LEVIKA SBA – Wettzell Radio-Telescope Positioning With a Tailor-Made Analysis Software

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Abstract The Geodetic Observatory Wettzell features three radio-telescopes dedicated to Geodesy: the 20-m telescope Wz (internally called RTW – Ratioteleskop Wettzell) has been in operation since 1984, and the two 13.2-m TWIN telescopes. Wn (TWIN 1, called "Wettzell North" by the IVS Coordinating Center) and Ws (Wettzell South) are VGOS-capable and were inaugurated in 2013. Wn is currently equipped with a tri-band receiving system (S/X/Ka) and regularly participates in routine IVS operations. Ws is equipped with a VGOS Elevenfeed and participates in the VGOS Pilot Test phase. Together, these three telescopes form a local triangle. The analysis software LEVIKA SBA (Short Baseline Analysis) was developed at the Observatory for local VLBI data adjustment. It serves the primary purpose of determining the relative positions of the three telescopes from original VLBI data and comparing these results with the local tie vectors from the precision engineering network regularly surveyed at Wettzell. In addition, the software was developed as part of a quality management initiative, in order to provide timely feedback to the engineers and operators regarding the health status of the overall system. Since telescopes with substantially different receiving systems are present at Wettzell, mixed-mode observations and analysis are of importance. This contribution depicts the analysis software, its functional basics and presents selected analysis results.

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Keywords Short baseline VLBI analysis, relative local radio telescope positioning, local ties

1 Motivation

The three radio-telescopes Wz, Wn, and Ws at Wettzell are surveyed regularly by terrestrial measurement equipment. The antenna reference point of the new TWIN telescopes Wn and Ws is not directly accessible and requires—though partly automatized—a major effort. However, the ties (connection vectors) between the telescopes can also be determined from the VLBI observations, and these "local VLBI ties" can be compared with the terrestrial ties.

The local VLBI correlator *GOWL* was installed at Wettzell for this very purpose. Local data quality assurance sessions require an a analysis software that is easy to use in order to warrant a rapid feedback to the VLBI engineers. Consequently, the development of a small, but straightforward baseline adjustment tool was fostered.

2 Equations & Observations

LEVIKA SBA processes VLBI group delay observations for any band separately. A geocentric formulation [Campbell, 2000] of the equations is preferred and fully sufficient for this purpose. The associated observation equation reads according to [Lu et al., 2014]:

$$\tau_G = -\frac{1}{c}\left(b_x cos(t) cos(\delta) - b_y sin(t) cos(\delta) + b_z sin(\delta)\right)$$

