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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 radio astronomy and geodesy. A 550-km optical fiber connects the Italian National Metrological Institute (INRIM) to the main radio telescope in Italy and is used for the primary Cs fountain clock stability and accuracy dissemination. We use an ultrastable laser frequency-referenced to the primary standard as a transfer oscillator; at the radio telescope, an 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 1.7e-16 accuracy. The fiber link never limits the experiment and is robust enough to sustain radio astronomical campaigns. This experiment opens the possibility of replacing 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 18th digit [1], [2] and optical frequency combs allow high-precision measurements of optical frequencies and the synthesis of high-spectral purity microwaves [3], [4]. The dissemination of optical frequencies at the e-19 level was achieved by sending ultrastable lasers over standard telecom fibers, where the length variations are actively Fabry–Perot through the Doppler stabilization technique [5]–[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 clock 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), which is a powerful tool both for radio astronomy 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 radio telescopes spread all over the Earth. Each pair 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, which are useful for monitoring geophysical changes.

The typical central observation frequencies span from 126 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, because 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 a target requires two relevant issues to be addressed: 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 vapor 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 1e-13

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at 1 s (1e-15 at 10 000 s) for good weather conditions and 3e-14 at 1 s (<1e-15 at 10 000 s) for very good weather conditions, these latter corresponding to a 100 µm 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 vapor radiometers (WVR) at the antennas, as pursued within the ALMA project [14]–[16]. Current WVRs already allow improvement by at least a factor of 3; thus, the instability contribution of WVR-corrected atmosphere in very good weather conditions can drop to the 1e-14 level at 1 s and to the e-16 level at 10 000 s, being already negligible if compared with 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 1 mm positioning precision, which cannot be achieved even with state-of-the-art HMs [19] and would require a frequency stability on the order of e-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 of delivering 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 an HM.

We realized a coherent fiber link from the Italian National Metrology Institute (INRIM) to the radio telescope 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 1.7e-16, and its frequency instability (Allan deviation) is 2.4e-13/$\sqrt{\tau}$, where τ is the measurement time [21].

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

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 5e-19 level. Recently, the Medicina radio telescope (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 <e-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 beat note 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 beat note 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., 1.5e-14 at 10 s and 1.2e-15 at 1000 s on a 1 Hz measurement bandwidth; the residual frequency drift is <e-19/s and a comparison with an independent comb, stabilized to the same reference, showed no frequency bias at the 3e-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 ∼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

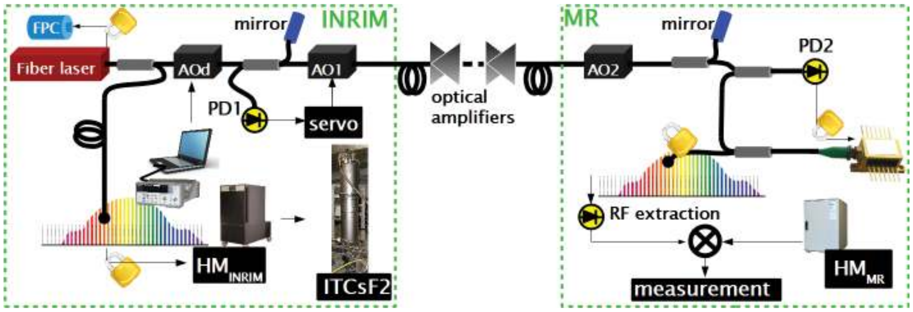

Fig. 2. Experimental setup: a fiber laser is frequency-locked to a Fabry–Perot cavity (FPC) and sent to an optical fiber comb; the comb is referenced to $\mathrm{HM_{INRIM}}$, which is in turn constantly measured against the Italian primary standard ITCsF2. The long-term instability of the laser is canceled by a digital frequency-stabilization of the beat note 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 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 the MR. Here it is frequency-shifted by the acousto-optic modulator AO2 and partly reflected back to INRIM, where it is compared with the local oscillator on photodiode PD1. This signal enables us to detect the noise added by the fiber, which is then Fabry–Perot**[AU2: Text missing here?]** 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 $S_v(f) = A/f$, with $A = 4\mathrm{e}6\ \mathrm{Hz}^2$ and a linewidth of several kilohertz [23]. This diode laser is phase locked 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 $\mathrm{HM_{MR}}$ is shown in Fig. 3 when the link is unstabilized (blue) and 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 ~60 Hz, and the bump at ~15 Hz is due to acoustic noise on the fiber and building vibrations. Below 10 Hz, the noise is limited by $\mathrm{HM_{MR}}$ in agreement with the manufacturer specifications (-100 dBc/Hz at 1 Hz offset frequency at 100 MHz).

