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Common-clock very long baseline interferometry using a coherent optical fiber link / Clivati, Cecilia; Aiello, Roberto; Bianco, Giuseppe; Bortolotti, Claudio; De Natale, Paolo; Di Sarno, Valentina; Maddaloni, Pasquale; Maccaferri, Giuseppe; Mura, Alberto; Negusini, Monia; Levi, Filippo; Perini, Federico; Ricci, Roberto; Roma, Mauro; Santamaria Amato, Luigi; Siciliani de Cumis, Mario; Stagni, Matteo; Tuozzi, Alberto; Calonico, Davide; Clivati, Cecilia; Aiello, Roberto; Bianco, Giuseppe; Bortolotti, Claudio; De Natale, Paolo; Di Sarno, Valentina; Maddaloni, Pasquale; Maccaferri, Giuseppe; Mura, Alberto; Negusini, Monia; Levi, Filippo; Perini, Federico; Ricci, Roberto; Roma, Mauro; Santamaria Amato, Luigi; Siciliani de Cumis, Mario; Stagni, Matteo; Tuozzi, Alberto; Calonico, Davide. - In: OPTICA. - ISSN 2334-2536. - 7:8(2020), p. 1031. [10.1364/OPTICA.393356]

Publisher:

OSA

Published

DOI:10.1364/OPTICA.393356

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Common-clock very long baseline interferometry using a coherent optical fiber link

CECILIA CLIVATI,^{1,*} ROBERTO AIELLO,^{2,3} GIUSEPPE BIANCO,⁴ CLAUDIO BORTOLOTTI,⁵ PAOLO DE NATALE,² VALENTINA DI SARNO,^{2,3} PASQUALE MADDALONI,^{2,3} GIUSEPPE MACCAFERRI,⁵ ALBERTO MURA,¹ MONIA NEGUSINI,⁵ FILIPPO LEVI,¹ FEDERICO PERINI,⁵ ROBERTO RICCI,^{1,5} MAURO ROMA,⁵ LUIGI SANTAMARIA AMATO,^{4,6} MARIO SICILIANI DE CUMIS,^{4,6} MATTEO STAGNI,⁵ ALBERTO TUOZZI,⁶ AND DAVIDE CALONICO¹

¹Istituto Nazionale di Ricerca Metrologica INRIM, strada delle cacce 91, 10135 Torino, Italy

²Istituto Nazionale di Ottica INO-CNR, via Campi Flegrei 34, Pozzuoli, Italy

³Istituto Nazionale di Fisica Nucleare INFN, Sez. Napoli, Complesso Universitario di M.S. Angelo, Via Cintia, Napoli, Italy

⁴Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo", ASI/CGS, Matera, Italy

⁵Istituto di Radioastronomia IRA-INAFA, via Gobetti 101, Bologna, Italy

⁶Agenzia Spaziale Italiana, ASI, Roma, Italy

*Corresponding author: c.clivati@inrim.it

Received 23 March 2020; revised 14 July 2020; accepted 14 July 2020 (Doc. ID 393356); published 20 August 2020

Among the most powerful techniques for the exploration of the Universe is very long baseline interferometry (VLBI), which is based on the simultaneous observation of radio sources in the sky with arrays of distant ground-based antennas. One of the effects currently limiting its ultimate sensitivity is the phase-instability of the reference clocks adopted at each antenna. This term can be made negligible delivering the same clock signal to multiple telescope sites using optical fibers. We realized such an infrastructure by disseminating a coherent optical frequency signal to two distant radio telescopes using a 1739-km-long fiber. We performed a 24 h geodetic VLBI campaign in which the same clock reference was used at both telescopes and analyzed it using standard VLBI procedures. The results were consistent with the expectations, confirming that the proposed approach is feasible and configures as a novel tool for studying the role of clocks, troposphere, and systematic effects in the ultimate VLBI resolution. © 2020 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

<https://doi.org/10.1364/OPTICA.393356>

1. INTRODUCTION

The transmission of optical signals with an ultrastable, well-known frequency using optical fibers dates back to the '90s, when specific techniques were first developed to cancel the effect of mechanical fiber noise on the optical phase [1,2]. This redesigned the experimental practice in fundamental frequency metrology, allowing the comparison of distant atomic clocks at their ultimate accuracy over increasingly longer distances [3–9], and other unprecedented experiments in high-resolution atomic [10–12] and molecular physics [13–15], relativistic geodesy [9], quantum communication [16,17], and even seismology, for what concerns the detection of underwater earthquakes in seas and oceans [18].

