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EDM-GNSS distance comparison at the EURO5000 calibration baseline: preliminary results

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Abstract: At the Pieniny Klippen Belt in Poland, the novel primary reference baseline EURO5000 is required as part of the European Research project GeoMetre to both validate refractivity-compensated EDM prototypes and investigate the metrological traceability of GNSS-based distances. Since the aimed uncertainty is 1 mm at 5 km ($k = 2$), the design, construction, and validation must be carefully prepared to fulfil the high standards of the GeoMetre field campaigns which are planned to be carried out in May 2022. This contribution describes the main features of the EURO5000 and presents the results of the preliminary validation which includes a first comparison between the results obtained by using precise currently available EDMs as well as GNSS techniques following the standard GNSS geodetic processing algorithms, on the one hand, and the improved GNSS-Based Distance Meter (GBDM+) approach developed at UPV, on the other hand. The preliminary validation presented in this contribution also permits (1) to detect potential problems in the use of the baseline such as potential geodynamic problems, atmospheric refraction or multipath limitations, (2) to produce a set of reliable results, and (3) to pave the way for the final field comparisons between the novel EDMs and the GBDM+ approach. The result of this metrological experiment may significantly contribute to overcome the limitations of current high-precision deformation monitoring applications that require their scale to be consistent with the SI-metre within 0.1 ppm in several km.

Keywords: air refractivity compensation; calibration baselines; GNSS-EDM comparison; SI traceability.

1 Introduction

At the Pieniny Klippen Belt in Poland, an area with extensive geodynamical research [1], several baselines of distances up to 5 km are being prepared by the Warsaw University of Technology (WUT) as primary references for long distance calibrations. These, which will be generically referred to as the EURO5000 reference baseline, constitute a novel primary reference baseline in Europe which will be eventually established as the European reference standard. The EURO5000 reference baseline provides electricity supply in each of its pillars to enable the use of the newly developed EDM prototypes Arpent and TeleYAG that are being developed, respectively, at the Conservatoire National des Arts et Métiers (CNAM) and the Physikalisch-Technische Bundesanstalt (PTB). The deployment of the EURO5000 reference baseline as well as the development of the two-colour EDM prototypes are part of the GeoMetre project [2], which aims at the determination of lengths directly traceable to the SI definition of the meter with uncertainties below 1 mm ($k = 2$) for distances up to 5 km. The project also seeks the development of a GNSS-based methodology for distance determination with complete characterization of the impact of each error source on the final distance, also expecting a corresponding uncertainty in the final distance below 1 mm ($k = 2$) for baselines up to 5 km, which is envisioned to be fulfilled by extension of the research already conducted at the Universitat Politècnica de València (UPV) for shorter baseline lengths [3].

A joint campaign at EURO5000 with participation of WUT, CNAM, PTB and UPV, with all their corresponding

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instruments and methodologies, is scheduled for summer 2022. Before this campaign is carried out, however, it was deemed necessary to perform a preliminary campaign by WUT (carried out in 5–9 September 2021) to obtain a first set of results and detect potential problems, whose results by means of precise currently available EDMs as well as GNSS techniques following the standard GNSS geodetic processing algorithms, on the one hand, and the improved GNSS-Based Distance Meter (GBDM+) UPV approach, on the other, are presented in this joint contribution.

2 EURO5000 main features

Concrete pillars of 30 cm diameter with a steel reinforcement have been constructed for each benchmark (Figures 1 and 2).

They allow for an instrument centering with tolerances of less than 0.1 mm (up to 0.05 mm) using a standard 5/8″ screw thread made of a brass alloy (Figure 3).

Suitable combinations of pillar pairs of the network (Figure 4, Table 1) provide a set of baseline lengths having approximate distances of 1 km, 2 km, 3 km, 4 km and 5 km, as detailed in Table 2, which is something desirable for the future European reference standard.

