JUMPING JIVE

Project ID: 730884

New correlator products

Deliverable:	D6.1
Lead beneficiary:	JIV-ERIC
Submission date:	30.7.2019
Dissemination level:	Public

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List of Acronyms

DiFX	Distributed FX (Software Correlator)
EVN	European VLBI Network
FRT	Fourfit Reference Time
HOPS	Haystack Observatory Postprocessing System
IVS	International VLBI Service
Mk4	Mark 4 data-acquisition and correlation system
RMS	Root Mean Square
SFXC	EVN Software Correlator developed at JIVE
SNR	Signal to Noise Ratio
TOTMBD	Total Multiband Delay
VGOS	VLBI2010 Global Observing System
vgosDB	vgos Data Base
VLBI	Very Long Baseline Interferometry
wRMS	weighted Root Mean Square

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730884

I. Introduction

In order to derive geodetic products from a VLBI correlator, a prerequisite is to ensure that the correlator can properly handle geodetic sessions which are scheduled with sub-netting. This task was accomplished at the end of 2017, the results of which were reported in Deliverable 6.2.

Afterwards, the correlated data must be fringe-fitted to compute the necessary delay and delay rate measurements used in subsequent processing. As HOPS is the software package used at this stage, the correlated data need to be exported into Mk4 format that can be read by HOPS. At this point, phase calibration information must be available to perform proper geodetic fringe fitting. With such implementation, one can then derive all geodetic observables. In the following, we focus on the Total Multiband Delay and SNR observables in X-band for testing that the implementation is correct.

Finally, once all the above steps are successfully accomplished, the data must be exported into vgosDB format, which is the current standard geodetic format. This corresponds to the so-called vgosDB file version 1.

A suitable way to test the whole path is to compare our results with an output from the DiFX correlator located at the Bonn Correlator Center, using an IVS session originally correlated, post-processed and exported in vgosDB format there.

In the following sections, we explain how all such developments were implemented and tested.

II. Implementation

To support geodetic analysis of experiments correlated with the EVN software correlator at JIVE (SFXC), we developed a sfxc2mark4 tool that converts the raw correlator output of SFXC into the Mk4 format that can be read by the HOPS post-processing package. The software creates the required VEX root files, as well as the type-1 files that contain the actual correlation products and the type-3 files that contain the required metadata. The Mk4 format is described by

https://www.haystack.mit.edu/tech/vlbi/hops/mk4_files.txt

Unfortunately, that description is not kept entirely up to date. Therefore, in addition to this documentation, we consulted the HOPS source code as well as the difx2mark4 source code that is part of the DiFX software correlator.

The sfxc2mark4 tool is distributed as part of the SFXC software correlator and is included in the 4.0 release. The source code is available through an SVN repository. The 4.0 release can be downloaded by checking out

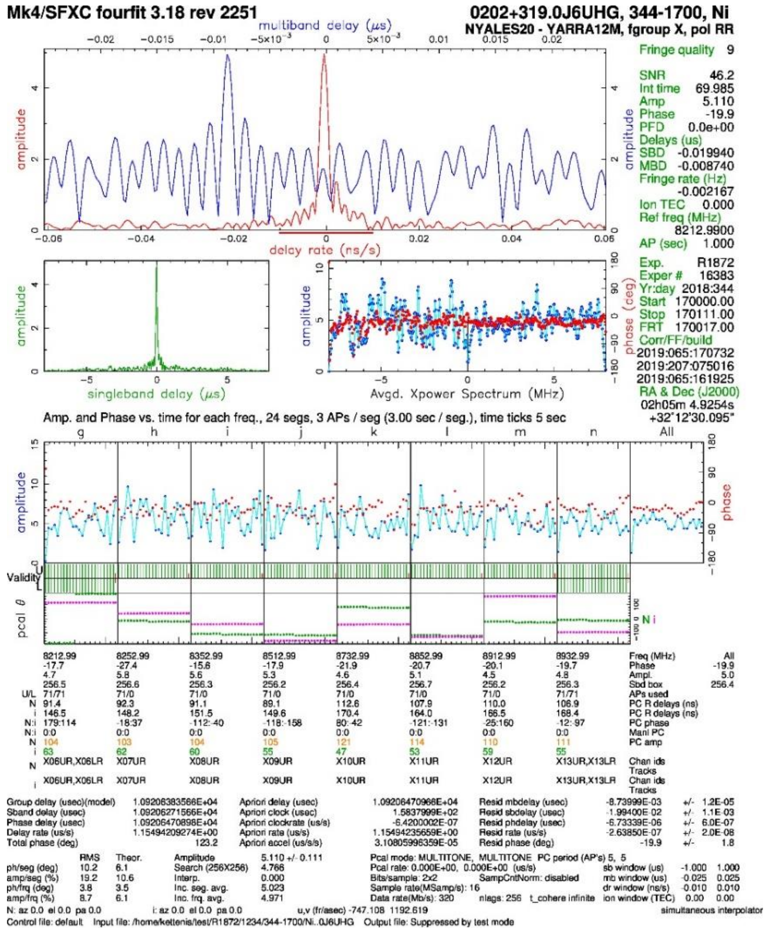
https://svn.astron.nl/sfxc/branches/stable-4.0

