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# QUASAR: Achieving Picosecond-Scale Time Synchronization in Distributed Cherenkov and Optical Telescopes with White Rabbit

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High-precision time synchronization in astronomy is applicable almost exclusively for applications like Very Long Baseline Interferometry (VLBI) with radio telescopes and for Imaging Atmospheric Cherenkov Telescopes (IACTs) observing extensive air showers from gamma-rays. IACTs require nanosecond-scale synchronization for real-time event tagging and stereo triggering, enabling coincidence detection across multiple telescopes. Even more stringent timing is necessary for intensity interferometry in the visible band, where fluctuations of light intensity from a source are sampled at multiple telescopes and correlated to reveal a source-size-dependent correlation peak, providing unique insights into the structure of astronomical objects.

We explore the integration of White Rabbit (WR) – a fiber-based Ethernet timing technology developed at CERN, into the clock distribution network for intensity interferometry on optical telescopes separated by kilometer-scale baselines. Built on top of the Precision Time Protocol (PTP), WR offers sub-nanosecond synchronization with deterministic latency. We demonstrate that a WR network can provide sufficient synchronization accuracy over kilometer-scale distances while efficiently enabling time sharing between optical and IACT observatories for joint intensity interferometry observations.

We investigate the effects of fiber temperature fluctuations and chromatic dispersion, which can impact long-distance timing stability during observations. Through lab experimental validation, we achieve 5 ps RMS time synchronization over a 5 km fiber link, and about 8 ps RMS for 10 km and 50 km links, demonstrating the feasibility of WR for high-precision astronomical applications like intensity interferometry.

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## 1. Introduction

Intensity interferometry (II), originally proposed and developed by Robert Hanbury Brown and Richard Q. Twiss in the 1950s [1], has recently gained renewed interest thanks to the construction of large arrays of Cherenkov telescopes. These instruments are naturally well suited for II: they feature fast ∼1,GHz sampling cameras and mirrors with large collecting areas (for example, the CTAO LST-1 telescope has a 23,m diameter mirror), enabling stellar observations and radius estimates. Cherenkov telescopes already employ nanosecond-scale clock synchronization for event tagging and stereo triggering: timestamps from all telescopes are sent to a central trigger system, which permits recording of only coincident events while discarding the rest. This approach enhances sensitivity by improving gamma–hadron separation. With a coincidence window of hundreds of nanoseconds, sub-nanosecond synchronization is sufficient for Cherenkov applications. By contrast, intensity interferometry imposes stricter timing requirements: light intensity signals must be sampled simultaneously at multiple telescopes and then correlated to reveal a source-size-dependent signature. Here, time synchronization must be at least comparable to the intrinsic jitter of the photon detectors (in the case of photon counting) or to the sampling period (in the case of ADC-based intensity measurements).

