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The SORDS trimodal imager detector arrays

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ABSTRACT

The Raytheon Trimodal Imager (TMI) uses coded aperture and Compton imaging technologies as well as the non-imaging shadow technology to locate an SNM or radiological threat in the presence of background. The heart of the TMI is two arrays of NaI crystals. The front array serves as both a coded aperture and the first scatterer for Compton imaging. It is made of 35 5x5x2" crystals with specially designed low profile PMTs. The back array is made of 30 2.5x3x24" position-sensitive crystals which are read out at both ends. These crystals are specially treated to provide the required position resolution at the best possible energy resolution. Both arrays of detectors are supported by aluminum superstructures. These have been efficiently designed to allow a wide field of view and to provide adequate support to the crystals to permit use of the TMI as a vehicle-mounted, field-deployable system. Each PMT has a locally mounted high-voltage supply that is remotely controlled. Each detector is connected to a dedicated FPGA which performs automated gain alignment and energy calibration, event timing and diagnostic health checking. Data are streamed, event-by-event, from each of the 65 detector FPGAs to one master FPGA. The master FPGA acts both as a synchronization clock, and as an event sorting unit. Event sorting involves stamping events as singles or as coincidences, based on the approximately instantaneous detector hit pattern. Coincidence determination by the master FPGA provides a pre-sorting for the events that will ultimately be used in the Compton imaging and coded aperture imaging algorithms. All data acquisition electronics have been custom designed for the TMI.

Keywords: Gamma-ray imaging, stand-off detection, homeland security, coded aperture, Compton imaging

1. INTRODUCTION

The TMI is a vehicle-mounted passive gamma-ray imager that can locate and identify point sources of radiation at stand-off (100m) distances while the vehicle is in motion ^[1,2]. The TMI detector arrays are two planes of sodium iodide (NaI) detectors, arranged in a manner to allow coded aperture and Compton imaging techniques to be performed simultaneously. The output of the detector arrays is a list-mode event stream of fully digitized data: energy, time and position. A coincidence status tag is included to allow selection of coincident events for Compton imaging. Detectors are self-calibrating and designed for a field-deployable system operated by a non-expert user. The detector arrays are ruggedized for use in a vehicle-mounted platform. Specific BAA requirements for the detector arrays are listed in Table 1.

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Table 1. BAA requirements for the TMI detector arrays.

<u>BAA Requirements for the TMI detector arrays:</u>	
	Required
- Gamma-ray energy range	100-1200 keV
- Energy resolution (662 keV, 122 keV)	7.5%, 17%
- Detected gammas per second in photopeak from 1 mCi Cs-137 at 100m	15
- Field of view in plane of motion, normal	>2 rad, >0.5 rad
- Point source angular resolution in plane of motion, normal	<0.3 rad, < 0.3 rad
- Size, weight, power (includes hardware extraneous to TMI detector arrays)	< 8 m³, < 1200 kg, < 3 kW
- No radioactive sources used in system	Yes

In addition to the above BAA requirements, the TMI concept suggested a number of design choices for the array mechanical structure, detectors, and front-end electronics. The remainder of this document details the design and performance of these elements of the TMI detector arrays.

2. ARRAY MECHANICAL DESIGN

The lightweight, rigid and movable mechanical structure allows a wide field of view, easy detector servicing and removal, and suspension appropriate for crystal support in a vehicle-mounted platform. The design is shown in Fig. 1 and the constructed arrays are shown in Fig. 2.



Fig. 1. Final conceptual design of the TMI arrays.

The front array structure (121" long and 45" high) comprises two support stands shock-mounted to a grid frame machined from a single sheet of aluminum. Detectors can be mounted in any location on the grid and on either side. The detectors are electrically isolated from the frame.

