Geodetic Astronomy with an Imaging Robotic Total Station

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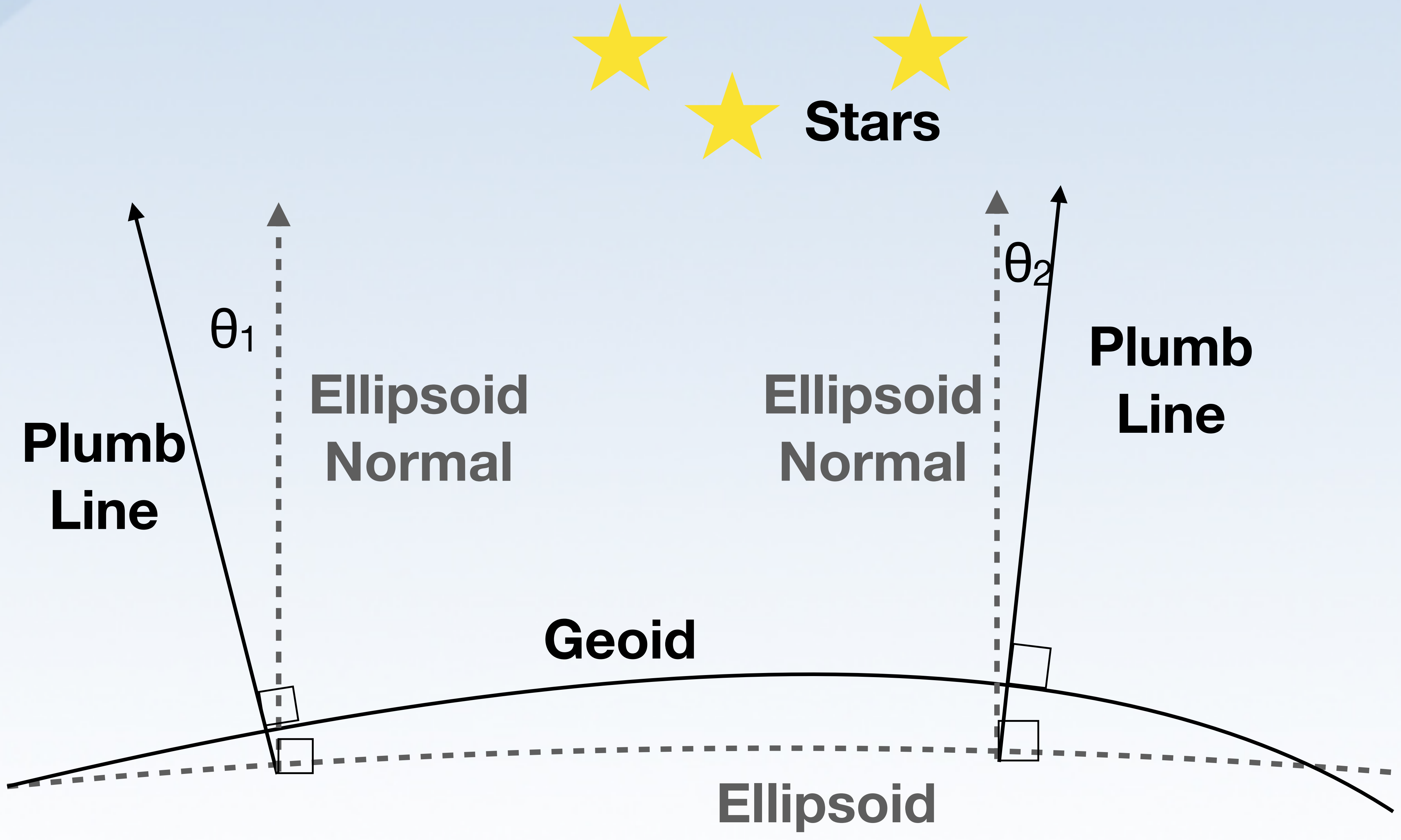
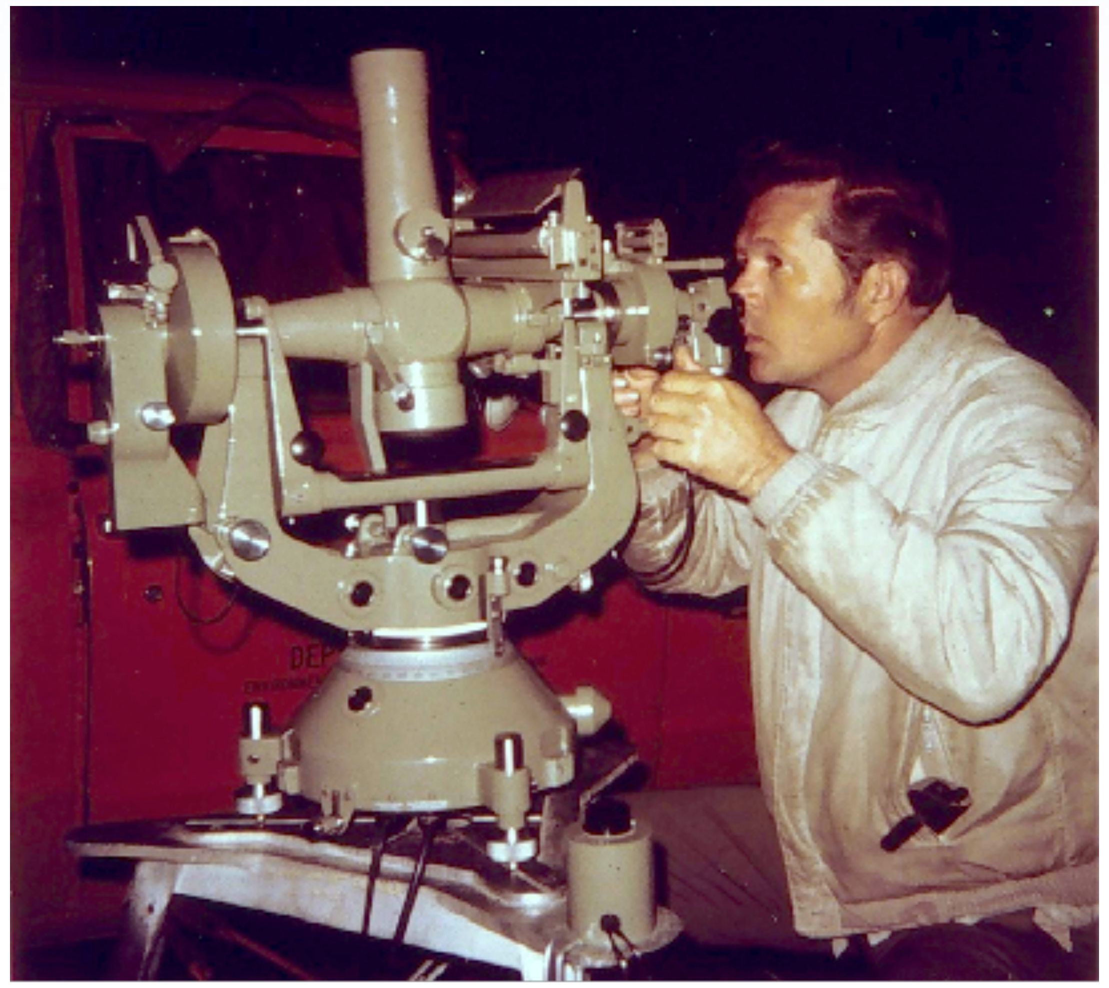
Motivation

- NOAA's National Geodetic Survey will use a **geoid model** to define the future **height** system of the United States, **NAPGD2022**
- **Deflections of the vertical** describe the absolute **direction of gravity** and the **slope of the geoid**
- Astronomical deflections of the vertical are a cost-effective way to profile the geoid where validation is difficult
- NGS has not performed astrogeodetic observations *with its own equipment* in over 30 years



