



## Guidelines for EUREF Densifications

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*This document outlines the procedure for computing station coordinates (and velocities) 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.*

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## 1 Introduction

This document outlines the procedure for computing EUREF densification campaigns in a realization of the European Terrestrial Reference System (ETRS89) using the EUREF Reference Frame product. The document can be used for national densifications of the ETRS89 and also describes the procedure to request a EUREF validation of this ETRS89 densification.

In the following, we will use the word “EUREF densification campaign” in a broad sense: it can refer to

- A GNSS observation campaign of a couple of days or weeks;
- A GNSS observation campaign over a long duration of time. The campaign can consist of:
  - sites that are continuously observed by permanent GNSS stations (preferred)
  - sites with repeated GNSS observations of a couple of days or weeks (discouraged)

For quality assessment purposes, the stations in a EUREF densification campaign are classified as follows:

- Class A stations with ETRS89 coordinates at the 1 cm precision and velocities at the 1mm/yr precision at all epochs;
- Class B stations with ETRS89 coordinates at the 1 cm precision at the epoch of minimal position variance of each station.

The advantage of having a Class A station is that the station velocities allow to extend the lifetime of the station coordinates, which is especially useful in zones with deformations. The user can use the dense velocity fields provided by the European Dense Velocities Working Group ([http://pnac.swisstopo.admin.ch/divers/dens\\_vel/000.html](http://pnac.swisstopo.admin.ch/divers/dens_vel/000.html)) or the EPN Densification Working Group (<https://epnd.sgo-penc.hu/velocities/>) to assess which zones are most affected.

If a Class A validation is desired or required for some stations, then the EUREF densification campaign must include, as a strict minimum, three years of observations for these stations. In this case, it will be necessary and possible to estimate station velocities.

If a Class B validation is desired for some stations, then the EUREF densification campaign should include as a strict minimum three non-overlapping (preferably consecutive) days of 24-hour data at a 30-second sampling rate for these stations. In order to avoid position changes due to plate motion and deformations during the EUREF densification campaign, the standard duration of such campaign should not exceed more than 1 month.

Similar to the procedures used in the early years of EUREF (See Annex 1), the basic principle of computing station coordinates (and velocities) in a European Terrestrial Reference Frame (ETRF) consists of two steps:

- 1) compute station coordinates (and velocities) in a realization of the International Terrestrial Reference System (ITRS)
- 2) transform them from this ITRS realization to a realization of the ETRS89 using EUREF TN-1 (Altamimi, 2018).

## 2 Reference Frame Product

To compute station coordinates (and velocities) in a realization of the ITRS, one must first select a reference frame product providing ITRF<sup>2</sup> coordinates and velocities as well as by-products such as the

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<sup>2</sup> International Terrestrial Reference Frame

coordinates time series, a list of position and velocity discontinuities, a list of outliers... From this reference frame product, the user must identify stable reference stations that he or she will process together with the data of his/her own densification stations. Finally, the user will align his/her densification solution to the reference frame solution using the selected reference stations and minimal constraints.

Such a reference frame product, based on the GNSS stations of the EUREF Permanent Network (EPN, Bruyninx et al., 2019), is maintained by EUREF (under the responsibility of the EUREF Reference Frame Coordinator, RFC). The present guidelines will show how to use the EUREF reference frame product to express a EUREF densification campaign in the ITRF. Therefore, section 2.1 first shortly describes the EUREF reference frame product and from where it can be downloaded. Section 2.2 describes the tool developed by the RFC to help selecting stable and suitable reference stations from the EUREF reference frame product. After that, sections 3 to 5, will provide the step-wise procedure on how to compute a EUREF densification campaign taking advantage of the EUREF reference frame product. Last, section 6 provides guidelines on how to request a validation of the EUREF Governing Board for the EUREF densification campaign.

## 2.1 EUREF Reference Frame Product

The EUREF reference frame product EPN\_IGb14\_CWWWW (WWWW indicates the last week of observations included in the computation of the product) is updated each 15 weeks and expressed in IGb14 since May 2020 (see Annex 3). It is available from:

- <https://epncb.oma.be/productservices/coordinates/>,
- <ftp://epncb.oma.be/epncb/product/cumulative/CWWWW/>
- or at <ftp://epncb.oma.be/epncb/station/coord/EPN> for the latest release

and it includes:

- Positions and velocities of EPN stations with at least 3 years of observations;
  - EPN\_IGb14\_CWWWW.SSC: station coordinates and velocities
  - EPN\_IGb14\_CWWWW.SNX.Z: SINEX file
- The list of position and velocity discontinuities (EPN\_discontinuities.snz in SINEX format) for all EPN stations ([ftp://epncb.oma.be/epncb/station/coord/EPN/EPN\\_discontinuities.snz](ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_discontinuities.snz) for the latest release);
- The list of days rejected from the EUREF reference frame solution for each EPN station EPN\_outliers.lst ([ftp://epncb.oma.be/epncb/station/coord/EPN/EPN\\_outliers.lst](ftp://epncb.oma.be/epncb/station/coord/EPN/EPN_outliers.lst) for the latest release);
- The residual position time series of all EPN stations; the dynamic plots of the position time series of the latest release are available at <https://epncb.eu/productservices/timeseries/>.

## 2.2 EUREF's On-line Reference Station Selection Tool

Not all stations in the EUREF reference frame product are of the same quality and suitable to be used as reference stations for a EUREF densification campaign. Therefore, to assess their “reliability” and “stability”, EUREF introduced a station categorization based on:

- The size of the seasonal signals and scattering of the position time series;
- The reliability of the velocity estimation;
- The stability of the station over its full history.

More details about these criteria, applied thresholds, and the different station categories are provided at [https://epncb.oma.be/productservices/ReferenceFrame/Station\\_Classification.php](https://epncb.oma.be/productservices/ReferenceFrame/Station_Classification.php).

In addition, EUREF provides an interactive tool that helps to select the most suitable EPN reference stations for EUREF densification campaigns, taking as input begin and end date of the EUREF

densification campaign. The tool is available from <https://epncb.oma.be/productservices/ReferenceFrame/> and it provides:

- 1) An **initial selection** of all potentially suitable EPN reference stations;
- 2) **Relevant information** (number of position or velocity discontinuities, post-seismic deformation, collocated stations with constrained velocities, ...) and plots (detrended position time series, selection criteria values, velocity variability) for each of the stations;
- 3) An interactive map showing the **geographical** location of the initial selection of reference stations and from which the user can select the reference stations that he or she will finally include in his GNSS network processing.

The usage of this tool is recommended for the selection of stable reference stations suitable to the preparation of the EUREF densification campaign (see section 3.2).

### 3 GNSS Data Analysis

This section provides guidelines for the analysis of EUREF densification campaigns. These guidelines are necessary to guarantee the consistency of the campaign analysis with the EUREF reference frame product. The present guidelines consider that the GNSS data analysis is done using the so-called “network approach”.

#### 3.1 GNSS Data from the Densification Area

The sites to be included in the EUREF densification campaign should be observed with GNSS receivers that comply with the present requirements for permanent EPN tracking stations, available from [https://epncb.oma.be/documentation/guidelines/guidelines\\_station\\_operationalcentre.pdf](https://epncb.oma.be/documentation/guidelines/guidelines_station_operationalcentre.pdf). It is recommended to use GNSS antennas, which have absolute calibrations values, preferably azimuth and elevation dependent values.

OPTIONAL, but recommended: request a DOMES number for your station marker from the International Earth Rotation and Reference Systems Service (IERS): [https://itrf.ign.fr/domes\\_request.php](https://itrf.ign.fr/domes_request.php).

#### 3.2 Reference Stations

To tie the densification campaign to the EUREF reference frame product, it is necessary to include in the GNSS data analysis “reliable” and “stable” reference<sup>3</sup> stations. EUREF’s on-line reference station selection tool (<https://epncb.oma.be/productservices/ReferenceFrame/>, see section 2.2) has been designed to assist with the selection of these reference stations by providing relevant information for the selection.

Selected reference stations should be:

- Included in EPN\_IGb14\_CWWWW (see section 2.1);
- Well distributed around the geographical area of the densification campaign;
- The most stable and reliable stations in the area of interest;
- For position-only solutions and during the full timeframe of the densification project:
  - Have observation data in the EPN reference frame solution<sup>4</sup>;

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<sup>3</sup> Called ‘fiducial’ stations in Bernese software

<sup>4</sup> Take into account that during winter periods, because of snow accumulation, EPN stations at high altitude or high latitude are often excluded from the EPN reference frame solution.

