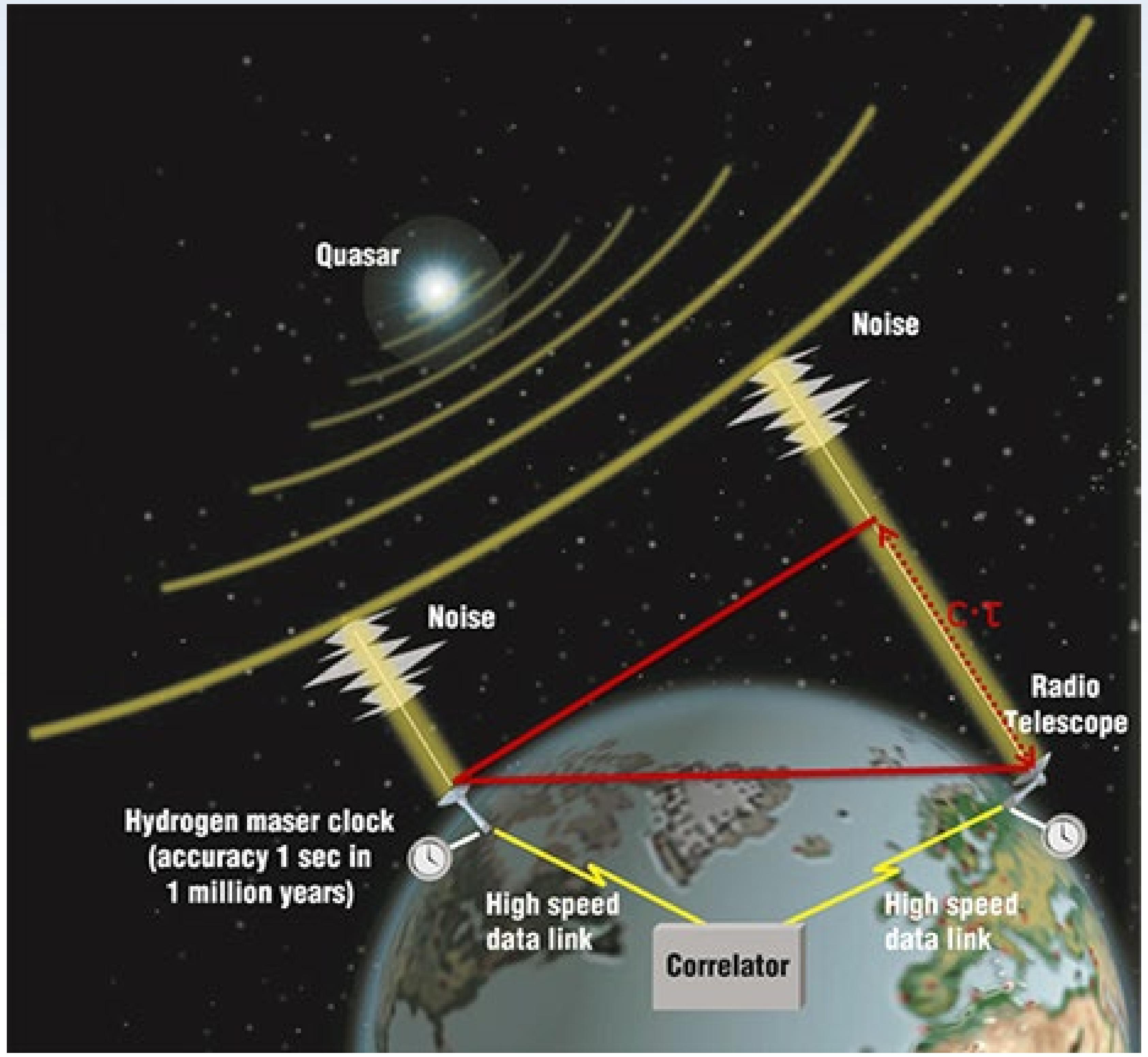
- The Coast & Geodetic Survey contributed to the International Latitude Service, measuring latitudes from static locations on clear nights to determine *variation of latitude (a.k.a. polar motion)*, or the arcsecond-scale wobble of Earth's rotation axis
- C&GS stations in Ukiah, CA and Gaithersburg, MD made tens of thousands of these observations from 1899 to 1982
- These methods were superseded by more precise radio techniques



