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Astronomy ESFRI & Research Infrastructure Cluster

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# Harsh Environmental White Rabbit Equipment Tests

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Abstract

Upcoming astroparticle physics experiments require time-synchronization with (sub-) nanosecond precision for all their detector components, distributed over mulit-km scale distances and operating under harsh environmental conditions. White Rabbit (WR), a new technology for time and frequency transfer, is an excellent candidate to be applied as a standard technology for various projects, like CTA, KM3Net, IceCube.

This study aims at an in-situ evaluation of the White Rabbit technology under harsh environmental conditions, in the TAIGA Gamma Observatory in the Tunka valley, Siberia. For this purpose we (1) develop a full end-to-end 2-layer WR-setup that allows precision time-stamping for all detector sub-systems, (2) adapt and implement a commercial, WR-compatible and cost-efficient central GPS clock and (3) develop a flexible, modular monitoring system for deadtime-nsec precision clock- and test-signal time-stamping. We obtained results from multi-year verification of the 2-layer 4-WR-Switch network, from physiscs detector stations, and for in-situ WR-component tests.

We conclude, that the WR-technolgy is excellently suited for precision timing in this class of projects. We have good experience the chosen GPS clock, which was adapted for WR by the manufacturer. We recommend, that the project design and implementation should from an early phase consider intrinsic monitoring and in-situ-verification of timing components performance.

# I. COPYRIGHT NOTICE



# II. DELIVERY SLIP

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# IV. APPLICATON AREA

This document is a formal deliverable for the GA of the project, applicable to all members of the ASTERICS project, beneficiaries and third parties, as well as its collaborating projects.

# V. TERMINOLOGY

A complete project glossary is provided at the following page: http://www.asterics2020.eu/glossary/

CTA - Cherenkov Telescope Array

DAQ – Data Acquisition System

GPS, GPSDO – Global Positioning System, GPS-disciplined Oscillator

HiSCORE – High Sensitivity Cosmic Origin Explorer

IceCube – IceCube Neutrino Observatory at the South Pole

PTP – Precision Time Protocol

TAIGA – Tunka Advanced Instrument for Cosmic Ray Physics and Gamma Astronomy

WR - White Rabbit

# VI. PROJECT SUMMARY

ASTERICS (Astronomy ESFRI & Research Infrastructure Cluster) aims to address the cross-cutting synergies and common challenges shared by the various Astronomy ESFRI facilities (SKA, CTA, KM3Net & E-ELT). It brings together for the first time, the astronomy, astrophysics and particle astrophysics communities, in addition to other related research infrastructures. The major objectives of ASTERICS are to support and accelerate the implementation of the ESFRI telescopes, to enhance their performance beyond the current state-of-the-art, and to see them interoperate as an integrated, multi-wavelength and multi-messenger facility. An important focal point is the management, processing and scientific exploitation of the huge datasets the ESFRI facilities will generate. ASTERICS will seek solutions to these problems outside of the traditional channels by directly engaging and collaborating with industry and specialised SMEs. The various ESFRI pathfinders and precursors will present the perfect proving ground for new methodologies and prototype systems. In addition, ASTERICS will enable astronomers from across the member states to have broad access to the reduced data products of the ESFRI telescopes via a seamless interface to the Virtual Observatory framework. This will massively increase the scientific impact of the telescopes, and greatly encourage use (and re-use) of the data in new and novel ways, typically not foreseen in the original proposals. By demonstrating cross-facility synchronicity, and by harmonising various policy aspects, ASTERICS will realise a distributed and interoperable approach that ushers in a new multi-messenger era for astronomy. Through an active dissemination programme, including direct engagement with all relevant stakeholders, and via the development of citizen scientist mass participation experiments, ASTERICS has the ambition to be a flagship for the scientific, industrial and societal impact ESFRI projects can deliver.

# VII. EXECUTIVE SUMMARY

We perform a harsh environmental test of the new White Rabbit technology for time and frequency transfer, that is planned to be used in several upcoming large-scale astroparticle physics projects. For this purpose, a mid-size end-to-end two-layer WR-setup is build for the TAIGA Gamma Observatory, located in the Tunka valley, Siberia.

We also extended the WR-node firmware to allow for nanosecond resolution time-stamping of level-0 trigger signals, as well as for extended multichannel monitoring. From long term operation, we conclude, that the WR-technology is well suited to provide the required sub-nsec precision synchronization in field application, and to be integrated into front-end electronics. We recommend, that intrinsic synchronization monitoring and online functional verification should be part of the baseline timing system design for complex applications.

# Table of Contents

# 1. Introduction

Upcoming astroparticle physics experiments require time-synchronization with (sub-) nanosecond precision for all their detector components, distributed over multi-km2 scale distances and operating under harsh environmental conditions. White Rabbit (WR), a new technology for time and frequency transfer [SER09], is an excellent candidate to be applied as a standard technology for various projects, like CTA [OYA15], KM3Net, IceCube.

This study aims at an in-situ evaluation of the White Rabbit technology under harsh environmental conditions and in a running observatory. For this purpose we (1) develop a full end-to-end WR-setup that allows precision time-stamping for all detector sub-systems, (2) implement and adapt a commercial, WR-compatible, and cost-efficient central GPS clock and (3) develop a flexible, modular monitoring system for deadtime-nsec precision clock and test-signal logging. We present results from multi-year verification of the 2-layer 4-WR-Switch network, from physics detector stations, and for in-situ WR- and GPS-component tests.

The harsh environmental test is done at the TAIGA Gamma Observatory in the Tunka Valley, Siberia. TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) is a multi-component astroparticle physics facility focused on gamma astronomy at energies above 10 TeV [TLU14, BUD17A, BUD17B]. First White Rabbit activities started in 2012, for the early prototype phase of TAIGA [BRU13].

A baseline White Rabbit (WR) setup is given in Figure 1.1 [SER09, WIS15]. The main ingredients are (1) WR-Switches (WRS) and (2) WR-Nodes, connected by standard Gigabit Ethernet fibres. The WRS are arranged like in a normal Ethernet-network; the central WRS (Grand Master Switch) acts as the time source. It is connected to a precision absolute clock, like a GPS server.

For an end-to-end timing system in a field experiment, two aspects need to be addressed (indicated by coloured circles in Fig.1.1):

1. Development of a WR-node, that can time-stamp trigger signals from the front-end components. The WR-node allows to interface the user system (e.g. 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 other periodic clock signals) to the detector, as indicated for the lower WR-node in fig.1.1 by “trigger” and “clock” signals (red dashed circle).

2. Selection and test/adaptation of a suitable, WR-compatible GPS clock that supplies the PPS and 10 MHz signals for the WR-GrandMaster Switch (purple dashed circle in Fig.1.1).

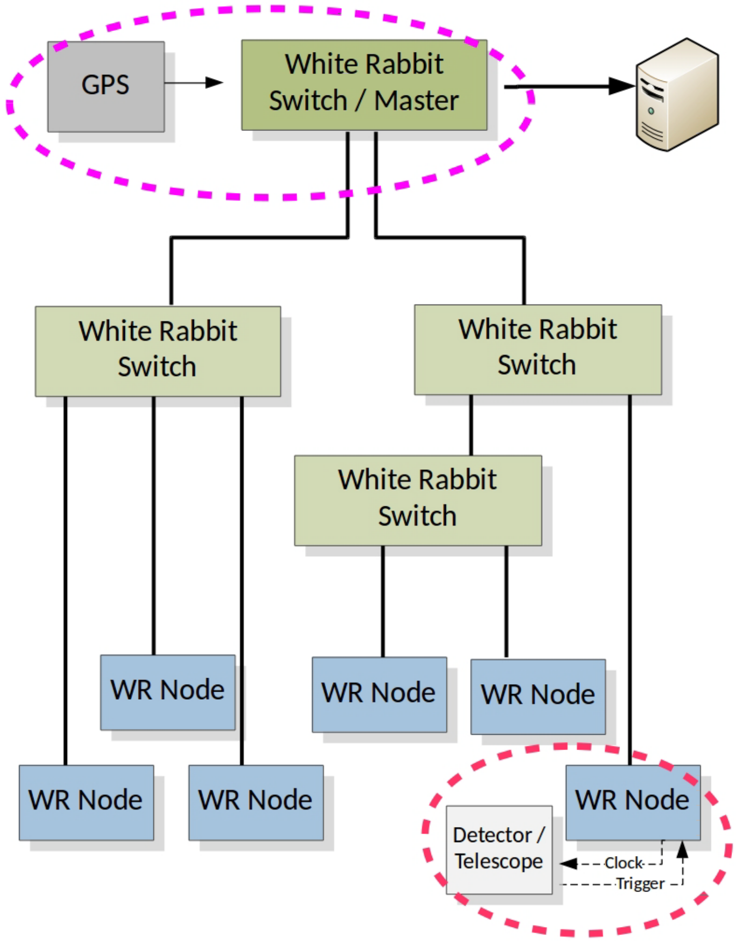


**Fig.1.1.** The White Rabbit network, made up of WR-Switches and WR-Nodes. Focus of this work: (1) Design of WR-Nodes to time-stamp trigger signals from detector stations or telescopes (red dashed circle), and (2) selection of a suitable GPS-Clock (purple dashed circle).

