Utilizing TWSTFT in a passive configuration

Carsten Rieck, Per Jarlemark, and Kenneth Jaldehag
Department of Measurement Technology,
SP Technical Research Institute of Sweden,
Borås, Sweden
E-mail: carsten.rieck@sp.se

BIOGRAPHY (IES)

Carsten Rieck was born in Eisenach, Germany in 1972. He received the M.Sc. degree in electrical engineering in 2000, and a degree of Licentiate of engineering in 2016, both from Chalmers University of Technology, Gothenburg, Sweden. He is currently with the time and frequency group of SP Technical Research Institute of Sweden, Borås, Sweden. His research interests are within time and frequency metrology using space geodetic methods, network time and generic PNT.

Dr. Per Jarlemark was born in Hjo, Sweden, in 1962. He received the M.Sc. degree in engineering physics from Uppsala University, Sweden, in 1986, and Ph.D. degree in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden, in 1997. His main interests are within space geodesy, and time and frequency metrology.

Dr. Kenneth Jaldehag was born in Partille, Sweden, in 1962. He received the M.Sc. and Ph.D. degrees in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden, in 1988 and 1995, respectively. His main interest is within time and frequency metrology.

ABSTRACT

In this paper we suggest the passive usage of Two Way Satellite Time and Frequency Transfer (TWSTFT). In a passive configuration a receiver observes, possibly multiple, codes sent by the active users of a TWSTFT-network. Common view observations of the same signals by a pair of observers can be used to compare their local clocks. Similar to GNSS, the users need to know their local coordinates and the orbit of the satellite in order to reduce the measurements by the geometry. As the orbit is usually poorly known, it is essential to establish an infrastructure that provides the users with satellite ephemerides and appropriated correction models.
In this initial study we use the ranging measurements performed by the active European network to TELSTAR 11N in order to estimate precise satellite positions. Residual ranges of the position estimates are well below 1 m. Based on the precise satellite positions and other regular TWSTFT measurements an extended Kepler description of the orbit is determined, which can be used to estimate ranges from the satellite to a passive user at arbitrary station positions and arbitrary epochs.
A passive use of TWSTFT will enable us to increase the number of measurements without increasing the noise level on the transponder. It will also reach out to a new group of users, both commercial and scientific, which will benefit from current and future developments of TWSTFT. NMIs will be able to offer an independent method for robust distribution of their national time scales.

INTRODUCTION

Two Way Satellite Time and Frequency Transfer **[**1**],** short TW hereafter, is an established time transfer method for both continental and inter-continental baselines, often used in conjunction with GNSS methods in order to mitigate diurnal variations in the measurements. Despite current performance problems, TW is the most accurate of the long distance methods used today and can be considered the backbone of international time keeping as it links about 58% of all the clock weight in TAI (MJD57599). However, only a few nations deploy the technique for national links.

TW, using Ku band frequencies, has a number of features for increased resiliency compared to GNSS. Most prominently are directive antennas, pointed at geostationary satellites usually at high enough elevation angles and with sufficient signal power levels, which make it difficult to locally disturb or spoof the signals to prevent proper time comparisons. However, the active nature of TW poses restrictions to its use. This prohibits for example the operation at installations that require radio silence, such as facilities for radio astronomy and space geodesy. Also, the typical active utilization in the European network is about 2% per bi-hour and link compared to about 40% of practically achievable common measurements during the same scheduled time period. This poor utilization is in principle a consequence of the limited number of receiving channels in a TW modem. In case of the commonly used SATRE modem [2], which offers one to three channels, usually only one is used in the currently agreed schedule. An observation schedule is a historically used tool to organize the operational activities of a network of TW stations. As the number of receiving channels is usually limited, the capacity of a schedule is limited as well. Figure 1 shows an example of the European/ North America network, which is almost fully populated, thus it is not allowing more stations to participate. In order to allow more stations to participate, a network simply needs to utilize several Rx channels and reorganize the schedule in an appropriated way.

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Figure 1 Bi-hourly TW schedule of the European/North American network as of January 2017. It is organized by the CCTF Working Group on Two-Way Satellite Time and Frequency Transfer (WGTWSTFT) [3]. The schedule utilizes a single Rx channel per station and schedules pairs of stations to observe each other’s codes. The measurements are organized in slots of 180 s with 60 s for preparation and 120 s for effective measurements. The current schedule allows for 18 slots, where one is always used for range measurements. The schedule is maintained by the chairman of the WGTWSTFT, as of 2017 Victor Zhang of NIST.

Yet, the performance of TW, as a pseudo noise code multiplexing technique, is limited by the number of concurrent transmitting stations sharing the same radio spectrum. Thus it is generally beneficial to keep the number of concurrent users low in order to maintain a certain level of *signal to noise ratio* that is needed to successfully perform measurements. It is thus only possible to apply time multiplexing in order to increase the number of TW links.

Today the largest problem with TWSTFT is the presence of *diurnal signatures*, which is a major obstacle for a real-time application of TW. The origin of these diurnals is not yet fully understood. Regular TWSTFT is an elegant and simple method that assumes a reciprocal signal path. Theoretical error sources, due to satellite motion (Sagnac) and the different up and down link carrier frequencies (ionosphere) amount to delay variations in the order of a few hundred picoseconds. Additional variations are due to instrumental phase jitter at the ground stations and in the satellite transponder, and delays caused by the environmental conditions in the ground stations, amounting to potential variations of another few hundred picoseconds. However, these theoretical error sources cannot fully explain the observed diurnals. It is suggested that code interference and individual variations between the receiving hardware of a TW link is a large contributing factor. Figure 2 shows an arbitrary example for a number of TW links to PTB. The visible diurnals are in the order of 500 ps RMS. They are in the long term neither constant in phase nor in amplitude, and they exhibit particular link based features [4] that significantly differ from a sinusoidal. This variability makes real-time predictions using TW difficult and causes uncertainties in the order of the diurnal amplitude. From the results of operational TW using the European/North American network it is clear that quite transponders are beneficial for the TW performance, thus a reduction of concurrent signals and the use of combinations of ‘good’ codes with minimal cross-correlation is preferred.

In summary: In order to improve TWSTFT we want to **a)** increase the number of potential users, and to **b)** increase the performance of the links by *decreasing the noise* and the *diurnals*. It is evident that the above mentioned individual measures are partly orthogonal in nature and will only solve either of the objectives. Thus a different approach is necessary.

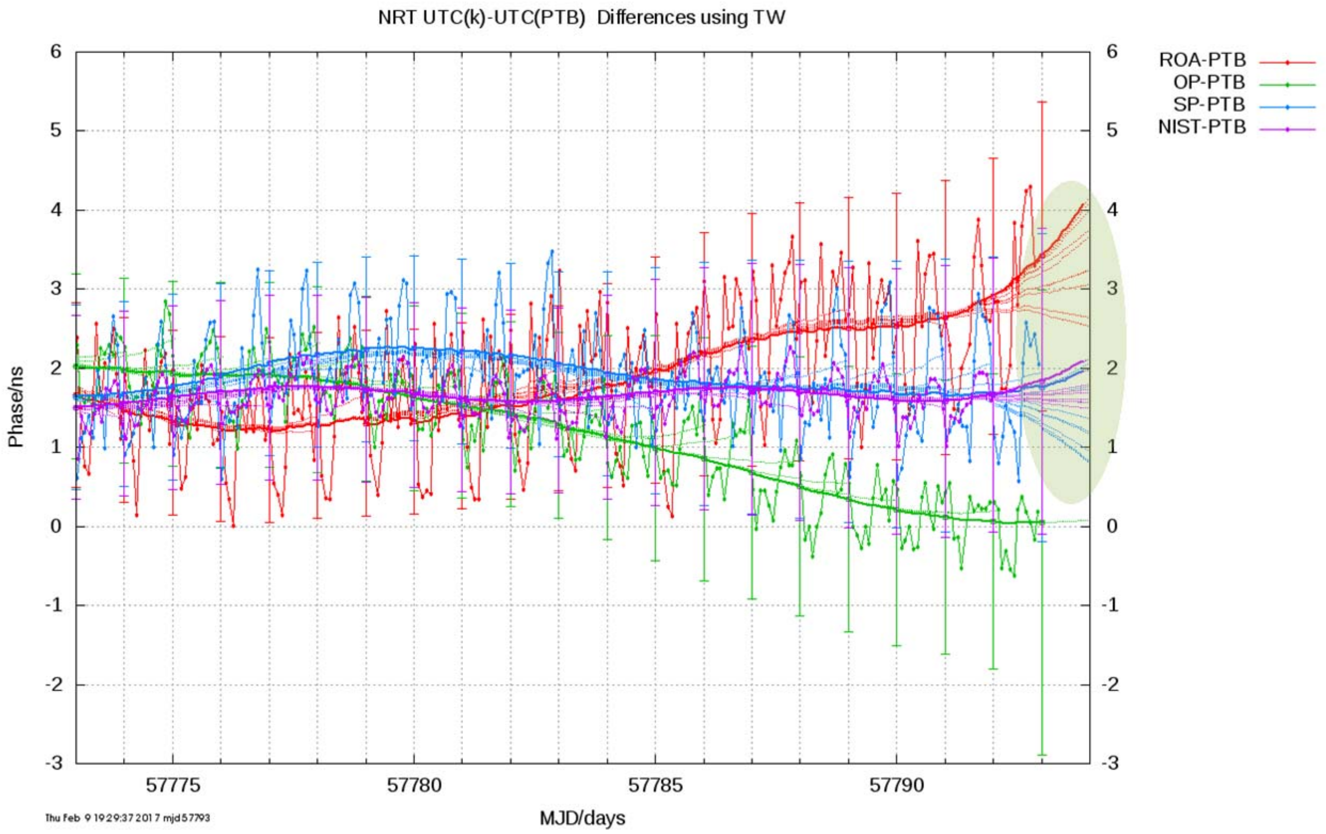

Figure 2 TW diurnal. Diurnal signatures in operational configurations are limiting the use of TW for real-time purposes. For the 1Mchip European/North American network via the Telstar 11N satellite, diurnals are in the order of about 500 ps RMS. The plot is an arbitrary example of the near real-time processing of the PTB-ROA-NIST-SP real-time network with UTC(k) differences to UTC(PTB). Point-lines are the ITU based TW differences from the files published at the BIPM [5]. Solid lines are the Kalman-filtered and smoothed estimates of the combination of ITU data and the one second data streamed by the SATRE modems at PTB, ROA, NIST and SP. OP is included in the plot for comparative purposes. Dotted lines are traces of estimates of previous runs of the link filter. The differences between the latest estimate and previous ones are an indication for the uncertainty in time scale difference predictions based on TW. The highlighted section shows bi-hourly diverting estimates and predictions of the time-scale differences for MJD57793 based on real-time data. [6]

