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The impact of estimating common tropospheric parameters for co-located VLBI radio telescopes on geodetic parameters during CONT17

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Abstract

The Continuous Very Long Baseline Interferometry (VLBI) campaign 2017 (CONT17) differs from previous CONT campaigns as there are three independent networks observing in parallel; two legacy VLBI networks observing in S/X band (Legacy-1 and Legacy-2) and one VGOS (the next generation VLBI system: VLBI2010) network observing in broadbrand. Co-located VLBI radio telescopes across the networks could be combined to strengthen the geodetic solutions from CONT17 by using local ties. Moreover, it is widely known that the co-located VLBI radio telescopes observe common effects such as the tropospheric delays in a similar way. Therefore, we can not only combine the station coordinates, but we can also combine the tropospheric parameters. In this work, we focused on the impact of combining the tropospheric parameters obtained at co-located VLBI telescopes on the estimated geodetic parameters during CONT17. We considered three case studies where we combined: (i) the Legacy-1 and the Legacy-2 networks, (ii) the Legacy-1 and the VGOS networks, and (iii) the Legacy-1, the Legacy-2, and the VGOS networks. The results show an improvement in station position repeatability when combining the tropospheric parameters w.r.t. applying only local ties by 28%, 15%, and 26% respectively. Station coordinates at the VLBI radio telescopes of the Legacy-1 network were not affected by this approach as they were used for the datum definition. In addition, the baseline length repeatabilities show no improvement when combining the tropospheric parameters. Moreover, the agreement between the tropospheric parameters from VLBI and tropospheric parameters from independent GNSS data analysis and ray-tracing through ERA5 improves due to the network combination.

Keywords: VLBI; Co-location telescopes; Tropospheric parameters; CONT17; Normal equation combination

1. Introduction

Very Long Baseline Interferometry (VLBI) is one of four space geodetic techniques that allow to estimate geodetic parameters and provide an important contribution to the International Terrestrial Reference Frame (ITRF) and the realization of the International Celestial Reference System (ICRS). In order to reach the Global Geodetic Observing System (GGOS) goals (Plag et al., 2009), one way is to combine the observations from co-located VLBI radio telescopes at co-location sites. With this method, the number of scans could increase by up to

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a factor of two (Nilsson et al., 2015). The essential information for connecting co-located VLBI radio telescopes is local ties between co-located VLBI radio telescopes. Our target is to reach a position accuracy of 1 mm according to the GGOS requirement. For this purpose, the local ties are required with sub-mm accuracy. However, many reasons, such as precisely accessing the reference points by other measurement techniques (during surveying or leveling), the unmodelled or improperly modelled temporal variations of the reference points' positions of space geodetic instruments, and the transformation of the measured local tie from local coordinates into geocentric coordinates (Glaser et al., 2019) could affect the local ties and cause biases in the combined VLBI geodetic solutions. In order to mitigate this effect, one could combine tropospheric parameters with tropospheric ties along with local ties since the co-located VLBI radio telescopes are subject to the same atmosphere. Balidakis et al. (2019) have shown that tropospheric ties slightly reduce the effect from biased local ties when combining space geodetic techniques through simulation. Moreover, tropospheric ties can be used to detect biases in local ties. The Continuous Very Long Baseline Interferometry campaign 2017 (CONT17) is a suitable VLBI dataset to investigate this aspect. The CONT17 campaign is a series of VLBI experiments observed during 28 November - 12 December 2017.[1] CONT17 is the latest in a succession of VLBI continuous campaigns that have been performed since 1994. However, CONT17 is an exceptional campaign compared to the previous CONT campaigns due to the observation of three networks in parallel. It consists of two S/X networks, namely Legacy-1 and Legacy-2, and one VGOS (the next generation VLBI system: VLBI2010) network (Behrend et al., 2020). The CONT17 campaign was designed for scientific investigation in many aspects like the previous CONT campaigns, such as improving the reference frame determination, determining sub-daily Earth Orientation Parameters (EOP), validating the ocean tide model, and studying tropospheric and ionospheric effects. In addition, the results could be compared to parameters obtained from other space geodetic techniques, e.g., Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), and Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS), for validation or combination of many scientific aspects (Bolotin et al., 2018).