White Rabbit is build on Gigabit Ethernet (1000base-BX10) and takes advantage of the Ethernet standard SyncE and the 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).

As mentioned above, clock/trigger signals between WR-node and detector/telescope can be exchanged in both directions: by either time-stamping signals *from the detector* and/or by supplying clock-information *to the detector.* By using both ways, it will be possible to verify the quality of time synchronization, its precision and stability (both online or offline). This information will be very useful to trace back system clock degradation, and e.g. generate online alerts. Note, that not both of the acquired time-information need to have high precision. From our experience, a failure is usually rapidly reaching micro-second deviation (or larger). Thus, simple clock systems will be sufficient to generate such 'redundant' clock/time data. In typical applications, a detector-internal clock is often available for free. In CTA, we labelled this principle "double clock/double time stamp" approach. Note, that the WR-setup described here for the TAIGA-HiSCORE stations is a special example of a full-precision redundant system, i.e. both WR and the DAQ-board are time-stamping with the same precision (see section 4.2. and figure 4.4). We recommend to implement for larger timing systems the capability for self-verification (i.e. 'redundancy').

This report is organized as follows:

- Section 2 describes our dedicated WR-Node developments: a 4-channel deadtime-free 1-nsec TDC, a sub-nsec resolution TDC (both realized on a WR-SPEC), and a 1-channel 1 nsec resolution deadtime-free TDC on the WR-ZEN.
- Section 3 describes the TAIGA-Observatory and its DAQ setup.
- Section 4 details the WR setup in TAIGA, and presents the main WR-related results.
- Section 5 is devoted to GPS Clock selection, adapted specifically for WR.
- Section 6 gives an outlook, Section 7 presents the summary and conclusions.

# 2. Time-Stamping WR Nodes for DAQ-Stations and Monitoring

Below, we summarize the development of WR-time-stamping nodes, that was done in this subtask, and was presented in [BRU17]. These nodes were used to design the WR-setup for the TAIGA Observatory, as discussed in sect.4 and Fig..4.1.

We present two new developments

- a deadtime-free 4-channel TDC with 1 nsec resolution on the SPEC and ZEN, and
- a TDC designed for improved time resolution up to 0.25 nsec with the WR-SPEC.

As the WR-node device we used for the TAIGA work mainly the "Simple PCIe FMC Carrier" (SPEC) Board. The WR-SPEC is a reliable, off the shelve workhorse of the WR-community [WIS15]. It features 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 digital trigger input , and to output control signals, and PPS/MHz clocks (e.g. for clock performance tests).

As a first development for the White-Rabbit end-to-end setup in the HiSCORE stations of the TAIGA observatory, we designed the WR-SPEC for time-stamping purpose, as described in detail earlier in [WIS15]. The firmware schematics of this deadtime-free 1-nsec TDC on the SPEC/5ChDIO-FMC is shown in Fig.2.1. It features one TDC channel; and up to 4 I/O lines for DAQ-control purposes can be used (e.g. trigger/ready/veto/PPS).

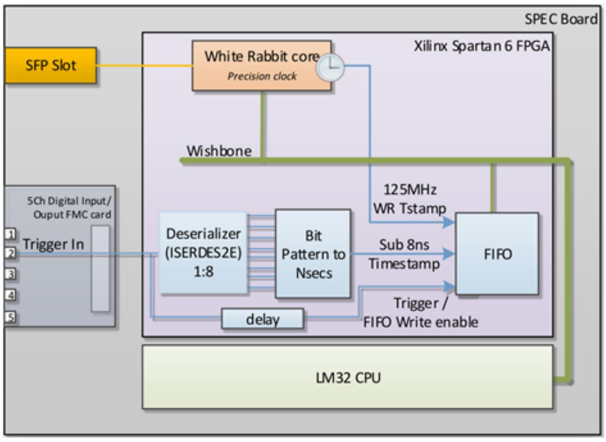


**Fig.2.1.** The modified SPEC firmware, for a SPEC with 5ChDIO card, and the in-FPGA SerDes blocks. Timestamps are written into a FIFO read out by the LM32 CPU. The basic 1 nsecTDC design uses the ISERDES blocks of the FPGA and the White Rabbit timing system. Implemented are 1 TDC-channel with 1 nsec resolution, and up to 4 I/O lines for DAQ-control purposes [BRU17].

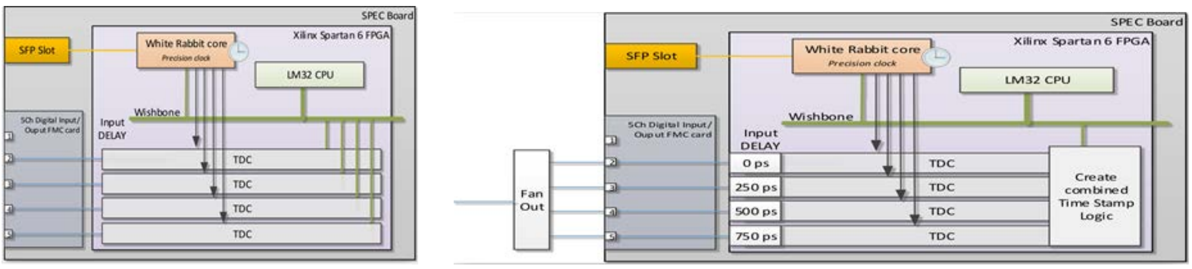


**Fig.2.2.** ***Left:*** The 4-Channel-TDC on the WR-SPEC equipped with a 5ChDIO card. Firmware schematics with TDC units to timestamp 4 input signals, with 1 nsec resolution each. ***Right:*** SPEC-based TDC for improved time resolution. With the help of FPGA IDELAYs blocks the resolution can be increased to 0.25nsec by delaying the incoming signal by n×0.25nsec, n=0,1,2,3 (the input signal is split by an external fanout; but implementation on a custom 5ChDIO board is also possible). See [BRU17] for details.

**4-channel 1-nsec TDC:** We developed a universal 4-channel TDC module, shown in Fig.2.2 (left), that is based on our 1-nsec 1 channel TDC design (SPEC or ZEN). The TDC has been instantiated 4 times to operate on 4 input signals. It shows excellent time-stamping performance, and provides deadtime-free multi-hit operation. Upgrade of the TDCs to larger channel density (8 or 16 TDC-channels per WR-node) is realistic, and only requires an upgrade of the cheap 5ChDIO-card.

**High-resolution TDC:** With the 4-channel TDC setup design, it is possible to increase the sampling frequency for a single input signal. This signal has to be split up into 4 signals with a simple fanout board and fed into the 4 TDC input channels of the DIO card (currently this is done by an external fanout; though a splitter can easily be implemented on the 5ChDIO). The FPGA design has been modified to delay the input signals in steps of 250ps, as shown in Fig.2.2 (right). We note, that the IDELAY blocks of the Spartan 6 FPGA (on the WR SPEC node) are not temperature compensated, which implies careful temperature calibration. We therefore plan to implement the design on the Zynq based ZEN board as well. This high-resolution TDC has been installed in TAIGA (SPEC-T2 in Fig.4.1), and is under long-term study.

These 4-channel TDC units allow for a flexible and cost-efficient design of precision timing setups: both for interfacing to experimental DAQ-components (like time-stamping of trigger signals issued by front-end DAQ units), as well as for monitoring any test-signals with nsec resolution (e.g. to verify the performance of timing system itself). Routine operation of an additional medium size monitoring system started in fall 2017 at TAIGA, which also includes verification of the central GPSDO-based timing (PPS signals). An example use case in displayed in Fig.2.3. The application in TAIGA is discussed in section 4.1 and 4.2.

