Fast Data Acquisition system based on NI-myRIO board with GPS time stamping capabilities for atmospheric electricity research

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Abstract. In the investigation of the fast physical processes, such as propagation of a lightning leader and detection of the correspondent radio emission waveforms, it is crucial to synchronize the corresponding signals in order to be able to create a model of the lightning initiation. Therefore, the DAQ system should be equipped with a GPS synchronization capability. In the presented report, we describe the DAQ system based on a NI-myRio board that provides detection of particle fluxes, the near-surface electric field disturbances and waveforms of radio signals from atmospheric discharges, all synchronized with an accuracy of tens of nanoseconds. The results of the first measurements made at Aragats high-altitude station of Yerevan Physics Institute in Summer-Autumn 2015 are presented and discussed.

1. INTRODUCTION: REQUIREMENTS ON DAQ SYSTEM

When designing a Data Acquisition Electronics (DAQ) system to be used in the high-energy physics and astrophysics experiments, the standard requirement is to achieve reliable and consistent registration of all electronic signals from the particle detectors with inherent correlations. The parameters of DAQ system should be continuously monitored to keep them stable. Electronics should not introduce any uncertainty in the particle detection due to changing efficiency and variations of the “dead times”. The particle energy released in the bulk of the plastic scintillators provides additional information on the type and energy of particles. DAQ electronics should be able to measure and store not only the number of registered particles in a definite time span (usually 1 sec or 1 minute), i.e. time series of count rates, but also histograms of energy releases, i.e. amplitudes of the Photomultiplier (PM) signals.

The PMTs, High Voltage Power Supplies, Buffer Preamplifiers as well as the Logarithmic Analog-to-Digital Converter (LADC), the 8-channel counter board (8CNT) with a programmable threshold are the same as were previously used in the Aragats Space Environmental Center (ASEC, Chilingarian et al., 2005, Arakelyan et al., 2009) DAQ systems. All these elements are highly integrated into the ASEC infrastructure; they proved to be robust and demonstrating a reliable performance for many years under severe climatic conditions.

The buffer preamplifier with a +1 voltage gain amplifies the PMT signals. The amplifier with the output resistance of 50 Ohm sends the pulse signal, completely repeating the shape of PMT anode current pulse, through the impedance matched 50-Ohm coaxial transmission line to the control room for further processing. Thus, the whole information about the event registered by the detector is delivered to the LADC without any losses. To transform the analog measurement in digital form the PMT signals are rectified, smoothed and compared with a reference voltage, which varies exponentially. To ensure the correct work of LADC and to control the threshold of comparator we use a voltage from the output of the Digital-to-Analog Converter. For investigation of such fast physical processes as propagation of lightning leader and detection of correspondent fast waveforms of radio emitting, the accuracy of the time stamp of the registered events should be several tens of nanoseconds. Therefore, the DAQ system should be equipped with a GPS synchronization capability. The registration of an Extensive Air Shower (EAS) – a gigantic cascade of particles propagating in the atmosphere with a velocity reaching the speed of light, the synchronization of different registration channels is very important as well. In the presented report, we describe the DAQ system and the first measurements made at Aragats high-altitude station of Yerevan Physics Institute in Summer-Autumn 2015.

2. THE NI-MYRIO BOARD

The heart of the DAQ system is National Instrument’s NI-myRIO board (see Fig. 1 and attachment). It combines the Xilinx Zynq All Programmable SoC with a ready-to-go Linux-based real-time OS (RTOS). It places 40 GPIOs (general propose input output), wireless capabilities, a dual-core ARM real-time processor, and a customizable Xilinx FPGA. The output pulses of the 8CNT board are fed to the FPGA of the myRIO board where the logic of event identifying, pulses counting and GPS time stamping is implemented.

A custom PCB is made based on a myRIO Expansion Port (MXP) Breakouts KIT. It includes the GPS module connection UART for NMEA sentences and a 1PPS signal for FPGA time keeping algorithm. The board is also equipped with a 20 pin 2.54mm pitch PCB IDC Connector to feed the output pulses of the 8CNT board to the FPGA of the myRIO board via a ribbon cable.

