NATIONAL GEOSPATIAL–INTELLIGENCE AGENCY
7500 GEOINT Drive, Springfield, Virginia 22150

WGS 84 (G2296) Terrestrial Reference Frame Realization

Office of Geomatics, National Geospatial-Intelligence Agency[1]

The National Geospatial-Intelligence Agency (NGA), Office of Geomatics, Global Navigation Satellite Systems (GNSS) Division is responsible for maintaining the World Geodetic System 1984 (WGS 84) Terrestrial Reference Frame (TRF) used by U.S. Department of Defense for its geolocation needs. In order to ensure adherence to international standards, facilitate interoperability with other GNSS, and satisfy US agreements and public commitments, NGA aligns the WGS 84 TRF to the International Terrestrial Reference Frame (ITRF) as closely as possible. The WGS 84 TRF is realized through a network of GPS monitoring stations, and an update is implemented when adopted by NGA in its precise GPS orbit determination process and by the US Space Force to generate the GPS broadcast navigation messages. [1]

A new WGS 84 TRF realization, WGS 84 (G2296), will become effective in NGA's orbit products on 7 January 2024 (the first day of the first full GPS week (2296) in 2024). This new WGS 84 frame realization is aligned to both the ITRF2020, the most recent ITRF realization, [2] and the IGS20, the frame used by the International GNSS Service (IGS). [3] In this case, alignment involves both the positions of the GPS monitor stations which define each frame as well as the Antenna Phase Center Offsets (APOs) of the GPS satellites as contained in the IGS20 ANTEX file.[2]

Historically, alignment between WGS 84 and ITRF was maintained by use of NGA's orbit determination software. This process involved fixing the positions of IGS GNSS monitoring stations to their ITRF coordinates while simultaneously estimating GPS orbits and

[1] For questions please contact geomatics@nga.mil
[2] The igs20.atx file may be found here: https://files.igs.org/pub/station/general

the position of the WGS 84 GPS monitoring stations. This was performed for a period of 10-14 days, with velocities being inherited from nearby IGS sites on the same tectonic plate. [4] Implementation dates of previous WGS 84 TRFs are shown in Table 1.

Name	Implementation date		Epoch	Accuracy
	GPS Broadcast Orbits	NGA Precise Ephemeris		
WGS 84	1987	1 Jan 1987		1-2 meters
WGS 84 (G730)	29 Jun 1994	2 Jan 1994	1994.0	10 cm/component rms
WGS 84 (G873)	29 Jan 1997	29 Sep 1996	1997.0	5 cm/component rms
WGS 84 (G1150)	20 Jan 2002	20 Jan 2002	2001.0	1cm/component rms
WGS 84 (G1674)	8 Feb 2012	7 May 2012	2005.0	<1cm/component rms
WGS 84 (G1762)	16 Oct 2013	16 Oct 2013	2005.0	<1cm/component rms
WGS 84 (G2139)	28 Mar 2021	3 Jan 2021	2016.0	<1cm/component rms

Table 1: Implementation dates of previous realizations of the WGS 84 TRF.

Starting with WGS 84 (G2139), the current frame as of this writing, NGA adopted a new technique to maintain alignment between ITRF and WGS 84. Formally, NGA now aligns to ITRF using the IGS precise orbit and clock products. These orbits are used to generate a multiyear time series of daily station positions, calculated by a Precise Point Positioning (PPP) technique, [5] for each of the GPS Monitor Stations which define the realization of WGS 84. From here, analysts fit a station trajectory model which provides position and velocity estimates for each site. This methodology exploits the close relationship between the IGS and the ITRF, as the IGS GNSS monitoring stations define the GNSS component of the ITRF. In addition to being substantially more computationally efficient, this technique allows NGA to directly estimate velocities for each WGS 84 station.

