Status of the EPN Troposphere Products

Wolfgang Söhne

Federal Agency for Cartography and Geodesy

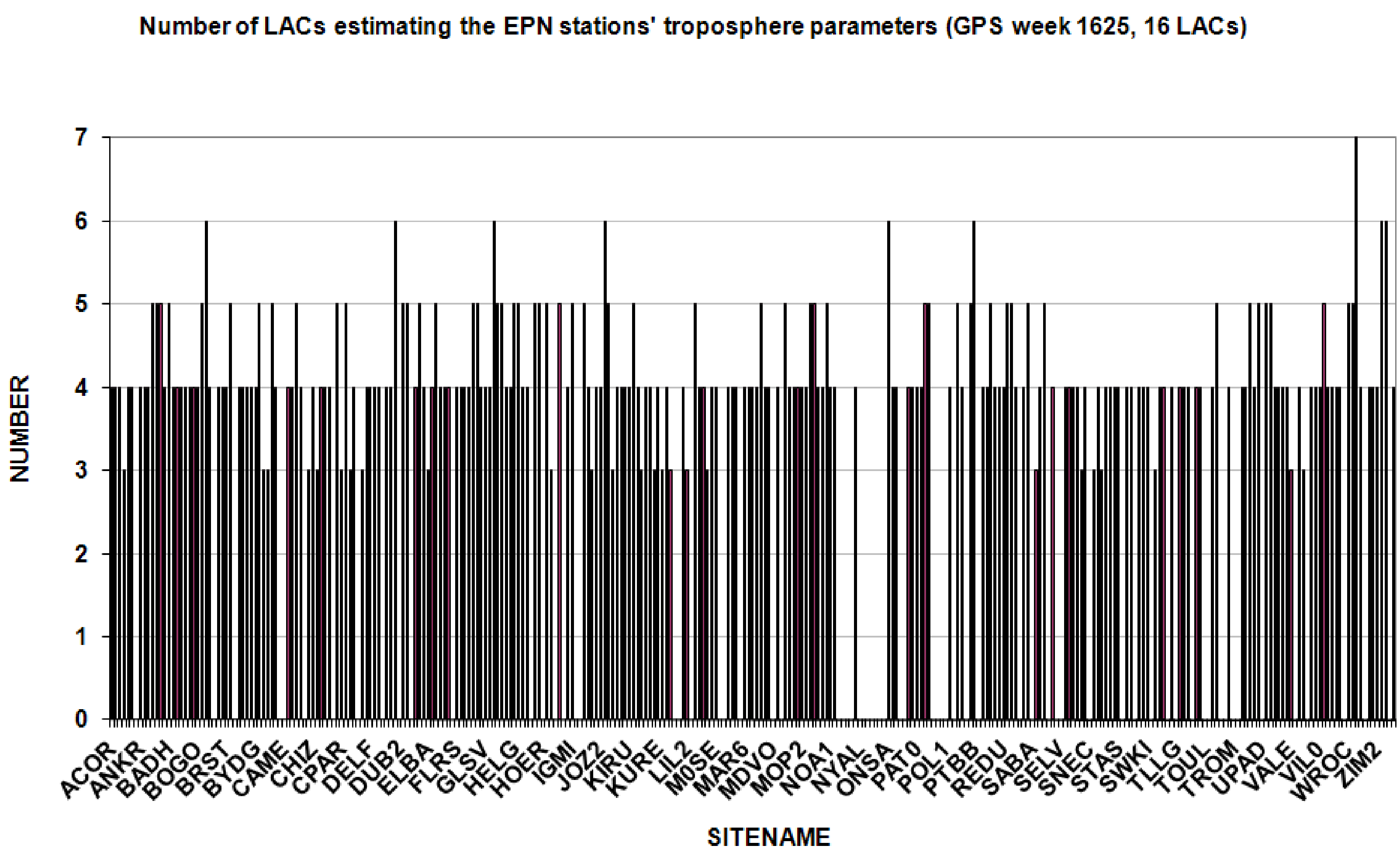
Outline

- **History & statistics**
- **ZTD results**
- **ZTD validation**
  - **Inter-technique comparison**
  - **Intra-technique comparison**
- **Summary & Outlook**

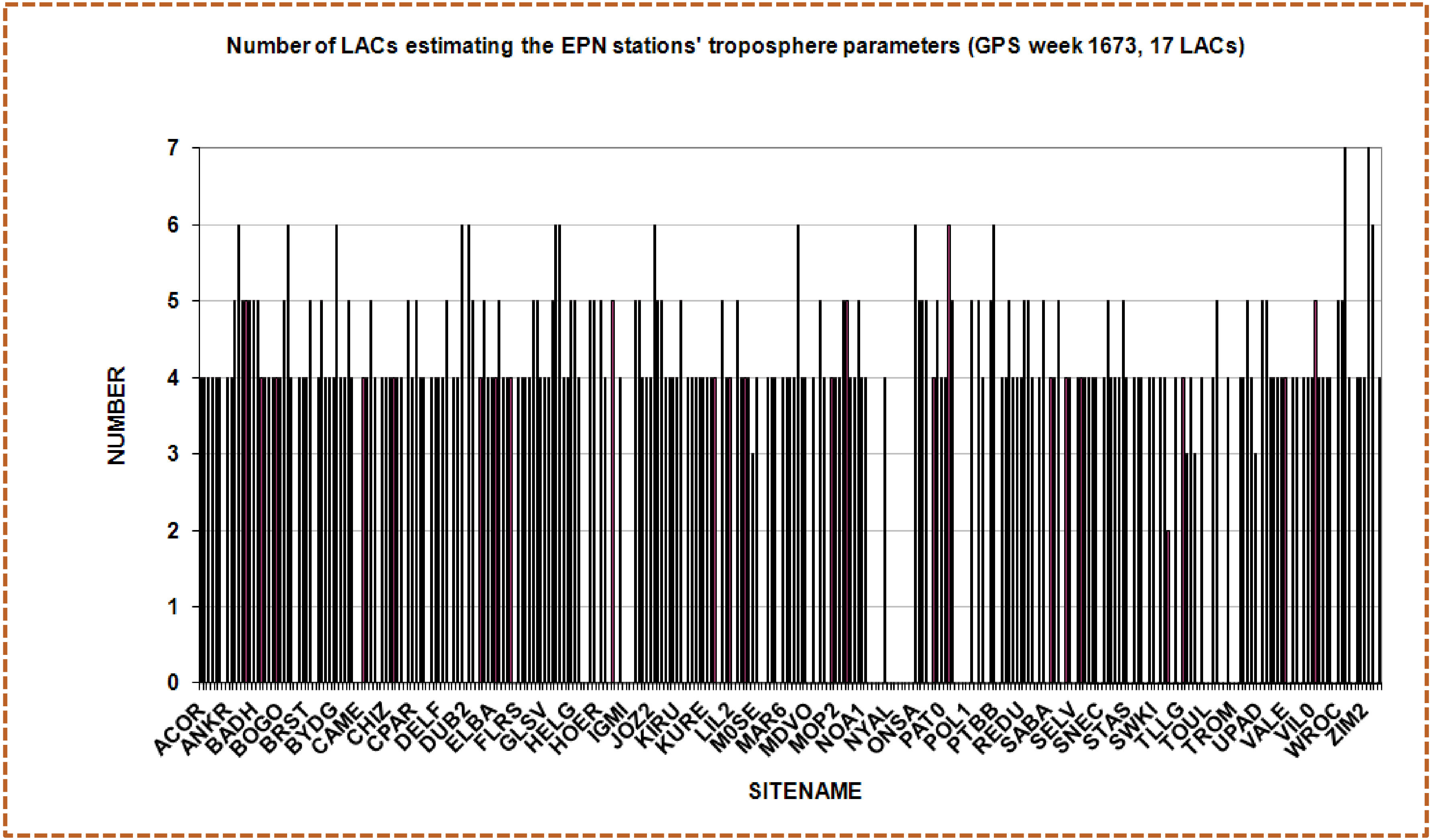
History

- **June 2008: resolution #1 at the EUREF symposium → operational status**
- **GPS week 1558: contribution of MUT**
- **GPS week 1600: COE using 'WET VMF1'**
- **GPS week 1617: ASI switched from MicroCosm to Gipsy**
- **GPS week 1632: IGS08 coordinates & velocities (No 5816)**
- **GPS week 1632: contribution of RGA (No 5815)**
- **GPS week 1632: ASI switching to Gipsy 6.0**
- **GPS week 1682: ZPD repro1 results released (No 6335)**
- **GPS week 1707: COE switching to BSW5.3**
- **GPS week 1730: BKG switching to BSW5.2 ('WET GMF')**
- **GPS week 1731: LPT switching to BSW5.2 ('WET GMF')**

EPN ZTD processing redundancy



EPN ZTD processing redundancy



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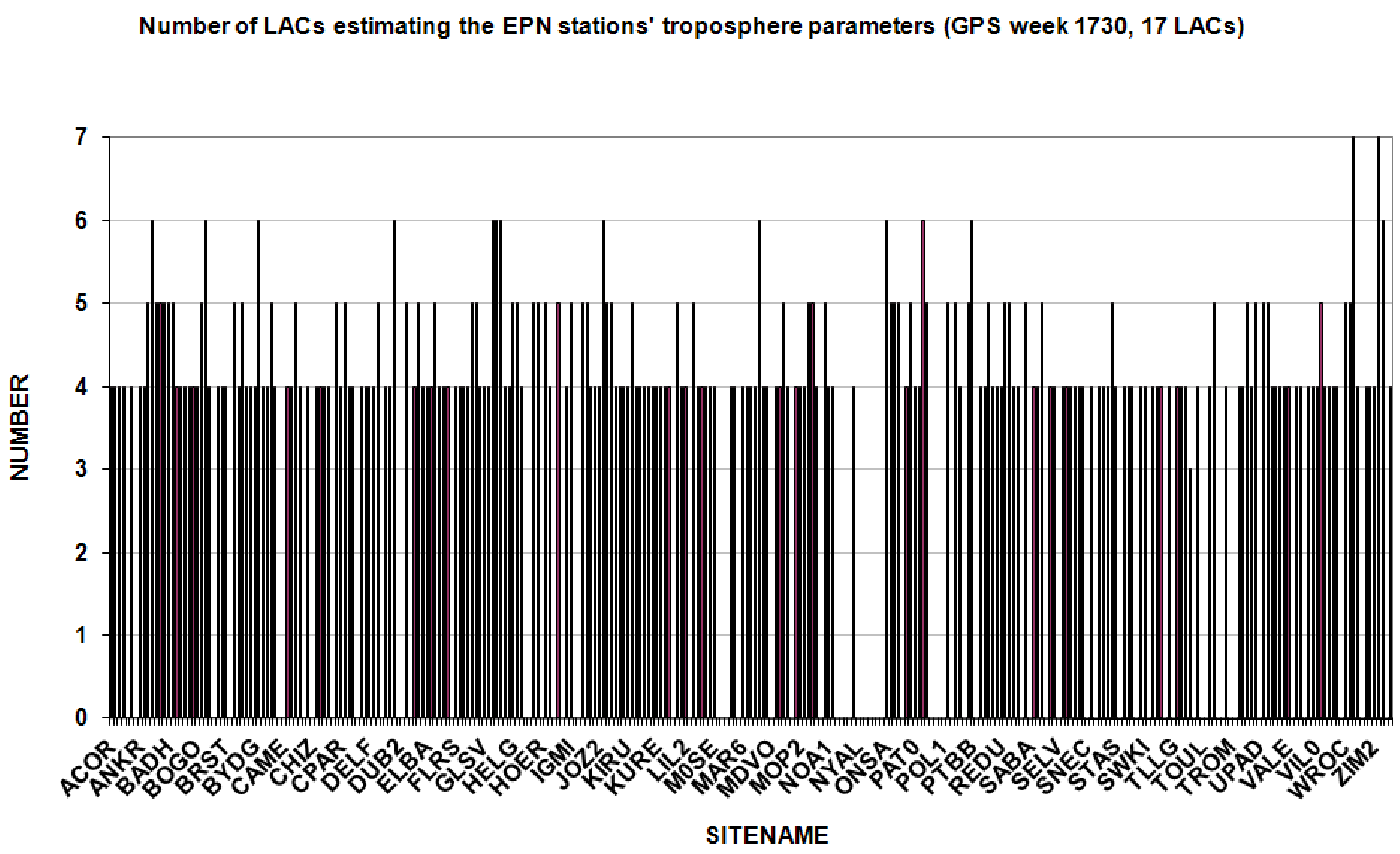