The need of distributing frequency reference signals between distant sites without deterioration arose even before in radio astronomy and geodesy, for deep-space communication and tracking [19] and the synchronization of radio telescope arrays. Connected-element arrays such as the Atacama Large Millimeter Array [20] already exploit fiber-based frequency distribution on maximum distances of a few tens of kilometers. More recently, also

driven by the development of continental-scale fiber networks for metrology applications [7,8], fiber-based time and frequency distribution started to be explored in the context of very long baseline interferometry (VLBI) [21–23], in which telescopes are separated by several hundreds of kilometers.

Today, VLBI allows the most advanced imaging of our universe in the radio spectrum and, in turn, investigation of active galactic nuclei and black hole formation [24]. In geodesy, it allows positioning at millimeter precision level within the International Terrestrial Reference Frame (ITRF) [25] and the accurate investigation of global geodynamic phenomena and tectonic movements [26]. These results are possible by correlating observations from many telescopes spread over the Earth [27]. At each telescope, the arrival time, or the phase, of the sky-signal is precisely recorded with respect to a local reference clock. Pairwise correlation of records from distant antennas allows the retrieval of the relative delays in the arrival times of the sky-signal for each baseline. These are then combined into a least squares fit to a global model that takes into account most known effects, such as the coordinates of sources and telescopes, and atmospheric as well as instrumental delays and

earth orientation parameters (EOPs). The best estimation of free parameters gives information about quantities of interest such as the EOPs (for the determination of the length-of-day and polar motion), the position of sources (for astrometric studies), and stations (for crustal motion studies).

The main uncertainty terms in VLBI are due to an incomplete modeling of the random fluctuations of the optical path length in the troposphere, which can account for up to ~ 70 ps uncertainty, the source structure (~ 35 ps), and instrumental delays such as those due to the antenna structure (~ 35 ps) and the clock with its synthesis chain (~ 20 ps) [28]. In addition to these aspects, statistical noise has to be addressed. In this respect, different observing strategies are being pursued, depending on specific applications. On one side, the new-generation geodetic VLBI Global Observing System (VGOS) exploits an increased observation bandwidth and a high number of short-duration scans (30 s each) with well-chosen geometry to average out the single-scan statistical uncertainty, mainly due to random variations in the propagation delay of the troposphere [25]. A similar approach is used, among others, in the Event Horizon Telescope [29], which adopts 10 s sampling. It is recognized that, to avoid decoherence effects in the interference pattern, the clocks must fulfill the relation $\sigma \tau \omega \ll 1$ rad, σ being the clock's relative frequency instability (Allan deviation [30]) at a measurement time τ and ω the observed angular frequency. At 200 GHz, this implies that $\sigma \ll 8 \times 10^{-14}$ at $\tau = 10$ s. Present H-masers are just fit to this requirement with $\sigma = 1 \times 10^{-14}$ at best on such an averaging time, making troposphere instability the dominant source of decoherence.

Another approach aims at reducing the single-scan statistical uncertainty by extending its duration. This requires addressing the main limit to coherence, i.e., the clocks and tropospheric instabilities [31]. Recent works suggest that there is a potential to go beyond tropospheric effects exploiting water vapor radiometry [32] and frequency phase transfer techniques, which, however, require multiband receivers [33]. Directly addressing and removing the clock-related term can support this challenge for an overall improvement of VLBI observations. In this respect, one possibility is to install at the antennas new-generation atomic clocks, e.g., the optical clocks [34]. This could be feasible when commercial, unmanned optical clocks become available with the same reliability as the present H-masers. Another effective strategy is the fiber-based dissemination of a common frequency reference signal to the various telescopes, which allows a full rejection of the oscillator's noise and a direct link between VLBI sites and Metrology Institutes and specialized laboratories where state-of-the-art atomic clocks are maintained. This can provide radio telescope facilities with up-to-date technology, as an alternative to maintain local clocks. Referencing radio telescope facilities with the primary frequency standards available in those laboratories could also support some of the modern challenges of radio astronomy, such as the study of long-term timing instability in pulsars. This allows a dynamic study of gravitational waves [35], as well as tests of cosmological theories and general relativity [36], and requires local oscillators' instability at the level of 10^{-15} over time scales of years.

