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Time synchronization and time calibration in KM3NeT

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The KM3NeT neutrino telescope is a next generation Cherenkov detector consisting of 3D arrays of optical modules installed in the deep waters of the Mediterranean Sea. The optical modules contain photomultiplier tubes that detect the Cherenkov light that is produced by particles that stem from a neutrino interaction. The signals from the photomultiplier tubes are timestamped by a clock inside the optical module. For the precise reconstruction of the neutrino direction, nanosecond precision synchronization between the optical modules is required. The White Rabbit system is used to synchronize the clocks inside the optical modules through Ethernet over optical fiber. This system was modified for the KM3NeT architecture to incorporate a clock distribution based on a fiber-optic broadcast. The calibration procedure to correct for the time offset of each photomultiplier tube in the detector is described. Application of the time calibration procedure to the first detection unit with 18 optical modules and its performance are presented.

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1. The KM3NeT neutrino telescope

The recent detection of cosmic neutrinos has opened new opportunities for exploring the Universe. To this end the KM3NeT collaboration started the construction of a neutrino telescope on the bottom of the Mediterranean Sea. The main scientific goal of the experiment is to detect neutrinos from astrophysical sources (ARCA [1]). The ARCA detector is mainly sensitive to neutrinos in the energy range 10^{11}–10^{16} eV and will consist of two so-called building blocks with a total size of about one cubic kilometer. Each building block consists of a 3D array of optical modules. The optical modules [2] are attached to 800 m strings, also referred to as detection units, that are held vertically upright by a buoy. Each optical module contains 31 photomultiplier tubes (PMT), and a so-called Central Logic Board (CLB) [3] with dedicated readout electronics. A building block will contain 115 detection units, each with 18 optical modules. The PMTs detect the Cherenkov light that is produced by charged particles that stem from a neutrino interaction. The analogue signals from the PMTs are timestamped by the CLB inside the optical module. The digital data are sent to shore where they are processed in real time by a farm of PCs. Besides the optical modules, a detection unit has a container at the bottom with an additional CLB. This is called the base of the detection unit. The first detection unit (DU) is now ready for deployment.

A building block with a reduced size will be constructed (ORCA [4]) in addition to ARCA. With this detector the mass hierarchy of neutrinos will be determined. Without loss of generality, the ARCA and ORCA detectors are considered as large Ethernet fiber-optic networks with nodes in the deep sea (the CLBs) and on shore (the PCs).

The key observable in order to reconstruct the particle trajectory from the Cherenkov light is the arrival time of the light on the PMTs. For the best possible angular resolution the relative arrival times should be known with an accuracy of about 1 ns. Therefore, an accurate time calibration of each PMT is required for the offline analyses and for the real-time filtering of the data. To achieve this required accuracy the CLBs are synchronized to a common clock signal which is generated on shore. The absolute time of a neutrino event is determined by the typical timescale of astrophysical phenomena and is of the order of seconds to milliseconds.

2. Clock synchronization

KM3NeT uses White Rabbit [5] for the time synchronization of the CLBs which uses the same fiber-optic network as for the data transfer. White Rabbit (WR) is a protocol for synchronizing nodes with sub-nanosecond accuracy and picosecond precision in an Ethernet network. A typical WR network is a hierarchical topology, consisting of WR-compliant devices, in which multiple WR links are replicated. A WR link is a pair of nodes, a master and a slave, that are connected via a bidirectional link. In the WR network a traceable grandmaster clock distributes the clock frequency and time to all clocks in the network. The absolute time synchronization is achieved by adjusting the clock phase and offset of each slave to that of its master. The synchronization is based on the measurements of the transmission time (t_1), reception time (t_2), re-transmission time (t_3) and reception time (t_4) of a reference signal sent from the master to the slave and back [6]. The total round trip time T_{RTT} can then be expressed as

$$T_{RTT} = (t_2 - t_1) + (t_3 - t_4) \tag{2.1}$$

The constant time offset between the master and the slave can be determined as

$$t_{offset} = \frac{T_{RTT} + \Delta T}{2} \tag{2.2}$$

where ΔT is the time asymmetry in the system:

$$\Delta T \equiv \sum_{downlink} T - \sum_{uplink} T \tag{2.3}$$

where *downlink* refers to the path from the master to the slave, and *uplink* to the path from the slave to the master. In the ideal case $\Delta T = 0$, but usually a non-zero time asymmetry arises due to the electronics, dispersion in the optical fibers and differences in the downlink and uplink paths.

