Publication Year	2015
Acceptance in OA	2020-04-24T16:38:10Z
Title	Time and frequency optical fiber links for space metrology
Authors	Calonico, D., Clivati, C., Frittelli, M., Zucco, M., Levi, F., PERINI, FEDERICO, BORTOLOTTI, CLAUDIO, ROMA, MAURO, Ambrosini, R., Costanzo, G. A., Mura, A.
Publisher's version (DOI)	10.1109/MetroAeroSpace.2015.7180654
Handle	http://hdl.handle.net/20.500.12386/24233
Serie	IEEE METROLOGY FOR AEROSPACE

Time and frequency optical fiber links for space metrology

D. Calonico, C. Clivati, M. Frittelli, A. Mura,
M. Zucco, and F. Levi
INRIM, Istituto Nazionale di Ricerca Metrologica,
Turin, Italy
d.calonico@inrim.it

F. Perini, C. Bortolotti, M. Roma, and R. Ambrosini
Radiotelescopi di Medicina
INAF, Istituto di Radioastronomia,
Bologna, Italy

G.A. Costanzo,
Electronics Departmernt
Politecnico di Torino,
Turin, Italy

***Abstract*—Optical fiber links offer the best performance to transfer time and frequency. They are beneficial to primary metrology, and there is a strong effort to develop a European network of T&F fiber links. In Italy, we realized a coherent optical fiber link from the National Metrological Institute INRIM to the INAF radio-antennas in Medicina, Bologna and the physics laboratories in Sesto Fiorentino, for a total haul of 642 km. We demonstrated the transfer of primary frequency references to the radio-antenna in Medicina, with potential impact for future development in radioastronomy and VLBI. The extension of this link targets to arrive to Matera, at the Space Geodesy Center of ASI. We describe here the space metrology interests of the optical fiber link, the present set-up of the experiment the preliminary results and the future developments.**

Keywords*—*optical fiber link, frequency space metrology, radioastronomy, vlbi, geodesy

I. INTRODUCTION

Coherent optical fiber links have been demonstrated to be a unique mean to transfer time and frequency signals or compare remote optical frequency standards [1-3]. With respect to satellite techniques, the improvement is as large as four orders of magnitude [4]. For example, they are the only viable method to compare optical clocks, thus they are a key metrological technology in view of a possible redefinition of the second based on those new standards. Moreover, optical links could allow a network of accurate clocks, especially in Europe. This network would establish a unique facility for testing fundamental physics, relativistic geodesy [5, 6].

Optical fiber link are beneficial for space metrology, improving the ground segment by the distribution of accurate and stable frequency standards beyond the local references. The Istituto Nazionale di Ricerca Metrologica (INRIM) is involved in three experiments of optical links for space metrology: their use in radioastronomy [7], in space geodesy [8] and in the atomic clock comparison for fundamental physics of the mission Atomic Clock Ensemble in Space (ACES) of the European Space Agency (ESA) [9]. In Italy, INRIM developed LIFT [3], a coherent optical fiber link that connects INRIM to the scientific pole in Sesto Fiorentino, Florence, for atomic physics application (642 km), and INRIM to the Italian-French border in Modane (150 km). After the 642 km fiber haul, LIFT provides a frequency reference with an instability of 3×10-19 at 1000 s (Allan deviation), and an accuracy of 5×10-19.

The Institute for Radioastronomy of the National Insitute of Astrophysics (INAF-IRA) in Medicina (Bologna) joined LIFT to study the possible benefits of fiber links to radioastronomy, such as the dissemination of better frequency references and the fiber synchronization of remote radiotelescopes, e.g. for VLBI and for ambitious projects as the Square Kilometer Array (SKA). IRA operates 3 radiotelescope facilities: the "Northern Cross Radiotelescope", in Medicina, two 32-m single dish antennas, in Medicina and Noto (Sicily) and the Sardinia Radio Telescope, a 64-m antenna in Cagliari. The dish antennas are part of the VLBI global network (150 days a year). As well, IRA is member of the Joint Institute for VLBI in Europe (JIVE), of the European VLBI Network (EVN) and of the International VLBI Service for Geodesy and Astronomy (IVS). It is involved in the astronomical projects ALMA, e-VLBI, SKA, LOFAR. The coherent optical link from INRIM to IRA radiotelescopes in Medicina is an extension of the link connecting INRIM to Florence, obtained splitting the optical signal in Bologna into equal arms to Medicina and Florence.

Fig. 1 LIFT Optical fiber link: present infrastructure.

