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Experience from geodetic very long baseline interferometry observations at Onsala using a digital backend

Abstract: The Onsala Space Observatory has installed a modern digital backend for geodetic and astronomical Very Long Baseline Interferometry (VLBI). This system consists of a Digital Base-Band Converter (DBBC) and a Mark 5B+ recorder. From 2011 until late 2014 this new system was run for geodetic VLBI observations in parallel with the old system consisting of a Mark 4 rack and Mark 5A recording system. Several of these observed sessions were correlated at the correlator in Bonn including both data sets. We present results from the analysis and comparison of these sessions. Both the original observed delays and corresponding geodetic parameters are compared. No significant differences are detected, for either the raw observations or for the geodetic parameters. This shows that the digital backend can be used operationally for geodetic VLBI observations.

Keywords: digital base-band converter, geodetic very long baseline interferometry, Mark 4, VLBI2010 Global Observing System

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1 Introduction

In 2011, the Onsala Space Observatory installed a modern digital backend for Very Long Baseline Interferometry (VLBI), a Digital Base-Band Converter (DBBC) (Tuccari et al., 2010), in parallel to the VLBI Mark 4 rack. The Mark 4 (Whitney et al., 2004) rack at Onsala has been used operationally for both astronomical and geodetic VLBI for more than 15 years. Since 2011, we started to test the DBBC and to gain experience with the new device for geodetic VLBI observations. We did parallel recordings with both the old Mark 4/Mark 5A system and the new DBBC/Mark 5B+ system during numerous geodetic VLBI-sessions. Several R1, T2 and EUR sessions, as well as sessions from CONT14, were correlated during the last two years by the Bonn correlator (La Porta et al., 2013) where Onsala was included both as station "On" (Mark 4/Mark 5A) and as a station "Od" (DBBC/Mark 5B+). We present results from these parallel sessions, from both the original correlation and from the analysis of the corresponding databases.

2 VLBI systems at Onsala

Since the introduction of the first DBBC to the Onsala Space Observatory in 2011, the aim has been to gradually phase out the old VLBI Mark 4 rack. This is both due to problems associated with maintaining the old equipment and to meet the observation mode requirements of a modern VLBI Global Observing System (VGOS) broadband system (Petrachenko et al., 2013). The first DBBC acquired in 2011 was a DBBC2 (Tuccari et al., 2010). Since then, it has been upgraded several times. The old and new backends, Mark 4/Mark 5A and DBBC/Mark 5B+, respectively, were run in parallel until October of 2014, when the VLBI Mark 4 rack was finally placed in the museum at the observatory. In 2013, a second DBBC was purchased. The current VLBI equipment in Onsala consists of:

- System-1: DBBC2#1/Mark 5B+, the primary operational system
- System-2: DBBC2#2/Mark 5C
- FlexBuff: e-VLBI recording machine
- Mark 5A: e-transfer machine

The time period from 2011 to late 2014 saw the DBBC/Mark 5B+ system move from a secondary recording system to a system in operational use. During this period, several zero-baseline tests for both International VLBI Service for Geodesy and Astrometry (IVS) and European VLBI Network (EVN) sessions were conducted. For EVN sessions, the DBBC has been in operational use since mid 2013. The Mark 5A system previously used with the Mark 4 rack today is used as an e-transfer machine, i.e.

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a machine to electronically transfer the recorded data via internet to the correlator after the observation session is finished. For geodetic e-VLBI sessions, i.e. real-time electronic data transfer to the correlator and near real-time correlation during an experiment, we previously operated a dedicated computer, PCEVN (Parsley et al., 2003). It has also been removed and we are currently working to replace it with a new computer, a so-called FlexBuff system (Mujunen and Salminen, 2013).

3 Parallel observations

During a time period between late 2011 and 2014, including the continuous 15-day long CONT14 campaign in May 2014, we recorded numerous geodetic VLBI sessions in parallel with the Mark 4/Mark 5A and DBBC/Mark 5B+ systems. The recorded IVS session types include R1, R&D, EUR, T2, and the CONT14 sessions.

The IVS-R1 sessions are a weekly 24-hour VLBI experiments observed on Mondays, which are aimed to produce estimates of the Earth Orientation Parameters (EOP) at the maximum latency of two weeks. The CONT campaigns, held every three years, are approximately 15 day long continuous VLBI sessions aimed at acquiring the best available data with the current equipment used globally.