CONT17 features three networks that are observed in parallel. However, if one of the networks has no station with accurate station coordinates (preferably in the latest ITRF2014 reference frame (Altamimi et al., 2016)), this network need to be aligned to the latest ITRF to ensure the consistency of the geodetic solutions produced by the analysis of the other two networks. During the CONT17 campaign, three telescopes belonging to different networks could be used as co-location sites. Therefore, these VLBI-VLBI co-location sites allow linking stations between networks when combining VLBI networks in CONT17. Typically, combining co-located VLBI radio telescopes can be done for the station coordinate parameters. However, normally, the distance between co-located telescopes is less than a few kilometers horizontally and less than 100 m vertically; thus, the atmospheric effects are expected to be similar (Teke et al., 2013; Hobiger and Otsubo, 2014). Nilsson et al. (2015) have investigated the possibility of combining the tropospheric parameters for co-located VLBI radio telescopes through simulations. An improvement in the station coordinates from combining tropospheric parameters between co-located VLBI radio telescopes was found if the distances between VLBI radio telescopes were less than 1 km. In addition, there were several studies where tropospheric parameters and station coordinates were combined with other techniques, e.g., GNSS, at the stations co-located with VLBI radio telescopes, e.g., by Krügel et al. (2007, 2014, 2019). These studies showed that combining the tropospheric parameters could improve the station coordinates and tropospheric parameters themselves. Therefore, combining the tropospheric parameters between co-located VLBI radio telescopes should improve the estimated geodetic parameters from VLBI during the CONT17 campaign.

This article investigates, based on observations of simultaneously observing co-located VLBI radio-telescopes during CONT17, the impact of combining tropospheric parameters at the normal equation level on geodetic parameters. Additionally, external tropospheric parameters from GNSS and the state-of-the-art ERA5 Numerical Weather Model (NWM) (Hersbach et al., 2020) are employed to validate the tropospheric parameters from the intra-VLBI combination. The data analysis, combination procedure as well as observations are presented in Section 2. The results are described in Section 3. Finally, the conclusions are presented in Section 4.

2. CONT17, co-located telescopes, ties and combination method

This section describes the dataset and the method to combine VLBI networks through co-located VLBI radio telescopes in the CONT17 campaign.

2.1. CONT17

The CONT17 campaign collected data of three parallel networks: two legacy S/X networks (Legacy-1 and Legacy-2), which are observed continuously for 15 days, from 00:00 UT to 23:59 UT from 28 November until 12 December 2017. Moreover, the VGOS network participated for five days in the middle of CONT17 (December 4–8, 2017). Thus, these networks were observed for the whole period of CONT17 independently. The Legacy-1 network consists of 14 globally distributed stations on five continents. The Legacy-2 consists of 13 stations, most of

[1] https://ivscc.gsfc.nasa.gov/program/cont17/.

