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Example Provisional Patent Application (PPA)

In due course, this Provisional patent application (PPA) was re-written and filed as a utility (non-provisional) patent application in the U.S. Patent Office. The patent was eventually granted as **US Patent No. 8,785,864**

The following example is provided for educational purposes only in connection with **ELG's Practical Guide to PROVISIONAL PATENT APPLICATIONS for the Cost-Conscious Inventor**.

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LOW-COST, ORGANIC-SCINTILLATOR COMPTON GAMMA RAY TELESCOPE

BACKGROUND OF THE INVENTION

Field of the Invention

[001] The present disclosure describes a device to image distant or nearby sources of gamma rays using the Compton effect. This type of device is generally called a *Compton gamma ray telescope* or Compton telescope.

Related Art

[002] A Compton telescope consists of one or many gamma ray detectors with electronics to determine the direction and energy of gamma rays incident on the telescope. Since gamma rays are not easily focused by refractive or reflective optics in the manner of visible light and lower energy photons, existing Compton telescopes usually do not rely on focusing optics to form images, but instead use the physics of Compton scattering and multiple particle interactions within the telescope to determine the energy and momentum (and hence direction) of incident gamma rays.

[003] Gamma ray detectors are classified into several types according to their composition and principles of operation. The different types vary widely in their cost, available size, and detection capabilities.

- *Gas Ionization* detectors such as the well-known Geiger-Müller Tube or Geiger Counter produce a pulse of electric current when a gamma ray or other energetic particle ionizes an inert gas in a high voltage chamber. Low-cost gas ionization detectors (< $200 each) such as the Geiger Counter count gamma rays above a certain energy threshold but cannot measure the energy of the gamma ray. More expensive Geiger-Müller *proportional ionization* detectors can measure the energy deposited by a gamma ray. Very expensive (> $100,000) multi-wire proportional gas ionization chambers can measure the energy and also track the momentum of charged particles that recoil from multiple gamma ray collisions, allowing imaging of gamma ray sources.

- *Organic scintillators* are solid organic polymers (plastics) like polyvinyl toluene (PVT) or liquid organic solvents like benzene containing fluorescent organic compounds (fluors) like 2,5-diphenyloxazole (PPO). When a gamma ray interacts with a scintillator, it deposits energy that excites nearby fluors. The fluors emit visible light proportional to the amount of energy deposited, and this visible light can be measured with photomultiplier tubes (PMTs) or photodiodes. Typical plastic scintillators in bulk quantities cost less than $80 per kilogram (1 kg PVT is about 1 Liter volume) [Ref. 1], while liquid scintillators may be an order of magnitude less expensive per unit volume. For large volume particle detectors, these materials are among the least expensive known. Organic scintillators are usually used for counting gamma rays but not for measuring their energy, because the low density and low nuclear charge Z of these organic materials result in poor capture efficiency: a gamma ray with energy over 100 keV will usually Compton scatter out of an organic detector several cm in size, depositing some but not all of its energy.
- *Inorganic scintillators* are typically fluorescing salt or oxide crystals of much higher density and higher nuclear charge Z than organic scintillators. The most common and least expensive is thallium-doped sodium iodide or NaI(Tl). Inorganic scintillators have much higher gamma ray capture efficiency than organic scintillators, and are often used to measure the energy of gamma rays in the range 10 keV to 3 MeV for laboratory, research, safety, environmental monitoring, minerals exploration, and security purposes. A typical block of inorganic scintillator can measure the energy of gamma rays between 500 keV and 3 MeV with 3% to 7% energy resolution. As a common laboratory example, a 7.5cm diameter x 7.5cm long cylinder of NaI(Tl) has about 30% efficiency in capturing the full energy of incident mono-energetic 2.2 MeV gamma rays from the nuclear reaction $n + p \rightarrow {}^{2}H + 2.2\ MeV\ \gamma$ [Ref. 2]. An energy spectrum of this gamma ray source in such a NaI(Tl) detector would show a peak at 2.2 MeV with a 5% full-width-at-half-maximum (FWHM) resolution. Sodium iodide scintillators in bulk quantities cost at least $2500 per cubic decimeter (Liter volume) [Ref. 3], while other inorganic scintillators with higher capture efficiency and better energy resolution cost from 3x to 10x as much per unit volume.

- *Semiconductor Gamma Ray Detectors* are based on doped silicon, germanium, and similar semiconductors, placed across high voltage electrodes and often cooled to cryogenic temperatures for better performance. When a gamma-ray interaction excites electrons from the valence band to the conduction band in these materials, a conduction current flows between the electrodes, giving a very accurate measurement of the energy deposited by the gamma ray. Detectors of this type usually have higher capture efficiency per unit volume than organic scintillators but lower capture efficiency than inorganic scintillators. Semiconductor detectors have the best energy resolution of all standard particle detectors, able to measure 100 keV to 3 MeV events with better than 1% energy resolution and in some cases better than 0.1% FWHM. Semiconductor detectors also have the highest cost per unit volume, over $100,000 per cubic decimeter [Ref. 4, 5], although semiconductor detectors greater than a few hundred cubic cm are never in practice manufactured as a single detector element, but typically as a segmented array of detector strips or blocks for particle tracking.

[004] Several Compton telescopes have been designed, built, and operated for astrophysical observations over the past three decades. These include the CompTel Gamma Ray Telescope, launched in 1991 on the Compton Gamma Ray Observatory satellite (CGRO). CompTel used a two-layer Compton telescope design consisting of organic Ne-213A liquid scintillator cells in the first layer and NaI(Tl) inorganic scintillator blocks in the second layer [Ref. 6]. It had an upper layer active area of 4188 cm^2 with a gamma ray capture efficiency from 1.2% to 0.5% for gamma rays in the energy range 0.8 MeV to 30 MeV. It had an energy resolution of 5% to 8% FWHM and angular resolution 2° to 4° for gamma rays over this energy range. Since CompTel was launched, the United States Naval Research Lab (NRL) along with many partner institutions has proposed several successor Compton telescope instruments including the ATHENA concept and the ACT concept [Ref. 7]. These proposed designs achieve higher performance than CompTel but require higher component costs, using arrays of semiconductor detectors typically in conjunction with scintillators to achieve higher gamma ray capture efficiency, better energy and angular resolution than CompTel, and in some cases a wider range of gamma ray energies.

[005] NRL has developed a significant theoretical breakthrough with the *3-Compton Principle* [Ref. 8, 9], showing how the energy and direction vector of an incident gamma ray can be

recovered in a Compton telescope if the gamma ray Compton-scatters 3 times or more inside the device. Prior to this discovery, CompTel and other early Compton telescopes only processed gamma ray events that interacted in exactly two detector layers. The 3-Compton Principle allows Compton telescopes of much higher capture efficiency, since an arbitrary number of layers of detector material may be used.

SUMMARY OF THE INVENTION

[006] The present invention is a design and set of manufacturing principles to make much lower-cost, large-collection-area industrial Compton telescopes using large arrays of mass-producible, identical organic scintillator elements that are individually calibrated by an automated process. Previous large-area Compton telescopes have been one-of-a-kind research instruments, with many hand-assembled components built by graduate students, laboratory engineers, and post-doctoral scientists, usually for astrophysical research applications. As a result, these large Compton instruments typically cost many millions of dollars. Smaller Compton-scatter imaging systems have been built for medical research applications [Ref. 10], but these generally use very expensive cryogenic semiconductor elements that cannot be scaled up cost-effectively to large collection areas.

[007] There are several current applications that would benefit from Compton telescopes with large collection area (from several square feet up to several square meters), high gamma ray capture efficiency, modest cost, and modest energy and angular resolution requirements. For example, in the field of Homeland Security, large area Compton telescopes would be very useful for monitoring points of national entry and major urban centers to search for smuggled nuclear weapons, radiological dirty bombs, or Special Nuclear Materials (SNMs). However, recent patterns in Homeland Security procurement suggest that the price-point where such a Compton telescope could be fielded in sufficient numbers to be cost-effective is between $300,000 and $800,000 per device [Ref. 11], far below the cost of previous Compton telescope designs. Another likely application is in the detection of large concealed explosives such as the roadside Improvised Explosive Devices (IEDs) used by insurgents in such conflict areas as Afghanistan and Iraq to attack convoys of vehicles, or concealed vehicle-born explosives moving through a

security checkpoint toward a sensitive target such as a federal building, landmark skyscraper, bridge, or crowded stadium. While conventional explosives do not emit gamma rays, they can be identified by the method of Prompt-Gamma Neutron Activation Analysis (PGNAA), using a neutron source to probe a suspected target and a gamma ray detector to analyze the element-specific gamma rays emitted by the material. In the past PGNAA has been used successfully to identify concealed explosives inside metal containers at ranges up to about 50 cm from a neutron source and gamma detector [Ref. 12]. To make a useful IED or vehicle-born explosive detector, the effective PGNAA range must be extended to at least several meters, and this requires a large area gamma ray detector with imaging capability to distinguish threatening concentrations of nitrogen from harmless background concentrations such as are found in air. As a third example, it has been estimated that there are billions of dollars of recoverable metals in mining tailings around the world. Currently, the cost of assaying very large fields of mining tailings is often high enough to prevent the recovery of much of this metal, since the process requires samples to be collected from survey locations, analyzed chemically in a laboratory for minerals of interest, and then after a delay, the mineral content of tailings zones is reconstructed from the lab results. PGNAA with a range of several meters could allow mineral concentrations for large volumes of tailings to be analyzed more promptly on site, making minerals recovery from tailings more profitable.

[008] The present invention differs from other Compton telescope designs in at least seven essential ways:

[009] (1) Costs are reduced relative to other Compton telescopes by using multiple layers of organic scintillators for all or most of the active gamma-detecting mass in the instrument. Most proposed and constructed Compton telescopes have used very expensive cryogenic semiconductor detectors or combinations of semiconductor detectors and inorganic scintillators, more than 10x as expensive per unit of detector mass than inorganic scintillators. Even in CompTel, which used low-cost organic scintillators for one of its two detection layers, over 85% of the active telescope detector mass was in the form of the much more expensive inorganic scintillator NaI(Tl). The use of much less expensive detector materials (organic scintillators) in the present invention allows the total gamma detection mass to be scaled up to large collection area and high collection efficiency at an acceptable price. Monte Carlo analyses have shown that

by placing five to ten organic scintillator layers in front of one another[see Fig. 1], the gamma ray capture efficiency can be boosted from the roughly 1% range achieved in the 2-layer CompTel instrument up to capture efficiencies near 15%. This has not been attempted in the past because the gamma ray literature describes organic scintillators as having poor energy resolution. However, although it is difficult to calibrate organic scintillator detectors due to their low gamma ray capture efficiency, when calibrated they have achieved energy resolution of 4% to 6% or better in the energy range 0.8 to 1.8 MeV [Ref. 13], and better than 4% energy resolution at higher energies.

[0010] (2) Costs are reduced and gamma ray capture efficiencies are increased in the present invention relative to other Compton telescope designs by optimizing the design for a particular gamma ray energy of interest, accepting modest energy resolution such as 5% at that design energy, and accepting modest angular resolution such as 0.05 to 0.09 radians (3° to 5°). The design requirements of other Compton telescopes specify energy and angular resolutions better than this over a very wide energy range, to observe a wide variety of different phenomena, and result in accordingly much higher detector costs. Industrial and security applications, however, can generally be served by a narrow energy range detector. For example, the 10.8 MeV gamma ray emitted by nitrogen is the primary energy of interest for PGNAA detection of large concealed explosives. Monte Carlo models show that for any given gamma ray energy, there is an optimal organic scintillator thickness that maximizes the multi-layer Compton telescope capture efficiency for that particular energy.