The R&D, EUR, and T2 sessions are aimed at various topical observing tasks (Research and Development), station position determination in the European geodetic VLBI Network, and bi-monthly Terrestrial Reference Frame (TRF) monitoring sessions, respectively.

Zero-baseline tests for these sessions were carried out using the DiFX software correlator (Deller et al., 2007) installed at Onsala. In addition to the local validation, a subset of the recorded sessions was sent to the Bonn correlator. For these sessions the correlator did fringe-testing and produced databases in Mark3-db format (Gipson, 2012), in which both recordings from Mark 4/Mark 5A and DBBC/Mark 5B+ were included as separate Onsala stations, On and Od, respectively. Henceforth the data in the databases will be referenced by their respective 2-letter codes, On and Od.

Figures 1 and 2 show fringe plots from zero-baseline tests carried out with DiFX for X- and S-band. These plots show that the zero-baseline correlation was successful and gave results with the highest possible quality code (fringe quality 9). The cross-spectra (Annotated as "Avgd. Xpower Spectrum (MHz)" in Fig. 1 and Fig. 2) clearly show the band-pass and the phase calibration signals. In all X- and S-band channels stable amplitude and phases were detected (Annotated as "Amp. and Phase vs. time for each freq" in Fig. 1 and Fig. 2).

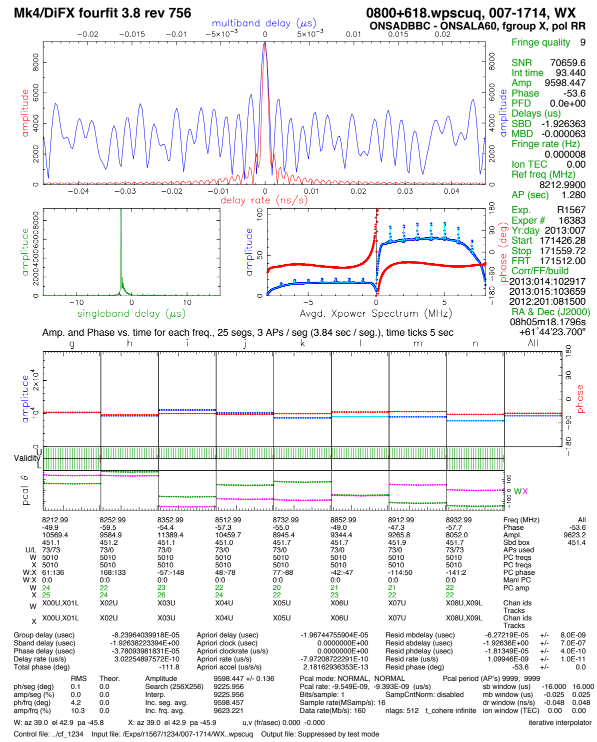

Figure 1: Fringe plot on X-band for the session R1.567 zero-baseline test done with DiFX. The station names, ONSADBBC and ONSALA60, correspond to Od an On, respectively.

We analyzed VLBI databases created by the Bonn correlator including both station On and Od for five R1 sessions between December 10th 2012 and November 18th 2013 and five CONT14 sessions during the spring campaign of 2014 in May. These sessions were analyzed in order to investigate the impact of using the two different backends on the geodetic parameters. In addition to the estimated geodetic parameters we also investigated directly the observed delays produced by the correlator for the various baselines in the sessions. We concentrated on the IVS-R1 and CONT14 sessions in order to have a cohesive and high quality data set with a sufficient number of databases in each session type, from which we can estimate all relevant geodetic parameters, e.g. station coordinates and EOPs. We investigated whether any significant systematic or stochastic differences can be detected in the results, when using On or Od as the Onsala station in the observation network.

