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This is the author's accepted version of the contribution published as:

*Original*

Intercontinental comparison of optical atomic clocks through very long baseline interferometry / Pizzocaro, Marco; Sekido, Mamoru; Takefuji, Kazuhiro; Ujihara, Hideki; Hachisu, Hidekazu; Nemitz, Nils; Tsutsumi, Masanori; Kondo, Tetsuro; Kawai, Eiji; Ichikawa, Ryuichi; Namba, Kunitaka; Okamoto, Yoshihiro; Takahashi, Rumi; Komuro, Junichi; Clivati, Cecilia; Bregolin, Filippo; Barbieri, Piero; Mura, Alberto; Cantoni, Elena; Cerretto, Giancarlo; Levi, Filippo; Maccaferri, Giuseppe; Roma, Mauro; Bortolotti, Claudio; Negusini, Maurizio; Ricci, Roberto; Zacchiroli, Giampaolo; Roda, Juri; Leute, Julia; Petit, Gérard; Perini, Federico; Chelvan, David; Tetsuya, 1696/6430 Bine 2026-11-15 N 1745-5473. - (2021). [10.1038/s41567-020-01038-6]

*Publisher:*

Nature publishing group

*Published*

DOI:10.1038/s41567-020-01038-6

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# Intercontinental comparison of optical atomic clocks via very long baseline interferometry

Marco Pizzocaro<sup>1\*</sup>, Mamoru Sekido<sup>2\*</sup>, Kazuhiro Takefuji<sup>2,†</sup>  
Hideki Ujihara<sup>2</sup>, Hidekazu Hachisu<sup>3</sup>, Nils Nemitz<sup>3</sup>,  
Masanori Tsutsumi<sup>3</sup>, Tetsuro Kondo<sup>2,4</sup>, Eiji Kawai<sup>2</sup>,  
Ryuichi Ichikawa<sup>3</sup>, Kunitaka Namba<sup>3</sup>, Yoshihiro Okamoto<sup>3</sup>,  
Rumi Takahashi<sup>3</sup>, Junichi Komuro<sup>3</sup>, Cecilia Clivati<sup>1</sup>,  
Filippo Bregolin<sup>1</sup>, Piero Barbieri<sup>1</sup>, Alberto Mura<sup>1</sup>,  
Elena Cantoni<sup>1</sup>, Giancarlo Cerretto<sup>1</sup>, Filippo Levi<sup>1</sup>,  
Giuseppe Maccaferri<sup>5</sup>, Mauro Roma<sup>5</sup>, Claudio Bortolotti<sup>5</sup>,  
Monia Negusini<sup>5</sup>, Roberto Ricci<sup>1,5</sup>, Giampaolo Zacchioli<sup>5</sup>,  
Juri Roda<sup>5</sup>, Julia Leute<sup>6,7</sup>, Gérard Petit<sup>6</sup>, Federico Perini<sup>5</sup>,  
Davide Calonico<sup>1</sup>, Tetsuya Ido<sup>3</sup>

<sup>1</sup>Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy.

<sup>2</sup>National Institute of Information and Communications Technology  
(NICT), Kashima, Japan.

<sup>3</sup>National Institute of Information and Communications Technology  
(NICT), Koganei, Tokyo, Japan.

<sup>4</sup>Chinese Academy of Sciences, Shanghai Astronomical Observatory,  
China.

<sup>5</sup>Istituto Nazionale di Astrofisica (INAF), Istituto di Radioastronomia  
(IRA), Bologna, Italy.

<sup>6</sup>Bureau International des Poids et Mesures (BIPM), Sèvres, France.

<sup>7</sup>LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS,  
Sorbonne Université, Paris, France.

\*Corresponding authors. Email: m.pizzocaro@inrim.it, sekido@nict.go.jp

<sup>†</sup>Present address: Japan Aerospace Exploration Agency (JAXA),  
Nagano, Japan.

ACCEPTED MANUSCRIPT

published as:

Pizzocaro, M., Sekido, M., Takefuji, K. et al.

Intercontinental comparison of optical atomic clocks through very long baseline interferometry.  
Nat. Phys. (2020).

<https://doi.org/10.1038/s41567-020-01038-6>

<https://www.nature.com/articles/s41567-020-01038-6>

1     The comparison of distant atomic clocks is foundational  
 2     to international timekeeping, global positioning and tests  
 3     of fundamental physics. Optical fibre links allow the  
 4     best optical clocks to be compared without degradation  
 5     over distances up to thousands of kilometres, but in-  
 6     tercontinental comparisons remain limited by the per-  
 7     formance of satellite transfer techniques. Here we show  
 8     that very long baseline interferometry (VLBI), although  
 9     originally developed for radio astronomy and geodesy,  
 10    can overcome this limit and compare remote clocks through  
 11    observing extragalactic radio sources. We developed  
 12    dedicated transportable VLBI stations that use broad-  
 13    band detection and we compared two optical clocks in  
 14    Italy and Japan separated by 9000 km. This system  
 15    demonstrates performance beyond satellite techniques  
 16    and can pave the way for future long-term stable inter-  
 17    national clock comparisons.

18    Atomic clocks based on optical transitions can reach fractional uncer-  
 19    tainties at the  $10^{-18}$  level<sup>1-3</sup> surpassing by two orders of magnitude the  
 20    microwave clocks<sup>4</sup> that realize the definition of the second in the Interna-  
 21    tional System of Units (SI) and are the basis of international timekeep-  
 22    ing<sup>5</sup>. Given the rapid progress of optical clocks, a redefinition of the SI  
 23    second as the unit of time is anticipated<sup>6</sup>. The remote comparison of dif-  
 24    ferent clocks worldwide is fundamental to check their consistency in view of  
 25    such a redefinition. It is also attractive for challenging experiments such as  
 26    tests of special and general relativity<sup>7-9</sup>, laboratory searches for the vari-  
 27    ations of fundamental constants<sup>10,11</sup>, and measurements of Earth's grav-  
 28    itational potential<sup>12-14</sup>. Future applications of clock comparisons include  
 29    the search for dark matter<sup>15</sup>, the establishment of quantum networks for  
 30    secure communications and timing<sup>16</sup> and gravitational wave detection<sup>17</sup>.  
 31    Optical fibre links have been shown to allow comparisons at the full accu-  
 32    racy of the clocks up to thousands of kilometres<sup>18</sup>. However, they have not  
 33    reached a transoceanic scale<sup>19</sup> and therefore intercontinental comparisons  
 34    are only possible by microwave satellite transfer techniques<sup>20</sup>. Among these  
 35    are two-way time-and-frequency transfer, which makes use of geostationary  
 36    telecommunication satellites<sup>21,22</sup>, or precise point positioning<sup>23</sup>, which relies  
 37    on the constellation of the Global Positioning System (GPS). These tech-  
 38    niques achieve a typical uncertainty at the level of  $10^{-15}$  at 1 d of averaging  
 39    time that limits the comparison of optical clocks.

40    Very long baseline interferometry (VLBI) is a technique developed for  
 41    radio astronomy and geodesy<sup>24,25</sup> based on the simultaneous observation  
 42    of remote radio sources with distant antennas, each referenced to a local  
 43    atomic clock. Since its early development, VLBI has been considered for

1 synchronization of the reference clocks<sup>26,27</sup> but it has never been exploited  
 2 for this task due to the convenient use of satellites. Recently, VLBI has  
 3 been proposed to improve intercontinental frequency links<sup>28</sup> and has been  
 4 suggested for the comparison of optical clocks<sup>29</sup>. Here we demonstrate a  
 5 VLBI system dedicated to frequency transfer with broadband detection that  
 6 allows for better performance than satellite techniques.