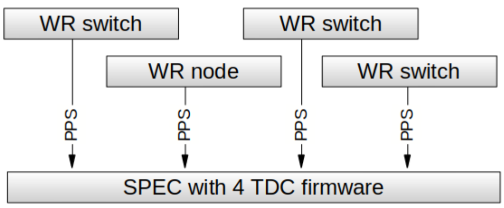


**Fig.2.3.** A simple use-case example for the 4-channel-TDC: monitoring the WRS-PPS phase alignment of a group of WR-switches and SPECs: a single WR-SPEC can monitor performance of four WR-switches or nodes. See Fig.4.1. for the TAIGA-implementation of this concept.

The SPEC firmware design in use at TAIGA are adapted to the low bandwidth needs of this project. For the IACT, and other applications, a higher-rate version has been developed. Tests give confidence that operation at rates well beyond 200 MHz is possible. It is also planned, to extend the SEPC operation by uplink the PTP status over the fiber - which will simplify monitoring of field-SPECs, since they are usually not easily accessible via their SPEC-UART.

# 3. The TAIGA Observatory

The new gamma-observatory TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) is currently under construction in the Tunka valley in Siberia, about 50km from Lake Baikal [BUD17A]. TAIGA is focused on registration of high energy gammas with energies above ~30 TeV. Gamma and cosmic ray shower are detected by their Cherenkov light on ground by two components, as sketched in Fig.3.1: (1) Air Cherenkov shower light front sampling detectors TAIGA-HiSCORE, with ~0.5sr viewing angle and distributed on a regular 100m/150m grid over ~1km2, and (2) Imaging Air Cherenkov Telescopes (IACT) located at distances of >300m from each other. The current TAIGA layout is given in Fig.3.2.

The hybrid detection principle followed by TAIGA will be a cost-effective way to instrument large areas (multi-km2) to reach sufficient detection sensitivity at energies well above 100 TeV: HiSCORE determines (1) direction, (2) location and (3) the total energy of the shower.

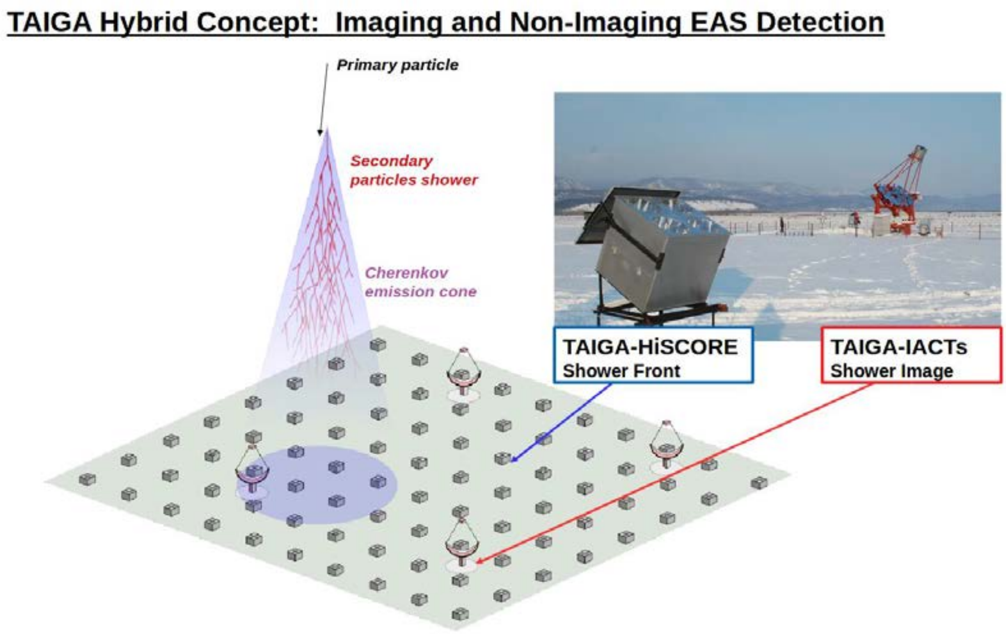


**Fig 3.1.** The TAIGA Gamma Observatory – a new hybrid detection principle for gamma ray/air showers. TAIGA is located in the Tunka Valley, Siberia. Main components are TAIGA-HiSCORE - an array of wide-angle Cherenkov stations, and TAIGA-IACT - Imaging Air Cherenkov Telescopes. All detector components are time-synchronized relative to each other at sub-nsec level.

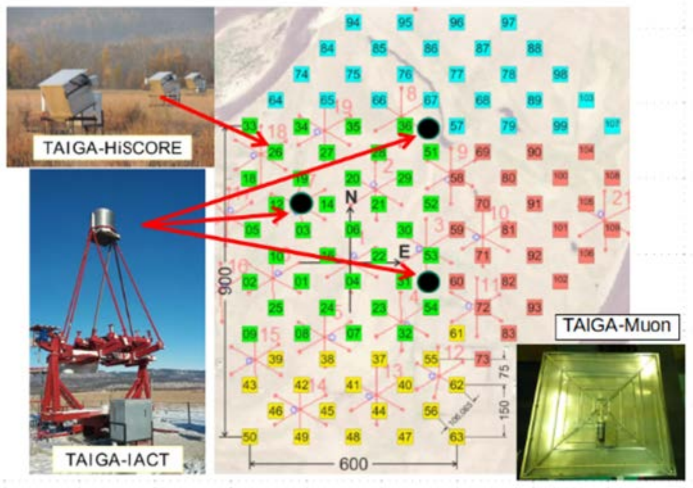


**Fig. 3.2.** Layout of the TAIGA Observatory: An array of ~100 TAIGA-HiSCORE stations, distributed over ~1km2 area (plan for fall 2019). In operation now are 54 stations in HiSCORE Cluster-1 (green symbols) and Cluster-2 (yellow), distributed over 0.5 km2. Three TAIGA-IACTs (Imaging Atmospheric Cherenkov Telescopes) are planned – the 1st IACT is in operation.

To reach best pointing precision of TAIGA-HiSCORE (~0.1deg), a relative time synchronization between HiSCORE stations of sub-nsec precision is required [TLU14]. The trigger timestamps of IACT events should have the same synchronization precision, to allow IACTs to be included into the array pointing reconstruction.

The layout of the data acquisition system (DAQ) of TAIGA-HiSCORE is given in Fig.3.3 [BUD17A. BUD17B]. Two time-synchronization systems are operated in parallel: A custom system using a 100 MHz clock over fiber, and the White-Rabbit system, described in the next section. The ‘100 MHz synchronization system’ is based on a clock signal (100 MHz) transmitted over separate fibers to each station (without any local dynamic delay compensation).

In the station DAQ (Fig.3.3), both time-stamping systems receive the same trigger pulse, which is clocked by the 100 MHz local clock. The WR node timestamps this 10nsec clock signal with its intrinsic 1 nsec resolution. Note: for standard physics offline processing, the PMT pulses are sampled with the 2GHz DRS4 unit, which allows sub-nsec pulse timing (necessary for air-shower reconstruction). In the next section, we will use the ‘raw signals’ recorded by the WR-node and by the DRS-board to verify the performance of both synchronization systems. Using both timestamps, the synchronization can be verified on a pulse by pulse comparison for each station, independent on additional calibrations.

Figure 3.4 shows the HiSCORE station DAQ-card, together with the WR-SPEC (FMC-connected) mounted on it. The custom DAQ and the WR-SPEC timestamp the same trigger pulse, which is aligned with the 100 MHz clock (i.e. 10nsec steps). The SPEC stamps the 100 MHz pulse with

1nsec precision. Both trigger pulses are available for direct comparison in the off-line analysis, see section 4.2.

When comparing data from both timing systems, one needs to consider that the master clock of the custom-DAQ ('MEGA-Host') has a limited absolute stability, that prevents direct comparison of times measured at nsec-precision for a single station for neighboring in time trigger signals with both time systems (DAQ-clock drift over 10-100ms is too large). Therefore, another method is applied in Section 4.2. for time-system stability checks: EAS shower registered in a pair of stations define an instantaneous moment, at which trigger signals are measured on both stations by the two different clocks.

