COMPARISON BETWEEN BROADCAST AND PRECISE ORBITS: GPS GLONASS GALILEO AND BEIDOU

A. Caporali and L. Nicolini

University of Padova, Italy

Summary

- Previous works
- Input data and method used
- Comparison between broadcast reference frames and ITRF
- Estimation of antenna phase offset (APO)
- Evaluation of coordinate and clock differences between broadcast and precise orbits

Previous works

Montenbruck et al. (2015) have performed an analogous work, with the following characteristics:

- One year (2013) of time-span considered
- Broadcast ephemerides from MGEX of IGS
- Precise ephemerides are taken from different AC’s: GFZ, TUM, JAXA and Wuhan University
- Antenna phase offset (APO) inferred from broadcast/sp3 comparison. For BeiDou broadcast ephemeris are assumed to refer to CoM.
- No Helmert transformation
- Evaluation of coordinate differences (RSW components + 10 m threshold for outliers rejection)
- Evaluation of the Signal-in-Space Range Error (SISRE)

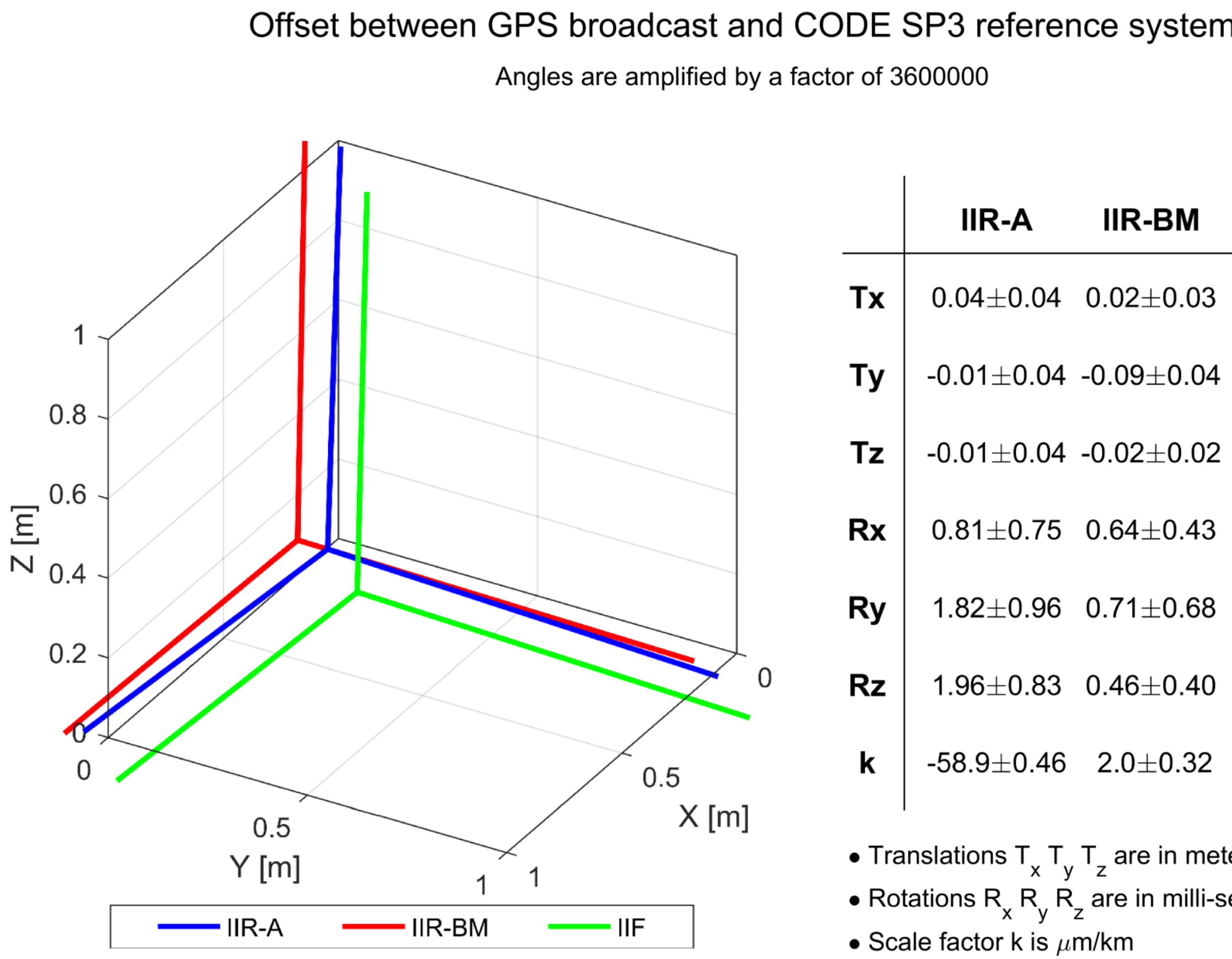
Input Data & Method

- One week (1950) of time span considered
- Broadcast ephemerides from MGEX of IGS (RINEX 3.03)
- Precise ephemerides from CODE (SP3-c): orbits are obtained from a double-difference network processing (carrier phase ionosphere-free linear combination) and referred to the middle day of 3-day-long arc.
- No antenna phase offset (APO) corrections
- Helmert transformation between reference frames
- Evaluation of difference between reference frames (broadcast vs ITRF)
- Evaluation of difference between coordinates (RSW components) and clock (after Helmert transformation + 5 m threshold for outliers rejection)

GNSS-specific considerations

- GPS satellites are divided in three blocks: IIR-A, IIR-B/M and IIF. Each block has different APO.
- GLONASS satellites belong to block M, except R09 which belongs to block K new generation
- Montenbruck et al. (2015) consider only 4 Galileo IOV satellites, whereas currently 3 IOV and 14 FOC satellites are operational
- BeiDou analysis is restricted to IGSO and MEO satellites, because CODE does not provide precise ephemeris for GEO satellites

GPS reference frames



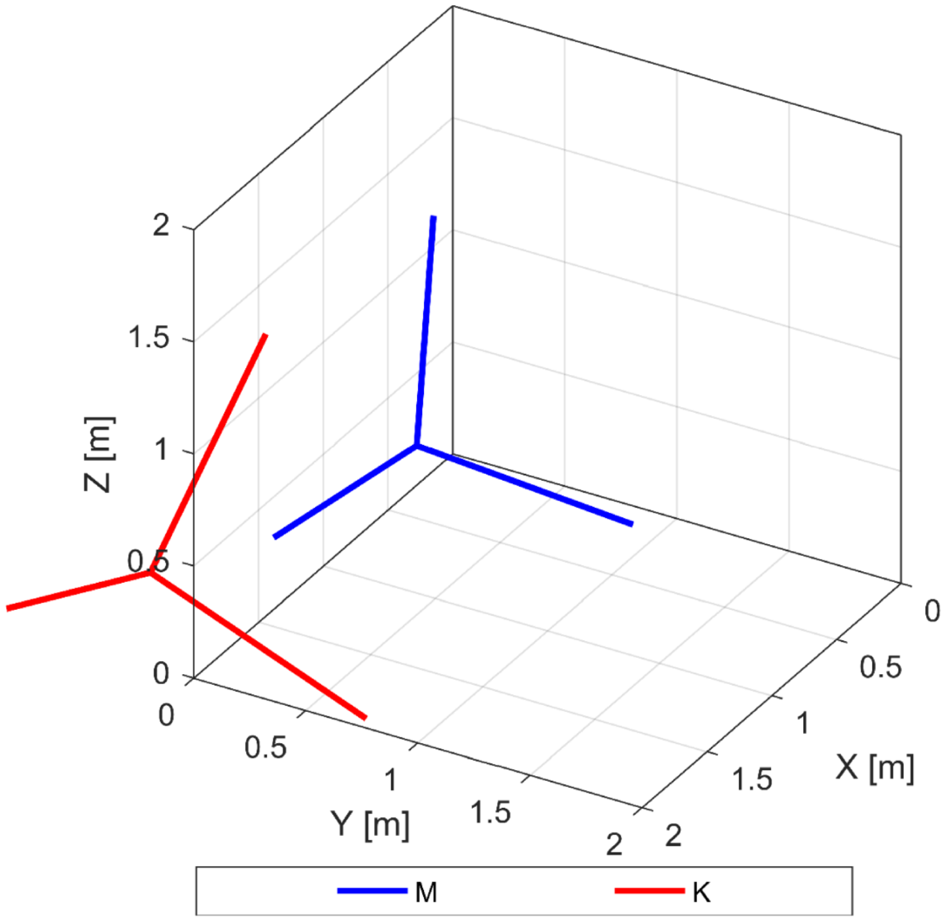
	IIR-A	IIR-BM	IIF
Tx	0.04±0.04	0.02±0.03	0.07±0.02
Ty	-0.01±0.04	-0.09±0.04	0.09±0.02
Tz	-0.01±0.04	-0.02±0.02	-0.07±0.03
Rx	0.81±0.75	0.64±0.43	0.78±0.55
Ry	1.82±0.96	0.71±0.68	1.06±0.51
Rz	1.96±0.83	0.46±0.40	1.50±0.86
k	-58.9±0.46	2.0±0.32	-41.2±0.47

