# Comparing Remote Atomic Clocks via VLBI Networks and Fiber Optic Links: the LIFT/MetGeSp Perspective

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**Abstract** Very Long Baseline Interferometry experiments require an extremely precise synchronization between the atomic clocks keeping the time and frequency standards at radiotelescope observatories. Recently the availability of fiber optic links from a few radio observatories and their national metrological institutes has made the streaming of extremely stable frequency standards via optical atomic clocks possible (even two orders of magnitudes better than Rubidium or Hydrogen maser standards). Firstly, we present the infrastructure of the Italian Link for Frequency and Time (LIFT) and results of the MetGeSp project aimed at finally creating a common clock between two of the antennas of the VLBI Italian Network. Secondly, the results are shown from VLBI experiments in which the rms phase noise was used to accurately compare the synchronicity of atomic clocks located at a few European stations (Medicina, Noto, Yebes, Torun, and Matera). VLBI clock timing proves a valid alternative to satellite-based techniques such as the Global Navigation Satellite System or the Two-Way Satellite Time and Frequency Transfer.

**Keywords** Instrumentation: atomic clocks, Instrumentation: optical fibers, Instrumentation: VLBI

## 1 Introduction

The comparison of atomic clocks is important both *per se* and for Very Long Baseline Interferometry (VLBI) applications. Atomic clock comparisons, in particular between optical atomic clocks, are utilized for relativistic geodesy ([1], [2]) and in the future they will be instrumental for the redefinition of the SI second [3]. At the moment the primary standard is provided by Cesium fountains having a stability of the order $10^{-16}$ after a few hundred seconds of integration. In the future optical atomic clocks based on the Strontium or Ytterbium lattice technology will achieve a stability a factor of two better on a comparable integration time. At continental distances, frequency standard dissemination via optical fiber links is the most reliable and stable way of comparing high performance optical atomic clocks. For intercontinental distances, satellite techniques such as Global Navigation Satellite Systems (GNSS) and Two-Way Satellite Time and Frequency Transfer (TWSTFT) are still the most utilized ones. VLBI observations, in particular geodetic VLBI sessions, are currently being explored as a viable alternative to the less reliable GNSS and more expensive TWSTFT techniques.

A more stable frequency standard is also useful for VLBI observations:

- a narrower fringe search window can be achieved;
- the loss of phase coherence between stations can be mitigated ($\delta\nu/\nu < 1/\tau\nu \leq 10^{-13}$ where $\nu$ and $\tau$ are the observing frequency and integration time);
- the synchronization of Square Kilometer Array stations will benefit [4].

Moreover a better spectral purity of the atomic clock frequency standard obtained by an optical fiber link means that less Local Oscillator (LO) phase noise will be measured in single-dish/VLBI observations. Phase noise problems get more detrimental in the millimeter band as the LO phase noise scales as the square

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of the number of multiplication steps from the 10 MHz RF signal to the sky frequency [5].

## 2 LIFT/MetGeSp Experiments

The LIFT (Italian Link for Frequency and Time) project and its successor (the Metrology for Geodesy and Space, in short MetGeSp, project) aim at providing Italy with an optical fiber link for frequency standard dissemination. The frequency standard generating clock is located at the Italian National Institute of Metrology (INRiM) in Turin. The link serves a metrological lab for relativistic geodesy in Modane (Frejus tunnel), the Milan Tech University, the INAF-Istituto di Radioastronomia radio station where radio and geodetic observations are performed, the Italian Lab for Non-linear Spectroscopy (LENS) in Florence where the accuracy of the optical clock frequency is tested, the Telespazio Facility in the Fucino Plain where one of the main stations of the European Galileo satellite network for global navigation is located, and finally the Matera geophysical station for space geodesy. The major radio astronomical goal of the MetGeSp project is the creation of a common clock between the Medicina 32-m radio telescope and the Matera 20-m radio telescope. A secondary goal of the project is providing the Medicina radio station with an accurate and stable frequency standard from Turin's INRiM for VLBI clock timing experiments with other (optical) atomic clocks abroad (see Section 4).