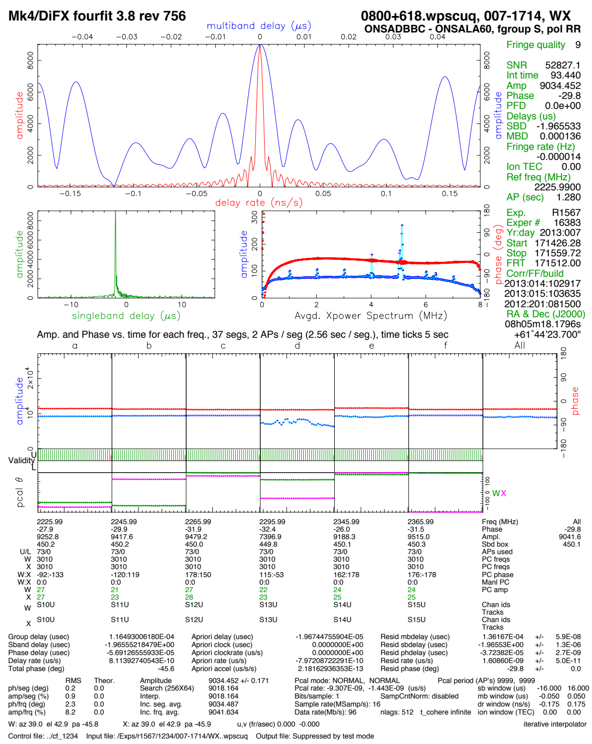

Figure 2: Fringe plot on S-band for the session R1.567 zero-baseline test done with DiFX. The station names, ONSADBBC and ONSALA60, correspond to Od an On, respectively.

4 Raw data comparison

In order to get a first impression on the data quality, we compared the raw observed delays as produced by the correlator. The version 2 databases for X-band were converted to National Geodetic Survey (NGS) cards, an ASCII format with a subset of data exported from a database in the Mark3-db format (Gipson, 2012), to conveniently obtain observed delays for all the baselines from the correlator output for each database. Observed delays for On-Od zero-baseline and a triangle of On, Od, and a third station (Wettzell), were investigated for misclosures. Crude outliers were removed using a 3-σ rule compared to the mean value for the delay of the baselines. The 50 ns ambiguities in the baseline triangle were easily detected and corrected during the processing. The corresponding misclosure histograms are presented for IVS-R1 and CONT14 sessions in Fig. 3 and Fig. 4 together with the histograms of the formal errors as reported by the correlator. We can conclude that there are no significant differences in the delays larger than the formal errors, since the median triangle misclosures are smaller than the median formal errors of the triangle misclosures. Table 1 presents these values for all the IVS-R1 and CONT14 sessions used in the analysis.

Table 1: Median baseline misclosure and corresponding formal errors for the triangle (On-Wz-Od).

	Median baseline misclosure (ps)	Median σ misclosure (formal) (ps)
R1	6.5	14.7
CONT14	3.2	9.4

5 Data analysis and results

We analysed the R1 and CONT14 VLBI data using the *CALC/SOLVE* analysis software (Ma et al., 1990). Using this software the different analysis steps result step-by-step in different versions of Mark3-db databases that keep the VLBI data. We started from version 1 and each database was analysed individually as a single-session to compute estimates for a set of geodetic parameters. First, to compute and add theoretical delays, partials, and geophysical contributions the databases were processed with the program *CALC* version 11.01 of the VLBI data analysis system *CALC/SOLVE*. The obtained version 2 databases were then processed to add cable and weather calibration information into the databases. The necessary cable and weather data were taken from the station log files. During the parallel recordings, log files were created for both On and Od, and corresponding cable and weather data were extracted for both stations respectively. For IVS-R1.563, IVS-R1.566, and IVS-R1.567 cable data were missing for Od, so the corresponding data for On were used for both.

In Fig. 5 a histogram of the cable differences between On and Od for the seven sessions is presented. We can conclude that these differences are less than the formal error of the group delay observations produced by the correlator. The latter are today on the order of 15 ps for standard geodetic VLBI sessions with signal-to-noise ratio (SNR) of 25 and an effective bandwidth of 360 MHz (Takahashi et al., 2000).

After the computation of theoretical delays and inclusion of cable and weather data we end up with a database of version 3.

