A high-frequency geodetic VLBI experiment for Optical Clock Comparison

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ABSTRACT

Abstract. We performed an intercontinental metrological clock comparison between Italy and the Republic of Korea by means of geodetic K-band VLBI observations. The comparison involved H-masers used in Medicina and Sejong radio telescopes. The same clocks were simultaneously compared by a satellite link and by high-precision optical clocks maintained at National Metrology Institutes, KRISS in Korea and INRIM in Italy, and delivered to VLBI antennas via optical fiber. The H-maser frequency difference was estimated by extrapolating the clock rate from VLBI data using two geodetic VLBI software. This was subsequently compared with clock differences derived by satellite link and by local optical clocks. Results were in agreement at the level of 10^{-15} s/s. This result is a first confirmation that standard geodetic VLBI campaigns could be a viable approach to conduct intercontinental clocks comparisons, now possible only via satellite links. This experiment was a pilot test in view of the installation of new-generation, high-frequency, wideband receivers on the involved telescopes. K/Q/W band geodetic observations will allow an improvement in the accuracy of the resulting group delays and a better estimation of the clock parameters of the stations. The frequency phase transfer (FPT) method will also be explored together with injected phase cal signal for improving phase stability and thus the uncertainty on the clock rate.

Keywords: Very Long Baseline Interferometry — Optical clocks — Optical fiber links

1. INTRODUCTION

Very Long Baseline Interferometry (VLBI) is among the scientific disciplines the one that most relies on accurate time and frequency reference signals, showing important synergy with fundamental metrology. It is based on the simultaneous observations of radio sources with an array of telescopes, each referenced to a local frequency standard. By correlating the radio signals received by the various telescopes it is possible to reconstruct pair-wise propagation delays, that depend on the baseline length and orientation, atmospheric effects and ultimately the radio source position and structure (Schuh & Behrend 2012). Discrepancies in the local clock frequencies and instrumental delays may also play a role. When all effects are taken into account, it is possible for VLBI to reconstruct with good fidelity a rich information, e.g., on the position of the radio telescopes, the Earth's Orientation Parameters (EOP), the source positions and structure. Specifically, VLBI and frequency metrology can take mutual advantage one from the other: on one side, VLBI resolution could be greatly improved with instrumentation and techniques that are traditionally maintained at Metrological Institutes. These include atomic clocks with state-of-the-art accuracy, today at the 10^{-18} level (Beloy et al. 2021; Brewer et al. 2019; McGrew et al. 2018; Ushijima et al.

2015), useful to investigate phenomena over timescales of months or years (Krishnan et al. 2020); high spectral purity oscillators (Nakamura et al. 2020; Xie et al. 2017) , crucial in mm- and sub-mm-wavelength observations (Raymond et al. 2024); sub-ns synchronization of remote sites (Dierikx et al. 2016; Serrano et al. 2009) and distribution of atomic clock signals to multiple telescopes over optical fiber, that enable to realize distributed common-clock arrays (Clivati et al. 2020a). On the other side, atomic clocks connected to the telescope can be compared worldwide via VLBI. This is especially important for fundamental metrology, as discussion is ongoing on a future redefinition of the second in the International System of units (Gill 2016; Lodewyck 2019; Riehle et al. 2018). Comparing distant atomic clocks is among the most urgent tasks to gain confidence on the best route to redefinition. Moreover, it allows fundamental physics tests at unprecedented resolution (Sanner et al. 2019; Lange et al. 2021), as well as advanced relativistic geodesy measurements (Grotti et al. 2018; McGrew et al. 2018; Takamoto et al. 2020). However, this is a challenging task: while regional clock comparisons can be performed with fiber optic links (Musha et al. 2008; Akatsuka et al. 2020; Lisdat et al. 2016; Droste et al. 2013; Clivati et al. 2020b, 2022; Husmann et al. 2021; Chiodo et al. 2015), intercontinental clock comparisons are mostly conducted with Global Navigation Satellite Systems (GNSS), though its performance may not meet the accuracy required for optical clock comparison.

