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# A coherent fiber link for Very Long Baseline Interferometry

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**Abstract**—We realize a coherent fiber link for application in Very Long Baseline Interferometry (VLBI) for radioastronomy and geodesy. A 550 km optical fiber connects the Italian National Metrological Institute (INRIM) to the main radiotelescope in Italy and is used for the primary Cs fountain clock stability and accuracy dissemination. As a transfer oscillator we use an ultrastable laser, frequency-referenced to the primary standard; at the radiotelescope, a RF signal is generated from the laser by using an optical frequency comb. This scheme now provides the traceability of the local maser to the SI second, realized by the Cs fountain at the  $1.7 \times 10^{-16}$  accuracy. The fiber link is never limiting the experiment and is robust enough to sustain radioastronomical campaigns. This experiment opens the possibility to replace the local hydrogen masers at the VLBI sites with optically-synthesized RF signals. This could improve VLBI resolution by providing more accurate and stable frequency references and, in perspective, by enabling common-clock VLBI based on a network of telescopes connected by fiber links.

## I. INTRODUCTION

In recent years, frequency metrology has moved to the optical domain: optical atomic clocks achieved accuracy at the 18<sup>th</sup> digit [1], [2] and optical frequency combs allow high precision measurements of optical frequencies and the synthesis of high-spectral purity microwaves [3], [4]. Last, the dissemination of optical frequencies at the  $10^{-19}$  level was achieved by sending ultrastable lasers over standard telecom fibers, where the length variations are actively cancelled through the Doppler stabilization technique [5], [6], [7], [8], [9]. Phase-stabilized optical links outperform the resolution of satellite time and frequency transfer techniques by five orders of magnitude [10]. In Europe, a fiber-based network is under development, that will enable more extensive atomic clocks comparisons in view of a new definition of the second in the International System of units (SI) and the generation of improved timescales. Moreover, frequency dissemination over fiber would improve other fields, such as high-precision spectroscopy [11], fundamental physics and relativistic geodesy [12].

In this paper we investigate the potential of optical links for Very Long Baseline Interferometry (VLBI), that is a powerful tool both for radioastronomy and geodesy. VLBI requires

high-quality frequency references; here, we investigate the possibility of replacing the currently used frequency standards with remotely-disseminated signals with higher stability and accuracy.

VLBI campaigns are based on scheduling successive observations of radio-sources in the sky from an array of radiotelescopes spread all over the Earth. Each couple of antennas is separated by many baselines  $D_i$ , measuring up to thousands of kilometers. The ultimate angular resolution of the array is improved by up to the ratio  $D_{\max}/d$  with respect to that of a single telescope with aperture  $d$ , where  $D_{\max}$  is the maximum baseline [13].

In addition, VLBI supplies geodetic data at the highest precision, because it provides access to the best available inertial reference system, defined by quasars located at the edge of the observable Universe. By cross-correlating the measurements taken at different antennas it is possible to retrieve the relative displacements between them and their variations over time. This allows the computation of orthometric models of the Earth and of its dynamics, useful for monitoring the geophysical changes.

The typical central observation frequencies span from 1 GHz to 26 GHz, with bandwidths from hundreds of megahertz to 1 GHz. Each antenna is equipped with a local oscillator for frequency down-conversion of the collected signal and for proper sampling and timing during the signal processing at each telescope. High spectral purity is demanded for the local oscillator as well as a good long term stability, since the measurement campaigns last for several hours.

The current challenge of VLBI is to increase the frequency range around 100 GHz: this would improve the resolution, allowing the search for new physics [14], [15]. However, such target requires to address two relevant issues: the first is the instability of the troposphere and the second is the phase noise of the local oscillator.

The troposphere has inhomogeneities in the water vapour concentration that affect the coherence of the sky-signal by introducing time-varying delays on the collected wavefronts. According to the literature, the typical instability contributions of the troposphere vary between  $1 \times 10^{-13}$  at 1 s ( $1 \times 10^{-15}$  at 10 000 s) for good weather conditions and  $3 \times 10^{-14}$  at 1 s ( $<1 \times 10^{-15}$  at 10 000 s) for very good weather conditions, these latter corresponding to a 100  $\mu$ m rms excess path length over a 100 m baseline [14]. This problem is likely to be mitigated up to the 98% level by co-locating water vapour radiometers (WVR) at the antennas, as pursued within the ALMA project [14], [15], [16]. Current WVR already