7 VLBI cross-correlates the signals arriving from astronomical radio sources  
 8 to different antenna locations. The geometrical delay between two stations  
 9  $\tau_{\text{geom}} = \mathbf{B} \cdot \mathbf{S}/c$  depends on the baseline between the antennas  $\mathbf{B}$  and  
 10 the unit vector to the radio source  $\mathbf{S}$ , with  $c$  the speed of light. The ob-  
 11 served value  $\tau_{\text{obs}}$  differs from the geometrical delay because of the timing  
 12 offset between the reference clocks  $\Delta\tau_{\text{clock}}$  and it is additionally affected by  
 13 the station-to-station difference in excess delays introduced by atmosphere  
 14  $\Delta\tau_{\text{atm}}$ , ionosphere  $\Delta\tau_{\text{ion}}$ , instruments such as antennas, cables, and receivers  
 15  $\Delta\tau_{\text{instr}}$ , and ultimately the radio source structure  $\Delta\tau_{\text{source}}$ :

$$\tau_{\text{obs}} = \tau_{\text{geom}} + \Delta\tau_{\text{atm}} + \Delta\tau_{\text{ion}} + \Delta\tau_{\text{instr}} + \Delta\tau_{\text{source}} + \Delta\tau_{\text{clock}}. \quad (1)$$

16 The different components of the delay can be either modelled, estimated  
 17 from the observations, or obtained as a result of separate measurements  
 18 depending on the application. Radio astronomy is interested in studying  
 19 radio source structure while geodetic VLBI seeks to minimize its effects by  
 20 selecting point-like sources in the interest of determining precise station co-  
 21 ordinates and monitoring variations in Earth rotation. The International  
 22 Celestial Reference Frame (ICRF) as adopted by the International Astro-  
 23 nomical Union (IAU)<sup>30</sup> provides a suitable list of extragalactic radio sources  
 24 that are regarded as fiducial points in the sky. Calibration of excess atmo-  
 25 spheric delay is made by an atmospheric model based on weather data<sup>31</sup>,  
 26 which is represented by a zenith delay and a mapping function for observa-  
 27 tions at different elevation angles generated by ray tracing techniques. The  
 28 ionospheric delay has a characteristic frequency dependence that allows its  
 29 calibration directly from observation data. VLBI measurements typically  
 30 use local active hydrogen masers as stable frequency references. When all  
 31 effects are considered, it is possible for VLBI measurements to provide the  
 32 frequency difference between the hydrogen masers and thus compare any  
 33 clocks or timescales locally linked to them.

34 We designed and built two transportable VLBI stations with 2.4 m diam-  
 35 eter Cassegrain antennas. These stations implement the concept of broad-  
 36 band VLBI observation proposed as VLBI Global Observing System (VGOS)  
 37 by the International VLBI Service for Geodesy and Astrometry (IVS)<sup>32</sup> to  
 38 reach 1 mm position accuracy in geodetic measurements. Whereas standard  
 39 geodetic VLBI only makes observations in narrow frequency ranges in the  
 40 S band (2.2 GHz–2.4 GHz) and X band (8.2 GHz–8.95 GHz)<sup>25</sup>, the stations

1 in this work can access frequencies from 3 GHz to 14 GHz. Our receivers  
 2 first acquire data with a sampling rate of 16 GHz and then digital filters  
 3 extract the signals in four 1 GHz wide channels spread over the wide fre-  
 4 quency range. Integration of the four channels determines precise group  
 5 delays using the bandwidth synthesis technique<sup>33</sup>. We employ a 2048 MHz  
 6 sampling rate in each channel, where conventional VLBI uses 32 MHz or  
 7 below, enhancing the signal-to-noise ratio by a factor of 8. Improved signal-  
 8 to-noise ratio allows for smaller overall dish area of the antennas. By itself,  
 9 the enhanced detection bandwidth is not sufficient for measurements over an  
 10 intercontinental baseline with easily transportable dish sizes. This is over-  
 11 come by including the 34 m radio antenna operated by NICT in Kashima  
 12 (Japan) in a joint node-hub style observation: the delay observable between  
 13 the transportable stations (nodes) can be calculated as the difference of the  
 14 two delays with the large antenna (hub) after applying a small correction  
 15 factor (see Methods). This measurement benefits from the improvement of  
 16 the equivalent dish area, which scales as the geometrical mean, without the  
 17 penalties specific to large antennas since the delay variations due to gravita-  
 18 tional distortion of the large dish or temperature dependence in long cables  
 19 are largely reduced as a common-mode noise.

20 Here, one node was installed at NICT headquarters in Koganei (Japan)  
 21 while the other was transported to the Radio Astronomical Observatory op-  
 22 erated by INAF in Medicina (Italy), forming an intercontinental baseline  
 23 of 8700 km (see Fig. 1). Observation data at Medicina and Koganei were  
 24 stored on hard-disk drives at each station and transferred over high-speed  
 25 Internet networks to the correlation center in Kashima for analysis. Ten  
 26 frequency measurements via VLBI were performed between October 2018  
 27 and February 2019 from which we calculated the frequency difference be-  
 28 tween the reference clocks at the two stations: the local hydrogen masers in  
 29 Medicina and in Koganei. Each session lasted from 28 h to 36 h and included  
 30 at least 400 scans observing between 16 and 25 radio sources in the ICRF  
 31 list. A least-squares fit of each run was used to calculate the observed delay  
 32 with typical residuals of 30 ps and a formal uncertainty in the frequency  
 33 comparison as low as  $1.5 \times 10^{-16}$  for a single run (see Extended Data Table  
 34 1). At this level of uncertainty, accurate modelling of atmospheric delays is  
 35 a crucial part of the analysis (see Methods).

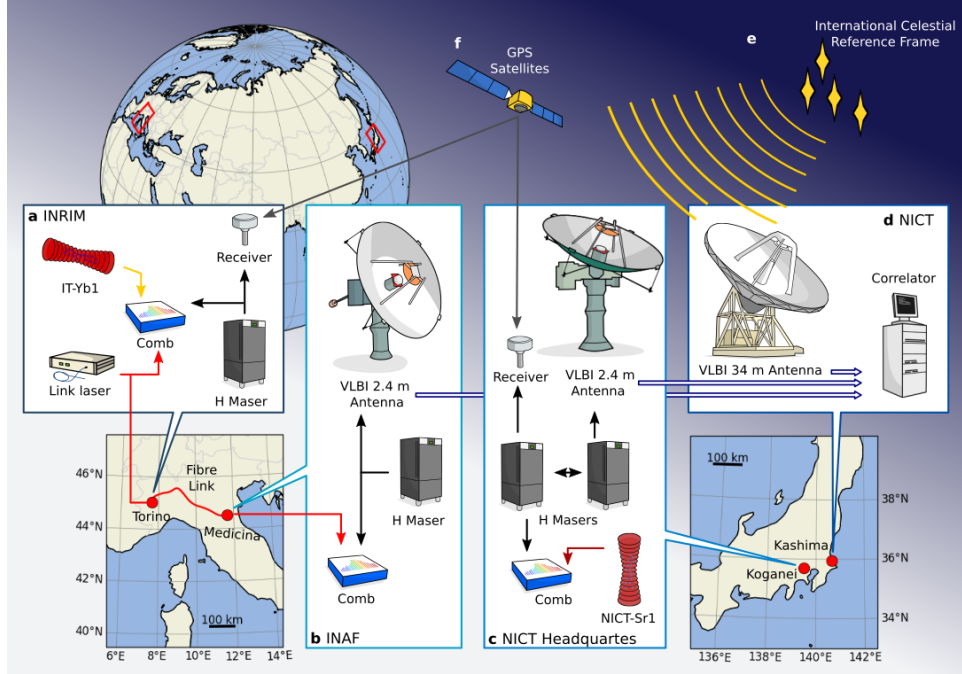
36 We used this VLBI frequency link to compare two optical clocks: the  
 37 ytterbium-171 optical lattice clock<sup>34</sup> IT-Yb1 at INRIM in Torino (Italy)  
 38 and the strontium-87 optical lattice clock<sup>35,36</sup> NICT-Sr1 in Koganei. Both  
 39 optical clocks are realizations of the unit of time, formally recognized within  
 40 the Metre Convention. This is possible because the frequency values of  
 41 ytterbium and strontium clock transitions are recommended as secondary  
 42 representations of the second in the list of standard reference frequency val-  
 43 ues<sup>6,37</sup> of the International Committee for Weights and Measures (CIPM)  
 44 with frequencies  $f(\text{Yb}) \approx 518 \text{ THz}$  and  $f(\text{Sr}) \approx 429 \text{ THz}$  and with rela-

tive uncertainties of  $5 \times 10^{-16}$  and  $4 \times 10^{-16}$  respectively. Therefore, the frequency ratio between IT-Yb1 and NICT-Sr1 can be compared to the officially recommended values in addition to previous measurements<sup>13,22,38,39</sup>.

