



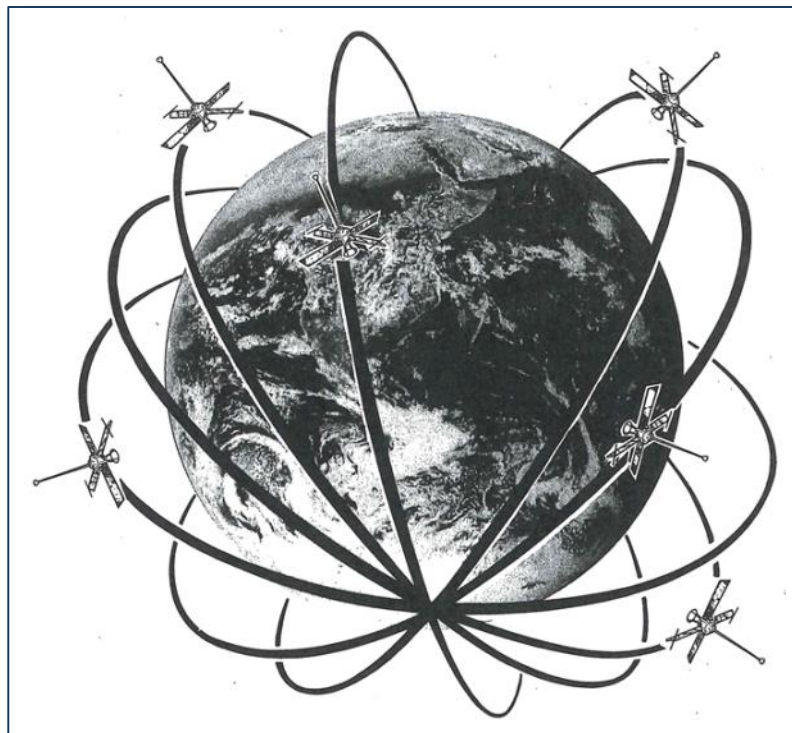
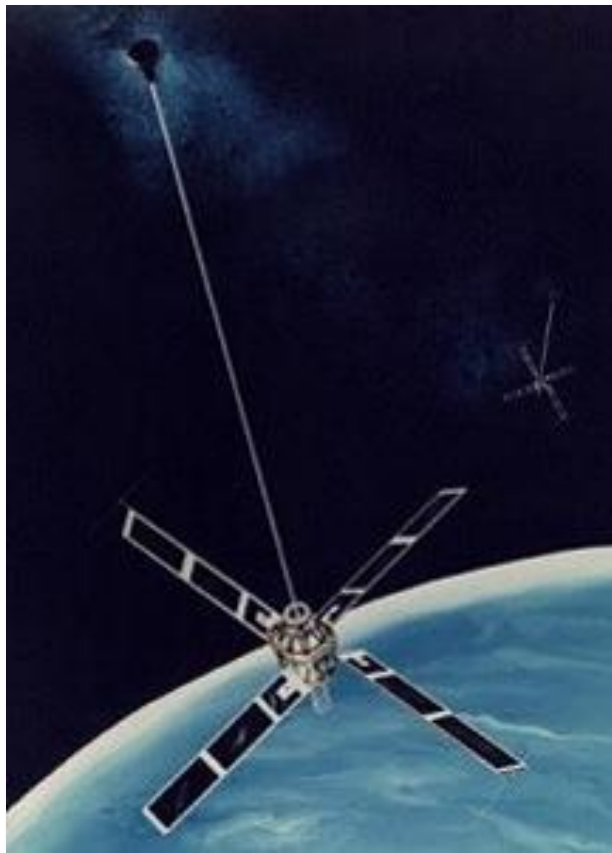
Evolution of the World Geodetic System 1984 (WGS 84) Terrestrial Reference Frame

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6 November 2018

Presented at ICG-13, Xi'an China

Navy Navigation Satellite System a.k.a. TRANSIT



Transit Satellites Form a “Birdcage” of Circular, Polar Orbits About 1075 km Above the Earth

Ref: The TRANSIT Navigation Satellite System, Thomas A. Stansell, Status, Theory, Performance, Applications, The Magnavox Government and Industrial Electronics Company, June, 1983

