Guidelines for EUREF Densifications

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Version 1: 26-05-2009
Version 2: 04-05-2010: Minor corrections/clarifications based on user feedback
Version 3: 24-05-2012: Encourage the use of GLONASS observations
Version 4: 13-06-2012: Modified links due to the EPN CB web site restructuring
Version 5: 28-05-2013: Replacement of ITRF2005 with IGb08 and additional clarifications

This document outlines the procedure recommended for computing station coordinates in the ETRS89 (European Terrestrial Reference System), in particular in the framework of national densifications of the ETRS89. The document also describes how to proceed to request a EUREF validation of the densification.

1. Introduction

A first set of guidelines describing how to compute EUREF densifications using products from the International GNSS Service (IGS) was presented at the 1994 EUREF symposium in Warsaw (Gurtner, 1994). The basic principle consisted in first performing all GPS computations in the ITRF (International Terrestrial Reference Frame) version in which the final IGS orbits are expressed to obtain coordinates in the ITRF at the central epoch of observation. During that process, the coordinates of GPS sites included in the ITRF realization were held fixed. In a second step the computed ITRF coordinates were converted to the ETRS89 (European Terrestrial Reference System).

In 1995, the EUREF Technical Working Group (TWG) complemented this set of guidelines with a list of deliverables for EUREF campaigns (Van der Marel, 1995). The goal was to provide the National Mapping Agencies with clear instructions on how to submit their national EUREF densifications to the EUREF TWG for validation; the paper also included a list of items that had to be provided to EUREF in order to include the campaign in the EUREF Campaign Database.

In 1997, the original densification guidelines were updated (Gurtner et al, 1997) in order to make full use of the IGS network and its European densification, both established in the mean time. In this paper, the basic concept was extended to use SINEX solutions from the EUREF Permanent Network. The idea was to combine the loosely constrained regional SINEX solution of the densification network (which included at least 3 surrounding EPN stations) with the SINEX solution from the EPN and to constrain or fix the ITRF coordinates of the best sites in the combined network.

In 2003, a paper by Z. Altamimi (Altamimi, 2003) introduced the concept of minimal constraints for aligning a regional solution to the ITRF. This concept, which differed from the original method where the coordinates of a set of reference sites were fixed or heavily constrained to their ITRF coordinates, proposes to align a regional solution to the ITRF using a transformation formula. The advantage of the minimal constraint approach is that it yields an optimal datum definition together with preserving the original characteristics of the regional solution.

The concept of the minimal constraints is just one example of the many evolutions within the geodetic and GNSS community since 1993. In praxis, most countries defined the geodetic datum of

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their national ETRF realization using campaigns by the method of "heavily constraining" ITRF coordinates and applying the transformation formulas according to Boucher and Altamimi (2011) to derive ETRF coordinates.
The EUREF Permanent Network (EPN), which was established in 1996 (Bruyninx, 2004) has in the mean time also reached maturity and is used today to densify geodetic networks.

2. EUREF Densification of the ITRF

Even while the number of permanent GNSS tracking sites in Europe has grown considerably (more than 240 EPN stations in 2013), only a selection of these sites (mostly the ones belonging to the International GNSS Service – IGS) have coordinates included in recent ITRS realizations.

To take full advantage of the EPN and ensure full consistency with EPN analysis procedures, the EUREF TWG decided at its meeting of Nov. 3-4, 2008 in Munich, to release regularly its own official updates of the ITRS/ETRS89 coordinates/velocities of the EPN stations. A first step in this process consisted in a densification of the ITRF2005 using all EPN data up to Dec. 2005 (the same observation period as covered by the ITRF2005), see Kenyeres, 2008. As decided at the EUREF TWG meeting of Feb. 26-27 2009 in Budapest, this densification is since that time replaced each 15 weeks by a new EUREF densification of the latest ITRS realization.