A straightforward approach to fiber-based frequency dissemination is the encoding of a radio frequency (RF) signal as a modulation of an optical carrier [22,23]. This approach can be used to replace local hydrogen masers at the telescope sites, but it does not improve the frequency stability over that of a local clock up to time scales of several minutes. Instead, the dissemination

of a coherent, narrow-linewidth optical signal takes advantage of the much higher frequency of the carrier and is currently the only method to disseminate any frequency standard without degradation both on the short and long term over thousands of kilometers.

In this work, for the first time, we disseminate an optical frequency reference from a Metrology Institute to two distant radio telescopes, separated by a baseline of 600 km in Italy, using a 1739-km-long phase-stabilized fiber link. A microwave signal is synthesized at each telescope site using an optical frequency comb and feeds the VLBI synthesis chain. The described infrastructure allows the dissemination of microwave and optical frequency standards to multiple sites, with up to 2 orders of magnitude improvement in accuracy and stability as compared to local hydrogen masers or fiber-based RF dissemination. As a proof-of-concept experiment, we used this infrastructure in a 24 h geodetic VLBI campaign where the two Italian telescopes shared a common fiber-delivered clock signal. These experiments demonstrated the feasibility of this approach and open up the possibility of more advanced studies on VLBI limiting effects.

2. DISSEMINATING THE SAME FREQUENCY REFERENCE TO MULTIPLE TELESCOPES

Our infrastructure is based on the dissemination of a common frequency reference from the Italian Metrology Institute (INRIM) located in Torino, to two radio telescope sites located in Medicina and Matera, operated, respectively, by the National Institute for Astrophysics and the Italian Space Agency (see Supplement 1 for details on these telescopes). A map of the infrastructure in its present status is shown in Fig. 1(a). It builds upon the connection between INRIM and Medicina Radio Observatory, which has been operative since 2015 [21], and extends the baseline to the Matera Space Geodesy Centre. The link also connects major research facilities of the Country, namely the European Laboratory for Non-Linear Spectroscopy (LENS) in Firenze [11,15] and the National Institute for Optics, which is part of the National Research Council (CNR-INO) in Pozzuoli, and is part of the atomic clock network under development in Europe [9]. Figure 1(b) shows a block diagram of the overall dissemination chain. It is based on the transmission of a laser signal at 1542.14 nm, whose frequency is stabilized on a high-finesse Fabry–Perot cavity to achieve a linewidth of a few Hz. On the long term, the laser's frequency is referenced to a hydrogen maser traceable to the definition of the second in the International System of units (SI) using an optical comb (see Supplement 1). Referencing to the INRIM Yb optical lattice clock [37] is also possible. The ultrastable laser is sent to the remote laboratories using fibers of the telecom network (see Supplement 1), to which operators have access for maintenance and upgrade. The backbone is divided in four cascaded segments, each identified by a different color in Fig. 1: Torino-Medicina, 535 km (red); Medicina-Firenze, 149 km (yellow); Firenze-Pozzuoli, 668 km (green); Pozzuoli-Matera, 387 km (blue). At each terminal, a diode laser is phase-locked to the incoming light and is injected into the next segment. Light is also partly reflected back toward the previous terminal and here compared to the launched radiation. This allows detection and cancellation of the noise added to the optical phase during the round trip into the connecting fiber [38]. Similarly, return light from the following terminal is compared to local light and used

