

Introducing TAXI: a Transportable Array for eXtremely large area Instrumentation studies

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Abstract. A common challenge in many experiments in high-energy astroparticle physics is the need for sparse instrumentation in areas of 100 km² and above, often in remote and harsh environments. All these arrays have similar requirements for read-out and communication, power generation and distribution, and synchronization. Within the TAXI project we are developing a transportable, modular four-station test-array that allows us to study different approaches to solve the aforementioned problems in the laboratory and in the field. Well-defined interfaces will provide easy interchange of the components to be tested and easy transport and setup will allow in-situ testing at different sites. Every station consists of three well-understood 1 m² scintillation detectors with nanosecond time resolution, which provide an air shower trigger. An additional sensor, currently a radio antenna for air shower detection in the 100 MHz band, is connected for testing and calibration purposes. We introduce the TAXI project and report the status and performance of the first TAXI station deployed at the Zeuthen site of DESY.

Keywords: TAXI, large area instrumentation, data acquisition, air shower detection

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INTRODUCTION

The measurement of charged cosmic rays and astrophysical neutrinos at the highest energies requires extremely large instrumented areas due to the low flux levels. Ultra-high energy cosmic rays (UHECR) and neutrinos are correlated due to the fact that the interaction of these protons with the cosmic microwave background radiation will produce a guaranteed flux of cosmogenic neutrinos [1]. Hence, the detection of those neutrinos will open a new window to astrophysics, cosmology, and neutrino physics at high center-of-mass energies. UHECR detectors operating today, the surface detectors of the Pierre Auger Observatory [2] and of the Telescope Array experiment [3], already instrument areas of the order of thousands of km². Next-generation detectors with sizes larger than 10000 km² are under study [4]. Recently, a 100 km² low-threshold air shower detector at the South Pole has been proposed [5] as an atmospheric muon veto for the IceCube Neutrino Observatory. Two 100 km² experiments aiming at the detection of cosmogenic neutrinos using radio techniques in ice are currently under construction: ARA [6] and ARIANNA [7]; large-area hybrid detectors combining optical, radio, and acoustic detection channels have been proposed [8].

All these detectors have the need for communication between detection units, low maintenance, decentralized power generation, clock distribution and trigger generation in common. They are built in harsh environments, from Antarctic climate to deserts with large daily temperature variations. Further, for site selection campaigns, long-term background measurements and signal propagation / detection studies have to be performed in-situ at different candidate sites. One project dedicated to study power generation in the field, mainly in Antarctica, but also at other locations is the ARA autonomous renewable power station [9]. We aim to generalize the approach of separating the physics detector from the underlying infrastructure requirements even further in the TAXI project: a Transportable Array for eXtremely large area Instrumentation studies.

THE TAXI CONCEPT

The goal of the TAXI project is to design and build a modular, autonomous detection station using well-understood reference air shower detectors and the possibility to connect any new type of sensor with waveform readout up to 180 MHz sampling rate. Possible options for the sensor include radio antennas for air shower or neutrino detection,

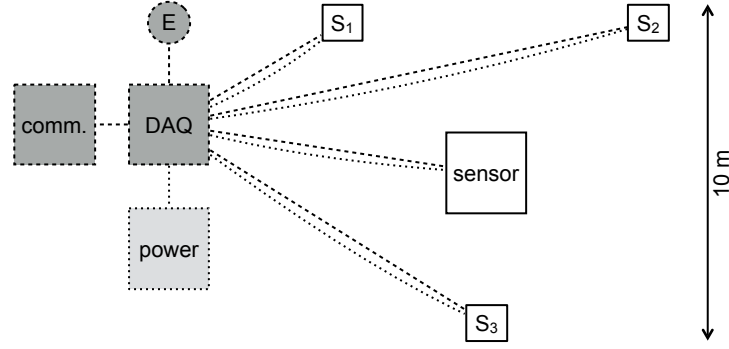


FIGURE 1. Schematic drawing of a single TAXI station: it comprises three scintillator reference detectors S_i deployed at typically 10 m mutual distance, a test sensor, power (dotted) and communication (dashed) links, and environmental monitoring E .

muon detectors of any type or hybrid (radio/muon/electron) detectors for air shower detection. Also photomultiplier tubes (PMTs) for non-imaging Cherenkov telescopes, or, at lower sampling rates, acoustic detectors can be connected. Transient electromagnetic signals in the GHz band can be recorded using signal envelope techniques. Well-defined power and communications interfaces will allow us to test different approaches to power generation and data transfer in the field. With a single station new sensors can be tested and calibrated with a known air shower trigger with excellent timing and basic directional sensitivity. A small array of four TAXI stations enables the development and long-term in-situ testing of new communication and power generation systems under realistic trigger conditions. This leads to the following requirements for TAXI:

High modularity allows easy interchange of components, especially the power supply and communication modules. The interfaces will be defined up to the connector types and pinouts including the underlying communication protocol.