The WR technology has been modified for the KM3NeT detector to incorporate a clock distribution based on a fiber-optic broadcast. Instead of having a bidirectional WR link for each node, as in standard WR, the grandmaster clock signal in the KM3NeT network is distributed via a unique unidirectional 1 Gb/s downlink to reach all KM3NeT slave clocks in the CLBs. In return, each CLB has a separate Gb/s uplink to shore for the transmission of the PMT (and other) data. Because of the inherent large asymmetry in the system due to the difference between the path of the clock signal to the CLBs and the path of the data, a hybrid approach is implemented. In this approach the WR broadcast system is used for the CLBs in the bases of the DUs, but partially used for the CLBs in the optical modules. The CLB in the bases are synchronized as in standard WR, by exchanging the transmission and reception times of a reference signal (see equation 2.1). However, WR that is running on the CLBs in the optical modules has been modified such that the clock is synchronized by setting its clock to the transmission time t_1 of the master. It does not re-transmit the time signal back to the master. As a result, the offset of the clock on the CLB in an optical module is entirely due to the downlink path. The uplink path has no effect on the time offset. As a consequence, standard Ethernet switches instead of WR switches can be used for routing the data from the optical modules to the PCs. A consequence of the broadcast is that the offset of the clock on the CLB in an optical module is fixed with respect to the master clock. This offset remains the same each time after power-up of the system. The KM3NeT fiber-optic network with this WR broadcast hybrid implementation is shown in figure 1.

3. Time calibration

The time calibration of each PMT is obtained by the combination of the calibration of the shore station (in figure 1 indicated by the the part *on shore*), the calibration of the seabed infrastructure (in figure 1 indicated by the off-shore *node for connecting multiple DUs*) and the calibration of a DU (in figure 1 indicated by the box *DU-1*). The time asymmetry in the shore station can be measured at all times. The time asymmetry in the seabed infrastructure has been measured separately before deployment. The effects of dispersion have been investigated and are known. The calibration of a DU requires:

- light signal measurements in the dark room
- measurement of the round trip time between the shore station and the CLB in the base using the same network setup

