Combining VLBI and GPS for inter-continental frequency transfer

T. Hobiger, C. Rieck, R. Haas, Y. Koyama

Abstract For decades the Global Positioning System (GPS) has been the only space geodetic technique routinely used for inter-continental frequency transfer applications. In the past VLBI has also been considered for this purpose and the method's capabilities were studied several times. However, compared to GPS current VLBI technology only provides few observations per hour, thus limiting its potential to improve frequency comparisons. We therefore investigate the effect of combining VLBI and GPSI on the observation level in order to draw the maximum benefit from the strength of each individual technique. As a test-bed for our study we use the CONT11 campaign observed in 2011. We perform a combined analysis of VLBI and GPS data on the observation level and demonstrate that our combination approach leads to small but consistent improvements for frequency transfer of up to 10%, in particular for averaging periods longer than 3000 s w.r.t. the GPS single technique solution. We discuss the implications of these findings and present our ideas about how VLBI can contribute to international frequency transfer tasks.

Keywords VLBI, GPS, frequency transfer, CONT11

1 Introduction

Given the fact that VLBI stations are equipped with highly precise and short-term stable frequency standards, usually hydrogen masers, comparing these atomic clocks appears to be straightforward. Since the early days of VLBI, several studies have dealt with the topic of applying this technology for time and frequency transfer (e.g., Clark (1972)). Also in Koyama (2012) the use of VLBI for time and frequency metrology is discussed and the potential of this technique is pointed out. However, it has been stated that VLBI systems have several drawbacks that compromise the application of VLBI for such purposes on a routine basis. First, current VLBI systems are not operating continuously. Observation sessions are usually scheduled to last for only 24 hours, which prevents frequency comparisons on time scales longer than one day. Second, as most of the cable and electrical path lengths in the VLBI system are not calibrated in an absolute sense and are designed to be variable, this technology cannot directly be utilized for time comparisons. Frequency transfer is still possible on time scales shorter than the variation, estimated to result in a few ns variation over several days.

Thus, VLBI is in principle able to directly determine the differences between clocks at two sites, if the Earth's orientation, the station positions, as well as ionospheric and tropospheric delays are known or simultaneously fitted.

1.1 Clock differences as a by-product of geodetic VLBI analysis

No technique is capable of providing absolute clock parameters at each site. Therefore it is necessary that one clock at one selected station in a network is kept fixed and all other clocks of the other stations in the network will be related to this reference clock. By doing so, clock differences can be obtained from geodetic post-processing, i.e. the adjustment of the unknown parameters. Since the clock difference parameters need to be estimated together with the other unknowns, one needs to pay attention that neither unmodeled effects bias the clock estimates, nor correlations among the unknowns absorb clock variations in other parameters. Moreover, the parametrization of the clock unknowns has to reflect the physical behaviour of the clock, i.e. providing a temporal sampling which can follow a random walk (in phase) noise process.

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1.2 Space geodetic data analysis with c5++

The software package ”c5++” has been developed with the purpose of supporting the combination of space geodetic data from VLBI, GPS and SLR on the observation level, and also to allow processing of single-technique solutions. Since c5++ uses consistent geodetic/geophysical models for all space geodetic techniques and all analysis steps, it is guaranteed that differences of the estimated parameters that are derived from e.g. VLBI and GPS do not originate from different models or inconsistent corrections, but are directly related to the performance of each technique. Moreover, the possibility to combine data on the observation level allows to study the impact of combining techniques, with the purpose to improve the target parameters. The concept of combination on the observation level has been successfully demonstrated in Hobiger and Otsubo (2014) and will be applied here.

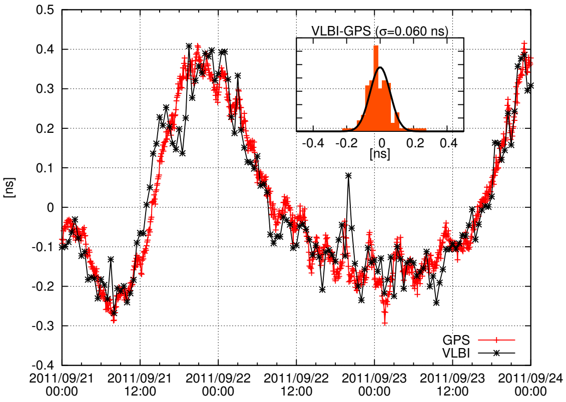

Fig. 1 Clock differences (after reducing a quadratic trend) as obtained from a 3-day batch solution for VLBI-only(red) and GPS-only(black) on the Wettzell-Westford baseline.

