EUREF's troposphere products – position paper
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Introduction/Motivation

One of the topics of the EUREF retreat held in November 2012 in Bern was "Link of EUREF to other geodisciplines", with two "position papers" given, one on geodisciplines and atmosphere and the other one on ionosphere. The troposphere, as main part of the presentation about geosciences, outlined the possible EUREF contribution to climate monitoring through, e.g., reprocessed homogeneous ZTD time series. Furthermore, it was stated in the minutes of the meeting that "*EUREF post processing and NRT and RT data and products for Numerical Weather Prediction and Nowcasting were presented. Several EPN LACs (ASI, BKG, GOP, IGE, LPT, NKG, ROB) are E-GVAP analysis centres and are processing, beyond others, EPN hourly data but not acting as EUREF. Link between EUREF and other initiatives: new proposed COST Action GNSS4SWEC.*"

During the discussion at the retreat it was mentioned that all EUREF ZTD comparisons (time series) available on the web should include a measure for precision. Meanwhile, this has been included for the time series of differences with respect to VLBI and radiosonde data. Furthermore, a revision of the description of the EUREF troposphere product for the EPN web site was encouraged.

Finally, in the minutes the following actions concerning troposphere and ionosphere were confirmed:
- Possible impacts of NRT and RT activities on EUREF troposphere product shall be investigated. The possible output of troposphere gradients shall be investigated.
- More stations required in the North and East of Europe, to improve the coverage.

The written version of the troposphere position paper is starting with a brief description about the **motivation** (this section). In the next section, a summary is given about the **status** quo **and** the **history** of the troposphere estimation within EUREF. A description of the **products** (temporal and spatial resolution, timeline, …) is following. Next, **shortcomings** of the existing procedures and products are discussed. Finally, some ideas for **improvement** are given.

Status and history of troposphere product

i.   Troposphere parameter estimation within EUREF started in 2001 (GPS week 1108) as a Special Project "Troposphere Parameter Estimation". In 2008, the Special Project was declared successfully finished and the troposphere product became part of the routine operation.

ii.   In section Management (http://www.epncb.oma.be/_organisation/management.php) the description of the tasks for the troposphere coordinator is given.

iii. Some old description is still available from the former Special Project (http://www.epncb.oma.be/_organisation/projects/trop_sp/). The old text described what had been done during the Troposphere Special Project and it should be left there as is and as it is done for the Time Series Special Project. Some information however, e.g. the link EUREF product directory as well as those in the participant's list, are outdated or no longer valid and they should be removed.

iv.   On the overview/introduction page of the products (http://www.epncb.oma.be/_productsservices/) the concise information about troposphere product seems to be sufficient (compared to the length of the descriptions of the other products).

v. Additional information about troposphere is available on the troposphere product page (http://www.epncb.oma.be/_productsservices/sitezenithpathdelays/). The text was updated following the first reprocessing. However, some corrections or clarifications seem to be worth:
- Introduction/second item: replace 'two hours sampling rate' with 'one hour sampling rate'.
- Product section: the title 'ZPD radiosonde time series' should be replaced (clarified) with 'ZPD time series Radiosonde minus EUREF'.
- Since for some stations there are also comparisons available with respect to VLBI, another column could be added to this product table.
- The horizontal distance between GNSS and radiosonde and the height difference between GNSS and VLBI, respectively, should be added to the plots.

vi. The EPN CB is providing interactive web pages where the user can choose the (subset of) LACs for which biases with respect to the EUREF combined solution should be plotted. In detail, there is one web page for the overall biases, http://www.epncb.oma.be/_dataproducts/analysiscentres/LAC/reporthelm-rms_tropocenter.php and one for each station, http://www.epncb.oma.be/_dataproducts/analysiscentres/LAC/reportneu_tropo.php. The information for both is taken from the ZTD combination summary file. However, the information about the station-dependent biases is redundant; similar plots (delivered offline by the troposphere coordinator) are available in the "TROPOSPHERE" row of the "Data Processing" section of each station.

vii. More details, e.g. some description about the processing, are found when calling one of the four "TROPOSPHERE" elements of the "Data Processing" section for each EPN station, e.g. http://www.epncb.oma.be/_networkdata/daily_zpd_biases.php.

viii. SINEX TRO format description is available as a link (http://www.epncb.oma.be/_documentation/formats/). However, the format description seems to be outdated and suffers from regularly updates, e.g. about the horizontal gradients (*see Appendix 1 for a brief summary of history and status*).

