Optical Fiber Links Used in VLBI Networks and Remote Clock Comparisons: the LIFT/MetGesp Project

R. Ricci, M. Negusini, F. Perini, C. Bortolotti, M. Roma, R. Ambrosini, G. Maccaferri, M. Stagni, M. Nanni, E. Kravchenko, M. Siciliani de Cumis, L. Santamaria, G. Bianco, C. Clivati, A. Mura, F. Levi, D. Calonico

Abstract The synchronization between atomic clocks plays an important part in both radio astronomical and geodetic Very Long Baseline Interferometry, as the clocks are responsible for providing time and frequency reference at radio stations. The availability of highly stable optical fiber links from a few radio observatories and their national metrological institutes has recently allowed the streaming of frequencies from optical clocks based on the Sr/Yb lattice technology (even two order of magnitudes more stable than H-maser clocks). We will present the current status of the Italian Link for Frequency and Time (LIFT) and the ongoing efforts to realize a geodetic experiment utilizing the radio stations in Medicina and Matera connected in common clock via the optical fiber link. We will then show the results from the latest VLBI clock timing experiments also making use of the LIFT link to compare atomic clocks of the three italian radio VLBI antennas (Mc, Sr and Nt) using the rms noise in the interferometric phase. VLBI clock timing proves more effective than Global Navigation Satellite System and less expensive than Two-Way Satellite Frequency and Time Transfer in synchronizing remote clocks.

Roberto Ricci · Monia Negusini · Federico Perini · Claudio Bortolotti · Mauro Roma · Roberto Ambrosini · Matteo Stagni · Mauro Nanni · Evgeniya Kravchenko
INAF-Istituto di Radioastronomia, Via Gobetti 101, Bologna, IT-40129 Italy

Cecilia Clivati · Alberto Mura · Filippo Levi · Davide Calonico
Istituto Nazionale di Ricerca Metrologica (INRiM), Via delle Cacce 91, Torino, IT-10135 Italy

Giuseppe Bianco · Mario Siciliani de Cumis · Luigi Santamaria
ASI-Centro di Geodesia Spaziale "Giuseppe Colombo" Località Terlecchia snc, Matera, IT-75100 Italy

(Correspondence: ricci@ira.inaf.it)

Keywords Instrumentation VLBI · Optical fiber · Frequency reference dissemination · Atomic clock timing

1 Introduction

Three are the main research areas in which frequency reference dissemination is important: (i) radioastronomy, (ii) relativistic geodesy and (iii) clock metrology. In radioastronomy time and frequency optical fiber links can offer faster operations, they will provide more stable clocks for mm-VLBI operating above 80 GHz (where the H-maser clocks are an important limit to phase stability together with atmospheric turbulence and a limit to the resolution, see (Rioja et al., 2012; Nikolic et al., 2013) for a reference. Existing mm-VLBI telescopes in Europe that could benefit from high stability in optical fiber links are in Germany (Effelsberg), Spain (IRAM and Yebes), Sweden (Onsala) and Finland (Metsahövi): better (angular) resolution from mm-VLBI runs including these observatories will positively affect the study of radio jets in compact radio sources. Moreover, in geodetic VLBI, in order to achieve 1-mm positioning accuracy clock uncertaninty at 10^{-16} are required (Neill et al., 2005). The study of radio pulsar will also gain through absolutely accurate time provided by fiber-optic streamed frequency references (Lyne et al., 2016).

The most performing clocks at the moment are optical clocks which utilize a transition in the optical band interrogated by a highly stable laser in a ultra cooled (μK) lattice of Strontium or Ytterium (Ushijima et al., 2015). The frequency stability and accuracy of the best optical lattice clock is nowadays about two order of magnitudes better (a few parts in 10^{-18} after a few

1000 s of operation). This huge accuracy and stability can be put to the use also in the field of relativistic geodesy, an example of which is chronometric levelling where the gravitationally shifted frequency difference of two portable optical clocks can determine their altitude difference with an accuracy of ~ 10 cm (Grotti et al., 2018). Optical fiber links are used to remotely compare the clocks.

