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Comparing remote atomic clocks via VLBI networks and fiber optic links: the LIFT/MetGeSp perspective

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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 possible the streaming of extremely stable frequency standards via optical atomic clocks (even two order of magnitudes better than Rubidium or Hydrogen maser standards). Firstly, I will 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, I will show the results of VLBI experiments in which the phase rms noise was used to accurately compare the synchronicity of atomic clocks located at a few EVN sites (Medicina, Noto, Yebes, Torun). VLBI clock timing proves a valid alternative to satellite-based techniques such as Global Navigation Satellite System or Two-Way Satellite Frequency and Time Transfer.

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1. Introduction

Atomic clock timing can be effectively used for Very Long Baseline Interferometry (VLBI) applications, but it can also be utilized for relativistic geodesy ([1], [2]) when comparing optical clocks and in the future networks of optical clocks it will provide a redefinition of the SI second [3]. Clocks based on Cesium fountains are at the moment the primary standard in time metrology, having a stability of the order of 10^{-16} after a few hundred seconds of integration, but in the near future Strontium or Ytterbium lattice optical clocks will achieve a factor-of-two improvement in stability and accuracy on a such time integration. The frequency signal dissemination via optical fiber links is for the time being the most effective and stable way of comparing high performance atomic clocks on continental baselines. For intercontinental distances two techniques are being used to synchronize clocks and spread frequency standards: the Global Navigation Satellite System (GNSS) and the better performing but more expensive Two-Way Satellite Time and Frequency Transfer (TWSTFT). VLBI clock timing techniques (in particular geodetic VLBI) are now becoming a valid alternative the former two.

In mm-VLBI applications an improved frequency stability could help mitigate the loss of phase coherence between stations ($\delta\nu/\nu < 1/\tau\nu \leq 10^{-13}$ where ν and τ are the observing frequency and integration time). The forthcoming Square Kilometer Array will also benefit from better synchronization techniques using fiber optics [4]. Finally a better clock spectral purity obtained from fiber-distributed frequency standards provides less Local Oscillator phase noise in both single-dish and VLBI observations: the LO phase noise scales as N^2 where N is the number of multiplication steps from the Radio Frequency (RF) to the sky frequency (see [5]).

2. Geodetic experiments

The LIFT (Italian Link for Frequency and Time) infrastructure spawned the MetGeSp (Metrology for Geodesy and Space) project with the aim of disseminating a highly stable and accurate frequency signal via an optical fiber link to a series of Italian facilities. The frequency generating station is located at the Turin's Italian Metrological Institute of Metrology (INRiM). The metrological lab for relativistic geodesy in Modane (under the 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 optical clock frequencies are 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 Centre for Space Geodesy are the current facilities utilizing LIFT. The main 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, but the link is also going to to provide the Medicina radio station with accurate and stable frequency for VLBI (optical) clock experiments (see Section 3 and 4).

A detailed description of the optical fiber link would be beyond the scope of this paper. In a nut shell 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 550-km dedicated fiber. To prevent the signal attenuation nine sub-stations equipped with Erbium-doped Field Amplifiers (EDFAs) are set along the link. A remote control in Turin is used to minimize gain instabilities over time. A frequency stability of the order of 10^{-19} in terms of Allan deviation over 1000 seconds can be obtained through a round-trip servo mechanism for noise cancellation. In Medicina the laser signal is regenerated and down-converted via another optical frequency comb to the RF domain. The resulting RF (5 MHz, 10 MHz and 1PPS) are used directly in the VLBI receiver chain and also for remote clock comparison. More details are found in [6] and [7].

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 [8]): 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.

A link monitoring campaign lasting from May until early July 2017 was carried out in order to evaluate its reliability as a few unlocks were present during the EUR experiment. The link performance was good with 97% up-time. H-maser comparison between Medicina and Turin showed a stability of $\sigma_y \simeq 2 \times 10^{-14}$ on the phase difference after 10^3 seconds in terms of Allan deviation, in agreement with expectations.

In order to further test the VLBI and link set-up in view of a common-clock experiment between Medicina and Matera steations 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 [9] and fringe fitted using the Haystack Observatory Post-processing Software *fourfit* [10]. The geodetic tools CALC/SOLVE and nuSolve [11] 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. The related plot is in Fig. 1.

3. VLBI clock timing experiments

An alternative way to study remote clock synchronicity using VLBI antennas involves the statistics of the interferometric phase [13]. To this end a series of VLBI clock timing experiments were performed with a network comprising the stations of Medicina, Noto, Matera, Yebes and Metsahovi 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 degrating effects the VLBI runs were performed 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 S/X-band observations (VT001) were performed with the stardard geodetic frequency set-up and bit rate. The C-band observations were performed with a radio astronomical VLBI

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 Metsahovi 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

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 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 [14]. The data were read out from AIPS into ASCII tables and the statistics on the phase stability were computed scan-by-scan according to [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. To match the scheme in [13] only Right-hand polarization data were taken and analyzed. The C-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 are shown in Fig. 2. The results are in good agreement with [13] on the same timescale. We also found similar statistical values for $\Delta t_{\rm rms}$ for remote and local clocks for the Medicina station (compare VT005 and VT006 columns).