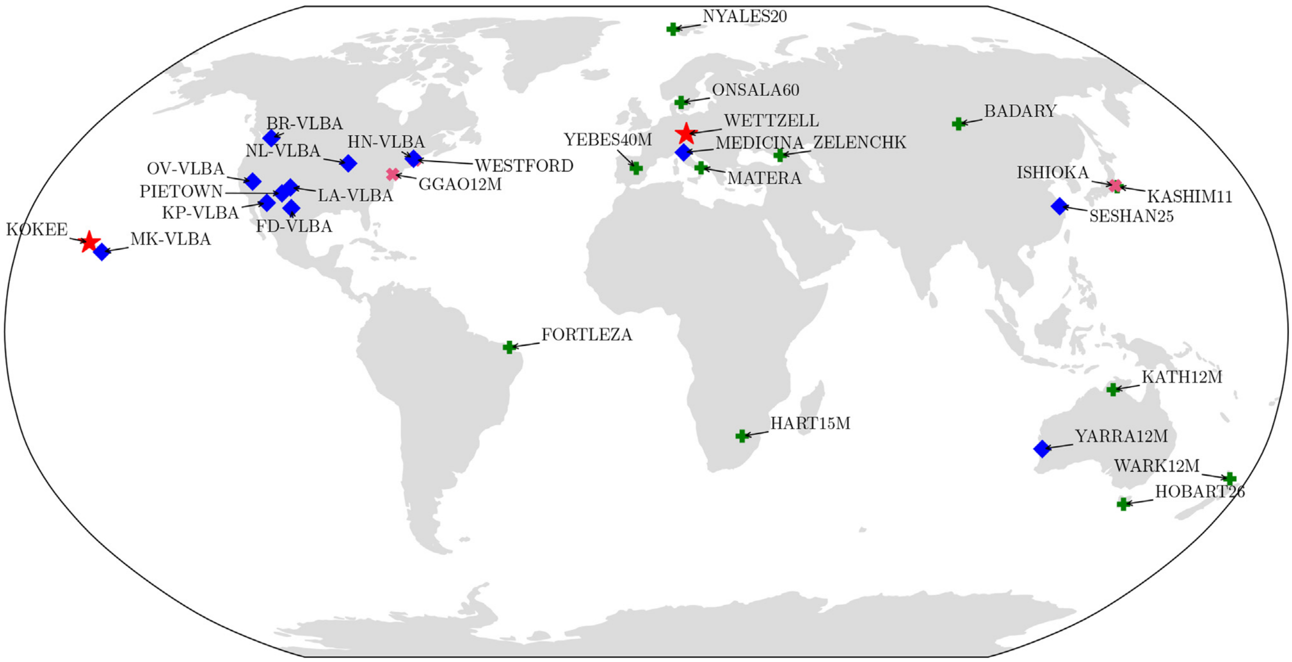


Fig. 1. Map of the VLBI stations that participate in CONT17. The Legacy-1 network stations are indicated as green plus. The Legacy-2 network stations are indicated as blue diamonds. The VGOS network stations are indicated as pink crosses. Red stars show co-location VLBI sites in CONT17.

which constitute the VLBA (Very Long Baseline Array), located in the USA. On the other hand, the VGOS network observes only six stations located in the northern hemisphere. The unique setup allows for an intra-VLBI combination, which is carried out in this study (see Fig. 1).

2.2. Co-located VLBI radio telescopes and GNSS stations during CONT17

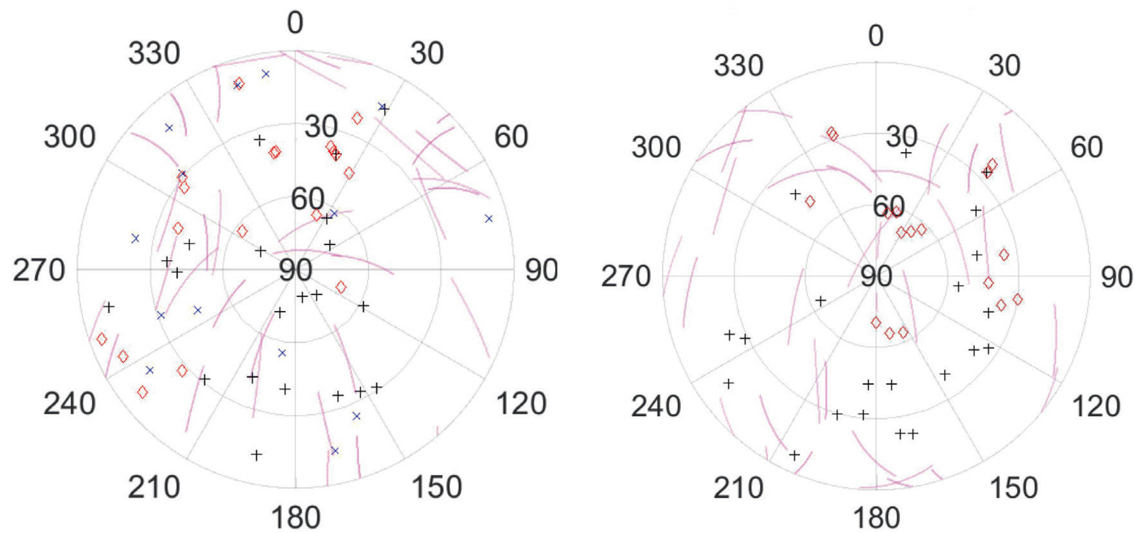
Co-located VLBI radio telescopes in the CONT17 campaign are located at Wettzell (Germany) (Neidhardt et al., 2011), Yebes (Yebes, Spain), and Kokee Park (Hawaii, USA) (Niell et al., 2016), and could be combined to improve the geodetic solutions from VLBI. In addition, the station coordinates and the tropospheric parameters from VLBI are expected to be enhanced due to the improvement of the observation geometry (Nilsson et al., 2015), which is shown in Fig. 2. The information about GNSS stations co-located with VLBI radio telescopes in CONT17 is listed in Table 1. However, the co-location at Yebes was not considered owing to the low data yield (one out of five days) of the VGOS radio telescope due to antenna pointing problems.

