Compatibility of Terrestrial Reference Frames used in GNSS Broadcast messages

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Methodology: Compare Terrestrial Reference Frames Realized through Broadcast Nav Messages to Reference Frame Realized through Post-Fit MGEX Experiment

Broadcast GNSS Ephemerides

- Predictions that must be used for direct (non-augmented) real-time Positioning, Navigation and Timing
- Represent a real-time realization of the operational Earth-Centered, Earth-Fixed Terrestrial Reference Frame
- Accessible by following procedures documented in respective space to user segment Interface Control Documents

Post-Fit Multi-GNSS (MGEX) Ephemerides

- Best available ephemerides for GPS, GLONASS, Galileo, BeiDou-2
- Based on International Terrestrial Reference Frame 2014 (**ITRF 2014**) Implemented in IGS on 29 Jan 2017 (**IGS14**)

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Terrestrial Reference Frames in GNSS

Data Span: 56 Days: 21 July-14 Sept 2019 (8 GPS Weeks: 2063-2070)

- Terrestrial Reference Frame used in Broadcast Ephemerides
  - GPS WGS 84 (G1762')
  - GLONASS PZ-90.11
  - Galileo GTRF19v01 (Implementation date TBC)
  - BeiDou CTRF2000

- Terrestrial Reference Frame used in Post-Fit MGEX Ephemerides
  - In ITRF2014 (IGS14) as realized by GFZ at 5-minute rate
    - GFZ= Deutsches GeoForschungsZentrum Potsdam
  - IGS14 is the IGS realization of ITRF2014

- All Broadcast and MGEX Ephemerides were obtained from: ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex
  - MGEX = Multi GNSS Experiment, Coordinated by the International GNSS Service (IGS)

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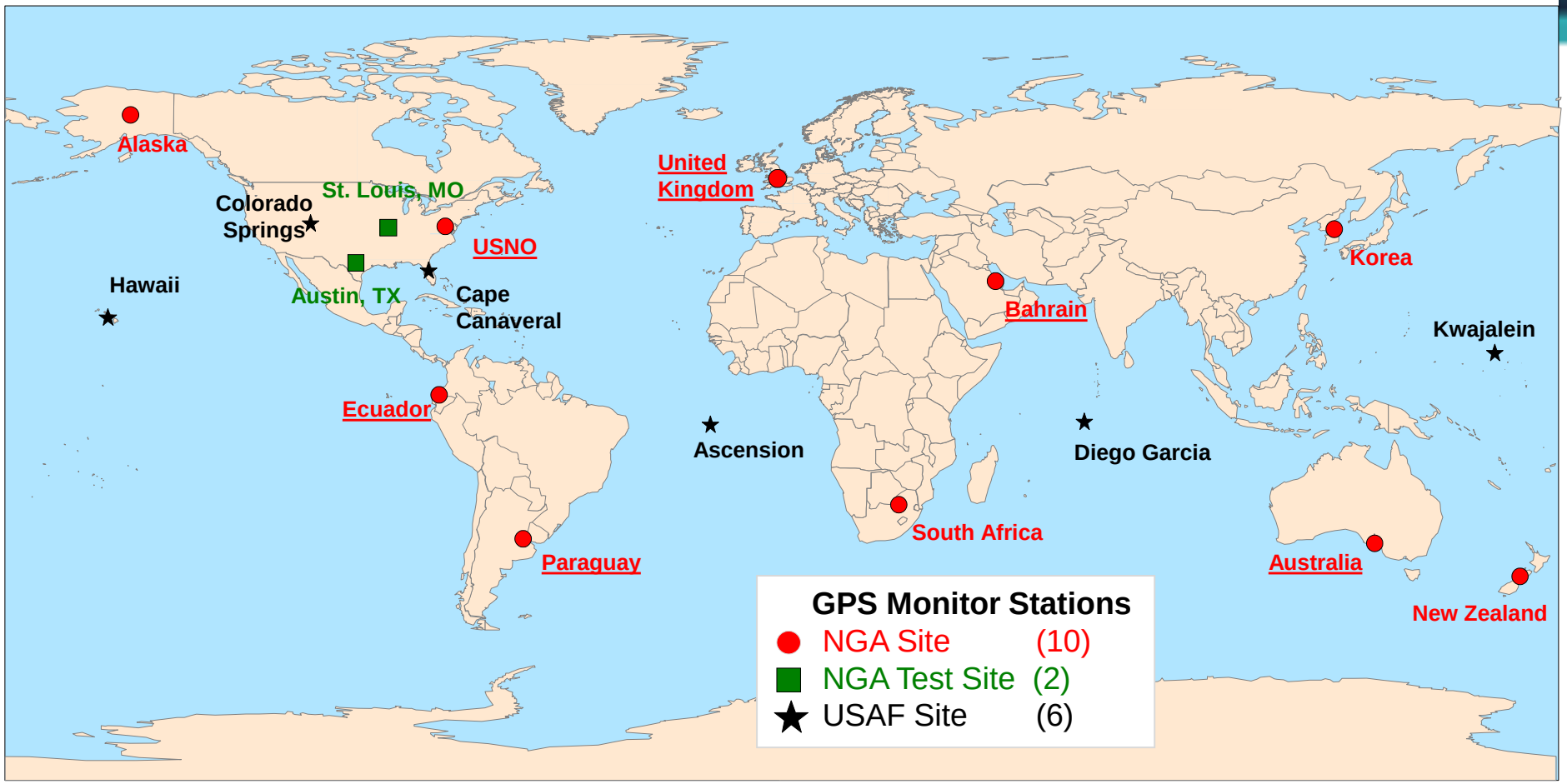
US GPS Operational Monitor Station Network

