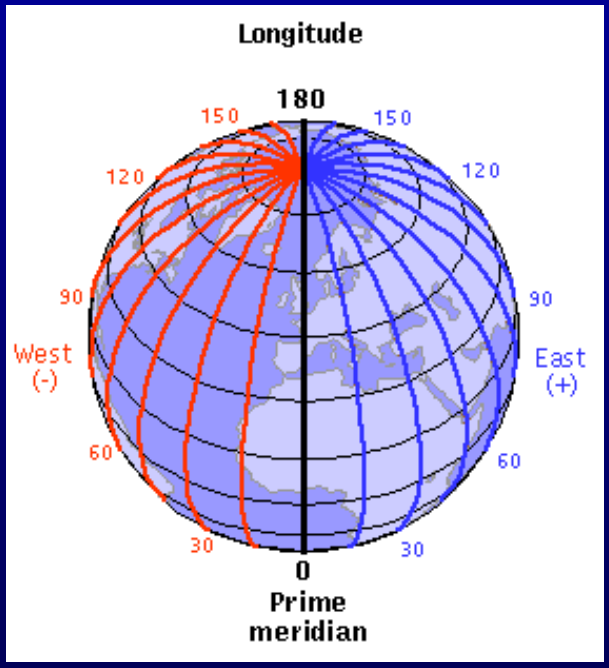
Why (and When) Did the Greenwich Meridian Move?



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This presentation is a summary of a paper in the *Journal of Geodesy*

- "Why the Greenwich Meridian Moved"

S. Malys, J. H. Seago, N. K. Pavlis, P.K. Seidelmann, G. H. Kaplan

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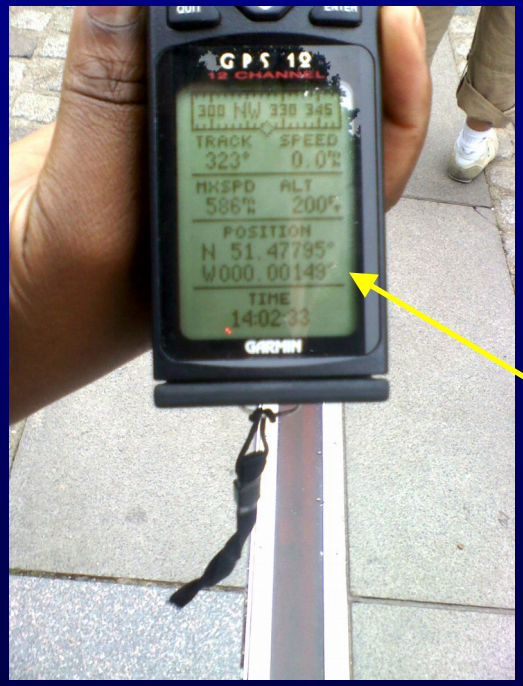
or

http://tinyurl.com/greenwich-moved

Zero Longitude Is Not Where it Used to Be



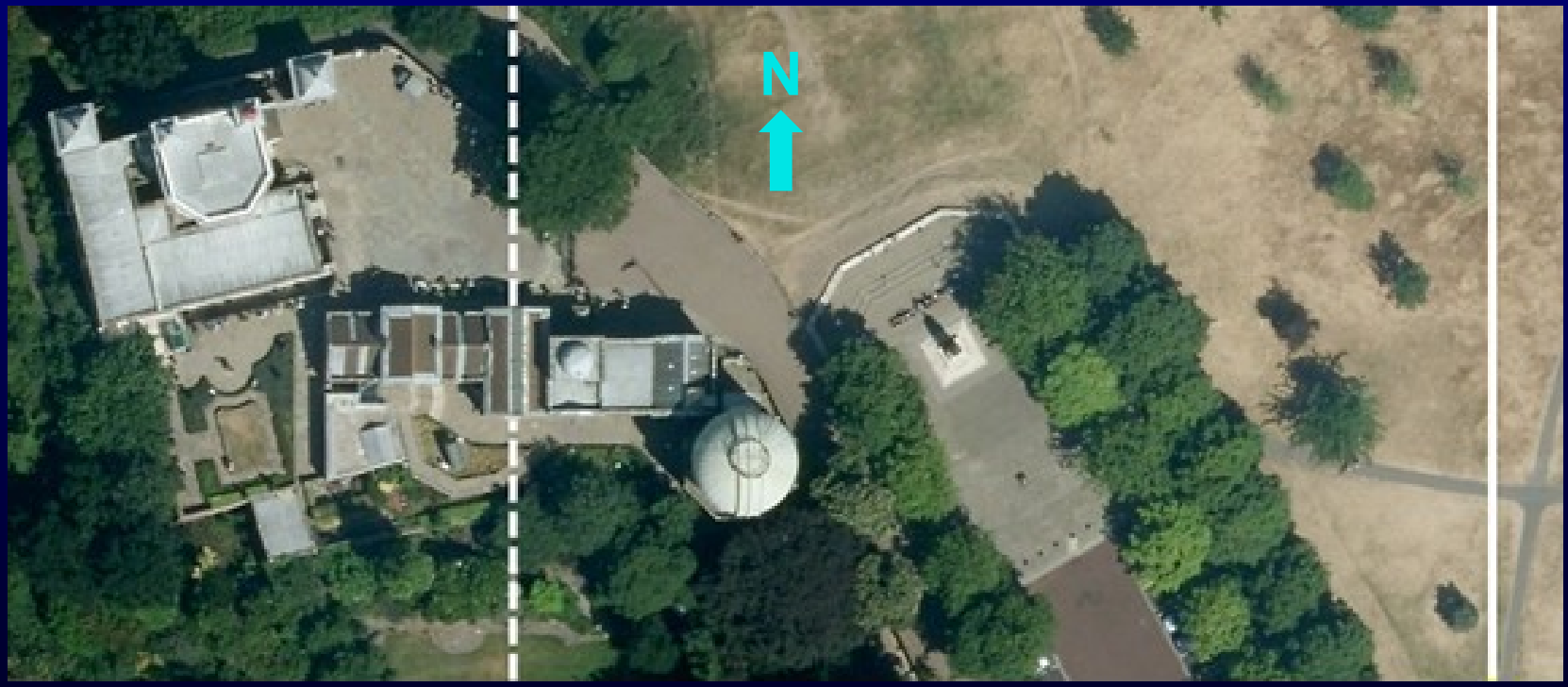
LONGITUDE
0°00’00”

W 000.00149°
(= W 5.36”)

It's 102 m to the East of the Old Line

Historical Prime Meridian

GPS longitude 0 = ITRF zero-meridian



Previous, Incorrect Explanations

- Polar motion
- Continental drift
- Move of Royal Greenwich Observatory in the 1950s from Greenwich to Herstmonceux
- Change of terrestrial reference systems
  - Obviously! But why, when, and how?
- Originated in the earliest Transit satellite geodesy
- Caused by GPS
- Change in system of astronomical constants

See published paper

It's All About Time…

- Astronomical time = UT1 = time kept by the rotation of the Earth
- Before the middle of the 20th century, the most accurate kind of time
  - Although there was accumulating astronomical evidence for irregularities in the Earth's rotation
- Accuracy finally exceeded by
  - 1930s: crystal oscillator clocks
  - 1950s: atomic clocks

