FINAL REPORT

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# A SEARCH FOR MICROSECOND GAMMA RAY BURSTS FROM PRIMORDIAL BLACK HOLES

For the period 1 November 2000 through 31 October 2003

Status August, 2004

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# Overview

The construction of the SHORT GAMMA RAY FRONT AIR CHERENKOV EXPERIMENT (SGARFACE) has been completed in March 2003, and the instrument has been taking data for 1 year. The personnel involved in this experiment are Stephan LeBohec (postdoc, now faculty at the University of Utah), Gary Sleege (electronics engineer), Patrick Jordan (undergraduate student) and Frank Krennrich (associate professor).

Over the last four years we have designed and constructed the electronics and data acquisition system required to search for $\gamma$-ray bursts with duration less than $100\mu$s, a largely unexplored astrophysical window. The scientific objectives are to search for primordial black holes and other short time scale phenomena at $\gamma$-ray energies. SGARFACE is used to search for cosmic bursts of E $>$ 200 MeV $\gamma$-ray emission using a novel technique (figure 1) based on atmospheric Cherenkov imaging and timing. This technique of detecting a wavefront of low energy $\gamma$-rays (Krennrich et al. 2000a) has uniquely high sensitivity for bursts on time scales between 100 ns and 100 $\mu$s. The concept and design of SGARFACE has been presented at various conferences (Krennrich et al. 2000b; LeBohec et al. 2001a; LeBohec et al. 2001b). The status of the experiment is discussed in this final report.

The telescope used is the Whipple Observatory 10 m imaging atmospheric Cherenkov telescope together with new multi-timescale digital electronics tailored for bursts of short duration. The multi-timescale trigger level-1 includes the readout of the digitized Cherenkov pulses for measuring their time profile. The system is operated in parallel with the standard Whipple TeV $\gamma$-ray electronics and does not require additional observation time. This is possible by introducing an analog splitter-summer. All trigger level-1 VME-modules and summer-splitter NIM-electronics are fully working and passed tests at the Whipple observatory and in our laboratory at Iowa State University. A regular observing program was started in March 2003.

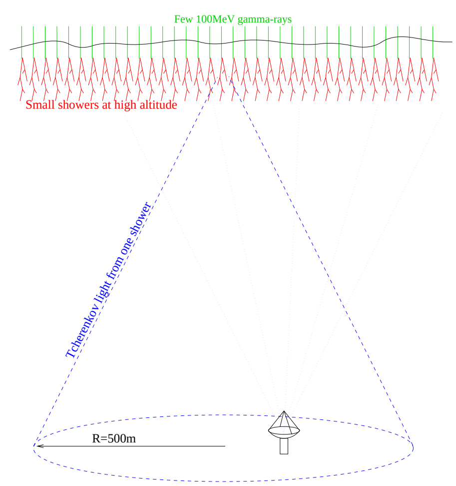


Figure 1: The SGARFACE principle technique showing the detection of the accumulative light from a short burst of low energy (sub-GeV) $\gamma$-rays.

This report consists of three parts, first describing the electronics modules and their status and the second part showing results from tests on the Whipple 10 m telescope in.

# Status of project

## 1. Electronics Design and Construction

The SGARFACE electronics (see figure 2a) will be attached to the Whipple 10 m telescope. The system consists of 3 components: a splitter-summer module (NIM board), a trigger level-1 including readout system (9U VME board) and a trigger level-2 coincidence unit (9U VME board).

The splitter accepts the signals from 389 photomultipliers (PMTs) of the GRANITE-III camera and fans them out into two branches. One is used for the standard air shower detection mode for TeV $\gamma$-ray measurements. The second branch provides the signals for SGARFACE. The signals for the SGARFACE electronics are combined to an analog sum of 7 neighbor pixels allowing to minimize the number of channels of the trigger logic. The large angular extent of images from bursts ($\approx 1°$) permits relaxing the imaging resolution to $\approx 0.36°$. The summed signals are fed into the multi-timescale trigger module (Trigger level-1: T1).