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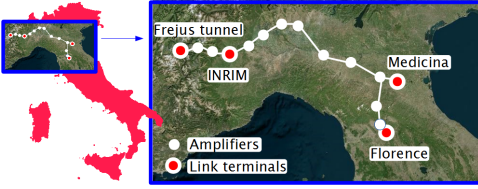


Fig. 1. A map of the facility for frequency dissemination in Italy.

allow at least a factor 3 or improvement; thus, the instability contribution of WVR-corrected atmosphere in very good weather conditions can drop to the  $1 \times 10^{-14}$  level at 1 s and to the  $10^{-16}$  level at 10 000 s, being already negligible if compared to the contribution of the local oscillator.

The most commonly used local oscillators are hydrogen masers (HMs), whose absolute frequency and long-term drift are periodically calibrated during specific frames before each VLBI session. However, it is well known that in multiplication chains the white phase noise increases as the square of the multiplication factor, becoming a dominant noise source around 100 GHz. Therefore, the use of lower phase noise oscillators such as cryogenic sapphire oscillators is being investigated [14], [17], [18]. The long-term HM instability is an issue as well: for instance, geodesy now targets the 1 mm positioning precision, that cannot be achieved even with state-of-the-art HMs [19] and would require a frequency stability on the order of  $10^{-16}$  after hours of measurement.

In this work, we demonstrate the possibility of using ultrastable and low-noise optical signals disseminated through coherent fiber links. This technique will offer the possibility to deliver the same frequency at multiple sites, allowing a complete rejection of the clock instability; moreover, it enables the frequency distribution of optical atomic clocks, whose stability is three orders of magnitude better than a HM.

We realized a coherent fiber link from the Italian National Metrology Institute INRIM to the radiotelescope in Medicina (Bologna) of the Italian Institute of Astrophysics (INAF), a 32-m dish which is part of the European VLBI network. The link disseminates an accurate and stable frequency standard referred to the SI second and has been used for the characterization of the HM located in Medicina. Similar techniques have been employed by other groups for the remote characterization of HMs and microwave links [20]: such experiments can set the basis of a more extensive investigation on remotely-disseminated frequency signals as local oscillators in VLBI measurements and pave the way for novel physical experiments.

## II. THE EXPERIMENT

INRIM realizes and maintains the SI second with the primary frequency standard ITCsF2, a nitrogen cooled Cs Fountain clock that is regularly used for the generation of the International Atomic Time. ITCsF2 accuracy is  $1.7 \times 10^{-16}$ , while its frequency instability (Allan deviation) is  $2.4 \times 10^{-13}/\sqrt{\tau}$ , being  $\tau$  the measurement time [21]. As shown in Fig. 1,

INRIM has developed up to 800 km of coherent fiber links for primary standards dissemination to several laboratories in Italy, and reached the French border in view of a future connection to other European Metrology Institutes [7], [22]. Each link shows a calibrated relative uncertainty at the  $5 \times 10^{-19}$  level. Recently, the Medicina Radiotelescope (MR) has been connected via a 550 km optical fiber.

The experimental setup is shown in Fig. 2. The frequency dissemination is based on the delivery of an ultrastable optical carrier, which is generated at INRIM by frequency-locking a fiber laser at 1542.14 nm to a high-finesse Fabry-Perot cavity. The laser linewidth is  $<10$  Hz and the relative frequency drift is  $<10^{-15}/s$  [23]. On the long term, the laser is frequency-stabilized to a hydrogen maser ( $HM_{INRIM}$ ) by using a fiber frequency comb, as already proposed by other groups [24]; our setup is based on a digital phase-locked loop and uses a dead-time free phase/frequency counter to detect the beatnote between the ultrastable laser and the closest comb mode; the counter is operated in the so-called Lambda-mode to sufficiently reject  $HM_{INRIM}$  high-frequency noise. The beatnote is then phase-stabilized via software to a fixed value by applying a correction to an acousto-optic modulator.  $HM_{INRIM}$  in turns is constantly measured against the ITCsF2 fountain. The locking bandwidth of our ultrastable laser to  $HM_{INRIM}$  is 0.04 Hz, a compromise between a tight lock and a good rejection of the maser noise. For times longer than the loop time constant, the laser instability reproduces that of  $HM_{INRIM}$ , i.e.  $1.5 \times 10^{-14}$  at 10 s and  $1.2 \times 10^{-15}$  at 1000 s on a 1 Hz measurement bandwidth; the residual frequency drift is  $<10^{-19}/s$  and a comparison with an independent comb, stabilized to the same reference, showed no frequency bias at the  $3 \times 10^{-16}$  level. These results confirm that the ultrastable laser can be used as a traceable frequency reference at the remote link end.