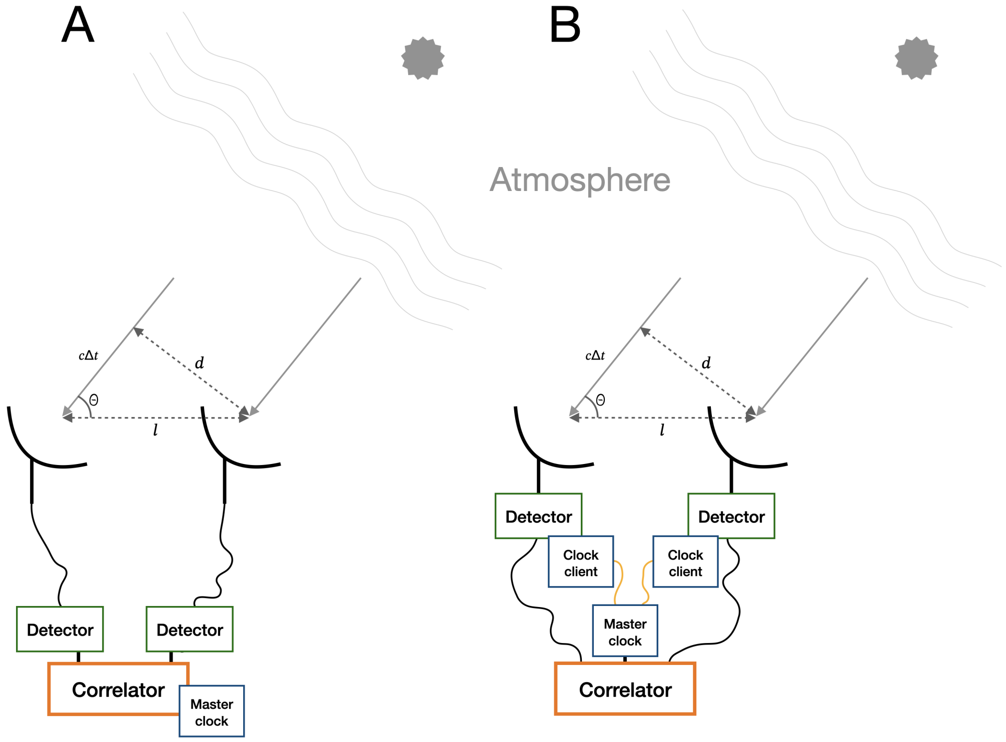

**Figure 1:** Intensity-interferometry typical realization schemes. Left panel, A - light intensity signal delivered to a common acquisition/correlator hardware. Right panel, B - Telescopes detect light intensity independently, but with their clocks synchronized to a central master clock. The telescopes are separated by the distance $l$, which for observations of a source with elevation $\Theta$ corresponds to apparent baseline $d$. Depending on the direction of observations the apparent delay between two telescopes is $\Delta t$.

In general, there are two main approaches to implementing the II technique on distributed system of telescopes:

**(A) Direct signal transport.** The simplest method is to avoid explicit time synchronization by performing transmission of the information on the source's intensity variation as electrical or as optical signal via cables or fibers directly to the acquisition hardware. Correlator in such scheme may be located near the acquisition hardware. In this case, the internal clock of the acquisition hardware ensures synchronization of the ADC pipelines for all the inputs. This approach is feasible when telescopes are located close together (within a few hundred meters) and signals are sampled at GHz rates, such that cable length variations during the night because of temperature change are negligible (Fig. 1, A). This method is currently employed at MAGIC/LST-1 [2] and VERITAS.

**(B) Independent detection with distributed clock.** Alternatively, the light can be detected locally at each telescope independently, with only a precise reference clock distributed to synchronize the readout systems (Fig. 1, B). This approach allows telescopes to be separated by distances of several to tens of kilometers, enabling much higher angular resolution which scales with distance between the telescopes. The achievable resolution scales with baseline ($d$) and observed wavelength ($\lambda$) as $\alpha \sim \lambda/d$. Detection of light in this case can be done using ADC sampling hardware, or using single-photon detectors (so-called photon counting approach), e.g. by using single-photon avalanche diode (SPAD) detectors [3]. Within QUASAR project we use such SPAD detectors to perform HBT measurements in the lab [4] to simulate the effect on the telescopes for future observations of accretion disks [5].

The QUASAR project is designed around the second technique. In this scheme, light collected by each telescope is dispersed by a spectrometer onto an array of SPAD detectors, with each SPAD receiving a narrow spectral band (0.01–0.1 nm). Off-site correlator software, in this scheme, will then process photon timestamps from each detector pixel, enabling inter-telescope correlations within each spectral band. Combining correlation peaks from multiple bands allows to enhance the SNR, which scales as a square root of number of channels. The scientific goal of QUASAR is to resolve the accretion disks of cataclysmic variables and active galactic nuclei (AGNs), whose angular sizes are on the order of a few microarcseconds [5, 6]. Achieving such resolution requires very long baselines, which are only feasible with the second approach (Fig. 1, B) where precise clock is distributed to each telescope. For such clock distribution across telescopes separated by kilometer-scale baselines, QUASAR will employ White Rabbit, a fiber-based Ethernet timing technology developed at CERN [7]. WR, built on top of the well-established and tested Precision Time Protocol (PTP), which is capable of microsecond synchronization jitters. By-design the WR protocol already provides sub-nanosecond synchronization surpassing the accuracy of PTP. With the addition of low-jitter hardware modifications and careful selection of transceivers and optical components, WR's performance can be further enhanced reaching tens of picoseconds over vast range of separations between the master clock and its clients. Since QUASAR relies on arrays of single-photon avalanche diode detectors with intrinsic jitter of about 10 ps RMS (rate dependent) [3], the synchronization system must achieve comparable precision in order to fully exploit the capabilities of these fast detectors.