- Translations T_x T_y T_z are in meters
- Rotations R_x R_y R_z are in milli-seconds of arc
- Scale factor k is μm/km

GLONASS reference frame

Offset between GLO broadcast and CODE SP3 reference system

Angles are amplified by a factor of 3600000



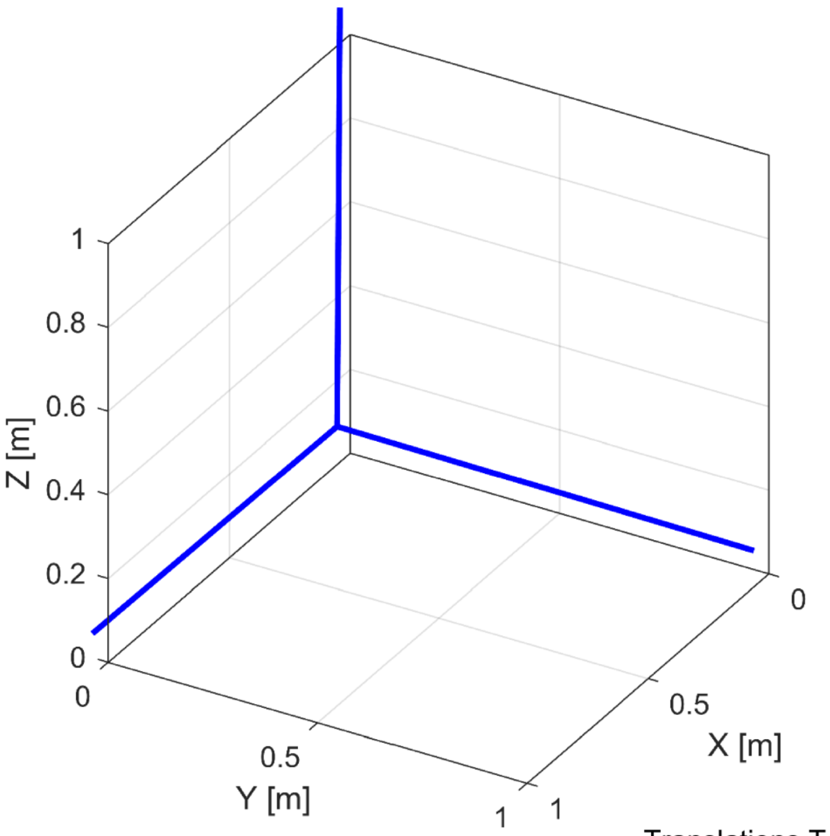
	M	K
Tx	-0.19±0.02	0.50±0.16
Ty	-0.27±0.04	-1.06±0.17
Tz	-0.13±0.10	-0.59±0.16
Rx	1.91±1.40	18.89±1.96
Ry	4.12±1.74	18.32±3.87
Rz	3.49±2.60	3.75±1.56
k	-83.2±0.45	-53.1±3.16

- Translations T_x T_y T_z are in meters
- Rotations R_x R_y R_z are in milli-seconds of arc
- Scale factor k is μm/km

Galileo reference frame

Offset between GAL broadcast and CODE SP3 reference system

Angles are amplified by a factor of 3600000



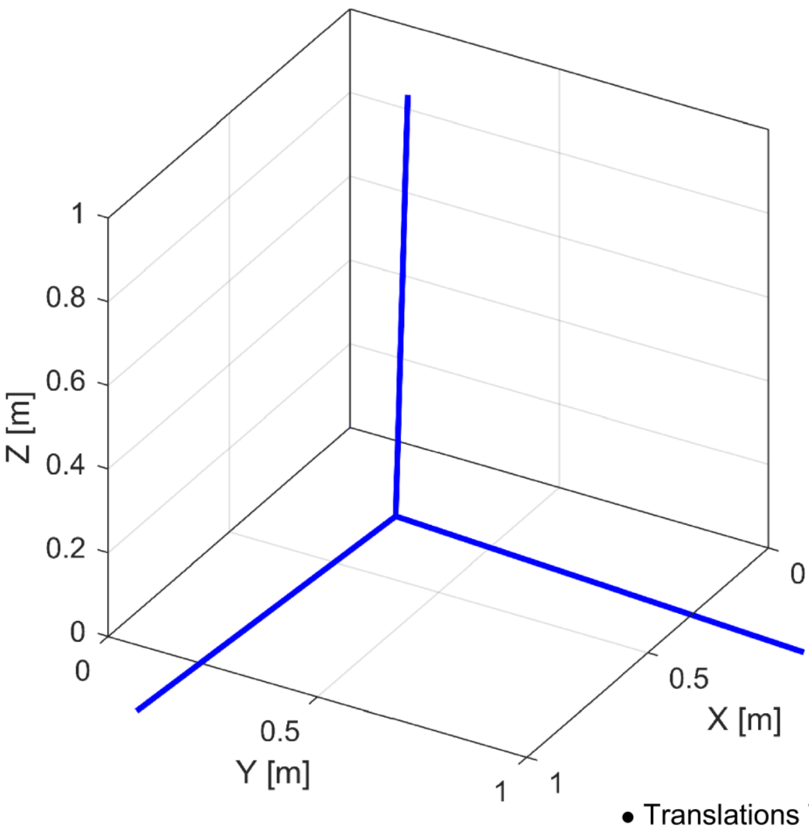
	GAL
Tx	-0.02±0.01
Ty	-0.04±0.01
Tz	0.04±0.03
Rx	0.28±0.20
Ry	0.17±0.18
Rz	0.39±0.24
k	-23.8±0.23

- Translations T_x T_y T_z are in meters
- Rotations R_x R_y R_z are in milli-seconds of arc
- Scale factor k is μm/km

BeiDou reference frame

Offset between CHI broadcast and CODE SP3 reference system

Angles are amplified by a factor of 3600000



	CHI
Tx	0.26±0.18
Ty	0.26±0.10
Tz	-0.01±0.07
Rx	0.90±0.81
Ry	1.30±0.71
Rz	2.39±1.36
k	-23.3±3.29

- Translations T_x T_y T_z are in meters
- Rotations R_x R_y R_z are in milli-seconds of arc
- Scale factor k is μm/km

Reference frames

- According to Montenbruck et al. (2015):
  - GPS (WGS84), Galileo (GTRF), and BeiDou (CGCS2000) should be aligned with ITRF
  - GLONASS PZ90.11 should be aligned with ITRF at mm level (Kosenko, 2015)
- We find that:
  - GPS and Galileo broadcast reference frames are aligned with ITRF: translations are less than 0.10 m and rotations are less than 2 milli-second of arc.
  - GLONASS M broadcast reference frame is offset to ITRF by at most 0.27 ± 0.04 m in Y and maximum rotation is 4 ± 2 milli-second of arc about Y.
  - GLONASS K broadcast reference frame is offset to ITRF by at most 1.06 ± 0.17 m in Y and maximum rotation is 19 ± 2 milli-second of arc about X.
  - BeiDou broadcast reference frame is offset to ITRF by at most 0.26 ± 0.18 in X and Y, and maximum rotation is 2 ± 1 milli-second of arc about Z.
  - Scale factors were used to estimate boresight offset between APC and CoM for homogeneous blocks of satellites.

Antenna phase offset

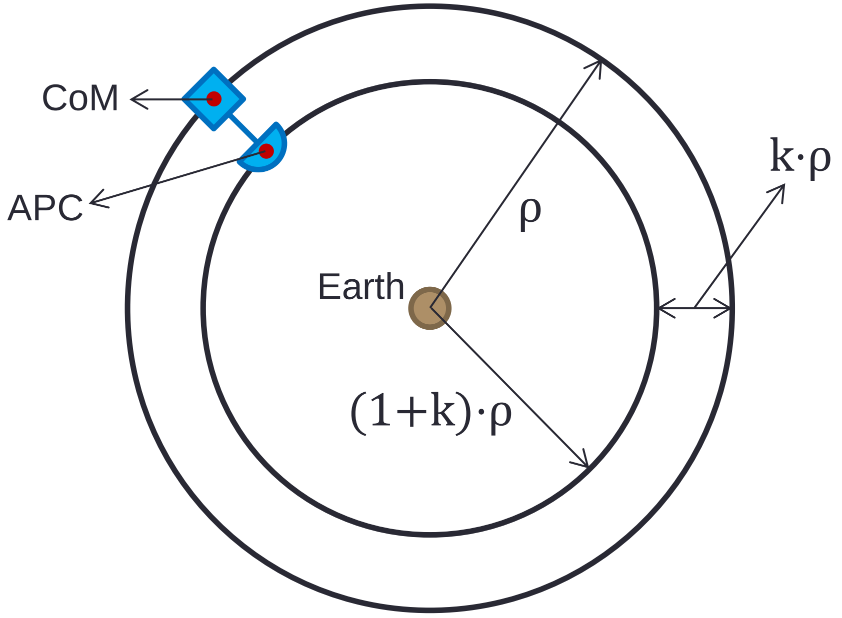
The effect of antenna phase offset on pseudorange is mostly due to boresight component (z-component), which direction is radial in RSW system.