The frequency comparison between IT-Yb1 and NICT-Sr1 followed the chain shown in Fig. 1. In Torino, the ytterbium clock was compared to a local hydrogen maser using an optical frequency comb<sup>40</sup>, which allows precise optical-to-microwave frequency comparisons. The comb in Torino also measured a narrow-linewidth laser at telecommunication wavelengths that was sent on a compensated optical fibre link<sup>41</sup> of 535 km to the Radio Observatory in Medicina. Here, another optical frequency comb compared the laser fibre-delivered from Torino with the hydrogen maser referencing the VLBI station. In Koganei, a third optical frequency comb was used for the comparison of the strontium clock with local hydrogen masers, including the maser used as reference for the VLBI station.

Since the optical clocks, optical link and VLBI link operated intermittently throughout this campaign we extrapolate the hydrogen maser frequencies<sup>42,43</sup> to calculate a frequency ratio for each VLBI run. Figure 2a shows the results of the ratio measurements, with uncertainties evaluated for each step of the frequency chain including the extrapolations (see Methods). The weighted mean for the campaign is the frequency ratio  $R = f(\text{Yb})/f(\text{Sr}) = 1.207\,507\,039\,343\,338\,05(34)$  measured via VLBI. This corresponds to a fractional deviation from the ratio  $R_0$  of the recommended frequencies for ytterbium and strontium of  $y(\text{Yb}/\text{Sr}) = R/R_0 - 1 = 2.5(2.8) \times 10^{-16}$  in agreement with previous measurements (see Fig. 2b). Over the course of the campaign, the overall VLBI measurement contributes a one-standard-deviation uncertainty of only  $9 \times 10^{-17}$  for a total measurement time of 300 h. The optical link, conversion to microwave signals, maser frequency extrapolation and systematic effects in the optical clocks contribute to the overall uncertainty of  $2.8 \times 10^{-16}$  as reported in Table 1. The gravitational redshift induced by the different gravitational potential at the position of the optical clocks<sup>34,35</sup> has been accounted for in the clock systematic shifts, bringing a relative correction of  $-1.765(2) \times 10^{-14}$  to the frequency ratio.

To confirm the results, we established an independent frequency link using GPS satellites between receivers at INRIM and at NICT (see Fig. 1). To achieve low uncertainty on this link, we calculated a precise point positioning solution with integer ambiguity resolution (IPPP)<sup>44</sup>. For this baseline, IPPP has an uncertainty of  $9 \times 10^{-16}$  at 1 d of averaging time. The comparison of the ytterbium and strontium optical clocks using the IPPP solution over the same time intervals as the VLBI runs is also shown in Fig. 2a. The weighted mean of the frequency deviation of the ratio is  $y(\text{Yb}/\text{Sr}) = -3.2(4.0) \times 10^{-16}$  measured via IPPP. As shown in Table 1, the GPS link contributes an overall uncertainty for the campaign of  $2.6 \times 10^{-16}$ . We can also compare the VLBI and IPPP results directly, closing the loop via the optical link, and the weighted mean of the differences for the entire



**Figure 1: Schematic representation of the frequency link between the ytterbium and strontium optical clocks via VLBI and satellite transfer.** **a**, In Torino, IT-Yb1 at INRIM is compared with the local hydrogen maser and the link laser using an optical frequency comb. The link laser is sent over compensated fibre link to Medicina. **b**, In Medicina, at INAF Radio Observatory, the incoming link laser is compared with the local hydrogen maser using another optical frequency comb. The first transportable broadband VLBI station is setup in Medicina and referenced to this maser. **c**, In Koganei, the second VLBI station at NICT headquarters is referenced to a local hydrogen maser. NICT-Sr1 is compared to the local hydrogen maser using a third optical frequency comb, ending the chain. **d**, The 34 m diameter radio telescope maintained by NICT in Kashima assisted in the node-hub style observations, increasing the signal-to-noise ratio. The observation data in Medicina and Koganei were transferred to the correlation center in Kashima over high-speed internet networks (blue arrows). The cross-correlation between the antennas and the following geodetic analysis allows to measure the reference clock difference. **e**, The VLBI link is established by observing several radio sources in the International Celestial Reference Frame. **f**, A satellite frequency link with GPS satellites is established between the receivers in Torino and Koganei.



**Table 1: Uncertainty budgets for the ratio and closure measurements.** The listed uncertainties are calculated for the weighted average of the points in Figure 2a and the weighted average of their difference. The VLBI and IPPP uncertainties are the statistical contribution for the frequency transfer. The clock contributions consist of the systematic uncertainties of both clocks, including the gravitational redshift. The extrapolation uncertainty is a statistical uncertainty due to the intermittent operations of the optical clocks and the optical link. The uncertainty for the combs arises from their accuracy and from the instability in the microwave to optical conversions. The optical link contribution is negligible for the present measurement. All uncertainties correspond to one standard deviation.

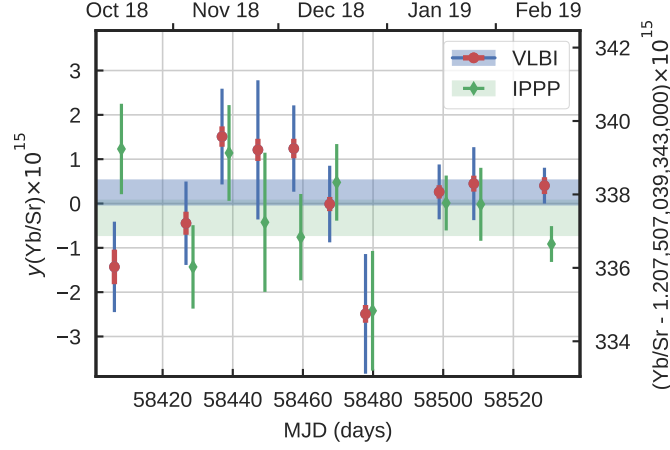
Yb/Sr ratio via VLBI		Yb/Sr ratio via IPPP		Closure	
Contribution	Uncer. ( $\times 10^{-16}$ )	Contribution	Uncer. ( $\times 10^{-16}$ )	Contribution	Uncer. ( $\times 10^{-16}$ )
VLBI	0.9	IPPP	2.6	VLBI	0.7
Clocks	0.9	Clocks	0.9	IPPP	2.3
Combs (microwave/optical)	1.1	Combs (microwave/optical)	1.1	Combs (microwave/optical)	1.1
Extrapolation	2.2	Extrapolation	2.6	Extrapolation	1.9
Optical link	<0.1			Optical link	<0.1
Total	2.8	Total	4.0	Total	3.2

1 campaign is  $y(\text{VLBI-IPPP}) = 3.5(3.2) \times 10^{-16}$ .

