Abstract We present results from observation, correlation and analysis of interferometric measurements between the three geodetic very long baseline interferometry (VLBI) stations at the Onsala Space Observatory. In total 23 sessions were observed in 2019 and 2020, most of them 24 hours long, all using X band only. These involved the legacy VLBI station ONSALA60 and the Onsala twin telescopes, ONSA13NE and ONSA13SW, two broadband stations for the next generation geodetic VLBI global observing system (VGOS). We used two analysis packages: $\nu$Solve to compare group- and phase-delay parameter estimation, and ASCOT to investigate e.g. the impact of thermal and gravitational deformation of the radio telescopes. Station positions obtained from group-delay analysis with the two software packages agree within $2\sigma$ for all components of both stations. We obtained weighted root mean square postfit residuals on the order of 10–15 ps using group delays (ASCOT and $\nu$Solve) and 3–5 ps using phase delays ($\nu$Solve). The best performance was achieved on the (rather short) baseline between the VGOS stations. As the main result of this work we determined the coordinates of the Onsala twin telescopes in VTRF2019D with sub-millimeter precision. This new set of coordinates should be used from now on for scheduling, correlation and as a priori for data analyses e.g. for the upcoming ITRF2020. We also find a systematic offset between the group- and phase-delay solutions from $\nu$Solve, suggesting the phase-delay implementation needs additional testing.

Keywords Onsala Space Observatory · Geodetic core sites · Geodetic VLBI · VGOS · Onsala twin telescopes · Short-baseline interferometry
1 Introduction

Geodetic very long baseline interferometry (VLBI) is a space geodetic technique that is of major importance (Bachmann et al., 2016) for the International Terrestrial Reference Frame (ITRF) (Altamimi et al., 2016). The ITRF is the most precise and accurate realization of a global geodetic reference frame (GGRF) that is needed by the scientific community as well as society as large. Its importance for a sustainable development of human society has been highlighted in a corresponding United Nation resolution (UN, 2017).

The basis for the creation and maintenance of the ITRF are space geodetic observations that are performed at so-called geodetic core (fundamental) sites. Geodetic core sites are equipped with co-located instrumentation for a variety of space geodetic measurements, such as e.g. geodetic VLBI and Global Navigation Satellite Systems (GNSS). To make the best possible use of the different space geodetic measurements at co-location sites, the local geometrical relations between the reference points of the different space geodetic instrumentation has to be known with high accuracy.

The Onsala Space Observatory (OSO) is one of these geodetic core sites and operates several co-located space geodetic instruments. Since 1979 the 20 m diameter radio telescope, ONSALA60 (ON), is used for geodetic VLBI and contributes regularly to the observing program of the International VLBI Service for Geodesy and Astrometry (IVS). This makes ONSALA60 the station with the longest time series of observations of all the VLBI stations that are active in the IVS.

During recent years, two new 13.2 m diameter radio telescopes were built at Onsala Space Observatory, ONSA13NE (OE) and ONSA13SW (OW), the so-called Onsala twin telescopes (OTT) (Haas, 2013; Haas et al., 2019). The OTT are instruments for the next generation VLBI system (Petrachenko et al., 2009), commonly referred to as VGOS (VLBI Global Observing System). VGOS is going to become the work horse of the IVS for the coming decades. Due to very fast slewing telescopes with insignificant structural deformation and dual-polarized broadband receivers, VGOS is expected to improve the performance by one order of magnitude compared to the so-called legacy S/X VLBI system (Petrachenko et al., 2009), and thus be able to reach the accuracy level that is necessary to address the societal needs in connection with the Global Geodetic Observing System (GGOS; Plag and Pearlman, 2009) and global change research in general.

In order to use the new VGOS telescopes and observations together with the other existing space geodetic observations, the so-called local tie vectors between the reference points of the new and the previously existing instrument have to be determined. Usually, local tie vectors between reference points for different space geodetic instrumentation are determined with classical geodetic survey, see e.g. Haas and Eschelbach (2005), Lügger et al. (2013, 2016). However, in the case of co-located instrumentation of the same space geodetic technique, also technique-inherent observations can be used to determine the local tie vectors. For this purpose, we performed during 2019 and 2020 a series of short-baseline local interferometry campaigns with the three co-located geodetic VLBI stations at Onsala, i.e. ON, OE and OW.

Section 2 presents briefly the three main instruments at Onsala that are used for geodetic VLBI. The design and setup of the short-baseline co-location experiments performed in 2019 and 2020 are described in Section 3. Section 4 explains data
correlation and post-correlation analysis. The methods of geodetic analysis of the resulting delay data is presented in Section 5 and the resulting positions and baseline vectors are given in Section 6. Finally, Section 7 gives a summary and outlook.

2 The geodetic VLBI systems at Onsala

The Onsala Space Observatory has the longest time series of VLBI observations in Europe, going back to the first astro/geodetic session already in 1968 (Whitney, 1974). In the early days, the 25 m radio telescope (built 1963, shown right in Fig. 1) was used for VLBI. During 1976 to 1979 the radome-enclosed 20 m radio telescope (ONSALA60, ON) was built (right in Fig. 1) and has been used since then for geodetic VLBI (Scherneck et al., 1998). This makes ON the VLBI station with the longest time series in the IVS. During the last decades, ON has participated in on the order of 50 S/X sessions per year, and has been involved in all continuous (CONT) campaigns that the IVS organised.

During 2015–2017 the OTT (left and middle in Fig. 1) were installed (Haas, 2013; Haas et al., 2019), following the design for the VGOS, the next generation VLBI system (Petrachenko et al., 2009). The OTT were inaugurated in May 2017 and in late 2017 they started to participate in first international VGOS test sessions. After thorough system tests, the OTT are now operating regularly in the IVS VGOS sessions since early 2019. Table 1 provides some technical parameters for comparing the three geodetic VLBI systems at Onsala.