Zenith telescope used at International Latitude Observatory in Gaithersburg (1900, C&GS Annual Report)

Sunset for Geodetic Astronomy

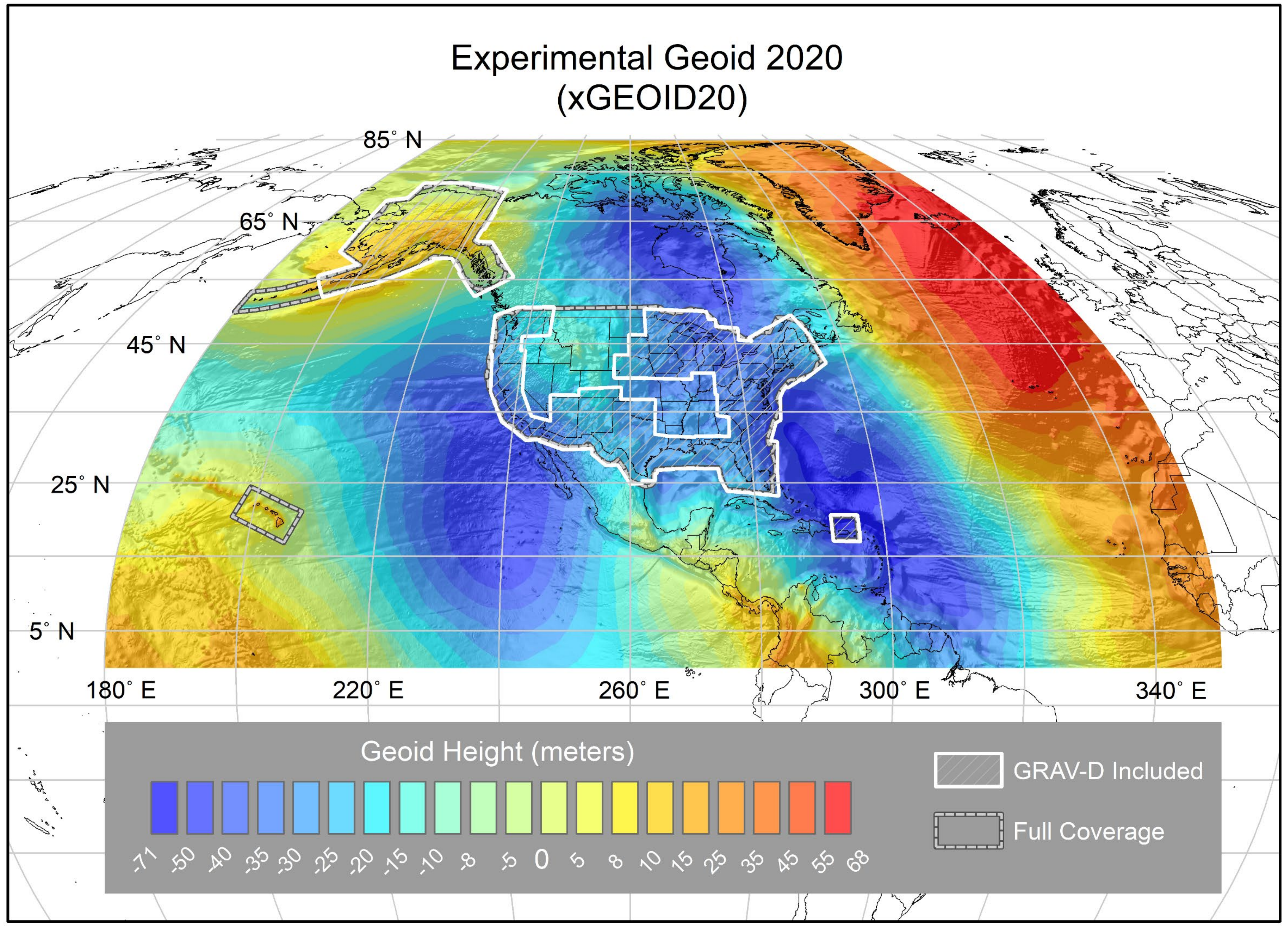
- Geodetic astronomy was ultimately superseded by radio-based techniques in the 1980s. The last astrogeodetic observation in NGS's database was from 1985.
- Radio-based satellite navigation (Transit or GPS) could be used in all weather conditions for geodetic positioning
- Very-long-baseline interferometry (VLBI), a radio astronomy technique, provided far better orientations for geodetic networks
- Deflections of the vertical could be predicted using dense terrestrial gravity observations