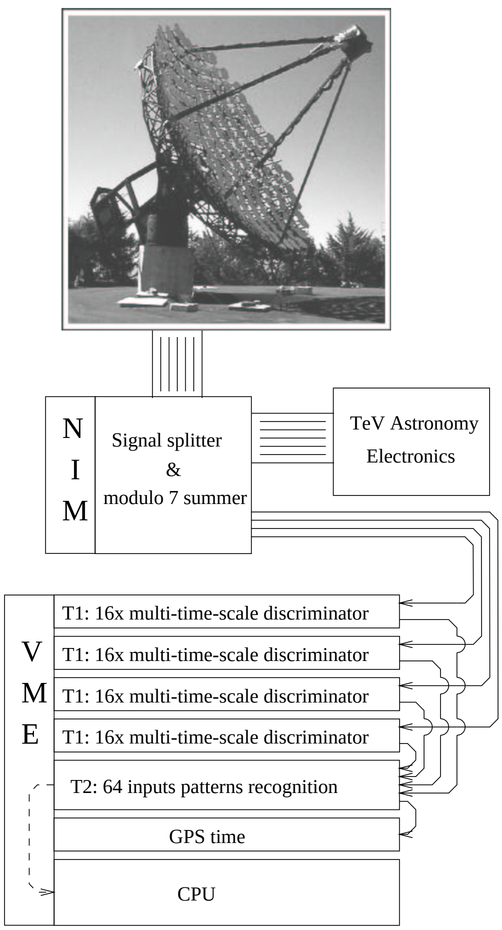


Figure 2a. SGARFACE on the Whipple 10 m.

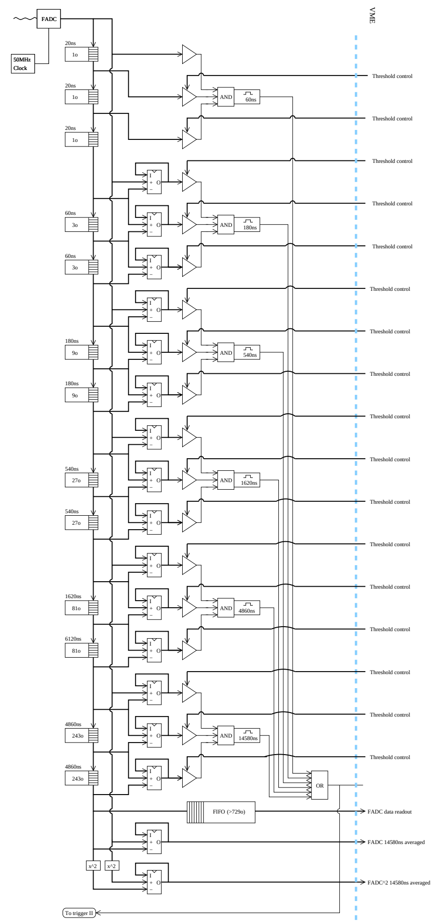


Figure 2b. Logic diagram of level-1 trigger.

T1 works as follows. The analog signals (modulo 7) are digitized at the inputs (16 inputs per module) of T1 using 50 MHz flash analog-to-digital converters (FADCs). This allows further processing solely based on digital electronics. The logic is based on XILINX Field

Programmable Gate Arrays (FPGAs XC400E-6PQ240C) and has the advantage, because those are reprogrammable, that it is highly flexible allowing the instrument parameters to be tuned. In parallel, the FADC information is piped into a memory stack while a trigger decision is reached for subsequent readout, providing charge information and time profile of pulses from 40 ns up to 1 ms.

The search for $\gamma$-ray bursts over a wide range of duration, requires the charge integration over various time scales in parallel. This is achieved by using a fan-in fan-out (FIFO) as shown in figure 2b. The difference between the input and output of a FIFO is continuously summed, providing the integral of the signal. The amplitude of this signal corresponds to the total charge of the pulse. This logic is replicated in a cascade for triggering on time scales from 60 ns to 14 $\mu$s[1] (as shown in figure 2b). Trigger signals from each time scale are sent to an OR which controls whether or not the signals stored in the memory stack are read out. A discriminator threshold is set to decide, given a specific amount of charge, as to whether a single channel goes high to participate in a potential trigger.