The sfxc2mark4 tool was entirely written in Python. Performance of the software is acceptable, being able to convert an entire 24-hour IVS session in a few hours.

The most important bit of metadata that is written into the type-3 files is the correlator model. The Mk4 file format expects the correlator model to be described by a 5th order polynomial which typically span intervals of 2 minutes. The SFXC correlator model is available as a binary file that simply contains the delay sampled at 1-second intervals. These delays are interpolated in the correlator using Akima splines. The conversion tool evaluates the Akima splines at 7 points linearly spaced over the requested time interval and fits a 5th order polynomial to these points. This was done using standard SciPy/NumPy functions. The differences between the constructed polynomial and the Akima splines actually used by the correlator are of the order of femtoseconds (10^{-15} s), so these polynomials are an accurate representation of the correlator model that was used during correlation.

Another important piece of metadata that is written into the type-3 files is the phase-cal information that is used to align the phases in different bands in order to allow fitting a physically meaningful multi-band delay. The SFXC correlator supports extracting phase-cal tones from the correlator input. However, the information is written in a format that requires a small amount of signal processing, implemented using SciPy/NumPy, to extract the individual tones as complex values. The extracted phases of the tones match the values found in the data correlated in Bonn. However, normalization of the amplitudes remains an open question. We have not found a description of what HOPS expects. In order to make the amplitudes match the values found in the data correlated in Bonn, we have used an adjustable factor to scale the amplitudes to comparable values. Since the amplitude is only used to accept or reject certain tones, we do not expect this to have a large impact on the results.

