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Timing Calibration and Synchronization of Surface and Fluorescence Detectors of the Pierre Auger Observatory

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Reconstruction of cosmic ray arrival directions for Surface Detectors (SD) and Fluorescence Detectors (FD) of the Pierre Auger Observatory requires accurate timing (25 nanoseconds or better) between measurements at individual detectors and instrument triggers. Timing systems for both SD and FD are based on Motorola Oncore UT+ GPS receivers installed into custom-built time-tagging circuits that are calibrated in the laboratory to a statistical precision of better than 15 ns. We describe timing calibration and synchronization methods applied in the field for both the SD and the FD systems in four areas: (1) checks of timing offsets within the SD using co-located station pairs and timing residuals on reconstructed showers, (2) calibration within the FD using a custom-build LED calibration system, (3) calibration between SD and FD using laser signals fed simultaneously into an SD station and across the FD via the Central Laser Facility (CLF), and (4) studies of synchronization between FD and SD through the analysis of events detected by both systems, called hybrid events. These hybrid events allow for a much more accurate reconstruction of the shower and for relatively tight constraints on timing calibration offsets. We demonstrate that statistical and systematic timing uncertainties have no significant impact on the event reconstruction.

1. Introduction: Time Tagging Systems for the Pierre Auger Observatory

The Pierre Auger Observatory, operated from Malargüe, Argentina, consists of two independent detector systems running together. The surface detector (SD) consists of 1600 water Cherenkov tanks spread in a triangular array (spacing 1.5 km) over an area of 3000 km^2. The fluorescence detector (FD) detects light from nitrogen gas ionized by the shower of charged particles with telescopes distributed in 4 FD station around the array [1].

Both detectors include circuitry for accurate time-tagging of signals detected by photomultiplier tubes (PMTs). The heart of this circuitry is a GPS receiver Oncore UT+ made by Motorola which is mounted as a daughter-board to each system. In both SD and FD stations, individual triggers are time-tagged using the 1 pulse-per-second (1 PPS) output of the GPS clock together with a serial readout correction term that allows for precision determination of the offset relative to the true GPS second for each pulse out.

Reconstruction of primary cosmic ray properties from measured extensive air showers requires accurate relative timing. The SD requires offline timing accuracy of better than 25 ns for pointing accuracy in reconstruction, and online timing accuracy of $< 1\mu$s for triggering. The SD uses a 100 MHz clock ($<$ 10 ppm precision) to latch the time of an event as well as the time of each 1 PPS. The SD electronics continually calibrates the clock to 1 μs over the full second range by measuring the true frequency and correcting the tagged event times that are transmitted for triggering. In addition, it records the 40 MHz system clock, and the GPS corrections necessary for later reconstruction.

2. Calibration of GPS receivers for SD stations

Each GPS receiver arrives from the factory with a fixed but unknown timing offset relative to the true GPS second. This offset can in principle vary as much as 100 ns from receiver to receiver. We have developed a technique to measure the offset for each receiver to be installed in an SD station and summary results are shown in Figure 1. Offsets were also measured during temperature cycling in a thermal chamber. Typical rms residuals for timing measurements were 10 ns to 15 ns. When we include estimated systematic errors due to sample binning of less than 15 ns, we claim an overall relative precision for calibrated GPS clocks to better than 20 ns.

