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Intercontinental optical clock comparison using the geodetic VLBI technique in K-band

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Abstract Comparing distant atomic clocks is very important for international timekeeping, global positioning and tests of fundamental physics. Optical clocks are the most technologically advanced devices for frequency generation with a stability of 10^{-18}. In the near future they could be used in the redefinition of the SI second replacing the current one defined using the microwave transition of a Cs atom. Optical fiber link networks allow the most performing optical clocks to be compared on distances up to two thousand kilometers, but for longer distances clock comparisons are limited by the performances of satellite frequency transfer techniques. In this presentation we show the use of high-frequency geodetic VLBI as an alternative technique for long distance frequency transfer. A K-band 24-hour experiment involving six antennas between Europe and Korea was carried out in order to estimate the clock rate between the H-masers of Medicina and KRISS sites. These masers were connected and calibrated against two Ytterbium lattice optical clocks in INRiM (Italy) and KRISS (Korea). The fractional frequency difference between the optical clocks was thus evaluated.

Keywords Optical clocks, VLBI technique, optical fiber links

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1 Introduction

Atomic clocks based on optical transitions can reach fractional frequency uncertainties at the 10^{-18} level (McGrew et al. (2018),Ushijima et al. (2015), Brewer et al. (2019)) already improving by two order of magnitude the performance of microwave clocks such as Cesium fountains (Wynards & Weyers (2005)) that are used to define the International System of Units (SI) second and are the standard in international timekeeping (Panfilo & Arias (2019)). Based on the fast improvement in optical clock technology it is foreseen that optical clocks will replace the Cs fountains in the definition of the SI second (Riehle et al. (2018)). The remote comparison of such clocks on intercontinental distances is fundamental to check their consistency in view of such a redefinition. Optical clocks are also already used in tests of special and general relativity (Sanner et al. (2019)), laboratory searches of the variation of fundamental constants (Godun et al. (2014)) and chronometric levelling (i.e. the usage of gravitational redshift to determine absolute height differences, (Grotti et al. (2018), Mehlstäubler et al. (2018)). Future applications of clock comparisons also involve the establishment of quantum networks for secure communications and timing (Komar et al. (2014)) and gravitational wave detection (Kolkovitz et al. (2016)). Coherent optical fibre links can disseminate frequency references via optical frequency combs up to about two thousand kilometres with frequency instabilities of the order of 10^{-19} (Calonico et al. (2014), Clivati et al. (2015), Clivati et al. (2020)) but they cannot be used on intercontinental distances. On such large distances optical clock comparisons rely upon GNSS frequency transfer (via the Integer Precise Point Positioning technique, (Petit et al. (2015)) and Two-Way Satellite Time and Frequency Transfer (TWSTFT, Fujieda et al. (2014)). A recent addition to this suite of frequency trasfer techniques is space geodesy: the Very Long Baseline Interferometry (VLBI) observations of distant quasars to study Earth crustal motions and orientation parameters (Pole wobbling and Length of Day). Clock model parameters in network antennas are also adjusted in the Normal Equation minimization and are then used to compare the behaviour (in particular the clock drift) of H-maser station clocks and thus optical clocks in a metrological chain.

A successful VLBI campaign to compare optical lattice clocks between National Institute for Communication Technology (NICT, Japan) and Istituto Nazionale di Ricerca Metrologica (INRiM, Italy) has been carried out in 2018-2019 (Pizzocaro et al. (2021), Sekido et al. (2021)), in which two small (2.4-meter diameter) transportable antennas (nodes), one located in Koganei (Japan) and the other at the radio station of Medicina have observed a list of bright quasars together with a large (34-meter) antenna (the hub) in Kashima (Japan), all three antennas being equipped with broadband (2-14 GHz) NINJA feeds. The node-hub configuration was chosen because the small antenna pair do 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 commanding 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 via a leg of the Italian Quantum Backbone (IQB) for optical fiber frequency reference dissemination (the Torino-Medicina 550 km link, Clivati et al. (2020)) 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 term of uncertainty with respect to the frequency deviation obtained via GPS-IPPP ($y(Yb/Sr) = -3.2(4.0) \times 10^{-16}$).

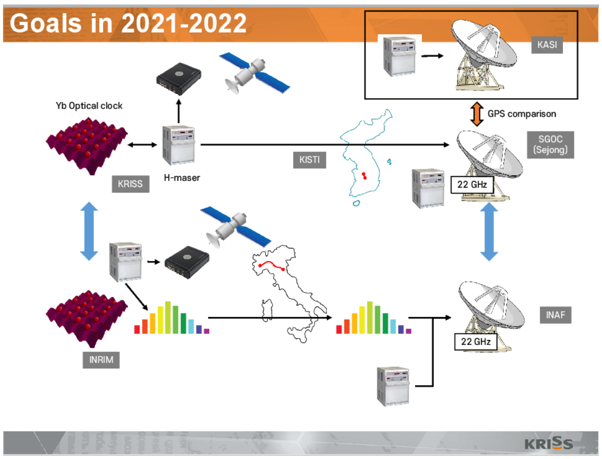

Fig. 1 Schematic view of the full experiment set-up in the 2021 Dec observations.