ix. Description about the delivery of the troposphere product by the LACs is available in the Analysis Center Guidelines (http://www.epncb.oma.be/_documentation/guidelines/guidelines_analysis_centres.pdf). These sections have to be revised and updated if necessary, e.g. at page 4/line 4 and 5 ITRF2005/IGS05 is now ITRF2008/IGS08, etc.

x. There are no text, no links in the EPN troposphere descriptions about Near Real-Time (NRT) processing. The general question is whether NRT processing could be done under EUREF umbrella. Many EUREF LACs are E-GVAP ACs as well and the personal involvement of many of the colleagues in both actions is clear. E-GVAP ACs have 'more freedom' than EUREF LACs, i.e., there are no strict guidelines to follow within E-GVAP as there are in EUREF, and the EPN Network is only a subset of the E-GVAP Network. EUREF (and IGS) should provide, as they are already doing, ZTD time series for climate applications where long-term stability is required and these time series should be worldwide recognized as reference solutions. Nevertheless, EUREF/IGS should promote the use of RT products for RT and NRT applications. Moreover, they should support multi-GNSS analysis for the development of multi-GNSS tropospheric products.
Considering the MoU between EUREF and E-GVAP as well as some suggestions given at the retreat that NRT processing for meteorology agencies with a EUREF approval could be beneficial for the ACs, a localization of NRT activities at the EPN web site could be useful.

In the 'Guidelines for EPN Stations & Operational Centres' (http://www.epncb.oma.be/_documentation/guidelines/guidelines_station_operationalcentre.pdf) and in the 'Guidelines for EPN Data Centres' (http://www.epncb.oma.be/_documentation/guidelines/guidelines_data_centres.pdf) the provision of hourly data is asked for but there is nothing written on the reason why they are required and within what latency.

Regarding the hourly coordinates solutions, in the 'Guidelines for EPN Analysis Centres' (http://www.epncb.oma.be/_documentation/guidelines/guidelines_analysis_centres.pdf) they are considered as on 'optional' product, in section 1.2 'Coordinate Combination' they are reported as well, but it is not clear how much effort has be devoted on this product so far (e.g., who are the users of the hourly combination?).

Maybe a link to the MoU between EUREF and E-GVAP could be added: in Menu 'ORGANISATION' after PROJECT one could add something like 'MoU with other organisations'; starting from this one could add some description on hourly troposphere processing.

xi. There are no text, no links in the EPN troposphere descriptions about Real-Time (RT) processing. Likewise there is no description about RT troposphere in the RT section (http://www.epncb.oma.be/_networkdata/data_access/real_time/). Here one could add a section 'Applications' after section 'Products' and RT/NRT troposphere parameter estimation could be described as an application of RT data and products.

So the conclusion is that there is sufficient information about the post-processing troposphere estimation but there isn't anything available about NRT and RT troposphere on the EPN web site.

Products

- Daily troposphere estimates of the EUREF LACs (EPN sub-networks), 1 hour sampling rate, delivered in SINEX TRO format, latency: 12-32 days (with respect to the first day of the GPS week of observations)
- Daily troposphere estimates of the EUREF combination, rapid solution (automatic, i.e. every Friday, independent of the number of contributions so far), 1 hour sampling rate, in SINEX TRO format; purpose: first inspection of the individual contributions, latency: 26 days
- Weekly troposphere estimates of the EUREF combination, final solution (interactive, following the weekly coordinate combination), 1 hour sampling rate, in SINEX TRO format, latency: 37-47 days
- Weekly summary files of the final weekly combination
- Static plots of ZTD time series for each EPN station
- Static plots of LAC biases time series for each EPN station
- Static plots of differences between ZTD from radiosondes and from EUREF final combination for a subset of EPN stations (~ 100)
- Static plots of differences between ZTD from VLBI and from EUREF final combination for small subset of EPN stations (~ 8)
- Interactive plots about the overall and station-dependent biases, derived from the ZTD combination summary files
- Localization of the products: EPN DC at BKG (http://igs.bkg.bund.de/root_ftp/EUREF/products/)
- Moreover, upload of the EUREF rapid combined solution to IGS (e.g. ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/sub/1753/) (is this still necessary?)