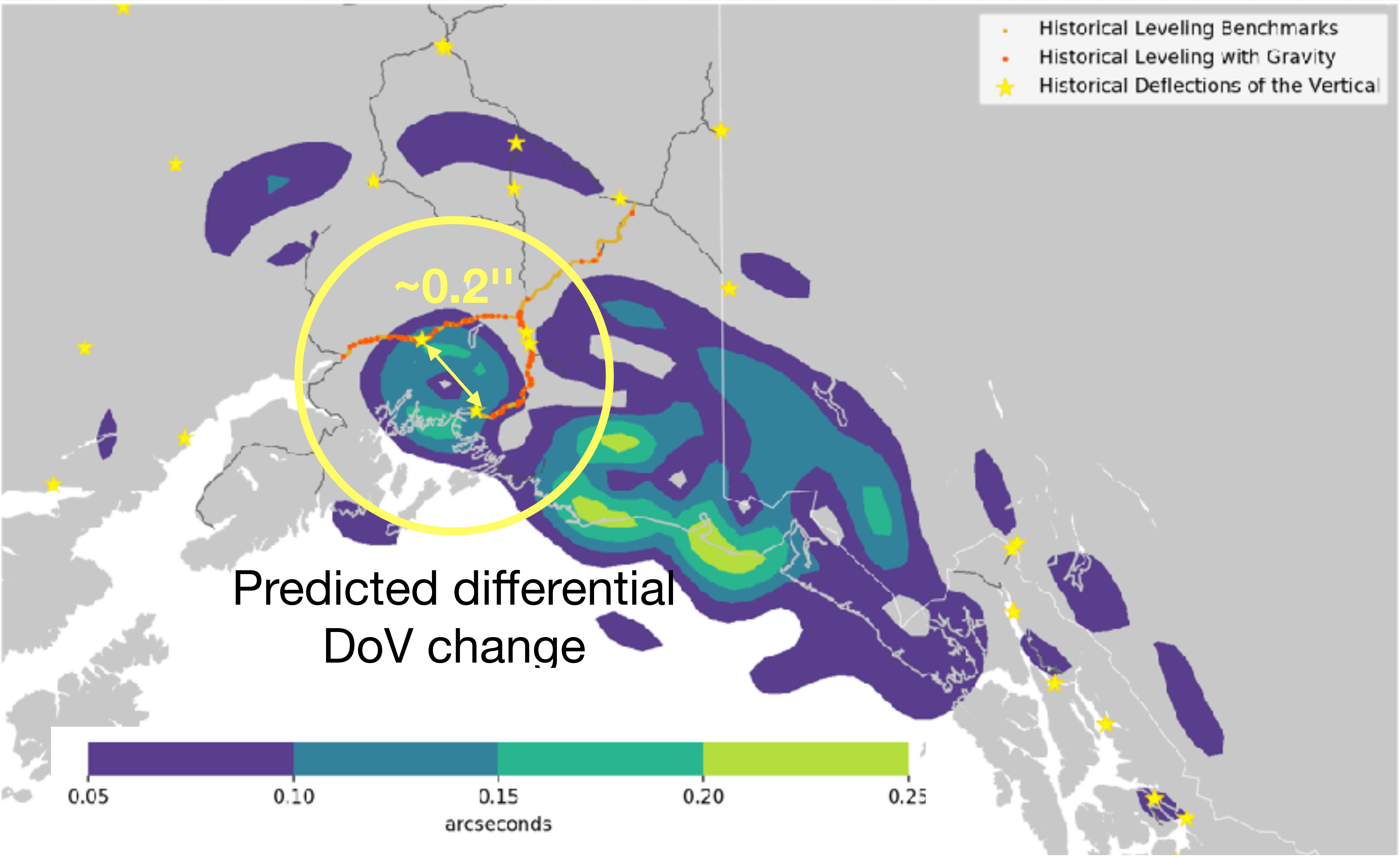


A Coast & Geodetic Survey surveyor performs geodetic astronomy with a Wild T-4 theodolite in 1955

Motivation

- NGS plans to measure past geoid change in Alaska by revisiting historical leveling and gravity observations from the 1960s
- Leveling is prohibitively expensive to repeat
- Deflections of the vertical can achieve comparable geoid profile accuracy with more spacing between measurements
- Revisiting historical astronomical sites may also reveal relative change of ~0.2"

Modeled total vertical deflection change (1954-2020)



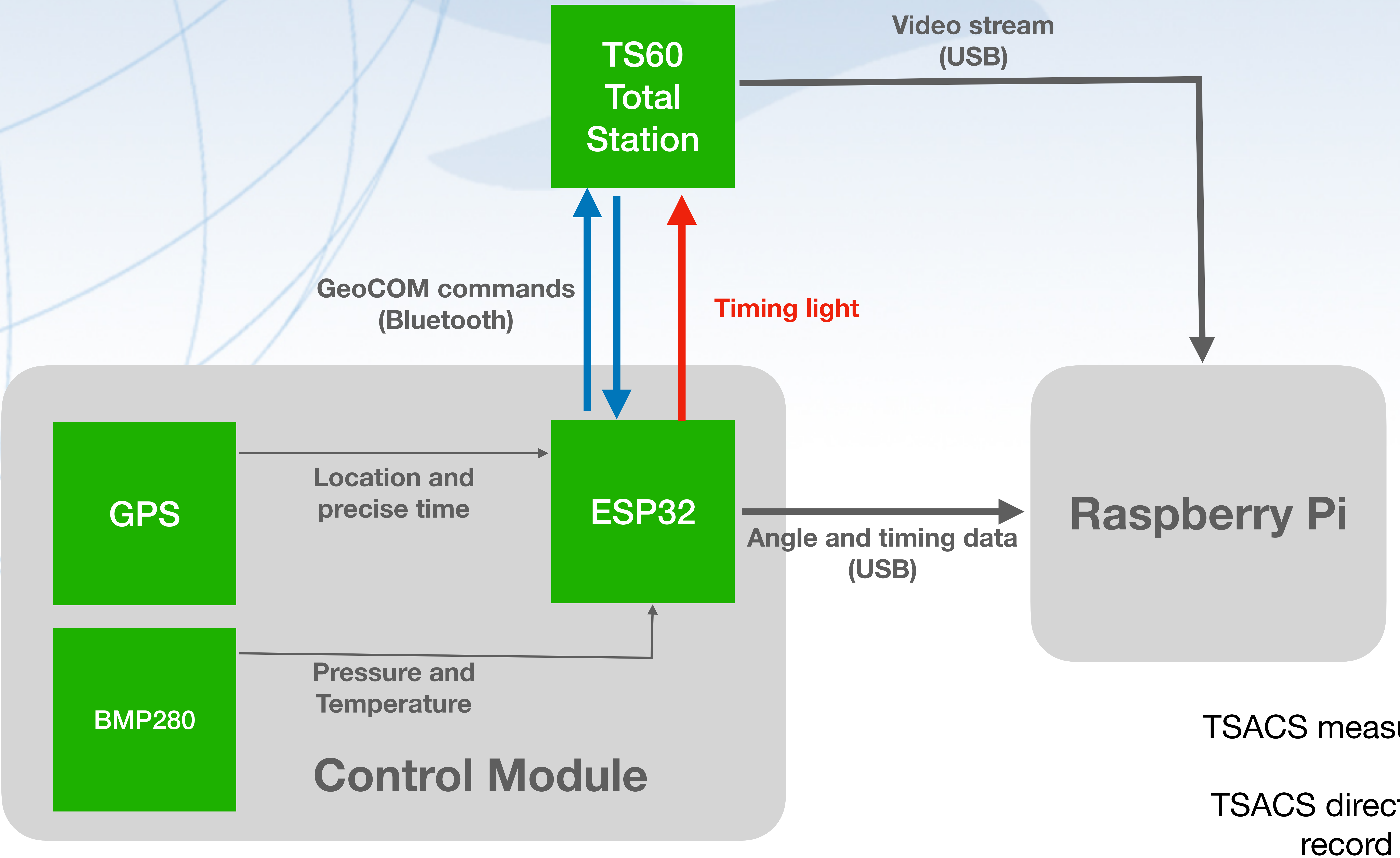
Hardy et al. (2021, in prep.)

Leica TS60 Robotic Total Station

- NGS owns a Leica TS60 robotic total station
- Existing solutions exist for measuring astronomical positions with total stations, such as QDaedalus (Hauk et al., 2016)
  - QDaedalus accuracy: ±0.15"
- QDaedalus uses an external imager to capture data from the total station telescope
- The Leica TS60 has a built-in video camera

Image: Leica Geosystems

Control System



T otal
S tation
A strogeodetic
C ontrol
S ystem

TSACS measures astronomical latitude and longitude.