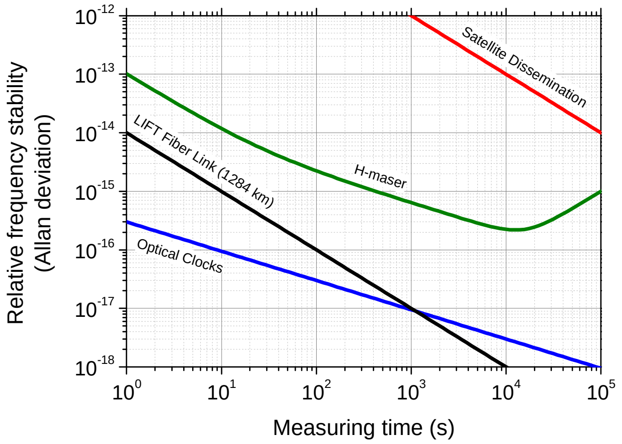

Fig. 2. Relative frequency Allan deviation of Hydrogen Masers, optical clocks and the transfer methods based on satellites or optical fibers.

Now, INRIM is planning to extend the link towards Rome and Matera, aiming to disseminate its clocks to the Space Geodesy Center of the National Space Agency.

II. ATOMIC CLOCKS TO DATE

Atomic clocks are the best time and frequency references both for accuracy and stability. Since 1967 the definition of second in the International System of Units is based on the hyperfine ground transition of the Cesium 133. The international timescale is the Universal Time Coordinated (UTC). It is based on TAI, a timescale generated from the atomic second, using few hundreds of atomic clocks (with less than ten accurate atomic Cesium fountains). TAI is corrected by the leap seconds, to obtain UTC, that must not differ from the timescale based on the astronomical second (UT1) by more than 0.9 s.

The accuracy and even more important the stability of atomic clocks is fundamental for space applications, as they are at the heart of modern radioastronomy, space geodesy, global navigation satellite systems (GNSS).

The most accurate realization of the SI second is presently obtained using Cs atomic fountains, based on laser cooled Cesium, capable of a stability as low as $1.5\times10^{-14}\tau^{-1/2}$ and an accuracy of 1.5×10^{-16}. A clock important in space applications is the active hydrogen maser, so far the best commercial atomic clock regarding the stability in the medium-long term. Indeed, almost all the radioastronomical antennas and the VLBI geodesy facilities adopt an H-maser. Its best stability is around 1×10^{-13} at 1 s, and reaches few parts in 10^{15} in 1000 s. In the long term, H-Masers exhibit a typical linear frequency drift, from few parts in 10^{16} to few parts in 10^{15} per day. Nowadays, there is a new generation of atomic clocks, called optical clocks, that exploit forbidden quantum transitions in the optical domain of alkaline-earth-like atoms (like Sr, Yb, Hg, and the ions Sr+, Hg+, Al+, Yb+). They are capable of an accuracy of parts in 10^{-18} and a frequency stability as low as $3\times10^{-16}\tau^{-1/2}$. Space metrology could greatly benefit from the introduction of optical clocks and their high stability, but optical clocks are typically laboratory developments realized at the national metrological institutes. Commonly used transfer method for time and frequency, i.e. satellite techniques, are not suited for the exploitation of maser stability, and even less optical clocks and fountain accuracy, in the medium term (100000 s). Nonetheless, optical links can transfer the best clocks performance s to space metrology laboratories in few hundreds of seconds, and therefore they can support further developments in frequency references for space metrology.

III. COHERENT OPTICAL FIBER LINKS

There are different techniques to realize an optical fiber link for time and frequency transfer. Here we report only about the coherent fiber link method [10], used for the experiments reported in this work. The conceptual scheme of the Coherent fiber link is reported in Fig. 3. An ultrastable laser radiation is impinged on a fiber connecting the origin and the remote laboratories. The ultrastable radiation is obtained by phase locking a laser with a narrow original linewidth (1-10 kHz) to an ultrastable Fabry-Perot cavity [11]. The laser is considered ultrastable when the stability is below 1×10^{-14} at 1 s. At the remote laboratory, a part of the radiation is extracted and it is the delivered signal. The remainder is reflected back to the origin laboratory, using the same fiber. It is mandatory to have a complete bi-directionality on the fiber, as well as the infrastructure must be a full optical one. In fact, the phase of the laser delivered at the remote end is affected by the environmental noise introduced by the fiber itself, due to the fiber length fluctuations (thermal and seismic perturbations). To achieve a proper transfer, the fiber noise needs to be cancelled; this is possible with the back-reflected signal at the origin lab. The beatnote of reflected and original signals measures the added noise, that is twice the detected phase in the stationary hypothesis. Then it is possible to correct and cancel the noise. Only bi-directionality ensures to correctly measure the fiber phase noise: two close fibers are not enough.