We compute antenna radial offset (ΔR) considering:

- k: Helmert scale factor
- ρ_{GNSS}: average orbit radius
- δR^i: satellite-specific average of radial residuals

$$\Delta R^i = -k \cdot \varrho_{GNSS} - \delta R^i$$

System	ρ_{GNSS} [km]
GPS	26560
GLONASS	25460
Galileo	29582
BeiDou IGSO	42146
BeiDou MEO	27888



Antenna phase offset in radial direction

System	IGS[1] z-offset [m]	Montenbruck et al. 2015[2] [m]	This paper [m]
GPS IIR-A	1.27 ± 0.14	1.61	1.56 ± 0.12
GPS IIR-B/M	0.79 ± 0.07	-0.04	-0.05 ± 0.12
GPS IIF	1.47 ± 0.10	1.16	1.09 ± 0.23
GLO-M	2.40 ± 0.07	2.05	2.12 ± 0.49
GLO-K[3]	2.08	2.05	1.35 ± 0.59
GAL IOV	0.95 ± 0.00	0.85	0.63 ± 0.16
GAL FOC	1.09 ± 0.02	-	0.72 ± 0.19
CHI	1.10[4] ± 0.00	0.00[5]	0.87 ± 0.49

[1] ftp://epncb.oma.be/pub/station/general/igs14_1967.atx

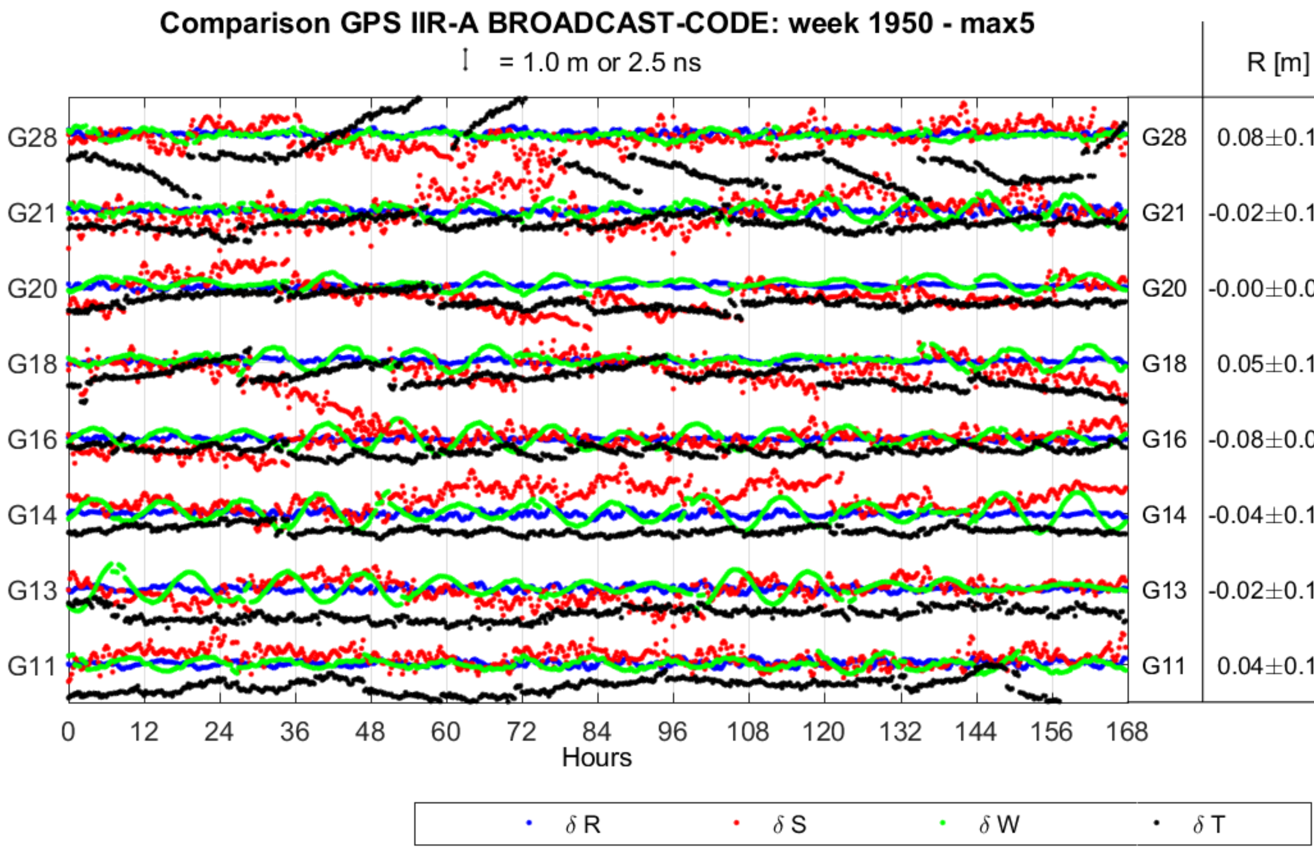
[2] It is unclear if the satellites analyzed by Montenbruck in 2013 are identical to those available in week 1950 we considered

[3] Our value refers to R09; Montenbruck probably used R08, R26, R27; for all the satellites IGS values range between 2.01 and 2.08 m

[4] Conventional MGEX values

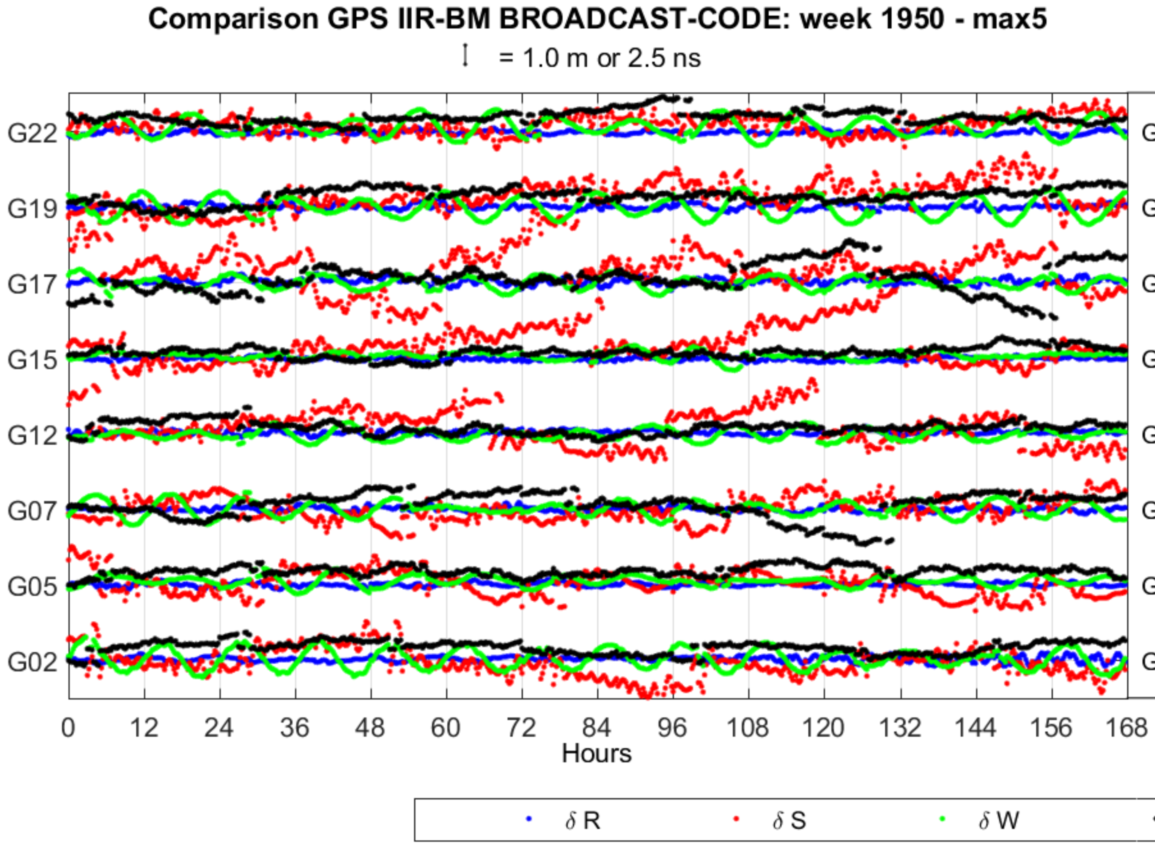
[5] Montenbruck assumes that broadcast ephemeris are referred to CoM