A detailed description of the optical fiber link is provided in [6] and [7]. For the purpose of this paper it will suffice to say that the RF signal generated by the INRiM clock is up-converted to the frequency of a 1.5 $\mu$m laser via an opto-electronic device (optical frequency comb), and the phase is kept in sync through a phase-locked loop. The laser signal is streamed through a 550-km dark fiber along which nine sub-stations equipped with Erbium-doped Field Amplifiers (EDFAs) counteract the signal attenuation. The EDFAs are remotely controlled from Turin to maximize their gain stability over time. A round-trip servo mechanism is also employed to provide a phase noise cancellation of the level of $10^{-19}$ in terms of frequency stability. Once at the Medicina radio station, the optical laser signal is regenerated and down-converted via an optical frequency comb to the RF domain. The resulting RF signal is compared to the local H-maser clock or used directly for VLBI.

The first geodetic experiment testing the LIFT infrastructure was the EUR137 in September 2015. The frequency standard provided by the LIFT link was alternated with the one of the local H-maser clocks and the data was analyzed as two separate stations in the same experiment. The results of this test are published in [8].

A few unlocks in the link suggested to us to start an unlock monitoring campaign lasting from May until early July 2017. During that campaign, a link uptime of about 97% was reported with very few and fixable unlocks caused by human activity at the commercial optical fiber sub-stations. H-masers in Turin and Medicina were compared and reported an Allan standard deviation of $\sigma_\tau \simeq 2 \times 10^{-14}$ on the phase difference after $10^3$ seconds in agreement with expectations.

On July 6–7, 2017 and again on April 3–4, 2018 two geodetic 24-hour S/X-band sessions utilizing the VLBI stations in Medicina, Noto, and Matera were carried out to test the performance of the optical fiber link from Turin. The data were correlated using the Bologna DiFX ([9]) correlator and fringe fitted in HOPS *fourfit* [10]. The analysis was performed with CALC/SOLVE and nuSolve [11].

A few unlocks were still present in the former of the two test sessions, but these problems were fixed at the data analysis stage. In the latter test session no unlocks were detected. In the April 2018 test session only observation pairs from the Medicina-Matera baseline were used in the geodetic analysis solution. A plot with the group delay wrms residuals vs. observing time from the July 2017 session is shown in Figure 1 together with related statistics.

## 3 Analysis of CONT14 Campaign

To study how the VLBI and GPS techniques compare in determining clock models, we analyzed the clock solutions of the nine pairs of co-located stations taking part in the CONT14 geodetic campaign. The co-located stations were (VLBI/GPS): HOBART/hob2, HARTRAO/hrao, KOKEE/kokv, MATERA/mate, NYALES20/nya1, ONSALA60/onsa, WETTZELL/wtzr, YEBES40M/yebe, and ZELENCHK/zeck. The clock solutions were derived

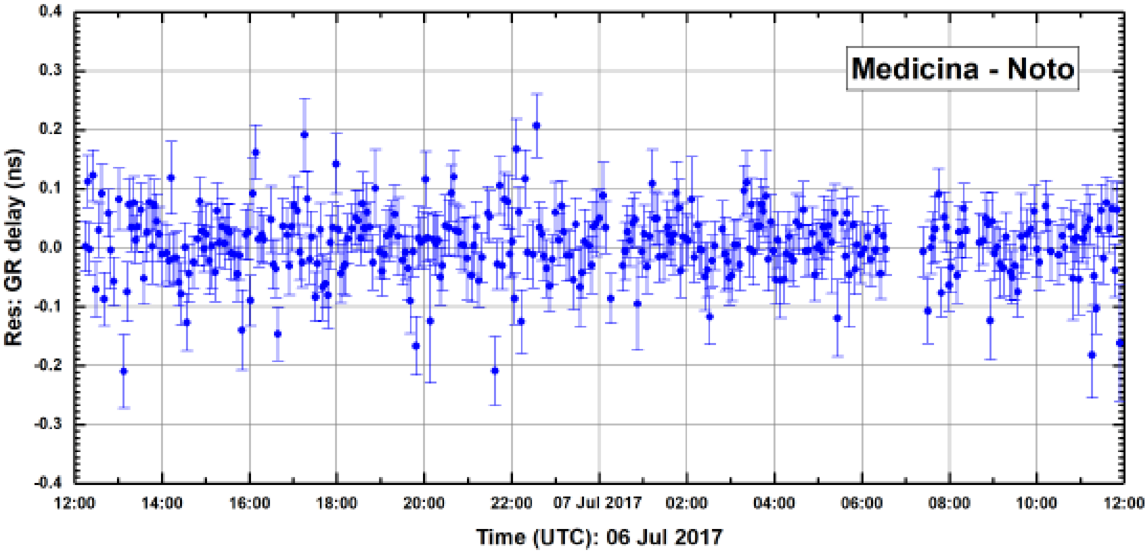

**Fig. 1** Group delay residuals vs. observing time for the July 2017 experiment: Mc-Nt baseline wrms=56 ps; Full experiment wrms=46 ps.