The results are reported in Fig. 4, where the stability of the LIFT optical link is reported [3]. The upper curve is the frequency stability of the link without any noise compensation, while the two other curves are obtained with the noise cancellation. The performance for LIFT are a short term stability of $1\times10^{-14}/\tau$ at 1 s, and at medium term, using a 5 mHz bandwidth, it is possible to achieve a short term stability of 3×10^{-19} at τ at 1000 s. The link is not adding any frequency offset at the level of 5×10^{-19}.

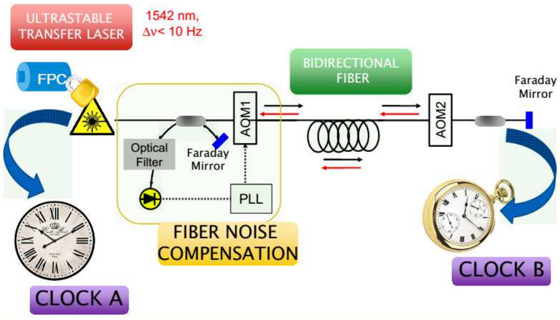

Fig. 3. Coherent optical fiber link: onceptual scheme.

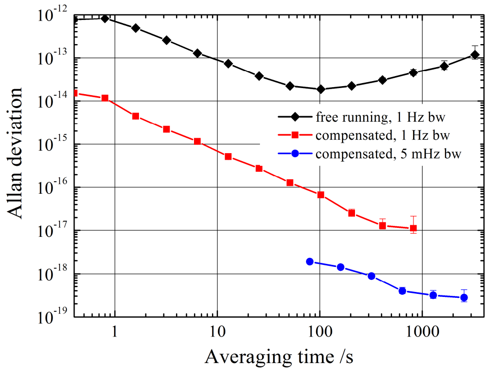

Fig. 4. Allan deviation of the LIFT fiber link. Upper curve: link without noise compensation; medium curve: link with noise commpensation and a bandwidth of 1 Hz; lower curve: ultimate performances with 5 mHz bandwidth

Further improvements in the technique were demonstrated to reduce the instability of a factor 4 [12, 13]. For the present experiment, the link INRIM-IRA is 544 km long, with total losses of 144 dB and it is based on a fiber hybrid architecture: a dedicated fiber is used from INRIM to Bologna (514 km) and then from Bologna to IRA (30 km), the dedicated ITU-44 channel in Dense Wavelenght Division Multiplexing is used. The metrological channel is operated at the same time with data channels. The losses are compensated by seven Bidirectional Erbium-Doped Fiber Amplifiers (EDFA) along the fiber and a remote amplification stage is implemented at Medicina, realized testing both EDFA and Brillouin amplification. At INAF-IRA, a diode laser at 1542 nm is phase locked to the incoming optical carrier from the link, and the locked diode laser is the reference for an optical frequency comb that generates the RF at 100 MHz to be used at the radio-telescope facility. The 100 MHz signal is compared to the radiotelescope present reference, an active Hydrogen Maser, monitored by a GPS receiver on the long term. At the conference we will present the details of the implementation and the first results. The further steps of the experiment and the perspectives of the use of optical links in radioastronomy will be described and discussed.

IV. VERY LONG BASELINE INTERFOREMETRY

Since a long while, a relevant application of atomic clocks is in Radioastronomy and in particular in the Very Long Baseline Interferometry (VLBI), where a network of remote radio-antennas is precisely synchronized to empower the resolution of the observation by autocorrelation techniques. As the baseline for VLBI is of the order of thousands of km, there is not a common clock technique, but each site operates its own clock, generally a Hydrogen Maser.

The stability of Hydrogen Masers is generally suited for many experiments in VLBI radioastronomy, nonetheless it is a relevant limitation for some developments under investigation in the most relevant radiotelescopes. We are referring in particular for the observation range well above the 100 GHz, where a better stability is needed of the local frequency reference at the antenna [14]. This frequency range has two main objectives. First, the investigation of different kind of signals emitted for example by different transitions of the molecules of the radio sources. Second, increasing the detected frequency is seen as a method to tame the limitation due to the tropospheric delays. It has been demonstrated that the limits due to the atomic clock stability and to the tropospheric delay are of the same order in the detection of signals above 86 GHz. Moreover, the tropospheric limit can be mitigated using local measurement of the sky brightness and proper models, thus improving the frequency reference is necessary, by replacing the H-Maser with a better clock. In such a situation, an optical fiber link is well suited to provide the state of the art atomic clock at a radio-antenna.