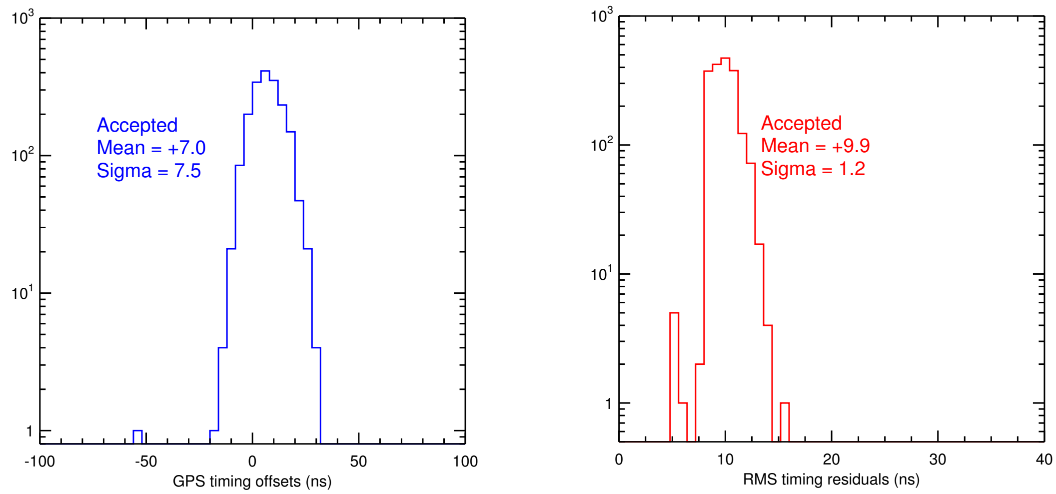

Figure 1. GPS receiver timing offsets and residuals as calibrated in the laboratory for all receivers to be used in the array. The vast majority of the receivers are calibrated with statistical residuals better than 15 ns.

A particularly effective technique for measuring directly the timing uncertainty on individual showers is to place two SD stations in close proximity at a location normally assigned to only one station. These "twin" stations allow us to directly compare timing measurement on real showers. Data from twins clearly indicate relative SD timing resolution of better than 15 ns.

Timing offsets are monitored in the field for stability by occasional re-calibration of selected field GPS receivers. Cosmic ray data from reconstructed showers can also be used to check for offset deviations. To date, this technique can rule out calibration offset errors larger than about 40 ns, but this number should improve as more statistics are gathered from the array.

3. Fluorescence Detector Timing

The FD timing is also derived from the Motorola GPS. The 1 PPS signal, a 10 MHz system clock and, external trigger signals are distributed from 1 central clock per FD station to the 6 telescope electronics. Time calibration in the FD stations is accomplished by a LED calibration system [2] that distributes a time-tagged light pulse via optical fibers to each of the telescopes simultaneously. Table 1 summarizes the results of the calibration for six telescopes each of the Los Leones and Coihueco FD stations. Except for outermost telescopes (#1 and #6), which have different cable length, we find time offsets for both buildings around 318 ns. The uncertainty due to systematic effects of the measurements and the not-well know propagation delay in the optical fiber is about 30 ns.

Table 1. Time calibration of offsets (in ns) for six fluorescence telescopes in each of two eyes using LED calibration system. Note* that cable lengths result in slightly smaller offsets for telescopes # 1 and # 6.

Telescope	# 1*	# 2	# 3	# 4	# 5	# 6*
Los Leones	289	313	322	322	319	286
Coihueco	291	318	316	317	319	288

4. Surface Detector vs. Fluorescence Detector Time Offset

The time synchronization between the FD and SD is important for a precise reconstruction of the shower geometry. This precision is obtained by using together time information from both detectors (hybrid reconstruction). So, it is crucial to have a good measurement of the SD/FD time offset (to within about 100 ns). The time offset between the surface detector and the fluorescence detector can be estimated using golden hybrid events or using lasers beams.

Golden Hybrid Events: Showers that triggered the FD and also at least 3 SD stations are called golden hybrid events. The geometry of those events can be independently reconstructed by either using only the SD information or by combining this information with FD data using a hybrid technique [3]. The location of the shower core reconstructed using the hybrid technique is sensitive to the SD/FD time synchronization. If the FD time is delayed (in relation with the SD time) the reconstructed core will be systematically pushed away from the FD location (increased distance to FD), and if the FD time is advanced, the reconstructed core will be systematically pulled toward the FD (smaller distance). Meanwhile, the core location that is reconstructed using only the SD information might also displaced, but this displacement direction will not be biased toward any particular direction. The left hand side plot in figure 2 shows the distribution of the Hybrid/SD core distance difference. This distribution shows that the mean is systematically off from zero by about -135 m. The right hand side distribution (in the same figure) shows that if we introduce to the hybrid reconstruction software a correction of 350 ns in the SD/FD time offset, the systematic in the core location is removed.