The latest ITRS realization is the ITRF2008 (Altamimi et al., 2011). Based on the ITRF2008, the IGS released the IGS08 and IGb08 (Rebischung et al., 2012; Rebischung, 2013), consisting in applying position corrections for 65 stations (out of 232 IGS08 selected stations) to ITRF2008 positions which were significantly affected by the different GNSS antenna calibration model used for the generation of the ITRF2008 (igs05.atx) and the models used in present-day GNSS data analysis (igs08.atx, in use since GPS week 1632). ITRF2008, IGS08 and IGb08 are however equivalent at the global level, in the sense that they share the same underlying origin, scale and orientation: it can be directly verified that comparing the ITRF2008 and IGb08 SINEX files by means of a 14 parameter transformation yields zero values for all, within one standard deviation. IGS08 and IGb08 are consistent with the igs08.atx antenna model.
The present version of the guidelines introduces for the first time the concept of using the latest IGS realization of the ITRS, the IGb08 (instead of the ITRF2008) as backbone for the densification of the ITRF.

In the EUREF densification, the EPN stations are categorized taking the station quality and the length of available observation span into account (Kenyeres, 2009):

- **Class A** stations with positions at the 1 cm precision[2] and velocities at the 1mm/yr precision at all epochs
- **Class B** stations with positions at the 1 cm precision at the epoch of minimal position variance[3] of each station

The latest EUREF densification of the ITRF/ETRF contains the following files:

A) For **class A** stations

[2] A station is moved to class A when the station has more than 1 year of observations, the formal uncertainly of the last velocity estimate is below 0.5mm/y and the agreement (in terms of repeatability) between the velocity estimates from the last 10 consecutive cumulative solutions (available internally each 5 weeks) is below 0.5 mm/y in all three velocity components. In addition, the last solution for that station should be not older than 2 years.

[3] When estimating for each site a position and velocity, the epoch of minimal position variance (EMPV) is the epoch which minimizes the variance of the position (positions with the best precision). The epoch of minimal variance often corresponds to the mean epoch of observations. For a detailed description of the EMPV, we refer to Altamimi et al., 2002.

A.1) in the ITRS, densifying the IGb08 frame:
- EPN_A_IGb08_CWWWW.SSC: site positions and velocities
- EPN_A_IGb08_CWWWW.SNX.Z: SINEX file

A.2) in the ETRS89, ETRF2000 frame (note: ETRF2000 is the conventional frame for the ETRS89):
- EPN_A_ETRF2000_CWWWW.SSC: site positions and velocities
- EPN_A_ETRF2000_CWWWW.SNX.Z: SINEX file

B) For **class B** stations

B.1) in the ITRS, densifying the IGb08 frame:
- EPN_B_IGb08_CWWWW.SSC: site positions at epoch of minimal variance, no velocities !

B.2) in the ETRS89, ETRF2000 frame:
- EPN_B_ETRF2000_CWWWW.SSC: site positions at epoch of minimal variance, no velocities!

Terminology:
EPN_[A/B]_[IGb08/ETRF2000]_C[WWWW]:
- A/B: class A or class B stations
- IGb08/ETRF2000: frame of the realization
- C: indicates that it is a cumulative solution
- WWWW: all EPN observations until GPS week WWWW are used for this solution

More details can be found in Kenyeres, 2012.

Only class A stations can be used as reference stations for the densification of the ETRS89. The associated files can be downloaded from the EPN Central Bureau; the most recent realization is available through the links:
- In the ITRS:
  - ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_A_IGb08.SSC
  - ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_A_IGb08.SNX.Z
- In the ETRS89:
  - ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_A_ETRF2000.SSC
  - ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_A_ETRF2000.SNX.Z

Note that previous releases are regularly moved to the archive directory
ftp://epncb.oma.be/pub/station/coord/EPN/archive/.

3. GNSS Data Analysis

This section provides guidelines for the analysis of GNSS campaigns with the goal to densify the ETRS89. These guidelines are necessary to guarantee the consistency of the campaign analysis with the official ETRS89/ITRS coordinates released by EUREF.

3.1 GNSS Data from the Densification Area

The sites to be included in the densification should be observed with GNSS receivers that comply with the present requirements for permanent EPN tracking stations, available from http://epncb.oma.be/_documentation/guidelines/guidelines_station_operationalcentre.pdf.
It is recommended to use GNSS antennae which have absolute calibrations values, preferably azimuth and elevation dependent values. Ideally, the observation period must cover at least 3 days

of 24 hour data at a 30-second sampling rate. If, GLONASS observations are available, then a combined GPS+GLONASS data analysis is recommended.

