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Atmospheric modeling for co-located VLBI antennas and twin telescopes

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Abstract In the next generation VLBI network, the VLBI Global Observing System (VGOS), there will be several twin telescopes, i.e. stations equipped with a pair of VLBI telescopes with identical design. In this work we test the possibility of combining the tropospheric parameters of these two telescopes within the VLBI data analysis. This is done through simulations of a possible future VGOS network containing one twin telescope. We simulate the tropospheric delays with the help of a turbulence model, approximately taking into account the distance between the antennas. The results show that the combination of tropospheric delays can

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improve the station position repeatability by about 15 % as long as the distance is smaller than 1 km. The main improvement is in the repeatability of the baseline vector between the antennas. However, the results are strongly dependent on how the observations are scheduled for the twin telescope. The simulation results are confirmed by an analysis of the CONT14 campaign, where the tropospheric parameters of the two Hobart antennas are combined. Furthermore, we also discuss the study of combining other parameters for the twin telescope, i.e. the clocks and/or the station positions.

Keywords VLBI, VGOS, atmosphere, turbulence, twin telescopes

1 Introduction

Currently the next generation geodetic Very Long Baseline Interferometry (VLBI) network, called VGOS (VLBI Global Observing System), is being constructed (Hase et al, 2012). One of the main aims of this system is to obtain repeatabilities of 1 mm or better for global baselines (Petrachenko et al, 2009), an increase in precision of about one order of magnitude compared to the current VLBI system. This will mainly be achieved by using very fast antennas with slew rates of up to 12°/s, following the VLBI2010 concept (Petrachenko et al, 2008) which are able to observe about 100 scans/hour, thus obtaining significantly more observables than the current VLBI system where the antennas typically only observe 10–15 scans/hour.

Another way to increase the number of observations per station is to have two (or more) VLBI telescopes at a site, so-called twin telescopes. If the local tie between the telescopes is know accurately, the telescopes and data acquisition system are provided with time and frequency derived from the same high precision frequency standard, and the atmosphere above them can be assumed to be practically identical, then the telescopes can be considered as one single telescope in the VLBI data analysis. Since two telescopes will be able to make about twice as many observations as one telescope, this will increase the number of scans by a factor of two. Several twin telescopes are currently being built or planned, e.g. the Twin Telescope Wettzell (TTW), Germany (Neidhardt et al, 2011), Onsala, Sweden (Haas, 2013), and Ny Ålesund, Spitsbergen, Norway (Langkaas et al, 2010).

Treating the two telescopes as one in the data analysis will of course only work if the above mentioned assumptions apply, which is challenging to achieve. Even though the telescopes can be connected to the same clock all clock-like errors (e.g. cable delays) need to be carefully calibrated. Since the aim is to reach a position precision of 1 mm, the local tie between the two telescopes needs to be known with sub-mm accuracy. Furthermore, in order to avoid that one telescope significantly block the horizon of the other, they need to be placed at least 70 m or further apart. Hence the atmosphere above them will not be exactly identical. Several studies have been performed in the past comparing tropospheric parameters estimated from co-located space geodetic techniques (distances usually smaller than a few hundred meters), e.g. Krügel et al (2007), and Teke et al (2011, 2013). These studies found that the estimated zenith total delays at co-located sites agree with RMS (Root-Mean-Square) differences of about 5 mm. It is, however, difficult to tell how much of these differences are due to instrumental and analysis effects and how much are true differences in the tropospheric delay. Furthermore, it is not clear how small the differences in the tropospheric delays need to be to allow for a meaningful combination of the tropospheric parameters. There have also been studies where tropospheric delays (and station coordinates) of co-located VLBI and GNSS (Global Navigation Satellite Systems) stations have been combined, e.g. by Krügel et al (2007) and Hobiger and Otsubo (2014). In these studies it was shown that the combination of tropospheric parameters can improve the station coordinates. However, it is not clear whether this will be the case for VGOS, where a much higher precision is targeted (1 mm).

In this paper we investigate the possibility to combine the tropospheric parameters of two co-located VGOS telescope though simulations. For this purpose, we have implemented an extended version of the simulation procedure presented by Nilsson and Haas (2010). The theoretical description of this procedure is presented in Sec. 2. The generation of the observing schedules as well as the data analysis of the simulated observations are described in Sec. 3, and the simulation results are presented in Sec. 4. In Sec. 5 we test the combination of the tropospheric parameters using real data from the CONT14 campaign. Finally, the conclusions are presented in Sec. 6.

2 Theory of simulating the VLBI observations

In this section we describe the procedure for simulating the tropospheric delays. This is procedure based on the structure functions for the tropospheric delays derived by Treuhaft and Lanyi (1987). These structure functions have been experimentally tested by e.g. Nilsson et al (2005), and the simulation method have shown to produce in e.g. Pany et al (2011) and Nilsson et al (2014). For more details, see Nilsson et al (2007) and Nilsson and Haas (2010).