NASA

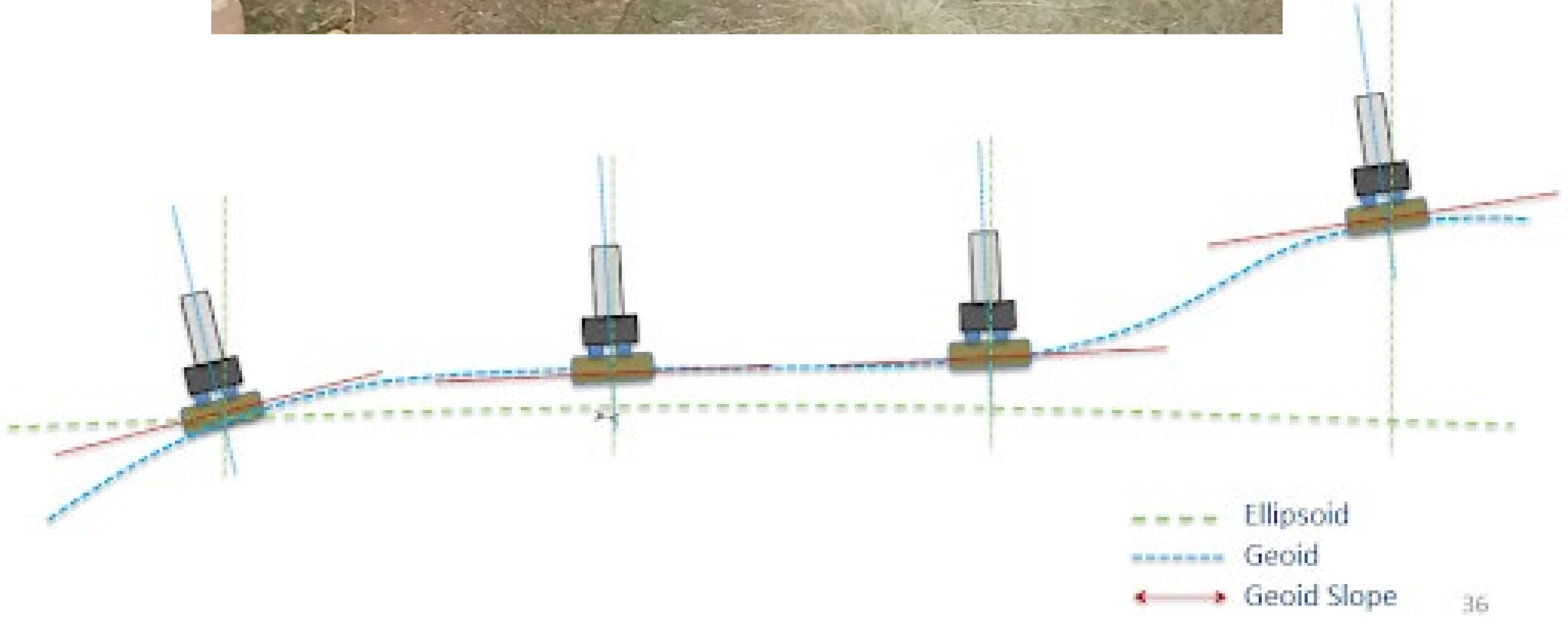
Renewed Interest in the Geoid

- The geoid is an ideal basis for a height system because it is a surface of equal gravitational potential. Heights above the geoid predicts which way water will flow.
- However, the best geoid models could not match the positioning precision of GNSS until the early 2000s
- Satellite gravity missions, including GRACE (2002) and GOCE (2009) made it possible to drive down the broad-scale errors in gravity models and produce 1-centimeter geoid models for most of the United States
- The promise of a 1-centimeter geoid demands better validation



Geoid Slope Validation Surveys

- Three surveys in Texas (2011), Iowa (2014), and Colorado (2017) measured 200 km profiles of the geoid at the centimeter level by measuring its slopes
- One tool for measuring the geoid slope was the CODIAC zenith camera developed by Sébastien Guillaume at ETH Zurich
- Zenith cameras point straight up to minimize refraction error, imaging faint stars. CODIAC can obtain precision on the order of 0.05 arcseconds.