2 Frequency transfer during CONT11

In total 14 VLBI stations participated in the CONT11 campaign, but only 11 of the network stations shared a common frequency standard with a co-located GPS receiver (Rieck et al., 2012). Furthermore, unfortunately some of the stations were excluded because they experienced technical or observational problems. For example, the stations Badary and Zelenchukskaya experienced strong radio frequency interference (RFI) disturbances in several of the observed frequency bands. The station Tigo Concepción performed rather poorly, mainly due to its small antenna size, and several other sites had clock jumps of the VLBI equipment or missing GPS data. Although small antennas, like Tigo, are very attractive as they can be easily deployed at arbitrary sites, technology which was available during CONT11 causes a significant performance degradation that comes with shrinking the antenna diameter w.r.t. the average size of the other VLBI dishes in the network. This drawback is currently being worked on and thought to be overcome by switching to broad-band receiving systems (cf. Sec. 3). Thus, the further analysis concentrates in the following mainly on a sub-set of 6 of the CONT11 stations.

As study from from Rieck et al. (2012) compare the potential of frequency transfer of each technique, showing that VLBI and GPS perform similarly with best case one day instabilities on the order of 10^{-15}. Fig. 1 depicts the clock estimates from two single-technique solutions on a particular baseline.

2.1 VLBI and GPS analysis with c5++

In order to assess both short- and long-term frequency stabilities, the data were processed with c5++ in non-overlapping batch solutions with three consecutive days, i.e. covering a period of 72 hours each. Thus, the whole CONT11 campaign could be analysed in five 72 hour batches. This was possible since the whole campaign had been re-correlated with a consistent delay model that prevents discontinuities at the day boundaries. As mentioned before, VLBI analysis requires that one station clock in the network is fixed to an arbitrary constant value, which is chosen normally to be zero. Doing so, all estimated clocks in the network represent the clock difference between that station’s clock and the clock of the reference site. The clock reference should be assigned to a station which is known to show no clock break during an entire session. The clock at Wettzell (Germany) was selected as reference. Another characteristic of VLBI analysis relating to clock estimates is the irregular temporal spacing of the original observational data. Depending on antenna and receiver characteristics and the flux density of the observed radio sources, optimized observation schedules require different scan-length and varying idle/slewing times. Moreover, hardware problems or operational problems can lead to larger temporal gaps during which a single station is not observing together with the other network sites. Therefore, constraints on the clock rate were chosen to reflect the physical variation of the atomic clock at the VLBI site. In addition, zenith wet delays (ZWDs), troposphere gradients and station coordinates need to be estimated in order to obtain clock estimates that are not degraded by the correlations among these parameters. The c5++ software allows to process un-differenced GPS observations with the precise-point positioning (PPP) approach, using the same geophysical models as used for VLBI analysis. PPP does not require GPS satellites in common-view, and becomes independent of the length of the baselines that are defined by the VLBI network geometry. Thus, even inter-continental frequency links can be established by this analysis method. However, satellite orbits and clocks need to be fixed to IGS final products since such parameters can not be estimated for this study, due to the small number of GPS receivers within the CONT11 network.

Since GPS observations are available with a regular and high sampling rate, clock parameters can be estimated without constraints. Moreover, PPP allows to directly access the behaviour of the station clock, and frequency transfer between two stations can be performed by differencing the PPP clock solutions of the two sites. Other parameters like zenith troposphere delays or station coordinates have to be estimated together with the clock model, subject to the same correlations as VLBI.