With WGS 84 (G2139), NGA utilized a straightforward linear trajectory model, including position and velocity terms, to align to ITRF2014. WGS 84 (G2296) remains a linear frame, meaning it is defined with only position and velocity. However, NGA has improved its estimation technique by fitting both an annual and semi-annual signal to the station position timeseries, [6] introduced better handling of station discontinuities due to antenna moves, and included post-seismic deformation terms (following the form of M. Bevis [7]) to those stations which have experienced a significant earthquake. These terms allow for a more accurate estimate of the residual position and velocity of each site along with bringing the WGS 84 update process into conformity with the models used by the ITRF. For this G2296 realization, a data span of 7.4 years was used from January 2016 through May 2023 in order to fit the trajectory model.

In addition, this realization adopts the Antenna Phase Center Offsets (APOs) of the GPS satellites as provided by the IGS20 ANTEX file. Prior to WGS 84 (G2139), NGA used U.S. Space Force-provided values for APOs when creating precise ephemerides. Starting in WGS 84 (G2139), NGA adopted the APO values from the IGS14 ANTEX file for all GPS satellites except for the GPS Block IIIs. [8] With WGS 84 (G2296), NGA has chosen to adopt the IGS20 ANTEX APO values for all GPS satellites because they take advantage of published, dual-frequency measurements from Lockheed Martin [9] along with providing the most accurate access to the ITRF scale factor. [3]

These changes have the net effect of bringing the agreement between WGS 84 (G2296) and ITRF2020/IGS20 well within NGA's desired metric of 2 cm per transformation component. [10] In keeping with previous updates, NGA provides a Seven Parameter Helmert Transformation between the previous realization (G2139) and the new one (G2296). These parameters were calculated by extrapolating the position and velocity of the seventeen WGS 84 GPS monitoring sites to the epoch 1 January 2024. From there, a least squares fit produces the frame transformation parameters for the origin, orientation, and scale shown in Table 2.

	Translations (mm)			**Scale (ppb)**	**Rotations (mas)**		
Component	d_x	d_y	d_z	**s**	r_x	r_y	r_z
Values	2.6	5.4	-0.9	0.06	-0.01	-0.07	0.00

Table 2: Seven parameter transformation parameters from WGS 84 (G2139) to WGS 84 (G2296) at 1 January 2024. Translations are given in millimeters, scale in parts-per-billion, and rotation in milliarcseconds. Note that the sign convention used for rotation parameters is consistent with Eq. 6 in [2] and opposite from Eq. 4.3 in the IERS 2010 conventions. [11]

A quick glance at Table 2 reveals that, for practical purposes of navigation, these two WGS 84 realizations are very close together. Indeed, at a mean Earth radius of 6371 km and integrating over a full 4π steradians (see Eq. 4 of [12] for details) the "distance" between frames is 6.33 mm. This value is consistent with the ITRF, as a similar distance calculation between the ITRF2020 and ITRF2014 realizations, using the ITRF-provided transformation parameters at 1 January 2024, [2] is 4.75 mm.

These incredibly small values are themselves a testament to the increasing accuracy and stability of modern Terrestrial Reference Frames. It is also worth noting that the larger distance between the NGA frames appears to be due to the differences in modeling station trajectories between WGS 84 (G2139) and WGS 84 (G2296). Thus, while this update to the WGS 84 TRF ensures that the frame remains as close as possible to the ITRF, thereby fulfilling the public commitments of the U.S., it is anticipated that this update will primarily impact high-accuracy users such as surveyors.

Improvement in Station Position Accuracy

In order to validate that this updated realization of the WGS 84 TRF represents an improvement in alignment to ITRF2020, NGA produced precise orbits using WGS 84 (G2296) station coordinates along with IGS20 APO values for GPS weeks 2265 through 2268. Next, two series of PPP solutions were calculated for the nine WGS 84 GPS monitoring stations included in the IGS network (and in ITRF2020) using precise orbits and APO values aligned to both the current and updated WGS 84 TRF. Lastly, the calculated positions were compared to the IGS published station positions, available at NASA CDDIS.[3]

A summary of the East, North, and Up differences from this comparison are presented in Figure 1. For each station, the ENU frame is defined by the median IGS position. Looking at the plots, there is very little change in the North and East directions. The biggest change is in the Up component, which improves by a median 0.7 cm. Additionally, there is significant improvement in the agreement between IGS and NGA-derived positions for MRL1 and MTV2, both of which experienced significant earthquakes in the past decade and have been more accurately modeled in WGS 84 (G2296).