2.3. Data analysis

2.3.1. Analysing VLBI and GNSS observations

In this study, we performed the single session VLBI data analysis for each network during the CONT17 campaign with the GFZ version of the Vienna VLBI software VieVS@GFZ (Nilsson et al., 2015). The station coordinates were estimated with a daily resolution. The datum was defined by applying no-net-translation (NNT) and no-net-rotation (NNR) conditions on all stations w.r.t. the ITRF2014 (Altamimi et al., 2016) for the Legacy-1 and Legacy-2 networks. However, the datum for the VGOS network was defined by applying NNT and NNR conditions on all stations w.r.t. a priori coordinates that were retrieved from NGS card formatted files,[2] since the VGOS stations were constructed after 2014 and were therefore not considered in the official ITRF2014 solution. The NGS Cards' coordinates are approximate values taken from the first results. The radio source coordinates were kept fixed to the ICRF3 catalog (Charlot et al., 2020) for the Legacy-1 and Legacy-2 networks. In contrast, radio source coordinates were estimated with daily resolutions and applying NNR w.r.t. the ICRF3 for the VGOS observations. VGOS observations are observed in the broadband frequency range between 3 GHz and 10.7 GHz; thus, the S/X-based coordinates may not be entirely valid for these frequencies. A priori EOP data was taken from the IERS final product, and the EOP were estimated with a daily resolution. The zenith wet delay and gradient parameters were estimated with an hourly resolution. The zenith hydrostatic delays were computed based on Saastamoinen (1972) with meteorological information from the Global Pressure Temperature 2 model (GPT2) (Lagler et al., 2013) and applying Vienna Mapping Function 1 (VMF1) (Böhm et al., 2006) to obtain the slant delays. The analysis models adhere to the IERS Conventions 2010 (Petit and Luzum, 2010).

[2] https://cddis.nasa.gov/archive/reports/formats/ngs_card.format.



(a) The blue marks show WETTZ13N (Wn) observations. The black crosses show WETTZELL (Wz) observations, the red diamonds show WETTZ13S (Ws) observations, and the pink lines show GNSS observations (WTZR).

(b) The red diamonds show KOKEE12M (K2) observations. The black crosses show KOKEE (Kk) observations, and the pink lines show GNSS observations (KOKB).

Fig. 2. Sky plots of the observations during 1 h (10:00 UT - 11:00 UT) from co-located VLBI radio telescopes along with GNSS observations. The left plot (a) shows Wettzell and the right (b) Kokee Park. These plots demonstrate an agreement of VLBI observation geometry with GNSS when co-located VLBI radio telescopes are combined.

Table 1
Co-located VLBI radio telescopes and GNSS stations in the CONT17 campaign.

Co-located sites	VLBI	GNSS
Wettzell	WETTZELL (Wz) WETTZ13N (Wn) WETTZ13S (Ws)	WTZR
Kokee Park	KOKEE (Kk) KOKEE12M (K2)	KOKB

Regarding the GNSS analysis, the Precise Point Positioning technique (PPP) (Kouba and Héroux, 2001) was performed based on the precise orbit and clock information from the International GNSS Service (IGS) multi-GNSS experiment and pilot project (MGEX) (Montenbruck et al., 2017) and GNSS observations from the co-located GNSS sites, such as Wettzell (WTZR) and Kokee Park (KOKB). The GFZ EPOS.P8 software package was used for data processing (Uhlemann et al., 2016). In the processing, observations from three constellations, GPS, GLONASS, and Galileo, were used to estimate daily station coordinates. The zenith hydrostatic delays were calculated consistently with the VLBI stations with the Saastamonien model, with meteorological data from GPT2, and mapped with VMF1 to slant delays. The zenith wet delay and gradient parameters were estimated with an hourly resolution. Ocean and atmospheric tidal effects were applied based on the IERS Conventions 2010 consistently to the VLBI analysis. Additionally, Phase Center Offsets (PCO) and Phase Center Variations (PCV) were modeled by applying the IGS14 ANTEX absolute calibration model, which is consistent with the ITRF/IGS2014 reference frame (Rebischung et al., 2016).

2.3.2. Tropospheric ties

Tropospheric ties are the difference between the atmospheric conditions quantified as zenith delays of co-located instruments due to the height differences. Tropospheric ties effectively provide the connection of tropospheric parameters between co-located VLBI radio telescopes. They can be calculated as the sum of the hydrostatic and wet part of tropospheric parameters differences

Table 2
Local ties vectors (m) in geocentric coordinates of co-located VLBI radio telescopes in CONT17.

Co-location stations	ΔX	ΔY	ΔZ
Kk - K2	6.0719	−19.2141	−23.7216
Wz - Wn	88.0363	38.7315	−77.1628
Wz - Ws	119.3444	89.2360	−113.2943

Table 3
Mean height differences and zenith total delay differences of co-located telescopes during CONT17.

Co-location stations	Height differences (m)	Mean ΔZTD difference (mm)
Kk - K2	8.02	−2.3
Wz - Ws	−3.44	1.0
Wz - Wn	−3.42	1.0

(Teke et al., 2011). Table 3 shows the height and mean zenith total delay (ZTD) differences for the Wettzell and Kokee co-located VLBI radio telescopes. In this study, however, only zenith wet delay differences were computed from analytical equations (Teke et al., 2011) based on meteorological information from station-wise VMF1 (Böhm et al., 2006) and height difference from a priori coordinates of the co-located stations. This is due to the fact that the hydrostatic components were corrected on the observation equation level; therefore, only wet parts remain to be estimated in VLBI data processing as presented in Section 2.3.1. We prepared tropospheric ties at every estimation epoch as essential information for combining tropospheric parameters.