GPS IIR-A Coordinate differences



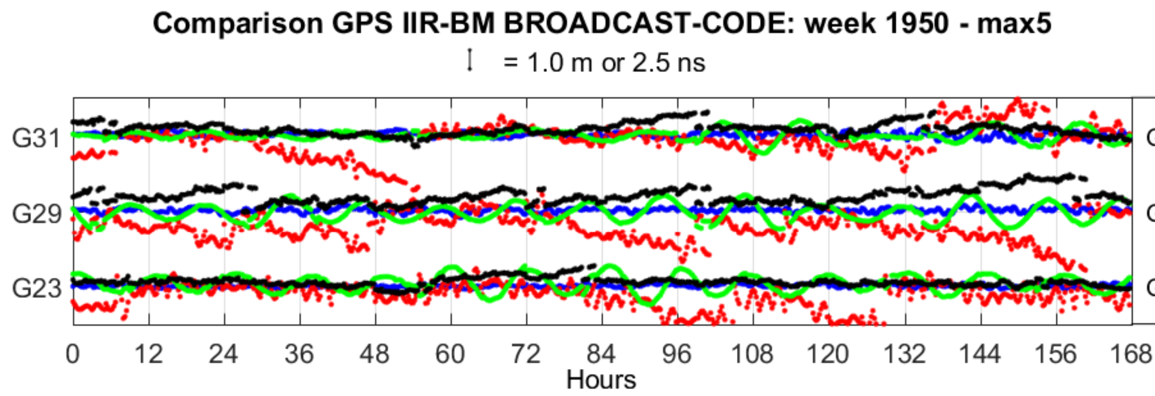
	R [m]	S [m]	W [m]	T [ns]
G28	0.08±0.13	-0.12±0.61	-0.02±0.18	-2.6± 3.9
G21	-0.02±0.12	0.02±0.82	0.03±0.38	-1.8± 0.8
G20	-0.00±0.09	-0.46±0.77	0.13±0.27	-2.0± 0.9
G18	0.05±0.10	-0.66±0.88	0.14±0.32	-2.1± 1.3
G16	-0.08±0.08	-0.18±0.50	-0.04±0.42	-1.8± 0.6
G14	-0.04±0.13	0.80±0.63	0.04±0.52	-2.3± 0.5
G13	-0.02±0.13	-0.11±0.57	0.04±0.47	-3.4± 0.8
G11	0.04±0.14	0.36±0.43	0.00±0.24	-3.1± 1.3

GPS IIR-B/M Coordinate differences



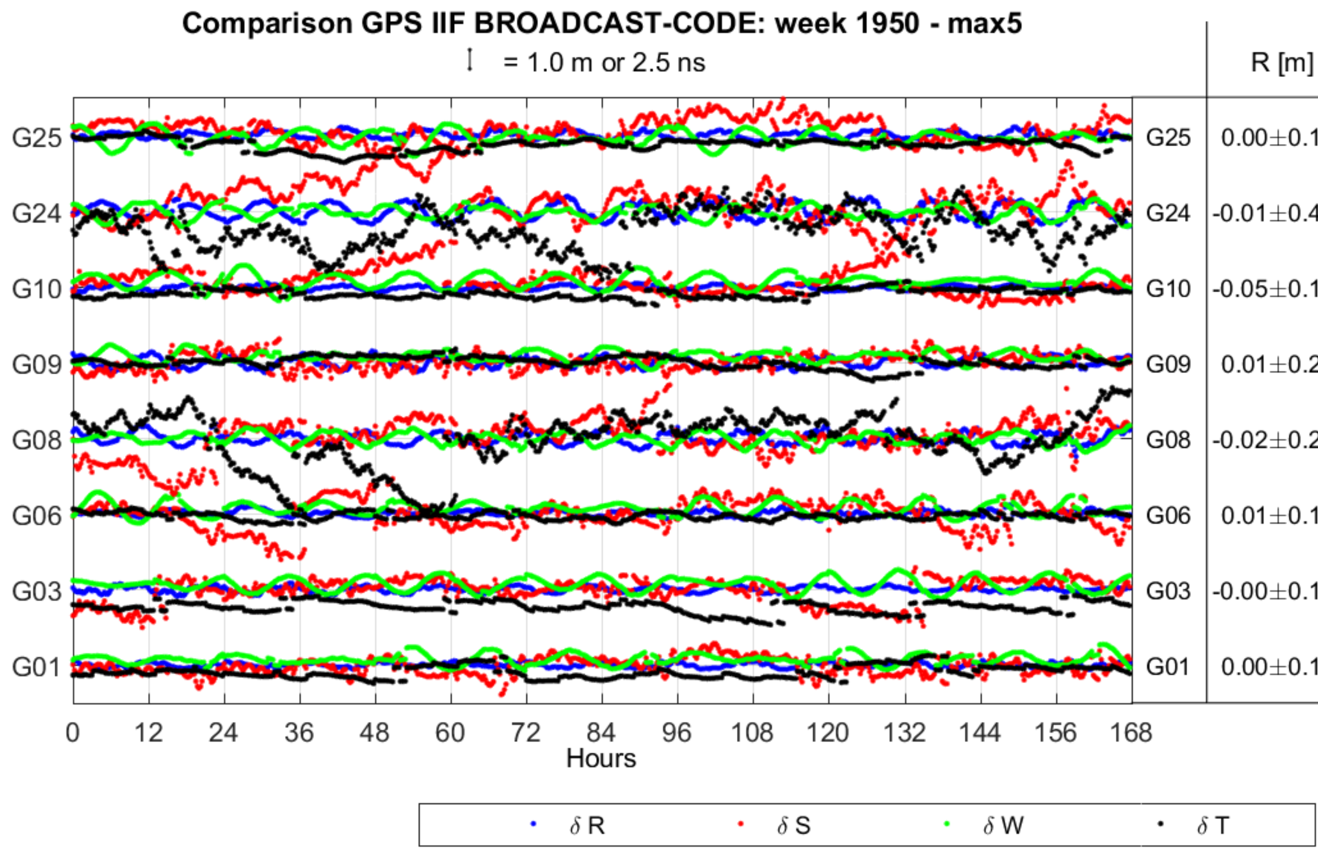
	R [m]	S [m]	W [m]	T [ns]
G22	-0.11±0.10	0.30±0.46	0.20±0.46	1.8± 0.8
G19	-0.02±0.13	0.50±0.77	-0.06±0.54	1.3± 1.0
G17	0.03±0.16	0.74±1.12	-0.05±0.31	0.4± 2.0
G15	-0.07±0.08	0.72±1.06	0.11±0.19	0.7± 0.7
G12	0.03±0.10	0.32±0.93	-0.07±0.28	0.7± 0.8
G07	-0.02±0.11	-0.03±0.62	-0.00±0.38	0.5± 1.7
G05	-0.00±0.10	0.02±0.66	0.19±0.25	1.8± 0.6
G02	0.05±0.13	-0.17±0.74	0.08±0.50	1.6± 0.8