In the following we suggest a common view method similar to GNSS, single frequency and single channel, common view using the signals transmitted by the active network and relayed by the geostationary satellite. The active network provides the measurements to determine the orbit of the satellite, which in turn is used by a pair of passive stations to reduce their own measurements of common observations in order to determine their time scale difference. The method has the potential to be usable by an unlimited number of users and may, if organized properly, reduce the diurnals and maximize the signal to noise ratio and the operational conditions. It may supplement the current metrological application of TWSTFT.

The method and results reported here are outcomes from work currently in progress. We already foresee future improvements.

METHOD

In the following, if not stated otherwise, examples refer to the European Network using Telstar 11N for TWSTFT.
Receive-only setups, as depicted in Figure 3, are an alternative to active TWSTFT. As the signal for passive users is generated by active stations, an active network is essential for a passive usage. The active network does not only supply the signals from space, but it is also used to determine the orbit of the satellite.

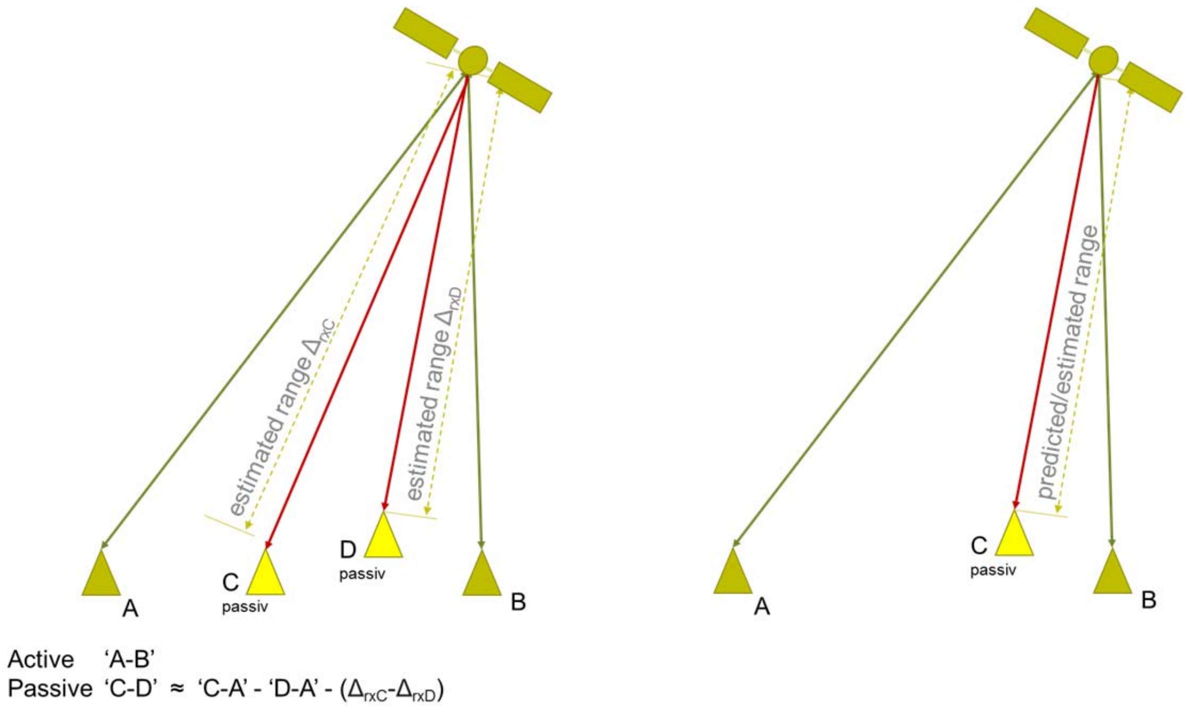

Figure 3 Typical passive configurations. A and B regularly engage in active TWSTFT, the stations are used to determine the orbit of satellite and are providing the signals used by the passive stations C and D.
Left: a purely passive setup. Both C and D observer the signals of either or both A and B and exchange their reading in order form common clock differences. By means of provided pseudo ranges C and D can relate their time scales.
Right: C observes the signals of either or both A and B and may relate its own reading to the time scales at A and B by means of the time information carried by the signals and provided pseudo ranges to the satellite.

The two variants of passive operation have their counterparts in typical GNSS applications, where the signals in space are used either as common clocks or as carrier of time information. The latter may be used for the purpose time dissemination, whereas the first may serve as method for metrological time comparisons between time scales. Common view is a convenient technique that cancels common mode errors for a pair of stations observing the same signal; this is especially beneficial for short baselines. However, a receive-only setup introduces a number of difficulties and unknowns that normally are reciprocal in TW:

1. Geometry
   a. Station positions
   b. Satellite position
   c. Tides
2. Atmospheric delays
   a. Neutral atmosphere
   b. Ionosphere
3. Instrumental delays
   a. Tx delay
   b. Rx delay
   c. Transponder delays

Figure 9 depicts the most important delays to be considered for the passive use of TW signals.

Geometry
Geostationary orbits are geometrically unfavorable for observers at high latitudes, such as in northern Europe. They are observed at relative low elevations, which has an impact on the induced atmospheric delays and corresponding signal attenuation. The measurements from a limited area used for orbit determination are correlated. For the unfavorable network setup depicted in Figure 4, the PDOP value is in the order of 500. However for a relative setup, such as the intended common view application of TW, the expected satellite positional errors are dominantly common mode for spatial interpolations, thus passive stations close to orbit defining stations will benefit. Extrapolations to places outside the area used to determine the orbit are generally problematic.

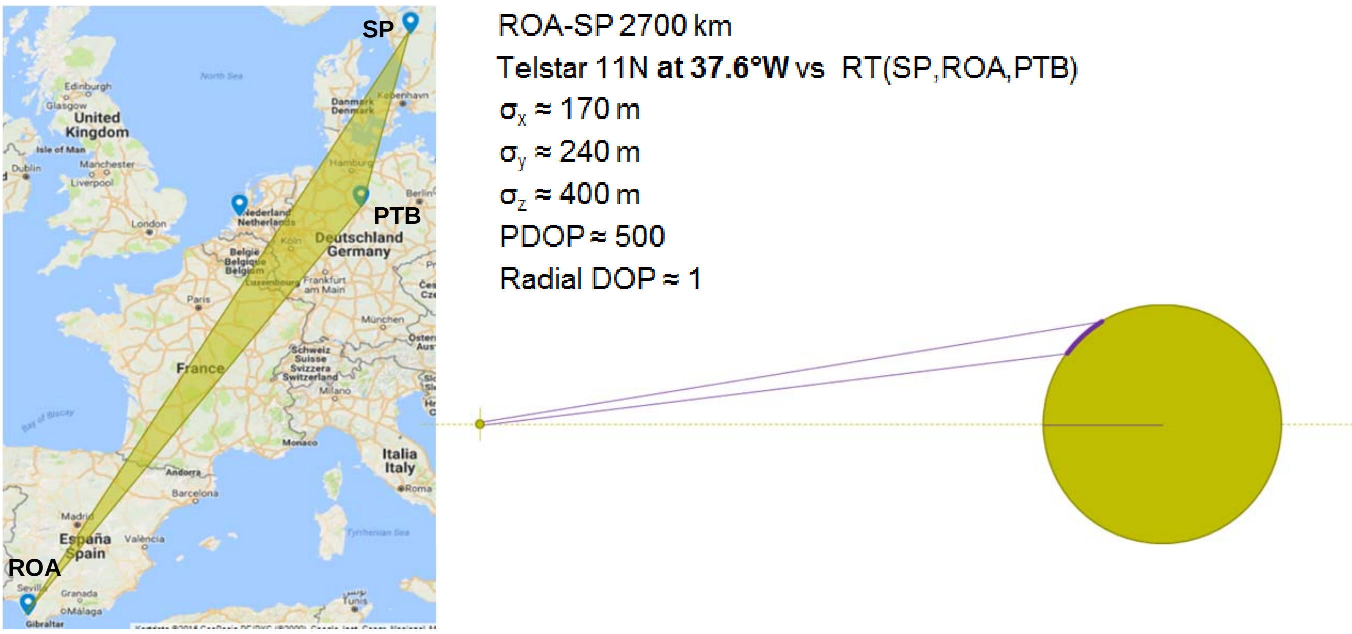

Figure 4 Example of the geostationary orbit of Telstar 11N roughly to scale with Earth and the area of the real-time observing stations in Europe. PDOP is in the order of 500. For ranging uncertainties in the order of 1 m, the z coordinate, as the largest error component, is uncertain in the order of 400 m. However, estimation of the radial component of the satellite position is good to about one meter. The pictured map is provided by [7].