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

Control Hardware

Timing Light

5V Power Bank

Raspberry Pi

GEV-234 Cable

Control Module

Observing Procedure

- The operator orients the total station telescope on Polaris and starts the controller
- The controller sets the total station azimuth based on Polaris once it has a GPS fix
- The controller selects 25 stars of 5th magnitude or brighter in the range of 59° and 61°, evenly spaced in azimuth
- The controller directs the total station to observe these stars with 10 fps video over 15 minutes

TS60 with Polaris in sight

Observing schedule

```
#Observing schedule for 2020-05-14 02:03:09 38.992470 -77.033912
 1,  18, 69673,+0.0,58.638436,121.356237
 2,  54, 72105,+2.3,58.356845,101.582857
 3,  90, 63608,+2.8,60.636474,160.912068
 4, 126, 50335,+3.4,58.618153,-110.444885
 5, 162, 73555,+3.4,60.198769,74.857994
 6, 198, 68756,+3.6,60.934103,21.647807
 7, 234, 67459,+4.0,60.523417,136.457840
 8, 270, 58948,+4.1,59.215013,-169.157866
 9, 306, 49593,+4.4,61.868735,-86.745846
10, 342, 48402,+4.5,59.736395,-47.372584
11, 378, 71995,+4.8,59.388885,104.075404
12, 414, 73695,+4.8,61.113876,60.090885
13, 450, 61960,+4.8,61.021039,174.246395
14, 486, 65721,+4.9,61.703873,149.579380
15, 522, 48113,+5.0,59.508023,-63.451022
16, 558, 48833,+5.1,60.573493,-73.650970
17, 594, 52353,+5.1,59.011460,-21.870586
18, 630, 56583,+5.1,58.813118,-9.778326
19, 666, 73909,+5.2,60.269754,46.050998
20, 702, 48682,+5.2,60.071821,-55.853690
21, 738, 52457,+5.0,61.417450,-115.568073
22, 774, 60998,+5.0,59.891300,-1.069233
23, 810, 61384,+4.9,59.079837,-0.334089
24, 846, 61281,+3.8,59.310152,-0.655481
25, 882, 54879,+3.3,60.065249,-136.450981
```

Data

- Two files are written to the Raspberry Pi's memory during each observation:
  - Telescope video file
    (110 MB, 10 fps, 15 minutes)
  - 1 Hz GeoCOM serial log and observation metadata (~203 kB)