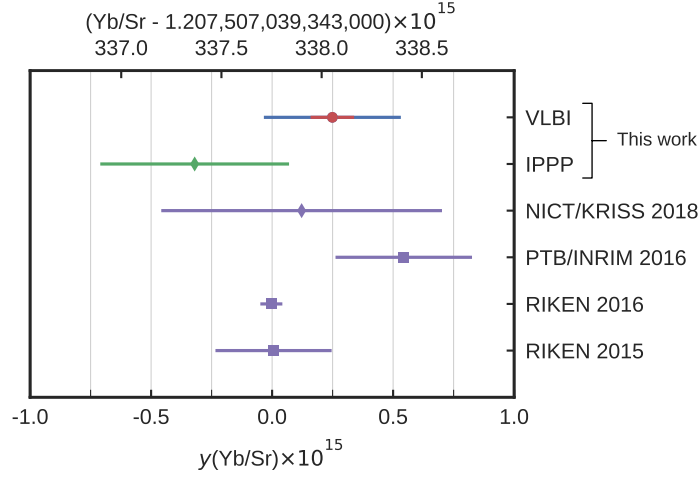
2 By leveraging broadband observations, our VLBI system surpasses the  
3 best satellite techniques and what is possible with traditional geodetic VLBI,  
4 resulting in a typical formal uncertainty of  $2 \times 10^{-16}$  at  $10^5$  s of averaging  
5 time. It has the potential to reach uncertainty in the low  $10^{-17}$  region at  
6 10 d of averaging time provided variations in instrumentation delay are min-  
7 imized, radio sources are carefully selected to minimize structure effects, and  
8 the atmosphere is accurately modelled. Although VLBI still requires optical  
9 to microwave conversions, this is an attractive technique for optical clocks  
10 comparisons. With increased operational duty times of the optical clocks  
11 and improved characterization of the combs<sup>45</sup> and of the frequency chains,  
12 it will allow for link uncertainties that approach the systematic uncertainties  
13 of optical clocks for manageable measurement times.

14 Our measurements show agreement between the VLBI link, the optical  
15 clocks and the GPS link at the low  $10^{-16}$  level. There is still some uncer-  
16 tainty on the optimal treatment for the calibration of the tropospheric delay  
17 in a VLBI experiment with a long single baseline and further investigation  
18 should clarify the correlation with the estimated clock frequency. We have  
19 estimated that thermal sensitivity of the cables and of the antennas con-  
20 tributed an uncertainty less than  $1 \times 10^{-17}$ . The microwave signal acquired  
21 by the antenna is transferred to the data acquisition system by amplitude

a



b



**Figure 2: Comparison of Yb/Sr frequency ratio measurements.** **a**, Ratio measurements for each VLBI run at a given Modified Julian Date (MJD) measured via VLBI or IPPP. Red bars represent the statistical uncertainty of the VLBI link only, while blue bars represent the total uncertainty for the VLBI comparisons (including optical clocks, optical combs, and extrapolations). Blue shaded region is the weighted mean of the VLBI comparison with its total uncertainty. Green points represent the IPPP comparisons with their total uncertainty. Green shaded region is the weighted mean of the IPPP comparison with its total uncertainty. Horizontal offset between the two dataset is for clarity. **b**, Optical frequency ratio  $f(\text{Yb})/f(\text{Sr})$  as measured in this work (red/blue and green points as in a) or in previous measurements where purple squares represent local measurements at RIKEN<sup>38,39</sup> and by PTB and INRIM<sup>13</sup> and the purple diamond denotes a remote measurement performed by NICT and KRISS<sup>22</sup>. All uncertainties correspond to one standard deviation.

1 modulation of an infrared laser over fibre. In Medicina, a 600 m long under-  
2 ground fibre is used, with frequency shifts less than  $8 \times 10^{-17}$  in a day. In  
3 our experiment, we observed excess delay residuals for 3 of the 35 observed  
4 sources caused by the source structure effect<sup>46,47</sup>. The increased residu-  
5 als are accounted for in the fit procedure but a careful selection of radio  
6 sources will help to avoid systematic effects in future clock comparisons. On  
7 the other hand, transportable broadband antennas may play a significant  
8 role to increase the density and extend the baselines in large networks of  
9 antennas, with the aim to improve investigations of source with structure.

10 The endpoint VLBI stations are transportable and can be deployed close  
11 to time-and-frequency laboratories just like traditional satellite antennas,  
12 supported by the node-hub topology. They can be operated without the  
13 need for a radio transmission license and, with a higher data transmission ca-  
14 pability, they may provide a continuous link instead of the separate sessions  
15 used in our measurements. Where laboratories lack the facilities or sky cov-  
16 erage to house a VLBI station, they can be connected by local optical fibre  
17 links, as demonstrated here. It is envisioned that optical clock comparisons  
18 will increasingly rely on local area fibre networks connected by non-fibre  
19 intercontinental links, with application in precision timing, searches for new  
20 physics and clock-based geodesy<sup>48</sup>. Proposals for improved intercontinen-  
21 tal links includes IPPP<sup>44</sup>, carrier-phase two way frequency transfer<sup>49</sup>, and  
22 the use of transportable optical clocks<sup>13</sup> or dedicated orbital systems such  
23 as the planned Atomic Clock Ensemble in Space (ACES) mission<sup>50</sup>. Our  
24 experiment realizes such a hybrid network with a high performance VLBI  
25 link, useful for primary metrology and fundamental physics.

## 26 **Methods**

### 27 **Broadband VLBI observation system**

28 In VLBI observations, the standard deviation of the observed group delay  
29 is given by

$$\sigma_\tau = \frac{1}{2\pi R_{\text{sn}} \Delta f_{\text{rms}}}, \quad (2)$$

30 where  $\Delta f_{\text{rms}}$  is the root mean square deviation of the observation frequencies  
31  $f_i$  while the signal to noise ratio is given by

$$R_{\text{sn}} = \eta \sqrt{\frac{A_1 A_2 B t}{T_1 T_2}} \frac{S}{2k_{\text{B}}}, \quad (3)$$

32 where  $A_j$  are the effective areas of the two antennas,  $T_j$  the system noise  
33 temperatures,  $B$  is the observation bandwidth,  $t$  is the integration time,  $S$   
34 is correlated flux density of the radio source,  $k_{\text{B}}$  is Boltzmann's constant

and  $\eta$  is a digital processing loss factor<sup>51</sup>. Delay observations can thus be improved by increasing the spread of observation frequency  $\Delta f_{\text{rms}}$  and the bandwidth  $B$  of the observations.

The VLBI observation system used in this experiment, GALA-V<sup>52</sup>, implements data acquisition according to the VGOS standard, which aims at making broadband observations spread over the frequency range of 2 GHz–14 GHz. NICT developed a unique broadband feed<sup>53</sup> named NINJA, with constant narrow beam size for wide frequency range, which enables broadband observation with existing Cassegrain antennas. The NINJA broadband feeds were installed in the two transportable 2.4 m diameter antennas and the Kashima 34 m diameter antenna. The transportable antennas acquire a single linear (V) polarization signal. To avoid a loss of correlation from the different polarizations observed by distant stations due to parallactic angle, the hub station in Kashima acquires both (V and H) polarizations. The VH and VV data sets are then processed coherently.

The data-acquisition we adopted uses four channels with  $B = 1024$  MHz bandwidth at frequencies  $f_1 = 6.0$  GHz,  $f_2 = 8.5$  GHz,  $f_3 = 10.4$  GHz and  $f_4 = 13.3$  GHz. This system is simpler than the prototype VGOS proof-of-concept implementation<sup>32</sup>, which acquires data on more than one hundred channels with 32 MHz frequency bandwidth. Our array of selected frequencies provides a sharply peaked delay resolution function (see Extended Data Fig. 1), and the large bandwidth of each channel allows the unambiguous determination of the absolute group delay using the technique of bandwidth synthesis<sup>33,54</sup>. Since the group delay has a linear phase slope over frequency, a stable phase relation between adjacent channels is essential and it is assured by a fully digital signal processing. We employ high-speed radio frequency direct sampling<sup>55</sup> to digitize the signal without any analog frequency conversions: the received signal is amplified, and then first converted to digital data with a 16 384 MHz sampling rate via the high-speed sampler K6/GALAS<sup>52</sup>. A digital filter implemented on a field programmable gate array (FPGA) extracts the four signal channels with 1-bit sampling at 2048 megasamples per second for each polarization. Observation data is stored on hard-disk drives at each station, and then transferred to the station at Kashima over high-speed research networks for correlation processing.