The tropospheric delay of the i:th observation, l_i, is given by:

$$l_i = \int_{S_i} [n(s) - 1] \, ds \tag{1}$$

where n is the refractive index of the air and S_i the path of the signal traveling through the troposphere. For the simulation of the tropospheric delays it is, however, more convenient to work with the equivalent zenith delay, l_i^z, which is the tropospheric delay divided by a symmetric mapping function m_i (e.g. Böhm et al, 2006):

$$l_i^z = \frac{l_i}{m_i} = \int_0^\infty [n(\mathbf{r}_i(z)) - 1] \, dz \tag{2}$$

where $\mathbf{r}_i(z)$ is the location of the signal of observation i at height z. We can assume that l_i^z consists of two parts: one mean part l_0^z which is constant and one fluctuating δl_i:

$$l_i^z = l_0^z + \delta l_i \tag{3}$$

The covariance between the fluctuation part of two tropospheric delays, δl_i and δl_j, can be calculated by:

$$\begin{aligned} C_{ij} &= \langle \delta l_i \, \delta l_j \rangle \\ &= \int_0^\infty \int_0^\infty \delta n(\mathbf{r}_i(z)) \, \delta n(\mathbf{r}_i(z')) dz \, dz' \end{aligned} \tag{4}$$

For the calculation of C_{ij} we need to know the covariance $\langle \delta n(\mathbf{r}_i(z)) \, \delta n(\mathbf{r}_i(z')) \rangle$. According to the Kolmogorov turbulence theory (Kolmogorov, 1941), the structure function of variations in the refractive index of air, δn, between $\mathbf{r}_i$ and $\mathbf{r}_j$ is given by (Treuhaft and Lanyi, 1987):

$$\left\langle [\delta n(\mathbf{r}_i) - \delta n(\mathbf{r}_j)]^2 \right\rangle = C_n^2 \frac{|\mathbf{r}_i - \mathbf{r}_j|^{2/3}}{1 + \frac{|\mathbf{r}_i - \mathbf{r}_j|^{2/3}}{L^{2/3}}} \tag{5}$$

Here C_n^2 is the refractive index structure constant and L the saturation scale length. By applying the expression:

$$\begin{aligned}\langle \delta n(\mathbf{r}_i)\, \delta n(\mathbf{r}_j)\rangle = \frac{1}{2}\Big[&\left\langle \delta n(\mathbf{r}_i)^2\right\rangle + \left\langle \delta n(\mathbf{r}_j)^2\right\rangle \\ &- \left\langle [\delta n(\mathbf{r}_i) - \delta n(\mathbf{r}_j)]^2\right\rangle\Big]\end{aligned} \tag{6}$$

and using the fact that (Treuhaft and Lanyi, 1987):

$$\left\langle n(\mathbf{r}_i)^2\right\rangle = \frac{1}{2} C_n^2\, L^{2/3} \tag{7}$$

it is possible to calculate C_{ij}.

With the above procedure we can calculate the covariance C_{ij} between tropospheric delays of different directions and/or at different locations. We are, however, also interested in modeling the variations over time. This can be done by applying Taylor's "frozen flow" hypothesis (Taylor, 1938), i.e. assuming that the temporal variations in the refractive index are caused by the spatial variations move with the wind velocity vector $\mathbf{v}$. Thus we have:

$$n(\mathbf{r}, t) = n(\mathbf{r} - \mathbf{v}(t - t_0), t_0) \tag{8}$$

where t is the time of observation and t_0 is some reference time. Using this expression, also temporal variations can be modeled with the expressions above.

Hence, with eqs. (4)–(8) it is possible to calculate the variance-covariance matrix for the tropospheric delays of all the observations. Then simulated equivalent zenith tropospheric delays can be obtained simply by generating a series of random numbers having this variance-covariance matrix and the expectation value l_0^z. This is an easy task if the tropospheric delays are assumed to have a Gaussian distribution, what normally is a good approximation (Poli et al, 2007). In a last step we multiply the equivalent zenith tropospheric delay with the mapping functions m_i to obtain the slant tropospheric delays.

For the simulations we need to know several parameters. First of all we need the mean tropospheric delay l_0^z. This can be chosen as the typical zenith delay at the site. In Nilsson and Haas (2010) several methods of obtaining the structure constant C_n^2 were reviewed. In general this parameter is height dependent. However, as discussed in Treuhaft and Lanyi (1987) and Nilsson and Haas (2010), for the purpose of calculating the covariance between tropospheric delay, a simple approximation of C_n^2 being constant up to the height H and zero above can be used. An appropriate value of H is the scale height of the wet refractive index, i.e. approximately 2 km. The saturation length scale L is the length over which the tropospheric variations can be assumed to be independent. Treuhaft and Lanyi (1987) suggested a value of 3000 km. Finally, for the temporal variations we need the wind vector $\mathbf{v}$. This can be chosen as the mean wind speed and direction at the site, or we can use a general value of 8 m/s as suggested by Treuhaft and Lanyi (1987) in a random direction.

