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Tools and methods for delay calibration before installation and in situ

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Abstract

This deliverable report provides an overview of the development of new tools and methods for calibration of hundreds of White Rabbit Ethernet nodes prior to installation as well as in situ calibration for CTA and KM3NeT.

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II DELIVERY SLIP

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IV Application 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

CTA	Cherenkov Telescope Array
DESY	Deutsches Elektron-Synchrotron
EEPROM	Electrically Erasable Programmable Read-Only Memory
FOM	Stichting Fundamenteel Onderzoek der Materie
FPGA	Field Programmable Gate Array
GPS	Global Positioning System
GUI	Graphical User Interface
KM3NeT	A multi-km^3 sized Neutrino Telescope
Nikhef	Nationaal Instituut voor Kernfysica en Hoge-EnergieFysica
NWO-I	Stichting Nederlandse Wetenschappelijk Onderzoek Instituten
PCB	Printed Circuit Board
PPS	Pulse Per Second
RX	Receiver
SFP	Small Form-factor Pluggable
SKA	Square Kilometre Array
TX	Transmitter
UvA	Universiteit van Amsterdam (University of Amsterdam)
WRE	White Rabbit Ethernet

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

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

This deliverable report provides an overview of the work undertaken within WP 5.1 of the ASTERICS project. The WP 5.1, *Time Synchronization*, is centered around the White Rabbit Ethernet (WRE) technology. Within this work package, a significant effort is devoted to the development of new tools and methods for calibration of hundreds of White Rabbit nodes prior to installation as well as *in situ* calibration for CTA and KM3NeT.

The general layout of CTA and KM3NeT can be considered as large Ethernet networks with hundreds to thousands of nodes, which are widely distributed. The reconstruction of high-energy gamma rays and neutrinos requires nanosecond level synchronization of all the detector elements. In order to provide such a faithful and accurate timing source to the detector arrays of CTA and KM3NeT, the WRE technology was adopted in the early stage of both projects. The remaining challenge is the calibration of hundreds of telescopes and thousands of optical modules.

Within WP 5.1, new software tools were developed to ease the relative calibration measurements for hundreds of WRE nodes prior to their installation. Furthermore, complete timing calibration procedures for CTA and KM3NeT have been developed in close collaboration with KM3NeT scientists and engineers at Nikhef and elsewhere. The development of the calibration methods detailed in this report includes both relative and absolute timing calibration of the detector elements. Furthermore, methods to monitor and cross-check the stability of the timing properties of the system in-situ were developed.

In conclusion, the work package has been instrumental for establishing a successful timing calibration procedure for KM3NeT and CTA and the deliverable "Tools and methods for delay calibration before installation and in situ" as explained in the grant agreement can be considered fully implemented.

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1 Introduction

Radio interferometers and other distributed astronomy facilities, such as CTA and KM3NeT, depend critically on the distribution of a common clock and frequency signal. Making use of the White Rabbit Ethernet (WRE) technology (1), which is already deployed in other physics detectors, allows us to overcome the need for expensive atomic or maser clocks and provides a highly standardised alternative to the intricate and custom-built timing solutions used in previous neutrino telescopes and radio telescope arrays.
One of the challenges of using the WRE technology for distributed, many element detectors is their calibration as well as the measurements and verification of the obtained calibration values in-situ. We therefore developed within the ASTERICS project new calibration and characterization tools for WRE equipment which are described in the following sections.

2 White Rabbit Relative Calibration

To calibrate a White Rabbit Ethernet network, the so called White Rabbit link model can be used which is shown in Figure 1. To be able to align the clock signal, especially the phase of the clock, the master-slave (δ_{MS}) and the slave-master delay (δ_{SM}) between the two White Rabbit nodes have to be determined. These delays are split up in three parts:

- The RX and TX delay of the White Rabbit *Master*, including the delays in the FPGA, the PCB and the SFP.
- The asymmetry in propagation delay from *Master* to *Slave* and vice versa, caused by chromatic dispersion in the optical fiber.
- The RX and TX delay of the White Rabbit *Slave*, including the delays in the FPGA, the PCB and the SFP.

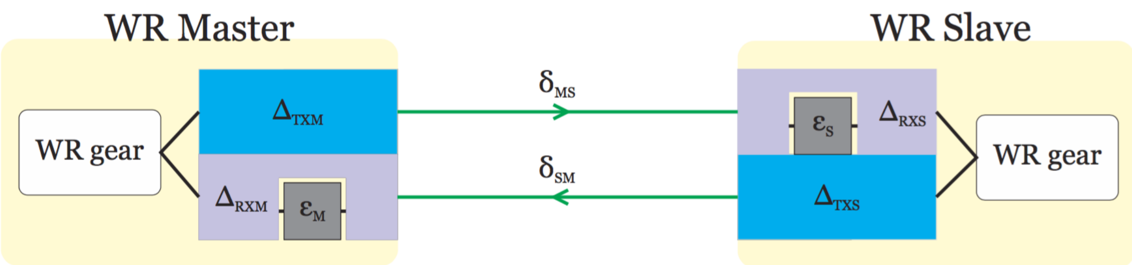

Figure 1: Schematic layout of the White Rabbit link model used for relative calibration; taken from (2).