## Node-hub style VLBI observations

Transportable VLBI systems have previously been investigated for geodetic VLBI<sup>56,57</sup>, although their sensitivity is limited by the physical size of the collecting area.

Our broadband observation system allows for smaller antennas by increasing the observation bandwidth (Eq. 3). Yet, even in this case, the transportable antenna pair does not have enough sensitivity for the reduced correlated flux density on an intercontinental baseline. This is overcome by

1 combining the small transportable antennas (nodes) with a high sensitivity  
2 antenna (hub). The baseline between the smaller stations is then deduced by  
3 a closure delay relation<sup>58</sup>. For two node stations A and B and a hub station  
4 R making an observation of a point-like radio source (see Extended Data  
5 Fig. 2) the time delay differences at time  $t$  for the arrival of an identical  
6 wave are related by the linear combination

$$\tau_{AB}(t) = \tau_{RB}(t) - \tau_{RA}(t) - \dot{\tau}_{AB}(t) \cdot \tau_{RA}(t). \quad (4)$$

7 Higher order terms in this relation are negligible for any terrestrial baselines  
8 when the radio source structure effect is negligible. The uncertainty of the  
9 delay  $\tau_{AB}$  calculated in this way is still dominated by the contributions of  
10 instruments, atmosphere and source structure at the nodes as if the delay  
11 had been measured directly. In obtaining the delay observable of the AB  
12 baseline, the delay properties of station R such as atmospheric delay, cable  
13 length change, and gravitational deformation of the dish are canceled out.  
14 In our case, with both the hub and a transportable station separated by only  
15 110 km, Eq. 4 is still valid even in the presence of radio source structure,  
16 because the short baseline is insensitive while only the effect on the baseline  
17 AB is observed.

## 18 VLBI signal processing and analysis

19 The data reduction procedure for the VLBI observation consists of three  
20 steps for each of the node-hub baselines: first, the individual VH and VV  
21 polarization pairs for each frequency band are cross-correlated and time inte-  
22 gration is made using the software correlator GICO3<sup>59</sup> running on a cluster  
23 of computers. Second, synthetic cross-correlation data is generated by com-  
24 bining the VH and VV data such that correlation amplitudes are maximized  
25 for each scan and frequency band. Third, wideband bandwidth synthesis<sup>33</sup>  
26 is applied to derive wideband group delay observables. Here we account  
27 for phase shifts of the propagating electromagnetic signal introduced by the  
28 ionospheric dispersive medium in the form of  $\phi = A \cdot \delta_{\text{TEC}}/f$ , where  $\delta_{\text{TEC}}$   
29 is the difference of total electron content (TEC) in the line of sight from  
30 each observation station,  $f$  is the radio frequency of the observations and  
31  $A$  is a constant given by  $e^2/(4\pi c \varepsilon_0 m_e)$ , with  $\varepsilon_0$  the vacuum electric permit-  
32 tivity and  $m_e$  the mass of the electron. The wideband bandwidth synthesis  
33 procedure calibrates ionospheric delay by simultaneously estimating  $\delta_{\text{TEC}}$   
34 and broadband group delay. Group delay data for all scans and baselines  
35 is stored in a Mark3 VLBI database. The virtual delays on the baseline  
36 between transportable antennas is analysed by a least-square fit using the  
37 Calc/Solve software<sup>60</sup>. The parameters of the fit were the coordinates of  
38 one station, the atmospheric delay parameters for both stations as piece-  
39 wise linear functions with 60 minutes intervals and a single clock offset and  
40 clock rate.

1 The observed radio sources were selected from the recently proposed  
 2 ICRF3 list<sup>61</sup>, which provides accurately known coordinates that predict the  
 3 geometrical delays. The a-priori delay calculation includes relativistic coor-  
 4 dinate transformation from the solar barycentric frame to a geocentric frame  
 5 comoving with the Earth, accounting also for the gravitational time delay<sup>62</sup>.  
 6 The excess path caused by dry atmosphere can be accurately predicted from  
 7 air pressure on the ground, height, and latitude of the station<sup>63</sup>. However,  
 8 the distribution of water vapour is hard to predict from ground weather  
 9 data, and the anisotropy of the atmosphere is difficult to estimate directly  
 10 from the VLBI data because the east-west long baseline results in a limited  
 11 sky coverage. Thus, we use the Vienna Mapping Functions 3 (VMF3)<sup>64</sup> for a  
 12 priori delay calibration. The VMF3 are computed by ray tracing within a nu-  
 13 merical weather model of the European Centre for Medium-Range Weather  
 14 Forecasts (ECMWF). They include dry and wet components, as well as gra-  
 15 dients, in the model data. Their data is publicly available and regularly  
 16 computed for most space geodetic observation sites including Kashima, Ko-  
 17 ganei, and Medicina. Residuals atmospheric contributions were estimated  
 18 in the least-squares analysis of VLBI data.

## 19 **Uncertainty of the optical clocks, optical link and combs**

20 The operation of IT-Yb1 and NICT-Sr1 is similar and presented in detail in  
 21 ref.<sup>34,35,42,65</sup>. In both systems, an ultrastable clock laser is stabilized to the  
 22 clock transition of atoms cooled to microkelvin temperatures and trapped  
 23 in an optical lattice at the magic wavelength<sup>66</sup>, 759 nm for ytterbium and  
 24 813 nm for strontium. Frequency combs measure the clock laser relative to  
 25 the local hydrogen masers.

26 For this campaign, the systematic frequency shifts of the clocks have been  
 27 characterized with an uncertainty of  $3.1 \times 10^{-17}$  for IT-Yb1 and  $8 \times 10^{-17}$   
 28 for NICT-Sr1. The lattice light shift, density shift and static Stark shift are  
 29 evaluated by interleaving measurements in different conditions. The black-  
 30 body radiation shift is calculated from the temperature of the physics pack-  
 31 age of each clock using known atomic parameters<sup>67–69</sup>, where the uncertainty  
 32 is dominated by temperature inhomogeneity. We calculated from known  
 33 atomic coefficients the lattice hyperpolarizability and multipolar shift<sup>70–72</sup>,  
 34 the quadratic Zeeman shift<sup>1,72–76</sup>, the background gas shift<sup>1,77</sup> and the probe  
 35 light shift<sup>1,78</sup>.

36 At both laboratories, we determined the gravitational redshift with re-  
 37 spect to the conventionally adopted gravity potential<sup>79</sup>  $W_0 = 62\,636\,856.0 \text{ m}^2\text{s}^{-2}$ .  
 38 At INRIM, the redshift is calculated from a gravitational potential difference  
 39 measured with a global navigation satellite system/geoid approach from the  
 40 geoid model of Europe EGG2015<sup>80,81</sup>, with an uncertainty of  $3 \times 10^{-18}$  cor-  
 41 responding to about 3 cm in height. At NICT, the redshift is calculated from  
 42 the geoid model of Japan GSIGEO2011<sup>82</sup> with an uncertainty of  $2 \times 10^{-17}$ ,

1 which includes oscillations from tidal effects whose 10-day mean is less than  
2 15 cm in height.

3 The operation of the combs in Torino and Medicina and of the connecting  
4 optical link were monitored by redundantly tracking beatnotes to detect and  
5 remove cycle slips in the phase-locked loops. For this task, acquisition in  
6 Torino and Medicina was synchronized using the Network Time Protocol at  
7 better than 100 ms. The average number of cycle slips during the uptime  
8 was less than one per hour. The fibre-delivered laser is loosely phase locked  
9 to the hydrogen maser in Torino using the comb to avoid frequency drifts.  
10 In these conditions, the optical link contributes less than  $1 \times 10^{-18}$  after  
11 1000 s of averaging time<sup>41,83</sup>.

