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Time Synchronization with White Rabbit - Experience from Tunka-HiSCORE

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Upcoming Gamma-Ray and Cosmic-Ray experiments require relative time calibration of all detector components with (sub-)nanosecond precision. White Rabbit, a new technology for time and frequency transfer, can be applied here.

We describe a White Rabbit (WR) based design for trigger time-stamping, originally developed for Tunka-HiSCORE - a timing array for Gamma-Ray astronomy now under construction. Sub-nsec synchronization results from cosmic ray shower data, in-situ artifical light source calibrations and laboratory tests taken over several years are presented.

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1. Introduction

We describe a modern timing system for astroparticle physics experiments, customized as a prototype for the Tunka-HiSCORE array. Tunka-HiSCORE is a large area wide angle detector for gamma rays from 20 TeV to few PeV, and cosmic rays above few PeV, under construction in the Tunka Valley, Siberia [1]. It is a non-imaging atmospheric Cherenkov light-front sampling array, covering an area of up to 100 km^2.

For precision reconstruction of the atmospheric air shower direction, Cherenkov light arrival times at all detector stations have to be measured with (sub-) nsec relative timing precision. To reach this we used - for the first time in a large astroparticle physics experiment - the new White Rabbit technolgy for precision time and frequency transfer [3]; thus avoiding the substantial design and construction effort for a custom-made solution.

This paper summarizes the laboratory test and long-term field experience, gained with the White Rabbit setups for the HiSCORE prototype timing system from 2012-2015. Section 2 briefly introduces the White Rabbit technology; section 3 describes the various setups used at HiSCORE, their methodics and physics results. We conclude, that White Rabbit fulfills all requirements for precision timing in next generation large experiments like CTA [4]. White Rabbit has the potential to become a standard technology in this field (“time-synchronization out of the box”).

2. Clock distribution and time-stamping with White Rabbit

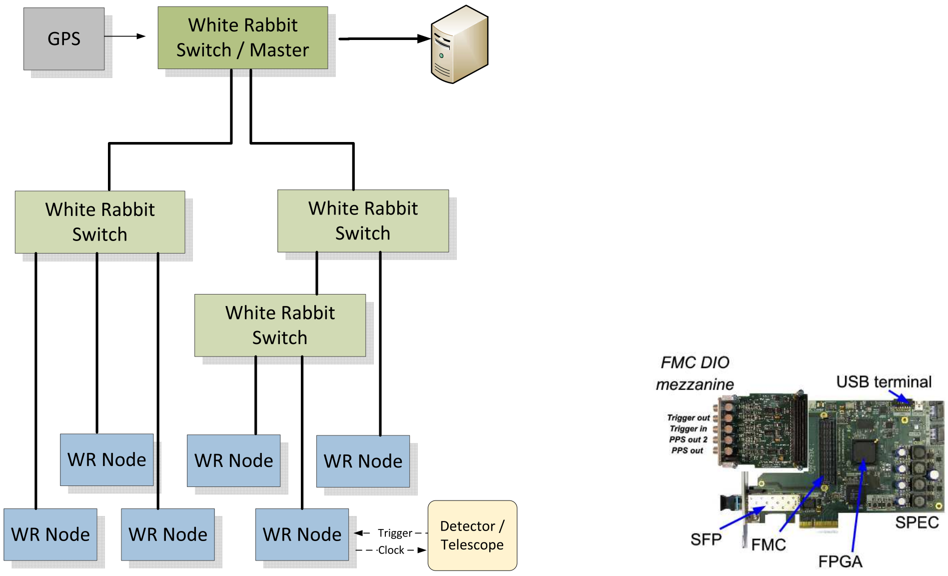
Figure 1(a) gives a typical White Rabbit (WR) setup [3, 5]. The baseline ingredients are (1) WR-Switches (WRS) and (2) WR-Nodes, connected by standard Gigabit Ethernet fibers. The WRS are arranged like in a normal ethernet-network; the central WRS (Grand Master Switch) acts as the time source (e.g. connected to a GPS antenna).

White Rabbit is build on Gigabit Ethernet (1000base-BX10) and takes advantage of the Ethernet standards SyncE and Precision Time Protocol. It offers sub-ns precision, with excellent clock phase stability. It utilizes one fiber for each WR-node for both synchronization and user data, and compensates dynamically for clock drifts due to e.g. environmental influences (temperature).