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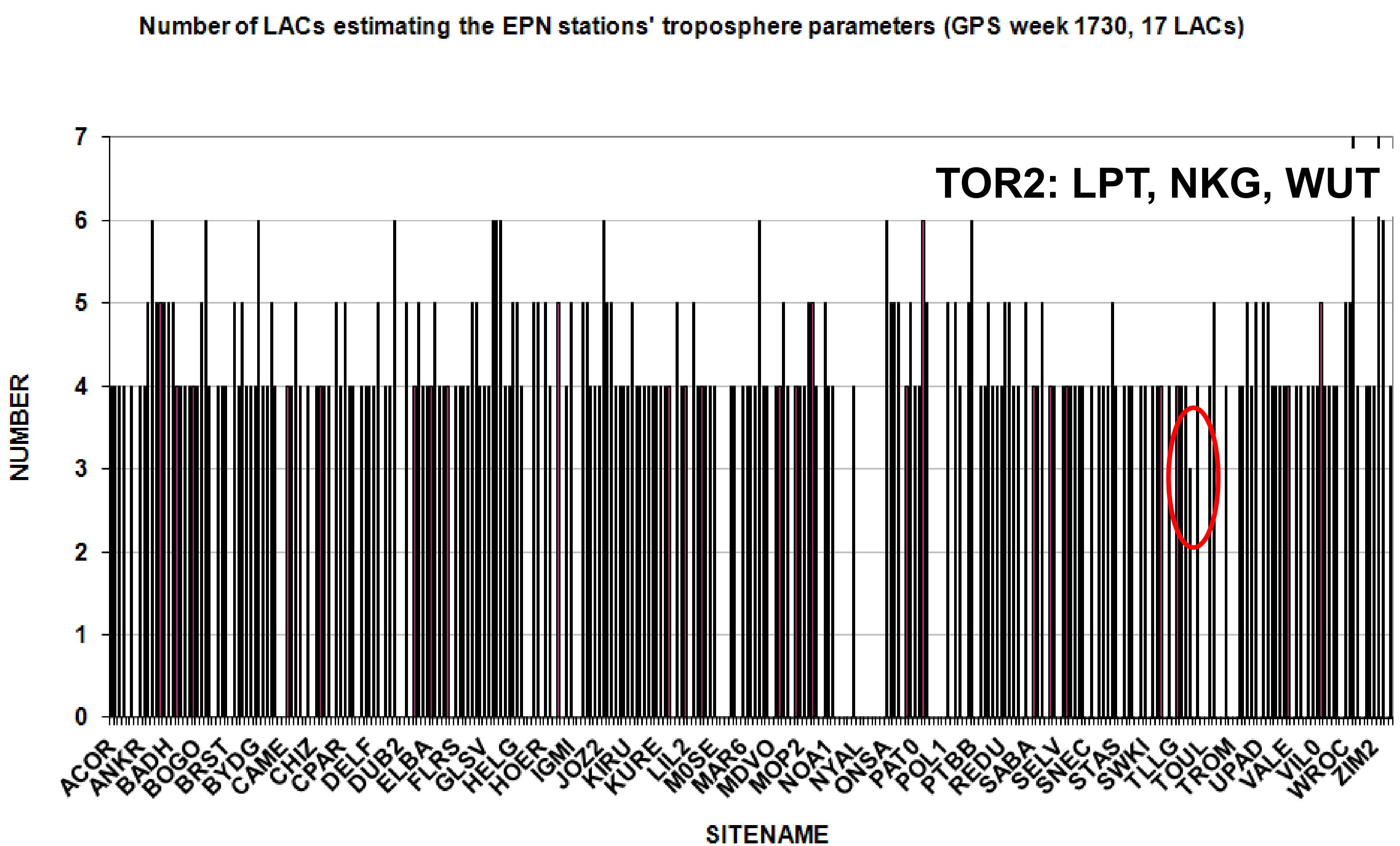
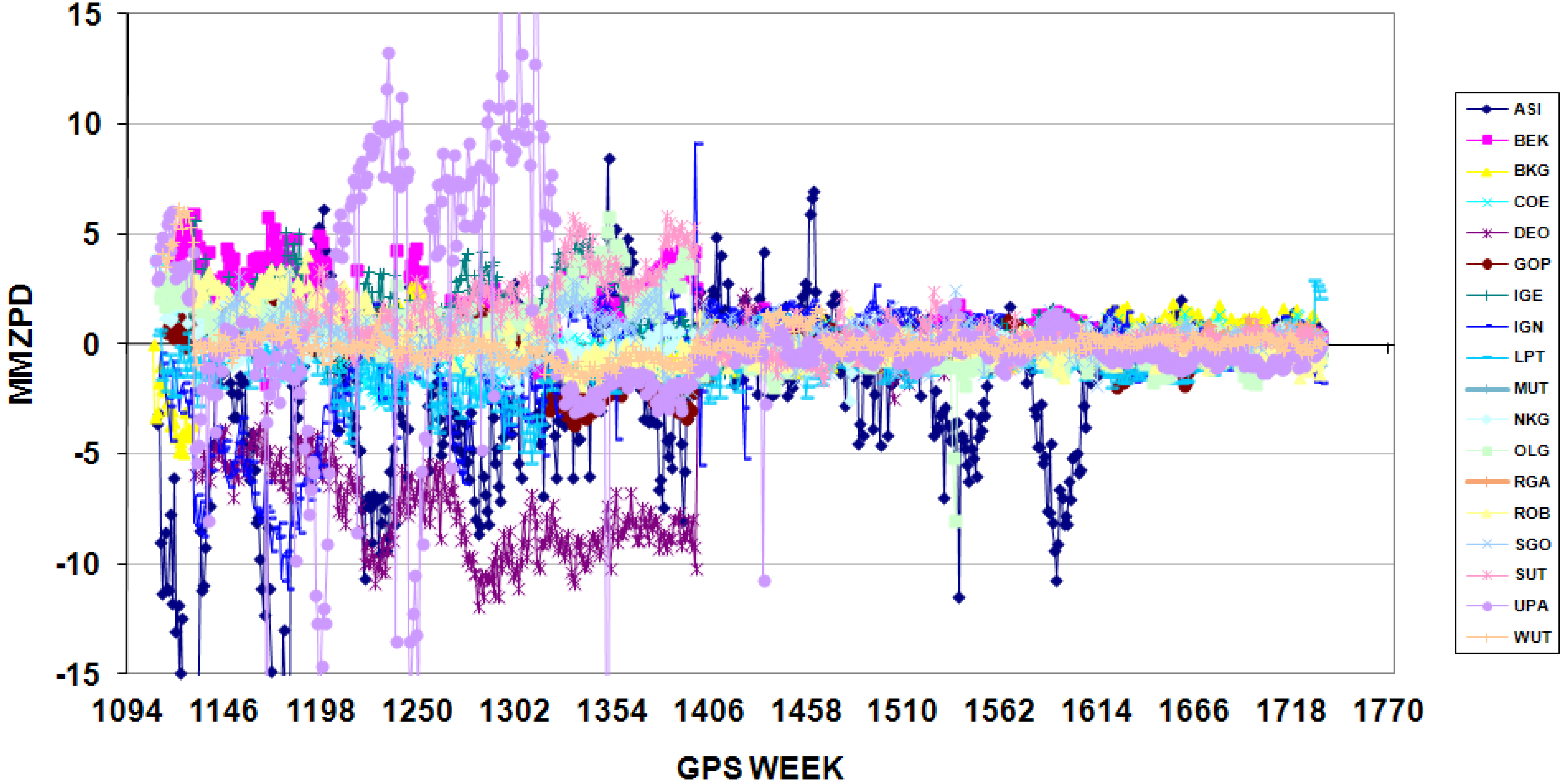


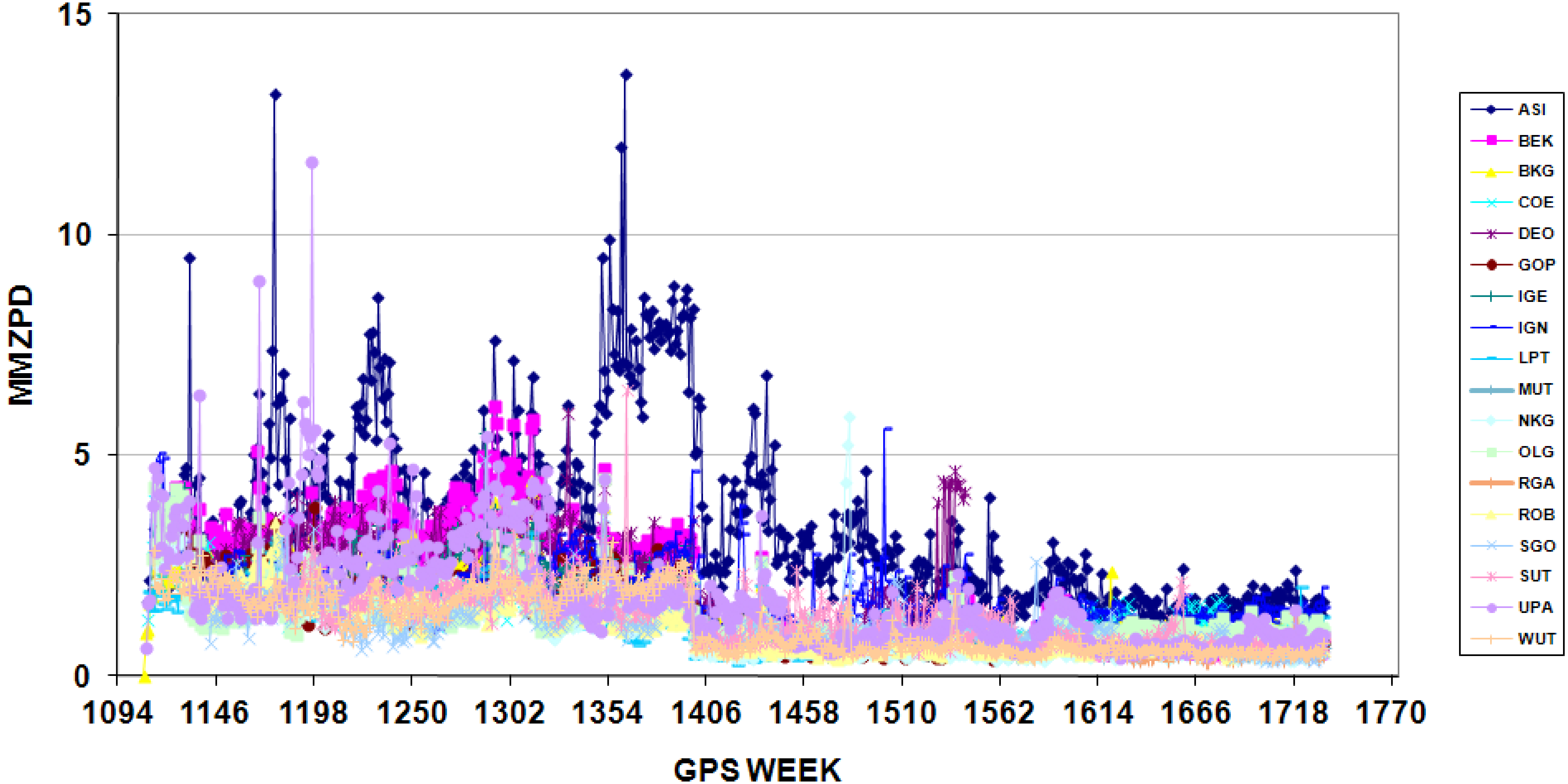
EPN ZTD processing consistency

Weekly mean biases of the individual LAC troposphere solutions with respect to the EPN combined solution



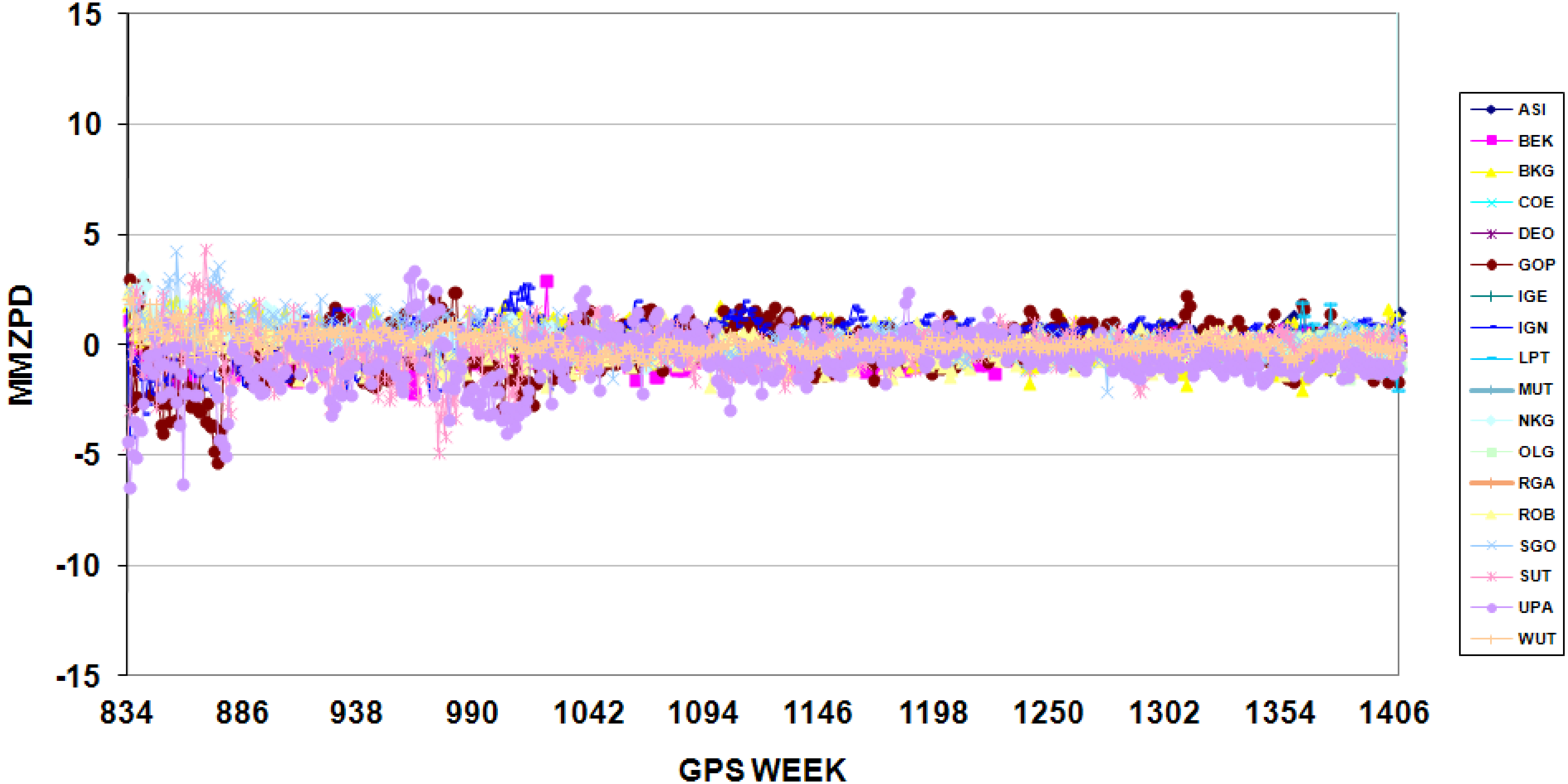
EPN ZTD processing consistency

Standard deviation of weekly mean biases of the individual LAC troposphere solutions with respect to the EPN combined solution



EPN ZTD processing consistency

REPRO: weekly mean biases of the individual LAC troposphere solutions with respect to the combined solution