Before the final parameter estimation can be performed, the databases still have to be pre-processed to re-

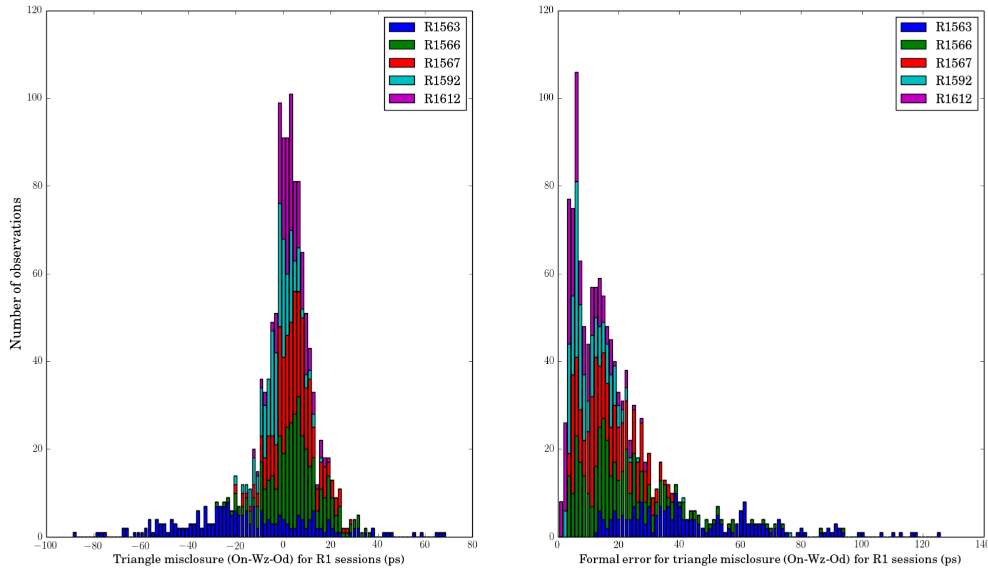

Figure 3: Histograms of the misclosures in the triangle (On-Wz-Od) for the five R1 sessions (left plot) and the corresponding formal errors for the miscloures (right plot). The median absolute values are 14.7 ps and 9.4 ps for the misclosures and the formal errors, respectively.

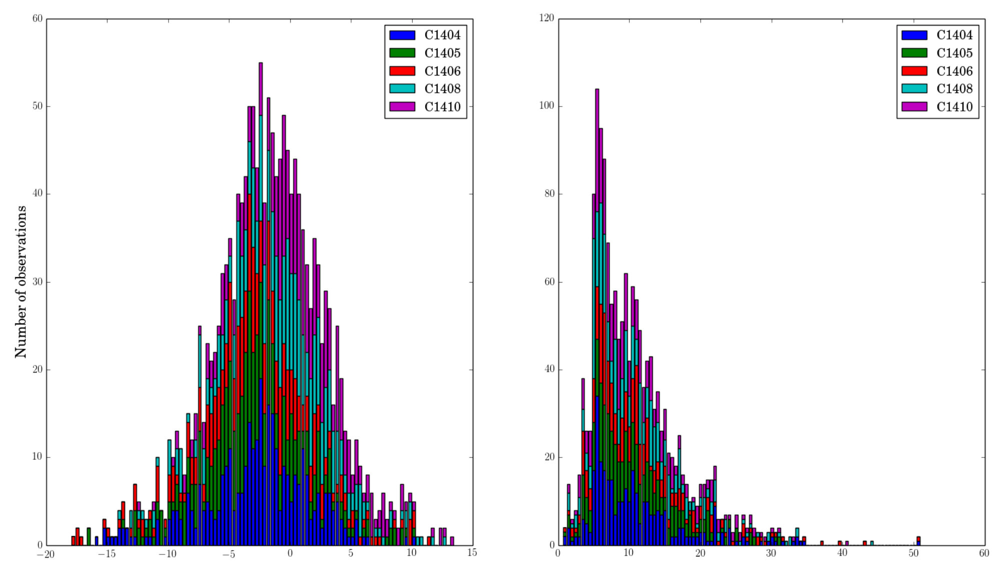

Figure 4: Histograms of the misclosures in the triangle (On-Wz-Od) for the five CONT14 sessions (left plot) and the corresponding formal errors (right plot). The median absolute values are 6.5 and 3.2 ps for the misclosures and the formal errors, respectively.

