Self-Calibration of Wet Troposphere Delay and Clock Phase Variations for VLBI Data Analysis

Oleg Titov[1], Simon Willcocks[1], Hana Krasna[2], Yulia Lopez[3], Angelina Osetrova[4]

Abstract The wet tropospheric component and clock phase variations are the most important factors that limit the accuracy of the geodetic VLBI products. These fast fluctuations can be introduced into the parametric model as a correlated stochastic noise and treated in a special way using the least-squares collocation method (LSCM). An a-priori covariance function is used to construct the non-diagonal covariance matrix. We have developed a procedure to calculate the wet troposphere delay and the clock offset for each observation epoch. The wet troposphere delays calculated by the LSCM are in perfect agreement with the water vapor radiometer (WVR) data, within the uncertainty of 2–3 mm. This information is then incorporated into the NGS data file and used in the second iteration. As a result, the procedure for analyzing the VLBI data becomes simpler and faster, since the remaining observational error is Gaussian, and the matrix of the observational covariance can be treated as diagonal. For the calibrated VLBI data, the simple least-squares method (without breaking the 24-hour experiment into small bins) is applied, followed by a reduction in the number of estimated parameters. All VLBI data between 1993 and 2023 were processed with pre-calibrated tropospheric and clock delays. The result was tested with two independent software packages, OCCAM and VieVS, and showed a good efficiency with respect to the traditional approach. The accuracy of the estimates reaches: 1 mm for VLBI site positions, 3 µas for UT1–UTC values, and 40 mas for X- and Y-pole components. The formal error of the most observed ICRF reference radio source positions drops to 1–2 µas, and the “floor” (or “inflated”) error for the future ICRF realization would also be reduced. This paper shows that the new data analysis procedure produces results which align with the announced VGOS goals for the S/X VLBI data. Finally we report a detection of the negative parallax effect with an amplitude of -15.8 (±0.5) µas.

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1 Introduction

The Very Long Baseline Interferometry (VLBI) technique measures the time difference (time delay) between the two epochs in which a signal from a distant radio source arrives at radio telescopes separated by a long baseline. The time delay is calculated by correlating the signals recorded at both stations using correlators. As many radio sources are observed over a long period of time, the positions of radio sources could be estimated with high accuracy.

Two previous fundamental catalogs of reference were released in 1995 [1] and 2009 [2]. The current International Celestial Reference Frame (ICRF3) is based on the positions of 4,536 objects observed between 1979 and 2018. Positions of 303 “defining” radio sources are used to fix the fundamental axis with the uncertainty of 30 µas [3]. The best formal errors of the radio source positions are about 6 µas.

One of the factors limiting the accuracy of observation is the highly variable atmosphere effects, including the ionosphere and neutral atmosphere delays. The ionosphere delay is calibrated due to dual-frequency observations in S-band (2.3 GHz) and X-band (8.4 GHz). Only the X-band observations are used for scientific data analysis after the calibration process. Propagation of the radio wave through the neutral atmosphere is split into the 'dry' and 'wet' components (also known as 'dry' and 'wet' delays). The theoretical modeling of the 'dry' delay is a routine procedure which uses the local meteo parameters measured at the radio telescope's location. In contrast, the 'wet' delay made of the water vapor in a state of the hydrostatic unequilibrium is a more complicated process.

2 Geodetic VLBI Data Used for New Solution

We processed 4,451 24-hour VLBI experiments from May 1993 to October 2023 (15,135,212 group delays). The new CRF solution aus2024a.crf[1] comprises coordinates of 5,428 radio sources with three or more observations. Since 2019, the group delays are published in the IVS databases in IVS vgosDB format. We developed a procedure to convert the data to the more compact NGS format files. The data files were processed using the OCCAM software [9] (v. 6.3). All reductions were calculated in accordance with IERS Conventions 2010 [4]. ITRF2020 station positions and velocities were used for the reduction [5].