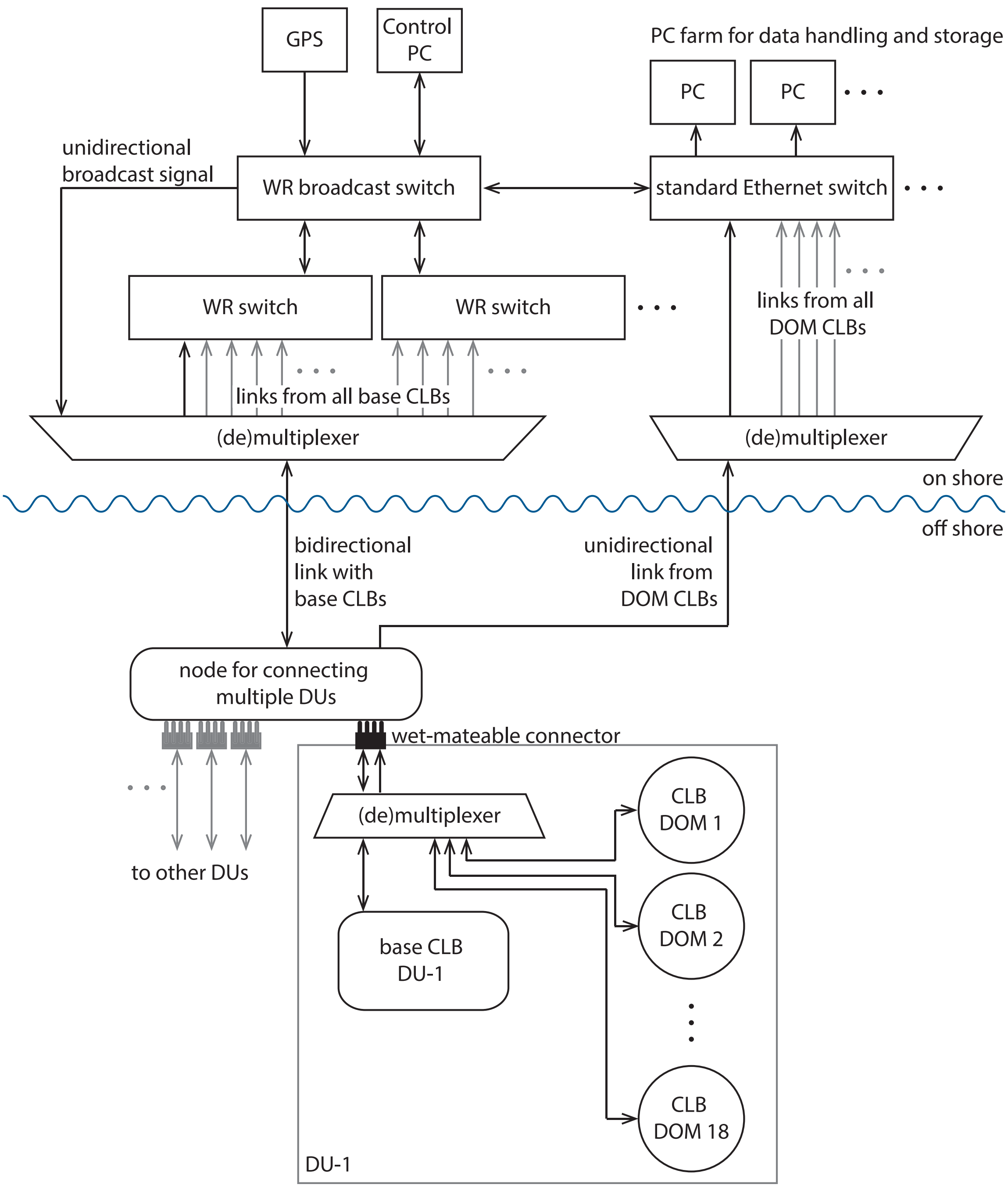

Figure 1: Schematic view of the fiber-optic network of KM3NeT where only the first DU is shown (DU-1). The time synchronization signal is sent from the WR broadcast switch to all CLBs in the detector. The return signals from the base CLBs are routed through the same fiber as the clock signal to the WR switch fabric. The data from the CLBs in the digital optical modules (DOM) are routed through a separate set of fibers and then distributed via a standard Ethernet switch to a farm of PCs. To allow for slow control communication between the Control PC and the CLBs in the optical modules the WR broadcast switch and the standard Ethernet switch are connected with a simple link.