move ambiguities in the observed group delays, as well as clock breaks and other sources of errors, such as large outliers or bad calibration data. We also computed the ionospheric calibration, thus we needed to process both X- and S-band databases. To do so we used *nuSolve* version 0.1.6 (Bolotin et al., 2012), which is the modernised counterpart of the *Solve* component of the VLBI data analysis system *CALC/SOLVE*. Group delay ambiguity spacing can vary between baselines due to lost channels at the stations. This often occurs for the S-band due to RFI (radio-frequency in-

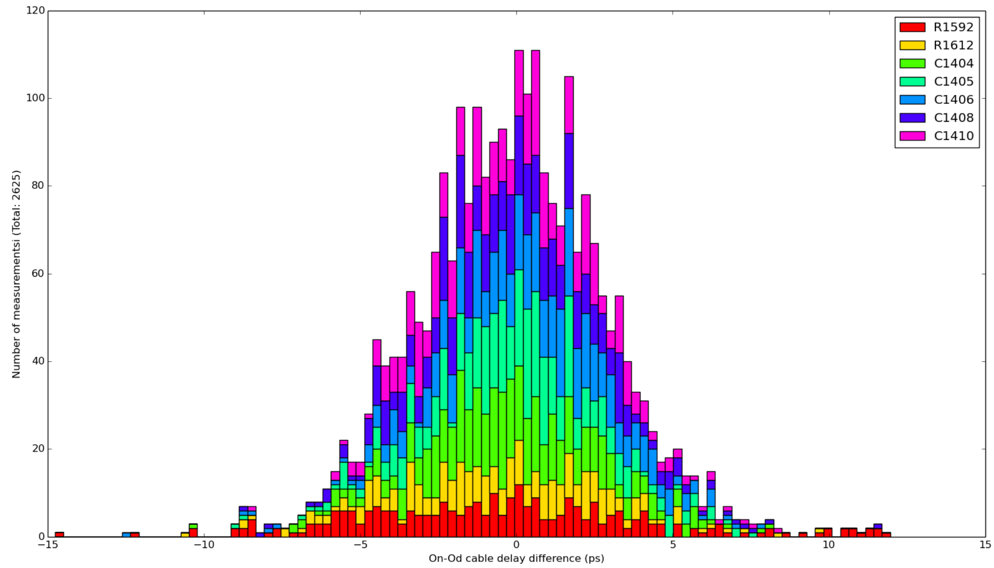

Figure 5: Differences between the cable calibration data for On and Od that were recorded in the respective log files for seven sessions.

terference), which complicates the correct ambiguity resolution. To resolve the ambiguities the automatic mode in *nuSolve* was used primarily, and the rest of the ambiguities were resolved manually. After this the ionospheric calibration was applied to the X-band databases. The sessions were analyzed by disabling either the On or Od station and estimating geodetic parameters like the EOPs, station coordinates for On/Od, zenith delays, atmospheric gradients, and station clocks. In order to emphasise the possible differences in the estimated station positions and to prevent them from being absorbed in other station coordinates in the observation network, the other stations were held fixed to their nominal VTRF positions (Böckmann et al., 2010). Additionally, to make the analysis more straightforward, two stations having experienced major earthquakes and still suffering post-seismic relaxation effects were disabled in the solutions. The station clocks were estimated as third order polynomials and B-spline piece-wise linear (PWL) functions with 60 minutes intervals. Both zenith delays and atmospheric gradients were also modeled as 60 minute interval PWL B-splines. Station coordinates were estimated as daily offsets, as well as both UT1-TAI rate and celestial pole offsets. Station positions were fixed when estimating EOPs, namely polar motion, UT1-TAI, UT1-TAI rate, and celestial pole offsets. The estimation procedure was done for On and Od separately, producing two set of estimates for the geodetic parameters, which could then be compared to assess whether the obtained values differed between data taken with the two backends. For each database we have a set of daily station coordinates, polar motion, UT1-TAI and UT1-TAI rate, celestial pole offsets, and 25 zenith wet delay (ZWD) values. The weighted root mean square (WRMS) differences of the geodetic parameters between On and Od in the IVS-R1 and CONT14 sessions are presented in Table 2.

Table 2: Comparison of geodetic parameters derived from On and Od data. Presented are mean formal errors ($\overline{\sigma}$) of the parameters, and the weighted root mean square (WRMS) differences between On and Od results of topocentric station positions (up, east, north), Earth rotation angle and its rate (UT1-TAI, UT1-TAI rate), polar motion (x_p, y_p), celestial pole offsets (dX, dY), and zenith wet delays (ZWD).