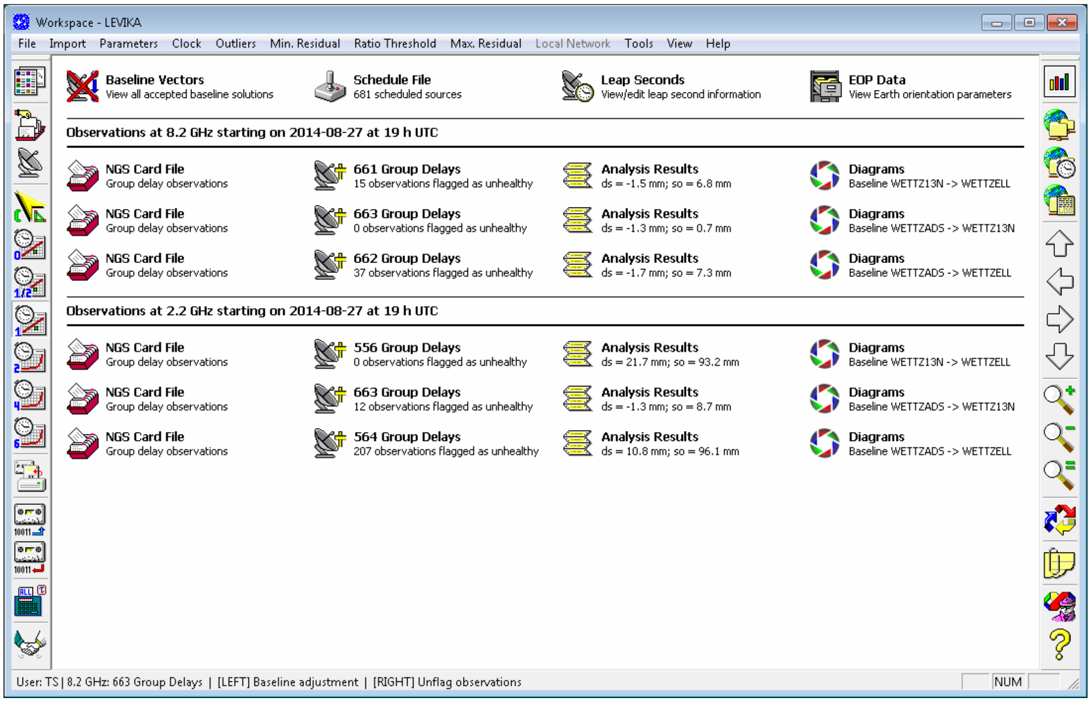

Fig. 1 LEVIKA SBA desktop screenshot. The short baseline analysis module of the LEVIKA software in support of local VLBI correlation is flexible in terms of group delay processing since each frequency band can be analyzed independently. This desktop shows three different setups for two different frequencies (X- and S-band). The baseline WETTADS to WETTZ13N is a zero baseline, the others refer to baseline Wn (TWIN 1) – Wz (RTW).

where τ_G is the group delay measurement, c is the speed of light, $b_{x,y,z}$ are the baseline components (coordinate vector) between the two telescopes, t is the hour angle, and δ is the declination of the radio source.

Figure 1 portrays the LEVIKA SBA desktop view displaying the different data sets analyzed during a local 24-hour session. You can see both data collected at X- (upper part) and S-band (lower part). The number of available and healthy observations in X-band is higher than in S-band (e.g., 661 group delays versus 556 delays). The reason is that S-band observations suffer from interference, yielding high correlation peaks on local baselines due to spatial correlation of the interference signatures. There is one exception: baseline WETTADS – WETTZ13N shows high numbers. This is a zero baseline; i.e., both groups of measurements refer to Wn/TWIN 1 and were sampled in parallel with a DBBC2 digital backend (refer to WETTZ13N) as well as an ADS3000+ sampler (refer to WETTADS). Environmental interference from mobile phone networks and similar differences cancel out in that case.

It is worth mentioning the following notes on observations and reductions:

- The *retarded baseline effect* [Brouwer, 1985] is compensated. It reaches significant values even over baseline as short as those at Wettzell (in the range of 100 m).
- Only *group delays* are currently processed in the software. The analysis of *phase delays* sounds attractive due to the high precision. However, our experience so far indicates that system-internal effects still dominate the error budget so that a smaller standard deviation of the observables will not lead to an increased accuracy of the baseline components.
- *Delay rates* were initially processed in the software. Though this type of observation usually yields centimeter precision of the baseline components in the end, the residuals showed height fluctuations and were difficult to interpret. It was therefore decided to exclude delay rates from analysis, because the added value in terms of quality feedback to the VLBI engineers is not clear.