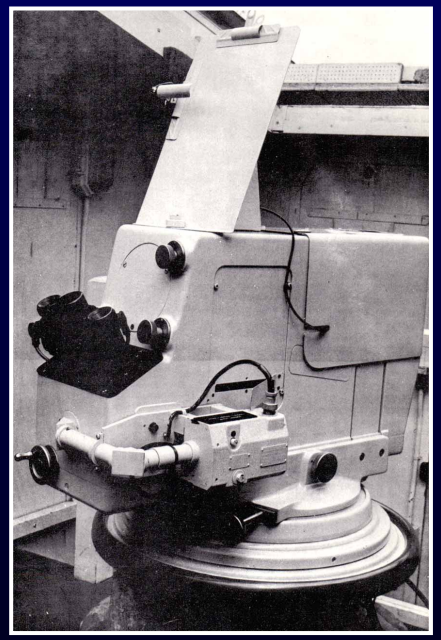
…and the Way it Has Been Measured

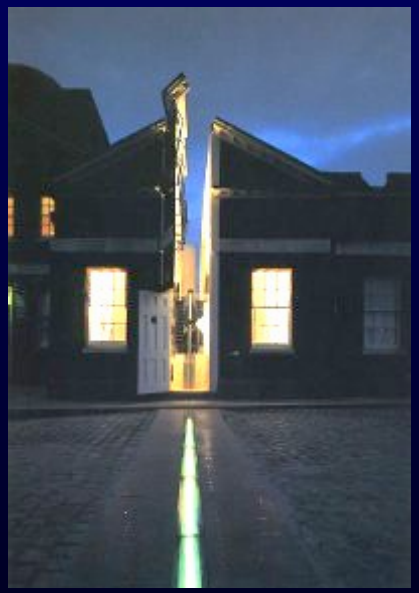
- Classical astronomical instruments measure when stars of known coordinates cross (transit) the local meridian
  - with respect to some conventional, internationally recognized time scale, distributed by telegraph or radio

transit telescopes

zenith telescopes

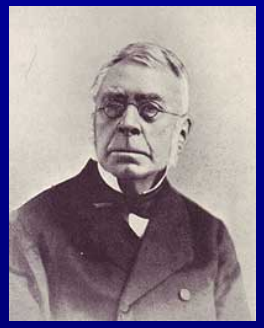
Danjon astrolabes





In Particular, at Greenwich, the Airy Transit Circle

Named for Sir George Biddell Airy, 7th Astronomer Royal



- Plane of the ATC's free motion (north-south) defines the Greenwich meridian
- Recognized as the Prime Meridian, and origin of "universal" time, by the International Meridian Conference (Washington, 1884)

  "…the Conference proposes to the Governments here represented the adoption of the meridian passing through the center of the transit instrument at the Observatory of Greenwich as the initial meridian for longitude."

  "...the Conference proposes the adoption of a universal day...to be a mean solar day...to begin for all the world at the moment of mean midnight of the initial meridian..."

International Coordination of Astronomical Time Measurements

- By the early 20th century, radio time signals made an international standard of time possible at a precision of 1-10 ms
- Coordination 1912−1988 was by the Bureau International de l'Heure (BIH) in Paris
  - several dozen observatories worldwide contributed
  - longitudes and latitudes of observatories also determined from same observations
  - longitude of ATC (and later Greenwich instruments) set to 0°00' 00"
- Even after atomic time (TAI and UTC) became the international standard for precise time, determination of UT1 remains important
  - as one of five Earth orientation parameters
  - to decide when leap seconds should be added to UTC
  - for geophysical studies

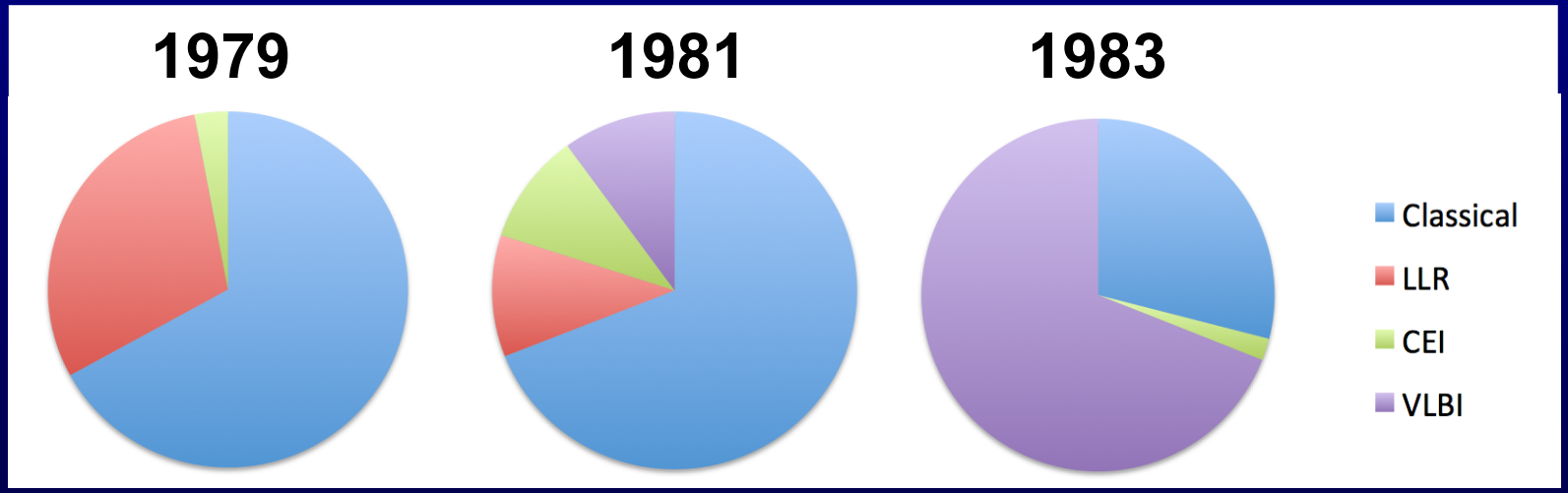
In the 1970s, New Techniques Came Online

- Very Long Baseline (radio) Interferometry (VLBI)
- Connected-Element (radio) Interferometry (CEI)
- Lunar Laser Ranging (LLR)
- Satellite Laser Ranging (SLR)
- Satellite Doppler

} Used for geodesy and polar motion, but not UT1

All of these techniques were also used for geodesy; the latitudes and longitudes of all instruments were determined from the same observations

The New Techniques Rapidly Replaced the Old



(Data from BIH Annual Reports)

By 1984, the classical astronomy techniques had been completely replaced

The Longitude System for the New Techniques

- No natural connection between old and new longitudes
- BIH required continuity in UT1 determinations between the classical and the new techniques, over the period 1980-1983

  ⇨ same UT1 value for same instant of atomic time (TAI or UTC)

- Corollary: The plane of meridian of longitude x in the new system, extended to infinity, sweeps out the same stars as a function of atomic time as the plane of meridian of longitude x in the old classical system

  –that is, meridians with the same longitude value in the old and new systems are parallel

- The "new system" was the BIH Terrestrial System of 1984 (BTS84)

  –which became the basis for WGS84 (used for GPS) and the International Terrestrial Reference Frame (ITRF)

But, a "Gotcha"

- The new meridian planes are defined differently from the old meridian planes

- Because…

The meridians of the classical instruments are calibrated to local gravity

  - a basin of mercury served as an optical element

The meridians defined by the new techniques are independent of local gravity, but pass through the center of the Earth