[0011] (3) For mass-production and rapid assembly, the preferred embodiment of the present invention uses a large array of identical organic scintillator pixels. Each pixel has several photodiodes or avalanche photodiodes in a regular pattern bonded onto a factory-cut or factory-molded organic scintillator block [Fig. 2]. The photodetectors with their appropriate power supply lines and pre-amplifiers will be attached to a printed circuit board, for example, by a "pick-and-place" machine with surface-mount and solder reflow technology, as is standard in the electronics industry for automated assembly of circuit boards. Then the printed circuit board with photodetectors will be bonded to the scintillator using index-matching optical adhesives of the type used for optical assemblies in the telecommunications industry. In this way hundreds or thousands of identical scintillator pixels can be assembled by automated machinery of the type that already exists in the electronics and telecommunications industries. The printed circuit boards that hold the photodetectors and scintillator pixels will then be mounted using board edge-connector sockets, Zero Insertion Force (ZIF) sockets, or similar socket devices, to a large chassis [Fig. 3] wired with circuit cables from the sockets to Compton telescope signal processing sub-units called Layer Data Processors and Vector Data Processors, as described below.

[0012] (4) While most scintillator-based gamma-ray detectors use photomultiplier tubes (PMTs) to capture the light resulting from gamma ray induced scintillation, the present invention uses an array of photodiodes or avalanche photodiodes instead, to reduce the amount of non-scintillator mass inside the telescope that would otherwise reduce the Compton telescope efficiency, to increase the mechanical robustness of the telescope, and to reduce the cost of telescope assembly by enabling the use of printed circuit board and optical telecommunications automated manufacturing techniques.

[0013] (5) With at least three photodetector elements on each pixel in a triangular array, or at least four photodetector elements on each pixel in a rectangular array, each pixel will produce multiple output signals when energy is deposited by a gamma ray. The signals from different photodetectors will vary as a function of the (x,y) position of the gamma ray collision in the pixel. The differences between adjacent photodetector signals will give the (x,y) location of the signal, and the sum of all photodetectors will indicate the total energy deposited in the pixel [see Fig. 2]. One of the main sources of uncertainty in scintillator measurements of gamma ray energy is the variation in signal strength as a function of the collision position within a scintillation detector. For conventional gamma ray detectors with one large PMT on one side of the scintillator, interactions at different locations produce slightly different efficiencies in coupling the scintillator light into the PMT. PMTs in general also have a slight non-uniformity in response across their face. However, with multiple photodetectors distributed across the face of the scintillator, the effect of interaction position on total signal can be corrected by calibration. The calibration process can be automated by programming a scanning X,Y stage at the pixel factory to move a newly assembled pixel across a collimated electron beam or collimated gamma ray source of known energy, recording the signals of the photodetector elements as a function of (x,y) position and saving the resulting data in a lookup table that generates an (x, y, Energy) value for a given combination of signals [see Fig. 4]. If many pixels are nearly identical in behavior, a single lookup table can serve as the calibration for an entire lot of pixels; or if pixels within one batch show significant variation, flash memory devices can be incorporated into the Compton telescope signal processor to store coefficients that approximate each lookup table for each individual pixel within a large Compton telescope.

[0014] (6) For Compton telescope applications that use PGNAA with an electronically-pulsed neutron source, the distance to an object producing neutron-activated gamma rays can be estimated by the time-of-flight between neutron pulse generation and the returned gamma ray signal. For example, if a 100-microsecond long pulse of neutrons is thermalized in a polyethylene moderator and then broadcast through a collimator at a variety of objects from 2 meters to 10 meters away, the neutron-activated prompt gamma rays from objects 2 meters away will mostly arrive at the Compton telescope between 0.5 milliseconds and 2 milliseconds after the neutron pulse is generated. Neutron-activated gamma rays from objects 5 meters away will mostly arrive at the Compton telescope between 1.3 milliseconds and 5 milliseconds after the pulse. And objects 10 meters away will produce prompt gamma rays mostly between 3 and 10 milliseconds later [Fig. 5]. Since organic scintillators have nanosecond response times, this technique could also work with pulses of fast or under-moderated (epithermal) neutrons.

[0015] (7) The cost of electronics in the present invention is greatly reduced by collecting the signals from the large array of pixels into Layer Data processors and Vector Data processors, so that full signal processing electronics do not have to be included for every pixel [Fig. 6, Fig. 7, and Fig. 8]. Each photodetector has a pre-amplifier to generate a voltage pulse when a gamma ray deposits energy in the pixel. Difference amplifiers generate (x,y) signals within the pixel, and a summing amplifier generates a total energy signal. If the total energy signal in one pixel exceeds a pre-set trigger threshold, then sample-and-hold circuits acquire the pixel sum signal and the two difference signals. These signals are passed forward to analog multiplexers for each layer of the Compton telescope. The analog trigger signals from pixels in each layer are processed by a digital encoder or fast Field Programmable Gate Array (FPGA) in the Data Layer processor to identify the pixel where each event occurred. The Data Layer processor then activates the analog multiplexers to select only the delayed analog pulses from the pixel of interest for digitization in the Analog-to-Digital (A/D) converters (digitizers). In this way only three digitizers are needed to acquire the (x, y, energy) signals from the entire array of pixels in one layer, as long as above-threshold events are separated in time by periods longer than the processing interval, approximately 20 to 100 nanoseconds. Finally, the FPGA for each layer of the gamma telescope generates the (x, y, energy, and time) coordinates of each above-threshold event and passes this numerical data to a Vector Processor. The Vector Processor uses the (x, y, energy, and time) information and the Compton scattering equations to group coincident multilayer events together, sum the total energy deposition from each gamma ray, and calculate the incident energy and momentum from gamma ray events that meet certain selection criteria. Monte Carlo simulations indicate that a 7-layer plastic scintillator telescope can achieve up to 15% capture efficiency for 10.8 MeV gamma rays using coincidence, energy, and momentum vector selection criteria.

[0016] Embodiments of the present invention include Compton telescopes using three or more layers of scintillator material to track Compton scattered incident gamma rays, in which at least two layers are organic scintillator layers.

[0017] Embodiments of the present invention include Compton telescopes that may have one or more layers of inorganic scintillator, such as NaI(Tl), along with at least two layers of organic scintillator.

[0018] Embodiments of the present invention include Compton telescopes using either liquid or plastic organic scintillators, including liquid or plastic scintillators incorporating dissolved or suspended organometallic compounds such as tetra-ethyl-lead, tetra-phenyl-lead, tetra-methyl-tin, or other organometallic compounds whose purpose is to increase the gamma ray stopping power of the organic scintillator.

[0019] Embodiments of the present invention include scintillator layers composed of arrays of square, rectangular, triangular, hexagonal, or cylindrical scintillator pixels. Each pixel consists of a block of scintillator material with at least three photodetectors mounted on it to provide (x, y, energy) information for gamma ray collisions within that pixel, and may include arrays of larger numbers of photodetectors in square, rectangular, triangular, or hexagonal grids mounted on the surface of each scintillator pixel.

[0020] Embodiments of the present invention include scintillator pixels that use photodetectors consisting of photodiodes, avalanche photodiodes, or solid-state photomultipliers, where the photodetectors may be mounted on one face of each pixel or may be mounted along multiple faces of the pixel to reduce obstruction of gamma rays traveling along the axis of the Compton telescope or to provide better energy resolution if needed.

DESCRIPTION OF THE DRAWINGS

[0021] Figure 1 shows a front view and side view of the pixel geometry of one embodiment of the present invention. In this embodiment the Compton telescope contains 7 layers of organic scintillator. Each layer contains 52 pixels arranged in a roughly circular array with approximately one square meter frontal area. This configuration was modeled with PVT plastic scintillator layers 10cm thick, 14x14cm square pixel faces, and with 10 cm gaps separating the first 6 layers to give an overall Compton telescope length of approximately 120 cm. Monte Carlo models of gamma-ray transport using the MCNP5 code developed at Los Alamos National Lab showed that up to 15% of 10.8 MeV gamma rays incident on the front face could be tracked by this Compton telescope geometry. Other embodiments could replace the PVT plastic scintillators with liquid-scintillator-filled cells of the same or similar dimensions, operating according to the same principles.

[0022] Figure 2 shows a subassembly of one possible embodiment in which four avalanche photodiodes (1) are mounted on a printed circuit board (2) at the corners of a square scintillator pixel (3). Pre-amplfiers, analog filters, and the other circuit components suggested in Figure 6 would be soldered onto the back of the printed circuit board by automated pick-and-place machines using solder reflow techniques. The circuit board has a card-edge connector (4) or similar socket-based electronic connector allowing signals and power supply traces to be interfaced quickly to a large chassis, and allowing damaged pixels to be replaced easily if needed. When the circuit board is fully populated with components, it passes through an automated quality-check system and then is placed into an optical components assembly line, where the printed circuit board and its avalanche photodiodes can be mounted onto the organic scintillator cube using index-matching optical adhesives of the type typically used in automated optical telecommunications assembly.

[0023] Figure 3 shows another subassembly of one possible embodiment, a cut-away view of part of a single layer of a chassis for holding tens or hundreds of identical organic scintillator pixels. Three example pixels (1) are shown at the top of the image. Each pixel slides into its mounting bracket (2) in the chassis frame, which could be constructed of metal, polymer, or composite materials depending on structural requirements. Clamps, fasteners, or similar devices lock each scintillator block in its place after the electronic connector (3) has been inserted into its electronic socket (4) along the side of each pixel mounting pocket. Ribbon cables or similar signal cables bring the signals from each pixel to the Layer Data and Vector Data signal processing systems (Figures 7 and 8). The full Compton telescope chassis consists of at least 3 layers rigidly mounted into a frame in a geometry like the one shown in Figure 1. The external frame also holds gamma ray and neutron shielding, and may include sheets of coincidence or anti-coincidence scintillator layers as needed to reject charged particles scattered into the detector through the telescope sides, or to detect electron-positron pairs escaping from gamma ray events within the Compton telescope. In one possible embodiment of this invention, each chassis layer has at least one associated Field Programmable Gate Array (FPGA) microprocessor to calculate the energy and coordinates of trigger-generating gamma ray events in that layer, and all layers communicate their events to the Vector Data processing system, which applies selection criteria to the events and reconstructs selected gamma ray tracks.

[0024] Figure 4 shows an example of an automated system, in one possible embodiment of the present invention, to calibrate each pixel after its circuit board is populated and mounted on the scintillator, but before the pixel is mounted into the Compton telescope chassis. A radioisotope (1) or electron beam source produces a collimated beam of electrons or gamma rays of known energy. Lead bricks with a small hole (2) provide collimation in the example shown. The scintillator pixel (3) is clamped onto a computer-controlled X,Y stage (4), and the pixel's electronic connector is inserted into a socket (5) as shown. A ribbon cable (6) or similar multi-wire cable brings supply power to the printed circuit board and carries the signals back to a data acquisition computer. A computer program scans the X,Y stage and analyzes all signals to map out the response of all photodetectors as a function of the position of incident electrons or gamma rays, providing the (x, y, energy) calibration for the pixel. Radioisotope sources with different gamma energy peaks may be used to calibrate the pixel response at multiple energies if this additional information proves to be useful. The calibration data are stored in a file and the pixel is tagged with an identifier unique to that calibration data set.

