Hb-Ho: Observations with the sibling telescope in Hobart

L. Plank, J. Lovell, J. McCallum, J. Böhm, D. Mayer

Abstract With the transition to VGOS, co-located radio telescopes will be common at many sites. This can be as a sibling telescope, when a VGOS antenna is built next to a legacy one or as the concept of a twin telescope, with two identical VGOS antennas. Besides a number of new observing possibilities in a network, such a configuration also allows for the investigation of local effects or antenna-specific systematics. This is for example the measurement of the local baseline with VLBI and the subsequent comparison with the local tie as determined with classical surveying. The comparison of redundant observations to other antennas can be used as independent verification and identify systematic delays specific to each antenna. Lastly, co-location offers new possibilities in analysis, by combining common parameters like station positions, tropospheric conditions or clock modelling. The two telescopes in Hobart, (12m-Hb, 26m-Ho) have observed in more than 70 common IVS sessions, offering a great dataset for studying the performance of a sibling telescope. In addition, dedicated Hb-Ho experiments were performed in 2014. We report on differences found in redundant observations, compare common parameters, determine the local baseline and its variations, and report on newly applied scheduling and analysis strategies.

Keywords Sibling Telescope, Analysis, Twin Telescope

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1 Introduction

With the erection of the AuScope VLBI network (Lovell et al., 2013) in 2010, the Mt. Pleasant observatory in Hobart, Australia, can be operated as a sibling telescope. This consists of the 26m legacy antenna (Ho), contributing to IVS sessions since 1989, and the 12m Hb dish, designed to become part of the future VGOS network and one of the busiest antennas within the IVS at the moment.

During the initialization phase of the Hb antenna (in 2010-2012) both telescopes observed regularly together in IVS (R-) experiments. Later on, the major workload was transferred to the Hb antenna and today the legacy Ho antenna only contributes to special CRF- or R&D-sessions.

In Figure 1 we show the results for the estimated baseline between the two co-located telescopes in Hobart, as determined from 72 common sessions. We find a mean length of 295.914 m and a wrms of 9 mm. This result differs 4 mm from the local tie measured in two surveying campaigns performed by Geoscience Australia in 2009 and 2014. Also, the distribution of the data points might indicate some systematic signal of about $\pm$1.5 cm, especially for the time before 2013. Unfortunately the common sessions are very sparse after that and are mostly CRDS sessions where the results for station positions are less accurate. It is worth mentioning that since the beginning of 2014 both Hobart telescopes are connected to the identical frequency maser, while they were running on different clocks before. Very promising are the results of the 15-day *CONT14* campaign in May 2014, revealing a baseline wrms of 2 mm for the sibling telescope.

This large dataset of Hb-Ho experiments offers a great opportunity for a more comprehensive study

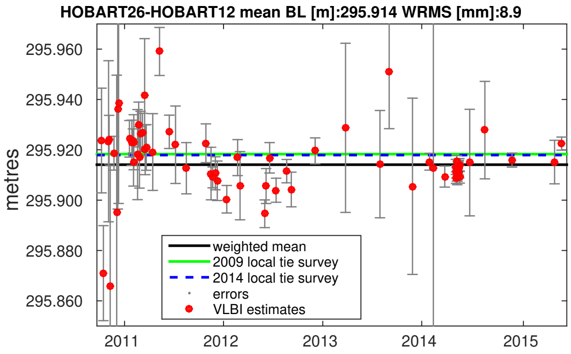

Fig. 1 The Hobart-Hobart baseline determined of 72 common VLBI sessions. The black line shows the mean calculated baseline length of 295.914 m, which is 4 mm off from the baseline determined in two local tie surveys.

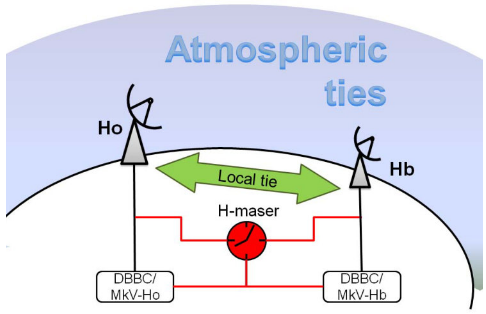

Fig. 2 The Hb-Ho sibling telescope offers new possibilities in the analysis: a combination of the parameters for the atmosphere, station coordinates and the identical clock.