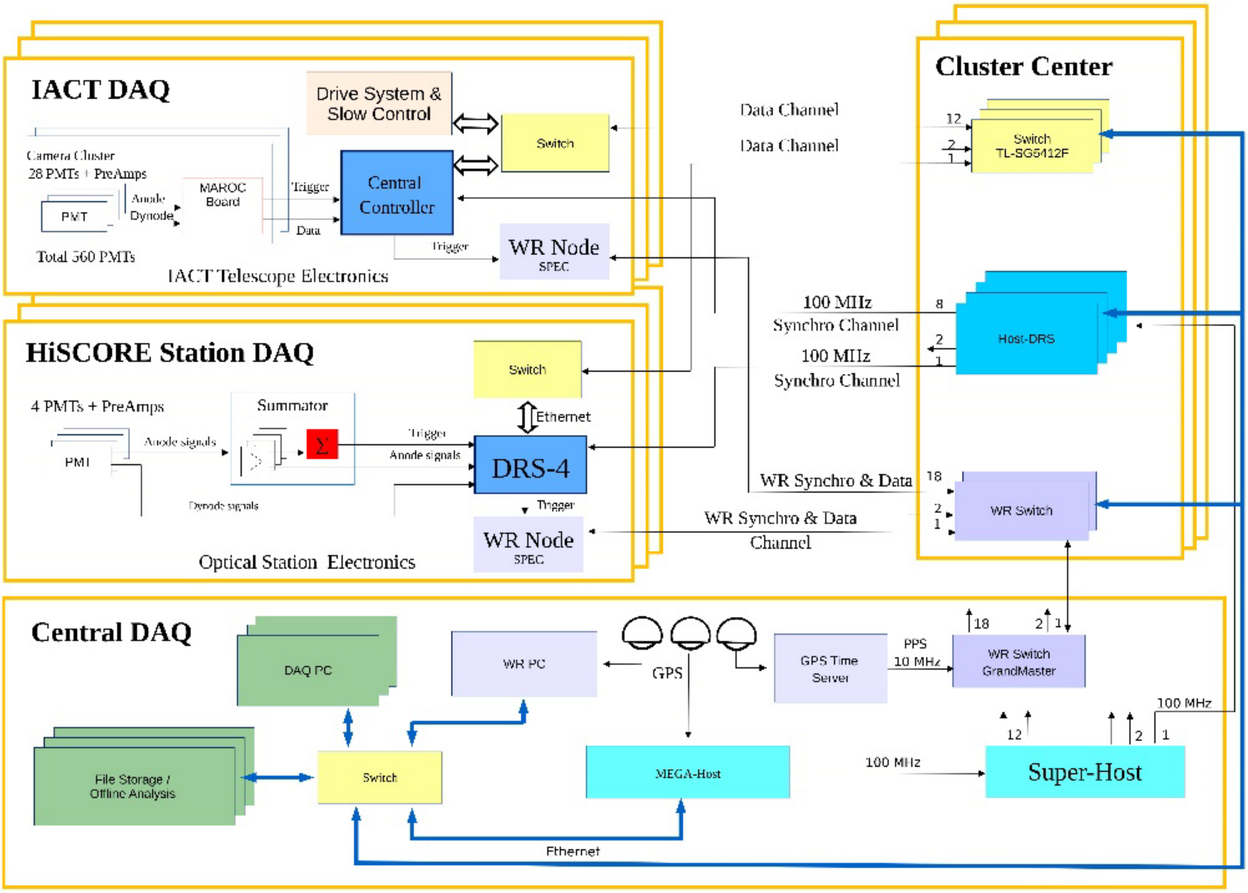


**Fig. 3.3.** The TAIGA Observatory data acquisition system: DAQ stations of the HiSCORE array, the IACT DAQ stations, and the Central DAQ with precision GPS WR-Time Server and other GPS clocks. Two time-synchronization systems operate in parallel: a custom 100 MHz design and White Rabbit (see fig. 4.1), see also [BUD17B].

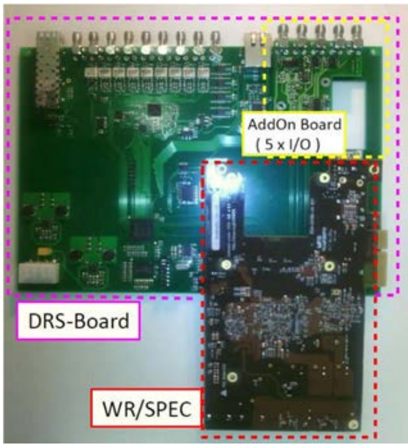


**Fig. 3.4.** The TAIGA-HiSCORE DAQ-board, comprising a DRS4-based trigger and readout board ("DRS-Board") and the WR-SPEC board (FMC-mounted to DRS-Board). The WR-SPEC time-stamps all trigger pulses and transmits them via its WR-fiber to the WR-Host, independently from the DRS-Board.

# 4. The WR Setup at the TAIGA Observatory

## 4.1. Layout

This section describes the end-to-end WR setup, developed and installed for the TAIGA Observatory. The WR-nodes used for HiSCORE stations are introduced in sect.2. above. The IACT uses the same WR-node to time-stamp camera trigger, see Fig.4.3.

Figure 4.1 gives an overview on the current layout of the TAIGA WR-setup (as of late 2018). By fall 2019, similar elements for HiSCORE Cluster-3 and Cluster-4 will be added. Figure 4.1 (left) shows the DAQ-Center with GrandMaster switch WRS1, synchronized to the GPS Clock (Meinberg Lantime M1000, see sect.5). WRS-1 synchronizes WRS-2, that connects to HiSCORE stations in Cluster-1, and also synchronizes WRS-3 in Cluster-2. WRS-1 also synchronizes the WR-LEN and WR-ZEN boards (connected over long fiber loop-backs over HiS-stations). Monitoring of WR-control signals is done by the 12 channels of deadtime-free nsec-resolution TDCs, developed on the WR-SPECs T1, T2, T3 (see sect.2).

Figure 4.1 (right) shows HiSCORE Cluster-2, with WR switches WRS-3 (layer 1) and WRS-4 (layer 2) synchronizing Cluster-2 stations. For direct monitoring of the WRS-4 synchronization, a fiber is routed back into the DAQ-center to SPEC T2 (loop-back). Here, SPEC-T2 measures the phase of the WRS-1 PPS, thus a full WRS layer-2 loop-back verification is conducted. Also shown: the WR-nodes in HiSCORE stations and IACT telescope. They time-stamp the station/IACT trigger signals, as explained in section 3.

In figure 4.2, the installed components discussed in fig.4.1 are shown: a field view with a number HiSCORE stations, the IACT and the DAQ-center; and the installation inside the main DAQ-center.

In addition to the fiber links shown in Fig.4.1, all WR-components in the DAQ and Cluster centers are readout over the control UART ports (or from WRS shell) to monitor the PTP-daemons. This allows to follow the PTP status (synchronization status) and the link parameters, like cable round-trip time (cable-rtt) and clock-offset. The UART is also used to setup the SPEC and to restart the ptp-service.