In order to estimate the satellite position with respect to a reference coordinate system, the positions of the observing stations need to be known in that reference system. The current TW data exchange is based on the ITU-R recommendation TF.1153, which allows defining station positions and a reference frame, but has no means to quantify positional uncertainties. In practice, station positions are in general poorly defined as the intention is to aid the calculation of the Sagnac [8] corrections. Furthermore, there is no agreed convention on where the antenna reference point is defined. TW uses directional antennas, where the phase center of the antenna is dependent on the local azimuth and elevation of the satellite to be observed. Figure 5 tries to visualize the geometry of a typical antenna setup and Figure 6 shows the visual accuracy of some station positions as published at the BIPM [5]. Proper station positions are necessary in order to define a consistent coordinate system for orbit determination that can be used to intra- and extrapolate to arbitrary locations on Earth.

There are other minor effects that dynamically influence the station positions of the active network. Local tides may be significant for long baselines, especially if they have large longitude components. We consider a simple model for the solid Earth tides.

Atmospheric delays
Signal propagation through the Earth's atmosphere is influenced by dispersion and refraction. Ionospheric delays and their variability are relatively small due to the high Ku-band frequencies at about 14 GHz up-link and about 11 GHz down-link. The frequency differences between up- and downlink give typically rise to about 200 ps of differential delay and should be considered for the determination of the orbit. Figure 7 gives an example for the downlink ionospheric delay from Telstar 11N to the stations of the European network. It is evident, that for the common view difference, delay differences due to the ionosphere are negligible, but ranges used for orbit determination are clearly deteriorated.

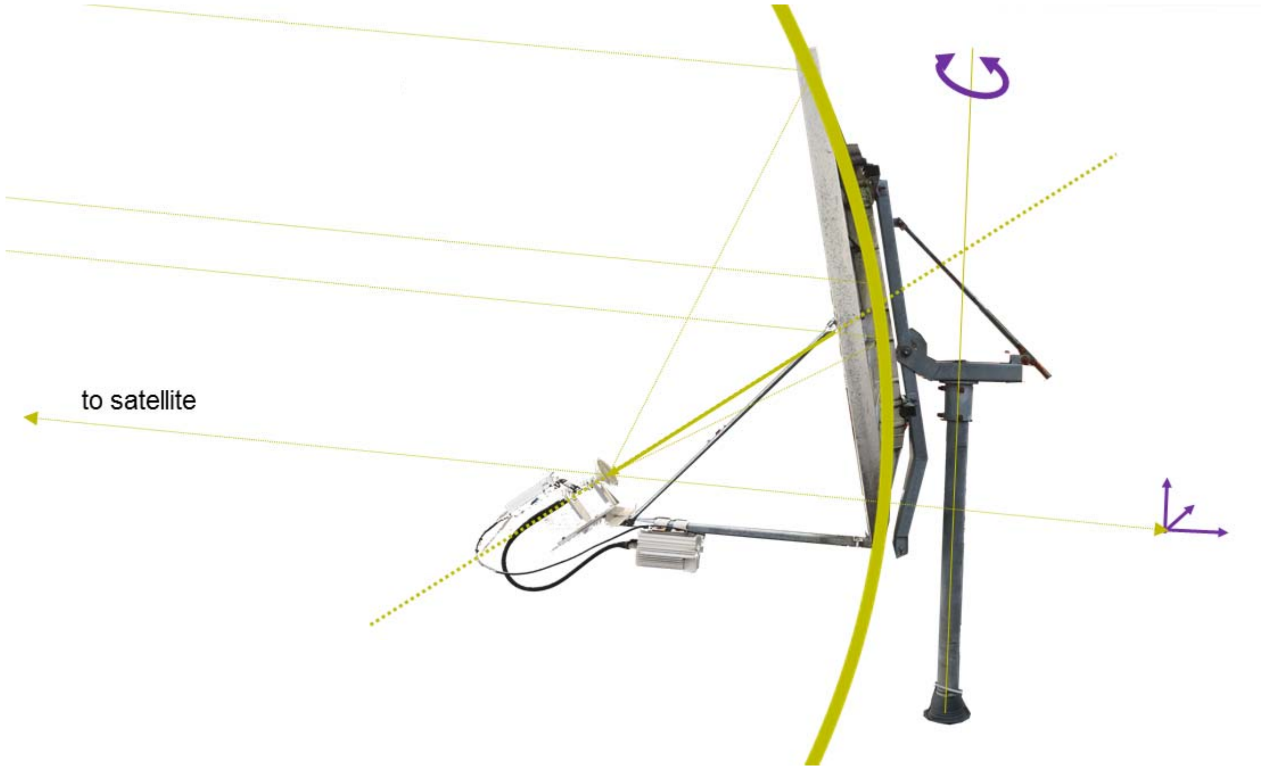

Figure 5 Prodelin 1184 1.8-meter offset dish at SP. The variable path of the signal is terminated at the antenna horn. Geometrically, this reference point is situated behind the antenna. In order to determine a universal antenna position, an accessible point on the rotational axis can be used. Coordinate transformations, depending on the antenna type and nominal satellite position, can be used to determine the antenna phase center for a particular setup. Accuracies within a few decimeters should be possible to achieve.

Figure 6 Visual accuracy of ITU reported station positions; green overlay roughly indicates the antenna. The pictured maps are provided by [7]

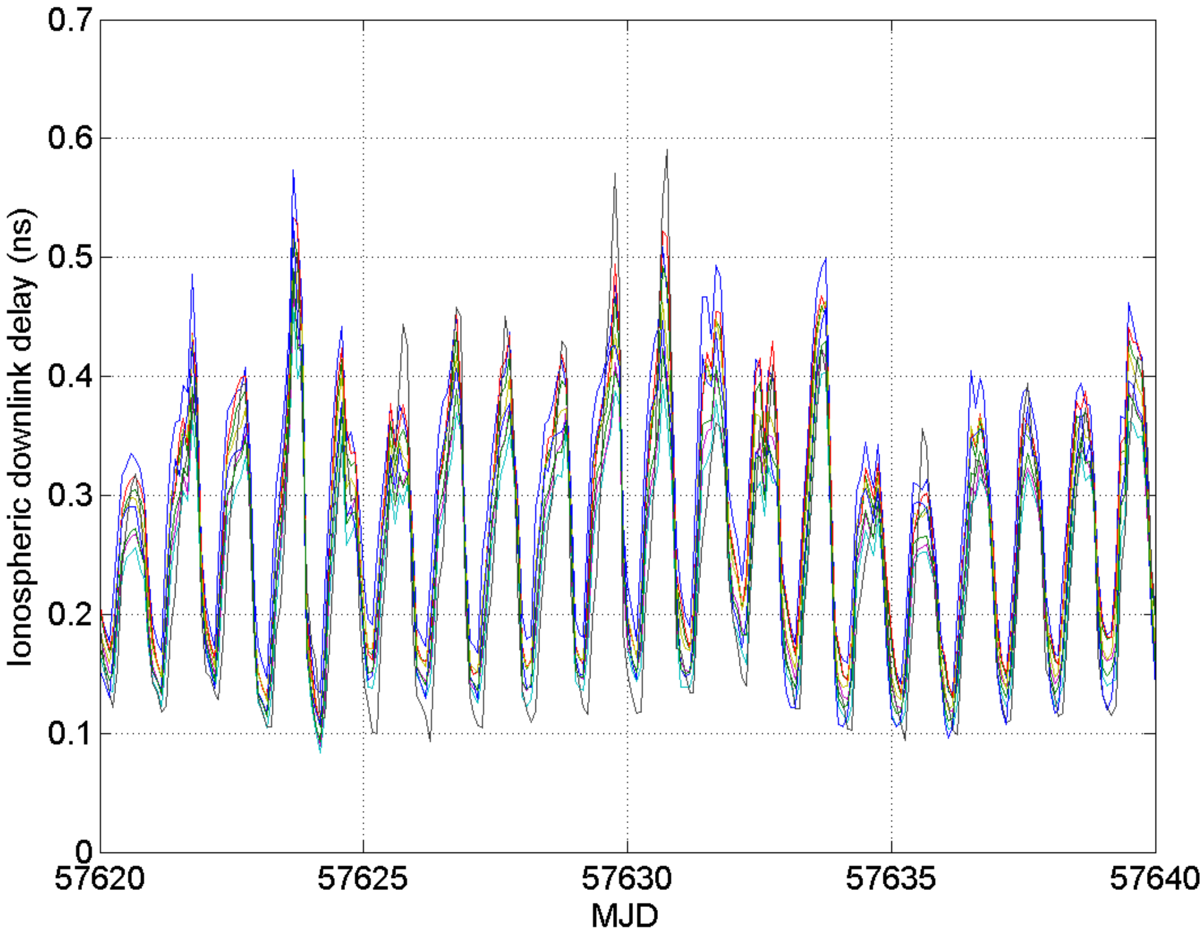

Figure 7 Example of the downlink ionospheric delays for the stations of the European network observing Telstart 11N during August/September 2016. Differential delays are in the order of tens of picoseconds. Data is derived using IGS TEC maps.