[0025] Figure 5 shows a top view of a shielded, moderated, collimated, pulsed neutron source (1), which is a part of one application for one possible embodiment of this invention. The pulsed neutron source is located about 1.5 meters from a shielded Compton telescope (2), as described in this invention. Concentric circles indicate the 2-meter, 5-meter, and 10-meter ranges from the neutron source. Most thermal neutrons travel in a range of velocities from about 1000 m/s to 4000 m/s, while gamma rays travel at the speed of light ($3x10^8$ m/s). Therefore a 100 microsecond-long pulse of thermal neutrons will exit from the neutron collimator after a few hundred microseconds have elapsed. Within 0.5 milliseconds the leading edge of the neutron pulse passes the 2-meter range (3). After 2 milliseconds have elapsed, the trailing edge of the neutron pulse is passing the 2-meter mark while the leading edge has already passed the 5-meter mark (4). Prompt gamma rays return to the Compton telescope in a few nanoseconds, negligible on the time scale of the thermal neutron time-of-flight. Therefore the neutron time-of-flight can be used to estimate the range of an object producing neutron-activation prompt gamma rays of interest that are detected by the Compton telescope. The length and duty cycle of the neutron pulsing can be modulated to maximize sensitivity for a given range. Gating the Compton telescope to select only events within certain time windows relative to the neutron pulse can enhance the signal to background ratio for events at a selected range.

[0026] Figure 6 shows a schematic diagram of some of the components that would be used on a single pixel printed circuit board. In one embodiment of the circuit board, a 2x2 array of four photodetectors (1) produce current pulses that are amplified by pre-amplifiers (2) with optimally matched active filters. The outputs of the four photodetectors go to a summing amplifier (3) to produce a signal proportional to the total energy deposited, and two difference amplifiers (4), which produce voltages proportional to an x-coordinate and a y-coordinate within the pixel. The output of the summing amplifier goes to a comparator (5), which produces a trigger pulse if the signal exceeds a set energy threshold. When the trigger fires, it activates three pulse-integrating analog sample-and-holds (6), which store the (x, y, and energy) signals from the pixel for a period from 20 to 100 nanoseconds as needed for downstream signal processing. The trigger signal and the three analog signals are passed through the electronic connector outputs (7) to the Layer Data and Vector Data processing subsystems.

[0027] Figures 7 and 8 show schematic diagrams of the signal processing subsystems for one example embodiment. In Figure 7, all pixels (1) in a layer pass their trigger and (X, Y, energy) analog signals along multiwire conductors (2), such as RF-shielded ribbon cables, to the Layer Data processor (3). As shown in Figure 8, the Layer Data processor for each layer digitizes selected events and then passes the digitized data to the Vector Data processor for further signal processing. To reduce the number of expensive signal-processing components such as fast analog-to-digital converters (digitizers), the analog pulses from all pixels in a layer are passed into inexpensive analog multiplexors (MUXs). The Layer Data signal processing subsystem receives a trigger signal from any pixel where an above-threshold event occurs. In most cases, a single energetic gamma ray will deposit energy in one pixel of one layer, then Compton scatter forward one or more times, depositing energy in one or more other layers. The trigger signals from the approximately 50 to 100 pixels in a single layer pass into a fast digital encoder system (which may include a fast Field Programmable Gate Array or FPGA) in the Layer Data subsystem. The digital encoder system generates an index number to select the analog (x, y, energy) signals in the analog MUX system from the pixel that was triggered. The selected (x, y, energy) signals are digitized by fast analog-to-digital converters. In this way, only 3 digitizers are needed (one x , one y, one energy signal) to capture all the relevant signal data for a layer of 50 to 100 pixels. The pixel index number, associated (x, y, energy) data, and trigger pulse from a triggered pixel in each layer are passed downstream to the Vector Data processing system. Coincidence detection circuits in the Vector Data processing system identify groups of trigger events that fall within a trigger time window (for example, within a 20 nanosecond period) across all layers of the Compton telescope. The Vector Data processing system can only calculate the gamma ray momentum vector for gamma ray events that Compton scatter and deposit sufficient energy in at least two layers of the Compton telescope. A fast FPGA will apply a series of selection rules to each set of time-coincident multilayer trigger events with their pixel index numbers and energy data, to see if the events represent a Compton scatter track for an incident gamma ray in an energy range of interest (for example, 10.8 MeV for gammas from nitrogen or 7.8 MeV from chlorine). In the occasional cases where two high-energy gamma rays over the energy threshold arrive within a single coincidence time window at the Compton telescope, anti-coincidence logic may be used in the Vector Data FPGA to reject one or both of the gamma ray tracks if the simultaneous events result in ambiguity or lost data. The number of digitizers and processors per layer could be increased if necessary to achieve higher event rate tracking. However, models of the likely applications of this invention show that an event tracking rate of 10 million events per second (any coincidence window shorter than 100 nanoseconds) is sufficient for the most likely operational scenarios.

[0028] Figure 9 shows a different possible embodiment of a photodetector array on a single pixel. The 3x3 square grid of photodetectors (1) on a square pixel (2) with dimensions between 10 and 20 cm on a side may have cost/performance advantages, as described below in section [0036]. Each 2x2 grouping of photodetector signals (3) (dashed circles) would be summed in a summing amplifier to measure energy deposition in that quadrant of the pixel, while diagonally opposite photodetectors in each 2x2 grouping would pass their signals to differential amplifiers to generate signals giving the (x,y) position of any gamma ray collision within that quadrant of the pixel (4) – dotted rectangles indicate two pairs of photodetectors that would produce differential signals. The other six rectangles have been omitted for clarity of the drawing.

[0029] Figure 10 shows the relationship between the energy of an incident gamma ray (E1), the energy of the scattered gamma ray (E2) after a Compton scatter interaction (1) in one layer of a Compton telescope, and the scattering angle θ between the incident ray and the scattered ray as determined by conservation of energy and momentum in a 2-body collision between an electron at rest and an energetic gamma ray. A successful capture of the energy from one Compton scatter event, plus the capture of the remaining energy from the scattered gamma ray (E2), allows the Vector Data system to compute the angle θ and reconstruct a cone-shaped zone of probability for the direction of the incident gamma ray. The width of the circular zone (dθ) is determined by the uncertainty in the (x,y,z) positions of the first and second interaction (2) and the uncertainty in the energy measurements.

[0030] Figure 11 shows experimental data from a small laboratory-scale Compton telescope viewing a cesium-137 radioisotope 662 keV gamma ray source a few cm away [Ref. 10]. The gray rings in the image show circular zones of probability generated by individual Compton-Scattering events. The intersection of many gray rings at a single point indicates the location on the image of the actual radioisotope source.

[0031] Figure 12 shows a simple 14x14x10cm rectangular scintillator pixel (1) with four 5x5mm avalanche photodiodes (APDs) mounted on it (2). This pixel was modeled using Monte Carlo methods to predict the optical signal measured by each photodetector as a function of the (x,y) position of a gamma ray scattering event in the pixel.

[0032] Figure 13 shows the results of the Monte Carlo simulation. In the upper left quadrant of the figure, the predicted signal from APD 1 in microAmps is lower when the Compton scatter event happens further away from that APD. In the upper right, the sum of all four photodetectors is nearly uniform, as expected. In the lower left, the difference signal between the left/right pairs of ADPs (3) gives a clear indication of the position of the Compton scatter event. In the lower right, we see some statistical noise in the difference signal between the top/bottom pairs of APDs, which accurately reflects the expected statistical fluctuation in the photon statistics from scintillation light hitting the APDs. Nevertheless, Signal Y still gives a good indication of the position of the Compton scatter event. This model predicts the result of the (x,y) calibration procedure shown in Figure 4 for the pixel geometry in Figure 12. The resulting data indicate that a lookup table or fit function can be created that uniquely maps the combination of the photodetector sum and (x) and (y) difference signals to the (x, y, energy) information required from each pixel.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0033] This invention has been described in accordance with the relevant legal standards, and therefore the description is exemplary rather than limiting in nature. Variations and modifications to the disclosed embodiment may become apparent to those skilled in the art and fall within the scope of the invention.

[0034] In one preferred embodiment of this Compton telescope, optimized for detection of 10.8 MeV gamma rays from materials at standoff ranges of 10 meters or more, this invention consists of 5 to 10 layers of plastic scintillator made of PVT containing dissolved fluors. The most likely candidate plastic scintillators are BC428 provided by Saint Gobain Crystals Inc. and EJ260 provided by Eljen Technology, because these scintillators are available at low cost and high quality, and they produce scintillation light in the blue-green range (490 nm) of the optical spectrum instead of the blue-violet range (410 nm) where most scintillators are active. Available photodiodes and avalanche photodiodes are more sensitive to green light than to blue light.

[0035] The scintillator layers will be arranged as shown in Figure 1. Each layer of the Compton telescope will consist of 50 to 100 pixels no larger than 15x15 cm in area x10 cm thick, producing a total collection area of at least one square meter. The number of layers, number of pixels per layer, and number of photodetectors per pixel will be determined based on an analysis of performance vs. cost, because increasing the number of photodetectors, pixels and layers will increase the size, cost, and performance of the instrument. For Department of Defense or Homeland Security applications, this cost/performance study requires the knowledge of classified security CONOPS (Concepts of Operations), and therefore a final cost/performance study for this particular embodiment is beyond the scope of this patent. The 10 cm thickness of each layer has been shown to be effective for Compton telescope capture and tracking of 10.8 MeV gamma rays, based on Monte-Carlo analysis of gamma ray transport using the MCNP5 code developed at Los Alamos National Labs, and separate Monte-Carlo analyses of scintillator light transport and diffuse reflection within each pixel. For other applications, generally thinner PVT layers would be chosen because most terrestrial gamma ray sources produce energies lower than 10.8 MeV.

[0036] One preferred embodiment of the pixel design is shown in Figure 9, a 3x3 square array of photodetectors, which has several cost and performance advantages. By summing the photodetector signals in square 2x2 groups of four (dashed circles), the energy deposited in any one quadrant of the pixel can be measured. By taking the difference signals between diagonally opposite photodetector pairs within any 2x2 group (two example pairs are emphasized in the two dotted rectangles), a measurement of the (x,y) collision position within that grouping can be uniquely determined. Notice that the photodetectors in the center and along the middle of each edge can serve double or quadruple duty by contributing to the sums and differences from multiple quadrants. In effect, this photodetector geometry achieves a better coverage of detector area per photodetector than any pixel with equivalent area per photodiode in a 2x2 configuration. This strategy to maximize component coverage, or equivalently to minimize component cost per unit area for a given performance, leads in its logical extreme to a single huge detector pixel with a grid of photodetectors covering the entire Compton telescope area; but this would not be practical. The cost advantages of small pixel mass-production would be lost in such a large single-plate geometry. In practice the marginal returns of lower component cost per unit detector area (at a given performance level) rapidly diminish for photodetector arrays larger than 3x3 or 4x4 photodetectors, which is why the 3x3 array is chosen as one preferred embodiment here.