- Have no position changes (see list of position and velocity discontinuities EPN\_discontinuities.snrx);
- For position/velocity solutions (see section 4.1):
  - Have as much as possible common observations with the EUREF reference frame product (time span and data rejection policy (list of days rejected));
  - Have as few position changes as possible and avoid velocity changes (see list of position and velocity discontinuities EPN\_discontinuities.snrx);

In addition, the reliability of the reference frame realization of the densification campaign will increase with growing number of reference stations included in the analysis (the realization will become less sensitive to a problem caused by an individual reference station) and with the geographical extent of the reference stations (Legrand and Bruyninx, 2009). As some of the originally selected reference stations might not be kept after their verification during the stacking (see section 4.3), it is recommended to start with at least 15 reference stations recommended by EUREF's reference station selection tool, including

- All reference stations within the densification area<sup>5</sup>
- At least 10 reference stations surrounding the densification area.

The goal is to keep the number of reference stations after iteration above 10 and preferably still surrounding the area.

### **3.3 Antenna Calibrations, Orbits and Earth Rotation Parameters**

Use the same antenna calibration values as used by the EPN analysis centres (see [https://epncb.oma.be/\\_documentation/equipment\\_calibration/](https://epncb.oma.be/_documentation/equipment_calibration/)), currently the epn\_14.atx, available from [ftp://epncb.oma.be/pub/station/general/epn\\_14.atx](ftp://epncb.oma.be/pub/station/general/epn_14.atx), which is based on the igs14.atx.

Use final or rapid orbits and Earth Rotation Parameters (ERPs) from the IGS or one of its analysis centres. Optimally these should be based on similar antenna models as used in the analysis of EUREF densification campaign. However, in practice, when processing older data, only orbits based on an older antenna model might be available. For example, for observations prior to GPS week 1934 (January 2017, date of the introduction of the igs14.atx/epn\_14.atx antenna model) orbits computed with the igs14.atx antenna model might not be available. In that case, it is still expected that these observations are processed using the latest epn\_14.atx calibration model even if this entails an inconsistency between antenna models.

### **3.4 GNSS Processing Method**

Generate daily network solutions by estimating site coordinates for all stations in the densification network, including the reference stations.

The GNSS data analysis should conform to the guidelines for EPN Local Analysis Centres ([https://epncb.oma.be/documentation/guidelines/guidelines\\_analysis\\_centres.pdf](https://epncb.oma.be/documentation/guidelines/guidelines_analysis_centres.pdf)) to guarantee consistency between the densification solution and the EUREF reference frame product.

Use minimal constraints to tie each of the daily solutions to the EUREF reference frame solution, using the reference stations selected in 3.2.

*Relevant verifications:*

- *Daily mean ambiguity resolution percentages;*

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<sup>5</sup> Other (not recommended) EPN stations in the densification area are preferably also be added, but they should not be included in the count of 15 reference stations

- Daily agreement between the estimated coordinates of the reference stations and their coordinates in the EUREF reference frame solution: the agreement should remain below 10 mm on the horizontal and 15 mm on the Up component. If large outliers are found (several cm), eliminate the reference station from the daily SINEX (or normal equations).
- Time evolution of the daily ITRS coordinates: remove stations with gross outliers and reprocess the affected days without the(se) station(s).

## 4 Stacking and Reference Frame Definition

After computation of the daily coordinates, the next step consists of stacking the daily network solutions at the SINEX (or normal equation) level to estimate, for each station, coordinates (and velocities, if Class A validation is requested, see section 1). This section explains how this stacking should be performed.

### 4.1 Velocity Estimation

The advantage of estimating velocities is to extend the lifetime of the station coordinates. This is especially relevant in deformation zones.