Delays due to the neutral atmosphere can partly be estimated by using ground based measurements. Slant hydrostatic delays amount to about 10 m for stations in northern Europe and exhibit a low variability. Wet-delays are generally one order smaller, but show a difficult to access variability that may annually amount to about 1 ns for typical stations in Europe. It is appropriate to use elevation mapped GNSS derived atmospheric delays of stations collocated with or in the vicinity of the TW stations.

Instrumental delays

A TW modem generates a pseudo noise sequence that has a fixed phase offset to some arbitrary reference time scale within the modem. This sequence is modulated onto the carrier frequency and by a chain of up-conversion and amplifiers sent to the satellite. The Tx delay is the group delay the coded signal experiences between its generation and the reference point at the antenna. Similarly, the received signal is after demodulation correlated with a local replica of the code sequence in question, which in turn has a constant and possibly different offset to the reference timescale internal to the modem. The Rx delay is thus the group delay experienced by the signal from antenna reference point to the timing of the local code replica.

Rx and Tx delays are often not separately known. In the TW case, its difference is part of the calibration value, published as CALR in the ITU files. A number of stations operate satellite simulators that can be used to determine and monitor the stability of Rx and Tx delays. For the sake of orbit determination, only the sum of Rx and Tx delays are of interest. In a passive setup the Rx delay is subject to a calibration.

Another delay of interest is the transponder group delay. According to [9] the transponder delay is dependent on the frequency offset from the transponder center frequency and can amount to several nanoseconds per MHz offset. As the Tx frequencies in operational TW are slightly offset from each other group delays can differ in the order of several 100 ps.

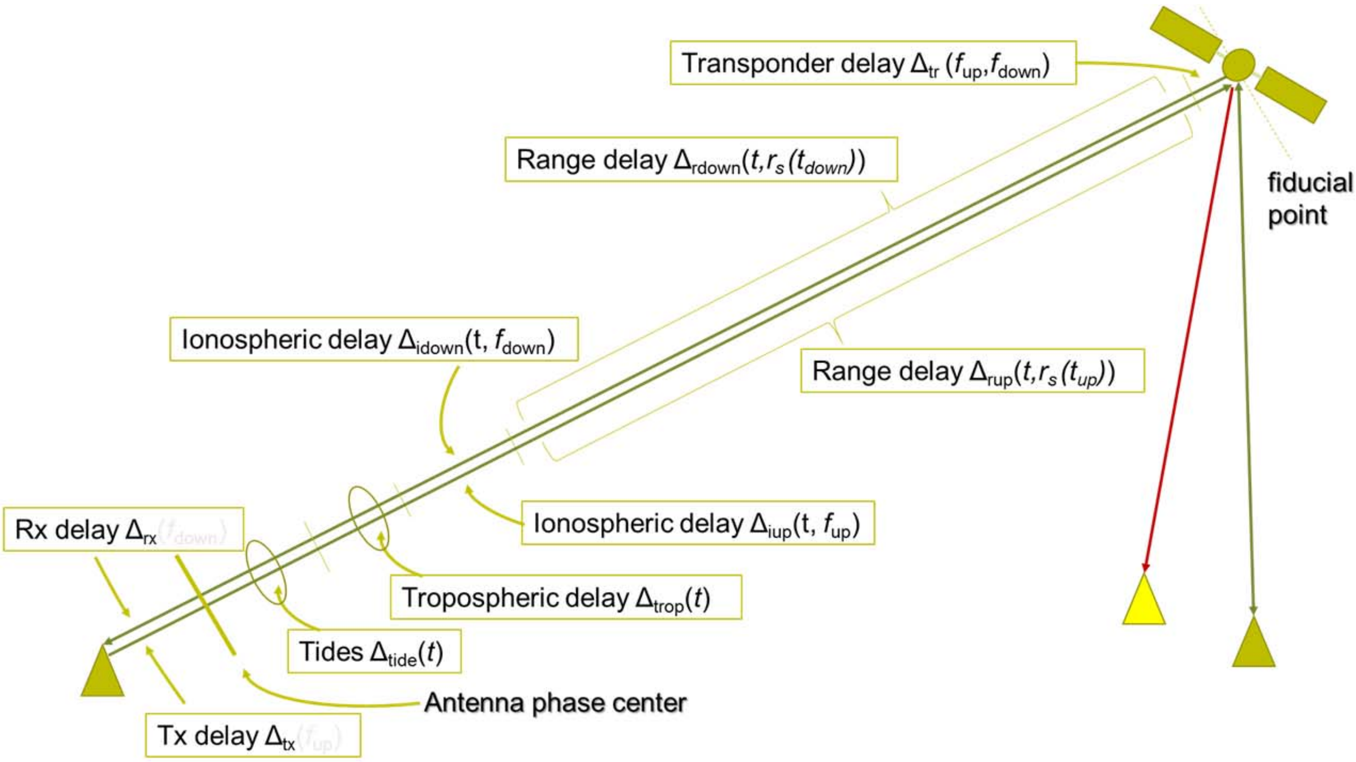

Figure 9 Delays in the propagation of TW signals. Range delays are dominant, followed by the instrumental Rx and Tx delays. Atmospheric delays are problematic due to their variability and need to be determined using other methods.

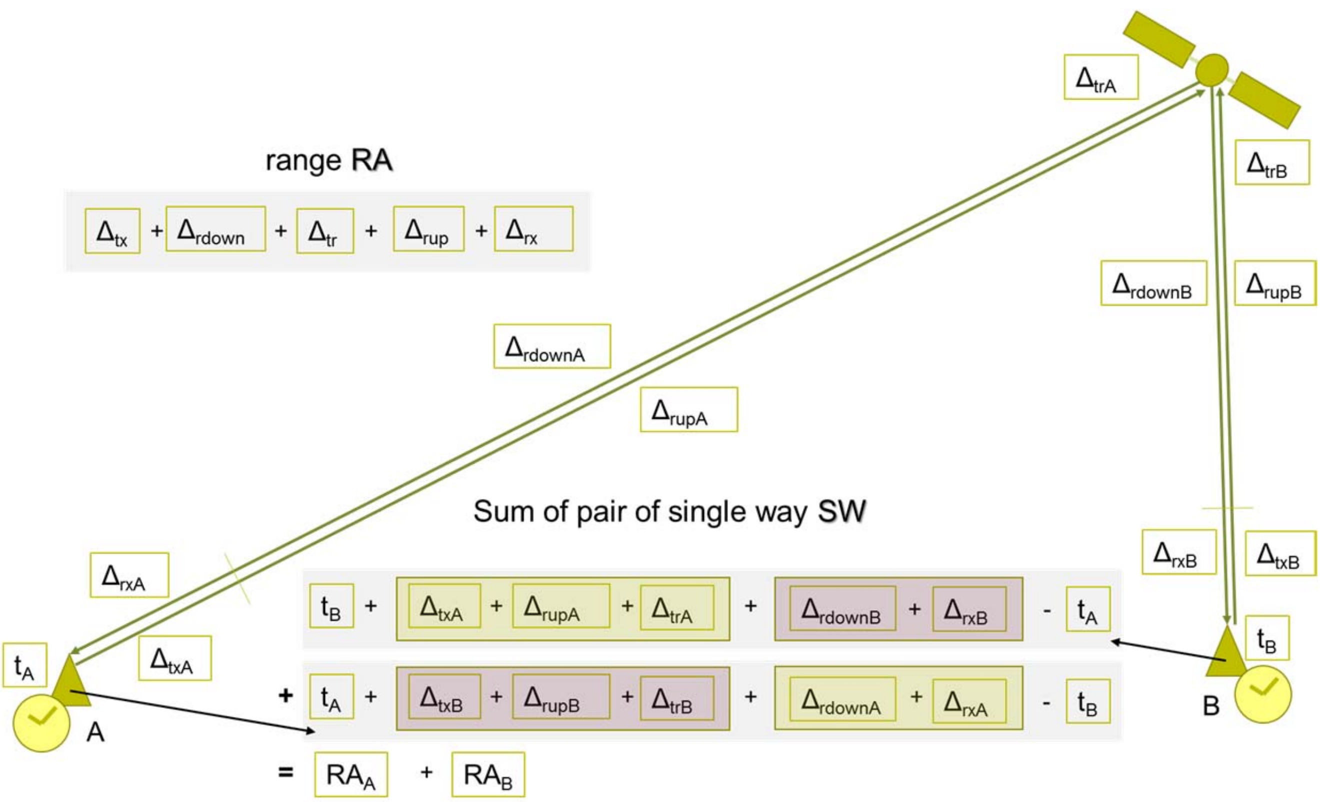

Figure 8 Observables used for orbit determination.

Ranging, **RA**, is the scheduled operation every station performs once during a session. It usually provides a health feedback to the station about its own transmitted signal, such as power levels, SNR and receive-frequency. Since ranging is done by all stations concurrently, it contains easily accessible information about the satellite orbit.

Single way measurements, **SW**, are used in the regular TW operation and are, in the scheduled form, always available in pairs. The sum of such concurrent measurements eliminates the influence of the local clocks and exposes the sum of the two involved ranges. These observables are abundant, but carry less information about the orbit than pure range measurements.

Orbit determination
Figure 8 depicts the two different observables that are considered for determining the orbit. All raw measurements are reduced with the estimates of the different atmospheric delays for up- and downlink and possibly the tidal variations of the ground station position. If the Rx and Tx delays are known, they should be removed from the raw measurements. If not, they are considered constant unknowns that need to be estimated together with the orbit of the satellite.