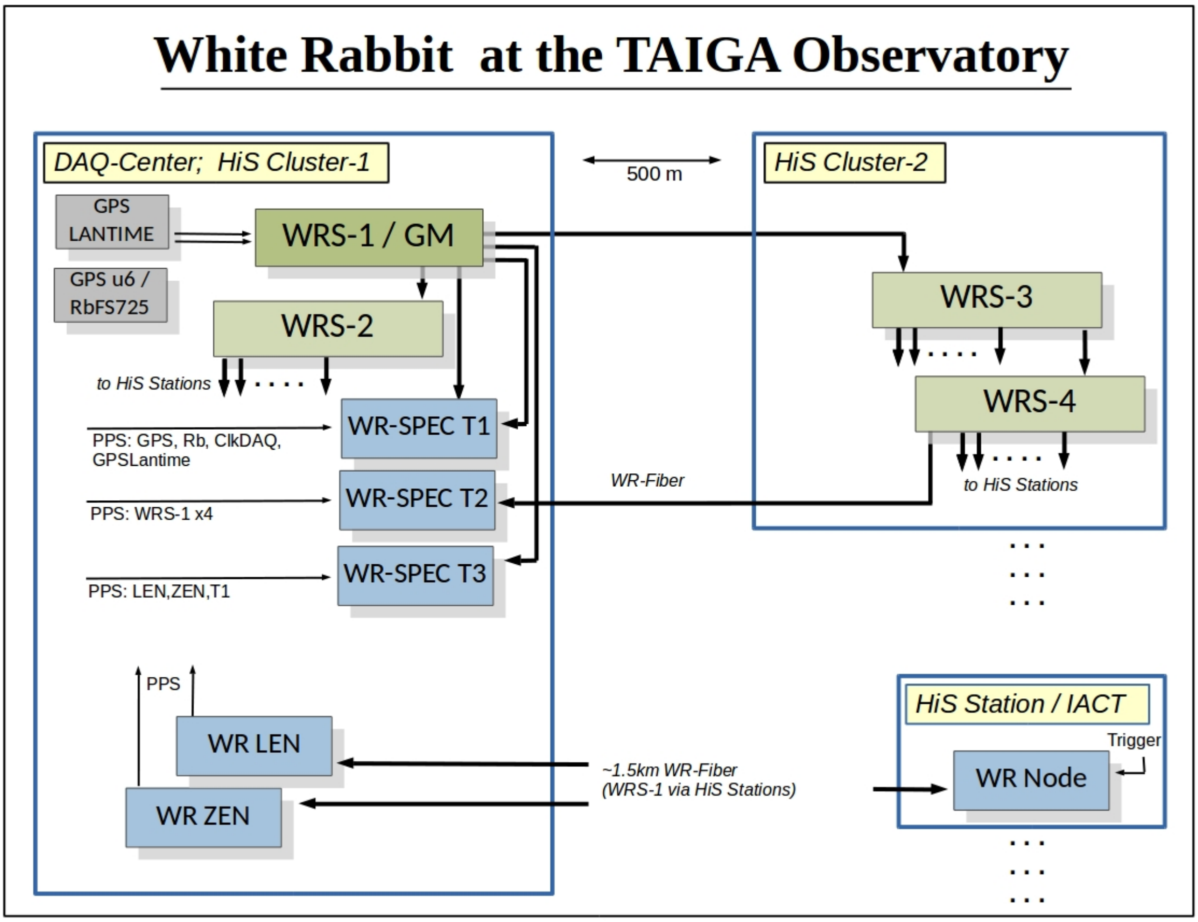


**Fig.4.1.** The White Rabbit setup at the TAIGA Observatory: General overview. See text for details. ***Left:*** DAQ-Center with GrandMaster switch WRS1, synchronized to GPS Meinberg Lantime M1000. It synchronizes WRS-2, and HiSCORE Cluster-1 stations, the WR-LEN and WR-ZEN boards (connected by long fiber loop-backs over HiS-stations). Monitoring of WR-control signals is done by 12 TDC channels with nsec-resolution (T1, T2, T3). ***Right:*** HiSCORE Cluster-2; WR switches WRS-3 (layer 1) and WRS-4 (layer-2) synchronizing Cluster-2 stations. A fiber is routed back to DAQ-Center (loop-back), synchronizing SPEC T2. SPEC T2 measures the phase of the WRS-1 PPS.

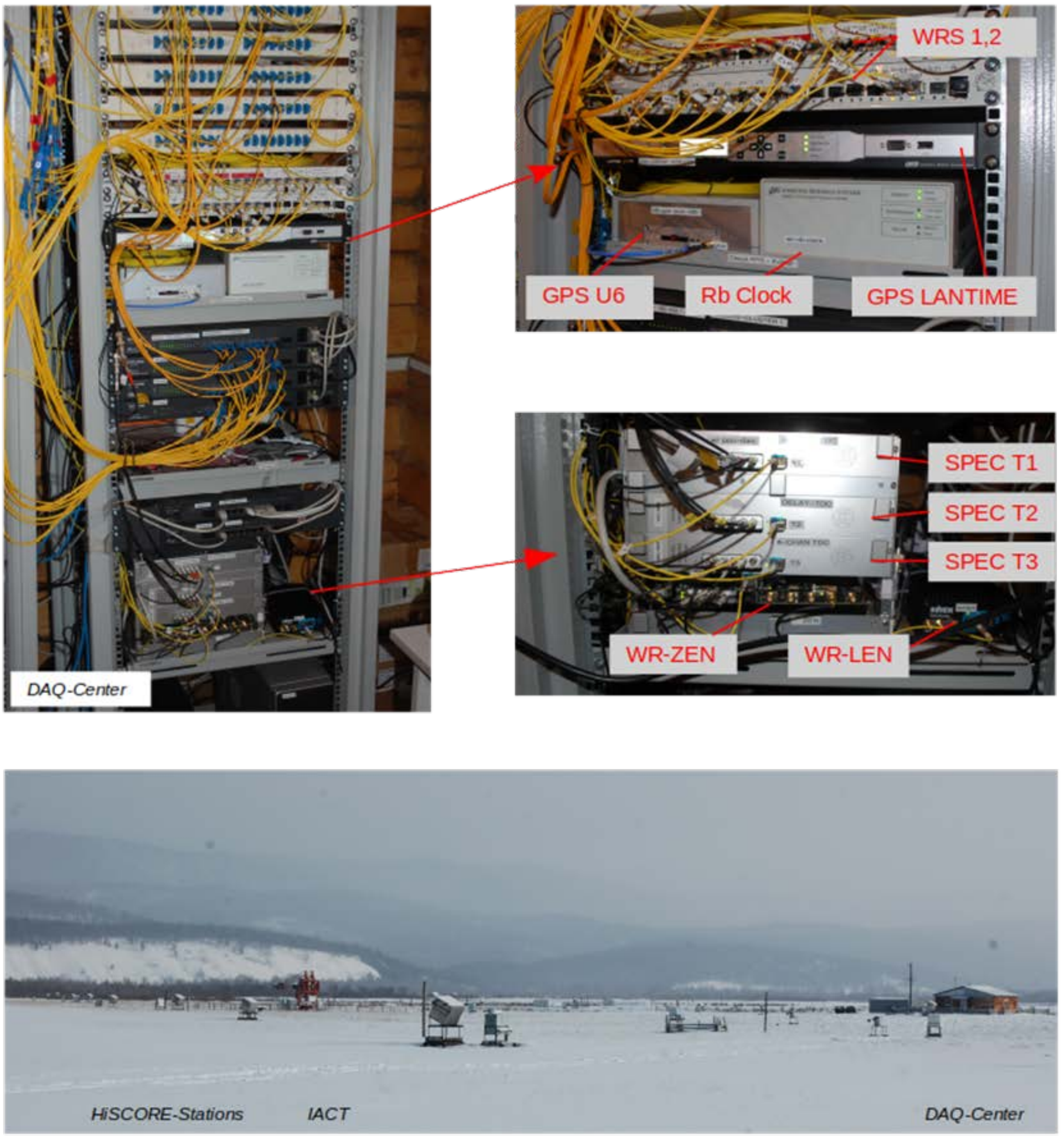


**Fig.4.2.** The components of the White Rabbit setup at the TAIGA Observatory.
***Lower panel:*** Areal view of the 1km2 array of HiSCORE stations (see e.g. left background, foreground, equipped with WR-SPECs), the IACT Telescope (WR-SPEC) and the wooden DAQ-Center building. ***Upper left***: DAQ-Center. Rack with central WR components, fiber patch panels, and DAQ switches. ***Upper right:*** WR-Switches (WRS-1, WRS-2), GPS-Clock Lantime M1000; GPSDO/Rb Clock FS725 with GPS-Clock (ublox6/8). ***Lower right:*** WR-SPEC nodes T1-T3 for the 12-channel 1-nsec resolution WR-clock signal monitoring; and the LEN and ZEN modules in long-term test. See also the general scheme in Fig.4.1.


**Fig.4.3.** The TAIGA Imaging Telescope (IACT #1). The metal box (foreground right) hosts the drive system control, local network gear, and the WR-SPEC node to time-stamp the IACT trigger signals (small white box inside).

## 4.2. Results

Over the last 2 years, a large data set was collected during daily operation of the TAIGA facility. Here, we demonstrate the variety of results on timing precision obtained by three examples. All data were recorded in routine experimental operation conditions. Plenty of logging information on subsystem status are recorded, they are used for fast (online) failure detection, for recovery from error conditions, and to analyze the system status in detail offline (like WR-PTP link parameters), see e.g. Fig.4.5. We note, that apart from system installation and upgrade, data were taken in full remote operation mode from Europe, with only rare local operator invention in failure cases. It is this operation experience, that guides our recommendation below regarding a timing system design for large facilities with sufficient intrinsic verification capability.