[3] Data available at cddis.nasa.gov/Data_and_Derived_Products/GNSS/station_position_product.htm

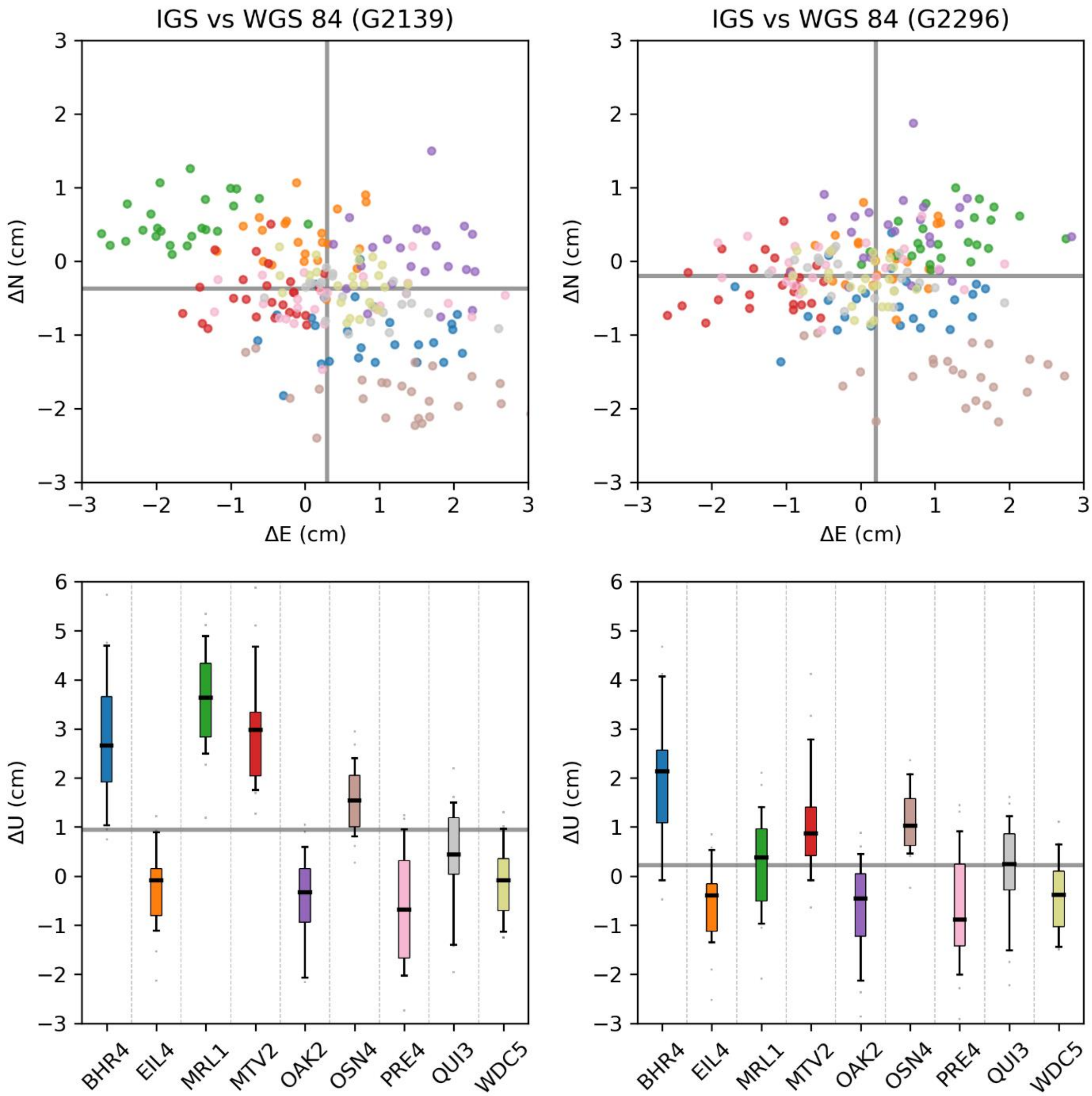

Figure 1: A comparison between the IGS published station positions and NGA-calculated positions for the nine WGS 84 GPS monitoring stations included in the ITRF2020. The left column presents the East, North, and Up differences between WGS 84 (G2139) calculated, daily positions and the IGS published positions. The right column represents the same comparison using WGS 84 (G2296) calculated, daily positions. The timespan for this comparison was 5 June 2023 through 30 June 2023 (26 days).

The box and whisker plots in the bottom row summarize differences in the Up direction for each station. The box bounds the 25th and 75th percentiles, the black line in the middle of each box represents the median, and the whiskers correspond to the 5th and 95th percentiles. Finally, for all four plots the gray line provides the median value across all stations for the differences in the East, North, and Up components respectively.

Impact to Estimated Satellite Clocks

The adoption of WGS 84 (G2296) will induce a change in the computed clock offsets of the GPS satellites provided in NGA's precise orbit products available at earth-info.nga.mil. This change largely comes from the adoption of the new APOs which, as described above, have been re-estimated by the IGS in order to align to the scale of the ITRF2020 frame and incorporate more accurate measurements of Block III satellite antennas from Lockheed Martin. The new APO values are primarily aliased into the clock solutions and, because WGS 84 (G2139) did not adopt the IGS APOs for the GPS Block III Satellite Vehicles (SVs), these experience the largest change.

This change is demonstrated visually in Figure 2, which plots the difference between estimated clock solutions for GPS week 2286 by SV. This represents a straightforward difference between the clock estimates for orbits aligned to WGS 84 (G2139) using the IGS14 and legacy GPS III APOs, and orbits aligned to WGS 84 (G2296) using the IGS20 APOs for all GPS SVs. The GPS Block IIIs experience a median, ionosphere-free, timing offset of 2.82 ns while the others are shifted by -0.21 ns.

This shift is consistent with the adjustments made in the Z component of the IGS20 APOs. As stated in the IGS 2022 Technical report, this value was adjusted for all GPS satellites as part of the realignment process. [3] Taking the difference between the previously used NGA APO values and the new IGS20 APO values, and combining them using the standard ionosphere-free weighting, one finds that the median change in the Z APO component is 2.85 ns for the GPS Block III SVs and -0.23 ns for all other satellites. As the differences in the APO values correspond nearly exactly with the timing offsets observed, it is almost certain that the clock differences are due to the adoption of these values in the NGA orbit estimation process. As a result, NGA recommends that all users of its orbit products also use the IGS20 APO values.