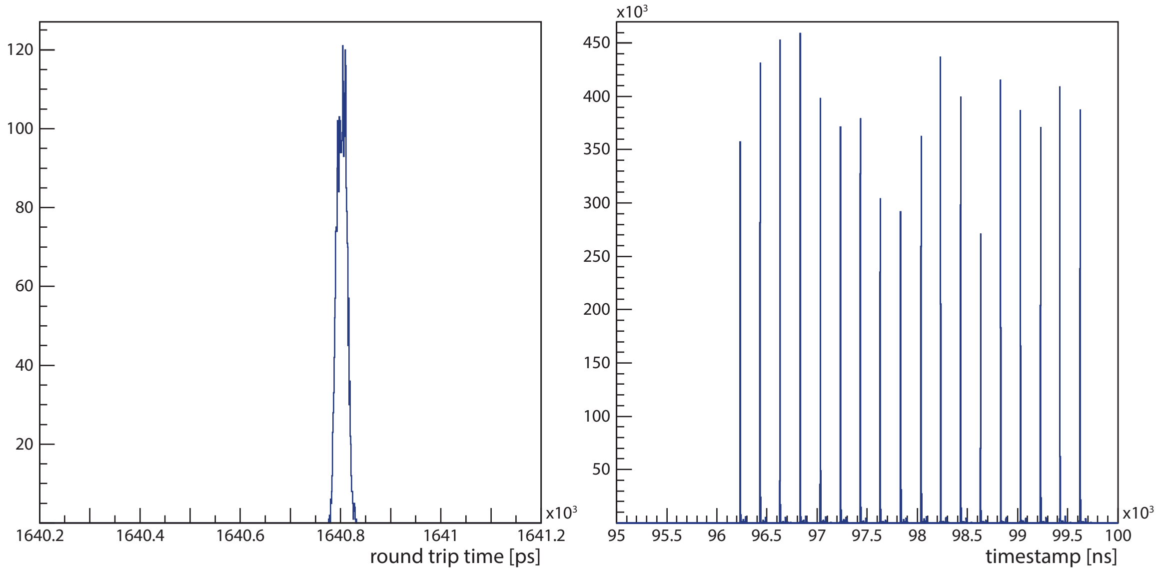

Figure 2: Left: the round trip time in the dark room setup between the WR broadcast switch and the CLB in the base, in ps. Right: the timestamp of the light signal detected by each of the 18 illuminated PMTs of the DU, in ns. These timestamps represent the time offset of the corresponding PMTs with respect to the master clock. With the light source flashing at 100000 ns, the most right signal represents the offset of the PMT in the lowest optical module (closest to the master) and the most left signal represents the offset of the PMT in the upper optical module. The light signals detected by two neighboring optical modules are about 200 ns apart, which corresponds to the distance between two optical modules on a DU.

- measurement of the round trip time between the shore station and the CLB in the base in situ, after deployment of the DU.

3.1 Dark room calibration

For the dark room calibration a DU is connected as a whole directly to the shore station (in figure 1 indicated by the part *on shore*). In this setup the downlink path is only a few meters. Since the deployment of the DU will have an effect on the time offsets of the PMTs due to the changed downlink path, the round trip time between the WR broadcast switch and the CLB in the base has to be measured before and after deployment. The round trip time is measured by WR with picosecond precision and is monitored during the operation of the DU in the dark room. It is shown for DU-1 in figure 2 on the left and it is found to be stable within 50 ps.

In the dark room one PMT in each optical module is illuminated by a single light source via optical fibers of equal lengths. This light flash arrives at the photo-cathode with a fixed time delay with respect to a known GPS time as can be seen in figure 2 on the right. The average difference between the time of the light flash, t_{flash}, and the measured arrival time of the light at a given PMT on DU n in optical module i, $t_{measured}(n,i,PMT)$, provides for the time calibration of the PMTs:

$$t_0^{darkroom}(n,i,PMT) = < t_{flash} - t_{measured}(n,i,PMT) > \tag{3.1}$$

As a result, the time calibration of the PMT refers to the downlink path from the master to the slave.

3.2 PMT calibration

The PMT calibration is the time offset to be applied to the measured arrival time of the light at a given PMT after deployment of the DU. After deployment the PMT timestamps only change due to the extra delay in the downlink path. This change is corrected for the propagation delay of the clock signal from the shore station to the wet-mateable connector of the DU (see figure 1). With WR the change in the downlink path is re-measured using the CLB in the base by measuring the round trip time of the clock signal. Any asymmetry in the system that is the same before and after deployment cancels, as is the case for the time asymmetry in the base. Hence this asymmetry cancels in the difference between the master–base delay before and after deployment. The difference between the master–base delays in the dark room and in situ, corrected for the time asymmetry found for the shore station and the seabed infrastructure and for the effects of dispersion, yields the propagation delay of the clock signal up to the wet-mateable connector of the DU (see figure 1) and is given by

$$\Delta T_{MB} = \frac{T_{RTT}^{insitu}(n,0)}{2} - \frac{T_{RTT}^{darkroom}(n,0)}{2} \tag{3.2}$$

The time calibration of a PMT, t_0, can then be expressed as

$$t_0(n,i,PMT) = t_0^{darkroom}(n,i,PMT) + \Delta T_{MB} \tag{3.3}$$

The measured arrival time of a photon at a given PMT can now be corrected offline for the time offset as follows:

$$t(n,i,PMT) = t_{measured}(n,i,PMT) + t_0(n,i,PMT) \tag{3.4}$$

In this way all PMTs in the detector are time calibrated.