## 2. White Rabbit setup

White Rabbit nodes (typically consisting of a single master clock and few clients, which can act as master clocks for the next tier of clients) allows synchronization of clocks on two independent sites located kilometers apart but connected with a single-mode fiber. Use of multi-mode fiber is not possible because of higher attenuation and light pulse dispersion due to numerous modes of light. As both WR master clock and client, we used two Seven WRS-3/18 White Rabbit switches with low jitter modification applied following WR OHL manual [*]. These switches are equivalent to modern Safran White Rabbit Switch - Low Jitter ones. Switches were connected together with 5, 10, and 50km spools of G.652.A single-mode fiber (see Fig. 2). For initial 5km testing the BiDi 1Gbps SFP transceiver operating at 1390 and 1490nm was used. Later tests with 10km and 50km fibers were performed with DWDM transceivers operating at wavelengths just 1.8 nm apart. In this case additional DWDM muxers were used to adapt duplex SFP modules to a bidirectional light propagation within a single fiber strand.

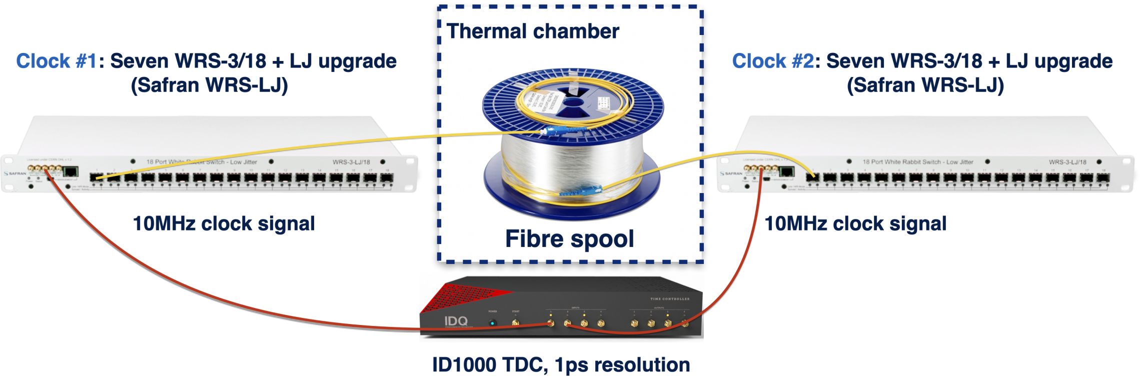

**Figure 2:** WR testing scheme. Two WR switches are connected with a spool of fibre in a thermal chamber. The 10MHz clock signals from each switch are sampled and correlated in real-time by a 1ps-capable Time-to-Digital converter.

The output 10 MHz signals from both master and clients were correlated using ID Quantique ID1000 TDC/correlator. By studying the drift of the correlation peak center, and its width, we can estimate how close are the two clocks and how accurate is the synchronization over long period of time when fiber length is affected by the temperature change. We investigate key challenges, including the effects of fiber temperature fluctuations and dispersion in the fiber, which can impact long-distance timing stability. We built a setup of two WR nodes separated by a spool of fiber of 5, 10 and 50 km (Fig. 2) placed in a thermal chamber. One of the challenges of such WR setup is the characterization of the clock synchronization jitter created during fiber elongation because of the temperature. To test that the temperature of the thermal chamber is being changed to simulate effects of ambient temperature change on site affecting the spools of fiber.

