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# Intercontinental Comparison of Lattice Clocks using a Broadband VLBI Technique

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**Abstract**—We performed a frequency comparison of lattice clocks in Tokyo and Torino for the first time using broadband VLBI technique. Two portable antennas with 2.4 m diameters were installed at NICT Koganei headquarters and INAF Medicina Radio Observatory, close to Bologna, Italy, realizing a VLBI network together with Kashima large-aperture antenna of 34 m diameter. The clock signal at INAF was evaluated by INRIM using an optical fiber link between Medicina and Torino. The fractional frequency difference that VLBI evaluated was consistent with the difference between two HM frequencies which were separately calibrated by a Sr lattice clock at NICT and a Yb lattice clock at INRIM.

**Keywords**—VLBI; frequency transfer; optical clock;

## I. INTRODUCTION

Very long baseline interferometry (VLBI) is routinely used for the measurement of earth rotation, contributing to the determination of leap seconds. Two physically separated antennas receive a common microwave from cosmic objects, and the time correlation of the two signals indicates the differential distance from the microwave source. Thus, VLBI is one of major geodesy tools like GNSS or satellite laser ranging (SLR). Correlation process requires a stable base clock in both sites. Currently hydrogen masers (HMs) are employed for the base clock owing to their superb short-term stability. Search of the correlation in two signals is not straightforward since the two base clocks are physically separated and are not synchronized. Furthermore, the effective delay of two signals varies with time owing to the earth rotation, propagation effects, and frequency difference of base clocks.

The analysis assumes the fractional difference of two HMs and attempts to find a maximum correlation strength under a certain fractional frequency difference of two HMs. This means that VLBI can measure the fractional difference of two HMs which are separated even in intercontinental distance. Here, we show such frequency comparison of two HMs, one in INAF, (Medicina, Italy) and the other in NICT (Koganei, Tokyo). This scheme of the VLBI comparison is realized by a close collaboration of three institutes, namely NICT, INRIM, and

INAF. Together with GNSS PPP process, the two HMs are precisely calibrated by optical lattice clocks and it was proved that the fractional difference led by VLBI technique is consistent with the calibrations. Note that the HM in INAF is calibrated by the Yb lattice clock in INRIM using LIFT infrastructure, which is the Italian fiber link from INRIM (Torino) to INAF (Medicina) [1].

## II. METHODS/RESULTS

The setup in Italy and Japan is schematically shown in Fig. 1. It is distributed in four campuses. Kashima equips large aperture antenna of 34 m diameter. We installed portable antennas with diameters of 2.4 m each in Koganei and Medicina. These three campuses already have VLBI activities routinely. Thus, they equip hydrogen masers and have access to high speed research network JGN and GARR, respectively, for the massive data transfer. Those two small antennas are node-station for clock measurement, and the large diameter antenna in Kashima works as a hub VLBI station to enhance the signal-to-noise ratio of this VLBI network observation [2]. We can calibrate the frequency of the HMs in Koganei and Medicina independently using optical lattice clocks. Koganei locally equips a strontium lattice clock [3]. Medicina, on the other hand, does not have reliable atomic frequency reference. However, the fiber-link between Medicina and Torino allows us to calibrate the HM in Medicina using a ytterbium lattice clock operated in Torino [4].

All three antennas load broadband (3.2 – 14.4 GHz) feeds which allow receiving the radio wave in 3-15 GHz. We choose four frequency bands around 6.0, 8.5, 10.4 and 13.3 GHz with the bandwidths of 1024 MHz each. These four broad band signals are synthesized to derive precise group delay by wideband bandwidth synthesis (WBWS)[5]. Two delay observables are derived by the WBWS for Koganei-Kashima and Kashima-Medicina baseline. Then delay observable between Koganei-Medicina is obtained by closure delay relation [6]. An advantage of this technique is that all the delay contribution of large diameter station can be canceled out, and drawback is influence of radio sources structure effect in