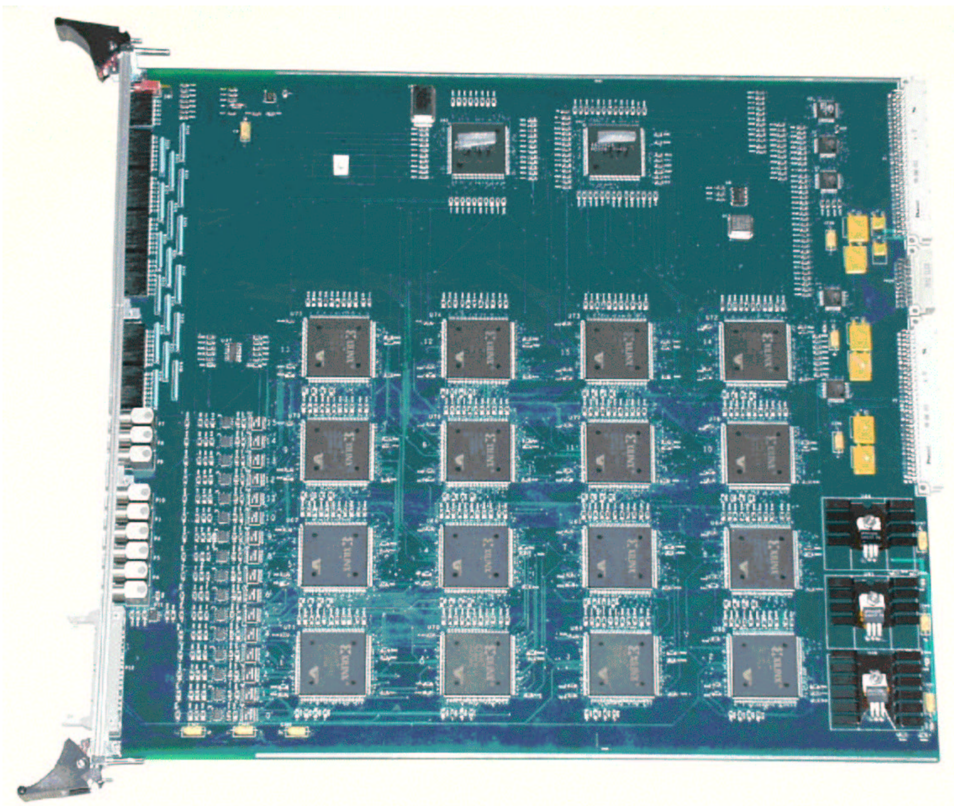

Figure 3. Trigger level-1 board. A complete module with 16 XILINX chips corresponds to a 16 channel board. This module is fully working and we have been taking data with it recording Cherenkov pulses using the Whipple 10 m telescope.

A coincidence of several channels provides good discrimination against random coincidences from night sky background light fluctuations. The use of the XILINX FPGAs allows to optimize the trigger algorithm for maximum sensitivity and versatility. The readout of

[1]We have also developed an algorithm that allows to trigger on signals up to 0.5 ms hence possibly extending the sensitivity of the instrument to longer duration bursts. The XILINX chip allows to change the trigger algorithm for different observing strategies at the beginning of the observation.

the digitized signals proceeds when a trigger from the coincidence unit (Trigger level-2: T2) occurs. Typically the whole memory stack will be read and the information processed off-line. The off-line analysis will be based on pulse shape and image analysis. One trigger module processes 16 channels (of 7 summed PMT signals) in parallel requiring 16 XILINX FPGA chips (see figure 3).

A system of six level-1 trigger modules (4 are required for SGARFACE plus 2 spares) has been constructed. A sideview of one VME level-1 trigger board is shown in figure 3 and a full system for SGARFACE is shown in figure 4.