GPS IIR-B/M Coordinate differences



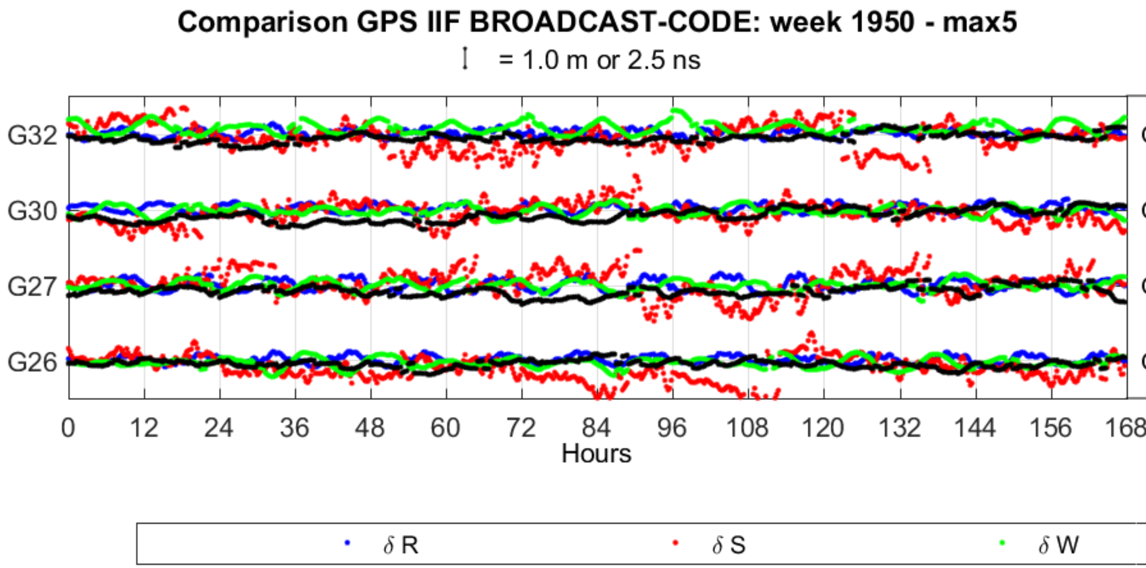
	R [m]	S [m]	W [m]	T [ns]
G31	0.04±0.13	-0.25±0.81	-0.00±0.29	0.8± 0.8
G29	0.06±0.12	-0.92±0.74	-0.07±0.45	2.0± 1.0
G23	0.01±0.08	-0.57±0.68	0.13±0.44	0.5± 0.6

GPS IIF Coordinate differences



	R [m]	S [m]	W [m]	T [ns]
G25	0.00±0.17	0.22±0.62	-0.17±0.37	-1.3± 0.8
G24	-0.01±0.42	0.56±1.11	-0.07±0.31	-2.6± 2.6
G10	-0.05±0.12	0.25±0.67	0.28±0.36	-1.0± 0.6
G09	0.01±0.27	0.04±0.42	0.30±0.27	-0.0± 0.8
G08	-0.02±0.29	0.00±0.95	-0.03±0.29	-0.2± 3.6
G06	0.01±0.15	-0.06±0.79	0.28±0.34	-0.3± 0.5
G03	-0.00±0.15	-0.08±0.62	0.27±0.35	-2.4± 0.8
G01	0.00±0.12	-0.09±0.44	0.30±0.27	-0.9± 0.8

GPS IIF Coordinate differences

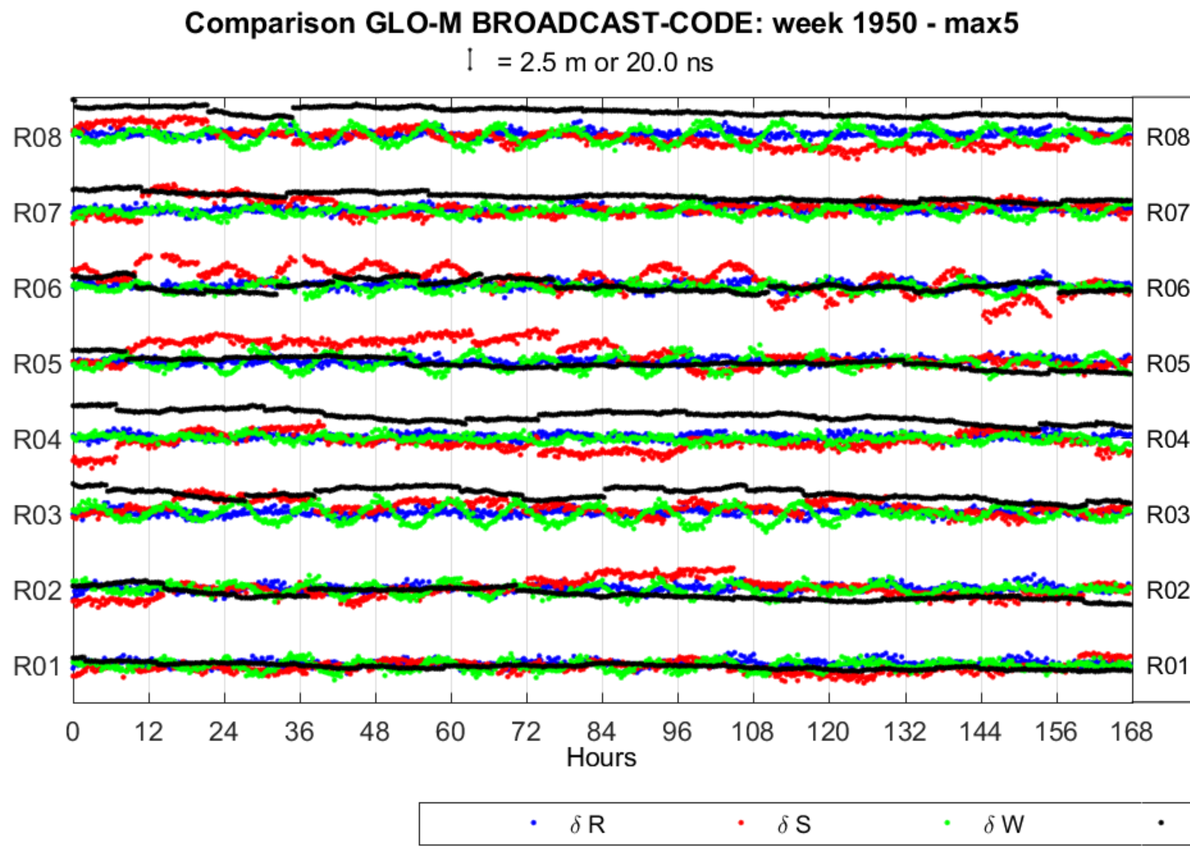


	R [m]	S [m]	W [m]	T [ns]
G32	0.01±0.19	-0.21±0.70	0.29±0.31	-0.6± 0.6
G30	0.03±0.22	-0.23±0.53	-0.09±0.25	-0.8± 0.8
G27	-0.02±0.30	0.08±0.68	-0.02±0.24	-0.9± 0.7
G26	0.03±0.21	-0.47±0.64	-0.13±0.26	-0.5± 0.5

GPS Coordinate differences

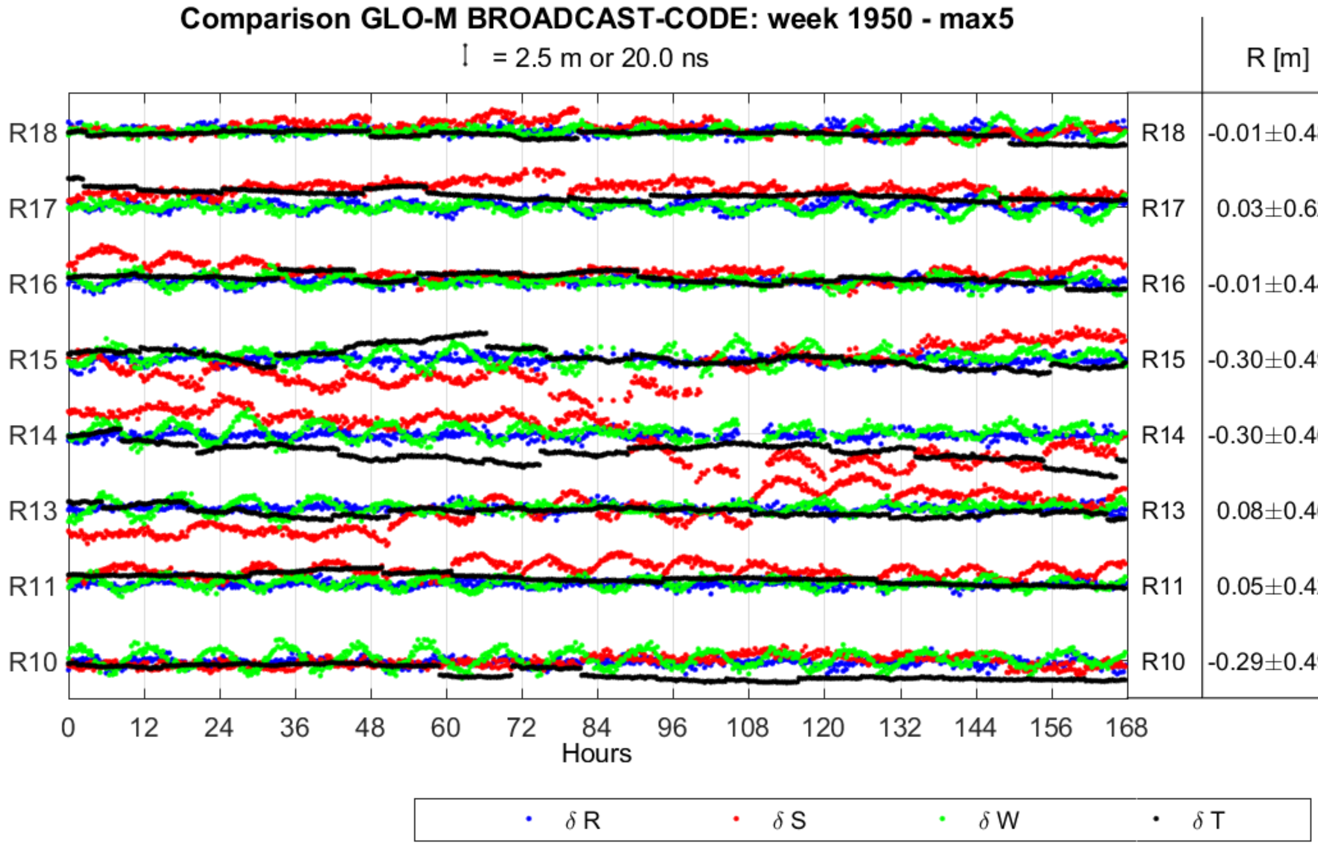
- We do not find block-specific observations for coordinate and clock differences
- Discontinuities affect mostly the along-track component.
- Radial component has an average RMS of 0.15 m. Discontinuities are about 0.2-0.3 m.
- Along-track component has an average RMS of 0.71 m. Discontinuities are up to 1.5 m.
- Out-of-plane component show an oscillating trend (T ≈ 12 hr), it has an average RMS of 0.34 m. Discontinuities are about 0.1-0.2 m.
- Clock ranges between -3.4 ÷ 2.0 ns with an average RMS of 1.1 ns. Discontinuities are about 1 ns.