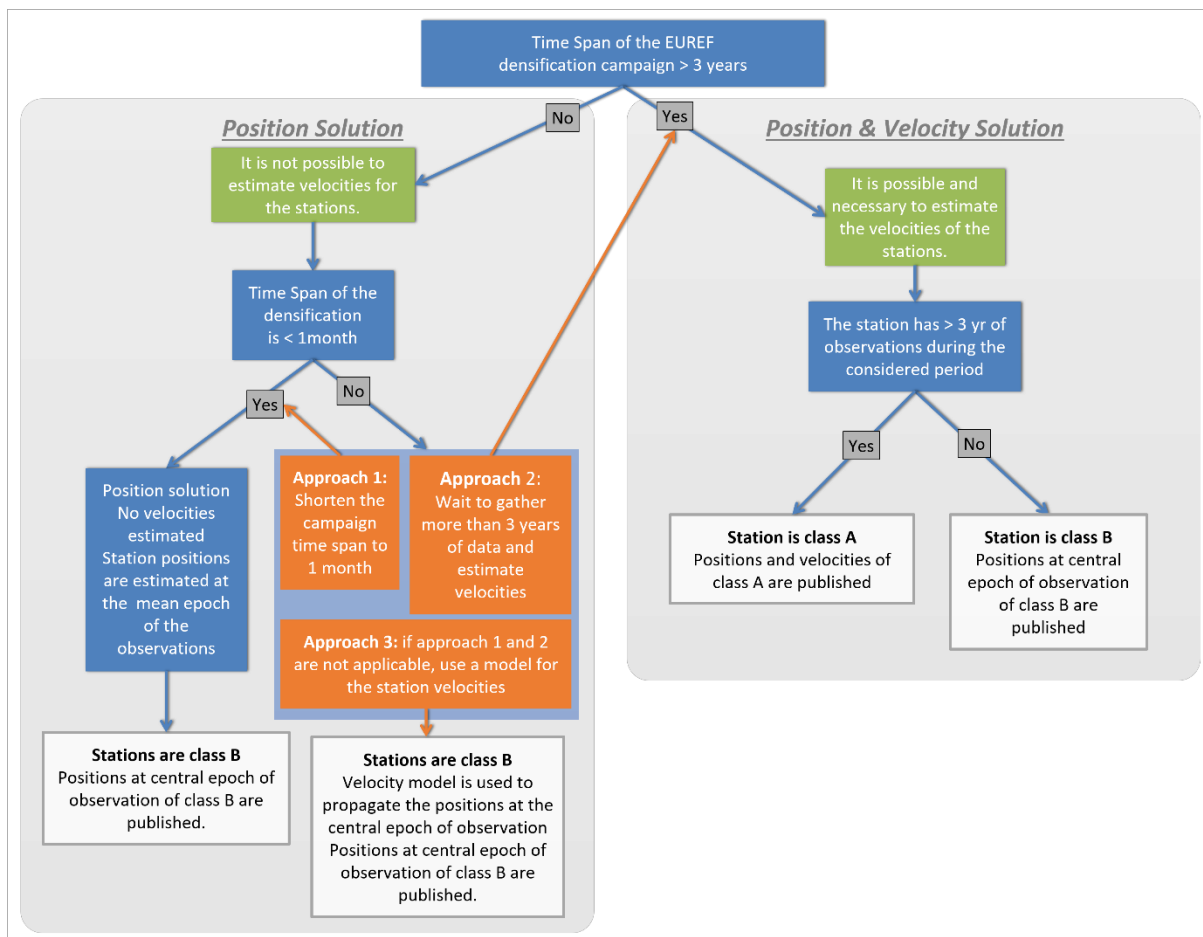


Figure 1: time duration of the EUREF densification campaign, velocity estimation and station classification

In order to estimate reliable and usable velocities, an observation time of at least 3 years is mandatory. In practice, 3 years is a strict minimum. The Figure 3 in Annex 2 illustrates the expected precision of

the velocity estimation as a function of the duration time. It highlights the importance of long time series in order to estimate reliable velocities, especially for the vertical component.

Figure 1 describes the relations between the time duration of the EUREF densification campaign, the estimation or modelling of the velocities, and their impact on the station classification (A and B).

For EUREF densification campaigns with more than 3 years of observations (right side of Figure 1), the velocities are mandatory estimated for all the stations. Stations with more than 3 years of observations will be published as class A stations (positions and velocities). The other stations will be class B (positions only).

For EUREF densification campaigns of less than 1 month of observations, the station positions will not change significantly due to the tectonic plate motion or deformations. Hence, velocities can be neglected (left side of Figure 1).

Densification campaigns between 1 month and 3 years (left side of Figure 1) are more complex. Because it is not possible to estimate a reliable velocity with such a short period and due to tectonics, post-glacial rebound or other local or regional effects, the position of the stations will change significantly during the duration of the densification campaign. Two straightforward approaches are to:

- Approach 1: Shorten the campaign duration and apply the rule of 1 month of observations and estimate a position only solution: stations will be class B
- Approach 2: Wait to gather at least 3 years of observations in order to be able to estimate velocities

If none of these approaches is possible, then, to reduce the effect of the tectonic plate motion and the deformations, it is necessary to choose a velocity model to propagate the station positions at the mean epoch of observation (Approach 3). Several options are possible: velocity model from the ITRF2014, velocity estimated based on a mean value of the surrounding EPN stations, usage of other existing velocity models or deformation models,...

Contact the EUREF Governing Board to discuss the different options as early as possible in the process.