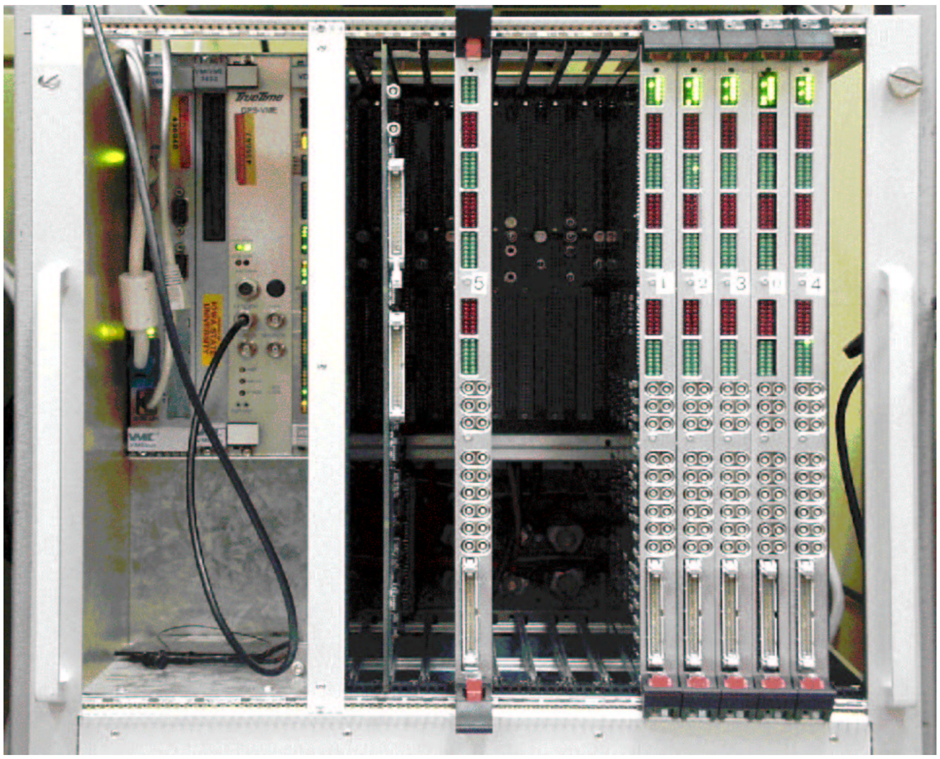

Figure 4. A full set of 4 trigger level-1 boards (incl. 2 spares) is shown. The LEDs are used to indicate basic VME functions (top set of green LEDs) and to display trigger occurring on various time scales (the 3 red and lower 3 green sets) . Each module has 16 inputs (lemo) and 16 outputs (TTL ribbon). Also a test input and an external trigger input are provided.

The design of the splitter and summer is shown in figure 5. The incoming photomultiplier (PMT) signals are split so that 86% of the signal amplitude continues to the standard Whipple data acquisition system and 14% are used for the SGARFACE electronics.

Figure 6 shows a picture of the SGARFACE electronics with a complete system of level-1 trigger modules and a 70% complete system of the splitter-summer modules. The system is essentially completed except for the coincidence logic module that is currently being designed.

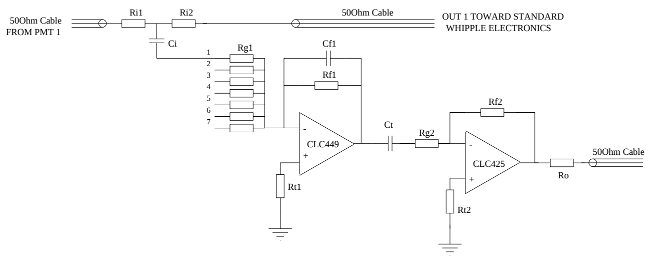


Figure 5. Splitter-summer design is based on a passive splitting. The signals for SGARFACE are summed in cluster of 7 neighbor pixels. A low noise 1.2 GHz amplifier (CLC449) is used to provide fast time response and low cross-talk at the inputs. A slower amplifier (CLC425) is used to amplify the signals for SGARFACE.