Once the tropospheric delays have been generated we can use these together with other simulated errors to generate simulated VLBI observations. For example, a VLBI delay L observed with the two stations $st1$ and $st2$ can be generated by (Pany et al, 2011):

$$L = L_{th} + l_{st2} - l_{st1} + c_{st2} - c_{st1} + w \tag{9}$$

L_{th} is the theoretical delay containing the geometrical delay and all other known contributions to the delay, l_{st1} and l_{st2} are the tropospheric delays at the two stations, c denotes the clock errors, and w is the observation noise. The clock errors are normally simulated as a random walk process plus an integrated random walk process, while the observation noise is simulated as white Gaussian noise.

3 Scheduling and simulation of a VGOS network

We performed simulations for a potential future VGOS network consisting of 24 VLBI telescopes: 22 single-telescope sites and one twin telescope (Wettzell). These are all potential sites for VGOS antennas (Hase et al, 2011). The locations of the stations can be seen in Fig. 1. Observing schedules were generated using the VieVS (Vienna VLBI Software Böhm et al, 2012) scheduling tool, VIE_SCHED, applying the source-based scheduling strategy where four different radio sources are scheduled simultaneously (Sun et al, 2014). For simplicity, we assumed that all telescopes of the network had identical specifications: 12 m diameter, azimuth-elevation mount, and slew rates of 12°/s in azimuth and 6°/s in elevation. All antennas were assumed to have an SEFD (System Equivalent Flux Density) of 2500 Jy, and the total recorded bandwidth and recording rate were 4 GHz and 8 Gbps, respectively. Two 24-hour schedules were generated, using different options for the scheduling of the observations with the twin telescope. In the first schedule both Wettzell telescopes were always scheduled towards the same source (same-source observations) while in the second schedule they were always scheduled to observe two different sources (multi-directional observations). In addition, to both schedules the so called “fill-in“ mode (Sun et al, 2014) was applied to schedule extra scans at times when the normal scheduling algorithm failed to schedule observations for two or more telescopes. Examples of sky plots for the Wettzell telescopes and the two schedules during a 15 min period are shown in Fig. 2. We can see that the sky coverage of the two telescopes is better for the multi-directional scheduling approach, as could be expected.

Table 1 shows the number of scans and observations made by the various VGOS telescopes in the two schedules. We can see that the number of scans is approximately the same for all stations, and relatively independent of what scheduling option was used for the twin telescope. In the same-source schedule the Wettzell telescopes obtained more observations than most other telescopes. The reason is that the twin telescope is located in an area with many other telescopes (Europe) and these tend to be scheduled to observe together often, resulting in many observations. However, for the multi-directional schedule normally only one of the Wettzell telescopes was scheduled to observe with the other European telescopes, while the other had to observe another source which was normally not observed by as many telescopes. Thus the number of observations for the Wettzell telescopes is significantly lower for this schedule. The reason for the slight difference in observations for the Wettzell telescopes in the same-source schedule is that the fill-in mode sometimes scheduled the two telescopes to observe different sources at one time. Similarly, it sometimes happened that the fill-in-mode scheduled the two Wettzell telescopes to observe the same-source in the multi-directional schedule.

For the two schedules we generated simulated VLBI observations using the simulation tools of VieVS, VIE_SIM, which applies the simulation algorithms described in (Pany et al, 2011) and in Sec. 2. For the tropospheric delay simulations, station specific values of the refractive index structure constant, C_n^2, were obtained from time series of ZWD estimated from GNSS data (acquired between 1 May and 30 June, 2012), applying the method described in Nilsson and Haas (2010). These values are presented in Table 2. The height H and wind speed were chosen as

2 km and 8 m/s, respectively, for all stations. The clock errors were simulated as random walk processes plus integrated random walk processes, assuming an Allan Standard deviation of $1.4 \cdot 10^{-14}$ @ 50 min, what is a typical performance of a hydrogen maser (including cable delays and instrumental effects) operated at a VLBI station (Rieck et al, 2012). The observation noise was simulated as white noise with a standard deviation of 10 ps. This is a somewhat conservative value; the expected precision of the phase delays obtained with VGOS is 4 ps (Petrachenko et al, 2009). This should however not have any significant effects on the results, since previous simulations have shown that the impact of the observation noise on the results is negligible compared to the tropospheric errors as long as the noise level is below 16 ps (Pany et al, 2011). The simulations were repeated 100 times, generating independent observations each time, in order to obtain good statistics for calculation of e.g. station position repeatabilities.