With the reconfigurable FPGA technology, we perform high-speed signal processing, high-speed control, inline signal processing, and custom timing and triggering. For the control systems, one can also run advanced control algorithms directly in the FPGA fabric to minimize latency and maximize loop rates.

LabVIEW FPGA Module”, which extends the LabVIEW graphical development platform, provides an alternative to HDL (Hardware description language) graphical programming approach that simplifies the task of interfacing to I/O and communicating data. This greatly improves the embedded system design productivity and reduces the time of project accomplishment.

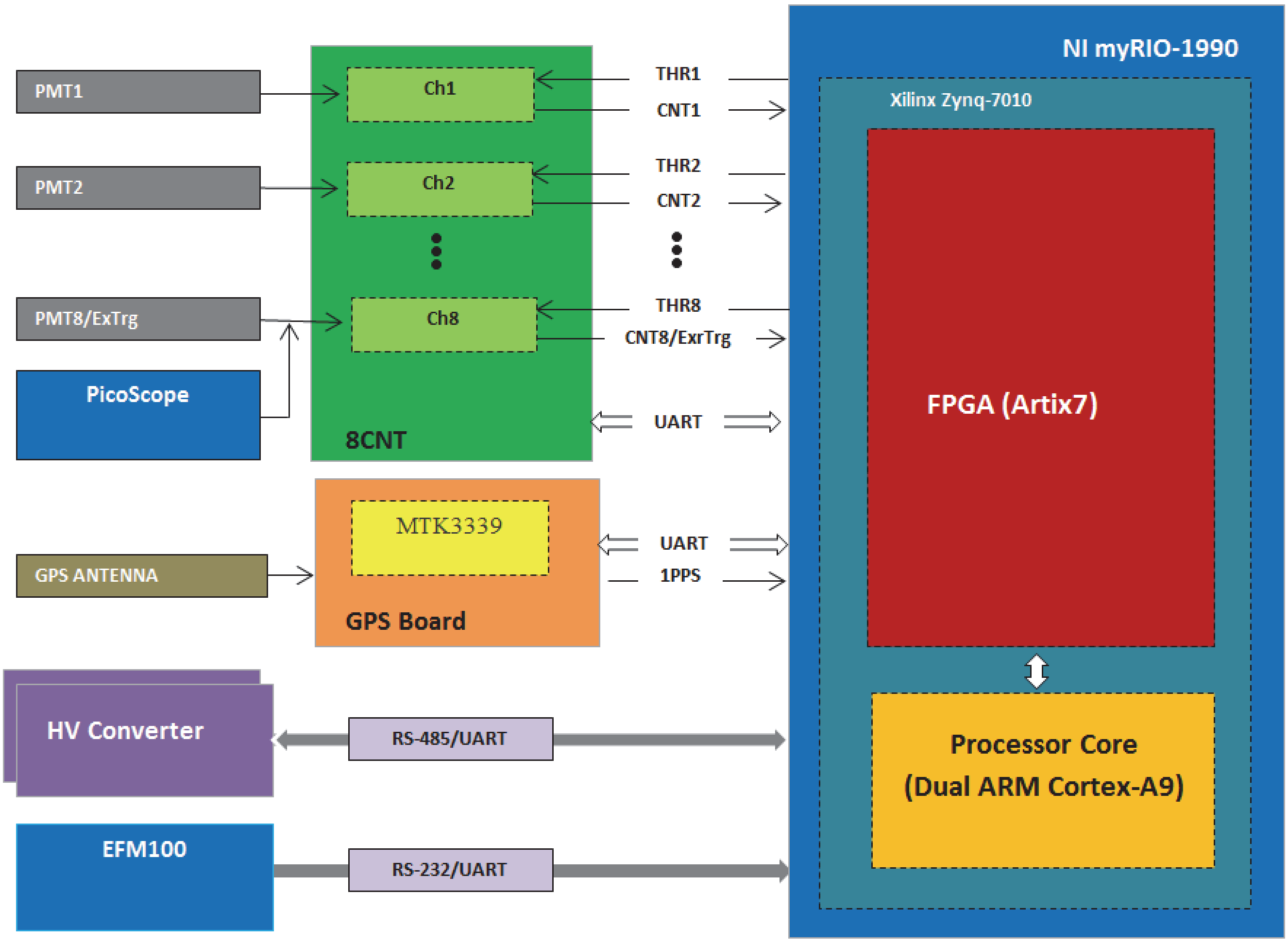

Figure 1. The DAQ system: Photomultipliers (PMT) FEU49, PM30 or other types; Programmable Local High Voltage Power Supply for PMT with RS-485 interface; Buffer Preamplifier; Board of 8 Logarithmic Analog-to-Digital Converter (LADC)/or 8-channel counter board (8CNT); GPS Module with an active antenna FGPMMOPA6H; NI-myRIO -1990.

The commercial GPS module directly supplies the date and "coarse" UTC time and reports geographic location (latitude and longitude) down to the equivalent of a few tens of meters. The GPS receiver sends two types of data-streams to the board. The first is RS-232 ASCII data, telling what time it is, at what latitude, longitude and altitude the receiver is, and information about the satellites the receiver is attaching. An embedded 25 MHz counter on FPGA gives the exact time of the event. The 1PPS (one pulse per second) stream of the 5V, 100-ms pulses resets this counter at each second. The leading edges of 1PPS signals from GPS receivers anywhere in the world are all synchronized within the accuracy of the non-military GPS system (about 100 ns.) This feature allows accurate time synchronization; the estimated resolution to meet is 100 ns. However, the GPS module FGPMMOPA6H (a 4th generation stand-alone GPS module with lightning fast TTFF (Time-to-First Fix), ultra-high sensitivity -165dBm, and low power consumption gives us 10 nsec resolution.