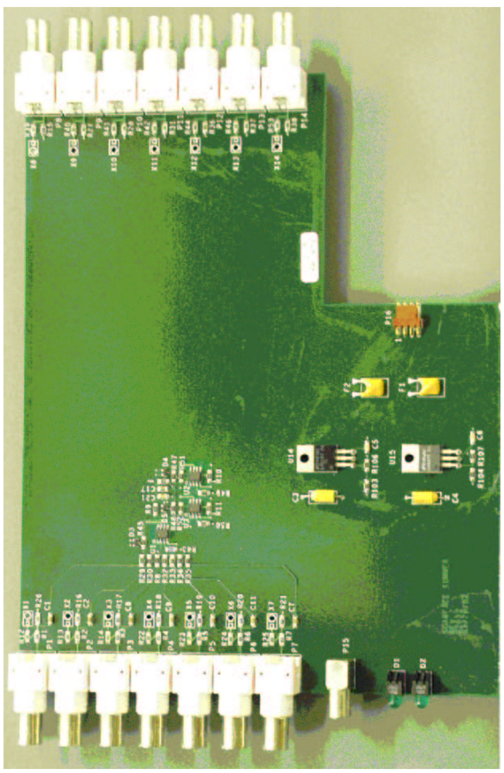

Figure 6. Splitter-summer module for picking up the signals of 7 PMTs that enter it via BNC connectors and exit it via BNC at the output. The analog sum of those 7 PMTs for SGARFACE are provided via a LEMO connector.

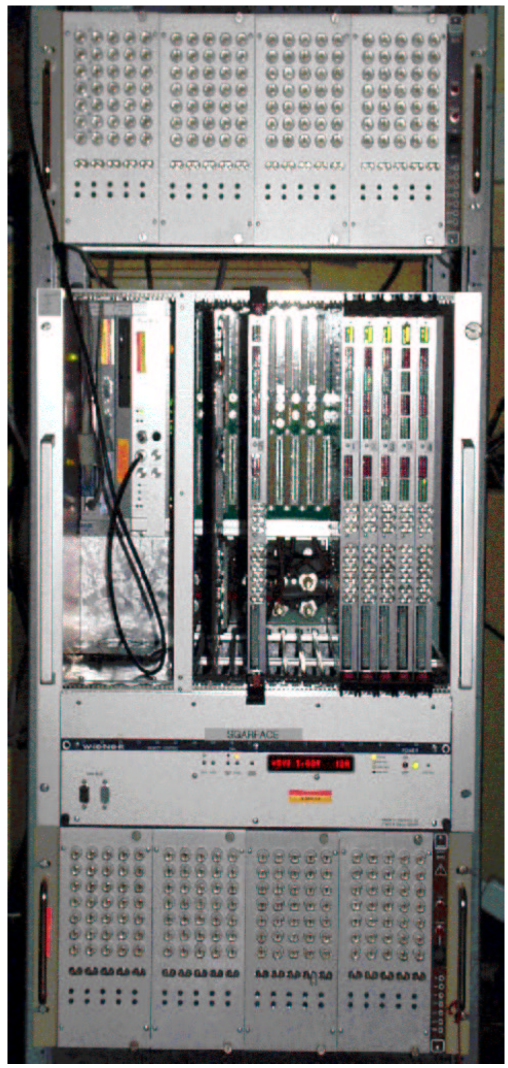


*Figure 7. The setup of the SGARFACE electronics with 8 tripple width splitter summer NIM modules (corresponds to 280 PMT channels) and one VME crate for the trigger modules and the GPS clock and crate computer.*

The level-2 trigger has been designed and is being reviewed for production. It is significantly less complex and, based on our experience with level-1, we expect it to be finished in 1 month time. In case of a delay, we were able to borrow a backup system consisting of TTL-to-NIM converters and two multiplicity logic units. This will allow us to operate SGARFACE in September 2002 with a simple coincidence of any n out of 55 channels rather than n neighbor pixels out of 55 channels as will be possible with level-2.