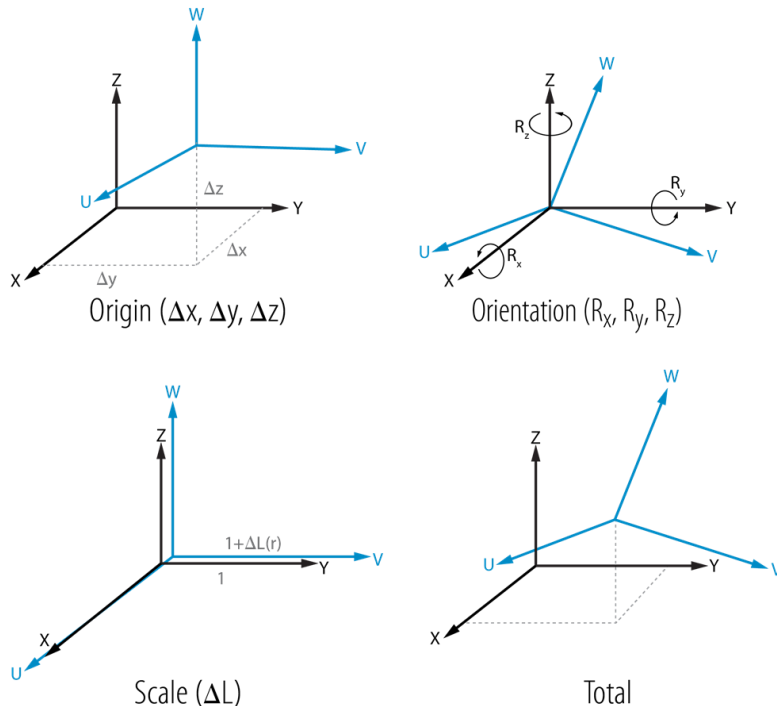
The Original WGS 84 Terrestrial Reference Frame

US Defense Mapping Agency adopted a transformation created by the BIH* Transforming TRANSIT Tracking station coordinates in 'NSWC-9Z2' into BTS 84**

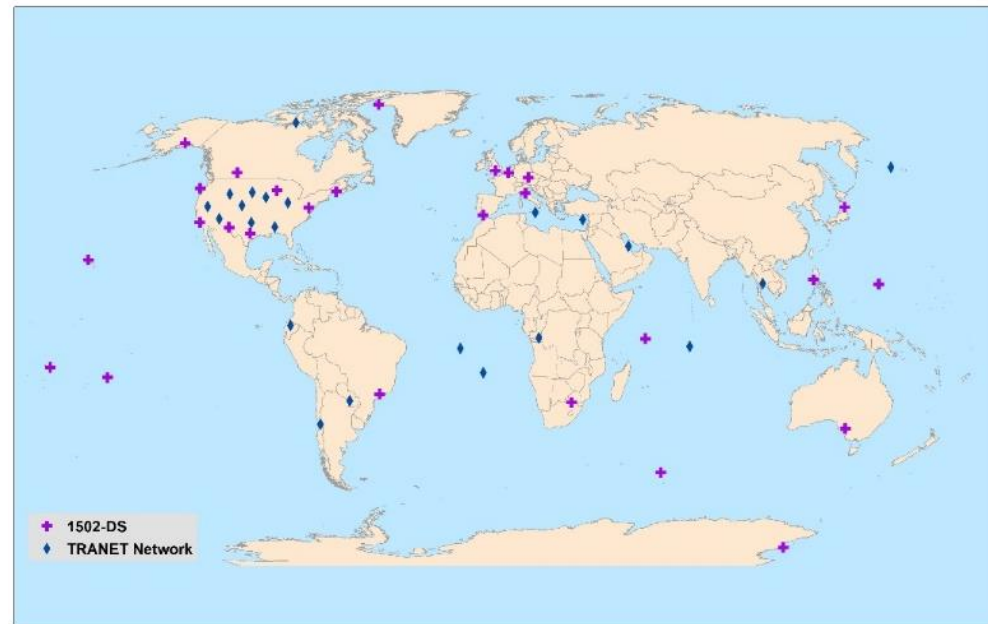
$$\Delta Z = 4.5 \text{ m}$$

$$R_z = 0.814 \text{ arc sec}$$

$$\Delta L = -0.6 \text{ ppm}$$



1986: 48-Station 'Doppler' Tracking Network



*BIH = Bureau International de l'Heure

** BTS84 = BIH Terrestrial System 1984

WGS 84 is a Global, Earth-Centered, Earth-Fixed Terrestrial Reference Frame and a set of Global Geophysical models

