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VLBI experiments with the dissemination of a common clock via coherent optical fiber link

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Atomic clock synchronization plays an important role in both astronomical and geodetic Very Long Baseline Interferometry, as time and frequency standards are provided by station clocks. National metrological institutes have recently started streaming (via optical fiber links) frequency references from ultra-stable clocks based on optical line transitions in Strontium/Ytterbium laser-cooled lattices. Optical lattice clocks are already two orders of magnitude more stable than the radio station H-masers. In this talk we will describe how the Italian Qauntum Backbone (IQB) was used to carry out a series of European geodetic VLBI experiments in which the Medicina and Matera radio stations were connected to the same remote clock located at the Italian Metrological institute in Turin, via the IQB optical link. In the foreseeable future a European VLBI network of radio stations could be connected via optical fiber links to a single very high-performance clock hosted by a European Metrological institute.

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1. Introduction

Time and frequency optical fibre links are important for radio astronomy for various reasons. They can provide (i) faster operations via better synchronizations of station clocks, (ii) better mm-VLBI phase stability above 100 GHz via the usage of highly performance atomic clocks [19, 20], (iii) better study of compact structure in extragalactic radio sources and stellar masers around evolved stars, as better angular resolutions can be achieved at increasing observing frequency if phase instability can be effectively mitigated. In geodetic Very Long Baseline Interferomery a position accuracy of one mm as in the upcoming VGOS network (Schuh & Behrend [21]) requires the ability of modelling the troposphere accurately but it also necessitates the availability of stable frequency references [15, 16]. Moreover the study of pulsars requires accurate absolute time determinations [12, 13].

Another field of research where high-performance optical atomic clocks play an important role is relativistic geodesy: the determination of absolute height between two reference points on Earth via the relativistic frequency shift caused by the difference in gravitational potential experienced by the optical clocks (see Grotti et al. [9] for the use of portable optical clocks and Mehlstäubler et al. [14] for a comprehensive review). This technique, also called chronometric levelling, is complementary both to GNSS levelling and to geometric geodesy which have a disagreement on the vertical datum of about 10 cm. With the usage of coherent wave optical fibre links (with frequency stability better than a few parts in 10^{19}) connecting optical clocks with fractional frequency uncertainty down to 10^{-18}, an absolute height difference of 1 cm could be achieved on integration times of a few thousand seconds, thus allowing the tracking of geodynamic effects such as the movement of fluid masses under the surface of the Earth (Bondarescu et al. [2]), a measurement not obtainable by GNSS techniques.

Ultra-stable coherent optical fibre links are also important in time and frequency metrology per se, as they are used to perform optical clock comparison on continental scales (Lisdat et al. [11]), in view of a redefinition of the SI second based on optical clock frequency standards (Riehle et al. [18]).

In the following sections we will describe how the Italian Quantum Backbone optical fibre link [3, 5] was used to perform a series of VLBI experiments in which two antennas forming a baseline utilize the same remote frequency reference realizing, a common-clock set-up on a scale length of 600 km.

2. Method

The Italian Quantum Backbone (IQB) is an optical fibre infrastructure serving seven research institutes including INAF-IRA in Medicina, the European Laboratory for Non Linear Spectroscopy in Florence, the Institute of Optics in Pozzuoli (Naples) and the ASI-Space Geodesy Centre in Matera. It also serves three industrial users (Galileo Telespazio facility, Thales Alenia and the Top-IX Consortium). IQB uses phase noise round-trip cancellation to minimize phase noise to a

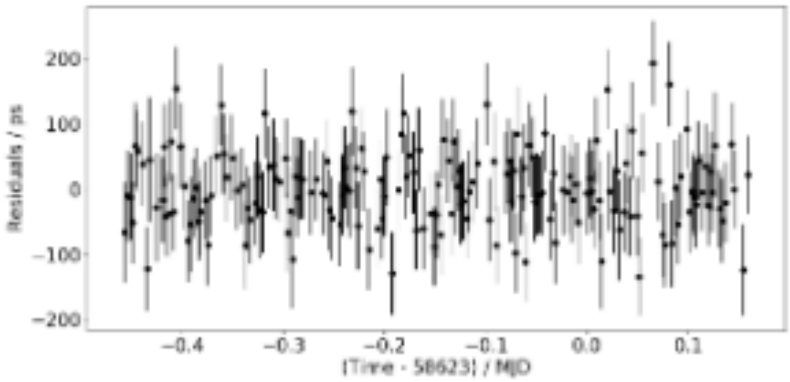

Figure 1: Post-fit group delay residuals as a function of observing time for the geodetic VLBI experiment VI007 in which Matera and Medicina shared the *same* remote frequency reference from INRiM (Torino).

Table 1: Summary of the observations in the 2020-2021 VLBI clock timing campaign: project code, observing dates, stations involved, bands used and presence of remote clock are shownin the columns.