12 For this measurement, the optical-to-microwave comparison at the combs  
13 in Torino, Medicina and Koganei has been evaluated at an uncertainty of  
14  $8 \times 10^{-17}$  each, while optical-to-optical comparisons are better character-  
15 ized<sup>84</sup> at less than  $1 \times 10^{-18}$ . We also conservatively estimated that each  
16 optical-to-microwave comparison at the comb introduces phase noise with a  
17 corresponding instability of  $2 \times 10^{-14}$  at 1 s of averaging time. The insta-  
18 bilities of the optical clocks are negligible compared to those of the maser  
19 frequency measurements, at about  $2 \times 10^{-15}$  at 1 s for the ytterbium clock  
20 and  $7 \times 10^{-15}$  at 1 s for the strontium clock.

## 21 Uncertainty in the frequency chain

22 The calculation of the frequency chain for the VLBI measurement of optical  
23 clocks follows the measurement model:

$$\frac{f(\text{Yb})}{f(\text{Sr})} = \frac{f(\text{Yb})}{f(\text{H}_\text{T})} \frac{f(\text{H}_\text{T})}{f(\text{H}_\text{M})} \frac{f(\text{H}_\text{M})}{f(\text{H}_\text{K})} \frac{f(\text{H}_\text{K})}{f(\text{Sr})}, \quad (5)$$

24 where the  $f(\text{Yb})/f(\text{H}_\text{T})$  is the frequency ratio between the ytterbium optical  
25 clock and the hydrogen maser in Torino measured at the comb,  $f(\text{H}_\text{T})/f(\text{H}_\text{M})$   
26 is the frequency ratio between the masers in Torino and in Medicina mea-  
27 sured using the optical fibre link,  $f(\text{H}_\text{M})/f(\text{H}_\text{K})$  is the frequency ratio be-  
28 tween the masers in Medicina and in Koganei measured using the VLBI  
29 comparison, and  $f(\text{H}_\text{K})/f(\text{Sr})$  is the frequency ratio between the hydrogen  
30 maser in Koganei and the strontium optical clock measured at the comb.

31 In the data analysis, each ratio  $r$  in Eq. (5) is expressed as a frac-  
32 tional deviation  $y = r/r_0 - 1$ , where  $r_0$  is an arbitrary reference ratio. We  
33 chose the reference ratios for the clocks to be consistent with the recom-  
34 mended frequencies of ytterbium and strontium as secondary representa-  
35 tions of the second<sup>37</sup>,  $f_0(\text{Yb}) = 518\,295\,836\,590\,863.6(3)$  Hz and  $f_0(\text{Sr}) =$   
36  $429\,228\,004\,229\,873.00(17)$  Hz. After linearization, the fractional correction  
37 of the result  $y(f(\text{Yb})/f(\text{Sr}))$  can be calculated as the sum of the fractional  
38 corrections of each ratio.

1 The four frequency ratios in Eq. 5 were not measured simultaneously and  
 2 need to be extrapolated to common intervals using the hydrogen masers as  
 3 flywheel oscillators<sup>34,35,85</sup>. After accounting for a linear drift, the dominant  
 4 contribution to the extrapolation uncertainty is due to the stochastic maser  
 5 behaviour<sup>42,43,86</sup>. We model the maser noise with a power-law model<sup>87</sup> de-  
 6 scribed by an Hadamard variance  $\sigma_H^2 = h_{-2}(\tau/s)^{-2} + h_{-1}(\tau/s)^{-1} + h_0 +$   
 7  $h_2(\tau/s)^2$ . The coefficients  $h_j$ , conventionally identified with white phase  
 8 noise, white frequency noise, flicker frequency noise and flicker-walk fre-  
 9 quency noise respectively, are deduced from comparisons with the optical  
 10 clocks or within the maser ensembles at INRIM and at NICT (see Extended  
 11 Data Fig. 3b). The  $h_2$  coefficient provides the best description of the long-  
 12 term behaviour observed at NICT and it predominantly affects extrapola-  
 13 tions over datasets longer than 10 d. There are no significant changes in the  
 14 overall result if using an alternative set of coefficients that sets  $h_2 = 0$  or re-  
 15 places it with a best-fit  $h_1$  coefficient associated with random-walk noise. We  
 16 calculated the uncertainty due to dead time by Monte Carlo methods, using  
 17 an algorithm for the generation of power-law noise<sup>88</sup> and simulating 500  
 18 repeated averages over the time periods involved<sup>23,34,35,85</sup>. The numerical  
 19 calculations agree with analytic results based on the power spectral density  
 20 of the modelled noise. The drift of each maser was determined from the com-  
 21 parison with the optical clocks and extrapolations were calculated as  $d\Delta t$ ,  
 22 where  $d$  is the measured drift and  $\Delta t$  is the time difference of the barycentres  
 23 of constituent data for the ratio under investigation. The averaging intervals  
 24 were carefully selected to only include periods of well-characterized maser  
 25 behavior. We note that we chose the averaging interval for each step of the  
 26 chain aiming to minimize the final uncertainty for the ratio via VLBI (see  
 27 Extended Data Fig. 3a).

28 The extrapolations have a typical uncertainty of  $1 \times 10^{-15}$  for each VLBI  
 29 measurement in Fig. 2a. For the last point on MJD 58529, this contribution  
 30 was reduced to  $2.8 \times 10^{-16}$  by operating all parts of the experiment simul-  
 31 taneously, with residual extrapolation uncertainties only due to downtimes  
 32 of the optical clocks and of the optical link.

33 At NICT, the VLBI station and the strontium optical clock were com-  
 34 pared to different masers in the available ensemble. Using the continuously  
 35 operated Japan Standard Time System<sup>89</sup>, the conversion between masers  
 36 can be calculated with a negligible uncertainty of  $2 \times 10^{-17}$  after  $10^5$  s of  
 37 measurement time.

38 The measurement models for the frequency ratio via IPPP and for the  
 39 closure difference between VLBI, optical link and IPPP employ a similar  
 40 sequence of calculations but require different extrapolations. The closure  
 41 calculation does not rely on optical clock data except through the extracted  
 42 maser drifts.



## 1 Averages and statistics of the frequency comparison

2 In our analysis, we consider the covariance matrix between the various mea-  
3 surements and calculate the weighted averages of Yb/Sr and closure ratios  
4 with the Gauss-Markov theorem, or generalized least-squares fit<sup>90,91</sup>. We  
5 assume the systematic uncertainties of each clock and each comb as fully  
6 correlated over time. In a limited number of cases, the same optical clock  
7 data contribute to the ratio evaluation of more than one VLBI run (see  
8 Extended Data Fig. 3a) and we account for this correlation.

9 For our measurements we averaged 190 h of ytterbium clock data, 790 h  
10 of the optical link data, 300 h of VLBI sessions and GPS link, and 130 h of  
11 strontium clock data. The Birge ratios<sup>91</sup> for the weighted averages over 10  
12 VLBI sessions are  $\sqrt{\chi^2/n} = 1.07$  for the VLBI measurement,  $\sqrt{\chi^2/n} = 0.90$   
13 for the IPPP measurement, and  $\sqrt{\chi^2/n} = 1.32$  for the closure, all with  $n = 9$   
14 degrees of freedom.

15 The Gauss-Markov method is used to establish optimal weights of the  
16 data points for each of these measurements. The changing allocation of  
17 weights results in a variation of overall uncertainty contributions (e.g., for  
18 VLBI and IPPP in Table 1 and for the extrapolation in Extended Data  
19 Figure 4) because the weights are calculated from the total uncertainty of  
20 each measurement.