3.2 Reference Stations

The reliability of the reference frame realization will increase with growing number of reference stations (the realization will become less sensitive to a problem in any individual reference stations) and with the geographical extent of the reference stations (Legrand and Bruyninx, 2009). The reference stations shall fulfill the following criteria:

- Class A EPN stations part of the latest EUREF realization of the ITRS/ETRS89, see ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_A_IGb08.SSC
- Have observation data covering the time frame of the densification project
- Without a GNSS equipment change since the last EUREF realization (indicated by the GPS week WWWW in the filename)
- Their estimated coordinates(/velocities) tied to the EPN_A_IGb08 should agree better than 10 mm for positions (if applicable, 3 mm/y for velocities) with the EPN_A_IGb08 values (Altamimi, 2003).

At least 5 reference stations around the densification area and all potential reference stations in the densification zone should be used by using their original tracking data available from the EPN Data Centres. In addition, the EPN station position time series (http://www.epncb.oma.be/_productsservices/timeseries/) should be verified to avoid reference stations with noisy time series or with large (exceeding 1 cm in amplitude) periodic signals. Take also into account that the coordinates of a reference station might change over time (due to e.g. equipment changes) and make sure you use the coordinates valid during the densification period by taking into account the solution numbers (see EUREF TWG, 2008).

3.3 Orbits and Earth Rotation Parameters

Use final IGS orbits and Earth Rotation Parameters and ensure yourself that they are based on similar antenna models (absolute or relative) as used in the GNSS data analysis of the densification. If GPS-GLONASS data are processed, combined GPS-GLONASS orbits are recommended as input.

3.4 GNSS Processing Method

Generate daily free (or minimally constrained - MC) network solutions by performing the GNSS data analysis conform with the guidelines for EPN Local Analysis Centers (http://epncb.oma.be/_documentation/guidelines/guidelines_analysis_centres.pdf) to guarantee consistency between the densification solution and the EPN solution.
Use the same antenna calibration values as used by the EPN analysis centers (see http://epncb.oma.be/_documentation/equipment_calibration/), currently the epn_08.atx, available from ftp://epncb.oma.be/pub/station/general/epn_08.atx.

4 Stacking and Datum Definition

In the next step, the daily network solutions should be combined to estimate a single set of coordinates for each site in the densification project.

4.1 Velocity Estimation

Depending on the observation time of the stations within the densification project, it might be necessary to estimate station velocities in addition to the site positions. Velocity estimation is mandatory for all stations with an observation time of 3 years or more in the densification project. For stations with shorter observation times, velocity estimation is necessary if intraplate deformations cannot guarantee the precision of the ETRS89 coordinates at the 1 cm level during the full observation period of the station in the densification project.

In case observations from before GPS week 1631 (April 2011, date of the introduction of the igs08.atx/epn_08.atx antenna model) are included in the densification project, it is expected that these observations are also processed using the latest epn_08.atx calibration model. If such a processing is really not possible, then position jumps can show up during the stacking at the epoch of a change of the antenna model and they might degrade the solution. Methods for reducing the coordinate jumps might be applied, e.g. using a latitude-dependent model (ftp://igs.org/pub/station/coord/new_calib/lat_models.txt). In any case, always carefully inspect the jumps and introduce position discontinuities where necessary.

4.2 Optional Combination with EPN SINEX Solutions

Depending on the available processing capacities, the weekly network solutions of the densification project can be combined with the final weekly combined SINEX solutions from the EPN (covering at least the period of the densification) to obtain an extended European-wide network including the densification network. The number of reference stations can then be increased. Weekly EPN solutions are available as SINEX files from the EUREF Regional Data Center at BKG. Only weekly EPN solutions generated using the same processing options as the densification project should be used.

4.3 Stacking and Computation of ITRS Coordinates

The daily network solutions (or the extended weekly densification network solutions (from 4.2)) are stacked to compute ITRS positions at the central epoch of observations, by tying the network to EPN_A_IGb08 using minimal constraints (MC) on the set of EPN Class A stations (see 3.2), and this on the positions as well as the velocities, if applicable. During this process the positions for all sites in the network are estimated. If necessary (see 4.1) site velocities can be estimated.