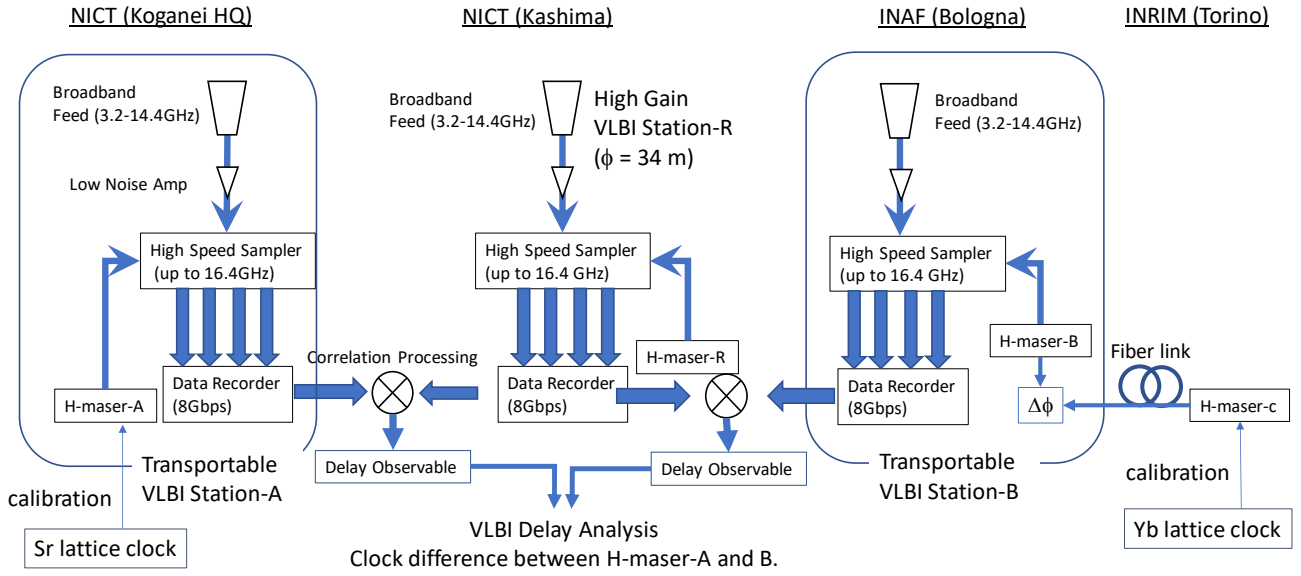


Fig.1. Schematic diagram of the experiment. VLBI technique connects three sites of NICT(Koganei), NICT(Kashima) and INAF(Medicina). Italian fiber link between Medicina and Torino realizes the frequency link all the way from a Sr lattice clock at NICT (Koganei) to a Yb lattice clock at INRIM (Torino).

closure delay [6]. Radio sources are selected to minimize the source structure effect. Time difference between the HMs in Koganei and Medicina is derived by geodetic analysis with the CALC/SOLVE package developed by NASA/GSFC. A result obtained by a VLBI session on 15 Oct. 2018 is shown in Fig. 2, where the linear fitting lead to the fractional frequency difference of two HMs.

We performed one session of the VLBI observation for 29 hours. The HM frequencies in Koganei and Medicina were monitored by lattice clocks in NICT and INRIM, respectively. The HM frequency provided to VLBI in Koganei was evaluated by intermittent operation of a Sr lattice clock [4]. In the month including the VLBI observation, the Sr clock was operated once in two weeks or more for 3 hours in NICT. On the other hand, INRIM sends an HM signal to INAF using a fiber link, and the phase difference between the HM in INAF and that in INRIM is always monitored in Medicina. The HM in INRIM is calibrated by a local Yb lattice clock. The two calibrations by Sr and Yb lattice clocks lead the fractional frequency difference of the two HMs to be  $4.134(11) \times 10^{-13}$ , which agreed with the slope in Fig. 2. In the presentation, we will also present the result obtained by NRCAN PPP (and possibly Atomium PPP) granting NRCAN and ROB institutes for the SW provision.

### III. ACKNOWLEDGEMENTS

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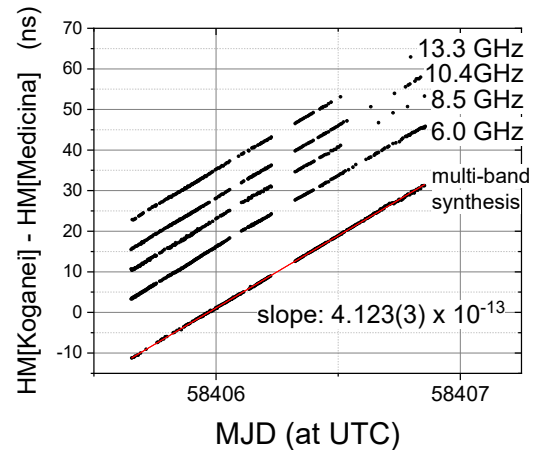


Fig. 2 Change of the time difference between two HMs in NICT(Koganei) and INAF(Medicina) using VLBI technique, where delays are measured in four frequency bands followed by multi-band analysis. The fractional frequency difference of two HMs is calculated from the slope.