Project code	Date	Stations	Band	rem clock?
VT010	20201129	Ma,Mc	X	No
VT011	20201209	Ma,Mc,Nt	X	No
VT012	20210213	Ma,Mc,Nt,Sr	X	Yes
VT013	20210224	Ma,Mc,Nt,Sr	X	No

stability level of 10^{-19} over 1000 s of integration time, and optical frequency combs to up-/down-frequency convert the frequency reference from optical to RF and viceversa (details of electronic scheme and link characterization are described in Clivati et al. [6]). The IQB link utilizes a dedicate 1800-km long dark fibre along the Italian peninsula and it is divided into four legs: INRiM/Torino to Medicina Radio station; Medicina Radio station to LENS/Florence; LENS/Florence to Institute of Optics/Pozzuoli; Institute of Optics/Pozzuoli to Space Geodesy Centre/Matera. At each leg terminal the fibre laser gets regenerated, fibre noise gets compensated and optical frequency combs allow for the 10 MHz RF to be extracted and used for scientific experiments. The IQB link reached Matera and saw the first light in November 2018 and since then it has been operating remotely from INRiM/Torino.

3. Results

On May 19th-20th 2019 the first geodetic common-clock experiment was performed. The 24-hour S/X-band session involved the antennas of Matera, Medicina, Yebes and Onsala. Matera and Medicina received their frequency reference remotely from an H-maser in INRiM/Torino via the IQB optical fibre link for the duration of the session. The remote frequency reference was used in the receiver chain of the two antennas for generating the time stamp and the Local Oscillator signal. Data were transferred electronically to the Bologna DiFX software correlator (Deller et al. [7]), correlated and fringe fitted with HOPS Fourfit (Cappallo [4]). The geodetic analysis was carried out using nuSolve (Bolotin et al. [1]) with standard parametrization for troposphere and clock modelling. The presence of frequency reference unlocks during the session resulted in using a shortened time interval of 15 hours in which no unlocks were present. The reasons for these unlocks is being investigated and mitigation schemes will be adopted in future campaigns. The wrms on group delay post-fit residuals (Fig.1) on the Matera-Medicina baseline was 58 ps. The drift (CL1 parameter in the nuSolve model) of the Matera clock with respect to the Medicina clock, used as reference, was consistent with zero to within 10^{-14} (s/s). This check reassured us that the frequency reference dissemination worked as expected. Details of the analysis are reported in Clivati et al. [6]. Further geodetic experiments were performed in Nov 2020 – January 2021 in order to make sure of the repeatibility of a common-clock VLBI experiments and better to characterize the effect on group delay residual statistics of baselines with common clock set-up with respect to hybrid baselines (remotely-locally distributed frequency reference) and to totally local-clock baselines. Up to seven unlocks were present in the 24 hour session. The results of this analysis will be published in a future paper.

Another way of comparing remote clocks using VLBI antennas utilizes the scatter on the inteferometric phase (Krehlik et al. [10]). For this reason a series of VLBI clock timing experiments was carried out with a network of stations including Matera, Medicina, Noto, Torun, Yebes and Metsahövi in January/February 2018 with geodetic S/X-band and C-band low (5 GHz) frequency set-up. In February 2019 a second series of phase scatter measurements was attempted with italian antennas at 6.7 GHz involving Medicina, Noto and the Sardinia Radio Telescope (SRT); for technical issues the Noto antenna could not take part in these two runs. The preliminary results of these initial timing tests were reported in the EVGA 2019 conference proceedings (Ricci et al. [17]). In the present report we will focus on the November 2020 – February 2021 campaign in which the antennas of Matera, Medicina, Noto and SRT were involved in 6-hour long runs at 8.4 GHz (see Table 1 for a summary of the observations). VT012 andVT013 were the first VLBI experiments involving *all* four Italian antennas. It is worth noticing also that Matera and Medicina in the VT012 experiment were in *common-clock* mode, both receiving their frequency reference from an H-maser located at INRiM.

Many factors contribute to the deterioration of the interferometric phase stability: tropospheric fluctuations, gain elevation effects, unmodelled source structure, antenna thermal deformation, cable thermal dilation. These effects can contribute to mask the clock frequency reference behaviour. In order to minimize these effects the VLBI runs were performed, as much as possible, at night during the winter season on a couple of point-like target sources in 15-min long scans at medium/high antenna elevation in 3-hour observing arcs per source.

The observations were specifically carried out at 8.4 GHz to allow both SRT and Matera to take part in the runs. The Italian Space Agency operates a 8.4 GHz narrow-band (40-MHz wide) receiver at SRT mostly used for satellite tracking purposes: this was the only frequency overlap with the S/X-band system mounted in Matera. The X-band observations were performed using a radio astronomical 2-bit sampling frequency set-up: a 40 MHz bandwidth was split into 8 contiguous sub-bands (four upper sideband and four lower sideband) of 4-MHz bandwidth, correlated with 32 frequency channels in each sub-band. The Bologna DiFX correlator was used to correlate

Table 2: RMS on the first difference of the interferometric phase based on Fourfit analysis for 1228+126: one of two sources observed in the 2020-2021 VLBI campaign. The measurement for each experiment baseline is expressed in term of time delay rms scatter $\Delta\tau_{\mathrm{rms}}$ in picoseconds. The sample number $\mathrm{N}_{\mathrm{samp}}$ represents the number of phase pairs used in computing the rms statistics. The numbers in round brackets represent the measurement uncertainty in the last digit.