2.3.3. Combination strategy

In this study, three combined solutions for CONT17 were calculated as detailed in Table 4.

As these networks observed in parallel, the datum relation is required to connect them. This study took the datum-free normal equations after independent analysis for each network to perform a combination. The Legacy-1 network was considered as a reference network for the combined network. The reason is that the Legacy-1 network has a better global distribution in CONT17. For that reason, we expect less systematic error from the Legacy-1 network. The Legacy-2 and VGOS networks retrieved the datum definition from the Legacy-1 network. Therefore, NNT/NNR conditions were applied on the Legacy-1 network for stations available in the ITRF2014 except for the co-location stations to retain minimum-constraint solutions from the lease-square adjustment. The KASHIM11 telescope was excluded from the datum definition due to site displacements and post-seismic motion caused by large Earthquakes since the ITRF14 does not describe the motion of this telescope properly. For the numerical values of local tie vectors, we used Schüler et al. (2018) for Wettzell and Niell (2019) for Kokee Park (see Table 2). We introduced the local tie vectors as pseudo-observations with an uncertainty of 10^{-4} mm to ensure the ties as conditions for the combination. This is related to the co-located VLBI radio telescopes having no common observations in CONT17. Regarding the network orientation, we combined EOPs between networks by forcing them to be identical and applying uncertainties of 10^{-5} mas, 10^{-5} mas, and 10^{-5} ms on polar motion, celestial pole offsets, and dUT1 parameters, respectively, to force the constraints to be fulfilled. The ZTD parameters of co-located VLBI radio telescopes were combined by introducing tropospheric ties with the approach described in Section 2.3.2 as pseudo-observations with an uncertainty of 10^{-3} mm. Similarly, the gradient parameters were combined by forcing them to be identical with an uncertainty of 10^{-3} mm. This approach was applied to all case studies.

Three solutions were calculated to investigate the impact of combining tropospheric parameters on the combined VLBI network during CONT17. Table 5 shows the parameters that were combined for each solution in this study. In the first solution, station coordinates of co-located VLBI radio telescopes along with the EOP were combined (T1). In the second solution, ZTD parameters of co-located VLBI radio telescopes for every estimation epoch were combined employing tropospheric ties along with station coordinates and the EOP (T2). Similarly, both ZTD and gradient parameters of co-located VLBI radio telescopes were combined along with station coordinates and the EOP (T3). The improvement of the station coordinate repeatabilities for the three case studies was statistically analyzed (see Section 3.1 and 3.2). Moreover, combined tropospheric parameters of co-located VLBI radio telescopes were compared to tropospheric delays calculated from GNSS data and ERA5 NWM with an hourly resolution for all case studies (see Section 3.3).

3. Results

In this section, we present the geodetic parameters, namely the station coordinates and ZTD parameters, estimated from combined VLBI networks. Additionally, we compared the polar motion from combined VLBI network w.r.t. IGS PM products (International GNSS Service (IGS), 1992). This allows us to approximately assess the impact of combining tropospheric parameters on EOP. We found no significant effect on the polar motion when combining tropospheric parameters in this study. This is expected because only few co-located VLBI radio telescopes were combined in this study. The results of baseline length repeatabilities are illustrated in this section as well.

Table 4
Description of combination strategy and co-located stations between networks in CONT17.

Case studies	Network combination	Co-location stations	NNT/NNR datum stations
S1	Legacy-1 and Legacy-2	Wz-Wn	Legacy-1 except KASHIMA11 and co-located stations
S2	Legacy-1 and VGOS	Wz-Ws, Kk-K2	Legacy-1 except KASHIMA11 and co-located stations
S3	Legacy-1, Legacy-2 and VGOS	Wz-Wn, Wz-Ws, Kk-K2	Legacy-1 except KASHIMA11 and co-located stations

Table 5
Description of common parameters in each solution.

Solutions	Combined parameters
T1	Station coordinates + EOP
T2	Station coordinates + EOP + zenith total delays
T3	Station coordinates + EOP + zenith total delays + gradients