through CALC/SOLVE with a quadratic model plus a one-hour Piece-Wise Linear continuous function with respect to the reference clock (Wettzell). These solutions were compared day-by-day with the ones obtained with GPS Precise Point Positioning, which were computed every 300 seconds and stored in the IGS repository. Before the comparison the GPS solutions were reduced to the same reference clock with the *Bernese* 5.2 software [12].

The Time Stabilty Analysis via Allan standard deviation showed $\sigma_\tau$'s at 1 second of comparable values between GPS and VLBI and in the range $10^{-12}$ – $-10^{-11}$. Both VLBI and GPS present a power-law behavior in the $\sigma$ vs. $\tau$ plots, with the former systematically exhibiting shallower slopes than the latter. Both VLBI and GPS slopes were also found to be shallower than the $\tau^{-1}$ expected behavior.

## 4 VLBI Clock Timing Tests

We performed a series of VLBI experiments to test clock timing during the months of January and February 2018. These observations involved the stations in Medicina, Noto, Matera, Yebes, Torun, and Metsahövi. Based on the work of [13] we used the interferometric phase rms noise statistics to estimate the synchronization of the station clocks. Atmospheric instabilities, gain-elevation effects, and thermal deformations of the antennas can all have degrading contributions to the inteferometric phase; therefore they should be minimized as much as possible. For these reasons the observations were carried out in the winter season on a point-like source (a bright geodetic standard calibrator: 1156+295) in 15-minute scans in three-hour runs at night time. While scheduling we also made sure that the observing target was at medium/high telescope elevations for all the antennas involved in each of the experiments in order to minimize the air mass absorption.

A summary of the observations reporting the 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 is provided in Table 1.

The S/X-band observations (VT001) were performed with the standard geodetic frequency set-up and bit rate. The reduction of these data is still on-going; therefore no results will be presented in this paper. The C-band observations were performed with a radio astronomical VLBI frequency set-up: the

**Table 1** Summary of the VLBI clock timing observations.

| 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 |

observing band was split into four contiguous 8-MHz wide sub-bands (IFs) of 32 frequency channels, each just below the sky frequency of 5 GHz. The data were correlated using the Bologna DiFX correlator and read into FITS files to be fringe fitted and analyzed with the radio astronomical software AIPS [14]. The data were read out from AIPS into ASCII tables, and the interferometric phase statistics were worked out scan by scan following the same scheme as in [13]: 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. This scheme was followed on the Right polarization RR of each sub-band and each baseline for the VT003, VT005, and VT006 experiments. For all the experiments we had a one-second sampling rate, and an 80% central band vector averaging was applied before reading out the phase ASCII tables from AIPS. 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 interferometric phase rms noise, and $\nu_0$ is the sky frequency at each sub-band center. The $\Delta t_{\rm rms}$ numerical values are in the range $1.1 - 1.9$ picoseconds for 15-minute scans — a result that is in good agreement with the values found by [13] on the same timescale. We also found similar statistical values for $\Delta t_{\rm rms}$ for remote and local clock set-ups for the Medicina station. Finally, the *even* statistics were found to be systematically larger than the *odd* ones within the relative error bars of 5% (*even*) and 6% (*odd*).

## 5 Conclusions

LIFT is an infrastructure able to deliver frequency standard signals from the Italian Institute of Metrology (INRiM) in Turin to remote locations via a fiber-optic link with unprecedented stability (Allan standard deviation of the order of $10^{-19}$).

Geodetic VLBI experiments are performed with remote frequency standards provided by INRiM in Turin at the Medicina radio station with tens of picoseconds wrms residuals in group delay. This result is in good agreement with experiments utilizing local clocks.

Interferometric phase rms noise statistics were successfully used in remote and local clock timing with the radio astronomical and geodetic VLBI techniques. The results of our tests are quantitatively comparable with the ones performed by [13] that triggered our observations.

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