The rear array structure (127" long and 46" high) comprises two support stands and four long channel pieces. All rear detectors are mounted together to four aluminum rods to prevent them from moving independently. The rods are then shock mounted to the long channels. Preloading is applied to the shock mounts to provide a slight compression between detector flanges when at rest. This is to reduce the risk of tensioning on the detectors when the vehicle is traversing rough roads. As for the front array the rear detectors are electrically isolated from the structure.

The arrays are spaced 75 cm apart, crystal center to crystal center, in the TMI. This leaves only a small inter-array region in which to service the front detectors. The arrays are designed so that both can be unbolted from the steel floor and slid on the floor to facilitate servicing. To this end both arrays are footed on Teflon-impregnated Delrin pads to reduce friction. When mounted in the TMI vehicle, the arrays are positioned to look out the curb side of the vehicle.

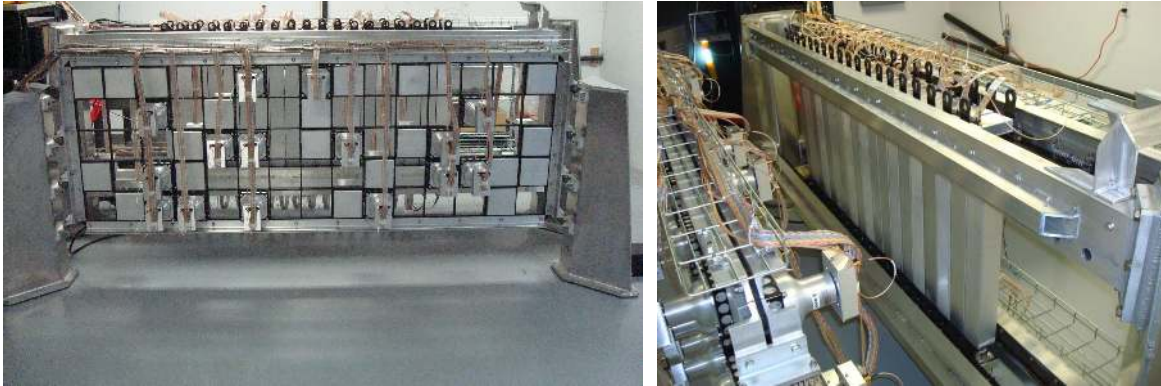


Fig. 2. Fully constructed TMI array structures in the BTI laboratory. A partial detector population is shown.

3. DETECTORS

There are 65 NaI detectors in the TMI: 35 front array detectors and 30 rear array detectors. These detectors are customized to meet the unique needs of the TMI. Saint Gobain Crystals manufactured all detectors.

In the design phase, one important concern was whether detectors could be made to the required geometries while maintaining very good energy resolution. Tests of the production units have confirmed that energy resolution for these detectors is exceptional. All 65 detectors show energy resolution better than the requirement of 7.5% (FWHM at 662 keV) and the median is 6.75%. For the 30 rear detectors the position resolution is better than 2" and the median is 1.5".

3.1 Front detectors

The front detectors form the active elements of the coded aperture mask and act as first scatterers for the Compton imager. Coded aperture techniques are important to the TMI in the lower energy regime less than 1MeV. To this end, the NaI detectors in the coded mask have good efficiency for low energy gamma absorption. This suggests a particular crystal thickness. Since off-axis performance up to 1 radian is required, the detectors also cannot be so thick as to occlude the apertures at this incident angle. Equally important is optimizing the crystal thickness to have good efficiency for Compton scattering, since Compton imaging is used in combination with coded aperture at energies greater than about 500 keV. Photomultiplier tubes, electronics, and mounting hardware are designed to be as small as possible to minimize both falsely coded gammas and undesirable scatterings in the dead mass that invalidate the Compton calculation. These considerations resulted in the design described below.

