Optical Clock Comparison Using K-band Geodetic VLBI Between Europe and Korea

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Abstract Geodetic VLBI has demonstrated its potential in comparing distant atomic clocks, a very important issue for international timekeeping, global positioning, and fundamental physics testing. Optical clocks are the most technologically advanced frequency generators with a stability of 10^{-18} and are expected to be used to redefine the SI second by replacing Cesium fountains. Fiber optic link networks allow best-performing optical clocks to be compared over distances of up to 2,000 kilometers, but for longer distances clock comparisons are limited by the performance of satellite frequency transfer techniques. In this work we present the use of high-frequency geodetic VLBI as an alternative technique for long-distance frequency transfer. A 24-hour K-band experiment involving six antennas between Europe and the Republic of Korea was carried out to estimate the clock frequency between the Medicina and Sejong H-masers. These masers were connected to and calibrated against two Ytterbium optical clocks located at INRiM (Italy) and KRISS (Korea). Results of the geodetic data analysis are presented.

Keywords Optical clocks, VLBI technique, optical fiber links

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1 Introduction

Microwave clocks such as Cesium (Cs) fountains [1] are used to define the International System of Units (SI) second and are the standard in international timekeeping [2]. Atomic clocks based on optical transitions can reach fractional frequencies uncertainties at the 10^{-18} level [3, 4, 5], already improving the performance by two orders of magnitude of the Cs fountains, and their use is expected in the definition of the second SI [6]. The comparison of such clocks on intercontinental distances is essential to verify their consistency in view of this redefinition. Optical clocks are already used in tests of special and general relativity [7], research on fundamental constants [8], and chronometric leveling (i.e., using gravitational redshift to determine absolute height differences [9, 10]). Future applications of clock comparisons also involve the creation of quantum networks for secure communications and timing [11] and gravitational wave detection [12].

Coherent optical fiber links can disseminate frequency references via optical frequency combs up to about 2,000 kilometers with frequency instabilities of the order of 10^{-19} [13, 14, 15], but they cannot be used on intercontinental distances. On such large distances optical clock comparisons rely upon Global Navigation Satellite Systems (GNSS) frequency transfer (via the Integer Precise Point Positioning technique (IPPP) [16] and Two-Way Satellite Time and Frequency Transfer (TWSTFT) [17]). In recent years, Very Long Baseline Interferometry (VLBI) has also demonstrated its ability to contribute to this type of research. In fact, geodetic experiments were designed, and the data collected during the observations were analyzed. The model parameters of the H-maser clocks, in particular their rate, were estimated for the stations involved in the network. These values were then used for comparison between optical clocks in a metrology chain.

An international cooperation between the National Institute of Information and Communications Technology (NICT, Japan), Istituto Nazionale di Ricerca Metrologica (INRiM, Italy), and Instituto Nazionale di Astrofisica (INAF, Italy) allowed a VLBI campaign to compare optical lattice clocks between Japan and Italy, carried out in 2018–2019 ([18, 19]). Two small (2.4-meter diameter) transportable antennas (nodes), one located in Koganei (Japan) and the other at the radio observatory of Medicina, observed a list of bright quasars together with a large (34-meter) antenna in Kashima (Japan); all three antennas were equipped with broadband (2–14 GHz) NINJA feeds. The node–hub configuration was chosen because the small antenna pair did not reach enough signal-to-noise ratio in geodetic observations on enough bright targets. The baseline between the small antennas is computed as a closure-delay relation starting from their baselines with the hub antenna. The relative fractional frequency difference between the H-masers used at the Koganei and Medicina small antennas was thus computed. This was a link in the metrological chain connecting the INRiM Yb optical clock to the NICT Sr optical clock thanks to the Italian Quantum Backbone (IQB) for optical fiber frequency reference dissemination (the Torino–Medicina 550-km link [15]) and optical fiber link in Koganei. The resulting frequency deviation between Ytterbium and Strontium clocks measured via the VLBI link was $y(Yb/Sr) = 2.5(2.8) \times 10^{-16}$ in agreement with previous measurements and an improvement in terms of uncertainty with respect to the frequency deviation obtained via GPS-IPPP ($y(Yb/Sr) = -3.2(4.0) \times 10^{-16}$).

A new collaboration between the Republic of Korea and Italy was launched in 2021 to perform optical clock comparisons using VLBI antennas, and the first experiment performed in December 2021 will be presented in the next sections.