4. Conclusions and future developments

LIFT is an infrastructure developed to stream frequency signals from the Italian Metrological Institute (INRiM) to remote facilities via an ultra-stable optical fiber link.

Geodetic VLBI experiments are being performed with the remote frequency signal provided to the Medicina radio station by Turin's INRiM with ten's of ps in group delay wrms residuals after standard geodetic data modeling. This results are in agreement with experiments utilizing local clocks.

Rms statistics on the VLBI interferometric phase in geo/radio VLBI test experiments were successfully used to time remote and local clocks following the same scheme by [13].

The Matera radio station has just been connected to the now 1800-km long LIFT link, thus becoming the farthest end in the frequency signal dissemination infrastructure. Tests on the link stability and up-time performances are underway. A VLBI experiment involving the Mc and Ma stations operating in common-clock mode (both receiving the **same** frequency signal from Turin's INRiM) is expected to take place in early 2019.

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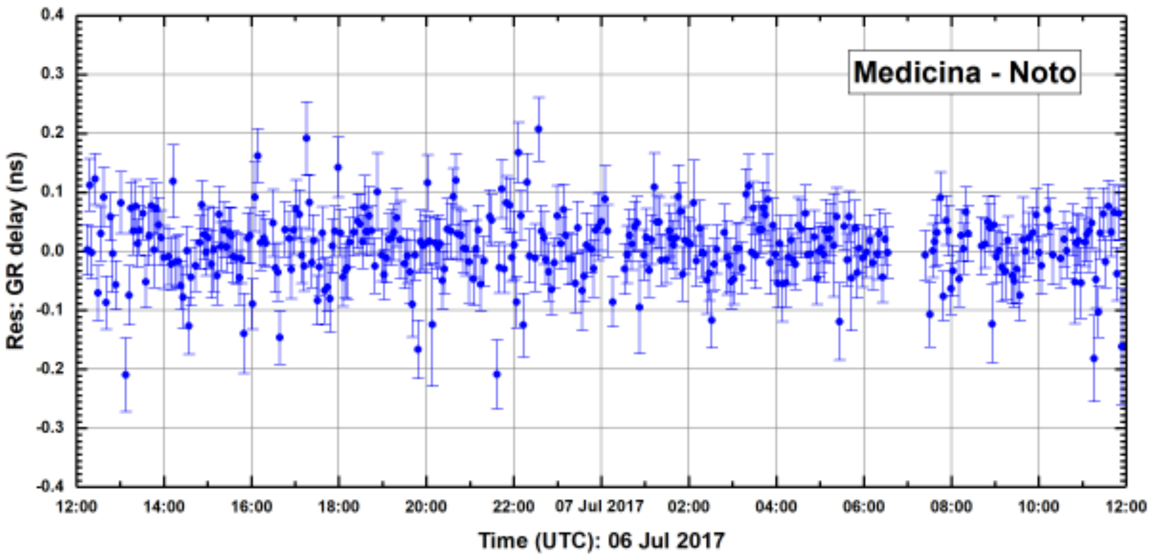

Figure 1: Group delay residuals vs observing time for July 2017 experiment.

		VT005 19/02		VT006 20/02		VT003 24/01	
		scan: No0002		scan: No0002		scan: No0002	
		Local H-maser		remote H-maser		local H-maser	
		even	odd	even	odd	even	odd
Mc-Nt	1RR	2.47(12)	2.53(15)	2.74(13)	2.78(16)	1.25(6)	1.13(7)
	2RR	2.41(11)	2.49(14)	2.65(13)	2.73(16)	1.74(9)	1.16(7)
	3RR	2.44(12)	2.62(15)	2.66(13)	2.64(15)	1.36(7)	1.13(7)
	4RR	2.50(12)	2.68(16)	2.63(12)	2.79(16)	1.35(7)	1.17(7)
		[444]	[296]	[444]	[296]	[450]	[300]
Mc-Tr	1RR	1.84(11)	1.78(14)	2.04(13)	1.76(13)	1.26(6)	1.04(6)
	2RR	1.82(11)	1.75(13)	2.68(17)	1.99(15)	--	--
	3RR	1.84(11)	1.70(13)	1.80(11)	1.65(13)	--	--
	4RR	2.02(13)	1.88(14)	1.83(11)	1.68(13)	--	--
		[258]	[172]	[258]	[172]	[450]	[300]
Nt-Tr	1RR	1.36(8)	1.37(10)	2.64(16)	2.54(19)	1.51(8)	1.51(9)
	2RR	1.58(10)	1.45(11)	3.25(20)	2.86(22)	--	--
	3RR	1.51(9)	1.52(12)	2.42(15)	2.24(17)	--	--
	4RR	1.54(10)	1.58(12)	2.35(15)	2.21(17)	--	--
		[258]	[172]	[258]	[172]	[450]	[300]

Figure 2: The $\Delta t_{\rm rms}$ in ps from the phase rms stats in the VT003, VT005 and VT006 experiments. Statistical errors are in round brackets. The sample numbers on which the stats are computed are in square brackets.