Earth-Centered, Earth Fixed coordinates and velocities for these stations form the basis for the Terrestrial Reference Frame realization WGS 84 G1762'



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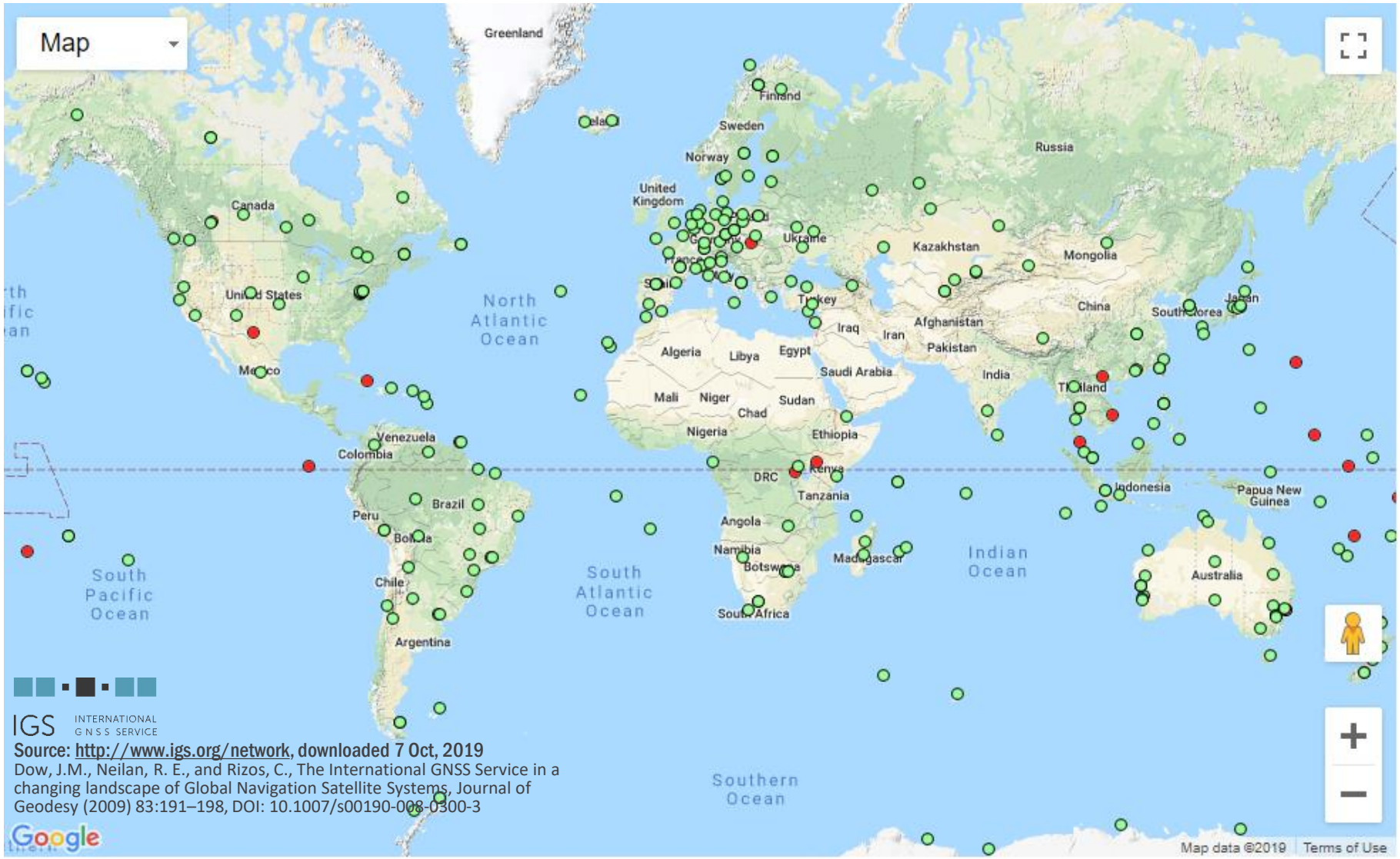
Multi GNSS Experiment (MGEX)