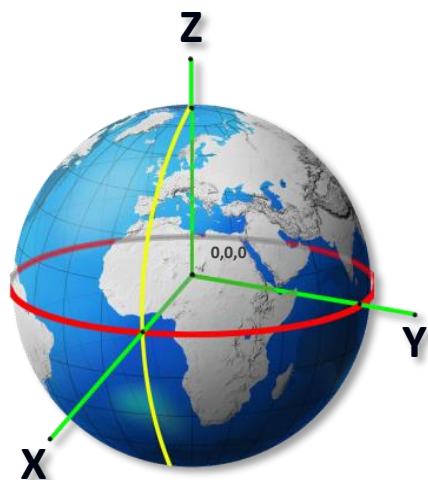
- Earth Gravitational Model
 - ▶ 1984 WGS 84 Spherical Harmonics $n=m=180$
 - ▶ 1996 EGM 96 Spherical Harmonics $n=m=360$
 - ▶ 2008 EGM 08 Spherical Harmonics $n=2160$

- Earth Orientation Parameter Prediction Model
 - ▶ Polynomial Model defined in ICD-GPS-211

- World Magnetic Model (Partnered with NOAA and British Geologic Survey)
 - ▶ 2000 WMM 2000, 2005, 2010, 2015 Spherical Harmonics $n=m=12$

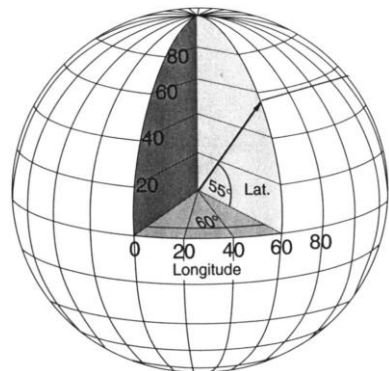
- Adopted from International Scientific Community
 - ▶ Plate Tectonic Models until individual Station Velocities were established
 - ▶ IERS Standards: IERS Tech Notes 3, 13, 21, 32, 36

World Geodetic System 1984 (WGS 84)



Origin for ALL modern Geospatial Data is at Earth's Center of Mass

Known in 3-D with uncertainty smaller than the size of a postage Stamp



Recent WGS 84 Frame Realizations

Realization	Absolute Accuracy	Date
Original (TRANSIT)	1-2 m	Jan 1987
G730	10 cm	Jun 1994
G873	5 cm	Jun 1997
G1150	2 cm	Jan 2002
G1674	1 cm	Feb 2012
G1762*	1 cm	Oct 2013
GXXXX **	1 cm	Oct 2018