EPN ZTD processing consistency

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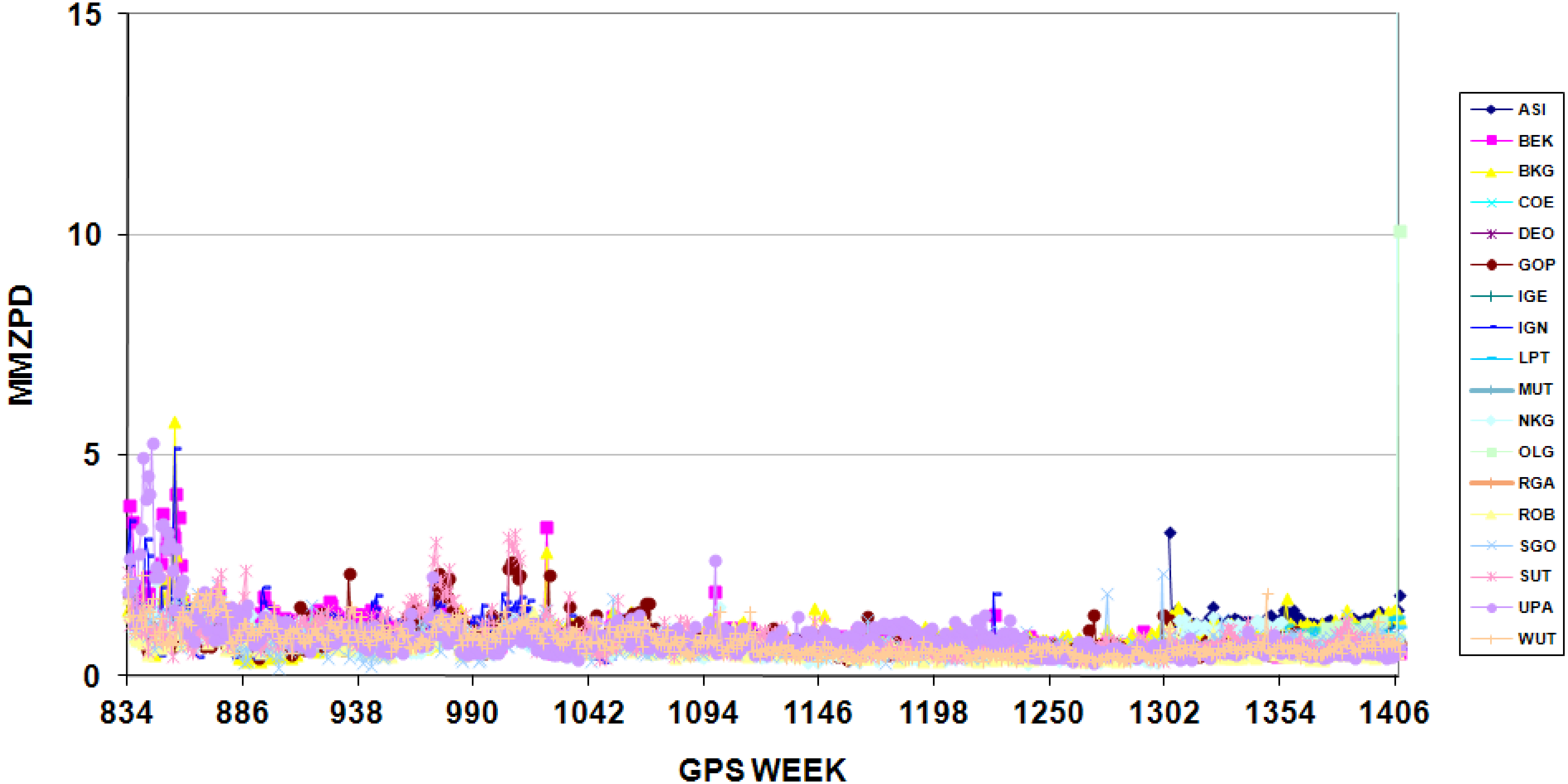
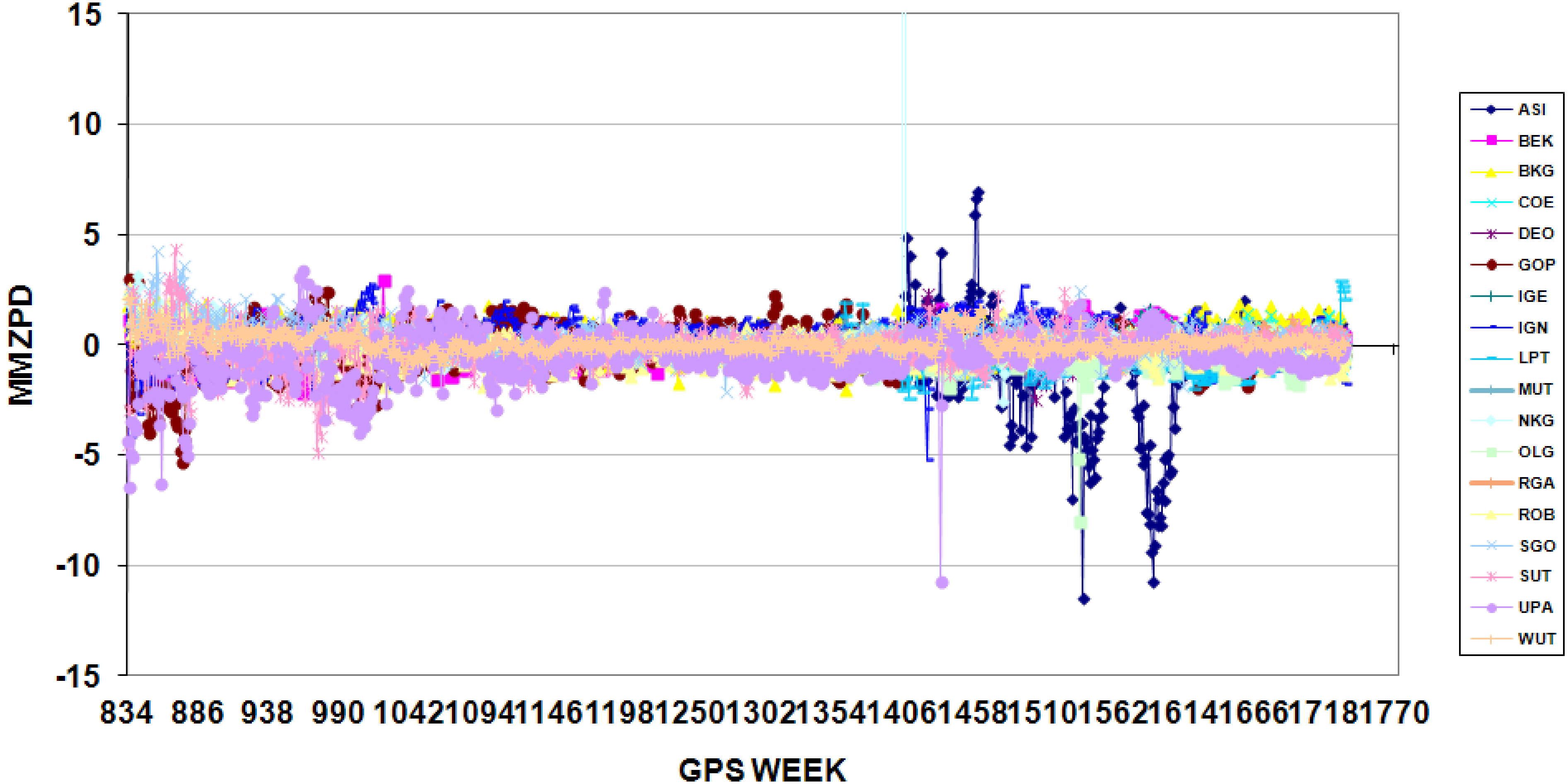


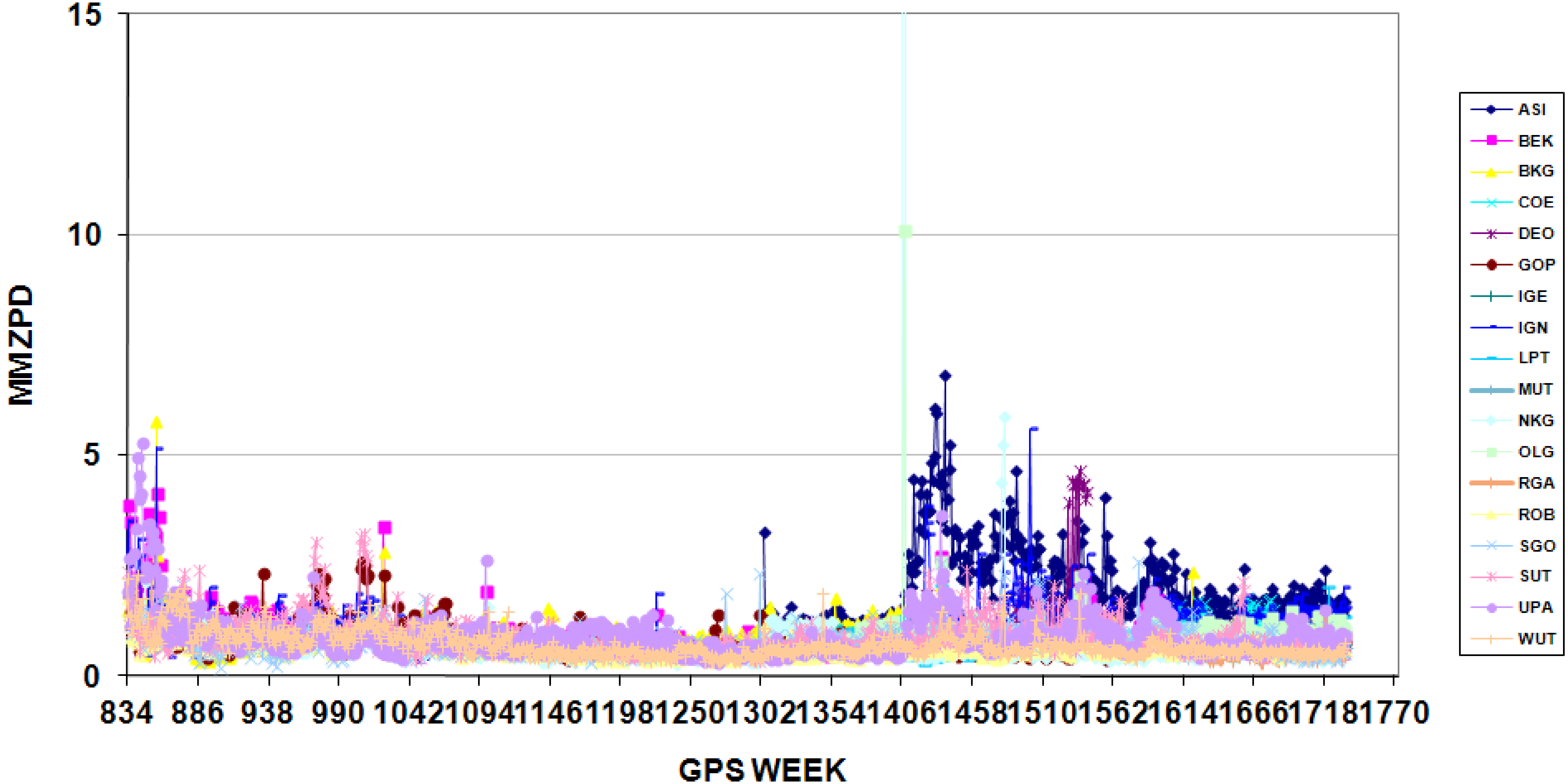
EPN ZTD processing consistency

REPRO/OPER: weekly mean biases of the individual LAC troposphere solutions with respect to the combined solution



EPN ZTD processing consistency

REPRO/OPER: standard deviation of weekly mean biases of the individual LAC troposphere solutions with respect to the combined solution



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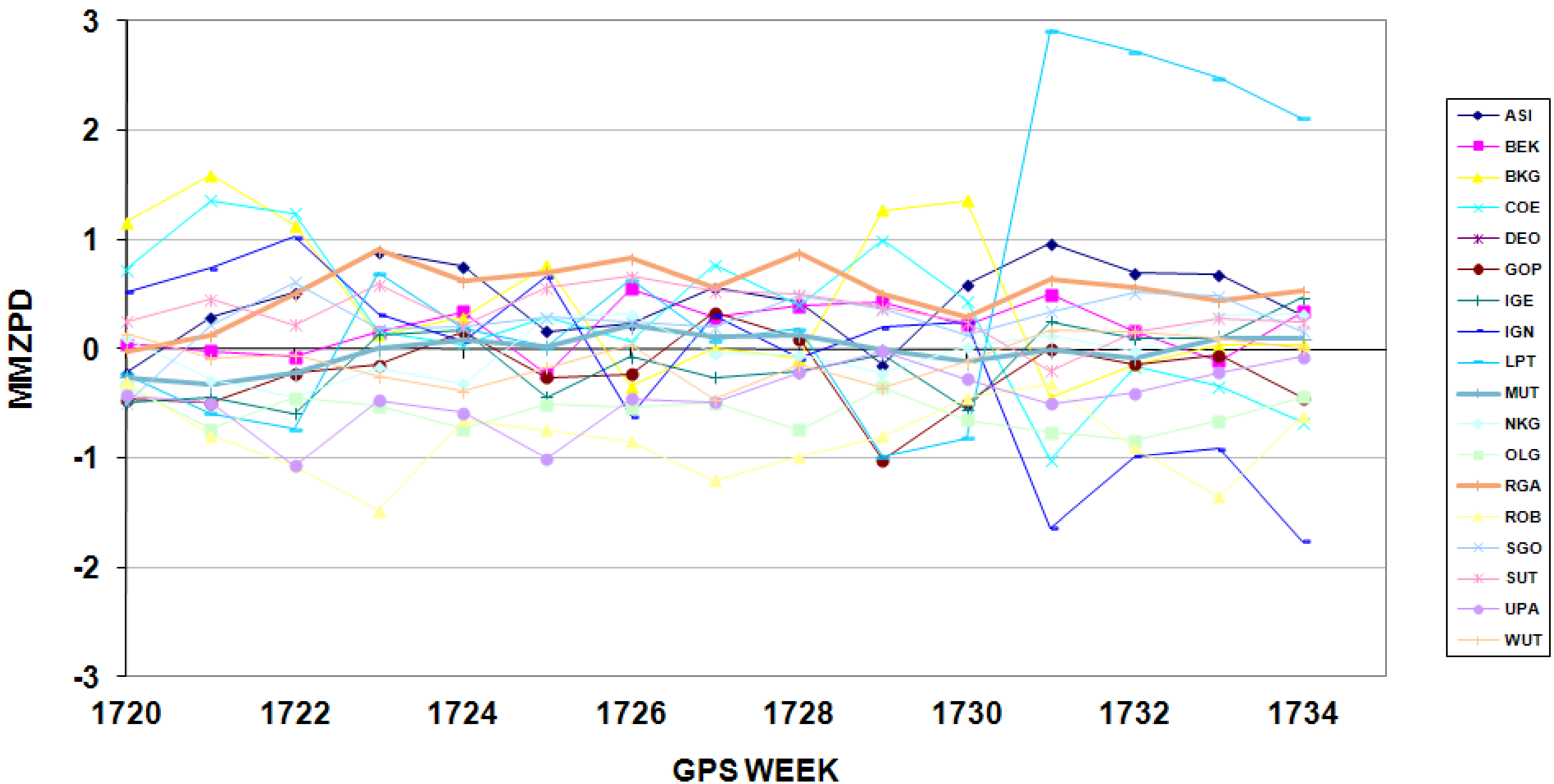