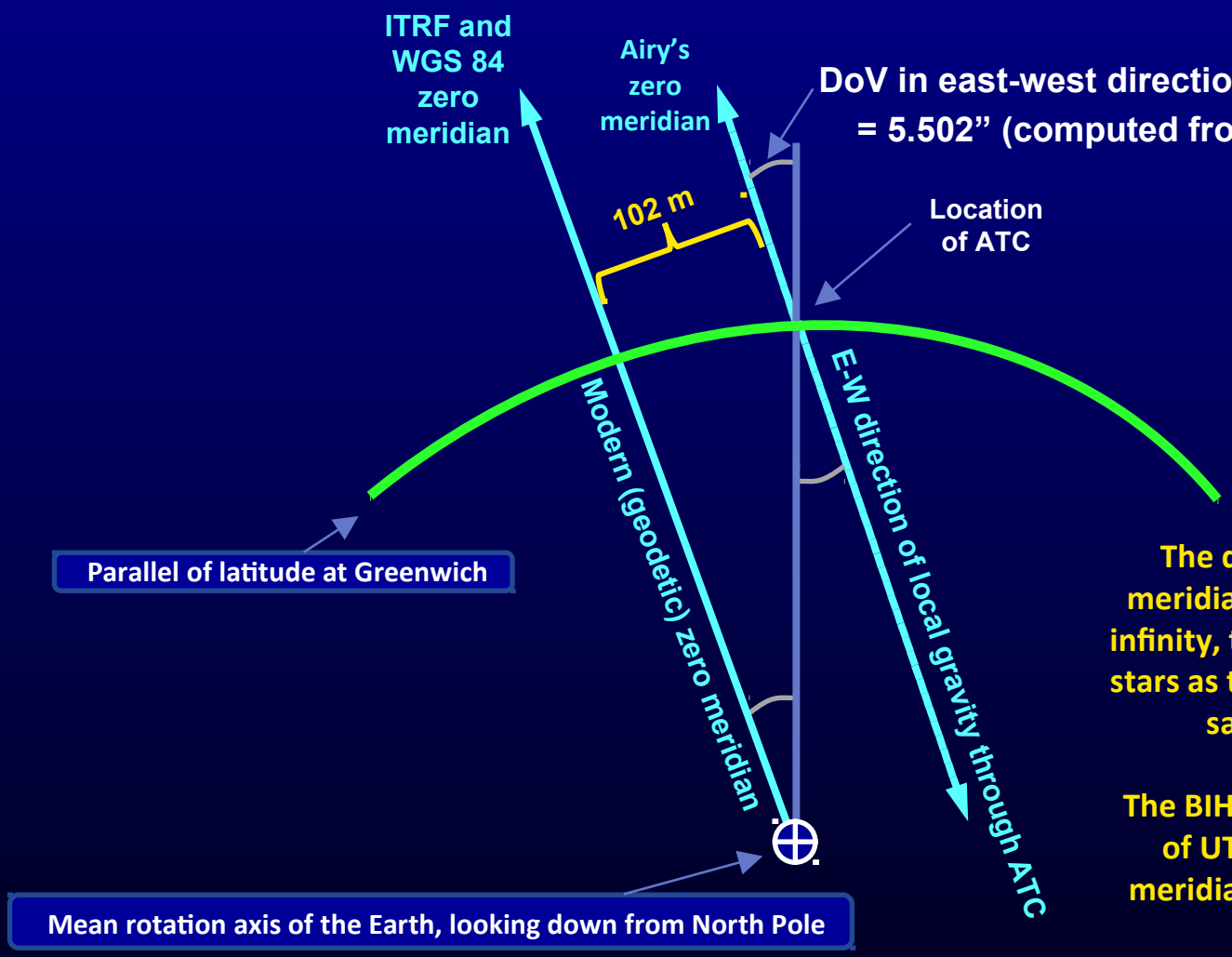
  - satellite techniques are tied dynamically to the Earth's center of mass
  - other new techniques are tied to same origin by co-location of instruments

“Gotcha” Continued

- Because the old meridian planes were defined by *local* gravity, they were subject to deflection of the vertical (DoV)
  - at Greenwich, the east-west component of DoV is 5.502” to the east, computed from Earth gravity model EGM2008 (± 0.5”)
- Old meridian planes at the classical observatories were often tilted east or west with respect to a line toward the center of the Earth
- A lateral shift of these planes would be required for them to maintain their orientation yet pass through the center of the Earth

Therefore, even though the old and new meridian planes of the same longitude value are parallel, they do not necessarily cut the surface of the Earth along the same line

Meridian Geometry



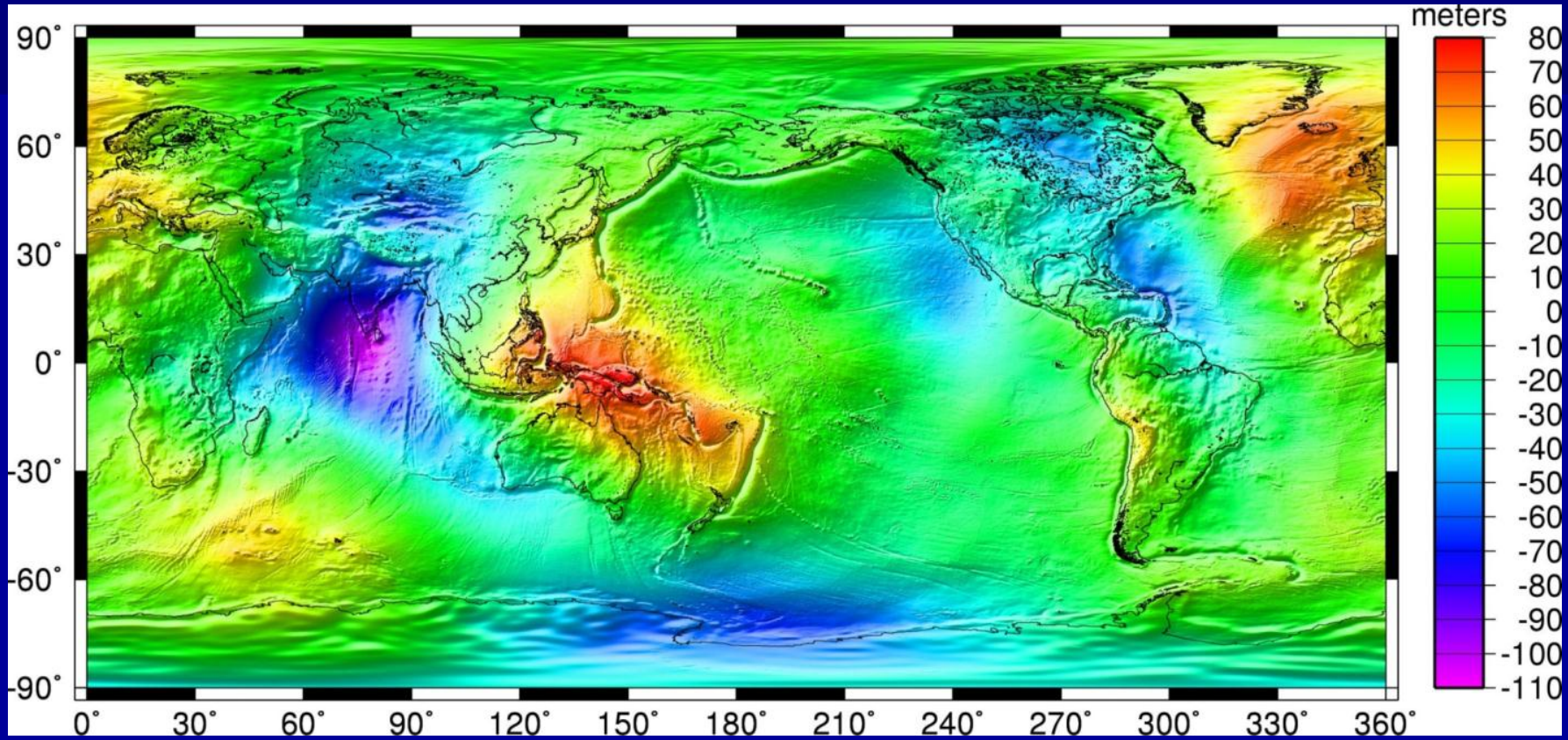
The dashed and solid light blue meridians are parallel. Extended to infinity, they sweep through the same stars as the Earth rotates, yielding the same astronomical time.

The BIH constraint on the continuity of UT1 is met, even though the meridians cut the Earth's surface at different places.