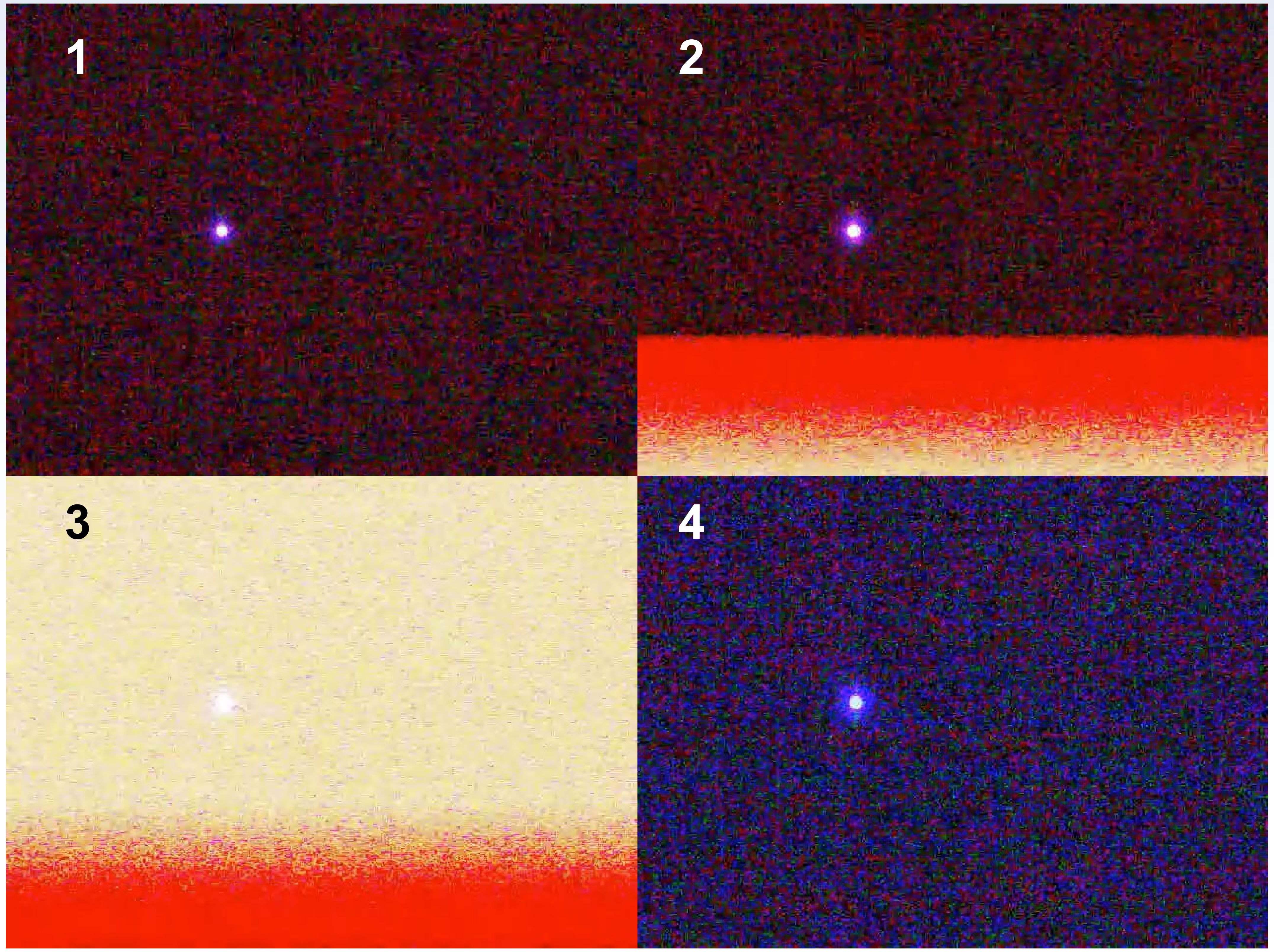
Developing a System for NGS

- CODIAC proved useful for NGS, but was ultimately borrowed. NGS needed its own modernized capability.
- NGS has two Leica TS60 imaging robotic total stations that can measure vertical angles with 0.5 arcsecond precision
- These total stations could be programmed to observe stars and record data on their elevation angles
- The QDaedalus system demonstrates that total stations could be used for geodetic astronomy, estimating latitude and longitude simultaneously