Table 1: The VLBI stations at the Onsala Space Observatory used for geodetic VLBI observations.

| VLBI station | ID | diameter | geodetic frequency range | polarization |
|--------------|----|----------|--------------------------|--------------|
| ONSALA60     | ON | 20.0 m   | 2.2 – 2.4 GHz and 8.1 – 9.0 GHz | R / R + L    |
| ONSA13NE     | OE | 13.2 m   | 3.0 – 15 GHz             | X + Y        |
| ONSA13SW     | OW | 13.2 m   | 2.2 – 14 GHz             | X + Y        |

3 K-experiment observations

We started to gain first experience with short-baseline experiments at Onsala in early 2019 as part of a master’s thesis project (Marknäs, 2019). The longest distance between the telescopes is only about 550 m which is short enough for differential ionospheric effects to be negligible, and therefore there is no need for dual-band (e.g. S/X) observations. Since the common overlapping frequency range for all three systems is 8.1–9 GHz (X-band), we focused entirely on this band. In this work we analyse 15 experiments split into 23 VGOS databases (vgosDb) as summarised in Table 2.

1 Channels excluded from fringe-fitting due to broadband RFI. Channels in parenthesis only excluded on the OE-OW baseline.
3.1 Scheduling

The schedules were prepared with the sked software (Gipson, 2010). We added the OTT to the necessary catalogues, e.g. the system equivalent flux density (SEFD) values. For OTT, we used conservative X-band SEFD values of 3000 Jy, as estimated during the commissioning phase. The corresponding values for the ON system in the sked-catalogue is 2000 Jy.

ON is one of the S/X telescopes in the IVS with medium-high slew speed, i.e. 3 degree/s in azimuth and 1 degree/s in elevation. The OTT are fast VGOS-class telescopes with 12 and 6 degree/s in azimuth and elevation, respectively. To simplify the scheduling, we used a minimum scan length of 30 s and forced the scheduling software to always schedule all three telescopes together. As a result, the majority of the scheduled scans were 30 s long, and only very few scans were longer.

Early tests only covered a few hours of observing time, but once we had gained enough experience, we scheduled the K-sessions for 24 h or even several days. The long sessions allow analysis on a range of different timescales. During a typical 24 h long session, about 1100 scans were scheduled during with more than 125
different radio sources observed, several of these up to 20 times. Figure 2 shows as an example a typical sky plot obtained during a 24 h long K-experiment.

3.2 Polarisation and frequency setup

The ON system was using right circular polarization (RCP; hereafter referred to as R), while the OTT systems were using linear dual-polarization (hereafter referred to as X and Y). The combination of circular and linear polarisation basis, sometimes referred to as mixed-mode, is not a standard mode of observing and limited support exist for this in various software packages. Mixed-mode observing was, however, the only available option given the telescope systems involved.

Various frequency configurations were tried in observations, aiming to avoid local radio frequency interference (RFI), as well as exploring the impact on the final analysis. Table 3 lists the frequency configuration used for all experiments included in this work. Initially, we simply used the standard frequency setup for IVS-R1 sessions with the ON DBBC2 backend (Tuccari et al., 2010), focusing on 8 channels of 16 MHz bandwidth between 8213.99 MHz and 8949.99 MHz (configuration A in Table 3). At the time, 16 MHz was the maximum available bandwidth for ON (DBBC2 firmware limitation), while the OTT (with DBBC3 backends) observed with 32 MHz bandwidth per channel. Table 3 shows the final correlated overlapping bandwidth used in the analysis. Starting with experiment K19135, the DBBC2 firmware was upgraded to v107 which allowed 32 MHz channels also for ON.
This allowed us to double the bandwidth and thereby increase the signal-to-noise (configuration B).

Configuration C was an attempt to avoid RFI in the lowest channels a,b which were often excluded from the analysis of data using configuration B (see Table 2). Unfortunately RFI appeared also in a new channel e, but we decided to stick with configuration C for all later experiments as it spanned a larger total frequency range than configuration B.

For all experiments, ON frequency channels were recorded as upper sideband (USB) while OE and OW data were recorded as lower sideband (LSB). This corresponds to the standard (S/X and VGOS) backend configurations for the respective systems.

3.3 Phase- and cable calibration

For standard geodetic VLBI sessions, ON is working with a 1 MHz phase-calibration (PCAL) system, while the OTT are equipped with more modern 5 MHz PCAL systems. It is well known that ON suffers from rather strong direction dependent cable delay variations (Dan MacMillan, private communication, 2002), which will affect the station position if not correctly compensated for in the analysis. This is usually done by using PCAL signals in the post-processing (fringe-fitting)

![Fig. 2: Example of a sky plot during a 24 h long K-experiment at the Onsala Space Observatory. The three systems ON-OE-OW always observe together and achieve in this particular example in total 1157 scans, with a total number of 127 different radio sources that were observed.](image)
Table 3: List of frequency configurations for all experiments listed in Table 2. The frequencies denote the lower-edge of each correlated BBC-channel in MHz with the bandwidth, 16 or 32 MHz, given in parenthesis.

| Configuration | Channel A (MHz) | Channel B (MHz) | Channel C (MHz) |
|---------------|-----------------|-----------------|-----------------|
| a             | 8213.99 (16)    | 8212.99 (32)    | 8244.99 (32)    |
| b             | 8253.99 (16)    | 8252.99 (32)    | 8284.99 (32)    |
| c             | 8353.99 (16)    | 8352.99 (32)    | 8384.99 (32)    |
| d             | 8513.99 (16)    | 8512.99 (32)    | 8544.99 (32)    |
| e             | 8733.99 (16)    | 8732.99 (32)    | 8764.99 (32)    |
| f             | 8853.99 (16)    | 8852.99 (32)    | 8884.99 (32)    |
| g             | 8873.99 (16)    | 8872.99 (32)    | 8924.99 (32)    |
| h             | 8933.99 (16)    | 8932.99 (32)    | 8964.99 (32)    |