INRIM –IRA experiment has demonstrated that this target is achievable. Preliminary results show a reliable dissemination of remote references for radioastronomical use: in Fig. 5 we report for example the short term stability of the H-Maser in Medicina as measured by its beatnote with the INRIM Maser reference transferred by the 550 km optical fiber link. The H-maser in Medicina at the present stage of the experiment could be monitored in real time towards the Cesium primary atomic fountain of INRIM, and the long term drift constantly removed or corrected, a feature not possible on a daily basis with proper uncertainty using of other techniques, like the GPS.

V. SPACE GEODESY

VLBI is a key technology also in space geodesy that is based on the use of VLBI, GNSS, and Satellite Laser Ranging (SLR). VLBI provides the orientation of the Earth in inertial space and the celestial reference frame (CRF) and moreover can measure the geodetic parameters associated with the shape of the Earth and orientation in inertial space. The orientation of the Earth in inertial space, as given by UT1-UTC and nutation, is necessary for accurate satellite orbit determination.

The present limitation of VLBI geodesy is about three millimeters, but there are long-term efforts to push the accuracy towards 1 mm, that will allow an unprecedented level of monitoring the Earth geodynamics. For the focus group of the International VLBI Service for Geodesy and Astrometry [8], it is mandatory reducing the main contributions, in particular the troposphere stochastic behavior, and the instability of the frequency standard.

The hydrogen masers at the existing antenna sites are satisfactory for the current level of accuracy of a few

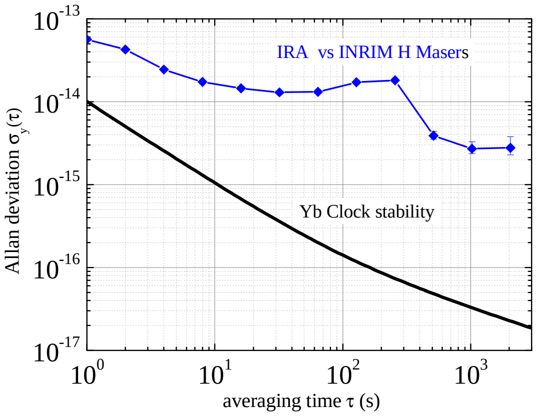

Fig. 5. Short term stability for the optical link INRIM-IRA telescope in Medicina. Upper curve: beatnote of INRIM and IRA H-Masers. Lower curve: expected stability for INRIM Yb optical clock

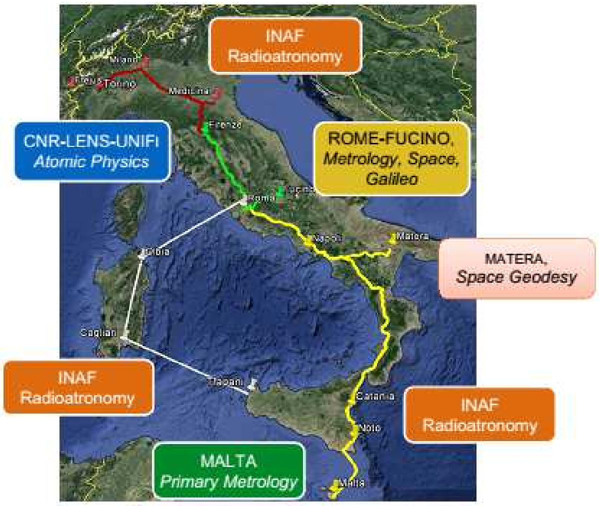

Fig. 6 View of the project for LIFT extension in Italy, with possible users for the dissemination of accurate atomic clocks signals.

millimeters, but their performance does not appear suited to support 1 mm accuracy. The requirements to reach that accuracy indicates that, ceteris paribus, frequency-standard performance must reach a stability level of a few parts in 10^{16} for averaging times longer than about 1 hour

We are planning the extension on the LIFT project to connect INRIM to the geodetic VLBI facility at the Space geodesy Center in Matera. The fiber haul will be ~1700 km, with total losses of about 450 dB, to be compensated by the use of 22 Erbium Doped Fiber Amplifiers. The expected stability transferred to Matera will be limited by the link instability in the short term. Considering the results of the haul INRIM-Florence, i.e. 1×10-14/τ at 1 s, 1 Hz bandwidth, over 1284 km, we expect an instability for the link Torino-Matera of 1,5×10-14/τ. This means that in only 100 s the fiber link noise will be compatible with the VLBI requirements for 1 mm accuracy.