## **4.2 Optional Combination with EPN SINEX Solutions**

Depending on the available processing capacities, the daily network solutions of the densification project can optionally be combined at the SINEX level with the final daily combined SINEX solutions from the EPN (covering at least the period of the densification). This combination can be useful to verify your results, but also to obtain an extended European-wide network allowing to increase the number of reference stations and the stability of the reference frame definition. It can also be used to increase the length of the position time series in the EUREF densification campaign. However, it must be noted that the process of combining with the daily EPN solutions is not always straightforward and it is therefore recommended that only expert GNSS analysts apply it. Daily EPN solutions are available as SINEX files from the EUREF Regional Data Centre at BKG (see <https://epncb.oma.be/productsservices/analysiscentres/combinedeurefsolution.php> for more information or <ftp://igs.bkg.bund.de/EUREF/products/WWW/eurWWWWD.snx.Z>).

To increase the consistency, both the daily densification and EPN solutions should be generated with the same processing options. However, if the densification campaign includes data before GPS week 1934, then it should be processed using `epn_14.atx`, although the daily EPN solutions before GPS week 1934 were generated using `epn_08.atx`. Therefore, the positions of the daily EPN solutions before GPS week 1934 should first be converted to `epn_14.atx` by applying the latitude-dependent model (annex 3). Such corrected daily EPN solutions are not publicly available, but they can be provided by the RFC.



*Relevant verifications:*

- *Time series of the position residuals of the daily combinations in order to detect outliers, systematic effects,...*

### **4.3 Stacking and Computation of ITRS Coordinates**

The daily network solutions (or the extended daily densification network solutions (from 4.2)) are now stacked (combined at the SINEX or normal equation level) to compute ITRS coordinates at the central epoch (epoch of observation) of the EUREF densification campaign. For that purpose, the network must be tied to the EUREF reference frame product using minimum constraints (MC) on the coordinates as well as the velocities (if applicable) of the selected EPN reference stations (see section 3.2). During this process, the coordinates of all stations in the network (including the reference stations) are estimated. If applicable (see section 4.1) site velocities must be derived. Take into account, that if a station is affected by coordinate jumps (*discontinuities*), then multiple sets of coordinates (each with a validity period and a solution number (soln)) have to be estimated for that station.

*Relevant verifications:*

- *Residual position time series:*
  - *Daily repeatabilities (in North, East, Up) of the residual position time series of the EUREF densification campaign: outliers should be identified, explained and eliminated.*
  - *Inspect the residual position time series to detect position changes (jumps) and velocity changes (changes in the trend): position/velocity discontinuities should be added when necessary.*
- *Agreement between position/velocity changes (discontinuities) and discontinuity list of the EUREF reference frame product ([ftp://epncb.oma.be/pub/station/coord/EPN/EPN\\_discontinuities.snx](ftp://epncb.oma.be/pub/station/coord/EPN/EPN_discontinuities.snx) for the latest version).*
- *Reference frame alignment:*
  - Difference between the estimated coordinates (and velocities, if applicable) and reference frame coordinates (and velocities, if applicable) in EPN\_IGb14\_CWXXX, expressed in North, East and Up. Before comparison, the coordinates of the reference stations must be expressed at the same epoch as the estimated coordinates (epoch of observation) using the reference station velocities and taking into account the EUREF reference frame discontinuity list. If the differences exceed the thresholds in Annex 2, then affected reference station (or its specific solution number) should be excluded and the stacking should be iterated.*
    - *Displaying the North, East and Up components of the position and velocity differences on a map allows visualising systematic effects;*
    - *Histograms of the coordinate/velocity differences in the North, East and Up components are useful to detect biases and identify outliers.*

### **4.4 Transformation to ETRS89**

Convert the ITRS coordinates at the epoch of observation (and velocities, if applicable) obtained from section 4.3 to the ETRS89 by using the published transformation parameters (in EUREF TN-1, Altamimi (2018)). The ETRS89/ITRS transformation tool on the EPN web site can also be used to carry out the transformation (see [https://epncb.oma.be/productsservices/coord\\_trans/](https://epncb.oma.be/productsservices/coord_trans/)). The actual ITRS frame to be used is the ITRF2014. 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 its coordinates in this frame in order to minimize coordinate changes with respect to the previous national realization (also see resolution no 1 of the EUREF symposium in Wroclaw, 2017).



Provide the list of the official national ETRS89 coordinates used in the country. For this purpose, update the (.ETRF) file with official ETRS89 coordinates used in the country available from [http://pnac.swisstopo.admin.ch/divers/etrf\\_monitor/](http://pnac.swisstopo.admin.ch/divers/etrf_monitor/) or create one for your country. Make sure to keep the historical information and to specify the date when the coordinates are being used officially. The “valid from” date indicates the date at which the coordinates are officially introduced in the country.