The WR-node allows to interface the user system (eg. the DAQ of a detector station or a telescope) to the WR-time system: by either time-stamping signals *from* the detector and/or by supplying clock-information (like PPS or periodic clock signals) *to* the detector, as shown for the lower WR-node in fig.1(a) by “trigger” and “clock” signals. As the WR-node device we use for this work the “Simple PCIe FMC carrier” (SPEC), shown in fig.1(b) - a reliable workhorse of the WR-community [6]. It has a Spartan-6 FPGA (with the WR PTP Core, optional custom firmware and software) and can accommodate FMC-mezzanine cards. We use the FMC-DIO5Ch, a 5 channel digital I/O card, for analog/digital trigger input, control signals, and PPS/MHz clock output (e.g. for clock performance tests).

We summarize the main arguments to decide for White Rabbit:

- Clock-driven architecture: precision clocks are localized inside the front-end stations (nodes)
- Time stamping at front-end enables complex digital trigger schemes (next neighbor or array)
- Availability and commercial support for all main components
- Open source approach (firmware/software), good documentation and community support



(a) (b)

Figure 1: *(a)* The White Rabbit network, made up of WR-switches (Grand Master and normal WRS) and of WR-nodes. The WR-nodes can deliver clock-signals *to*, and/or extract trigger time-stamps *from* the associated detectors, as symbolized for the lower-right WR-node (see text). *(b)* Example of a WR-node: The SPEC card, the WR-node used for this work. The precision time, kept on the Spartan-6 FPGA is synchronized through the fiber cable (SFP) to the central WR-switch.

- Application interfacing can be reduced to simple, passive FMC mezzanines
- Design simplicity and flexibility for even large scale setups
- Detailed calibration procedures and online performance monitoring supported
- Cost- and time-efficiency compared to custom-made solutions (manpower and investment).

3. Experimental setups at HiSCORE

Tunka-HiSCORE [1, 2] is a non-imaging atmospheric Cherenkov light-front sampling array, build of many optical detector stations, located at typical distances of 100-200 m. The detector is under construction, it will cover an area of 1 km^2 in the inital, and up to 100 km^2 in the final phase.

3.1 The HiSCORE-SPEC and Laboratory tests

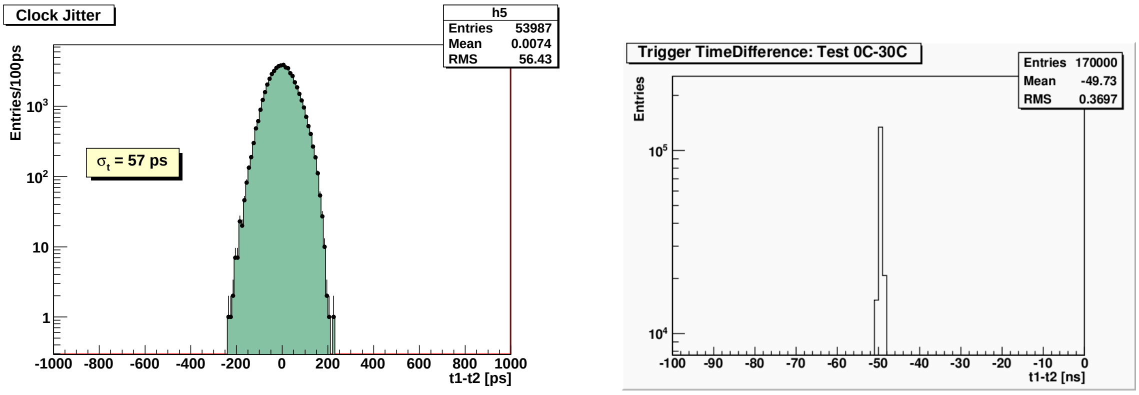
To apply White Rabbit for trigger time-stamping in HiSCORE, the standard performance of the SPEC-node has been extended. As presented in [5], the SPEC FPGA-design was modified and allows now to

(1) time stamp external digital trigger signals with ns-precision, and transfer the time-stamps and counter information via WR-fiber to the WR-master; or

(2) form the trigger decision on the WR-node by ns-sampling of an analog input signal, dicriminated against a comparator threshold; a trigger being generated after $\geq$ N consequtive ns-samples

being high (typically set to 9 ns). The trigger signal is time-stamped and transported, like for (1); additional DAQ-I/O signals are generated, see [5, 8].