Since the end of 1970's geodetic VLBI uses the S/X band receivers with the aim of monitoring the parameters of the Earth's orientation, studying the movements of the Earth's crust and other geophysical phenomena, realizing the international terrestrial and celestial reference frames (ITRF and ICRF). Its application for time and frequency transfer has been investigated since the beginnings (e.g. (Counselman et al. 1977; Clark et al. 1979; Hurd et al. 1979)) and an uncertainty of 1.5×10^{-15} for a time period of 1 day has been reported in an earlier study (Rieck et al. 2012). For local H-masers, which have a relative frequency instability well below 10^{-12}, the VLBI-determined clock rate is equivalent to the difference in the coordinate rate of the two clocks. The uncertainties that can be achieved with legacy S/X band observations are not sufficient for optical clocks comparison, so new possibilities are being explored, such as VLBI observations performed with broadband receivers.

In 2018/19, an intercontinental comparison of optical clocks was carried out using a VLBI link between Italy and Japan with an uncertainty of $2.8 \text{ x } 10^{-15}$, lower than achievable by a satellite link and thus particularly promising in a metrological perspective (Pizzocaro et al. 2021). However, in that campaign data were collected and analysed in non-standard fashion, and dedicated equipment had to be specifically developed, such as small transportable antennas and broadband NINJA feeds, which can cover the frequency range 3-14 GHz (Sekido et al. 2021).

A new generation of broadband and high-frequency receivers (> 20 GHz) is becoming available in standard VLBI too, which would be highly effective in calibrating tropospheric phase fluctuations in the millimeter waveband, significantly enhancing the precision of group delay measurements through broad bandwidth synthesis from 20 to 100 GHz. Moreover, they have the potential to reduce frequency-dependent systematic errors, such as source structure—ones. Frequency metrology can also take advantage from those new receivers to improve the accuracy of VLBI clock-comparison.

A project involving the Korea Astronomy and Space Science Institute (KASI) and the Italian Institute of Astrophysics (INAF) allows the installation of Korean Compact Triple-band Receivers (CTRs) that operate simultaneously in K(18-26 GHz), Q(35-50 GHz), and W(85-115 GHz) bands (Han et al. 2017) on all three INAF antennas (Medicina, Noto and SRT). Waiting the installation and commissioning phases to be completed, we explore the use of an intercontinental network of operational VLBI antennas to conduct metrological clock comparisons. Importantly, our strategy was to exploit procedures and instrumentation that are routinely used at most radio telescopes today. This would leverage the use of the existing VLBI network for various scientific tasks, including metrology. Our test campaigns were thus conducted as geodetic ones, with K-band observations and standard scheduling and analysis, with the aim to identify ultimate limits, critical aspects and achievable metrological performances.

This paper will describe the international frame, experimental setup and analysis procedures, and discuss current results and future perspectives. In details: in Section 2 the VLBI-optical clock comparison experiment is explained, in Section 3 the VLBI observations and geodetic data analysis are presented. In Section 4 the comparison via VLBI, optical clocks and GNSS are shown; in Section 5 the results are discussed and some conclusion and outlook are drawn in Section 6.

2. VLBI-OPTICAL CLOCK COMPARISON EXPERIMENT

In our collaboration, we compare the frequencies of H-masers used in VLBI observations at Medicina and Sejong radio telescopes via a VLBI geodetic link and,