Easy transport and setup allows site studies for future projects using custom sensors with full waveform readout. This includes long-term monitoring of backgrounds and in-situ signal propagation studies (signal speed, attenuation, refraction, and others).

Operation at isolated sites requires low power consumption and a self-sustaining power supply like photovoltaic, wind, or similar systems. Further, the system shall operate in the full range of Antarctic to hot climate zones.

Figure 1 shows schematic drawing of a single TAXI station.

DESIGN AND PERFORMANCE OF THE FIRST TAXI STATION

A first TAXI prototype station has been constructed and has been deployed on the Zeuthen site of DESY in June 2013. As air shower reference detectors segmented 1 m^2 plastic scintillator plates with nanosecond time precision [10] are used. In each plate four $50 \times 50 \text{ cm}^2$ segments are read out separately. Every segment is read out with two PMTs in coincidence mode for noise suppression; two Hamamatsu R5900-03-M4 four-channel PMTs are installed for this purpose. The scintillator plate, PMTs, and HV generation are housed in a weather-proof aluminum housing that is supplied with a voltage of $\pm 12 \text{ V}$. The eight PMT signals are transmitted via differential signalling over shielded twisted pair cables to the station DAQ.

In the first prototype station, the PMT signals are processed by a VME-based DAQ system, which is read-out via USB by a Raspberry Pi¹ single board computer. The signals of all 12 segments (three plates, four segments each) are split and are i) discriminated and recorded by a time-to-digital converter (TDC) with 1 ns time resolution and ii) integrated by a charge sensitive ADC for calibration and monitoring purposes.

¹ <http://www.raspberrypi.org/>

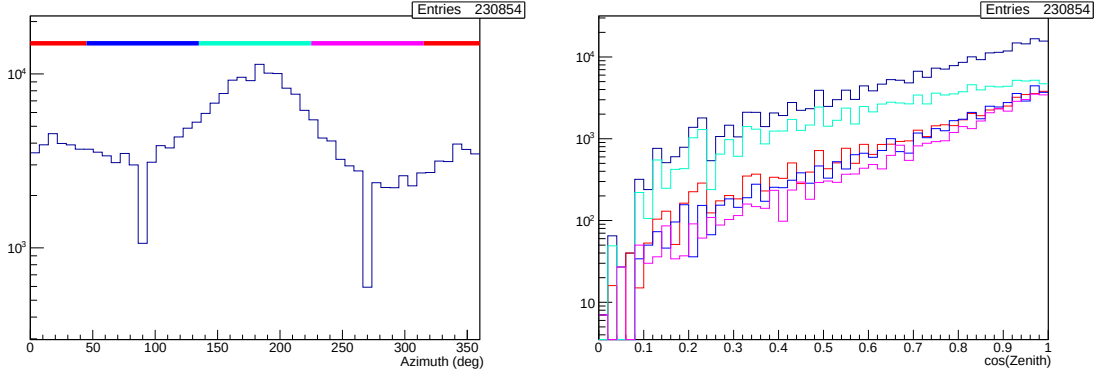


FIGURE 2. Air shower directions reconstructed from the arrival time differences in the scintillation reference detectors. The colored zenith-histograms correspond to the four different azimuthal ranges indicated by the horizontal band in the azimuth distribution.

The discriminated signals are routed to a custom-made trigger board. A FPGA on the trigger board allows programming arbitrary trigger conditions between the 12 segments. Currently we require at least one segment in each of the three scintillator plates to record a signal above threshold in a 400 ns time window.

For the waveform readout of the test sensor the digitizer board developed for the Auger Engineering Radio Array (AERA) [11] is used (see e.g. [12] for a detailed description of the board). For TAXI we currently employ two of the four 180 MHz ADC channels with a buffer depth of 7 seconds. On an external trigger signal from the DAQ of the scintillation detector, 11.4 μ s (2048 samples) of waveform data around the trigger time are stored together with the scintillation detector event and the data are timestamped using the GPS module integrated on the AERA board. As a test sensor we currently use a Short Aperiodic Loaded Loop Antenna (SALLA) for radio air shower detection from the Tunka-Rex experiment [13], originally developed for the LOPES experiment [14]. The E-W and N-S polarization are read out separately by the two ADC channels on the AERA digitizer board.