[0037] When a 10.8 MeV gamma-ray is incident on the front face of this Compton telescope, a number of interactions may occur. Most commonly, the gamma ray will pass through one or several layers of the plastic scintillator with no interaction, and then will Compton scatter from an electron in one of the scintillator layers. Typically between 1 MeV and 10 MeV of the gamma ray energy will be transferred to the electron, while the scattered gamma ray continues forward in a new direction carrying the remainder of the original 10.8 MeV energy. The recoil electron from the Compton scatter event deposits its energy in the plastic scintillator near the location of the first collision, producing a fluorescent signal that is measured by several photodetectors on that pixel to determine its (x,y) location within the pixel and the amount of energy deposited. If the scattered gamma ray then goes on to deposit the rest of its energy in subsequent layers of the Compton telescope, this two-point or multi-point interaction often gives enough information to calculate the initial momentum and direction of the incident 10.8 MeV gamma ray.

[0038] While hundreds of thousands of gamma rays are expected to hit the Compton telescope per second, over 99.9% of them will be ignored by the signal processing system because their total energy will be below 9 MeV. Since the plastic scintillators and photodetectors in this design have a 10-nanosecond response time, even a million gamma ray events per second can easily be separated in time by fast analog triggering. At the individual pixel level, only events depositing more than 0.6 MeV (or some revised threshold based on later laboratory data) will trigger the sample-and-hold amplifiers that pass the signal on to Layer Data and Vector Data systems (see Figures 6 , 7, and 8). Clusters of multiple pixel trigger events that occur in multiple layers within a 20 nanosecond gamma-ray time-of-flight window will be summed across all telescope layers using the fast FPGA in the Vector Data processor. Only those clusters of events whose total energy sums to a value over 9.0 MeV (or some revised threshold based on later lab data) will be selected for further vector analysis in the Vector Data Processor.

[0039] The Vector Processor will apply a series of selection rules to each qualifying cluster events to determine if that gamma ray momentum is trackable by Compton Scattering laws. The first selection rule requires the event cluster to deposit at least 0.6 MeV (or other appropriate threshold to be determined) in at least two different detector layers to produce useful vector information. Event clusters that pass the first selection rule are then calibrated to improve their energy resolution using the lookup tables that were generated by pixel calibration during instrument fabrication. The second selection rule requires the energy-calibrated events to sum to a total energy between 9.3 and 11.3 MeV (or other thresholds to be determined). The third selection rule evaluates the (x,y,z) position and energy deposited in the first collision event, and compares that to the (x,y,z) position of the second collision event, and the total energy of all concurrent events, to see if the direction vector and gamma ray energies before and after the first collision are consistent with the law of Compton scattering for a 10.8 MeV gamma ray incident on the front face of the Compton telescope.

[0040] The law of Compton scattering, based on the conservation of momentum and energy in a 2-body collision between a gamma ray and an electron, requires that the scattering angle θ of the gamma ray, as shown in Figure 10, must fulfill the following condition:

$\cos(\theta) = 1 - mc^2 (1/ E_1 - 1/E_2)$,

where m = the rest mass of the electron, c = the speed of light, E_1 = the energy of the incident gamma ray, and E_2 = the energy of the Compton-scattered gamma ray. If a cluster of events within a 20-nanosecond time window produces a result incompatible with the Compton scatter relation and the detector geometry—for example, if the calculated angle implies that the gamma ray came from behind or through the sides of the Compton telescope rather than from the front—then that cluster of events will be rejected as an artifact. Non-Compton-scatter artifacts can be produced for example when the first gamma-ray interaction in the Compton telescope is an electron-positron pair production, followed by positron annihilation, instead of a Compton scatter event. Other examples of artifacts include cases where gamma rays pass through the telescope shielding at the back or sides of the Compton telescope, where two energetic gamma rays happen to enter the Compton telescope within the same 20 nanosecond time window, or where a Compton recoil electron generates a high energy bremsstrahlung photon that carries too much of the energy from the first Compton scatter into another layer of the Compton telescope. MCNP5 models indicate that a Compton telescope with 7 layers of PVT-based scintillator, each 10 cm thick, will achieve a clean Compton scatter event, followed by capture of enough of the remaining gamma ray energy in subsequent layers to apply the Compton scatter law, in up to 15% of cases where a 10.8 MeV gamma ray is incident on the front face of the Compton telescope. By Comparison, the CompTel 2-Layer Gamma Ray Telescope had a capture efficiency less than 2% for this scenario.

[0041] The digital data from those events that meet all the selection criteria including the Compton scatter law are passed from the Vector Processor to a data acquisition system on a computer with hardware and software that generates an image of the 9 MeV to 11 MeV gamma ray landscape in the field of view of the Compton telescope.

[0042] Since the scattering angle θ of the first Compton scatter interaction in the telescope does not uniquely determine the direction of an incident gamma ray, the intensity of the gamma ray image must be expressed as a cone-shaped zone of probability for each gamma ray event acquired, as indicated in Figure 10. The opening angle θ of the cone-shaped zone is derived by the Compton Scatter relation, and the width of the band around that angle is a function of the estimated uncertainty in the (x,y,z) positions of the interactions that define the energy depositions (1) and (2), and the estimated uncertainty in the energy measurements themselves, which lead to an uncertainty band (dθ) around the calculated angle θ. It is clear then that a single gamma ray event cannot yield a very good image with high statistical confidence. However, as multiple gamma rays are acquired, the circular zones of confidence for a given gamma ray source at a given energy (10.8 MeV in this example) overlap only in the direction of the actual source, producing a high confidence image of that source, as shown in the laboratory data from NRL in Figure 11.

[0043] Other relevant data, such as data from coincidence or anti-coincidence detectors, from time-of-flight measurements related to a pulsed neutron source, or from visible/infrared image acquisition systems may be integrated with the gamma ray image in the data imaging computer, and post-processing of the data in this computer may provide interpretive results (such as statistical confidence of a threat detection or object of interest) to the Compton telescope user, depending on operational and user interface requirements.

[0044] The foregoing invention has been described in accordance with the relevant legal standards, thus the description is exemplary rather than limiting in nature. Variations and modifications to the disclosed embodiment may become apparent to those skilled in the art and fall within the scope of the invention.

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What is claimed:

[COMPTON TELESCOPE APPARATUS CLAIMS 1-19]

1. An apparatus (a Compton telescope) for detecting and imaging sources of gamma rays, substantially as disclosed.
2. An apparatus (a *Compton telescope*) for detecting and imaging sources of gamma rays, said apparatus comprising:
   - at least three layers of gamma ray detectors, with at least two layers, including all or the majority of the active gamma ray detecting mass, made of organic plastic and/or organic liquid scintillators;
   - each layer of gamma ray detectors made of a large number of identical scintillator pixels, which can be mass-produced using automated manufacturing methods from the electronic printed circuit board and optical telecommunications industries, such as the pick-and-place machines used for populating printed circuit boards;
   - each pixel including a block of scintillator material with at least three semiconductor-based high-gain photodetectors mounted on it to determine the (x,y) position and total energy deposited by a gamma ray collision inside that pixel;
   - each pixel having an associated printed circuit board with the photodetector power supply traces, photodetector preamplifiers, and a standard socket-based electronic connector attached to the scintillator pixel;
   - a chassis consisting of several layers of rigid supports, each layer containing a large number of pixel mounting brackets or mounting sockets for mounting the identical pixels securely onto the chassis, and each mounting place on the chassis is accompanied by a standard electronic connector socket to allow the rapid mounting of the pixels with their attached printed circuit board electronics into the chassis and chassis electronics systems;
   - electronic signal processing systems on or near the chassis that receive trigger signals from pixels registering significant events, and that multiplex the analog signals from many pixels—only a few of which are active at any one instant—into a few fast A/D converters for digital signal processing;

- Field Programmable Gate Arrays (FPGAs) or similarly fast programmable microprocessors that perform digital signal processing on groups of events to identify the tracks of gamma ray events of interest, and to filter out background or uninteresting events;
- FPGAs or similarly fast programmable microprocessors that calculate the incident direction of tracked gamma rays of interest and pass that information on to a data imaging and analysis system;
- and a data analysis and imaging system consisting of computer software and hardware to generate an image of the gamma ray field of view of the Compton telescope based on the accumulation of multiple gamma events of interest in the Compton telescope detectors.

3. The apparatus of Claim 1, wherein said organic plastic or organic liquid scintillators contain up to 20% heavy metals by weight in the form of organometallic compounds.
4. The apparatus of Claim 1, wherein said organic plastic or organic liquid scintillator layers are designed with thicknesses that maximize the probability of capturing the energy of a single Compton scatter event in one layer followed by complete or nearly complete capture of the remaining energy of a Compton scattered gamma ray in the ensemble of the remaining layers, for gamma rays of a particular energy of interest incident on the front face of the Compton telescope.
5. The apparatus of Claim 1, wherein said gamma ray detector pixels are individually calibrated by an automated method to improve their (x,y) position and energy resolution.
6. The apparatus of Claim 1, wherein said identical gamma ray detector pixels are calibrated by lot or as a group, using one or a few samples to represent the response of the whole lot, to improve their (x,y) position and energy resolution.
7. The apparatus of Claim 1, wherein said photodetectors are low-noise photodiodes.
8. The apparatus of Claim 1, wherein said photodetectors are avalanche photodiodes.
9. The apparatus of Claim 1, wherein said photodetectors are solid state photomultipliers (arrays of Geiger-mode avalanche photodiode pixels).

10. The apparatus of Claim 1, wherein said photodetectors are located on the scintillator pixel in a rectangular, triangular, hexagonal, or similar array such that the difference between the signals of any pair or group of adjacent photodetectors is a well-defined function of the position and total energy deposited by a gamma ray in that region of that pixel.
11. The apparatus of Claim 1, wherein said photodetectors are located along several different faces or sides of the scintillator pixel to reduce obstruction of gamma rays traveling along the axis of the Compton telescope, or to improve energy or (x,y,z) position resolution.
12. The apparatus of Claim 1, wherein said photodetectors are located on a square scintillator pixel in a 3x3 grid as shown in Figure 9, with each 2x2 grouping of four photodetectors sending their preamplifier signals to a single sum amplifier, and each diagonal pair of photodetectors within each 2x2 grouping of four photodetectors sending their preamplifier signals to a single differential amplifier, to achieve better (x,y,energy) performance per component cost than could be achieved with 2x2 photodetector arrays on smaller pixels with equivalent detector area per component.
13. The apparatus of Claim 1, wherein said printed circuit board also contains analog sum amplifiers to sum the signals of all photodetectors or of adjacent pairs or groups of photodetectors on the scintillator pixel.
14. The apparatus of Claim 1, wherein said printed circuit board also contains analog differential amplifiers to subtract the signals of adjacent pairs or groups of photodetectors on the scintillator pixel.
15. The apparatus of Claim 1, wherein said printed circuit board also contains at least one analog signal threshold detector, such as a comparator amplifier, that generates a trigger signal when a pre-set trigger threshold is exceeded on one or several of the photodetectors signals or their sum.
16. The apparatus of Claim 1, wherein said printed circuit board also contains one or several analog sample-and-hold amplifiers that acquire and hold an analog voltage, or the next peak (extremum) analog voltage, immediately after receiving a trigger signal from a threshold detector like that described in Claim 11; and where the analog sample-and-hold amplifiers are reset by a trigger from a timer chip or similar time-out mechanism occurring a preset time after the threshold trigger.