The ultrastable laser is sent to MR through a Doppler-stabilized optical link, with a total loss of  $\sim 150$  dB compensated by 8 bidirectional Erbium-doped fiber amplifiers. Their gain is carefully adjusted to minimize the amplified spontaneous emission and undesired amplitude modulation. The last part of the fiber (40 km) is shared between INRIM metrological channel and the MR data traffic. The network implements a Dense Wavelength-Division-Multiplexed (DWDM) architecture, where channel 44 of the International Union Grid is dedicated to our experiment and two Optical Add and Drop Multiplexers are used to properly route the metrological signal and the data stream. The link stabilization is based on a Michelson-interferometer configuration [25], in which the laser is split into two beams: one is used as a local oscillator, the other part is sent to MR. Here it is frequency-shifted by the acousto-optic modulator AO2 and partly reflected back to INRIM, where it is compared to the local oscillator on photodiode PD1. This signal enables us to detect the noise added by the fiber, which is then cancelled by a phase-locked loop (PLL) acting on AO1. A detailed description of the noise cancellation scheme can be found in [7].

At MR the coherent signal is extracted and regenerated by a diode laser, which has a free-running frequency noise of the type  $S_\nu(f) = A/f$ , with  $A = 4 \times 10^6 \text{ Hz}^2$  and a linewidth of several kilohertz [23]. This diode laser is phase-locked

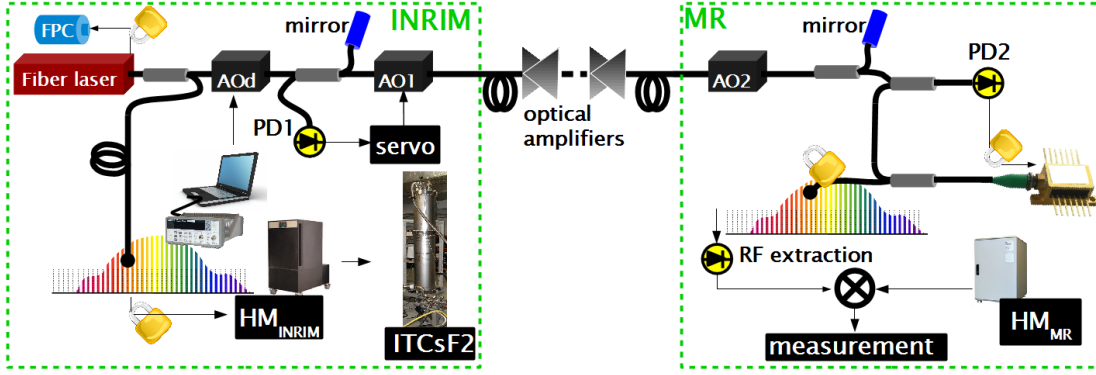


Fig. 2. Experimental setup: a fiber laser is frequency-locked to a Fabry-Perot cavity (FPC) and sent to an optical fiber comb; the comb is referenced to  $HM_{INRIM}$ , which is in turn constantly measured against the Italian primary standard ITCsF2. The long-term instability of the laser is cancelled by a digital frequency-stabilization of the beatnote with the optical comb. The actuator for this loop is the acousto-optic modulator AOd. The laser is sent to MR along a 550 km phase-stabilized fiber, where AO1 is the actuator of the optical link noise cancellation and AO2 is a fixed frequency shifter. At the remote end, the signal is extracted and regenerated with a phase-locked loop acting on a diode laser. This is also used as a reference for an optical fiber comb; the 40th harmonic of the repetition rate is extracted and divided by 100, then compared with the local HM.

to the incoming radiation with a 50 kHz bandwidth and is used as a reference for an optical fiber frequency comb. A harmonic of the comb repetition rate (250 MHz) is phase-locked to the diode laser with a bandwidth of  $>200$  kHz by using an intra-cavity electro-optic modulator; the carrier-envelope-offset frequency is locked to the local RF reference by acting on the laser pump power. The 40th harmonic of the repetition rate is extracted and divided by 100, to obtain the 100 MHz reference signal used to measure the local HM.

