Fiber Optic Time Transfer from UTC(k) to a VLBI Antenna in a Coherent Communication Network

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***Summary*—The local time scale at Onsala Space Observatory is connected to UTC(SP) through a White Rabbit time transfer system operating on the Swedish University Computer Network SUNET. The time transfer enables a robust synchronization of the VLBI and the IGS stations operating at the observatory and can potentially improve the reliability and availability of traceable time at sufficient accuracy. Several months of data are gathered to evaluate long term events and stability metrics.**

Keywords—White rabbit, fiber, WDM, time dissemination, synchronization,

I. Introduction

Several efforts have been made to connect European NMIs, operating UTC(k) realizations, through optical fibers, and the recent results comparing optical clocks are impressive [1]. It is however identified that it is also of significant importance to establish fiber-based time and frequency dissemination to non-metrology organizations such as academic institutions and space observatories. With the short distance and well-established collaboration between RISE Research Institutes of Sweden and Onsala Space Observatory, (OSO), the development of present GNSS-Common View (GNSS-CV) time transfer to fiber-based solutions is apparent.

Both RISE and OSO are connected to the Swedish university computer network, SUNET, which is a dense wavelength division multiplexed (DWDM) network with add-and-drop-off wavelengths in the connection nodes of the users, and standard amplifiers in between. The communication utilizes coherent techniques and offers capacity up to 100 Gbps at each single wavelength channel, prepared for 400 Gbps on a single wavelength if needed. Previous studies have evaluated the performance of proprietary time transfer systems [2] with excellent results. Here we show the performance of time transfer on the same network and distance, using standardized White Rabbit components. The benefit of an open standard and competitive product is evaluated with respect to performance.

This work was supported by the TiFOON 18SIB06 Project through the EMPIR Programme co-financed by the Participating States and through the European Union's Horizon 2020 Research and Innovation Program.

II. Background

SUNET is an all-optical DWDM fiber optic network designed for coherent transmission at 100 Gbit/s and 400 Gbit/s on each single wavelength channel. It covers all the university cities from Ystad in the south to Kiruna in the North, a distance exceeding 1500 km in a straight line. For the White Rabbit (WR) link to be connected via SUNET, the project is assigned a wavelength and a power level that must be transmitted from the equipment. The network routes this specific wavelength using Reconfigurable Optical Add-Drop Multiplexers, ROADMs, the shortest available route between RISE and Onsala.

Since SUNET is an operator that rents fiber from different fiber owners, the connection does not necessarily follow the shortest route. In the present case, the 70 km distance between the two nodes travels through 160 km of fiber, as indicated in Fig 1. Also, since the assigned wavelength is within the C-band of the DWDM spectrum, the transmission must be in duplex mode (single direction in each fiber, parallel fibers), while several other WR experiments operate in simplex mode (bidirectional transmission in single fiber) [3]

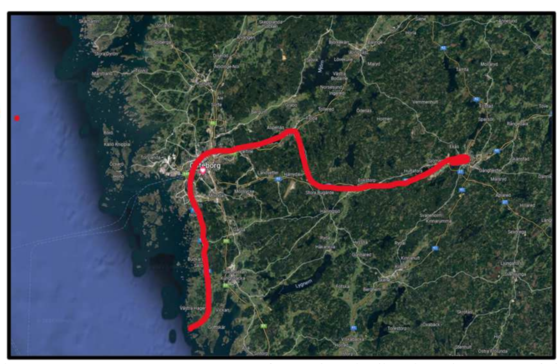

Figure 1: Map over west coast of Sweden, indicating the route of the fiber.

To transmit the UTC(SP) signal to OSO via fiber, two White Rabbit switches are used for the experiment, operating at 1 Gbit/s intensity modulated signal on 1548,51 nm (CH36).

Since the transmission is in a duplex setup, identical wavelength is chosen in both directions.