17. The apparatus of Claim 1, wherein said printed circuit board has a board edge-connector and each pixel mounting place on the chassis is accompanied by a board edge-connector socket to connect to the circuit board.
18. The apparatus of Claim 1, further including walls of neutron shielding, gamma ray shielding, or coincidence/anti-coincidence detectors as needed, mounted on and around the chassis to improve the signal/background ratio
19. The apparatus of Claim 1, wherein the top-level FPGA digital signal processors or the lowest level data analysis and imaging systems on the control computer receive trigger pulses from a pulsed neutron source, allowing the data analysis system to filter out or gate-suppress Compton telescope background events that occur during neutron pulses, and to assign probable ranges or distance estimates to neutron activated prompt gamma ray sources based on neutron time-of-flight after each neutron pulse.

[MASS-PRODUCTION METHODS CLAIMS 20-22]

20. A mass-production method, substantially as shown and described.
21. A method wherein said printed circuit board is used to mount the photodetectors and associated circuitry, with components on the circuit board mounted by automated pick-and-place machinery common to the electronics industry; and then the printed circuit board with photodetectors is attached as a unit to the scintillator, to facilitate mass production and automation of manufacturing of pixels.
22. A method wherein said photodetectors are mounted to the scintillator using index-matching optical adhesives such as are used in the optical telecommunications industry.

[PIXEL CALIBRATION METHODS CLAIMS 23-28]

23. A method of calibrating large numbers of identical scintillator pixels, substantially as shown and described.
24. A method of calibrating large numbers of identical scintillator pixels using a computer controlled (x,y) translation stage, data acquisition system, and collimated gamma ray or

electron beam source of known energy, as shown in Figure 4, to create a calibration data set like that modeled in Figure 13.

25. A method of calibrating large numbers of identical scintillator pixels by measuring the performance of a representative number of pixels using the method illustrated in Figure 4, and then using statistics to infer the behavior of the entire lot.
26. A method of correcting the energy measurement from each pixel using a calibration lookup table or coefficients based on calibration data like that modeled in Figure 13.
27. A method of deriving the (x,y) position in a pixel using the difference signal between two adjacent photodetectors or groups of photodetectors divided by the sum signal from all neighboring photodetectors, such as the photodetector groupings shown in Figure 9.
28. A method of deriving the (x,y) position in a pixel using the difference signal between two adjacent photodetectors or groups of photodetectors and the sum signal from all the photodetectors, and a lookup table or calibration coefficients based on calibration data such as those modeled in Figure 13.

[SIGNAL PROCESSING METHODS CLAIMS 29-33]

29. A method of identifying gamma ray tracks that interact in multiple layers of the Compton telescope, substantially as shown and described.
30. A method of identifying gamma ray tracks that interact in multiple layers of the Compton telescope, by selecting gamma ray or energetic particle event clusters that generate groups of trigger signals coincident within a time window, which may be as short as 1 nanosecond or as long as several hundred microseconds.
31. A method of rejecting background gamma ray events or energetic particle events that do not contribute to the gamma ray image of interest, because the energy depositions in all layers of the telescope for that event do not produce a sum in the range of 9.3 to 11.3 MeV (in the preferred embodiment for 10.8 MeV gamma rays), or do not sum to approximately the gamma ray energy of interest (in other embodiments).
32. A method of rejecting clusters of background gamma ray events or energetic particle events that do not contribute to the gamma ray image of interest because the event

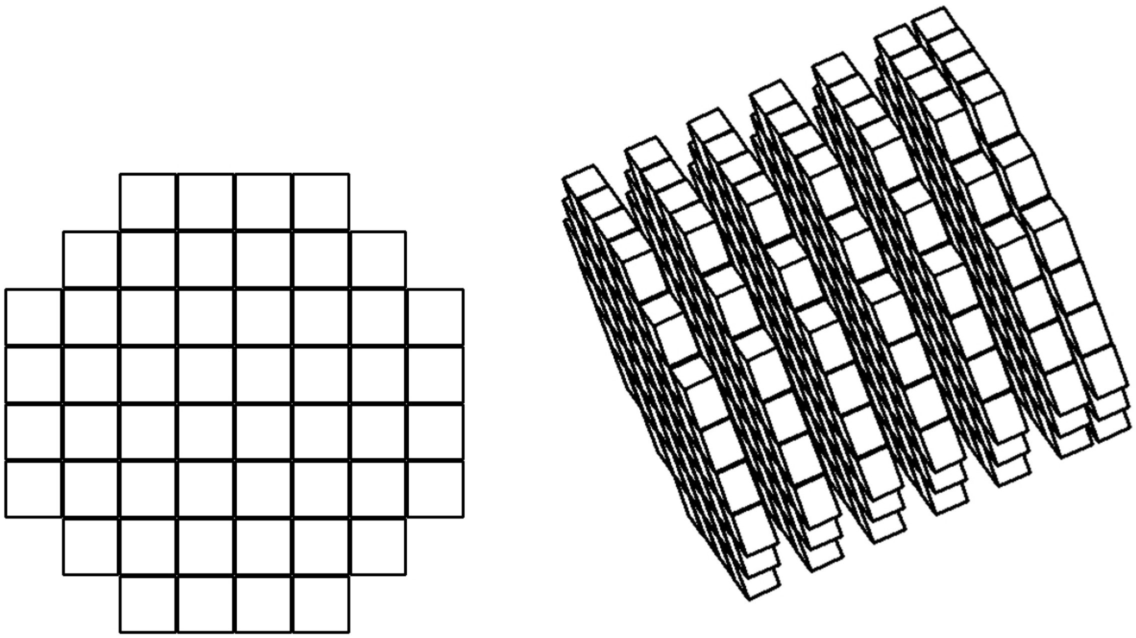
clusters do not generate pixel triggers in at least two distinct layers of the Compton telescope.

33. A method of rejecting clusters of background gamma ray events or energetic particle events that do not contribute to the gamma ray image of interest because they do not produce a result consistent with the Compton scatter law and the field of view and angular acceptance of the Compton telescope.

ABSTRACT

Apparatus and methods for imaging distant or nearby sources of gamma rays with a large area, comparatively low-cost Compton telescope; and methods for constructing and calibrating such a device using mass-production and automation technologies from the electronic circuit board and optical telecommunications industries. This Compton telescope design uses multiple layers of low-cost organic plastic or liquid scintillator, arranged in large arrays of identical scintillator pixels that can be mass produced with automation to reduce labor costs. The scintillator layer thickness is optimized to achieve maximum efficiency for a specified gamma ray energy of interest, while the pixel and component counts are optimized to achieve the required instrument performance in angular and energy resolution at minimal cost. Photodiodes, avalanche photodiodes, or solid-state photomultipliers are used to read out the fluorescent pulses from scintillator pixels instead of the usual photomultiplier tubes, minimizing efficiency losses from inactive material within the telescope volume. Methods are presented to reduce signal processing electronics cost by multiplexing multiple scintillator pixels into a few fast A/D converters and a few fast FPGA programmable digital microprocessors. Methods are presented to maximize signal to background ratio for gamma ray energies of interest. Selection rule methods are presented for processing multiple near-simultaneous gamma ray collisions within the Compton telescope to identify trackable events that yield gamma ray image data of interest. A calibration method is presented to achieve 5% or better energy resolution along with (x,y) position information in pixels made of organic scintillator with multiple photodetectors.

Methods are presented to use synchronization trigger signals from a pulsed neutron source to maximize the signal to background ratio for prompt gamma neutron activation analysis (PGNAA) of objects at greater than 2 meters range, and to estimate the range to PGNAA sources using neutron time-of-flight analysis.



