Agilent Acqiris Gigahertz FADCs Help Astronomers Probe Deep Space Using Gamma Rays

Customer Article Reprint

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Abstract

Since the midpoint of the 20th century, the story of astronomy has been largely one of extending mankind's ability to observe the universe using an ever-expanding portion of the electromagnetic (EM) spectrum. The development of radio astronomy following World War II enabled astronomers to identify galactic collisions and remnants of exploding stars that visible observations only hinted at, or missed entirely.

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Each decade since has seen new realms of the spectrum come into focus, resulting in new or revised models of how stars, planets, and galaxies form and evolve. Observations in the infrared region have enabled us to visualize the centers of galaxies and the process of star formation. Ultraviolet astronomy has opened up detailed views of the solar corona and helped us understand the structure and evolution of especially hot stars. More recently, the ability to observe the X-ray sky has permitted the observation of certain types of variable stars and active galaxies, as well as the remnants of the largest supernova explosions.

The opening of the wider electro-magnetic spectrum has been facilitated by, and also helped to drive, significant advances in instrumentation and equipment. Some of these developments have allowed astronomers to detect difficult-to-observe types of radiation. For example, in X-ray telescopes, low-incident-angle mirrors focus Xrays through a series of "grazing" encounters to form an image. Others have enabled the faint signals from astronomical sources to be distinguished from sometimes overwhelming amounts of background radiation; these include the use of supercold optics and equipment to isolate infrared observations from the heat generated by surrounding materials.

Another way of distinguishing real data from background "noise" is to improve the quality of observations, using instrumentation that provides better time or space resolution.

In this article, we describe an example of this approach – the use of a new ultrafast analog-to-digital converter (ADC) to help study a here-to-fore unexplored region of the gamma-ray spectrum.

Closing a Gap in Gamma Ray Observations

One of the most exciting, recent developments in astronomy has been the emerging ability to observe gamma rays, which occupy the highest energy reaches of the EM spectrum. Gamma ray photons, usually generated as a result of nuclear reactions, have energies above 10 KeV (1 KeV = 1 thousand electron volts), several thousand times greater than those of visible light. A range of astronomical processes generate gamma rays, from super-massive black holes at the centers of active galaxies to pulsars left over from supernova explosions; these gamma ray photons may have energies of billions of electron volts (GeV).

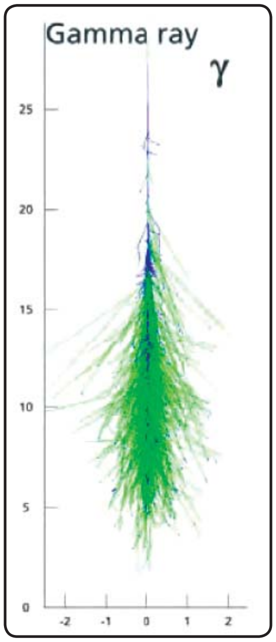

Figure 1

Gamma rays from astronomical objects cannot be directly observed from ground-based observation points, because they are absorbed in the upper reaches of the atmosphere. This has led to two complementary approaches to gamma ray observations. The first is to observe from above the atmosphere – this was the mission of NASA's Compton Gamma Ray Observatory (CGRO), an orbital platform that used a number of gamma ray detectors and imaging instruments for observations from 1991 to 2000. However, in addition to the other drawbacks associated with orbital platforms (such as expense and the inability to upgrade systems and components), CGRO was unable to observe gamma rays above energies of 30 GeV.

The second technique converts a drawback, the absorption of gamma rays high in the atmosphere, into an observation tool. When a gamma ray is absorbed by an atomic nucleus in the upper atmosphere, it generates an electronpositron pair (a positron is the antimatter equivalent of an electron, with a positive charge). This pair goes on to generate a cascade of high-energy particles, which spread into a cone whose axis corresponds to the gamma ray's original line of flight (Figure 1). Because some of the electrons generated in this cascade move faster than the speed of light in air, they generate light known as Cherenkov radiation (Cherenkov radiation is the electromagnetic analog of the sonic boom created when planes travel faster than the speed of sound).

The Cherenkov radiation from a gamma ray interaction is faint and brief (lasting only a few nanoseconds), and its peak luminosity occurs at about 8 km above the ground. However, ground-based telescoped are sensitive enough to record this "air shower" light, and in principle use it to reconstruct the direction from which the gamma ray originated.

The first successful demonstration of this concept was at the University of Arizona's Whipple Observatory; since then, a number of Cherenkov air shower detectors have been built. A limitation for the first generation of such detectors is that they are unable to detect air showers resulting from gamma ray photons with energies less than about 250 GeV. Combined with the ~30 GeV upper limit of orbital detectors, this left a wide gap (from 30 to 250 GeV) in the observable gamma ray spectrum (Figure 2). Unfortunately, many interesting cosmic events are thought to generate gamma rays in this energy range.