Shortcomings

- There is a lack of users for the troposphere products; are there statistics available to know how many files have been downloaded so far etc.?
- Connection to IGS: IGS combination of IGS ACs solutions with two hours sampling rate – where EUREF also contributed regularly with its combined solution – has been replaced by PPP solutions (Gipsy until April 2011, currently with Bernese GNSS Software) with 5 minutes sampling rate since GPS week 1304. These PPP solutions have a higher noise level than the network solutions (with one estimates per hour, generally) due to the much higher sampling rate.
- SINEX_TRO format (*see Appendix 1*).

Ideas for improvements

- Closer connection to Near-Real Time analysis
  - Focus on EUREF benefit in promoting the usage of NRT and RT data for troposphere estimates
  - EUREF is promoting the usage of NRT/RT data and products for troposphere estimates but how can these NRT/RT estimates be used within EUREF itself (i.e, in positioning applications) – GNSS tropo grid creator, correction coming from Numerical Weather prediction, streaming of troposphere corrections, …?
- Preparation for a Real-Time ZTD product, derived from EPN Real-Time infrastructure;
- Estimation, and combination if appropriate, of horizontal gradients ($\rightarrow$ *see Appendix 2*);
- Time series analysis of co-located or double stations ($\rightarrow$ *see Appendix 3*);
- (Interactive) plots with all available ZPD time series (e.g. PP, NRT, RT, RS, VLBI, …) for the EPN stations (possible connection with the troposphere database J. Dousa is developing);
- Derived Integrated Water Vapor time series from ZTD time series at EPN stations;
- Push the calibration of meteorological sensors at EPN stations. Review the pros and cons of using in data processing (calibrated) meteo data collected at EPN stations.

Appendix 1: SINEX_TRO Format

Tropospheric products are distributed using the SINEX_TRO format. The officially accepted troposphere SINEX_TRO description (Version 0.01, March 01, 1997) is available at http://igscb.jpl.nasa.gov/igscb/data/format/sinex_tropo.txt.

This format was thought be used on one hand by the IGS Analysis Centers to submit their results for the combination and on the other hand for the distribution of the combined products. The Analysis Center should submit daily files containing the estimated total zenith path delay parameters from all considered sites, applying the following naming convention *cccwwwwd.tro*, where *ccc* is the AC acronym and *wwww* is the GPS week. For the combined products, delivered for the customer interested in time series of water vapor at a site, it was thought to be convenient to have a product with separate files for each site. Therefore the products are weekly files for each site. Weekly files were preferred (instead of daily) to save disc storage by storing those information only once which normally is not varying from day to day.

The files are named:

- *ssswwww.zpd* for zenith path delay product,

- *ssswwww.tro* for water vapor product.

Based on SINEX 1.00, the recognized fields in the TROP/DESCRIPTION Block are:

- TROTOT - Total zenith path delay [mm]

- TROWET - Wet zenith path delay [mm]

- PWV - Precipitable water vapor [mm]

- STDDEV - stddev of the values in the column before

- PRESS - Pressure (mbar)

- TEMDRY - Dry temperature (deg Celsius)

- HUMREL - Relative Humidity (percent).

In November 2010, JPL, former IGS tropospheric coordinator, expanded slightly the format to accommodate the addition of gradients and changed the naming convention to *sssdoy0.yyzpd* [see IGSMAIL-6298]. It means that TGNTOT, TGETOT (formerly N_GRAD and E_GRAD) fields were introduced in the 'SOLUTION_FIELDS_1' line of the header section of the sinex_tropo. This expanded format has never officially accepted.

The file now called "sinex_tropo" is not a "true sinex" if compared to the SINEX 2.02 definition (http://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex__cont.html, December 01, 2006), because of:

- Many of the labels used in sinex_tropo, e.g., "TROP/SOLUTION" are not defined in SINEX 2.02. In other words, sinex_tropo is a different file format; it is not a subset of SINEX 2.02;

- The parameters labeled "PRESS," "TEMDRY," "HUMREL" "PWV" are defined in sinex_tropo but are not defined in SINEX 2.02. Gradients are labeled in SINEX 2.02 as:

  - TGNWET = troposphere gradient in north for the wet part [m]

- TGNDRY = troposphere gradient in north for the dry part [m]

- TGNTOT = total troposphere gradient in north (wet + dry part) [m]

- TGEWET = troposphere gradient in east for the wet part [m]

- TGEDRY = troposphere gradient in east for the dry part [m]

- TGETOT = total troposphere gradient in east (wet + dry part) [m].