The noise power spectrum of the phase comparison between the delivered signal at 100 MHz and  $HM_{MR}$  is shown in Fig. 3 when the link is unstabilized (blue) or stabilized (red). The high-frequency noise is limited by the RF synthesis from the optical comb. The residual noise of the stabilized fiber link is evident between 10 Hz and 500 Hz: the noise cancellation bandwidth is  $\sim 60$  Hz, whilst the bump at  $\sim 15$  Hz is due to acoustic noise on the fiber and building vibrations. Below 10 Hz the noise is limited by  $HM_{MR}$  in agreement with the manufacturer specifications ( $-100$  dBc/Hz at 1 Hz offset frequency at 100 MHz).

When measuring the absolute frequency of  $HM_{MR}$ , the most relevant sources of uncertainty are cycles slips on any of the PLLs in the chain. They may happen on a statistical basis [26] and are strongly dependent on the signal-to-noise ratio (SNR) and on time-varying Rayleigh-scattering events along the link. To properly detect them we track the control beatnote of the optical link with independent voltage-controlled oscillators, and we discard all data which deviate by more than 0.4 Hz. All other beatnotes are continuously measured, and all measurements where the counted beatnotes differ from the lock-frequencies by more than 0.7 Hz are discarded as well. The thresholds are chosen according to the minimum cycles-slips amplitude, i.e. 0.5 cycle on the optical link and 1 cycle on other beatnotes. These slips correspond to 0.5 Hz and 1 Hz frequency outliers on a 1 s measurement time respectively. If a 30 dB SNR on a 100 kHz bandwidth is provided on the beatnote, we observe no cycles slips or few cycles lost per hour on the optical link. On the other hand, the optical

regeneration needs optimization of the polarization axis every few hours to compensate for the long-term polarization drift of the incoming signal and for the consequent drop of SNR on this beatnote. Fig. 4 shows three typical data series: points affected by cycles slips on the optical link and on the optical regeneration are shown in green and red respectively. As it can be seen, the optical regeneration is currently the less robust stage of the metrological chain; this issue will be mitigated in the future by implementing an automatic polarization adjustment tool.

To guarantee the correct removal of data affected by cycles slips, a proper synchronization of the measurements in the two laboratories is needed. During the campaign, we daily measured the delays in the synchronization by applying a square-wave modulation on the frequency of our laser and observing the consequent modulation on all the other beatnotes. The measured delays were then corrected by post-processing at better than 1 s; this could be further reduced in the future

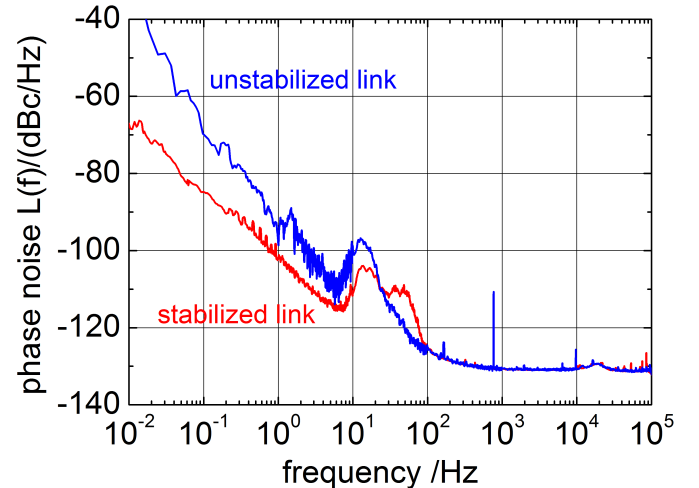


Fig. 3. The phase noise power spectrum of  $HM_{INRIM}$  vs  $HM_{MR}$  at 100 MHz when the link is unstabilized (blue) or stabilized (red).

