Atmospheric Modeling in the Data Analysis of Twin Telescope Observations

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Abstract We investigate the possibility of combining the atmospheric parameters of the two antennas of a twin telescope in the VLBI data analysis. For this we perform simulations for a hypothetical future VGOS network, containing one twin telescope. The distance between the twin telescope antennas is varied between 0 m and 50 km to find out the distances over which it is possible to assume that the atmosphere above the antennas is identical. We find that the combination of the atmospheric parameters improves the station position repeatability when the distance between the antennas is less than 2–3 km. Thus, for the planned twin telescopes we expect that a common treatment of the atmosphere will increase the station position precision.

Keywords VLBI, Intensives, atmosphere, twin telescopes, VGOS

1 Introduction

In the upcoming year the VGOS (VLBI Global Observing System) network will start to operate [3]. It is expected that this system will result in about one order of magnitude improvement in accuracy compared to the current VLBI system. This will be achieved through using the more precise phase delays, as well as increasing the number of observations significantly by having faster antennas and observing a larger bandwidth. One idea is also to use so-called twin telescopes, i.e., equipping one station with two (or more) identical telescopes. This will further increase the number of observations—two telescopes should be able to make about twice as many scans as a single one—hence the accuracy will get even better. Furthermore, only with twin telescopes will continuous observations (24 h per day, seven days per week) be possible; when one telescope undergoes maintenance, the other one can still observe. For the VGOS network there are several twin telescopes planned, for example in Wettzell [5], Onsala [2], and Ny-Ålesund [4].

The idea is that the two antennas of a twin telescope can be treated as one in the data analysis. This requires that the local tie between the antennas be precisely known, that the antennas be connected to the same clock, and that the atmosphere above them can be assumed to be identical. All these assumptions may be challenging to achieve. For example, in order to consider the clock to be identical, it is not enough to just connect the two antennas to the same clock. The cable delays etc. need to be accurately calibrated as well. In this work, we have investigated the third assumption, i.e., whether the atmosphere above the antennas can be considered identical. Thus, in the following we have assumed that the local tie and the identical clock can be achieved without errors.

We investigated the atmospheric variations between the antennas of a twin telescope through simulations. To do this we applied an extended version of the simulation method presented by Nilsson and Haas (2010) [6], which is able to properly take into account the distance between the antennas. We then made simulations for a possible future VGOS network, including one twin telescope at Wettzell. The distance between

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the antennas was varied in order to determine how far away from each other it is possible to place the antennas and still assume a common atmosphere.

2 Simulations

To simulate the atmospheric delays we applied the method presented by Nilsson and Haas (2010) [6]. This method uses the theory of atmospheric turbulence to model the atmospheric fluctuations. The spatial variations in the refractive index n between the positions $\mathbf{r}_1$ and $\mathbf{r}_2$ can be described by the structure function [9]:

$$\left\langle [n(\mathbf{r}_1) - n(\mathbf{r}_2)]^2 \right\rangle = C_n^2 \frac{|\mathbf{r}_1 - \mathbf{r}_2|^{2/3}}{1 + \left[\frac{|\mathbf{r}_1 - \mathbf{r}_2|}{L}\right]^{2/3}} \qquad (1)$$

Here C_n^2 is the refractive index structure constant, and L is the saturation scale length. The temporal variations can be modeled by assuming that these are caused by the air moving with the wind (the frozen flow hypothesis). Using Equation 1, it is possible to calculate a variance-covariance matrix for the variations in atmospheric delay, which can then be used to generate simulated atmospheric delays. In [6], the variations in time and as a function of the direction were considered. In this work we extend this to also contain the spatial variations between two antennas of a twin telescope.

For the simulations, we needed the structure constant C_n^2, the saturation scale length L, and the wind speed. We assumed that C_n^2 is constant up to a height of 2 km and zero above, and we obtained station specific values from GNSS data [6]. For all stations we used L =3000 km and a wind speed of 8 m/s [9].

In this work we made simulations for a hypothetical future VGOS network consisting of 23 stations (see Figure 1), all equipped with very fast (12°/s slew speed) VGOS antennas. At Wettzell we assumed a twin telescope, and at the other stations, we assumed just single antennas. We generated an observing schedule for this network with the Vie_Sched software [8]. Then, for each scan of this schedule, we created simulated VLBI observations [7]. These were generated from the simulated atmospheric delays as well as simulated clock errors (assuming the clocks to have an Allan standard deviation of 10^{-14} @ 50 min) and white observation noise (standard deviation of 10 ps).