Earth-Centered, Earth Fixed coordinates and velocities for these stations are the basis for the Terrestrial Reference Frame realization IGS14



Source: http://www.igs.org/network, downloaded 7 Oct, 2019

Dow, J.M., Neilan, R. E., and Rizos, C., The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, Journal of Geodesy (2009) 83:191–198, DOI: 10.1007/s00190-008-0300-3

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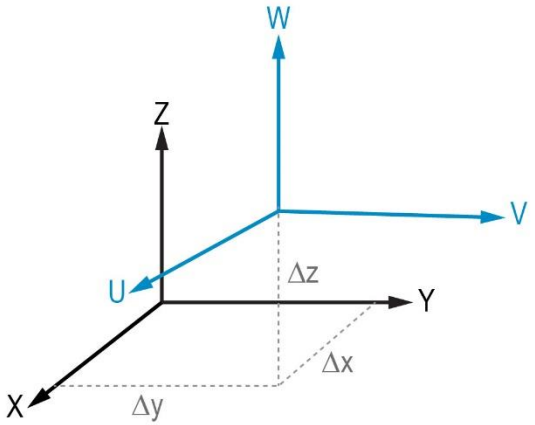
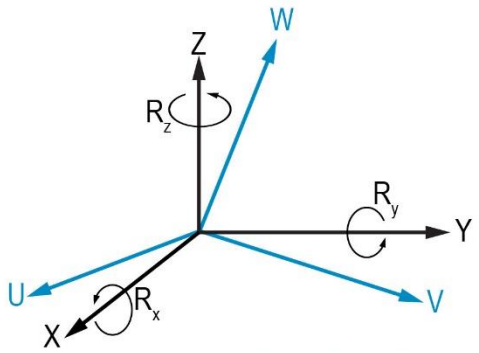
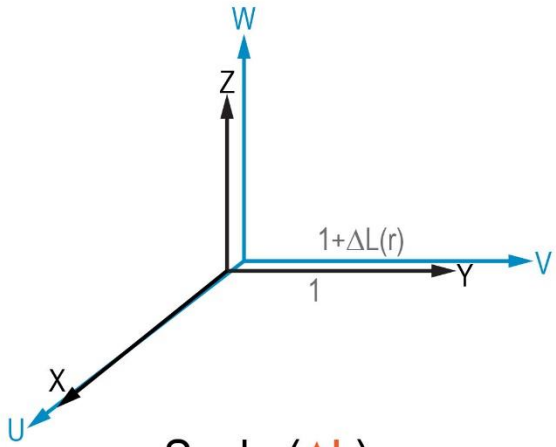
Comparing Terrestrial Reference Frames
7 Parameter Transformation