In general, both PCAL and cable cal are therefore necessary to obtain accurate telescope positions. However, the early K-sessions were observed without PCAL. The reasons were that a) phase calibration and cable delay measuring system (CDMS) of OW was not working in first part of 2019 and needed to be repaired at Haystack observatory, and b) that we were concerned about how to deal with the potential correlation of the PCAL signals themselves. In the second half of 2019, the OW system was repaired, and we also learned about the possibility of

Fig. 3: Cable delay calibration data for ON (top), OE (middle) and OW (bottom) for session 20AUG15VB. Note that the values for ON are one order of magnitude larger than for OE and OW.
using notch filters in post-processing to reduce the impact of correlating PCAL-sIGNALS. Therefore, PCAL was enabled in the K-experiments starting with K19323. We note that the ON PCAL/cable system was malfunctioning during experiment K20223, but was repaired for K20227.

3.4 Data recording

The data were recorded using jive5ab (Verkouter, 2020) on the Onsala flexbuff computers. ON data were sampled using a DBBC2 backend and recorded as single-thread 8-channel 2-bit sampled VDIF files. For the early 16 MHz K-experiments, this meant 512 Mbps data rate, while for the later 32 MHz experiments it meant 1 Gbps data rate.

OE and OW data were sampled using two DBBC3 units and, in early K-experiments, recorded as 8-thread 8-channel 2-bit VDIF data, at 2 Gbps. The multi-thread data were converted to single-thread 64-channel data using the tool vmux (bundled with DiFX) for efficient correlation. This worked, but delayed correlation due to the extra processing time and space needed for the conversion process. In later experiments, jive5ab version 3.0 was used which allowed recording the 8 streams from each OE/OW DBBC3 into 8 separate single-thread VDIF files. These could be correlated directly without vmux, allowing quicker processing of the data.

4 Correlation and post-correlation processing

In this section we described in detail the correlation of the VDIF data, as well as the post-processing steps applied after correlation to obtain vgosDbs for geodetic analysis.

4.1 Correlation using DiFX

The OTT systems are equipped with DBBC3 (Tuccari et al., 2018) backends which, in the current firmware used for VGOS observations (v123 or 124), only allows a channel width of 32 MHz. This meant a bandwidth mismatch between ON (16 MHz) and OTT (32 MHz) in initial experiments (of which K19114 and K19120 are included in this work). To overcome this, we used the zoomband capability of the DiFX software correlator (Deller et al., 2007; Deller et al., 2011) to correlate matching 16 MHz channels on all baselines. In theory, we could correlate 32 MHz channels on the OE-OW baseline and 16 MHz on the ON-OE/OW baselines. While this could improve the signal-to-noise on the OE-OW baseline, we opted for 16 MHz everywhere in the early experiments for simplicity.

Starting with experiment K19135, all telescope recorded 32 MHz channels and therefore we correlated these with 32 MHz channel width on all baselines. Surprisingly, we found it necessary to use zoomband option in DiFX also for the 32 MHz channels (although all channels matched perfectly). If not, no correlation products were obtained for the OE-OW baseline. We suspect this is related to the current
mixed-mode software limitations, possibly in relation to ON sampling USB and OE/OW sampling LSB, but found the zoomband workaround acceptable.

The data were correlated on one of the Onsala flexbuff computers using the latest available stable DiFX release version 2.6.1. For data-logistic reasons different machines were used to correlate different experiments, but all running identical software. On a typical machine (12 CPUs at 4.6 GHz, 128 GB RAM, 36x12 TB storage) the correlation wall-time was about 1:1 compared to the observing time (when excluding the vmux-step necessary for early multi-thread experiments). The spectral resolution used for correlation was 0.25 MHz (corresponding to 128 lags per 32 MHz channel bandwidth).

4.2 Fringe-fitting with HOPS fourfit

The post-correlation processing was done with the latest stable version 3.21 of the Haystack Observatory Postprocessing System (HOPS) (MIT/Haystack2020). To achieve proper PCAL extraction for multi-stream VDI, version 1.7 of difx2mark4 (from the DiFX trunk repository) was used to convert from SWIN (difx output) to MK4 (fourfit input) format. Fringe fitting was done using HOPS fourfit where, as standard geodetic analysis-software is only able to process one polarisation product per baseline, pseudo-stokes I was formed on the OE-OW baseline, and RX+RY on the ON-OE/OW baselines. An example result, showing one scan of the source NRAO150 on baseline ON-OE observed in experiment K20227, is shown in Figure 4. This one of the brightest sources; a histogram of the SNR obtained on the three baselines in experiment K20227 is presented in Figure 5.

For antennas lacking PCAL and/or cable calibration during a significant part of the experiment, manual PCAL was used in fringe-fitting. In this case, channel based phase corrections were determined using one scan on a bright source (often NRAO150), with pc_mode manual being used in fourfit. ON R-pol was used as reference, i.e. corrections were found for OE/OW X/Y-pol. Where PCAL and cable calibration was present, pc_mode multitone PCAL was used in fringe-fitting. Additional channel-based phase-corrections, on top of multitone PCAL, were determined for the OE/OW X and Y polarisations (ON R-pol) as reported by fourfit (using option -m 1 pc_phases on a bright source (in most experiments NRAO150).