The simulated VLBI observations were analyzed with the GFZ version of VieVS, VieVS@GFZ. The parameter estimation was performed with the classical least-squares method. For each simulated session, we estimated station and radio source coordinates, Earth Orientation Parameters (EOP), clock offsets with 30 min resolution, Zenith Wet Delays (ZWD) with 10 min resolution, and tropospheric gradients with 30 min resolution. The datum for the station coordinates was defined by applying No-Net-Translation (NNT) and No-Net-Rotation (NNR) condition on all stations except the two Wettzell antennas, while the celestial datum was defined by applying NNR to the ICRF2 defining sources. For each schedule, four different solutions were calculated, handling the tropospheric parameters of the twin telescope in different ways. In the first solution, all station-specific parameters (troposphere, clocks, and station coordinates) were estimated independently for the two Wettzell telescopes. In the second solution, the tropospheric gradients of the twin were combined by forcing the gradient time series of the two telescopes to be identical. Similarly, in the third the ZWD were combined, and in the fourth solution both gradients and ZWD were combined.

4 Simulation results

4.1 Same-source schedule

We first present the results achieved from the analysis of simulated observations that were scheduled following the same-source strategy.

Figure 3 depicts the station coordinate repeatability of the twin telescope in Wettzell (shown is the mean repeatability of the two antennas since the repeatabilities of the individual antennas are practically identical). The distance between the Wettzell telescopes was here assumed to be 100 m in the north-south direction, what is close to the actual distance between them (75 m). The repeatability obtained when not combining any parameters is practically identical to what is obtained if we would only have one single telescope at Wettzell. The repeatabilities agrees agrees well with the results of MacMillan and Sharma (2008) for similar values of C_n^2. No significant differences can be observed when combining the tropospheric parameters compared to not doing so. This is because the two Wettzell telescopes were almost always observing in the same directions. Thus, the observations from the two telescopes contain in principle the same information about the troposphere and hence there is almost no benefit from combining the tropospheric parameters.

We also tested the dependence of the distance between the Wettzell telescopes by varying this distance between 10 m up to 50 km. The same observing schedule was used in all cases. The results are presented in Fig. 4. We can see that for distances smaller than 1 km there is practically no impact on the station position repeatability, regardless whether the tropospheric parameters are treated independently or are combined. However, if the distance is larger than 1 km then the repeatability gets worse for the cases when the tropospheric parameters are combined, in particular for the cases when the ZWD is combined. Apparently, over such large distances the troposphere is so heterogeneous that the tropospheric parameters cannot be assumed identical. Thus, combining the tropospheric parameters in the analysis causes errors in the other estimated parameters, like the station positions.

In Fig. 5 the repeatability of the baseline vector between the two Wettzell telescopes is shown for the case when the distance is 100 m. We can first note that this difference in position is determined much more precisely than the absolute station positions. The reason is that the troposphere is the dominant error source for geodetic VLBI, and since the telescopes were almost always pointing in the same direction the errors in the station positions (and other parameters) caused by the troposphere are highly correlated. Thus, when calculating the difference in position between the telescopes most of the errors disappear. We can also note that there is a clear improvement in the repeatability when combining the tropospheric parameters. When combining the tropospheric gradients the repeatabilites of the horizontal components are reduced by about 25%, while the repeatability of the vertical component is reduced by about 20%. When combining the ZWD the repeatability of the vertical component is reduced by about 50%, while the horizontal components do not change significantly. That the combination of ZWD mostly affects the vertical component while the combination of gradients has a stronger influence on the horizontal components is not surprising. It is well known that the ZWD – which describes the azimuthal symmetrical part of the tropospheric delay – is strongly correlated with the vertical position error (Nilsson et al, 2013), while the gradients – describing the azimuthal variations of the tropospheric delay – are more correlated with the horizontal position error.

We also investigated what happens to the repeatability of the baseline vector if the distance is larger than 100 m. The results are not presented graphically in this manuscript since they are similar to the results for the absolute positions shown in Fig. 4. As the distance is getting larger than 1 km there is no more improvement when combining the tropospheric parameters. Instead the repeatability gets worse as the distance increases.

Furthermore, we investigated the effect of the combination on other parameters estimated in the VLBI analysis. Firstly, we compared the simulated equivalent zenith wet delays with those calculated from the estimated ZWD and gradients. When the telescope distance was smaller than 1 km, we obtained about the same level of agreement (RMS difference of 3.8 mm) independent on whether the tropospheric parameters were combined or not. For longer distances the agreement got worse when combining the troposphere. Furthermore, we investigated the impact on the coordinates of the other stations in the network. However, practically no impact was found with differences of less than 0.001 mm. Also, no impact on the estimated EOP could be observed.

4.2 Multi-directional schedule

The investigations done for the same-source scheduling approach were repeated for the multi-directional scheduling approach.