When measuring the absolute frequency of $\mathrm{HM_{MR}}$, the most relevant sources of uncertainty are cycle slips on any of the PLLs in the chain. They may happen on a statistical basis [26] and are strongly dependent on the SNR and on time-varying Rayleigh-scattering events along the link. To properly detect them, we track the control beat note of the optical link with independent voltage-controlled oscillators, and we discard all data which deviate by more than 0.4 Hz. All other beat notes are continuously measured, and all measurements where the counted beat notes differ from the lock-frequencies by more than 0.7 Hz are discarded as well. The thresholds are chosen according to the minimum cycle-slip amplitude, i.e., 0.5 cycle on the optical link and 1 cycle on other beat notes. 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 beat note, we observe no cycle 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 beat note. Fig. 4 shows three typical data series: points affected by cycle slips on the optical link and on the optical regeneration are shown in green and red, respectively. As can be seen, the optical re-

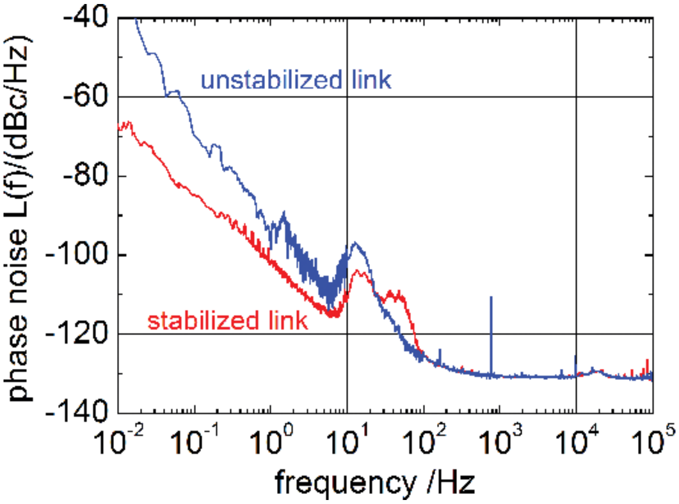

Fig. 3. The phase noise power spectrum of $\mathrm{HM_{INRIM}}$ versus $\mathrm{HM_{MR}}$ at 100 MHz when the link is unstabilized (blue) or stabilized (red).

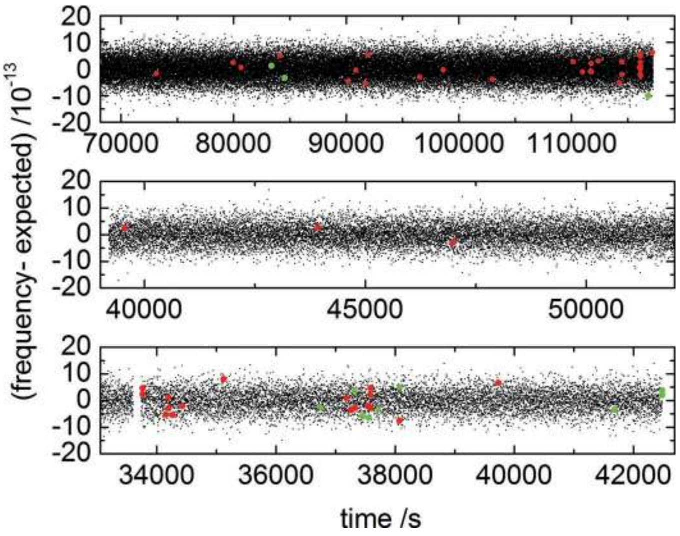

Fig. 4. Three typical data series showing the offset between the measured frequency and the expected value. Points affected by cycle slips on the optical link and on the optical regeneration are shown in green and red, respectively.

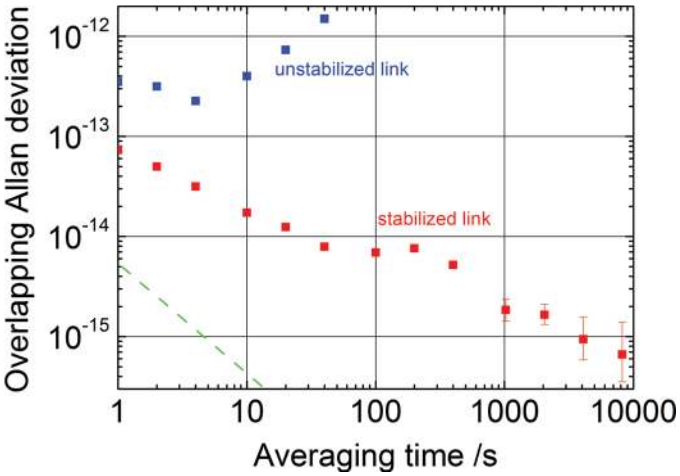

Fig. 5. Frequency instability of $\mathrm{HM}_{\mathrm{INRIM}}$ versus $\mathrm{HM}_{\mathrm{MR}}$ as measured through a 550-km optical link when the link is unstabilized (blue) or stabilized (red); the link contribution is shown by the dashed green line.

generation is currently the least 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 cycle 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 beat notes. The measured delays were then corrected by post-processing at better than 1s; this could be further reduced in the future by connecting all PCs to a network time protocol server, which is capable of guaranteeing <10 ms uncertainty on the timestamps. However, we observed no significant deterioration on the accuracy and stability of the delivered signal even if cycle slips were not removed, because of their low rate and typical amplitude (few cycles) under normal operating conditions.