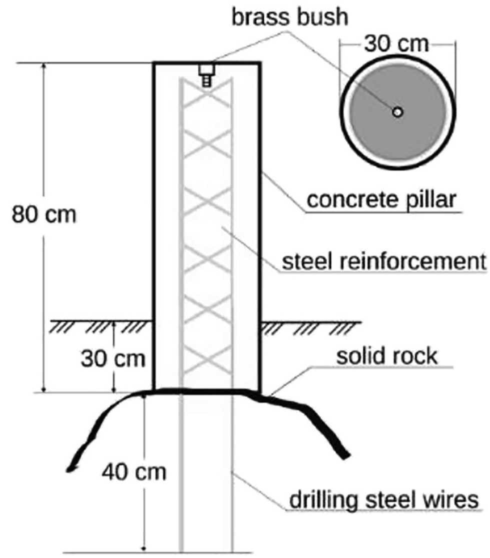

Figure 2: Constructive details of EURO5000 baseline pillars.

Figure 3: Top view of EURO5000 baseline pillar.

Figure 1: EURO5000 baseline pillar.

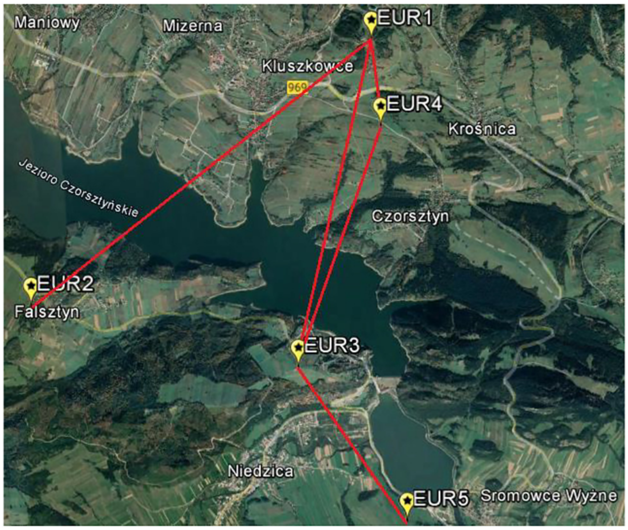

Figure 4: Layout of EURO5000 baseline.

Table 1: EURO5000 approximate point coordinates.

Point	Latitude	Longitude
EUR1	49°27′22.2″	20°19′12.0″
EUR2	49°25′39.0″	20°15′49.6″
EUR3	49°25′15.2″	20°18′29.4″
EUR4	49°26′49.4″	20°19′18.5″
EUR5	49°24′15.0″	20°19′35.0″

Table 2: EURO5000 baseline lengths and elevations.

Baseline	Approximate distance (m)	Approximate elevation between baseline ends
EUR1–EUR4	1021.95	−4.03°
EUR3–EUR5	2391.97	−2.93°
EUR3–EUR4	3074.44	1.45°
EUR1–EUR3	4016.10	−2.16°
EUR1–EUR2	5177.17	−0.79°

3 EDM length determination

In the remaining part of this contribution, for the sake of conciseness we restrict the presentation to the EUR1–EUR2 baseline, which due to its longer length (approximately 5177.17 m.) constitutes the most difficult challenge in terms of achievable accuracy.

In the September 2021 observation campaign, EDM measurements were performed during 1 h at intervals of 2 min with the Leica TC2002 total station, an instrument which yields an accuracy of 1 mm ± 1 ppm after proper correction of meteorological conditions. These were performed from meteorological observations taken at the baseline ends with Vaisala barometers of 0.2 h Pa accuracy and Assmann Aspiration Psychrometers of 0.5 C accuracy by following the Ciddor and Hill formula [4] as corrected by Pollinger [5].

The final distance resulted 5177.1758 m with an experimental standard deviation of 0.0073 m ($k = 1$) as computed from the available measurement sample.

4 GNSS length determination

As previously mentioned, the distance for the EUR1–EUR2 baseline has been determined by two different approaches: on the one hand, the team at WUT determined the distance following the standard GNSS geodetic processing algorithms using Trimble Business Center (TBC) software, and on the other hand, the team at UPV determined the distance by using the improved GNSS-Based Distance Meter (GBDM+) approach which is being developed at UPV with their corresponding software. A set of continuous GNSS multiconstellation (GPS, Galileo, Glonass and Beidou-2) data for both EUR1 and EUR2 stations, which spanned more than 3 consecutive days between the 5th and the 9th of September 2021 (approximately 88 h of common time) with 30 s observation epochs, was available for the baseline length determination.