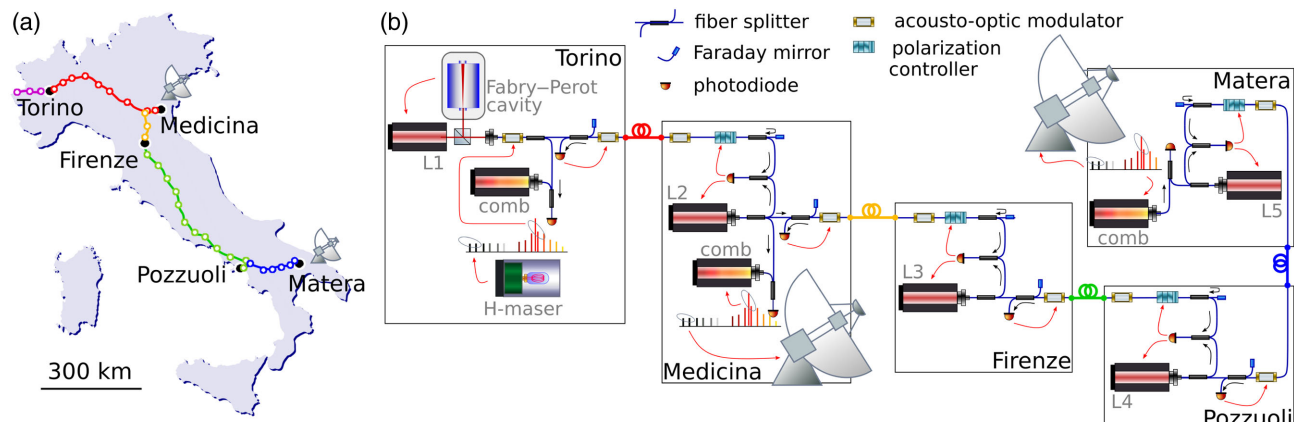


Fig. 1. (a) A map of the fiber-based network for VLBI in Italy. Different colors indicate the four segments of the link. Red, Torino-Medicina, 535 km. Yellow, Medicina-Firenze, 149 km. Green, Firenze-Pozzuoli, 668 km. Blue, Pozzuoli-Matera, 387 km. Purple, connection to the French border and European atomic clock network. Circles, optical amplification sites. (b) A block diagram of the infrastructure. L1, master laser, frequency stabilized on a high-finesse Fabry–Perot cavity and on a H-maser-referenced optical comb. L2–L5, local regenerating lasers, phase-stabilized to the link-delivered optical signal. At the Medicina and Matera VLBI sites, the optical signal is coherently divided to the RF domain using local optical combs. Phase noise of the connecting fibers is detected by comparing the round trip radiation to the local light in a Michelson interferometric scheme, and corrected using acousto-optic modulators. Red arrows indicate referencing and active feedback systems; black arrows indicate the direction of light.

to stabilize the fiber in between. At the Medicina and Matera terminals, the local laser that is phase-locked to the incoming light is coherently divided down to 100 MHz using an optical frequency comb. The synthesized RF signal is therefore phase-coherent with the original signal located in the transmitting laboratory. Details on the design of terminal stations are given in Supplement 1.

The link segmentation is beneficial from several points of view [39]. First, phase-stabilization of fiber segments shorter than the full link allows a larger control bandwidth, as this latter is limited to $c/4L$, being L the span length and c the speed of light into the fiber [38]. In our setup, the fiber noise was stabilized on bandwidths of 60 Hz, 150 Hz, 70 Hz, and 100 Hz on the four spans, respectively, while the locking bandwidth would be limited to <30 Hz if the full length of the link was stabilized. In addition, the optical regeneration allows a better managing of the optical loss, which would exceed 480 dB for the full link and could not be recovered with erbium-doped fiber amplifiers (EDFAs) only. At the same time, it filters broadband optical noise introduced by EDFAs. Finally, at every node, an ultrastable, optical reference traceable to the SI unit is available, which can be used for local applications. This approach is particularly effective in our facility, where the same reference signal has to be provided to multiple sites.

VLBI experiments have a typical duration of several hours or days; hence, continuous operation and phase coherence of the disseminated reference must be maintained over these time scales. The most critical aspect to meet these requirements is the robustness of the various optical phase-locked loops involved in the chain, which in turn depend on the optical beatnotes' signal-to-noise ratio at detection. This is mainly affected by variations in the signal polarization as it travels the link, and gain instability of the EDFAs, which can lead to >10 dB variation in the beatnotes' power. To cope with such issues, polarization and gain of the EDFA chain are actively stabilized, allowing up to several days of continuous uptime. Residual failures are due to fast flips of the signal polarization, which we attributed to human work along the line and cannot be tracked by our system. To further improve the uptime and

reduce the operator intervention, we are investigating novel phase-detection techniques based on dual-polarization receivers [40], and we are upgrading the system to allow completely unmanned failure-recovery capability. With these solutions, optical frequency dissemination can move to a regime where the maintenance activity becomes similar to that required for local standards [39].