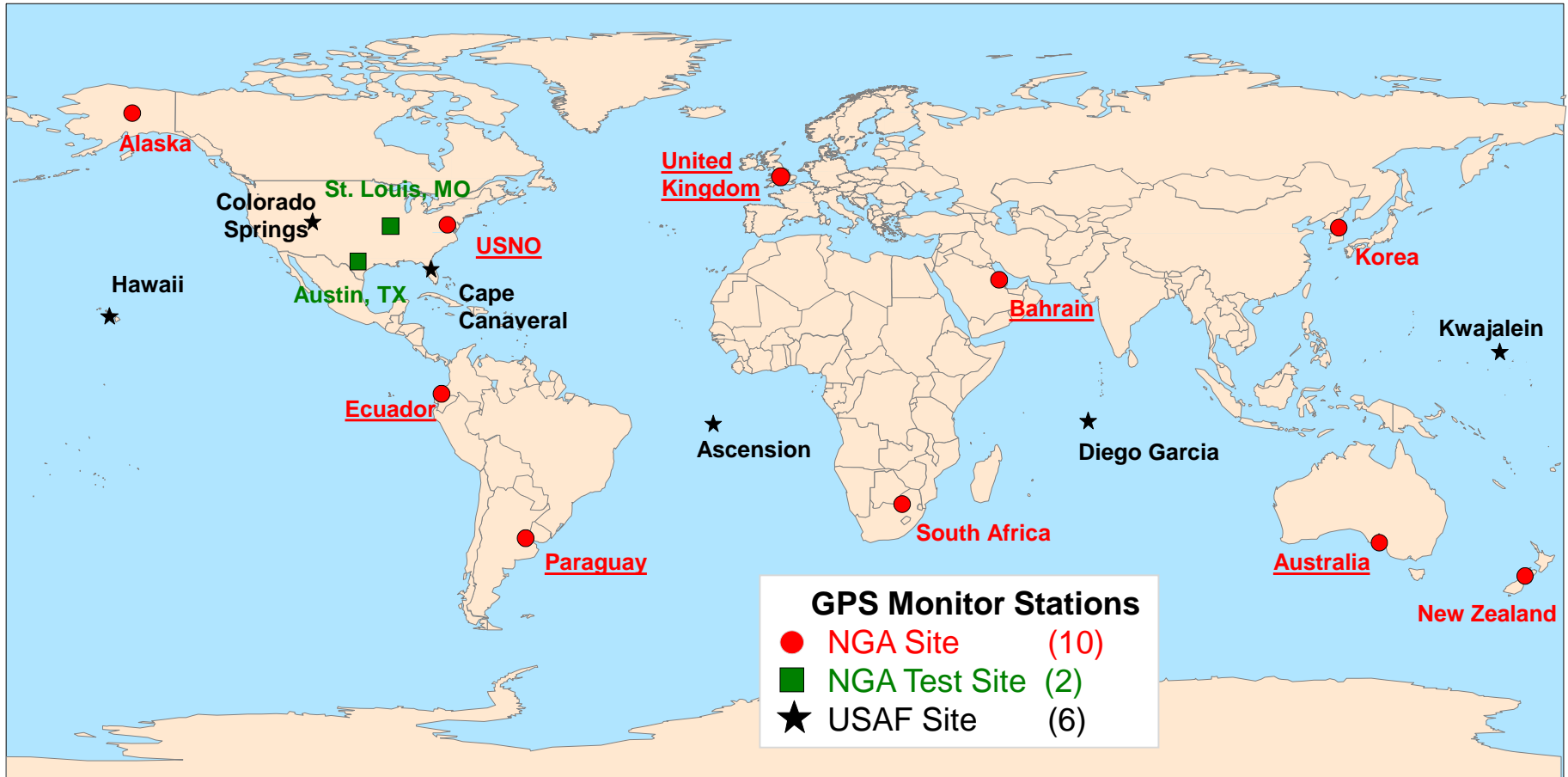
WGS 84 defined in NGA.STND.0036

* Aligned to ITRF08

** Aligned to ITRF14

NGA Predecessor Agencies – Developed the First (1958) Global Reference Frame and Geophysical Models for Modern Geospatial Information including WGS 60, 66, 72

US GPS Monitor Station Network



Four Decades of TRF Refinements by the IERS

Using the best each method has to offer: VLBI, SLR, GNSS, DORIS

Sci. Comm. TRF	# GNSS Stations	IGS Data Span (IGS began in 1994)
BTS84	34(TRANSIT)	9 Years (Transit)
ITRF88	0	0
ITRF89	0	0
ITRF90	0	0
ITRF91	14	
ITRF92	13-48	
ITRF93	44	
ITRF94	26-69	1-3 years
ITRF96	36-132	2-5 years
ITRF97 <i>ITR97 IGS97</i>	40-145 IGS	2-7 Years
ITRF2000 <i>IGS00 IGb00</i>	156-167 IGS	5-9 Years
ITRF2005 <i>IGS05</i>	<338 IGS	10 Years
ITRF2008 <i>IGS08 IGb08</i>	395 IGS (TBC)	12.5 Years
ITRF2014 <i>IGS 14</i>	578 IGS (TBC)	21.1 Years