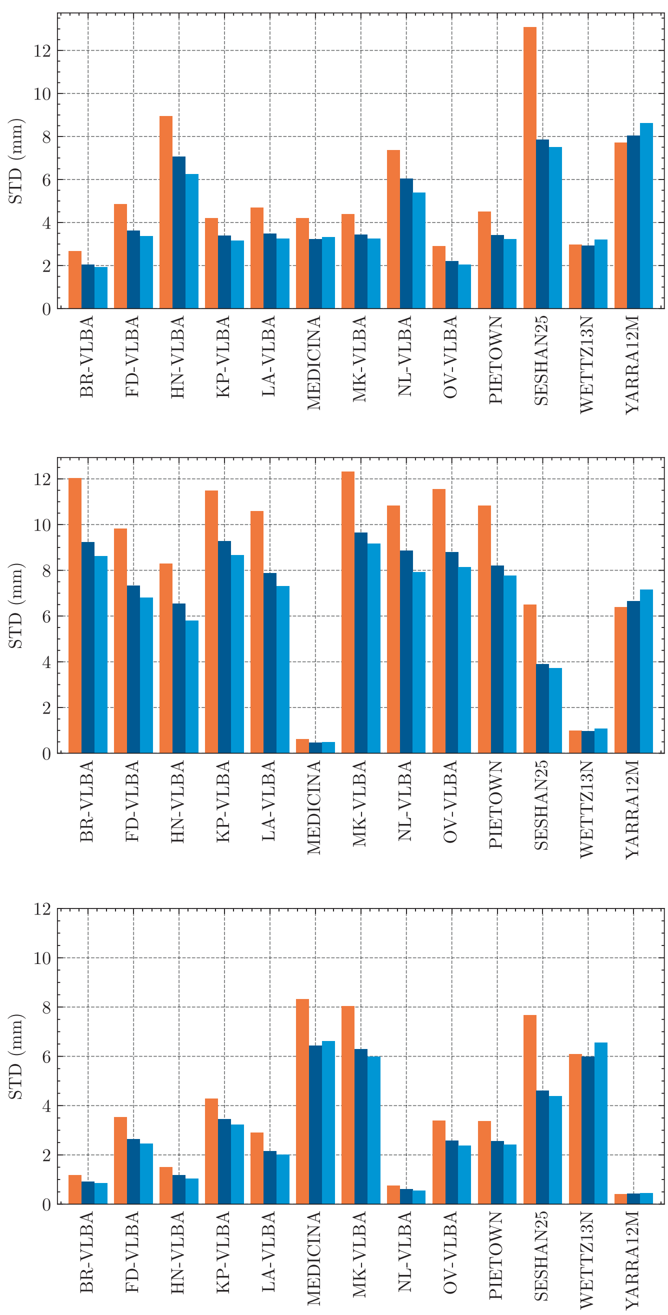


Fig. 3. Station coordinate repeatabilities (STD in millimeters) of the Legacy-2 network in the local topocentric frame for S1. The results were computed based on the 15 daily solutions. East, north, and up components are on top, middle, and bottom, respectively. The orange, dark blue, and light blue bars represent T1, T2, and T3 solutions, respectively.

3.1. Site coordinates

The station coordinate repeatabilities were computed as standard deviation (STD) from time series during the 15 days of CONT17. These allow us to analyze the impact of applying tropospheric ties for S1 statistically. However, station coordinate repeatabilities were calculated for only five days for S2 and S3 due to the VGOS data availability. As demonstrated in Fig. 3, T1 showed a large STD up to 1 cm for some telescopes in the VLBA network for S1, especially in the north component. This is unexpectedly large since the expected STD to be in the millimeters range due to the combination. This shows that an unexpected bias occurs in local ties, which degrades station coordinates. Figures of the S2 and S3 results can be found in the supplement material. Applying tropospheric ties (T2) improved the overall station coordinate repeatabilities w. r.t. the T1 solution by 26%, 7%, 23% for S1, S2, and S3, respectively. Likewise, T3 improved the overall station coordinate repeatabilities w.r.t. the T1 solution by 28%, 15%, 26% for S1, S2, and S3, respectively. The impact of applying tropospheric ties on the east, north, and up components for all cases are shown in Fig. 3. The Legacy-1 telescopes showed no significant improvement for any of the cases. The results can be found in supplement materials. This is expected because the NNT/NNR conditions were imposed on the stations of this network. Moreover, the station coordinate repeatabilities of co-located stations in both networks were practically identical for S1, S2, and S3. This is related to the impact of imposing local ties as constraints on these co-located stations.

3.2. Baseline length repeatabilities

Another quantitative measure of the impact of combining tropospheric parameters is the baseline length repeatabilities. We calculated them as weighted root-mean-squares (WRMS) scatter of the baseline lengths. Moreover, we fitted curves of baseline length repeatabilities for T1, T2, and T3 by the equation $y = \sqrt{a^2 + (b \cdot x)^2}$ where y is the WRMS in mm and x is the baseline length in km. According to Fig. 4, there is no apparent improvement in the fitted curve of baseline length repeatabilities for S1. The same applied to S2 and S3. Therefore, it is unclear whether combining tropospheric parameters shows an improvement of baseline lengths but it also does not degrade them. This is expected because there are just a few co-located telescopes during CONT17. As the baseline lengths represent a network improvement, the impact on baseline lengths cannot be too large involving a small number of co-location sites.