Initial validation of the tool was done by running the HOPS Fourfit program on the SFXC-correlated data processed through sfxc2mark4 and comparing plots from the HOPS Fourfit program with plots made from data correlated in Bonn. An example plot from data converted with sfxc2mark4 can be seen in Figure 1.



```
Mk4/SFXC fourfit 3.18 rev 2251                    0202+319.0J6UHG, 344-1700, Ni
                                         NYALES20 - YARRA12M, fgroup X, pol RR

Fringe quality   9

SNR            46.2
Int time     69.985
Amp           5.110
Phase         -19.9
PFD       0.0e+00
Delays (us)
SBD     -0.019940
MBD     -0.008740
Fringe rate (Hz)
        -0.002167
Ion TEC     0.000
Ref freq (MHz)
        8212.9900
AP (sec)    1.000

Exp.        R1872
Exper #     16383
Yr:day   2018:344
Start   170000.00
Stop    170111.00
FRT     170017.00
Corr/FF/build
2019:065:170732
2019:207:075016
2019:065:161925
RA & Dec (J2000)
02h05m 4.9254s
+32°12'30.095"

Amp. and Phase vs. time for each freq., 24 segs, 3 APs / seg (3.00 sec / seg.), time ticks 5 sec

     8212.99      8252.99  8352.99   8512.99    8732.99  8852.99    8912.99  8932.99      Freq (MHz)          All
     -17.7        -27.4    -15.6     -17.9      -21.9    -20.7      -20.1    -19.7        Phase             -19.9
     4.7          5.8      5.6       5.3        4.6      5.1        4.5      4.8          Ampl.               5.0
     256.5        256.6    256.3     256.2      256.4    256.7      256.2    256.3        Sbd box           256.4
U/L  71/71        71/0     71/0      71/0       71/0     71/0       71/0     71/71        APs used
  N  91.4         92.3     91.1      89.1       112.6    107.9      110.0    106.9        PC R delays (ns)
  i  146.5        148.2    151.5     149.6      170.4    164.0      166.5    168.4        PC R delays (ns)
N:i  179:114      -18:37   -112:-40  -118:-158  80:-42   -121:-131  -25:160  -12:-97      PC phase
N:i  0:0          0:0      0:0       0:0        0:0      0:0        0:0      0:0          Manl PC
  N  104          103      104       105        121      114        110      111          PC amp
  i  63           62       60        55         47       53         59       55
  N  X06UR,X06LR  X07UR    X08UR     X09UR      X10UR    X11UR      X12UR    X13UR,X13LR  Chan ids
                                                                                          Tracks
  i  X06UR,X06LR  X07UR    X08UR     X09UR      X10UR    X11UR      X12UR    X13UR,X13LR  Chan ids
                                                                                          Tracks

Group delay (usec)(model)  1.09206383566E+04  Apriori delay (usec)       1.09206470966E+04  Resid mbdelay (usec)  -8.73999E-03  +/-  1.2E-05
Sband delay (usec)         1.09206271566E+04  Apriori clock (usec)          1.5837999E+02  Resid sbdelay (usec)  -1.99400E-02  +/-  1.1E-03
Phase delay (usec)         1.09206470898E+04  Apriori clockrate (us/s)     -6.4200002E-07  Resid phdelay (usec)  -6.73339E-06  +/-  6.0E-07
Delay rate (us/s)          1.15494209274E+00  Apriori rate (us/s)        1.15494235659E+00  Resid rate (us/s)     -2.63850E-07  +/-  2.0E-08
Total phase (deg)                      123.2  Apriori accel (us/s/s)     3.10805996359E-05  Resid phase (deg)            -19.9  +/-      1.8

               RMS   Theor.   Amplitude          5.110 +/- 0.111   Pcal mode: MULTITONE,  MULTITONE  PC period (AP's) 5,  5
ph/seg (deg)   10.2  6.1      Search (256X256)   4.766             Pcal rate: 0.000E+00,  0.000E+00  (us/s)    sb window (us)   -1.000  1.000
amp/seg (%)    19.2  10.6     Interp.            0.000             Bits/sample: 2x2       SampCntNorm: disabled  mb window (us)   -0.025  0.025
ph/frq (deg)   3.8   3.5      Inc. seg. avg.     5.023             Sample rate(MSamp/s): 16                      dr window (ns/s) -0.010  0.010
amp/frq (%)    8.7   6.1      Inc. frq. avg.     4.971             Data rate(Mb/s): 320   nlags: 256  t_cohere infinite  ion window (TEC)  0.00  0.00
N: az 0.0  el 0.0  pa 0.0          i: az 0.0  el 0.0  pa 0.0          u,v (fr/asec) -747.108  1192.619                simultaneous interpolator
Control file: default   Input file: /home/kettenis/test/R1872/1234/344-1700/Ni..0J6UHG   Output file: Suppressed by test mode
```

Figure 1. Fourfit output plot obtained from data of IVS-R1872 session correlated at JIVE.

III. Testing

In order to test the procedure implemented at JIVE, a 24-hour IVS session, R1872 (conducted on December 10-11, 2018) was selected. This experiment involved eight IVS stations and 1069 scans.

We performed a validation procedure divided into two stages to assess the post-processing of data. The first stage comprised checking our ability to find fringes and to produce a vgosDB file version 1. This was done using the correlated Mk4 files and post-processed data provided by the Bonn Correlator Center for IVS session R1872. We compared our results at the level of vgosDB files, after the post-processing of data.

Our post-processing was done using Fourfit (Hops 3.18 rev 2251) and the result was exported into vgosDB format by means of vgosDbMake-0.4.3. The selected version of

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each software was not arbitrary: it was the same as that used at Bonn in order to avoid potential differences due to software version or other issues.

Figure 2 shows the results after comparing the vgosDB file sent by Bonn and our own vgosDB file obtained from Bonn correlated data. We have focused here on the main geodetic observables: the Total Multiband Delay (TOTMBD) and Signal to Noise Ratio (SNR) in X band. There are no appreciable differences between the two datasets for any observation (in this context, an “observation” is one baseline observing a few-minute scan of one radio source). This is replicated for S-band and for all the other observables e.g., single-band delays. This initial check guarantees that no bias will come from local-implementation or software-version differences and confirms that we are able to produce vgosDB file version 1.