2 Data

A network of antennas between Europe (Medicina 32-m antenna in Italy and Yebes 40-m antenna in Spain) and Korea (Sejong 22-m antenna managed by the National Geographic Information Institute and the 21-m antennas Tanma, Yonsei, and Ulsan of the Korean VLBI Network (KVN) managed by the Korea Astronomy and Space Science Institute, KASI) has been used with the aim of determining the fractional frequency difference between H-maser clocks in Korea and Medicina and thus indirectly compare the Yb optical lattice clocks located in INRiM (Italy) and Korean Research Institute for Standards and Science (KRISS) by estimating their relative frequency deviation. During the VLBI sessions, a metrological campaign was performed. The KRISS H-maser clock signal was transferred to Sejong station via an optical fiber link provided by the Korean Institute of Science & Technology Information (KISTI), while the IQB optical fiber link connects the optical clock disciplined H-maser clock in Torino with the Medicina station H-maser clock. Data collected by GNSS stations in the same time period was analyzed with a GPS-IPPP approach for the comparison between the two techniques (see Figure 1 for a scheme of the full experimental set-up and Figure 2 for the clock campaign uptimes).

3 Analysis

A 24-hour VLBI experiment, involving the six antennas, at K-band in the frequency range 21–21.4 GHz was performed on 16–17 Dec 2021. To schedule the run, the *sur_sked* routine was used. 450 scans were created with targets chosen from a list of tens of sources in a typical geodetic scheme: short scans (2–3 min) were performed spanning all azimuths and elevations available at the observing stations in order to better characterize the tropospheric parameters. The raw data from the six antennas were transferred to the Bologna and KASI data centers for correlation with DiFX [20].

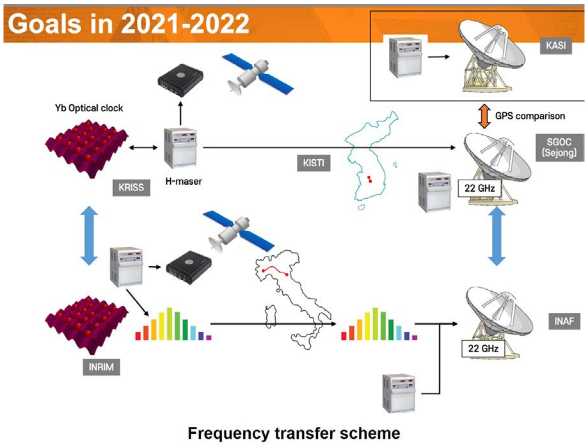

Fig. 1 Schematic view of the full experiment setup in the December 2021 observations.

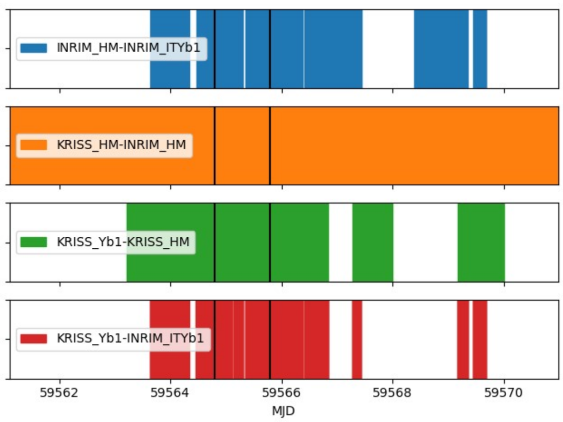

Fig. 2 Uptimes for the clock campaign carried out in December 2021. In blue INRiM, in orange GPS, in green KRISS observations, and in red the combined uptime.

Fringe fitting was performed with HOPS *fourfit* and a vgosDB database was created and analyzed with *nuSolve* [21], with a standard parametrization. The group delay residuals vs. observing time are shown in Figure 3 together with the relevant clock parameters (clock rate and its uncertainty) estimated on the baseline between Medicina and Sejong. An open issue, which concerns single band data, is the correction for ionospheric effects on antenna delays; so VieVS v3.3 [22] was also used for analysis. An External Ionospheric File matching the observing scan sequence was created in VieVS taking the vertical Total Electron Content values from the International GNSS Service Global Ionospheric maps. The comparison work between the quantitative results obtained by the Bologna and KASI datasets is still ongoing and final geodetic and metrological results will be published in a forthcoming paper.