GeoCOM serial log

```
2020-05-05 00:37:36.463, 6072, %R1P,0,0:0
2020-05-05 00:37:36.508, 6117, %R1P,0,0:0
2020-05-05 00:37:36.552, 6161, %R1P,0,0:0
2020-05-05 00:37:36.597, 6206, %R1P,0,0:0,6.268645196078433,0.895236883528358,0.00000235619449,3911936,0.000283560104936,0.000088513417318,0.000003141592654,3911938,0
2020-05-05 00:37:38,6609
2020-05-05 00:37:38.085, 6695, %R1P,0,0:0,6.268643482466136,0.89523698854186,0.00000235619449,3912488,0.000281429117494,0.000088782463593,0.000003141592654,3912488,0
2020-05-05 00:37:39,7609
2020-05-05 00:37:39.085, 7695, %R1P,0,0:0,6.268643839882877,0.895237324123668,0.00000235619449,3913487,0.000281920390072,0.000089058340757,0.000003141592654,3913487,0
2020-05-05 00:37:40,8609

2020-05-05 00:37:40.090, 8699, %R1P,0,0:0,6.268644438587902,0.895236869285014,0.00000235619449,3914486,0.000282501880624,0.000088618323264,0.000003141592654,3914487,0
2020-05-05 00:37:41,9609
2020-05-05 00:37:41.085, 9695, %R1P,0,0:0,6.268644441077452,0.895235937053972,0.00000235619449,3915486,0.000282382564491,0.000087620138704,0.000003141592654,3915487,0

2020-05-05 00:37:42,10609
2020-05-05 00:37:42.137, 10745, %R1P,0,0:0,6.268644436035058,0.895237071843261,0.00000235619449,3916488,0.000282609808701,0.000088065664994,0.000003141592654,3916488,0

2020-05-05 00:37:43,11609
2020-05-05 00:37:43.160, 11769, %R1P,0,0:0
2020-05-05 00:37:43.162, 11771, %R1P,0,0:0,2020,5,5,0,37,43,9
2020-05-05 00:37:43.191, 11800, %R1P,0,0:0,6.268644434596119,0.895236733687835,0.00000235619449,3917587,0.0002825891757,0.000088482806085,0.000003141592654,3917584,0

