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VLBI and GPS-based Time-transfer Using CONT08 Data

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Abstract

One important prerequisite for geodetic Very Long Baseline Interferometry (VLBI) is the use of frequency standards with excellent short term stability. This makes VLBI stations, which are often co-located with Global Navigation Satellite System (GNSS) receiving stations, interesting for studies of time- and frequency-transfer techniques. We present an assessment of VLBI time-transfer based on the data of the two week long consecutive IVS CONT08 VLBI campaign by using GPS Carrier Phase (GPSCP). CONT08 was a 15 day long campaign in August 2008 that involved eleven VLBI stations on five continents. For CONT08 we estimated the worst case VLBI frequency link stability between the stations of Onsala and Wettzell to ≈ 1e-15 at one day. Comparisons with GPSCP confirm the VLBI results. We also identify time-transfer related challenges of the VLBI technique as used today.

1. Introduction

Work in the field of time- and frequency-transfer using Very Long Baseline Interferometry (VLBI) originated in the 1970s and was often driven by the need of the Deep Space Network (DSN) ground station time synchronization. Already in the early 1980s VLBI frequency link instabilities on the order of 1e-14@1d were reported [1], and time-transfer reached ns level precision. The time-transfer accuracy was verified with the help of clock transports [2] or by comparisons with independent techniques, such as Global Positioning System (GPS) or Two Way Satellite Time and Frequency Transfer (TWSTFT) [3]. In order to reach ns and sub-ns uncertainties it is necessary to use differential station calibration techniques [4, 5].

Most recent work presented in [6] resulted in frequency link instabilities surpassing GPS Carrier Phase (GPSCP) with better than 1e-15@1d modified Allan deviation (MADEV). The intent of this paper is to investigate the potential of VLBI time-transfer and gain a better understanding of the local VLBI system delays.

An additional motivation is the fact that some of the IVS sites maintain UTC realizations. Traditional long distance time-transfer methods are often heavily dependent on active third parties that are not necessarily dependable in the long term. GPS and TWSTFT are today the backbone of international time metrology and can fast become outdated due to economical or political reasons, thus VLBI could become an alternative and independent passive time-transfer method.

2. Time and Frequency Within the VLBI System

The frequency source in a VLBI system is usually a hydrogen maser that supplies the local oscillators (LO) of the front-end, the phase calibration system (PCAL), and the video converters (VC) of the back-end with a 5 MHz reference frequency. The time stamping of the data recording is governed by the time scale that is maintained by the formatter clock. Often the formatter clock has a 1PPS output that is used to monitor the VLBI clock offset during the experiment. A VLBI time-transfer system needs to assure at least three items on the equipment side:

1. The formatter clock has to be calibrated and constantly measured using a reference delay measurement system to another clock or timescale, such as a UTC(k) representation.
2. The signal chain from the fiducial point of the antenna system to the formatter clock needs to be calibrated by measuring equipment delays or by using differential calibration techniques.
3. Delays induced by environmental changes have to be estimated. PCAL is used for bandwidth synthesis and could also be used to measure the momentary delay of the receiver chain.

We have used a 50 ps time interval counter (TIC) in order to quantify the timing noise level of the Onsala station. Compared to the local timescale the formatter 1PPS output experiences several times as much noise as the source clock at any time interval, with an Allan deviation of about 2.6e-15@1d and RMS levels of about 150 ps. It is not clear if the formatter 1PPS output represents the noise that is apparent in the recording time stamps, but a reference delay measurement system based on the formatter clock output will presently dominate the noise of the VLBI time-transfer.

3. VLBI Time-transfer Using the CONT08 Experiment

The continuous sessions of the IVS have been a tool for assessing the VLBI technique and are of special scientific value. The CONT08 experiment was carried out from August 12 through August 26 in 2008 and involved eleven stations on five continents using a 512 Mbit/s recording.

Besides its main scientific goal, the study of high frequency sub-diurnal earth orientation parameters (EOP), CONT08 was also used to assess the improvement of the VLBI technique and its geodetic accuracy, and to make comparisons with co-located techniques like GNSS, SLR, and DORIS. Figure 1 shows the station network of CONT08. All captured data of the experiment were correlated in 24-hour batches by the Washington correlator (WACO) using the Kokee Park station (KOKEE) as its reference. `(http://ivscc.gsfc.nasa.gov/program/cont08/)`

Figure 1. CONT08 VLBI station network.