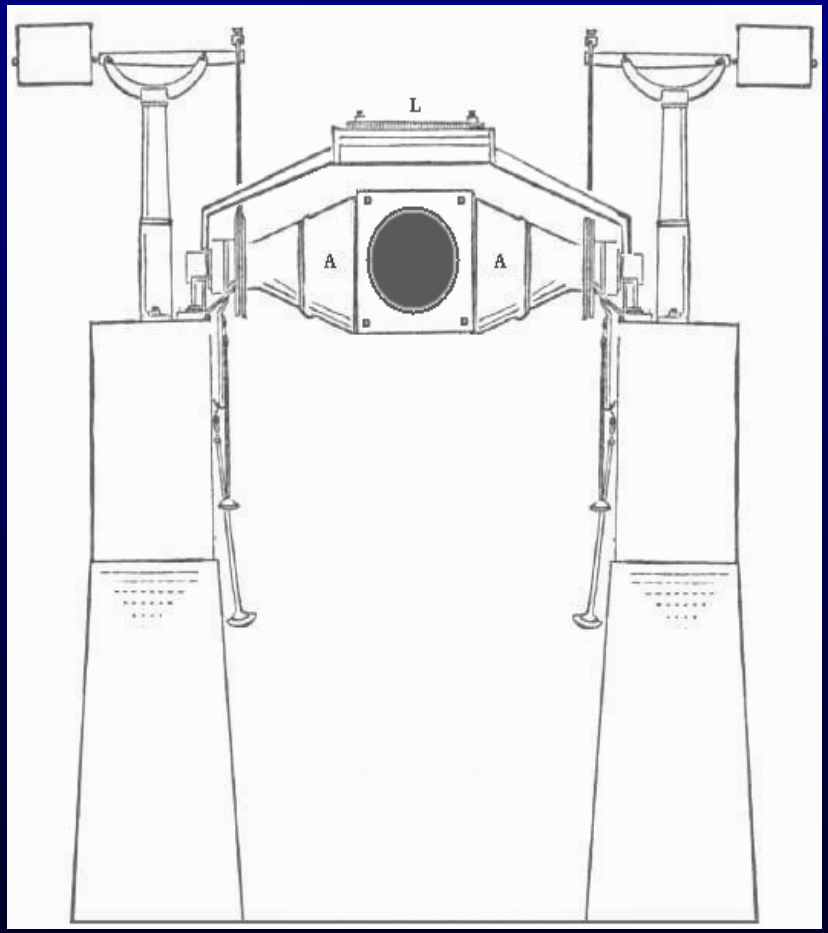
Conclusions

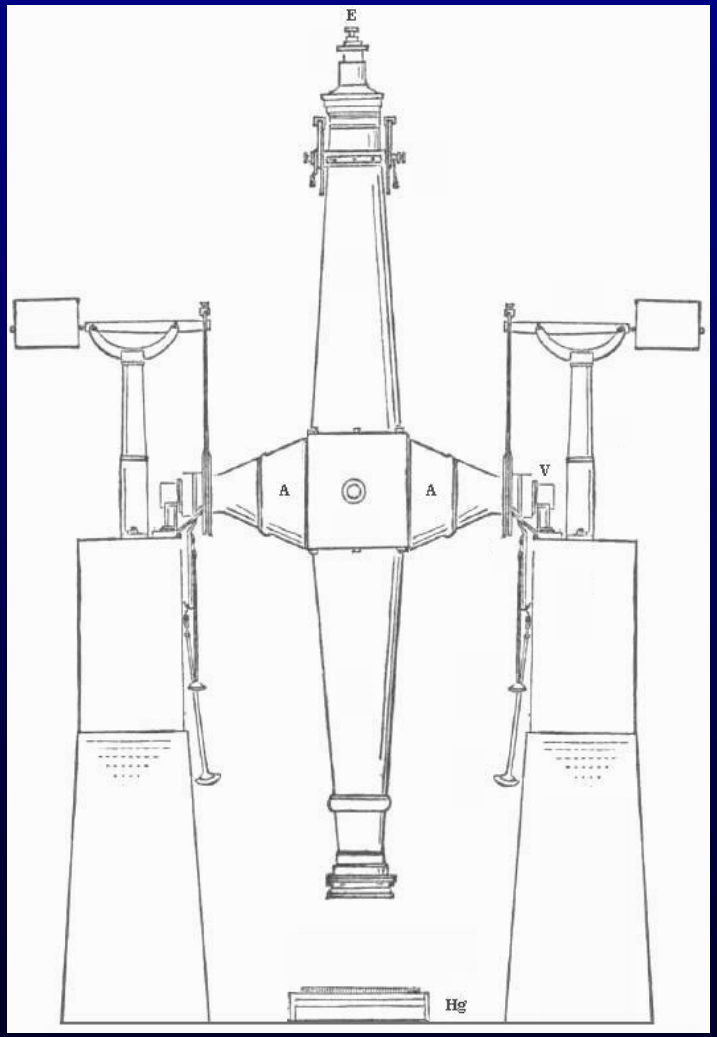
- The east-west value of the DoV at Greenwich, together with the BIH constraint on the continuity of UT1, is sufficient (within the uncertainties) to completely explain the 102 m offset of the new and old zero longitude meridians there
- The new and old zero-longitude meridians are parallel planes
- The situation at Greenwich is repeated for all of the classical observatories, but with different DoV values
- Because the DoV values are different at different latitudes, conceptually, any of the classical meridians traces a wiggly line across the Earth's surface
- There has been no systematic shift of the entire longitude system; the situation at Greenwich is local to Greenwich

Geoid Undulations from the Earth Gravitational Model 2008 (EGM08)



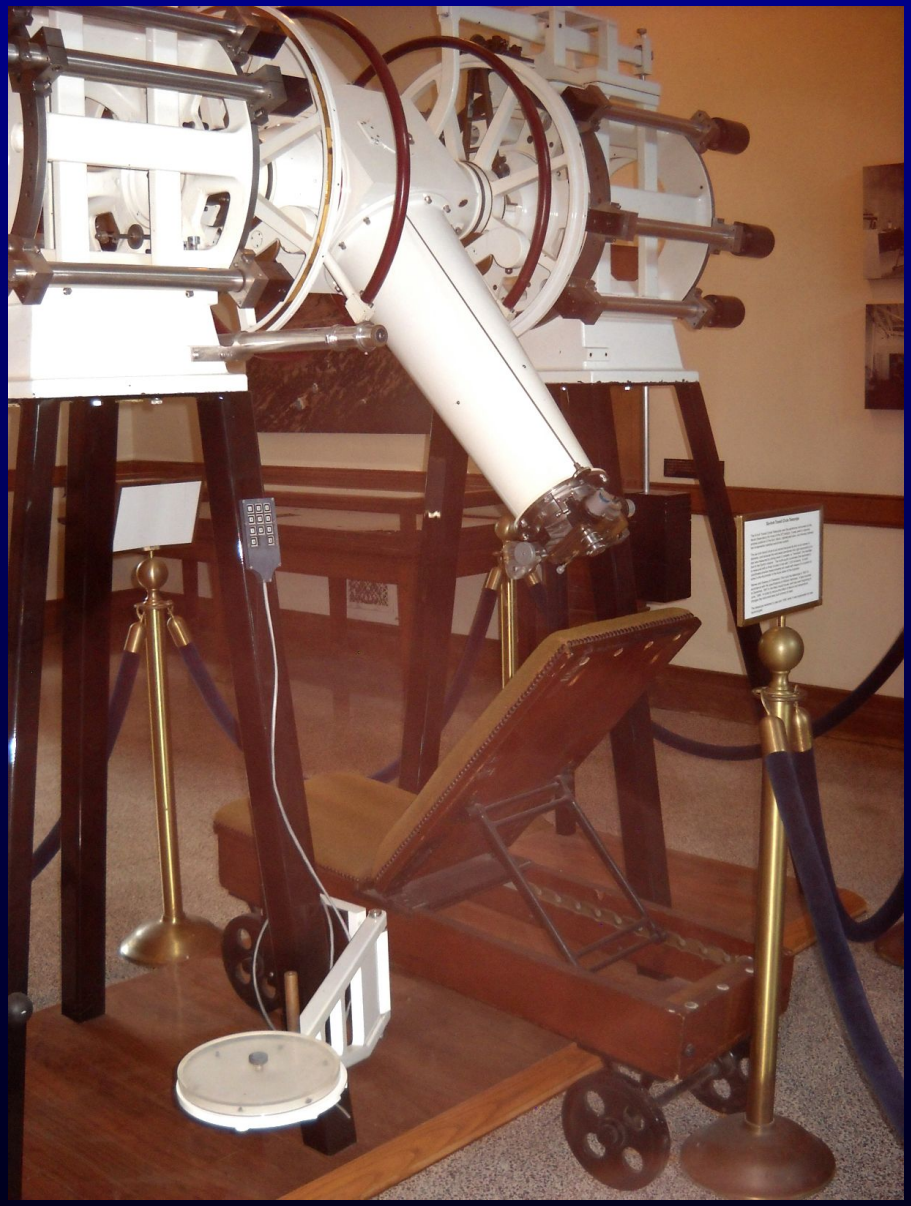
Schematic of a Typical Transit Circle





Adapted from: Norton, W.A. (1872) *A Treatise on Astronomy, Spherical and Physical*, 4th ed., John Wiley & Son, New York, p. 31.