Relevant verifications:

- Compare the obtained ETRS89 coordinates with the coordinates obtained from previous EUREF densification campaigns.
  - If the reference epochs are different, take (if available) the estimated velocities expressed in the chosen ETRS89 reference frame into account.
  - If the frames are different, convert from one frame to the other to reduce the impact of the frame change.

## 5 Summary of the Procedure

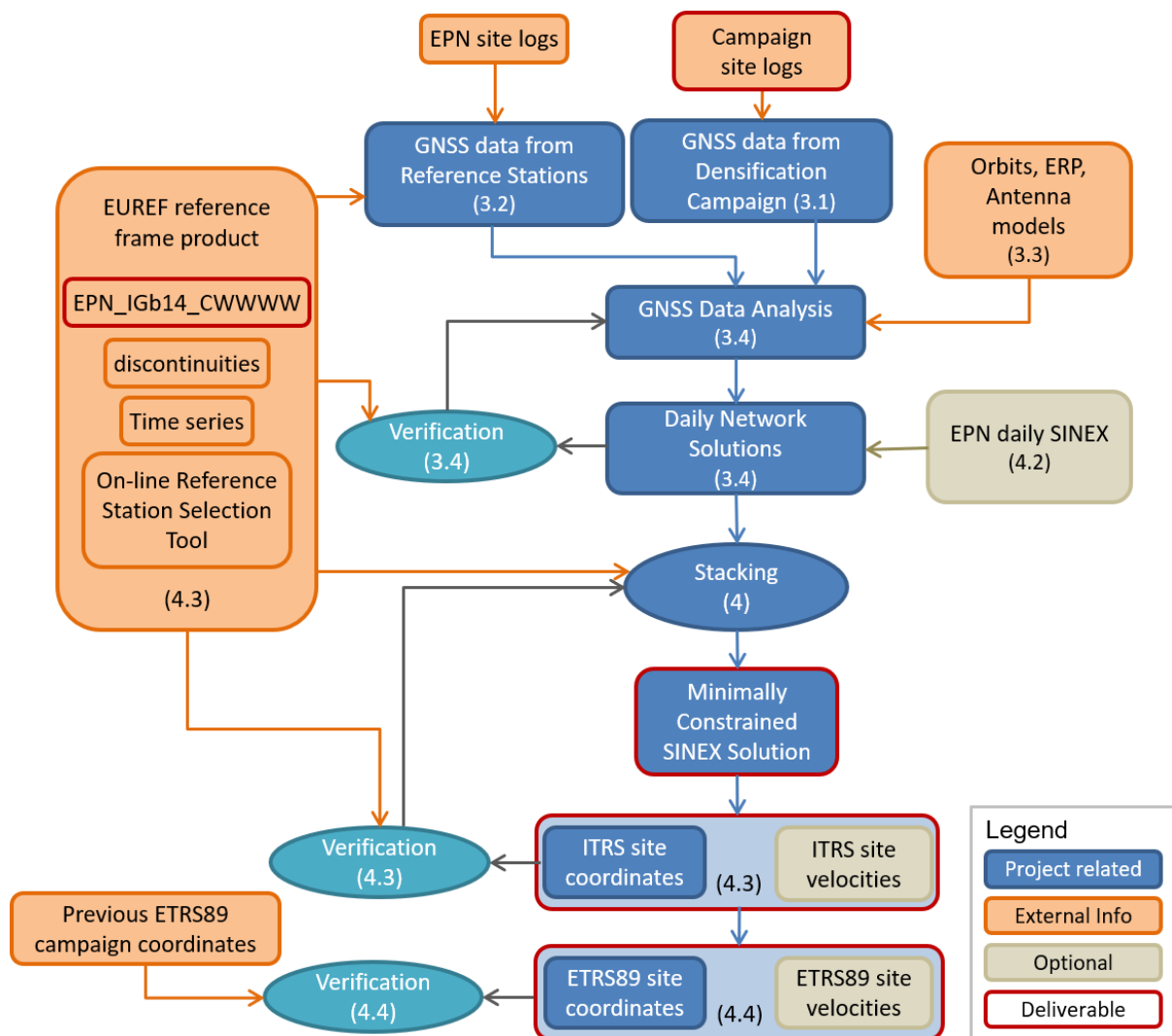


Figure 2: Summary of the procedure

## 6 Validation and Deliverables

If validation by the EUREF Governing Board (GB) is requested, then a full report of the EUREF densification campaign must be submitted to the EUREF GB at least 2 weeks before the next GB meeting and the analysis centre should present the results at this EUREF GB meeting.