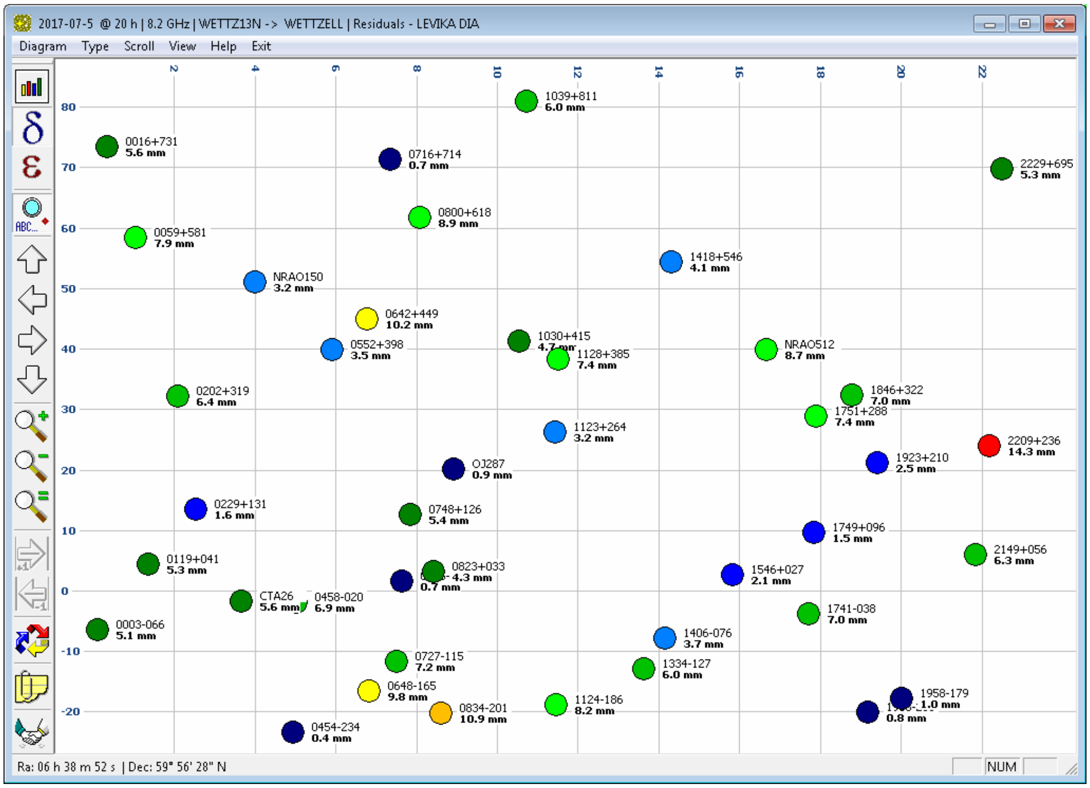

Fig. 2 Various graphical outputs are supported by LEVIKA SBA. This screenshot portrays the maximum residuals per radio source scanned (in metric units). The x-axis is the right ascension, the y-axis is the declination of the radio source. The data were derived from a local WHISP experiment lasting 24 hours. All sources scheduled are actually shown in the image.

- *Tropospheric propagation delays* are accounted for. The height difference between the reference points of Wz (RTW) and Wn (TWIN 1) is only 3.4 m. Approximately 8 m of height difference map into less than 3 mm of hydrostatic delay difference in zenith direction [Saastamoinen, 1972]. Though the hydrostatic delay effect is small, it is already at a magnitude to induce systematic errors. We can clearly see that the VLBI short baseline solutions deteriorate slightly with respect to the height when tropospheric corrections are disabled. Also note that the delay error at an elevation of 5° is ten times higher compared to zenith direction. In default mode, the total delay is compensated using a so-called “blind model”, i.e., tropospheric correction based on climatology, but properly accounting for height reduction. Either the WAAS-model [RTCA, 2009] can be used or the in-house model TropGrid2 [Schueler, 2014]. Though TropGrid2 is considerably more sophisticated in terms of parametrization and made of a database comprising nine years of numerical weather model data, we hardly observe any differences in the adjustment results.

Figure 2 illustrates the (maximum) residuals for a local 24-hour experiment in X-band. One and the same radio source is usually scanned several times during such a session. Only the maximum residual is displayed in this right ascension – declination view. Individual residuals can be shown in an azimuth-elevation view. Further graphical outputs comprise the outlier ratio, the statistical redundancy of each observation, the clock drift time series, and a histogram of the residuals.

3 Parameters

LEVIKA SBA can handle the following set of parameters:

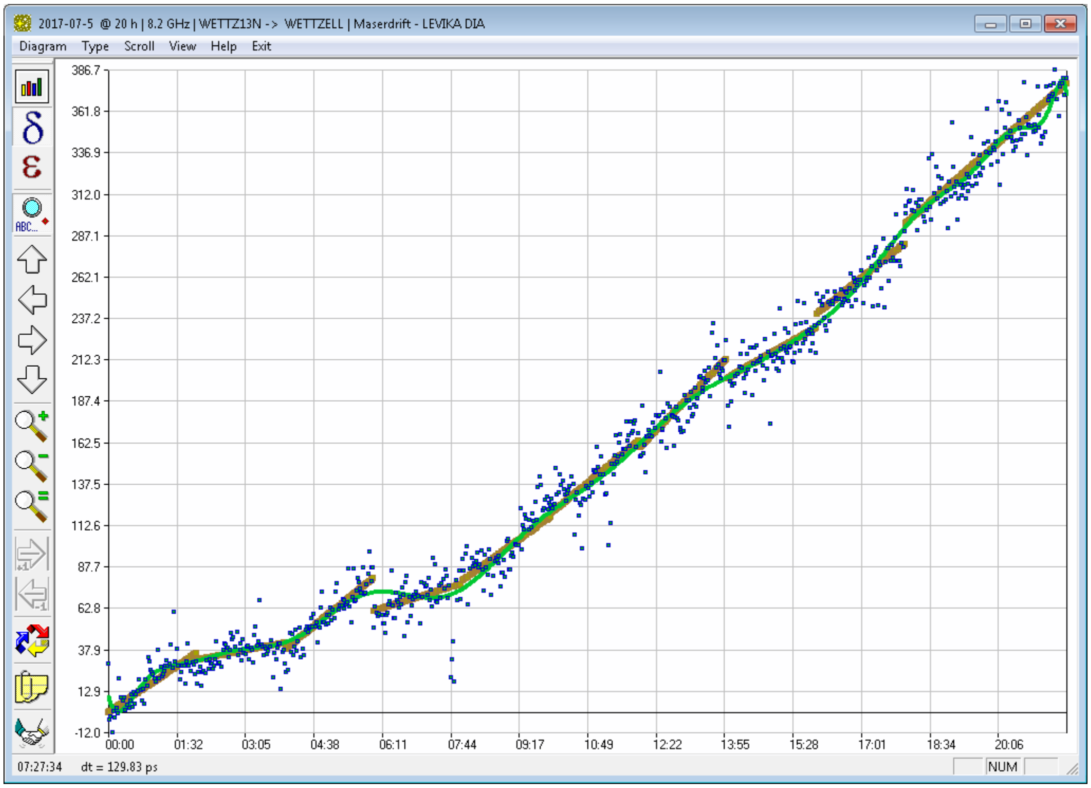

Fig. 3 Diagram of the master clock drift behavior. The software estimates piece-wise independent linear compensation functions shown in brownish color. The dots indicate the associated clock residuals of each scan. The green line is the result of smoothing (Chebychev polynomial).

- *Baseline vector*: Naturally speaking, the coordinate components are the primary set of unknowns we are interested in. However, it can also be justified to fix them in case quality assurance is of primary concern, since the terrestrial survey is very precise. In that case, the user can constrain the coordinates in the software (tight constraint = fixed as constants).
- *Zenith tropospheric delay*: Though applying a tropospheric correction model is sufficient in the vast majority of the cases, the software can estimate the zenith delay difference between both telescopes. The motivation to include this option stems from the fact that the tropospheric wet delay features a scale height of just 1.4 km compared to 8 km for the pressure (hydrostatic delay). Consequently, subtle variations of humidity between the two telescopes might result in noticeable delay errors. However, as mentioned just before, we have not yet observed session results yielding clearly significant tropospheric delay parameters. The tropospheric model compensation is always enabled, i.e., only a residual tropospheric delay difference will be estimated.
- *Clock drift*: Clock drift compensation is carried out using piece-wise linear functions. The resolution (time span) and the exact start of each independent linear function can be chosen by the user. The drift can be disabled for common clock experiments.

All other input data such as radio source locations, pole positions, and length-of-day information is injected as tight constraints into the analysis.

Figure 3 shows the clock error drift during a 24-hour session in units of picoseconds (x-axis is time in format hh:mm UTC). The hydrogen maser is apparently drifting over a bit less than 0.4 ns during that period. The clock error scatter is well within small bounds (though we wish to even reduce it further) and can be compensated by linear drift functions well in most cases (an exception can be seen around 06:11 UTC).

4 Clock Jumps and Outlier Handling

Initially, the software had no handling of clock jumps, because such events used to be extremely rare at Wettzell at that time (2014 to 2017). The situation worsened when we experimented with common clock modes so that an interactive as well as an automatic clock jump detection algorithm were implemented. Effectively, clock jump handling only requires to adapt the start times of the nearest clock drift compensation function properly.

Several outlier detection and handling methods are available. A minimum residual can be specified for X- and S-band observations separately. The outlier detector will only investigate residuals higher than this threshold. A conventional outlier detector based on à posteriori statistics is used [Pope, 1976]. This detector is implemented as an iterative algorithm rejecting the highest-probable outlier during each iteration. In addition, an “erazer” is usually activated. It deletes the residuals exceeding a pre-defined threshold. Though this type of outlier rejection should not be necessary in theory, we observed one session that essentially required such an additional step to yield good results in automatic processing mode, i.e., the outlier detector failed to identify one remaining unhealthy observation.

5 Results and Outlook

A number of local experiments have been performed at the local baseline Wn-Wz so far. The 3D distance compares well to the local precision survey and is at the sub-millimeter level on average. Further details can be found in [Schueler et al., 2016] and [Phogat et al., 2018]. However, note that deviations in height can accumulate to few millimeters.

Development of the LEVIKA short baseline analysis tool has been completed. A few outstanding points comprise the network combination module taking the temperature compensation into account.

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