3. HIGH PRECISION DAQ SYSTEM IN HIGH-ENERGY ATMOSPHERIC RESEARCH

The research of the high-energy physics in the atmosphere is still in the earliest stage and each year new interesting phenomena are discovered (Chilingarian et al., 2010, 2011, Chilingarian, 2014). Measurements of the amplitude, duration, energy spectra of the particle fluxes from the thunderstorm atmosphere, the so-called Thunderstorm Ground Enhancements (TGEs) performed at Aragats Space Environmental center (ASEC) prove vast variability and richness of new phenomena. Recently at ASEC, we started the correlation analysis of the TGEs and lightnings that pose additional requirements on the time resolution and synchronization of particle detectors, near surface electric field sensors and sensors of the fast radio waveforms of atmospheric discharges. The DAQ electronics being developed can solve such problems.

The four inputs of DAQ (Fig. 1) are used for feeding signals from STAND1 detector comprised of 3 vertically stacked 1 cm thick and 1 m^2 area plastic scintillators and 1 stand-alone 3 cm thick plastic scintillator of the same area (near the SKL experimental hall). The DAQ pulse counting system can provide very short time series down to 1 millisecond that will enable to investigate in much more details the dynamic of TGE development and its relation to the lightning initiation.

Signals from the sensor of "slow" near surface electric field disturbances (from the "electric mill" EFM-100 of Boltek company) are fed to the myRio board by the TCP-IP connection (WiFi). The firmware application provided by Boltek has a feature to share E-Filed data via network. It acts as a server for a client running under myRIO for E-Field measurements.

The EFM-100 has also an analog output for direct measurements but, unfortunately, it is not optically isolated. It is directly connected to the field mill and a lightning hazard exists at those connections. There are plans to implement optical connection and use direct analog measurements utilizing 500 kHz 12 bit analog inputs on the myRIO device.