GLONASS M coordinate differences 1/3



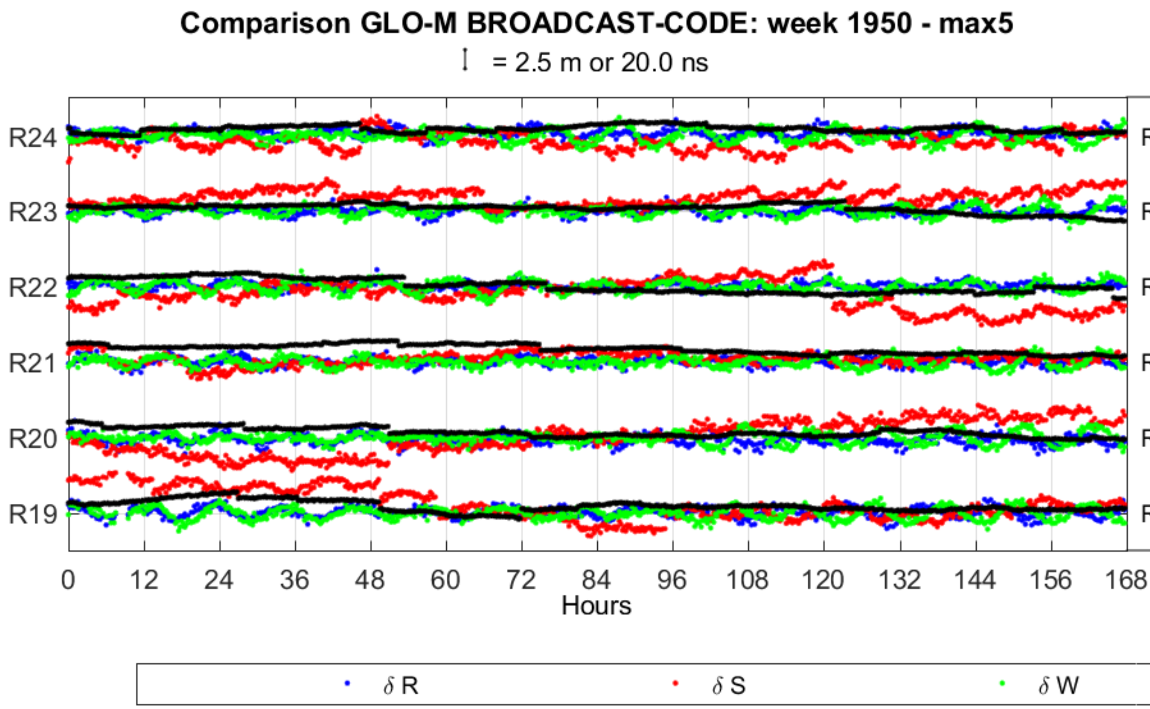
	R [m]	S [m]	W [m]	T [ns]
R08	0.12±0.41	-0.41±1.15	-0.15±0.97	24.3± 4.4
R07	0.14±0.38	0.46±1.01	-0.12±0.62	14.6± 4.3
R06	0.16±0.47	0.79±1.72	-0.17±0.54	0.1± 5.9
R05	0.08±0.39	1.22±1.58	-0.18±0.90	-1.5± 5.8
R04	0.08±0.41	-0.72±1.10	-0.16±0.45	22.2± 6.3
R03	0.08±0.40	0.78±0.87	-0.12±0.97	20.1± 6.0
R02	0.07±0.44	-0.03±1.13	-0.14±0.67	-6.1± 5.8
R01	0.10±0.41	-0.42±0.70	-0.19±0.62	-2.4± 3.0

GLONASS M coordinate differences 2/3



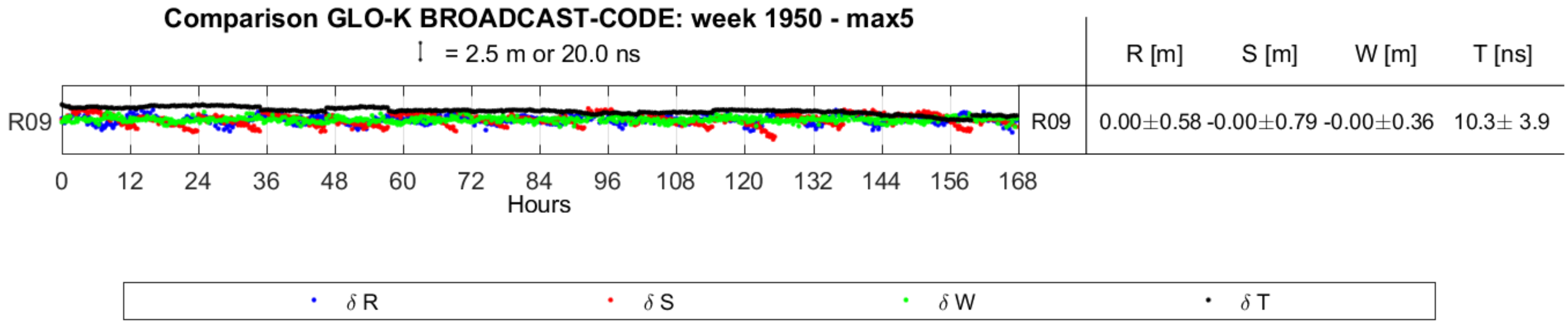
	R [m]	S [m]	W [m]	T [ns]
R18	-0.01±0.48	0.31±0.87	-0.15±0.76	-4.6± 4.3
R17	0.03±0.62	2.31±0.88	-0.13±0.74	11.8± 5.0
R16	-0.01±0.44	1.31±1.12	0.09±0.69	3.7± 5.2
R15	-0.30±0.49	-1.13±2.32	0.09±0.99	0.6± 9.9
R14	-0.30±0.46	-0.23±2.94	0.14±0.93	-20.2± 9.7
R13	0.08±0.46	-0.31±2.35	0.15±0.73	-3.1± 4.7
R11	0.05±0.42	1.91±0.89	0.18±0.65	6.4± 5.3
R10	-0.29±0.49	-0.21±0.73	0.18±1.06	-13.9± 7.2

GLONASS M coordinate differences 3/3



	R [m]	S [m]	W [m]	T [ns]
R24	0.18±0.57	-0.96±1.02	-0.09±0.79	6.2± 3.5
R23	-0.05±0.52	1.78±0.97	-0.08±0.67	2.2± 4.7
R22	0.03±0.46	-1.17±1.87	-0.07±0.72	0.0± 7.5
R21	0.02±0.53	0.35±0.82	-0.08±0.66	13.1± 4.7
R20	-0.35±0.64	0.01±2.19	-0.11±0.71	5.1± 4.8
R19	0.06±0.66	1.06±2.00	-0.09±0.78	6.9± 5.9