Because all three telescopes PCAL systems are tied to the same hydrogen maser, the PCAL signals correlate strongly. To reduce the impact of correlating PCAL signals when fringe-fitting, notches were used in fourfit every 5 MHz to remove the PCAL signals of the OTT. The notch filters removed ±0.5 MHz of bandwidth around the PCAL tones, significantly reducing the impact of correlating PCAL signals on fringe-fitting. This causes regular drops in the cross-power spectra, also visible in Figure 4. Minor residuals, resulting from the periodic structure of the removed PCAL signals, can be seen in the singleband delay panel in Figure 4. For clarity we note that the PCAL data, extracted by DiFX, were available to fourfit for use in fringe-fitting. The notch filters just removed the problematic channels from the visibility data, in the same way that one can mask out correlating narrow-band RFI. Channels completely removed due to broadband RFI are listed in Table 3.
Fig. 4: Example of fringes obtained during session K20227. This is a fourfit plot showing one scan on the radio source NRAO150 between OE and ON. To maximise the signal-to-noise for the geodetic analysis, the mixed-basis (RX,RY) correlation products are added together in the fringe-fitting as YR+XR. The regular drops in amplitude every 5 MHz correspond to channels with cross-correlating phasecal signals which have been excluded from fringe-fitting using notches in fourfit.
4.3 Creation of VGOS databases

After fringe-fitting, the obtained VLBI delay observations were exported to the so-called vgosDb format (Bolotin et al., 2015) that can be read by standard geodetic VLBI analysis software packages. Three database wrappers were created using utilities bundled with the latest νSolve software package version 0.7.1 (Bolotin et al., 2012). Wrapper 1 was created from fringe-files using vgosDbMake 0.5.1. In this step we decided to split observations spanning several days into separate databases with approximately 24 h in each database: see Table 2. Wrapper 2 was created using vgosDbCalc 0.4.1. Finally, Wrapper 3 was created using vgosDbProcLogs 0.5.1 which appended relevant supplemental data from the observing logfiles (temperature, pressure, humidity etc.). In this final step, we used pressure-corrected logfiles as described in Sect. 5.1.2.

5 Geodetic data analysis

We used two software packages for the geodetic analysis: νSolve version 0.7.1 (Bolotin et al., 2012) and ASCOT version 2020 (Artz et al., 2016). Both software packages have their advantages and disadvantages.
\(-\) \(\nuSolve\) is capable of analysing both group-delay and phase-delay observations. Phase-delay analysis should provide more precise and accurate results. However, \(\nuSolve\) currently cannot model neither thermal nor gravitational deformation of radio telescopes (S. Bolotin, personal communication, 2020).

\(-\) \(\text{ASCOT}\) is able to model both thermal (Nothnagel, 2009) and gravitational (see e.g. Nothnagel et al., 2019; Lösl et al., 2019) deformation of radio telescopes, which has a significant impact on the local-tie vectors (see Sect. 5.4.4). However, at the time of writing \(\text{ASCOT}\) can only analyse group-delay (not phase-delay) observations.

Thus, the two software packages are complementary. A comparison of results from the two software packages is presented in Sect. 5.2.

5.1 A priori data and modeling

Both \(\text{ASCOT}\) and \(\nuSolve\) make use of a priori data, such as initial station positions, site velocities and Earth Orientation Parameters (EOP). Some of these parameters may have a significant impact on the final results, and therefore we strive to use identical a priori information when possible.

The ON position was fixed to the value presented in VTRF2019D (BKG, 2019). Initial positions for OE and OW were based on Real-time Kinematic (RTK) GPS measurements carried out in 2016, plus information taken from the construction drawings.

All three stations were assumed to have velocities identical to the values for ONSALA60 in VTRF2019D (BKG, 2019). We used axis offsets of 0 mm for OE, OW and −6 mm for ON (Haas and Eschelbach, 2005). The necessary EOP information was extracted from the file \text{usno\_finals.erp}\ (Created 2020.08.19-23:00:17; last date with real data 2020.08.19).

Source positions of the quasars observed were assumed as their ICRF3 S/X values (Charlot et al., 2020).

Corrections for cable delay variations (CDMS for OTT) were applied in the analysis if, and only if, the antennas had working PCAL which could be used in fringe-fitting. For antennas labelled with \text{Manual PCAL} in Table 2, no cable calibration was applied when analysing the particular vgosDb.

In the analysis with both software packages, we added 5 ps to the formal standard deviations before parameter estimation, to enable reaching a reduced \(\chi^2 = 1\). In \(\nuSolve\) the \text{reweighting} option was used to rescale the weights during estimation.

5.1.1 No ionosphere corrections

In standard dual- and multi-frequency VLBI observations, ionospheric corrections are usually applied in the analysis. Such corrections were not possible to apply in our case since we only observed X-band. However, the three stations ON, OE and OW are located within about 550 m distance, i.e. the differential ionospheric effects are negligible. Ionospheric corrections could thus be omitted without any significant impact on the analysis.

\footnote{Available via \url{http://hpiers.obspm.fr/icrs-pc/newwww/icrf/icrf3sx.txt}}
5.1.2 Pressure correction of observing log files

All three telescope systems at OSO use the same meteorological station, and the corresponding data are recorded identically in the three individual logfiles. However, the ellipsoidal height of this meteosensor is not identical to the ellipsoidal height of neither the reference point (intersection of telescope’s azimuth and elevation axes) of ON, nor of OTT.

We therefore corrected the pressure readings as recorded in log files correspondingly, using a height-dependent pressure correction (Berg, 1948). The corrected pressure $P_n$ is calculated according as

$$P_n = P_r \times (1 - 0.0000226 \times (h - h_r))^{5.225}$$

where $P_r$ is the original field-system wx log value, $h$ is the height of ON (59.3 m), OE (53.2 m) or OW (53.2 m), and $h_r$ is the height of the OSO pressure sensor (46.6 m). The approximate changes with respect to the original observing log-values are ON = −1.5 hPa, OE = −0.8 hPa, OW = −0.8 hPa. Since the ellipsoidal heights can be assumed to be accurate within 10 cm, the pressure corrections are expected to be accurate within 0.1 hPa. Using the corrected pressure values in the vgosDBs ensure that the zenith hydrostatic delays can be modelled as good as possible. We note that the log files available via the IVS are the corrected logfiles, with the pressure correction already applied.