Environmental monitoring is performed with a commercial weather station. In addition, temperature and humidity sensors are installed in the central DAQ housing. Further, the temperature of the Raspberry Pi single board computer and of the AERA digitizer board are monitored continuously.

The first TAXI prototype station is operating without problems since deployment; more than one year of data have been collected now. The thresholds for the scintillation detector are set to a trigger rate of 40 Hz for each segment after the coincidence of the two PMTs reading out the segment. Requiring at least one triggered segment in each of the three plates this results in a global trigger rate of approx. 1 min^{-1} .

The measurement of the signal arrival time differences in the three scintillator plates with the TDC allows the reconstruction of the direction of the air shower assuming a plane wave front. The reconstructed arrival directions for all showers where the corresponding system of linear equations had a solution, are shown in Fig. 2. The deficits visible at azimuthal angles of 90° and 270° are an artefact of the reconstruction algorithm used. The colored zenith-histograms correspond to four different azimuthal ranges as indicated by the band in the azimuth histogram. It can be seen that for vertical showers the rate in all azimuthal ranges is equal while in three azimuthal sectors the shower rate is suppressed for inclined showers. This structure can be explained by the shadowing through buildings surrounding the TAXI prototype station on the roof of the mechanical workshop at the Zeuthen site of DESY.

NEXT STEPS

To meet the low-power requirement the VME-based DAQ system for the scintillation detector will be replaced by a new single-board DAQ system that will incorporate the TDC functionality, FPGA based triggering, monitoring, and slow control. In addition, it will optionally offer the possibility to record PMT waveforms from the scintillators for monitoring and calibration purposes via a DRS4 switched capacitor array [15]. Figure 3 shows a block diagram of the TAXI readout board currently under development. The TDC functionality will be realized in the FPGA with an expected precision of 1 ns. With the DRS4 and corresponding ADCs powered off, the TAXI readout board will require

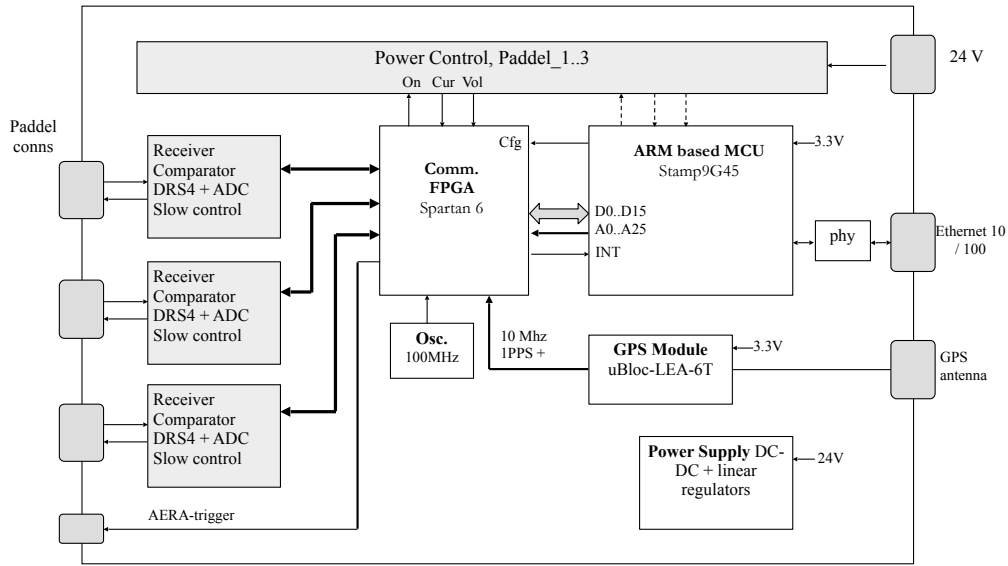


FIGURE 3. Block diagram of the TAXI readout electronics currently being developed.

less than 10 W of power which can be supplied in the field by solar panels or wind turbines.

We expect to construct and install four TAXI stations using the new readout board by the end of 2014. This first mini-array will use solar power and commercial WiFi for communication.

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