3.1. Network Analysis (NA)

The data were processed in batches of 24 hours using Calc/Solve [7]. In the analysis we used ONSALA60 as the clock reference, and the clock offsets of all other stations were estimated as quadratic terms with constraint (5e-14 s/s) deviation estimates every 1200 s. The batch processing gives rise to discontinuities at the day-boundaries, which affects all parameters that are expected to be continuous, such as clocks and atmospheric delays. During CONT08 the clock discontinuities are generally on the order of a few hundred picoseconds, often much larger than the formal uncertainties of the estimates, which are on the order of 30 ps. The last two days of the experiment, MJD 54703 and 54704, show excessive day-boundary offsets of about 50 ns with an almost inverted behavior between the two days. The magnitudes of these offsets are not explainable from the modeling and are believed, but so far unverified, to be an effect of the correlation. Throughout CONT08 the KOKEE station clock experienced an excessive 1 ns diurnal signature likely caused by the environment at KOKEE. This can be one reason for correlator-introduced biases, because the correlation was based on a badly behaving clock/distribution. From a geodetic point of view additional biases are no problem as long as they are constant during one common period of correlation and analysis. These disturbing conditions, i.e. **a)** discontinuities through analysis, and **b)** possible biases from correlation, prevent an absolute time-transfer.

The output of the Calc/Solve analysis allows concatenating two adjacent solutions because of overlapping estimates. This removes any meaning of a phase bias, but can be useful for the evaluation of a frequency-transfer. Day-boundary offset removal likely introduces errors in the estimated frequency offset of the combined time series. Allan deviations (ADEV) for the CONT08 VLBI-derived and 2nd order detrended clock differences, see Figure 2, represent the link stability of VLBI by assuming that the intrinsic stability of the station clocks is better than the link stability during time intervals shorter than one day. Removal of the quadratic phase term removes most of the long term instability of a maser clock. This assumption is dependent on the actual clock performance during the experiment, but can be used to identify a worst case link instability. The Onsala-Wettzell baseline outperforms all other differences with an ADEV of 1.2e-15@1d.

3.2. Clock Constraints in Single Baseline Analysis (SBA)

Because of its good performance in the network analysis we used the Onsala-Wettzell baseline in a single baseline analysis in order to study the effect of **1)** an alternative processing strategy and **2)** the influence of different clock constraints on the time-transfer results. In a geodetic setup the clock parameters are often loosely constrained, e.g., 1e-13 s/s at 1 hour sampling, in order to allow the absorption of unmodeled effects, such as certain loading types or errors in the atmospheric delay mapping. For timing purposes the actual clock constraints should be adjusted to the stability of the involved station clocks. Figure 3 shows the Allan deviations of different 2nd order detrended clock solutions. Constraints harder than 5e-14 s/s seem to create problems in the processing where the clock performance is overestimated and the LSQ analysis cannot separate the clocks from instrumental noise. The clock difference between the network and single baseline solution for the same constraint is significant and can be seen as a frequency offset of about 50 ps per day. Even the different SBA/NA solutions differ, most noticeably, by phase jumps at the day-boundaries with their magnitude roughly proportional to the constraint difference. This indicates systematic differences in the estimated day-boundaries offsets.

4. GPSCP Time-transfer and Comparative Results

All IVS stations have co-located IGS receivers, where seven out of eleven used a common clock as the frequency source for both the VLBI equipment and the IGS stations. Table 1 summarizes the situation during the CONT08 experiment. In order to assess the correctness of the VLBI derived clock difference frequency offsets we have used comparisons with GPSCP solutions for the seven common clock cases. Due to the global distribution of the stations, Precise Point Positioning (PPP) derived station clocks, using NRCANPPP [8], were differentiated in order to create matching clock differences to the Onsala H-maser. NRCANPPP is capable of continuously processing arbitrary

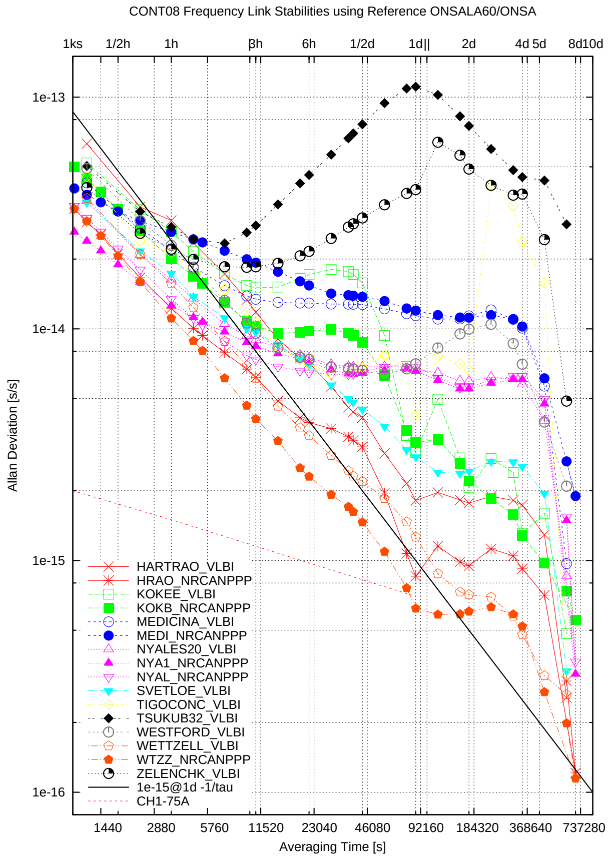

Figure 2. CONT08 VLBI and NRCANPPP derived frequency link stabilities (ADEV) of 2nd order detrended time series. TSUKUB32 experienced a dramatic frequency change during CONT08.