One channel is reserved for the synchronization pulse (the trigger) from the device recording a fast waveform. A flat-plate antenna followed by a passive integrator is used to record fast electric field change waveforms. The output of the integrator is directly connected to the digital oscilloscope (Picoscope 5244B) with 60 cm long RG58 coaxial cable. The waveforms are recorded with a sampling rate of 62.5MS/s, (sample interval 16ns) and 8-bit resolution. Data capture length is 500ms, including 100ms pre-trigger and 400ms post-trigger time. The oscilloscope trigger is connected to the GPS time-stamping system described above. Any fast electric field waveform recorded by the oscilloscope that is above the trigger threshold forces the GPS system to trigger and produce a timestamp. *A special output will be generated at any triggering signal* containing precise times of each particle arrival 100 msec before and 400 msec after trigger, near surface electric field value and other information (number of satellites used by GPS system, etc). Thus, the fast waveform patterns will be synchronized with particle arrival to detector with an accuracy of a few tens of nanoseconds.

Two from three units of the STAND1 type detectors that compose a network for the TGE and lightning research are equipped with the new DAQ system (the third one will be equipped with myRio board electronics in summer 2016). Universality of the system will allow solving of the EAS registration problem as well. The unit installed in MAKET experimental hall is attached also to 3 channels of the muon detector (channels 5-7) comprised of 3 vertically stacked plastic scintillators interlayered with a total of 15 cm of lead and 60 cm of carbon. Several channels of 18NM Neutron Monitor located nearby will be attached to the DAQ system too. The Neutron Monitor and Muon detector are sensible to Extensive Air Shower (EAS) cores that occasionally hit the MAKET building (Chilingarian, Hovsepyan and Kozliner, 2016). Thus, DAQ electronics will register simultaneously EAS particles, near surface electric field and TGE.

The mechanism of particle acceleration is due to the existence of free electrons in the atmosphere as well as on the origination of a Lower positive charge region (LPCR, Chilingarian and Mkrtchyan, 2012), which, together with the negatively charged region in the middle of the cloud, forms a positive dipole that accelerates the ambient cosmic-ray electrons downward to the Earth. A mature LPCR is a necessary condition for unleashing of a Relativistic Runaway electron avalanche (RREA) and registering a TGE on the Earth's surface. LPCR as well do not let a lightning leader to reach the Earth, changing its direction horizontally. Usually no cloud-to-ground lightnings (-GC) are registered during TGE, just intracloud (-IC) lightnings are. The second mechanism that connects the lightning discharge with EASes postulates that the lightning leaders follow the EAS path in the atmosphere. If a large EAS hits the thundercloud during TGE, the huge amount of EAS electrons can enable the lightning leader propagation through the LPCR and TGE will abruptly terminate. The new DAQ electronics will help us to observe in details these very complicated phenomena and unambiguously establish the relation between EAS, TGE and lightning initiation. Large EAS detection is a rather rare event and registration of EAS on the nanosecond time scale will help to reveal the 3-dimensional structure of these gigantic particle showers. The DAQ system will store the current data from the muon detector and neutron monitor channels by the abruptly enhanced muon detector coincidences, reflected passage of numerous high-energy muons from EAS core through particle detectors.

4. FIRST DETECTION OF PARTICLE FLUXES AND ATMOSPHERIC DISCHARGES

In August and September 2015, two myRio boards were installed in MAKET and SKL experimental halls at Aragats station. To the myRio boards are attached 4 channels of the STAND1 detector, see Fig. 2. The top row of the picture shows the photo and the drawings of STAND1 detector. The three plots in the middle show the correlations