Data analysis was organized in two steps. The first solution produces wet troposphere delays and two gradients and clock phase delays for each observation.

The troposphere delays obtained with VLBI and water vapor radiometer (WVR) for station Onsala60 during the CONT11 campaign are shown in (Figure 1). At the second step, the troposphere and clock variations were added as a priori (similar to the ionosphere delays), so the data analysis is made with the plain least-squares method as no more stochastic parameters are left in this scenario. Moreover, it was found that the troposphere calibration is done so perfectly that the constant troposphere parameters should not be estimated at the second step. Therefore, the list of parameters includes only three parameters (XYZ) for each station position, three clock parameters for each station (except the reference one), eight EOP parameters, and positions of astrometrically unstable radio sources [2, 7].

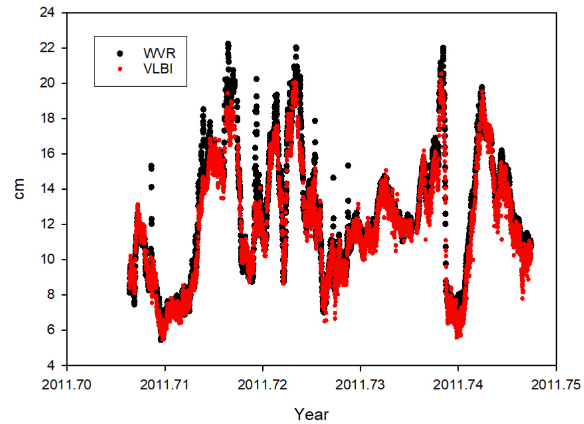

Fig. 1 Wet troposphere delay variations calculated with WVR (black dots) and VLBI (red dots).

To test the troposphere and clock phase variations calculated with VieVS [6] we processed the new NGS files in several modes:

1. binning the 24-hour interval into one-hour bins with estimation of tropo and clock parameters for each one-hour bin (reference mode);
2. binning the 24-hour interval into 20-minute bins with estimation of tropo and clock parameters for each 20-minute bin;
   and three next modes with using the calibration data for the troposphere and clock;
3. binning the 24-hour interval into one-hour bins with estimation of tropo and clock parameters for each one-hour bin (reference mode);
4. estimating of the tropo and clock as daily parameters;
5. no estimating of the clock and troposphere at all.

Figure 2 shows the formal errors of the Wettzell station geodetic components, and Figure 3 shows the formal errors of the EOP for the first four IVS-R1 and R4 experiments in January 2023. The change of the interval length from one hour to 20 minutes does not change the statistics if the calibration is not applied. In contrast, if the calibration is applied, the formal error reduces dramatically. Even for the same number of parameters (one-hour bins) the statistics has improved (compare

