First Local Ties from Data of the Wettzell Triple Radio Telescope Array

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Abstract The Geodetic Observatory Wettzell features three radio telescopes. Local ties between the reference points are available from terrestrial precision surveying with an expected accuracy below 0.7 mm. In addition, local VLBI data analysis is currently investigated to provide independent vectors and to provide quality feedback to the engineers. The preliminary results presented in this paper show a deviation from the local survey at the level of one millimeter with a clear systematic component. Sub-millimeter precision is reached after removal of this bias. This systematic effect is likely caused by omission of thermal expansion and gravity deformation, which is not yet implemented in our local VLBI analysis software.

Keywords Local baseline processing, local ties, local correlation, Wettzell radio telescope triple

1 Introduction

The Geodetic Observatory Wettzell features a 20-m radio telescope (RTW) as well as two new 13.2-m TWIN telescopes. While RTW has performed routine operations since 1984, the first of the TWIN telescopes, TTW1, entered its productive phase in mid-2014, and TTW2 has just been equipped with an Eleven feed broadband receiving system.

The triple telescope array at Wettzell establishes a geodetic short baseline interferometry network. Local correlation yields group delay observations for baseline estimation from VLBI data alone without any immediate augmentation by terrestrial measurements. Apart from relative positioning of the telescopes, these are versatile capabilities for an end-to-end quality control of the VLBI data.

Most components of such a local VLBI-based monitoring system are already available, with the exception of the local VLBI-data correlator (up to now, this part has been carried out at the Bonn Correlator). Moreover, the scheduling mechanisms will have to be optimized for short baseline observations in the future.

Results from local VLBI data analysis will be portrayed in this contribution and compared to the local ties from precision terrestrial surveying.

2 Regional and Local Monitoring

The region around the Geodetic Observatory Wettzell is regularly monitored by geodetic means:

1. *Footprint network:* The footprint network consists of geodetic GNSS reference stations located at distances ranging from 4–14 km (inner ring of stations) up to 90 km (outer ring). Six of these stations are directly operated and maintained by the Observatory's staff, six sites are operated by the regional surveying authority, and one EUREF station completes the network.

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Fig. 1 The three Wettzell radio telescopes and the 3D distances between them as derived from local terrestrial precision surveying (survey data from the year 2012).

2. *Local GNSS network:* Similarly to the footprint network, an array of more than seven local GNSS receivers is operated on site. The term "on site" (at the Observatory) means that these receivers are located at distances not exceeding 250 m.
3. *Local survey network:* The local surveying network covers the area of the Geodetic Observatory Wettzell and some surrounding places. This network is measured with precision terrestrial total stations yielding a point precision of usually 0.2–0.4 mm. Digital leveling is performed to enhance the accuracy of the vertical coordinate component. Several GNSS points can be co-located with terrestrial equipment and serve as ground control points to transform the local coordinates into Earth-centered, Earth-fixed (ECEF) coordinates.
4. *Reference points:* The monitoring of the reference points is theoretically a part of the local network surveying. However, the reference points of the SLR and VLBI telescopes are usually not accessible directly. Consequently, special surveying procedures must be applied to indirectly determine the reference points.

The motivation behind all these efforts can be characterized as follows. The footprint network is primarily operated in order to verify that the local measurements at the Wettzell Observatory are representative for the entire region (i.e., neither local nor regional deformation is occurring). Surveying the local network also helps to sense small variations in position (e.g., during dry summer periods), but the primary purpose is to provide the vectors between the various co-located instruments (commonly referred to as "local ties").

Recently, we have started to compute independent, weekly system-specific ties for the local GNSS array that partially coincides with the terrestrial network, and more care is exercised to provide physical connections between the two networks (combined targets with reflectors and GNSS antennas). As an extension, this contribution deals with the determination of system-specific ties between the radio telescopes from VLBI data.

3 Methodology

The methodology is explained in more detail in [Schüler et al. (2015a)]. Group delay observations are used to determine the vector between the two telescopes. The local surveying results are taken as a reference here. The 3D distances between all three telescopes are graphically illustrated in Figure 1.

The work-flow is illustrated in Figure 2. A suitable *schedule* is generated depending on the specific purpose. A schedule to quickly deliver quality information to the VLBI engineers regarding the overall system performance may require an experiment of just one hour duration. In contrast, a local baseline determination may preferably be based on an experiment covering a full day.