Awaiting the deployment of DU-1 this procedure has been tested in the dark room by including a 25 km fiber between the switch fabric (operating as the shore station) and DU-1. The round trip time between the master and the CLB in the base was re-measured, of which the results are shown in figure 3 on the left. When the same PMTs are illuminated by a light source as was done in figure 2 (right), and the measured timestamps are corrected for the offsets that were then found using equation 3.1, the timestamp of the detected light signal peak of the illuminated PMTs is equal to the difference in master–base delay found by equation 3.2. When applying the correction given in equation 3.3 to the timestamps the calibration for these PMTs is restored, as can be seen in figure 3 on the right.

The relative time calibration of the PMTs inside the same optical module can be obtained from an analysis of the decays of ^{40}K in the glass sphere of the optical module (in the dark room) or in the sea water (in situ, after deployment) [7]. The expected resolution of this procedure is better than 1 ns.

4. Conclusion

A hybrid solution based on WR has been developed to synchronize the optical modules that are part of the KM3NeT neutrino telescope. The time calibration obtained before deployment can be restored in the sea. LED beacons installed inside the optical modules, laser beacons at the sea bottom, ^{40}K decays and atmospheric muons [7] can be used to monitor the time calibration in situ.

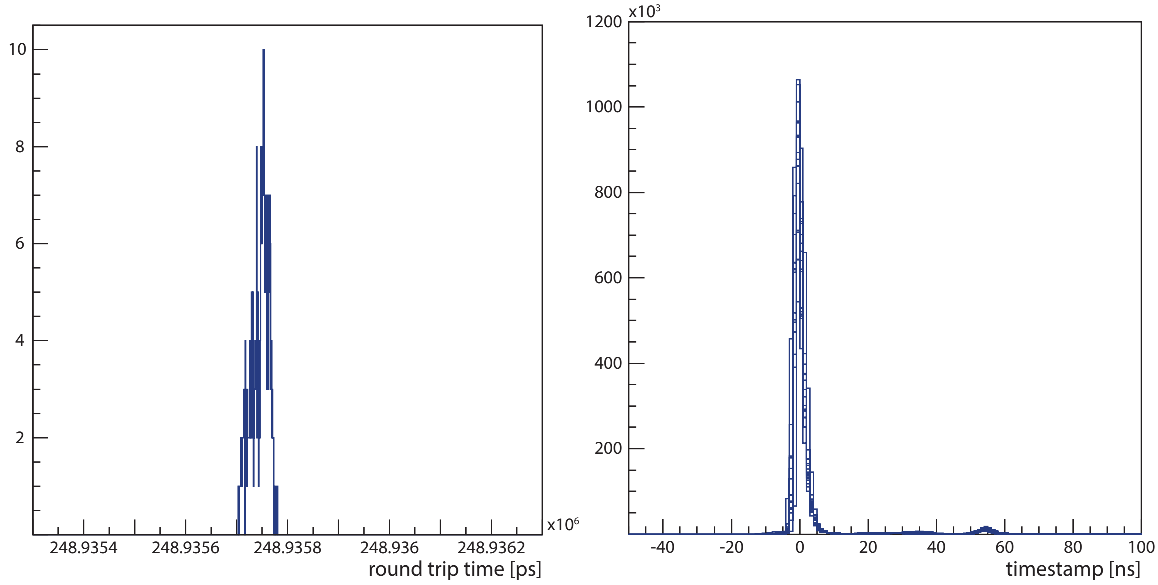

Figure 3: Left: the round trip time in the dark room setup between the WR broadcast switch and the CLB in the base, in ps. A fiber of 25 km was added between the master and the DU, as if it had been deployed. Right: the timestamp of the light signal detected by each of the 18 illuminated PMTs of the DU, in ns, after the offset correction that was obtained in the darkroom, and after the master–base delay correction that was obtained after the WR round trip time measurements before and after the simulated deployment.

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