by connecting all PCs to a Network Time Protocol server, which is capable to guarantee  $<10$  ms uncertainty on the timestamps. However, we observed no significant deterioration on the accuracy and stability of the delivered signal even if cycles slips were not removed, thanks to their low rate and typical amplitude (few cycles) in normal operating conditions. The frequency instability of  $\text{HM}_{\text{INRIM}}$  vs  $\text{HM}_{\text{MR}}$  is shown in Fig. 5 both when the link is unstabilized (blue) or stabilized (red): it is dominated by the intrinsic instability of  $\text{HM}_{\text{MR}}$ , in agreement with the specifications of  $8 \times 10^{-14}$  at 1 s and  $2 \times 10^{-15}$  at 1000 s on 1 Hz measurement bandwidth. The instability of the fiber-disseminated signal is  $<10^{-14}$  at 1 s (dominated by the ultrastable laser and by the optical link) and  $1.2 \times 10^{-15}$  at 1000 s (dominated by  $\text{HM}_{\text{INRIM}}$ ) and hence barely affects the results on these timescales. The excess of instability at 200 s is attributed to environmental effects on the fiber comb at INRIM. However, this is not an issue, as the typical duration of VLBI sessions is longer than 1000 s. The contribution of the optical link to the instability is  $5 \times 10^{-15}$  at 1 s on a 1 Hz measurement bandwidth. The presence of cycles slips deteriorates the phase-coherence of the delivered optical frequency: as a result, the Allan deviation averages down more slowly than the expected  $\propto \tau^{-1}$  behaviour of the optical link for  $\tau \gtrsim 100$  s. Nevertheless, the link contribution is still negligible at all timescales when comparing the HMs; its expected instability is shown by the dashed green line.

We performed repeated measurements of  $\text{HM}_{\text{MR}}$  frequency during 11 days (start Modified Julian Date (MJD): 57070.5, stop MJD: 57080.5). The results have been corrected in order to account for the height above sea level of ITCsF2, which had been determined in 2006 during a specific levelling campaign [27]. They are shown in Fig. 6, together with a linear fit of the measurements. The uncertainty of each single point in the graph is the combined statistical uncertainty of  $\text{HM}_{\text{INRIM}}$  vs  $\text{HM}_{\text{MR}}$  and  $\text{HM}_{\text{INRIM}}$  vs ITCsF2. During the campaign, the average frequency offset of  $\text{HM}_{\text{MR}}$  with respect

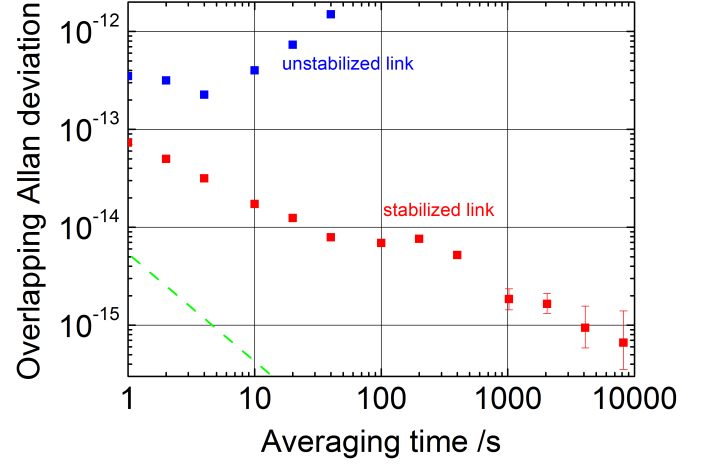


Fig. 5. Frequency instability of  $\text{HM}_{\text{INRIM}}$  vs  $\text{HM}_{\text{MR}}$  as measured through a 550 km optical link when the link is unstabilized (blue) or stabilized (red); the link contribution is shown by the dashed green line.

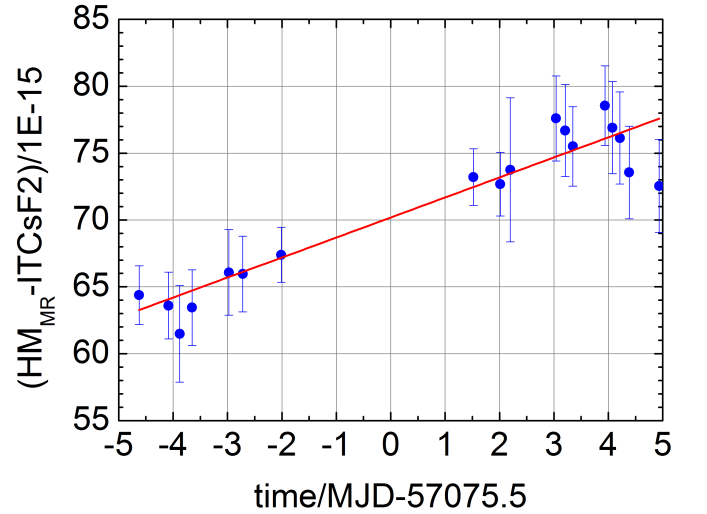


Fig. 6. Results of  $\text{HM}_{\text{INRIM}}$  vs  $\text{HM}_{\text{MR}}$  frequency comparisons during the whole measurement session. The date is expressed in Mean Julian Date. The line is a linear fit of the data.