USNO 6-inch Transit Circle



But Wait, There's More…

1. The slight longitude shift of 1968
2. A look at some of the alternative explanations
3. Our venture into forensic geodesy (and archeology?)

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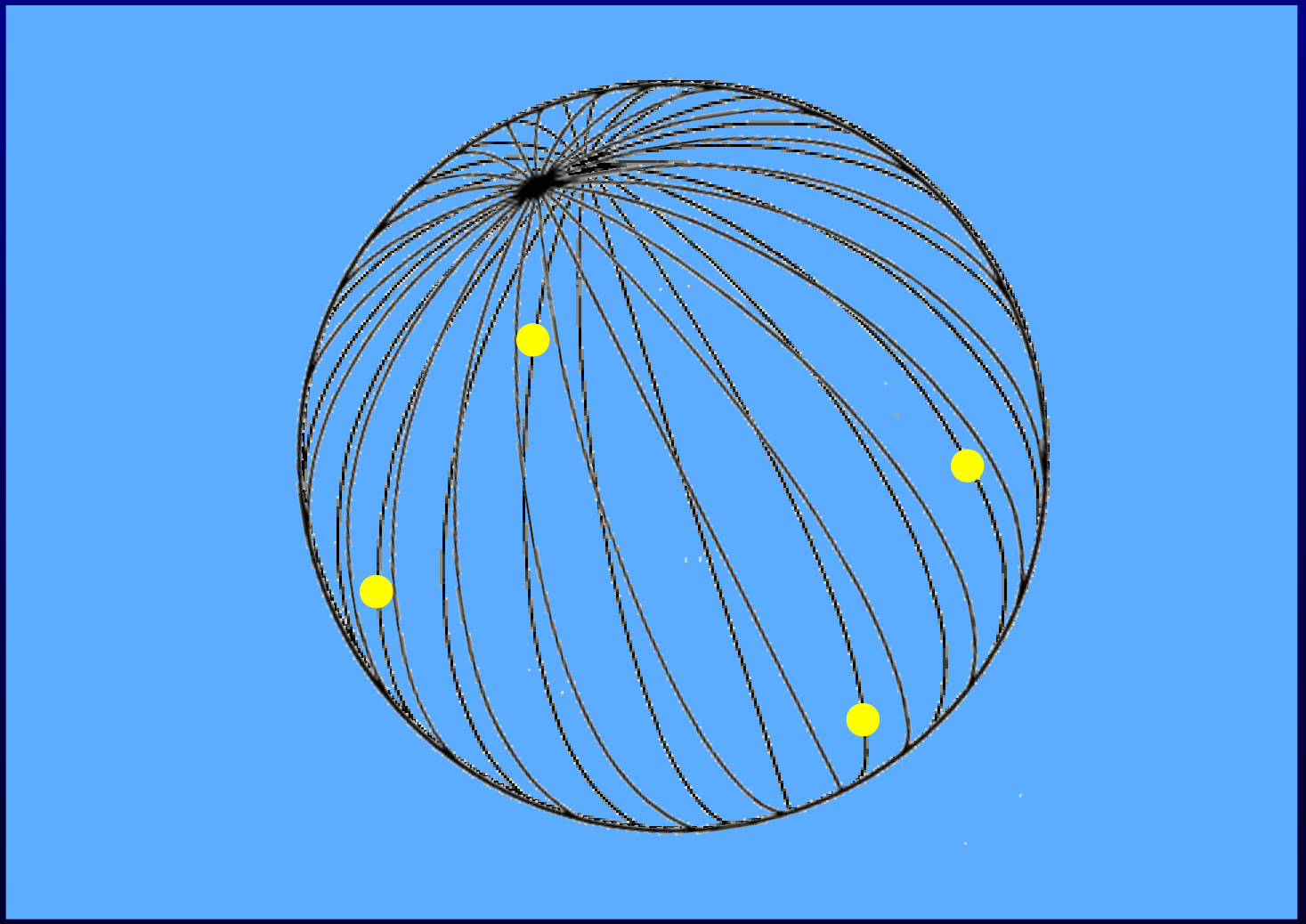
The Greenwich Observatory in the 20th Century

- Regular time observations ended on the Airy Transit Circle in 1927
  - observations transferred to smaller instruments nearby, but data was adjusted to refer to longitude 0
  - Greenwich instruments retained longitude “0 0 0,000” in the BIH system until…
- Royal Greenwich Observatory moved to Herstmonceux, East Sussex, about 70 km southeast of Greenwich (longitude 0°20’ E) in 1957
- Last transit circle observations at Herstmonceux made in 1982.
- RGO moved to Cambridge in 1992.
- RGO closed in 1998.

The BIH Pole & Longitude Shift of 1968

- Polar motion not included in UT1 determinations for most of the 20th century due to delays in polar motion analysis
  - Polar motion determined by International Latitude Service (ILS), renamed in 1962 to International Polar Motion Service (IPMS)
- Efforts to include it began in the 1950s, with various reference points used as the nominal geographic pole ("stake in the ground")
- In 1968, the BIH standardized on the ILS pole of 1900-1905 as its reference point, called the Conventional International Origin (CIO).
- This shift of pole caused a small shift in the longitudes of all contributing observatories — in particular, the BIH longitude of the ATC at Greenwich (and the line in the sidewalk) shifted to 0.2927″ W (about 6 m) at that time
  - But who knew?

Change of Pole = Change of Longitudes



BIH Choices in 1968
(from BIH Annual Report for 1968)

b - Change of the longitude origin.

As the international unions have not made the choice of a new origin of the longitudes after the change of the polody origin, three processes were in effect possible :

(1) to keep the equatorial reference point defined by the 1967 mean observatory : there would be so no discontinuity of UT1, but all longitudes would have to be corrected by :

$$-(x_{CIO} - x_M) \sin L \, tg\, \varphi + (y_{CIO} - y_M) \cos L \, tg\, \varphi \; ;$$

(2) to keep the Greenwich (Airy instrument of the old observatory) longitude : UT1 would show a step independent of the choice of the mean observatory ; the longitudes of other observatories would have to be changed ;

(3) to keep the initial longitudes : each $UT1_i$ would show a step ; the UT1 step being their mean and depending on the choice of the mean observatory.

We have applied the first process.