The active coded aperture is a random pattern half-filling a 5x15 grid. The active elements are 5x5x2" NaI crystals coupled to a 4" bialkali PMT on the 5x5" face. The 4" PMT is a custom model built by Hamamatsu specifically for the TMI. Though this PMT does not subtend the greatest possible extent of crystal it achieves equal performance in energy resolution to a 5" PMT with only 40% of the mass. The crystal is housed in 1mm aluminum and the PMT is shielded against light and EMI by an aluminum shield. Magnetic shielding is provided by a 16 micron thick cobalt alloy foil wrapped in several layers and affixed directly to the PMT bulb. This magnetic shielding was selected to provide immunity to the Earth's magnetic field to a level of maximum 0.5% gain drift between orientations. The detectors are flangeless to allow tight stacking. Affixed to the PMT base is a low-profile 4x2" circuit card that houses a high voltage supply and discriminator circuitry. The circuit card is shielded against EMI and for high-voltage protection by a 0.030" aluminum box. The electronics assembly mounts directly by a ring clamp to the plastic PMT key, eliminating the need for a heavier mounting assembly.

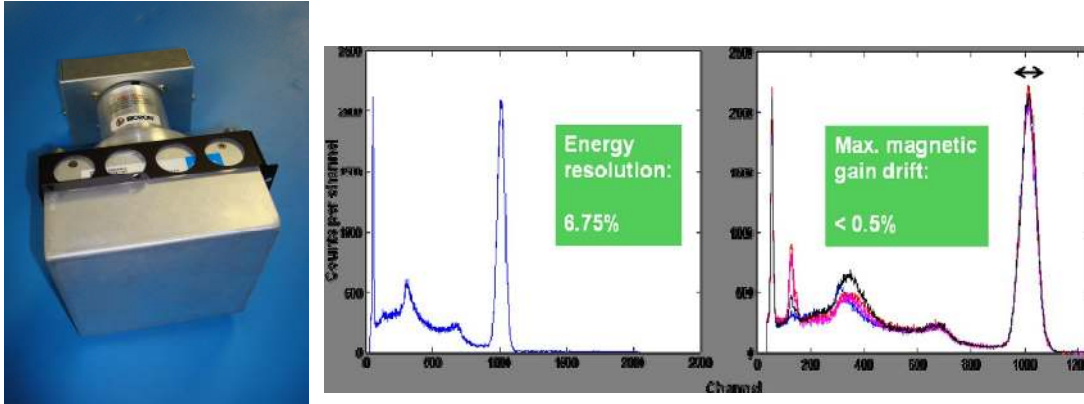


Fig. 3. Front detector (left) energy resolution when broadly irradiated with Cs-137 (middle); and magnetic immunity performance when irradiated with Cs-137 and detector rotated to several compass points (right).

3.2 Rear detectors

The rear detectors form the detector plane for the coded aperture, as well as the full-absorption plane for Compton imaging. It is important to have both good energy resolution and good position resolution in this plane since this directly determines the angular resolution of the system. A trade study was conducted using simulations to determine optimal dimensions and detector population for this plane. This study balanced performance against the practical considerations of weight and cost and what detector dimensions could realistically be constructed by the detector manufacturer. These considerations resulted in the design described below.

The rear detector plane comprises a tightly stacked array of thirty 2.5x3x24" NaI detectors, mounted vertically, and read out at both ends by Hamamatsu 2" superbi-alkali PMTs. The incident surface is the 3x24" face. This results in a discrete event position in the horizontal axis and a continuous event position in the vertical axis.

The first priority in rear detector design was to ensure that the position resolution requirement for the normal axis could be achieved. The requirement for imaging was 2" or better FWHM position resolution for collimated Cs-137. This needed to be achieved while maintaining the best possible energy resolution. Position information is measured by charge division, not by timing. For this to be possible the pulse height amplitude as measured at one end must vary substantially and predictably along the length of the detector. This implies a controlled attenuation of light along the length of the detector which has a direct negative effect on the achievable energy resolution. The 1/e attenuation length of these bars is approximately the length of the bar and the attenuation is exponential in nature. The calculation for position and energy reconstruction is simple in the case that the attenuation is truly exponential in form, since position-independent measurements of energy and position can be calculated using the product and ratio of pulse height amplitudes. Further simplification of these calculations is achievable if detectors are gain matched and detector-specific correction factors can be avoided. Gain matching is achieved through automatic high voltage tuning using an LED reference signal piped to a port at the center of the detector face. This process is described in detail in the next section.