In Fig. 6 the station position repeatability for the twin telescope in Wettzell is shown, assuming a distance between the Wettzell telescopes of 100 m. When no tropospheric parameters are combined we can see that the repeatability is similar to the same-source schedule, and the two schedules show the same performance. However, for the multi-directional schedule an improvement can be observed when combining the tropospheric parameters. There is a slight improvement in the horizontal components when the gradients are combined, mostly in the north component. The reason for the improvement being mostly in the north component could be related to the Wettzell telescopes being placed on a north-south baseline, however, this requires further investigations. Combing the ZWD reduces the repeatability of the vertical component by 17 %. Since the Wettzell telescopes were almost always pointing in different directions, the sky coverage obtained using the scans made by both the Wettzell telescopes is much better than what is obtained with just one antenna. Hence, the precision of the tropospheric parameters is improved. Consequently the precisions of the other parameters that are highly correlated with the tropospheric parameters, like the station coordinates, are improved as well.

Figure 7 shows how the 3D station position repeatability changes depending on the assumed distance between the Wettzell telescopes. We can see that for distances shorter than 1 km there is an improvement when combining the tropospheric parameters, in particular when combining the ZWD. However, similarly as for the same-source schedule, as the distance gets larger than 1 km, the results get worse when the tropospheric parameters (especially ZWD) are combined.

The repeatability of the baseline vector between the Wettzell telescopes are shown in Fig. 8. We can note that here this vector is not determined with the same precision as in the same-source schedule case. The reason is that the two telescopes are almost never pointing in the same direction, thus the coordinate errors induced by the troposphere will not be as highly correlated and will not be canceled out completely. However, similarly as for the same-source schedule, there are clear improvements when the tropospheric parameters are combined. The repeatabilities of the horizontal components are reduced by 30 % when the gradients are combined, while the vertical component is almost unchanged. When the ZWD are combined the repeatability of the vertical component reduces by 55 %, while the horizontal components remain practically unchanged.

Also here we investigated the effect of the combination on other parameters estimated in the VLBI analysis. Firstly, we compared the simulated equivalent zenith wet delays with those calculated from the estimated ZWD and gradients. We found a slight improvement in the agreement when the tropospheric parameters were combined: the RMS difference were 3.7 mm when the tropospheric parameters were combined and 3.8 mm when not, using a distance between the telescopes of 100 m. For telescope distances above 1 km, the agreement got worse when combining the troposphere, just as for the station coordinates. Thus, this indicates that the troposphere is better retrieved when estimating common tropospheric parameters for both telescopes and distance between them is below 1 km. Furthermore, we investigated the impact on the coordinates of the other stations in the network. However, this impact was found to be of the order of 0.01 mm, i.e.

negligible. Generally, the EOP got slightly better when the tropospheric parameters were combined, at least for UT1-UTC and the dX nutation angle where the repeatabilities improved by 1.5 %. The reason for the small impact on the EOP (and the other stations coordinates) is that only one station (out of 23) has a twin telescope, thus the impact on the global parameters is small.

The results presented are valid for the assumed atmospheric conditions at Wettzell. The results could be different under other atmospheric condition, e.g. another time of year or at another station location. To test how much this can change the results, we made simulations where other values of the wind speed and the structure constant C_n^2 were assumed. Using a different wind velocity only marginally changed the results. In general, the station coordinate repeatabilities get worse when a larger C_n^2 value is used, as could be expected. However, the station coordinate repeatabilities still improve by 10–15 % when the tropospheric parameters are combined, as long as the distance between the telescopes is smaller than 1 km. For a very small value of C_n^2, e.g. smaller by a factor ten, the distance over which the tropospheric delays can be combined even increases, probably due to the fact that other error sources (e.g. observation noise) get relatively more important when the troposphere is less turbulent.

4.3 Combination of other parameters

For a twin telescope it is in principle also possible to combine other station dependent parameters. If the two telescopes are connected to the same clock, and the cables etc. connecting the clock to the receivers are well calibrated, it will be possible to also combine the clock parameters. Furthermore, if the local tie vector between the telescopes is precisely measured, it will be possible to fix this vector in the data analysis and thus only estimating one set of coordinates for the twin telescope. We also performed tests, using the multi-directional schedule, where we also combined the clock parameters and/or the positions. In these simulations we assumed that these parameters can be combined without any error, what is an ideal case. In reality, this will of course not be the case. The delays in the cables and receiving equipment will never be perfectly calibrated, thus giving rise to clock-like errors that are individual to each twin. Furthermore, local tie measurements always contain some level of uncertainty as well.