4.4 Transformation to ETRS89

Convert the obtained ITRS positions at the epoch of observation to the ETRS89 by using the published transformation parameters (Boucher and Altamimi, 2008). The "ETRS89/ITRS TRANSFORMATION" utility on the EPN web site can be used to carry out the transformation (see http://epncb.oma.be/_productsservices/coord_trans/). The ITRS frame to be used is the ITRF2008. The ETRS89 frame to be used depends on the national situation, e.g. a country whose previous EUREF densification is in the ETRF97 might wish to express again its coordinates in this frame in order minimize coordinate changes with respect to previous national realizations. However, the EUREF TWG recommends expressing the ETRS89 coordinates in the ETRF2000, which is the conventional frame of the ETRS89. Useful details on how to convert from any ITRF/IGS frame to any ETRF frame are also published in (Boucher and Altamimi, 2011).

5 Verification

Validate your results by performing the following tests:

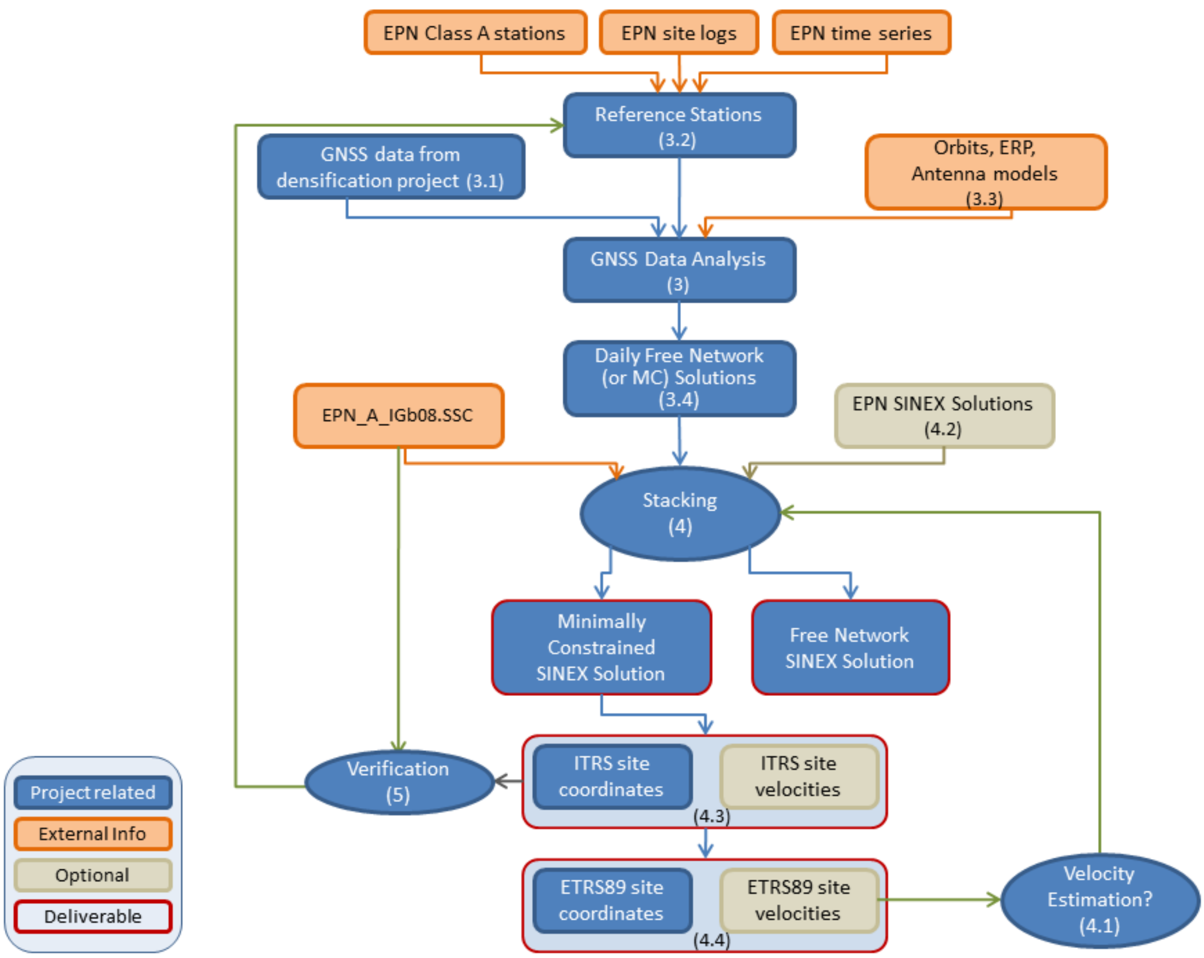
- Verify the ambiguity resolution
- Verify the daily repeatability (in North, East, Up) of the densification solution. Examples of valid repeatabilities are available from the weekly summary files of the EPN LAC (at BKG). Explain and eliminate outliers.