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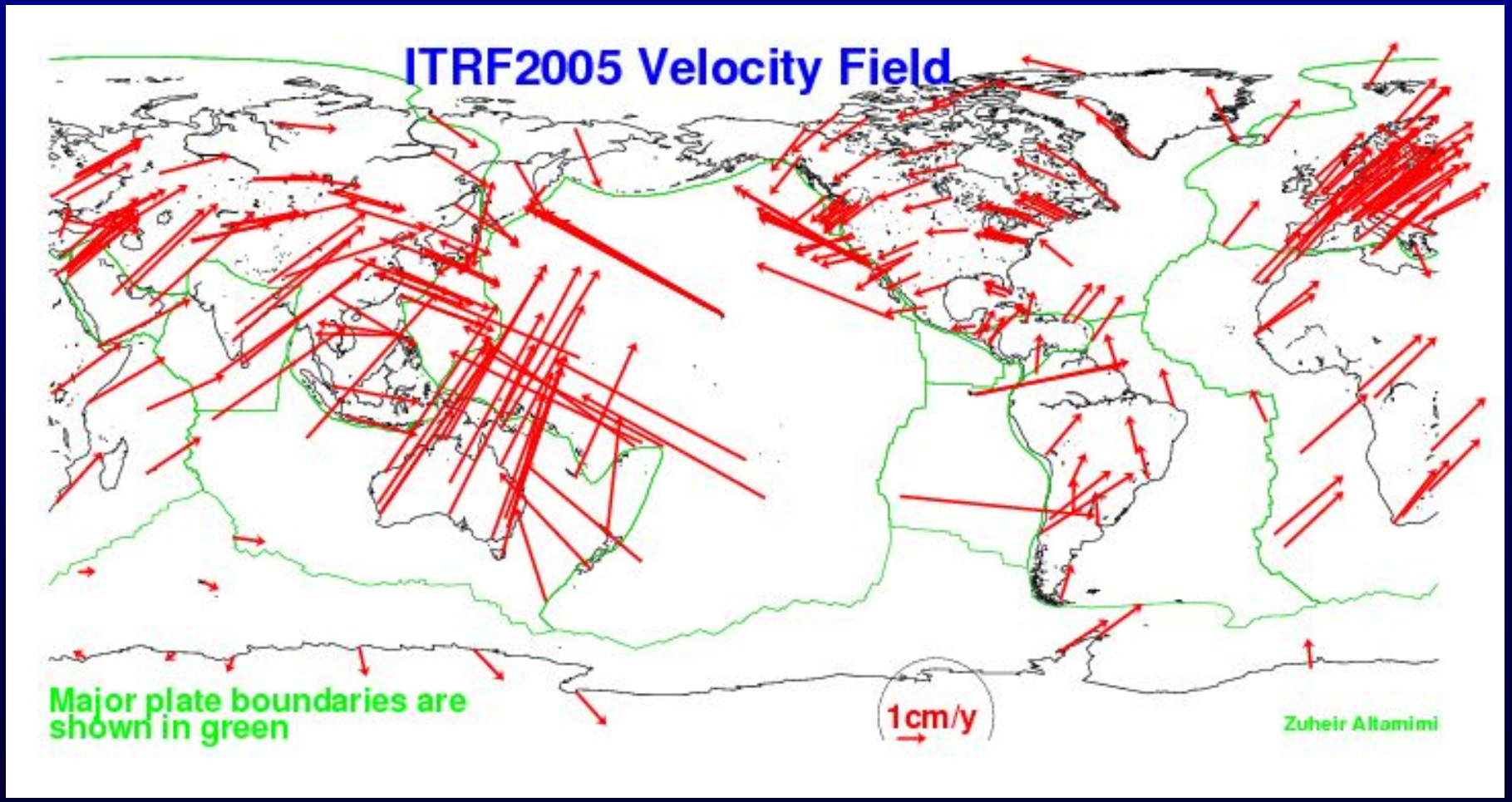
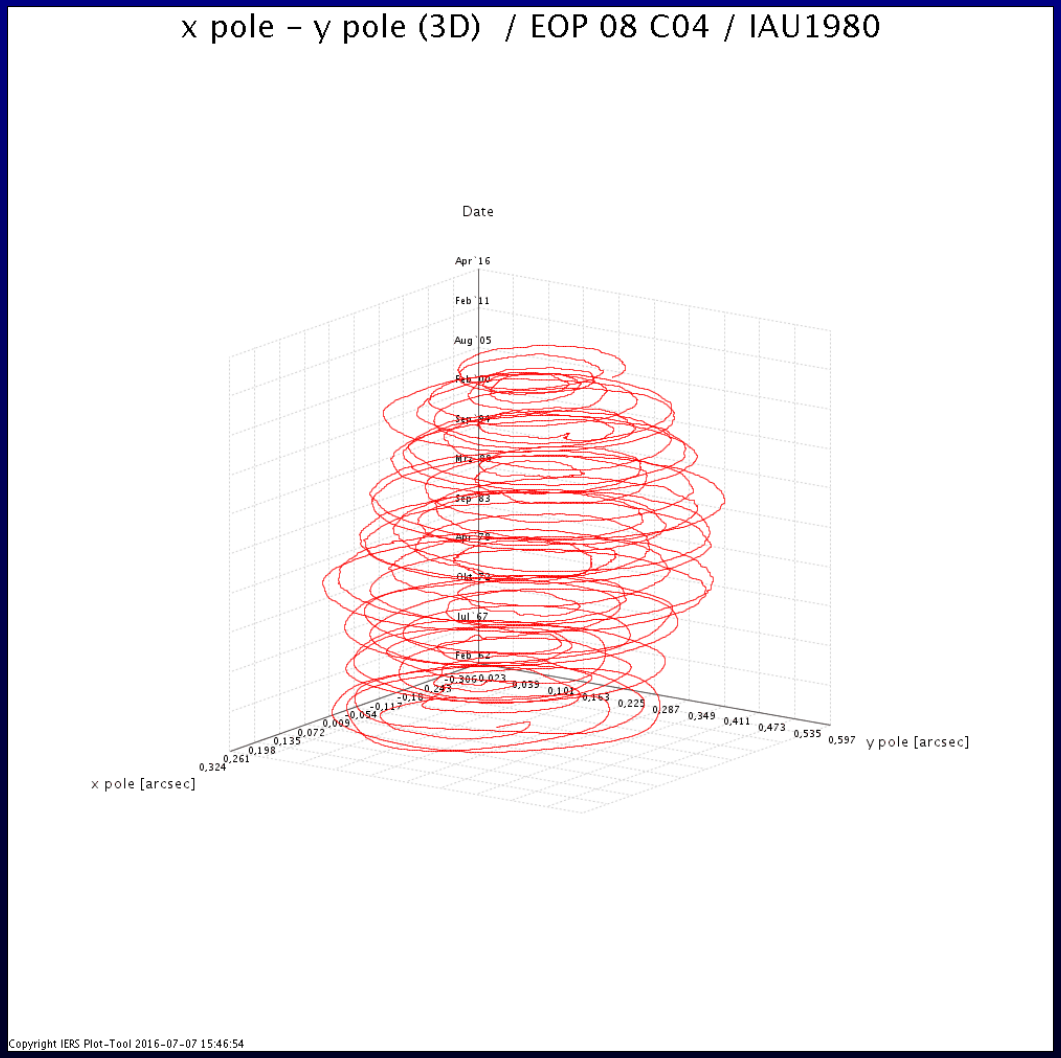
Continental Drift



Stations near the UK are moving NE at about 2.5 cm/year

Polar Motion/Wander



Secular drift of the pole of rotation

~0.5”/cy

~15 m/cy

Change in Astronomical Constants

- IAU (1976) System of Astronomical Constants
  - adopted in 1976
  - implemented in 1984
- Included a 1”.1/cy change in precession, and recommended an equinox correction for the FK5 star catalog, which turned out to consist of an offset of 1”.163 and a rate of 1”.275/cy.
- However, an IAU resolution passed in 1976 required that “the expression for Greenwich mean sidereal time at 0^h UT shall be amended by the same equinox correction and motion as adopted for the FK5 in order to avoid a discontinuity in UT.”
- New expression relating UT1 and sidereal time given in Aoki, et al. (1982) *Astron. Astrophys*. 105, pp. 359-361.

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Was There a Global Shift in Longitudes?