Laboratory tests of a WR-system, with all components located closeby, offer the possibility to ultimatively check the clock performance (precision, resolution) for an ensemble of WR-nodes by comparing them directly against each other or to precisely defined reference signals (all brought by direct cable connections). With such “table-top” setups, including climate chamber temperature tests (fiber: -20...+40^{o}C; SPEC: 0...+30^{o}C) the basic timing precisison (clock jitter) was measured to be better than $\sigma_{WR} \sim 0.2$ ns [5]. A recent precision measurement with a HydraHarp-400 setup by PicoQuant [11] with picosecond event timing precision, shown in figure 2(a), gives a time jitter for two SPEC-nodes $\sigma_{WR} < 60$ ps. Also, the stability of the nsec-trigger-stamping is excellent. The result for the “jitter” of the digital time-stamps from two WR-SPECs is shown in fig.2(b) [5]. All measurements are in agreement with a clock precision better than 0.15 ns per WR-node for the full temperature range investigated.



(a) (b)

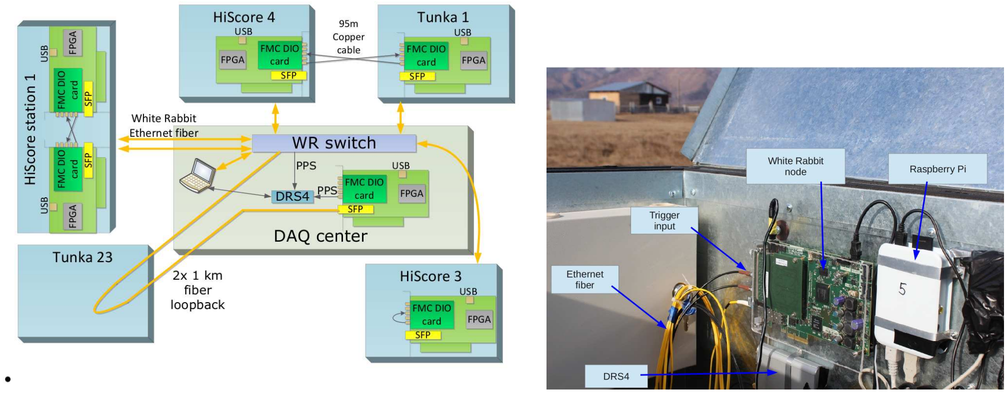
Figure 2: Sub-nsec precision WR-timing in laboratory tests. *(a)* Clock phase stability: Distribution of time difference between PPS clock-pulses from two WR-nodes (SPEC1/2), for a 15-hour run with a HydraHarp-400 setup. *(b)* Trigger stamping: Difference of digital trigger time-stamps (1 ns resolution) of the PPS pulses from SPEC1/2. SPEC2 and the 500 m fiber-coil were subjected to climate chamber temperature ramps between 0° and 30^o C. For details see [5] (time-offset $\neq$0 due to cabeling).

3.2 Setups at Tunka-HiSCORE

We report results from various HiSCORE setups, that operated between 2012 and 2015.

- **Baseline tests**

  With the HiSCORE-3 prototype array (winter season 2012/13) we deployed WR-nodes in each of the three stations - mainly for methodical tests, as shown in figure 3. Clock phase stability and trigger stamping performance between different stations, and for independent (redundant) WR-nodes located inside a single station was obtained. With a “table-top”-like setup in the data-center, the temperature dependent fiber-delay compensation was studied



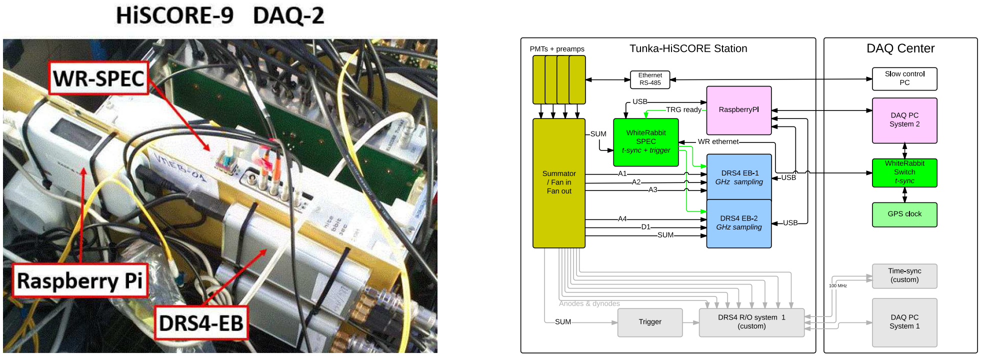
(a) (b)

Figure 3: *(a)* The complex HiSCORE WR field-setup, as operated in 2012/13 to evaluate time-synchronization and nsec-trigger time-stamping by monitoring WR-nodes [7]. *(b)* HiSCORE prototype station (2012/13) with DAQ and WR components.