Figure 2(a) shows the phase noise introduced by the four link segments. All of them show similar features: noise is dominated by a flicker-phase process in the low-frequency range, with a peak around 12 Hz that is attributed to human activities such as traffic and building vibrations. The segment connecting Pozzuoli to Matera (blue) shows a significant noise excess around few Hz Fourier frequency. This is attributed to the presence of about 5 km of aerial cables, which are presumably subject to dangling due to wind. This span also shows higher polarization instability. During the EDFA installation, we were able to measure the integrated fiber noise between the transmitting terminal and various intermediate locations. These measurements were made by reflecting back the light at the intermediate stations and recording the fiber noise in an unstabilized condition. Figure 2(b) shows the phase noise power spectral density at 1 Hz Fourier frequency for various fiber spans, normalized to the span length. This gives indication of the average spatial density of the noise as the span length increases. On the first part of the Torino-Medicina link (red), the noise density is rather constant, indicating that the overall noise scales linearly with length, as expected in a homogeneous environment [38]. Interestingly, a lower noise density is observed in the urban Torino area. On the other hand, higher noise density is measured on segments including the metropolitan area of Milano, with its impact being progressively washed out when averaging over longer distances. The noise density of the Medicina-Firenze link (yellow) is considerably higher than on other spans, although the reason for that is unknown. On the Firenze-Pozzuoli link (green), the noise density shows weak dependence on the length, which might be related to the absence of large metropolitan areas along the fiber path. On the Pozzuoli-Matera link (blue), the noise density is

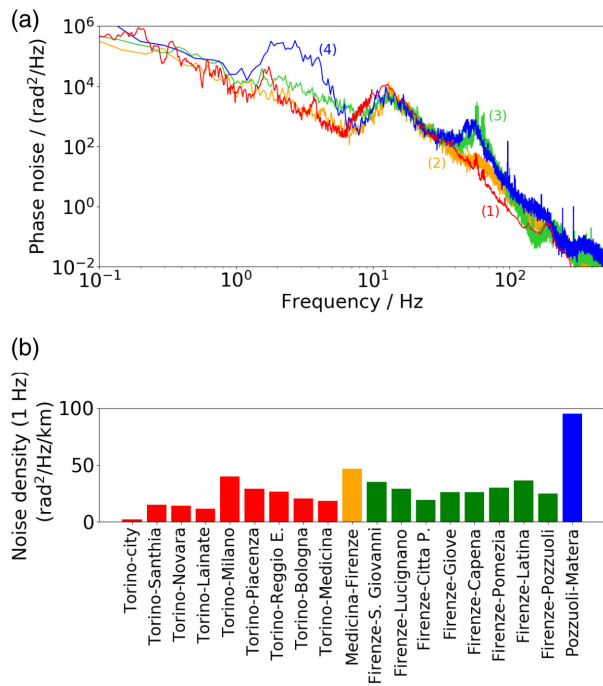


Fig. 2. (a) Phase noise of the four link segments. (1) Red, Torino-Medicina; (2) yellow, Medicina-Firenze; (3) green, Firenze-Pozzuoli; (4) blue, Pozzuoli-Matera. (b) Spatial noise density at 1 Hz Fourier frequency for various spans of increasing length. Different colors indicate different segments.

affected by the presence of aerial paths. Overall, these measurements confirm the large variability of noise levels recorded in land fibers, mostly due to the acoustic environment to which they are exposed. Although the noise levels recorded on this backbone are considerably higher as compared to other infrastructures realized elsewhere (see [41] for a comparison), efficient rejection can be achieved through Doppler noise cancellation up to acoustic frequencies, preserving the phase coherence between the launched and the received signal.

3. FIBER-BASED COMPARISONS OF REMOTE HYDROGEN MASERS

At each telescope, the comb-synthesized RF signal, which is referenced to the INRIM hydrogen maser, is constantly compared to the local maser. Figure 3(a) shows the phase noise of the comparisons in Medicina (red curve, 1) and Matera (blue curve, 2) at 10 MHz. Signature of the residual link noise is visible at acoustic frequencies between 1 and 100 Hz, while for lower frequencies, the measurement is limited by the noise floor of local hydrogen masers. The comparison in Matera shows a higher noise floor in the range 1 kHz to 1 MHz, which is consistent with the specified noise of the local hydrogen maser. Spurious signals at harmonics of the 50 Hz power line frequency are introduced by the RF dividers and the measurement chain. Figure 3(b) shows the long-term instability, in terms of the Allan deviation [30], of a three-day pairwise frequency comparison after the linear drift of the hydrogen maser frequency is removed. More details on the measurement procedure are given in Supplement 1. The measured instabilities are in agreement with the local hydrogen masers' specifications, indicating no contribution from the dissemination chain. Unlike RF dissemination