Front View

Side View

Figure 1

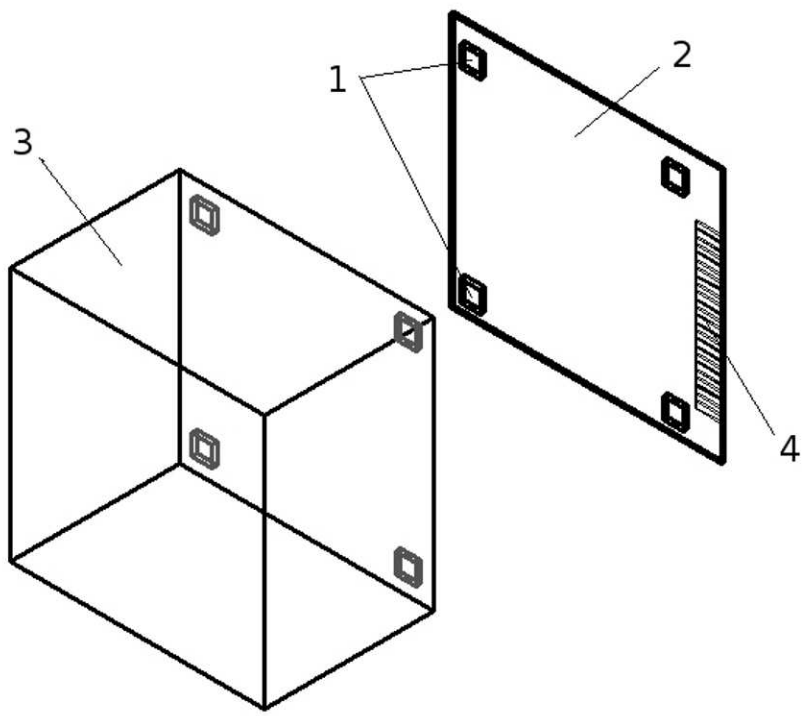


Figure 2

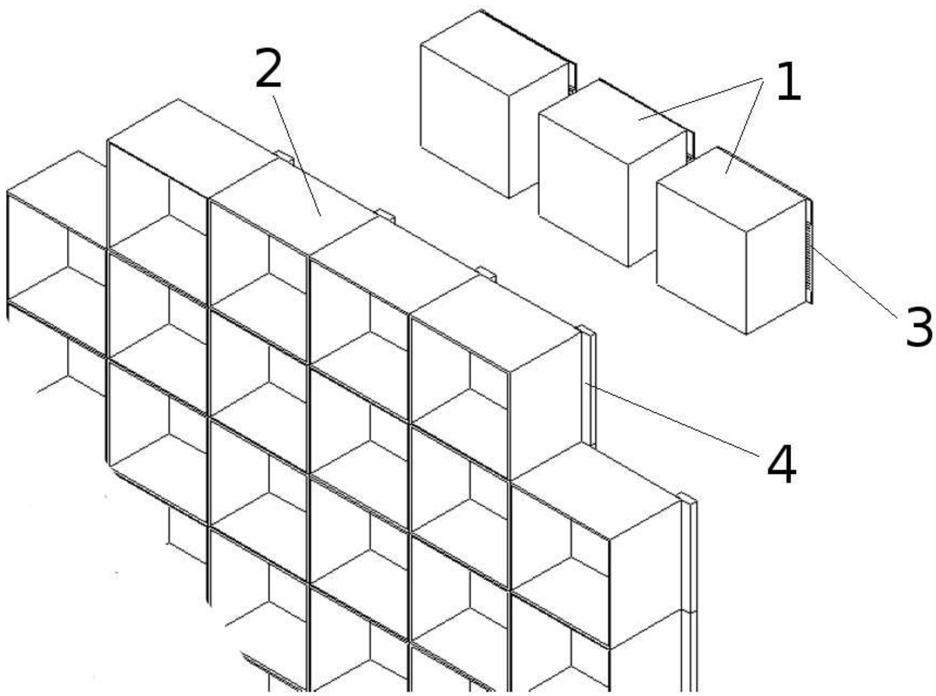


Figure 3

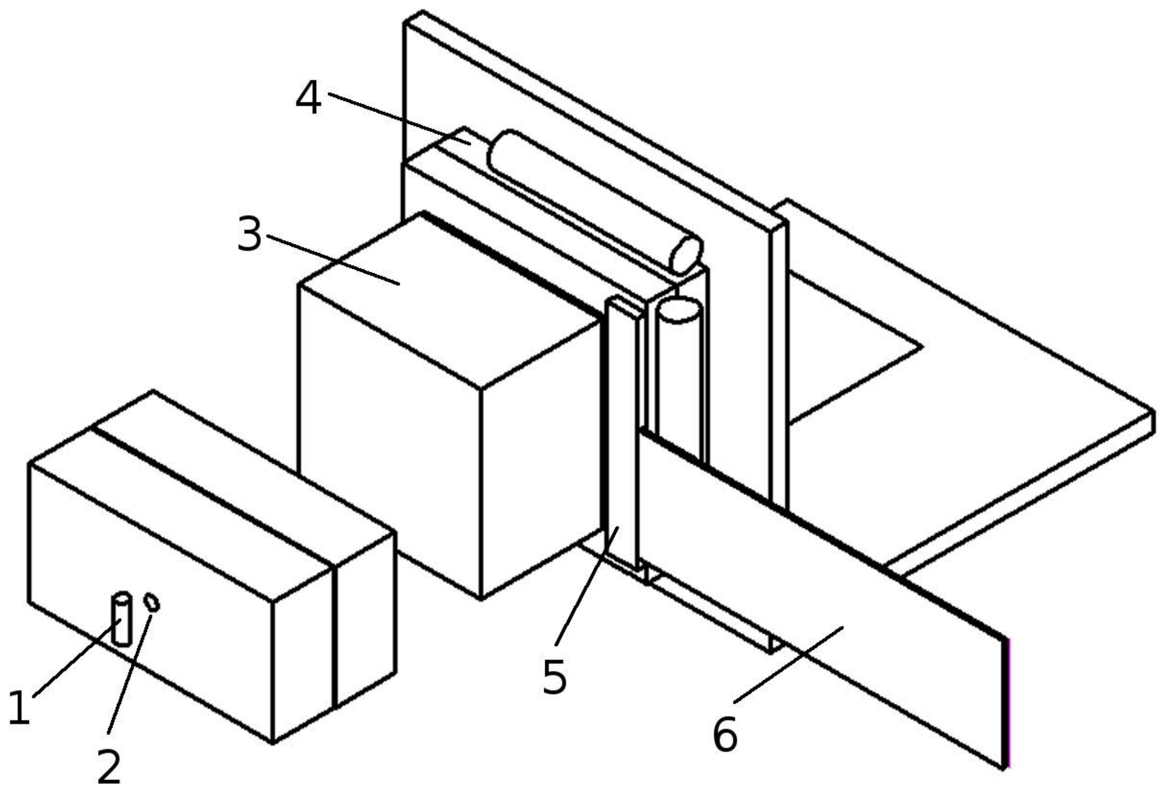


Figure 4

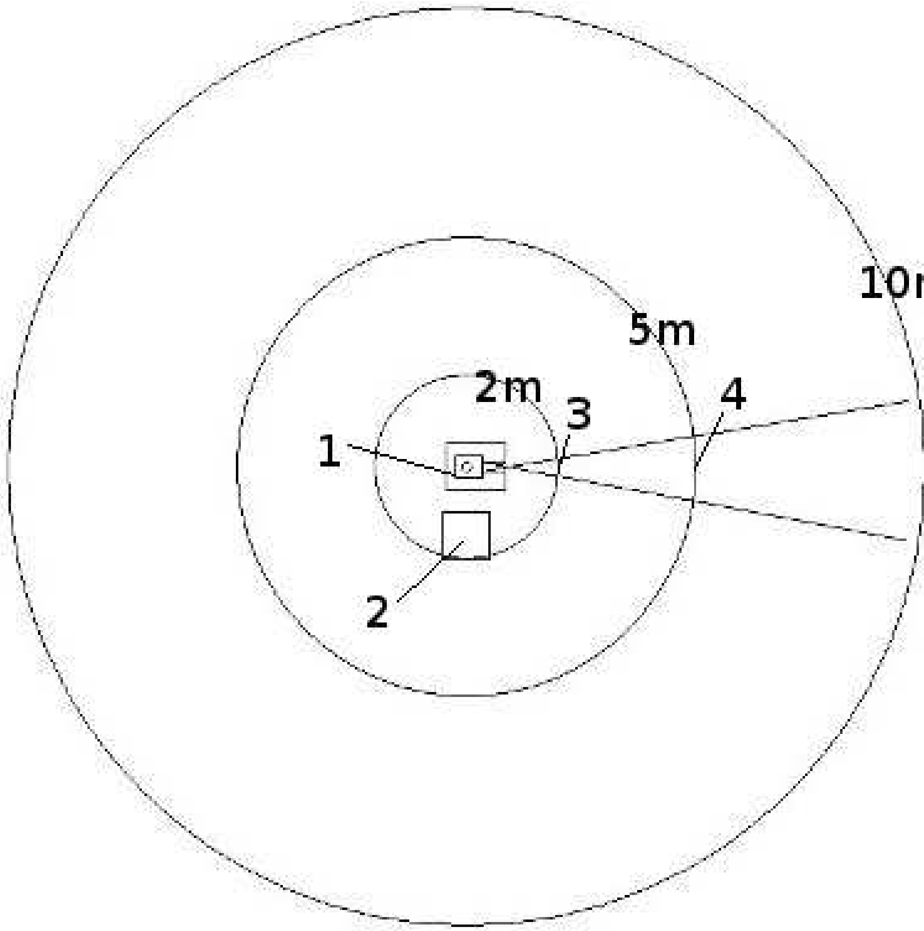


Figure 5

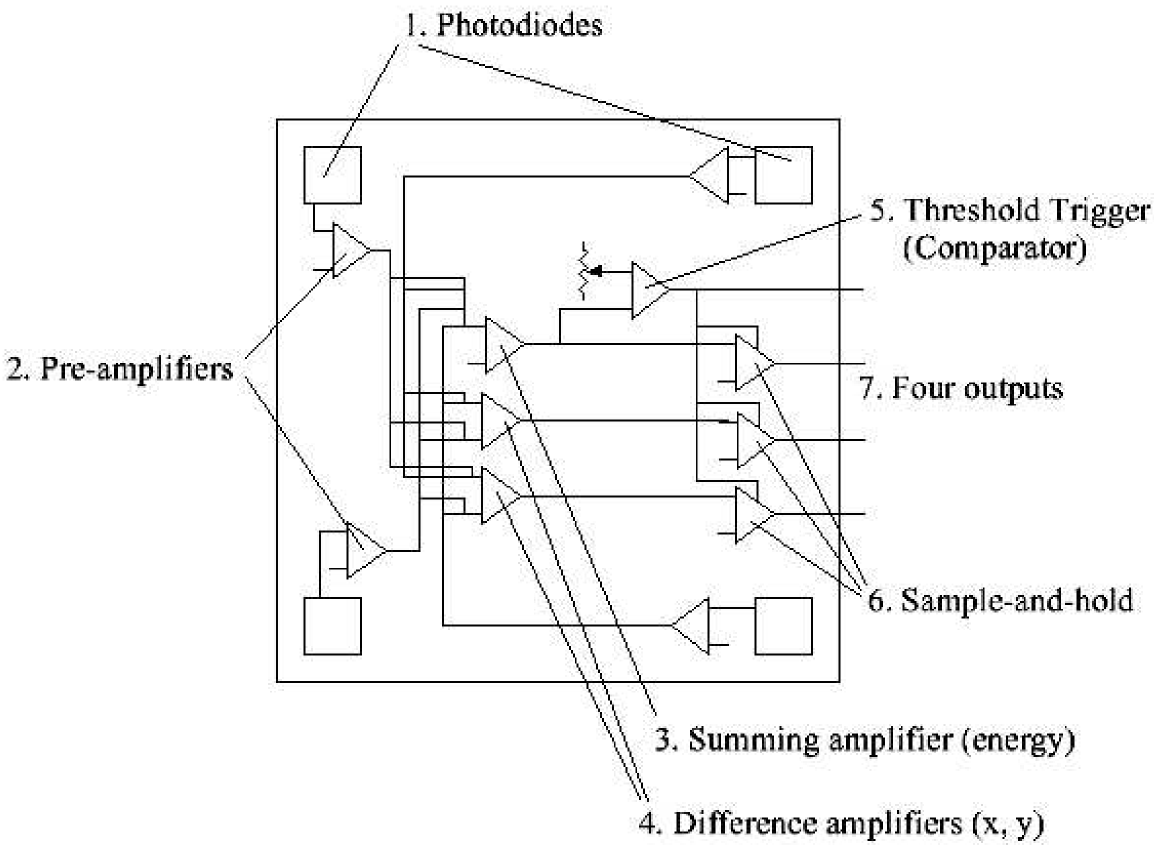

1. Photodiodes
5. Threshold Trigger
(Comparator)
2. Pre-amplifiers
7. Four outputs
6. Sample-and-hold
3. Summing amplifier (energy)
4. Difference amplifiers (x, y)

