A Broadband VLBI experiment with transportable stations between Japan and Italy with a new observation scheme using closure delay relation

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Abstract A broadband VLBI system inspired by the concept of VGOS was developed by NICT and implemented in the Kashima 34 m antenna and in two transportable stations utilizing 2.4 m diameter antennas. The transportable stations were conceived as a tool for intercontinental frequency comparison but are equally useful for geodesy. In the procedure of node-hub style (NHS) VLBI, the closure delay relation provides a virtual delay observable between 'node' stations, thanks to joint observation with a large, high sensitivity 'hub' antenna. This overcomes the limited sensitivity of the small diameter node antennas, while error sources associated with large diameter antennas (e.g., gravitational deformations) are eliminated. This scheme does not increase the sensitivity to radio source structure if the hub antenna is located at intermediate position between two nodes. We performed VLBI experiments utilizing this approach over 8700 km baselines among Medicina, Koganei, and Kashima, with the aim of comparing two remote optical clocks. We used the Vienna mapping function (VMF3) for atmospheric delay corrections including its anisotropic components. The performance of NHS VLBI scheme was evaluated to be comparable with IVS-R1 and R4 sessions via baseline length repeatability. The NHS VLBI scheme can be applied at VGOS observation stations, and it may become a tool for improving the global distribution of geodetic VLBI station and for co-location with other space geodetic techniques. Our measurements revealed signatures of structure effects in the correlation amplitude of several of the observed radio sources. We present a model of the frequency dependent source size for 1928+738 derived from correlation amplitude data observed in four frequency bands. Finally, this system demonstrated in intercontinental frequency comparison performance beyond satellite techniques and can potentially be used for future long-term stable international clock comparison that is fundamental to international timekeeping, global positioning and test of fundamental physics.

Keywords Broadband VLBI, Direct RF-sampling, Closure delay

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1 Introduction

Redefinition of the SI second as the unit of time is being discussed in the metrological community (Riehle, 2015), thanks to the development of high accuracy optical frequency standards reaching 10^{-18} accuracy (Riehle et al., 2018). Accurate frequency comparison between atomic clocks at distant locations is an important issue and requires accurate methods. Frequency transfer by optical fiber-link reaches uncertainties below 10^{-18} (Lopez et al., 2012; Predehl et al., 2012; Calonico et al., 2014), then, several attempts of intercontinental frequency link have been tried. Two-way satellite time and frequency transfer (TWSTFT) using signal's carrier phase has the potential to reach instabilities on the order of 10^{-17} (Fujieda et al., 2016). The availability of suitable communication satellites and the need to license radio transmissions limit its applicability. Precise Point Positioning (PPP) methods using the carrier phase of Global Navigation Satellite Systems (GNSS) are used to maintain time links between national time standards agencies. Integer-ambiguity techniques (IPPP) (Petit et al., 2015) can also reach instabilities of order 10^{-17}, but need continuous measurements over longer averaging durations.

VLBI application for time and frequency transfer has been investigated since the 1970s (e.g. (Counselman et al., 1977; Saburi, 1978; Clark et al., 1979(@)), and an uncertainty of $1.5 \cdot 10^{-15}$ for a time period of 1 day has been reported in an earlier study (Rieck et al., 2012). VLBI is not restricted by the availability of communication satellites or the requirement of licensed radio transmission and relies on observing extragalactic radio sources of the international celestial reference frame (ICRF).

The concept of broadband VLBI observation proposed as VLBI Global Observing System (VGOS) (Petrachenko et al., 2012; Niell et al., 2018) improves the delay measurement precision by one order of magnitude over conventional S/X-band VLBI, using a ten times wider bandwidth of observing radio frequency. A higher data acquisition rate contributes to improvement of observing sensitivity as well. We developed the broadband VLBI system named 'GALA-V' (Sekido et al., 2017) with the aim to enable intercontinental precise frequency comparison. Transportable broadband VLBI stations can be installed at selected locations, such as metrology institutes operating next-generation frequency standards. The 34 m antenna located at Kashima Space Technology Center provides the high sensitivity used to boost the SNR of observations.

2 Broadband VLBI System and NHS observations

NICT (National Institute of Information and Communications Technology) developed the NINJA feed system (Ujihara et al., 2019) to use existing Cassegrain antennas, which have narrower bean size with respect to VGOS stations (e.g., 34 ° for the Kashima 34 m antenna), for broadband observations (in the range of 3.2-14 GHz). It was installed on the Kashima 34 m antenna (Kas34) and two 2.4 m diameter antennas (MBL1 and MBL2). The receiver employs a room-temperature low noise amplifier rather than a cryogenic LNA to save cost and time for development, installation, and maintenance. The NINJA feed allows simultaneous observation of V and H linear polarization. Signals of both polarizations are acquired in Kas34, while the 2.4 m antennas only record the V-polarization signal. This is a compromise, in particular because data recorded at a remote site have to be transferred to the correlation center at the Kashima Space Technology Center. Although it was performed over high-speed research networks, the present data transfer rate is only about half of the data acquisition rate for a single polarization, therefore the acquisition of both polarization would result in doubling the turnaround time. Thus, single polarization observation were performed at the remote sites and the correlation data were synthesized to form an emulated polarization-aligned dataset.