Project code	Baseline	$\Delta\tau_{\mathrm{rms}}\,[ps]$	$\mathrm{N}_{\mathrm{samp}}$
VT010	MaMc	4.0(3)	180
VT011	MaMc	9.4(6)	181
VT011	McNt	10.0(8)	140
VT011	MaNt	6.3(6)	116
VT012	MaMc	14(1)	180
VT012	MaNt	9.4(7)	180
VT012	MaSr	4.9(4)	180
VT012	McNt	2.5(2)	220
VT012	McSr	2.8(2)	220
VT012	NtSr	3.3(2)	221
VT013	MaMc	1.7(1)	177
VT013	MaNt	2.1(2)	162
VT013	MaSr	2.0(2)	163
VT013	McNt	1.15(8)	200
VT013	McSr	1.7(1)	201
VT013	NtSr	1.6(1)	200

the e-transfered VDIF (for Mc, Nt and Sr) and Mark5b (for Ma) data which were then fringe fitted via HOPS Fourfit. The Fourfit output was then used to extract the interferometric phase information for all baselines over all scans for all four experiments, together with SNRs and fringe delay rates for each scan. DiFX output data were also transformed into FITS files and read into AIPS (Greisen et al. [8]) where they were independently fringe fitted with the AIPS task FRING. Visibility amplitude/phase tables were then extracted using the AIPS task UVPRT. The statistics on the interferometric phase scatter for each source separately (3-hour observing arcs) were then computed using the same method described in Krehlik et al. [10], namely the root-mean-square of the first difference in the interferoemtric phases. The Fourfit derived phases have a time sampling of 22 seconds and phase resolution of 4 deg, while the AIPS processed phases have a finer sampling of 1 second and 1 deg. The central 80% of each sub-band was used in the AIPS analysis, in order to remove the less sensitive regions of the stations' bandpass shapes near the edges of the sub-bands. The time scatter was computed using the formula:

$$\Delta\tau_{\mathrm{rms}} = \frac{\Delta\phi_{\mathrm{rms}}}{2\pi\nu_0}$$

where $\Delta\tau$ is the rms time scatter, $\Delta\phi_{\mathrm{rms}}$ is the rms phase noise and ν_0 is the central sky frequency in each sub-band. Preliminary results of VT010-VT013 VLBI experiments obtained by the Fourfit analysis are shown in Table 2. The Fourfit results are in good agreement with the AIPS ones and they clearly show that the tropospheric phase instabilities are dominating the rms time scatter: the

$\Delta\tau_{\rm rms}$ values span between 1.6 ps in VT013 in the best weather conditions (on baseline Nt-Sr) and 14 ps in VT012 in the worst weather conditions (on baseline Ma-Mc). The characterization of the different contributions to the rms phase noise is ongoing: clock fractional frequency differences and their uncertainties with respect to a reference clock will be evaluated as a function of phase delay derivates by taking into account the tropospheric, ionospheric, geometric, source structure, cable and electronic delay terms. The results of these analyses will be the object of a dedicated publication.

4. Conclusions and outlook

The Italian Quantum Backbone 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) obtained by round-trip phase noise cancellation.

The IQB optical fibre link was used to perform a geodetic VLBI experiment in which the ASI-Centre for Space Geodesy Matera 20m antenna and the INAF-IRA Medicina 32m antenna received the *same* remote frequency reference from INRiM (Torino). The Matera clock drift with respect to Medicina (used as a reference) was found to be consistent with zero to within 10^{-14} (s/s) in the geodetic analysis. This demostrates that a common-clock architecture can function in VLBI observations.

RMS stastistics on the interferometric phase noise was tested in clock timing experiments utilizing the VLBI technique.

For the first time on 13 Feb 2021 *all* four Italian antennas took part in a VLBI experiment. Medicina and Matera received their frequency reference remotely from INRiM (Torino). Even if the phase noise statistics were completely dominated by tropospheric phase instabilities on the Ma-Mc baseline, this experiment opens a new possibity for clock fractional frequency comparison and testing in a common-clock architecture.

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;
- characterization of the different contributions (troposphere, ionosphere, source structure, cable, antenna deformations and clock) to the interferometric phase scatter in VLBI clock timing experiments with and without common-clock set-up
- usage of interplanetary space probe tones and the ΔDOR (Differential One-way Ranging) technique to compare clocks at two receiving radio stations;
- usage of the IQB link for future VLBI timing experiments between the Italian INRiM and Korean KRISS optical clocks

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