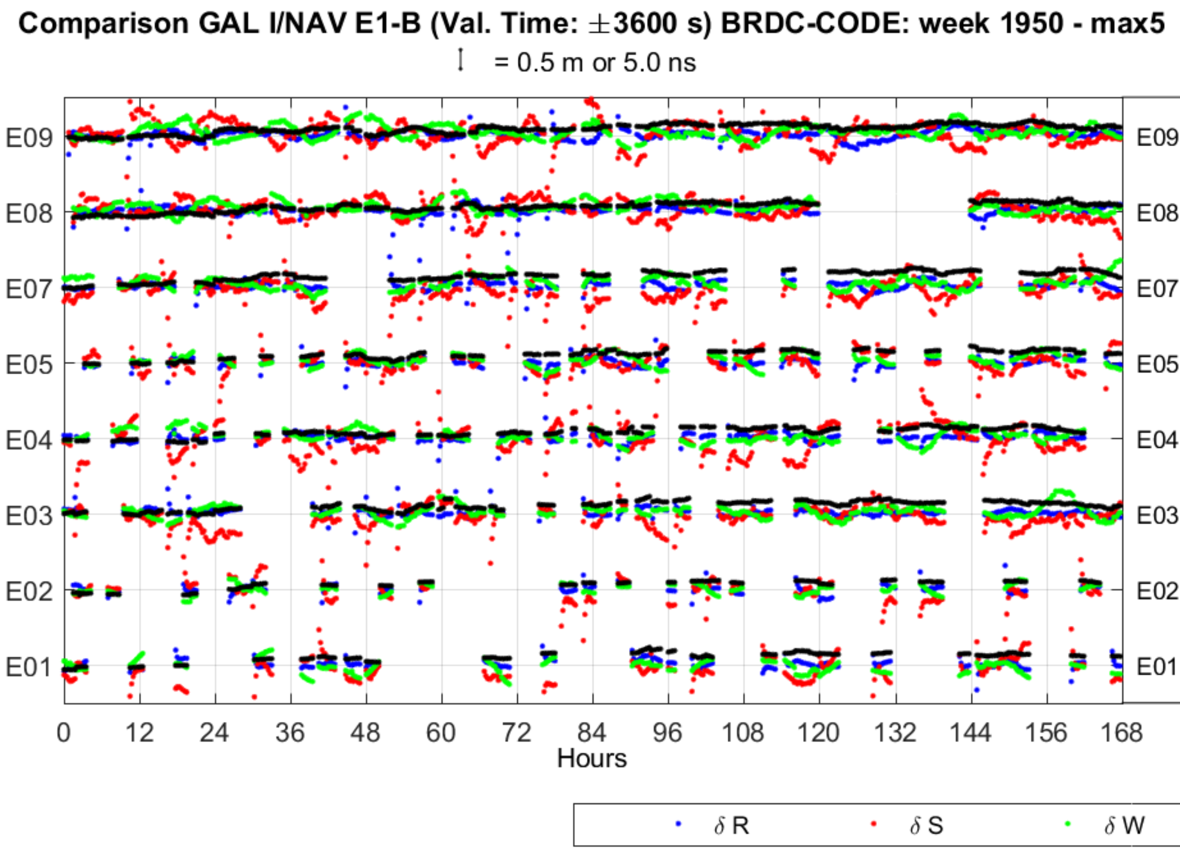
GLONASS K coordinate differences



GLONASS Coordinate differences

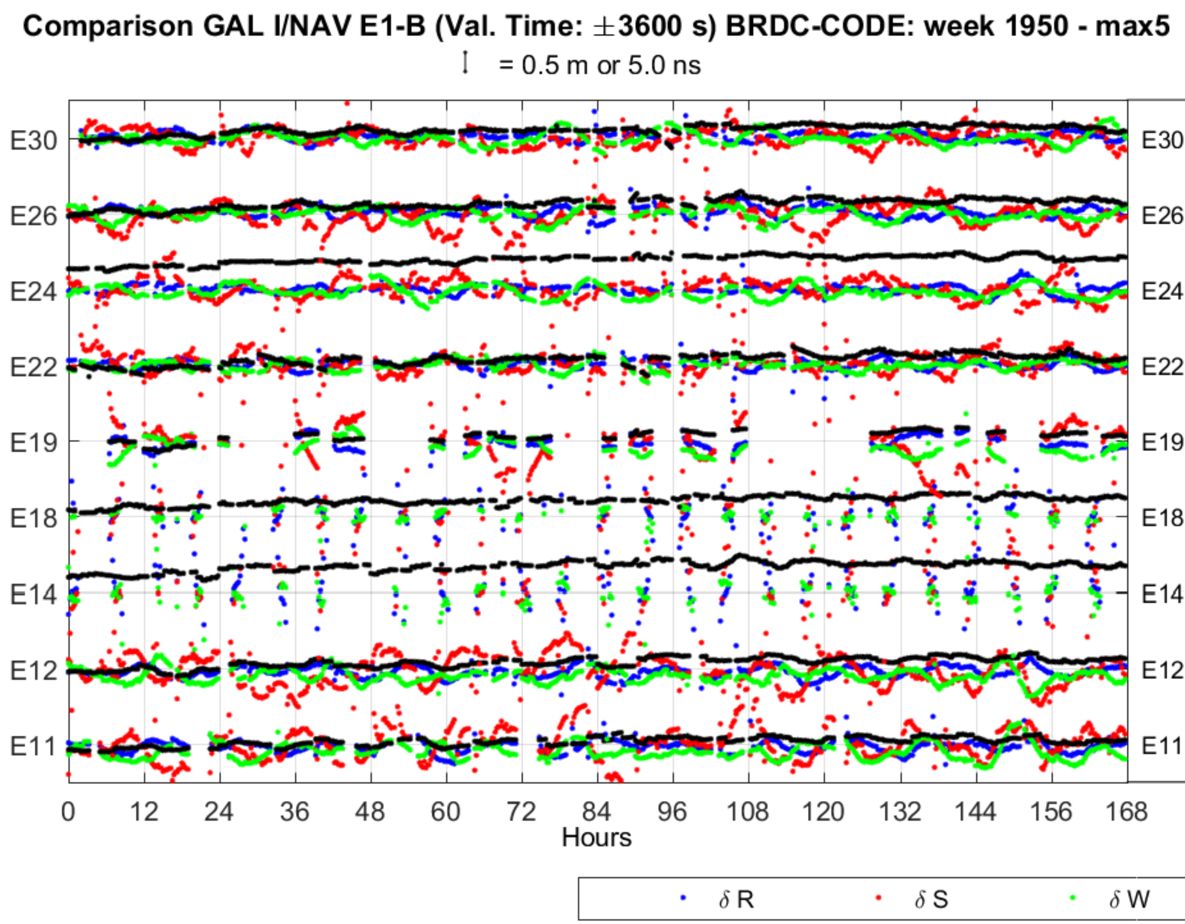
- Discontinuities affect mostly the along-track component and clock difference.
- Radial component has an average RMS of 0.48 m. Discontinuities are about 0.2-0.3 m.
- Along-track component has an average RMS of 1.38 m. Discontinuities are up to 3 m.
- Out-of-plane component has an average RMS of 0.78 m. Discontinuities are about 0.2-0.5 m.
- Clock ranges between -20 ÷ 24 ns with an average RMS of 5.6 ns. Discontinuities are up to 8 ns.
- Coordinates differences show an oscillating trend with T ≈ 12 hr

Galileo Coordinate differences 1/2



	R [m]	S [m]	W [m]	T [ns]
E09	0.02±0.13	0.05±0.31	0.08±0.18	1.7± 1.2
E08	0.01±0.11	0.03±0.25	0.09±0.15	1.0± 1.2
E07	0.03±0.12	-0.11±0.29	0.10±0.16	2.8± 1.3
E05	-0.01±0.11	-0.01±0.26	0.06±0.16	2.1± 1.1
E04	0.00±0.10	-0.06±0.38	0.06±0.16	1.6± 1.2
E03	0.03±0.10	-0.11±0.27	0.05±0.17	2.1± 1.2
E02	0.01±0.13	-0.06±0.31	0.01±0.13	1.3± 1.1
E01	0.02±0.12	-0.14±0.30	-0.06±0.17	2.2± 1.3