## 2. Test of SGARFACE at the 10 m Whipple Telescope

Before constructing the complete electronics system for SGARFACE, we have tested the splitter summer and a trigger level-1 module in June 2002 using the Whipple 10 m telescope. Figure 8 shows a Cherenkov pulse as it occurred on the event display that was triggered and recorded with the level-1 trigger module.

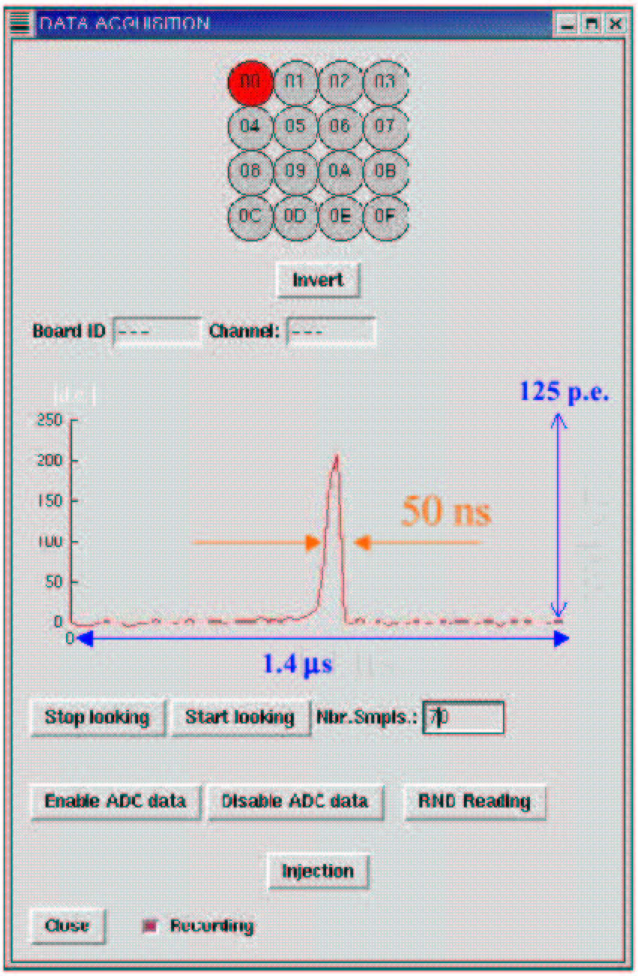


Figure 8. Cherenkov air shower pulse triggered and recorded with the level-1 trigger. The display allows to select one of 16 channels of the level-1 module for displaying its recorded pulse shape. The horizontal axis corresponds to time and the vertical scale shows the amplitude of the signal in photoelectrons. This cosmic-ray event was triggered by the shortest time scale of the T1 module (60 ns) .

The cosmic-ray event recorded with T1 was triggered by the shortest time scale trigger of 60 ns. Events from cosmic-ray induced showers can be easily recognized by their short pulse width (typically less than 40 ns, see Krennrich et al. 2000a) and image shape and can be suppressed at the hardware level or in the off-line analysis.

In order to determine the trigger threshold and the typical background rate for the various time scales of our search, we have measured the trigger rate of a single channel (a sum of 7 neighbor phototubes) as a function of the discriminator threshold. Those measurements show that the singles rates for the time scales of 120 ns and longer are a fraction of a Hz at a few photoelectron trigger threshold. These measurements indicate that there will be a very small accidental rate and hence a small background rate at the hardware level.

In addition we have tested and verified that the splitter preserves the signals that continue to the Whipple data acquisition. Figure 9 shows the Cherenkov pulse from an air shower, channel 1 corresponds to the PMT signal as it enters the splitter, channel 3 displays the output of the splitter. The signals are not significantly broadened, both are 11.1 ns wide (F.W.H.M.). We have also determined the cross talk between the split signals of neighboring channels to be less than 0.5%.