The current default calibration procedure for a White Rabbit Ethernet network is a relative calibration method where a reference master calibrator is chosen and all White Rabbit equipment is calibrated relative to this master calibrator. The official calibration guidelines can be found in (2).

2.1 Development of a WRE calibration software package

To ease the calibration measurements, a complete software package was developed including a user-friendly GUI interface shown in Figure 2. It allows the user, in addition to making sure that the calibration values are obtained in a consistent way and verified, to keep track of these measurements and store the obtained values in a database for bookkeeping purposes. This enables easier maintenance of the WRE network when single components have to be replaced during the life time of the experiment and can be used for verification and validation of the required timing precision and accuracy over time.

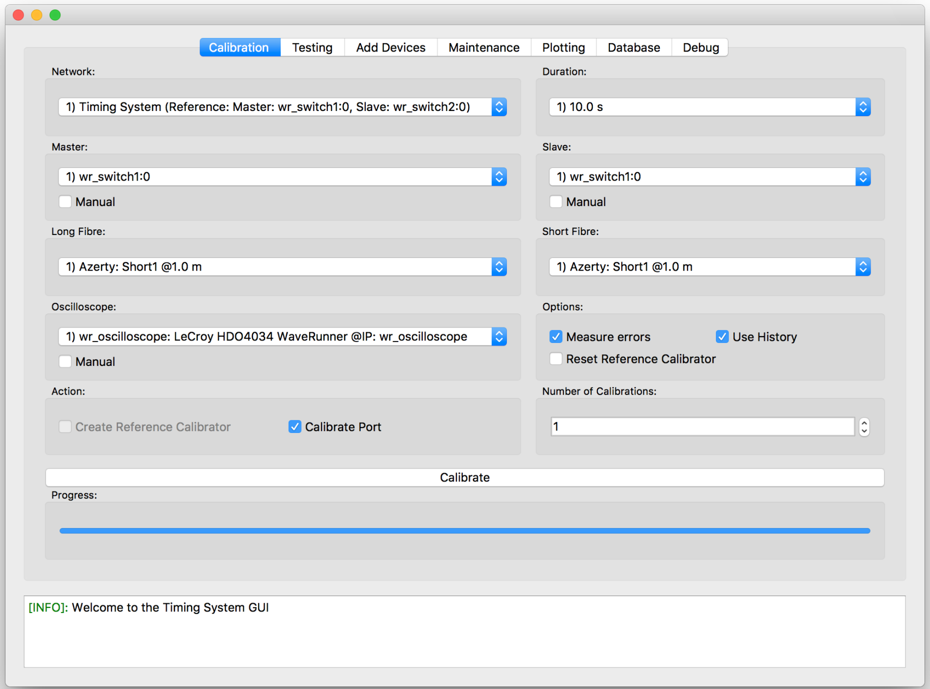

Figure 2: GUI interface for the developed White Rabbit Timing System Tools.

2.2 Calibration studies for a CTA-like system

A mock setup of a many-element Timing System, similar to the one proposed for use in CTA, has been installed in the Amsterdam lab. It consists of a single White Rabbit Master Switch which is connected to an external GPS clock to provide absolute timing information. The master switch then distributes the reference time and frequency over a network of intermediate White Rabbit Switches via optical fibers to dedicated White Rabbit timing nodes which provide the interface between the Timing System and the telescope cameras in CTA. The White Rabbit timing nodes used here are the ZEN-CTA boards developed by Seven Solution which are based on the WR-ZEN board design (3) with additional time stamping capabilities dedicated for the use in CTA. After the successful commissioning of these ZEN-CTA boards, we used 32 of these timing boards for our Timing System lab setup. They are connected to the intermediate White Rabbit Switches with optical fibers of different lengths (up to 5km), mimicking a CTA array with 32 telescopes.
Using the *White Rabbit Timing System Tools* described in Section 2.1, the Timing System setup has been calibrated in the lab. Afterwards, several verification measurements have been performed to study the influence of various parameters on the relative calibration of such a White Rabbit Network and to refine the calibration procedure for CTA (4). An example measurement of the PPS skew of the calibration, i.e., the difference between the PPS signals seen between two devices after calibration, is shown in Figure 3. It can be clearly seen that the PPS skew measurements are well below the order of a few hundreds of picoseconds and therefore well within the CTA timing requirements.