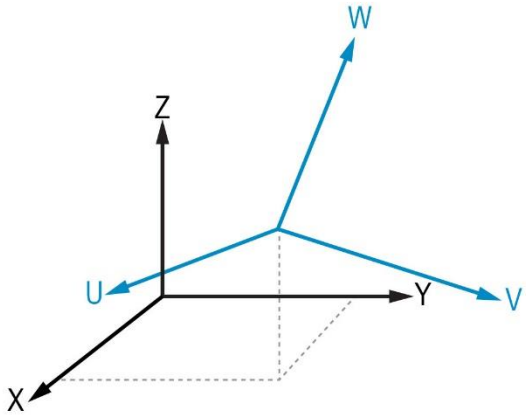
Origin ($\Delta x, \Delta y, \Delta z$)



Orientation (R_x, R_y, R_z)



Scale (ΔL)



Total

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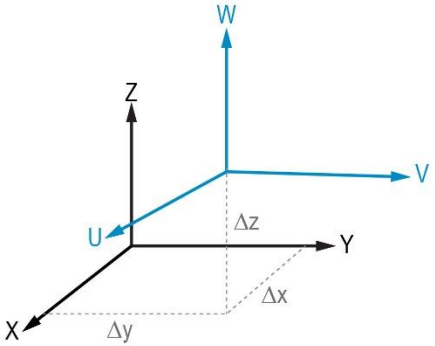
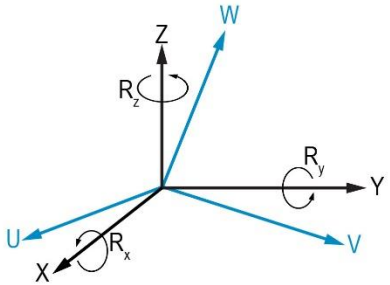
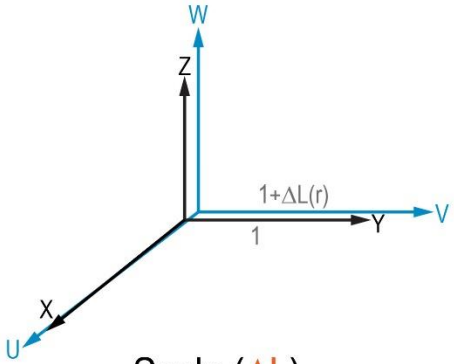
A Single Simplified Metric for Comparing Terrestrial Reference Frame Realizations



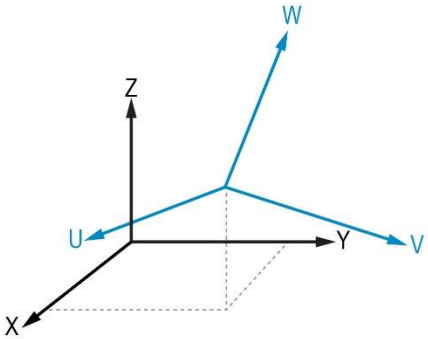
Origin (Δx, Δy, Δz)



Orientation (R_X, R_Y, R_Z)



Scale (ΔL)