Temperature-induced fiber elongation is driving phase drift between the two WR nodes. The WR protocol actively measures the length of the fiber and counteracts this change by constantly adjusting the delay between the two nodes. Bidirectional communication employed by WR protocol in

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[*] https://ohwr.org/projects/wrs-low-jitter/

a single fiber strand is typically performed on different wavelengths (1310 nm & 1490 nm), resulting in different light dispersions depending on temperature. This asymmetry in light propagating on different wavelengths needs to be calibrated preemptively for a specific fiber used [7].

In our tests, by using WR hardware compatible with both IACTs and II acquisition hardware, we conclude that such WR networks can be efficiently shared between optical and IACT observatories for joint intensity interferometry observations.

## 3. Thermal testing and results

Initial testing was performed using bidirectional transceiver operating at 1310nm and 1490nm. It was found that the clock offset between the two WR nodes connected with 5km fibre was dependent on the temperature. The drift was about 25ps when the temperature was changed from 20°C to 21.5°C with a gradient of 0.3°C/h. Correction of the offset using FPGA temperature data and internal measurements of the corrected round trip time (CRTT) value allowed to remove the drift and obtain a synchronization accuracy of $5.006 \pm 0.001$ ps. Such corrections in case of intensity interferometry observations can be applied to photon arrival timestamps in off-line mode before correlation or data storage.

Later tests were performed using a dense wavelength-division multiplexing (DWDM) transceiver operating at 1550.12nm and 1548.51nm (1.8 nm separation between RX and TX optical signals). Unfortunately, bidirectional DWDM transceivers are not commercially available, so we had to route two fibers from each transceiver into a DWDM optical add-drop multiplexer (OADM) to have two optical signals delivered within a single strand of single-mode fiber to eliminate any possible length differences for TX and RX signals. Such a setup was used to perform the following tests:

- 10 km fiber spool, temperature between 20°C to 25°C with a gradient of 0.3°C/h. Observed clock synchronization offset jitter was $9.9 \pm 0.2$ ps.
- 50 km fiber spool, temperature between 20°C to 25°C with a gradient of 0.2°C/h (Fig. 3). Observed clock synchronization offset jitter was $7.919 \pm 0.011$ ps (Fig. 4).

Observed clock offset for the fiber spools of 10 km and 50 km (Fig. 3 and Fig. 4) for temperature gradients of 0.3°C/h and 0.2°C/h respectively, confirms that temperature change is the biggest challenge for the WR protocol, which has no problem maintaining 5 ps synchronization jitter when temperature is not changing (less than 0.05°C/h within 0.5°C range), but offset increases the higher is the gradient. Effects of the temperature are thus secondary, the biggest effect on the accuracy of the sync has the temperature change gradient. Since fiber is usually buried in the ground, we don't expect temperature variations more than 0.2°C/h, so the observed jitter satisfies requirements (time synchronization jitter <10 ps) we set for the interferometry setup used for QUASAR project.

## 4. Conclusions

The White Rabbit (WR) protocol achieves time synchronization by distributing a common clock over single-mode fiber links between two WR nodes, where one node serves as the master and the other as the client. The protocol continuously compensates for propagation delay variations