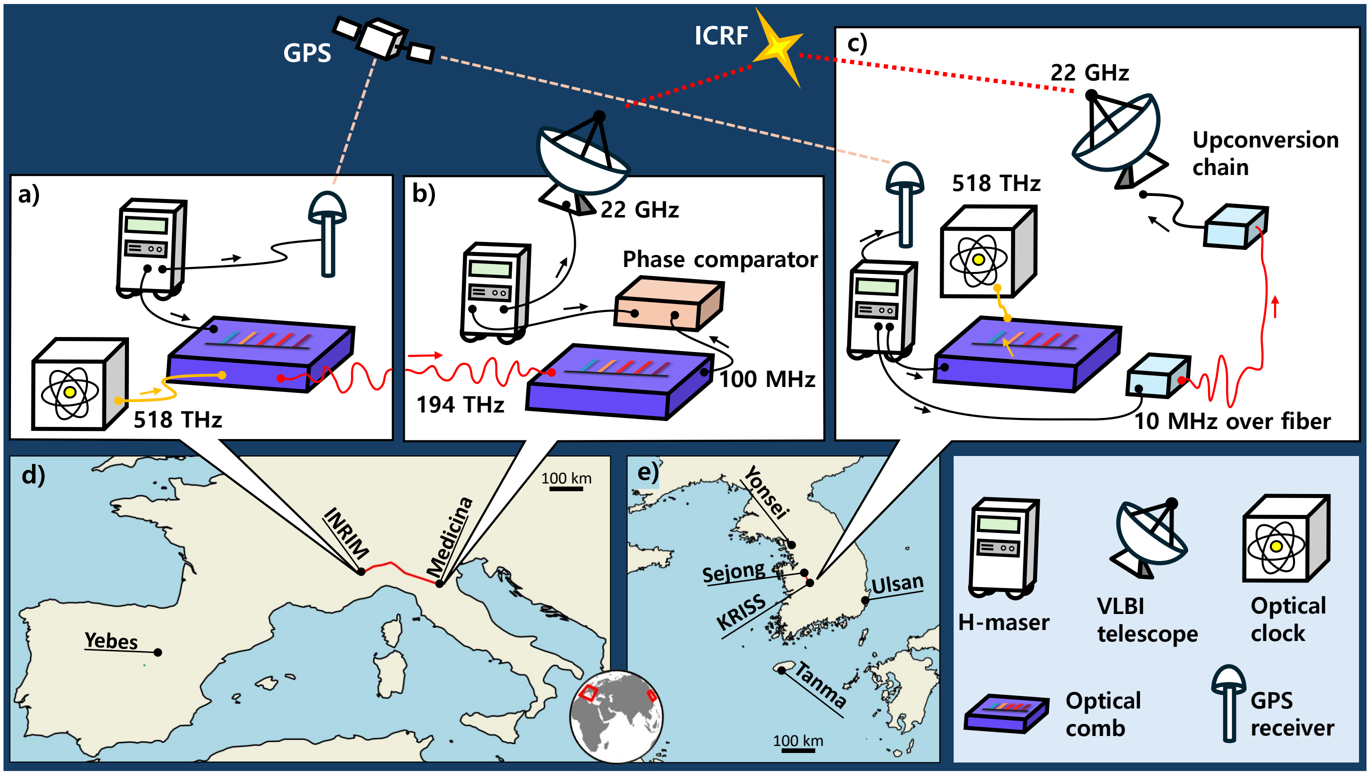

Figure 1. Schematic view of the full experiment set-up. a) At INRIM, in Italy, radiation from an infrared laser is referenced to IT-Yb1 clock via an optical comb and sent to Medicina with a phase-stabilised fiber. IT-Yb1 was also compared to KRISS-Yb1 via a direct GPS link to KRISS, using INRIM H-maser as flywheel oscillator. b) In Medicina, the incoming radiation is coherently converted to a microwave and used to calibrate the local H-maser, which is used for the VLBI observation. c) In Korea, a 10MHz signal referenced to KRISS-Yb1 is sent to Sejong VLBI antenna with a phase-stabilised fiber; here, after demodulation, it seeds the antenna synthesis chain and is used for VLBI observation. KRISS H-maser is also calibrated by KRISS-Yb1 and compared to INRIM via GPS. d) and e) Map of Europe and Korea with involved telescopes and Metrological Institutions.

simultaneously, by calibration to high-precision optical clocks maintained at National Metrology Institutes (NMIs) KRISS in Korea and INRIM in Italy. (Fig. 1). During the VLBI sessions, a GNSS link based on GPS Precise Point Positioning was operational between INRIM and KRISS for consistency check and comparison.

Thus, we could compare the H-masers in Sejong and Medicina via three independent methods: calibration against optical clocks, VLBI and GNSS.