EPN ZTD processing consistency

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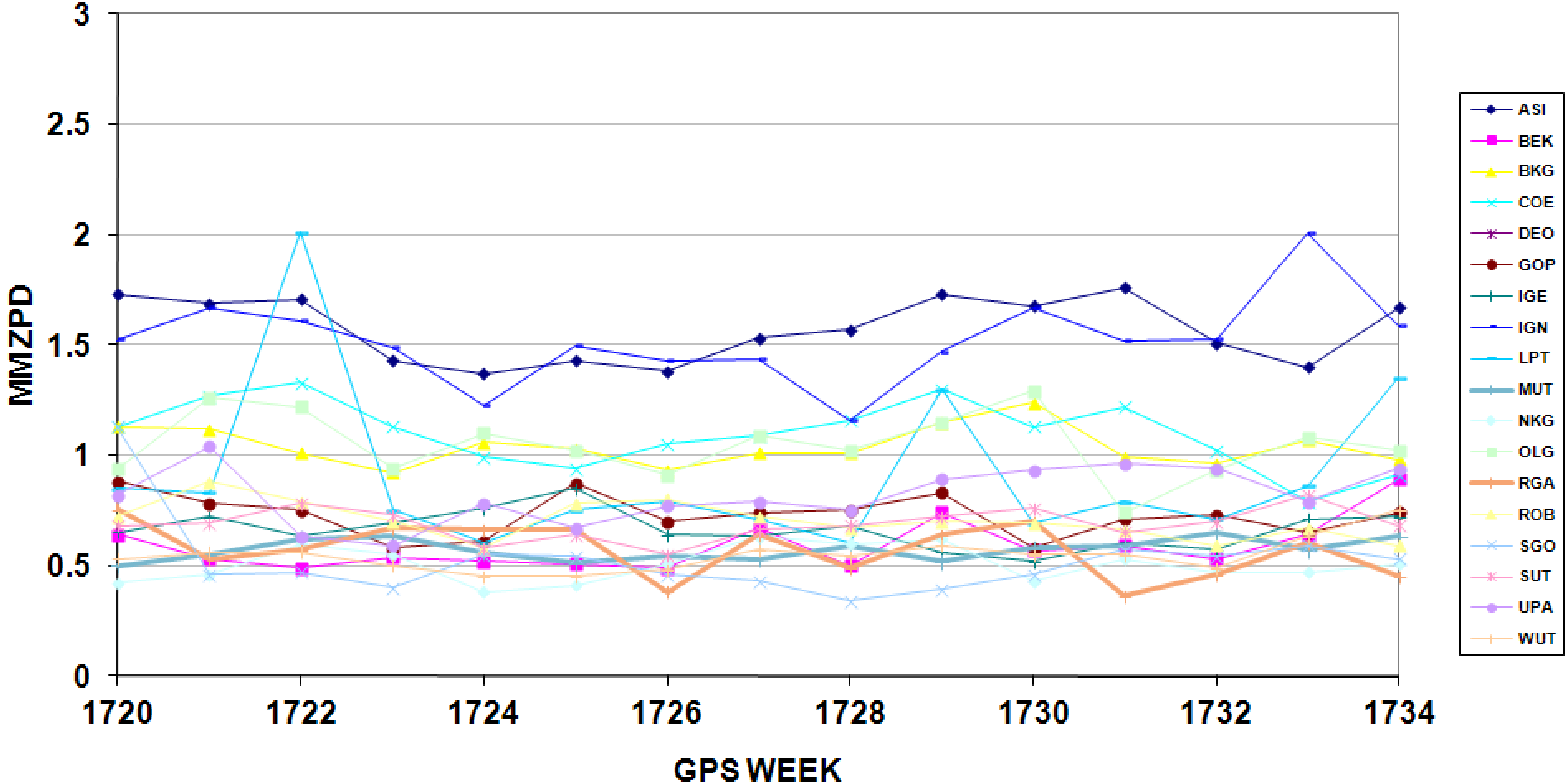
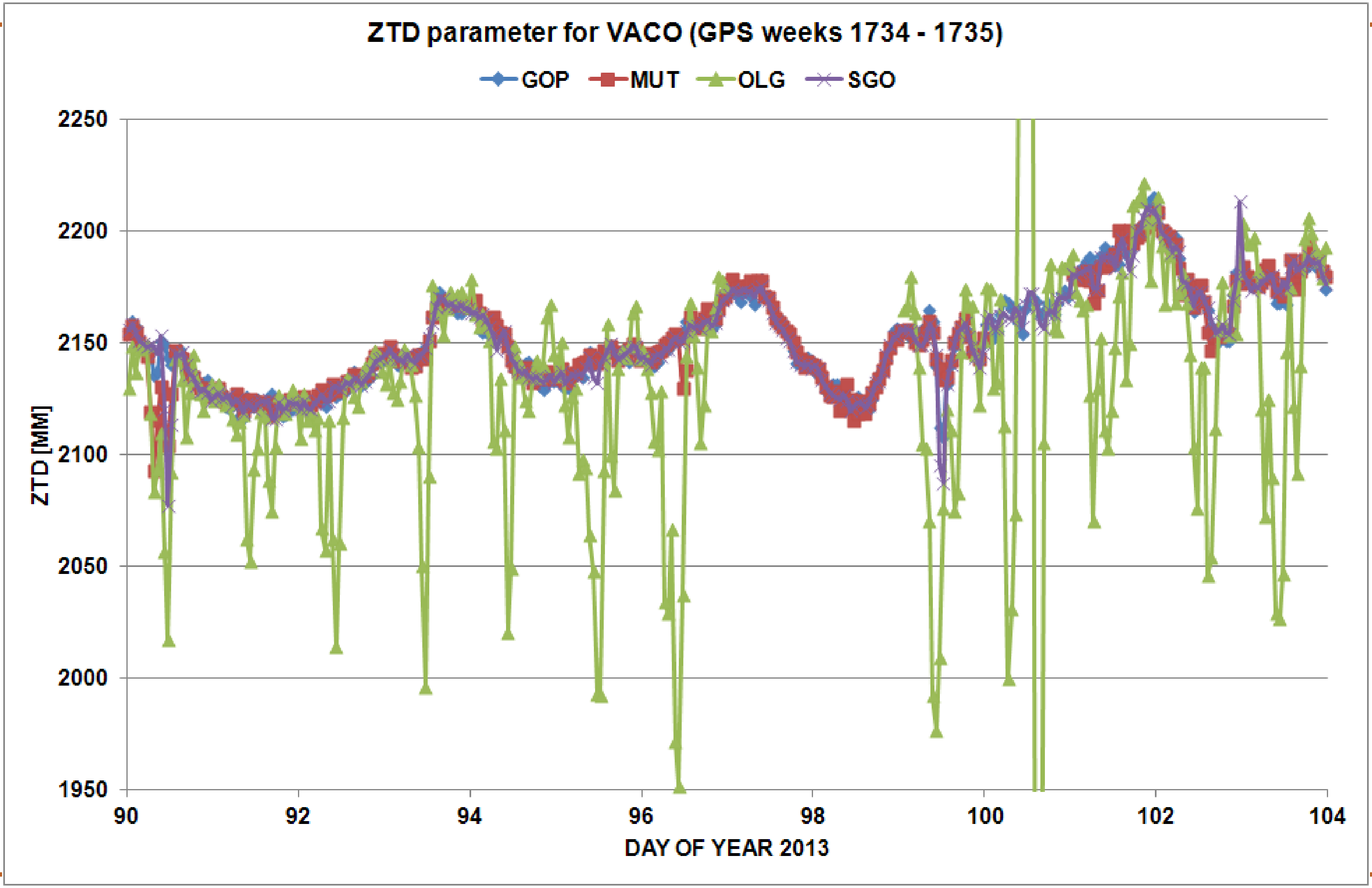
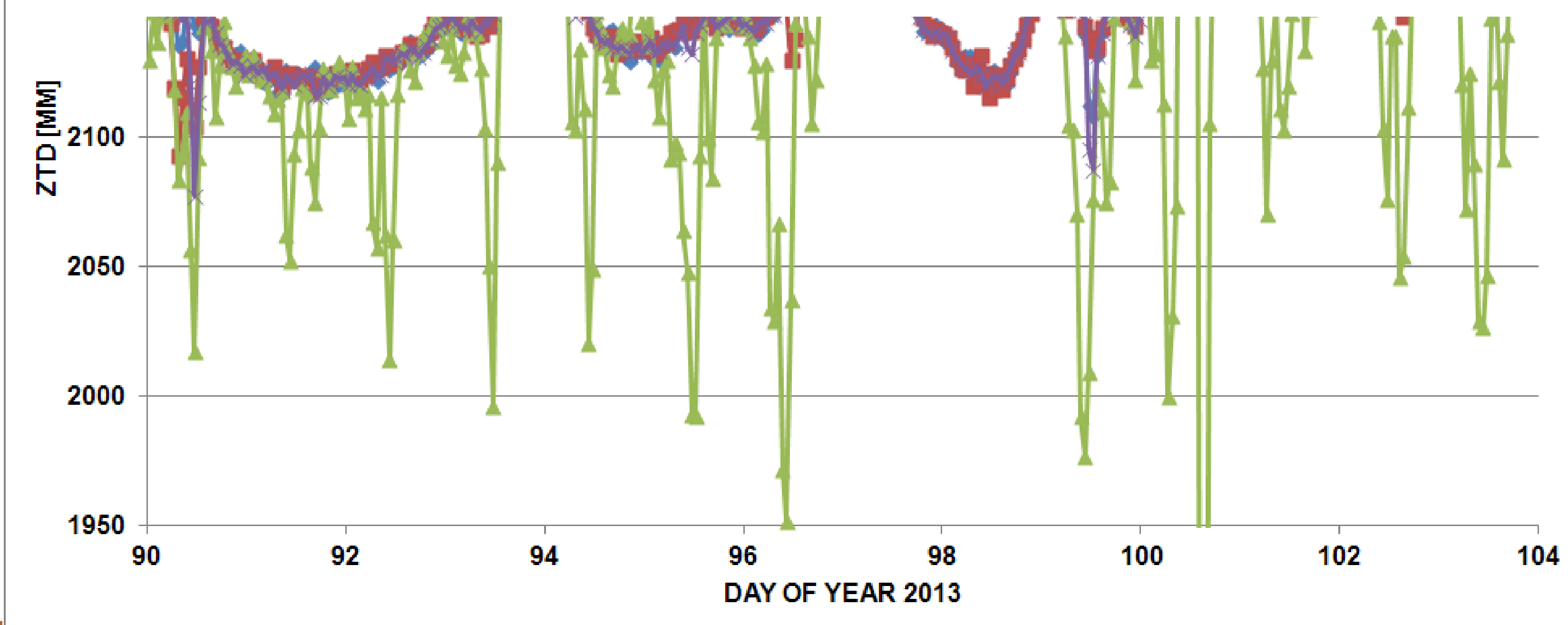


Examples

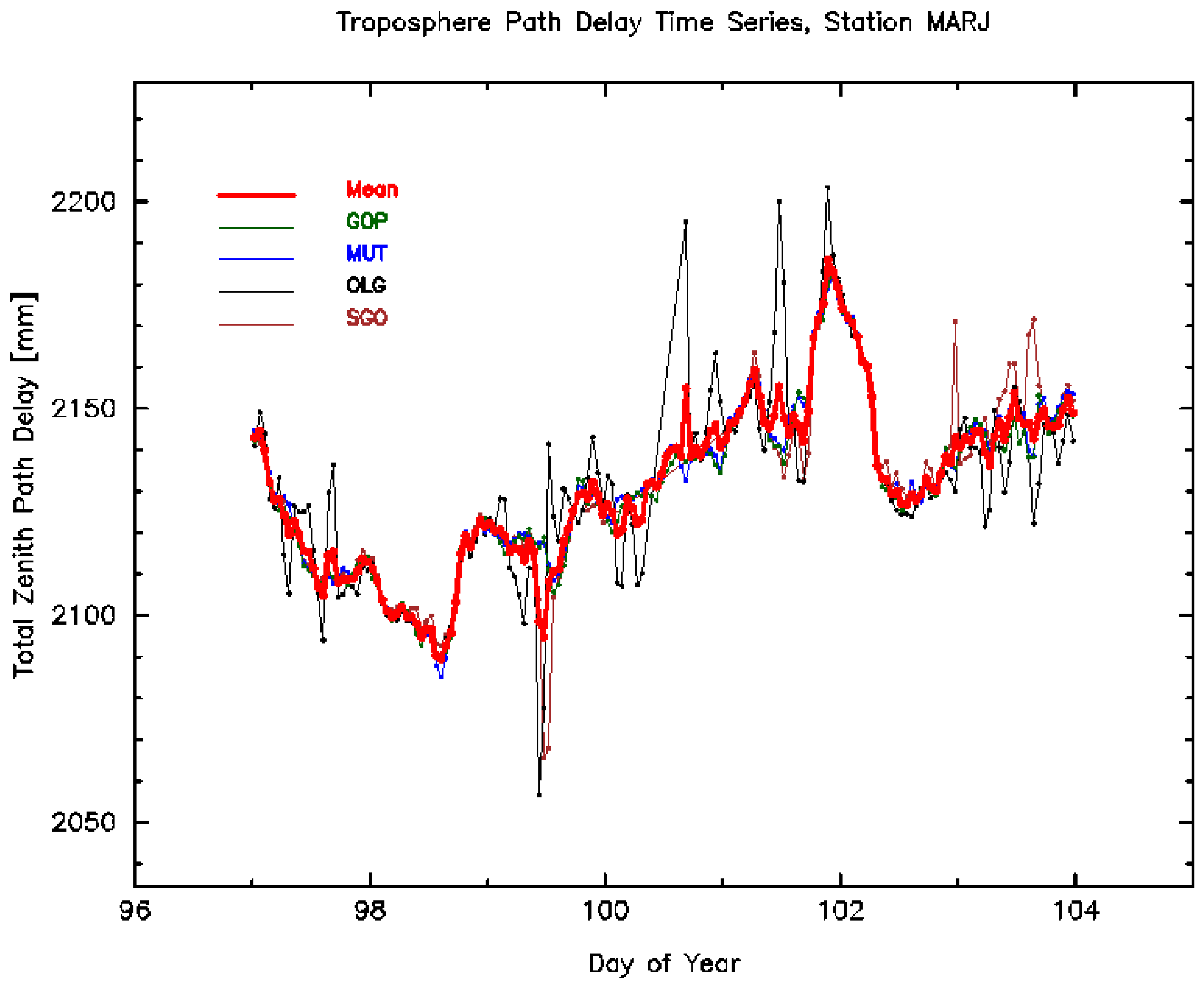

ZTD parameter for VACO (GPS weeks 1734 - 1735)
GOP
MUT
OLG
SGO
2250
2200
2150
2100
2050
2000
1950
ZTD [MM]
90
92
94
96
98
100
102
104
DAY OF YEAR 2013

Examples

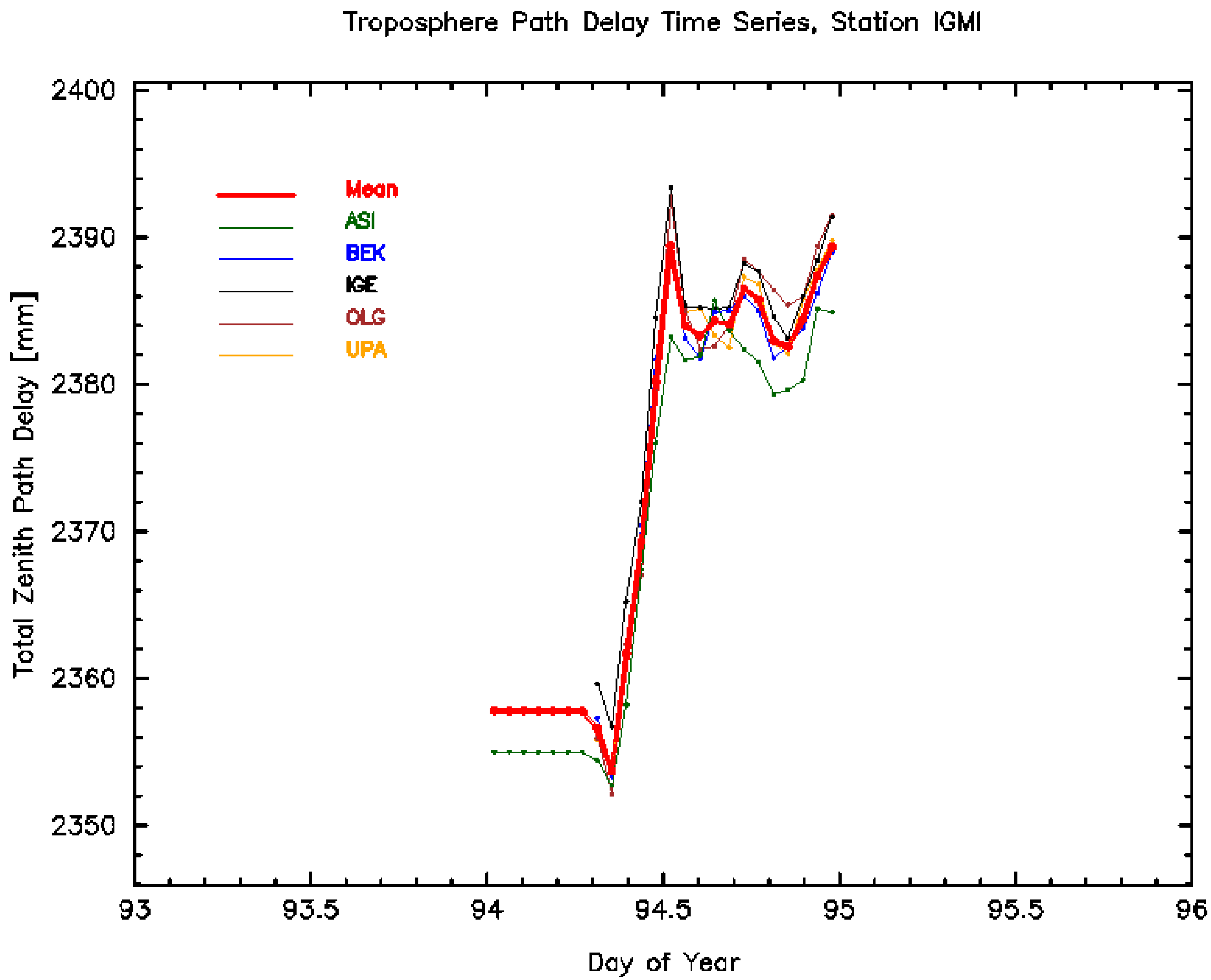
- ZTD parameter ok until GPS week 1706
- No solutions for VACO between 1707 and 1712.4
- Problems with VACO since GPS week 1712.5
- Less visible in SNX combination