Total

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

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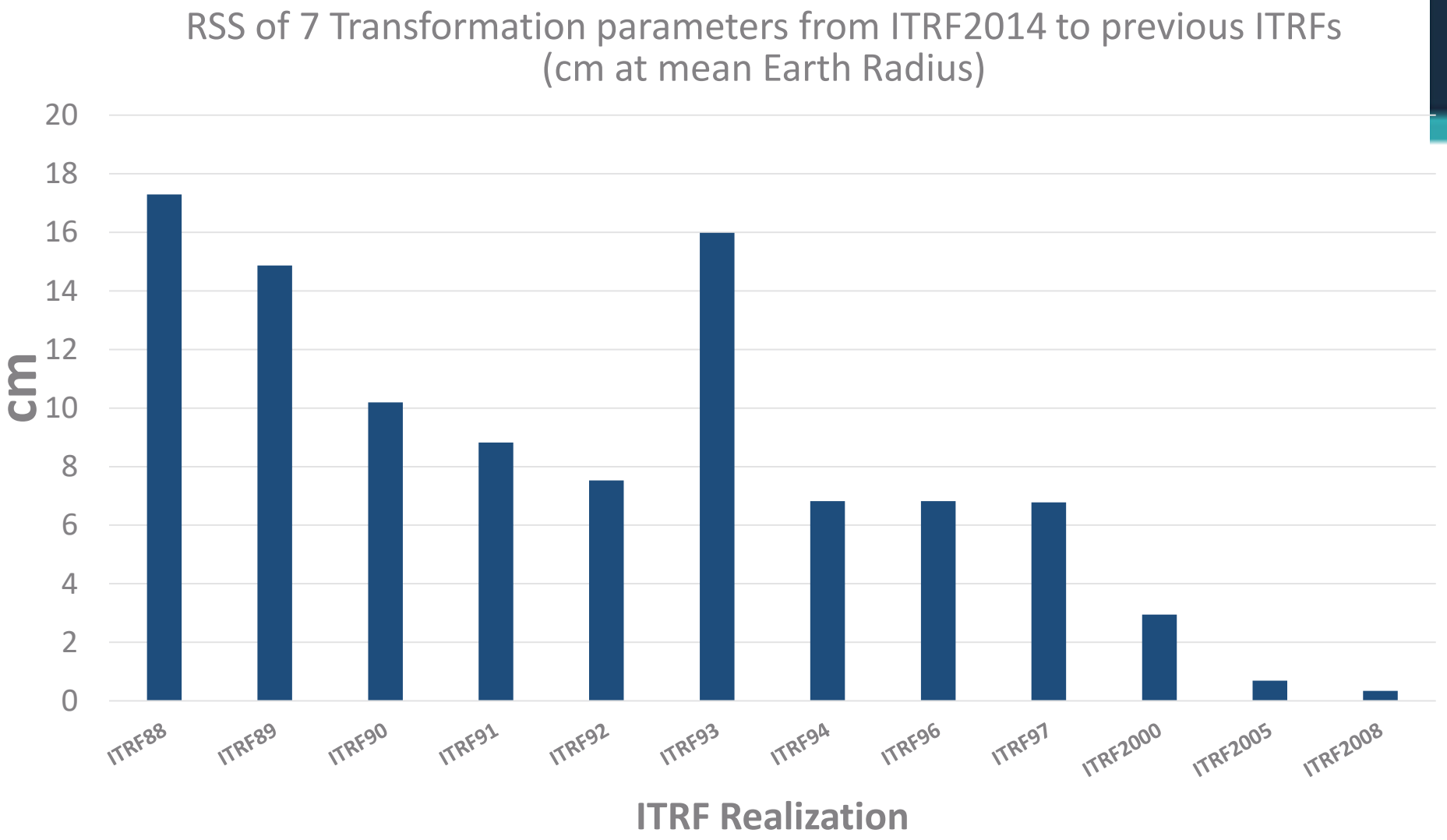
Evolution of ITRF Realizations



Data Source: http://itrf.ign.fr/doc_ITRF/Transfo-ITRF2014_ITRFs.txt, downloaded 29 Oct, 2019

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GNSS Contributions to 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 *ITR97 IGS97*	40-145 IGS	2-7 Years
ITRF2000 *IGS00 IGb00*	156-167 IGS	5-9 Years
ITRF2005 *IGS05*	<338 IGS	10 Years
ITRF2008 *IGS08 IGb08*	395 IGS (TBC)	12.5 Years
ITRF2014 *IGS 14*	578 IGS (TBC)	21.1 Years