[1] https://cddis.nasa.gov/archive/vlbi/ivsproducts/crf/

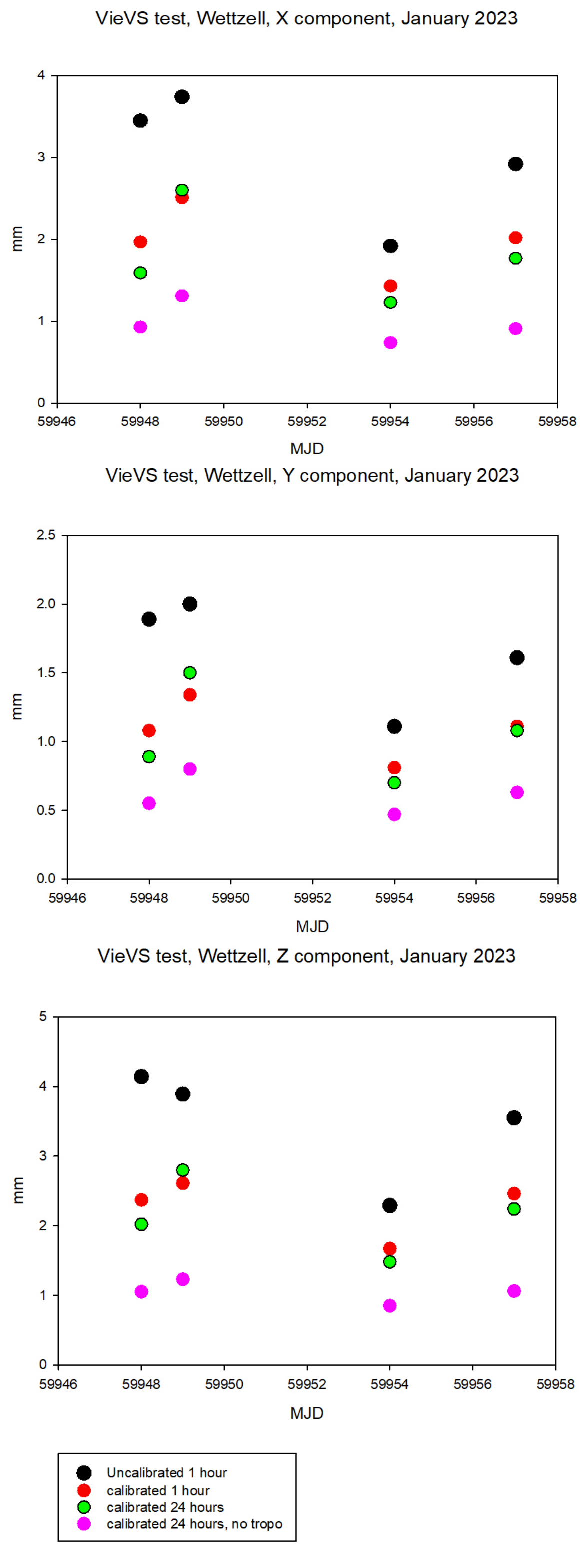

Fig. 2 Accuracy of the Wettzell XYZ component estimates for four IVS experiments in January 2023 with VieVS.

