The Optical Fiber Link LIFT for Radioastronomy

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***Abstract*—Optical fiber links are beneficial not only for frequency metrology, but also for other fields of physical research, such as radioastronomy and geodesy. We realized the first optical fiber link from a National Institute of Metrology to a Radiotelescope used for Very Long Baseline Interferometry and for geodetic measurements, over a distance of 544 km. We performed a remote calibration of the hydrogen-maser used as a frequency reference at Medicina Radiotelescopes, in central Italy, against the Italian Cs fountain primary frequency standard. The comparison was limited by the statistical uncertainty of the hydrogen-masers. This experiment demonstrates that optical links can provide radioastronomical facilities with very accurate and stable frequency references, in perspective better than the currently used hydrogen-masers. This opens new perspectives in the ultimate limits of VLBI and a more precise space geodesy.**

***Keywords*—coherent optical links; frequency dissemination; space geodesy; VLBI**

I. INTRODUCTION

Phase-stabilized optical links have proved to be the most effective way to transfer ultrastable frequency signals over continental distances [1]–[4]. In fact, the stability of frequency dissemination via optical fiber is improved by 5 orders of magnitude with respect to that of satellite links, achieving the 10^{-19} level in hours of operation [5]. This represents an important technology for primary metrology, as it is the only way to compare remote optical clocks at their intrinsic level of uncertainty, now 10^{-18} [6], [7]; in addition, also remote primary standards can be effectively compared in hours instead of days. For this reason, many National Metrology Institutes are developing long-haul fiber backbones that can replace satellite links over continental distances on the time-base of some years. A more stable and more accurate frequency dissemination will be not only beneficial to primary metrology, but also to a variety of other applications, such as fundamental physics, geodesy and Very Long Baseline Interferometry (VLBI).

In this work, we investigate the potential impact of fiber-based frequency dissemination on VLBI techniques.

VLBI is based on the simultaneous measurement of the same radio-source in the sky with different antennas, separated by many baselines D_i, each up to thousands of kilometers long. The final angular resolution of the array, obtained by correlating all data streams, is improved by the ratio D_{max}/d with respect of that of a single dish with aperture d [8]. The typical central observation frequencies span from 1 GHz to 26 GHz, with bandwidths from hundreds of megahertz to 1 GHz; thus, each antenna is equipped with a hydrogen-maser (HM) that serves both as a local oscillator for frequency down-conversion of the collected signal and for proper sampling and timing during the signal processing at each radiotelescope.

VLBI plays an important role also to obtain high-precision geodetic data, as it provides access to the best possible inertial reference system, made by quasars located at the edge of the observable Universe. Modern geodynamic VLBI measurement campaigns are based on successive observations of radio-sources all over the sky from many radiotelescopes spread all over the Earth. The differential delay resolution achievable by cross-correlating VLBI data is related to several parameters, among which is also the instability of the local HM.

Although HM frequency stability is adequate for present radioastronomy applications, the challenge of observations at higher frequency [9] and improved methods to model the tropospheric delay [10] raise the issue of the local oscillator instability. In geodesy, the goal of 1 mm positioning precision cannot be achieved with state-of-the-art HMs [11].

Optical links may offer some solutions: from one point of view, they enable the frequency distribution of optical atomic clocks, whose stability is three orders of magnitude better than that of a HM; in addition, they enable the dissemination of the same frequency standard at multiple antennas, that will allow a complete rejection of the clock instability.

Here, we present the first realization of a phase-coherent optical link and the ultrastable frequency dissemination from a National Metrology Institute to a VLBI site. The Italian National Metrology Institute (INRIM) realizes and maintains in Italy the definition of the SI second with the new nitrogen-cooled Cs Fountain primary frequency standard ItCsF2, that is fully operative since 2013. Its Type-B uncertainty is 1.7×10^{-16} , while its short term stability in the high-density regime is 2×10^{-13} [12], [13]. ItCsF2 has been used to calibrate TAI providing nine frequency evaluations during 2014, for a total measurement time of 165 days.