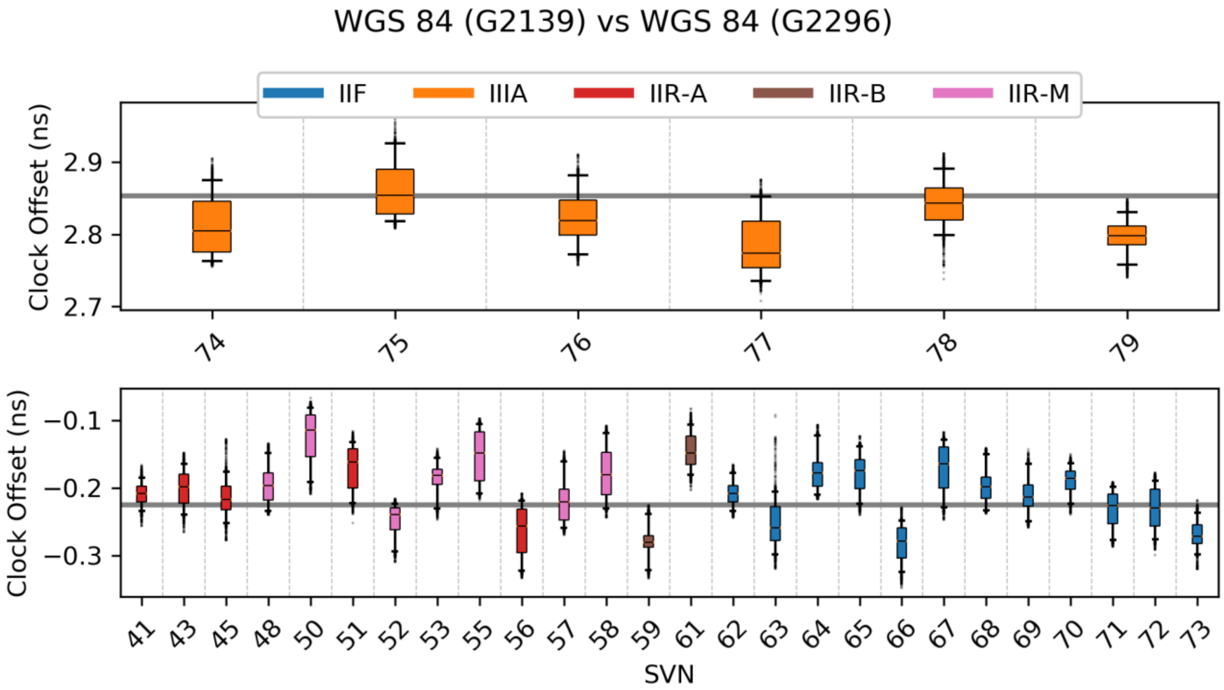

Figure 2: Clock differences between NGA orbit products for GPS Week 2286 calculated using WGS 84 (G2139) positions and APO values and WGS 84 (G2296) positions and APO values. The top plot contains only GPS Block III satellites and the bottom contains all other satellites. Note the different scales on the y-axis for both plots.

In the plots, the box bounds the 25th and 75th percentiles, the black line in the box represents the median, and the whiskers correspond to the 5th and 95th percentile. The gray line represents the expected clock offset as calculated from the APO value differences as described in the text.

Finally, below are two tables that provide the APO values used when generating WGS 84 (G2139) and WGS 84 (G2296). Note that for the non-GPS-Block-IIIs only the Z APO was updated, whereas for the Block IIIs all values changed due to incorporating newer measurements from Lockheed Martin. All offsets are provided relative to satellite body centered coordinates following IGS body axes conventions. [13]

Block	SVN	X	Y	Z		
				2139	2296	Δ
IIR-A	41	-2.50	-1.70	1304.50	1236.57	67.93
IIR-A	43	-2.40	-1.60	1348.30	1287.12	61.18
IIR-A	44	1.40	4.70	999.50	936.22	63.28
IIR-A	45	-3.40	2.90	1359.10	1290.31	68.79
IIR-A	46	-0.70	-1.20	1117.80	1053.86	63.94
IIR-B	47	-2.20	2.20	850.60	771.03	79.57
IIR-M	48	-0.40	5.00	822.40	757.00	65.40
IIR-M	49	0.00	0.00	963.20	865.42	97.78
IIR-M	50	-3.30	-0.30	778.00	742.63	35.37
IIR-A	51	1.00	-3.20	1313.50	1262.44	51.06
IIR-M	52	-0.80	5.80	912.50	837.04	75.46
IIR-M	53	3.00	1.00	770.90	711.51	59.39
IIR-A	54	13.90	0.30	1248.60	1182.12	66.48
IIR-M	55	4.50	1.90	622.80	575.59	47.21
IIR-A	56	12.60	-6.90	1468.70	1389.15	79.55
IIR-M	57	10.90	-4.50	791.80	722.82	68.98
IIR-M	58	10.20	-5.60	767.80	710.74	57.06
IIR-B	59	8.60	-0.60	808.20	718.61	89.59
IIR-B	60	15.40	6.80	766.10	701.85	64.25
IIR-B	61	1.30	-1.10	728.80	681.86	46.94
IIF	62	394.00	0.00	1517.40	1454.15	63.25
IIF	63	394.00	0.00	1501.80	1421.47	80.33
IIF	64	394.00	0.00	1522.10	1462.16	59.94
IIF	65	394.00	0.00	1407.10	1351.80	55.30
IIF	66	394.00	0.00	1522.30	1436.32	85.98
IIF	67	394.00	0.00	1467.00	1411.46	55.54
IIF	68	394.00	0.00	1522.60	1460.09	62.51
IIF	69	394.00	0.00	1550.60	1482.26	68.34
IIF	70	394.00	0.00	1534.80	1471.74	63.06
IIF	71	394.00	0.00	1503.50	1433.58	69.92
IIF	72	394.00	0.00	1501.40	1427.68	73.72
IIF	73	394.00	0.00	1515.10	1429.49	85.61