- Tropospheric values (delays, gradients) can be distributed in a SINEX file or sinex_tropo file. But if they are distributed in a SINEX file, any other simultaneously-estimated parameters (e.g., station clocks) have to be included in that file, because for any parameters disseminated in a SINEX file the solution covariance matrix must be included as well.

Due to the lack of standardization, different organizations have started using different field names to refer to the same variables, particularly in the case of tropo gradients. For example IVS is using a slightly different format (http://ivs.nict.go.jp/mirror/products-data/sinex_v2_trop.txt) from the sinex_tropo format IGS is using and the TGNTOT, TGETOT reported in IGS sinex_tropo are GRN_EST, GRE_EST in IVS sinex_v2_trop.

EUREF combined tropospheric solutions are delivered in SINEX_TRO Version 0.01.

Discussion on format standardization of tropospheric parameters has been recently revitalized among members of the IGS Troposphere Working Group.

Appendix 2: Estimation of tropospheric horizontal gradients

Within the IGS the tropospheric (horizontal) gradients are estimated, usually with one value for 24 hours in the network solutions. Within the PPP solutions they have the same sampling rate as for the ZTD parameter.

With Bernese GNSS Software V5.2 it is possible to deliver horizontal gradients with the same sampling as the ZTD values, using the SINEX_TRO format. The plots below show some comparisons using first results of LACs using BSW V5.2. For completeness, also the ZTD results are presented.

In addition, three global solutions from IGS are used for comparison: COD (old CODE solution with three day arc length; sampling rate 24 hrs) and COF (new CODE solution with 1 day arc length; sampling rate 24 hrs) network solutions; JPL PPP results (5min sampling rate).

Only few stations are used which are present in different solutions:

- PTBB available from BKG, COE and LPT EPN solutions as well as from COD, COF and JPL IGS solutions (plots: weeks 1739-1742)
- ZIMM available from COE, LPT and RGA EPN solutions (plots: weeks 1741-1745)
- CFRM available from BKG and RGA (plots: weeks 1741-1745)