The optical link extension to Matera will have a second scientific gal. In 2016 and for 36 months, both INRIM and SGC will host the ground stations of the ESA space missions Atomic Clock Ensemble in Space (ACES) [9]. In this experiment, two atomic clocks will be launched a hosted by the International Space Station. The two clocks are a n Hydrogen Maser and a laser-cooled Cs primary frequency standard.

The two clocks will be compared with ground clocks using a microwave link in the Ka-band and an optical link in free space. INRIM will host a microwave ground transceiver, whilst Matera will host an optical ground station. The presence of a terrestrial optical fiber link between the two station allows the unique possibility to compare the two metrological comparison technique. Moreover, this frequency triangle, sweeping a wide space-time area, could be used for relativistic experiments.

VI. CONCLUSIONS AND PERSPECTIVES

In the present contribution, we describe the use of the optical fiber link method to improve the performances in space metrology, in particular VLBI observations for radioastronomy and for space geodesy. The preliminary results of the first comparison between INRIM and the IRA Radiotelescope in Medicina are presented, as well as the experimental set-up. The plan to extend the link towards other users like space has been presented, together the envisaged experiments for this unique link. The next future perspectives are to implement a robust dissemination and to use it for an effective VLBI experiment. A second step, new more stable references will be disseminated, like the Ytterbium optical clock. A further collaboration with the radioastronomical and space community is envisaged. A third development will be the implementation of different fiber link techniques, such as the so called White Rabbit, to be compared with the results from the Coherent optical fiber link. Last, the planned extension to Matera will be defined and designed.

ACKNOWLEDGMENT

This work is supported by the project SIB02-NEAT-FT of the European Metrology Research Programme EMRP. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

REFERENCES

[1] K. Predehl, et al., “A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th decimal place,” Science 336, 441-444 (2012).

[2] O. Lopez, A. Kanj, P. Pottie, D. Rovera, J. Achkar, C. Chardonnet, A. Amy-Klein, and G. Santarelli “Simultaneous remote transfer of accurate timing and optical frequency over a public fiber network,” Appl. Phys. B 110, 3–6 (2013).

[3] D. Calonico, et al., “High accuracy coherent optical frequency transfer over a doubled 642 km fiber link,” Appl. Phys. B **117**(3), 979-986 (2014).

[4] A. Bauch, et al.,” Metrologia 43, pp. 109–120 (2006).

[5] C. W. Chou, D. B. Hume, T. Rosenband, D. J. Wineland, “Optical clocks and relativity,” Science 329, pp. 1630 (2010).

[6] J. Müller, M. Soffel. S. A. Klioner, “Geodesy and relativity”, J Geod. (2008) 82:133–145

[7] J. F. Cliche, B. Shillue, “Precision timing control for radioastronomy: maintaining femtosecond synchronization in the Atacama Large Millimeter Array,” IEEE Contr. Syst. Mag. 26, pp. 19–26 (2006).

[8] A. Niell, A. Whitney, B. Petrachenko, W. Schlüter, N. Vandenberg, H. Hase, Y Koyama, C. Ma, H. Schuh, and G. Tuccari, “VLBI2010: Current and Future Requirements for Geodetic VLBI Systems”, Report of Working Group 3 to the IVS Directing Board 2005

[9] L. Cacciapuoti, and Ch. Salomon, “Space clocks and fundamental tests: The ACES experiment”, European Phys. J. Special Topics, 172, pp 57-68 (2009).

[10] 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 25, 1284-1293 (2008)

[11] C. Clivati, et al., “Planar-waveguide external cavity laser stabilization for an optical link with 10^{-19} frequency stability,” IEEE Trans. Ultrason. Ferroelectr. Freq. Contr., vol. 58, no. pp. 12, 2582-2587, Dec. 2011.

[12] C. E. Calosso, E. Bertacco, D. Calonico, C. Clivati, G. A. Costanzo, M. Frittelli, F. Levi, A. Mura, and A. Godone, “Doppler-stabilized fiber link with 6 dB noise improvement below the classical limit,” Opt. Lett. **40**(2), 131-134 (2015).

[13] C. E. Calosso, E. Bertacco, D. Calonico, C. Clivati, G. A. Costanzo, M. Frittelli, F. Levi, A. Mura, and A. Godone, “Frequency transfer via a two-way optical phase comparison on a multiplexed fiber network”, Optics Letter, 39, 1177 (2014).

[14] M. Rioja, R. Dodson, Y. Asaki, J . Hartnett, and S. Tingay, “The impact of frequency standards on coherence in vlbi at the highest frequencies”, The Astronomical Journal, 144:121, (2012).