2.3 Development of a calibration procedure for KM3NeT

The timing calibration procedure for KM3NeT was developed in collaboration with KM3NeT scientists and engineers at Nikhef and elsewhere. The calibration procedure covers 1) the relative timing calibration

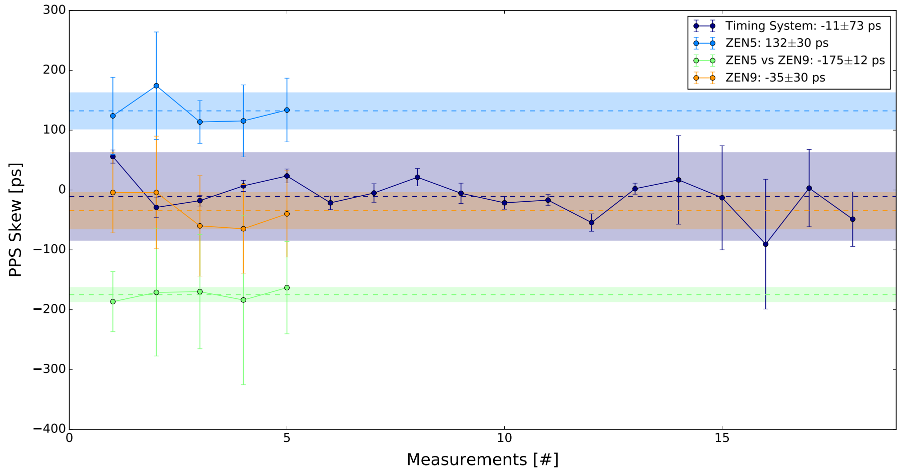

Figure 3: Shown is the verification PPS skew of the calibration of a mock CTA Timing System, i.e., the PPS skew between the *GrandMaster* switch and two White Rabbit nodes called *ZEN5* and *ZEN9* as well as the PPS skew between the two nodes themselves.

of the 31 photo-sensors that make up a KM3NeT optical module, 2) the relative time offsets of the 18 optical modules that make up a detection string, 3) the relative offsets of the detection strings with respect to each other and the propagation delay in the approximately 100 km cable that connect the detection array to the shore.
For items 1) and 2) both lab-based and in-situ calibration methods have been established, allowing cross-checks and vital measurements of the stability. In addition, the White Rabbit system allows to monitor the delays in the individual optical fibres in the 100 km cable while the detector is operating (see Figure 4).

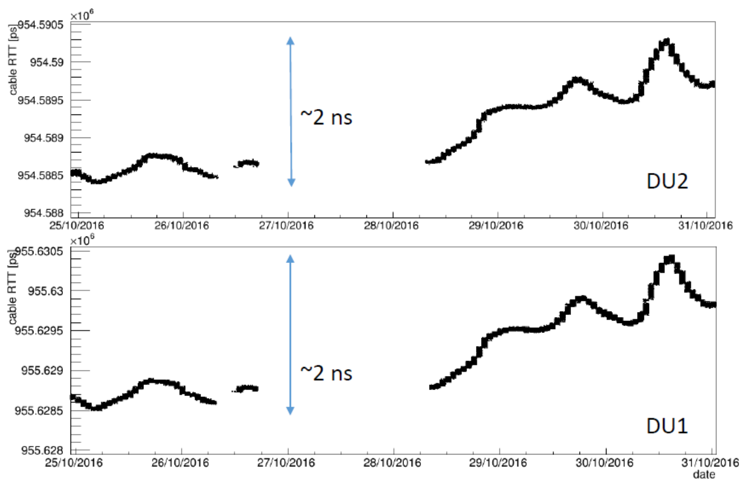

Figure 4: Stability of the round-trip-time in the ~100 km cable between two deployed detection lines and the shore station in Sicily. Variations are observed of the order of 2ns, which are fully correlated in both signals. This illustrates the ability of the KM3NeT White Rabbit implementation to monitor sub-ns variations in the relative timing of the detection elements.

The implementation of the White Rabbit system in KM3NeT and the timing calibration procedure have been documented in (5). The procedures developed have been positively reviewed by a panel of international experts in Feb 2017 and have, moreover, been validated by the operation of the first deployed KM3NeT detection lines.

3 White Rabbit Absolute Calibration

As an upgrade to the relative calibration method described in Section 2, absolute calibration enforces standardization since it enables independent developers and/or vendors to exchange their WRE gear while achieving absolute sub-nanosecond timing. Furthermore, absolutely calibrated WRE devices can be used as "golden standards" for the relative calibration procedure.