2.1. *VLBI setup*

A network of six antennas between Europe and the Republic of Korea was involved in K-band 24-h geodetic session: Medicina 32-m antenna (Italy, managed by INAF) and Yebes 40-m antenna (Spain, managed by the Yebes Astronomical Centre) in Europe (Fig. 1d), and Sejong 22-m antenna (managed by the National Geographic Information Institute - NGII) and the three Tanma, Yonsei and Ulsan 21-m Korean VLBI Network antennas (KVN, managed by KASI), in Korea (Fig. 1e). The Sejong station receives a clock signal (10MHz) from a Hydrogen maser at KRISS via the Korea Research Environment Open Network (KREONET), a research fiber network provided by the Korean Institute of Science & Technology Information (KISTI) (Fig. 1c). The delivered signal is directly-demodulated and multiplied to 1.4GHz, to feed into the Round Trip System (RTS), which sends the 1.4GHz signal to the antenna receiver room for VLBI observation with the fiber-induced noise suppressed. At Medicina station, in Italy, the local H-maser is used for VLBI observations, but its frequency is constantly measured against a clock signal delivered from INRIM over the Italian Quantum Backbone (IQB), a fiber infrastructure for metrological time and frequency distribution in the whole Country (Fig. 1a and b). More details on the fiber-based clock distribution to the two telescopes are given in Section 2.2

The experiment schedule was generated using NASA's software *SKED* which is widely used to schedule geodetic and astrometric VLBI observations. We compiled a catalog with over 230 sources, which are included in the ICRF3 K-band catalog (Charlot, P. et al. 2020) and generally strong (> 0.4 Jy at K or X band), flat-spectrum sources in the Radio Fundamental Catalog (Petrov & Kovalev 2024). The best 69 targets, primarily ranked by sky coverage, were automatically selected by *SKED* for the six-station network from UT 2021-Dec-16 19:00 to 2021-Dec-17 19:00. The sequence of source scans is well-separated in hour angle and elevation over time to improve astrometric accuracy and help separate the tropospheric effect from other parameters. A total of 451 scans were scheduled, each with a duration of 120 seconds per source. We recorded right circular polarization (RCP) at a frequency range between 21184 and 21696 MHz with a total data rate of 2048 Mbps. The total bandwidth of 512 MHz was divided into 16 intermediate frequency (IF) bands. Since the KVN has its own field system supporting the NRAO VLBI scheduling program *SCHED*, the observing scans from *SKED* were modified to *SCHED* format.

2.2. *Optical clocks and fiber distribution*

To calibrate H-masers, we used KRISS-Yb1 and IT-Yb1, two Yb optical lattice clocks with uncertainty of $2x10^{-17}$, respectively (Pizzocaro et al. 2020; Kim et al. 2021). Both clocks contribute regularly to the generation of the International Atomic Time (TAI). INRIM and KRISS are also equipped with GNSS receivers for satellite clock comparison and frequency transfer. The main reference oscillator at KRISS is a H-maser (KRISS-HM) traceable to UTC(KRISS); its frequency is calibrated by KRISS-Yb1 via an optical frequency comb. The 10 MHz signal from the hydrogen maser is transferred to Sejong VLBI antenna via a 50km fiber link. We used a commercial fiber-optics frequency distribution system (OSTT, PikTime) to actively compensate the fiber noise (Fig. 1c).

The additive noise due to the fiber link was measured at KRISS to be 10^{-13} at 1 s and 2×10^{-16} at 10^4 s, so the fiber link did not degrade the performance of the VLBI measurement.

In Italy, the Medicina telescope is connected to INRIM via a 535km optical fiber which is part of the Italian Quantum Backbone. Among other research facilities, this infrastructure connects two of the main Italian radiotelescopes, Medicina and Matera, and has already been used to carry out a common-clock VLBI experiment (Clivati et al. 2020a). The frequency distribution chain is based on an ultrastable laser, stabilized at INRIM to a high-finesse Fabry-Perot cavity and calibrated by IT-Yb1 via an optical comb (Fig. 1a). The radiation is sent to Medicina and here used to reference a second optical comb, from which an ultra-low noise microwave at 10GHz and 100MHz is extracted and phase-compared to the local H-maser (Medicina-HM) (Fig. 1b). The fiber is stabilized using the Doppler noise stabilization technique, so that the frequency signal delivered at the telescope has a short term stability of a few parts in 10^{-14} and $< 10^{-16}$ at 10^4s (Clivati et al. 2015).