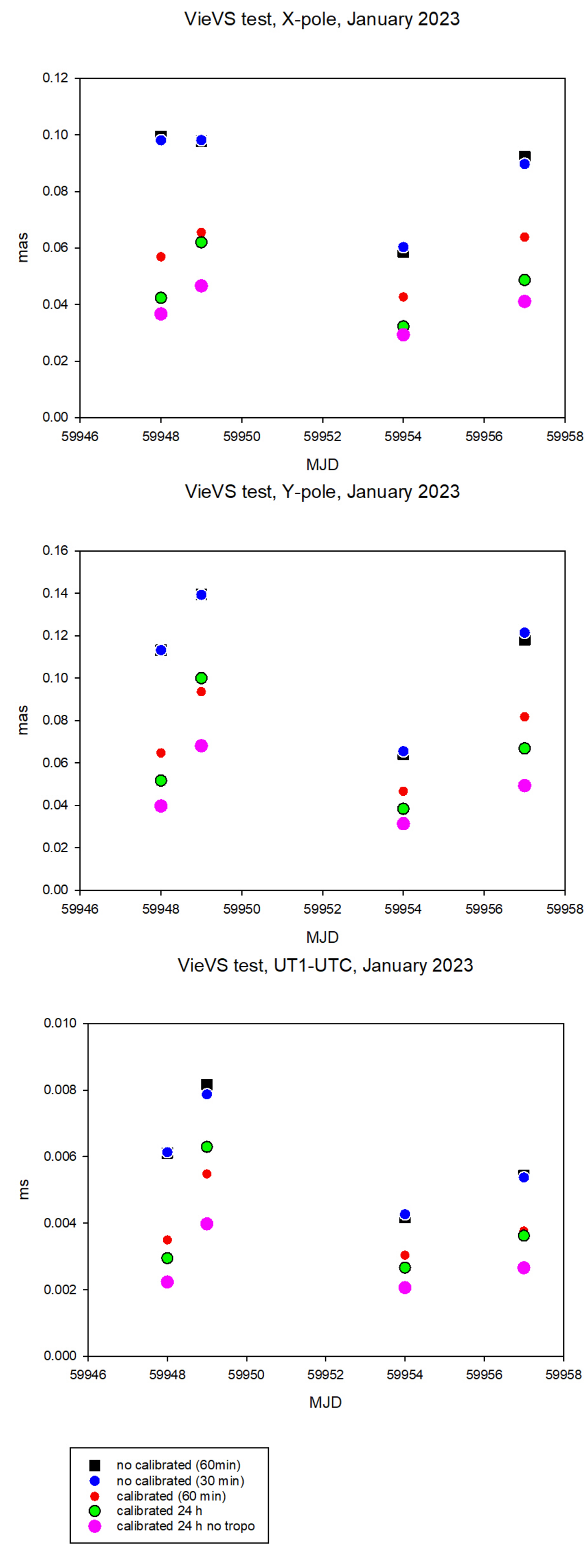

Fig. 3 Accuracy of the EOP estimates for four IVS experiments in January 2023 with VieVS.

black and red dot, on Figures 2 and 3). Further reduction of the number of parameters is followed by the statistical improvement, so if we fully rely on the calibrated data and do not estimate the stochastic parameters at all, the formal errors (pink dots) are about three times smaller than for the reference mode formal errors (black dots).

3 Analysis

The aus2024a.crf catalog comprises positions of the 5,428 radio sources estimated as single parameters over a 30-year time interval (1993–2023). Table 1 displays the six parameters (rotation and dipole) linking the ICRF3 and aus2024a fundamental axes.

Table 1 Six parameters for aus2024a–ICRF3 differences: R1–R3 for rotation, D1–D3 for dipole.

Parameter	Estimate (µas)	Parameter	Estimate (µas)
R1	14 ± 3	D1	3 ± 1
R2	-7 ± 3	D2	0 ± 1
R3	-6 ± 1	D3	7 ± 6

The formal uncertainty of the radio source coordinates estimated with the new method is approximately three times better than the uncertainty from the standard solution aus2022b[2] (Figure 4) due to application of the calibrated troposphere and clock data a priori. The catalog aus2022b used for comparison was obtained by the traditional method. Its formal error for the most observed radio sources is about 6 µas. This value is consistent with the uncertainty of the ICRF3 catalog as well as the recent solutions by other groups, e.g., the vie2022b solution [8].

The astrometric annual parallax effect is known to be negligible for extragalactic radio sources due to the large distance. However, we tried to estimate it with the geodetic VLBI. The parallactic delay caused by the time propagation difference τ between two radio telescopes (Figure 5) is given by

$$\tau_{par} = \frac{(r_2 s)^2 - (r_1 s)^2 - {r_2}^2 + {r_1}^2}{2c|r_s|} \quad (1)$$

or, after truncating of small order effects in (1)

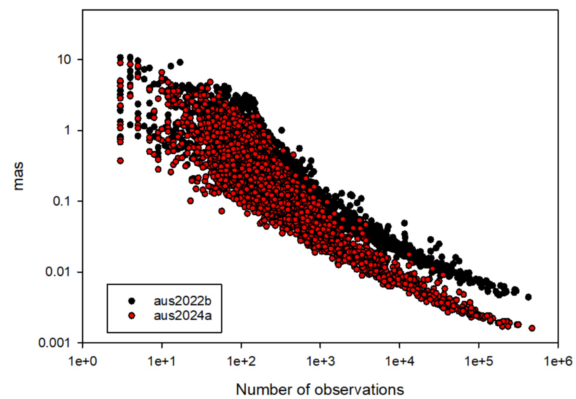

Fig. 4 Formal errors on declination for two CRF solutions, aus2022b and aus2024a.

$$\tau_{par} = \frac{|r_2|}{|r_s|}\frac{N(s(bs)-b)}{c} = \Delta\theta\frac{N(s(bs)-b)}{c} \quad (2)$$

where c is the speed of light, $|r_s|$ is the distance to the radio source, r_1 and r_2 are the barycentric vectors of the radio telescopes, $N = \frac{r_2}{|r_2|}$ is the unit vector directed from the barycenter towards the stations, and s is the vector of the radio source position.