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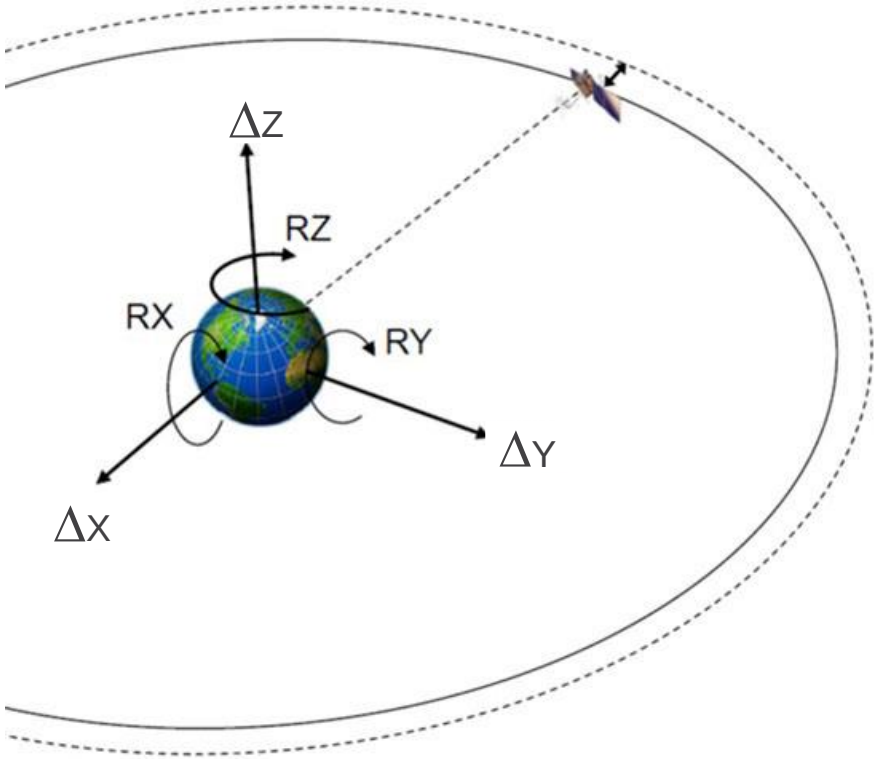
7-Parameter Transformations using Ephemerides



- For each GNSS, 7-parameter Helmert transformations were computed between the IGS reference frame (IGS14) and the Earth-fixed coordinate frames used by the navigation messages.
- A Helmert transformation consists of
  - 3 translation parameters (ΔX, ΔY, ΔZ)
  - 3 rotation parameters (RX, RY, RZ)
  - 1 scale parameter
- Note that at Earth's surface,
  - 1 mas ≈ 3.09 cm
  - 1 ppb ≈ 0.64 cm

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Constellations and Tracking Networks Used

Constellation	# of Satellites	# of IGS Stations Used to Obtain Navigation Messages	Satellites Tracked (PRN) (SC s/n for GLONASS)	Number of Data Points
GPS	31	140	01, 02, 03, 05, 06, 07, 08, 09, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32	**495,600**
GLONASS	21	128	730, 747, 744, 742, 745, 743, 802, 717, 853, 723, 721, 716, 736, 851, 854, 720, 719, 855, 731, 732, 735	**318,503**
Galileo	14	132	01, 02, 03, 04, 05, 07, 08, 09, 11, 12, 19, 24, 26, 30	**224,465**
BeiDou-2 Phase 2 Only	5 GEO	49	01, 02, 03, 04, 05	**76,038**
	7 IGSO	73	06, 07, 08, 09, 10, 13, 16	**111,851**
	3 MEO	96	11, 12, 14	**46,784**

Notes: Data Span: 56 Days: 21 July-14 Sept 2019 (8 GPS Weeks: 2063-2070)
BeiDou: MGEX ephemerides are available only for BeiDou Phase 2 Spacecraft

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Numerical Results: Mean values

Data Span: 56 Days: 21 July-14 Sept 2019 (8 GPS Weeks: 2063-2070)