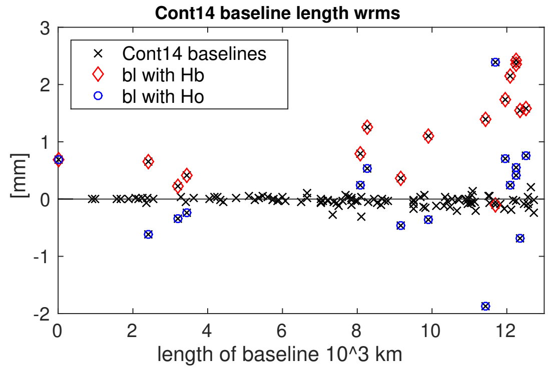

Fig. 3 Differences in baseline length wrms between a classical solution of the *CONT14* data and applying additional constraints for common parameters in the analysis. Positive values indicate an improvement for the new analysis. Differences are mainly found for baselines to one of the co-located antennas marked with red diamonds (Hb) and blue circles (Ho).

of the performance of a sibling telescope. With the prospect of the transition to VGOS in the next years, co-located telescopes will be common: either as a sibling telescope consisting of a legacy and a new antenna or as the new twin telescope concept with two identical antennas. For an optimal combination of the observables, the determination of the local tie between the co-located telescopes will be of major importance, as will be any systematic effects. The configuration of a sibling (twin) telescope offers new ways in the analysis, which need to be implemented and tested. This is introduced in Section 2. In order to better understand the differences we found in redundant observations of the sibling telescope we performed a dedicated Hb-Ho experiment, *AUST65*. A session description, including the scheduling and the analysis is given in Section 3. We end this report with the introduction of our new project *Sibling Telescopes* in Section 4, which will concentrate on a thorough investigation of the optimal use of co-located VLBI antennas.

2 Improved analysis

As illustrated in Figure 2, observations of the sibling telescope in Hobart pass through the (quasi-) identical atmosphere, large-scale station motions are expected to be the same for both telescopes and a single clock is used at the station. These parameters can be combined in the analysis (e.g. Nilsson et al., 2015; Hobiger and Otsubo, 2014).

Using the Vienna VLBI Software (Böhm et al., 2012) we introduced additional constraints in the estimation part between site positions, zenith wet delays, and atmospheric gradients of the two Hobart antennas. Applied to the data of *CONT14* (a 15-day continuous global VLBI campaign comprising 17 antennas), we find improved results in the wrms of daily determined baseline lengths. This is shown in Figure 3: For baselines to one of the Hobart antennas (marked with larger red and blue symbols) we largely find improvements, up to 3 mm compared to the classical solution. This improvement is larger for baselines to the Hb antenna than for baseline to the Ho antenna. A reason for this is that in the classical solution the repeatabilities for Ho are slightly better than for Hb. Through the combination of the station coordinates, the total results are approximately equal, meaning an improvement for Hb and a slight worsening for the Ho antenna. However, the combination of the tropospheric parameters adds an additional significant improvement. The results for other baselines are only marginally different, at the tenth of a millimetre level.

Despite this promising result, there are still things to work on: in a careful study the optimal weights for the combination of the parameters have to be determined. How strong should the common parameters be forced to be identical? Next, rather than combining the parameters of the two antennas by additional constraints, the ultimate goal would be to actually only estimate one parameter for both antennas, where all observations contribute. Further, our results for combined clocks are not convincing so far, revealing worse results than without a combination. A possible reason for this is the fact that, besides the pure clock drifts themselves, the estimated clock terms often include other (instrumental) delays which may be different for the two antennas.

This is also evident when studying the ionospheric delays. Due to its dispersive behavior the effect of the ionosphere can be *removed* from the data by combining the X-band group delays with the measurements done in S-band. In VieVS we use the data provided via the so-called *NGS-files*, which are based on the level 4 database files and explicitly give the determined ionospheric delay. At this stage the data has been also adjusted for ambiguities and for closures within the network.