3.3. Tropospheric parameters

The combination of tropospheric parameters at co-located telescopes affects the station coordinates and the

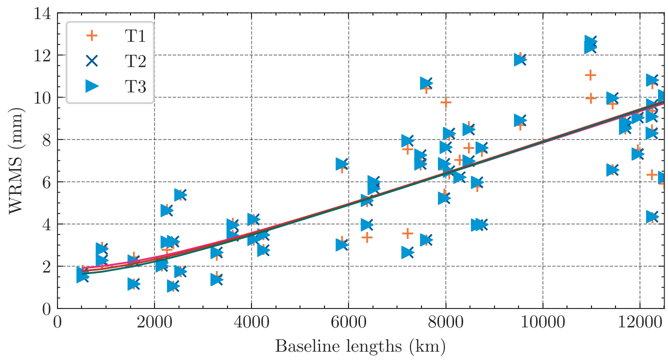
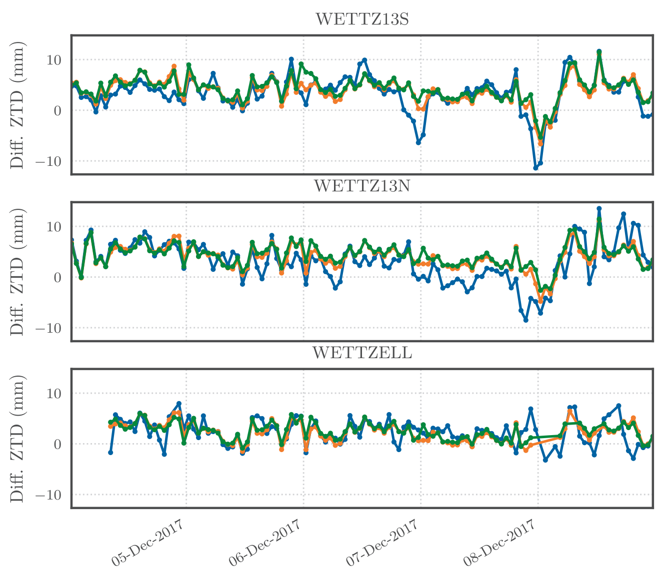
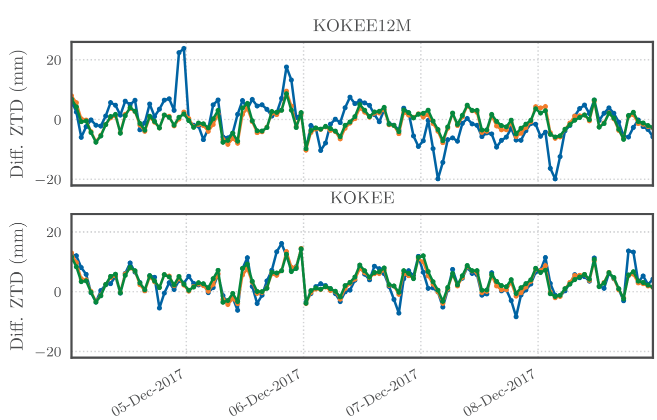


Fig. 4. Baseline length repeatabilities for combined Legacy-1 and Legacy-2 networks (S1).



(a) Wettzell co-location site



(b) Kokee Park co-location site

Fig. 5. The differences of zenith total delay at five stations: WETTZ13S, WETTZ13N, WETTZELL, KOKEE12M, and KOKEE, for the five days from the solution combining Legacy-1, Legacy-2 and VGOS networks (S3) w.r.t. GNSS-derived tropospheric parameters. The blue, green, and orange lines represent T1, T2, and T3 solutions, respectively. Different scales are used in sub-figures a and b.

tropospheric parameters themselves. Therefore, the ZTD parameters at the co-located sites (Wettzell and Kokee Park) were compared with those from the co-located GNSS stations. In order to compare the ZTD parameters from VLBI and GNSS, the tropospheric ties between GNSS and VLBI were calculated with the approach described in Section 2.3.2 and applied to the ZTD parameters from VLBI. Fig. 5 presents the improvement of the ZTD parameters from T1, T2, and T3 w.r.t. the GNSS. Table 6 lists the WRMS of the ZTD parameters for the co-located telescopes for each case study w.r.t. the GNSS-derived ZTD parameters. 37% and 39% improved the WRMS of KOKEE12M telescopes of the S2 solution for T2 and T3 solutions w.r.t. T1 solution, respectively. This progress is caused by the improvement of the implied observation geometry similar to GNSS observation geometry, which is shown in Fig. 2. However, the improvement of the ZTD parameters did not exceed the sub-millimeter level for the WETTZELL, WETTZ13N, WETTZ13S, and KOKEE telescopes. These telescopes made observations in a way much more in agreement with GNSS observation geometry, as demonstrated in Fig. 2. The ZTD parameters at VLBI co-located telescopes were compared to the ZTD parameters from ERA5 for external validation. Table 7 presents the WRMS of ZTD w.r.t. ERA5 for S1, S2, and S3 solutions. T2 and T3 improved by 21% and 22% w.r.t. the T1 solution at the KOKEE12M telescope. On the other hand, the agreement of the ZTD parameters with ERA5 at WETTZELL, WETTZ13S, WETTZ13N, and KOKEE telescopes were not significantly improved for any case studies.