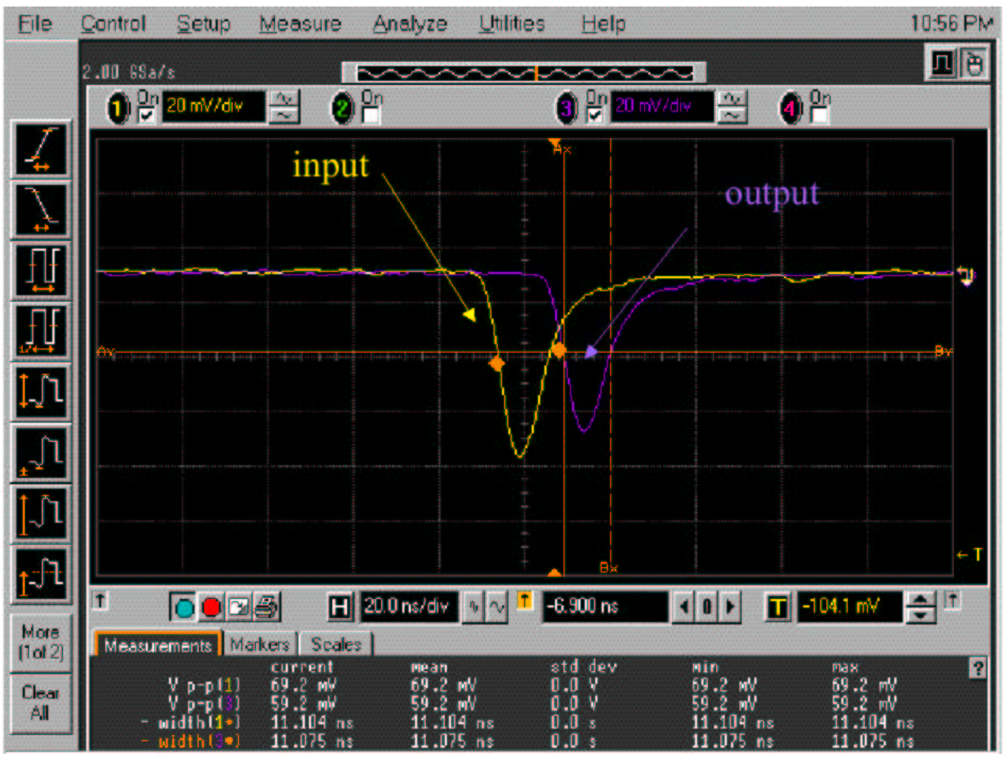


Figure 9. Cherenkov air shower pulse before (input) and after it passes through the splitter. Apart from a 14% reduction in amplitude no change of pulse width or noise is apparent.

## 3. Summary and Outlook

The SGARFACE experiment is running and we expect to take data until summer 2005 to conclude the search for microsecond bursts. A technical paper is currently in preparation describing the instrument and its sensitivity, a second paper with results from a search for bursts will be prepared in 2005. Further details of the sensitivity of the instrument can be found in a pre-print of the technical paper attached to this report.

The development of SGARFACE involved the following personnel: postdoc Stephan LeBohec, electronic engineer Gary Sleege, Harold Skank at the early design phase and Frank Krennrich. Furthermore, undergraduate Student, Patrick Jordan has helped to develop the data acquisition software.

# References


[1] Krennrich, F., S. Le Bohec & T.C. Weekes, (2000a), ApJ, 529, 506

[2] Krennrich, F., S. Le Bohec & T.C. Weekes, (2000b), in proceedings of High Energy Gamma Ray Astronomy (Heidelberg), eds. F. Aharonian & H. Völk, 574

[3] Le Bohec, S., Krennrich, F. (2001a), 27th ICRC (Hamburg), 2756

[4] Le Bohec, S. & Krennrich, F. (2001b), invited talk at Snowmass 2001: the future of particle physics, session P4.2, Snowmass

[5] Le Bohec, S., Krennrich, F. & Sleege, G. 2004, in preparation