Unlike VGOS, the received RF signal is amplified and separated into lower (0–8192 MHz) and upper ($>$ 8192 MHz) signals by a power divider and filters. Each of these signals is then directly digitized at 3-bit quantization by a high-speed sampler K6/GALAS (Takefuji et al., 2012; Sekido, 2015) with 16,384 MHz sampling rate. The sampler then extracts the four desired signals with 1024 MHz bandwidth per polarization at 6.0, 8.5, 10.4, and 13.3 GHz. This data acquisition process named RF-direct sampling (RFDS) digitizes the signal in early stage without analog frequency conversion. It reduces relative phase variation of the channels, consequently improves stability of group delay measurement. The RFDS technique brings large benefits for phase calibration, polarization synthesis, and wideband bandwidth synthesis in the signal processing.

Emulating the polarization aligned cross correlation products is formed by synthesizing two correlation products VH and VV by compensating the parallactic angle difference of the long baseline (see Sekido et al. (2021)). Then, group delay is derived by wideband bandwidth synthesis (WBWS) software 'komb' (Kondo and Takefuji (2016)). Differently from conventional S/X observation, the WBWS requires simultaneous estimation of differential ionospheric electron column density in the line of sight together with broadband group delay (e.g. Cappallo (2016)).

When applying VLBI for long-distance frequency comparisons, small 'node' stations are convenient for installation near the frequency standards, but it may be impossible to obtain the delay observable between the two due to reduced correlated flux for long baseline. Joint measurements with a high sensitivity 'hub' station overcome this problem by evaluating the closure relation for the full measurement network, in a scheme named 'Node Hub style' (NHS) VLBI. Thanks to the large effective bandwidth (2.7 GHz), the delay precision is achieved with minimum SNR. Besides flexibility and low cost, a small VLBI station also avoids gravitational antenna deformation and can help reduce temperature-dependent signal transmission cable length change. A delay observable in the NHS VLBI scheme is schematically depicted in Figure 1, where also Kas34, MLB1 and MLB2 antennas are displayed. A detailed discussion can be found in Sekido et al. (2021).

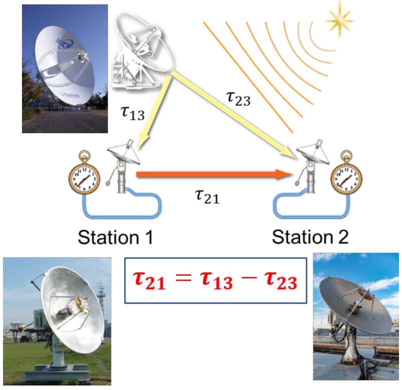

Fig. 1 NHS scheme and the three antennas involved in the project: above Kashima, on the left MLB1 installed at the Medicina Observatory and on the right MLB2 located in Koganei.

3 Optical clock comparison between Italy and Japan

The MBL2 antenna was installed at NICT Headquarters in Koganei and MBL1 was moved from Japan to Medicina Observatory in August 2018. The observed RF signal was converted to optical within the temperature controlled receiver box and then transferred to the Medicina VLBI station, over approximately 600 m of optical fiber placed in an underground trench, where the data acquisition system was placed. The purpose of the installation was to compare optical atomic frequency standards between NICT and INRiM (Istituto Nazionale di Ricerca Metrologica, Torino), connected to INAF via optical fiber link (Calonico et al., 2014). Several hydrogen maser frequency references were used as flywheels to bridge interruptions in operation of clocks and links. More details on the frequency link are described in Pizzocaro et al. (2021). A series of VLBI sessions during October 2018–February 2019 focused on comparing optical atomic frequency standards (the Yb clock at INRiM and the Sr clock at NICT) to a fractional uncertainty of only a few parts in 10^{-16}. In addition to the VLBI measurements, results from GPS data analysis, using improved integer ambiguity solution of Precise Point Positioning (IPPP) (Petit et al., 2015) were produced and compared, demonstrating consistent determination of differential clock behavior between two observation nodes across multiple VLBI sessions.

4 Evaluation of error source for NHS VLBI

The VLBI sessions were analyzed with Calc/Solve and the overall quality of the solutions can be stated with the WRMS of post-fit residuals of the single sessions of the order of a few tens of picoseconds. The use of Vienna Mapping Function (VMF3) (Landskron et al., 2018) to compute the a priori atmospheric delays included in data analysis contributed to overcome the problem of a single intercontinental baseline, which made it difficult to estimate anisotropic properties of the atmosphere, usually parameterized by atmospheric gradients. We examined baseline length repeatability (BLR) to evaluate the performance of NHS VLBI observations between the two small antennas and we found that the results are comparable to the IVS-R1 and R4 sessions using legacy S/X antennas (Figure 2). Moreover, IVS-R1 and R4 sessions take advantage of network observations with five to eleven stations, providing better sky coverage and a better estimation of atmospheric contributions, in particular the anisotropic component. The effectiveness of network observation with respect to single baseline is displayed for the two baselines: Wettzell(Wz)-Tsukuba(Ts) baseline (8840 km) and Wz-Kokee(Kk) baseline (10360 km), in Table 1. Using atmospheric gradients and network observation more effectively improves BLR for very long baselines. The group delay observable is affected by various factors, including instrumental delay and source structure effects. Table 2 gives an overview of the magnitude of uncertainty contributing to delay residual from each component, which are discussed separately in Sekido et al. (2021). We discussed how these effects affect the result of a single scan and the group delay instability is presented as a RMS-deviation from the mean.