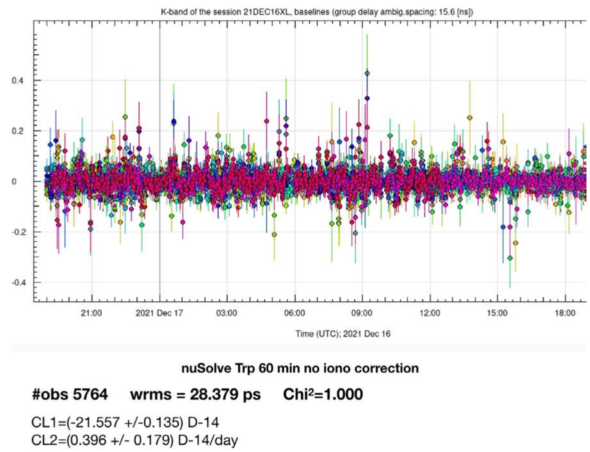

Fig. 3 Residuals of the group delays in the December 2021 experiment, analyzed using *nuSolve*.

4 Conclusions and Outlook

We have described why it is important to compare distant optical clocks for the redefinition of the SI second by 2030 and how this aim will be achieved over longer distances—where fiber optic links become unavailable—using GNSS, TWSTF transfer, and VLBI techniques. We described the Italy–Japan optical clock comparison via the VLBI technique using small transportable antennas, which improved the performance of the GNSS frequency transfer measurement campaign, carried out simultaneously, by almost a factor of 2. Then, we reported on the start of a campaign of observations and measurements aimed at comparing optical clock frequency differences over the intercontinental distances between Italy and Korea, using the K-band VLBI geodetic technique, as a pilot project in view of future developments.

In fact, the Italian–Korean collaboration involving metrological and radio astronomy institutes will make use of the Korean Compact Tri-band Receivers (CTRs) that operate simultaneously in K, Q, and W bands [23] and space geodesy techniques. The CTR is being installed on Italian radio antennas and in Korea on the KVN Yonsei and Pyeonchang antennas. KISTI, KRISS, and KASI are also working to implement a fiber optic coherent frequency link between KRISS and KVN antennas. This time frame will allow our collaboration to test the overall infrastructure and observation techniques. In addition to the experiment described in this paper, a further campaign was performed last March, in which the H-maser of Medicina was connected to the INRiM Cs fountain via IQB fiber link and the H-masers of Sejong and Yonsei were connected to the KRISS Cs fountain and Ytterbium clocks via KISTI fiber link.

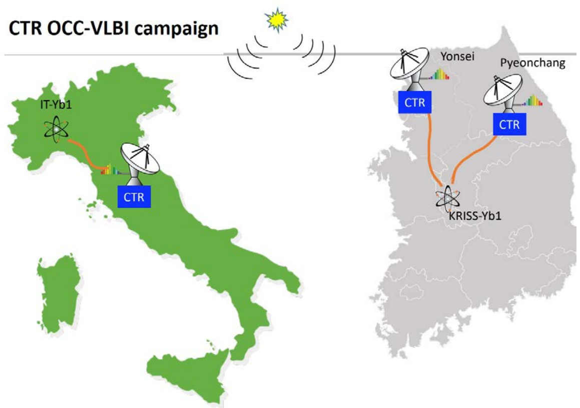

Fig. 4 Planned CTRs OCC-VLBI campaigns.

The future prospect is the use of CTRs in Medicina, Pyeonchang, and Yonsei for OCC campaign (Figure 4). An optimal frequency setup in the range 18–116 GHz on the CTRs will be selected. Target sources in common view between Italy and Korea and based on antenna sensitivity and absence of source structure will be chosen from the International Celestial Reference Frame [24]. VieSched++ [25] will be used to simulate the best scheduling strategy. High-speed dedicated link for data transfer will be implemented by GARR (Italy) and KISTI (Korea). The large volume of raw data will be correlated by the DiFX correlator both in Italy and Korea. This will be performed by an upgraded Bologna computing cluster and Korea national supercomputer. Data analysis of the correlated fringe-fitted datasets will be performed on VieVS, nuSolve, and PIMA [26]. The Source Frequency Phase Referencing technique [27] will also be explored together with injected phase cal signal for improving phase stability and thus the uncertainty on the clock rate. At the same time as the VLBI sessions, a GPS-IPPP measurement campaign will also be carried out in order to compare the two techniques. The project's ultimate goal by 2026 is to measure clock frequency differences with a relative uncertainty level of 10^{-17}.

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