5.2 Comparison of ASCOT and $\nu$Solve

Since we use two different packages to analyse the data, it is important to verify that the two agree. Therefore we analysed the data using a method that is available in both software packages: group-delay analysis, without correcting for neither thermal nor gravitational deformation. For this comparison we used the same subset of experiments used in the final position determination, i.e. those with PCAL and cable calibration applied. We estimated clock parameters every hour while modeling the zenith hydrostatic delays (ZHD) using the locally observed pressure data (corrected for height differences, see Sect. 5.1.2). We note that zenith wet delays (ZWD) were not estimated for this comparison. A comparison of the OE and OW positions obtained from ASCOT and $\nu$Solve, using similar settings, is shown in Figure 6 for the 16 vgosDBs with PCAL and cable-calibration. The results agree within 2$\sigma$ for all position components of both stations.

As an illustration of typical results, we present in Figure 7 three histograms of the post-fit residuals on the three baselines from the analysis of group-delay observations of all K-experiments with ASCOT. Normal distributions are fitted to these histograms and show that the mean residuals are below 1 ps on all three baselines, with standard deviations below 15 ps. As expected, the short baseline between the modern VGOS antennas OE and OW gives the best performance.

5.3 $\nu$Solve analysis: group-delays vs phase-delays

We used $\nu$Solve to obtain, for each vgosDb in Table 2, both group-delay solutions and phase-delay solutions. Phase-delay solutions for all experiments are presented in Figure 8.
Fig. 6: Comparison of group delay positions from ASCOT and νSolve for OE (panel a) and OW (panel b). The errorbars are 2σ uncertainties obtained by adding in quadrature the uncertainties from each software.
As noted in Sect. 3.3, ON suffers from direction dependent cable delay variations (Dan MacMillan, private communication 2002), which will affect the observed delays if not correctly compensated for in the analysis. Indeed, we find a significant systematic offset of about 1 cm in X and Z (see Figure 8) between experiments with/without PCAL and cable corrections for ON (listed in Table 2).

As expected, we find that \( \nuSolve \) reports smaller uncertainties for phase-delay solutions than group-delay solutions. The average weighted solution RMS is 3.6 ps vs 12.2 ps respectively (comparing data with both PCAL and cable calibration applied).

However, contrary to expectations, we find a significant systematic offset between the group- and phase-delay positions obtained with \( \nuSolve \), see Table 4 and Figure 8. While phase-delays should be more precise, there should not be any systematic offset between the two methods. Phase-delay analysis is, however, a relatively new addition to \( \nuSolve \), and the developers suggest additional testing is needed to understand this discrepancy (S. Bolotin, private communication). We therefore use group-delays as our method to determine the OE and OW station positions. We have seen that group-delay results are in good agreement between \( \nuSolve \) and \( \text{ASCOT} \), see Figure 6. However, because \( \text{ASCOT} \) can better model the effects relevant for ON, OE, OW, we use \( \text{ASCOT} \) for the rest of our analysis. We focus in the following on the vgosDbs where PCAL was available for all three stations.

Fig. 7: Histograms of postfit residuals (blue) from group delay analyses of all 23 K-experiments using \( \text{ASCOT} \). The red lines are the corresponding fitted normal distributions, and their mean values \( \mu \) and standard deviations \( \sigma \) are given.
Fig. 8: $\nu$Solve phase-delay positions for OE (blue stars) and OW (red circles), with $3\sigma$ uncertainties. The average $\nu$Solve group-delay position has been subtracted. Two significant offsets can be seen: a) about 1 cm in X and Z between experiments with/without cable- and phase-cal, and b) about 2 mm between the phase-delay and group-delay average positions (see also Table 4).

Table 4: Change in the average position obtained with phase-delay estimation in $\nu$Solve, compared to group-delay estimation.

| antenna | $\Delta X$ (mm) | $\Delta Y$ (mm) | $\Delta Z$ (mm) |
|---------|-----------------|-----------------|-----------------|
| OE      | 1.82 ± 0.32     | 0.34 ± 0.09     | 2.37 ± 0.39     |
| OW      | 1.39 ± 0.32     | 0.11 ± 0.13     | 2.26 ± 0.42     |

5.4 ASCOT analysis

In this section we investigate how various effects, which are possible to model in ASCOT, impact the estimated OE and OW positions and local-tie vectors.

5.4.1 Impact of clock parameter interval length

In order to investigate the impact of the clock parameter interval length, we compared the estimated OTT positions using both 1 hour and 20 minutes intervals. Using 20 minutes increase the number of parameters to be estimated by a factor of three (compared to 1 h), but did not cause a problem for the analysis due to
the large number of observations during the usually 24 hour long K-sessions, with well above 1000 observations per baseline.

Table 5 provides the observed changes in the weighted mean of the estimated station positions for the OTT from all K-experiments. We find that station positions are not impacted significantly by the choice of clock parameter interval length. This finding is confirmed from a similar analysis of individual K-sessions with $\nu_{Solve}$.

As an illustration, Figure 9 depicts the clock estimates for OE and OW from two 24 h sessions. In most experiments, OE and OW follow closely (e.g. panel a). In others, there are significant differences (e.g. panel b). ON, OE, OW all share the same maser clock so any variations between the three systems are likely due to telescope-specific instrumental instabilities.