The third reason to operate long-haul highly stable optical fiber links is clock metrology (Lisdat et al., 2016). Apart from the italian case, France, Germany, the UK and Poland are equipping themselves with optical fiber links to connect each other's national metrological institutes. This will make possible the comparison of highly performing optical lattice clocks across Europe. At the same integration time the optical links are orders of magnitude more stable than satellite-based frequency reference dissemination techniques such as Global Navigation Satellite Systems and Two-way Satellite Frequency Transfer. This international optical fiber network for clock metrology will bring to the redefinition of the SI second in the near future (Riehle, 2017).

2 Method

The MetGeSp (Metrology for Geodesy and Space) project is an offshoot of the LIFT (Italian Link for Frequency and Time) infrastructure. MetGeSp aims at disseminating a highly stable and accurate frequency reference signal via an optical fiber link to a series of Italian facilities. The Italian National Institute of Metrology (INRiM) in Turin generates the frequency reference which is streamed via the LIFT link to Modane (under the Frejus tunnel) to study relativistic geodesy, to the Milan Financial District, to the INAF-Istituto di Radioastronomia radio station for radio and geodetic VLBI experiments, to Florence's Italian Lab for Non-linear Spectroscopy (LENS) for tests on optical clock frequency accuracy, to the Fucino Plain (Telespazio Facility) for global satellite navigation (Galileo network) and finally to Matera (Centre for Space Geodesy). The creation of a common clock between the Medicina and Matera radio stations is the main radio-VLBI related goal of the MetGeSp project (see Section 5).

A detailed description of the optical fiber link would be beyond the scope of this paper. Briefly the RF signal generated by the INRiM clock is up-converted to the frequency of a 1.5 μm laser via an opto-electronic device (an optical frequency comb) and the phase is kept synchronized via a phase-locked loop. The laser signal is beamed along a dedicated (dark) fiber. In order to prevent signal attenuation Erbium-doped Field Amplifiers (EDFAs) are set along the link. A remote control in Turin is used to minimize gain instabilities over time in the EDFAs. Excellent noise cancellation is achieved via a round-trip servo mechanism which allows to reach a frequency stability of the order of 10^{-19} in terms of Allan deviation over 1000 seconds. On Nov 7th 2018 the LIFT link saw its first light in Matera CSG (Fig. 1). With a span of 1800 km LIFT is now one of the longest frequency reference dissemination link in the world. The total span between Turin and Matera is covered in 4 legs and the laser signal is regenerated in Medicina, Florence (LENS), Pozzuoli (Institute of Optics) and Matera (ASI-CSG). In Matera and Medicina the signal is down-converted via another optical frequency comb to the RF domain. The resulting RF (5 MHz, 10 MHz and 1 PPS) are used directly in the VLBI receiver chain and for remote clock comparison. More details are found in Calonico et al. (2014) and Clivati et al. (2015).

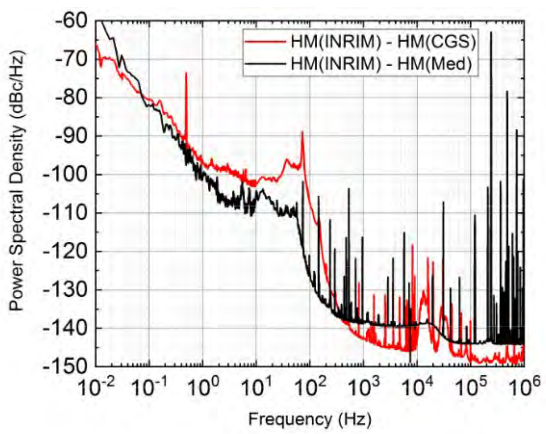

Fig. 1: First light of the LIFT link in Matera: Ma-Mc H-maser comparison via the power spectral density

3 Results

The first VLBI test making use of the LIFT optical fiber link between the Medicina radio station and Turin was the geodetic experiment EUR137 in September 2015 (published in Clivati et al. (2017)): the local and remote H-maser frequency signals were alternately injected into the VLBI data acquisition chain and the data from the two clocks were analyzed as two separate experiments.