### 6.1 Report to EUREF Governing Board

The report should contain:

1. Description of the densification project
  - a. List of densification stations (full names, 9-char ID, DOMES numbers, map)
  - b. Observation period (duration, permanent, campaign type)
  - c. GNSS equipment (IGS standard names for receiver and antenna/radome) and elevation cut off setting
  - 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 daily combined 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 (using the so-called “network approach”)
  - e. Modelling of loading effects
  - f. Ambiguity resolution strategy
  - g. Modelling of troposphere (e.g. a priori model, mapping function, constraints, gradients, ...)
  - h. Modelling of ionosphere (e.g. higher order corrections)
  - i. As far as they exist, alternative strategies used for test purposes
4. Results from the daily processing
  - a. Daily mean ambiguity resolution percentages, separated per system in case of a multi-GNSS solution
  - b. Daily agreement in North, East, and Up component between the estimated ITRS coordinates of the reference stations and their coordinates in the EUREF reference frame solution
5. Method of stacking the daily solutions
  - a. Method for stacking the daily network solutions in one densification solution
  - b. Parameters used to tie the densification solution to the EPN reference stations: name of the EPN SSC file (see section 3.2), parameters of the minimum constraint procedure, including list of EPN reference stations and used reference coordinates/velocities (and validity periods)
  - c. List of introduced discontinuities
6. Results from stacking the daily solutions
  - a. Residual position time series: comparison of the daily coordinate estimates of each station (repeatabilities in North, East and Up) with respect to the stacked solution. Outliers should be identified, explained and eliminated.
  - b. Comparison between estimated coordinates (and velocities, if applicable) and reference coordinates (and velocities, if applicable) in EPN\_IGb14\_CWXXX.SSC, expressed in

North, East and Up. Stations used as reference stations should be listed/mentioned (used in 5.b).

7. Transformation to ETRS89
  - a. Transformation to the ETRS89 (including parameters used and selected realization).
  - b. Comparison between new ETRS89 coordinates and ETRS89 coordinates from previous ETRS89 campaigns (expressed in North, East and Up).
  - c. Update of the country file with official ETRF coordinates used in the country, make sure to describe any specificities and to keep the historical information.

Remark: the SINEX files must be compliant with the official specifications and contain all the mandatory blocks.

## 6.2 Deliverables

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

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. Minimally constrained solution that is aligned to the EUREF reference frame product in SINEX format
3. List of position and velocity discontinuities (soln) of the densification solution
4. List of coordinates for all stations in the network in the ITRS at epoch of observation  
or  
List of coordinates and velocities for all stations in the network in the ITRS (for densification campaigns requiring velocity estimation)
5. List of coordinates for all stations in the network in the ETRS89 (indicate the frame used) at the epoch of observation  
or  
List of coordinates and velocities for all stations in the network in the ETRS89 (indicate the frame used)
6. List of EPN reference stations
7. Coordinates and velocities used for the EPN reference stations (including their validity period and name of the EPN\_IGb14\_CWXXX file, see 3.2.)
8. File with the official ETRS89 coordinates used in the country. For the format, please refer to existing files in [http://pnac.swisstopo.admin.ch/divers/etrf\\_monitor/](http://pnac.swisstopo.admin.ch/divers/etrf_monitor/).

## Annex 1: Historical Background

A first set of guidelines describing how to compute EUREF densifications using products from the International GPS Service was presented at the 1994 EUREF symposium in Warsaw (Gurtner, 1994). The basic principle consisted in first computing coordinates in the ITRF at the central epoch of observation by performing all GPS computations in the same ITRF (International Terrestrial Reference Frame) version as the one of the used IGS orbits. 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) using the Memo by Boucher and Altamimi (2011).

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 meantime. 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, 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 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.

In the meantime, the EPN, which was established in 1996 (Bruyninx, 2004), reached the maturity and reliability to be used directly to densify in Europe realisations of the ETRS89 or ITRS. In 2009, the "Guidelines for EUREF Densifications" outlined how this densification can be done and used the EPN station class A and B introduced by Kenyeres (2009). In the present guidelines, this classification is not used anymore for the EPN reference stations.