Table 3: APO values for non-GPS-III SVs for WGS 84 (G2139) and WGS 84 (G2296). Note that the same value is used for L1 and L2 and that there were no changes in the X or Y components with the transition from IGS14 values to IGS20 values. All distances are given in millimeters.

SVN	Frequency	X			Y			Z		
		2139	2296	Δ	2139	2296	Δ	2139	2296	Δ
74	G01	-59.00	-59.94	0.94	17.50	17.48	0.02	1090.00	1179.80	-89.80
	G02	-59.00	-59.26	0.26	17.50	15.60	1.90	1090.00	687.83	402.17
	G05	-59.00	-59.33	0.33	17.50	15.67	1.83	1090.00	726.06	363.94
75	G01	-72.80	-64.42	-8.38	21.00	19.48	1.52	1074.00	1188.42	-114.42
	G02	-72.80	-64.79	-8.01	21.00	22.06	-1.06	1074.00	702.29	371.71
	G05	-72.80	-64.92	-7.88	21.00	20.85	0.15	1074.00	705.85	368.15
76	G01	-65.20	-66.51	1.31	19.70	19.09	0.61	1062.00	1183.82	-121.82
	G02	-65.20	-64.88	-0.32	19.70	17.12	2.58	1062.00	707.30	354.70
	G05	-65.20	-66.25	1.05	19.70	16.30	3.40	1062.00	725.61	336.39
77	G01	-63.90	-63.55	-0.35	22.50	23.19	-0.69	1099.00	1187.67	-88.67
	G02	-63.90	-61.89	-2.01	22.50	25.83	-3.33	1099.00	701.34	397.66
	G05	-63.90	-59.60	-4.30	22.50	24.92	-2.42	1099.00	684.05	414.95
78	G01	-66.00	-65.94	-0.06	22.60	20.44	2.16	1102.00	1185.75	-83.75
	G02	-66.00	-64.32	-1.68	22.60	20.34	2.26	1102.00	681.61	420.39
	G05	-66.00	-65.30	-0.70	22.60	21.31	1.29	1102.00	689.52	412.48
79	G01	-66.00	-65.94	-0.06	22.60	20.44	2.16	1112.60	1185.75	-73.15
	G02	-66.00	-64.32	-1.68	22.60	20.34	2.26	1112.60	681.61	430.99
	G05	-66.00	-65.30	-0.70	22.60	21.31	1.29	1112.60	689.52	423.08

Table 4: GPS Block III APOs for WGS 84 (G2139) and WGS 84 (G2296). Distances are given in millimeters.

WGS 84 Position Values

Below is a table containing the official WGS 84 (G2296) positions and velocities at the epoch 1 January 2024 for the nine WGS 84 GPS monitoring stations included in ITRF2020. Data from these sites is publicly available at NASA CDDIS[4] through a data sharing partnership between NGA and IGS.