(long fiber to Tunka-23), for details see [7, 10]. Note the "monitoring WR-node" as in Station-1 (fig. 3(a)) - an example of a possible verification configuration, when there is no external, independent source of precision time signals to be fed to the stations (WR-nodes).

- **Physics Setup: HiSCORE-9**

  The 9-station array HiSCORE-9, operating over the winter-season 2013/14, was the first astroparticle physics setup using WR for longterm operation (see sects. 3.3 and 3.4 below). Two independent DAQ-systems were build for HiS-9 [2, 8]. The WR-based DAQ-2 is outlined in fig.4; emphasis was on an end-to-end functional test of the WR time-synchronization functionality with a prototype DAQ.



(a) (b)

Figure 4: The HiSCORE-9 DAQ-2 system, with DRS4-Evaluation Board and White-Rabbit timing system. *(a)* Station setup (with DRS4-EB, WR-SPEC and MiniPC). *(b)* Schematics of the setup in Station and Center for DAQ-2 (DAQ-1 in grey). See also [8].

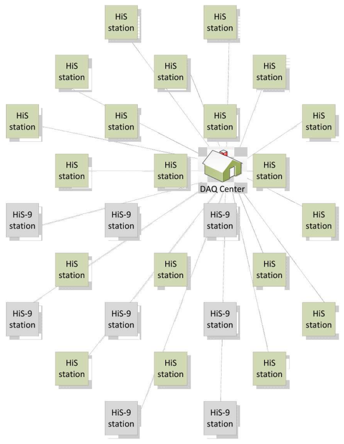


Figure 5: HiSCORE-28 array layout: 28 stations at 100 m spacing forming a super-cell structure, on a total area of 450 m × 600 m. The HiS-9 stations are indicated, as well as the DAQ-center.

Figure 6: A HiSCORE optical station, with four 8“ PMTs and Winston Cones, inclined by 25^o southwards.

- **Physics Setup: HiSCORE-28**

  HiSCORE-9 was upgraded in 2014 to the HiSCORE-28 array [2], see figs. 5 and 6. The HiS-28 DAQ combines the DAQ-1 timing system with the WR-SPECs, which time-stamp all DAQ-1 generated trigger; giving a long-term direct cross-verification of both clock systems. First results indicate very good precision of < 0.3 ns relative jitter (analysis in progress).

3.3 Calibration with a pointlike LED source

Dedicated LED-calibration runs were performed with a powerful LED located ∼100 m outside the HiSCORE-9 array, generating simultaneous light flashes in all stations (see fig.7) - to calibrate residual time offsets (PMTs, FE-electronics), and to verify the relative time calibration and precision of the DAQ-1/2 systems. For both, good agreement was found, as shown for WR in fig.8 for the fitted time-residuals; it gives an upper WR-precision limit of 0.45 ns [8].

3.4 Operation with Air Shower

A final verification of precise and stable timing operation is the full reconstruction of cosmic-ray air showers, registered in routine operation with HiS-9 for 2013/14 and HiS-28 (2014/15; in progress). Using the calibration from LED runs, reconstruction of the shower front direction and position is done for HiS-9 [2, 8]. Figure 9 displays a reconstructed shower event (based on WR-timing only); the fitted time-residual distribution indicates an upper limit for σ_{WR} of <0.5 ns [8].

4. Summary

We applied the new White Rabbit technology for sub-nsec precision time-synchronization of the HiSCORE DAQ-system in various construction phase setups. The harwdare solution is

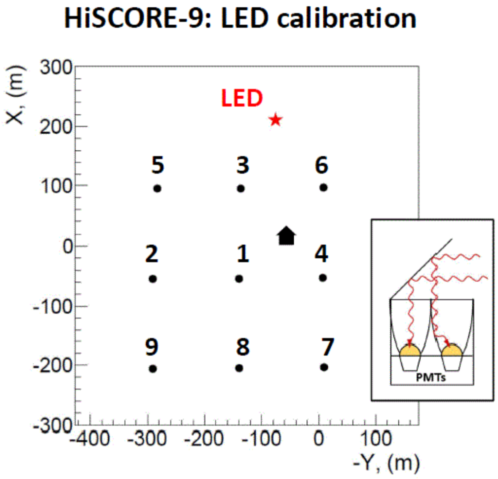


Figure 7: The HiS-9 array layout: Nine stations and LED source position (red star) for calibration runs; insert: station setup for calibration runs with 45^o inclined reflectors.