2020-05-05 00:37:44,12609
2020-05-05 00:37:44.086, 12695, %R1P,0,0:0,6.268644078896731,0.895236759261068,0.00000235619449,3918486,0.000282051234399,0.000088463615835,0.000003141592654,3918486,0
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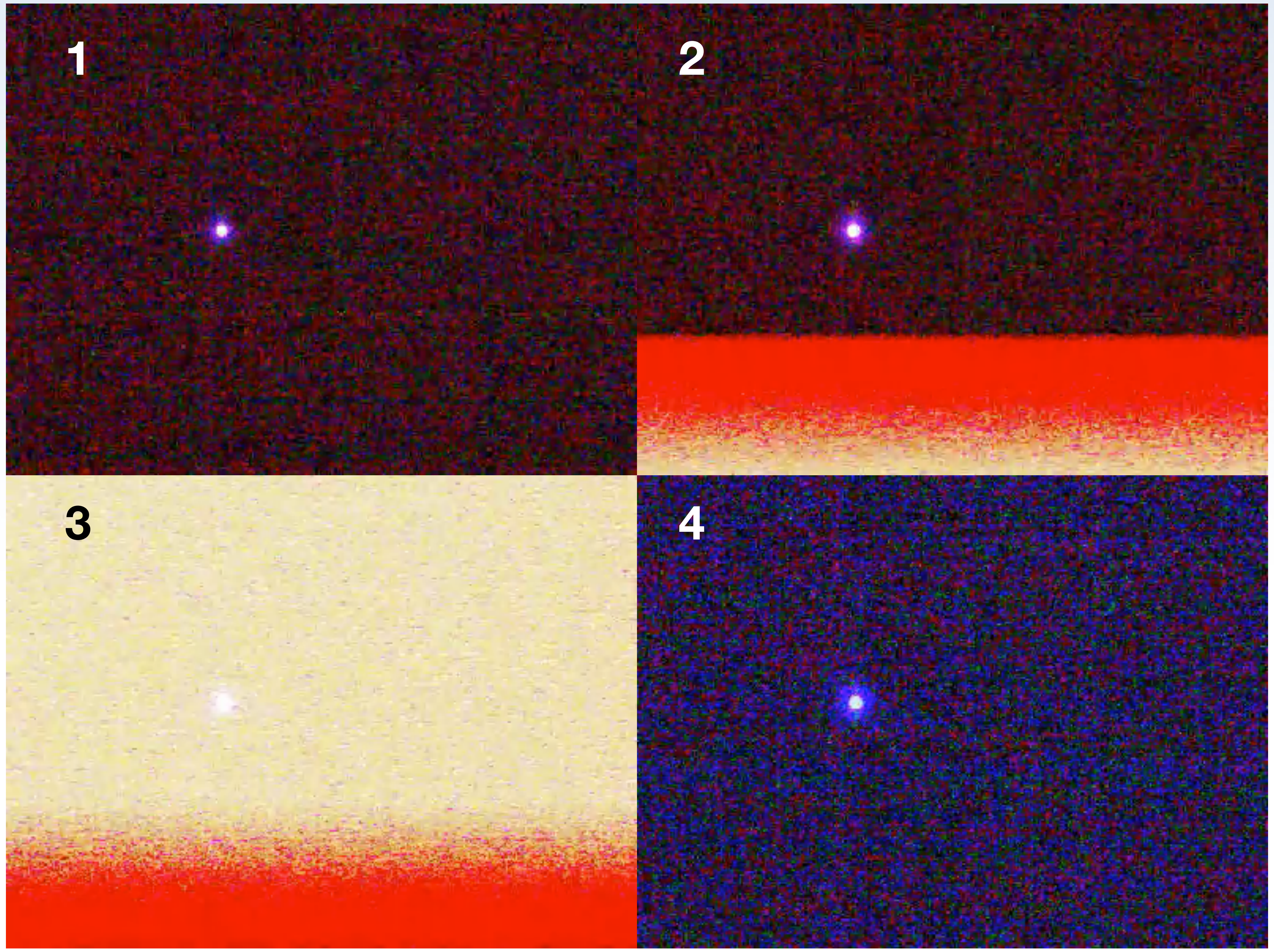


Sequence of video frames showing starlight and a timing light flash with rolling-shutter artifact

Solution

1. Analyze video frames to extract timing flashes and star positions
2. Use timing flashes register video frames to UT1
3. Predict horizontal and vertical star positions in frame as a function of time and location
4. Jointly fit collimation and occasional azimuth drift errors
5. Correct deflection components to mean pole

Observation Equations

$$\begin{bmatrix} \Delta y \\ \Delta x \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & 1 & 0 & 0 \\ \sin\alpha \sin h & -\cos\alpha \sin h & 0 & 1 & t \end{bmatrix} \begin{bmatrix} \xi \\ \eta \\ y_0 \\ x_0 \\ \dot{\alpha} \end{bmatrix}$$

Δx, Δy — Residual star positions in frame

α — Azimuth

h — Elevation angle

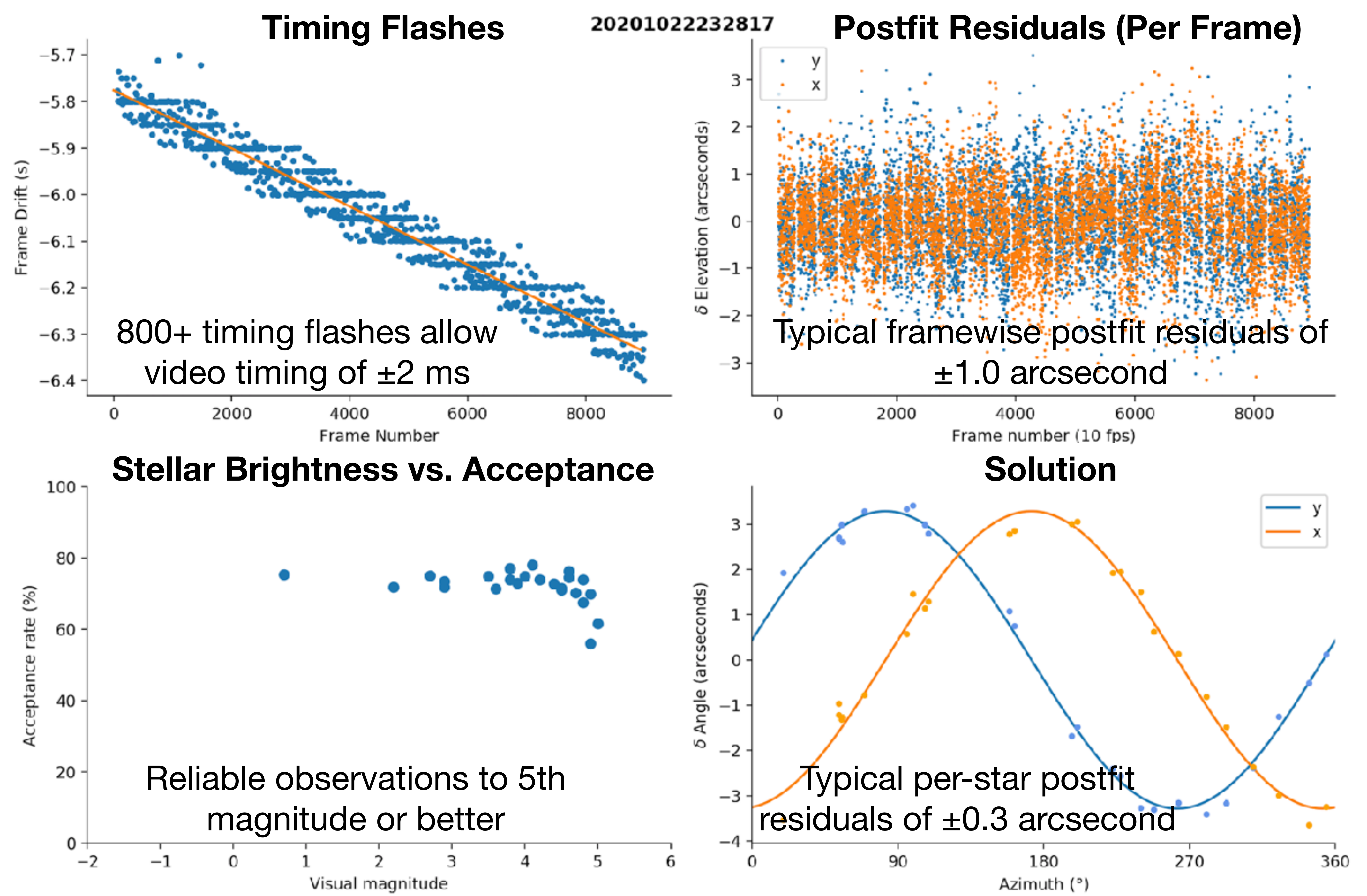
ξ, η — Deflection of the vertical

y_0, x_0 — Collimation bias

$\dot{\alpha}$ — Azimuth drift

Typical Solution

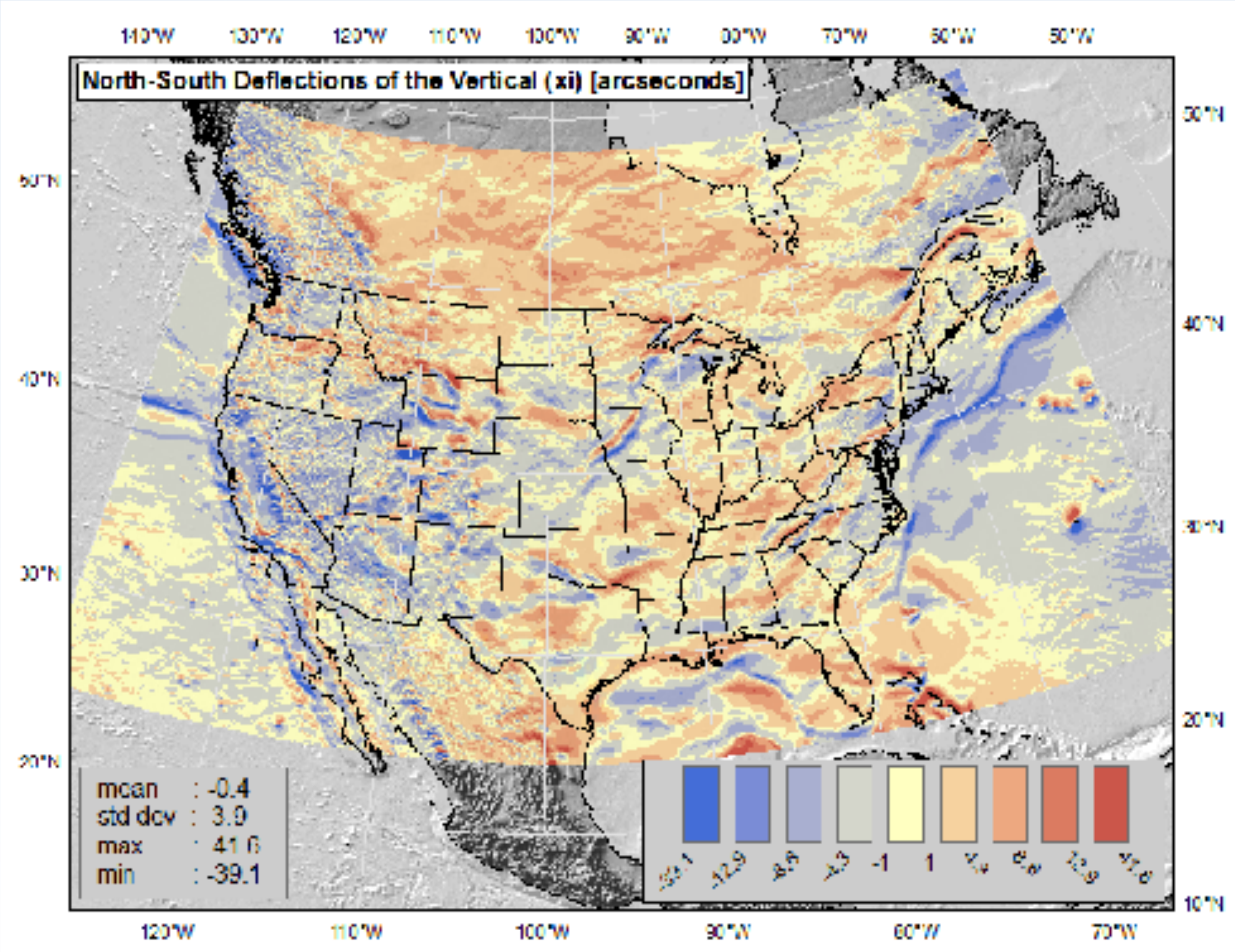
- Fitting to both elevation and azimuth mitigates problems with observing geometry
- Strenuous outlier rejection applied during deflection solution
- ±0.12" formal error in both η and ξ