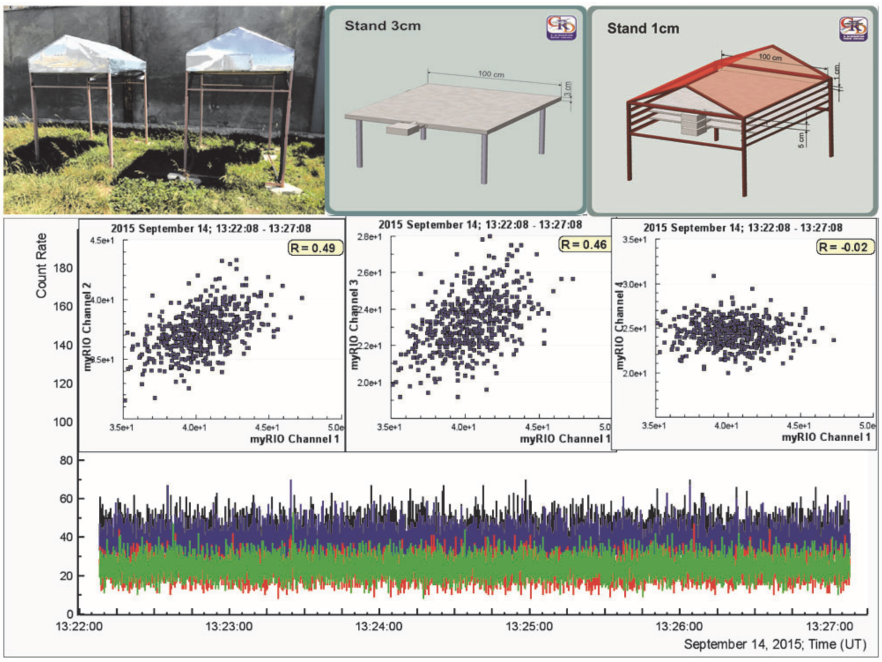

Figure 2. Correlations of 50 msec time series; top row – the photo of detector near the SCL experimental hall and charts of detector; the middle row – correlations of top scintillator with other 3; bottom row – 50 msec time series of 4 scintillators.

of the STAND1 detector's layers. The correlation of the top scintillator and stand-alone 3 cm thick scintillator is minimal, due to small fraction of particle showers with size of ~ 1 m and larger. The correlation of stacked scintillators is significantly larger due to the penetrating high-energy muons and electrons. In the bottom of Fig. 2, the 50 msec time series of STAND1 detector's scintillators are shown.

First large TGE of Autumn 2015 occurred on 7 October at 14:42-14:47, (see Fig. 3). One-minute time series of the STAND1 detector demonstrate huge enhancement, reaching ~100 standard deviations (100σ).

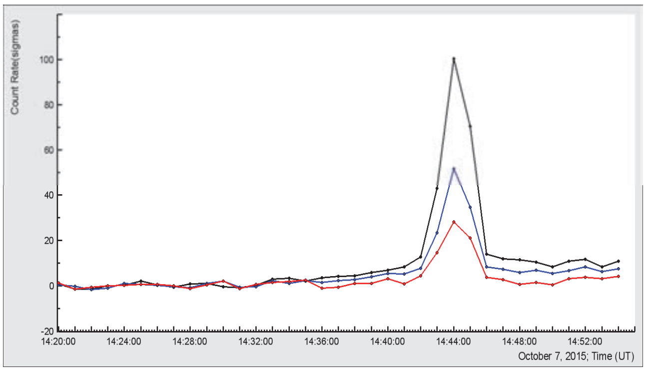

Figure 3. The TGE observed by STAND1 scintillators by 1-minute time series of count rates in number of standard deviations; the upper curve corresponds to upper scintillator, middle curve – to the middle scintillator and bottom curve to the bottom scintillator.

In Fig. 4, we show the two-second time series of the 60 cm thick scintillator of the ASNT detector; the abrupt decay of the count rate is apparent at 14:45:07. From 14:45:05 to 14:45:11 the count rate diminished by 11.6% (from 3263 to 2839 – the background value). The negative lightning that occurred in this time span raises the near surface electric field from -29 to +43 kV/m, i.e. the amplitude of lightning as measured by the near-surface electrostatic field was 72 kV/m (measured by the EFM-100 electric mill located on the roof of MAKET building).

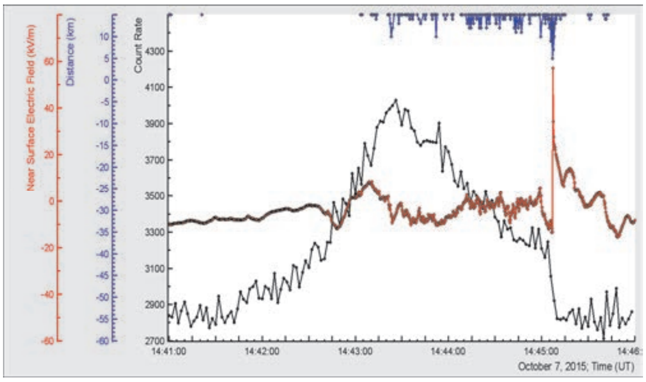

Figure 4. The same TGE as in Figure r observed in 2-second time series of the 60-cm thicj scintillator of the ASNT detector.; in the middle – disturbances of electric field with lightning coinciding with particle flux decline; in the top – distance to lightning by EFM-100 MAKET.