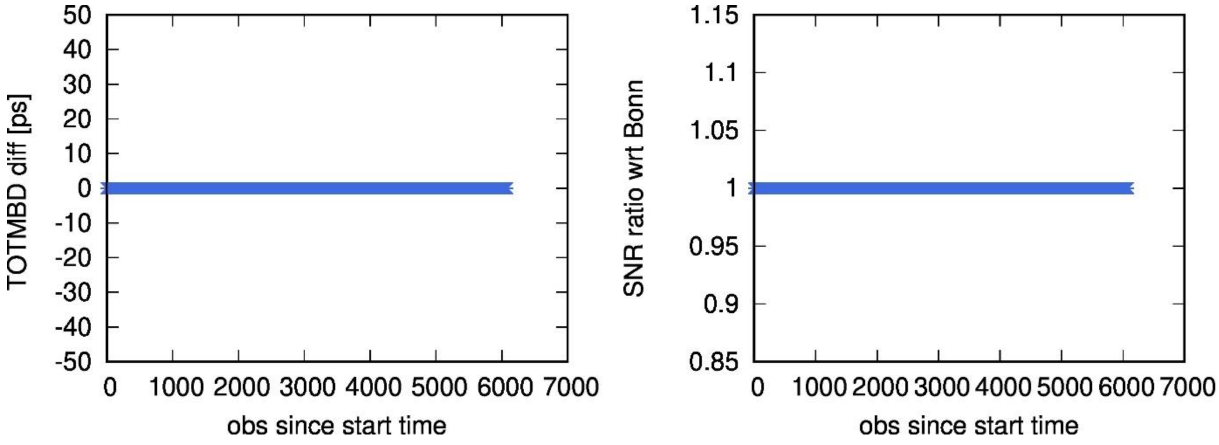

Figure 2. Differences in TOTMBD (left-hand panel) and SNR ratios (right-hand panel) obtained after comparing the original (from Bonn) and reproduced vgosDB files for the IVS-R1872 session.

The second stage of the validation comprised the comparison of fringe-fitted data obtained after the correlation conducted by SFXC with respect to those obtained at the Bonn Correlator Center.

Due to differences in the correlation process and correlator architecture, the comparison shown previously was not as straightforward.

The time of each observation is tagged according to what is called the Fourfit Reference Time (FRT), which can sometimes differ by typically 0.5 s from one correlator to the other. This is because there are differences in the way that each correlator searches for the first valid sample in each scan. This situation can lead to discrepancies in the TOTMBD just because we are evaluating TOTMBD at different FRTs.

In order to reproduce the previous analysis but now comparing the output of both correlators, we took all those observations that have the same FRT and a statistically significant fringe detection; 3462 of the 5826 observations passed this filter. Figure 3 shows the TOTMBD differences and SNR ratios (JIVE SFXC wrt Bonn DiFX correlator) for this data.