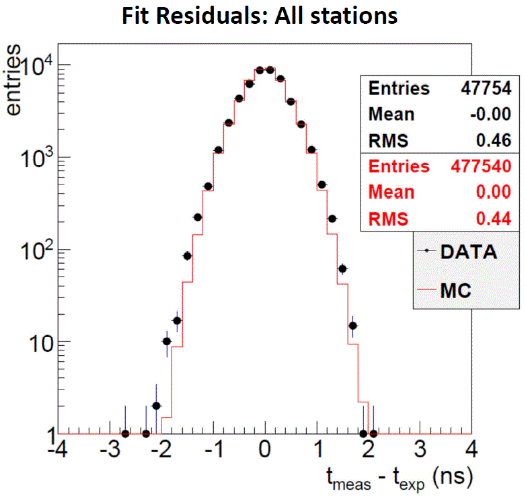


Figure 8: LED calibration: Distribution of fit residuals for LED events (all nine stations superimposed). Black dots: data; Red line: simulated events.

based on standard WR-components (SPEC, DIO5Ch and WRS), with HiSCORE-specific firmware developed for nsec-time-stamping, triggering, DAQ-control; and with support for WR monitoring.

Laboratory and special field setups yielded a timing-precision σ_{WR} of better than 0.2 ns (< 60 ps in table-top setups). We gained long-term field experience with the HiSCORE-9 array, with WR embedded into the full DAQ, and routinely recoreded cosmic-ray data from 2013-2015. From external LED-calibration and air-shower reconstruction we obtain an upper limit for the WR-precision σ_{WR} of better than 0.5 ns (likely driven by dominant non-WR systematics: hardware, air-shower). An ongoing, direct harwdare test installed with HiSCORE-28 indicates σ_{WR} <0.3 ns under real life conditions.

We emphasize an advantage of the WR-architecture, beyond precision timing: digital, fully calibrated times are instantaneously available at the front-ends, which (1) significantly simplifies the DAQ, and (2) allows for digital trigger concepts based on nsec timing and next-neighbor/array topologies - which can be fast, complex, and yet simple to design [9]. Last not least: interfacing a given experiment to WR can be kept as simple as designing a (passive) mezzanine-interface card. Precision, stability and overall system performance of the White-Rabbit based timing makes it a prime candidate for next generation large scale experiments like CTA [4].

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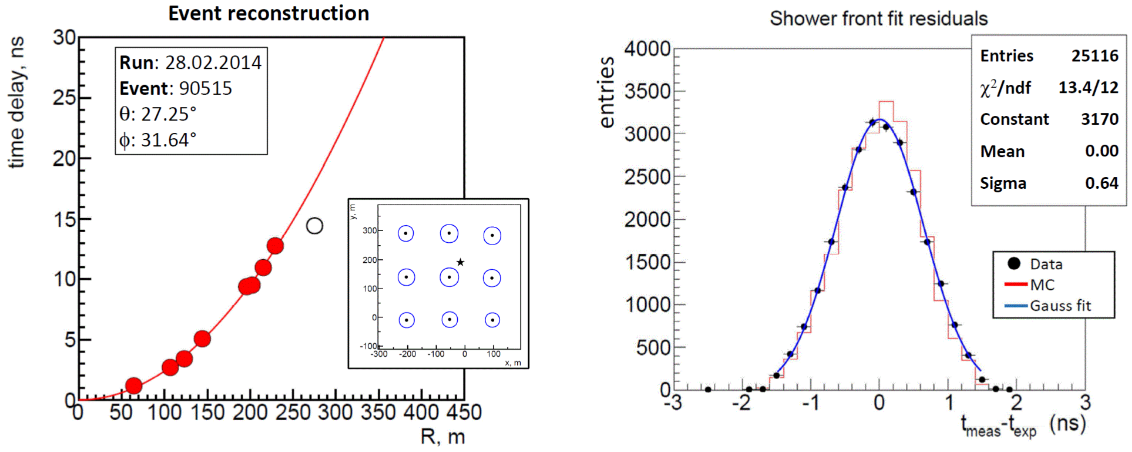

(a) (b)

Figure 9: EAS shower reconstruction. (a) Arrival time delay vs distance R from the shower axis; for an event. Red/white dots: stations retained / excluded in the final fit; red line: reconstructed shower profile. Small panel: Reconstructed core position (black star), the area of the circles is proportional to *logA*, with *A* the station signal amplitude. (b) Distribution of fit residuals after shower reconstruction. Black dots: data; Red line: simulated events; Blue line: gaussian data fit.

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