As a general conclusion, we find the reliability and operational stability of the WR components in the system (see fig.4.1.) reliable and well performing. There were three serious issues only: one White Rabbit switch (power supply) and 2 SPECs broke. However, individual component glitches like hanging occurred approximately every 1-3 days, and required manual intervention under field conditions, and special handling (reboot, link shutdown, PTP restart). In one (30%) of the cases the unit, typically a SPEC or ZEN, had to be powered up again.

Our conclusion for a large WR-based system: the design should allow the possibility to re-power any critical timing component remotely and without serious side-effects. Surely, this will imply in some cases a restart of subsytems or alike. As we mentioned earlier, it is important that such ‘non-standard’ situations (timing performance degradation or failures) can be detected reliably and in-situ by the system (e.g. by an intrinsic redundancy-concept, as mentioned in fig.1.1). During early system deployment, this will be an important issue.

**Result 1:**

The main precision test result of this study is given in figure 4.4., as an example for two runs: 10.04.2018 and 06.01.2019 (left and right 2x2 panels). The analysis is based on the trigger times as obtained from the two independent TAIGA timing systems on an event-by-event basis, and as discussed in sect.3. Fig.4.4 (a) Upper left: The time difference distribution for two channels in Cluster-1 ($\Delta t^{DAQ}$, $\Delta t^{WR}$), as directly measured by the WR- and 100 MHz systems. Both distributions agree very well. (b) Upper right: Distribution of difference of the time-differences from (a) for each event, $\Delta t^{DAQ}$-$\Delta t^{WR}$. (c) Lower left: same as (b) for two channels from Cluster-2. (d) Lower right: same as (b) for two channels from Cluster-1 and Cluster-2 (inter-cluster timing). Perfect timing in both systems would result in a ’delta-function’ in plots (b)-(d) (Note: an average ≠0 is due to trivial offsets like cable/phase; like a different offset between both years, i.e. 01/2019 and 03/2018). Note: the rare extra-events at -10ns, -20 ns (for 06.01.2019) are not related to the WR components; they are due to the DAQ-card (10ns is the 100MHz period); a more detailed investigation is in progress.

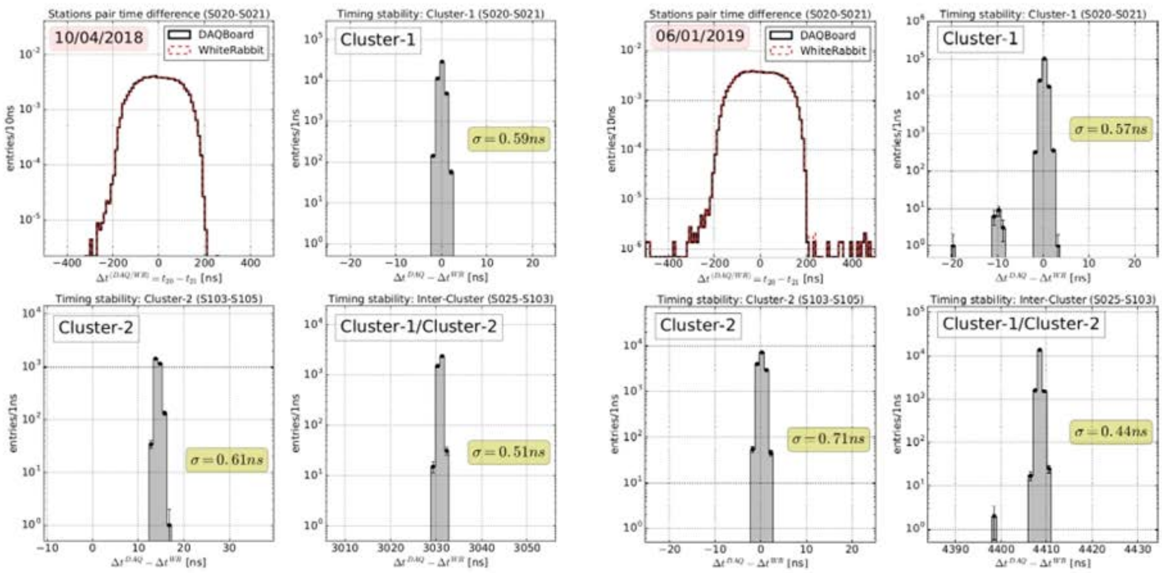


**Fig.4.4.** The main precision test of this study: evaluating the performance of the two independent nsec-TAIGA timing systems, by comparing the trigger times on an event-by-event basis. Two days are shown: ***Left:*** 10/04/2018, ***Right:*** 06/012018. ***(a) Upper left:*** time difference for two channels, as directly measured by the WR- and the 100MHz systems. ***(b) Upper right:*** difference of the times from (a) for each event, $\Delta t^{DAQ}$-$\Delta t^{WR}$. ***(c) Lower left:*** same as (b) for two channels from Cluster-2. ***(d) Lower right:*** same as (b) for two channels from Cluster-1 and Cluster-2.

A main conclusion of this test is the excellent combined and individual stability performance of the timing systems. As indicated in Fig. 4.4, the rms of the differences of time-differences is <0.7ns, which implies a rms well below<0.5ns for each time-system independently. We are currently investigating, if smaller variations due to daily or seasonal temperature variations can be found.

This result is relevant for TAIGA as well: it proves independently that both Clusters are stable synchronized relative to each other (Fig.4.4 d).

**Result 2:**

The WR-Setup in TAIGA was designed to allow an extended permanent monitoring of the time-synchronization status of components, as well as of devices under dedicated performance tests. Fig. 4.1 gives details of the setup.

**Result 2.1: Verification of the WRS-network layer-2 performance:**

A loop-back fiber connects from WRS-4 (layer-2) back to the central DAQ, and synchronizes their SPEC-T2, which time-stamps the PPS pulse of WRS-1.
In figure 4.5 (left side; upper panel) we show the PPS-phase as function of time for a 4-day period in March 2018, and measured once per second. This phase is absolutely stable at 73.0 nsec (this absolute value is irrelevant, it only depends on cable routing etc.). At the same time, the ambient temperature varies by almost 40 C for that period (see lower panel). The cable round trip time (Cable RTT on panel 3), as measured by the PTP core on SPEC-T2 varies by 400ps (from SPEC-UART-logging). We observe an rtt-modulation that follows the main trend of the temperature variation. In addition, there seems to be a small additional trend. One explanation is slow, delayed warm-up of the ground layers in spring (fiber is 0.2-0.5m below surface), but minor temperature effects induced by WRS-4 or SPEC-T3 room temperatures are not fully excluded (see also [LIP13], while in our case environmental conditions for all components are less precisely traceable). For completeness, the PTP-estimated 'clock offset' is also given (panel 2).

**Result 2.2: Verification of the WR-LEN performance:**

We performed a long loopback test for the WR-LEN module. The WR-LEN will be used by IceCube-Gen2 in their upgrade [HUB17]. The WR-LEN is synchronized by WRS-1 over a 1.5km fiber (double looped to HiSCORE station S019), see Fig.4.1. The PPS pulse of the WR-LEN is time-stamped on SPEC-T3 (in turn directly synchronized by WRS-1).
This plot shows a 3-day period, with ambient temperature difference of ~30$^{o}$ C. The PPS phase is absolutely stable, like for the WRS-loopback above.