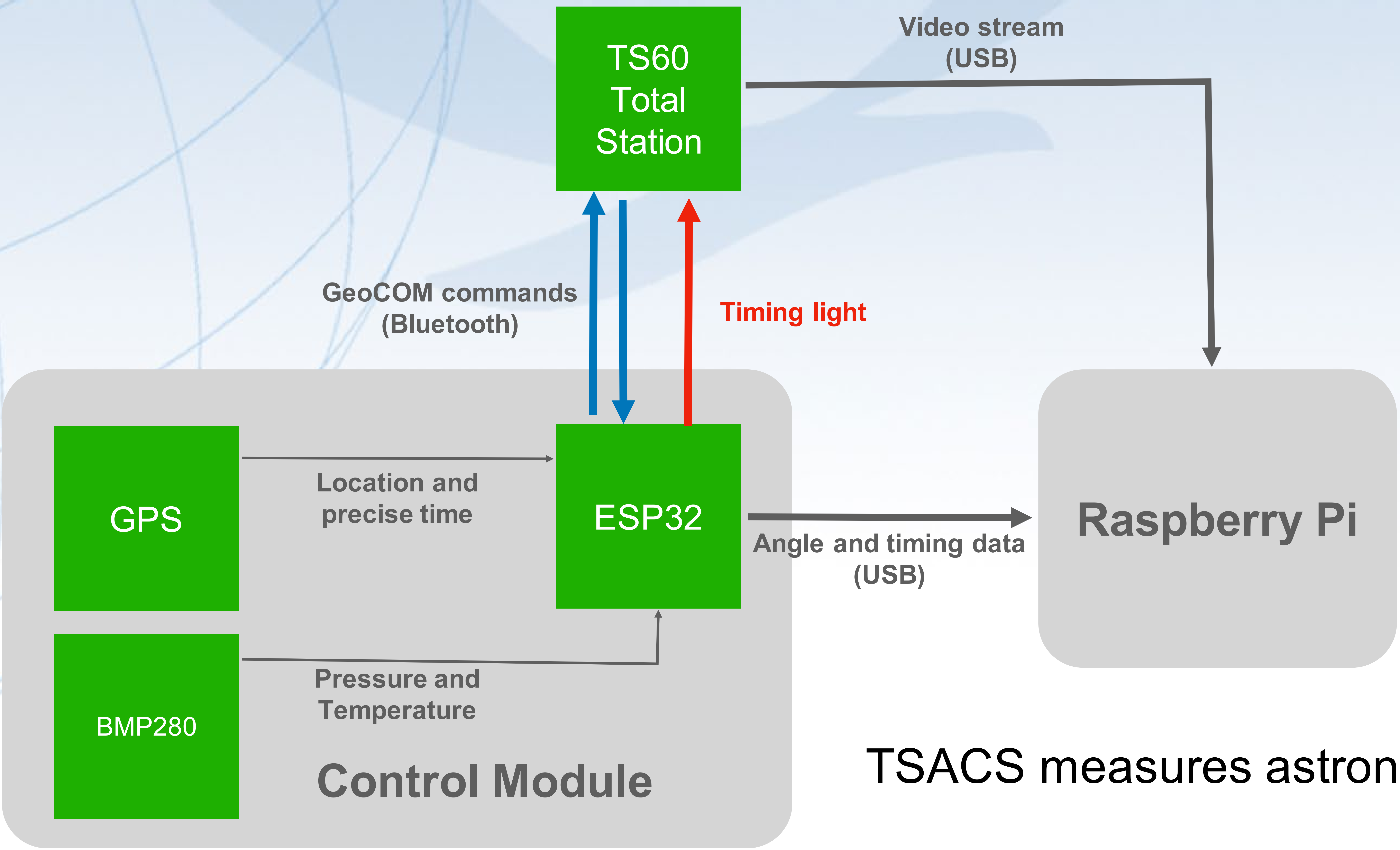
Image: Leica Geosystems

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 latitude and longitude simultaneously
- A single observation sequence takes 15 minutes and a site can be robustly observed with precision better than 0.2 arcseconds 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
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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