Subsequently, the quasar signals are *measured* by the radio telescope receiving systems. Currently, only the 20-m RTW (Radio Telescope Wettzell) and the TTW1 (TWIN Telescope Wettzell 1) are available for this purpose. TTW2's availability is scheduled for mid-2016. Also note that only TTW1 and TTW2 are currently connected to a common maser frequency refer-

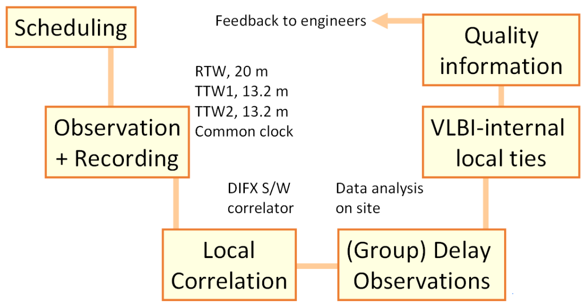

Fig. 2 Basic flowchart for the local end-to-end VLBI observation and analysis sessions.

ence, whereas RTW is connected to a different one. A clock common to all three telescope is foreseen during 2016 too.

Data correlation between the telescopes is carried out right after completion of the measurements. This is a central part of the processing chain, and it will be very beneficial to perform this correlation step locally at the Geodetic Observatory Wettzell, preferably using the same software and methods employed at the Bonn correlator. Up to now, the data have been transferred to Bonn and correlated there using the DiFX correlator [Deller et al. (2011)].

The *group delay observations* are adjusted using in-house software particularly tailored to the needs of the Observatory. Each band can be analyzed independently in such a way that separate S- and X-band results can be computed. Clock drifts are currently compensated via a polynomial compensation approach from order 1 (one hour sessions) up to order 4 (full day sessions). In the future, using a common clock should reduce the number of parameters required for that purpose. Note that the set of radio source positions in the analysis is currently directly taken from the header section of the NGS Card File supplied. Identification and usage of radio sources particularly suited for short baseline interferometry is the subject of future work.

Finally, the *estimated baseline vectors* from VLBI data are reviewed and collected for a further network adjustment. Since we currently only have two telescopes available for real use, the network adjustment module has not been fully implemented yet. Equally important, *quality information* can be extracted from the various results, providing feedback to the VLBI engineers in order to improve the systems.

4 Realization

Apart from organizational aspects regarding the realization of this end-to-end planning-measurement-analysis-feedback chain, the technical aspects with special focus on the receiving systems of the three individual telescopes can be guessed from Figure 3.

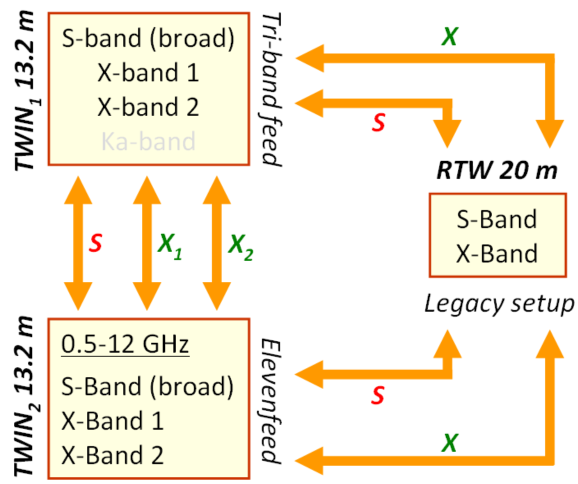

Fig. 3 Current receiving systems in the Wettzell radio telescopes and common observation modes.

1. *RTW (20 m):* This telescope entered routine operation in 1984 and is equipped with a legacy S/X receiving system. Although there are plans to upgrade the telescope regarding improved capabilities for astrometry, there is no plan to upgrade it with a focus on VGOS capabilities. This means that all baselines processed in conjunction with RTW are naturally limited to this legacy observing mode. This applies to all results presented in this paper.
2. *TTW1 (13.2-m):* This VGOS-ready telescope is currently equipped with a tri-band receiving system featuring a 700 MHz S-band window, a 4 GHz X-band window, and a Ka-band section. Ka-band can only be measured, but not analyzed locally, because there is no partner telescope available at Wettzell. A specific plan to upgrade TTW1 to broadband capabilities does exist but will not turn into action until late 2017.
3. *TTW2 (13.2-m):* This second TWIN telescope features a broadband receiving system sensitive from 0.5 to 12 GHz. Consequently, baselines between

TTW1 and TTW2 could be observed using one S-band window and up to two X-band windows (frequencies between 6 and 10 GHz). Theoretically, even a fourth band could be extracted, but the down-converter in TTW1 does not support that, because its fourth receiving chain is dedicated to the Ka-band support.

Note that the TTW1 results obtained from S-band group delays are heavily contaminated by radio-frequency interference (RFI). In legacy mode, these delay observations are already less precise compared to X-band due to their smaller bandwidth. Hence, we only present results derived from X-band observations (the ionosphere correction is disabled, because it is not of concern over a 123 m baseline).

