Data Acquisition System and GPS timing in CHICOS Ultra-high Energy Cosmic Ray Detectors

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Abstract

In this report we report the possibility of using commercial GPS receivers and National Instrument 6602 Data Acquisition Card to build the Data Acquisition System in CHICOS Ultra-High Energy Cosmic Ray Detectors. Timing accuracy of the detectors were tested and the accuracy between two independent detectors was able to reach 10nsec.
Acknowledgments

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Chapter 1

Introduction

To build an ultra large Extensive Air Shower (EAS) array it is necessary to tag event times at locations remote from one another, with high accuracy, and without physical wire connections. In order to build a low-cost, feasible and large area array (> 5000 km$^2$) of cosmic ray detectors, a possible method is using National Instrument 6602, a high-speed counter for PCI or PXI Bus System, with Motorola Oncore UT+ GPS receivers. In this paper we will discuss the experimental setup, the data acquisition system and the timing performance of the 2 independent prototype cosmic ray detectors.

1.1 Prototype System Overview

In CHICOS, each prototype event time-tagging system consists of three main components,

1. A low cost commercial GPS receiver module. The GPS receiver module used is Motorola Oncore UT+ GPS receivers, which is a 8 channel C/A code receiver. It is designed for precise timing purpose and it claims that it has 50ns timing accuracy provided it is in position-hold mode and while SA is ON. A 1 pulse per second (1 PPS) output is provided from the receivers which the rising edge gives a precise 1 second time.

2. The custom electronics usually consists of a updating discriminator. It
is used to convert an analog signal into a 5V TTL signal. As the National Instruments 6602 counter requires a TTL as input for counting, an updating discriminator is necessary since the width of the pulse is proportional to how many muons pass through the detectors at the same time. This information can tell how the cosmic ray muons are distributed throughout a large area.

3. A PC type computer for control and data acquisition purposes. The Data Acquisition System software is developed under Labview which features interactive graphics, a user-friendly interface and a powerful graphical programming language. A 6602 counter is installed into a PC computer controlled by Labview. 6602 counters offers 8 32-bit resolution counter with 80MHz internal timebase. Thus, the timing accuracy is up to 12.5 ns. With various measurements method, one can design the ones own program for specific data acquisition scheme.
Chapter 2

Data Acquisition System

In CHICOS data acquisition system, the following quantities are addressed. First is the arrival timing of the individual cosmic ray muons. Once the arrival timing information is gathered then it is possible to seek the coincidence of the cosmic ray muons. The measurements of the coincidence can help to identify a huge cosmic ray showers and the incoming direction of the showers. Second issue is the distribution of the cosmic ray muons, this can provide the location of the core of the cosmic ray showers and thus to deduce the energy of the primary cosmic rays.

2.1 Experimental Setup

Counter 1: monitoring the GPS 1PPS signal. (Buffered Period Measurement) This information is used to normalize the timing between each Data Acquisition System.

Counter 2: measure the timing of rising edge of the detectors pulses. (Buffered Period Measurement).

Counter 3: measure the time interval between the leading edges of 1PPS signal and the first detectors pulse after the 1PPS signals. (2-edge separation measurement). The informations from Counter 2 and 3 one can used to deduce the timing of each cosmic ray muons, with respect to each 1sec PPS time mark.
Chapter 2  Data Acquisition System

Counter 4: measure the pulse width of the detector pulses (Buffered Period Measurement) The width of each pulses is correlated to height of the incoming analog pulse. If one can get the correlation between the width of the pulse to the height of the pulse (i.e., ADC vs TDC), the height of the pulse can be deduced by measuring the pulse width of the detector signals.

Counter 5: count how many pulses within 1sec time interval. Since it is not possible to determine how many pulses within 1sec time mark by looking though the data stream. This is useful to seek coincidence.
Chapter 3

Comparison of GPS receivers

On Monday July 24, 2000 four GPS receivers were compared. These included the Motorola Oncore UT+ Oncore, used in the Kellogg Laboratory, and three portable ones (Garmin GPS 12 Personal Navigator, Magellan 315 and Tripmate). Readings of longitude, latitude and altitude were taken and compared at two locations of the laboratory of the roof.

3.1 Experimental Result

The most inaccurate readings were of the altitude. At the lower position the 4 GPS receivers are agreed to within 58 feet of each other. At the higher position the 4 GPS receivers are agreed to within 5 feet. (But trip-mate varies much so it is not reliable)

The readings for longitude and latitude were much more consistent. At the lower location the latitude of the 4 GPS receivers are agreed to within 0.12 seconds. While the longitude values are agreed to within 0.3 seconds of each other.

