ITA-JPN Broadband VLBI Experiment for Optical Clock Comparison

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Abstract NICT has developed a broadband VLBI (very-long-baseline interferometry) system for intercontinental frequency transfer. After domestic tests in Japan, a 2.4 m diameter VLBI station was exported and installed at Medicina astronomy observatory of INAF in Italy in 2018. We have started VLBI experiments for optical clock comparison on an Italy-Japan intercontinental baseline. Reference signals generated by an ytterbium (Yb) optical lattice clock at INRiM in Torino and by a strontium (Sr) lattice clock at NICT headquarters in Koganei are compared by a series of links, which include a coherent optical fiber link between INRiM and Medicina and intercontinental VLBI observation between Medicina and Koganei. A series of VLBI experiments was performed from Oct. 2018 to Feb. 2019. Yb and Sr lattice clocks were repeatedly operated throughout the same period for frequency comparison.

Keywords Broadband VLBI, Frequency Comparison

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1 Introduction

Driven by fast development of high accuracy optical frequency standards reaching 10^{-18} accuracy (Riehle et al., 2018), re-definition of the “second” as the unit of time is being discussed in the metrological community (Riehle, 2015). For this, accurate frequency comparison between atomic clocks at distant locations is an important technology. Frequency transfer by optical fiber-link reaches uncertainties below 10^{-18} (Lopez et al., 2012; Predehl et al., 2012; Calonico et al., 2014), but it requires an infrastructure of suitable fibers and bidirectional optical amplifiers. Two-way Satellite Time & Frequency Transfer (TWSTFT) is another technique used for international time and frequency links over distances of thousands of km. Advanced TWSTFT using carrier phase has a potential to reach instabilities in the order of 10^{-17} (Fujieda et al., 2016). This relies on the availability of suitable communication satellites. Limited available bandwidth and high operating costa are additional drawbacks. Observation of GPS satellites is routinely used to maintain time links between national time standards agencies. The lowest uncertainty of frequency links by GPS signals is in the order of 10^{-16}, achieved by a technique of precise point positioning processing with integer ambiguity solution(IPPP) (Petit et al., 2015). VLBI is another space geodetic technology with potential for precise frequency comparison over intercontinental distance. In contrast to TWSTFT, VLBI is not restricted by the availability of communication satellites or the requirement of licensed radio transmission. The VLBI technique relies on observing extragalactic radio sources of the international celestial reference frame (ICRF). These form fiducial points in the sky, whereas GPS observations rely on estimated satellite orbits, that vary with time. High precision GPS processing observes phase signals that require careful processing to avoid errors from cycle ambiguities. Broadband VLBI provides an absolute group delay observable that is free from ambiguity, and precision in the order of pico seconds. These properties are the foundation for long-term stable VLBI frequency links. Based on this perspective, we have developed a broadband VLBI system for an intercontinental frequency link. We expect to achieve uncertainties in the order of 10^{-17} with comparing stable hydrogen maser (HM) standards over several days of time span.

The concept of broadband VLBI observation proposed as VLBI Global Observing System (VGOS) (Petrachenko et al., 2009; Niell et al., 2018) is an innovative system to improve the delay measurement precision by one order of magnitude over conventional S/X-band VLBI. This is achieved by ten times wider bandwidth of observing radio frequency. A higher data acquisition rate contributes to improvement of observing sensitivity as well. Based on these advanced properties, we implemented a broadband VLBI system using small diameter transportable VLBI station for frequency comparison.

2 Broadband VLBI System and Observation Scheme

2.1 Broadband VLBI System

Our broadband VLBI system named GALA-V (Sekido et al., 2017) implements the broadband VLBI concept of the VGOS. Radio telescopes capable of observing the frequency range of 3-14 GHz are used for observation. The employed observation mode differs slightly from the prototype VGOS 'Proof of Concept(PoC)' implementation (Niell et al., 2018) developed by MIT Haystack observatory and NASA/GSFC. In contrast to the PoC VGOS terminal, which acquires data on more than one hundred channels with 32MHz frequency width, we adopted a simpler data acquisition using four channels of 1 GHz bandwidth. A unique technique in our data acquisition system (DAS) is the use of RF-Direct sampling (RFDS) (Takefuji et al., 2012). The observed radio signal of one polarization is amplified by low noise amplifier and divided into two upper and lower frequency band, limited to 8192 MHz width by anti-aliasing filters. Each signal is then digitized at radio frequency with 16,384 MHz sampling rate. Frequency selection and band shaping are performed by digital signal processing implemented in the sampler. Four streams of 2048 Msps 1bit quantization data comes out via optical fiber cables as Ethernet packet stream in VDIF format (Whitney et al., 2014) per single polarization. Compared to 16 MHz width conventional S/X-band VLBI, 1024 MHz bandwidth provides a sensitivity advantage by a factor of $\sqrt{1024/16} = 8$ for single channel fringe detection.