To perform the frequency dissemination on a national scale, INRIM has developed the LIFT project (the Italian Link for Time and Frequency) [3]. The present partners of this project are the European Laboratory for Non Linear Spectroscopy and the Institute of Optics in Florence, and the Institute of Radioastronomy of the National Institute of Astrophysics (INAF-IRA) in Bologna. INAF maintains in Italy three single-dish radiotelescopes, located in Medicina (Bologna), Noto (Sicily) and Cagliari (Sardinia). These antennas are part of the VLBI global network and of the European VLBI Network. INAF-IRA is member of the Joint Institute for VLBI in Europe and of the International VLBI Service for

Fig. 1. The map of the present LIFT backbone. A single fiber link connects INRIM (Turin) to Bologna, in central Italy. Here the radiation is split: one of the arms connects INRIM to the European Laboratory for Non Linear Spectroscopy in Florence (total length 642 km); the other arm connects INRIM to Medicina Radiotelescope (total length 544 km).

Geodesy and Astronomy (IVS).

The map in Fig. 1 shows the present backbone for frequency dissemination in Italy. The 642 km link branch between INRIM and LENS is under operation since 2013. In 2014, we have realized a second branch, by splitting the radiation in equal parts in Bologna shelter, in central Italy. This arm connects INRIM to Medicina Radiotelescope (MR), at a distance of 544 km, and has been used to perform a remote calibration of the hydrogen-maser there located.

Our experiment demonstrates that remotely disseminated frequency standards can be a viable alternative to local HMs. This is a first step towards more extensive studies, where a remotely disseminated frequency will replace the local reference in VLBI observations. In the following paragraphs we will describe the apparatus and the experimental results, and discuss the main criticalities and possible solutions.

II. THE EXPERIMENT

The setup of our experiment is shown in Fig. 2. An ultrastable laser is generated by frequency-locking a 1542 nm fiber laser to a high-finesse Fabry-Pérot optical cavity (FPC), with a residual instability of 8×10^{-15} at 1 s. The frequency drift of this source is typically $\leq 10^{-15}$/s [14]. To allow its use as an absolute frequency reference, we lock the laser to an HM ($\mathrm{HM_{INRIM}}$) by using a fiber optical frequency comb. The control-loop is implemented via software, as the ultrastable laser and the optical comb are in two different laboratories. A control bandwidth of 0.05 Hz is chosen as a compromise between an adequate rejection of the HM noise and a sufficiently tight locking; the correction is applied once per second on a Acousto-Optic Modulator (AOM). $\mathrm{HM_{INRIM}}$ is in turns continuously measured against the Italian primary frequency standard ItCsF2. The ultrastable laser is sent to the optical comb via a 100-m long phase-stabilized fiber. Another phase-stabilized optical link, 544 km long, delivers the laser frequency from INRIM to MR. This link is part of the backbone going to Florence and described in [3]. In Bologna, a part of the radiation is extracted and delivered to MR along a multiplexed optical fiber, where a single channel of the ITU grid is dedicated to our experiments. The total loss for this link is 150 dB. 7 bidirectional Erbium-Doped-Fiber-Amplifiers (b-EDFAs) are used along the link, and another b-EDFA is placed in MR. It is operated slightly above threshold to avoid lasing effects induced by the presence of a mirror at a short distance. To perform the phase-stabilization, a part of the signal is back-reflected from MR to INRIM and here beaten with the original signal on photodiode PD1, following the typical scheme of Doppler-stabilized links [15]. In this way, we can detect the phase noise added onto the optical carrier by the double pass in the fiber and we compensate it with a phase-locked loop (PLL) acting on a Acousto-Optic Modulator (AOM1). The beatnote signal to noise ratio (SNR) changes with time from 27 dB to 32 dB in a 100 kHz bandwidth, hence it needs to be regenerated by a tracking filter to improve the SNR and filter out spurious signals. Cycles-slips on this PLL may happen on a statistical basis; their occurrence is strongly dependent on the SNR [16] and on time-varying Rayleigh-scattering events along the link. Thus, the beatnote is split into three equal parts and tracked by three independent voltage-controlled oscillators; in this way it is always possible to determine if the cycles-slips have occurred to the in-loop tracking filter. At MR, the optical signal is beaten with a narrow-linewidth diode laser on photodiode PD2; the diode laser is then phase-locked on the incoming radiation on a bandwidth of 50 kHz and used as a reference for a fiber optical frequency comb. The 40th harmonic of the repetition rate (250 MHz) is extracted and divided by 100; the resulting 100 MHz signal is directly compared to the output of the HM there located ($\mathrm{HM_{MR}}$).