2.2 Combining VLBI and GPS data on the observation level

Combination on the observation level reflects the concept of using all available geodetic data at a site in order to overcome potential deficits of a single technique. Since co-located instruments often share the same infrastructure (e.g. frequency standards) and are expected to experience the same environmental conditions, in particular the atmospheric conditions, one can estimate parameters related to these influences in a common model which only considers biases between the different techniques. It was demonstrated in Hobiger and Otsubo (2014) that the combination of GPS and VLBI on the observation level leads to a small but significant improvement of the geodetic target parameters and in particular improves the stability of the site coordinate time series. Since troposphere and clock parameters were estimated in Hobiger and Otsubo (2014) by a station-wise model it was obvious to investigate how the combination of these two techniques on the observation level can be utilized for the benefit of frequency transfer. As described in Hobiger and Otsubo (2014), troposphere parameters can be estimated with a common model that considers an offset between GPS and VLBI, caused by the height difference between the VLBI and GPS reference points, resulting in a hydrostatic delay difference which remains very stable over time.

On the other hand, a common clock model can be estimated by combining VLBI and GPS only if one considers that instrumental delays are not stable over time but are influenced by temperature-induced changes in reflections (cable multipath) and electrical lengths; for VLBI these can also depend upon the orientation of the antenna. It was suggested in Hobiger and Otsubo (2014) to estimate these inter-technique delay changes by a PLO model with a temporal resolution that is sufficient for representing at least a diurnal signal. A low temporal resolution, i.e. with a PLO step-width of more than 12 hours, bears the risk of not modelling all inter-technique delay changes properly. However, a high temporal resolution reduces the benefit of combining GPS and VLBI since a large fraction of the information provided by the second technique gets absorbed into this parameter. Therefore, the proper choice of the temporal resolution for this crucial parameter is explored in Sec. 2.4.

Another issue that arises from the combination of different observation types is related to the question on how to weight the data of each technique. In order to handle this problem with a proper stochastic model one needs to select an estimation strategy as described in the following.

2.3 Results from combined analysis with c5++

Combining VLBI and GPS on the observation level is the most natural way to estimate common parameters at geodetic colocation sites. With this approach, biases and technique-specific considerations can be taken into account before the observations are combined directly within the adjustment process. Two of such inter-technique biases are those related to troposphere and clock variability. The former one being mainly caused by different heights of the reference points of co-located instruments, which translate into a hydrostatic delay that can be either modeled or, as done in the present study, estimated as a constant offset during each 72 hours batch analysis. The latter offset, hereafter denoted as $\Delta_{clk}(t)$, is expected to be caused by temperature-induced cable delay variations and can either be estimated as a constant offset or parametrized by a PLO model with sufficient temporal resolution to follow cable delay changes. It is obvious that the choice of this inter-technique delay potentially absorbs any benefit that could result from the estimation of a common clock between the two techniques. A too-short temporal resolution of $\Delta_{clk}(t)$ bears the risk that a large fraction of valuable information from the second technique is not being reflected in the estimated clock. On the other hand, an insufficient model representation of the mostly diurnal cable length changes potentially degrades the combined solution and the obtained clock parameters. Therefore, different choices for the temporal resolution of the inter-technique cable delay model $\Delta_{clk}(t)$ have been used and their impact on the frequency transfer stability has been evaluated.

2.4 The impact of the choice for the temporal resolution of the inter-technique cable delay model

In order to evaluate whether the combination of VLBI and GPS leads to an improvement of the frequency transfer stability w.r.t. the GPS-only solution, the ratio

$$\kappa(\tau) = \frac{\frac{1}{N}\sum_{N}\mathrm{MDEV}_{GPS}(\tau)}{\frac{1}{N}\sum_{N}\mathrm{MDEV}_{GPS+VLBI}(\tau)} \qquad (1)$$

is defined, where N is the number of baselines that are averaged. The ratio $\kappa(\tau)$ describes the average improvement/degradation when combining VLBI with GPS on the observation level for frequency transfer, compared to a GPS-only solution. Since the intervals for the PLO clock model were set to 5 minutes in both solutions one can compute $\kappa(\tau)$ in a straightforward way. Improvements in the overall frequency transfer performance will then be reflected as $\kappa(\tau) > 1$, whereas degradations can be recognized when $\kappa(\tau) < 1$. Figure 2 depicts $\kappa(\tau)$ for solutions with different choices for the temporal resolution of the inter-technique

