A Coherent Optical Fiber Link for Very Long Baseline Interferometry

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Abstract: We realize a phase-stabilised optical fiber backbone that connects the Italian National Metrology Institute with two radio telescopes over a 600 km baseline. This allows referencing of Very Long Baseline Interferometry (VLBI) facilities with the best atomic frequency standards available today and the implementation of a common-clock architecture, which we are now using to assess VLBI ultimate performances.

1. Introduction

Very Long Baseline Interferometry (VLBI) is among the most powerful techniques in radio astronomy and geodesy. The high quality images of the Universe provided by VLBI are crucial to the evolution of cosmologic theories, enabling the study of active galactic nuclei, black holes and gravitational waves [1]. VLBI is also a key technique in Earth sciences, providing few-millimeter precision positioning within the International Terrestrial Reference Frame (ITRF) and allowing the study of global phenomena and tectonic movements. VLBI is based on the observation of radio sources in the sky with an array of telescopes spread over the Earth. By correlating the arrival times of the sky signal to the various telescopes, it is possible to reconstruct the source position and its shape. On the other hand, when the coordinates of reference sources in the International Celestial Reference Frame (ICRF) are fixed, the precise position of telescopes on Earth can be derived.

Low-noise sampling of the sky signal phase in the radio spectrum is achieved using hydrogen masers. However, VLBI at millimeter wavelengths may benefit from clocks with higher stability and accuracy [2]. Such devices are available at Metrological Institutes and can be distributed without degradation using phase-stabilised optical fiber links [3]. Fiber-based dissemination of a RF frequency reference to radio telescope sites has already been realized in a local area at the Atacama Large Millimeter Array [4], and over longer distances in Australia [5], Poland [6], Sweden [7] and Italy [8].

Here, we describe the dissemination of an optical frequency reference from the National Metrology Institute to two radio telescopes located at a distance of over 600 km in Italy. Our facility is based on the dissemination of an ultra-stable optical carrier, traceable to the Italian primary frequency standard and optical clocks over a phase-stabilised, 1700-km long optical fiber link. In spite of the higher complexity of the setup, the dissemination of a high-spectral purity optical carrier allows ultimate stability and accuracy well beyond those allowed by RF dissemination. This is the only way to afford optical frequency standards dissemination and the implementation of a network in which telescopes share the same clock.

The realized infrastructure is successfully used to perform a geodetic VLBI campaigns in which the two telescopes share the same clock, delivered from the Metrology Institute. On one side, this is a seminal work towards the dissemination of more accurate and stable clocks than hydrogen masers, which could be beneficial to address specific tasks. On the other side, the dissemination of the same clock to multiple telescopes allows deeper investigation of some of VLBI ultimate limitations.

2. Optical Frequency Dissemination

The present facility builds upon a pre-existing 535-km long fiber link that we realized between the Italian National Metrology Institute (INRIM) in Turin and the VLBI site maintained by the Italian Institute of Astrophysics in Medicina [8]. This connection has now been extended to the Space Geodesy Centre maintained by the Italian Space Agency in Matera, for a total length of 1739 km optical fiber.

The dissemination chain is based on a narrow-linewidth laser at 1542 nm, whose frequency is referenced to a hydrogen maser traceable to the Italian primary frequency standard and to the Universal Coordinated Time (UTC) at INRIM. Ultrastable light is sent to the VLBI sites using the standard telecom network. Optical length fluctuations of the fiber, due to temperature and acoustic environmental noise, are actively stabilised via the Doppler noise cancellation technique, so that the high accuracy and stability of the optical carrier can be transferred with no degradation at the telescope sites. The link is composed of four cascaded segments, each of them is independently phase-stabilised. The equipment is remotely controlled and capable of autonomous operation. At the telescopes sites, an optical frequency comb coherently transfers the accuracy and spectral purity of the incoming signal to the microwave domain.

During the month of May, 2019, we collected over 200 h of measurement time in which we compared local masers in Turin, Medicina Radio Observatory and Matera Space Geodesy Centre. Results indicate a residual contribution of the optical link noise at acoustic frequencies, while on the rest of the Fourier spectrum the measurement is limited by local hydrogen masers. The instability of the comparisons in Medicina and Matera are at the level of $4\cdot10^{-14}/\tau$ and $1\cdot10^{-13}/\tau$ respectively, τ being the measurement time in seconds. This is consistent with the local masers specifications and indicates that optical fiber dissemination does not deteriorate the instability of the delivered clock. On the long term, calibration of the masers frequencies performed via the Global Positioning System confirms results obtained with optical fiber dissemination, within the limitation of the satellite technique ($6\cdot10^{-16}$ between Turin and Medicina, and $2\cdot10^{-15}$ between Turin and Matera).

The realised infrastructure was used in a 24-h VLBI geodetic campaign in which the two Italian telescopes shared the same clock signal delivered from INRIM. The observation schedule was designed on purpose as a test of the infrastructure. The quality of the delivered signal at the telescope sites enabled successful correlation of the data and analysis to retrieve geodetic parameters of interest, following the routine procedure in use in the VLBI community.

3. Conclusion

We realised an infrastructure for optical frequency dissemination from a National Metrology Institute to two radio telescopes, separated by a baseline of over 600 km. This infrastructure was used to calibrate local hydrogen masers at the two VLBI sites and allowed the realization of standard geodetic VLBI campaign in which the two telescopes shared the same clock. Extended test are now planned on the same infrastructure to further investigate achievable performances.

Our experiments demonstrate that optical dissemination has the required reliability to replace local hydrogen masers at VLBI sites. On one hand, the availability of frequency references with higher accuracy and stability can be beneficial for specific VLBI tasks that require superior clock performances, such as the analysis of long-term pulsars timing instability or geodetic positioning at the millimetre-level. On the other hand, we report on the successful realization of a common-clock VLBI experiment, which paves the way for a deeper investigation of VLBI ultimate performances.

4. References

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