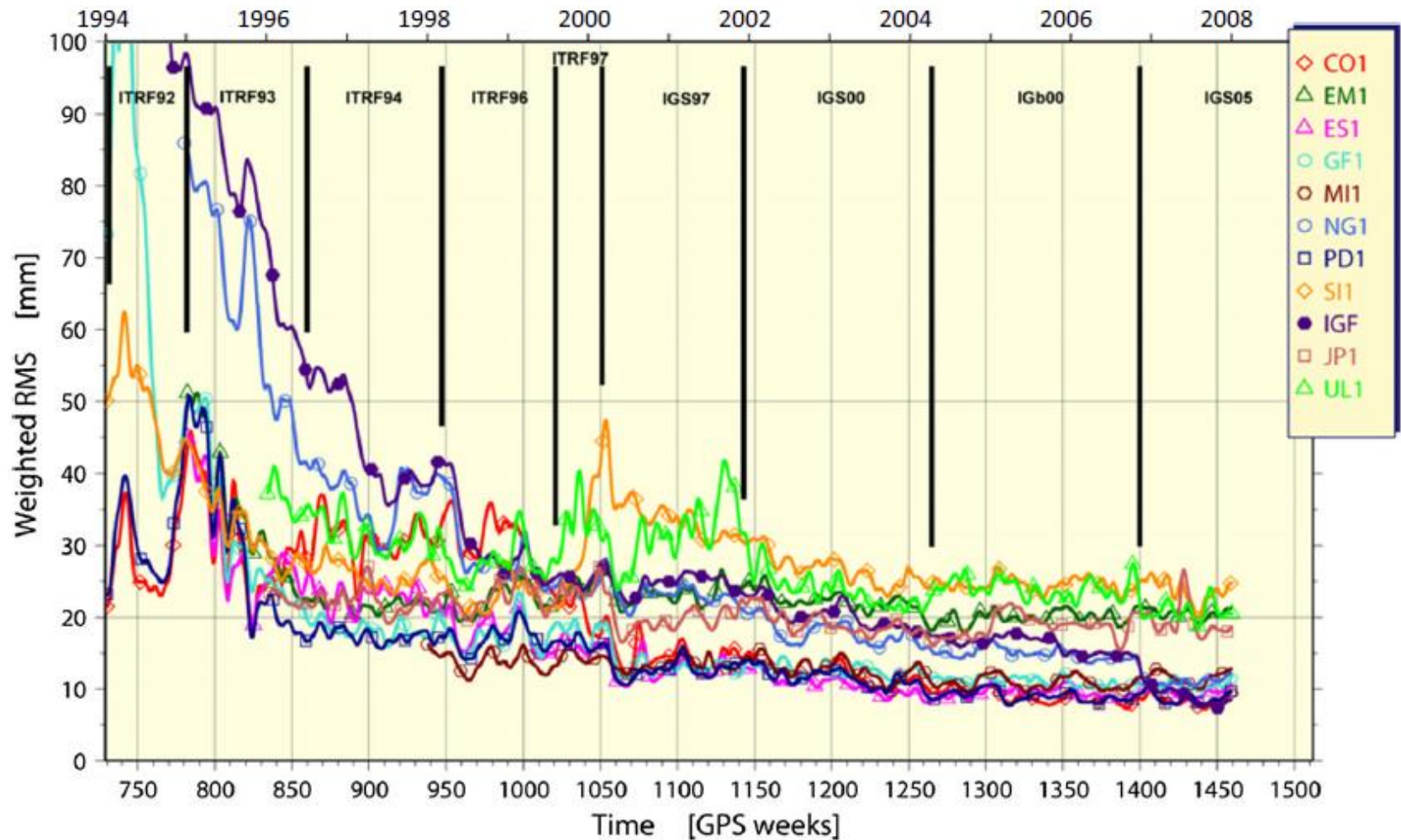
Evolution of TRFs used by IGS*

Start Week	Stop Week	TRF used by IGS
	781	ITR92
782	859	ITR93
860	964	ITR94
947	1020	ITR96
1021	1064	ITR97
1065	1142	IGS97
1143	1252	IGS00
1253	1399	IGb00
1400	1631	IGS05
1632	1708	IGS08
1709	1933	IGb08
1934		IGS14

Compare, via post-fit orbits to WGS 84 TRF realizations

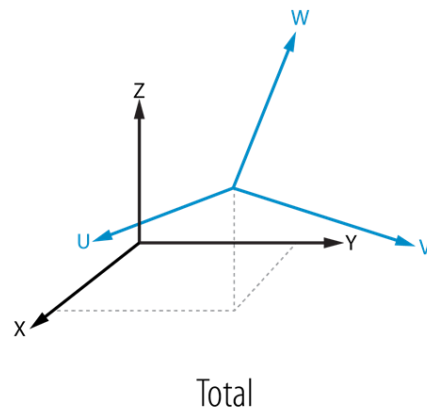
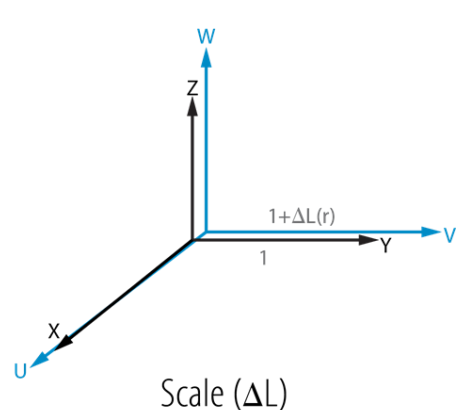
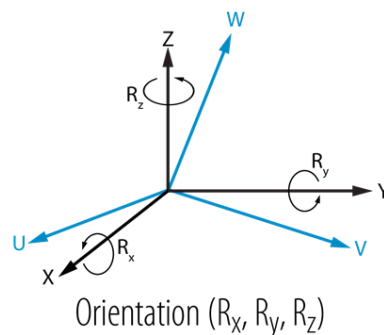
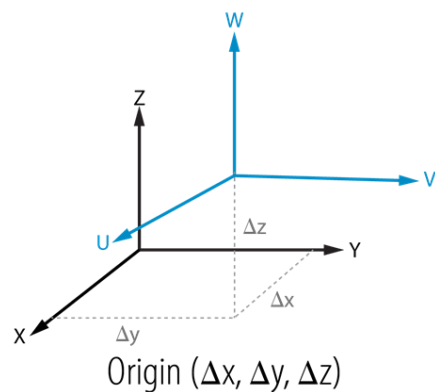
* Personal Communication, Jake Griffiths, Naval Research Laboratory, 2 Oct 2018

