Supplemental Document

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Common-clock Very Long Baseline Interferometry using a coherent optical fiber link: supplementary material

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This document provides supplementary information to the article "Common-clock Very Long Baseline Interferometry using a coherent optical fiber link". Here, we provide details on the radio telescopes involved in this experiment and on the realised optical fiber backbone and terminal stations. We also provide details on the measurement procedures and on the analysis of the common-clock VLBI experiment described in the main text.

1. THE MEDICINA AND MATERA RADIO TELESCOPES

The Medicina Radio Observatory hosts a 32-m telescope, equipped with L, S/X, C, K, band receivers covering the 1.35 GHz - 26 GHz spectrum. This is mainly used for radioastronomy observations both in single-dish and VLBI configuration, but is available for geodetic VLBI as well. The observatory also hosts two GPS receivers, one belonging to the Italian Space Agency and the other to the University of Bologna, and is part of the European VLBI Network (EVN) and the International VLBI Service for Geodesy and Astrometry (IVS).

The Space Geodesy Centre in Matera is instead focused on geodetic VLBI and, with a Satellite Laser Ranging apparatus, provides laser telemetry of geodetic satellites, geodetic positioning based on satellite techniques and orbital tracking. It is part of the IVS and of the International Laser Ranging Service. The main geodetic antenna is a 20-m dish with a Cassegrain configuration equipped with S and X band receivers covering the 2210 MHz-2450 MHz and 8180 MHz-8980 MHz spectrum respectively.

2. FIBER BACKBONE ARCHITECTURE

We use a dedicated fiber where the metrological signal travels on the dense-wavelength-division-multiplexed (DWDM) channel 44 of the International Telecommunication Union (ITU) grid. On the same fiber, a data link is established on ITU channels 28 and 29 for remotely controlling our equipment. On the 40 km span between the town of Bologna and Medicina Radio Observatory, the ITU channel 21 is used for VLBI data transmission. The average loss of our fiber is 0.27 dB/km. It rises up to 0.36 dB/km in metropolitan areas, and up to 1 dB on the Bologna-Medicina span, partly due to the presence of optical Add/Drop Multiplexers. 30 bidirectional Erbium-doped Fiber Amplifiers (EDFAs) are installed every $\sim$60 km. Each of them is remotely-controlled and accessible from both sides of the backbone to provide the required redundancy against fiber cuts.

3. OPTICAL FREQUENCY DISSEMINATION

The disseminated frequency reference signal is an ultrastable optical carrier at 1542.14 nm, whose linewidth is narrowed down to few hertz by stabilization to a high-finesse Fabry-Perot cavity [1]. Its frequency is referenced to a H-maser using an optical comb. To do so, the comb's repetition rate is stabilised to the H-maser, which in turns fixes the frequency of all combs teeth. The beatnote between the ultrastable laser signal and the closest comb tooth is measured on a dead-time free frequency counter and actively stabilised by applying a proper correction to an acousto-optic frequency shifter. The stabilisation is performed with a digital algorithm which rejects the H-maser noise at Fourier frequencies >30 mHz, where it is higher than that of the ultrastable optical carrier, and takes advantage of the superior stability of the H-maser at lower Fourier frequencies. As a result, the disseminated optical signal has a short-term instability of $\sim 10^{-14}$, still partly affected by the H-maser noise, while its long term stability copies that of the H-maser ($6 \times 10^{-14}/\sqrt{\tau}$, for averaging times $\tau > 10$ s). The resulting signal is sent to the remote terminals through phase-stabilised optical fibers.The phase noise introduced by the optical fiber is detected with an interferometric scheme, where the round-trip signal is heterodyned with that of a short reference arm (see Fig. 1 in the main document), and is corrected by a phase-locked loop which acts on an acousto-optic frequency shifter. This scheme is independently adopted for each of the four connecting segments. At the telescope sites, light is coherently down-converted to the RF domain by using local optical combs. To do so, we detect the beatnote between the ultrastable optical signal and the closest comb's tooth. This signal is used to stabilise the comb's repetition rate. As a result, the repetition rate and all combs teeth preserve the relative stability of the optical signal. An harmonic of the repetition rate is detected on a low-noise photodiode and electronically processed to produce a coherent 100 MHz signal which feeds the VLBI synthesis chain.

A detailed sketch of a typical terminal station is shown in Fig. S1. Incoming light from previous segment passes through a fixed acousto-optic frequency shifter (AOf), then it is reflected by a Faraday mirror to allow fiber noise detection at the previous terminal. Only radiation which actually reaches the terminal is frequency-shifted, allowing its spectral separation from spurious backreflections occurring along the link. The incoming light is used as a reference to phase-lock a diode laser (servo-loop S1). The beatnote on photodiode PD1 with the local light needs to be detected with at least 50 dB signal-to-noise ratio (SNR) in a bandwidth of 100 kHz to avoid cycles slips. Therefore, polarization of incoming light is automatically adjusted to maximise the beatnote power if it drops below a certain threshold. The servo loop (P) is based on a digital optimisation algorithm which acts on an electro-optic controller. This feedback loop has a recovery time of few tens of ms and is still subject to occasional failures in case of fast polarization flips, due e. g. to maintenance activity along the fiber. This is the most frequent reason for laser unlocks. The beatnote frequency is measured by a multi-channel synchronous counter with a gate time of 1 s. Cycles slips are identified as deviations from the nominal lock frequency higher than 0.1 Hz. Light from the local laser is then partly routed to photodiode PD2 by a Faraday mirror and used as a phase-reference. The remainder is injected into the next fiber segment, and return light is beaten with the local reference beam. Two voltage-controlled oscillators are phase-locked (S2 and S3) to the beatnote on a bandwidth of about 100 kHz, which allows efficient rejection of wideband noise introduced by the electronics and EDFAs. At least 30 dB SNR in this bandwidth are required to ensure cycle-slips-free tracking of the beatnote. The output of one oscillator is phase-compared to a stable RF reference to detect the link phase noise. This is then cancelled by a phase-locked loop (S4) acting on the acusto-optic frequency shifter (AOa). The two voltage-controlled oscillators signals are sent to the phase/frequency counter. Any discrepancy in the measured frequencies higher than 0.1 Hz identifies the occurrence of a cycle slip on the fiber phase-stabilization loop. Data are timestamped and can be removed off-line. In Firenze and Pozzuoli, a GPS-disciplined Rb oscillator is used as a reference for all the equipment. In Medicina and Matera, the frequency reference is directly derived from the comb-synthesized RF signal. Slight variations in the gain of cascaded optical amplifiers build up along the link and can cause up to 10 dB power drops on the beatnote detected by PD2. This is kept stable within 1 dB by automated equalization of the EDFAs gain. Each terminal is equipped with autonomous operation and remote-control capabilities for fault monitoring and recovery.