3. VLBI OBSERVATIONS AND DATA ANALYSIS

3.1. *Campaign overview*

The 24-hour VLBI experiment was carried out at 6 stations from UT 2021-Dec-16 19:00 to 2021-DEC-17 19:00. The weather conditions were different between Europe and the Republic of Korea. The weather was good at Medicina and Yebes. The KVN observations were completed without any major problems except for bad weather: snow and strong wind were reported at Sejong station. A data loss of about 46% was reported at Yebes station starting at UT 2021-Dec-17 12:28, thus affecting the last part of the experiment.

The optical clock and fiber-based distribution systems operated almost continuously from a few hours before to a few hours after the campaign. During the 24-hour-long campaign IT-Yb1 and KRISS-Yb1 had an uptime of 94% and 97% respectively. The GNSS link was operational during the campaign without interruption.

3.2. *VLBI data correlation and fringe fitting*

Data was transferred from each station to the Daejeon and Bologna Correlator and correlated, using the Distributed FX (DiFX) software (Deller et al. 2007), by performing fast Fourier transform (FFT) followed by a complex multiplication of the raw visibilities data of each antenna taken in pairs. Prior to this, the estimation of parameters such as station positions and velocities, source coordinates, and Earth orientation parameters were calculated to achieve the best possible delay model using the Calc software (Gordon et al. 2017).

After the correlation was completed, the DiFX files were converted into Mark4 directories and then fringe-fitted using Haystack Observatory Postprocessing System *fourfit* (Hoak et al. 2022). In the fringe fitting procedure the peak intensity as a function of delay and delay rate is computed scan by scan and sub-band by sub-band and then applied to the fringe visibility data in order to flatten the phases in the frequency channels in each sub-band. Manual phase calibration and Lower Side Band (LSB) offset were inserted for all stations before running the fitting routine.

After the fringe fitting was applied, the data appeared in the Mark3 format, but the commonly used software programs for geodetic data analysis work with databases. For this reason the Mark3 fringe fitting output files were converted into vgosDb (Bolotin et al. 2017) databases containing observed delays, *a-priori* models, instrumental delays corrections and weather parameters.

3.3. *Geodetic data analysis*

The data analysis software νSolve (Bolotin et al. 2014) was used to analyze the vgosDb database, named 21DEC16XF νSolve solves for the normal equation calculating the adjustments of a set of parameters by comparing model group delays with observed ones on antenna pairs for each source scan in an observing session. The software estimates the clock parameters through a quadratic model (offset, clock rate and quadratic term) plus a piece-wise linear function. Tropospheric parameters, station positions and Earth Orientations Parameters (EOPs) are also estimated in the single session solution.

Geodetic data analysis software are not designed for extracting the clock parameters, so for verification, an additional analysis was conducted using the Vienna VLBI & Satellite Software for astrometry and geodesy (VieVS) (Böhm et al. 2018) developed by the Vienna geoinformatics group as an alternative to other software for geodetic analysis in order to be a self-contained tool for session simulation (useful for scheduling) and session and global analysis.

At variance with νSolve which is able to perform ionospheric correction only in dual-band sessions (e.g S/X-band), VieVS is able to perform ionospheric delay correction even in single-band sessions (e.g. K-band). It utilizes GNSS generated Global Ionospheric Maps (GIMs) to compute ionospheric correction at the position of each station at the time of each observing scan in the session. Such maps have a latitude/longitude resolution of 2.5/5.0 degrees and are provided daily by the International GNSS Service (IGS) through the CDDIS repository ((Noll 2010)). The corrections obtained from this external model were applied to the obseving session database.

4. RESULTS

4.1. *Comparison via VLBI*

νSolve was run on the 21DEC16XF database using standard settings for the parametrization: (i) clock parameters (CL0: offset; CL1: clock rate and CL2: quadratic term) plus piece-wise linear (PWL) function (linear B-Splines model) with intervals of 60 min; (ii) tropospheric parameters: PWL function with intervals of 60 min and azimuthal gradients estimated every 6 hours through a PWL function; station coordinates; dUT1 rate; Nutation angles and baseline-based clock offsets (the last four parameter sets estimated once in the 24-hour session). As stated in Section 3 no ionospheric corrections were applied as the dataset is single-band. After the least-square minimization using 5793 observation pairs, a WRMS of the group delay residuals of 25.55 ps obtained). The groups delay residuals as a function of observing time are shown in Fig. 2 (top). The estimate of the second term (CL1: clock rate) and third term (CL2: clock acceleration) of the clock model are reported in Table 1.