At the higher position the latitute are agreed within 0.18 seconds. While the longitude values are agreed to within 0.18 seconds of each other.

During these measurements it was observed that a metal railing on the roof around the GPS receivers seems to affect the values recived. This may be the
<table>
<thead>
<tr>
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<th>Latitude</th>
<th>Longitude</th>
<th>Altitude (feet)</th>
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</thead>
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<tr>
<td>Motorola Oncore</td>
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<td>-118°7.507'</td>
<td>817</td>
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<td>-118°7.512'</td>
<td>873</td>
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<td>Trip-mate</td>
<td>34°8.186'</td>
<td>-118°7.509'</td>
<td>868</td>
</tr>
</tbody>
</table>

Table 3.1: comparison of 4 receivers at lower altitude

<table>
<thead>
<tr>
<th>Model</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Altitude (feet)</th>
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<tbody>
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<td>815</td>
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<tr>
<td>Trip-mate</td>
<td>34°8.191'</td>
<td>-118°7.512'</td>
<td>817</td>
</tr>
</tbody>
</table>

Table 3.2: comparison of 4 receivers at higher altitude

due to large variations of the altitude.
Chapter 4

Accuracy and Stability of GPS receivers

The objective of CHICOS project is to find out the position and the angle of the high energy cosmic ray showers. To find out the angle of a shower it is necessary to know the timing information of each particle when it hits the detectors. Thus, a very accurate and stable clock is required. As our clock, we are going to use *Global Positioning System (GPS)*. It provides accurate timing without expense of buying an atomic clock for each site. GPS can able to synchronize the time easily even the detectors are separated by several kilometers apart.

Since CHICOS project will use GPS to synchronize all timing in all detectors and provide timing information of the incoming particles, it is important to test the accuracy and the stability of the GPS.

4.1 Accuracy measurement of GPS

4.1.1 Method

In order to know the accuracy of the GPS, it is necessary to know the precision of the 1PPS signal. In this experiment, National Instruments 6602 counter is
used to count and compute the exact timing between the rising edge of the first 1PPS pulse and the rising edge of the second 1PPS pulse. This is done with Labview using a buffered period measurement. The 6002 card counts the number of clock cycles of its 80MHz clock between the rising edges of pulses. The values are counted for each second and hourly data was gathered and the distribution of the timing was plotted.

4.1.2 Result

![Graph](image)

Figure 4.1: 1 hour result of the period measurement of the 1PPS signal on 26 July, 2000

Figure 4.1 shows the distribution of the period of the 1PPS signal over 1 hour. It was observed that there exist 3 peaks instead of 1 peak. The seperations between peak and peak is about 100ns. The existence of the 3 peaks imply that the period of the 1PPS signal is jumping around ± 100ns. While the spread of each peak is only about 7.5ns. It seems that the ± 100ns jittering is due to some external errors, not due to the random errors.
4.2 Stability measurement of GPS

4.2.1 Method

Since the period of the 1PPS signal is jumping around ± 100ns, it is necessary to see the variations of 3 peaks over time. 41 hours of data were recorded, which include peak position, peak amplitude and the standard deviation of the 3 peaks. The same procedure of gathering data was used as in the Accuracy Measurement experiment. The position of the three peaks was determined by finding the maxima of each of the 41 graphs produced. Most had three local maxima. This information was then graphed to show the changes in "position" of the peaks. The position of a peak on the histogram is an indication of the number of clock cycles in each "one second" period. The graph created shows a plot of the first peak positions of the 41 hours of data in the order that the data was taken. It does the same for the other two peaks.

4.2.2 Result

Figure 4.2: 42 hours result of the 3 peaks measurements of the 1PPS signal
Figure 4.2 shows that the centroid of the 3 peaks varies over time. In particular, there exist some periodic pattern plus a slow systemic drift. Notice the 3 peaks are shifted systematically. This implies the jumping of the peak values are independent of time.

![Graph showing peak positions over time]

Figure 4.3: The difference in position of 2 consecutive peaks over 42 hours

Figure 4.3 shows that the jumping of the peaks is really independent of the time, while the jumping is about 8 bins, which is about 100ns. The 100ns jumping was likely caused by GPS receivers. Indeed, it was discovered that the jumping is called saw-tooth error. Because the GPS receivers has a 10MHz internal clock. When the receivers trigger and fire a 1PPS signals. However, the receiver is only capable of firing pulse at the leading edge of the 10MHz internal clock. Thus the accuracy is limited to 100ns.
Chapter 5

Deadtime Measurement of 6602 counter

In the end of the July the Data Acqision System (which is written in Labview) is being tested with the Scintillation detectors to get the timing information of the cosmic ray particles. However, error -10920 is reported, which means that some data points are lost during data acquisition. The reason to cause data lost may due to the dead time of the counter, which is defined as the time that the counter cannot receive any signals within this time interval. Thus, the aim of this experiment is to determine the dead time of the 6602 counter.