To adjust the dispersion and the power levels, dispersion compensating modules based on chirped fiber Bragg gratings, and commercial Erbium Doped Fiber Amplifiers (EDFA) are used in both nodes.

III. Experiments

A. *Local baseline characterization*

Before connecting the equipment in the two distant laboratories, the baseline of the equipment is characterized using a phase comparator. The WRS equipment is connected to the same time and frequency reference, an active hydrogen maser, with only a 3 m jumper duplex fiber inserted in between. The setup uses a pair of short range 1310 nm duplex SFPs. The modified Allan deviation (MDEV) is shown in Fig 2a, and the phase comparison between the 10 MHz input and output in Fig 2b.

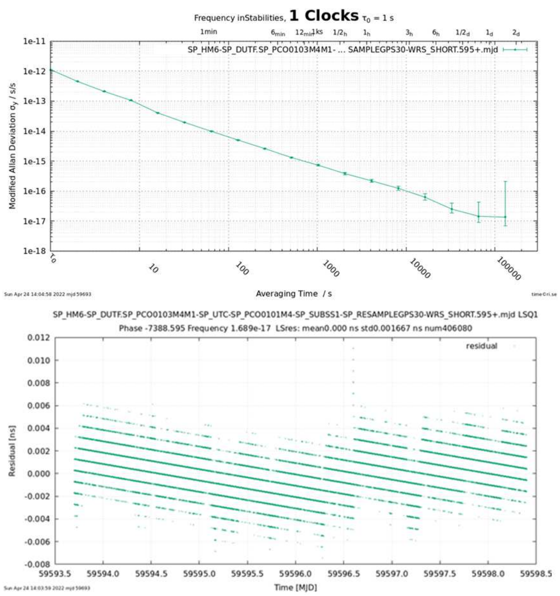

Figure 2: a) Modified Allan Deviation of the link measured back-to-back. b) residual difference after removing average delay.

In the measurement of local baseline, a 1 ps resolution of the measurement system is visible in Fig 2b) but the output jitter of the WRS is slightly larger and limits the overall performance, in the short term., The estimated slope of $1.7x10^{-17}$ indicates the uncertainty in this zero-clock measurement setup. The MDEV also indicates a measurement floor of about 10^{-17} at one day integration time with the used equipment.

B. *Lab testbed*

The complete time transfer setup, including dispersion compensation, filters and amplifiers was verified in a lab experiment, where 80 km fiber on spools are applied. The same measurement setup as described above was used. Fig 3 shows the MDEV, and the instability at longer integration times is apparent. There is a plateau on low 10^{-15} between 1000 and 100 000 s (approx. 15 minutes – 24 hours). At longer integration times, exceeding 100 000 s, the stability improves, with MDEV almost reaching 10^{-17}. The uncertainty in the rightmost points is rather large, as indicated by the error bars, and thus the graph should mainly be used to indicate general behavior, rather than definite conclusions of long-term stability.

In the time resolved graph shown in figure 3b), daily variations of 200 ps are visible. The variations seem to be deterministic and correlated to a diurnal parameter, but any correlation with parameters of the vicinity, e.g. temperature, has been unsuccessful.

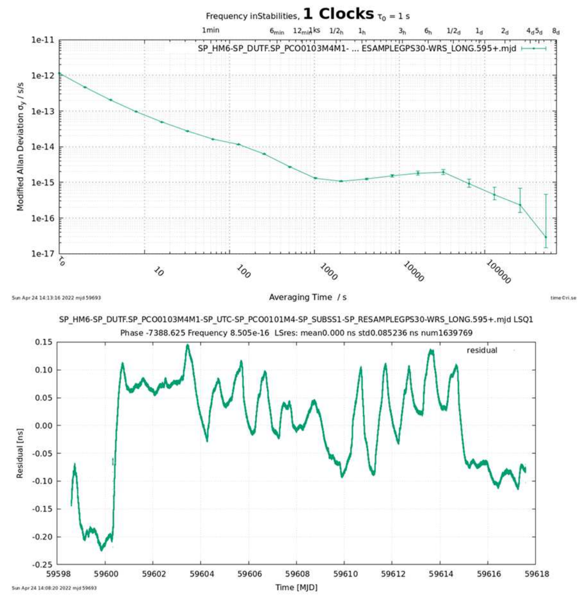

Figure 3: a) Modified Allan Deviation of the link measured in the lab with 80 km fiber distance. b) residual difference after removing average delay.