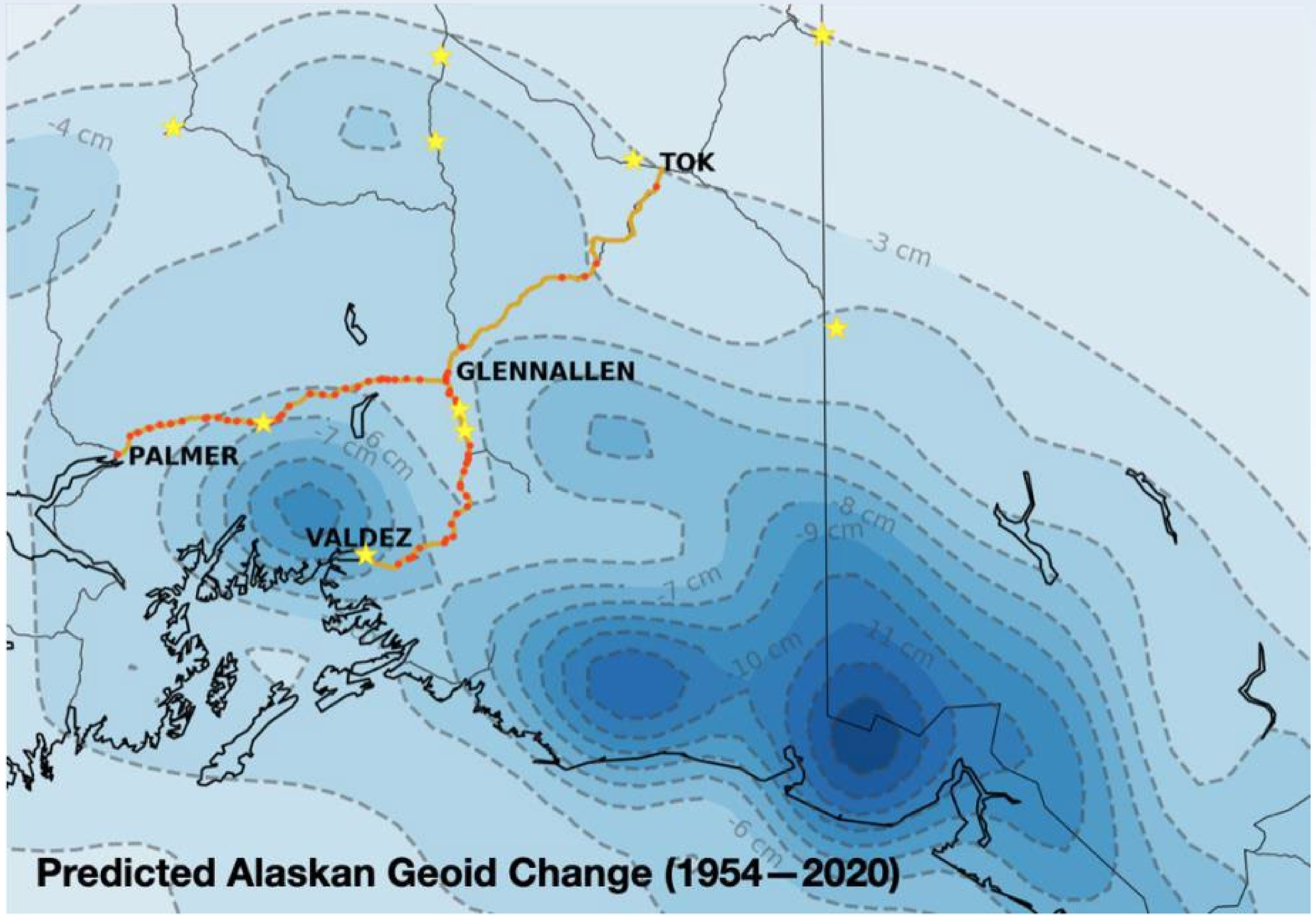
TSACS Testing

- TSACS was tested in the DC area in 2020. The est sites were chosen to revisit historical sites and to get a wide range of comparisons with NGS's deflection of the vertical models
- TSACS testing against historical measurements in the DC area and CODIAC measurements in Virginia reveals 0.16 arcsecond precision for a single measurement, with unknown systematic biases of 0.1 arcseconds.
- TSACS is highly portable and can be operated by a single person in a variety of settings

TSACS being tested at the International Latitude Observatory historical site in Gaithersburg, MD

TSACS in Alaska

- NGS is interested in how the geoid changes on decadal timescales to maintain 1 centimeter accuracy. See webinars:
  - *The NGS Geoid Monitoring Service (Kevin Ahlgren)*
  - *Geoid Change in Alaska (Ryan Hardy)*
- Ice mass loss, plate tectonics, and other factors contribute to rapid changes in height, gravity and the geoid in Alaska.
- NGS has developed models of these changes, which predict height changes of tens of centimeters, but needs data to tune them.