5.1 Experimental Setup

5.1.1 Preparation of special pulse

In order to find out the dead time of the 6602 board, a very special pulse is required. This special pulse is composed of 2 pulses, for which the duration (which is defined as the timing between the falling edge of the first pulse and the rising edge of the second pulse) can be tuned externally. This pulse can be obtained via the following procedure.

1. Obtain a signal, 5 Volt TTL pulse using Dual Gate Generator which is
triggered by the 1PPS (pulse per second). Thus, each second a TTL pulse is given.

2. Pass this through a Fanin/Fanout to obtain 2 identical pulses.

3. Pass one of the signals into a delay box and set the delay to the width of the first pulse.

4. Pass this delayed signal into a variable delay box.

5. Put the two signals (one has no delay and the other has a delay) into a Quad Coincidence circuit and set it to OR gate.

6. The 2 pulses are added up individually and thus 2 pulses are obtained with a duration that can be tuned by varying the delay time of the delay box.

The dead time of the 6602 board is not noticeable in applications that do not require accurate timing, but when the data is coming in at high rates it can be a serious problem. Our cosmic ray detectors usually do not receive signals every nanosecond but sometimes two particles may strike it within a short interval. This can cause data loss, because the 6602 needs some time to deal with the information. The goal of this experiment is to find the length of the dead time.

5.1.2 Specification of the pulse

The pulse generated each second is triggered by the 1PPS signal from the GPS receiver. We intentionally set the rate to 1Hz in order to prevent data overflow. In this experiment, the pulse width of the first pulse is 100ns and the initial duration is 375ns and the pulse width of the second pulse is 100ns. With each pulse being 100ns long the time interval in-between is 175ns. This is changed by changing the delay time of the later pulse. By slowly reducing the time between the pulses we can find out the resolution of the 6602 card.
5.1.3 Data Acquisition Hardware Setup

The 6602 counter is connected into a computer with Intel Celeron 533MHz processor with 128MB RAM. The PCI bus Clock Cycle is set into 33MHz. During the experiment, all 3 DMA channels are available and 10 free IRQs are also available. The operating system is Windows NT workstation 4.0 with Service Pack 6. The Data Acquisition Software is circular buffered event counting-adv(NI-TIO).vi, which is written by National Instruments. The reason to use this program is that it support circular buffered which can perfrom real-time data acquisition. In this experiment, only one counter is used because if the CPU needs to moniter many counters, the CPU time for each counter will be reduced and this will definitely affected the measurements.

5.2 Result

5.2.1 Buffered Semi-period measurement

The special pulse is fed into PFI 38, which is the Gate 0 of the counter. The program is set for Buffered Semi-period measurement. We found that when the duration between 2 pulse is larger than 250ns, no error is reported. If the duration between 2 pulse is smaller than 250ns, error is reported immediately, thus the dead time of the semi-period measurement is 250ns.

5.2.2 Buffered Period measurement

The special pulse is fed into PFI 38 and the program is set for Buffered Period measurement. It was found that no matter the duration is between 2 pulse, no error is reported. (The closest approach of 2 pulses is 30ns)
5.2.3 Buffered pulse-width measurement

The special pulse is fed into PFI 38 and the program is set for Buffered pulse width measurement. We found that no matter the duration is between 2 pulse, no error is reported. (The closed approach of 2 pulses is 30nS)

5.3 Possible Explanation

The possible explanation of the dead time of the 6602 card is due to the limitation of the PCI bus system. Since at the completion of each semiperiod interval, the HW save register (which is inside 6602) will lathe the count value for software read. An interrupt will notify CPU after each semiperiod so that the the interrupt software can read the value in the HW save register. However, If the software read from the HW save register does not occur before another save operation is attempted, the previous value is erased and thus some data is lost. This also explain why there is no data lost with either period measurement or pulse width measurement. The reason is these measurements they are counted in half-period way, thus the CPU has enough time to read the value from HW save register before another save operation is attempted. And this will preserved all counts values.
Chapter 6

Performance in 2 - independent cosmic ray detectors

The detectors in CHICOS are composed of more than 70 independent cosmic ray detectors spread over a very large area. We required that those detectors are physically separated. 2 prototype of the cosmic rays detectors were built using separate computers, GPS modules and 6602 Counters. The timing accuracy of 2 physically separated cosmic ray detectors are tested.