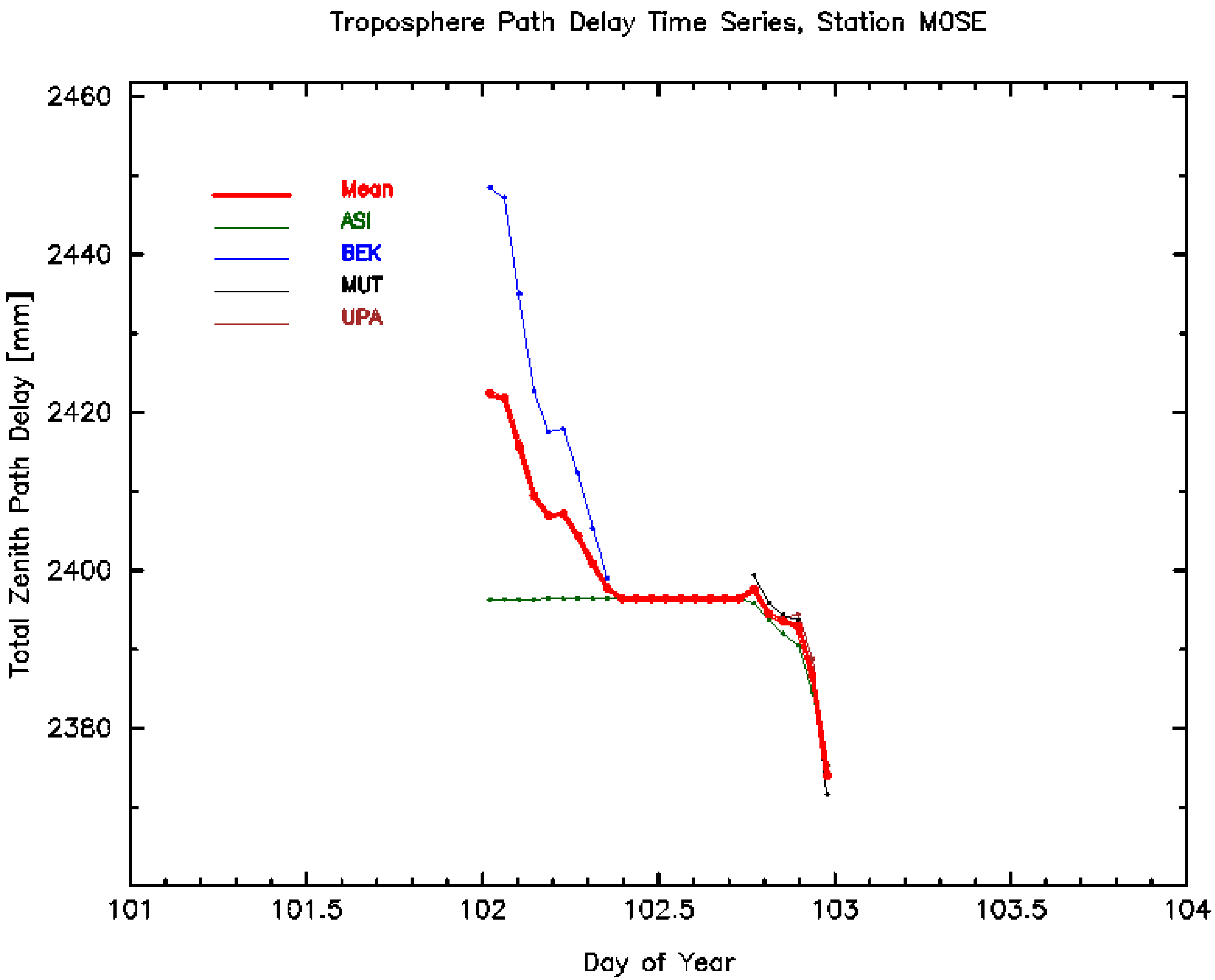
Examples


Troposphere Path Delay Time Series, Station MARJ
Mean
GOP
MUT
OLG
SGO
2200
2150
2100
2050
Total Zenith Path Delay [mm]
96
98
100
102
104
Day of Year

Examples


Troposphere Path Delay Time Series, Station IGMI
Mean
ASI
BEK
IGE
OLG
UPA
Total Zenith Path Delay [mm]
2400
2390
2380
2370
2360
2350
93
93.5
94
94.5
95
95.5
96
Day of Year

Examples


Troposphere Path Delay Time Series, Station MOSE
Mean
ASI
BEK
MUT
UPA
Total Zenith Path Delay [mm]
2460
2440
2420
2400
2380
101
101.5
102
102.5
103
103.5
104
Day of Year

ZTD validation
inter-technique comparison RS

- Since 2009 comparison between Radiosonde (RS) data and EPN combined solution
- Time span could be extended back to 1996 (week 847) thanks to Henrik Vedel (DMI)
- Horizontal distance between GNSS and RS up to 0.5 degree chosen to be ‘co-located’
- Comparison for ~ 105 stations computed and included in EPN web page

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ZTD validation inter-technique comparison RS

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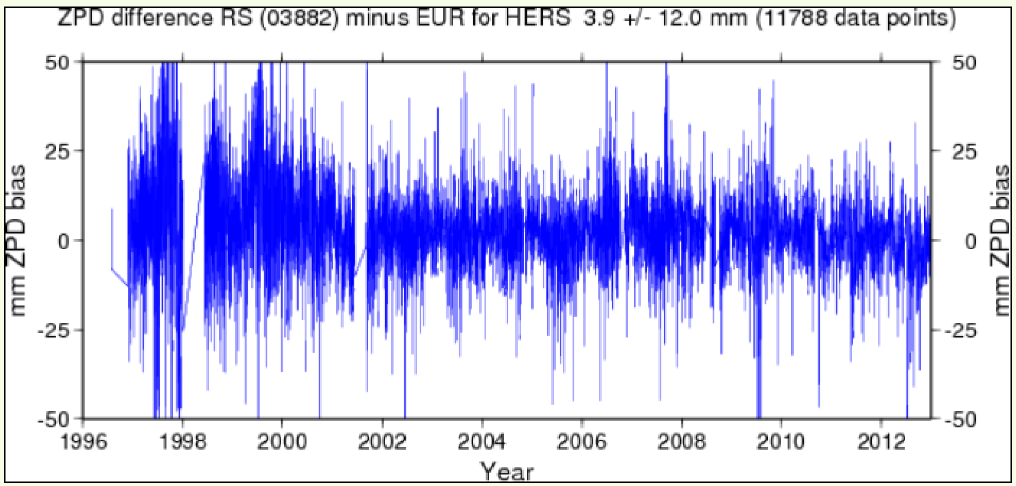
NETWORK & DATA > STATION LIST > HERS 13212M007 > ZPD RADIOSONDE BIASES



Explanations

Purpose

- Validate EUREF combined Zenith Path Delay (ZPD) parameters with ZPD derived from radiosonde (RS) data at co-located sites
- Variations and differences are influenced by the horizontal distance between the two stations
- Time series of differences reflect changes in analysis strategy

Procedure

- Download of RS data provided by EUMETNET, based on the EUREF-EUMETNET MoU
- Processing ZPD parameters (software provided by H. Vedel, Danish Meteorological Institute (DMI))
- Geoid undulations at co-located sites are taken into account
- Differences at co-located sites for identical points in time

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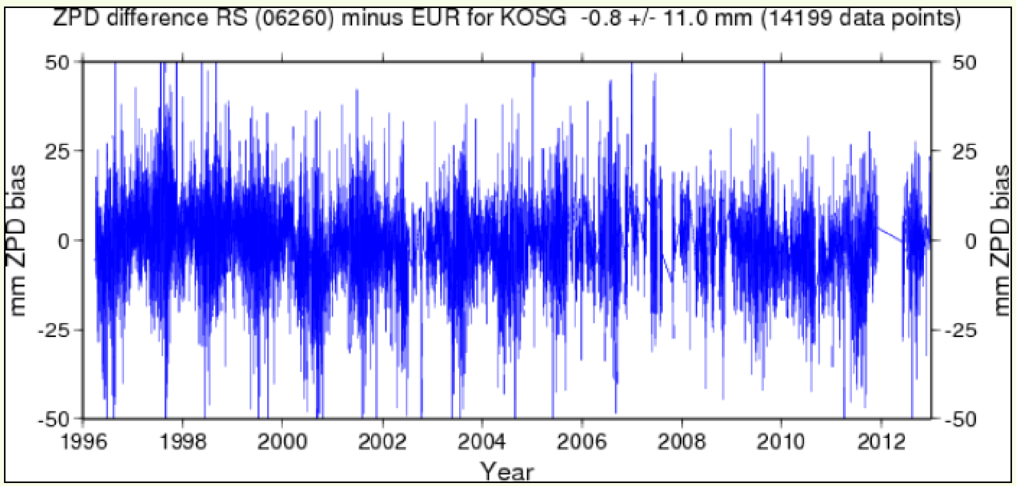
NETWORK & DATA > STATION LIST > KOSG 13504M003 > ZPD RADIOSONDE BIASES



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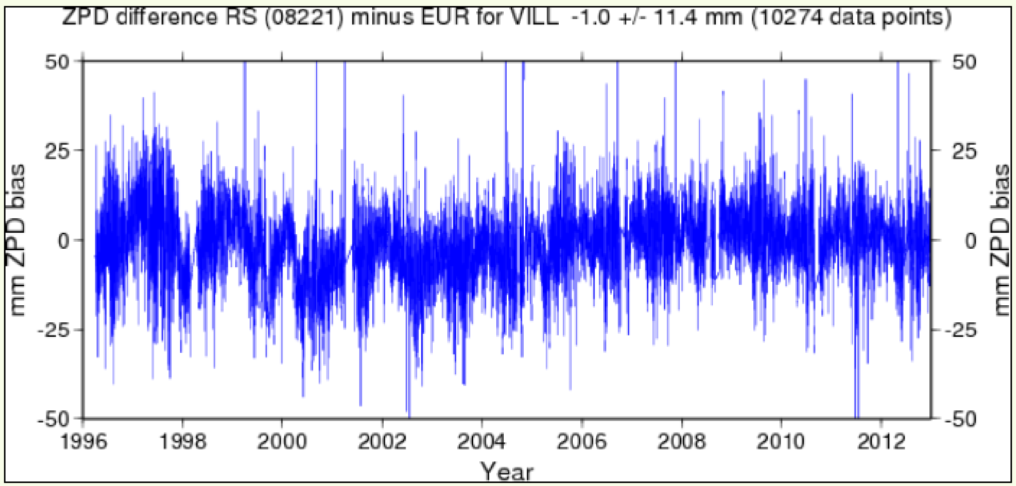
NETWORK & DATA > STATION LIST > VILL 13406M001 > ZPD RADIOSONDE BIASES



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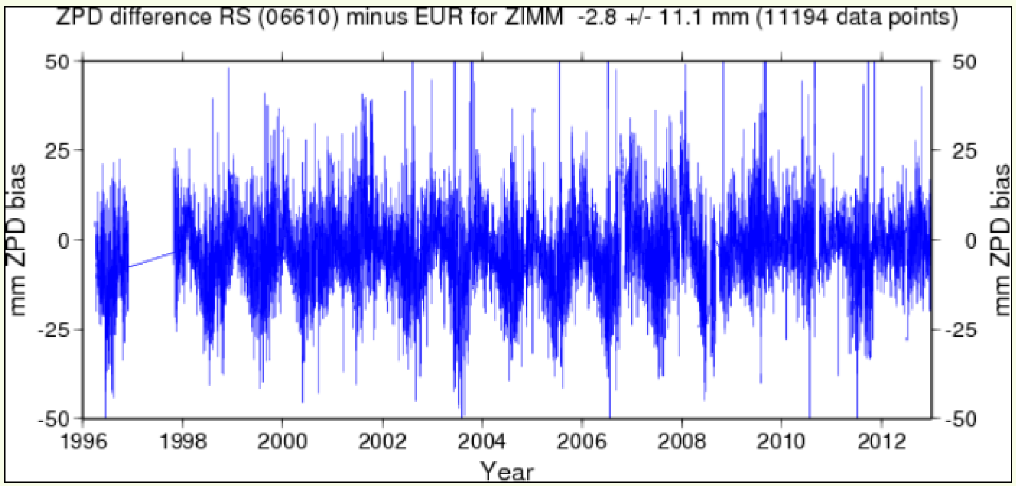
NETWORK & DATA > STATION LIST > ZIMM 14001M004 > ZPD RADIOSONDE BIASES



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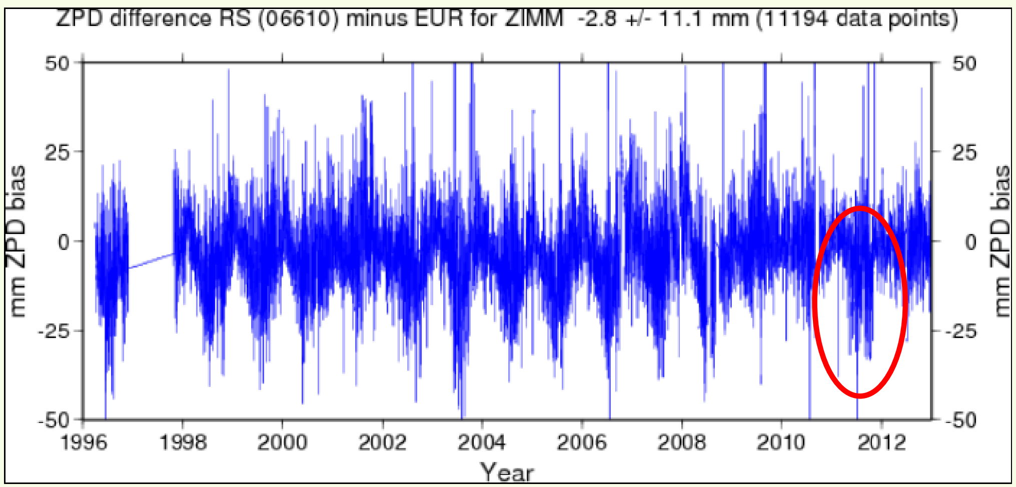
NETWORK & DATA > STATION LIST > ZIMM 14001M004 > ZPD RADIOSONDE BIASES



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ZTD validation
inter-technique comparison VLBI

- Since 2012 comparison (differences) between EPN combined solution and VLBI solution
- Time span from 2002 (week 1147) to present
- No corrections for e.g. height differences applied
- Available for 10 EPN stations (MATE, MEDI/MSEL, NYAL/NYA1, ONSA, SVTL, WTZR, YEBE, ZECK)
- Stdev of mean differences “VLBI minus GNSS” between 4.0 and 6.3 mm ZTD:

ZTD validation inter-technique comparison VLBI

EPN Station	Mean diff. [mm]	Stdev of mean [mm]	# of samples
MATE	-0.2	5.7	17026
MEDI	-2.0	5.6	5118
MSEL	-6.4	6.2	4437
NYA1	-0.5	4.0	26368
NYAL	+0.3	4.1	11225
ONSA	-1.6	4.0	4385
SVTL	-1.3	5.0	4716
WTZR	+0.3	4.0	40559
YEBE	-7.4	5.5	1034
ZECK	-1.8	6.3	6200