## 21 Yb/Sr ratio via satellite link

22 The ratio between the ytterbium clock and the strontium clock with the  
23 satellite link reported in the main text only used data coinciding with VLBI  
24 runs. We can average the GPS data to calculate a Yb/Sr frequency ratio  
25 without this limitation, looking for the best overlap of ytterbium and stron-  
26 tium data in the 130 d of the campaign. We calculated this ratio using both a  
27 precise point positioning (PPP) solution and the IPPP solution over the en-  
28 tire campaign (see Extended Data Fig. 4), resulting in frequency deviations  
29  $y(\text{Yb/Sr}) = -2.4(4.0) \times 10^{-16}$  using PPP and  $y(\text{Yb/Sr}) = -3.1(2.5) \times 10^{-16}$   
30 using IPPP. For these measurements we averaged 180 h of ytterbium clock  
31 data, 580 h of satellite transfer and 140 h of strontium clock data. The Birge  
32 ratio for the weighted average of these measurements are  $\sqrt{\chi^2/n} = 0.53$  for  
33 PPP and  $\sqrt{\chi^2/n} = 0.29$  for IPPP, both with  $n = 9$  degrees of freedom. As  
34 expected, IPPP results in a better uncertainty corresponding to a frequency  
35 ratio  $f(\text{Yb})/f(\text{Sr}) = 1.207\,507\,039\,343\,337\,38(30)$ . The significantly longer  
36 measurement time ultimately allows this measurement to achieve the same  
37 uncertainty as the VLBI result.

## 1 Acknowledgements

2 Development of the broadband feed system was supported by Prof. Kenta  
3 Fujisawa of Yamauchi University. We acknowledge Shingo Hasegawa, Yuka  
4 Miyauchi of NICT/Kashima Space Technology Center, Fumimaru Naka-  
5 gawa, Hiroshi Ishijima of NICT/Headquarters, and Takatoshi Ikeda of KDDI  
6 Research Laboratory for their contribution to achieve this work. We thank  
7 Alice Tabellini of IRA/INAF, Annalisa Dondi and Massimo Alberghini of  
8 the Bologna Customs Agency for the management of the temporary im-  
9 portation of the transportable VLBI antenna from Japan to Italy. The  
10 broadband feeds were realized through the grant of Joint Development Re-  
11 search on “Development of Broadband receiver system of Kashima 34m”  
12 (2013-2015) supported by the Research Coordination Committee, National  
13 Astronomical Observatory of Japan (NAOJ), National Institutes of Natural  
14 Sciences (NINS). The development of the ytterbium optical clock and of the  
15 optical link were supported by the European Metrology Program for Inno-  
16 vation and Research (EMPIR) projects 15SIB03 OC18, 15SIB05 OFTEN,  
17 17IND14 WRITE, 18SIB05 ROCIT; by the Italian Ministry of Education,  
18 University and Research (LIFT and Metgesp projects); by the Horizon 2020  
19 Marie Skłodowska-Curie Research and Innovation Staff Exchange (MSCA-  
20 RISE) project Q-SENSE (Grant Agreement Number 691156). The EMPIR  
21 initiative is co-funded by the European Union’s Horizon 2020 research and  
22 innovation programme and the EMPIR Participating States. J.L. was sup-  
23 ported by the French National Research Agency under the LABEX Cluster  
24 of Excellence FIRST-TF (ANR-10-LABX-48-01). Fast data transfer from  
25 Italy to Japan for quick turn around of the experiments was realized by sup-  
26 port of high research networks JGN, Internet2, TransPAC, APAN, GEANT,  
27 and GARR. IPPP results make use of the GINS software developed by the  
28 French Space Agency CNES.

## 29 Author’s contributions

30 D.C., T.I., and M.S. designed, prepared and coordinated the experiment  
31 with contributions from F.P. and F.L. M.S., K.T., H.U., M.T., J.K., and  
32 R.I. designed and built the broadband VLBI system. M.S., K.T., H.U.,  
33 M.T., E.K., K.N., Y.O., and R.T. set up and operated the VLBI stations in  
34 Koganei and Kashima. M.S., K.T., M.T., H.U., K.N., Y.O., and R.T. set up  
35 and operated the VLBI station in Medicina with support from G.M., M.R.,  
36 C.B., G.Z., J.R., and F.P. M.P., F.B., and P.B. evaluated and operated the  
37 ytterbium clock and the comb in Torino. C.C. and A.M. evaluated and  
38 operated the optical fibre link and the combs in Torino and Medicina with  
39 support from M.R. and C.B. H.H., N.N., and T.I. evaluated and operated  
40 the strontium clock and the comb in Koganei. M.S., K.T., and T.K. carried

1 out the correlation analysis of the VLBI delay data. M.S., M.N., and R.R.  
2 carried out the geodetic VLBI analysis. E.C., G.C., R.I., J.L., and G.P.  
3 carried out the data analysis of the satellite links. M.P. and M.S. performed  
4 the data analysis for the frequency comparisons with contributions from  
5 N.N., C.C., J.L. and G.P. M.P. wrote the manuscript with support from  
6 M.S., N.N., and C.C. All authors discussed the results and commented on  
7 the paper.

## 8 **Competing interests**

9 The authors declare no competing interests.

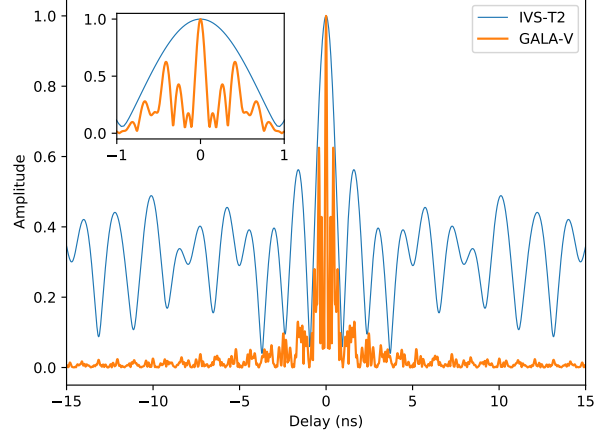
## 10 **Data Availability**

11 The data that support the plots within this paper and other findings of this  
12 study are available from the corresponding authors upon reasonable request.

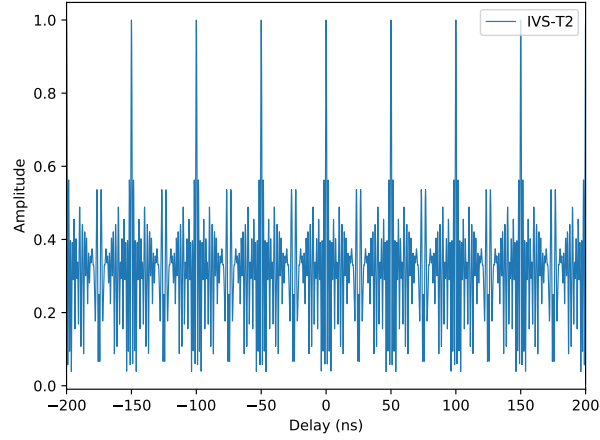
**Extended Data Table 1: VLBI sessions used for frequency comparison.**

Date	Duration /h	Scans	Sources	Delay res. /ps	Rel. Freq. Unc.
14/10/2018	29	448	22	32	$3.9 \times 10^{-16}$
04/11/2018	31	463	16	39	$2.6 \times 10^{-16}$
14/11/2018	29	464	24	24	$2.3 \times 10^{-16}$
24/11/2018	29	445	23	29	$2.5 \times 10^{-16}$
04/12/2018	29	471	23	33	$2.2 \times 10^{-16}$
15/12/2018	29	457	22	26	$1.6 \times 10^{-16}$
25/12/2018	29	476	24	22	$2.0 \times 10^{-16}$
15/01/2019	29	479	25	24	$1.5 \times 10^{-16}$
25/01/2019	28	506	23	26	$1.8 \times 10^{-16}$
14/02/2019	36	786	21	29	$1.9 \times 10^{-16}$