GNSS	ΔX (cm)	ΔY (cm)	ΔZ (cm)	RX (mas)	RY (mas)	RZ (mas)	Scale (ppb)	RSS of 7 Parameters (cm at Re)
GPS	0	0	5	-0.01	0.28	1.06	-0.27	**6.0**
GLONASS	0	0	10	0.21	0.00	1.76	-9.71	**13.0**
Galileo	2	0	5	-0.10	-0.22	-0.34	-3.31	**5.9**
BeiDou-2 (MEO)	11	3	42	-0.63	0.15	5.04	-16.61	**47.5**
BeiDou-2 (MEO, IGSO)	17	66	16	1.06	-2.38	7.51	-13.11	**74.7**
BeiDou-2 (MEO, IGSO, GEO)	39	59	44	-0.31	-2.70	3.83	-11.37	**84.9**

Largest value for each row shown in red

At mean Earth Radius
1 mas = 3.09 cm
1 ppb = 0.64 cm

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

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Numerical Results: Standard Deviations

Data Span: 56 Days: 21 July-14 Sept 2019 (8 GPS Weeks: 2063-2070)

GNSS	ΔX (cm)	ΔY (cm)	ΔZ (cm)	RX (mas)	RY (mas)	RZ (mas)	Scale (ppb)	RSS of 7 Parameters (cm at Re)
GPS	1	1	2	0.57	0.87	1.17	0.11	**5.4**
GLONASS	2	2	6	0.26	0.52	2.78	0.57	**11.0**
Galileo	1	1	1	0.09	0.09	0.25	0.35	**1.9**
BeiDou-2 (MEO)	6	5	8	1.48	4.91	3.52	5.46	**22.5**
BeiDou-2 (MEO, IGSO)	10	10	7	1.64	3.16	3.01	2.25	**21.4**
BeiDou-2 (MEO, IGSO, GEO)	17	13	15	2.03	3.91	3.60	4.06	**31.6**

Largest value for each row shown in red

At mean Earth Radius
1 mas = 3.09 cm
1 ppb = 0.64 cm

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

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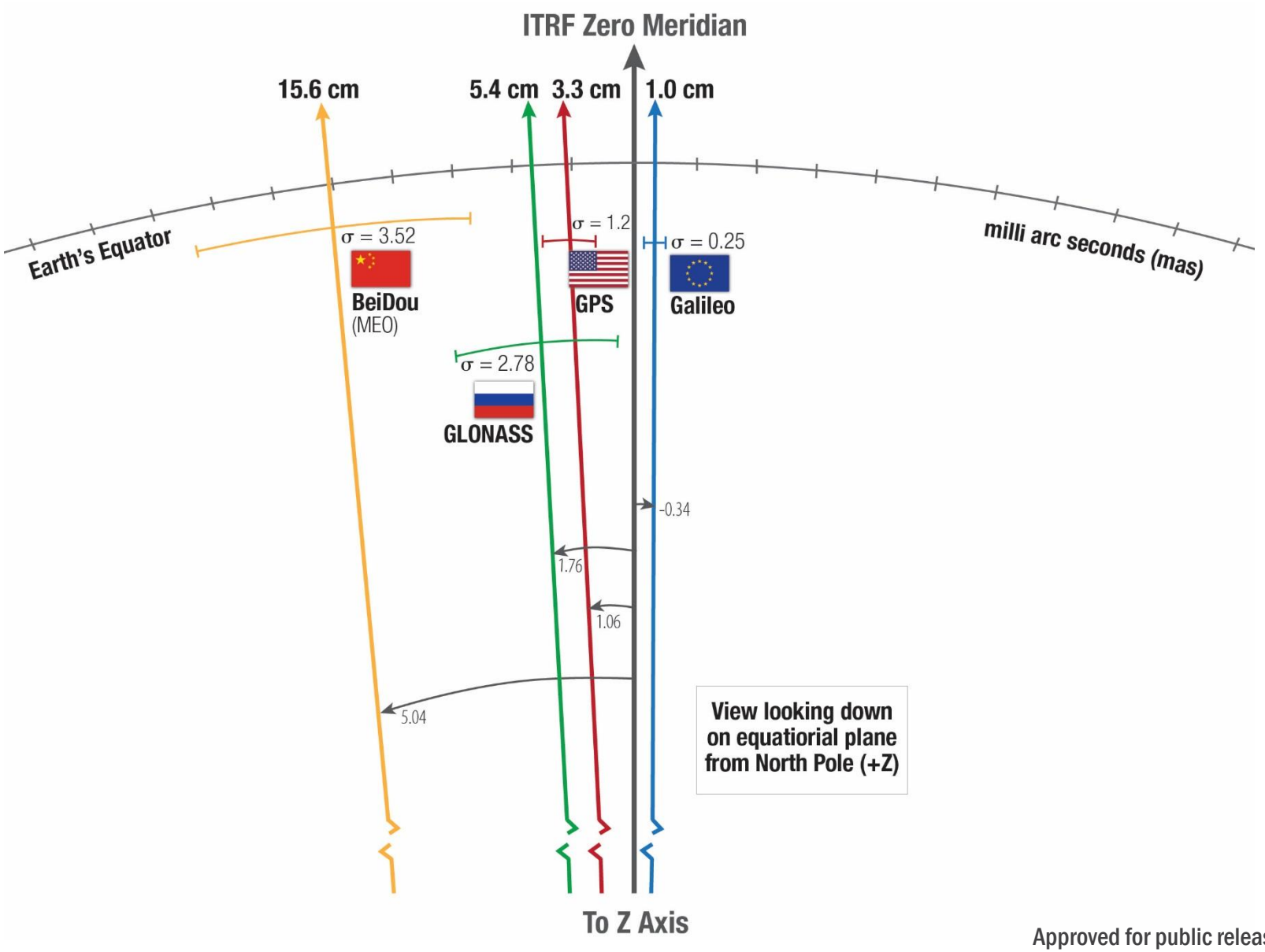
Rotation around Z (Rz) => Location of Zero Meridian as realized through GNSS broadcast messages