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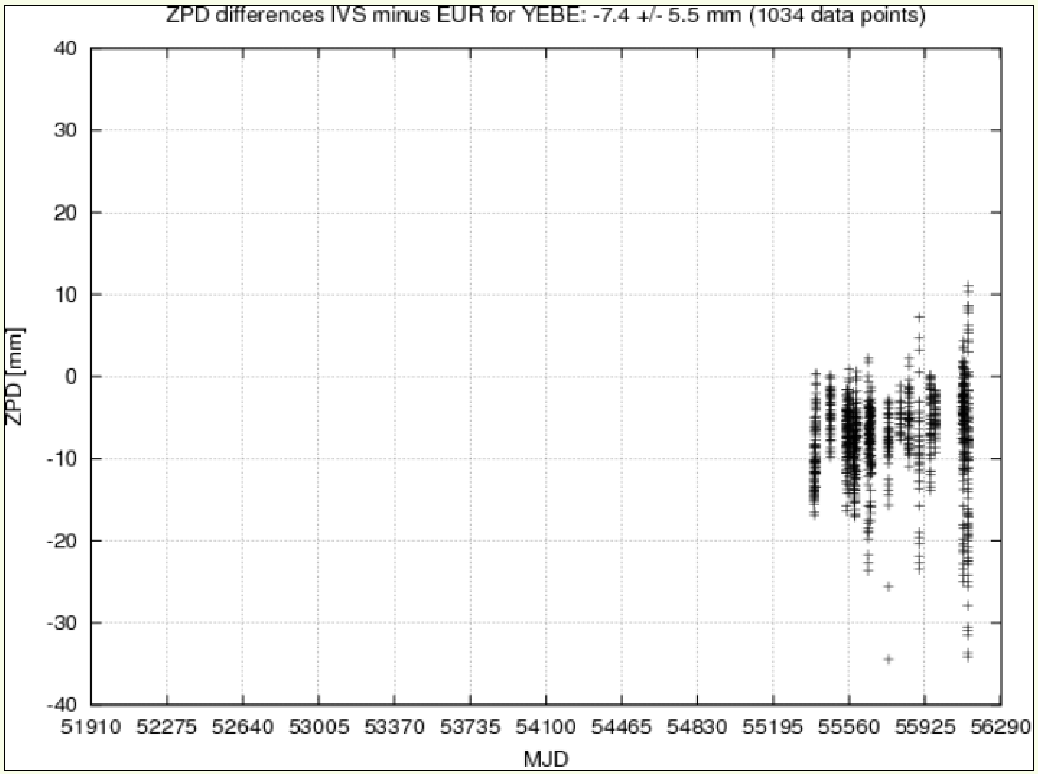
NETWORK & DATA > STATION LIST > YEBE 13420M001 > **Comparison with VLBI ZPD**



Purpose

- Validate EUREF combined Zenith Path Delay (ZPD) parameters with ZPD derived from Very Long Baseline Interferometry (VLBI) data at co-located sites
- Variations and differences are influenced by the distance between the two stations
- Time series of differences reflect differences and changes in analysis strategy

Procedure

- Download of VLBI ZPD parameters, provided by the International VLBI Service (IVS)
- Combination of tropospheric estimates by R. Heinkelmann, Deutsches Geodätisches Forschungsinstitut (DGFI)
- Height difference at the co-located site is not taken into account
- Differences at co-located sites for identical points in time (interpolation)

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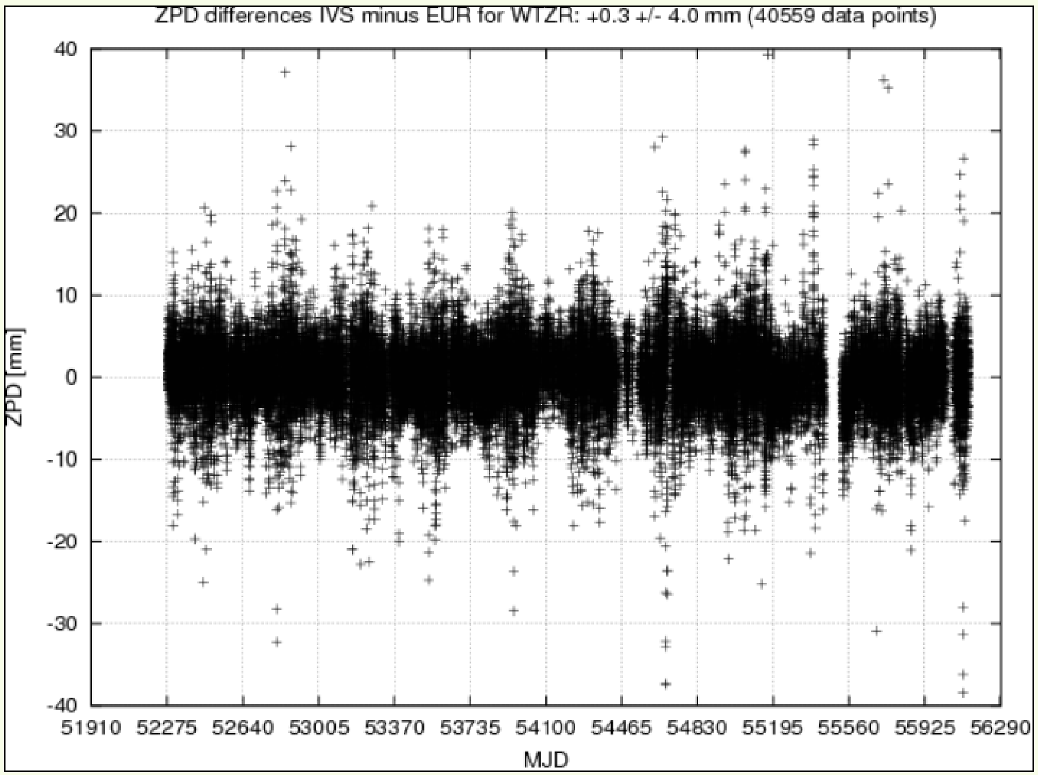
NETWORK & DATA > STATION LIST > WTZR 14201M010 > **Comparison with VLBI ZPD**



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ZTD validation inter-technique comparison VLBI

Comparison of GNSS (EUREF) and VLBI (EVGA) tropospheric delays

GFZ Helmholtz Centre Potsdam

Robert Heinkelmann[1], Wolfgang Söhne[2], and Harald Schuh[1]

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2: Bundesamt für Kartographie und Geodäsie (BKG), Frankfurt am Main, Germany

Bundesamt für Kartographie und Geodäsie

Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences

Poster-EGU2013-7942

Introduction and motivation

> The troposphere is the main contributor of noise and systematic errors in the analysis of space-geodetic techniques at radio frequencies, such as Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI).

> The troposphere may provide a common parameter space for the combined analysis and may thus play an important role for the International Association of Geodesy's (IAG) Global Geodetic Observing System (GGOS).

> With tropospheric parameters we denote the group of parameters associated with the modeling of the dry and wet constituents of the non-dispersive atmosphere. It would be more appropriate to call those parameters neutrospheric parameters.

> Tropospheric delays have been used to measure and model atmospheric water vapor, a key parameter of the greenhouse effect and a driving factor for various climate feedback mechanisms, which is usually insufficiently observed by meteorological techniques.

> Tropospheric delays provide a valuable basis for checking the consistency of individual contributions to a combined product (intra- as well as inter-technique related).

> Various authors have determined and compared tropospheric delays of the space-geodetic techniques, but discrepancies remain, which could not yet be completely assessed and explained.

> Our investigations are concerned with a closer look on the European stations, which are associated with the European Reference Frame (EUREF) and the European part of the International VLBI Service for Geodesy and Astrometry (IVS), called European VLBI group for Geodesy and Astrometry (EVGA).

> Since 2012, time series of differences between the EUREF combined solution and the EVGA combined solution are displayed on the EUREF Permanent Network's (EPN) webpage (http://www.epncb.oma.be) for eight co-located sites (Table 1), covering the period from 1996 to present (http://www.euref.eu/symposia/2011Chisinau/P-02-p-Soehne.pdf).

Galery of European VLBI - GNSS co-location sites

Table 1: European co-located VLBI - GNSS antennas, some antenna specifications (see Figures 1 & 2) and the height difference of the specific antenna reference points (dH)

VLBI antenna	mount	focus	h_s	h_v	GNSS antenna	h_a	dH
MATERA	AZEL	secondary	5.7	3.8	MATE	0.11	7.8
MEDICINA	AZEL	primary	9.3	4.3	MEDI	0	17.2
NYALES20	AZEL	primary	8.6	2.4	NYA1	0	3.1
ONSALA60	AZEL	secondary	5.5	3.4	ONSA	0.995	13.7
SVETLOE	AZEL	secondary	10.6	1.9	SVTL	0.029	9.4
WETTZELL	AZEL	secondary	7.9	3.7	WTZR	0.071	3.1
YEBES40M	AZEL	secondary	13.8	5.0	YEBE	0	7.1
ZELENCHK	AZEL	secondary	10.6	1.9	ZECK	0.045	8.7

www.gfz-potsdam.de

Reference height of the troposphere delay

Each antenna of a space-geodetic technique has a unique geometrical reference point, where the terrestrial coordinate refers to. The zenith delay is usually also referred to this point, c.f. IERS Conventions (2010), where for the calculation of zenith a priori delay the height of the antenna reference point is recommended. However, there is a difference between the geometrical reference point and the tropospheric reference point.

In case of **VLBI**, the geometrical reference point is the invariant point, where the two antenna axes theoretically intersect. The geometrical delay is corrected by the estimated clock parameters and calibrated by phase and cable calibration to refer to this point. At the same time tropospheric delays, which are independent of the elevation angle, e.g. the extra path due to reflections of the received signal at the primary and secondary reflectors of the VLBI antenna are considered by the clock offset. The delay due to troposphere, however, refers to the point where the signal actually enters the electronic antenna components, i.e. the wave guide in the feed horn, a point which is usually slightly above the geometrical reference point. European VLBI antennas are all of azimuth-elevation (AZEL) type of mount (Table 1, Figure 1). The antenna axes offset - the geometrical delay is corrected for this - points in horizontal direction and does not affect the height of the tropospheric reference point. Depending on the antenna focus the following equations describe the reference height of the tropospheric delay:

(1.a) $H_{trop\_sec} = H + h_v \sin(\varepsilon)$

(1.b) $H_{trop\_prm} = H + (h_v + h_s) \sin(\varepsilon)$

Equations (1) depend on the elevation angle (ε) and are therefore not absorbed by the clock model. Since a priori tropospheric delays are usually corrected on the observation level, the elevation angle of the specific observation can be used, while, for the estimated troposphere delay, a mean elevation angle during one hour has to be used. **Mapping functions** should refer to the reference height of the tropospheric delay instead of the geometrical reference height.

In case of **GNSS** (Figure 2), the geometrical reference point usually equals a surface marker at the pillar ("Reference point"), where the antenna is mounted - in this case the „Antenna height" (Table 1: h_a) is different from zero - or it directly equals the „Reference point of antenna", which is very close to the actual „Phase centers of the two frequencies L1 and L2. Since the height difference between the phase centers and the „Reference point of antenna" is typically less than 20 cm, the troposphere reference height can be considered at the „Reference point of antenna" within the desired level of precision.

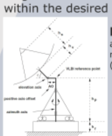

Figure 1: VLBI antenna of azimuth-elevation mount and respective reference points (Nothnagel, 2008)

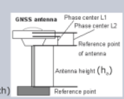

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Table 2: GNSS - GNSS (EUREF) co-locations

GNSS (1)	GNSS (2)	from - to EUREF reprocessing routine operation	mean difference (mm)	standard deviation (mm)	comments
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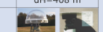
BORJ	BORK	2005-06-08 - 2006-12-28 2006-12-22 - 2007-06-03	-1.8 -1.6	2.8 1.5	
HERS	HERT	2003-03-17 - 2006-12-28 2003-08-15 - 2013-01-18	0.3 2.9	1.9 3.0	+2.9 mm (ii) +1.0 mm (i)
JOZ2	JOZE	2002-10-22 - 2006-12-28 2003-09-12 - 2013-01-18	-3.9 -2.6	4.0 4.3	-6.2 mm (ii) -4.1 mm (i)
MATE	TARS	2004-11-27 - 2005-04-12 2004-12-18 - 2005-04-12	-2.4 -9.7	8.6 8.8	d=51 km, dH=408 m
MOP2	MOPI	2008-08-16 - 2013-01-18	10.8	5.1	
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TRO1	TROM	1999-08-30 - 2006-12-28	-1.9	1.9	
YEBE	VILL	2000-09-29 - 2006-12-28 2001-05-27 - 2013-01-18	-7.5 -9.0	11.4 12.4	d=74 km, dH=325 m
WTZR	WETT	1996-01-06 - 1997-02.01	-2.9	11.0	
ZIM2	ZIMM	2007-12-14 - 2013-01-18	-1.3	2.0	+3.5 mm (ii)

VLBI - GNSS inter-technique comparison and conclusions

For the comparison the GNSS ZTD were interpolated at VLBI ZTD epochs and running mean values were adjusted due to antenna change and change of the processing strategy (see above), if indicated. **Standard deviations** between VLBI and GNSS interpolated ZTD (Table 3) are slightly larger than between co-located GNSS stations, but with a maximum of 6.7 mm still in an acceptable range (6.7 mm ZTD equals 1.0 mm precipitable water assuming that most of the standard deviation is due to ZWD). The **mean values** of the ZTD differences including the height correction are smaller than expected from the GNSS intra-technique comparison (Table 3). In general, the mean values of VLBI ZTD are stable, while GNSS ZTD mean values show variations. The height correction considers the height difference of the tropospheric delay reference heights of the VLBI and the GNSS antennas, respectively. It includes the dimensions presented in Table 1 and works slightly better than considering the difference of the geometrical reference heights for the tropospheric delay. In spite of our refined height correction, mean values of the differences between VLBI and GNSS ZTD at European sites are not centered at zero and thus systematic effects are still present, which need to be explained.

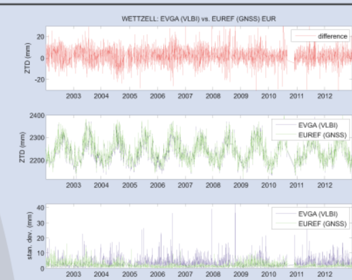

Figure 5: ZTD, ZTD differences, and standard deviations (mm) at Wettzell. Germany. VLBI standard deviations are too pesimistic. GNSS standard deviations are quite realistic.

GNSS intra-technique comparison

For the assessment of the tropospheric systematics and error floor of the GNSS technique, we compare zenith total delays (ZTD) at sites with multiple GNSS antennas (Table 2). There are two significant effects causing shifts of the running mean value of the ZTD difference at co-located GNSS stations:

(i) **Changes in the EUREF processing:** results from 1996 until end of 2006 are coming from EUREF reprocessing, whereas 2007 to present is covered by routine operation.

(ii) **Equipment changes:** most of the EPN stations had receiver and/or antenna changes over time (Table 2). While the receiver change does not significantly affect the running mean value, the antenna change usually does.

From the GNSS intra-technique comparison, we draw the conclusions:

> **The running mean value** is affected by antenna and other equipment changes (see Figure 3), the average effect is 4 mm, and by changes in the EUREF processing, the average effect is 3 mm. Without such effects no shift is observed (e.g. NYAL - NYA1). The ZTD height correction works well even for larger height differences of up to about 400 m (MATE - TARS). MOPI - MOP2 shows a significant bias, which is probably due to the different antennas and the usage of a dome: „TZGD" (see Table 2).

> **The standard deviation** between co-located and neighboring GNSS sites varies between 1.6 mm (NYAL - NYA1, co-location) and 13.5 mm (SVTL - PULK, d = 90 km) depending on the amount of water vapor, the type of GNSS antenna and on the distance (d) and height difference (dH) of the antennas. The dependence on water vapor shows a seasonal signature. In our tests, GNSS ZTD agree well up to a distance of 90 km (Figure 4).