Validation Data

- CODIAC zenith camera observations made in Woodford, VA
- Dozens of historical astronomic measurements made in DC area. Sources:
  - NGS Integrated Database (IDB)
  - NASA Directory of Observation Station Locations (1973)
  - Coast and Geodetic Survey Special Publications
- Historical sources require longitude corrections
- NGS's xDEFLEC20 model integrates terrestrial, airborne, and satellite gravity

xDEFLEC20, NOAA (2020)



NOAA (1971)

> A special gravity survey was accomplished in the vicinity of Washington, D.C., to provide gravimetric deflections of the vertical at the astronomic testing station at Beltsville, Md.; the C&GS latitude observatory at Gaithersburg, Md.; and the U.S. Naval Observatory in Washington, D.C. To determine these deflections, a network of about 250 stations was observed over a circular region of about 70-km radius. The gravity survey was designed to achieve an accuracy of 0.1 arc second in the relative deflections of the vertical, thus providing the desired intercomparison of astronomic position observations at the three sites.

1960s gravimetric survey of Washington, DC area for precise modeled deflections of the vertical

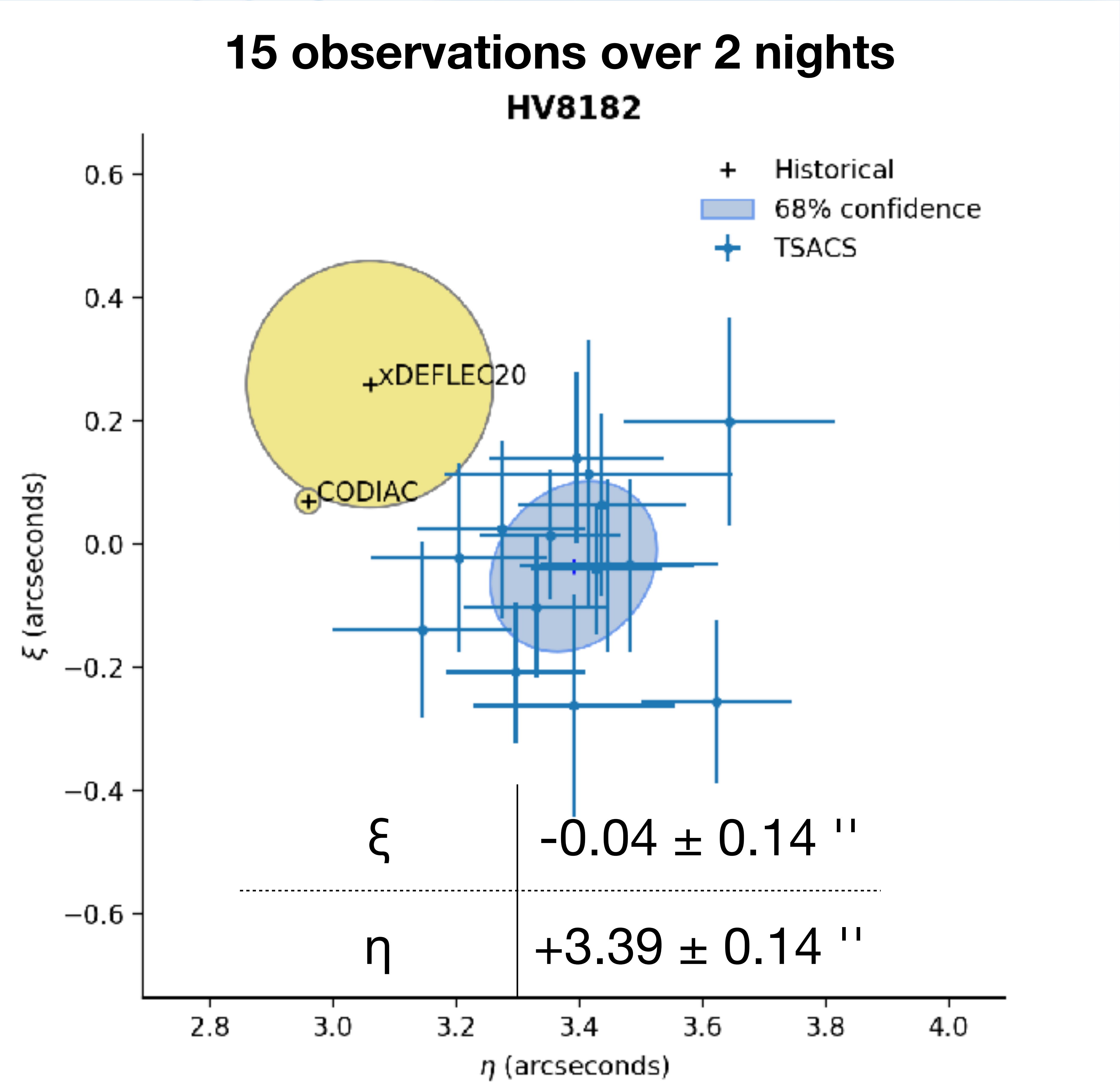
Testing

Woodford, VA

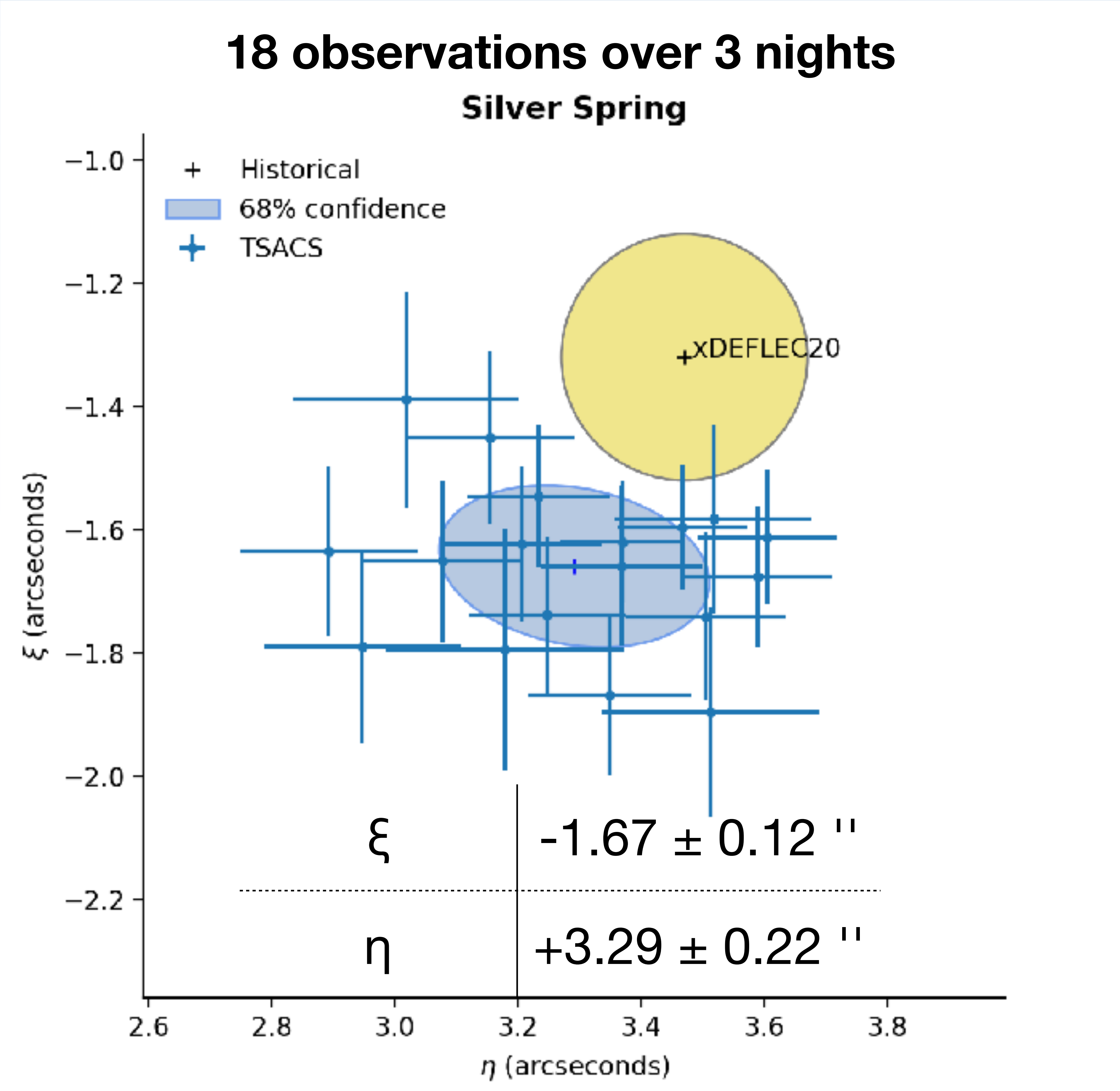
Silver Spring, MD

Testing

Woodford

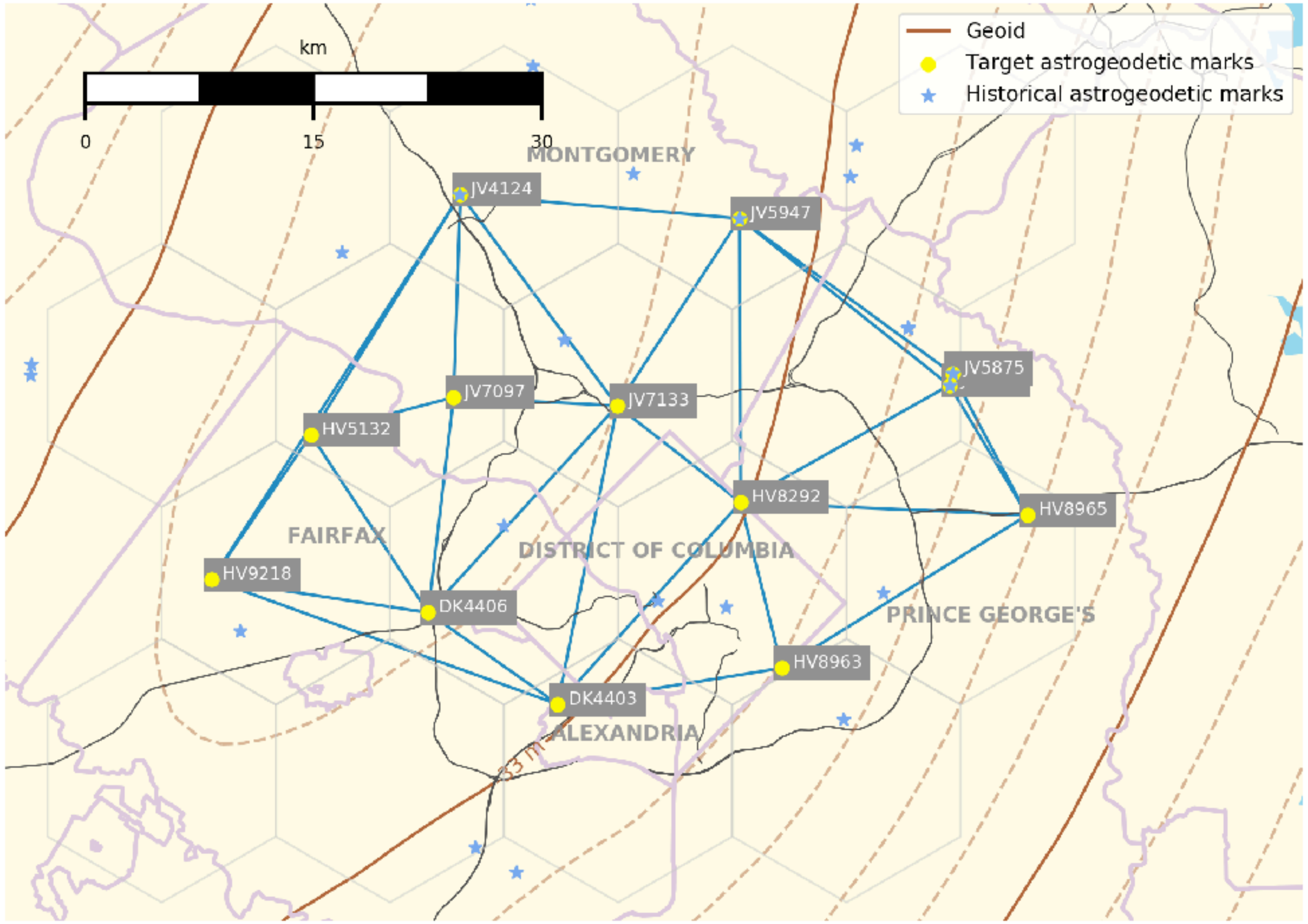


Silver Spring



DC Astrogeodetic Survey

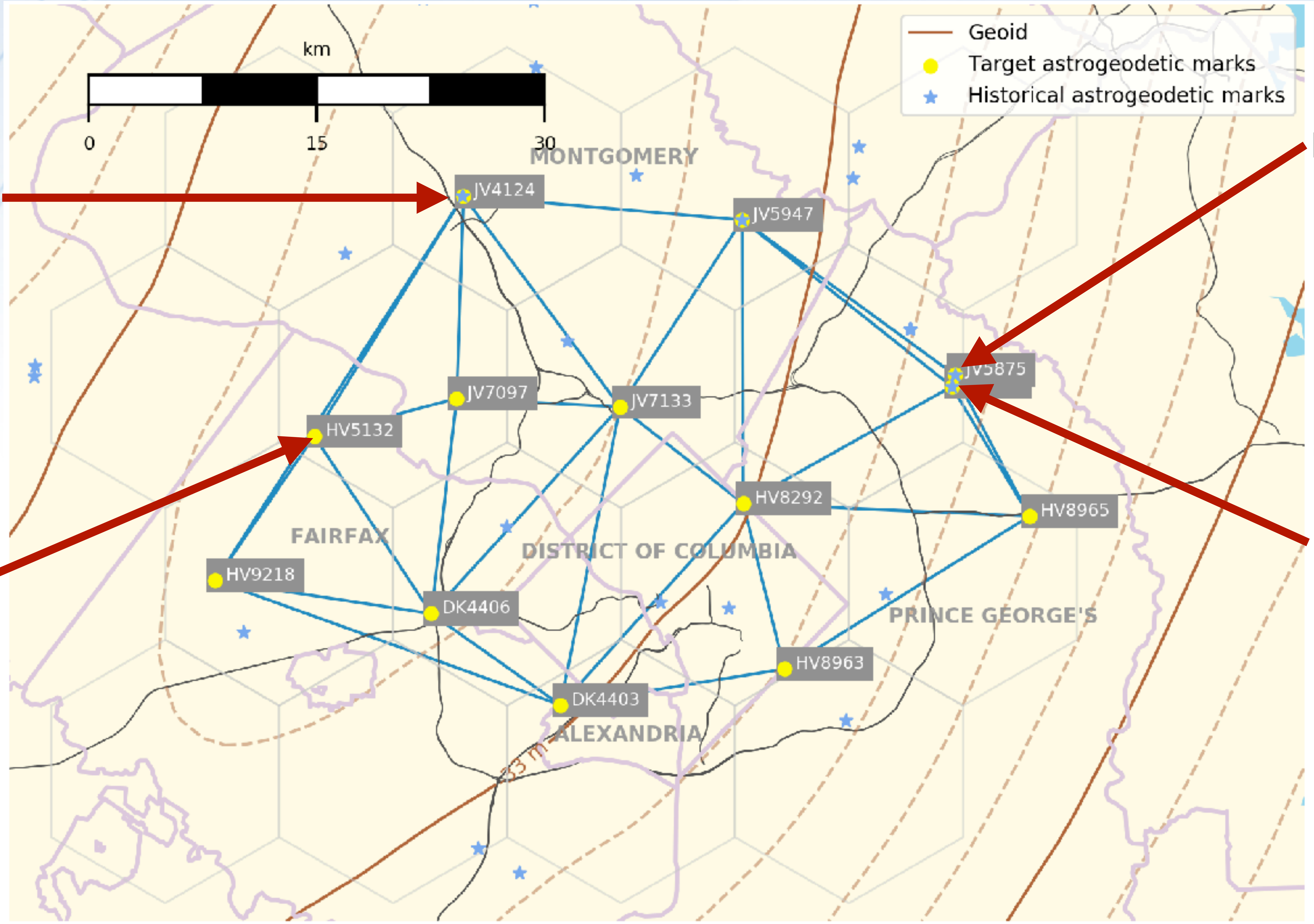
- **Goal:** Revisit historical astrogeodetic sites in the DC area and intermediate sites to validate TSACS