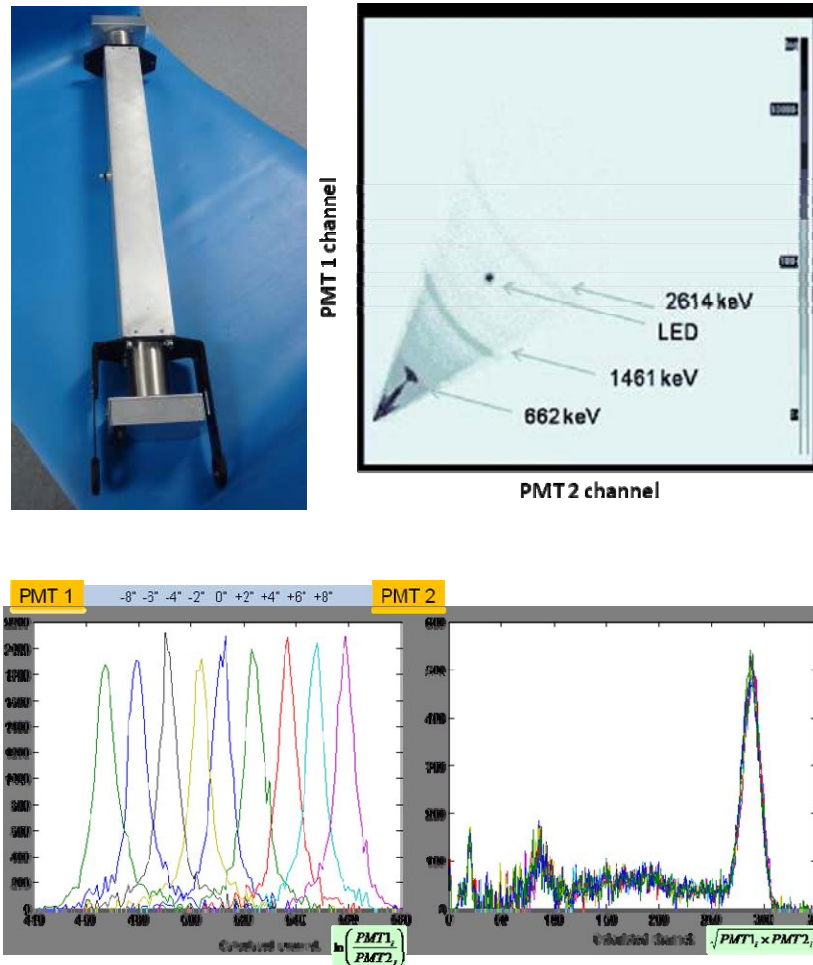


Fig. 4. Rear detector (top left); event by event plot of pulse height amplitude as measured at both ends of the detector (top right); reconstructed event position for a collimated Cs-137 source at 9 positions along the detector each separated by 2" (bottom left); reconstructed energy for the same 9 cases, superimposed – note that there is no broadening (bottom right).

3.3 Gain matching

Gain matching is an automated algorithm that runs continuously on the rear detectors. For a rear detector to be gain matched, both PMTs must register an identical charge output when exposed to an identical amount of light. Practically, a scintillation event at the center of the detector should be read out at each end with equal voltage. In the laboratory it is easy to gain match a detector using a collimated check source at the middle and adjusting each high voltage to match the pulse height amplitude. This is not so simple in the TMI since it must auto-calibrate and track gain drifts, with the additional requirement that radioactive sources not be used anywhere in the system design.