The advanced delay precision and sensitivity of the broadband VLBI open the possibility to utilize small diameter stations for geodesy and frequency transfer over intercontinental distances. Besides wideband data acquistion, we employ joint observation with a large diameter antenna (*R*) to compensate the low sensitivity of small diameter antennas (*A,B*). By using the closure delay relation, the delay observable of the *A-B* baseline is composed of a linear combination of *R-A* and *R-B* baselines. This scheme is not only useful for using small VLBI stations, but also for eliminating the delay variation due to large diameter antennas; such as gravitational distortion and electric cable length variation due to temperature and stress change. We name this type of observation "Node-Hub" style (NHS) (Sekido, 2017), and have confirmed it by domestic evaluation in Japan and intercontinental experiments between Italy and Japan.

2.2 Frequency Link with Transportable Broadband VLBI Station.

Prior to the experiments over intercontinental baseline, we evaluated the system in a collaboration between National Metrology Institute of Japan (NMIJ) and NICT, two national metrological agencies in Japan, that generate the local time scales UTC(NMIJ) and UTC(NICT). These time scales are regularly compared with UTC and reported to BIPM. This provides an excellent basis to evaluate the NHS VLBI frequency link with respect to the other techniques, and we confirmed that eliminating the delay variation caused by large diameter antenna indeed results in an improved post-fit delay residual: The experiments show a weighted RMS of about 10 pico seconds.

The difference of UTC(NMIJ)-UTC(NICT) obtained by precise point positioning (PPP) analysis of GPS data is routinely published by BIPM (BIPM, 2017). Integer-ambiguity PPP (IPPP) processing (Petit et al., 2015) provides further improvements. G. Petit and J. Leute of BIPM have courteously provided IPPP data for the UTC(NMIJ)-UTC(NICT) time difference. Comparison of double difference data between VLBI-GPS(IPPP) and GPS(PPP)-GPS(IPPP) over a 10 days span indicates that the VLBI frequency link has better performance than GPS(PPP), at least for long time spans.

3 Intercontinental Broadband VLBI between Italy and Japan

After the domestic experiments in Japan, a 2.4 m diameter broadband VLBI station (MARBLE1) was transported to the Medicina astronomy observatory of INAF/IRA for experiments on an intercontinental baseline. INRiM and NICT are both operating optical lattice clocks as secondary frequency standards. The reference frequency generated by the Yb optical lattice clock at INRiM (Torino) is transferred to Medicina observatory by a coherent fiber link (Clivati et al., 2015), and is used to evaluate a local hydrogen maser (HM). The HM signal is used as the reference of broadband VLBI observation with the 2.4m antenna. In the same way, a HM at NICT headquarters (Koganei) is evaluated using Sr lattice clock NICT-Sr1. The HM provides the reference signal for the counterpart 2.4m VLBI station (MARBLE2) at Koganei. The Kashima 34m antenna contributes to this broadband VLBI in order to improve signal to noise ratio. Observations between the two small VLBI stations are realized by the NHS processing scheme. Fig. 1 shows an overview of the project to link the Yb clock at INRiM and the Sr clock at NICT.

The 2.4m dish and components of VLBI station were delivered to Medicina in July 2018 and assembled over the course of few days (Fig.2). Local infrastructure was prepared by INAF and INRiM, such as optical fiber for signal transmission to the observation room and access to the high speed research networks GARR and GEANT. Thanks to the antenna control software FS9 developed by NASA/GSFC, pointing observations to establish the antenna model were easily realized, along with remote antenna operation from Japan. An initial fringe test was conducted with the support of Ishioka VGOS station of the Geospatial Information Authority of Japan (GSI). Except for the antenna control of Ishioka station, all operation (antenna & DAS control, data transfer, correlation processing) for the fringe test was performed remotely from Medicina during the installation visit, and interferometer fringes were successfully detected. The main series of broadband VLBI experiments via the NHS scheme were then conducted from Oct. 2018 to Feb. 2019 with session length about 30 h, repeated at a 10 days interval (Table 1).

Table 1 VLBI sessions performed from Oct.2018 to Feb. 2019. VLBI observation between MARBLE1(Medicina) and MARBLE2(Koganei) is formed by the NHS scheme in joint observation with the Kashima 34m antenna.