3.1 Development of an absolute calibration procedure

The calibration of a White Rabbit Ethernet node for the absolute calibration can be done in any lab or on site since no reference master calibrator needs to be used. Absolute calibration is achieved by measuring the time relationship ($\Delta_{\mathrm{TXcal}}, \Delta_{\mathrm{RXcal}}$) between the external electrical phase planes of the PPS signal and the interface to the Electrical-Optical/Optical-Electrical converter (EO/OE, usually the electrical SFP connector) as shown in Figure 5. EO/OE converters have their own calibration parameters that define the relationship between their electrical and optical phase planes and these calibration parameters are stored in the EEPROM such that the system can automatically reach absolute calibration during link initialization.

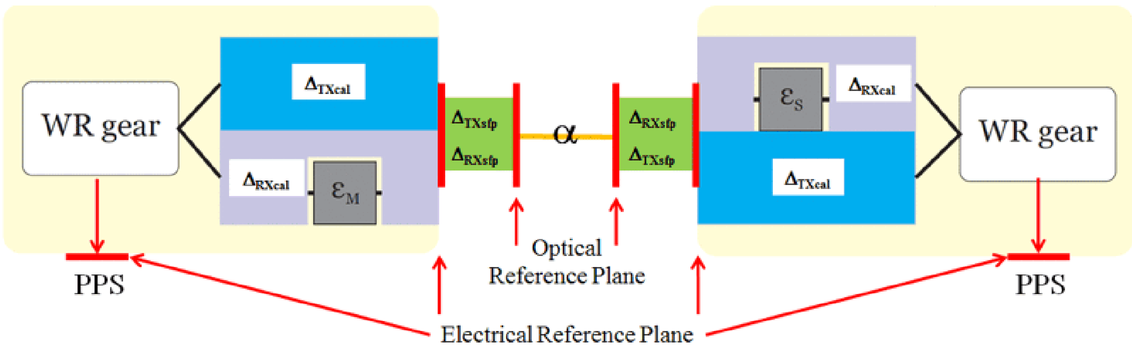

Figure 5: Schematic layout of the White Rabbit link model used for absolute calibration; taken from (6).

In order to perform the measurements for absolute calibration, described in detail in (6), a special Timing Calibration Module (SFP+ loopback calibration probe) and a high-speed oscilloscope are needed.

3.2 SFP+ Timing Calibration Module

The purpose of the Timing Calibration Module developed at Nikhef (7) is to measure the absolute timing on the reference (phase) plane on a White Rabbit Node or Switch. To measure it correctly, a special probe is developed that loops the Ethernet signal back to the node and provides a tapped ethernet signal routed to a couple of coax connectors, such that it can be easily connected to a oscilloscope with sufficient bandwidth. All the relevant module delays that are known in order to trace absolute timing back from oscilloscope to the reference (phase) plane are stored inside the EEPROM of the module and can be read via the I2C interface.

3.3 Multi SFP Crate

In order to be able to accurately measure the delays of Small Form-factor Pluggable (SFP) modules a Multi SFP Crate was developed (8). It is needed to accurately determine the delays of the Timing Calibration Module module (described in Section 3.2) and the eo/oe delays of SFP modules itself. Software (9) was developed to readout and program the EEPROM of SFP modules such that they can be updated with valid delay information according to a standardizes format (10).

3.4 In-situ asymmetry coeffient determination

The White Rabbit asymmetry coefficient (α) between forward- and backward propagation delay over the fiber can be measured in the lab using the relative calibration method described above. However, this needs either access to both ends of the link, i.e., having them at the same physical location, or an extra fiber is needed as a probe for the distant PPS signal. This is not feasible when WR is deployed in existing networks. Moreover, there is a need to verify and monitor the asymmetry coefficient in existing networks.
Therefore, a new measurement procedure was developed which can be applied in-situ by deducing the α-coefficient from the round-trip time while operating the White Rabbit link at different wavelengths. Moreover, by using a tunable laser SFP, only a single SFP calibration is needed and the asymmetry coefficient can be determined while the link is continously up and synchronized.
NOTE: A publication about this breakthrough of the in-situ α-determination is currently in preparation and the content discussed here should be treated confidential until published in a journal! (11)

4 Summary & Conclusion

We have developed methods for the relative and absolute timing calibration of White Rabbit Ethernet equipment. Methods to monitor and cross-check the stability of the timing properties of the system in-situ were developed. Furthermore, we have shown that the developed tools can be used for the calibration of the many-element detectors CTA and KM3NeT and that the WRE, once calibrated, will meet the timing requirements of each experiment. In addition to this intra-experiment application, the WRE technology can interconnect facilities into coherent networks, and thus enables highly synchronised real-time observations of the same astronomical objects by widely separated instruments, providing a unique "multi-messenger" view of astrophysical phenomena.
In conclusion, the ASTERICS work package WP 5.1 has been instrumental for establishing a successful timing calibration procedure for KM3NeT and CTA and the deliverable "Tools and methods for delay calibration before installation and in situ" as explained in the grant agreement can be considered fully implemented.

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