4.1 GNSS geodetic processing

Processing of GNSS observations using TBC software was performed in a single-baseline solution. The static double-differenced dual-frequency L_1/L_2 code and carrier-phase observation model were used with the elevation cut-off parameter of 10 deg and 30 s measurement interval.

This resulted in 5177.1735 m with an uncertainty of 0.0013 m ($k = 1$), in good agreement with the value determined by EDM (that is, well within the corresponding uncertainty limits).

4.2 GNSS-based distance meter

Specially tailored to the optimal determination of distance is the methodology developed at the UPV named as improved GNSS-Based Distance Meter (GBDM+). It stems from previous works by the group originated in the “Development of methodology and algorithms for GNSS application to high precision absolute distance determination” 2012–2015 research project funded by the Spanish Ministry of Science and Innovation, and the publications [3, 6–10] where the distances concerned were shorter than 1 km, now improved to allow for longer distances up to 5 km.

The mathematical model permits the study of the impact of all relevant error sources on the particular distance and, in consequence, permits to mitigate the influence of these error sources in the determination of the distance. By principle, the focus is thus kept on the baseline distance and its corresponding accuracy while leaving aside the possible optimization of the determination of other parameters (baseline azimuth and height difference).

The carrier-phase observation equation for receiver i and satellite k can be written (slightly adapted from [3]) as

$$\Phi_i^k = \rho_i^k + \lambda N_i^k + c\mathrm{d}t_i - c\mathrm{d}t^k - I_i^k + T_i^k + \mathrm{MP}_i^k + \delta_i - \delta^k + \varepsilon_i^k \quad (1)$$

where λ is the carrier wavelength, Φ_i^k is the carrier phase observation in length units (that is $\lambda\varphi_i^k$ with φ_i^k in full cycles), ρ_i^k is the geometric distance between satellite and receiver (at the particular point of reception of the antenna), N_i^k is the integer ambiguity, c is the light speed in the vacuum, $\mathrm{d}t_i$ and $\mathrm{d}t^k$ are the receiver and satellite clock offsets, respectively, I_i^k and T_i^k are the slant ionospheric and tropospheric delays, respectively, MP_i^k is the carrier phase multipath error, δ_i and δ^k represent hardware biases and initial carrier phase offsets in the receiver and the satellite, respectively, and ε_i^k is the remaining (unmodelled) observation error.

It is worth noting that this formulation explicitly includes a multipath term, MP_i^k, in order to highlight the existence of this error, contrary to other expressions that incorporate this error in the lumped term ε_i^k. Antenna phase center offset and phase center variations are assumed to have been previously corrected with absolute calibration models: the latest release of the IGS ANTEX file as of the time of the observation, for the case of satellite antennas, and individual (if available) or generic (the same IGS ANTEX file) antenna calibration models for the case of receiver antennas.

For a pair of receivers i and j and a pair of satellites k and l, the following scheme of double differences can be formed

$$(\cdot)_{ij}^{kl} = (\cdot)_j^l - (\cdot)_j^k - (\cdot)_i^l + (\cdot)_i^k \quad (2)$$

resulting in the equation

$$\Phi_{ij}^{kl} = \rho_{ij}^{kl} + \lambda N_{ij}^{kl} - I_{ij}^{kl} + T_{ij}^{kl} + \mathrm{MP}_{ij}^{kl} + \varepsilon_{ij}^{kl} \quad (3)$$

where common errors have cancelled.

Using some approximate coordinates for the receivers (helding fixed those of receiver i) along with coordinates for the satellites (from precise ephemerides) it is possible to use a linear expansion in terms of unknown corrections to the approximate coordinates of receiver j, $\mathrm{d}X_j$, $\mathrm{d}Y_j$ and $\mathrm{d}Z_j$

$$\Phi_{ij}^{kl} - \rho_{ij0}^{kl} = \lambda N_{ij}^{kl} + \left(\frac{\partial\rho_{ij}^{kl}}{\partial X_j}\right)_0 \mathrm{d}X_j + \left(\frac{\partial\rho_{ij}^{kl}}{\partial Y_j}\right)_0 \mathrm{d}Y_j + \left(\frac{\partial\rho_{ij}^{kl}}{\partial Z_j}\right)_0 \mathrm{d}Z_j - I_{ij}^{kl} + T_{ij}^{kl} + \mathrm{MP}_{ij}^{kl} + \varepsilon_{ij}^{kl} \quad (4)$$

The least-squares solution of a system of equations of the form of Eq. (4) is standard in the literature. However, we make the following improvements and particularizations aiming at a better study and determination of the baseline distance.