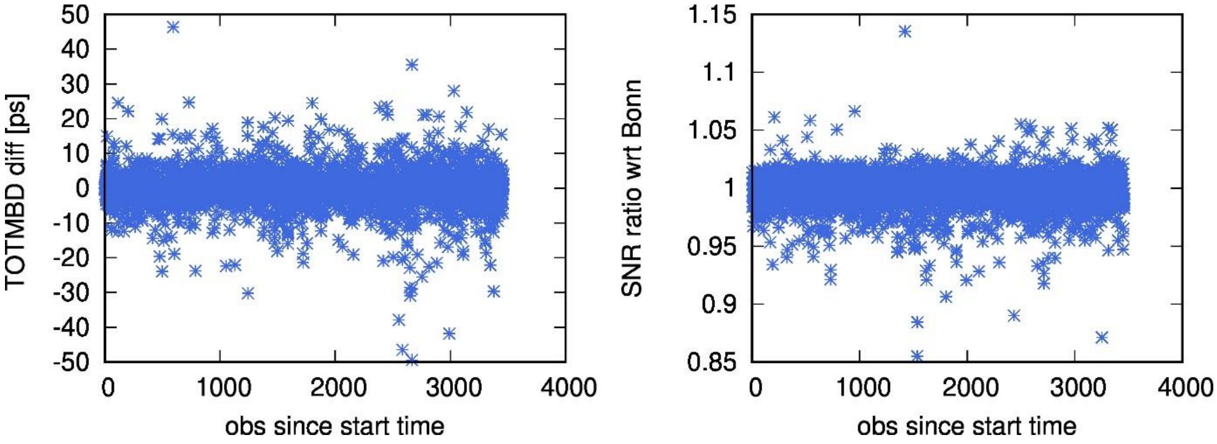

Figure 3. Differences in TOTMBD (left-hand panel) and SNR ratios (SNR_{JIVE}/SNR_{Bonn}, right-hand panel) obtained after comparing the vgosDB files produced by SFXC and the Bonn DiFX correlator for the IVS session R1872. The comparison is limited to those observations that have the same FRTs.

All TOTMBD differences are below 50 ps and 80% are below 5 ps (Fig. 4). The ensemble has a mean of -0.09 ps and a wRMS of 5.5 ps. These values are in line with the expectations as explained in Corey & Titus (2012).

Regarding the SNR, the ratios SNR_{JIVE}/SNR_{Bonn} show values close to 1 with a mean value of 0.998. In order to go further, we inspected also the relationship between the TOTMBD differences and SNR given by the following equation of Rogers et al. (1993):

$$\sigma_{MBD} = \frac{1}{2\pi(SNR)\Delta f_{rms}}$$

where σ_{MBD} represents the standard error of the TOTMBD and Δf_{rms} is the RMS bandwidth over all the individual base-band channels in X-band.

For IVS session R1872, the spanned bandwidth is 720 MHz and the RMS bandwidth is 280.4 MHz, so this equation can be written as σ_{MBD} [ps] = 567/SNR. As expected, we see that our TOTMBD differences decrease as SNR increases, and that 99 % of them are below the 1σ standard error value (Fig. 5).

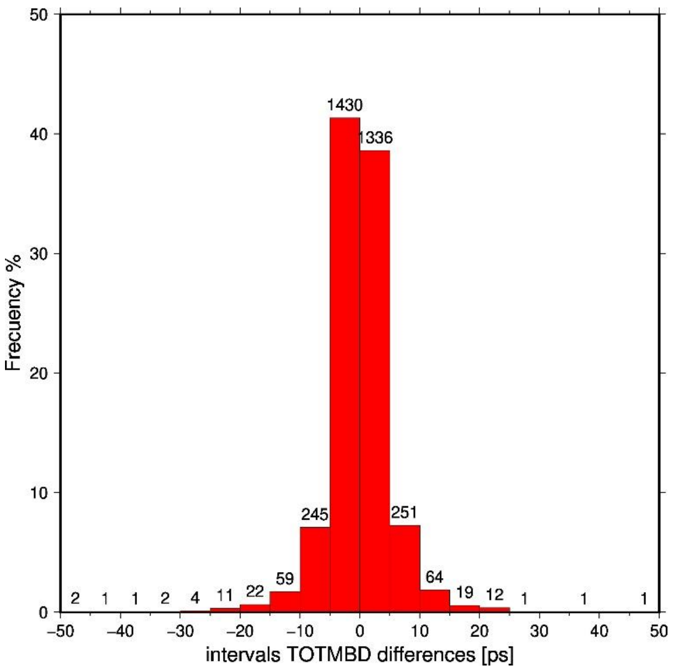

Figure 4. Histogram of the TOTMBD differences shown in Figure 3.