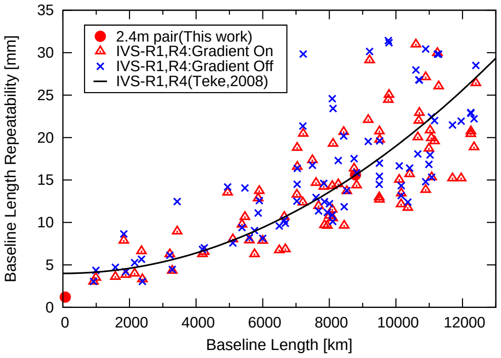

Fig. 2 BLR for NHS baselines (red circle) and our re-evaluation of IVS-R1 and R4 sessions during 2011–2013 with Gradients ON (red triangle) or OFF (blue cross). The solid line represents a regression function of BLR for IVS-R1 and R4 sessions presented in Teke et al. (2008).

Table 1 Baseline repeatability (BLR) for Wz-Ts and Wz-Kk baselines.

BLR (mm)	Atm. Grad. OFF		Atm. Grad. ON	
	Single	Network	Single	Network
Wz - Ts	12.8	12.1	12.4	9.9
Wz - Kk	48.3	12.4	37.2	11.7

Table 2 Group delay uncertainty for NHS VLBI.

Error Source	Uncertainty (ps)
Sensitivity ($\propto 1/\mathrm{SNR}$)	6.4
Instrumental	12.7
Troposphere	8.2
Ionosphere	1.7 - 17.2
Radio Source Structure	22.0 - 33.0

The influence of radio source structure on group delays has been investigated through closure delays (e.g. (Xu et al., 2019)). In our measurement, we did not achieve sufficient SNR on the baseline between the two small antennas. However, we found that the correlation data output of the Kas34-MBL1 baseline, after the polarization synthesis, provided information about radio source structure. Some high latitude sources have been observed through the NHS campaign. As an example, we present a simple ellipsoidal Gaussian model of 1928-738 derived from correlation amplitude data for each frequency band (Figure 3). Despite the limited sensitivity of the small antennas, the spatial resolution is sufficient to resolve sub-milliarcsecond structure. The data in Figure 3 show a larger deviation from the model at higher frequencies, suggesting that these frequencies better resolve the source structure. The observation of band-dependent source structure has additional implications for broadband VLBI. That can be an error source of broadband group delay determination by coupling with dispersive ionospheric phase delay contribution.

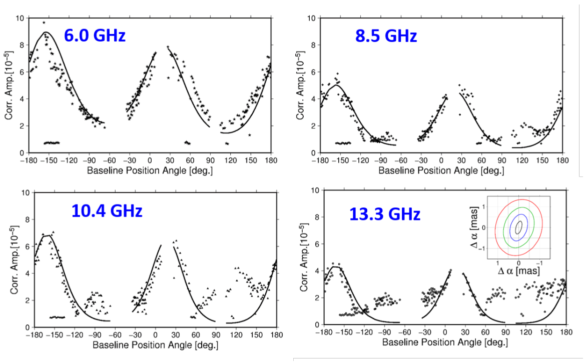

Fig. 3 Model of the frequency dependent source size for 1928+738.

5 Summary and outlook

Two transportable 2.4 m broadband VLBI stations were installed at Medicina and Koganei for a intercontinental frequency link experiment, using Kashima 34 m antenna in a Node-Hub Style scheme. Precise frequency comparison between the Yb lattice clock at INRiM and the Sr lattice clock at NICT has been performed with broadband VLBI sessions, carried out from October 2018 to February 2019. The experiments made use of signal processing for polarization and broadband bandwidth synthesis, and confirmed that the 2.4 m diameter size radio telescopes achieved a precision of few tens of picoseconds in NHS measurements over an intercontinental baseline.

The frequency ratio Yb/Sr between optical clocks was measured as $+2.5(2.8) \cdot 10^{-16}$ on 9000 km distance. Dominating delay error sources are ionospheric delay ($\approx$2-17 ps) and radio source structure (20-30 ps). NHS VLBI has potential to reduce structure effect in group delay observable.

Legacy (equipped with broadband systems) or VGOS antennas could be used as Hub stations in the NHS scheme. VLBI stations with coherent optical fiber links can play a role to compare optical clocks of National Metrology Institutes over intercontinental distances. High speed network for fast data transfer and dedicated resources for correlation processing will the required condition for it.

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