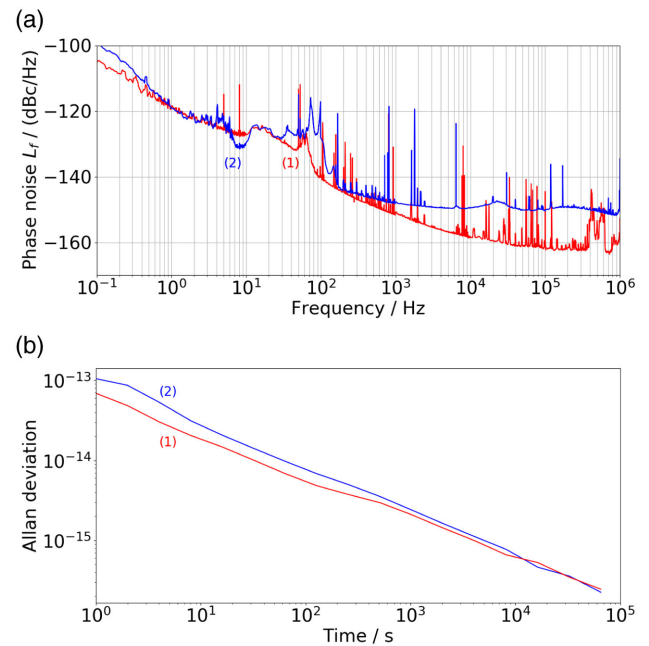


Fig. 3. (a) Phase noise of the RF signal generated in Medicina (red, labeled 1) and Matera (blue, labeled 2) as compared to local hydrogen masers. Phase noise is referred to 10 MHz. (b) Allan deviation from three days of continuous comparison between the local masers and the link-disseminated RF signal in Medicina (red, labeled 1) and Matera (blue, labeled 2). The linear frequency drift of hydrogen masers was removed.

techniques, optical frequency dissemination allows the distribution of clock signals with higher stability than hydrogen masers and the effective implementation of a common-clock architecture.

We note that the offline comparison described here is not strictly required in VLBI observations, where the fiber-delivered optical signal is scaled to the RF domain and directly employed in the synthesis chain instead of the local hydrogen maser. Nevertheless, it allows continuous calibration of local masers at a much higher resolution than currently available at VLBI sites, which is based on satellite techniques. This feature still offers the possibility of absolute referencing of VLBI frequency standards while relaxing reliability constraints in the dissemination chain, as offline calibration does not require continuous uptime owing to the high predictability of the hydrogen maser behavior. In addition, the combination of local and remote frequency standards could be an option in case of longer or noisier fiber segments, considering the limited bandwidth of the fiber noise cancellation. This approach combines the long-term stability and traceability to primary standards offered by fiber-based dissemination with the higher spectral purity of local oscillators in the 10 Hz to 1 kHz range.

During the month of May, 2019, we routinely compared the masers in Torino, Medicina, and Matera. The total measurement time, resulting from the combined uptime of all steps of the chain within the measurement campaigns, exceeded 200 h. Hydrogen masers were also compared in the same time intervals using geodetic Global Positioning System (GPS) receivers installed at the two telescopes. The difference between results of the hydrogen maser comparisons obtained using the fiber or the GPS is shown in Table 1 for the baselines Medicina-INRIM and Matera-INRIM (see Supplement 1 for details on the data analysis),

Table 1. Results of the Closure Test between Fiber-Based and GPS Comparison of the Hydrogen Masers at INRIM, Medicina, and Matera

$$\begin{aligned} &(\text{Medicina} - \text{INRIM})_{\text{fiber}} - (\text{Medicina} - \text{INRIM})_{\text{GPS}} = \\ &(0.15 \pm 0.69) \times 10^{-15} \\ &(\text{Matera} - \text{INRIM})_{\text{fiber}} - (\text{Matera} - \text{INRIM})_{\text{GPS}} = \\ &(-2 \pm 2) \times 10^{-15} \end{aligned}$$

and shows agreement within the limits set by the GPS resolution. In particular, a higher uncertainty is observed on the GPS baseline Torino-Matera due to higher instability of the GPS receiver in Matera.