VieVS was run on the same database using standard settings for the parametrization. The main differences with νSolve concerned the use of the VMF3 mapping function (D. Landskron 2018) for the troposphere parameters estimation, and of the *a priori* GPT3 model (D. Landskron 2018) for estimating their azimuthal gradients. Two VieVS solutions were obtained with and without the application of the ionospheric correction, respectively. There was no significant difference between the two solutions. The bottom plot in (Fig. 2 shows the group delay residuals with the ionospheric correction applied. Using 5784 observation pairs, we obtained a WRMS of 26.41 ps. The estimate of the clock rate and clock acceleration of the clock model are reported in Table 1. We adopted clock parameters obtained using VieVS as the best estimation because they were obtained using a better tropospheric and ionospheric modeling. However, the two methods were consistent within uncertainty.

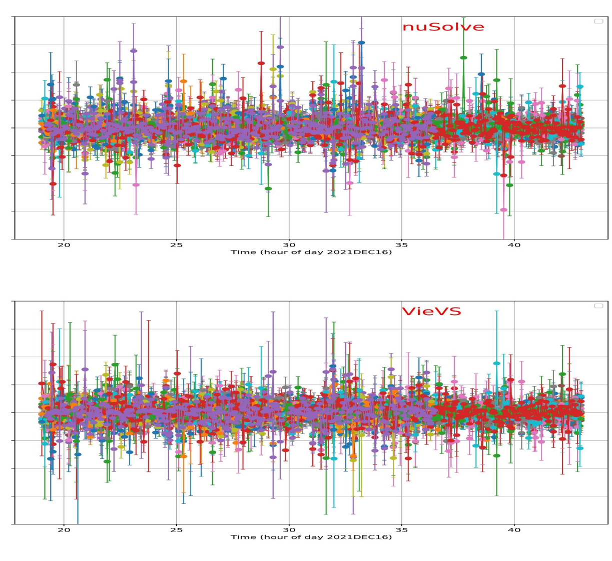

Figure 2. Group delay residuals as a function of observing time during the Dec 2021 geodetic session obtained by νSolve (top) and by VieVS (bottom).

Table 1. Clock parameter estimates obtained from the geodetic analysis performed on νSolve and VieVS.

Tool	CL1	CL2
	~~s/s~~ (1 x 10^{-14})	day^{-1} (1 x 10^{-14})
νSolve	-21.43 ± 0.15	0.21 ± 0.23
VieVS	-21.25 ± 0.11	-0.07 ± 0.10

4.2. *Comparison by optical clocks*

H-masers used for the VLBI measurements at Sejong and Medicina were calibrated by KRISS-Yb1 and IT-Yb1. By calibration we mean that the absolute frequencies of the two masers are available, as the two Yb clocks are secondary representations of the SI second (Margolis et al. 2024). In calculating the frequency difference between two H-masers we will assume that, being based on the same atomic species, the two Yb clocks have the same frequency within their uncertainty. In this way, we calculated the average relative frequency difference y of the masers during the campaign as y(KRISS-HM - Medicina-HM, OC) = -213.26(8) x 10^{-15}, where OC is the acronym of the optical clock. Here the uncertainty includes the instability (7 x 10^{-18} and 1.1 x 10^{-17}) and the systematic uncertainty (2 X 10^{-17} and 7.3 x 10^{-17}) respectively for IT-Yb1 and KRISS-Yb1. The uncertainty includes an extrapolation uncertainty of 4 x 10^{-17} for Medicina-HM and 7 x 10^{-17} for KRISS-HM due to the dead-time in the optical clock measurements calculated from the known noise of the two masers (Yu et al. 2007; Hachisu & Ido 2015). This approach is common for optical clocks operating intermittently (Grebing et al. 2016; Leute et al. 2016; Hachisu et al. 2017; Pizzocaro et al. 2020, 2021; Nemitz et al. 2021). The optical fiber link connecting IT-Yb1 in Torino to the H-maser in Medicina has been characterized to better than 1 x 10^{-18} and contributes negligibly to the uncertainty of the measurement.