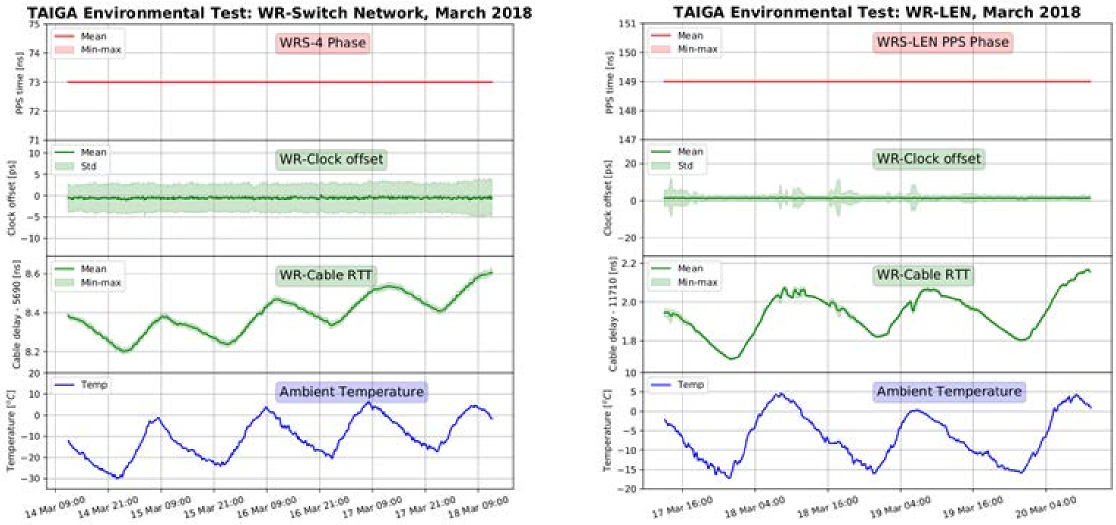


**Fig. 4.5.** Long-term environmental test of White Rabbit time-synchronization at the TAIGA Observatory. ***Left:*** The WR-network loop-back test. WRSwitch-4 (layer 2) synchronizes SPEC-T2, that is time-stamping the WRS-1 PPS. ***Right:*** Long loopback test for the WR-LEN module, that is synchronized by WRS-1 over a 1.5km fiber (double looped to HiSCORE station S019). The WR-LEN PPS is time-stamped on SPEC-T3 (synchronized by WRS-1).
See text and fig.4.1 for details.

We mention, that ambient winter temperatures reach at Tunka -40°C and less. In some occasions, when heating problems occurred, DAQ-Center equipment was exposed to room temperatures around 0°C. For such periods, we observed temperature induced precision issues (nsec-scale drifts) on our reference TDC channels (e.g. SPEC T1-PPS time-stamped on SPEC-T3. Similar observations are reported as e.g. "virtual" effects [LIP13]. Under normal conditions (15-25°C), all intrinsic precision verification performs well.

**<u>Result 3:</u>**

Figure 4.6 displays an exciting result, obtained by the whole TAIGA-HiSCORE array, after it was fully calibrated. HiSCORE observed an "unexpected point source" - a Lidar Laser operating on-board the ISS [CATS] and pointing downwards to the earth, as sketched in Fig.4.6. In total, ten ISS-Lidar passages were recorded between 2015 and 2017, see [POR17] for details. At one occasion, a simultaneous observation by HiSCORE and the closeby optical telescope MASTER could be conducted. This allowed an explicit verification of the absolute pointing precision of TAIGA-HiSCORE of ~0.1deg. Sub-nsec timing precision is required to precisely reconstruct each laser pulse direction, emitted with 4 kHz from the ISS, orbiting at 400km height and at a speed of 7.7 km/sec for a total passage time of <1sec. Shown in Fig.4.6 is one ISS passage, with ~1000 recorded events (observation time from early to late: blue to red, lower left insert). Precision timing calibration was achieved using the custom made DAQ (100 MHz fiber signal clock) and by the WR-system. Time-synchronization precision is the only system parameter that determines the pointing precision for the LIDAR-class events. Observation of the ISS in turn also allowed to verify the WR-station time offsets, see above in Fig.4.4.

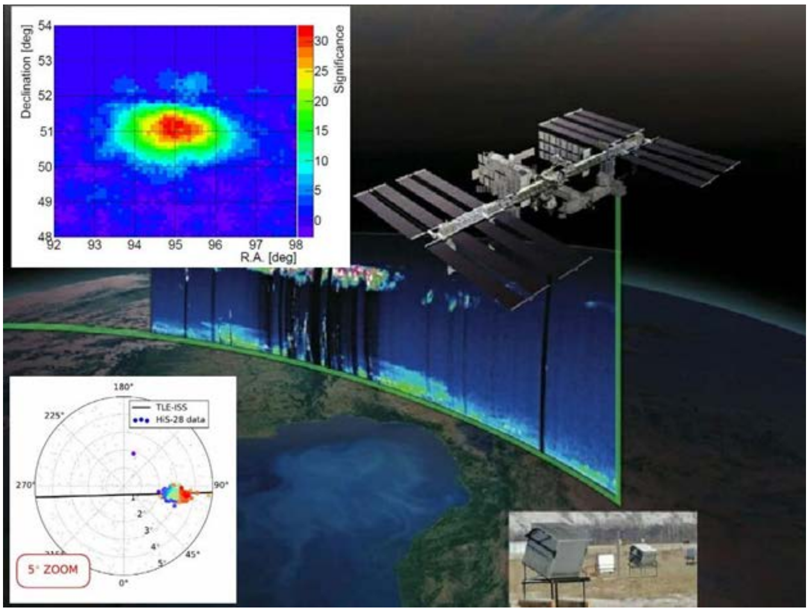


**Fig.4.6.** The serendipitous discovery by precision timing at the TAIGA Observatory: bright laser signals from the CATS Lidar [CATS], operating on-board the International Space Station. The pulses are synchronously seen by the array of HiSCORE stations [POR17]. The upper left plot shows the 33-sigma detection significance above background shower events for the ISS passage, as given by the standard point-source-search.

# 5. The GPS for the WR GrandMaster

A key element of a White Rabbit-based time synchronization setup for an observatory is the central reference clock that drives the WR-Grandmaster switch (labelled “GPS” in Fig.1.1). For many applications, indeed a GPS Clock will be the most economic option for the precision central clock, given the absolute UTC clock precision requirements (typically not better than a microsecond). WR requires the reference clock to supply (1) a high stability 10 MHz signal, which is used to synchronize the GM-WRS internal clock, and (2) a PPS signal that follows the phase alignment of PPS-10MHz, as required in the WR-interface document [WLO12].

Since selection of an affordable, commercial GPS for WR was not a simple task, we introduced as a temporary solution a GPS-disciplined oscillator (GPSDO), made of an ublox8-GPS receiver and a commercial RbClock (Stanford FS725). This unit served for 2016-2018 as main TAIGA WR-Grandmaster clock. Its stability was monitored against a “free” parallel running GPS (ublox6) and was found to be well performing. Its stability and reliability were outperforming the local TAIGA-DAQ GPS unit in use for the custom DAQ (see Fig.2.3).

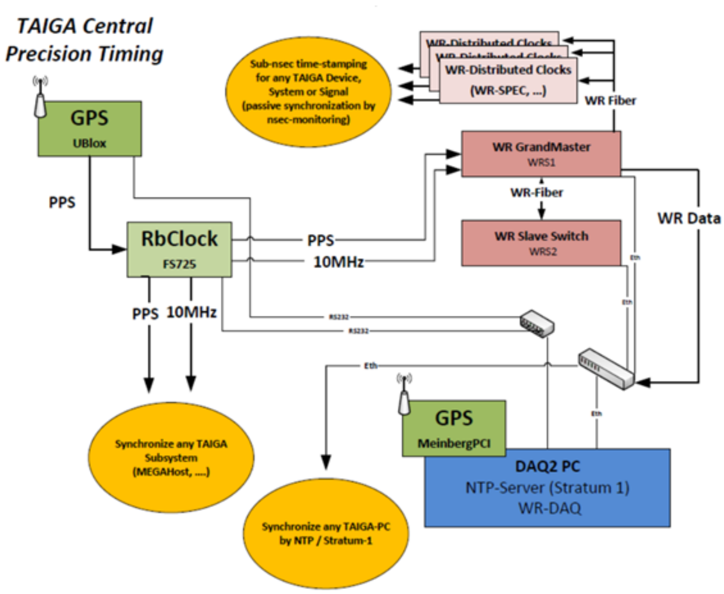


**Fig.5.1.** Structure of the temporary WR-setup for the TAIGA-HiSCORE array as used in 2016/2018. The central clock system was based on WR with GSPDO/Rb (ublox8-GPS and Stanford FS725). As a result of this work, as central GPS clock a Meinberg Lantime M1000 is in operation [MEIN].