4. COMMON-CLOCK VLBI EXPERIMENT

The infrastructure was used in a geodetic VLBI campaign in which Medicina and Matera telescopes were operated in a common-clock architecture, using the frequency reference disseminated from INRIM as input for the VLBI synthesis chain. The campaign was a standard geodetic VLBI run lasting 24 h between May 19, 2019, 07:00UT and May 20, 2019, 07:00UT. The experiment described here consisted in several scans with varying duration of few minutes, during which a list of radio sources selected from the International Celestial Reference Frame version 2 (ICRF2) [42] was observed. The analysis was performed following the standard geodetic routine: the observation delays for each baseline are combined into a multiple parameter least squares fit, where effects such as Earth's orientation, station coordinates, ionospheric and tropospheric delays, and clocks' phase differences are taken into account. Each of these effects is modelled by specific relations and free parameters, whose best estimates are produced as output at the end of the least squares adjustment process. In preparation to this test, several campaigns with duration between 6 and 24 h were performed since 2017 involving Medicina and Matera radio telescopes as well as other Italian and European stations. In such preliminary tests, Medicina, at the time the only station reached by the optical fiber, was operated using either the local or the fiber-disseminated signal, and no significant differences were observed in the quality of the results.

In the present experiment, the lock of the ultrastable laser to the hydrogen maser at INRIM was lost, as a consequence of a permanent damage of the INRIM optical comb. This led to a highly nonlinear wander of the disseminated laser frequency, with short-term drifts as high as 5×10^{-15} /s, and instantaneous deviations from the nominal frequency value of up to 2×10^{-12} . These performances are several orders of magnitude worse than that of a hydrogen maser, whose typical frequency drift is $< 10^{-15}$ /day. We chose to perform the common-clock VLBI campaign even in such a challenging condition, given the limited availability of observing time at the antennas and the difficulty in rescheduling the experiment. In fact, the clocks' frequency deviations are expected to be highly correlated in Matera and Medicina, as the same signal is distributed to both sites. The analysis of the experiment verified this hypothesis, by retrieving this information from VLBI data.

A least squares fit to the group delays is performed on the scans of the Medicina-Matera baseline over 15 h of data free from clock breaks; 181 out of 238 scans (76%) were used in the analysis because of RF interference and anomalous noise in the receivers, which did not depend on the fiber-disseminated frequency reference. Fit residuals are shown in Figure 4 for valid scans. The

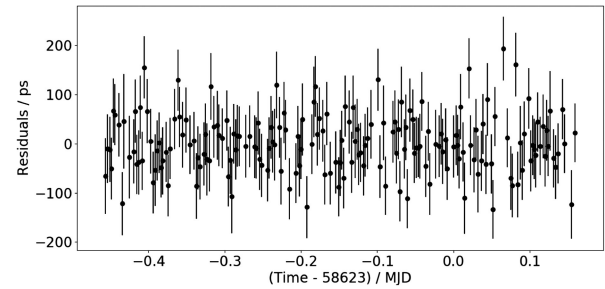


Fig. 4. Residuals on the group delay versus observing time as a result of the geodetic analysis of the May, 19–20, 2019, observing session on the baseline Medicina-Matera. Every data point represents a single scan.

weighted root mean square value of residuals is 58 ps. Typical values of residuals on standard geodetic campaigns involving Medicina or Matera telescopes on international baselines range between 15 ps and 60 ps, where the variability depends on several factors, including the number of telescopes and baselines, experimental conditions, and data quality. The value obtained in this experiment allowed standard geodetic analysis and confirms the suitability of common, fiber-disseminated clock signals to VLBI observations.

For the considered period, the time delay Δt between the clocks in Medicina and Matera was modelled in the least squares adjustment process as

$$\Delta t = t_0 + y_0(t - t_{\text{start}}) + d(t - t_{\text{start}})^2, \quad (1)$$

where t_{start} is the start time of the considered period and t_0 , y_0 , and d are estimated by the algorithm. From Eq. (1) the instantaneous relative frequency difference between the two clocks is derived,

$$y = y_0 + 2d(t - t_{\text{start}}). \quad (2)$$

The best fit estimation of the clocks' parameters during the considered experiment, derived from standard analysis, is $y_0 = (-0.43 \pm 1.16) \times 10^{-14}$ and $d = (-1.46 \pm 1.66) \times 10^{-14}$ /day. The result shows that within the uncertainty set by the global solution, no difference is appreciated between the two clock signals delivered at each of the VLBI facilities. This result is in agreement with the assumption that the telescopes in Medicina and Matera actually shared the same clock, and confirms that the realized infrastructure does not introduce additional noise to the system and can be effectively exploited in VLBI campaigns. We note that such results were obtained in exceptional experimental conditions where the frequency instability of the disseminated signal was much worse than that of a typical H-maser. Still, this did not lead to major anomalies in the experimental outcome owing to the fact that the same frequency signal was delivered to both telescopes. Higher-order effects might have been present, which, however, are not observed within the current measurement uncertainty.