Data set: 56 Days (21 July-14 Sept 2019)



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Conclusions (slide 1 of 2)

- Terrestrial Reference Frame Realizations Accessible via Broadcast GNSS Messages During the 8 weeks of 2019 are:
  - Coincident with the ITRF14 (IGS14) at a level of
    - < 6 cm for GPS and Galileo
    - < 13 cm for GLONASS
    - < 47 cm for BeiDou-2 MEO with larger differences when IGSO and GEO SVs are included
  - Repeatable on a daily and weekly basis at a level of
    - ~ 5 cm for GPS
    - ~ 2 cm for Galileo
    - ~ 11 cm GLONASS
    - ~ 22 cm for BeiDou-2 MEO with larger values for IGSO and GEO

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Conclusions (slide 2 of 2)

- The same Reference Frame comparison method was first performed in 2017 (Using first 8-10 weeks of 2016)
  - Using ITRF2008 (IGS08) as a truth standard

System	8 weeks in 2016 (vs. IGS08)		8 weeks in 2019 (vs. IGS14)	
	RSS_7 (cm)	σ (cm)	RSS_7 (cm)	σ (cm)
GPS	**4.3**	**4.2**	6.0	5.4
GLONASS	14.5	11.5	13.0	11.0
Galileo	5.2	5.7	**5.9**	**1.9**
BeiDou-2 (MEO)	25.7	26.0	47.5	22.5

Smallest values for each data period shown in green
=> Best Consistency with ITRF

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Acknowledgements

- Many Thanks to:
  - The MGEX Participants
  - The IGS
  - The IERS
  - NASA/CDDIS

- Colleagues at NSWC Dahlgren who performed the processing and analysis:
  - Jason T. Drotar
  - Russell Solomon

- Graphics
  - Pam Bailey

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Summary of 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

International Science Community

- IERS- International Earth Rotation and Reference System Service (Since 1987)
- IGS – International GNSS Service for Geodynamics (Since 1994)
- IVS – International VLBI Service (Since 1999)
- ILRS- International Laser Ranging Service (Since 1998)
- IDS – International DORIS Service (Since 2003)

- 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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