The employed solution is to use a controlled LED flash in the center of the crystal to achieve gain matching. Periodically, an LED flashes a brief pulse several hundred nanoseconds in duration. This light is piped by a fiberoptic cable to a port at the geometric center of one 3x24" face of the rear detector. This port consists of a hermetically sealed window to the crystal and an SMA-type connector. The light emitted into the crystal is diffused evenly between the two ends of the NaI bar, such that the light incident on each PMT photocathode will be approximately equal. LED pulsing is controlled by the individual detector electronics. Since the detector FPGA controls the timing of the LED pulse it can stamp LED events based on time of collection, thus separating these from scintillation events. As backup, pulse shape discrimination can separate LED from scintillation events and also removes cases of contamination between the two. The gain matching algorithm runs continuously and independently on each detector, iterating voltages as necessary to

not only match gains, but to aim for a mean voltage that provides good dynamic range for the system. Continuous tracking is used to correct for any gain drifts which would affect each PMT uniquely.

3.4 Energy calibration

Energy calibration refers to the conversion of the representation of scintillation light amplitude from digital count (ADC) values into physical energies. Like the gain matching algorithm, the calibration process runs continuously on each detector to ensure tracking of gain drifts. The process is identical for front and rear detectors except that rear detectors must be gain matched prior to energy calibration.

A two-point calibration is made by measuring the zero-energy channel and the centroid channel of the K-40 peak. The zero-energy channel is measured by forcing ADC readout when no real event trigger is present. Candidate K-40 peaks are found in the spectrum by an automatic search. There are several tests of peak validation to ensure that the correct peak is selected as K-40 (1460.8 keV). Once K-40 is found, the detector high voltage is adjusted so that the peak centroid is set to a place in the energy scale appropriate for the desired dynamic range of the system. For the TMI, the upper limit of the energy scale is 3 MeV. It is therefore advantageous to place the K-40 at around 50% of the full scale range to maximize the dispersion at the low end of the scale.

The final correction to this two-point calibration is to account for the non-proportionality of light output which is characteristic of the sodium iodide crystal. This is done event-by-event by using a lookup table created from interpolated measured data. Once a detector is calibrated it is considered operational and ready to send data to imaging algorithms. Detector firmware continuously updates the calibration spectrum and every two minutes recalculates the two-point calibration factors with the most recent ten minutes of data.

4. FRONT-END ELECTRONICS

The front-end electronics architecture of TMI is designed to process gamma-ray events occurring in the NaI detectors that comprise the sensor suite. The electronics are separated into three types of circuit card assembly (CCA): the high voltage CCA (HVCCA), the Sensor CCA, and the Event Characterization Unit (ECU). There are 95 HVCCAs, one for each PMT; 65 Sensor CCAs, one for each detector; and one ECU. Roughly, the HVCCA produces the analog PMT output, the Sensor CCA calculates energy, time, and position, and the ECU provides a master clock and determines the coincidence status of events. These functions are described in the following sections.

4.1 Electronics overview

The ECU is connected to all 65 Sensor CCAs via serial connections and to the TMI analysis system (not described here) via ethernet. The serial connections are used both as input lines to receive nuclear data from each Sensor CCA, and as output lines to provide master clock synchronization pulses to each Sensor CCA. It is necessary to maintain time synchronization among all detectors because the relative time between events in different detectors is a crucial piece of information for coincidence determination, and because the absolute event time is used to merge nuclear with geospatial data. The ECU is also used to remotely configure the FPGAs on the Sensor CCAs.

The Sensor CCAs are rack-mounted and all connections are made along the front panel. The sensor inputs are one or two channels from the HVCCAs and the output is a serial line to the ECU. The Sensor CCA converts the analog and digital signals from the HVCCA into a data stream that contains energy, time, and position. A compound gated integrator is used to process the analog signals. Strategically timed samples of the output of the gated integrator are required to fully characterize the energy of the event and to produce a clean pulse-pileup signal. The choreography of the sampling process is directed by the Sensor CCA FPGA. The type of ADC used is event driven. By choosing the time of digitization judiciously, the essential information of the signal from the gated integrator can be measured without using an enormously high sample rate. The Sensor CCA also performs all detector level health checking.