Test: There are two ways to obtain the deflection of the vertical:

1. Computed from a global (satellite-derived) gravity model, in our case EGM2008

2. Measured from *in situ* measurements — simply differencing the old (astronomical) and new (geodetic) station coordinates

Basically, BIH − GPS

For longitudes, the second will equal the first only if there is no bias in longitude, i.e., no systematic shift in longitude has occurred

Comparisons of DoV in Longitude

BIH Code	Annual Reports	Location	φ	λ	H (m)	$\Lambda-\lambda$ (")	$\eta\sec\varphi$ (")	$\sigma_{\eta\sec\varphi}$ (")	$\Lambda-\Lambda_{grav}$ (")
G	33-55	Greenwich	51°28'40.1"N	0°00'05.3"W	41	5.3	4.9	0.47	0.4
BLI	68-83	Belgrade	44°48'00.5"N	20°30'46.9"E	244	1.0	1.5	1.44	−0.5
BOI[c]	68-74	Borowiec	52°16'30.7"N	17°04'29.7"E	77	7.1	7.4	0.72	−0.3
BOJ[c]	72-81		52°16'30.7"N	17°04'28.9"E	77	7.6	7.4		0.2
BG[b]	68-83	Borowa Góra	52°28'31.9"N	21°02'05.1"E	104	8.6	8.9	0.77	−0.3
BS[a]	68-73	Besançon	47°14'53.0"N	5°59'21.3"E	307	−6.3	−6.4	0.67	0.1
CT[a]	68-69	Cape Town	33°56'05.3"S	18°28'39.0"E	9	1.2	−0.4	0.66	1.6
G[a]	68-83	Herstmonceux	50°52'21.2"N	0°20'14.5"E	27	1.7	1.5	0.44	0.2
GRA[a,c]	71-77	Grasse	43°45'7.26"N	6°55'25.09"E	1271	10.9	12.2	0.88	−1.3
GRB	79-80								
GRC	79-80								
MA	68-83	Moscow Astr.	55°42'04.8"N	37°32'30.6"E	191	9.6	9.2	1.81	0.4
MAP	71-83		55°42'02.2"N	37°32'22.5"E	189	9.6	9.2		0.4
MS[a]	68-83	Mt. Stromlo	35°19'15.4"S	149°00'23.07"E	761	−4.4	−4.5	0.77	0.1
NK	68-83	Nikolaiev	46°58'19.4"N	31°58'25.2"E	51	2.3	4.5	0.78	−2.2
O[d]	68-70	Ottawa	45°23'35.7"N	75°42'52.9"W	85	−6.3	−5.1	0.61	−1.2
OJP[b]	75-83	Ondřejov	49°54'50.4"N	14°47'01.2"E	532	8.1	7.1	0.90	1.0
OS	71-83	Ottawa Shirley	45°24'00.7"N	75°55'08.3"W	72	−4.5	−4.2	0.60	−0.3
PA[a]	68-83	Paris	48°50'08.6"N	2°20'13.5"E	61	2.0	2.3	0.47	−0.3
PAN[a]	70-72	Paris-Nord	48°50'09.7"N	2°20'13.3"E	62	2.0	2.3		−0.3

Comparisons of DoV in Longitude

PTA[a,c]	68-83	Potsdam	52°22'48.5"N	13°03'53.9"E	91	6.5	6.4	0.56	0.1
PTQ[a,c]	80-83		52°22'48.5"N	13°03'53.9"E	91	6.5	6.4		0.1
PTJ[a,c]	68-74		52°22'48.1"N	13°03'53.6"E	91	6.8	6.4		0.4
PTP[a]	75-82	Potsdam	52°24'18.1"N	13°06'11.2"E	72	6.8	6.7	0.55	0.1
PUG[a,d]	71-83	Pulkovo	59°46'12.2"N	30°19'34.3"E	78	4.2	4.0	1.43	0.2
PUH[a,d]	72-83								
PYD[b]	70-83	Pecný	49°54'50.5"N	14°47'12.1"E	549	8.4	8.1	0.90	0.3
RCA	68-78	Richmond	25°36'50.8"N	80°23'03.0"W	8	7.2	7.8	0.42	−0.6
RCP	74-83		25°36'50.4"N	80°23'02.9"W	8	7.4	7.8		−0.4
SFA[a]	70-83	San Fernando	36°27'56.8"N	6°12'18.0"W	25	0.7	−0.3	0.44	1.0
SFI[a]	68		36°27'55.0"N	6°12'20.2"W	25	1.0	−0.3		1.3
SJ[a]	70-83	San Juan	31°30'34.0"S	68°37'25.6"W	705	14.5	14.4	1.38	0.1
SP[a]	68-72	San Paulo	23°39'08.7"S	46°37'20.6"W	803	−1.0	0.3	1.58	−1.3
TFA[b]	81-83	Rio Grande	53°47'08.5"S	67°45'03.8"W	19	−1.1	0.6	1.02	−1.7
UA[a,b]	68-73	Uccle	50°47'50.0"N	4°21'31.6"E	102	−3.8	−4.7	0.52	0.9
UB[a]	71-72		50°47'52.2"N	4°21'33.2"E	104	−4.5	−4.7		0.2
W[a,b,d]	68-83	Washington	38°55'17.1"N	77°04'01.4"W	86	4.4	4.7	0.46	−0.3

[a] Position supplied/confirmed by affiliated personnel.

[b] Co-located with GPS station.

[c] Co- located with SLR station.

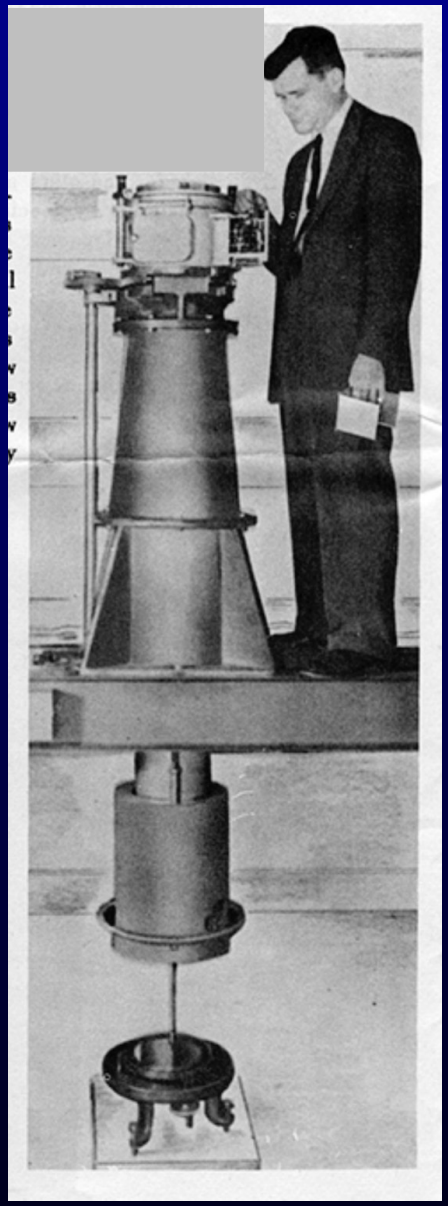
[d] With respect to conventional longitude.

No Overall Shift in Longitude System

- Weighted average of last column = 0.06″ ± 0.14″ (1σ)
  ⇨ No significant overall rotation of longitude system
- The difficult part was obtaining the GPS coordinates of the old instruments!
  - many of the old instrument sites/buildings were gone and no longer obvious
  - current staff members at many observatories were not able to help
  - Google Earth became an important tool for us

Belgrade

At First, USNO Seemed to be a Problem



USNO PZT

1970s Aerial Photo of USNO

PZT Building Now Gone Without a Trace

But…It Doesn't Matter...

UNITED STATES

Historically all longitudes published as longitudes of Washington PZT instruments have actually referred to the longitude of the clock house. The longitudes of the clock house used for PZT #3 in the past, sometimes called 'conventional' or 'effective' longitudes, are:

	s
14 April 1956 to 31 December 1960	15.780
1 January 1961 to 31 December 1961	15.740
1 January 1962 to 31 December 1968	15.729
1 January 1969 to the present	15.7494

A measured difference, −0^{s}.0400, must be added to these longitudes in order to obtain those of PZT #3.