5 Results

Figure 4 portrays an excerpt of baseline estimation results from X-band data deduced from experiments (24-hour duration) during the summer period of 2015 (June to September). The baseline names have the following meaning:

1. *WETTZELL:* RTW (20-m) telescope, analog backend (video converters).
2. *WETTDBBC:* RTW (20-m) telescope with DBBC digital backend [Tuccari et al. (2010)].
3. *WETTZ13N:* TWIN 1 (13.2-m) telescope with DBBC digital backend.

Consequently, the baseline *"WETTZELL-WETTDBBC"* refers to one and the same telescope—that is, it features a zero baseline. Although, these measurements were purposefully collected, we do not discuss that part in this paper.

Moreover, the following columns are part of the table of results:

1. *FREQ:* frequency in gigahertz (here: X-band only).
2. *OBS:* number of observations actually used in the adjustment procedure.
3. *DEL:* percentage of observations (group delays) automatically deleted by the two-stage outlier cleaning procedure upon adjustment.
4. *DX, DY, DZ:* deviation of the (X,Y,Z)-coordinate component (ECEF) from the local precision survey in millimeters.
5. *DS:* deviation of 3D spatial distance from the local precision survey in millimeters.

Regarding the data processing, it is worth mentioning that the estimated parameters may comprise:

1. The three baseline vector coordinate components.
2. Up to four clock error compensation coefficients.
3. One tropospheric adjustment factor.

Note that the tropospheric adjustment factor is usually not statistically significant for this short baseline. However, a tropospheric delay model is applied in order to account for the difference in height between the two telescopes.

When looking at the results, it is obvious that most results deviate by about 1 mm from the local survey. A clear systematic difference between these two sets of results can be identified. We intentionally did not remove it here. Please refer to the following section for an explanation and interpretation.

Subtraction of the systematic part yields sub-millimeter precision as is usually required for local ties. Note that one important goal of this work is to quickly transfer reference coordinates to a new telescope. From this point of view, these results are promising for future work in this field. This method is attractive, because the very high degree of correlation of all atmospheric propagation delays yields a higher accuracy of the new telescope's coordinates compared to long baseline adjustment procedures that have to deal with the annoying effects of tropospheric delays.

6 Conclusions

Following some initial values presented in [Schüler et al. (2015b)], the results given in this paper for the telescope vector between the 20-m radio telescope RTW and the new 13.2-m TWIN 1 telescope show a very satisfactory level of agreement with the results from the local precision survey.

A bias of about 1 mm between the two techniques can be identified. The possible sources of these discrepancies are likely related to the fact that the following corrections/reductions have not been implemented in our local analysis software yet:

YYYYMMDD	HH	FROM	TO	FREQ	OBS	DEL	DX	DY	DZ	DS
20150622	17	WETTDBBC	WETTZ13N	8.213	441	15%	1.4	0.7	1.5	2.0
20150622	17	WETTDBBC	WETTZELL	8.213	477	3%	0.9	0.4	1.0	1.3
20150622	17	WETTZ13N	WETTZELL	8.213	439	5%	0.9	0.6	1.0	1.3
20150629	17	WETTZ13N	WETTZELL	8.213	386	4%	1.2	0.7	1.4	1.8
20150713	17	WETTDBBC	WETTZ13N	8.213	320	5%	1.2	0.7	1.3	1.7
20150713	17	WETTDBBC	WETTZELL	8.213	361	4%	0.5	0.2	0.5	0.8
20150713	17	WETTZ13N	WETTZELL	8.213	369	6%	1.0	0.6	1.2	1.5
20150723	18	WETTZ13N	WETTZELL	8.213	271	4%	0.9	0.6	1.2	1.5
20150730	18	WETTZ13N	WETTZELL	8.213	234	6%	1.1	0.8	1.2	1.6
20150804	17	WETTZ13N	WETTZELL	8.213	508	5%	0.9	0.6	1.0	1.2
20150811	17	WETTZ13N	WETTZELL	8.213	391	1%	1.1	0.7	1.4	1.7
20150817	17	WETTZ13N	WETTZELL	8.213	344	7%	1.0	0.7	1.1	1.5
20150831	17	WETTZ13N	WETTZELL	8.213	414	3%	1.0	0.6	1.1	1.3
20150914	17	WETTZ13N	WETTZELL	8.213	386	2%	1.3	0.7	1.6	2.0
20150928	17	WETTZ13N	WETTZELL	8.213	437	1%	1.0	0.6	1.0	1.3

zero baselines!

Fig. 4 Results from local VLBI experiments conducted in common observation mode between RTW (20 m) and TTW1 (13.2 m); excerpt from a longer list of results. The FREQ values have units of gigahertz, and the DX, DY, DZ, and DS values have units of millimeters.

1. *Telescope expansion:* The effect of thermal expansion of the telescope structures has not been taken into account.
2. *Gravitational correction:* Similarly, no model to account for the deformation of the antenna dish due to the weight of the structure was used.

We assume that inclusion of these two main corrections should further improve the results.

Acknowledgements

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