The HVCCA is a low profile card that houses a local high voltage supply (1500V), the resistive divider chain to support the PMT, discriminator circuitry and trigger generation. The analog preamplifier output from the HVCCA is fed to the Sensor CCA via coaxial cable. The other connection to the Sensor CCA is a 20-pin ribbon connector which supplies the required low voltage power required by the HVCCA and also transmits the discriminator trigger. The high voltage is remotely set by the Sensor CCA by transmitting a pulse-width modulation signal through the ribbon cable.

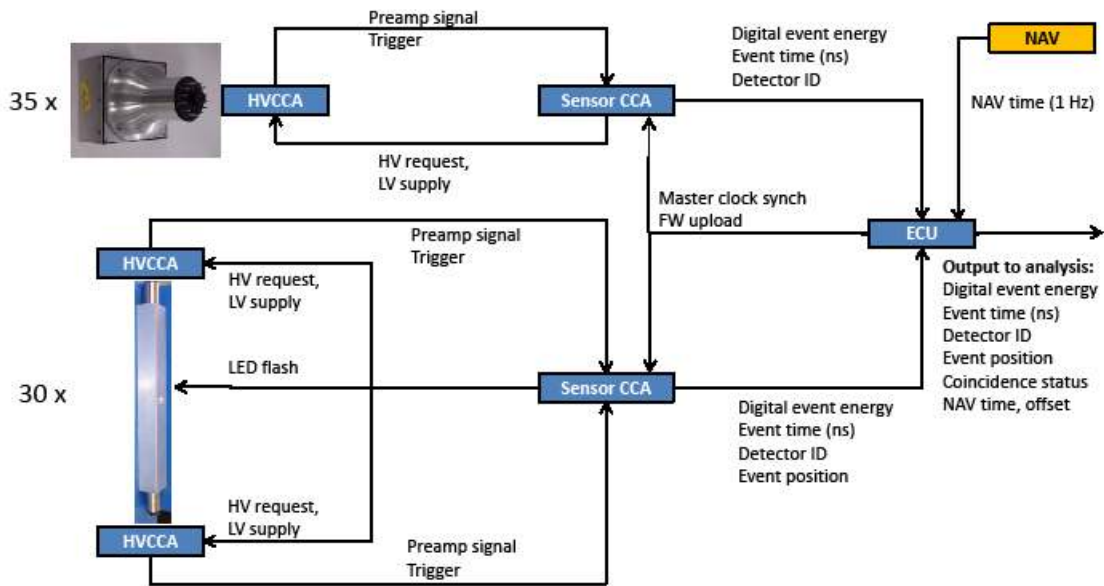


Fig. 5. Data flow diagram showing location of the three circuit card assemblies that comprise the front-end electronics: the high voltage CCA, Sensor CCA, and ECU.