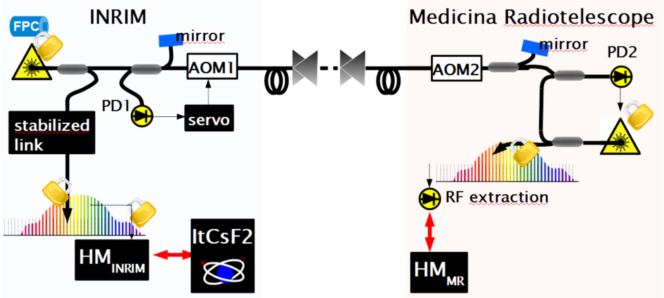

Fig. 2. The setup of our experiment. A fiber laser is frequency-locked to a high-fineese Fabry-Pérot cavity (FPC) and used as a transfer laser. Its frequency is measured against $\mathrm{HM_{INRIM}}$ using a fiber optical frequency comb; $\mathrm{HM_{INRIM}}$ is constantly measured by the primary frequency standard ItCsF2. The transfer laser is sent to Medicina Radiotelescope (MR) via a phase-stabilized optical link and here regenerated by phase-locking a diode laser to it. The regenerated radiation is used as a reference to stabilize an optical comb; the 40th harmonic of the repetition rate is extracted, divided by 100 and compared to $\mathrm{HM_{IRA}}$. AOM:acousto-optic modulators; PD: photodiodes; triangles represent bidirectional Erbium-Doped Fiber Amplifiers

This setup is robust and currently capable to operate continuously for extended periods of time. The most critical issue are the large polarization changes of the signal travelling the optical link. They causes slow but continuous variations of the SNR on the PD2 beatnote, and periodic polarization adjustment is required to prevent PLL unlocks. An automatic polarization-adjustment stage has been developed and

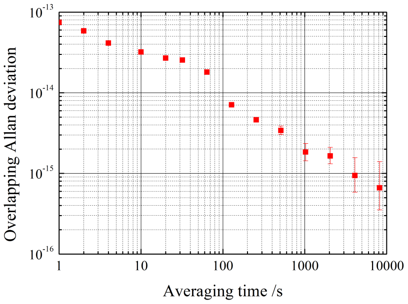

Fig. 3. The instability of the comparison between $\mathrm{HM_{MR}}$ and $\mathrm{HM_{INRIM}}$.

will be implemented at MR in the next month, in view of another measurement campaign. To constantly monitor the proper operation of the whole apparatus and the occurrence of cycles-slips on any of the PLLs involved, each beatnote was continuously measured and all points differing from the lock-frequency by more than a specified threshold were discarded from the HMs comparison. We performed daily calibration runs to ensure a proper synchronization of the measurements in the two laboratories. The main source of delay between the measurements is due to the internal clocks of the PC used for data recording and can achieve several seconds; this issue could be easily mitigated in the future by connecting them to Network Time Protocol (NTP) servers. Since the synchronization was limited to 1 s during this measurement session, we also discarded the points adjacent to a cycle-slip. The typical instability of the HMs comparison is shown in Fig. 3. On the averaging times of few seconds, it is limited by $\mathrm{HM_{MR}}$, whose specified instability is 8×10^{-14} on 1 Hz bandwidth. The short-term instability of the delivered optical signal, 1×10^{-14} on 1 Hz bandwidth, is negligible on this timescales. At measurement times longer than 5 s, the instability starts to be dominated by that of the delivered optical signal (ultrastable laser+$\mathrm{HM_{INRIM}}$). The intrinsic instability of the HMs is achieved on a timescale of few hours.