IGS Orbit Statistics Show Steady Improvement



Griffiths, J, Combined orbits and clocks from IGS second reprocessing, Journal of Geodesy, May 2018, doi: 10.1007/s00190-018-1149-8

A Single Simplified Metric for Assessing Coincidence of Terrestrial Reference Frame Realizations



Mean Earth Radius = 6371000.0 m

mas = milli arc second

ppb = part per billion

At Mean Earth Radius

1 mas = 3.09 cm

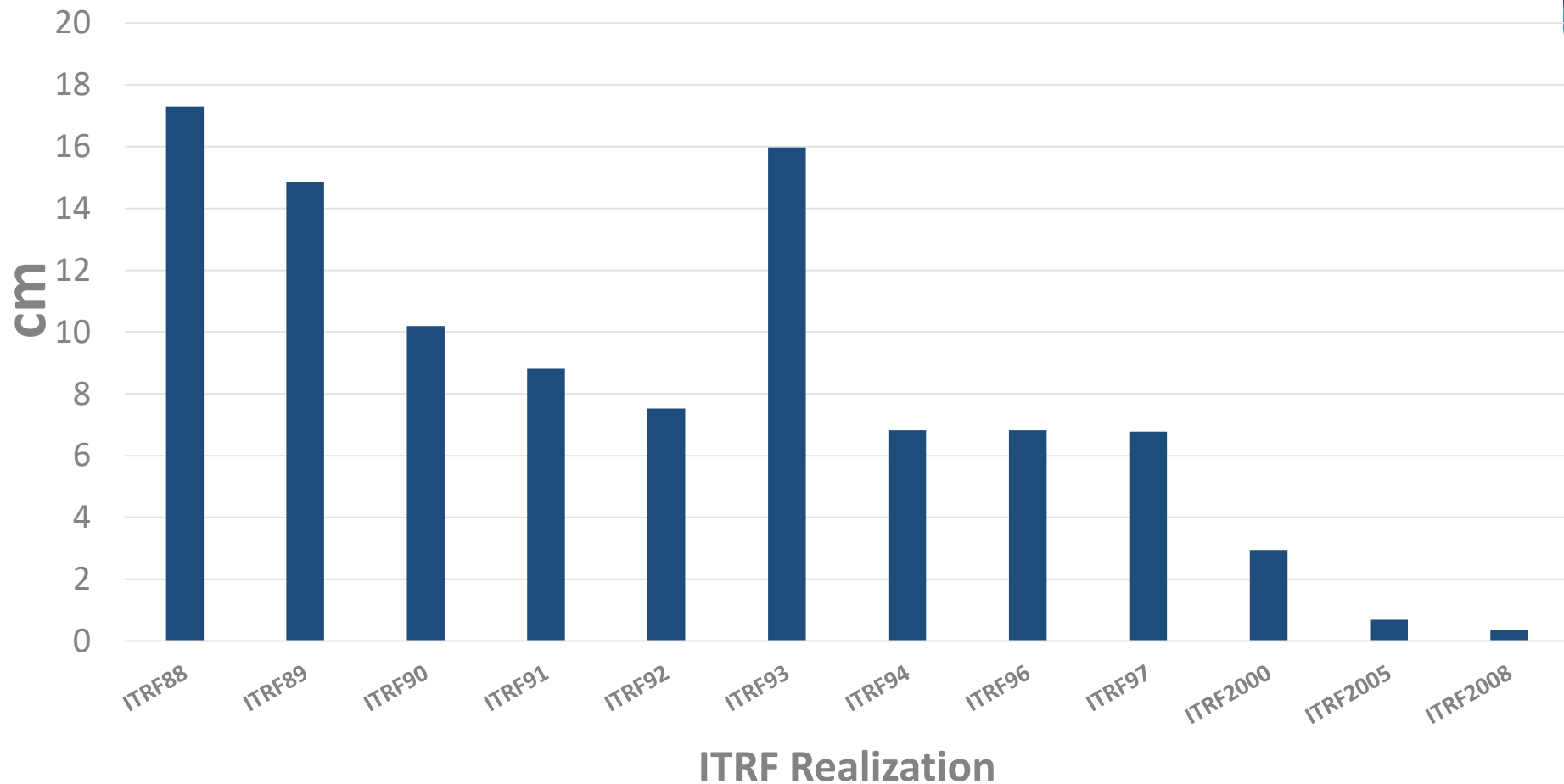
1 ppb = 0.64 cm

$$RSS_7 = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2 + \Delta L^2 + R_X^2 + R_Y^2 + R_Z^2}$$

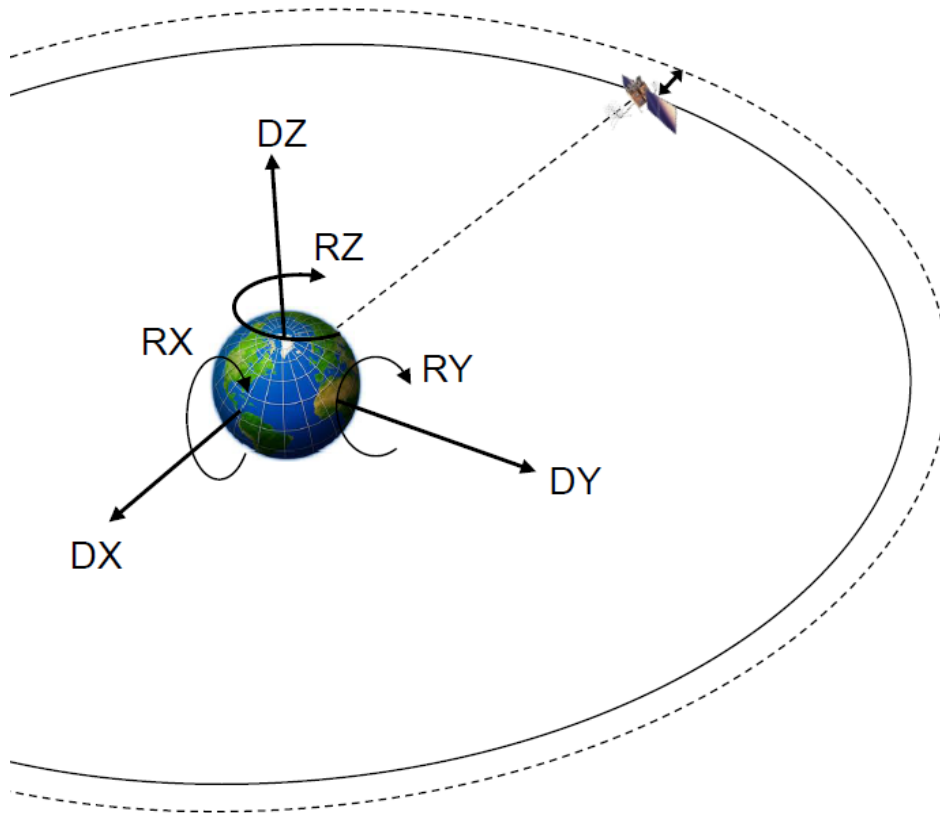
Where all units are cm. ΔL and Rs converted at the mean Earth radius

Evolution of ITRF Realizations

RSS of 7 Transformation parameters from ITRF2014 to previous ITRFs
(cm at mean Earth Radius)



7-Parameter Transformations using Ephemerides



- For each GNSS, 7-parameter Helmert transformations were computed between the IGS reference frame (ITRF 2008) and the Earth-fixed coordinate frames used by the navigation messages.
- A Helmert transformation consists of
 - ▶ 3 translation parameters (DX, DY, DZ)
 - ▶ 3 rotation parameters (RX, RY, RZ)
 - ▶ 1 scale parameter