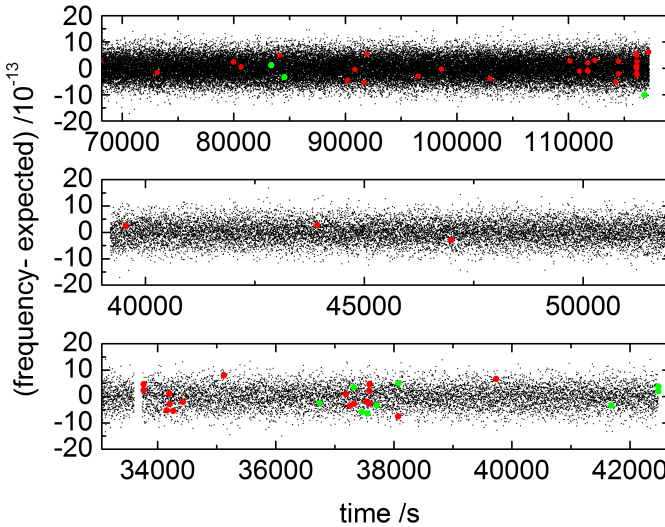


Fig. 4. Three typical data series showing the offset between the measured frequency and the expected value. Points affected by cycles slips on the optical link and on the optical regeneration are shown in green and red respectively.

to the SI second was  $(70.2 \pm 0.4) \times 10^{-15}$ , where the total uncertainty is the composition of the statistical uncertainty from the fit with the fountain accuracy; the frequency drift was  $(1.5 \pm 0.1) \times 10^{-15}$  /day.

### III. DISCUSSION AND PERSPECTIVES

In this experiment, we have delivered a frequency signal referenced to the primary standard ITCsF2 and we have also provided a real-time absolute calibration of  $\text{HM}_{\text{MR}}$ , otherwise not possible for the telescope facility at this level of accuracy. This system is capable to operate for several hours without interruptions and without loss of coherence. We note that these are stringent requirements in VLBI, and hence we plan to further extend this period by implementing minor technical improvements, such as automatic polarization adjustment. The occurrence of cycles slips on the delivered signal is not an issue, as typical phase-jumps are at the level of  $<1$  cycle/hour



in the optical domain, which means that their contribution on the microwave frequency is  $<5 \times 10^{-18}$ . This uncertainty is negligible not only with respect to the typical performance of HMs and atomic fountains but also with respect to the current state of optical clocks, and it could be reduced with a better control of the link hardware. The obtained results can be further improved if more stable oscillators are used as a reference for the transfer laser, such as cryogenic sapphire oscillators [17], [18] or optical clocks. In addition, local high-finesse optical cavities, phase-locked to the incoming radiation with bandwidths of  $<1$  Hz, can be used to reject the link unsuppressed noise and further improve the spectral purity of the disseminated signal.

We mention that other fiber frequency distribution techniques may also be used as an alternative to the direct optical phase stabilization, which do not make use of optical frequency combs [28], [29], [30]. These may be an opportunity in view of the realization of large telescope arrays, where they could allow a significant cost reduction.

Stronger interconnections between metrology and VLBI techniques can be extremely fruitful for what concerns the current challenges of radioastronomy and geodesy. A feasible scenario could be the replacement of local HMs with frequency references disseminated by National Metrology Institutes during VLBI observations; this scheme allows a direct improvement of the local oscillator performances and requires very little intervention on the existing VLBI hardware. We will perform this experiment at MR during a measurement campaign that will take place in Fall 2015. In perspective, a fiber-based network of multiple antennas connected to a single clock can be envisaged, with improved spectral purity and long-term stability. This will be useful for high-resolution VLBI and could open the possibility of direct fringes comparisons in addition to the well-established protocols where the data are processed at a correlator. In addition, this new class of experiments could reconnect, at comparable resolutions, the measurements of physical quantities now defined with atomic standards to their counterparts derived from astronomical observables, that are tight to the inertial Celestial Reference Frame. Such inter-comparisons seem feasible considering the wide community and the large number of radiotelescopes in Europe, together with the availability of optical fibers between them. In fact, optical links are already used for the normal Internet traffic as well as for real time VLBI experiments at many astronomical stations and, as shown also in this experiment, the metrological signal is fully compatible with them.