First, assuming the integer ambiguity values could be known and subtracted from the left-hand side, and ionospheric and tropospheric delays as well as the multipath errors could be either neglected or determined somehow and subtracted from the left-hand side, the system of equations could be represented as

$$\boldsymbol{k} + \boldsymbol{r} = \boldsymbol{A}\boldsymbol{x} \quad (5)$$

where vector $\boldsymbol{k}$ contains the values $\Phi_{ij}^{kl} - \rho_{ij0}^{kl}$, vector $\boldsymbol{r}$ contains the values $-\varepsilon_{ij}^{kl}$, and $\boldsymbol{A}$ is the corresponding coefficient matrix (whose elements are the above partial derivatives) for the vector of unknowns

$$\boldsymbol{x} = \begin{pmatrix} \mathrm{d}X_j \\ \mathrm{d}Y_j \\ \mathrm{d}Z_j \end{pmatrix} \quad (6)$$

We can make use of the Jacobian and rotation matrices $\boldsymbol{J}$ and $\boldsymbol{R}$ that permit to directly obtain the correction to the approximate distance $\mathrm{d}D_{ij}$ as the first unknown (which will be of particular interest for analyzing the impact of each error source in the resulting distance) as well as corrections to the approximate azimuth and height difference, respectively $\mathrm{d}\alpha_{ij}$ and $\mathrm{d}z_{ij}$

$$\boldsymbol{x}' = \boldsymbol{J}\boldsymbol{R}\boldsymbol{x} = \begin{pmatrix} \mathrm{d}D_{ij} \\ \mathrm{d}\alpha_{ij} \\ \mathrm{d}z_{ij} \end{pmatrix} \quad (7)$$

$$\boldsymbol{k} + \boldsymbol{r} = \boldsymbol{B}\boldsymbol{x}' \quad (8)$$

with the new coefficient matrix $\boldsymbol{B}$ that can be obtained as

$$\boldsymbol{B} = \boldsymbol{A}\boldsymbol{R}^{\boldsymbol{T}}\boldsymbol{J}^{-1} \quad (9)$$

The solution of the system of equations in Eq. (8)

$$x' = \left(B^T P B\right)^{-1} B^T P k \qquad (10)$$

where $\boldsymbol{P}$ is the weight matrix of the equation system, permits to obtain as the first unknown $\boldsymbol{x}(1)$ the correction to the initial approximate distance in terms of the approximate coordinates used for the receivers, as well as the corresponding precision in the first element of the covariance matrix, $\boldsymbol{C_X}(1,1)$, which is obtained as

$$C_{x'} = \hat{\sigma}_0{}^2 \left(B^T P B\right)^{-1} \qquad (11)$$

where $\hat{\sigma}_0{}^2$ is the variance of unit weight.

Considering that the dedicated measurement campaign of the Geometre project is being carried out in summer 2022, we are aiming to obtain in the current contribution some preliminary results by using the above-mentioned initial campaign measured by WUT. Several ingredients of the approach currently followed need to be clarified.

In [11] it was demonstrated that the availability of accurate coordinates (at the level of 3 cm of accuracy or better) for the receivers permits to avoid the estimation of ambiguities, thus strengthening the estimation capabilities of the model, provided the other sources of error are of a smaller order. For baselines of the order of a few kilometers not necessarily horizontal, which are the current objective, this may be difficult to ensure due to the possible sizes of the double differenced ionospheric and tropospheric delays, as well as the double differenced carrier phase multipath, that is, I_{ij}^{kl}, T_{ij}^{kl}, and MP_{ij}^{kl}, respectively, in Eq. (4). Ambiguity resolution is therefore required in the case of not short and not horizontal baselines possibly with not little multipath effect.