U. S. NAVAL OBSERVATORY INSTALLATIONS

by

James A. Hughes (Chairman)
Peter Espenschied
Dennis McCarthy
David K. Scott
Thomas C. Van Flandern

Coordinates Committee, Naval Observatory

We Know Where the Center of the Clock House (Bldg 3) Is

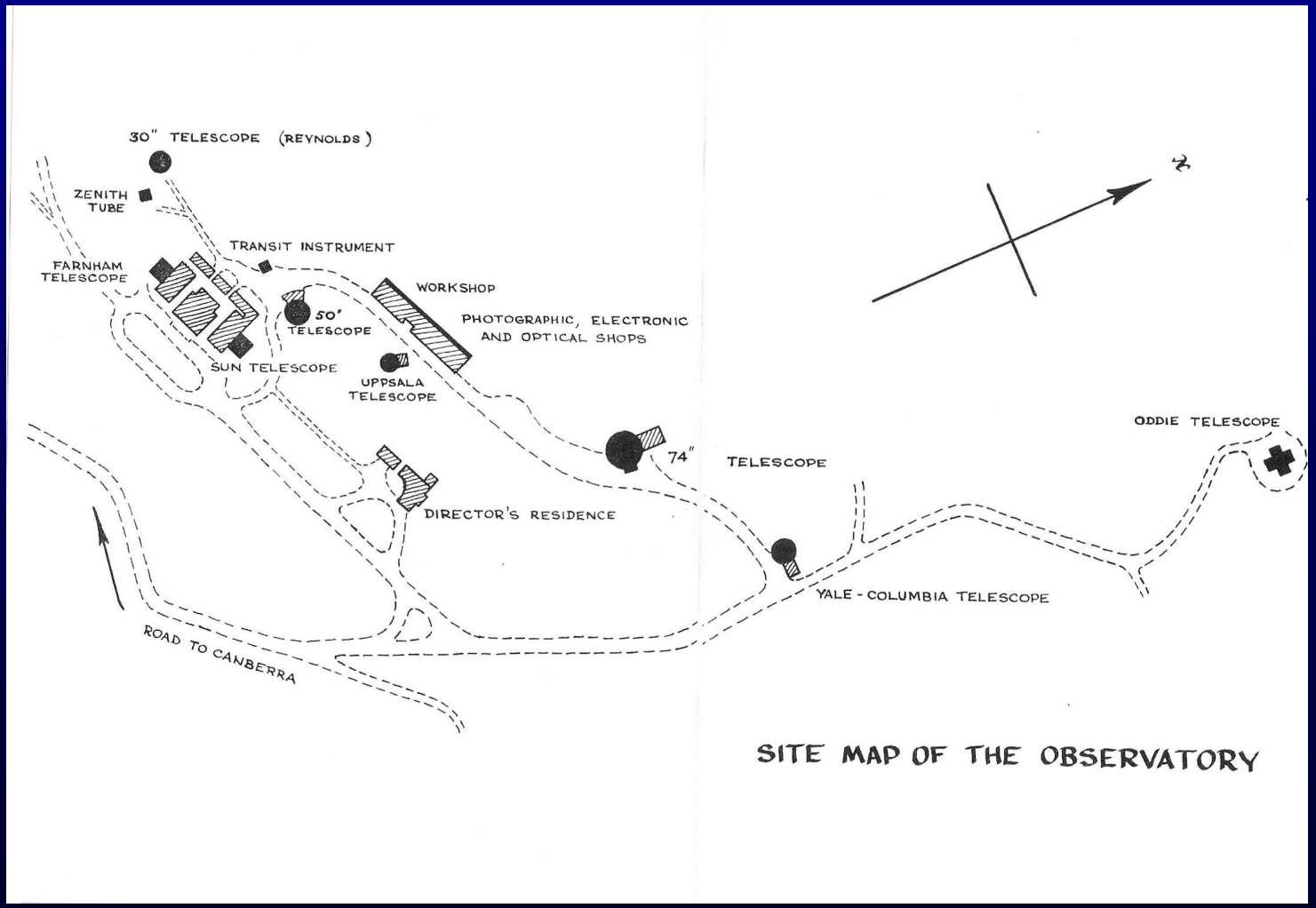
The Meridian of Washington

Mt. Stromlo PZT

Photographic Zenith Tube. The only such instrument in the southern hemisphere, it is used to measure the rotation of the Earth and the variation of latitude.

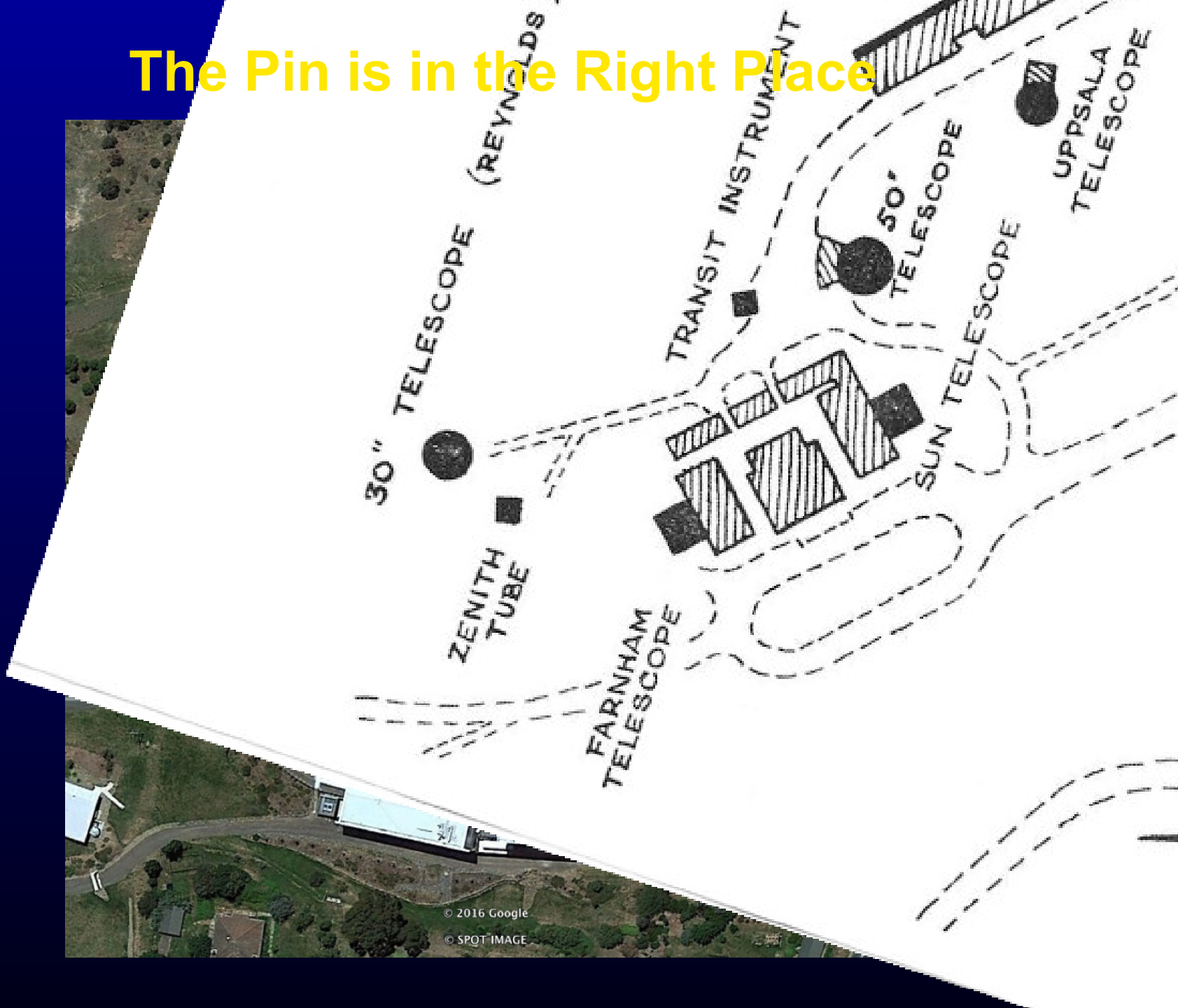
Was It Really in the Middle of a Road?

No! The Roads Have Been Reconfigured



From a Mt. Stromlo info pamphlet.

The Pin is in the Right Place



More Information

tinyurl.com/greenwich-moved

gpsworld.com/prime-meridian-on-the-move

Or google “Why the Greenwich Meridian Moved”