In order to know the accuracy of the detectors, we need to do the test separately. As there are 2 main error sources in the detectors. First, as each cosmic ray detectors has a 6602 counter which has a 80Mhz internal clock inside, they are not normalized to 80MHz. Second source of error was come from the 10MHz GPS sawtooth error,(100ns jumping). 2 Experiments were setup and investigated independently.
6.1 Experimental setup to measure the time resolution of 2 GPS

6.1.1 Method

Because the different sites will have different GPS receivers (Motorola Oncore UT+) it is important to see how closely two receivers will agree. In this experiment we try to see the resolution of the 2GPS system. 2 independent GPS receivers are used and the 1PPS signals are fed into 1 6602 Card. The card has many gates so it is capable of processing many sets of data. In this experiment it recieves two sets of data (one from each receiver). This can eliminate the error from the 6602, which is caused by the difference between the clocks in each 6602. (They are not exactly 80MHz.)

6.1.2 Result

![Diagram](image)

Figure 6.1: Time resolution of 2 GPS system using 1 Card
Figure 6.1 shows the timing resolution of 2 GPS receivers. The standard
derivation $\sigma$ is 3.667, which corresponding to 46ns. This value was agreed to
the specification of the GPS receivers, which the timing accuracy is about 50ns
in position hold mode.

6.2 Experimental setup to measure the time
resolution of 2 6602 Card

6.2.1 Method

In this experiment we try to see the resolution of the 2 6602 Cards. 2 independent 6602 Cards are used and the ONE 1PPS signal is split into 2 identical
copies and fed into 2 6602 Cards. This is done by putting the output from one
GPS receiver into a Fanin/Fanout and thus taking two identical signals. Then
each signal is sent to a different card. The period of the signal coming from
each card can then be observed and compared using Labview. It is important
to eliminate this error because each detector site will have at least one 6602
card. One concern about the 6602 is that clocks in the different cards are not
identical. The cards are also affected by temperature and different cards may
have a slightly different response.

6.2.2 Result

Results show that the timing resolution between 2 6602 card is very good.
The error is only about 8ns. Here we have normalize all values with respect to
80MHz, as the internal time base of each card not calibrated to exact 80MHz.
6.3 Timing accuracy of 2 prototype cosmic ray detectors

6.3.1 method

In this experiment, the raw signals from cosmic ray detectors are fed into 2 prototype Data Acquisition System. Each System consisted of 1 GPS receivers and 1 6602 Card. The timing was compared.

6.3.2 result

![Image of timing accuracy measurement under Labview](image_url)

Figure 6.2: A snapshot of the timing accuracy measurement under Labview Results show that the timing accuracy was limited by the accuracy of the GPS system.
Chapter 7

timing accuracy improvement of the cosmic ray detectors

In the previous experiment, the timing accuracy of the cosmic ray detectors is about ± 50nsec. In this section we are going to develop a "moving" average method to improve the timing accuracy of the cosmic ray detectors.

7.1 Theory

Figure 7.1: 42 hours result of the 3 peaks measurements of the 1PPS signal
Figure 7.1 shows that there exist 3 peaks in the 1PPS signal. Obviously, the 2 extra peaks was due to the "saw-tooth" error from the GPS receivers and those tick marks are responsible for unaccurate timing. However, as we have seen, the jittering of the 1PPS value is stable over the long period of time and one would do a "moving-average" method to remove the jitter.

### 7.2 Result

![Graph](image1)

Figure 7.2: Timing accuracy before average

![Graph](image2)

Figure 7.3: Timing accuracy after average

Figure 7.2 shows the timing resolution of the detectors before doing any correction. The standard derivation \( \sigma \) is 3.667, which corresponding to 46\( \mu \)sec. This value was agreed to the specification of the GPS receivers, which the timing accuracy is about 50\( \mu \)s in position hold mode.

Figure 7.3 shows the timing resolution of the detectors after doing moving average correction. The standard derivation \( \sigma \) is 0.6391, which corresponding to 8\( \mu \)sec.

After doing moving average method, the timing accuracy was able to improve from 46\( \mu \)sec down to 8\( \mu \)sec. This work is significant to the cosmic ray detectors as the accurate timing of the cosmic ray flux implies the ability to
determine the shower direction more precisely.