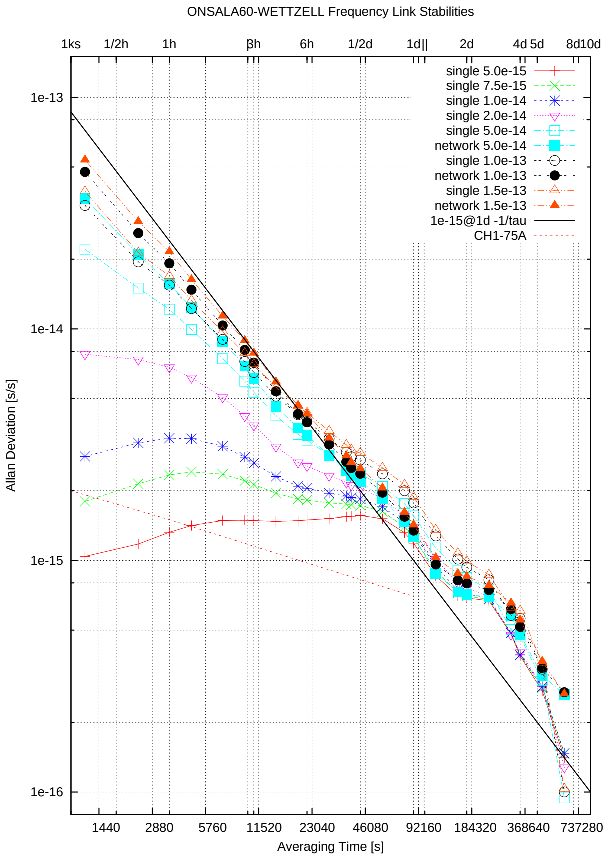

Figure 3. VLBI ADEV stability of ONSALA60-WETTZELL using different analysis strategies and constraint settings. The network solutions exhibit more noise than similar single baseline solutions.

long time series without introducing day-boundary offsets. Figure 2 gives the estimated PPP link stabilities. The last two columns in Table 1 compare VLBI and NRCANPPP. The Onsala-Wettzell baseline, using the WTZZ receiver and the VLBI network solution, show the best agreement and stability. The link difference has a significant relative frequency offset of about 5e-16. This offset can be attributed to either technique, e.g., the absence of integer ambiguity resolution in PPP and frequency biases introduced by the VLBI day-boundary fix.

5. Conclusions

Day-boundary offsets caused by batch-analysis and possible correlator introduced biases make VLBI time-transfer challenging. CONT08 derived frequency link stabilities of ≈ 1e-15@1d (ADEV) do not match results reported in [6]. Practical VLBI time-transfer will require changes to the equipment and processing, a consistent calibration, and a continuous correlation and analysis process. VLBI2010 (`http://www.haystack.mit.edu/geo/vlbi_td/2010`) with is wideband 24/7 observations may improve the time link noise and may make absolute VLBI time-transfer possible.

Table 1. CONT08 summary. VLBI, NRCANPPP time-transfer results and comparison.

VLBI	**IGS**	**CommonClk**	**VLBI@1d**	**GPSCP@1d**	**GPSCP-VLBI**	**RMS**
HARTRAO	HRAO	Y:EFOS C	1.9e-15	8.5e-16	3.8e-17	260ps
KOKEE	KOKB	Y:SigmaTau	3.0e-15	3.2e-15	7.4e-17	210ps
MEDICINA	MEDI	Y:EFOS 4	1.2e-14	1.2e-14	1.2e-15	340ps
NYALES20	NYAL	Y:APL 2	6.8e-15	6.5e-15	-4.5e-16	110ps
	NYA1			6.8e-15	-6.6e-16	140ps
ONSALA60	ONSA	Y:CH1-75A	CALC/SOLVE/GPSCP CLK REFERENCE			
SVETLOE	SVTL	N:CH1-80/int	2.8e-15	1.1e-12	no common clock	
TIGOCONC	CONT	Y:EFOS24	4.3e-15	no GPS data available		
	CONZ	N:internal		6.1e-9	no common clock	
TSUKUB32	TSK2	N:RH401A	1.2e-13	8.2e-14	no common clock	
	TSKB	5071A(IGS)		6.5e-14	no common clock	
WESTFORD	WES2	N:APL 3/4	7.1e-15	8.4e-14	no common clock	
WETTZELL	WTZR	Y:EFOS 18	1.2e-15	1.9e-14	8.9e-15	1.9ns
	WTZZ			6.2e-16	4.8e-16	70ps
ZELENCHK	ZECK	N:CH1-80/int	4.0e-14	4.1e-10	no common clock	

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