ExpCode	Start Time(UT)	Length[h]	No. Scans
GV8278	05 Oct.2018 07:39	31	593
GV8287	14 Oct.2018 15:35	30	460
GV8297	24 Oct.2018 21:00	29	436
GV8308	04 Nov.2018 02:30	29	464
GV8318	14 Nov.2018 08:00	29	464
GV8328	24 Nov.2018 13:30	29	415
GV8338	04 Dec.2018 19:00	29	471
GV8349	14 Dec.2018 00:30	29	457
GV8359	25 Dec.2018 06:00	29	476
GV9015	15 Jan.2019 06:00	29	479
GV9025	25 Jan.2019 03:00	36	573
GV9035	04 Feb.2019 03:00	31	706
GV9045	14 Feb.2019 03:00	36	786

Fig. 3 shows an example of the delay residuals of the VLBI analysis over the Medicina-Koganei baseline. The weighted RMS of the delay residual was 24 ps in this case. A peculiar splitting of the delay residual for radio sources 3C418 and 2022+542 is clearly visible in the plot. Xu et al. (2019) have reported that 3C418 shows strong signatures of radio source structure in group delay measurement. Investigation on calibration techniques for the radio source structure effects has been continued (Bolotin et al., 2019; Xu et al., 2019). Thus we need to minimize the influence of radio source structure by careful selection of radio sources in scheduling the VLBI session until the calibration method will become widely available. A detailed discussion of geodetic results and frequency comparisons obtained in these experiments will be reported in separate publications.

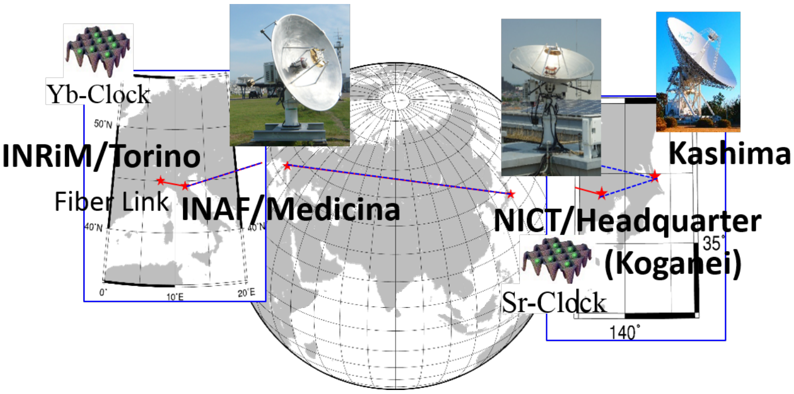

Fig. 1 Overview of the project to compare optical lattice clocks via intercontinental VLBI observation. The Yb lattice clock at INRiM and the Sr clock at NICT are compared by a series of links including optical fiber link between INRiM and Medicina, and intercontinental VLBI observation between Medicina and Koganei.

Fig. 2 Installation of transportable VLBI station at Medicina. The transportable 2.4m antenna consists of separate assemblies for the dish and Az/El drive system. Three persons are sufficient to assemble the system in two days of work (Left and Center). A small air-conditioned box, located 30 m from the antenna, contains antenna control system(right).

4 Summary

A transportable 2.4m broadband VLBI station was installed at Medicina astronomy observatory of INAF for an intercontinental frequency link experiment. Precise frequency comparison between the Yb lattice clock at INRiM and the Sr lattice clock at NICT has been performed by using intercontinental broadband VLBI, with local hydrogen masers acting as flywheels. VLBI sessions were conducted from Oct. 2018 to Feb. 2019 with both Yb and Sr clocks operating throughout the same period. The experiments make use of newly developed signal processing for polarization synthesis and broadband bandwidth synthesis, and confirmed that the 2.4 m diameter size radio telescopes achieve a precision of few tens of pico seconds in NHS measurements over an intercontinental baseline. In addition, radio source structure effects were clearly detected in our data. Until a calibration technique for this effect will become available, we are going to minimize this influence by source selection in scheduling the VLBI session.