We note that in December 2021 the optical clocks IT-Yb1 and KRISS-Yb1 provided an extended set of data to contribute to the realization of TAI. IT-Yb1 contributed 5 days of data (MJD 59564-59569) that appeared in Circular T n. 410. KRISS-Yb1 contributed 35 days of data (MJD 59544 59579) that appeared in Circular T n. 408. A direct comparison of the two measurements shows the agreement of the two optical clocks with the relative frequency difference of y(IT-Yb1 - KRISS-Yb1) = 3(12) x 10^{-16}, where the uncertainty (1.2 x 10^{-15}) was limited by satellite link over the 5-day measurement time of IT-Yb1 as appeared in Circular T, and where we included an extrapolation uncertainty using the TAI stability to consider the different measurement time of the two clocks (Pizzocaro et al. 2021). Still, consistency in the two clocks at the 10^{-17} level is expected from the two uncertainty budgets.

4.3. *Comparison via GNSS*

A GPS-based independent and calibrated time and frequency transfer link was established to validate the VLBI intercontinental link, using two geodetic receivers for timing applications at INRIM and KRISS. These receivers track the code and phase signals emitted by the GPS satellites, and allow comparing them with the internal receiver clock, in turns synchronized and frequency locked to the external signal that is object of comparison. At INRIM, two Septentrio PolaRx4-TR receivers were used, connected to UTC(IT) and the H-maser at INRIM; at KRISS, a GTR55 receiver (MESIT asd) was used to connect to KRISS H-maser which is the master clock for KRISS-Yb1. Among various possible processing algorithms, we chose the Precise Point Positioning (PPP) (Héroux & Kouba 2001) as it includes the compensation of a significant set of atmosphere, geodynamics, and satellite effects (Héroux & Kouba 2001). Intending PPP as a way of processing, different implementations are available worldwide. We chose NRCan PPP, produced by Natural Resources Canada and optimized for timing applications also with contribution of INRIM, now in use for more than 10 years by the BIPM for the computation of the TAI and UTC international time scales. Precise IGS estimations for GPS satellites' orbits and clocks were retrieved from the IGS repositories.

The PPP solution was obtained processing data for the period including the VLBI campaign from MJD 59562 to MJD 59571 and then combining them with data from the optical-VLBI link.

We calculate the average difference of the maser frequency during the campaign using GPS as y(KRISS-HM - Medicina-HM, GPS) = -215.7(20) x 10^{-15}.

The uncertainty is limited by the averaging time of the PPP solution over 1 day. We note that other campaigns using GPS data at INRIM (Clivati et al. 2022) revealed a possible problem with the GPS solution at the level of 3 x 10^{-16} in the considered period of time. This effect is negligible for the measurement presented here.

Table 2. Average frequency difference in relative units of the H-masers at Sejong and Medicina during the campaign, measured using VLBI, the GPS link and the calibration by optical clocks.

	Maser frequency difference y (1 x 10^{-15})	Uncertainty $u_{\rm tot}$ (1 x 10^{-15})
VLBI	-212.5	1.1
GPS	-215.7	2.0
Optical clocks	-213.26	0.14

Table 3. Closure difference in relative units of the measurements between the 3 techniques.

	Closure difference Δy (1 x 10^{-15})	Uncertainty $u_{\rm tot}$ (1 x 10^{-15})
VLBI - OC	0.8	1.1
GPS - OC	-2.4	2.0
VLBI - GPS	3.2	2.3

5. DISCUSSION

The 3 measurements of the average maser frequency difference obtained with VLBI, optical clocks and GPS are presented in Table 2. From these values we can calculate 3 closure differences as shown in Table 3. These measurements show a good agreement between the different techniques. Specifically, the agreement between the VLBI measurement and the optical clock measurement is within 2σ.

The uncertainty associated with the VLBI result is not yet sufficient to contribute to the final goal of this project. Compared to the previous work (Pizzocaro et al. 2021), the value is one order of magnitude worse and this can be explained by a couple of considerations. First, in the previous experiment ad hoc instruments (small transportable antennas, wideband receivers in the frequency range 3-14 GHz) and analysis techniques were used, also making assumptions on the local maser modeling, that are not possible in this case. Second, the final result was obtained from a 6-month long experiment campaign.