In order to further test the VLBI and link set-up in view of a common-clock experiment between Medicina and Matera stations two 24 hour-long S/X-band geodetic experiments were carried out on in July 2017 and April 2018 utilizing the Medicina, Noto and Matera stations. Medicina received the frequency signal from Turin for the all duration of the runs. The data were correlated in Bologna with the local DiFX correlator (Deller et al., 2007) and fringe fitted using the Haystack Observatory Post-processing Software *fourfit* (Cappallo, 2017). The geodetic tools CALC/SOLVE and nuSolve (Bolotin et al., 2014) were used to analyze the correlated data. In the former of two test sessions a few unlocks were found and fixed at the geodetic analysis stage. The latter geodetic session ran smoothly without any link unlocks, but problems with correlating Noto scans resulted in the usage of only the Medicina-Matera observation pairs in the geodetic analysis. The group delay weighted rms residuals after station, clock and atmosphere model subtraction are 56 ps on the Mc-Nt baseline and 46 ps on the full July 2017 experiment.

An alternative way to study remote clock synchronization using VLBI antennas makes use of the statistics of the interferometric phase (Krehlik et al., 2017).

Table 1: Summary of the VLBI clock timing observations: project codes, the observing dates, the stations involved, the bands used and whether the Medicina station was receiving or not the remote frequency standard from INRiM. Baselines with Metsahövi could not be correlated because of a data format problem.

Project code	Date	stations	Band	Mc rem clock?
VT001	20180118	Mc,Nt,Ma,Ys,Mh	S/X	No
VT003	20180124	Mc,Nt,Tr	C	No
VT005	20180219	Mc,Nt,Tr	C	No
VT006	20180220	Mc,Nt,Tr,Ys	C	Yes
VT007	20181123	Ma, Eb, On	S/X	No
VT008	20190205	Mc, Sr	C-hi	Yes
VT009	20190204	Mc, Sr	C-hi	No

To this purpose a series of VLBI clock timing experiments were performed with a network comprising the stations of Medicina, Noto, Matera, Yebes and Metsähovi in January/February 2018 (Effelsberg station accepted to take part in one run but it was wind stowed for the full time). Many factors contribute to the deterioration of the interferometric phase stability, the most important being atmospheric instabilities, gain elevation effects and antenna thermal deformations. In order to minimize these performance degrading effects the VLBI runs were carried out at night during the winter months on a point-like radio source (15-min scans in 3-hour runs at medium/high antenna elevation to minimize air mass absorption). In Table 1 we report a summary of the VLBI clock timing observations. The VT007-9 experiments were 6 hours long on two calibrator arcs and were carried out in February 2019.

The S/X-band observations (VT001 and VT007) were performed with the stardard geodetic frequency set-up and bit rate. The C-band observations were performed with a radio astronomical VLBI frequency set-up: the observing band was split into 4 contiguous 8-MHz wide sub-bands (IFs) of 32 frequency channels each just below the sky frequency of 5 GHz. The C-hi observations set-up has 8 4-MHz wide contiguous sub-bands in dual polarization mode at a centre frequency of 6.7 GHz. The Bologna DiFX correlator was used to correlate the station data which were then read into FITS files. The fringe fitting and frequency averaging were done in AIPS (Greisen, 2003). The data were read out from AIPS into ASCII tables and the statistics on the phase stability were computed scan-by-scan according to Krehlik et al. (2017): the scan samples were separated into couples (*even statistics*) and triplets (*odd statistics*) and then first differences and interpolated-value differences were computed together with their root mean square. The C/C-hi band experiments had 2-bit sampling and 1-sec time integration. The central 80 % of the bandpass was used in the analysis, thus removing the less sensitive sloping wings. The time synchronization was computed using the formula:

$$\Delta t_{\rm rms} = \frac{\Delta\phi_{\rm rms}}{2\pi\nu_0},$$

where $\Delta t_{\rm rms}$ is the rms time synchronization between clocks, $\Delta\phi_{\rm rms}$ is the phase rms noise and ν_0 is the sky centre frequency in each sub-band. The results of the VT008/9 experiments are shown in Table 2. The results are in good agreement with Krehlik et al. (2017)

Table 2: Results of the VLBI timing experiments in C-hi band: the tag rem(loc) means that Medicina was using remote(local) H-maser frequency reference. Only *even* statistics is shown.

Project code	pol	HM	Δt_{rms}	error bar
VT008	RR	rem	3.08	0.03
VT009	RR	loc	2.31	0.03
VT008	LL	rem	3.79	0.04
VT009	LL	loc	2.79	0.03

on the same timescale. We also found similar statistical values for Δt_{rms} for remote and local clocks for the Medicina station.

4 Conclusions and outlook

The LIFT infrastructure is able to deliver a frequency reference signal from the Italian Metrological Institute (INRiM) to remote locations via an optical fiber link with unprecedented stability (of the order of a few parts in 10^{-19} in 1000 s integration time based on Allan standard deviation).

Geodetic VLBI experiments are performed with the remote frequency reference provided to the Medicina radio station. The wrms residuals in the group delays are in agreement with the statistics found in experiments using local clocks.

The ASI-Centre for Space Geodesy (ASI-CSG) in Matera was reached by the LIFT link and the first light was achieved in Matera on Nov 7th 2018. The link now spans 1800 km of optical fiber in four legs: Turin-Medicina, Medicina-Florence, Florence-Pozzuoli and Pozzuoli-Matera. At the end of each leg the laser signal is regenerated and kept in phase synch.

RMS stastistics on the interferometric phase noise was successfully used in remote and local clock timing experiments utilizing the radio/geodetic VLBI technique. The level of synchronization between clocks is estimated to be better than a few pico-seconds over 900-second observing scans in good to excellent observing conditions.

In the near future the following developments are planned:

- a VLBI vs GPS frequency stability analysis in the CONT14 and CONT17 campaigns focusing in particular on the co-located stations of Matera and Onsala compared to Wettzell;
- a series of *common-clock* geodetic experiments in which both Medicina and Matera stations are going to receive remote frequency reference from Turin;
- a comparison of Japan's NICT and Italy's INRiM optical clocks via VLBI utilizing the portable Japanese MARBLE 2.4-metre antennas, one of which is at the moment installed at the Medicina radio station (see Sekido et al., 2019, for details on this project);
- the usage of interplanetary space probe tones and the ΔDOR (Differential One-way Ranging) technique to compare clocks at two receiving radio stations;
- the usage of the LIFT link for possible future VLBI timing experiments between the Medicine/Turin and Polish Torun/KM-FAMO optical clocks;
- the testing of the White Rabbit/Precise Time protocol technology for digital dissemination of frequency reference signals and for clock synchronization.

Acknowledgements We thank the VLBI partners from Yebes Observatory (B. Tercero Martínez, J. González García, P. de Vicente), Torun Observatory (A. Marecki, P. Wolak, M. Gavroǹski), Metsahövi Observatory (J. Kallunki, J. Tammi), Effelberg Observatory (A. Kraus, U. Bach), Matera CSG (G. Colucci, M. Paradiso, F. Schiavone), Noto radio station (P. Cassaro, S. Buttaccio), Onsala Observatory (R. Haas, J. Yang, M. Lindqvist), Sardinia Radio Telescope (S. Poppi, G. Surcis) and the staff of the Medicina radio station for their support during the VLBI runs.

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