In theory (also see Section 3) we do not expect any ($\ll$ 1 mm) delay due to the ionosphere on the Hb-Ho baseline. Neither should there be differences between the ionospheric delays on identical observations to a third antenna, e.g. between the ionospheric contribution for the same scan on the Hb-Katherine and the Ho-Katherine baseline. The fact is, however, that in the *CONT14* data we find (a) huge offsets in the ionospheric correction between the Hb and the Ho antenna of up to 10 ns ($\approx$ 30 m) and (b) an rms difference of $\approx$ 1 cm after removal of these offsets. This is also true for observations on the Hb-Ho baseline.

We therefore conclude that the ionospheric delay as given in the *NGS-files* (resp. database level 4) has to include other effects than solely those of the ionosphere. To first order, these are large ambiguities. But also other effects, e.g. of instrumental origin, may be the reason for these differences (e.g. Alizadeh et al., 2013, Sec. 4.2.4). In order to get more insight into these discrepancies we performed a dedicated experiment (*AUST65*) which, after correlation, was fully processed in-house.

3 AUST65

On November 29 2014, *AUST65* was performed with the antennas in Katherine (Ke), Yarragadee (Yg), Warkworth (Ww) and the sibling telescope in Hobart. Hereby, Hb and Ho did redundant observations, i.e. they observed the identical sources at identical epochs. To realise this in the scheduling, the sensitivity in terms of antenna target sensitivity (in terms of the system equivalent flux density - SEFD) of the large 26m dish was set to the lower values of the 12m antenna. Without the need to adjust the slew speeds or schedule one antenna as tag-along, we got 456 common observations using the scheduling module of the VieVS software. In total, Hb had 463 scheduled observations over 24 hours and Ho 458, using the *AUSTRAL* observing mode with 1 Gbps recording.

After correlation (at Curtin University) we ran fourfit and created a database. Using νSolve, the ionospheric correction was added to the level 4 *NGS-files*. The subsequent analysis was done with VieVS.

First thing to notice are problems with the ionospheric delays. We find that almost all observations on the Hb-Ho baseline have extremely high ionospheric delays of up to ± 4 ns, most likely a result of the strong local RFI in S-band. This causes troubles in the analysis. The simplest solution is to exclude all observations on the Hb-Ho baseline. Another possibility is to simply set the contribution of the ionosphere on the local baseline to zero. In Figure 4 we compare the estimated 3D station position offsets for Hb and Ho during *AUST65*. Without taking care of the huge ionospheric delay on the Hb-Ho baseline, we find station position offsets of about 15 ± 3 cm for the two stations (not shown). Excluding observations on the Hb-Ho baselines we find offsets of 3 and 1.5 cm for the Hb and Ho antenna respectively. These estimates improve marginally when we choose to keep the observations on the local baselines and set the ionospheric contribution to zero. Due

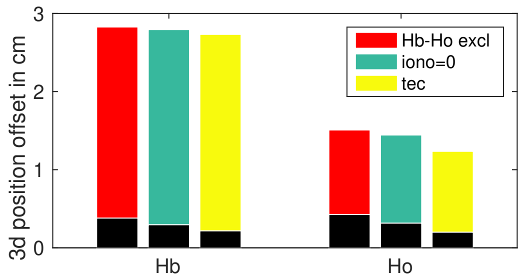

Fig. 4 Estimated 3D station position offsets in *AUST65* using different ionospheric corrections. The black bars indicate the corresponding nominal 3D position errors.

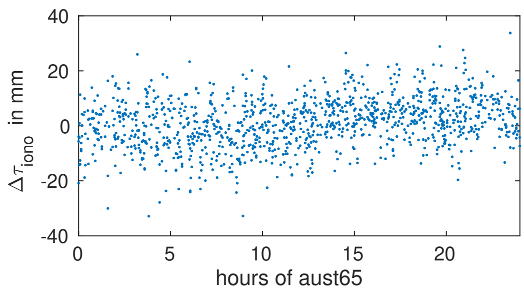

Fig. 5 Difference in the ionospheric delay of redundant observations of the Hobart sibling telescope in *AUST65*.

to the additional observations, the formal uncertainties (shown with the black bars) of the estimates could also be improved.