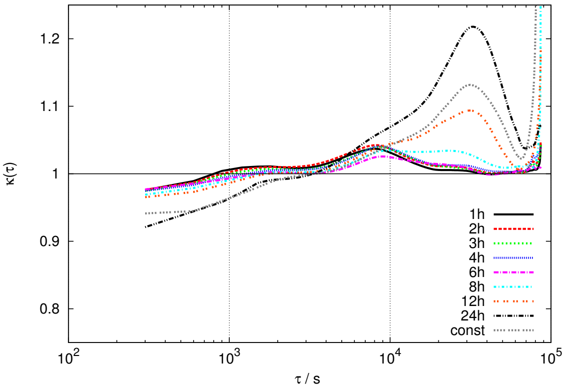

Fig. 2 Average improvement/degradation of the frequency transfer stability, measured as ratio $\kappa(\tau)$, when comparing the combined GPS-VLBI solutions against the GPS-only solution. Results are shown for different temporal resolutions (1 h, 2 h, 3 h, 4 h, 6 h, 8 h, 12 h and 24 h) of the inter-technique delay model as well as for the parametrization with a constant cable delay between the two techniques. Values of $\kappa(\tau) > 1$ indicate improvement

cable delay model $\Delta_{clk}(t)$. Overall, it can be seen that the combination of VLBI with GPS tends to improve the average frequency transfer stability w.r.t. the GPS-only solution. However, as anticipated in the previous section, the choice of the temporal resolution of $\Delta_{clk}(t)$ is crucial. The use of an interval length of 1 hour for the PLO of $\Delta_{clk}(t)$ absorbs almost all benefit gained from adding VLBI. On the other hand, it is clearly visible that daily estimates or parametrization as a constant lead to a degradation of the short term stability while improving the long-term stability more than any of the other choices for the temporal resolution of $\Delta_{clk}(t)$. In general, one can see that VLBI improves the frequency transfer stability for averaging periods between 3,000 and 20,000 seconds as well as for periods close to one day. The latter improvement can be explained by the fact that VLBI helps to smooth the jumps introduced by day boundary discontinuities of the used IGS orbit and clock products. However, one needs to consider also the lower significance (higher uncertainty) of the MDEV at the far end of the long averaging period domain. The improvement between 3,000 and 30,000 seconds is thought to have its origin in the parametrization of tropospheric estimates, which become more robust against data artifacts, when combining VLBI and GPS. In addition, a temporal resolution of 12 hours or longer for $\Delta_{clk}(t)$ leads to an improvement for averaging periods of 12 hours, which might relate to the orbital period of GPS satellites.

3 Discussion and outlook

On average the combination approach performs consistently better than the GPS-only solution, revealing an improvement of the frequency transfer stability of up to 10 %. This leads to the question how VLBI can efficiently contribute to efforts of precise inter-continental frequency transfer.

It is very unlikely that time and frequency laboratories will deploy expensive and difficult to maintain radio telescopes which are necessary for VLBI operations. However, one could imagine a mutual benefit if a VLBI site is located in the vicinity of a timing laboratory and frequency is provided from this time lab over fiber to that VLBI site. This would imply that frequency standards at the VLBI sites can be omitted and the remotely provided frequency signals from the timing lab could be used for VLBI operations. One could then use global VLBI experiments to support inter-continental frequency transfer by a combination of GPS and VLBI on the observation level, as described in this study. However, the cable delay changes of the VLBI hardware and other time-dependent delays have to be monitored in order to gain benefit from adding VLBI. Estimation of such biases and delays, as performed in this study, helps to a certain extent, but monitoring and calibration of these inter-technique delays is crucial for the estimation of a common clock model among different space geodetic techniques. This requires efforts to study all back-end components and their delay characteristics, a task which is expected to be more straightforward when phasing out analog systems and replacing them with digital equipment. In addition, one needs also to raise the awareness of such a demand in the geodetic VLBI user community in order to develop and deploy such delay calibration and monitoring systems.

Note: This paper summarizes the main findings of a study which has been published as Hobiger et al. (2015).

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