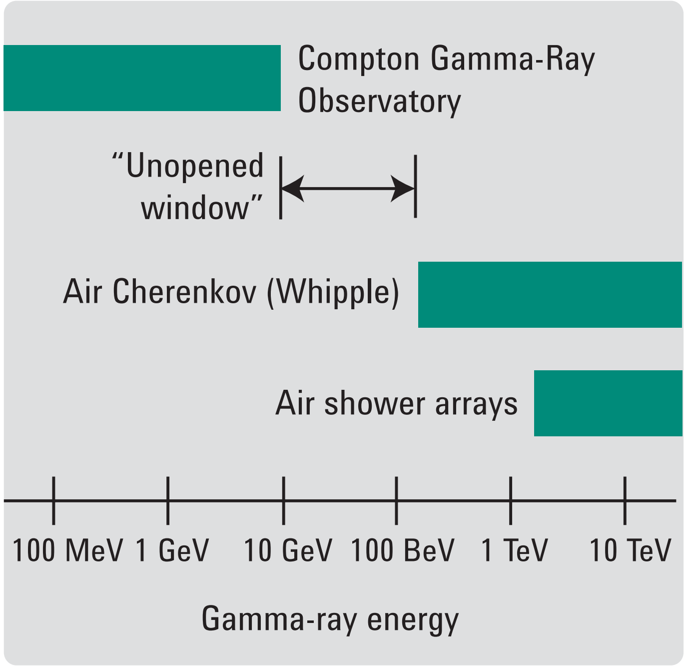

Figure 2

Figure 3

The Solar Tower Atmospheric Cherenkov Effect Experiment, or STACEE, is designed to bridge this gap. STACEE is based on the use of large mirrors (known as heliostats) located at an existing solar research facility, the National Solar Thermal Test Facility, at Sandia National Laboratories in Albuquerque, NM. During the day, these huge mirrors (212 of them, each with an area of 37 square meters) reflect the sun's light to a central tower, where it is studied (Figure 3).

The night sky, however, belongs to STACEE; 64 of the 212 mirrors are used to reflect Cherenkov light from gamma ray showers to the central tower for analysis. Each of the mirrors can be "steered" to track specific locations in the sky. Because the ability to detect gamma ray events using air showers depends to some extent on the size of the light collector, STACEE, with nearly 2400 square meters of collecting surface, is able to push the lower limit of observable gamma ray energies to 50 GeV.

GHz FADCs Unearth the Gamma Ray Needle in the Cosmic Ray Haystack

Looking at the sky to detect Cherenkov air showers is only the first step in observing gamma ray sources. Unfortunately, gamma rays are not the only cause of such particle cascades; in fact, they are outnumbered approximately 400:1 by showers resulting from the collisions of cosmic rays (mostly protons) with atoms in the upper atmosphere.

One of the most significant challenges in gamma ray astronomy using Cherenkov detection is identifying relatively rare gamma ray events against the high background of cosmic ray events. The two types of high-energy collisions generate air showers that are different in size, angular spread, and types of particles (Figure 4).

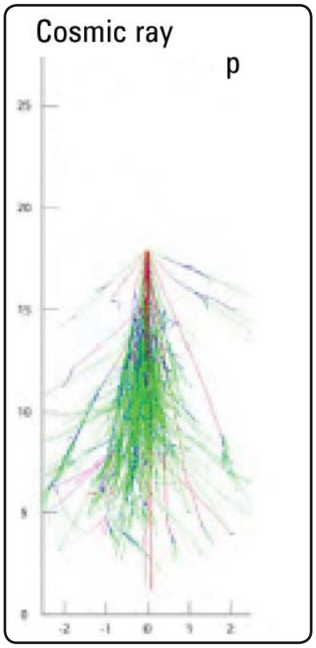

Figure 4

It is at this point that STACEE's sophisticated electronics, including several Agilent Acqiris 1 GHz flash analog-to-digital converters (FADCs), come into play.

Each of the 64 heliostat mirrors used by STACEE reflects Cherenkov light to one of five secondary mirrors located in the central tower, which in turn reflect the incoming light to photomultiplier tubes (PMTs), The electronic signal from each PMT is amplified and sent into the STACEE electronics suite. From there, the signals are split and fanned out to a VME trigger/delay unit and to the 1 GHz FADCs.

STACEE's event analysis electronics are housed in four 8-slot compact PCI crates; two crates are driven by 333 MHz CPUs with 128 MB of RAM, while the other two are driven by 500 MHz CPUs with 256 MB of RAM. The CPUs in each crate run RTLinux 3.0, providing accurate and reliable event timing readouts. Each crate, in turn, houses four Agilent Acqiris DC270 digitizers FADCs, each capable of sampling 4 inputs at a rate of 1 GHz.

In this way, the 16 FADCs can sample the signals from all 64 STACEE PMTs once every nanosecond (Figure 5).