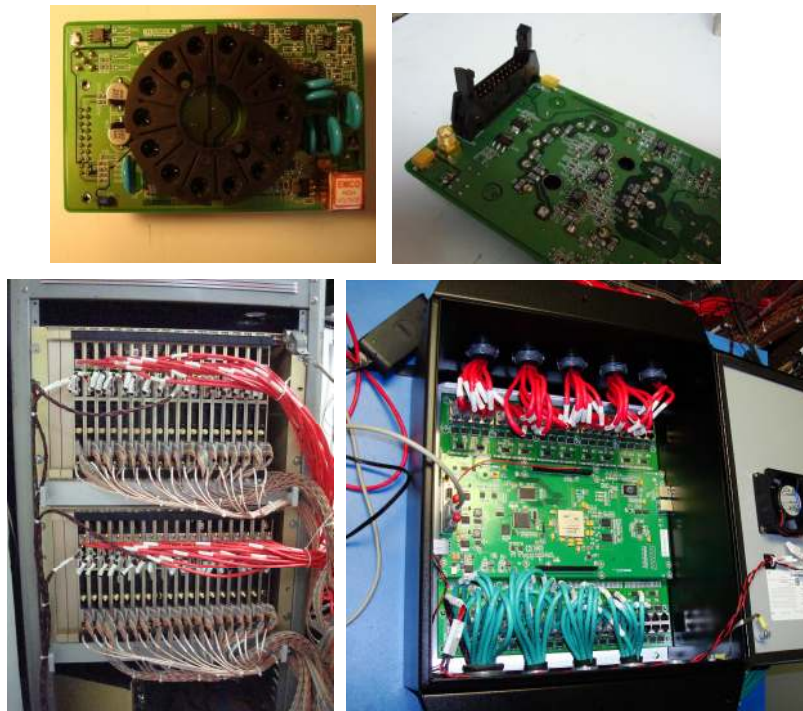


Fig. 6. Front-end electronics on the bench, clockwise from top left; the HVCCA; HVCCA output connector view; Sensor CCAs for front array; ECU.

4.2 Event timing and synchronization

Events are time-stamped at the Sensor CCA. The event timing process is generally that:

- Pulse amplitudes above a discriminator level generate a timing pulse on the HVCCA that is sent to the Sensor CCA. There are two discriminators on the HVCCA, fast and confirm. An event must pass the confirm trigger to be counted, but the timing is based on the related fast trigger, which skims the noise threshold.
- Each Sensor CCA has a 100 MHz (period 10 ns) oscillator running asynchronous to both the ECU and all other sensors. To get timing better than 10 ns a TDC is used on the Sensor CCA.
- The ECU contains the master clock, an oscillator that is used to generate a 1 MHz synchronization pulse that is fed up to the sensors simultaneously on equal length cabling. A TDC on each Sensor CCA measures the phase of the local oscillator against the synchronization pulse.
- The time of arrival of the trigger pulse at the Sensor CCA is converted to a timestamp. Events are time-stamped to sub-nanosecond precision, and up to 1 millisecond for the most significant bit.
- The real-world system time from year down to millisecond is provided to the ECU by an interface to the TMI navigation system (not described here). This interface allows time-stamping of events with the coarse precision that is used to correlate radiological and navigational data.

The relevant requirement for timing is that the accuracy between detectors must be good enough to determine coincidences. Even assuming the synchronization between detectors as described in the previous section is perfect, there are other physical effects to consider when comparing the simultaneity of events. These include, in order of magnitude: time-walk with pulse amplitude, time-of-flight between the arrays, and time-walk with position in the bar. These effects are all predictable and are correctable in software. The second is correctable by either the ECU or the imaging algorithms and the first and third corrections are made in the Sensor CCA firmware.

4.3 Coincidence determination

Coincidence determination is made by the ECU FPGA by examining the timestamps of events which arrive at the ECU within a short window of time. This coarse window is settable, and usually on the order of one microsecond. The coarse window must be wide enough to ensure that all real coincidences are trapped, accounting for latencies in the electronics. The coarse window cannot be too wide, since the processing time needed to sort through timestamps increases with the number of noise events in the set. A fine discrimination window is then set on all events within the coarse window. This fine window acts on the actual timestamps of all events in the coarse window.

In this way, coincidence determination is useful for trapping real coincidences and for minimizing the background from random coincidences. However, some random coincidences will leak in and additional cuts are placed on those which are kinematically disallowed. Additionally, the more dominant background to Compton imaging is due to real coincidences from the natural background. Kinematic cuts and the discrimination of the target point source from the diffuse Compton background are both tasks of the TMI imaging algorithms.

5. SUMMARY

The SORDS trimodal imager detector arrays have been presented. The TMI detector arrays are presently fully built and integrated and all design requirements are met or exceeded. Integration with the other components of the TMI is currently underway.

6. ACKNOWLEDGEMENT

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