For the sake of system simplicity, and in particular to minimize the number of procedures and components, including level adapter, converter, need for direct GPS-control by serial ports etc, we searched for a fully integrated solution by a commercial supplier, at affordable costs. While plenty of GPS receivers are commercially available, including low-cost high stability versions like the ublox-series, only a few GPS systems generate 10 MHz pulses with the required stability. Some GPS systems adjust the 100 ns pulses by several nsec pulse-by-pulse, and do not keep track of phase between PPS and 10MHz signals even at the 10-100nsec level.

The Meinberg Lantime M1000 [MEIN] was found in a test to fulfil all requirements (at moderate cost), except for a ‘random phase alignment’ at initialization between the PPS and 10MHz pulses (which thereafter is stable at <<1ns). The company agreed to develop a firmware version that fixed the PPS/10MHz adjustment, and fulfils all WR-specifications. This

Lantime M1000 with “WR-adapted firmware” is operating since >1 year with high stability in the TAIGA setup. See also Fig.4.1 and Fig.4.2. The specific model is commercially available.

# 6. Next Steps

For the upcoming 2 years, additional laboratory and field upgrade work is planned.

Project upgrade & hardware development (WR-SPEC):

- Extend the TAIGA WR-setup to HiSCORE Cluster-3 and -4 (to be. installed 2019).
- SPEC with improved time-resolution (0.25ns): perform laboratory temperature calibration, also for the used auxiliary custom devices (fanouts)
- Site infrastructure update: improved logging of counting room temperatures at relevant locations, acquisition of WR-SPEC temperatures; install remote subsystem power control for improved failure handling

Data collection / analysis:

- Collect statistics to check for multi-year cycle of environmental time-shifts in HiSCORE-stations and IACTs. Attempt to find sub-nsec temperature induced variations (combined operation of WR and 100MHz DAQ)
- Install daily routine time-difference analysis after each observation runs
- Continue field tests of WR-nodes (LEN,ZEN), invite for suggestions from other projects (e.g. CTA, IceCube)

We are open for more detailed exchange of experience, discussions with other projects that design larger WR-installations, including monitoring and redundancy aspects.

# 7. Summary and Conclusions

In the context of this Work-Package “Harsh environmental test of WR-technology” the following was delivered.

- Design of an end-to-end White Rabbit installation for nsec-precision time stamping in a typical astroparticle physics facility - the TAIGA Observatory in the Tunka Valley, Siberia, as shown in fig.4.1. TAIGA is among the first mid-size applications of White Rabbit in an astroparticle physics project. This installation was evaluated in long-term routine operation. Typical ambient temperatures ranged from -40 to +20$^{o}$C over 3 seasons.

- WR nodes for nsec time-stamping were developed for the WR-SPEC (FMC-5ChDIO), which operate as deadtime-free, 1-nsec-resolution TDCs, with absolute TAI (UTC) time basis and without an external trigger signal.

- The developed SPEC firmware comes in 3 variations: (i) single channel TDC with optional DAQ control signal handling, (ii) 4-channel TDC, and (iii) 1 channel TDC with improved 0.25ns resolution. The SPEC multi-channel design can easily be extended to more channels with a simple custom FMC board. Additionally, a similar 1nsec TDC was implemented on the standard ZEN-node (with FMC-5ChDIO).

- To verify the field performance in a physics application case, the time-stamping WR nodes were interfaced with the custom-made time-synchronization system in the TAIGA DAQ, which is operating in parallel. This allowed an event-by-event comparison during physics data-taking, and allowed to verify the precision and stability (over hours) of both systems to below <0.5 ns rms under field conditions. See figure 4.4 for the results.

- A key element of the WR-based TAIGA setup was the selection and verification of a suitable GPS clock, compliant with WR. A temporary GPSDO solution was built with an ublox-GPS driving a commercial RbClock, and operated for 2 years. In 2018, a robust, cost-efficient commercial solution was tested. On our request, the manufacturer adapted the firmware to fully comply with WR. This WR-compatible Meinberg Lantime M1000 model operates successfully for 1 year at the TAIGA site, and is passively verified by the GPSDO/Rb (FS725).

- While the TAIGA setup is based on the SPEC card as WR-node, field-tests for the WR-LEN and WR-ZEN (standard version) were also conducted. WR-Nodes based on these cards are planned to be used in IceCube and CTA, respectively. The SPEC cards developed in this work for TAIGA are now also installed in the Neutrino Telescope GVD, for time synchronization between Clusters located at 1.0-1.5km underwater in Lake Baikal / Siberia.

- We draw conclusions regarding large scale timing system design, like intrinsic performance verification (by e.g. passive redundancy for critical components, or by double time-stamping as discussed in sect.1). Active performance control is in particular recommended for an early installation phase of large-scale projects. We add, that the suggested control/verification measures do by no means imply that White Rabbit is performing unstable or unreliable.

Our main conclusion regarding White Rabbit as precision timing system for large scale research infrastructures, is very positive. Given careful design of a complex high precision system, it will for sure outperform in probably all parameters over custom-made systems; at the very least regarding precision, reliability, manpower, maintenance and cost-efficiency. White Rabbit is already a quasi-standard for precision timing systems in distributed detector systems.

### Acknowledgements

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### References

[SER09] J. Serrano, et al., The White Rabbit Project., ICALEPS 2009, ICALEPCS TUC004, 2009
http://accelconf.web.cern.ch/accelconf/icalepcs2009/papers/tuc004.pdf
M. Lipiński, et al., ISPCS2018, CERN, Switzerland, 2018

[OYA15] I. Oya et al., "Status and plans for the array control and data acquisition system of the Cherenkov Telescope Array", in Proceed. 34th International Cosmic Ray Conference, 2015, The Hague, The Netherlands, PoS (ICRC2015); and M.Brückner and R.Wischnewski, "Array Time Synchronization - First Tests with White Rabbit", CTA-Consortium Meeting, Amsterdam, Netherlands, May 2012, unpublished

[TLU14] M. Tluczykont et al., Astropaticle Phys. 56, 42 (2014)

[BUD17A] N. Budnev et al. (TAIGA Collaboration) Nucl. Instr. Meth. Phys. Res. A 845 (2017) 330–333. http://iopscience.iop.org/article/10.1088/1742-6596/718/5/052006/pdf

[BUD17B] N. Budnev et al. (TAIGA-Collaboration), "The TAIGA experiment - a hybrid detector for very high energy gamma-ray astronomy and cosmic ray physics in the Tunka valley", in Proceed. 35th International Cosmic Ray Conference, Busan, Korea, 2017, PoS (ICRC2017) 768

[BRU13] M. Brückner and R. Wischnewski, "A White Rabbit setup for sub-nsec synchronization, timestamping and time calibration in large scale astroparticle physics experiments", in Proceedings 33rd International Cosmic Ray Conference, Rio de Janeiro, Brazil, July 2-9, 2013, p.1146; Braz. J. Phys. 44 (2014) no.5, p 1146

[WIS15] R. Wischnewski, M. Brückner and A. Porelli, "Time Synchronization with White Rabbit - Experience from Tunka-HiSCORE" in Proceed. 34th International Cosmic Ray Conference, 2015, The Hague, The Netherlands, PoS (ICRC2015) 1041

[BRU17] M. Brückner and R. Wischnewski, A time stamping TDC for SPEC and ZEN-platforms based on White Rabbit, ICALEPS-2017, doi:10.18429/JACoW-ICALEPCS2017-THPHA088

[LIP13] M. Lipinski. (2013, May) Torture report. ttps://www.ohwr.org/project/white-rabbit/uploads/9499d6742a17ba43ee4c7daa1ebd68fb/tortureReport.v3.2.pdf

[HUB17] T. Huber et. al (IceCube--Gen2 collaboration), in Proceed. 35th International Cosmic Ray Conference, Busan, Korea, 2017, PoS (ICRC2017) https://pos.sissa.it/301/401/

[CATS] CATS – The Cloud-Aerosol Transport System, 2015, http://cats.gsfc.nasa.gov/

[POR17] A. Porelli e t al (TAIGA Collaboration) TAIGA-HiSCORE observation of the CATS-Lidar on the ISS as fast-moving point source”, in Proceed. 35th International Cosmic Ray Conference, Busan, Korea, 2017, PoS (ICRC2017) https://pos.sissa.it/301/754/

[WLO12] T. Wlostowski, https://www.ohwr.org/project/white rabbit/uploads/ae3282acd8f9f6c5a9067b061202277d/wr_external_reference.pdf

[MEIN] https://www.meinbergglobal.com/