4. Conclusions

The results suggest the benefits of combining tropospheric parameters at co-located VLBI radio telescopes on the estimated geodetic parameters such as the station coordinates and the tropospheric parameters. The main improvement lies in the coordinate repeatability of stations in the Legacy-2 and the VGOS networks. In addition, combining the tropospheric parameters improves the datum transfer from the Legacy-1 network to the Legacy-2 and the VGOS networks. The baseline length repeatabilities show no improvement when tropospheric parameters at co-located VLBI radio telescopes are combined. Importantly, combining the Legacy-1 and VGOS networks and the Legacy-1, Legacy-2, and VGOS networks are preliminary results because the VGOS network observed only five days.

Moreover, the agreement between the tropospheric parameters from VLBI and GNSS improved when combining tropospheric parameters at co-located VLBI radio telescopes compared to using only local ties due to the significant improvement of the implied observation geometry, as demonstrated at the KOKEE12M telescope. Combining the tropospheric parameters at co-located VLBI

Table 6
WRMS of ZTD w.r.t. GNSS for the co-located VLBI radio telescopes in three case studies.

Stations	Legacy-1 + Legacy-2 (S1)			Legacy-1 + VGOS (S2)			Legacy-1 + Legacy-2 + VGOS (S3)		
	T1 (mm)	T2 (mm)	T3 (mm)	T1 (mm)	T2 (mm)	T3 (mm)	T1 (mm)	T2 (mm)	T3 (mm)
WETTZELL	2.0	2.1	1.9	2.4	1.4	1.5	2.3	1.8	1.6
WETTZ13S	x	x	x	3.3	2.5	2.5	3.0	2.3	2.2
WETTZ13N	3.3	2.2	2.1	x	x	x	3.8	2.3	2.1
KOKEE	x	x	x	4.1	3.6	3.5	4.1	3.6	3.5
KOKEE12M	x	x	x	5.6	3.5	3.4	5.8	3.5	3.4

Table 7
WRMS of ZTD w.r.t. ERA5 for the co-located VLBI radio telescopes in three case studies.

Stations	Legacy-1 + Legacy-2 (S1)			Legacy-1 + VGOS (S2)			Legacy-1 + Legacy-2 + VGOS (S3)		
	T1 (mm)	T2 (mm)	T3 (mm)	T1 (mm)	T2 (mm)	T3 (mm)	T1 (mm)	T2 (mm)	T3 (mm)
WETTZELL	4.4	4.3	4.3	4.8	4.4	4.5	4.8	4.2	4.3
WETTZ13S	x	x	x	5.6	5.3	5.1	5.1	4.5	4.5
WETTZ13N	4.5	4.3	4.3	x	x	x	4.8	4.5	4.4
KOKEE	x	x	x	7.3	7.0	7.0	7.3	7.1	7.1
KOKEE12M	x	x	x	9.1	7.1	7.1	9.2	7.1	7.2

radio telescopes also improved the agreement between the tropospheric parameters from VLBI and the ERA5.

This study demonstrates the benefit of connecting parallel VLBI networks by combining the tropospheric parameters at co-located telescopes on geodetic parameters, especially the station coordinates and the tropospheric parameters. Our findings suggest that tropospheric ties reduce a possible bias from local ties, which affects the VLBI geodetic parameters, especially the station coordinates. Thus, we recommend tropospheric ties to be applied along with local ties when combining co-located VLBI telescopes to connect the parallel networks, such as those during CONT17. This ensures that the parallel networks are in the same datum if coordinates of one sub-network are not available in the ITRF reference frame, e.g., the VGOS network. The results were obtained for combinations of networks that share just a few co-location sites, a fact that does not allow to generalize the improvement of combining tropospheric parameters for co-located VLBI radio telescopes. Nevertheless, combining tropospheric parameters shows promising results for the combination of VLBI parallel networks such as those in CONT17.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.asr.2022.02.013.

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