Having resolved the ionospheric differences on the local baseline, we now have a look at the baselines to third antennas. With this we mean comparing observations within the same scan, Hb-antenna$_x$ to Ho-antenna$_x$. We call these *redundant observations*. For the data of *AUST65*, we find significant differences in the ionospheric corrections of these redundant observations, with an rms of 1.2 cm or 40 ps (Figure 5). At this stage it is not clear whether these differences are purely the precision of the measurements or whether they occur due to other (systematic) differences between the two Hobart antennas. A comparison of these differences versus elevation or azimuth did not reveal any clear correlation either. In theory (calculated using ionospheric TEC maps), however, the difference in the ionospheric delay should not exceed the 30 μm (10 fs) level on these redundant observations. Accounting for this, we ran a new solution using the ionospheric delays as calculated from GNSS-derived ionospheric TEC maps (Tierno Ros et al., 2011) instead of the ones created by the combination of the S-band and X-band data. Comparing the results to our previous two solutions, we find a further slight improvement in the estimated station position offsets for the sibling telescope in *AUST65* (Figure 4). However, the use of TEC-maps does not seem to be sufficient for longer baselines, as we find considerably larger (additional 1-2 cm) offsets for the other three antennas in *AUST65*. Hence, we keep the second solution with setting the ionospheric delays on the Hb-Ho baseline to zero as our default solution.

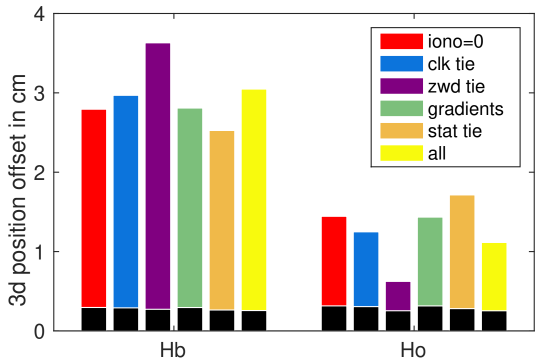

Fig. 6 Estimated 3D station position offsets in *AUST65* using different analysis options for combining common parameters of the sibling telescope. The black bars indicate the corresponding nominal 3D position errors.

In a final investigation we applied the new analysis options of combining common parameters of the sibling telescope to *AUST65*. The results in terms of 3D station position offsets are presented in Figure 6. On the very left the results for the reference solution are shown. We then applied a combination of a single parameter in the analysis, namely clocks, zenith wet delays, atmospheric gradients, and station coordinates. The bars on the right indicate our results when combining all four parameters in the solution. We find that additional constraints for the clocks and the zenith wet delays can significantly change the results in terms of station positions. However, for one station to the better and for the other to the worse. At the moment, constraining the clocks does not have a big influence and we do not find any changes for combining the atmospheric gradients in the analysis. One reason for this could be that both antennas observe (almost) identical scans, so that there is no additional information through observations in a different azimuthal direction. We conclude from this initial experiment that the various combination strategies do change the results; but they have to be tested carefully and the right values for the constraints need to be found.

4 Outlook

Studying previous and more recent observations with the Hobart twin telescope do raise some questions which need further investigation. In July 2015, the new project *Sibling Telescope* was started, funded by the Austrian Science Fund (FWF). In the upcoming three years, dedicated research will be performed on the topics of:

- Local tie discrepancy: in order to tackle the present discrepancy between the baseline measured by VLBI and the local survey, we have multiple plans; first, we intend to add the Ho antenna more frequently to the standard IVS experiments, in order to extend the baseline observations shown in Figure 1. We further investigate the option of local single-baseline VLBI sessions to derive the local tie, with *hob001* and *hob002* already under analysis at the moment. Lastly, a combination between VLBI and GPS observations within the AuScope network also revealed to be promising for this purpose (Plank et al., 2015).
- Improved analysis: a first step is done by implementing additional constraints in the VieVS software. Now the new options can be tested thoroughly and further refinements will be done. For the single baseline *hob* experiments, we also plan to do a phase delay solution.
- Scheduling strategies: In combination with the new analysis options, new scheduling options will also be developed. The scheduling and simulation tools integrated in VieVS are perfectly suitable for this work.

Acknowledgments

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