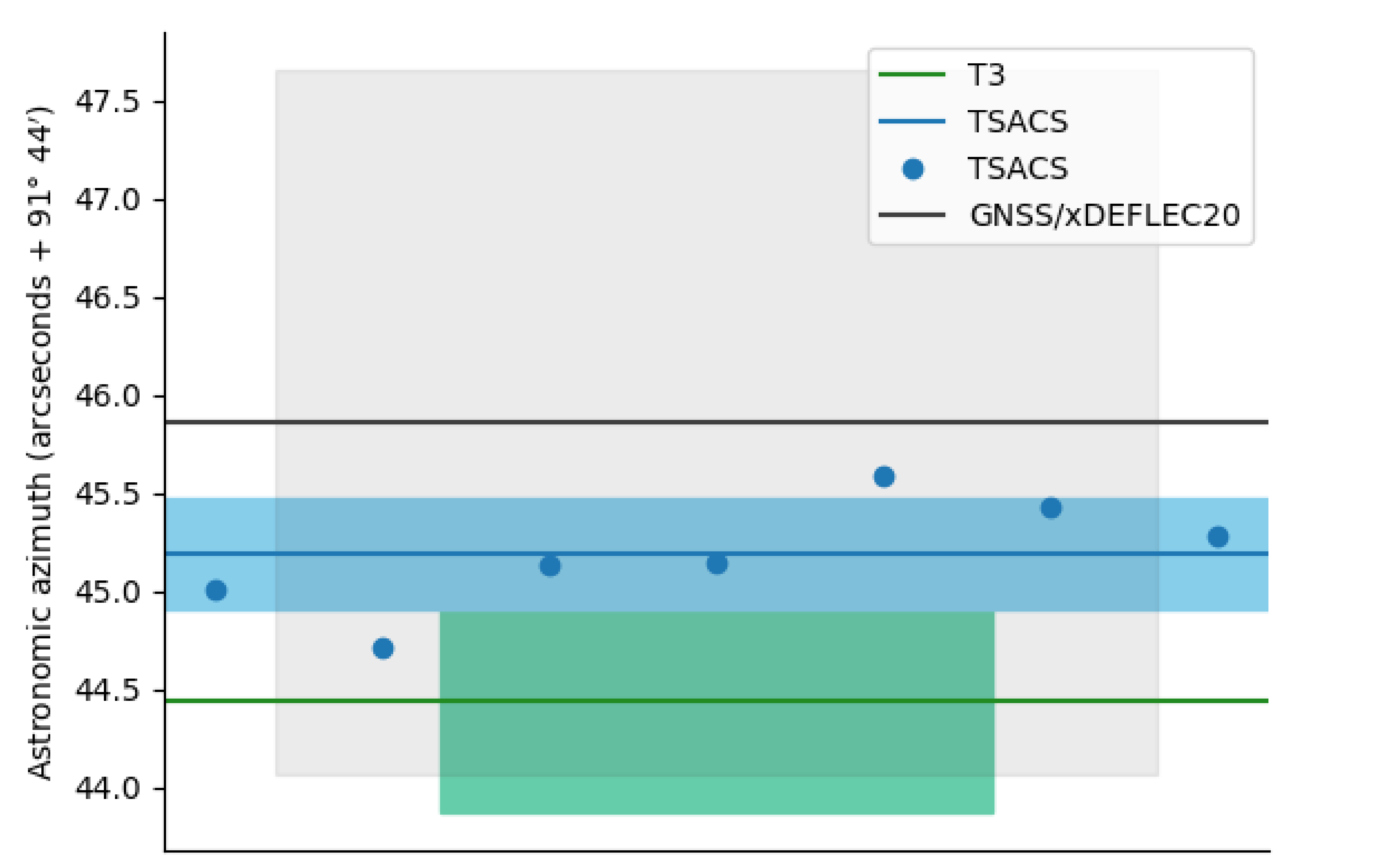
Predicted Alaskan Geoid Change (1954—2020)

TSACS in Alaska

- Following the 1964 earthquake, the Coast & Geodetic Survey and USGS collected gravity and precise leveling data along hundreds of kilometers of Alaskan roadways, taking a snapshot of Alaska's gravity field and crustal shape
- We revisited these observing sites in September 2021, using TSACS to measure the present-day geoid and use it to connect present-day GNSS heights to historical leveling
- We also revisited historical astronomic sites (ca. 1940s) and re-measured deflections of the vertical to determine how the gravity field had changed
- We observed 38 out of 55 planned targets due to weather limitations

Azimuth Experiments

- NGS is also experimenting with observing astronomic azimuths using TSACS
- For small-scale networks, like IERS observing sites, astronomic azimuths may offer better global orientations than GNSS
- This required performing classical observations with the antique Wild T-3 for comparison
- Initial results suggest 0.3 arcsecond repeatability, or 1.5 mm per km
- These outperform both GNSS and classical methods for orientation



The Future of Geodetic Astronomy

- The total station has proven to be a versatile tool for geodetic astronomy
- Deflections of the vertical can be used to measure or validate the geoid in rough topography with minimal sensitivity to vertical errors
- Deflections of the vertical may be used to compare historical leveling with modern-day GNSS heights
- Astronomic azimuths and deflections could be used to orient local surveys to the ITRF with higher precision than GNSS