2 Method

We used the geodetic VLBI technique in a network of antennas between Italy (32-m antenna in Medicina), Spain (40-m Yebes antenna) and Korea (one 22-m National Geographic Information Institute Sejong VLBI antenna and three 21-m Korean VLBI Network antennas, KVN) to determine the fractional frequency difference between H-maser clocks in Korea and Medicina and thus indirectly compare the Yb optical lattice clocks in the national metrological institutes INRiM (Torino, Italy) and Korean Research Institute for Standards and Science (KRISS, Korea) by estimating their relative frequency deviation. 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

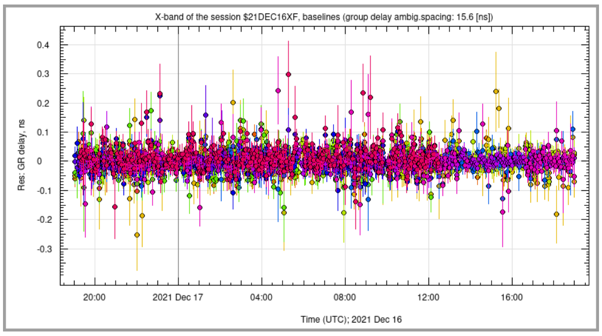

Fig. 2 Residuals of the Group Delays in the 2021 Dec experiment analysed using nuSolve. No ionospheric correction was applied at this stage.

disciplined H-maser clock in Torino with the Medicina station H-maser clock. The VLBI sessions are matched by a GPS-IPPP measurement campaign for the comparison between the two techniques (see Fig. 1 for a scheme of the full experimental set-up).

3 Results

The first observing session in the Optical Clock Comparison VLBI campaign was performed on Dec 16th-17th, 2021 in a 24-hour experiment in K-band at the frequency range 21-21.4 GHz. Six antennas were involved: Medicina, Yebes, Sejong (already part of the IVS network) plus the three antennas of the Korean VLBI Network (Tanma, Yonsei and Ulsan). Sur_sked was used to schedule the run made of 450 scans with targets chosen from a list of tens of sources in a typical geodetic scheme: short scans (2-3min) were performed spanning all azimiths and elevations available at the observing stations in order to better characterise the tropospheric parameters. The LEVEL0 raw data from the six antennas were transfered to the Bologna and KASI data centres for correlation. Fringe fitting was performed in HOPS *fourfit*. A VGOSdb database was created and read into nuSolve (Bolotin et al. (2014)) and VieVS v3.2 (Boehm et al. (2018)) for analysis. As the data are single-band in order to correct for ionospheric effects on antenna delays 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. Standard a-priori model set-ups were used in the data modelling including Vienna Mapping Functions v3 (VMF3, Landskron & Boehm (2018)) for the treatment of tropospheric delay. The group delay residuals vs observing time are shown in Fig. 2. The relevant clock parameters (clock rate and its uncertainty) on the baseline between Medicina and Sejong were extracted from the VieVS LEVEL3 parameter output structure. The comparison 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.

4 Conclusions and outlook

Here we described why it is important to compare distant optical clocks for the redefinition of the SI second by 2030 using an optical frequency transition as the standard and how this purpose will be achieved: on the longest distances, where optical fiber links become unavailable, using the GNSS, TWSTF transfer and VLBI techniques. We then moved to describe the Italian-Japanese optical clock comparison via the VLBI technique achieved through the use of customed built small-dish transportable antennas which improved on the performance of the GNSS frequency transfer measurement campaign carried out simultaneously by almost a factor of 2. Finally we reported on the start of an observing and measuring campaign aimed at comparing optical clock frequency differences on intercontinental distances between Italy and Korea using the geodetic VLBI technique in K-band.

The Italian-Korean collaboration involving metrological and radio astronomical institutes will make use of the Korean-designed Compact Tri-band Receivers (CTR) operating simultanously at K-, Q- and W-band (Han et al. (2017)) and of space geodesy techniques. The CTR will also be installed on Italian radio antennas in 2024 and in Korea on the KVN Yonsei antenna and on the new Pyeonchang antenna. KISTI, KRISS and Korea Astronomy and Space Science Institute (KASI) are also working on implementing coherent wave optical fiber frequency link between KRISS and the Korean antennas. This time gap will allow our collaboration to test the general infrastructure and observing techniques. An optimal frequency set-up 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 (Charlot et al. (2020)). VieSched++ (Schartner & Boehm (2019)) 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 LEVEL0 data will be correlated by the DiFX (Deller et al. (2007)) 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 or nuSolve. The Source Frequency Phase Referencing technique (Rioja & Dodson (2020)) will also be explored together with injected phase cal signal for improving phase stability and thus the uncertainty on the clock rate. A GPS-IPPP measurement campaign will be also carried out commensally to the VLBI sessions in order to compare the two techniques. The final goal of the project by the year 2026 is to to measure clock frequency differences with a relative uncertainty level of 10^{-17}.

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