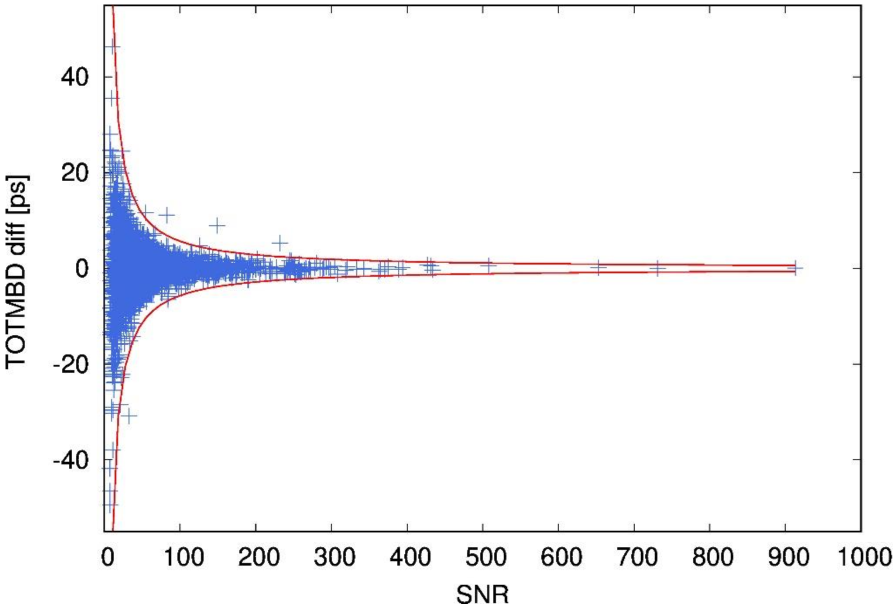

Figure 5. TOTMBD differences vs. SNR for X-band. The red curves represent ±1σ; it can be seen that with a few exceptions all of the differences are below this standard error.

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For the remaining observations that had time tag differences (2364 observations out of a total of 5826 observations), we shifted the times of the TOTMBDs of JIVE to the Bonn FRTs by using the total delay rate also estimated by Fourfit. Figures 6a and 6b depict the TOTMBD before and after correcting for FRT discrepancies. Figure 6c is the same as Figure 6b but after eliminating outliers (58 observations with TOTMBD differences greater than 50 ps, corresponding to FRT differences greater than the typical 0.5 s). The results indicate that the differences in FRT can explain the TOTMBD discrepancies. This ensemble of post-FRT-alignment TOTMBD differences has a mean of -1.0 ps and a wRMS of 8.5 ps (Fig.7). The wRMS is similar, although slightly larger, to that derived for those observations without time tag discrepancies; this is consistent with the expected size of second-order residuals arising from the use of a linear correction to the TOTMBDs of JIVE, based on propagating the delay-rate over the 0.5 s FRT difference.