It can be seen from the figures below that the values are linearly interpolated. The good agreement between BKG and RGA on the one hand and between COE and LPT on the other hand shows that the same strategy (independent daily solutions on the one hand and three day solutions on the other hand) is applied. The modest agreement between COE/LPT and BKG/RGA shows the differences coming from the different strategies applied.
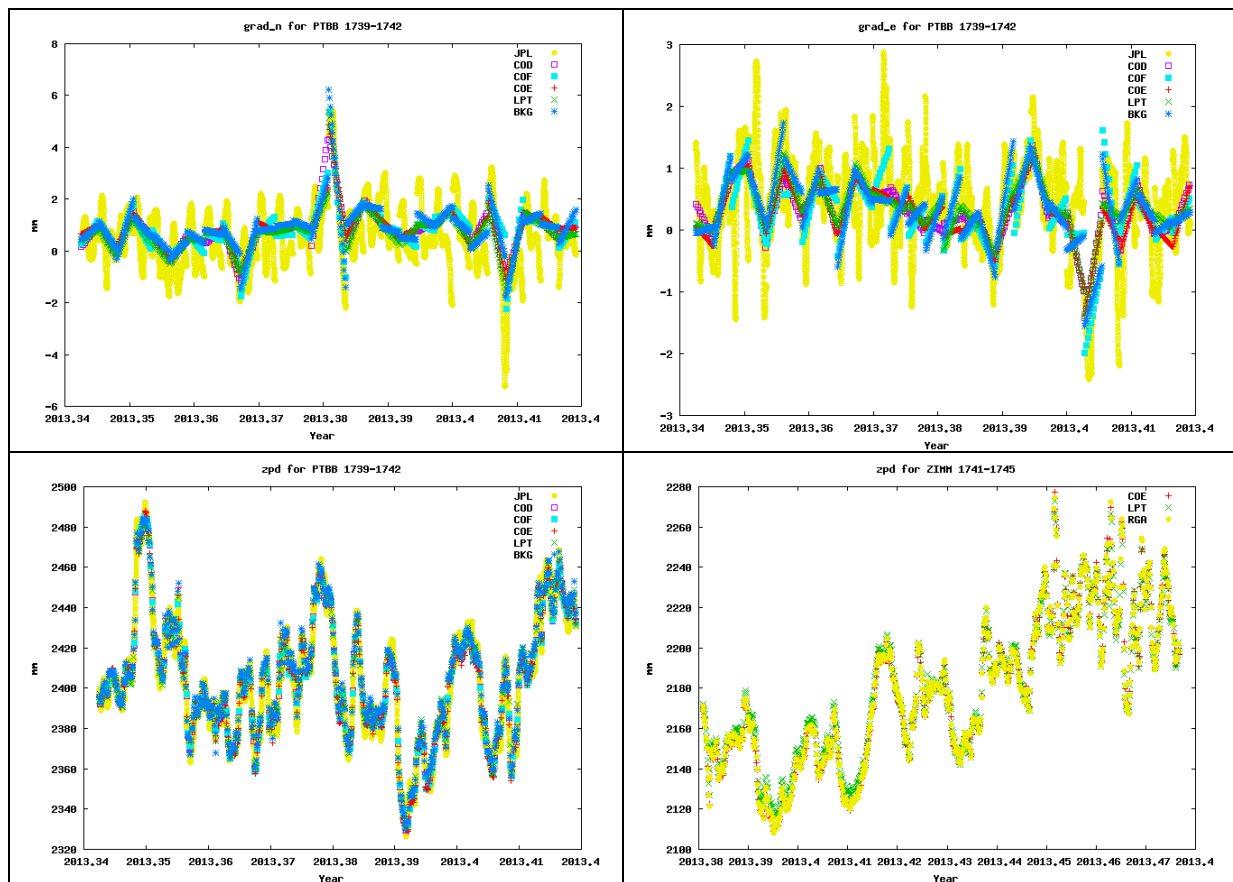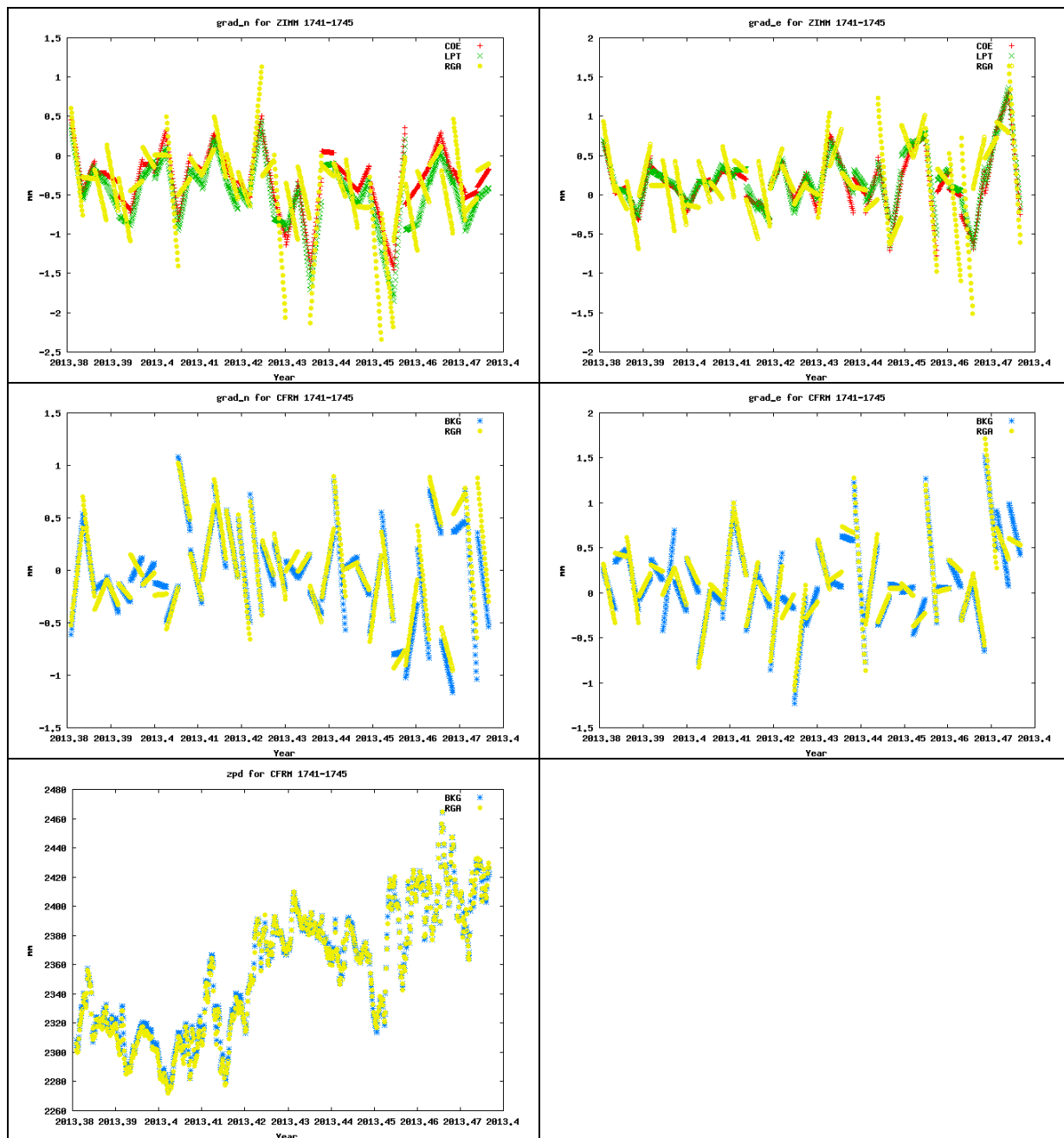
Appendix 3: Differences of ZTD estimation at EPN "double stations"