– Verify the agreement of the estimated positions (and velocities) of the reference stations with EPN_A_IGb08 (at the same epoch); all reference stations should agree better than 10 mm for positions and, if applicable, 3 mm/y for velocities with the EPN_A_IGb08 values. If not, eliminate the reference station, notify the EPN Central Bureau and iterate.

– Verify if the obtained ETRS89 coordinates have a variation due to intraplate deformations below 1 cm during the period of the densification project. This can be verified by inspecting the residual position time series of the densification sites expressed in the ETRS89. If some of the time series show a clear trend in their north, east and up components and the residual values exceed 1 cm, then the velocity of this site in the ETRS89 cannot be neglected over the period of the densification project. To account for this, it will be necessary to estimate ITRS site velocities (see 4.1) during the stacking of the daily solutions. The ETRS89 velocities derived from the estimated ITRS velocities (using the Memo by Boucher and Altamimi, 20011) will then complement the ETRS89 positions of these specific stations.

– Compare the obtained ETRS89 coordinates with the coordinates obtained from previous EUREF densification campaigns. Take, if the reference epochs are different, the ETRS89 velocities into account.

6 Summary of the Procedure



7 Validation and Deliverables

7.1 Report to EUREF TWG

If validation by the EUREF TWG is requested, then a full report of the densification campaign must be submitted to the EUREF TWG at least 2 weeks before the next TWG meeting and the results should be presented by the analysis center at the next EUREF TWG meeting.
The report should contain:

1. Description of the densification project
    a. List of densification stations (full names, 4-char ID, domes numbers, map)
    b. Observation period (permanent, campaign type)
    c. GNSS equipment (IGS standard names for receiver and antenna/radome)
    d. Monument description
2. Other data used in the processing
    a. List of reference stations and list of verifications performed to check their performance during the time frame of the densification project
    b. If used, list of EPN SINEX solutions
    c. Orbits, ERP
    d. Antenna calibration models
3. Processing strategy
    a. Software (and version)
    b. Schematic processing method
    c. Elevation cut off
    d. Positioning mode (double difference network mode, …)
    e. Modeling of loading effects
    f. Ambiguity resolution strategy
    g. Modeling of troposphere (e.g. a priori model, mapping function, constraints, gradients, …)
    h. Modeling of ionosphere (e.g. higher order corrections)
    i. Alternative strategies for test purposes
    j. Method for combining daily free network solutions in one densification solution
    k. Parameters used in minimal constraints, including identification of reference stations and their set of reference coordinates (name of the EPN Class A SSC file, see section 3.2)
    l. In case velocities have been estimated: list of introduced discontinuities and access to the residual position time series
4. Results from the processing
    a. Daily mean ambiguity resolution percentages
    b. Comparison of the daily coordinate solutions of each station (repeatabilities in North, East and Up). Outliers should be identified, explained and eliminated.
    c. Comparison between estimated ITRS coordinates (after minimal constraints) and EUREF densification of ITRS (used in 3.k) , expressed in North, East and Up
    d. Transformation to the ETRS89 (including parameters used)
    e. Comparison between new ETRS89 coordinates and ETRS89 coordinates from previous ETRS89 densifications (expressed in North, East and Up)