C. *Field implementation*

In the full setup, one WR switch is based at OSO, together with supporting equipment. The setup is installed in an airconditioned room without any reliable temperature regulation. Power is supplied through an uninterrupted power source (UPS) secured power outlet.

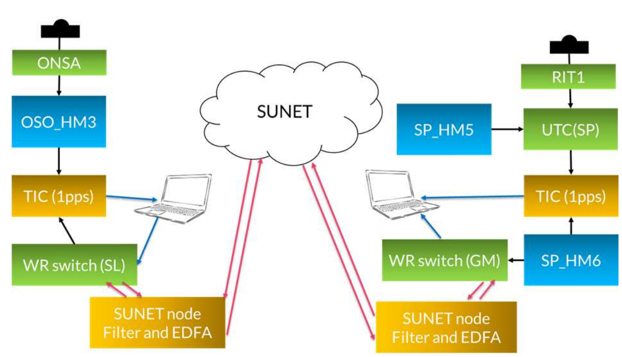

Figure 4: Schematic setup of field experiment.

A sketch of the full experimental setup is shown in figure 4. ONSA and RIT1 are GNSS receivers, the latter is also used for time transfer and traceability of UTC(SP) and is reported to the International Bureau for Weights and Measures, (BIPM). OSO_HM3 and SP_HM6 are the two H-masers compared in the experiment, while SP_HM5 is the maser used as the primary source for UTC(SP). Two Time Interval Counters (TIC) are used to measure the time interval between 1pps from the local references and the used the input and output of the WR link (Pendulum CNT-91 at OSO and TimeTech MCTIC at RISE). The WRS's are White Rabbit Low Jitter switches from Seven solutions, where (GM) is the server and (SL) the client. It should be noted that the WRS setup configures $\alpha = 0$ and thus assumes the same wavelength for both the used SFPs.

The communication equipment in the SUNET nodes is for the transmission and are mainly amplifiers and optical filters. To connected on the correct wavelength, the amplitude must be appropriate in comparison to the other channel. In the present setup, a power level of 0 dBm is ideal and thus requested by SUNET. Finally, the structure of SUNET requires each user to extract their assigned wavelength using an optical bandpass filter at the receiving end.

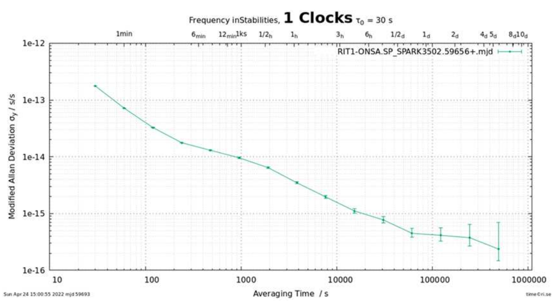

Figure 5: MDEV of the used GNSS PPP link, using the receivers ONSA and RIT1. The link determines the limit for the comparison with WR over fiber.

The results of the WR connection are compared with GNSS using NRCANPPP . The stability of this link is shown in Fig 5, indicating a limit of view parts in 10^{16} for days of averaging.

IV. RESULTS

During the present measurements, there has been no additional calibration of the equipment of the setup. Stability is evaluated with respect to GNSS using a precise point positioning (PPP) solution based on a mutual aligned starting point.