		IVS-R1		CONT14	
Parameter	Unit	$\overline{\sigma}$	WRMS	$\overline{\sigma}$	WRMS
up	mm	4.91	2.97	2.72	2.48
east	mm	1.44	0.96	0.83	0.22
north	mm	1.40	2.20	0.80	0.49
UT1-TAI	μs	5.81	2.95	1.73	0.12
UT1-TAI rate	μs	17.52	3.13	5.83	0.70
x_p	μas	127.11	35.25	36.32	5.34
y_p	μas	78.38	10.52	35.60	4.65
dX	μas	69.09	0.01	29.60	0.00
dY	μas	63.16	0.01	30.51	0.01
ZWD	mm	4.22	2.59	3.16	2.49

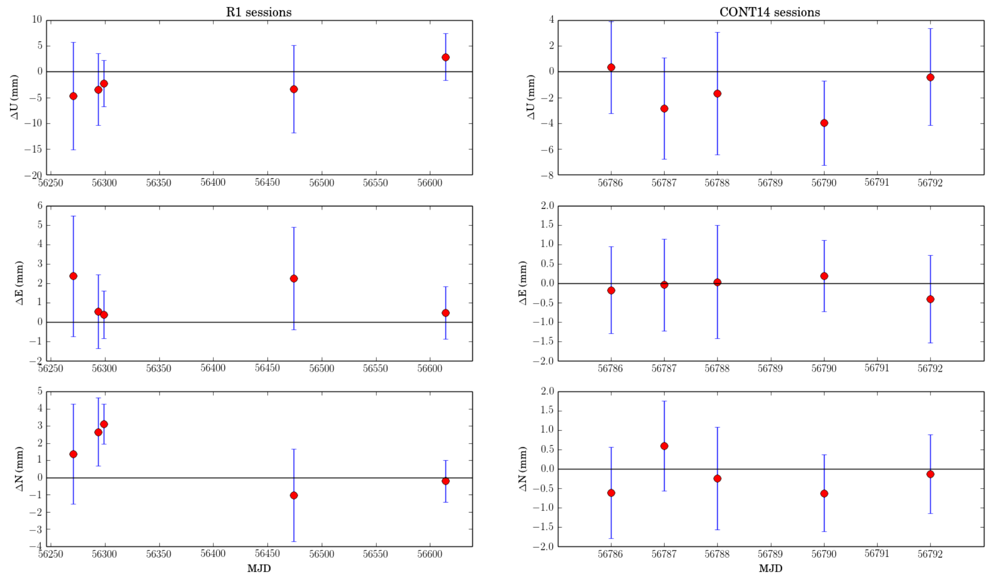

Figure 6: Onsala station position differences in up (top row), east (middle row), and north (bottom row) from IVS-R1 (left column) and CONT14 sessions (right column).