Given the uncertainties obtained in this first campaign, we chose to present results in the form of H-masers differences. In this picture, optical clock data are used to assess the VLBI link. However, the same data can be interpreted as an optical clock comparison via VLBI that in perspective could complement other existing techniques at transcontinental scale.

Results from Tab. 2 confirm previous results (Pizzocaro et al. 2021), that the VLBI is capable of potentially lower uncertainty than GPS for the same uptime. However, other aspects need to be considered in perspective of using VLBI as a way to compare clocks. First, GPS today achieves low 10^{-16} uncertainty after several days of measurement, and sub-10^{-16} uncertainty with iPPP algorithms (Petit 2021). The use of VLBI should be considered in this perspective, and it will be interesting to assess the capability of VLBI campaigns with standard equipment to reach this level of uncertainty. For taking the best advantage from VLBI, single, week-long runs (e.g. geodetic ones) should be preferred to several day-long campaigns. This statement highlights other challenges, such as the large amount of data that would be produced in such an experiment, the complexity in the pre-processing stages and finally in the analysis, which are higher for VLBI than for conventional GPS-based clock comparisons.

Our goal in this preliminary step was to investigate whether higher frequency receivers can be used in geodetic experiments to obtain reliable clock parameters, which we can state. Furthermore, we can say that the ionospheric correction does not affect the final solution of the clock parameters, while a different behavior can be observed for the troposphere parametrization.

To improve the accuracy of the group delay, we plan to use the new broadband receivers (CTRs) and K/Q/W-band geodetic observations that, thanks to the recent results obtained by the KVN (Xu et al. 2024; Xu et al. 2024), have demonstrated their effectiveness. The multi-frequency system is highly effective in calibrating tropospheric phase fluctuations in the millimeter band, significantly improving the accuracy of the group delay measurements through the wideband synthesis from 20 to 100 GHz and the use of the frequency phase transfer (FPT) method. In the FPT method, high frequency observations are calibrated using scaled solutions obtained from a lower and more easily manageable frequency ((Jung et al. 2011), (Rioja & Dodson 2020). It demonstrated the feasibility of extending geodetic VLBI observations from centimeter to millimeter wavebands, quite challenging due to various factors, including the increased effects of atmospheric opacity and turbulence at millimeter wavelengths (Xu et al. 2024). Furthermore, it has the potential to reduce frequency-dependent systematic errors, such as the source structure, a major source of error in our previous work in the centimeter bands (Pizzocaro et al. 2021; Sekido et al. 2021), which is typically expected to be smaller at higher frequency bands. These advances make it feasible for K/Q/W-band observations to achieve higher accuracy.

6. CONCLUSION

We designed, organized and implemented a geodetic OCC-VLBI campaign at K-band, with the aim of exploiting the feasibility of optical clock comparison with the existing VLBI network. This was a pilot experiment in view of deploying high-frequency, wideband receivers that will be available at several VLBI stations in the near future. Many scientific researches will utilize this new infrastructure; we will explore its use for metrology. Our test campaign was therefore conducted as a geodetic one, with K-band observations and standard scheduling and analysis, aiming to identify the potential and critical points of this methodology. The results obtained in this work with different approaches were in agreement at the 10^{-15} s/s level, which states that standard geodetic VLBI campaigns could be used for intercontinental clock comparisons, currently only possible via satellite techniques.

For the future, an optimal frequency set-up in the range 18-116 GHz will be studied to optimize the next VLBI observations, exploiting the new wideband and high frequency receivers (CTRs), which, thanks to the recent results obtained by KVN (Xu et al. 2024) that have demonstrated their effectiveness in improving the accuracy of the resulting group delays, will allow a better estimation of the clock parameters of the stations. We plan to carry out longer experiments with a larger network including other international stations equipped with the same receivers, which will allow us to connect to the international metrology community. This will bring with it additional challenges because we will have to deal with a large amount of data that will have to be stored and then transferred via the network to the correlators in Italy and Korea.

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