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#### REFERENCES

- [1] I. Ushijima, M. Takamoto, M. Das, T. Ohkubo, H. Katori, "Cryogenic optical lattice clocks," *Nature Photonics*, vol. 9, p. 185, 2015.
- [2] B. J. Bloom, T. L. Nicholson, J. R. Williams, S. L. Campbell, M. Bishof, X. Zhang, W. Zhang, S. L. Bromley, and J. Ye, "An optical lattice clock with accuracy and stability at the  $10^{-18}$  level," *Nature*, vol. 506, p. 71, 2014.
- [3] T. M. Fortier, F. Quinlan, A. Hati, C. Nelson, J. A. Taylor, Y. Fu, J. Campbell, S. A. Diddams, "Photonic microwave generation with high-power photodiodes," *Opt. Lett.*, vol. 38, p. 1712, 2013.
- [4] A. Haboucha, W. Zhang, T. Li, M. Lours, A. N. Luiten, Y. Le Coq, G. Santarelli, "Optical-fiber pulse rate multiplier for ultralow phase-noise signal generation," *Opt. Lett.*, vol. 36, p. 3654, 2011.
- [5] S. Droste, F. Ozimek, T. Udem, K. Predehl, T. W. Hansch, H. Schnatz, G. Grosche, and R. Holzwarth, "Optical-frequency transfer over a single-span 1840 km fiber link," *Phys. Rev. Lett.*, vol. 111, article no. 110801, 2013.
- [6] O. Lopez, A. Haboucha, B. Chanteau, Ch. Chardonnet, A. Amy-Klein, and G. Santarelli, "Ultra-stable long distance optical frequency distribution using the Internet fiber network," *Opt. Express*, vol. 20, p. 23518, 2012.
- [7] D. Calonico, E. K. Bertacco, C. E. Calosso, C. Clivati, G. A. Costanzo, M. Frittelli, A. Godone, A. Mura, N. Poli, D. V. Sutyryn, G. M. Tino, M. E. Zucco, and F. Levi, "High accuracy coherent optical frequency transfer over a doubled 642 km fiber link," *Appl. Phys. B*, vol. 117, p. 979, 2014.
- [8] K. Predehl, G. Grosche, S. M. F. Raupach, S. Droste, O. Terra, J. Alnis, T. Legero, T. W. Hänsch, T. Udem, R. Holzwarth, H. Schnatz, "A 920-kilometer optical fiber link for frequency metrology at the 19th decimal place," *Science*, vol. 336, p. 441, 2012.
- [9] M. Fujieda, M. Kumagai, S. Nagano, A. Yamaguchi, H. Hachisu, and T. Ido, "All optical link for direct comparison of distant optical clocks," *Opt. Express*, vol. 19, p. 16498, 2011.
- [10] A. Bauch, J. Achkar, S. Bize, D. Calonico, R. Dach, R. Hlavac, L. Lorini, T. Parker, G. Petit, D. Piester, K. Szymaniec, and P. Urich, "Comparison between frequency standards in Europe and the USA at the  $10^{-15}$  uncertainty level," *Metrologia*, vol. 43, p. 109, 2006.
- [11] A. Matveev, C. G. Parthey, K. Predehl, J. Alnis, A. Beyer, R. Holzwarth, T. Udem, T. Wilken, N. Kolachevsky, M. Abgrall, D. Rovera, C. Salomon, P. Laurent, G. Grosche, O. Terra, T. Legero, H. Schnatz, S. Weyers, B. Altschul, T. W. Hansch, "Precision Measurement of the Hydrogen 1S-2S Frequency via a 920-km Fiber Link," *Phys. Rev. Lett.*, vol. 110, article no. 230801, 2013.
- [12] D. Calonico, M. Inguscio and F. Levi, *Europ. Phys. Journ.*, in press.
- [13] R. Thompson, J. M. Moran, G. W. Swenson, *Interferometry and Synthesis in Radio Astronomy*, 2nd Edition, Wiley-VCH, 2001.
- [14] M. Rioja, R. Dodson, Y. Asaki, J. Hartnett, and S. Tingay, "The impact of frequency standards on coherence at the highest frequencies," *Astron. J.*, vol. 144, 2012.
- [15] B. Nikolic, R. C. Bolton, S. F. Graves, R. E. Hills, J. S. Richer, "Phase correction for ALMA with 183 GHz water vapour radiometers," *Astronomy & Astrophysics*, vol. 552, A104, 2013.
- [16] M. Rioja and R. Dodson, "High-precision astrometric millimeter very long baseline interferometry using a new method for atmospheric calibration," *Astron. J.*, vol. 141, p. 114, 2011.
- [17] J. G. Hartnett, N. R. Nand and C. Lu, "Ultra-low-phase-noise cryocooled microwave dielectric-sapphire-resonator oscillators," *Appl. Phys. Lett.*, vol. 100, article no. 183501, 2012.
- [18] N. R. Nand, J. G. Hartnett, E. N. Ivanov, G. Santarelli, "Ultra-Stable Very-Low Phase-Noise Signal Source for Very Long Baseline Interferometry Using a Cryocooled Sapphire Oscillator," *IEEE Trans. Microwave Techn.*, vol. 59, p. 2978, 2011.
- [19] A. Neill, A. Whitney, B. Petrachenko, W. Schluter, N. Vandenberg, H. Hase, Y. Koyama, C. Ma, H. Schuh, G. Tuccari, "VLBI2010: Current and Future Requirements for Geodetic VLBI Systems," Report of Working Group 3 to the IVS Directing Board, September 2005.
- [20] S. Droste, C. Grebing, J. Leute, S.M.F. Raupach, A. Matveev, T. W. Hansch, A. Bauch, R. Holzwarth, G. Grosche, "Characterization of a 450-km Baseline GPS Carrier-Phase Link using an Optical Fiber Link," arXiv:1505.02144, 2015.