a

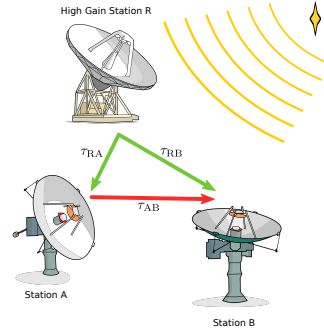


b

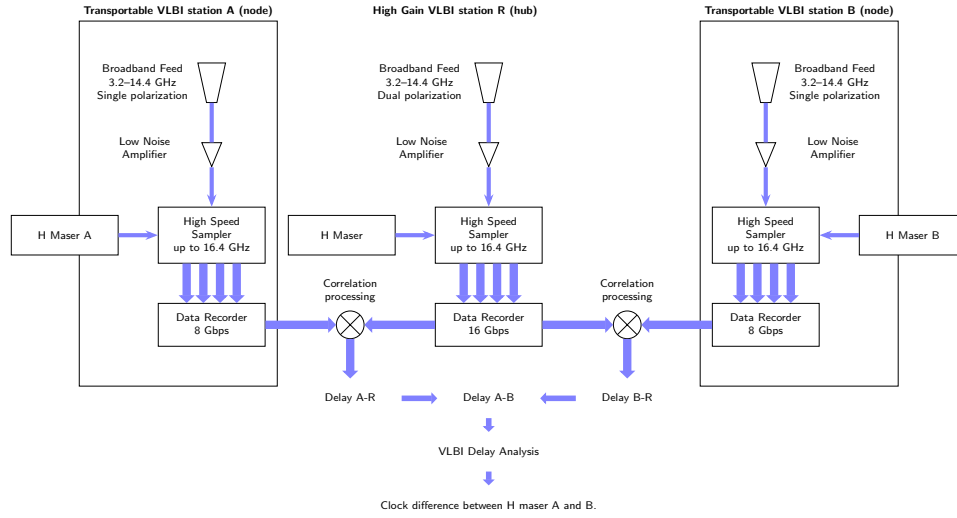


**Extended Data Figure 1: Delay resolution function of GALA-V and standard geodetic VLBI (IVS-T2 session).** **a**, Delay resolution functions for the frequency array of GALA-V described in the text and for standard geodetic VLBI (Experiment code T2126). GALA-V delay resolution function shows a single peak and fine delay resolution that allows the derivation of the absolute group delay without ambiguity. **b**, The delay resolution function formed from the frequency array of standard geodetic VLBI shows a delay ambiguity with a period equal to the reciprocal of the greatest common denominator of the frequency interval.

a

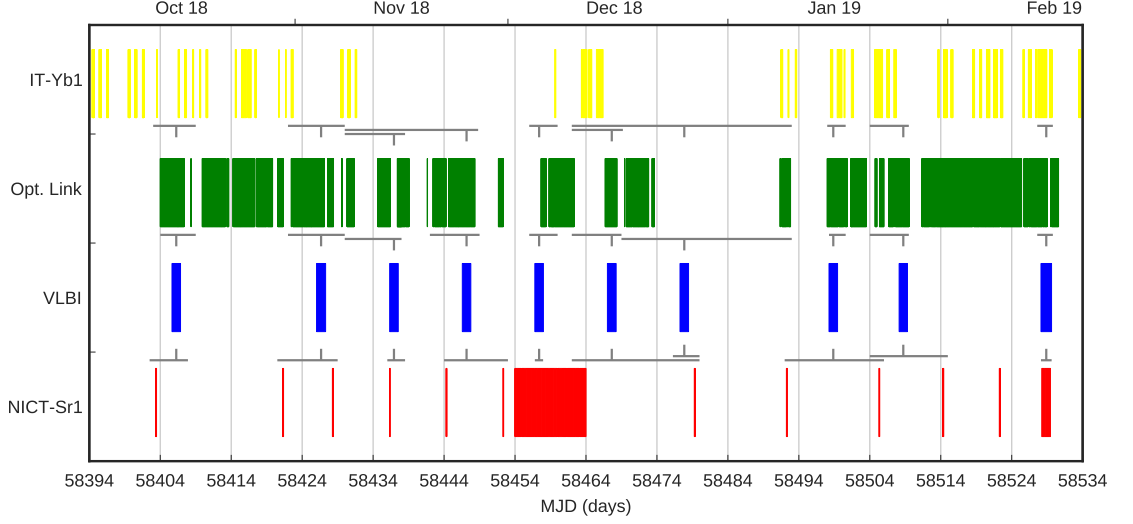


b



**Extended Data Figure 2: Node-hub style observations with transportable broadband VLBI stations.** **a**, Transportable small VLBI stations A and B can be used for intercontinental baseline by using a Node-hub style VLBI scheme with the station R. Delay data of AB baseline is computed by linear combination of delay data on RA and RB baselines. **b**, Block diagram of the Node-hub measurement with the broadband VLBI system.

a

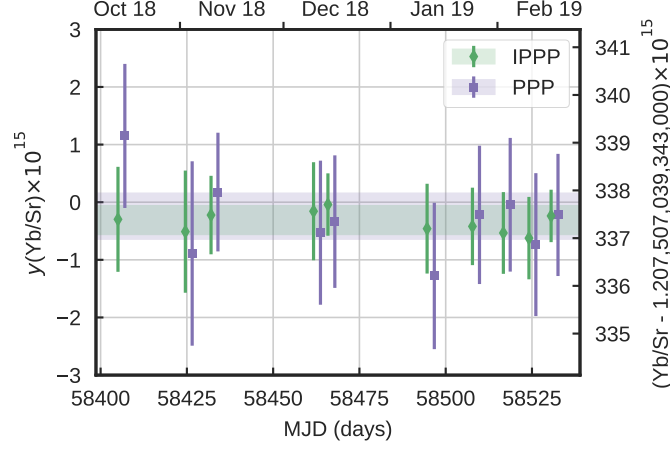


b

Maser	$h_{-2}^{1/2}$	$h_{-1}^{1/2}$	$h_0^{1/2}$	$h_2^{1/2}$
$H_T$	$1.5 \times 10^{-13}$	$3.5 \times 10^{-14}$	$5 \times 10^{-16}$	$2.5 \times 10^{-22}$
$H_M$	$1.5 \times 10^{-13}$	$2.8 \times 10^{-14}$	$4 \times 10^{-16}$	$2.5 \times 10^{-22}$
$H_K$	$1.1 \times 10^{-13}$	$4.5 \times 10^{-14}$	$8 \times 10^{-17}$	$2.5 \times 10^{-22}$

**Extended Data Figure 3: Extrapolations over dead times using the masers as a flywheel.** **a**, Uptimes of IT-Yb1 (yellow), optical link (green), VLBI link (blue) and NICT-Sr1 (red) marked as colored regions as a function of MJD. Gray horizontal bars represent evaluation intervals corresponding to each VLBI session, as marked by a vertical notch. For each evaluation interval the extrapolation was calculated for the masers at INRIM (between IT-Yb1 and the optical link), INAF (between the optical link and VLBI), and NICT (between VLBI and NICT-Sr1). **b**, Noise models used for extrapolations for the masers at INRIM, INAF, and NICT, describing the Hadamard variance  $\sigma_H^2 = h_{-2}(\tau/s)^{-2} + h_{-1}(\tau/s)^{-1} + h_0 + h_2(\tau/s)^2$ .

a



b

Yb/Sr ratio via PPP		Yb/Sr ratio via IPPP	
Contribution	Uncer. ( $\times 10^{-16}$ )	Contribution	Uncer. ( $\times 10^{-16}$ )
PPP satellite transfer	3.3	IPPP satellite transfer	1.4
Clocks	0.9	Clocks	0.9
Combs (microwave/optical)	1.1	Combs (microwave/optical)	1.1
Extrapolation	1.8	Extrapolation	1.4
Total	4.0	Total	2.5

**Extended Data Figure 4: Yb/Sr frequency ratio measurements between INRIM and NICT measured with a GPS link using IPPP or PPP.** **a**, Plot of the frequency ratio measurements. Green points represent the IPPP comparison with its total uncertainty. Green shaded region is the weighted mean of the IPPP comparison with its total uncertainty. Purple points represent the PPP comparison with its total uncertainty. Purple shaded region is the weighted mean of the PPP comparison with its total uncertainty. Horizontal offset between the two dataset is just for clarity. **b**, Uncertainty budget for the satellite comparisons.



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