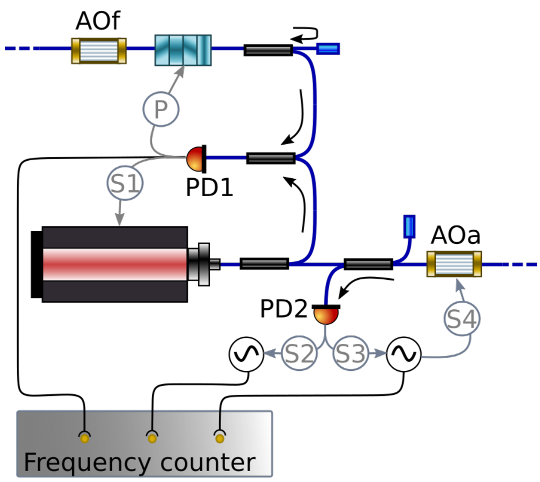

Fig. S1. Sketch of intermediate fiber nodes. AOf: fixed acousto-optic frequency shifter at the end of the previous segment; AOa: acousto-optic frequency shifter used to compensate the noise of the following segment. PD1 and PD2: photodiodes for phase-locking the local laser to the incoming light and to detect and compensate the fiber noise. Circled S indicate servo loops: S1: phase-locks the local laser to incoming light; S2 and S3: voltage-controlled oscillators track the beatnote between local and return light; S4: stabilises optical path to following terminal. P: a digital control optimizes beatnote power using an electro-optic polarization controller.

4. OFF-LINE COMPARISON OF LOCAL HYDROGEN MASERS VERSUS THE FIBER-DELIVERED SIGNAL AT TELESCOPES SITES

At each telescope, the fiber-delivered signal is down-converted to 100 MHz using an optical comb and continuously phase-compared to the local hydrogen maser. Phase measurements are obtained with a dead-time-free frequency counter operated

in the averaging mode with 1 s gate time and equivalent measurement bandwidth of 0.5 Hz. A common-mode local oscillator down-converts the 100 MHz RF signals generated by the local hydrogen maser and by the comb. This enhances the counter resolution by two orders of magnitude, to the $2 \times 10^{-14}\ /(\tau/\mathrm{s})$ level, τ being the measurement time.
During the uptime period, the average number of cycles slips on the final hydrogen maser comparison was less than one per hour. This accounts for failures in the phase-lock loops of the INRIM ultra-stable laser to the hydrogen maser, cancellation of the fiber noise on the four segments, regeneration lasers and optical combs. All failures were locally detected at each link terminal, and their occurrence showed temporal coincidence with outliers in the hydrogen maser comparisons at the telescopes sites. Such points were removed from the final measurement. All remaining data chunks with duration of at least 1000 s were averaged to a single point.

5. DESIGN AND ANALYSIS OF THE COMMON-CLOCK VLBI EXPERIMENT

The common-clock experiment was designed as a standard 24-h geodetic VLBI run. A network of four stations was set up, involving besides Matera and Medicina also Yebes and Onsala antennas. A list of 120 radio sources from the ICRF2 catalogue were chosen by the VLBI scheduler SKED according to the following set criteria: X-band SNR $>$ 15, S-band SNR $>$ 25, minimum scan length of 120 s. All the other major and minor parameter settings in SKED were left to default. The scan sequence was computed by the autosked task in such a way to optimize the sky coverage and the source signal intensity for each baseline and scan in the specific network configuration (Medicina, Matera, Yebes, Onsala) of our session. For the aim of this paper, we focussed on the Matera-Medicina baseline, only.
Data from each telescope were correlated by the Medicina Radio Observatory staff with the local DiFX correlator [2] and fringe fitted using the Haystack Observatory Post-processing Software *fourfit* in order to retrieve relative delays between the arrival time of the sky signal to each telescope. The geodetic tools CALC/SOLVE and νSolve were used to analyze the correlated data. The standard geodetic analysis consists in a multiple parameter Least Squares fit of the observation delay for each baseline. Modelled effects included Earth's orientation, station coordinates, ionospheric and tropospheric delays and clocks' phase difference. The sources' coordinates were instead considered as fixed parameters. Ionospheric and tropospheric delays were calibrated following routine approaches: the former by performing observations at different frequencies, the latter by combining measurements at different elevation angles and corresponding zenith delays modelled by mapping functions. The clocks' phase difference was modelled by a second order polinomial, whose initial parameters estimation was derived by calibration versus GPS time. In such a kind of geodetic experiments, the sources are all bright unresolved objects, whose internal structure and associated phase shifts can be neglected. Adjustment of parameters provides a global solution which takes in consideration parameters correlation as well.

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