Accurate coordinates for the receiver positions are nevertheless used as a starting point. They have been obtained by Precise Point Positioning using the CSRS-PPP service version 3 [12], which gives coordinates with accuracies between 1 and 4 mm ($k = 2$) for EUR1 and EUR2 stations with the observed dataset. The CSRS-PPP service also gives estimates for the values and corresponding uncertainties of the receiver clocks and zenith tropospheric delays, as well as observation residuals. No estimates for the ionospheric delay are currently provided.

It was concluded in the *Good practice guide for high accuracy global navigation satellite system based distance metrology* [13] referring to ionospheric and tropospheric delays, multipath effects and antenna phase center variations that “uncertainties of these estimations are mostly unknown, and especially their propagation into the final results”. This has critically damaged so far the metrological value of GNSS-based distance determinations.

We will now study how the estimated error in the tropospheric delays enters into the particular scheme of double difference equations used and propagates to the final distance estimation.

Figure 5 gives an idea of the size of the double-differenced tropospheric delay for the particular double difference equations formed in the case of the EUR2–EUR1 baseline using the first hour of GNSS observations (5-Sep-2021 time interval 17:32:30-18:32:29). They have been computed from the zenith tropospheric delays estimated by the CSRS-PPP.

As we can see, they reach several centimeters; these are mainly due to the existing height difference of around 70 m. It seems to be clear that this double differenced error should not be disregarded, but how could we compute the effect onto the final distance estimation?

The least-squares solution to the equation system, namely Eq. (10), can be written by defining a new matrix

$$M = \left(B^T P B\right)^{-1} B^T P \qquad (12)$$

as

$$x' = Mk \qquad (13)$$

and the effect of some type of particular errors (or uncertainties if the estimated values are used as corrections in the model) in each of the observations (here the estimated double-differenced tropospheric delay errors or uncertainties $u_{\text{DD-tr1}}$, $u_{\text{DD-tr2}}$, etc.) onto the final distance can be obtained by the law of covariance matrix propagation

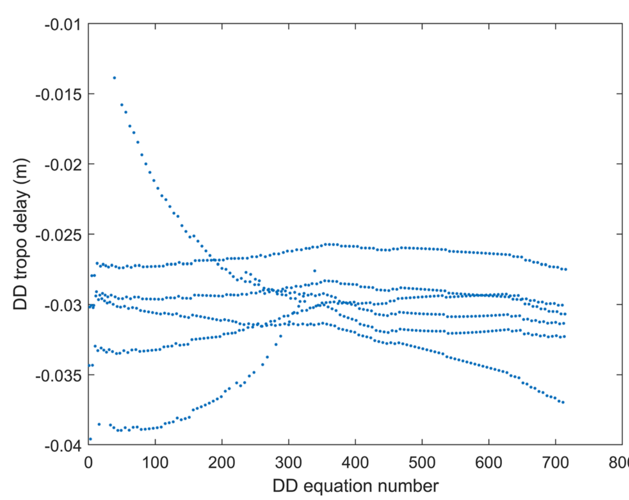

Figure 5: Double-differenced tropospheric delay for EUR2–EUR1 baseline (5-Sep-2021 17:32:30-18:32:29) as computed from hydrostatic and wet delay (with horizontal gradients) CSRS-PPP estimates mapped onto the slanted observations ($k = 2$).

as

$$\boldsymbol{C}_{x'} = \boldsymbol{M}\boldsymbol{C}_k\boldsymbol{M}^T \tag{14}$$

where

$$\boldsymbol{C}_k = \begin{pmatrix} {u_{\mathrm{DD-tr1}}}^2 & & \\ & {u_{\mathrm{DD-tr2}}}^2 & \\ & & \dots \end{pmatrix} \tag{15}$$

and

$$u_{\mathrm{D_{tr}}} = \sqrt{\boldsymbol{C}_{x'}(1,1)} \tag{16}$$

is the estimated error (or uncertainty if the estimated values are used as corrections in the model) in the final distance.