## **Annex 2: Thresholds for Verification of Reference Stations**

To verify the selected EPN reference stations, the difference between estimated coordinates (and velocities, if applicable) and coordinates<sup>6</sup> (and velocities, if applicable) in the EUREF reference frame solution must be checked against pre-defined thresholds. If these thresholds are not met for a specific reference station (or solution number), then it is advised to not use the affected station (or its solution number) as reference station.

For the positions-only solutions, the threshold for the difference is at 1 cm.

For the position and velocity solutions:

- Coordinates: the threshold for the difference is at 1 cm, but a much smaller difference can be expected (< 5 mm).
- Velocities: indicative thresholds are provided in the plot below. As can be seen from this plot, the thresholds depend on how long a reference station has been included in the EUREF densification campaign. The longer, the better the agreement of the velocities (and therefore also the positions) will be and consequently the reference frame definition of the EUREF densification campaign.

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<sup>6</sup> propagated to the epoch of observation of the campaign.

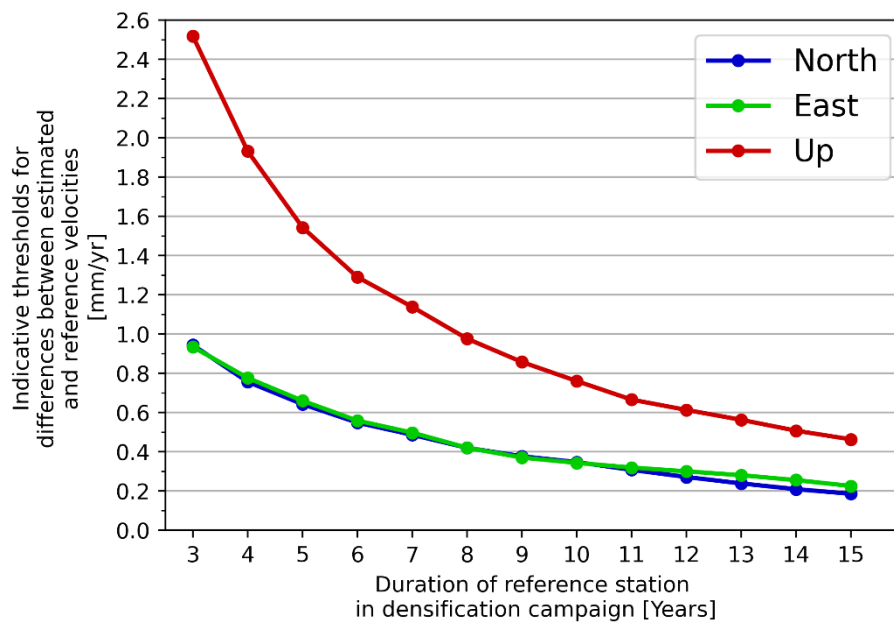


Figure 3: Indicative thresholds for difference between estimated velocities and EUREF reference frame velocities.

For the sake of comparison, when aligning the EUREF reference frame solution C2130 to the IGB14, 48 reference stations have been selected and the agreement between the solutions was better than resp. 2.5, 2.5 and 5 mm on the North, East and Up components for the positions and better than 0.2, 0.2 and 0.5 mm/yr on the North, East and Up components for the velocities.

### Annex 3: ITRFYYYY, IGSYY, IGBYY Frames

Throughout the years, the International Earth Rotations and Reference Systems Service (IERS) has released different realisations of the ITRS, the latest being ITRF2014 (Altamimi et al., 2016). However, to express coordinates in any frame, it is imperative that orbits, reference station coordinates and antenna calibrations are consistent. Therefore, to account for changing GNSS antenna calibrations, after recent ITRF releases, the International GNSS Service (IGS) corrects the ITRF coordinates of selected IGS stations to be fully consistent with the actual GNSS data analysis models. The lists of corrected station coordinates are known as IGSyy and their revisions IGByy, with yy referring the underlying ITRF. At the global level, the IGSyy and the IGByy are equivalent to the ITRFyyyy in the sense that they share the same underlying origin, scale and orientation.

In January 2017, the IGS published the IGS14 (Rebischung et al., 2016) together with a latitude-dependent models of position offsets expected from ground antenna calibration updates from igs08.atx to igs14.atx. The latitude dependant model can be used to estimate and remove or reduce the position offset that is expected when switching from igs08.atx to igs14.atx.

In May 2020, the IGS switched to IGB14 (Rebischung, 2020) for the generation of its products (orbits and coordinates/velocities). IGB14 is consistent with the igs14.atx antenna calibration model and is equivalent to the ITRF2014.

Consequently, from May 2020, the EUREF reference frame solution is aligned to the IGB14 reference frame solution.

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