Vertical Laser Beams: Another way of measuring the SD/FD time offset is using laser beams. The Central laser Facility (CLF) built near the center of the ground array [4] fires vertical laser beams every night of FD operation. The laser beam is split and part of the laser light is sent through an optic fiber toward the nearest ground array station (this station is called Celeste). The laser intensity is sufficient to trigger Celeste as well as the FD telescope # 4 in Los Leones and # 3 in Coihueco, thus providing time-tagged signals in both systems. By a direct comparison of the reconstructed laser fire times in each system, we obtain the FD/SD time offset.

Due to the large distance between CLF and FD telescopes (between 25 km and 30 km) the width of the pulses seen by individual pixels are between 4000 ns and 5000 ns long. The long pulses and the fact that the analysis requires assumptions on the telescopes alignment in elevation angle restrict the accuracy of this method. However, regular laser measurements are well suited to monitor the relative SD-FD synchronization over time. Figure 3 shows the drift of the measured SD-FD offset from January 2004 till April 2005 for the Los Leones telescope # 4. The offset is stable within the resolution of 100 ns.

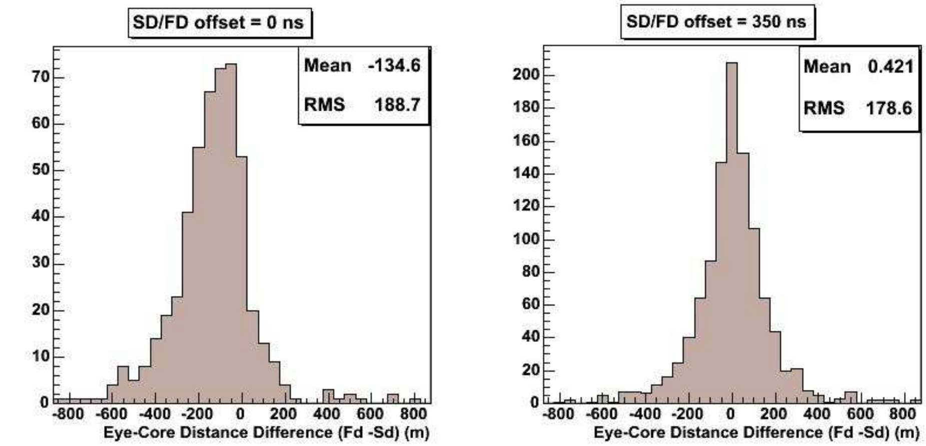

Figure 2. Distribution of the difference between the SD only and Hybrid reconstructed Eye-Core distance. The Hybrid reconstruction was performed using **Los Leones** site. For the left hand side distribution the hybrid core was reconstructed assuming a SD/Los Leones time offset of 0 ns, and for the right hand side distribution it was assumed a SD/Los Leones time offset of 350 ns (offset = SD - FD).

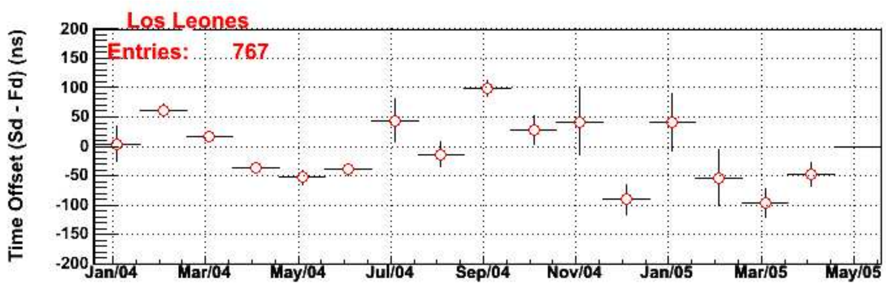

Figure 3. Relative SD-FD time offset (using vertical lasers) for each month since January 2004.

5. Conclusions

Based on several techniques for monitoring timing information we conclude that the relative timing for surface stations is measured to better than the 20 ns and that timing offset between FD and SD are known to better than 100 ns. The contribution of timing uncertainties to reconstructed shower parameters, including arrival direction and primary energy determination are small compared to contributions from other sources.

References

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