Station Information			Station Positions—Geocentric (m)			Station Velocities (m/yr)			EPOCH
NGA IDs		IGS IDs	X	Y	Z	X	Y	Z	
URUGM	85403	MTV2	2914537.0335	-4349790.4159	-3630033.2932	0.0022	-0.0075	0.0085	2024.0
ENGLM	85404	OAK2	4011440.6345	-63375.4207	4941877.2641	-0.0130	0.0172	0.0097	2024.0
BAHRM	85405	BHR4	3633910.0128	4425277.9238	2799863.4081	-0.0329	0.0097	0.0270	2024.0
ECUADM	85406	QUI3	1275746.5857	-6252216.7587	-15440.9118	0.0019	0.0017	0.0106	2024.0
USNOM	85407	WDC5	1112158.5681	-4842855.6117	3985496.9874	-0.0149	-0.0003	0.0024	2024.0
ALASKM	85410	EIL4	-2296304.4940	-1484805.9927	5743078.2062	-0.0224	-0.0042	-0.0077	2024.0
NEWZM	85411	MRL1	-4749991.7288	520984.3839	-4210603.3336	-0.0279	0.0114	0.0295	2024.0
SOAFM	85412	PRE4	5066223.4502	2719223.3231	-2754406.2095	-0.0020	0.0195	0.0162	2024.0
OSANM	85413	OSN4	-3068341.3246	4066863.7631	3824756.8354	-0.0280	-0.0132	-0.0092	2024.0

Table 5: Position and velocities for nine of the WGS 84 GPS monitoring stations which define the WGS 84 TRF. These sites are included both ITRF2020 and the IGS GNSS station network. The NGA IDs match those provided in Table 2 of Reference [1] and the IGS IDs match the names found in the products on the CDDIS.

[4] See the following for details on obtaining data for these sites: https://cddis.nasa.gov/Data_and_Derived_Products/GNSS/daily_30second_data.html

References

[1] National Geospatial-Intelligence Agency, "Department of Defense World Geodetic System 1984," Office of Geomatics, St. Louis, 2014.

[2] Z. Altamimi, P. Rebischung, X. Collilieux, L. Métivier and K. Chanard, "ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions," *Journal of Geodesy,* vol. 93, no. 47, 2023.

[3] International GNSS Service (IGS), "IGS Technical Report 2022," Astronomical Institute, University of Bern, Bern, Switzerland, 2023.

[4] E. Swift, "History of Satellite Orbit Determination at NSWCDD," Dhalgren Division Naval Surface Warfare Center, Dahlgren, VA, 2018.

[5] B. W. Tolman, "GPS Precise Absolute Positioning via Kalman Filtering," in *Proceedings of the 21st International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS 2008),* Savannah, GA, 2008.

[6] J. Bogusz and A. Klos, "On the significance of periodic signals in noise analysis of GPS station coordinates time series," *GPS Solutions,* vol. 20, pp. 655-664, 2016.

[7] M. Bevis, "Trajectory models and reference frames for crustal motion geodesy," *Journal of Geodesy,* vol. 88, pp. 283-311, 2014.

[8] National Geospatial-Intelligence Agency, "Recent Update to WGS 84 Reference Frame and NGA Transition to IGS ANTEX," NGA Office of Geomatics / GNSS Division, St. Louis, 2021.

[9] Lockheed Martin, "GPS Technical References," December 2021. [Online]. Available: https://navcen.uscg.gov/gps-technical-references. [Accessed 20 November 2023].

[10] Department of Defense, "World Geodetic System 1984 (WGS 84) Criteria for Spatial Reference Frame Alignment," Department of Defense, Washington DC, 2023.

[11] IERS Conventions Centre, "IERS Conventions (2010)," International Earth Rotation and Reference Systems Service, Central Bureau, Frankfurt, 2011.

[12] S. Malys, R. Solomon, J. Drotar, T. Kawakami and T. Johnson, "Compatibility of Terrestrial Reference Frames used in GNSS broadcast messages during an 8 week period of 2019," *Advances in Space Research,* vol. 67, pp. 834-844, 2021.

[13] O. Montenbruck, R. Schmid, F. Mercier, P. Steigenberger, C. Noll, R. Fatkulin, S. Kogure and A. Ganeshan, "GNSS satellite geometry and attitude models," *Advances in Space Research,* vol. 56, no. 15, pp. 1015-1029, 2015.