Ranging measurements are most straight forward and describe the distance to the satellite as observed by the station. It is intuitive to use them in order to determine the position of the satellite at the mean epoch of transmission and reception. The second observable to be used is based on the regular TW measurements. Instead of differencing, the summation of single way measurements removes the first order impact of the local clocks assuming approximately synchronized systems. Thus a sum includes two equivalent range measurements to the satellite, but has the disadvantage of less information than a single range measurement. In the example of the European network, ranging is done every second hour, whereas pairwise single way measurements are scheduled about 18 times during the same time interval.

It worth noting that due to the skewed geometry between the satellite and the TW stations, ranging is not concurrently performed. As an example, in Europe the common clock differences of fairly synchronized ground stations differ in the millisecond range, ROA-SP about 8 ms and PTB-SP 1.5 ms. The satellite's velocity relative to the reference frame is in the order of meters per second, thus errors due to the geometry of the observing network are at most on the cm level for the European network. For larger baselines with asymmetric geometry to satellite the lack of concurrency may be of importance.

The suggested method for orbit determination is done in two steps:

1. Determination of precise satellite positions $p_s(t)$ using range measurements $r_i(t)$ from a number of ground stations i
    - 9 ground stations (VSL, SP, ROA, PTB, OP, NPL, IT, CH, AOS) concurrently measured every second hour,
    - known Rx+Tx delay at 3 stations (VSL, CH, SP).
2. Determination of an interpolating orbit description with help of GPS style Kepler orbits with 15 parameters using $p_s(t)$ for a limited number of epochs that is supported by the
    - assimilation of the sums of pairs of single way measurements used for regular TW, and
    - assimilation of additional ranging measurements (ROA,SP).

Both steps are iteratively calculated using a least squares method. The timing of the observations is depicted in Figure 10.

Precise satellite positions
We describe

$$\Delta\bar{r} = \mathbf{A}\Delta\bar{p}$$

where **A** defines a design matrix that describes the relation of the range measurements in $\bar{r}$ to the satellite positions and unknown site dependent Rx+Tx delays in $\bar{p}$. The elements of **A** are mainly the partial derivatives of the range measurements and the positional vector to the satellite in the form of $\partial|\bar{r}|/\partial p_j$, with j the being x, y or z components of the orbital position. The iteration starts with the nominal position of the satellite with zero inclination. In order to estimate to constant Rx+Tx delays a time series of range measurements needs include a large portion of the daily satellite motion. Due to the noise in the measurements it is difficult to distinguish between the constant Rx+Tx delays and the positional errors of the ground stations. As a result of the errors in the station coordinates, the realized coordinate system will differ from ITRF. This is for instance visible in the mean p_z component of satellite position, which describes the apparent motion about the equatorial plane and should nominally be zero.

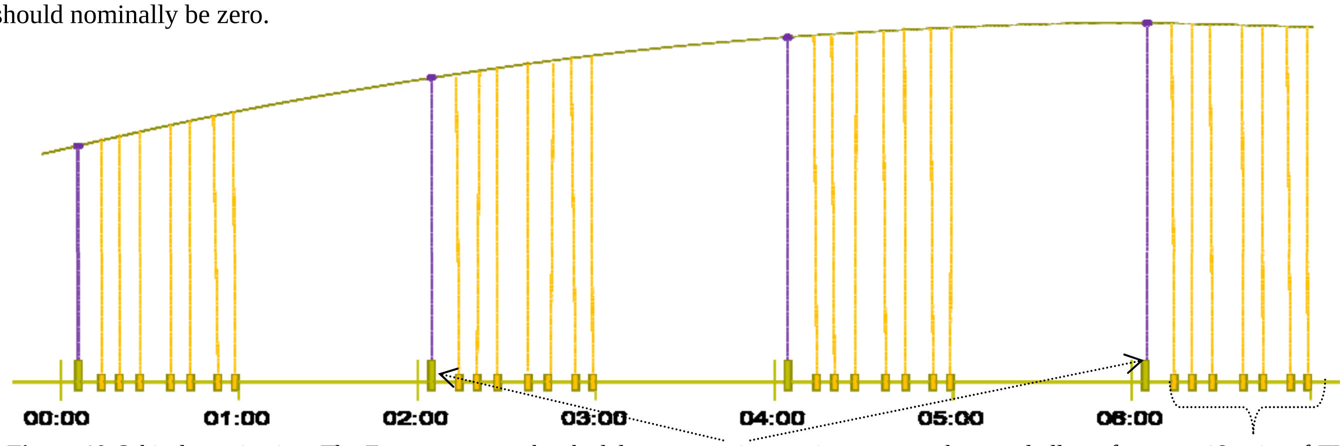

Figure 10 Orbit determination. The European network schedules one ranging session per even hour and allows for up to 18 pairs of TW measurements. Regular ranging measurements are used to determine precise orbit positions at the ranging epochs. Pairs of single way measurements support the determination of GPS style Kepler parameters using the precise satellite positions at fixed ranging epochs.

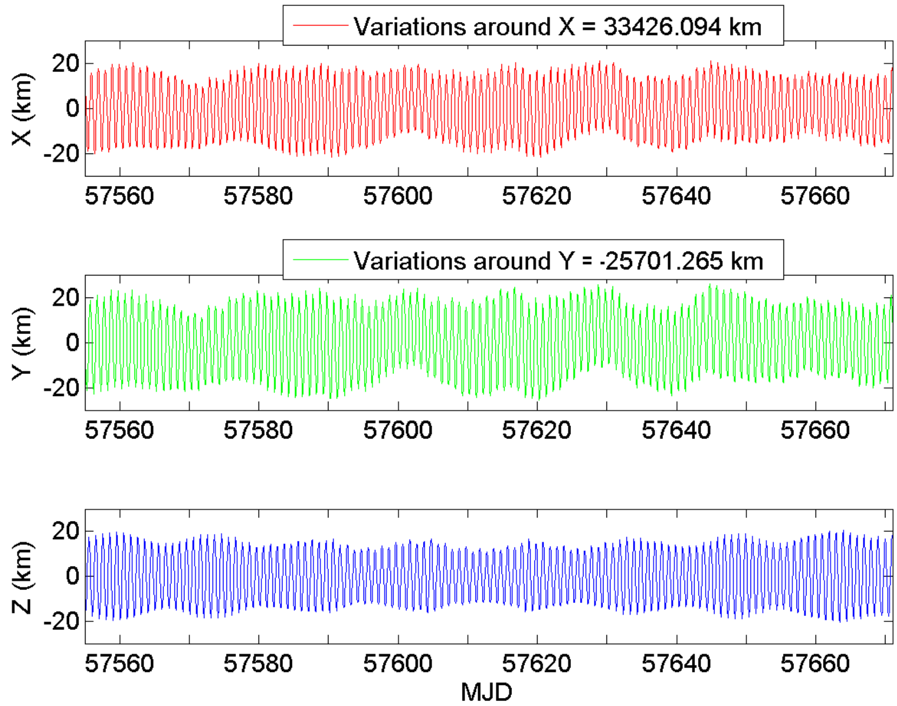

Figure 11 Precise orbit positions of Telstar 11N as estimates from the bi-hourly range measurements of nine stations of the European TW network. Typical apparent daily motion in the ITRF is in the order of 10 km for each of the components.

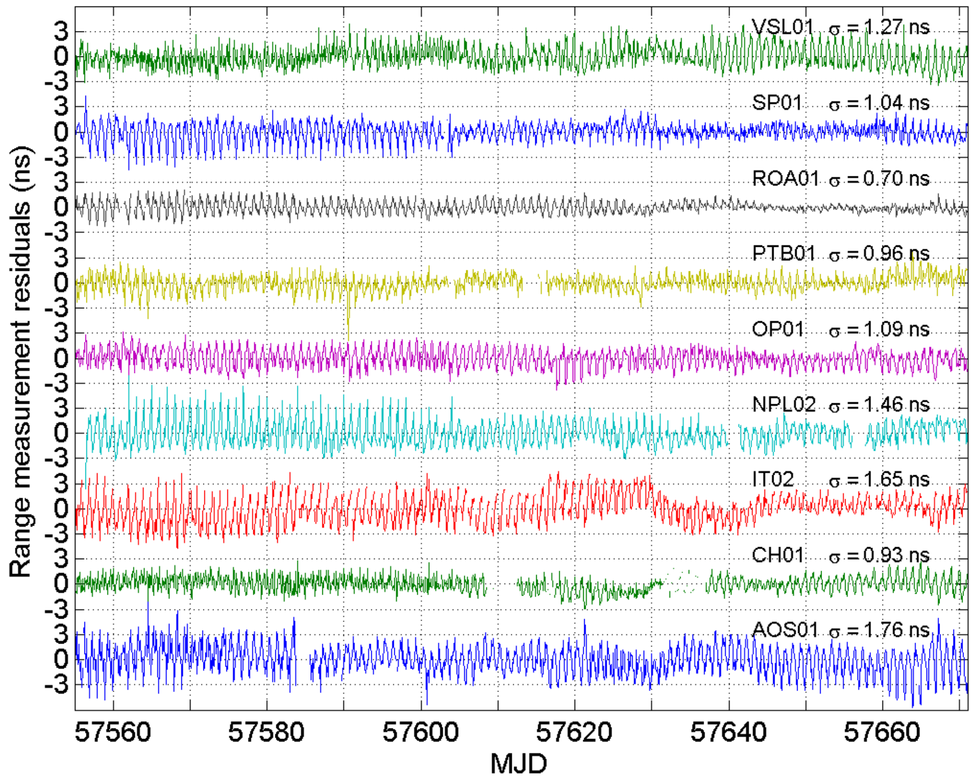

Figure 12 Residuals of the precise orbit positions. For the experimental period between MJD57555 and MJD 75672, the estimated satellite positions are consistent with range measurements. Typical RMS of the range residuals are in the order of about 1 ns, the residuals show characteristic diurnals.