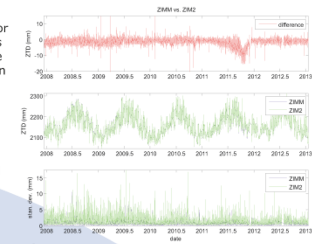

Figure 3: ZTD, ZTD differences, and standard deviations (mm) at the EUREF GNSS co-located site Zimmerwald, Switzerland. The shift of the running mean value at the end of 2011 is caused by a change of the pre-amplifier of the antenna (see National Report of Switzerland at 2012 EUREF Symposium).

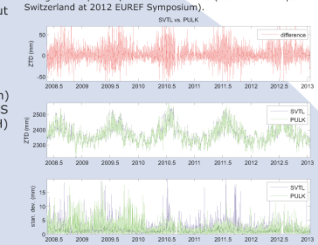

Figure 4: ZTD, ZTD differences, and standard deviations (mm) at the EUREF GNSS sites Svetloe and Pulkovo, Russia. The sites are about 90km separated (+24.5m height difference, which is corrected for) from each other, but still sense almost the same tropospheric delays. During the summer, when the amount of atmospheric water vapor is larger, the standard deviation significantly increases.

Table 3: VLBI (EVGA) - GNSS (EUREF) co-locations.

VLBI (EVGA)	GNSS (EUREF)	mean diff. (mm)	standard deviation (mm)
MATERA	MATE	3.2	6.2
MEDICINA	MEDI	6.0	6.3
NYALES20	NYA1*	1.4	3.9
ONSALA60°	ONSA°	3.1	4.3
SVETLOE	SVTL°	1.3	6.3
WETTZELL	WTZR*	1.7	4.7
YEBES40M°	YEBE	-4.0	5.8
ZELENCHK	ZECK*	1.3	6.7

°: antenna is covered by a radome

*: antenna is covered by a snow dome

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ZTD validation
inter-technique comparison VLBI

Federal Agency for Cartography and Geodesy

Comparison of GNSS (EUREF) and VLBI (EVGA) tropospheric delays

Robert Heinkelmann[1], Wolfgang Söhne[2], and Harald Schuh[1]
1: Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany
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Poster-EGU2013-7942

GFZ Helmholtz Centre Potsdam

Bundesamt für Kartographie und Geodäsie

Introduction and motivation

> The troposphere is the main contributor of noise and systematic errors in the analysis of space-geodetic techniques at radio frequencies, such as Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI).
> The troposphere may provide a common parameter space for the combined analysis and may thus play an important role for the International Association of Geodesy's (IAG) Global Geodetic Observing System (GGOS).
> With tropospheric parameters we denote the group of parameters associated with the modeling of the dry and wet constituents of the non-dispersive atmosphere. It would be more appropriate to call those parameters neutrospheric parameters.
> Tropospheric delays have been used to measure and model atmospheric water vapor, a key parameter of the greenhouse effect and a driving factor for various climate feedback mechanisms, which is usually insufficiently observed by meteorological techniques.
> Tropospheric delays provide a valuable basis for checking the consistency of individual contributions to a combined product (intra- as well as inter-technique related).
> Various authors have determined and compared tropospheric delays of the space-geodetic techniques, but discrepancies remain, which could not yet be completely assessed and explained.
> Our investigations are concerned with a closer look on the European stations, which are associated with the European Reference Frame (EUREF) and the European part of the International VLBI Service for Geodesy and Astrometry (IVS), called European VLBI group for Geodesy and Astrometry (EVGA).
> Since 2012, time series of differences between the EUREF combined solution and the EVGA combined solution are displayed on the EUREF Permanent Network's (EPN) webpage (http://www.epncb.oma.be) for eight co-located sites (Table 1), covering the period from 1996 to present (http://www.euref.eu/symposia/2011Chisinau/P-02-p-Soehne.pdf).

Galery of European VLBI - GNSS co-location sites

Table 1: European co-located VLBI - GNSS antennas, some antenna specifications (see Figures 1 & 2) and the height difference of the specific antenna reference points (dH)

VLBI antenna	mount	focus	h_r	h_v	GNSS antenna	h_s	dH
MATERA	AZEL	secondary	5.7	3.8	MATE	0.11	7.8
MEDICINA	AZEL	primary	9.3	4.3	MEDI	0	17.2
NYALES20	AZEL	primary	8.6	2.4	NYA1	0	3.1
ONSALA60	AZEL	secondary	5.5	3.4	ONSA	0.995	13.7
SVETLOE	AZEL	secondary	10.6	1.9	SVTL	0.029	9.4
WETTZELL	AZEL	secondary	7.9	3.7	WTZR	0.071	3.1
YEBES40M	AZEL	secondary	13.8	5.0	YEBE	0	7.1
ZELENCHK	AZEL	secondary	10.6	1.9	ZECK	0.045	8.7

www.gfz-potsdam.de

Reference height of the troposphere delay

Each antenna of a space-geodetic technique has a unique geometrical reference point, where the terrestrial coordinate refers to. The zenith delay is usually also referred to this point, c.f. IERS Conventions (2010), where for the calculation of zenith a priori delay the height of the antenna reference point is recommended. However, there is a difference between the geometrical reference point and the tropospheric reference point.

In case of **VLBI**, the geometrical reference point is the invariant point, where the two antenna axes theoretically intersect. The geometrical delay is corrected by the estimated clock parameters and calibrated by phase and cable calibration to refer to this point. At the same time tropospheric delays, which are independent of the elevation angle, e.g. the extra path due to reflections of the received signal at the primary and secondary reflectors of the VLBI antenna are considered by the clock offset. The delay due to troposphere, however, refers to the point where the signal actually enters the electronic antenna components, i.e. the wave guide in the feed horn, a point which is usually slightly above the geometrical reference point. European VLBI antennas are all of azimuth-elevation (AZEL) type of mount (Table 1, Figure 1). The antenna axes offset - the geometrical delay is corrected for this - points in horizontal direction and does not affect the height of the tropospheric reference point. Depending on the antenna focus the following equations describe the reference height of the tropospheric delay:

(1.a) $H_{trop\_sec} = H + h_v \sin(\varepsilon)$
(1.b) $H_{trop\_prm} = H + (h_v + h_r) \sin(\varepsilon)$

Equations (1) depend on the elevation angle (ε) and are therefore not absorbed by the clock model. Since a priori tropospheric delays are usually corrected on the observation level, the elevation angle of the specific observation can be used, while, for the estimated troposphere delay, a mean elevation angle during one hour has to be used. **Mapping functions** should refer to the reference height of the tropospheric delay instead of the geometrical reference height.

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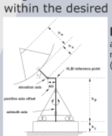

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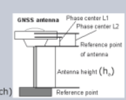

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GNSS intra-technique comparison

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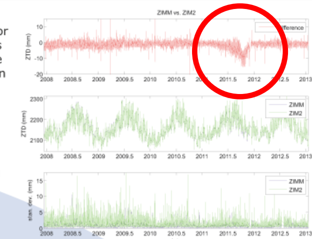

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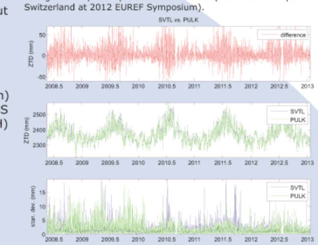

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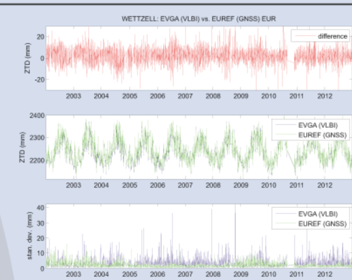

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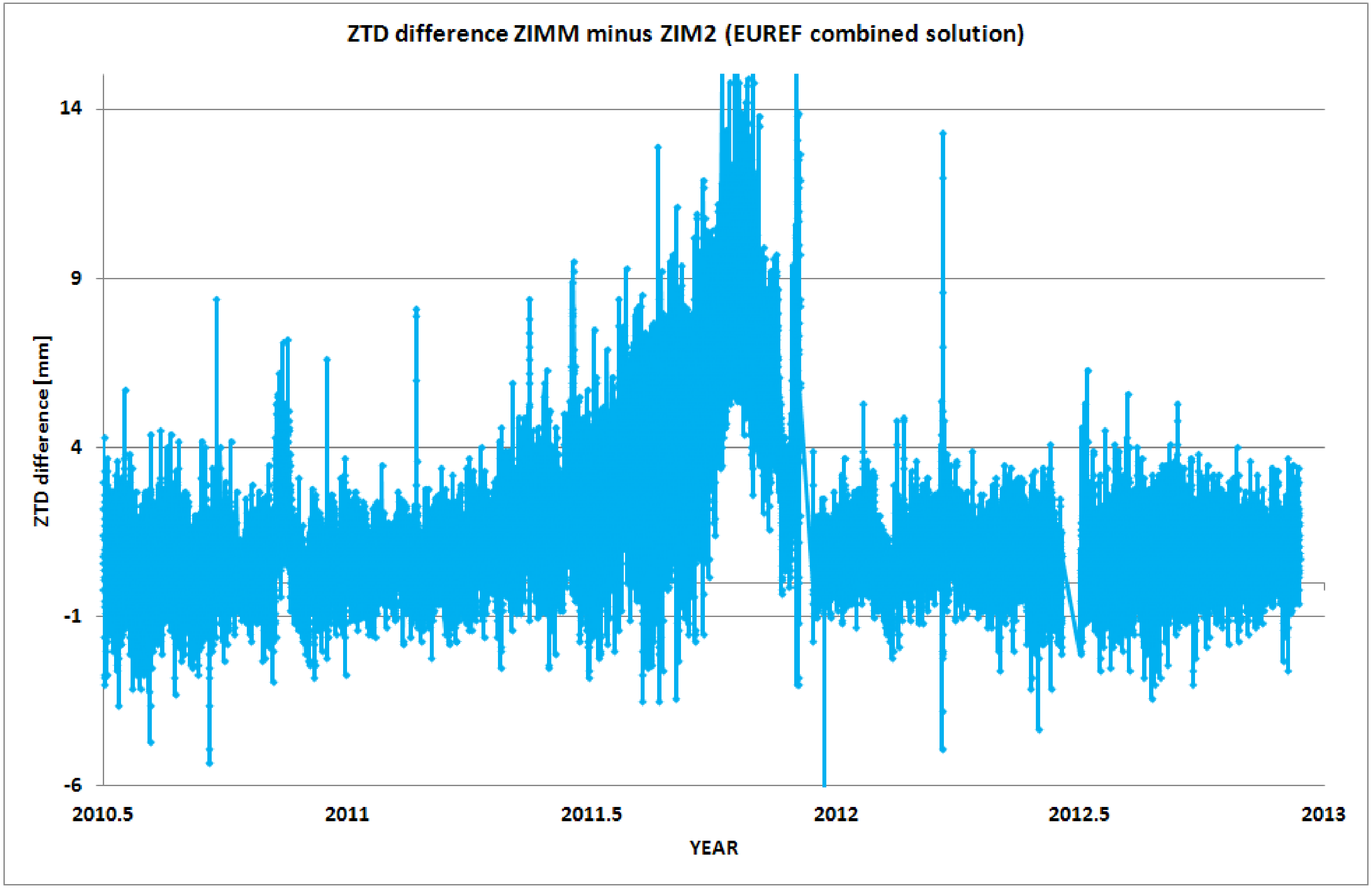
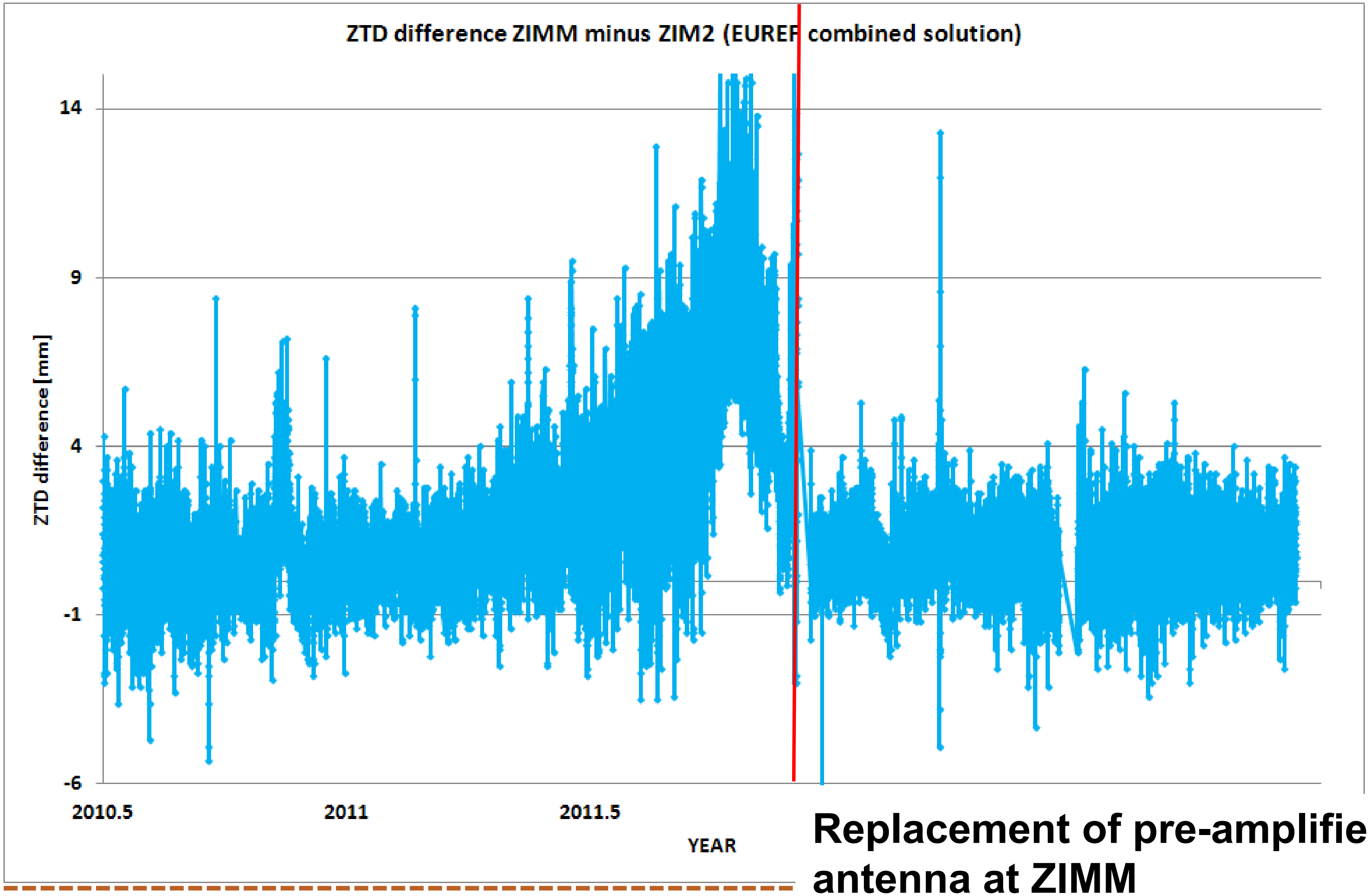
ZTD validation
intra-technique comparison