The 50 ms time series of STAND1 detector can bring additional evidence on the relations of lightning and particle flux decay. In Fig. 5 we demonstrate four seconds of the count rates of 3 cm thick outdoors plastic scintillator including the lightning time and particle flux decline time. In the left two "pre-lightning" seconds the count rate is larger than in the two "right" seconds. The lightning started at 14:45:07 and reached its maximum at 14:45:07.10 (the start and maximum are denoted by arrows in Fig. 5). The count rate declined at 14:45:7.175 and returned to the background level after the electric field reached its maximum, i.e. after the return stroke deposited the negative charge on the ground and the overall electric field in the cloud generally rearranged. Thus, after charge redistribution in the thundercloud the electric field, which accelerates electrons downward during TGE declines and particle flux abruptly terminates. The synchronization signal from Picoscope arrives before the lightning struck at 14:45:6:95.

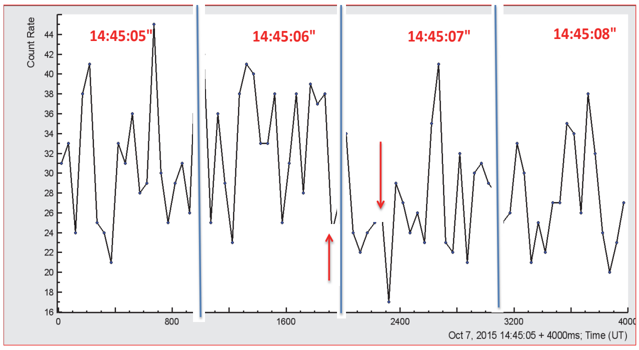

Figure 5. Four seconds of 50 msec time series before and after sharp decline of particle flux at 14:45:07 as measured by 1-sec time series; seconds are separated by the vertical lines; the picoscope (fast waveforms) trigger at 14:45:06.95 and maximum of near surface electric field (return stroke) at 14:45:07.15 is denoted by an arrows.

The exact time synchronization can be checked by the Picoscope trigger pulse and by the corresponding myRio registrations. In Fig. 6a we show the TGE occurred on October 14 2015 along with disturbances of the near-surface electrostatic field and solar radiation. As usual, the particle flux increased when the field was in the negative domain. Before the TGE several lightnings occurred, some of which generated triggers in the picoscope. In the zoomed Fig 6.b we show the time of the picoscope triggers. The corresponding GPS time stamps from myRio were as follows: 13:22:25.291, 13:23:17.586 and 13:24.23.634. Thus, we have now time stamp of picoscope trigger with at least one-millisecond accuracies. In this way we can synchronize particle fluxes and fast waveforms with the same accuracy.