- Sites were selected with an approximate 15 km spacing
- Reconnaissance was conducted in September 2020, finding 5 suitable historical sites
- Observations at 13 sites were conducted in October and November of 2020



DC Astrogeodetic Survey

International Latitude Observatory
City of Gaithersburg

Former Nike Missile Defense Site and NGA Tracking Facility
Fairfax County, VA

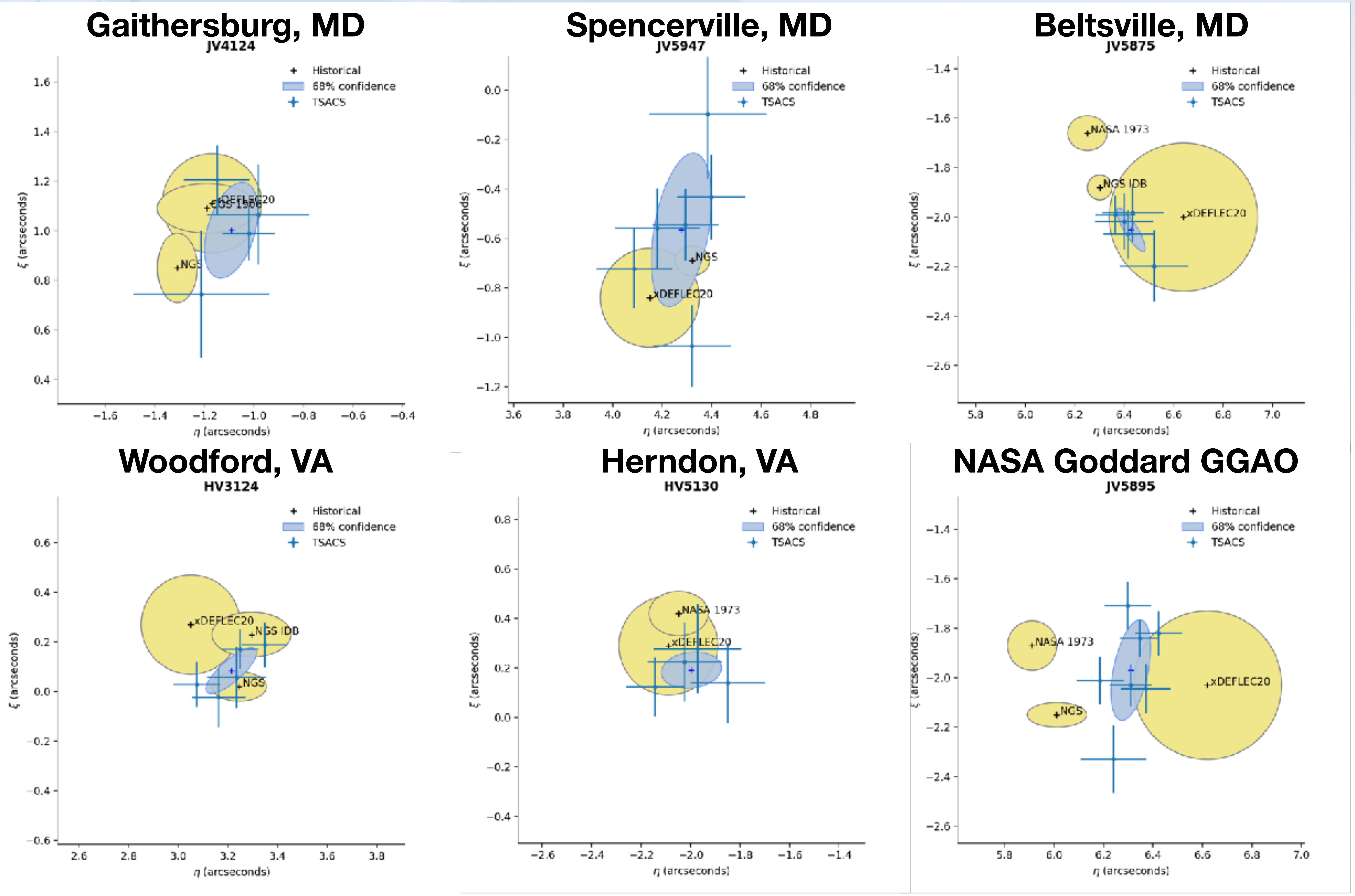


Coast & Geodetic Survey BC-4 Satellite Triangulation Facility
USDA, Beltsville, MD

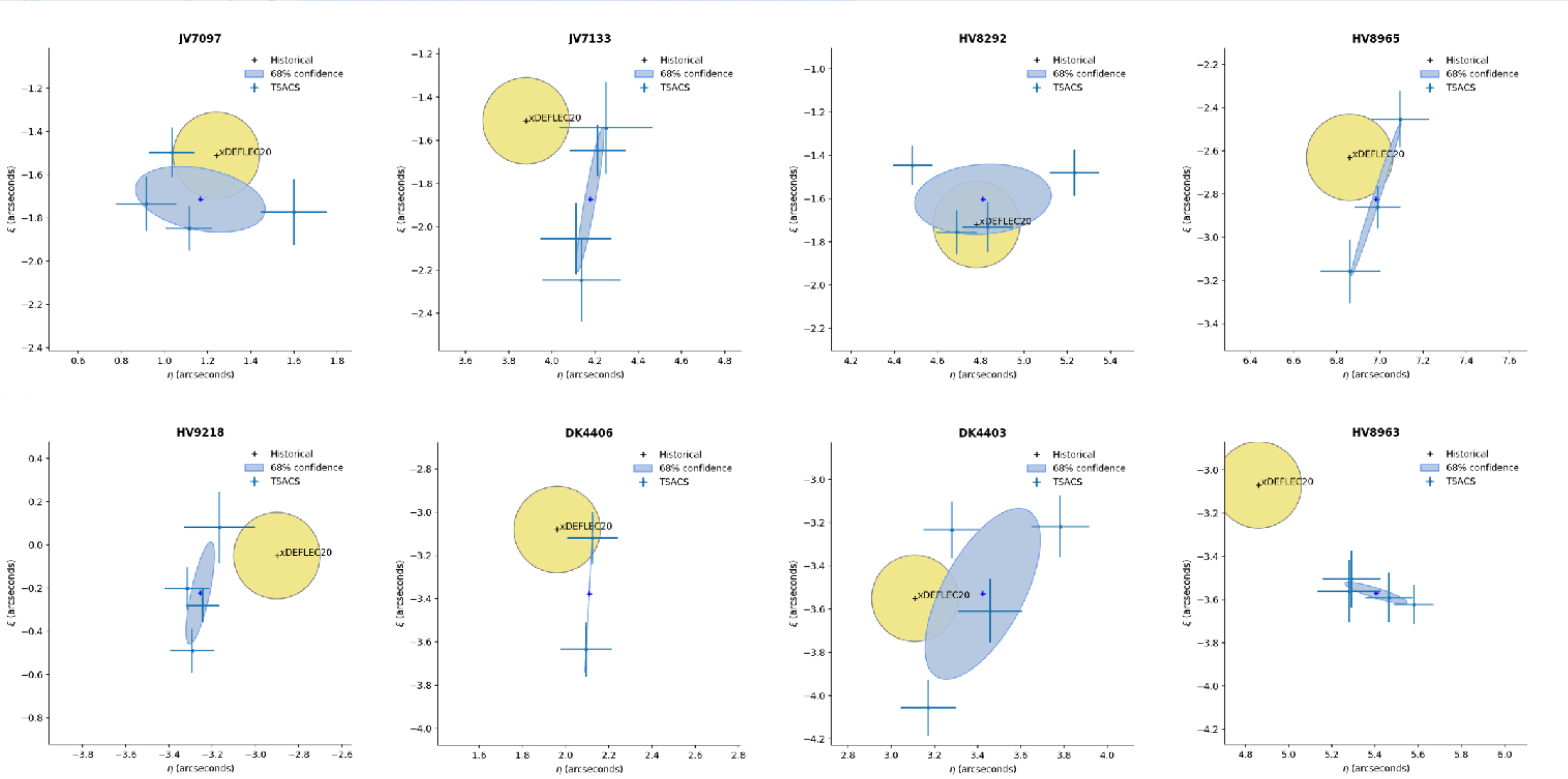
Goddard Geophysical and Astronomical Observatory
NASA, Beltsville MD

Sites visited

Results: Historical Comparisons



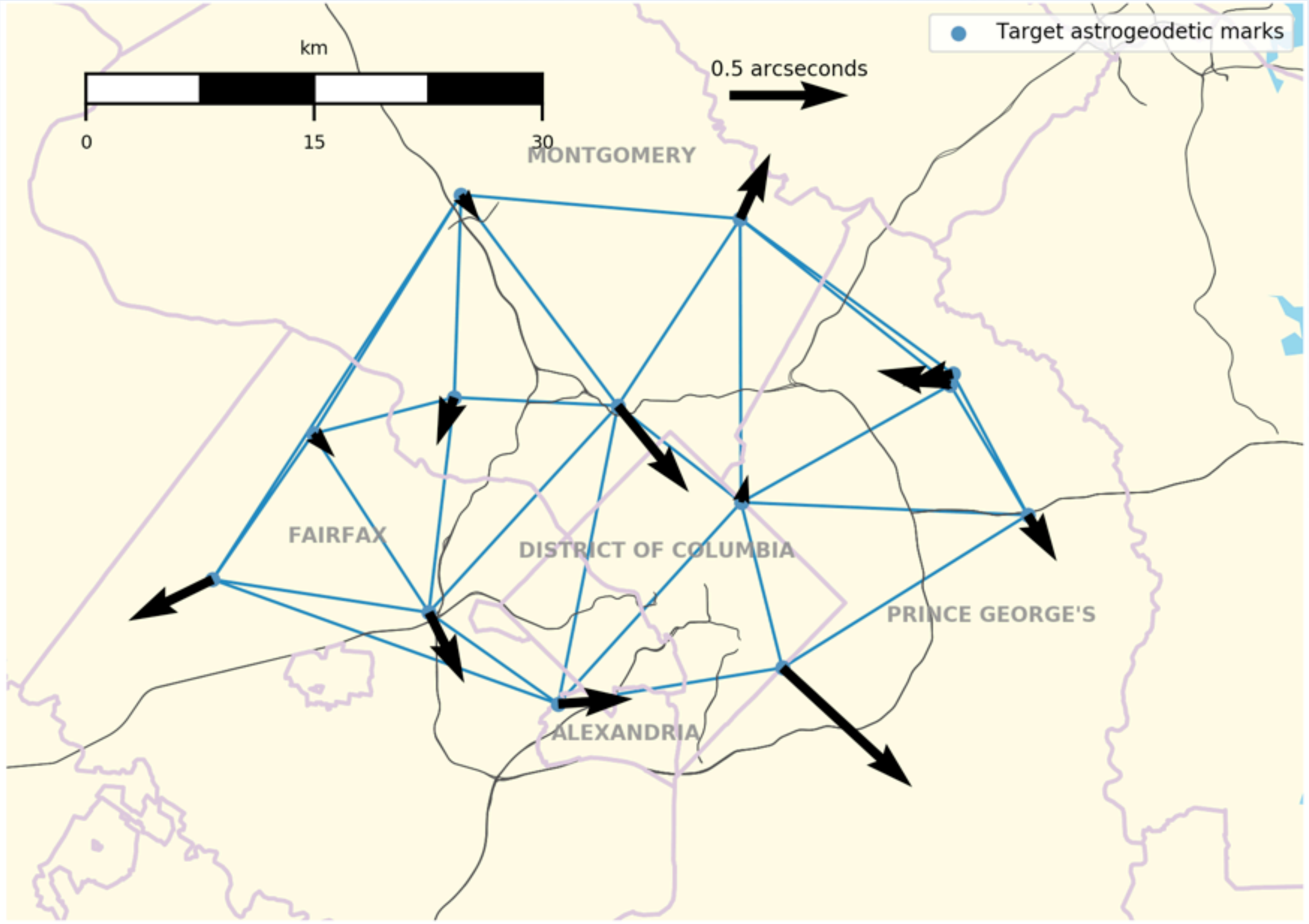
Results: Model Comparisons



Results: Model Comparison

- Sites closest to DC have the largest errors with respect to xDEFLEC20
- Typical errors are smaller than 0.5" in magnitude

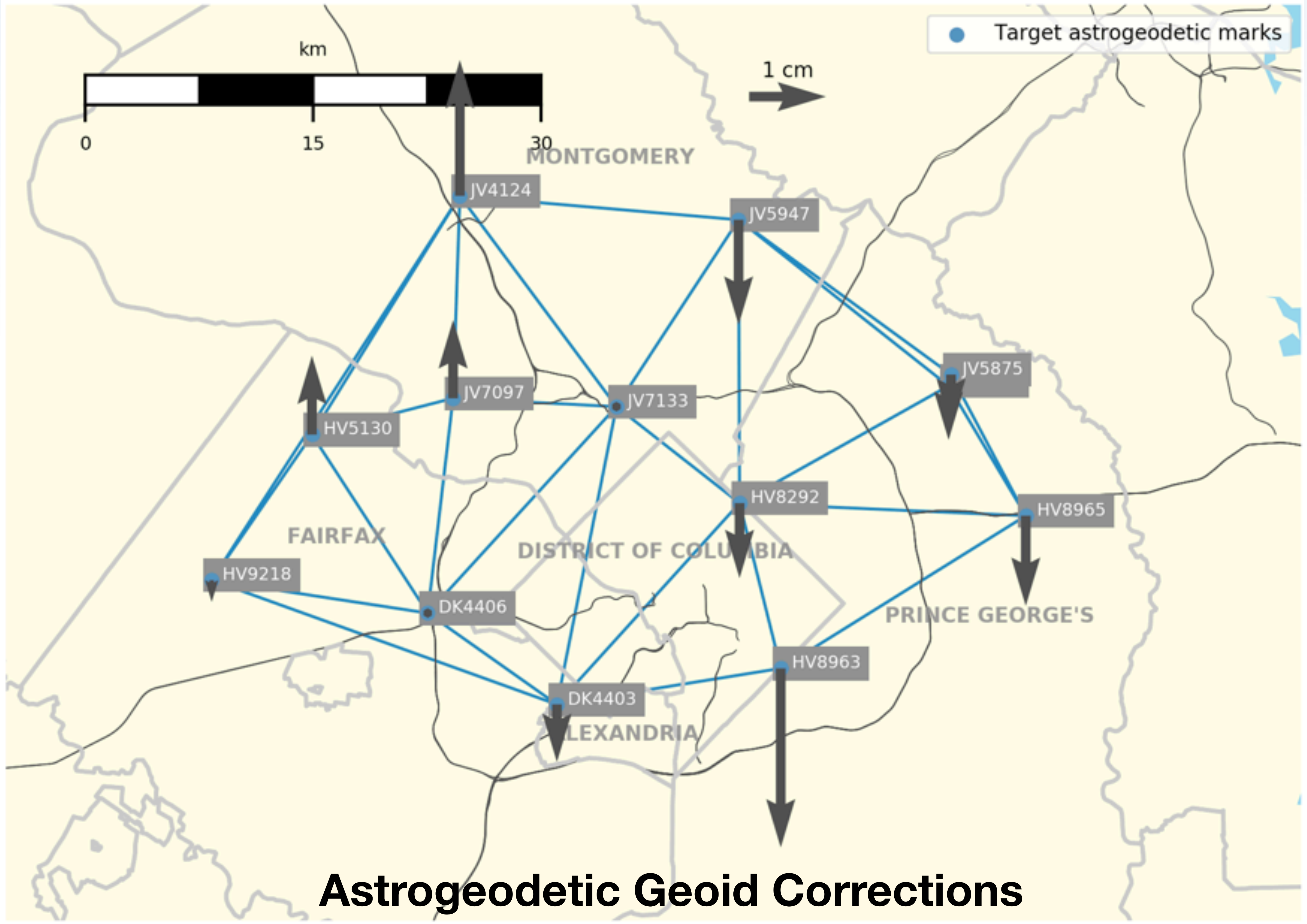
TSACS Deflections minus xDEFLEC20



Astrogeodetic Leveling

- Deflections of the vertical can be used to predict geoid height differences between sites
- We use xDEFLEC20 and xGEOID20 as a background model and compute corrections
- Level net forms 51 baselines with 13 unknowns
- Adjusted heights agree with xGEOID20 within ±1.1 cm (1σ)
- Planar fit to geoid adjustments suggest TSACS bias of
    - +0.09 ± 0.02 " to east (~8 ms of time)
    - –0.12 ± 0.04 " to north

$$\Delta N_{ij} \approx -\frac{d_{ij}}{2}\left((\eta_i + \eta_j)\sin\alpha_{ij} + (\xi_i + \xi_j)\cos\alpha_{ij}\right)$$