Table 5: Effect on the weighted mean station positions of OE and OW when changing from clock interval length of 1 hour to 20 minutes, expressed in a topocentric east-north-up (ENU) coordinate system.

| antenna | $\Delta E$ (mm) | $\Delta N$ (mm) | $\Delta U$ (mm) |
|---------|----------------|----------------|----------------|
| OE      | $-0.023 \pm 0.022$ | $-0.008 \pm 0.017$ | $+0.061 \pm 0.043$ |
| OW      | $-0.023 \pm 0.021$ | $-0.032 \pm 0.019$ | $+0.031 \pm 0.061$ |

### 5.4.2 Impact of estimating Zenith Wet Delay (ZWD)

All three stations are located within 550 m and thus to a large extent share the same common local troposphere. Furthermore, the K-sessions were scheduled in a way that all three stations observed each scan together, i.e. the antennas had almost identical azimuth and elevation directions. However, in principle, small variations in the local troposphere and atmospheric turbulence effects could affect the delays on the three baselines in a differential way.

Since the elevation angles for the three antennas were almost identical, it is not possible to estimate antenna-specific tropospheric parameters for all three antennas. However, it is possible to estimate differential ZWD parameters for OE and OW as piece-wise linear offsets every 20 minutes, while not estimating any tropospheric parameters for ON. Table 6 provides the observed changes in the weighted mean of the estimated station positions for the OTT from all K-experiments when analysing with and without estimating ZWD for OE and OW. The changes are expressed in a topocentric east-north-up (ENU) coordinate system. While the horizontal components are not affected by more than 30 $\mu$m, we note a significant reduction in the up-components of the antennas, on the level of 0.3 mm to 0.8 mm.

### 5.4.3 Impact of thermal deformation

Figure 10 depicts the expected impact of thermal deformation on a VLBI delay observation for antenna ON and OE/OW following the model by Nothnagel (2009). This delay model uses mainly the antenna dimensions, the expansion coefficients
Fig. 9: Example of estimated clock values (every 20 min) for two 24 h experiments.
Table 6: Effect on the estimated station positions of OE and OW, expressed in a topocentric (ENU) coordinate system, when estimating ZWD for OE and OW as piece-wise linear offsets with 30 minute interval length, compared to not estimating ZWD.

| antenna | \( \Delta E \) (mm) | \( \Delta N \) (mm) | \( \Delta U \) (mm) |
|---------|---------------------|---------------------|---------------------|
| OE      | -0.030 ± 0.040      | -0.006 ± 0.027      | -0.784 ± 0.261      |
| OW      | +0.006 ± 0.037      | -0.023 ± 0.026      | -0.321 ± 0.226      |

of the material, and the temperature difference with respect to a reference temperature. A temperature of 10 K higher than the reference temperature for the Onsala site is used for this graph. A strong dependence on elevation is visible for both ON and OE/OW. However, since the actual telescope towers have rather similar dimensions, the two curves are rather similar. The largest differential effect for a delay observation on the ON-OE/OW baseline is on the order of 1.5 ps for an observation at zenith direction. Table 7 presents the effect on the estimated weighted mean topocentric positions of OE and OW when including thermal deformation. While the change is largest for the topocentric up-component, none of the changes are significant.

Table 7: Effect of including thermal deformation modelling (Nothnagel, 2009) in the analysis. Presented are the corresponding changes in the weighted mean topocentric positions of OE and OW.

| antenna | \( \Delta E \) (mm) | \( \Delta N \) (mm) | \( \Delta U \) (mm) |
|---------|---------------------|---------------------|---------------------|
| OE      | -0.001 ± 0.002      | +0.001 ± 0.001      | +0.000 ± 0.001      |
| OW      | -0.001 ± 0.001      | +0.000 ± 0.001      | +0.040 ± 0.079      |

5.4.4 Impact of gravitational deformation

Modelling of gravitational deformation of radio telescopes (Nothnagel et al., 2019; Lösler et al., 2019) was not included in ITRF2014, but is strongly recommended by the IVS analysis coordinator, in particular for the preparations for analyses to prepare the upcoming ITRF2020 (John Gipson, private communication, 2020). We therefore used ASCOT to investigate the impact of gravitational deformation on the analysis of the K-experiments.

Figure 11 depicts the effect of gravitational deformation on the VLBI delay observation for the antennas ON (Nothnagel et al., 2019) and OE/OW (Lösler et al., 2019). Both antenna types again show a clear elevation dependence. However, while OE/OW are rather stiff and stable antennas with a maximum effect of about 2 ps, ON is deforming much more and suffers from delay effects of almost 20 ps between observations in zenith and at the horizon. The largest differential effect for a delay observation on the ON-OE/OW baseline is \( \sim 19 \) ps for an observation at the horizon.

Table 8 presents the effect on the estimated weighted mean topocentric positions of OE and OW. The up-component changes significantly, more than 5.3 mm, while the horizontal changes are not significant. We note that modelling both
Fig. 10: Thermal deformation effect on the VLBI delay (Nothnagel 2009) for the antennas ON (red) and OE/OW (blue).

Thermal and gravitational deformation together changes the up-component of the positions determined for OE and OW by more than 5.4 mm. This approach also gives the lowest WRMS scatter of the post-fit residuals.

Table 8: Effect of including gravitational deformation modelling (Nothnagel et al. 2019; Löschler et al. 2019) in the data analysis. Presented are the corresponding changes in the weighted mean topocentric positions of OE and OW.

| antenna | $\Delta E$ (mm) | $\Delta N$ (mm) | $\Delta U$ (mm) |
|---------|-----------------|-----------------|-----------------|
| OE      | $+0.003 \pm 0.002$ | $-0.014 \pm 0.003$ | $+5.387 \pm 0.009$ |
| OW      | $+0.005 \pm 0.002$ | $-0.014 \pm 0.004$ | $+5.387 \pm 0.011$ |

5.5 Determining OE/OW positions and ON/OE/OW local-tie vectors

In this work we aimed to obtain positions for OE and OW relative to a known position for ON. In addition to modeling OE and OW as good as possible, it was important to use the same models for ON as were used to determine the ON position that we use as reference, e.g. VTRF2010D. This means that to obtain the best possible stations positions for OE and OW, we should account for all effects described above, except the gravitational deformation for ON. Since gravi-
tational deformation was not modelled for ON in VTRF2019D, using it here would introduce a systematic shift in our derived OE and OW positions.