Figure 9 shows the station position repeatabilites of the Wettzell telescopes when the clocks or positions are combined as a function of the distance between the telescopes. For comparison the cases when combining no parameters, the troposphere (ZWD and gradients), and all parameters (troposphere, clocks, and positions) are also plotted. We can see that the repeatabilities improve also when combining the clocks or the positions, even slightly more than when combining the troposphere only. Since we have assumed that the combination of the clocks and the positions are error-free, there is no degradation as the distance between the telescopes increases. In reality, of course, we would have errors related to the combination of these parameters that would increase as the distance gets larger (e.g. the accuracy of the local tie vector will be lower over longer distances). We can also see that combining all three parameters does not result in further improvement. This is also the case when only combining two of the parameter groups. In general, there are high correlations between the errors of the vertical coordinate, the ZWD, and the clock, since it is difficult to separate these parameters in the data analysis (Nilsson et al, 2013). By combining one of these parameters, we improve the precision of this parameter as well as the other two, and the correlations between them get reduced. Thus we do not gain improvement in precision when combining more than one parameter group. For example, in the simulations presented here the combination of one parameter group limits the possibility of the tropospheric delays influencing the clock or the vertical coordinates, hence the position precision is improved. Since this possibility is limited already with the combination of one parameter, there is no gain when combining more than one parameter group.

5 Test of real data from CONT14

Although none of the twin telescopes planned for VGOS are currently operational, there are several VLBI stations that are equipped with two geodetic VLBI antennas, and there are VLBI sessions where both these antennas are observing simultaneously. Thus, these sessions can be used for testing the combination of the tropospheric parameters with real data.

We tested the combination of the tropospheric parameters for the two antennas at the Hobart station in Tasmania (Australia); the new 12 m antenna, Hobart12, and the old 26 m antenna, Hobart26. The distance between the antennas is about 295 m. We did the combination for the 15 day long CONT14 campaign, where both antennas participated together with 15 other telescopes distributed worldwide. The CONT14 data set demonstrate the state-of-the-art of geodetic VLBI, thus it is well suited for such an investigation. The schedules for CONT14 were generated at the NASA Goddard Space Flight Center, USA, using the SKED software (Gipson, 2010). The schedules were optimized w.r.t. local sky coverage at the stations. When generating the schedules the SEFD requirements for the Hobart26 baselines were loosened in order to avoid it slowing down the other antennas, otherwise no special parametrization w.r.t. the Hobart station was applied. It turned out for most of the time the two Hobart antennas were observing the same sources, but not always. On average Hobart12 and Hobart26 participated in 419 and 401 scans per day, respectively; 332 scans were in parallel. Thus the schedule used does not correspond to any of the schedule considered in the simulations w.r.t. the handling of the twin telescope, but can be said to be in between. For more information about CONT14, see Behrend et al (2014) and `http://ivscc.gsfc.nasa.gov/program/cont14/`.

We analyzed the CONT14 data with VieVS@GFZ estimating daily station positions, daily EOP, daily source coordinates, ZWD with 30 min resolution, and gradients with 2 h resolution. An issue that we needed to consider was the difference in the tropospheric delay due to the fact that the antennas are at different heights (24 m height difference). This was solved by applying the tropospheric ties as described in Teke et al (2013), using the pressure, temperature, and humidity measured at the antennas.

The obtained station position repeatabilities (mean of the two stations) are presented in Fig. 10. We can see that also here there is an improvement when combining the tropospheric parameters. Similarly as for the simulations, the largest improvement are when the ZWD are combined. This improves the repeatability of the vertical component by 15 %. The impact on the other station coordinates when combining the tropospheric parameters is very small.

Figure 11 shows the repeatability of the baseline vector between the two antennas at Hobart. These results confirm the findings of the simulations that the repeatability of the baseline vector is significantly improved when combining the tropospheric parameters. The repeatability of the height difference is reduced by

70 % when all tropospheric parameters are combined (mostly due to the combination of the ZWD). However, the horizontal components remain practically unchanged.

6 Conclusions

The results of the simulations show that it is possible to combine the tropospheric parameters for a twin telescope, and that this improves the station position estimates. This was confirmed by combining the troposphere for the two antennas at Hobart during CONT14. The combination of the tropospheric parameters works well and improves the results as long as the two telescopes are separated by 1 km or less. This limit seems to be relatively independent of the assumed C_n^2 value, hence this should also hold for other, more turbulent stations. For larger separation distances the atmosphere is too heterogeneous to be combined without causing big errors. For the TTW (separation about 75 m) there should thus be no problems combining the tropospheric parameters. We could assume that this will also be the case for the other planned twin telescopes where the separation will be around 100 m. It should, however, be noted that the simulations assumed that there are no systematic difference in the tropospheric delays between the telescopes. In reality such a difference can be present, e.g. due to a height difference between the telescopes, which needs to be calibrated. If the height difference is small (a few meters) and well-known, we would expect that this can be done with a high precision.