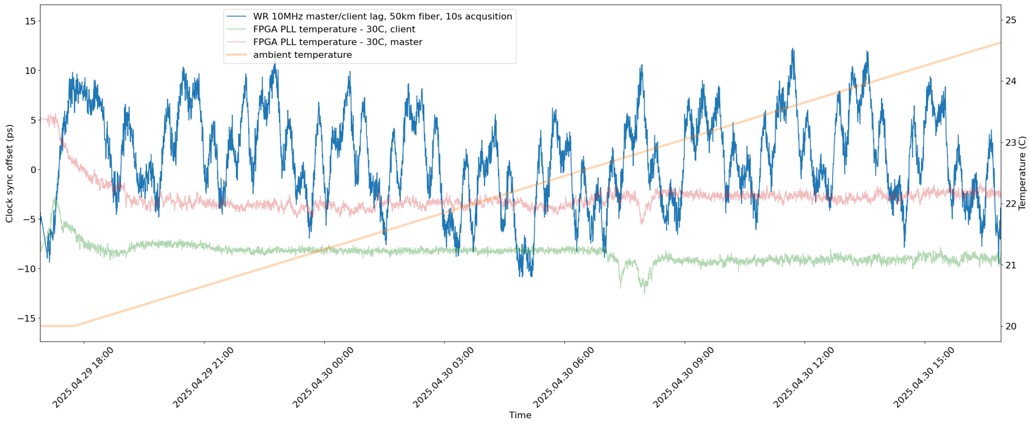

**Figure 3:** Blue: WR clock offset between two WR nodes connected with 50 km fiber. Thermal chamber temperature was changed between 20°C to 25°C with a gradient of 0.2°C/h (orange). FPGA internal temperature for master clock (red) and the client clock (green).

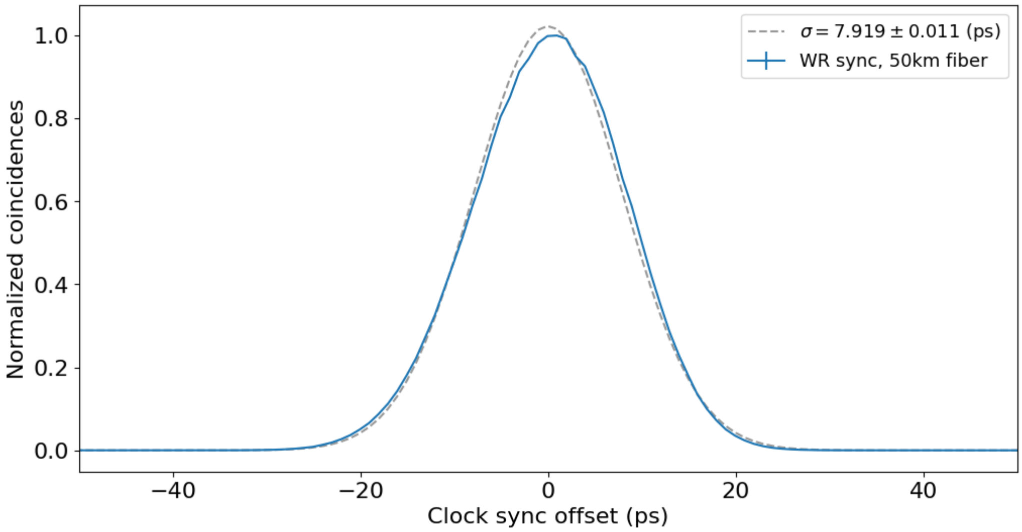

**Figure 4:** Block offset distribution between two WR nodes obtained for offset on Fig. 3.

caused by fiber elongation as ambient temperature changes, thereby minimizing clock offset between the two nodes. To evaluate its performance under conditions relevant for astronomical observational sites, we carried out a series of laboratory tests using a thermal chamber and fiber spools up to 50 km in length. These tests demonstrated that WR hardware can maintain a relative synchronization accuracy of better than 10 ps RMS for all the considered cases, even under temperature variations exceeding those on observing sites.

In particular, a laboratory setup with two WR nodes connected through fiber up to 50 km placed in a thermal chamber environment was used to emulate ther setup and conditions expected at the Paranal site, where telescopes are separated by similar distances. Under an ambient temperature gradient of 0.2°C/h, we measured an offset jitter of $7.92 \pm 0.01$ ps, confirming the suitability of WR for synchronizing multi-telescope intensity interferometry arrays using DWDM transceivers.

These results indicate that WR not only provides the sub-nanosecond synchronization needed for Cherenkov telescopes but also achieves the stricter picosecond-level timing required for photon-correlation measurements in optical intensity interferometry.

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