Building on this experiment, future campaigns are planned. On one hand, collecting more statistics will allow the quantitative assessment of improvements achievable by operating the telescopes in a common-clock topology. On the other hand, we will investigate how this topology could be exploited to reduce the problem complexity from the statistical point of view.

5. DISCUSSION

We realized a fiber backbone for optical frequency dissemination to VLBI facilities and demonstrated its use in standard geodetic

campaigns. The dissemination of a high spectral purity optical carrier allows fiber phase noise cancellation at the highest resolution and is the only technique currently suited for the effective implementation of a common-clock architecture on very long baselines, in which the noise of both the clock and its distribution chain is rejected.

The realized infrastructure also allows a hybrid operational mode, where the local oscillators can be steered or calibrated against the fiber-disseminated signal with lower uncertainty than with satellite techniques. Local oscillators can be hydrogen masers, cryogenic sapphire oscillators [43], or, in the future, even high-finesse optical cavities [44]. The combination of local clocks and fiber-based dissemination can also further reduce the clock-related downtime of the VLBI facility. Hence, we envisage that coherent optical frequency distribution over fiber can overcome the clock-related issues in VLBI experiments for a long while, supporting the technical improvements that the VLBI and geodetic communities are pursuing on other limitations.

We then performed a proof-of-concept geodetic VLBI experiment in which two distant radio telescopes separated by a 600 km baseline shared the same clock reference. Data were successfully correlated, and a consistent global solution was found.

Our results demonstrate a novel approach that directly addresses the clock-related term of the VLBI global solution. Although the clocks' instability is generally not the leading term in random fluctuations, its impact is non negligible, and, as research is addressing other terms, it is strategic to investigate methods to reduce it as well. Moreover, we stress that a common-clock experiment could take advantage of a simplified data analysis where the number of parameters to be estimated in the least squares adjustment is reduced. This can allow a more accurate characterization of some of the other limiting factors and open up the possibility of scaling experiments that are now only possible on small-size arrays. Particularly, it could help the refinement of atmospheric models generally used in the computation of VLBI solutions, the structure modeling of extragalactic radio sources [45], and the assessment of instrumental noise on the receivers and microwave synthesis chain. The present facility could realize a unique experimental setup to study systematic VLBI effects, as well as cross talk between the various effects playing a role in the adjustment of global parameters, and to assess the suitability of VLBI as a way to perform clock comparisons on transcontinental distances [46]. This experiment is a first step in view of more specific investigations on these aspects.

Funding. Ministero dell'Istruzione, dell'Università e della Ricerca (20152MRAKH), (MetGeSp); Agenzia Spaziale Italiana (DTF-Matera); European Metrology Programme for Innovation and Research (EMPIR-17IND14-WRITE), (EMPIR-18SIB06-TIFOON).

Acknowledgment. We thank the VLBI partners of Yebes and Onsala observatories, Matera Space Geodesy Centre, and Medicina Radio Observatory for their support during the VLBI runs; Saverio Bartalini at PPQSense, Marco De Pas, Alessio Montori, Mauro Giuntini at the electrical workshop at LENS for fruitful collaboration in the development of link terminal electronics, especially for laser drivers; Consortium TOP-IX, in particular Matteo Frittelli and Alessandro Galardini for support in the development of remote control systems; consortium GARR for support in the backbone installation and operation; Marco

Pizzocaro at INRIM for useful discussion; Elena Cantoni and Giancarlo Cerretto at INRIM for providing GPS data. Processed data are openly available [47].

We acknowledge funding from: Projects EMPIR-18SIB06-TIFOON and EMPIR-17IND14-WRITE, which have received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme; Italian Space Agency (DTF-Matera); Italian Ministry of Education, University and Research (MIUR) through the Progetti Premiali program (MetGeSp). V. Di Sarno thanks the grant support by Progetti di Ricerca di Interesse Nazionale (PRIN), Project No. 20152MRAKH of the Italian Ministry of University and Research.

Disclosures. The authors declare no conflicts of interest.

See [Supplement 1](#) for supporting content.

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