We performed repeated frequency measurements of $\mathrm{HM_{MR}}$ vs $\mathrm{HM_{INRIM}}$ for two weeks. During the whole period the frequency of $\mathrm{HM_{INRIM}}$ was measured by the Italian primary frequency standard ItCsF2. The results of the absolute calibration of $\mathrm{HM_{MR}}$ are shown in Fig. 4. The points have been obtained by a non-weighted average of the frequency data, after the removal of points which were affected by cycles-slips on any of the PLLs. In the last two measurements, the laser was not actively locked to $\mathrm{HM_{INRIM}}$ and the HMs comparison was obtained by post-processing synchronous measurements of the laser frequency performed in the two laboratories. The uncertainty was in most cases limited by the combined instability of the measurements $\mathrm{HM_{INRIM}}$ vs ItCsF2 (u_{INRIM}) and $\mathrm{HM_{INRIM}}$ vs optical system (u_{MR}). In the last two measurements, when the laser was not actively locked to $\mathrm{HM_{INRIM}}$, the uncertainty was given by

$$u = \sqrt{u_{\mathrm{INRIM}}^2 + u_{\mathrm{MR}}^2 + (d\tau)^2} \tag{1}$$

where $d\tau$ is a possible systematic uncertainty associated with a frequency drift d in the ultrastable laser and a delay τ between the measurements in the two laboratories [17]. In those measurements, we observed a maximum laser drift of

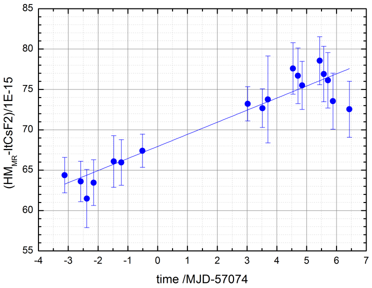

Fig. 4. The absolute frequency of $\mathrm{HM_{MR}}$ measured in different days; the line represents a linear fit of the data.

5×10^{-16} /s and 10^{-15} /s respectively, and set τ= 1 s. This places an upper limit to the actual contribution of this term.

The interpolated frequency drift for $\mathrm{HM_{MR}}$ is $(1.5 \pm 0.1) \times 10^{-15}$ /day. The obtained results are in agreement with the data obtained by GPS measurements of $\mathrm{HM_{MR}}$.

III. DISCUSSION AND CONCLUSIONS

We realized the first optical link between a National Metrology Institute and a VLBI antenna, and performed the absolute characterization of the HM there located, at the level of its statistical uncertainty. These measurements are a preliminary step towards the direct use of the optically-delivered frequency reference in VLBI observations.

From the operational point of view, among the main requirements of VLBI measurements is the capability of sustaining several days of uninterrupted operation. This is feasible with the present apparatus, as the main issue are the long-term polarization changes at the remote link end. This problem will be avoided in our next measurement campaign by using an automatic polarization-adjustment stage. From a more fundamental point of view, the presence of cycles-slips might induce a loss of phase-coherence on the delivered microwave. Nonetheless, it is important to stress that typical phase-jumps are the level of <1 cycle/hour in the optical domain, which means that their contribution is $\ll 5 \times 10^{-15}$. This is negligible with respect to the typical performance of a HM.

In conclusion, the results shown in this paper demonstrate that optical links are a suitable tool to perform high-quality frequency dissemination to VLBI antennas. In perspective, a fiber-based network of multiple antennas connected to a single clock can be envisaged; in addition, optical links can provide better frequency references than HMs. This is a prerequisite to investigate the ultimate performances of VLBI and opens the door to 1 mm precision in geodetic positioning via VLBI-based space geodesy.

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