For completeness we determined OE and OW positions using ASCOT for all 23 vgosDbs. We modeled thermal deformation (for ON, OE and OW), gravitational deformation (only for OE, OW), ZHD (from meteodata), and estimated clocks (every 20 min), differential ZWD (for OE, OW; every 30 min) and station positions (OE, OW). We added 5 ps additional noise (to improve reduced $\chi^2$) and used an outlier cutoff of 1 ns. The resulting positions obtained for all vgosDbs are presented in 11 and 12 in Appendix A. We note that, to be consistent with VTRF2019D, we should only include experiments with both PCAL and cable-calibration applied to calculate the final results. We therefore formed weighted average positions for OE and OW using this subset of data (16 vgosDbs), and these are presented in Table 9.

When estimating local-tie vectors we wanted to model all effects for all telescopes. Because the local-tie vectors are relative, we here included also gravitational deformation for ON in our estimation. This should provide the best match to measurements obtained via a future local site-survey. Our resulting local-tie vectors are presented in Table 10.
6 Results

Our weighted average positions for OE and OW are presented in Table 9. Our weighted average local-tie vectors between ON, OE and OW are presented in Table 10. Both the weighted average positions and the weighted average baseline vectors are calculated from the 16 vgosDbs where PCAL and cable-calibration were available for all three stations. Note that the vectors are not simply the difference in station positions, as explained in Sect. 5.5.

Table 9: VTRF2019D (epoch 2010.0) positions (in m) and their standard deviations (in mm) for OE and OW, obtained as described in Sect. 5.5.

| antenna | X     | Y     | Z     | σX   | σY   | σZ   |
|---------|-------|-------|-------|------|------|------|
| OE      | 3370889.29752 | 711571.19917 | 5349692.04831 | 0.36 | 0.09 | 0.47 |
| OW      | 3370946.77873 | 711534.50687 | 5349660.92546 | 0.28 | 0.10 | 0.38 |

Table 10: Local-tie vectors (in m) and their standard deviations (in mm), obtained as described in Sect. 5.5.

| Baseline | dX     | dY     | dZ     | σX   | σY   | σZ   |
|----------|--------|--------|--------|------|------|------|
| OE-ON    | 283.45679 | −346.47713 | −138.82125 | 0.32 | 0.09 | 0.41 |
| OW-ON    | 340.93799 | −383.16945 | −169.94419 | 0.26 | 0.09 | 0.37 |

7 Summary and outlook

During 2019 and 2020 we performed a series of short-baseline interferometry experiments to connect ONSA13NE and ONSA13SW, the Onsala twin telescopes, to the ONSALA60 VLBI station. These co-location sessions were performed using X-band only observations. The sessions were scheduled, observed, correlated and analysed at the Onsala Space Observatory. The coordinates of the Onsala twin telescopes could be determined in VTRF2019D with uncertainties on the sub-mm level. This new set of coordinates (see Tab. 9) should be used from now on for scheduling, correlation and as a priori for data analyses e.g. for the upcoming ITRF2020. The vgosDb of these sessions is available via the IVS.

Positions obtained with group-delay analysis performed with ASCOT and νSolve, using similar settings, agree within 2σ for all components of both stations. We also compared phase delay and group delay solutions in the νSolve software, finding systematic shifts which suggest the phase delay implementation in νSolve needs additional testing and development. Using the ASCOT software, we investigated the impact of various effects such as thermal and gravitational deformation.

From the experience gained, we have developed procedures that allows us to repeat these kind of observations and the corresponding data processing and analysis on a regular basis. Thus, regular monitoring of the baselines between the three
stations can be done several times per year. These regular sessions can, with proper continuous amplitude calibration measurements, also provide regular flux-density monitoring observations of quasars.

The plan is to also perform a classical geodetic survey of the local tie vectors between the OTT and the reference points of the other geodetic stations at Onsala. Furthermore, we want to do a GNSS-based local tie survey following the approach described in [Ning et al. (2015)]. We also aim at connecting the fourth VLBI station in the Onsala telescope cluster, the 25 m radio telescope, using similar interferometric measurements at C-band.

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Declarations

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Competing interests

The authors declare that there are no competing interests.

Availability of data and material

The DiFX output and derived data products that support the findings of this study are available from the corresponding author upon reasonable request. All vgosDbs are available via the IVS.

Code availability

νSolve is available via https://sourceforge.net/projects/nusolve/, ASCOT is available from the corresponding author upon reasonable request.

Authors’ contributions

EV and RH scheduled, observed, and correlated the observed data. EV, RH, analysed the data, using various software packages. Both authors contributed to writing the manuscript and read and approved the final version of the manuscript.
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A Positions of OE and OW for all vgosDbs

Positions of OE and OW, obtained as described in Sect. 5.5, are presented for each vgosDb in tables 11 and 12.
Table 11: VTRF2019D (epoch 2010.0) positions for OE. The reference date and time for the estimated position is also listed, as well as the formal uncertainties reported by ASCOT.