The main improvement when combining the tropospheric parameters is seen in the repeatability of the baseline vector between the telescopes. This could be explained by the fact that this baseline is highly correlated with the differences in the tropospheric parameters, thus fixing the latter the precision of the baseline vector improves significantly. Regarding the scheduling options for the twin telescope, it is clear from the simulations that the best option is to use multi-directional observations if the tropospheric parameters are combined. An exception is when it is the goal to estimate the baseline vector between the two telescopes with high accuracy, e.g. in order to validate the results of local surveys. In this case the same-source schedule is recommended. As indicated by the simulations this should provide the local tie vector with a precision much better than 1 mm, especially when the tropospheric parameters are combined. This could for example also be an interesting possibility for obtaining precise local tie between the new VGOS antennas. Furthermore, it could be used to obtain the tie to co-located legacy VLBI antennas, what is important for ensuring the long-time stability of the ITRF, although the precision will probably not be as good as between two VGOS telescopes due to the slower slew rates of the legacy antennas.

Apart from the tropospheric parameters, it is also possible to combine the station positions and/or the station clocks of a twin telescope. The simulation results of Sec. 4.3 show that the combination of one of these parameters (assuming this combination is error-free) gives approximately the same improvement in station position precision as the combination of the troposphere. However, combining two or three common parameter groups does not give any significant further improvement in the station positions.

In this work, just one (out of 23 stations) was simulated as a twin telescope. In the future we will also study the effects of having twin telescopes at more stations. For example, it will be interesting to study the effects on the global parameters like the EOP. In this work the EOP estimates were only minimally affected when combining the tropospheric parameters. This is hardly surprising since the improvement was only at one site. With a larger number of twin telescopes we might, however, expect to see a more significant improvement also in the EOP.

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Table 1 Statistics regarding the number of scans and observations made by the Wettzell telescopes and the other telescopes (here the mean value is shown) in the two schedules.

	Same-source		Multi-directional	
	# Scan	# Obs.	# Scan	# Obs.
Wettz13n	2485	18598	2454	14920
Wettz13s	2485	18619	2451	14308
Other	2416	13641	2437	13445

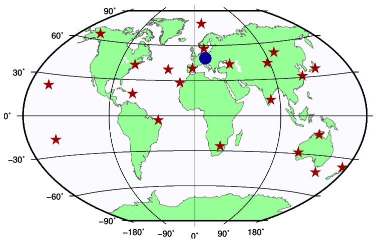

Fig. 1 The network of VGOS stations used for the simulations. The network consists of 22 single-telescope sites (red stars) and one twin telescope (blue circle).

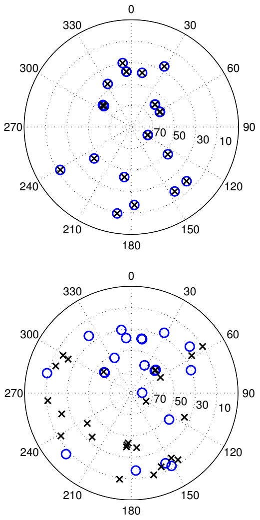

Fig. 2 Sky plots of the observations in a 15 min period (11:00–11:15) made by the Wettzell twin telescope. Upper plot shows the sky-plot for the same-source scheduling approach and lower plot for the multi-directional approach. The blue circles shows and the black crosses indicates observations by the Wettz13n and Wettz13n telescopes, respectively.

Table 2 Station-specific values of the refractive index structure constant C_n^2 used for the simulations in this work.

Station	Lat.	Long.	C_n^2
	[°]	[°]	$[10^{-14}\ \mathrm{m}^{-2/3}]$
Arecibo	293.3	18.3	4.36
Azores	328.8	39.5	7.24
Badary	102.2	51.8	1.61
Canaries	343.4	28.3	0.86
Fortaleza	321.6	-3.9	7.78
Gilcreek	212.5	65.0	1.77
Hartrao	27.7	-25.9	1.12
Hobart	147.4	-42.8	2.46
India	80.3	13.1	3.10
Katherine	132.1	-14.4	3.88
Kokee	200.3	22.1	2.37
Ny-Ålesund	11.9	78.9	0.50
Onsala	11.9	57.4	2.89
Seshan	121.2	31.1	13.10
Tahiti	210.6	-17.7	5.86
Ishioka	140.1	36.1	8.94
Urumqi	87.2	43.5	3.03
Warkworth	174.7	-36.4	2.96
Westford	288.5	42.6	8.94
Wettzell	12.9	49.2	4.08
Yarragadee	115.3	-29.1	3.39
Yebes	356.9	40.5	2.76
Zelenchukskaya	41.6	43.8	3.53

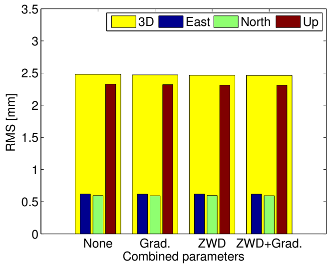

Fig. 3 Station position repeatabilities obtained from the analysis of simulated data using the same-source scheduling approach. The distance between the twins is 100 m. Shown from left to right are the station repeatabilites when atmospheric parameters are estimated independently (None), only the horizontal gradients are combined (Grad.), only the ZWD are combined (ZWD), and both ZWD and gradients are combined in the estimation process (ZWD+Grad.).