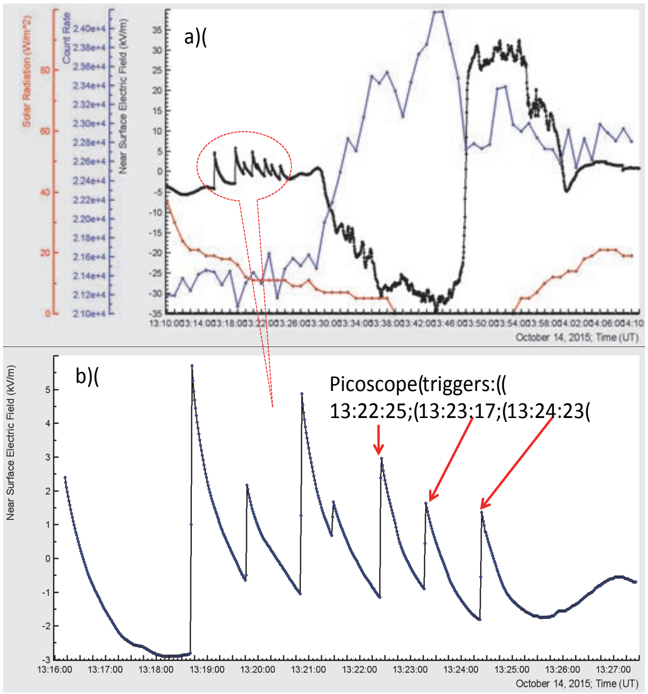

Figure 6 .The enhancement of the particle flux by the 1-minute time series of the upper scintillator of STAND1; in the bottom solar radiation decreasing till zero at TGE time (thick cloud was sitting just on the station. In the Fig. 6b zoomed version of the 5 negative discharges, 3 of which generate picoscope trigger.

5. CONCLUSION

New DAQ electronics based on NI myRio boards proves high effectiveness for the lightning-TGE research. DAQ electronics provides continuous registration of the 50 msec time series of count rates from 10 particle detectors.

The time stamp from the external trigger provides synchronization of the particle fluxes and fast waveforms of electric field with an uncertainty not worse than 1 μc.

The dynamics of the TGE events will be registered with all necessary details. For the first time it will be possible to solve long standing problems of the particle-lightning relations (Chilingarian et al., 2015a and 2015b):

Are particles born in the lightning bolt?

Do lightnings follow the path of Extensive air showers (EASes)?

On what stage of its development does a lightning abruptly cease the particle fluxes?

Do particle avalanches from the thundercloud initiate lightning?

Do LPCR prevent cloud-to-ground lightning, transforming it to an inter-cloud one?

The achieved synchronization accuracy will be very helpful in the lightning initiation researches planned in 2016.

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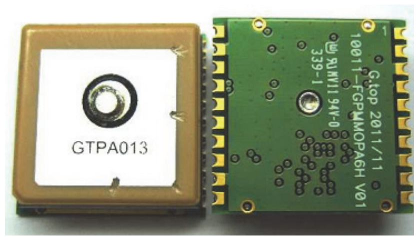
ATTACHMENT: HARDWARE DETAILS

NI myRIO-1900

The National Instruments myRIO-1900 portable reconfigurable I/O (RIO) device integrates a dual-core ARM real-time processor, and a customizable Xilinx FPGA, and I/O on a single printed circuit board (PCB). It is ideal for low- to medium-volume applications and rapid prototyping.

- Xilinx FPGA and dual-core ARM Cortex-A9 processor
- Wireless, USB Host Port, USB Device Port
- 10 analog inputs (12bit, 500 kS/s)
- 6 analog outputs (12bit, 345 kS/s)
- 40 digital I/O lines

GPS Module

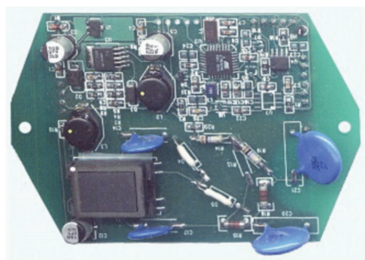


MediaTek MT3329 is a compact solution for adding GPS functionality to any device.

It features a high performance positioning engine with up to 12 multi-tone active interference canceller. It supports up to 210 PRN channels with 66 search channels and 22 simultaneous tracking channels. There is also an “Antenna Advisor” that helps with the detections of different antenna statuses, including active antenna connection, antenna open circuit and antenna shortage.

And the most attractive there is a high accuracy 1-PPS timing support with only 10ns jitter.

Programmable Local High Voltage Power Supply



Features:

- Voltage programming in two hardware selectable ranges ± 900V to 2100V and ±1500 to 3000V in 2V steps
- Output voltage ripple less than 1mV
- Max. output current 1.2 mA for ± 900V to 2100V range; 0.8 mA for ±1500 to 3000V range
- Input voltage from +12V to +15V
- Absolute output voltage regulated to accuracy ±1V
- Optional temperature sensor
- RS-485 half-duplex 2-wire 9600 baud interface for programming and monitoring the output voltage