Figure 6

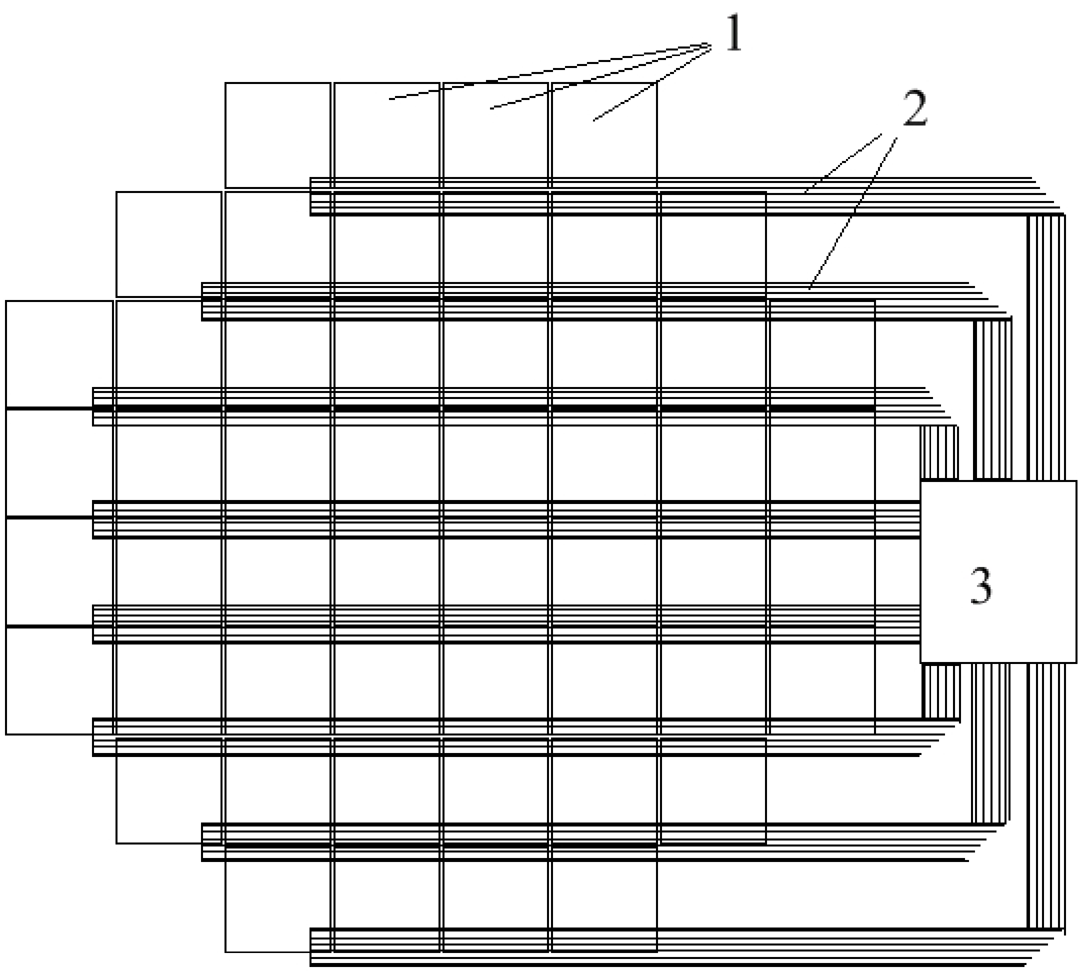


Figure 7

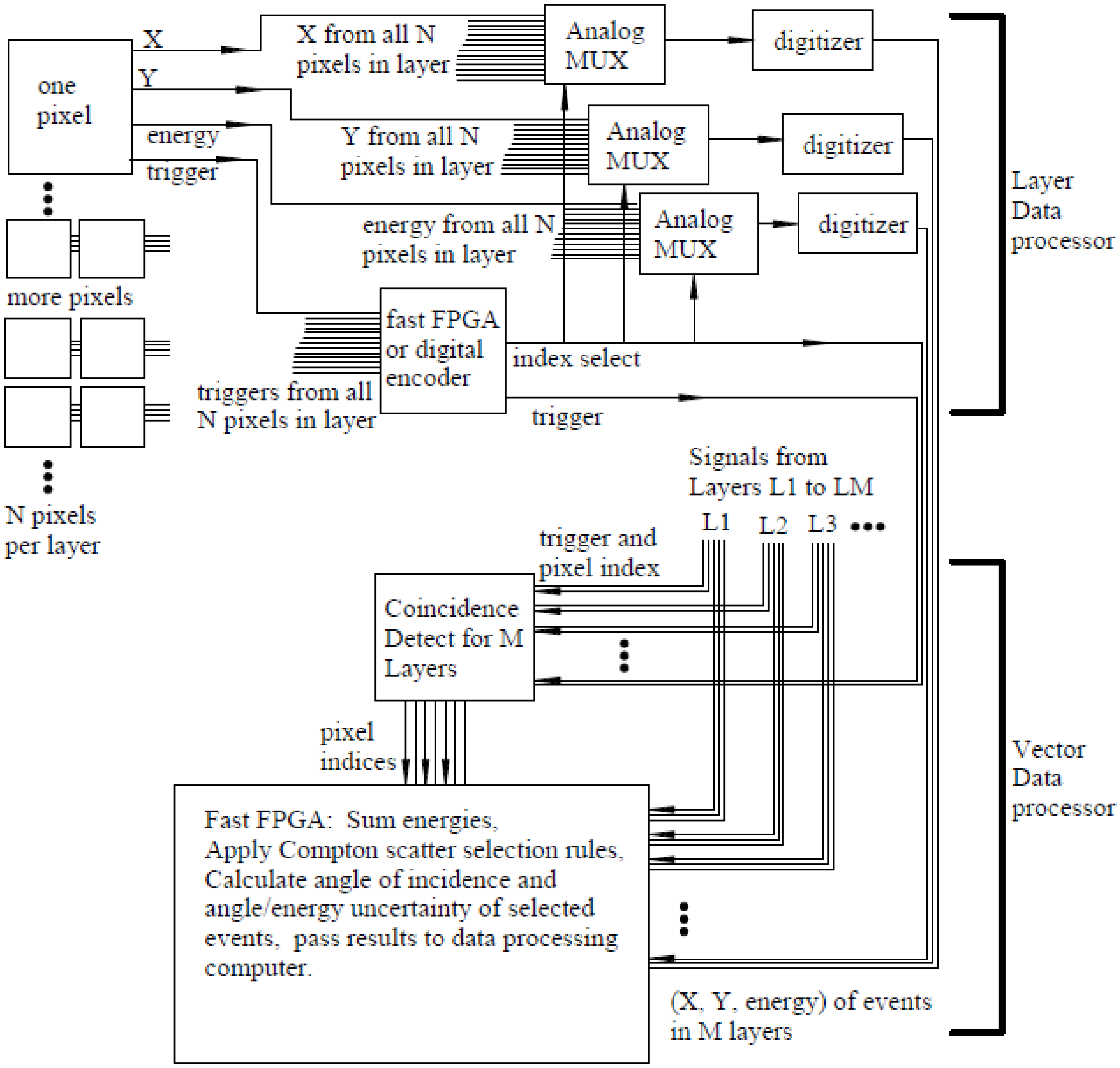

one pixel
X
Y
energy
trigger
X from all N pixels in layer
Analog MUX
digitizer
Y from all N pixels in layer
Analog MUX
digitizer
energy from all N pixels in layer
Analog MUX
digitizer
Layer Data processor
more pixels
fast FPGA or digital encoder
index select
triggers from all N pixels in layer
trigger
N pixels per layer
Signals from Layers L1 to LM
L1 L2 L3
trigger and pixel index
Coincidence Detect for M Layers
pixel indices
Fast FPGA: Sum energies, Apply Compton scatter selection rules, Calculate angle of incidence and angle/energy uncertainty of selected events, pass results to data processing computer.
(X, Y, energy) of events in M layers
Vector Data processor