The parameter $\Delta\theta = \frac{|r_2|}{|r_s|}$ in (2) is the correction to the elongation θ of the radio source from the barycenter measured from station 2 (Figure 5), i.e., $\cos\theta = \frac{-(r_2 s)}{|r_2|}$, and $\Delta\theta$ is consistent with the annual parallax.

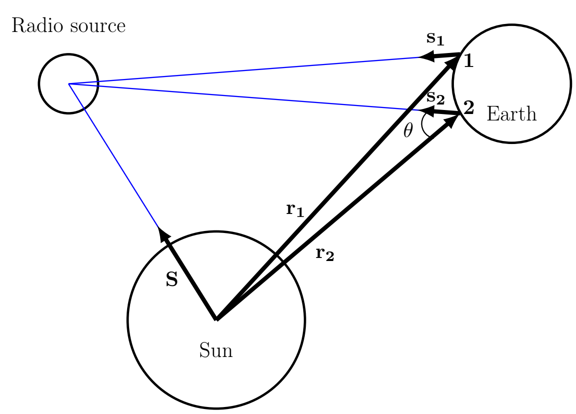

Fig. 5 Mutual positions of the Sun, Earth, and radio sources.

The traditional effect of stellar annual parallax π caused by the Earth orbital motion results in the reduc-

2 https://cddis.nasa.gov/archive/vlbi/ivsproducts/crf/

tion of the elongation angle θ for the apparent radio source position with respect to its unpertubed catalog position, i.e., π is always positive and $\Delta\theta$ is always negative, and $\pi = -\Delta\theta$. In more general definition, the negative meaning of parallax is permitted and corresponds to the positive correction $\Delta\theta$.

Table 2 Estimates of the negative parallax for different data subsets.

Solution	Estimate (µas)
All observations (1993–2023)	-15.8 ± 0.5
Even years (1993–2023)	-18.3 ± 0.7
Odd years (1993–2023)	-13.5 ± 0.7
1993–2003	-13.0 ± 1.1
2004–2013	-25.8 ± 0.9
2014–2023	-9.4 ± 0.7

The parallax effect estimated using Equation 2 was found to be statistically significant and equal to -15.8 ± 0.5 µas (Table 2) with the full 30-year set of VLBI data. Additionally, we split the full set of data into several groups to check a variability of the effect with time. Table 2 shows that the parallax is negative both on different ten-year time intervals and for subsets of the even and odd years.

4 Conclusions

The wet troposphere delays, gradients, and clock phase variations were calculated for all geodetic VLBI data since April 1993 and used for the adjustment by the least-squares method without the traditional procedure of the estimation of the stochastic parameters for 1–2 hour bins. This new approach is capable of reducing the formal error of all geodetic VLBI parameters roughly by a factor of three. In particular, the CRF formal errors of most observed radio sources changed from 6 µas to 2 µas. The daily estimates of the radio telescope geodetic positions and EOP have similar improvements. For the best IVS S/X experiments (IVS-R1, R4) the formal error of the geodetic positions reach 1 mm for all three components, consistent with the VGOS requirement. The results were verified independently with the VieVS software [6].

We report here a detection of the negative parallax with amplitude of approximately -15.8 ± 0.5 µas. This effect is detectable with different subsets of VLBI data and is also consistent with the recent GAIA EDR3 estimate of the negative parallax (-17 µas) [10].

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