The typical number of iterations is 3.

Figure 11and Figure 12 show the results of the precise satellite position determination using range data measured between MJD57555 and MJD 75672. Typical residual deviations are in the order of one nanosecond. The residuals show characteristic diurnals, which are mostly site dependent. Figure 13 shows the mean site diurnals per day. Some of these, such PTB and OP, are completely out of phase and will remain in a passive common clock difference. Since ranging data is almost always measured under similar conditions, such as power and number of concurrent signals in space, it is possible that it is caused by instrumental changes due to the local environment. Other causes are not excluded here; these site separated signatures are an interesting tool and should be more systematically studied for longer time series.

The choice of the network of stations used for the determination of the satellite orbit is important for the time transfer performance of a passive station. The errors in the station positions and the inability to distinguish them from Rx+Tx delays make spatial extrapolations difficult. Figure 14 and Figure 15 show examples of such situations.

Interpolating orbit description

In the example of the European network precise satellite positions are available every two hours. A passive station would like to make continuous measurements and thus needs to be provided with range estimates for every epoch of passive measurements. An interpolating function, such as a Kepler description of the satellite orbit, is needed. From experience a six parameter Kepler is insufficient for the time intervals and accuracy of interest. A 15 parameter set, identical to those published within the GPS ephemerides [10] is a good compromise.

Similar to the estimation of precise satellite positions, an iterative least-squares setup is used. A set of 3 to 4 successive precise orbit positions are the base input. Referring to the illustration in Figure 10, the sum of pairs of single way measurements and possibly other range measurements are used to aid the Kepler parameter estimating:

$$\begin{bmatrix}\Delta\bar{p}\\ \Delta\bar{r}\end{bmatrix} = \mathbf{A}\Delta\bar{k}$$

where $\mathbf{A}$ is the design matrix, defining the coupling between the Kepler parameter set $\bar{k}$ and the precise satellite positions $\bar{p}$ and additional range information $\bar{r}$. The elements of $\mathbf{A}$ are partial derivatives, which are not given here, but can be derived using the relation of the extended Kepler parameters to an Earth centered Earth fixed XYZ coordinate system, like the ITRS.

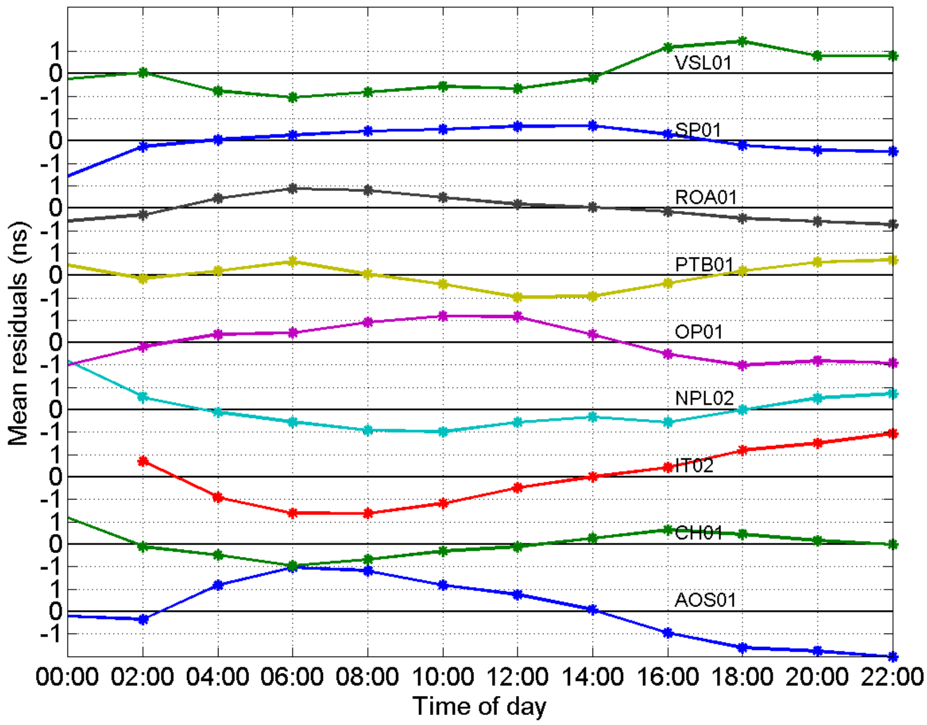

Figure 13 Residual diurnal signatures. The mean of the superposition of the residuals of Figure 12 reveals a site based signature of the ranging signals. The estimated satellite position should absorb any common mode errors, making site based behavior visible.

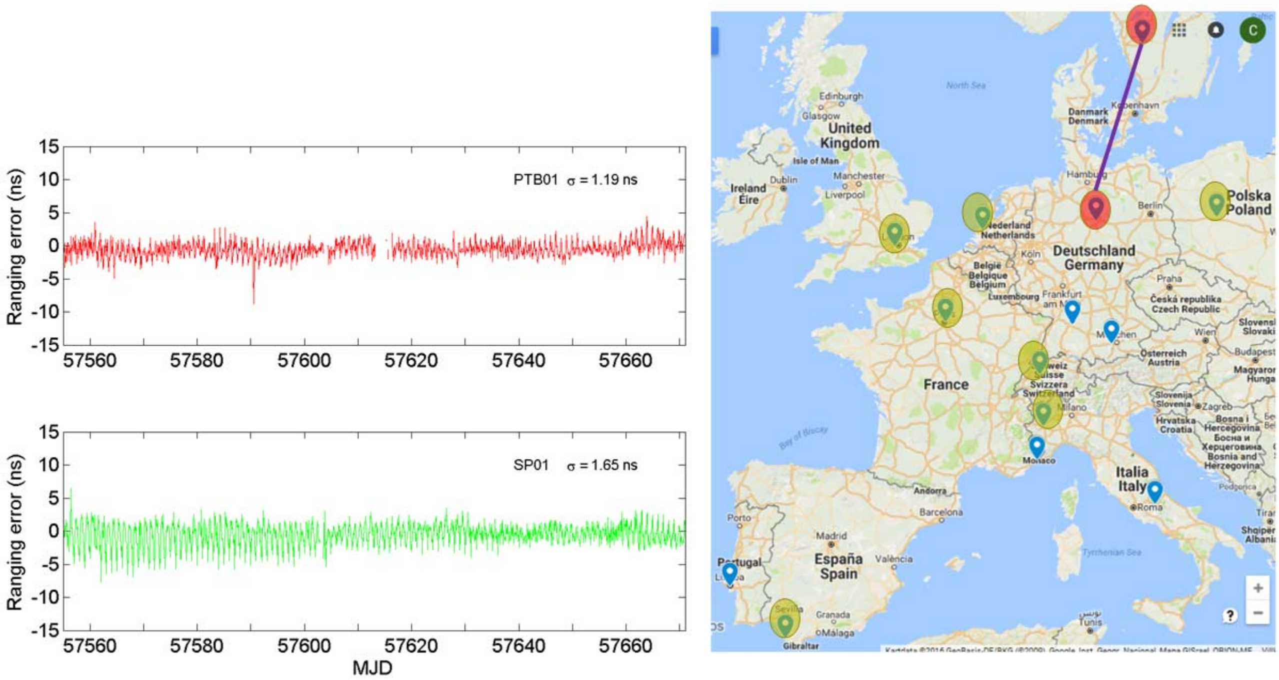

Figure 15 Network sensitivity. The exclusion of range data from PTB and SP in the estimation of the precise orbits, results in little deterioration relative to measured ranges at PTB (0.96 ns versus 1.19 ns), slightly larger in the case of SP (1.04 ns versus 1.65 ns). For PTB the network is still including the station well. SP is also reasonably covered due to the influence of ROA in the solution. The pictured map is provided by [7].