Figure 8

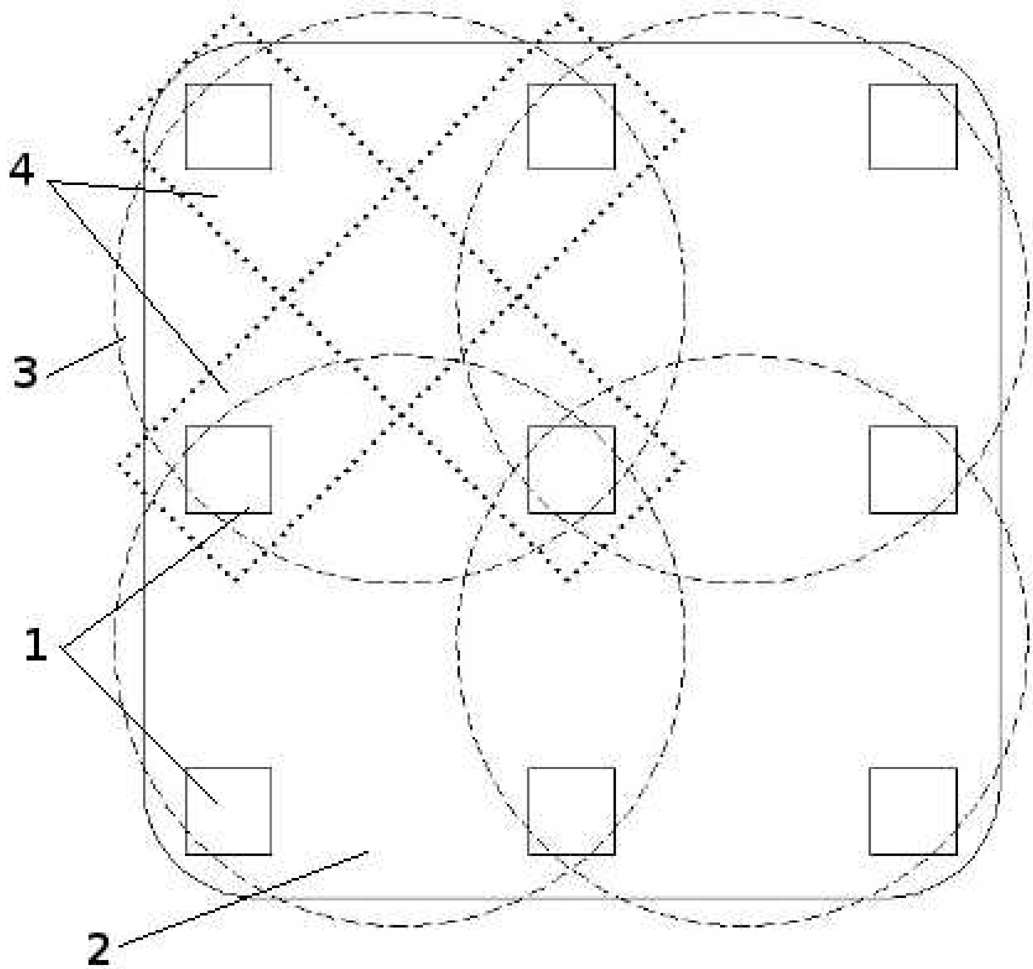


Figure 9

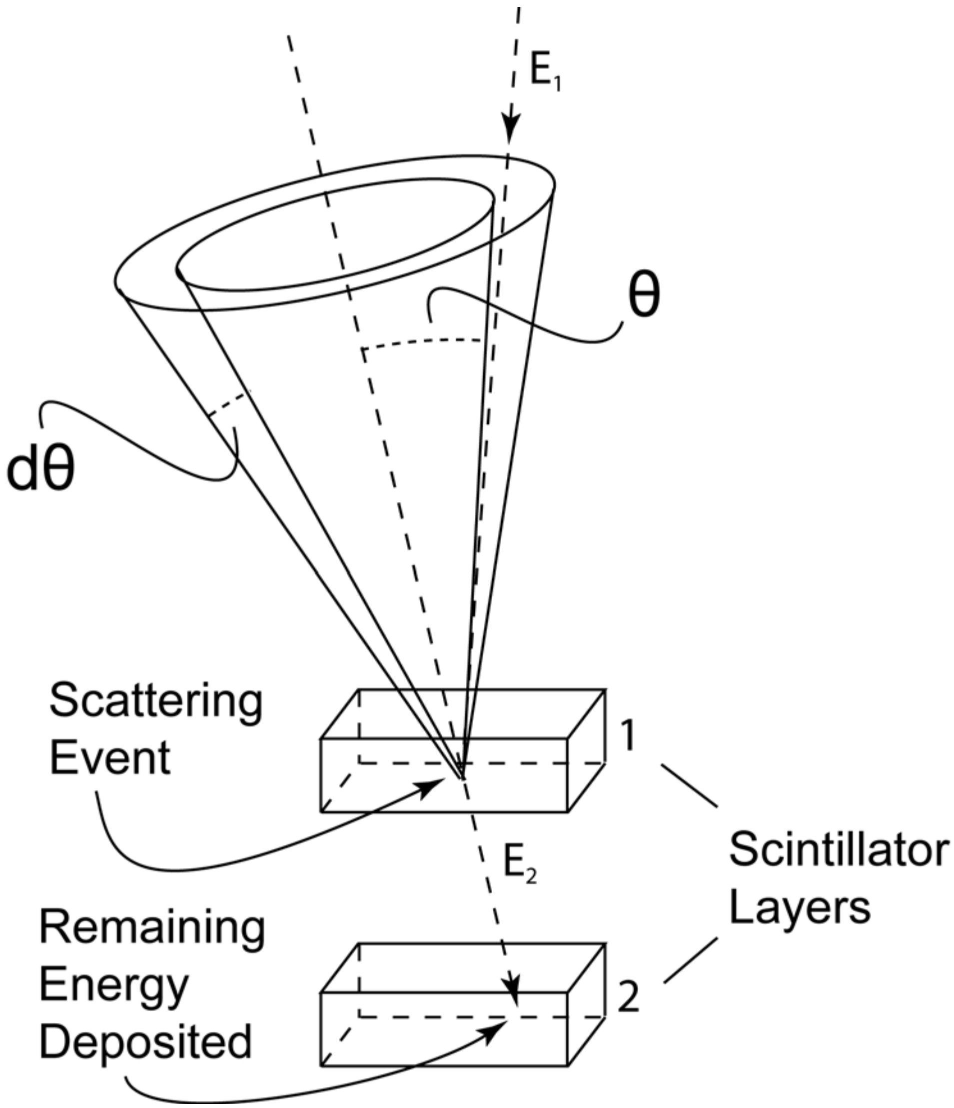

E1
θ
dθ
Scattering
Event
1
E2
Scintillator
Layers
Remaining
Energy
Deposited
2

Figure 10

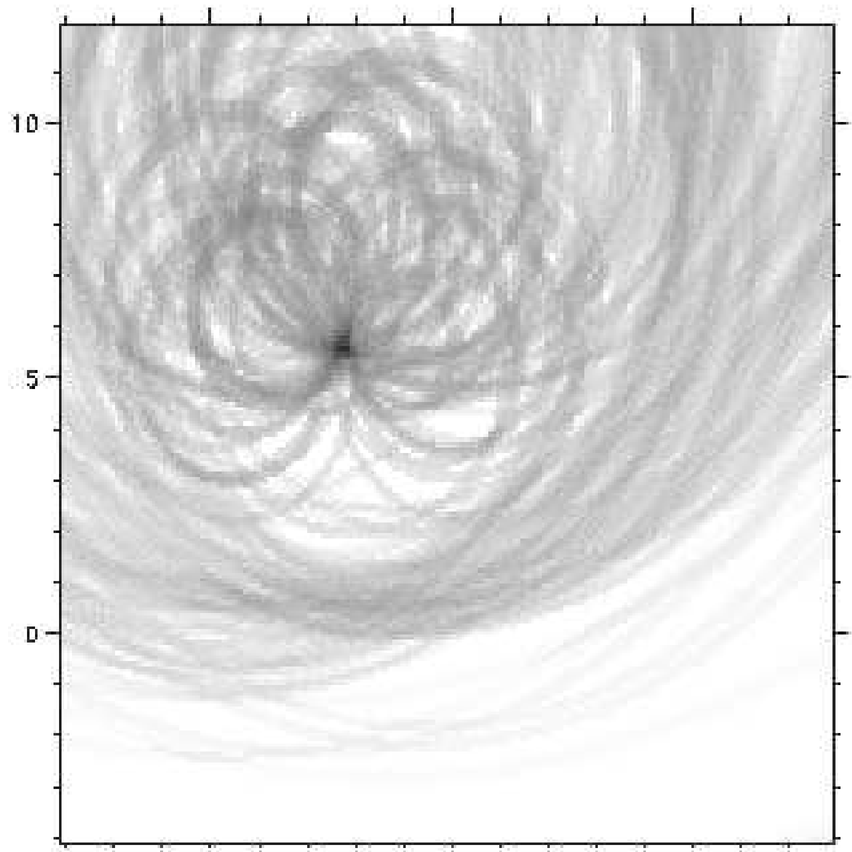


Figure 11

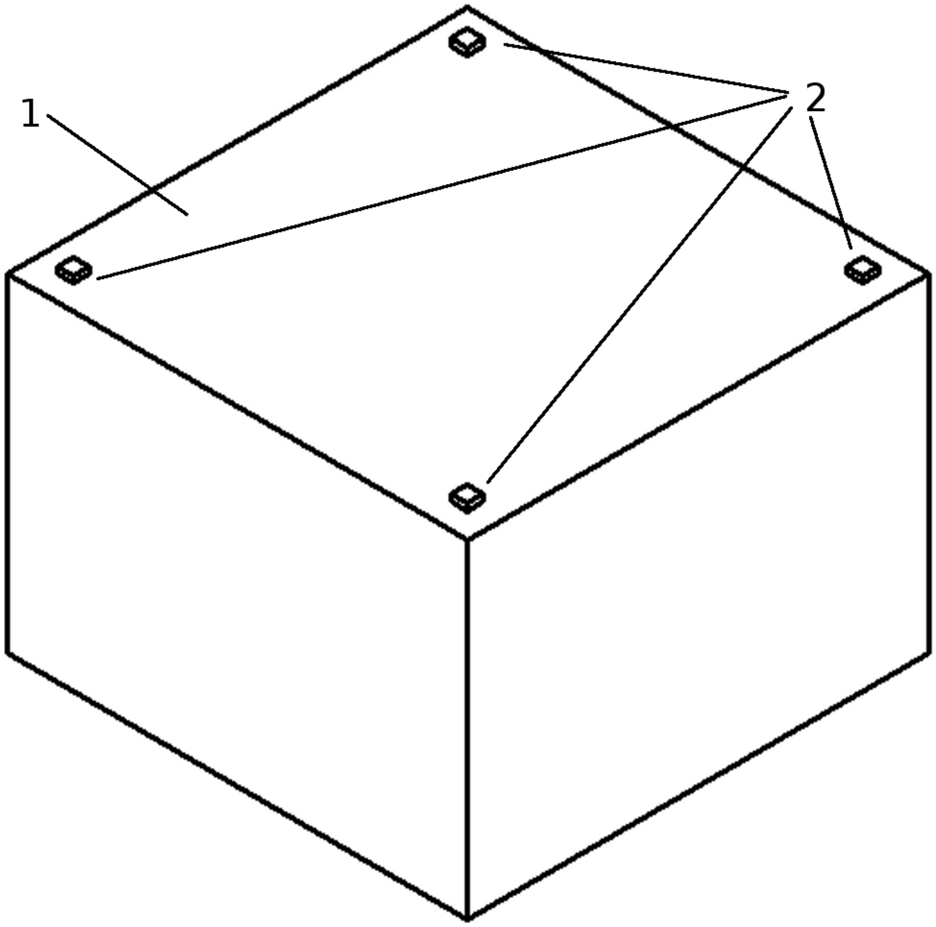


Figure 12

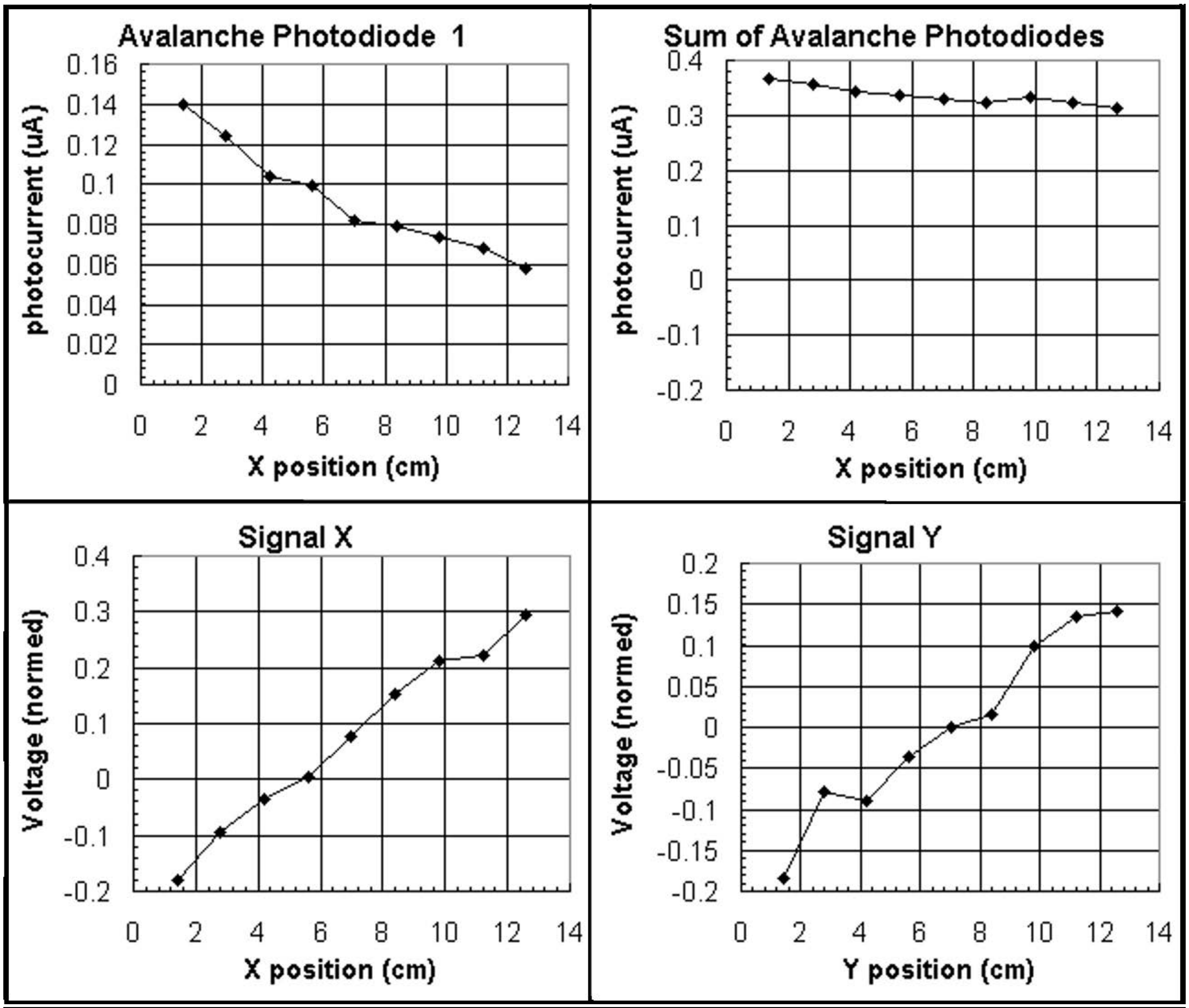

Avalanche Photodiode 1
photocurrent (uA)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0 2 4 6 8 10 12 14
X position (cm)
Sum of Avalanche Photodiodes
photocurrent (uA)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0 2 4 6 8 10 12 14
X position (cm)
Signal X
Voltage (normed)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
0 2 4 6 8 10 12 14
X position (cm)
Signal Y
Voltage (normed)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0 2 4 6 8 10 12 14
Y position (cm)

Figure 13