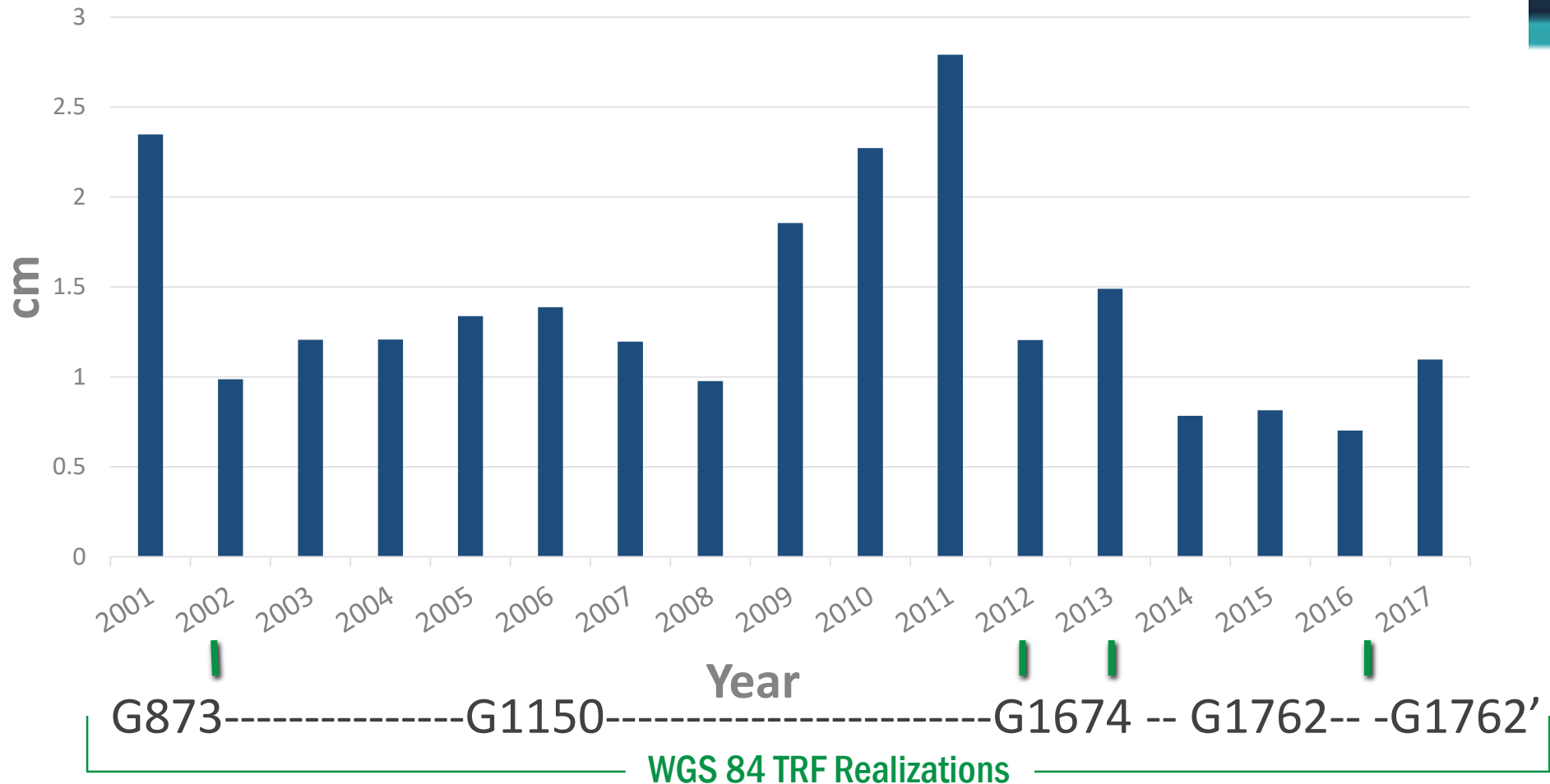
Note that at Earth's surface,

1 mas \approx 3.09 cm

1 ppb \approx 0.64 cm

Evolution of WGS 84 TRF Realizations

RSS of 7 Transformation Parameters (in cm at mean Earth radius)
Between WGS 84 and Contemporaneous ITRF Realization via GPS Post-Fit
Ephemerides



Summary & Conclusions

The WGS 84 Terrestrial Reference Frame

- ▶ Has, since inception, sought to be as coincident as possible with the Scientific Community's Best Terrestrial Reference Frame – Beginning with BTS84
- ▶ Has evolved and benefited significantly from the efforts of the IERS, IGS, IVS, ILRS, and the IDS
- ▶ Provides a global Earth-Centered, Earth-Fixed coordinate system for countless real-time and post-processing GPS users
- ▶ Remains coincident with the latest ITRF on the order of 1cm
- ▶ Facilitates real-time interoperability with other GNSS



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