| YYYY | DDD | HH | X (m)       | Y (m)       | Z (m)       | σ_X (mm) | σ_Y (mm) | σ_Z (mm) |
|------|-----|----|-------------|-------------|-------------|----------|----------|----------|
| 2019 | 114 | 19 | 3370889.30112 | 711571.19966 | 5349692.05599 | 1.25     | 0.78     | 2.27     |
| 2019 | 121 | 10 | 3370889.30043 | 711571.20016 | 5349692.05304 | 0.38     | 0.18     | 0.57     |
| 2019 | 122 | 15 | 3370889.29965 | 711571.19968 | 5349692.05211 | 0.46     | 0.22     | 0.68     |
| 2019 | 136 | 11 | 3370889.29972 | 711571.19999 | 5349692.05115 | 1.14     | 0.65     | 1.75     |
| 2019 | 137 | 02 | 3370889.29885 | 711571.20018 | 5349692.05142 | 0.48     | 0.25     | 0.71     |
| 2019 | 142 | 20 | 3370889.30033 | 711571.20054 | 5349692.05385 | 0.98     | 0.45     | 1.56     |
| 2019 | 324 | 04 | 3370889.29610 | 711571.19964 | 5349692.04697 | 0.35     | 0.17     | 0.53     |
| 2020 | 011 | 04 | 3370889.29506 | 711571.19884 | 5349692.04495 | 0.35     | 0.18     | 0.52     |
| 2020 | 081 | 04 | 3370889.29578 | 711571.19917 | 5349692.04621 | 0.34     | 0.19     | 0.52     |
| 2020 | 083 | 04 | 3370889.29712 | 711571.19885 | 5349692.04756 | 0.35     | 0.19     | 0.53     |
| 2020 | 178 | 05 | 3370889.29847 | 711571.19967 | 5349692.05036 | 0.38     | 0.21     | 0.58     |
| 2020 | 179 | 04 | 3370889.29900 | 711571.19975 | 5349692.05037 | 0.41     | 0.21     | 0.61     |
| 2020 | 180 | 02 | 3370889.29858 | 711571.19938 | 5349692.04899 | 0.46     | 0.22     | 0.66     |
| 2020 | 181 | 01 | 3370889.29727 | 711571.19909 | 5349692.04754 | 0.46     | 0.24     | 0.69     |
| 2020 | 224 | 00 | 3370889.29772 | 711571.19939 | 5349692.04842 | 0.51     | 0.27     | 0.76     |
| 2020 | 228 | 05 | 3370889.29773 | 711571.19940 | 5349692.04861 | 0.43     | 0.23     | 0.65     |
| 2020 | 229 | 05 | 3370889.29810 | 711571.19833 | 5349692.04873 | 0.44     | 0.23     | 0.67     |
Table 12: VTRF2019D (epoch 2010.0) positions for OW. The reference date and time for the estimated position is also listed, as well as the formal uncertainties reported by ASCOT.

| YYYY | DDD | HH | X (m)   | Y (m)   | Z (m)   | σ_X (mm) | σ_Y (mm) | σ_Z (mm) |
|------|-----|----|---------|---------|---------|-----------|-----------|-----------|
| 2019 | 121 | 10 | 3370946.78258 | 711534.50717 | 5349660.92809 | 0.39 | 0.18 | 0.58 |
| 2019 | 136 | 11 | 3370946.78042 | 711534.50717 | 5349660.92763 | 1.20 | 0.68 | 1.85 |
| 2019 | 137 | 02 | 3370946.78044 | 711534.50717 | 5349660.92744 | 0.53 | 0.27 | 0.79 |
| 2019 | 142 | 20 | 3370946.78133 | 711534.50717 | 5349660.92823 | 1.05 | 0.46 | 1.67 |
| 2019 | 142 | 20 | 3370946.78082 | 711534.50717 | 5349660.92831 | 0.47 | 0.25 | 0.71 |
| 2019 | 137 | 02 | 3370946.78191 | 711534.50673 | 5349660.92744 | 0.53 | 0.27 | 0.79 |
| 2019 | 142 | 20 | 3370946.78082 | 711534.50717 | 5349660.92831 | 0.47 | 0.25 | 0.71 |
| 2020 | 011 | 04 | 3370946.77881 | 711534.50648 | 5349660.92485 | 0.65 | 0.34 | 1.01 |
| 2020 | 012 | 00 | 3370946.77916 | 711534.50717 | 5349660.92485 | 0.65 | 0.34 | 1.01 |
| 2020 | 012 | 20 | 3370946.77886 | 711534.50717 | 5349660.92485 | 0.65 | 0.34 | 1.01 |
| 2020 | 080 | 03 | 3370946.77770 | 711534.50634 | 5349660.92451 | 0.36 | 0.18 | 0.54 |
| 2020 | 081 | 04 | 3370946.77763 | 711534.50634 | 5349660.92451 | 0.36 | 0.18 | 0.54 |
| 2020 | 082 | 04 | 3370946.77745 | 711534.50661 | 5349660.92374 | 0.35 | 0.20 | 0.54 |
| 2020 | 083 | 04 | 3370946.77782 | 711534.50654 | 5349660.92466 | 0.36 | 0.20 | 0.55 |
| 2020 | 083 | 04 | 3370946.77790 | 711534.50691 | 5349660.92624 | 0.39 | 0.22 | 0.59 |
| 2020 | 083 | 04 | 3370946.77790 | 711534.50691 | 5349660.92624 | 0.39 | 0.22 | 0.59 |
| 2020 | 179 | 04 | 3370946.77911 | 711534.50695 | 5349660.92567 | 0.41 | 0.21 | 0.61 |
| 2020 | 180 | 02 | 3370946.77942 | 711534.50720 | 5349660.92674 | 0.46 | 0.22 | 0.67 |
| 2020 | 181 | 01 | 3370946.77771 | 711534.50593 | 5349660.92373 | 0.46 | 0.24 | 0.69 |
| 2020 | 228 | 05 | 3370946.77828 | 711534.50714 | 5349660.92536 | 0.55 | 0.29 | 0.81 |
| 2020 | 229 | 05 | 3370946.77784 | 711534.50670 | 5349660.92473 | 0.45 | 0.23 | 0.69 |