The trigger/delay unit analyzes the input from all 64 PMTs to check for likely gamma ray events, based on highly selective predetermined trigger logic. The trigger logic is sufficiently discriminating in that it is satisfied by only about 2% of cosmic ray shower events, lowering the incoming background about 50-fold.

If the VME trigger/delay unit recognizes a possible gamma ray event, it signals the FADCs to record a data sample of 192 nanoseconds, centered on the anticipated position of the incoming data pulse. Each event recording is time-stamped using a GPS clock, and the position of the trigger in the FADC buffer is recorded; this ensures nanosecond accuracy in measuring the absolute timing of pulses recorded from each of the 64 heliostats. A typical data recording run, lasting 28 minutes,generates about 200 MB of cPCI/VME data. These data are then transferred to a separate computer for subsequent analysis.

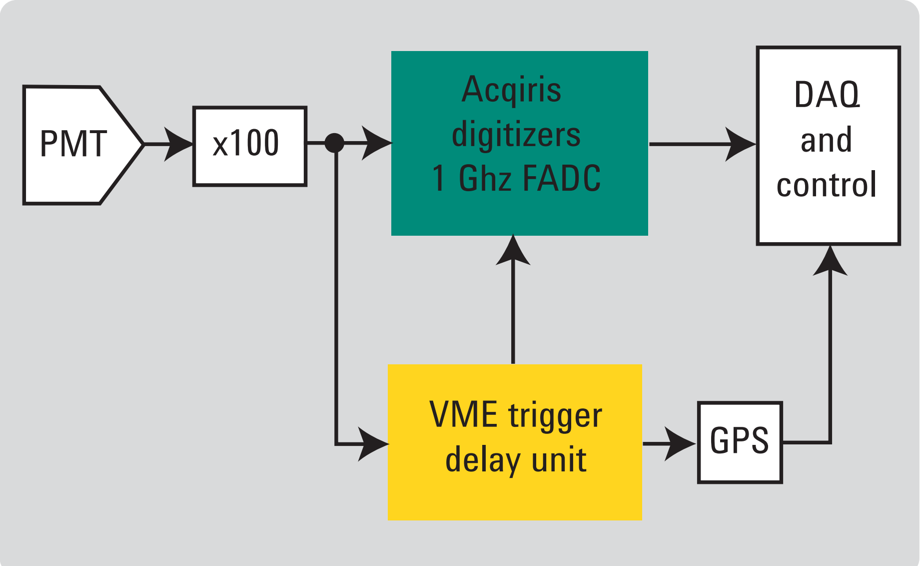

Figure 5

The ability of the GHz FADCs to record the incoming pulses at nanosecond resolution facilitates the second level of discrimination between gamma ray and cosmic ray air showers. Earlier ADCs were capable of only recording the total charge (reflecting total light input) from the PMTs, while the GHz FADCs provide a complete time-resolved trace showing pulse width and pulse height.

The brightness of Cherenkov radiation from gamma ray showers is relatively uniform at ground level, while that of cosmic ray showers, because of the nature of the particles in the shower, varies significantly from point to point. Therefore, the ability to accurately record timeresolved pulse heights provides a way to discriminate between the two types of event: the variability of the pulse heights observed across multiple heliostats is less for gamma ray than for cosmic ray showers. By selecting only events with relatively low variability in recorded pulse heights, most of the background events are removed while preserving "true" gamma ray events. Because gamma rays in the energy "gap" targeted by STACEE have a low variability, this technique preferentially enriches collection of these photons.

STACEE: Present and Future

Simulation runs using the STACEE electronics system have confirmed the usefulness of these discrimination techniques in identifying true gamma ray events. STACEE has been able to accurately record gamma rays emanating from some recognized sources in our own galaxy, such as the Crab Nebula (the remnant of a supernova whose explosion was observed on Earth in 1054 AD); as well as extra-galactic sources such as blazars (quasars whose main energy output is in gamma rays).

STACEE is now fully operational and beginning its experimental program. With the resolution and discriminating capability provided in part by the GHz FADCs, STACEE is expected to shed light on some important questions in current astronomy, such as:

"What is the energy source for blazars and active galactic nuclei?"

"Can the energy patterns of gamma rays from pulsars help explain how particles are accelerated in these objects?"

"Are there previously undiscovered types of sources of gamma rays in the energy range of 50-250 GeV?"

By adapting an existing facility and using commercially available, high-end electronic components, STACEE will provide extremely valuable information at a relatively low cost. The results from STACEE are expected to augment those of other programs exploring this energy range, including CELESTE (a French project similar to STACEE), VERITAS (a multitelescope project at the University of Arizona), and GLAST (an orbital observatory slated for 2006 launch). Together, these programs should provide a much more detailed picture of the gamma ray universe.

More information about STACEE can be found at the STACEE web site:

www.astro.ucla.edu/~stacee/

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