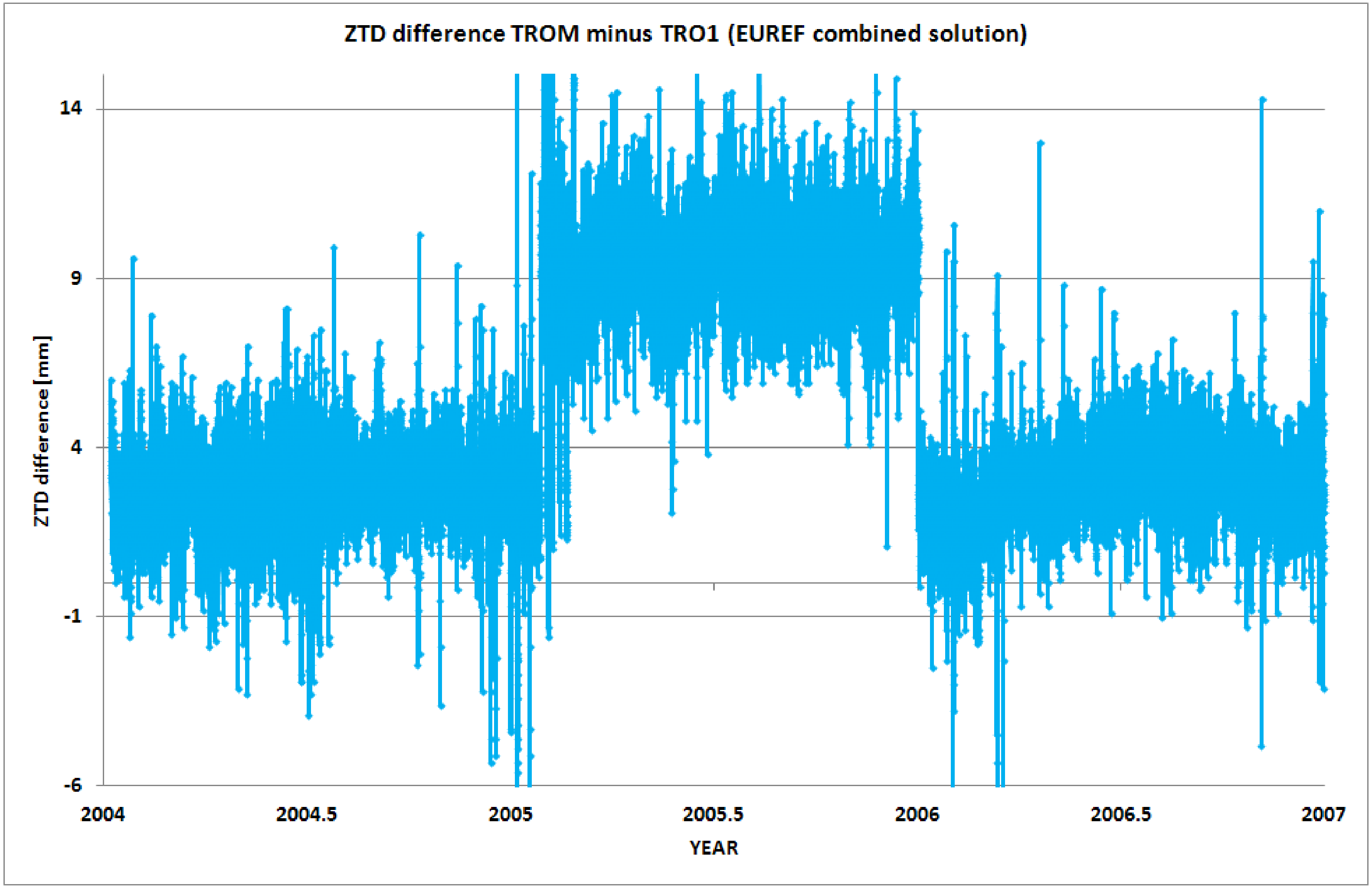


ZTD validation intra-technique comparison



Replacement of pre-amplifier of antenna at ZIMM

ZTD validation
intra-technique comparison



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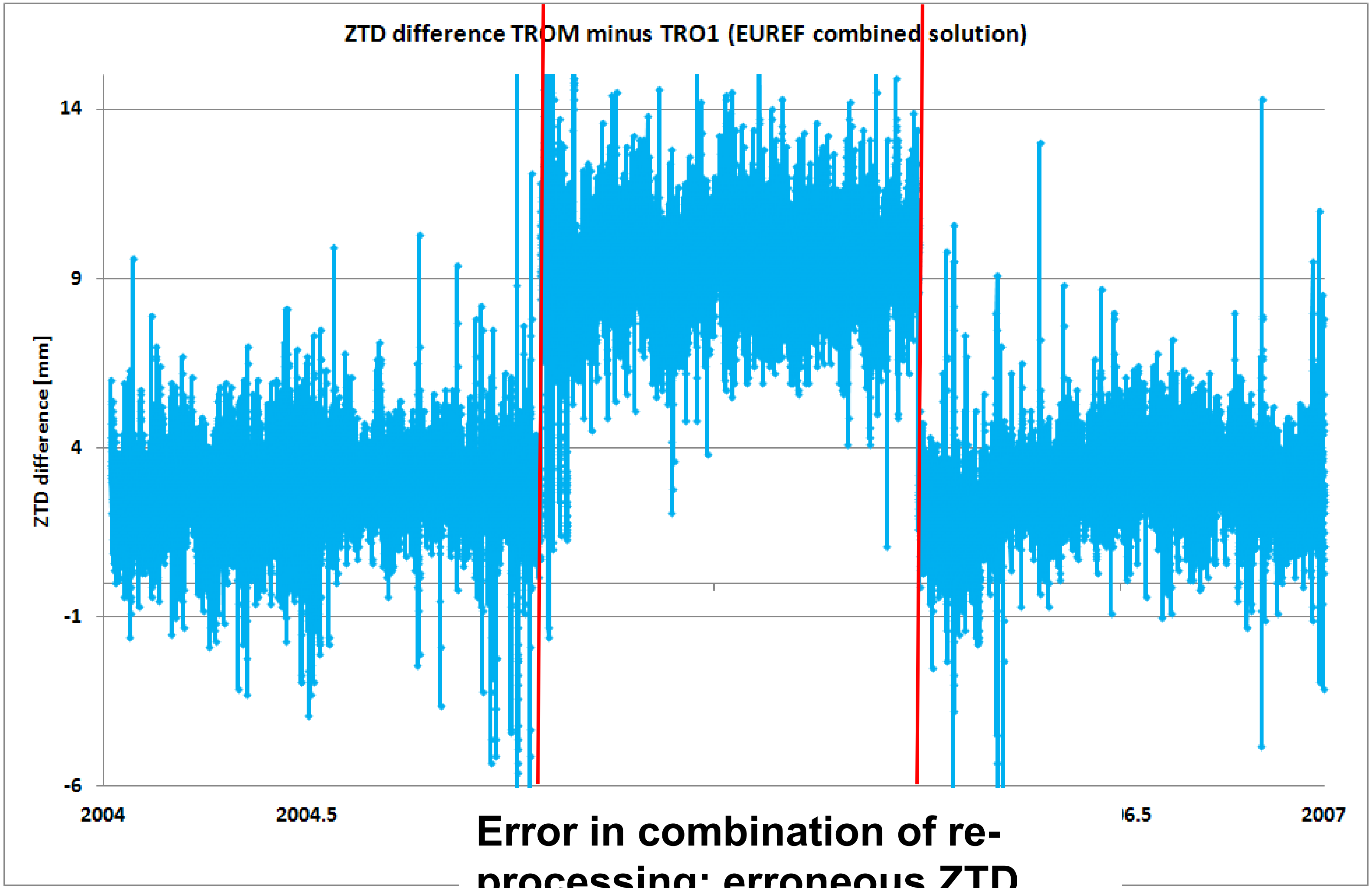
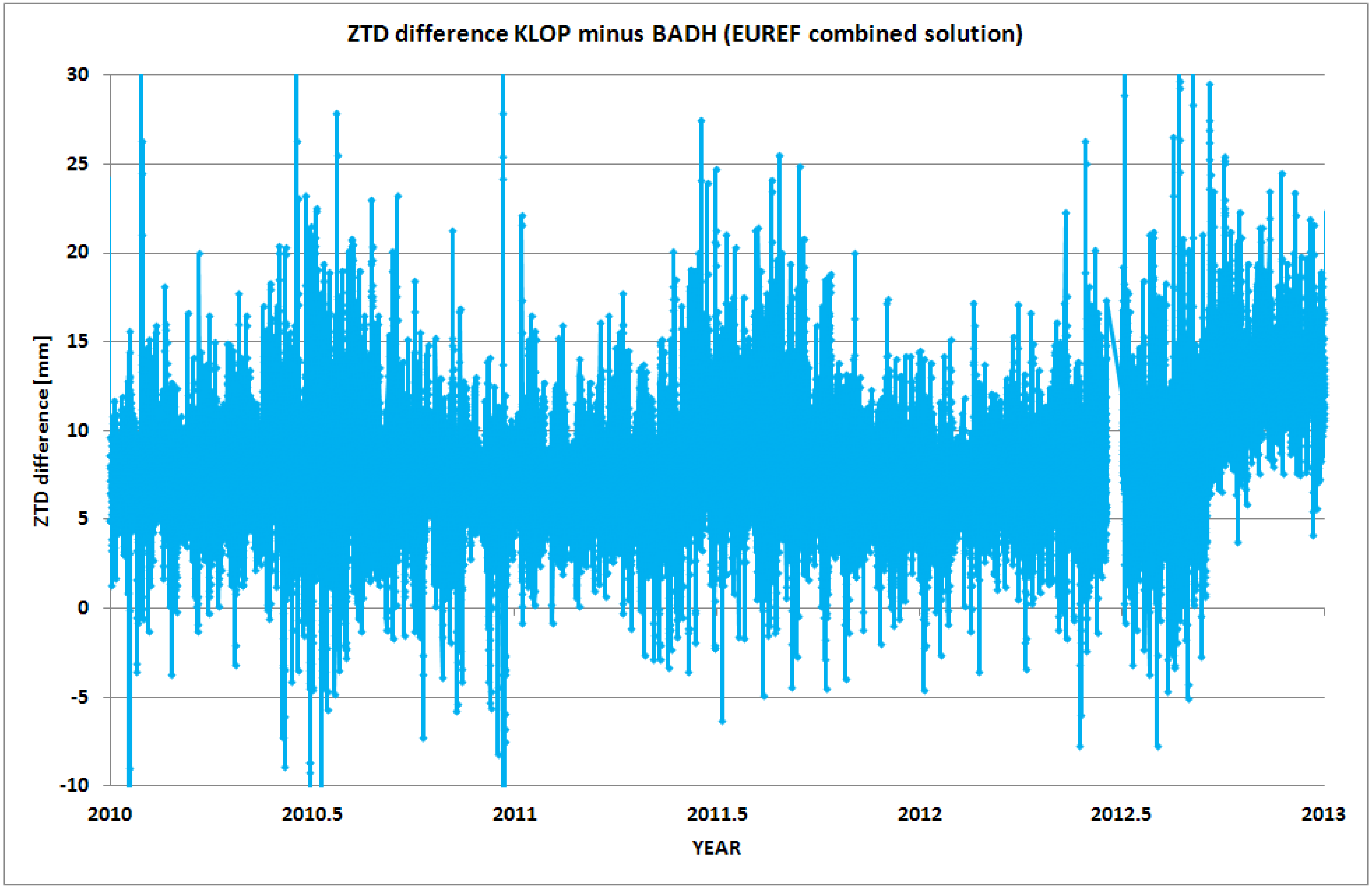


Error in combination of re-processing: erroneous ZTD solution of one LAC used

ZTD validation
intra-technique comparison



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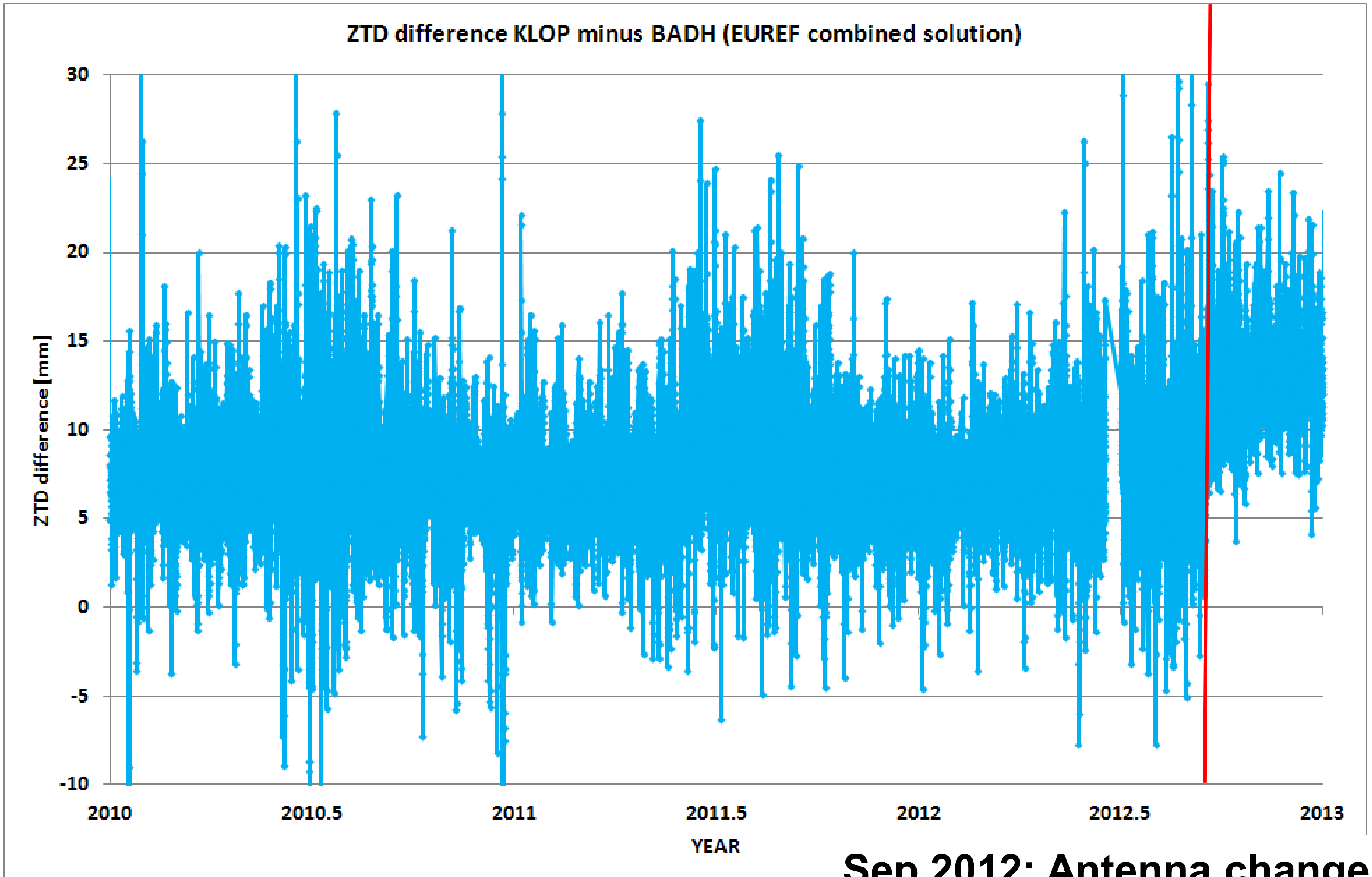
ZTD validation intra-technique comparison



Sep 2012: Antenna change from Trimble to Leica at BADH?

Points for discussion

- Results (ZPD differences) for co-located (or neighbored) GNSS stations useful → time series added to EPN web page?
  - Introduction of special sections on EPN web for co-location sites?
- Review of EPN Troposphere planned within TWG → could lead to new or modified products
- Number of external users of the product limited → how to improve?
- BKG is intending to retire from EPN Troposphere Coordinator position