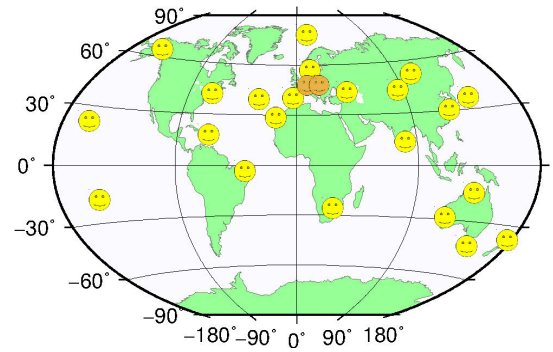

Fig. 1 The VGOS network used for the simulations in this work. At Wettzell (orange/dark gray) there is a twin telescope. All other stations (yellow/light gray) are assumed to have only one antenna.

The simulated observations were then analyzed with the Vienna VLBI Software, VieVS [1]. In the data analysis we estimated the clocks as piece-wise linear functions with 1-hour intervals, the tropospheric zenith wet delays with 10-minute intervals, tropospheric gradients with 30-minute intervals, daily station coordinates, and daily offsets of each of the five Earth orientation parameters. For the station-specific parameters of the twin telescope in Wettzell we tested four different options: (1) treating the two antennas completely independently, (2) combining the atmospheric parameters (zenith wet delays and gradients) of the antennas, (3) combining the atmospheric parameters and the clocks, and (4) combining atmospheric parameters, clocks, and station coordinates.

For the twin telescope in Wettzell, we varied the distance between the antennas between 0 m and 50 km. Of course, in reality a distance of 0 m is not possible, but it is in the simulations and corresponds to the case where the atmosphere above the two antennas is identical. For each distance we ran 100 independent simulations in order to have a sample size big enough for, for instance, the calculation of the station position repeatabilities.

3 Results

Figure 2 shows the station position repeatability of the Wettzell twin telescope as a function of the distance between the antennas for the four different analysis options. As can be seen, when no parameters are com-

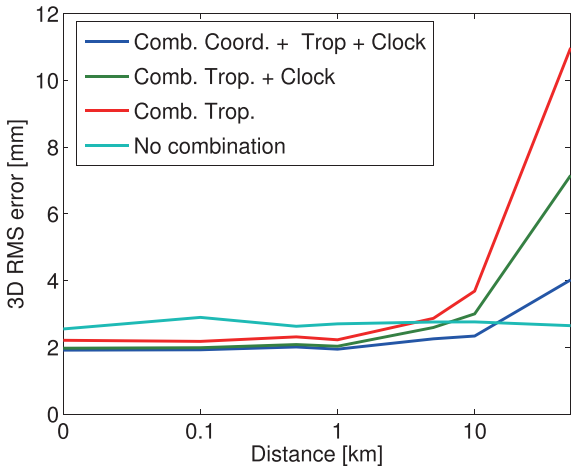

Fig. 2 3D station position repeatability of the Wettzell twin telescope as a function of the distance between the antennas. Shown are the results when treating the antennas independently in the data analysis (cyan), when combining the atmospheric delays (red), when combining atmosphere and clocks (green), and when combining atmosphere, clocks, and station coordinates (blue).

bined, there is no significant dependence on the distance. This is expected because we do not make any use of the fact that the two antennas are close to each other. When we combine the atmospheric parameters, the repeatability improves when the distance between the antennas is smaller than a few kilometers, and further improvements are obtained when also combining the clock and station coordinates.

For distances between the antennas above 5 km, the results get worse when combining the atmospheric delays. Obviously, for these large distances the assumption of an identical atmosphere above both antennas is no longer valid, which leads to errors in the estimated coordinates (and other parameters). When combining also the clocks and the coordinates the degradation of the repeatability for distances over 5 km is not that large. The reason is that unmodeled atmospheric delays mainly tend to be absorbed by a combination of station coordinates and clocks in the least squares adjustment. Thus, by limiting also these parameters, the possibility that the atmospheric variations cause errors in the station coordinates is reduced. It should however be noted that we assumed that the station coordinates and the clocks could be combined without errors, which will not be the case in reality.

4 Conclusions

The results show that combining the atmosphere for a twin telescope can reduce the errors of the estimated coordinates if the distance between the antennas is less than 2–3 km. Of course, the presented results are only valid for simulating a twin telescope in Wettzell. For another station the local conditions may be different (e.g., a more turbulent atmosphere), but we do not expect this would change the general conclusions of this work significantly. Thus, the combination of the atmospheric parameters should not be a problem for any of the planned twin telescopes but instead usually improves the station position; the actual distance between the antennas of the Wettzell twin telescope is about 75 m, and for the other planned twin telescopes, the distance will also be around 100 m.

Bigger problems will probably be obtaining an accurate enough local tie between the two antennas and connecting them to the same clock. How well this can and needs to be done is beyond the scope of this work. But the results show that even if the coordinates and clocks cannot be combined in the data analysis, the combination of the atmospheric parameters still leads to a significant increase in the station position repeatability (about 15%–20%).

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