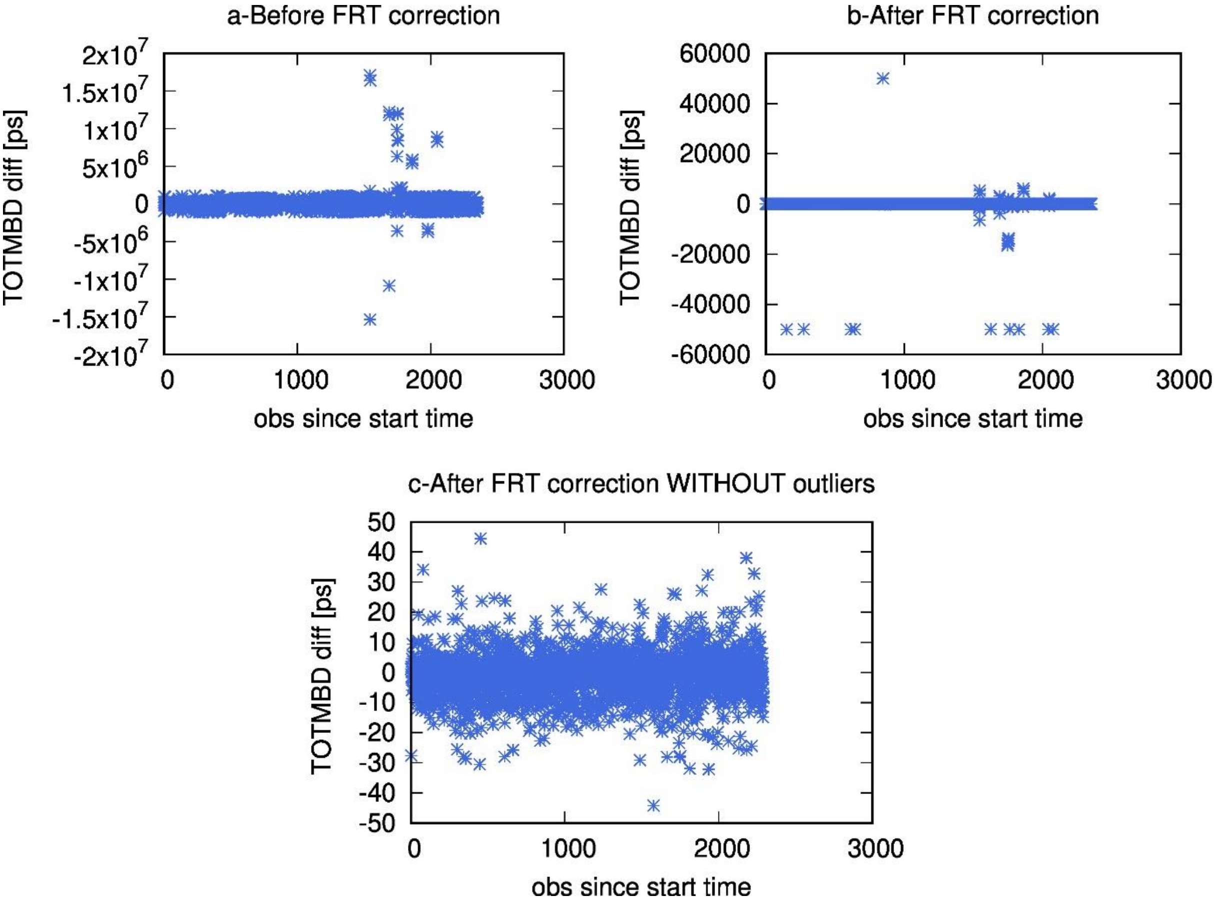

Figure 6. Differences in TOTMBD before (a) and after (b) considering FRT differences, and after eliminating outliers (c).

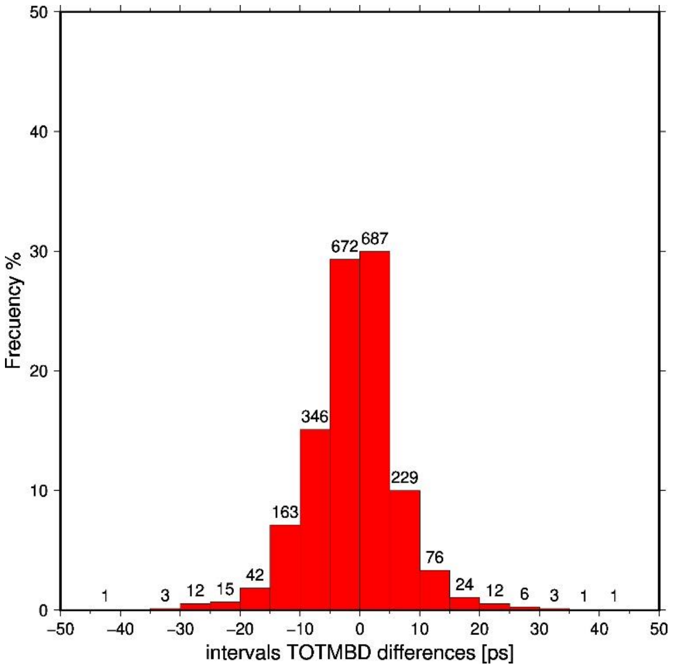

Figure 7. Histogram of the TOTMBD differences shown in Figure 6c.

IV. Conclusions

A typical 24-hour IVS session that took place in December 2018 has been fully processed with the EVN software correlator at JIVE (SFXC). The results of the correlation with SFXC were then converted to Mk4 format, post-processed with HOPS and exported into vgosDB format, following the standard geodetic path.

The comparison of those results with the results from the DiFX correlator at the Bonn correlation center, where the session was originally correlated, post-processed and exported, indicates agreement at the 5 ps level, which is the level of consistency expected. This confirms that Task 1 has been successfully achieved. In other words, any geodetic-style session correlated with SFXC can now be post-processed, exported into standard geodetic format and analysed with the most common geodetic tools.

References:

Corey, B.E. and Titus, M.A. (2012). Multiband delay differences between Mk4 hardware and DiFX software correlations. MIT Haystack Observatory memorandum, 2012 September 18.

Rogers, A.E.E. et al. (1993). Improvements in the Accuracy of Geodetic VLBI. Smith D. E. and Turcotte D. L. Eds., Geodynamics Series. DOI: https://doi.org/10.1029/GD025p0047.