7.2 Deliverables

Once the densification has been validated by the TWG, it will be included in the EUREF densification data base. For that purpose, the following deliverables need to be submitted to the EUREF TWG:

1. Site description forms (complete the appropriate fields in the Site Information Form available from ftp://epncb.oma.be/pub/station/general/blank.log)

2. Free network solution in the SINEX format
3. Minimally constrained solution in the SINEX format
4. List of coordinates for all stations in the network in the ITRS at epoch of observation
   or
   List of coordinates & velocities for all stations in the network in the ITRS (for densification projects requiring velocity estimation)
5. List of coordinates for all stations in the network in the ETRS89 (indicate the frame used) at epoch of observation
   or
   List of coordinates & velocities for all stations in the network in the ETRS89 (indicate the frame used)
6. List of reference sites
7. Coordinates and velocities used for the reference sites (and name of the EPN Class A SSC file, see 3.2.)

8 References

Altamimi Z. (2003), Discussion on How to Express a Regional GPS Solution in the ITRF, EUREF Publication No. 12, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, pp. 162-167

Altamimi Z., Collilieux X., Métivier L. (2011), ITRF2008: an improved solution of the international terrestrial reference frame, Journal of Geodesy, Volume 85, Issue 8, pp.457-473

Boucher C., Altamimi Z. (2011), Memo: Specifications for reference frame fixing in the analysis of a EUREF GPS campaign, http://etrs89.ensg.ign.fr/memo-V8.pdf

Bruyninx C. (2004), The EUREF Permanent Network: a multi-disciplinary network serving surveyors as well as scientists, GeoInformatics, Vol. 7, pp. 32-35

EUREF TWG (2008), The EUREF Densification of the ITRF2005, ftp://epncb.oma.be/pub/station/coord/EPN/EUREFDensificationITRF2005.pdf

Gurtner W. (1994), The use of IGS Products for the Densification of Regional/Local Networks, EUREF Publication No. 3, Veröffentlichungen der Bayerischen Kommission für die Internationale Erdmessung, Bayerischen Akademie der Wissenschaften, Munich, pp. 184-199

Gurtner W., Boucher C., Bruyninx C., Van der Marel H. (1997) The use of the IGS/EUREF Permanent Network for EUREF Densification Campaigns, EUREF Publication No. 6, Veröffentlichungen der Bayerischen Kommission für die Internationale Erdmessung, Bayerischen Akademie der Wissenschaften, Munich, pp. 50-51

Legrand J., Bruyninx C. (2009), EPN Reference Frame Alignment: Consistency of the Station Positions, Bulletin of Geodesy and Geomatics, Vol. LXVIII, no. 1, pp. 19-34

Kenyeres A. (2008), Analysis and validation of the ITRF2005 densification solution created by the EPN Time Series Analysis Project, available from
http://www.euref.eu/TWG/EUREF%20TWG%20minutes/48-Munich2008/03-c-3 ITRFdens_TWGrep.pdf

Kenyeres A. (2009), Maintenance of the EPN ETRS89 coordinates, presented at the EUREF TWG 2009 Spring Meeting, Feb. 26-27, 2009, Budapest, available from

http://www.euref.eu/TWG/EUREF%20TWG%20minutes/49-Budapest2009/03-e-ETRSmaint_TWGrepBP.pdf

Kenyeres A. (2012), The implementation of IGS08 in the EPN ETRS89 maintenance products, available from ftp://epncb.oma.be/pub/station/coord/EPN/IGS08_densification_V4.pdf

Van der Marel H. (1995), Deliverables for EUREF Campaigns, EUREF Publication No. 4, Veröffentlichungen der Bayerischen Kommission für die Internationale Erdmessung, Bayerischen Akademie der Wissenschaften, Munich, pp. 275

Rebischung P., Griffiths J., Ray J., Schmid R., Collilieux X., Garayt B. (2012), IGS08: the IGS realization of ITRF2008, GPS Solutions, 16(4):483-494, doi:10.1007/s10291-011-0248-2.

Rebischung P. (2013), [IGSMAIL-6663] IGb08: an update on IGS08, available from http://igscb.jpl.nasa.gov/pipermail/igsmail/2012/007853.html