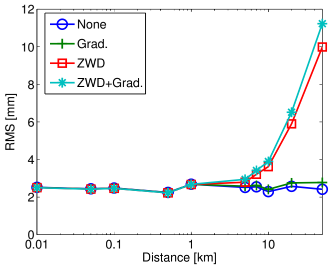

Fig. 4 Station position repeatability (3D) obtained from the analysis of simulated data using the same-source scheduling approach as a function of the distance between the twin telescopes and the combination of tropospheric parameters.

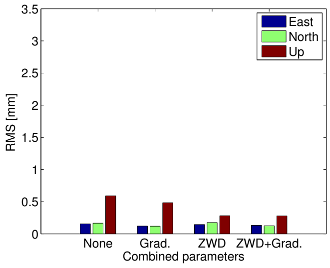

Fig. 5 Repeatability of the baseline vector between the two Wettzell telescopes obtained from the analysis of simulated data using the same-source scheduling approach. The distance between the twins is 100 m. Shown from left to right are the station repeatabilites when atmospheric parameters are estimated independently (None), only the horizontal gradients are combined (Grad.), only the ZWD are combined (ZWD), and both ZWD and gradients are combined in the estimation process (ZWD+Grad.).

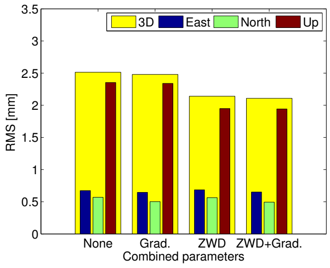

Fig. 6 Station position repeatabilities obtained from the analysis of simulated data using the multi-directional scheduling approach. The distance between the twins is 100 m. Shown from left to right are the station repeatabilites when atmospheric parameters are estimated independently (None), only the horizontal gradients are combined (Grad.), only the ZWD are combined (ZWD), and both ZWD and gradients are combined in the estimation process (ZWD+Grad.).

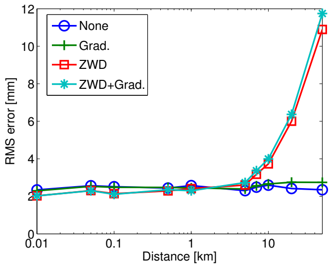

Fig. 7 Station position repeatability (3D) obtained from the analysis of simulated data using the multi-directional scheduling approach as a function of the distance between the twin telescopes and the combination of tropospheric parameters.

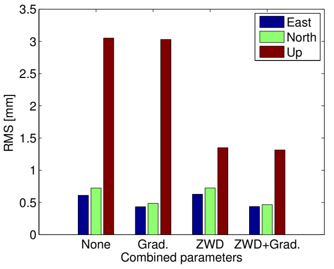

Fig. 8 Repeatability of the baseline vector between the two Wettzell telescopes obtained from the analysis of simulated data using the multi-directional scheduling approach. The distance between the twins is 100 m. Shown from left to right are the station repeatabilites when atmospheric parameters are estimated independently (None), only the horizontal gradients are combined (Grad.), only the ZWD are combined (ZWD), and both ZWD and gradients are combined in the estimation process (ZWD+Grad.).

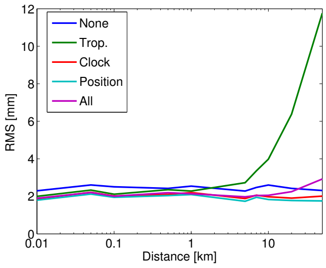

Fig. 9 Station position repeatability (3D) obtained from the analysis of simulated data using the multi-directional scheduling approach as a function of the distance between the twin telescopes and the combination of different parameters groups.

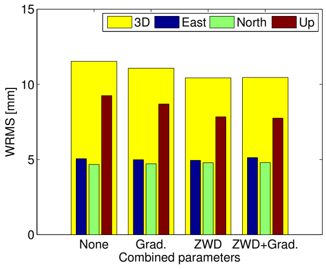

Fig. 10 Station position repeatabilities of the two Hobart telescopes obtained from the analysis of the CONT14 data set.

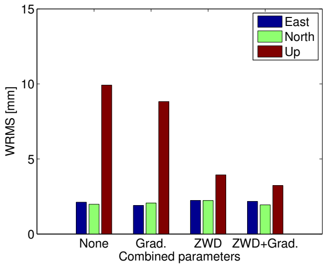

Fig. 11 Repeatability of the baseline vector between the two Hobart telescopes obtained from the analysis of the CONT14 data set.