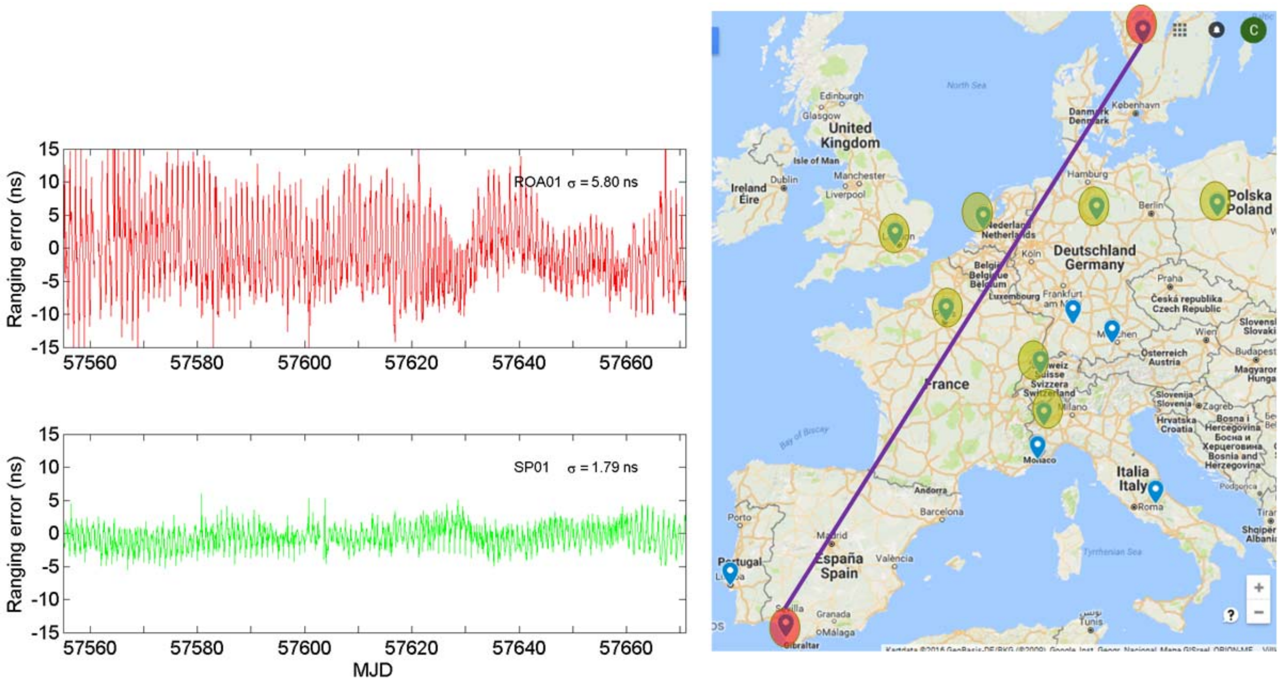

Figure 14 Network sensitivity. The exclusion of range data from ROA and SP in the estimation of the precise orbits, results in a large deterioration of ranges to ROA (0.7 ns versus 5.8 ns), whereas in the case of SP the estimated range error is still acceptable (1.04 ns versus 1.79 ns). For ROA the network is insufficient. The pictured map is provided by [7].

The iteration starts with a simple Kepler parameter set derived from 24 hours of precise satellite positions. In order to fit 15 parameters, data has to be typically iterated 7 times.

Even if the precise satellite positions are of good quality, they are not always usable to describe a Keplerian orbit. There are a number of different forces, such as deviations in the Earth gravitational field, gravitational forces of Sun and Moon, solar radiation pressure, to name a few, that make the satellite change its orbit. The satellite operator has the task to keep the orbit of the geostationary satellite within an allocated angular slot. For this the satellite orbit is regularly corrected, a maneuver that the user is normally not informed about. However, from the evaluation of the interpolating Kepler orbit it is clear that these events happen, and that they have to be detected. Station keeping accelerates the satellite and invalidates the current orbit description. In a post processing scenario it is relatively easy to identify the station keeping events and to define a valid orbit description for most of the epochs the satellite is observed. For a real-time processing, a station keeping event creates a dead-time where the network needs to gather enough information in order to be able to fit a new set of Kepler parameters. Figure 16 below shows the displacement detected by the evaluation of the Kepler orbits using the first ranging measurement after the set that is used for orbit determination. It clearly shows large movements of the satellite.

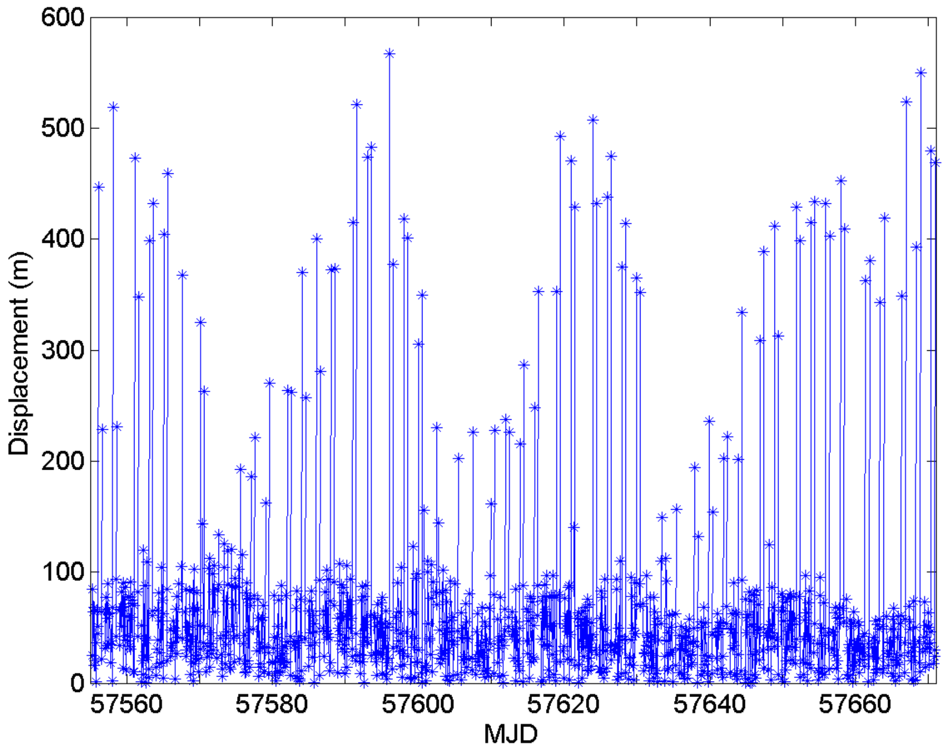

Figure 16 Station keeping events. The plot shows the estimated displacement of the satellite as the difference of a range estimate using an interpolating Kepler description and a range measurement. It is often visible that station keeping is done in pairs of events about 12 hours apart. The frequency of station keeping is sidereal.

PASSIVE TIME TRANSFER RESULTS

In order to be able to form common clock differences, a pair of passive stations has to observe the same signal. The current European schedule does not offer any such observations; the schedule instead maximizes the number pairs of TW links. For testing the passive method, SP01, with SATRE modem number 262, is using its second channel to concurrently lock onto the same signals as PTB01. In that way, SP01 is able to perform regular active TW and evaluate the passive method on a typical baseline. For simplicity it is assumed that the inter-channel bias between the two receive channels is known and constant.
For the time period of MJD57560 to MJD 75670, orbits were determined and sampled every 30 seconds matching the typical downlink epochs recorded in the ITU files. All the common clock differences between PTB and SP were recorded using the real-time streaming of PTB and SP. This data was then sampled according to the ITU recommendation and timing of the operational schedule. In order to compare active and passive measurements that are not performed at the same time, the active measurements were continuously Kalman filtered and smoothed resulting in the most likely time series of the phase offset between UTC(PTB) and UTC(SP). The differences to the active and passive measurements are presented in Figure 17.

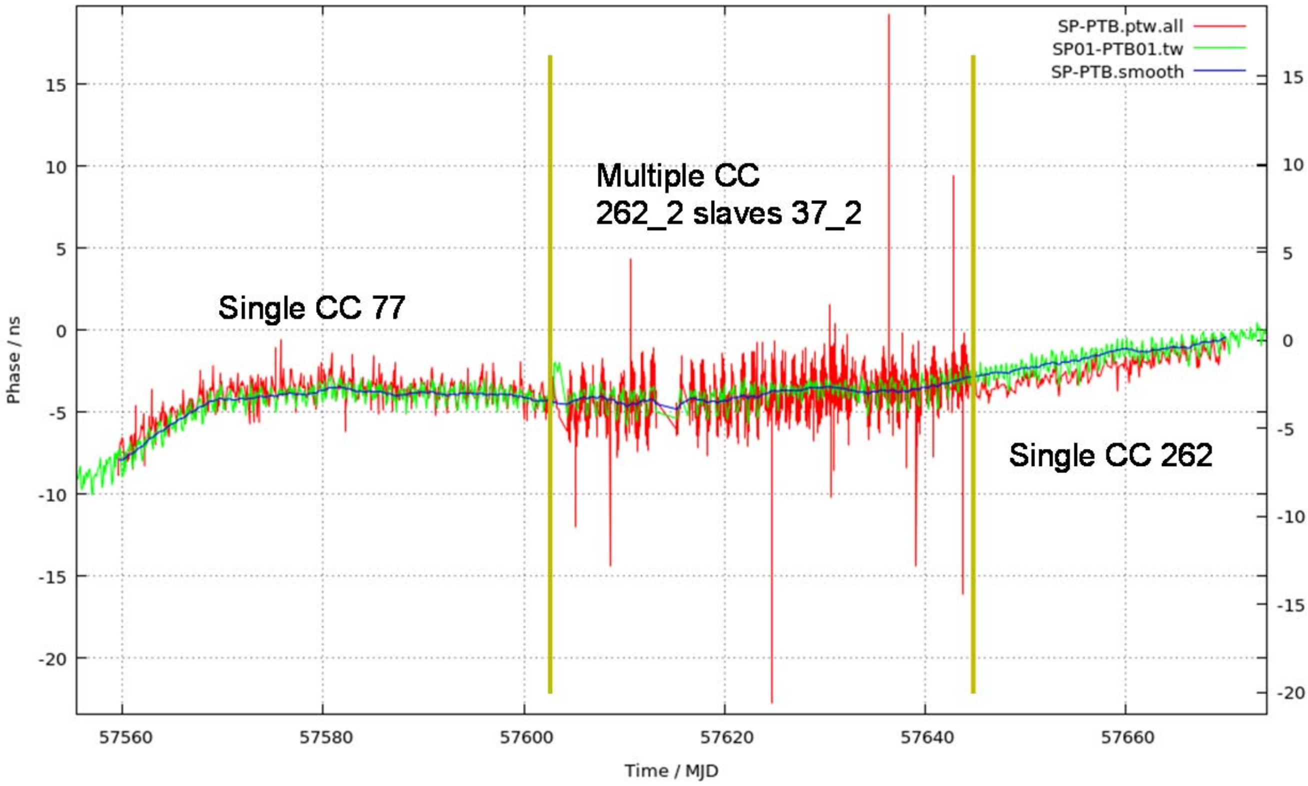

Figure 17 Passive time transfer results. Blue is the continuously Kalman filtered and smoothed time series of the active TW link between SP and PTB as depicted in green, which uses the main receive channel of SP01. In red, with an arbitrary offset removed, the passive time transfer using the second channel of SP01 during three distinct periods. To the left the common view results to a single code, modem 77 OP, are shown. In the middle, all achievable common measurements are used, and the right part illustrates common clock measurements with SP01.