In the graphs the measured phase is presented in purple (left scale) and the residual after removing a predicted maser drift is shown in green (right scale). In the data shown in Fig.6, the residual time difference between the H maser OSO_HM3 in Onsala and SP_HM6 in Borås during 35 days of measurements is shown in green. The daily variations are apparent in conjunction with a slow change due to maser frequency drift on the monthly scale.

When focusing on a shorter time span, 5 days variations are shown in Fig. 7, the diurnals are within ± 0,3 ns most of the time. This could be sufficient for many applications, but further improvement is possible by studying the Round-Trip Delay (RTD). As shown in Fig. 7b) RTD is correlated with the diurnals of the maser comparison and this can potentially be used for additional correction to improve the time transfer.

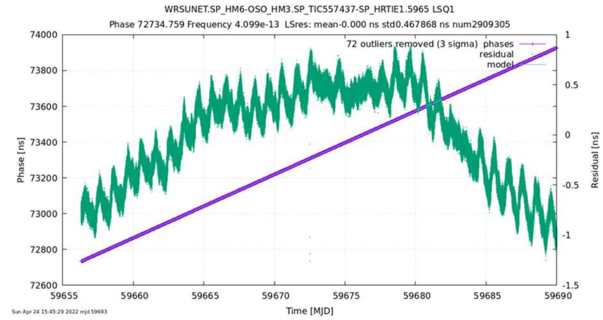

Figure 6: 35 days of time resolved measured data of the H maser at OSO in comparison with the H maser at RISE, which is traceable to UTC.

It can be deduced that the existing asymmetry of the link, caused by differences in the dispersion compensation, the transmission and other no-reciprocal parts of the link, such as amplification, causes daily RTD changes in the order of 200 ns. Furthermore, the change in the observed diurnal is slightly delayed compared to the estimated RTD. If a proper time- or environmental dependent model can be established, a large portion of the diurnal could be suppressed improving the stability of the link. Also, the wavelength uncertainty of the used SFPs should be studied to determine a proper α parameter.

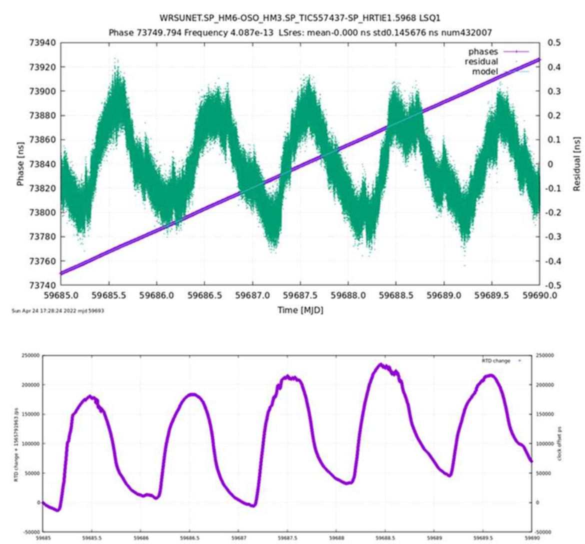

Figure 7: a) 5 days of data for visualization. Diurnals of ± 0,3 ns in the comparison of the masers. b) Round trip delay (RTD) measured in the WR equipment.

The H maser at OSO is presently, and since several years, monitored and compared to UTC(SP) and the clocks in Borås using GNSS CV and using PPP. The experiment using WR over SUNET is thus also a comparison of time transfer techniques and implementation. The graph in figure 8 shows the time resolved difference of the two links. The diurnals is presumed to origin from the fiber transmission.

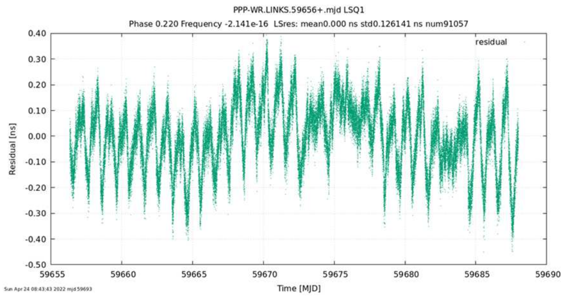

Figure 8: Time resolved difference between WR over SUNET and GNSS CV PPP.