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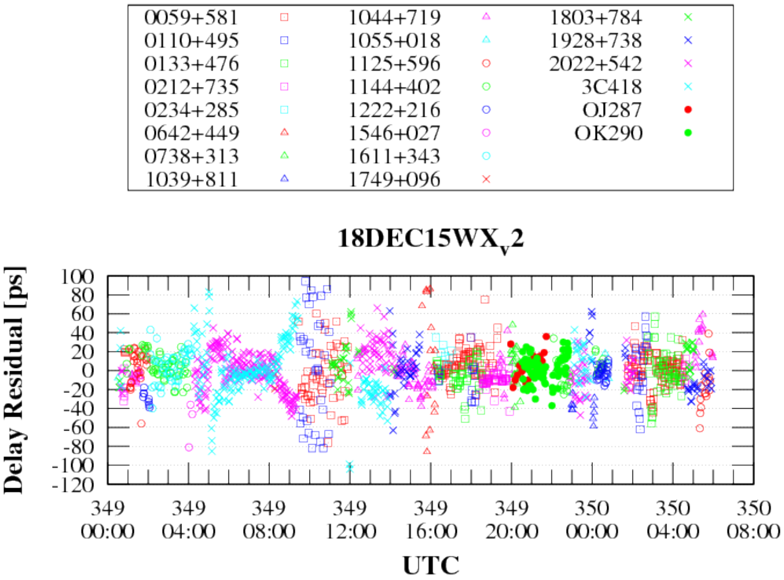

Fig. 3 Post-fit delay residual plotted for each source measured by 2.4m diameter antenna pair over the Medicina-Koganei baseline. We attribute the split of residual for 3C418 to radio source structure.

References

BIPM(2017) Local representation of UTC, *BIPM Annual Report on Time Activities*, 12, ISBN 978-92-822-2268-3, ISSN 1994-9405 41.

Bolotin, S, et al. (2019) The source structure effect in broadband observations, *Proc. of 24th Meeting of the European VLBI Group for Geodesy and Astrometry*.

Calonico, D. et al.(2014) High-accuracy coherent optical frequency transfer over a doubled 642-km fiber link, *Appl. Phys. B*, 117, 3, 979-986.

Clivati ,C., et al. (2015) A Coherent Fiber Link for Very Long Baseline Interferometry, *IEEE Trans on Ultrason. Ferroel. Freq. Contr.*, 62, 1907-1912.

Fujieda M., et al.(2016) Advanced two-way satellite frequency transfer by carrier-phase and carrier-frequency measurements, *J. Phys. Conf. Ser.* 723 doi: 10.1088/1742-6596/723/1/012036 .

Lopez, O, et al.(2012) Ultra-stable long distance optical frequency distribution using the Internet fiber network, *Opt. Express*, 20, 21, 23518-23526. doi: https://doi.org/10.1364/OE.20.023518.

Niell, A., et al. (2018) Demonstration of a Broadband Very Long Baseline Interferometer System: A New Instrument for High-Precision Space Geodesy, *Radio, Sci.*, 53, doi: https://doi.org/10.1029/2018RS006617.

Petit, G., et al (2015) 1×10^{-16} frequency transfer by GPS PPP with integer ambiguity resolution, *Metrologia*, 52, 301-309.

Petrachenko, B., et al.(2009) Design Aspects of the VLBI2010 System, *Progress Report of the VLBI2010 Committee*, NASA/TM-2009-2014180.

Predehl, K., et al.(2012) A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place, *Science*, 336, 6080, 441-444. doi: 10.1126/science.1218442.

Riehle F.(2015) Towards a Re-definition of the Second Based on Optical Atomic Clocks, *Comptes Rendus Physique*, 16, 5, 506-515, doi: https://doi.org/10.1016/j.crhy.2015.03.012 .

Riehle, F., et al.(2018) The CIPM list of recommended frequency standard values: guidelines and procedures, *Metrologia*, 55, pp. 188-200.

Sekido M. (2017) Node - HUB Style VLBI with Broadband System, *IVS NICT-TDC News* 37, 22-25, `http://www2.nict.go.jp/sts/stmg/ivstdc/news_37/pctdc_news37.pdf`

Sekido, M., et al. (2017) Broadband VLBI System GALA-V and Its Application for Geodesy and Frequency Transfer, *Proceedings of the 23rd European VLBI for Geodesy and Astrometry Meeting*, 5-9.

Takefuji K, et al. (2012) High-order Sampling Techniques of Aliased Signals for Very Long Baseline Interferometry, *Pabl. Astr. Soc. Pacific* 124, 1105-1112, doi: https://doi.org/10.1086/668232.

Whitney A., et al. (2014) VLBI Data Interchange Format (VDIF) Specification, `https://vlbi.org/vlbi-standards/vdif/`

Xu .M. H., et al. (2019) Structure effects in broadband VGOS data, *Proc. of 24th Meeting of the European VLBI Group for Geodesy and Astrometry*.