The frequency instability of $\mathrm{HM}_{\mathrm{INRIM}}$ versus $\mathrm{HM}_{\mathrm{MR}}$ is shown in Fig. 5, both when the link is unstabilized (blue) and stabilized (red); it is dominated by the intrinsic instability of $\mathrm{HM}_{\mathrm{MR}}$, in agreement with the specifications of 8e-14 at 1 s and 2e-15 at 1000 s on 1 Hz measurement bandwidth. The instability of the fiber-disseminated signal is <e-14 at 1 s (dominated by the ultrastable laser and by the optical link) and 1.2e-15 at 1000 s (dominated by $\mathrm{HM}_{\mathrm{INRIM}}$) and hence it 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, because the typical duration of VLBI sessions is longer than 1000 s. The contribution of the optical link to the instability is 5e-15 at 1s on a 1 Hz measurement bandwidth. The presence of cycle slips deteriorates the phase-coherence of the delivered optical frequency; as a result, the Allan deviation averages down more slowly than the expected $\propto \tau^{-1}$ behavior 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 $\mathrm{HM}_{\mathrm{MR}}$ frequency during 11 d (start modified Julian date (MJD): 57070.5, stop MJD: 57080.5). The results have been corrected to account for the height above sea level of ITCsF2, which had been determined in 2006 during a specific leveling 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 $\mathrm{HM}_{\mathrm{INRIM}}$ versus $\mathrm{HM}_{\mathrm{MR}}$ and $\mathrm{HM}_{\mathrm{INRIM}}$ versus ITCsF2. During the campaign, the average frequency offset of $\mathrm{HM}_{\mathrm{MR}}$ with respect to the SI second was $(70.2 \pm 0.4) \times$ e-15, where the total uncertainty is the composition of the statistical uncertainty from the fit with the fountain accuracy; the frequency drift was $(1.5 \pm 0.1) \times$ e-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 $\mathrm{HM}_{\mathrm{MR}}$, otherwise not possible for the telescope facility at this level of accuracy. This system is capable of operating 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 cycle slips on the delivered signal is not an issue, because typical phase jumps are at the level of <1 cycle/h in the optical domain, which means that their contribution on the microwave frequency is <5e-18. This uncertainty is negligible not only with respect to the typical performance of HMs and atomic fountains, but also with respect to the

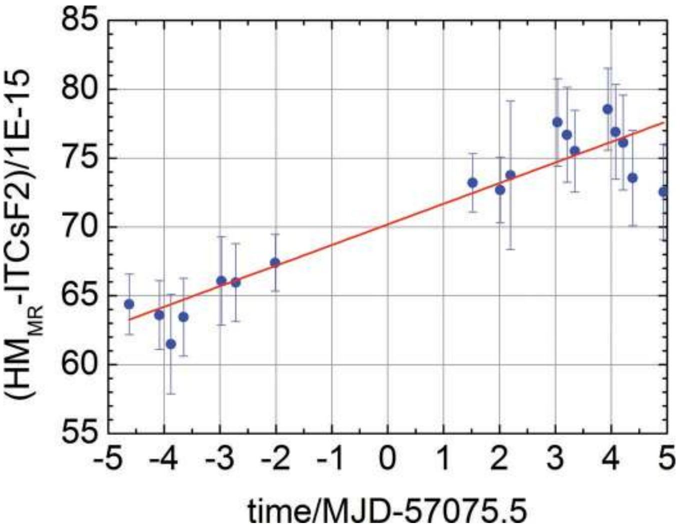

Fig. 6. Results of HM$_{\mathrm{INRIM}}$ versus HM$_{\mathrm{MR}}$ frequency comparisons during the whole measurement session. The date is expressed in mean Julian date. The line is a linear fit of the data.

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's 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]–[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 the concerns of the current challenges of radio astronomy 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 the fall of 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 fringe 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**[AU3: tightly related?]** to the inertial celestial reference frame. Such inter-comparisons seem feasible considering the wide community and the large number of radio telescopes in Europe, together with the availability of optical fibers between them. In fact, optical links are already used for normal Internet traffic as well as for real-time VLBI experiments at many astronomical stations and, as was shown in this experiment, the metrological signal is fully compatible with these uses.

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Authors’ photographs and biographies were unavailable at time of publication.**[AU6: Would you like to submit bios?]**