There are several sites within the EPN with two permanent GNSS stations running in parallel over a certain time span. For these sites time series of ZTD differences can be processed.
Moreover, there are stations with only a short distance between both stations where processing of such a time series could be worth as well.
In the following figures the ZTD time series for almost all sites with two co-located stations are displayed. In addition, differences for some station pairs are shown to get an impression of the noise level of such time series. The distance between both stations is given in the plot (East [km]/North [km]/Up [m]).

ZPD differences ZIM2 minus ZIMM from EUR: -0.4 +/- 2.4 mm (47454 data points)

ZPD differences WETT minus WTZR from EUR: -2.9 +/- 10.9 mm (9011 data points)

ZPD differences BORK minus BORJ from EUR: +2.1 +/- 2.5 mm (13332 data points)

ZPD differences MAD2 minus MADR from EUR: +1.3 +/- 4.7 mm (39952 data points)

ZPD differences NYAL minus NYA1 from EUR: +0.1 +/- 1.2 mm (61727 data points)

ZPD differences OBET minus OBE2 from EUR: +4.4 +/- 3.8 mm (15147 data points)

ZPD differences THU1 minus THU3 from EUR: -3.6 +/- 5.6 mm (2656 data points)

ZPD differences TROM minus TRO1 from EUR: +3.4 +/- 2.9 mm (57995 data points)

ZPD differences MSEL minus MEDI from EUR: +3.9 +/- 4.0 mm (67102 data points)

Dist. <1 km / <1 km / 1 m

ZPD differences BADH minus KLOP from EUR: -8.8 +/- 4.0mm (69870 data points)

Dist. 8 km / 1 km / 39 m

ZPD differences KIRU minus KIR0 from EUR: +27.6 +/- 3.8 mm (136076 data points)

Dist. 4 km / 2 km / 108 m

ZPD differences BRON minus MDOR from EUR: +18.9 +/- 3.1 mm (504 data points)

Dist. 10 km / 8 km / 74 m

ZPD differences MDOR minus SJDV from EUR: +33.5 +/- 5.0 mm (51910 data points)

Dist. 10 km / 9 km / 98 m

ZPD differences GUIP minus BRST from EUR: -30.0 +/- 4.4 mm (57128 data points)

Dist. 6 km / 7 km / 89 m

ZPD differences ILDX minus LROC from EUR: +2.2 +/- 3.3 mm (481 data points)

Dist. 3 km / 17 km / 1m

ZPD differences SMNE minus MLVL from EUR: +11.8 +/- 3.5 mm (74811 data points)

Dist. 8 km / 0.5 km / 34 m

ZPD differences TLMF minus TLSE from EUR: -2.5 +/- 3.1 mm (59230 data points)

Dist. 9 km / 1 km / 14 m

ZPD differences IENG minus TORI from EUR: -1.0 +/- 3.7 mm (75206 data points)

Dist. 2 km / 5 km / 6 m

ZPD differences BOLG minus MEDI from EUR: -13.5 +/- 6.7 mm (68855 data points)

Dist. 23 km / 2 km / 50 m

ZPD differences EUSK minus EIJS from EUR: -43.6 +/- 11.7 mm (128400 data points)

Dist. 76 km / 9 km / 141 m

ZPD differences WARE minus EIJS from EUR: -26.8 +/- 6.1 mm (138478 data points)

Dist. 31 km / 7 km / 84 m