Combining VLBI and GPS for inter-continental frequency transfer

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Summary

For decades the 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 in order to draw the maximum benefit from the strength of each individual technique using data from the the CONT11 campaign. First we review the frequency transfer performance that can be achieved with independent technique-specific analyses. In doing so, GPS and VLBI, show similar frequency link instabilities at the level of 10^{-14} to 10^{-15} (MDEV) on inter-continental baselines for averaging times of one day. We also 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.

VLBI – comparing clocks by nature

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. In case of absolutely calibrated cable and instrumental path lengths, the clock difference follows when subtracting the theoretical delay. 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.

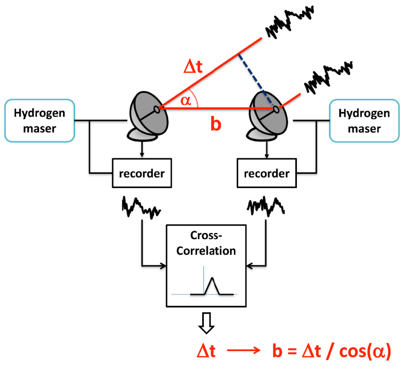

Figure 1: *Since signals from radio sources observed with radio telescopes are recorded and time-tagged using stable frequency standards (e.g. hydrogen masers) frequency transfer emerges as a logical application of VLBI.*

VLBI network

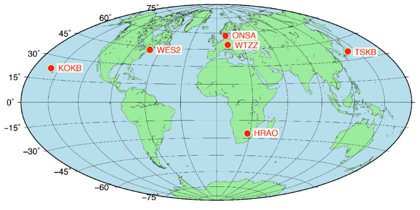

Figure 2: *Location of the six CONT11 stations that were considered for this study. Only sites were selected where a common frequency standard was connected to both VLBI and GPS equipment and no major technical or observational problems occurred.*

Analysis with independent software

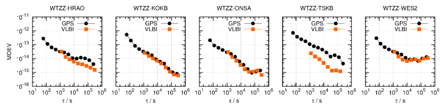

Figure 3: *Modified Allan deviation (MDEV) plots for frequency links on 5 baselines connecting to Wettzell, as obtained from GPS (black) and VLBI (orange) single-technique solutions with the software packages NRCAN-PPP and Calc/Solve, respectively. It becomes clear that the loss of lock at the TSKB GPS receiver, that was not accounted for in this analysis, deteriorates the GPS-performance on the corresponding baseline.*

Results from c5++

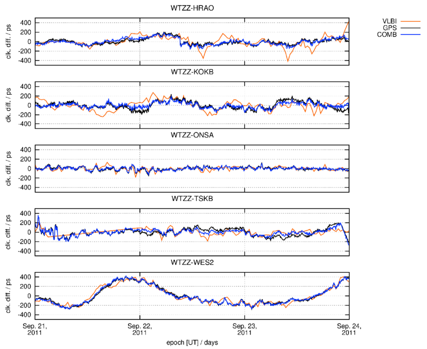

Figure 4: *Clock differences (after reducing a quadratic trend) as obtained from a 3-day batch solution for VLBI-only (red), GPS-only (black) and the combined solution (blue). Only baselines connecting to Wettzell are shown here. As for the combined solution, inter-technique delay changes are modeled by a constant offset.*

Freq. transfer stability (single-techn.)

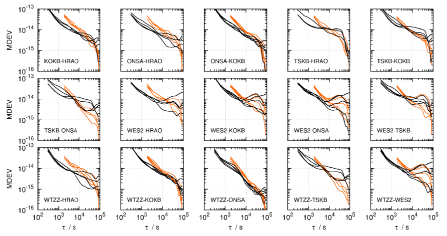

Figure 5: *Modified Allan deviation (MDEV) plots for frequency links over all baselines in the 6 station CONT11 network, as obtained from the three-daily GPS (black) and VLBI (orange) single-technique solutions with c5++.*

Gain of combining VLBI and GPS

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

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

is defined. Thus κ describes the average improvement or degradation when combining VLBI with GPS on the observation level for frequency transfer, compared to a GPS-only solution.

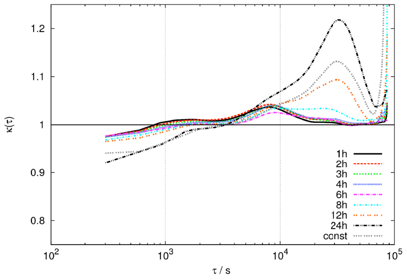

Figure 6: *Average improvement/degradation of the frequency transfer stability, measured as ratio κ(τ) when comparing the combined GPS-VLBI solutions against the GPS-only solution. Results are shown for different temporal resolutions (1 h, 2 h, 3 h, 4 h, 6 h, 8 h, 12 h and 24 h) of the inter-technique delay model as well as for the parametrization with a constant cable delay between the two techniques. The improvement between 3000 and 30000 seconds is thought to have its origin in the parametrization of tropospheric estimates and the improvement at 12 hours or longer is likely caused by better mitigation of GPS orbital errors.*

Which frequency link benefits?

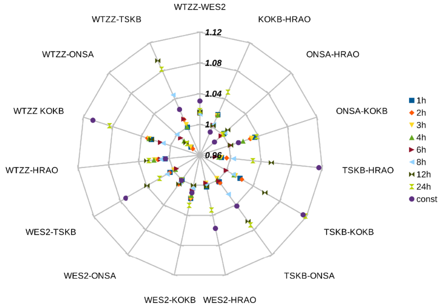

Figure 7: *Average improvement/degradation of the frequency transfer stability after re-sampling κ(τ) to 28 logarithmically equally spaced data points for all baselines in the station network. Values of κ(τ) >1 indicate improvement.*

Conclusions

In this study we confirm that VLBI single-technique solutions can provide similar or slightly worse frequency transfer performance as compared to GPS PPP solutions. However, we also demonstrate that the combination of GPS and VLBI on the observation level results in an improvement of the frequency link stability at various averaging periods. 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.

Further reading

Hobiger T., C. Rieck, R. Haas & Y. Koyama, Combining GPS and VLBI for inter-continental frequency transfer," Metrologia, vol. 52, iss. 2, pp. 251-261, 2015.

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