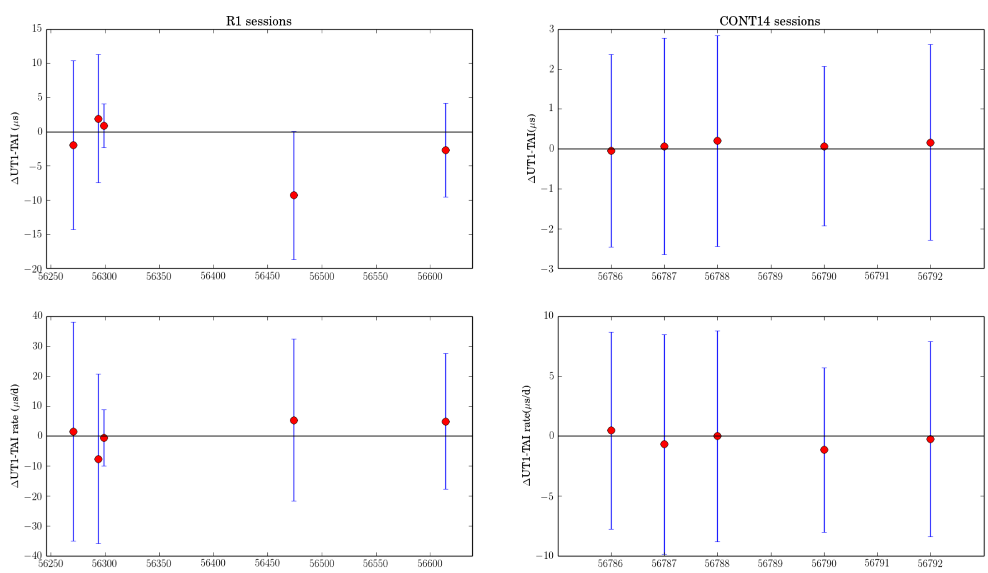

Figure 7: The differences in UT1-TAI (top row) and UT1-TAI rate (bottom row) from IVS-R1 (left column) and CONT14 (right column) sessions, when either On or Od data are used in the analysis.

The values in Table 2 in general show a good agreement between the estimates derived with the On and Od data, respectively, since the WRMS differences are smaller than the mean formal errors of the parameters. The only exception is the north component for the R1 sessions. This is also visible in Fig. 6, where the largest discrepancies are seen in the up and north components of the station positions in the IVS-R1 sessions. Figures 7, 8, and 9 show that for the EOPs the differences fall within their respective limits of uncertainty from zero for both IVS-R1 and CONT14 ses-

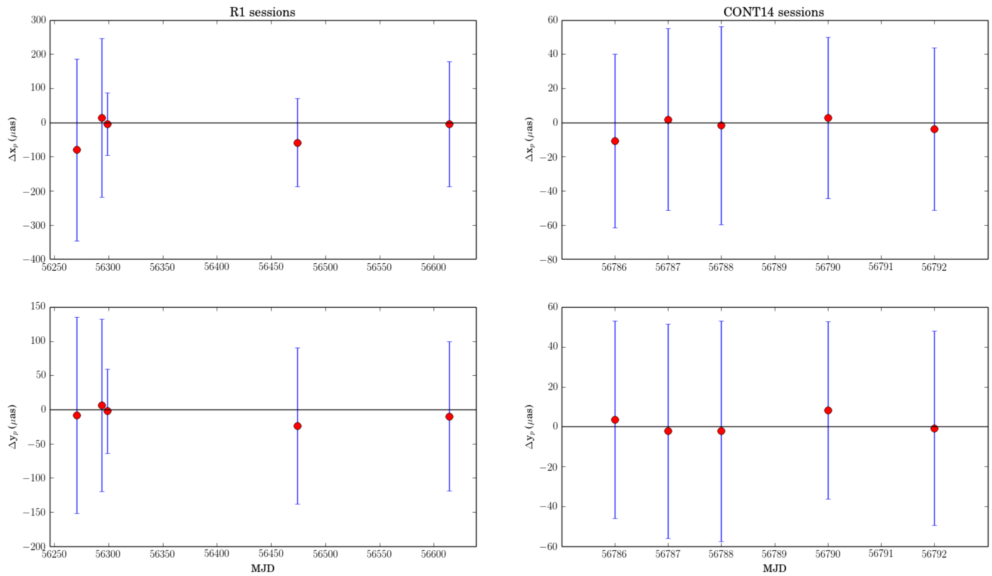

Figure 8: The differences in polar motion components x_p (top row) and y_p (bottom row) from IVS-R1 (left column) and CONT14 (right column) sessions, when either On or Od data are used in the analysis.