We can now study the degree of accuracy of double-differenced tropospheric delay corrections to obtain, e.g., uncertainties of, say, 0.4 mm or less (for the particular baseline and a particular observation time span). Figure 6. shows the impact onto the estimated baseline distance of several errors or uncertainties in the double differenced tropospheric delay again for the EUR2–EUR1 baseline using the particular double difference equations formed for different time spans starting on 5-Sep-2021 17:32:30.

As it can be seen, the use of at least 3 or 4 h-time spans permits to go below 0.4 mm in the final distance for errors or uncertainties in the double differenced tropospheric delays of 1 cm. This error size is only a theoretical value that serves as a general indication, but a particular analysis using each of the errors or uncertainties in the double differences as an input in Eq. (15) should be preferred.

This scheme is also valid to study the effect of the errors or uncertainties in the other error sources onto the final distance, provided these errors or uncertainties are reliably known.

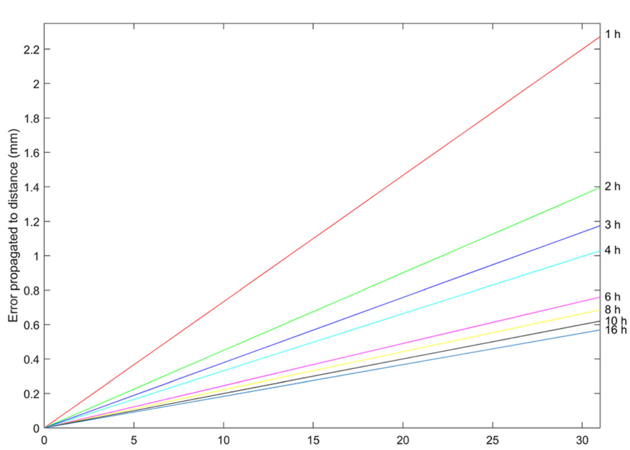

Figure 6: Impact onto the estimated baseline distance of several errors or uncertainties in the double differenced tropospheric delay for the equations used in the EUR2–EUR1 for different computation time spans starting on 5-Sep-2021 17:32:30.

For the case of the carrier phase multipath we can obtain a correction model and the corresponding uncertainty estimations by means of the sidereal filtering approach [3]. This strategy is only valid, however, for the usage of GPS observations due to the apparent repeat period of the constellation of one sidereal day. In the present case, we experienced differences amounting to only 0.1 mm in the final distance for the sidereal filtering technique to cope with the multipath with respect to disregarding the effect. This is little surprising as the multipath effect influence tends to cancel out with long observation time spans. Furthermore, it is clear that the sidereal filtering matching could be better done with higher observation rates (e.g. 1 s) and may perform suboptimal with the available observation epochs of 30 s.

In the case of the ionospheric delay, it is well-known that it can be safely eliminated in the double-differenced equations for lengths of a few kilometers by means of the L_3 carrier phase combination. An alternative approach might consist in the use of the Klobuchar model, which is known to correct only around 50% of the (absolute) ionospheric delay, but in the present case seems to cancel the effect in the double differences so well that the results show little discrepancies (less than 1 mm) with respect to those of L_3. This has to be further researched, however.

Also pending is the way to estimate the uncertainties in antenna phase center offsets and variations and their impact on the final distance, although some related research has been already conducted [14, 15].

All in all, we present in Table 3 a summary of the GBDM+ results obtained for the EUR2–EUR1 baseline distance after averaging the results of adjustments for observation blocks of various time spans.

If we group the observations in blocks of, say, 1 h time span we can compute 88 baseline lengths (remember we had 88 h of observation). We can obtain the mean value of the sample of results as well as the median and the standard deviation of the mean. As each of the resulting

Table 3: EUR2–EUR1 baseline lengths obtained by the GBDM+ methodology for different observation time blocks.

Observ. blocks	Mean	Median	σ_{mean}	Averaged mean
1 h	5177.1747	5177.1751	0.0009	5177.1749
2 h	5177.1737	5177.1744	0.0007	5177.1736
3 h	5177.1744	5177.1734	0.0007	5177.1742
4 h	5177.1737	5177.1738	0.0006	5177.1734
6 h	5177.1740	5177.1737	0.0006	5177.1737
8 h	5177.1733	5177.1730	0.0003	5177.1731

88 baseline lengths comes with its corresponding standard deviation, which has been determined in the least squares adjustment, we can also use these standard deviations along with the corresponding baseline lengths to compute an averaged mean.