Three different cases are depicted, common view with a single alien code, all possible common view observations, and common view with a code of one of the stations. As seen in the plot, not all station keeping events are properly detected; this creates outliers in the passive time transfer. Figure 19 shows a detail of the single code section, with similar results as the active TW. Diurnals are not suppressed; the STD of the difference to the reference time series is slightly larger, 700 ps versus 500 ps for the active TW results.
Time transfer with multiple signals is shown Figure 18. Here the time scale difference is differentiated with the reference time series and plotted with offsets for the different codes that were observed. It shows code dependent mean offsets, disagreeing with more than one nanosecond.

SUMMARY AND OUTLOOK

In this paper we have shown how to utilize the measurements of an active TWSTFT network for determination of the orbit of the used satellite, which in turn can be used to facilitate passive measurement in, for instance, common view for time and frequency transfer. The performance of passive measurements is comparable to those of active measurements. We suggest the use of the passive method to supplement the current active measurement schedule for the reduction of noise and possibility to offer TWSTFT to an extended community of new users.

During the work with orbit determination and interpolation we have seen the need for further studies of TW diurnals and their causes. We will follow up this work with several improvements of the method, such as a single step estimation of the extended Kepler orbits and the real-time capable station-keeping-detection and orbit recovery [12,13]. We also plan to offer an ephemerides service to the TW community. One important issue, not addressed in this work, is the question of calibration of passive system. For a metrological use, calibration is a necessity and thus the impact of station positions of the orbit defining network and the stability of local Rx/Tx delays has to be analyzed. In the long term we plan to design a passive ground station using SDR technology. It will be part of a resilient, GNSS complementing, national time distribution of UTC(SP).

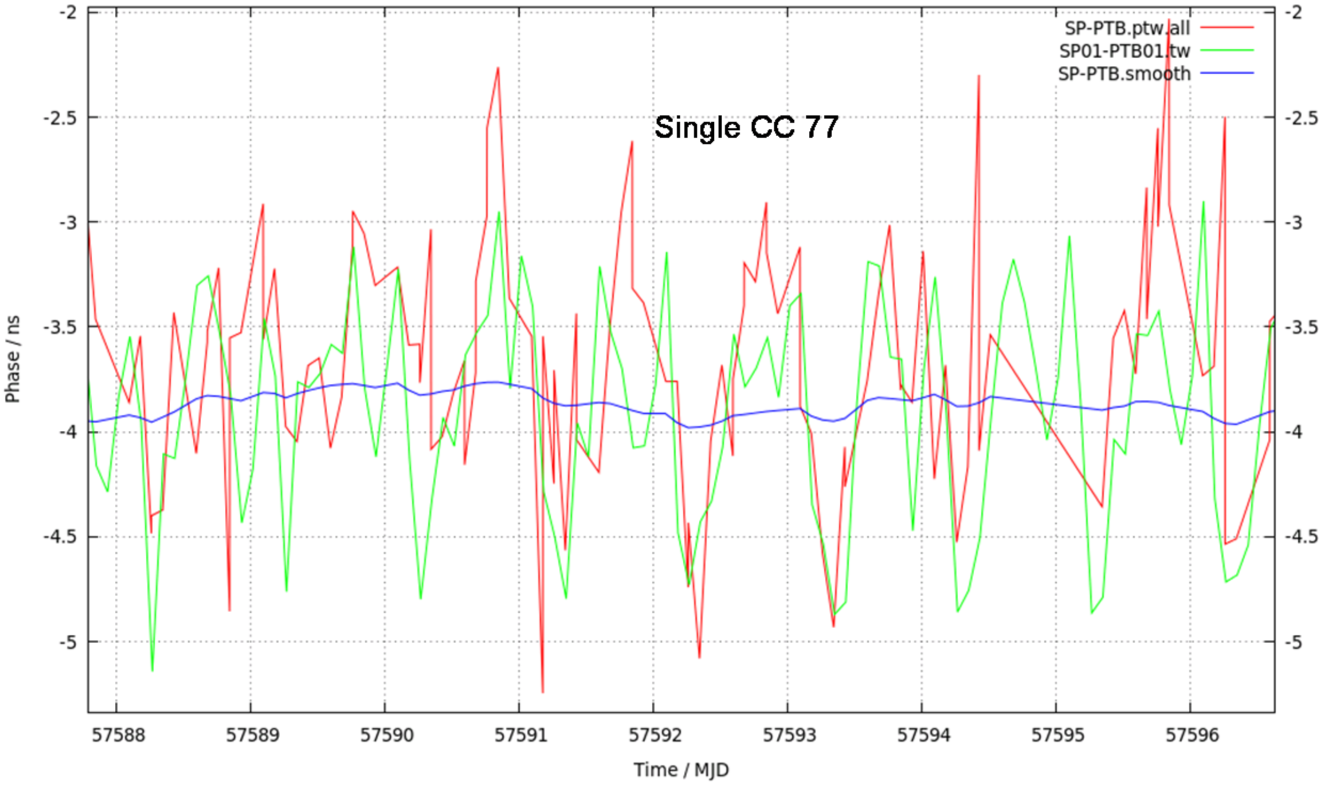

Figure 19 Common view using a single remote code. The passive time transfer results are comparable with the active TW results. Both follow a similar diurnal signature. Active TW has a STD from its filter value of about 500 ps, the passive versions is slightly more variable with a STD of about 700 ps.

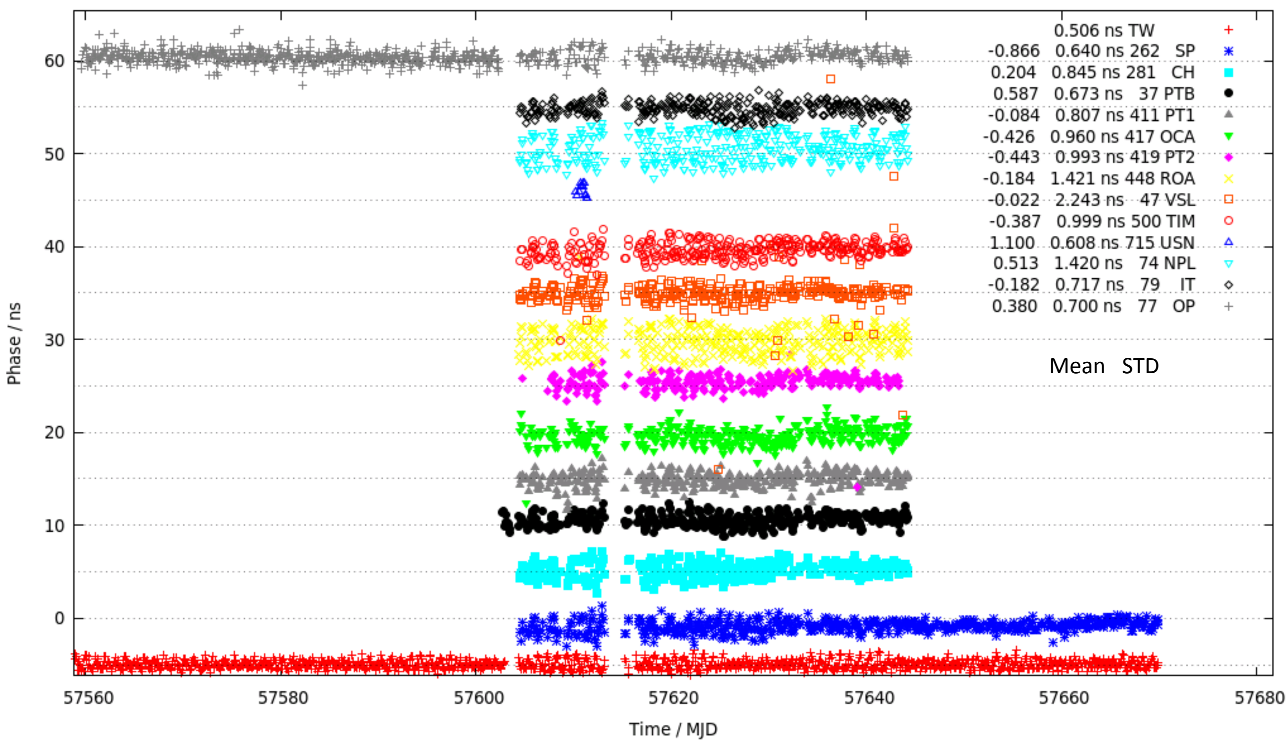

Figure 18 Passive time transfer using different codes, sequentially observed. The plot shows the difference to the filtered reference time series derived from active TW. For visibility the residuals of the time transfer using different signal sources are offset from each other with 5 ns. There are significant code dependent differences between the sources, the maximum mean differences are about one nanosecond.

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