Finally, the H maser at OSO is compared to UTC(SP) using WR over SUNET. The MDEV and Time deviation (TDEV) are presented in figure 9 a) and b), respectively. From these calculations and graphs, it is clear that the present WR synchronization over DWDM channel in duplex configuration is slightly worse than could be realized with GNSS PPP. When comparing the frequency stability of the 160 km field transmission in Fig. 9a) with the 80 km lab experiment in Fig. 3a) it can be seen that the plateau repeats itself, on a level one order of magnitude worse. However, as discussed above a clear improvement is possible in the fiber system, reducing the difference in stability.

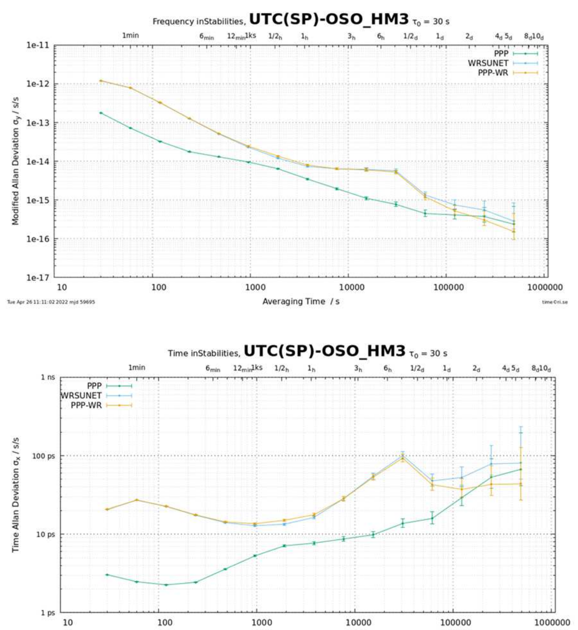

Figure 9a) MDEV, and b) TDEV, of difference between HM_OSO3 and UTC(SP) using WR over SUNET compared with GNSS PPP. The frequency drift of HM_OSO3 is not limiting.

A. Additional comments

During the experiment, one of the fiber cross-connect nodes was changed and thus the fibers rerouted. This did cause a lack of data as well as a new asymmetry in the link. This kind of event is not uncommon in operational communication networks, and happens when connection nodes are physically moved, or when the operator changes fiber network supplier. Redundant optical communication systems are not affected by this, but from a time transfer point of view a well-established contact with the network service provider is paramount.

The WR server needs supervision to reset occasionally. In the ongoing experiment, the switch jams approximately every other month, requiring a manual restart.

V. Discussion/Interpretation

The time transfer of this system shows stability exceeding present code based GNSS CV methods, and close in performance with modern PPP techniques however with the benefit of a real time operational time transfer, rather than exchange of data for post calculations. Complementary studies include the fiber optic connection of optical clocks for VLBI antennas [4], however they target a different set of observatories.

VI. Conclusions

The aim of the work presented here is the use of synchronizing VLBI antennas and IGS stations via optical fiber to nearby UTC(k) realizations, utilizing the UTC network for the improved timing accuracy of VLBI campaign. While the actual benefit of space observation still is under investigation, the the long-term frequency transfer performance presented here can already be considered suitable. Furthermore, robust time transfer using existing fiber optic networks are paramount for the future establishment of timekeeping in a digital society. The connection to research facilities already equipped with high performance oscillators enables an independent and informative analysis of expected performance to a wider dissemination.

Acknowledgment

Roger Hammargren and Lars Eriksson at Onsala Space Observatory are acknowledged for all assistance during the setup of the experiment. We also acknowledge NRCAN for the provision of NRCANPPP web service.

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