- [21] F. Levi, D. Calonico, C. E. Calosso, A. Godone, S. Micalizio and G. A. Costanzo, "Accuracy evaluation of ITCsF2: a nitrogen cooled caesium fountain," *Metrologia*, vol. 51, p. 270, 2014.
- [22] C. Clivati, D. Calonico, M. Frittelli, A. Mura, F. Levi, "A fiber link for the remote comparison of optical clocks and geodesy experiments," proc. of the Joint International Frequency Control Symposium and European Frequency and Time Forum, Denver, 12-16 April 2015.
- [23] C. Clivati, D. Calonico, C.E. Calosso, G. A. Costanzo, F. Levi, A. Mura, A. Godone, "Planar-Waveguide external cavity laser stabilization for an optical link with  $10^{-19}$  frequency stability," *IEEE Trans. Ultrason. Ferroelectr. Freq. Contr.*, vol. 58, p. 2582 2011.
- [24] S. M. F. Raupach, T. Legero, C. Grebing, Ch. Hagemann, T. Kessler, A. Koczwar, B. Lipphardt, M. Misera, H. Schnatz, G. Grosche, U. Sterr, "Subhertz-linewidth infrared frequency source with a long-term instability below  $5 \times 10^{-15}$ ," *Appl. Phys. B*, vol. 110, n. 4, pp. 465-470, March 2013.
- [25] P. A. Williams, W. C. Swann, and N. R. Newbury, "High-stability transfer of an optical frequency over long fiber-optic links," *J. Opt. Soc. Am. B*, vol. 25, p. 1284, 2008.
- [26] G. Ascheid and H. Meyr, "Cycle Slips in Phase-Locked Loops: A Tutorial Survey," *IEEE Trans Commun.*, vol. 30, p. 2228, 1982.
- [27] D. Calonico, A. Cina, I. H. Bendea, F. Levi, L. Lorini and A. Godone, "Gravitational redshift at INRIM," *Metrologia*, vol. 44, n. 5, L44-L48, 2007.
- [28] L. Sliwczynski, P. Krehlik, A. Czubla, L. Buczek, M. Lipinski, "Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km," *Metrologia*, vol. 50, no. 2, p. 133, 2013.
- [29] O. Lopez, A. Amy-Klein, M. Lours, C. Chardonnet, and G. Santarelli, "High-resolution microwave frequency dissemination on an 86-km urban optical link," *Appl. Phys. B*, vol. 98, no. 4, pp. 723-727, 2010.
- [30] B. Wang, C. Gao, W.L. Chen, J. Miao, X. Zhu, Y. Bai, J.W. Zhang, Y.Y. Feng, T.C. Li, and L.J. Wang, "Precise and continuous time and frequency synchronisation at the  $5 \times 10^{-19}$  accuracy level," *Sci. Rep.*, vol. 2, p. 556, 2012.