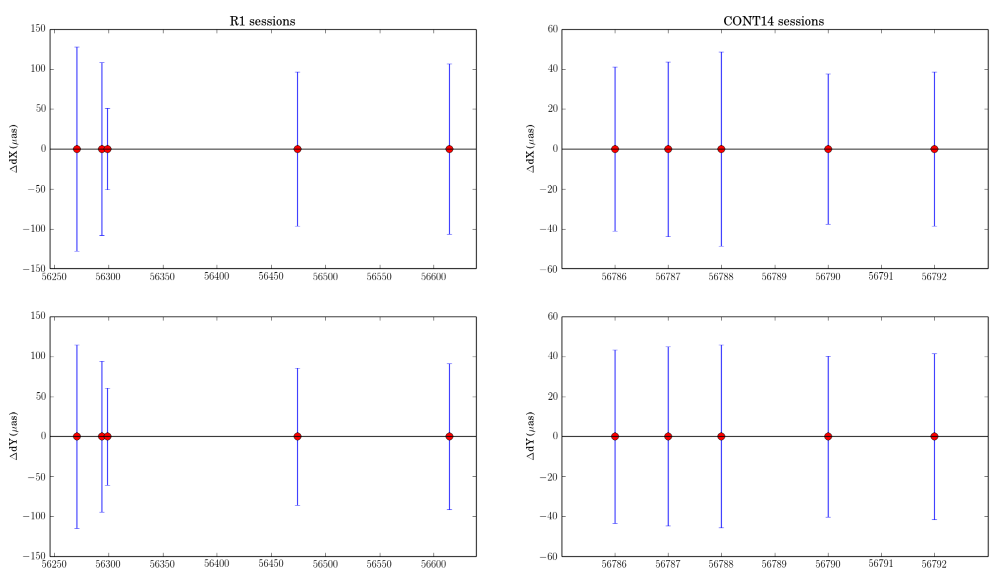

Figure 9: The differences in nutation components dX (top row) and dY (bottom row) from IVS-R1 (left column) and CONT14 (right column) sessions, when either On or Od data are used in the analysis.

sions. The higher quality of the estimates from CONT14 sessions are due to a better network geometry. Especially the exclusion of the stations affected by the earthquakes (see above) degrades the quality of the estimates from the R1 sessions, since the network geometry is affected strongly, more than in the CONT14 sessions, which have more and geographically well distributed stations. The station coordinate estimates which do not fall within the uncertainty are scattered around zero with no apparent systematic behavior. Figure 10 depicts the histograms of the ratio of the

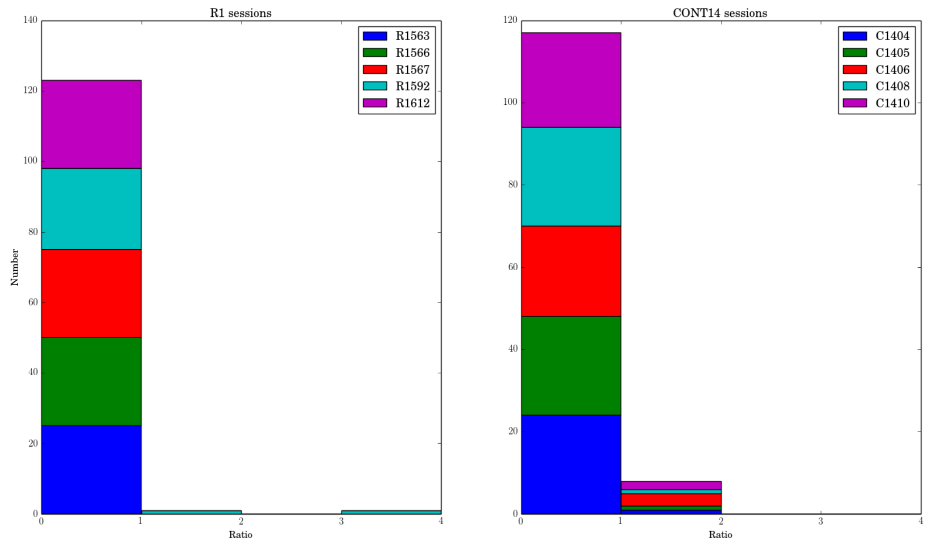

Figure 10: Histogram of the ratio between absolute ZWD differences (On-Od) and their formal errors for IVS-R1 (left) and CONT14 (right) sessions.

absolute ZWD differences between On and Od and their corresponding formal errors. The histograms show that most of the ZWD differences are within one standard deviation from zero.

6 Conclusions and outlook

Based on the comparison between the data obtained in parallel with the two backends at Onsala we can conclude that there are no significant differences between the results from these two systems. We found no systematic differences either in the raw data from the original correlation or the geodetic parameters obtained from the corresponding analysis of the databases. The DBBC/Mark 5B+ system at Onsala has performed reliably in numerous IVS sessions and in the recent CONT14 campaign. Furthermore, zero-baseline tests conducted both at Bonn and Onsala indicate no problems with the new system compared to the old Mark 4/Mark 5A system. The DBBC/Mark 5B+ system will continue to be used operationally as the main recording system in all the upcoming IVS VLBI sessions.

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