One could expect that the values given by the mean and the median be relatively close to each other, provided all errors had been properly corrected or cancelled. This seems not to be the case of the 2 and 3 h time blocks, where the discrepancies between mean and median are 0.7 and 1.0 mm, respectively. One could also expect that the standard deviation of the mean is small. As we can see in Table 3 it is decreasing as the length of time blocks increases. These two features seem to be due to the presence of residual, uncorrected, errors in the observations which get increasingly diminished for longer observation time blocks. This issue is little unexpected, as we were already reasoning for the results in Figure 6.

In view of the above, we can conclude that the results are relatively reliable for observation time blocks of 4, 6 and 8 h. These give for the baseline length values between 5177.1731 and 5177.1737 (if we refer to the averaged means), perfectly consistent with the determinations both by traditional GNSS geodetic methods and the use of precise EDM as given before. We are not tempted, however, to select one and only one of the results in Table 3 as the correct length before some additional research is done. In fact, the longer observation time and the smaller standard deviation might lead us to select the 8 h result as the best, but its difference of 0.3 mm between mean and median is certainly not preferable to the difference of only 0.1 mm between mean and median for the 4 h result (which has, however, a higher standard deviation).

A definite choice will not be fixed until some issues, which have not been completely addressed for the moment, are properly dealt with. This is the case of individual antenna calibration models, since in the current case we have used only a generic antenna calibration model (the last IGS ANTEX model as of the time of the observation). This is also the case of the proper estimation and propagation of all relevant sources of error to the final result. The ionospheric double difference error, for example, is still left to be properly estimated.

Some other interesting results we have come across with regarding the use of different strategies are summarized in Table 4.

Even focusing on the millimeter order of magnitude only, we can draw some useful conclusions:

- Neglecting the double differenced tropospheric delay causes a significant bias of the baseline length of around 8 mm. The tropospheric delay entering the double difference equations is significant and should not be neglected, at least for this baseline with an existing height difference of around 70 m.
- The use of one tropospheric model or other (the results of the two included in Table 4 are given as obtained by Leica Infinity), or the use of the estimated delays given by the CSRS-PPP service, provide very similar results to the level of a few tenths of a millimeter only.
- Also of few tenths of a millimeter was the difference between the results by the L_3 combination and those by L_1 with Klobuchar model, but the use of L_1 without any ionospheric model produces lengths with a consistent bias of the order of 1.5 mm.

Table 4: EUR2-EUR1 baseline lengths obtained with different assumptions or models.

Strategy	Resulting length
No tropospheric correction	5177.1813
Use of CSRS-PPP tropospheric delays	5177.1734
Use of GPT2 tropospheric model with VMF	5177.1733
Use of Hopfield tropospheric model with VMF	5177.1735
L_1 with no ionospheric model (no Klobuchar)	5177.1750

5 Conclusions

The EURO5000 reference baseline, which constitutes a novel primary reference baseline in Europe eventually to be established as the European reference standard, has been presented. Its preparation as part of the European research project GeoMetre complements other efforts aiming at the determination of lengths directly traceable to the SI definition of the meter with uncertainties below 1 mm ($k = 2$) for distances up to 5 km, which include the development of two-color EDM prototypes and a GNSS-based methodology (named GBDM+) which will be contrasted in a joint campaign.

The GBDM+ methodology is expected to be completely developed by summer 2022, where it will be applied to the observation campaign of the EURO5000 baseline. Some significant advancements have been already carried out, they have been presented in the current contribution and yielded some useful preliminary results for the EURO5000 baseline. Among them we can mention the determination of a baseline length with a bias of around 8 mm if double differenced tropospheric delays are neglected, the determination of a baseline length with a bias of around 1.5 mm if double differenced ionospheric delays are neglected, and no significant impact of the multipath effect (after significantly long averaging times) on the final results.

Other aspects, including the impact of the use of individual antenna calibration instead of a general model are still to be researched. They will be applied in the final field comparisons between the novel EDMs and the GBDM+ approach.

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