Astrogeodetic Geoid Corrections

Overall Precision and Accuracy

Variability

- Performed one-way ANOVA (104 measurements, 16 groups) to find internal and external variability of TSACS measurements
- TSACS has internal variability smaller than ±0.2'' for single occupation

Standard Deviations

	TSACS		Historical Data	
	ξ	η	ξ	η
TSACS	0.20''	0.17''		
Historical Data	0.17''	0.17''	0.18''	0.07''
xDEFLEC20	0.20''	0.25''	0.16''	0.31''

Bias

- Note: Datasets do not yet completely overlap, so biases do not close
- No strong evidence of bias larger than ±0.1''

Total Bias

	Groups	ξ	η
TSACS – Hist. Data	7	-0.07 ± 0.07''	-0.15 ± 0.05''
TSACS – xDEFLEC20	16	-0.15 ± 0.05''	+0.07 ± 0.06''
Hist. Data – xDEFLEC20	7	0.00 ± 0.07''	-0.11 ± 0.13''

Summary

- The Total Station Astrogeodetic Control System (TSACS) can direct an NGS-owned Leica TS60 robotic total station to observe stars and measure deflections of the vertical
- The system has been field-tested in the DC area and may soon see use in geoid studies
- The system can measure the deflection of the vertical within ±0.2 arcseconds with one 15-minute occupation
- Calibration and refinement of analysis still in progress

Credits

Observers

Kendall Fancher • Steve Breidenbach

Site Reconnaissance

Roy Anderson • Courtney Lindo

Instrument Development

Kendall Fancher • Ben Erickson • Charlie Geoghegan • Steve Breidenbach

Strategic Guidance

Kevin Ahlgren • Derek van Westrum • Steve Hilla

NRC Adviser

Xiaopeng Li