Galileo Coordinate differences 2/2

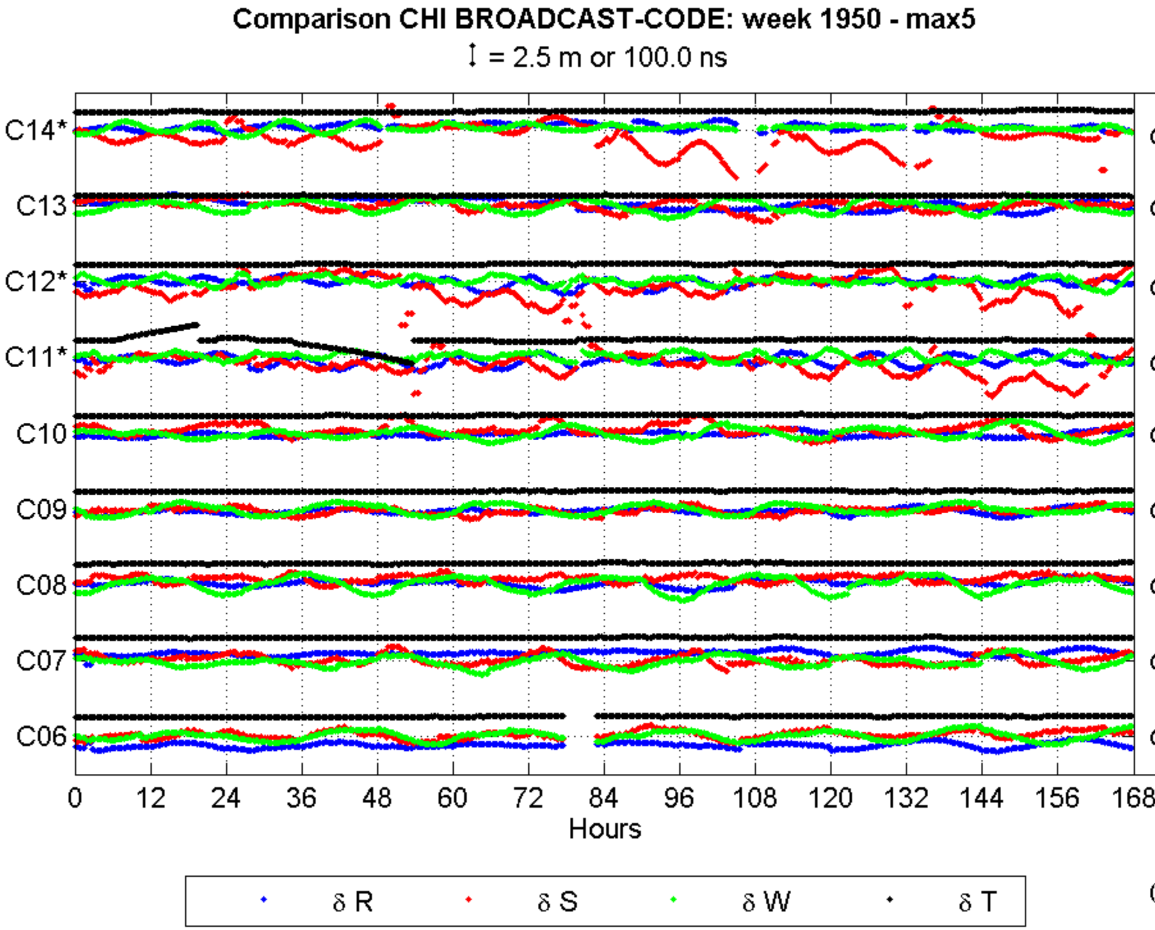


	R [m]	S [m]	W [m]	T [ns]
E30	0.03±0.12	-0.01±0.23	-0.01±0.16	2.0± 1.2
E26	0.03±0.14	-0.09±0.31	-0.02±0.16	2.5± 1.3
E24	0.00±0.12	0.01±0.26	-0.08±0.17	7.8± 1.1
E22	0.01±0.13	0.04±0.26	-0.02±0.13	1.4± 1.5
E19	-0.07±0.16	-0.06±0.50	-0.21±0.21	1.1± 1.5
E18	0.04±0.36	-0.03±2.05	-0.00±0.50	4.1± 1.2
E14	0.05±0.47	0.05±2.11	-0.12±0.84	6.7± 1.3
E12	-0.08±0.15	-0.06±0.40	-0.20±0.18	1.6± 1.4
E11	-0.07±0.16	-0.03±0.43	-0.20±0.21	0.7± 1.2

Galileo Coordinate differences

- Discontinuities affect mostly the along-track component.
- Radial component has an average RMS of 0.16 m. Discontinuities are about 0.1-0.2 m.
- Along-track component has an average RMS of 0.52 m. Discontinuities are up to 1 m.
- Out-of-plane component has an average RMS of 0.23 m. Discontinuities are about 0.1-0.3 m.
- Clock ranges between 1 ÷ 8 ns with an average RMS of 1.3 ns. Discontinuities are about 1-2 ns.
- Coordinates differences show an oscillating trend with $T \approx 12$ hr

BeiDou Coordinate differences



	R [m]	S [m]	W [m]	T [ns]
C14*	0.45±0.39	-0.94±1.65	0.34±0.41	99.9± 3.1
C13	0.26±0.66	0.11±0.66	-0.05±0.74	55.8± 1.6
C12*	-0.01±0.58	-0.76±1.54	0.07±0.49	93.1± 2.5
C11*	-0.37±0.62	-0.99±1.42	0.08±0.51	88.4±27.2
C10	-0.15±0.28	0.49±0.74	-0.02±0.66	95.5± 2.3
C09	-0.28±0.34	-0.23±0.45	-0.03±0.60	94.8± 2.0
C08	0.30±0.47	0.84±0.44	0.07±0.89	113.6± 2.4
C07	0.98±0.32	0.08±0.66	-0.16±0.64	121.5± 2.0
C06	-1.16±0.36	0.23±0.50	0.08±0.59	104.8± 2.2

(*) MEO satellite

BeiDou Coordinate differences

- Discontinuities affect mostly the along-track component, especially for MEO satellites, and clock differences.
- Radial component has an average RMS of 0.45 m. Discontinuities are about 0.1-0.3 m.
- Along-track component has an average RMS of 0.90 m. Discontinuities are up to 1 m for IGSO satellites and up to 3 m for MEO satellites.
- Out-of-plane component has an average RMS of 0.61 m. Discontinuities are about 0.1-0.3 m.
- Clock differences range between 56 ÷ 122 ns with an average RMS of 5.3 ns. Discontinuities are about 1-5 ns.
- Coordinates differences show an oscillating trend. The period of IGSO satellites is about the double respect to the period of MEO satellites (≈ 12 hr)

Conclusions

- Reference frames:
  - GPS and Galileo broadcast reference frames are aligned with ITRF: translations are less than 0.10 m and rotations are less than 2 milli-second of arc
  - GLONASS M broadcast reference frame is offset to ITRF by at most 0.27 ± 0.04 m in Y and maximum rotation is 4 ± 2 milli-second of arc about Y.
  - GLONASS K broadcast reference frame is offset to ITRF by at most 1.06 ± 0.17 m in Y and maximum rotation is 19 ± 2 milli-second of arc about X.
  - BeiDou broadcast reference frame is offset to ITRF by at most 0.26 ± 0.18 in X and Y, and maximum rotation is 2 ± 1 milli-second of arc about Z.
- Antenna phase offset:
  - Antenna phase offsets are consistent with those provided by IGS for GPS blocks IIA and IIF, GLONASS, Galileo and BeiDou, since the differences are lower then 2·σ (about 0.30 m for all satellites except R09 for which we find a difference of 0.70 m)
  - For GPS block IIR/M we find an offset of -0.05 ± 0.12 m, whereas IGS provide 0.79 ± 0.07 m.

Conclusions

- Coordinate differences:
  - Coordinate differences show an oscillating trend. They show discontinuities in correspondence of some ephemeris change, in an non-predictable manner. These discontinuities are more evident in the along-track component, in which they are at meter-level (about 1 m for GPS, Galileo and BeiDou IGSO and up to 3 for GLONASS and BeiDou MEO), compared to radial and out-of-plane components, in which they are at decimeter-level.
  - GPS and Galileo broadcast ephemeris show the better accuracy, since the RMS of differences of radial, along-track, out-of-plane components are 0.15, 0.71, 0.34 m for GPS and 0.16, 0.52, 0.23 m for Galileo.
  - GLONASS and BeiDou broadcast ephemeris are 2 times less accurate: the RMS of differences of radial, along-track, out-of-plane components are 0.48, 1.38, 0.78 m for GLONASS and 0.45, 0.90, 0.61 m for BeiDou.
- Clock differences:
  - Clock differences, as coordinate, show discontinuities in correspondence of some ephemeris change, in an non-predictable manner. These discontinuities are larger for GLONASS and BeiDou (up to 5-8 ns) and smaller for GPS and Galileo (about 1-2 ns).
  - The average values of satellites clock differences are comprised between few nanoseconds for GPS and Galileo, and between about 40 and 70 nanoseconds for GLONASS and BeiDou.
  - The RMS of clock differences are about 1 ns for GPS and Galileo, and 5-6 ns for BeiDou and GLONASS