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(12) **United States Patent**
Newman

(10) **Patent No.: US 10,838,085 B2**
(45) **Date of Patent: Nov. 17, 2020**

(54) **COMPACT DIRECTIONAL RADIATION DETECTOR SYSTEM**

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(72) Inventor: **David Edward Newman**, Poway, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/830,631**

(22) Filed: **Mar. 26, 2020**

(65) **Prior Publication Data**

US 2020/0284925 A1 Sep. 10, 2020

Related U.S. Application Data

(63) Continuation of application No. 16/377,195, filed on Apr. 6, 2019, now Pat. No. 10,605,932.

(60) Provisional application No. 62/661,072, filed on Apr. 22, 2018, provisional application No. 62/726,295, filed on Sep. 2, 2018, provisional application No. 62/756,060, filed on Nov. 5, 2018, provisional application No. 62/830,356, filed on Apr. 5, 2019.

(51) **Int. Cl.**

G01T 1/29	(2006.01)
G01T 1/18	(2006.01)
G01V 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G01T 1/29*** (2013.01); ***G01V 5/0091*** (2013.01)

(58) **Field of Classification Search**

CPC G01T 3/06; G01T 1/20; G01T 1/2907; G01T 1/29; G01T 1/18; G01T 3/065; G01V 5/0091

See application file for complete search history.

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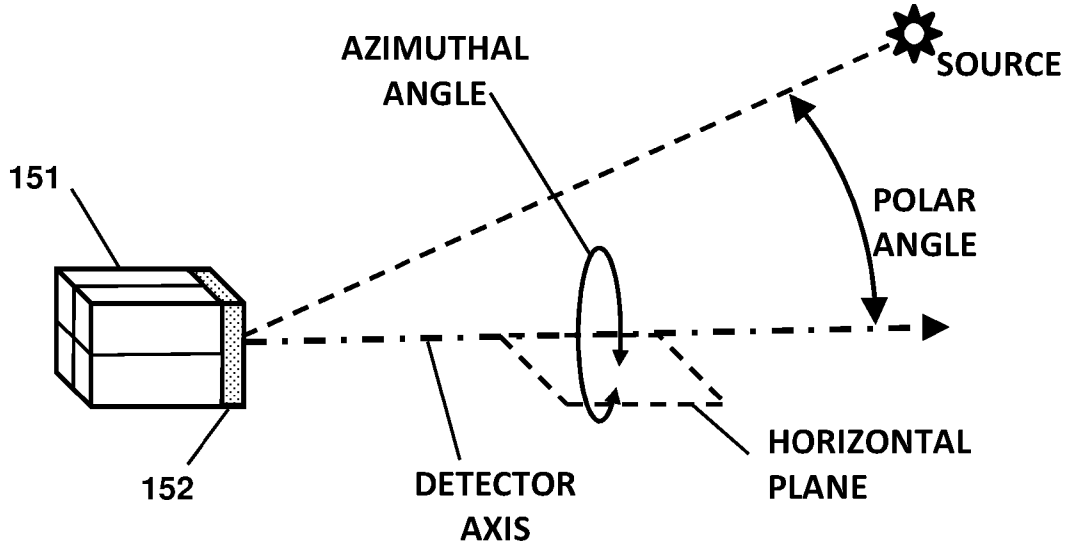
Primary Examiner — David P Porta
Assistant Examiner — Fani Boosalis

(57) **ABSTRACT**

Disclosed is a directional gamma ray or neutron detector system that locates a radioactive source both horizontally and vertically. In some embodiments, the system comprises four "side" detectors arrayed around a detector axis, and an orthogonal "front" detector mounted frontward of the side detectors. Embodiments can calculate the azimuthal angle of the source based on the detection rates of the side detectors, while the polar angle of the source may be calculated from the front detector rate using a predetermined angular correlation function, thereby localizing the source from a single data set without iterative rotations. In applications such as hand-held survey meters, walk-through portals, vehicle cargo inspection stations, and mobile area scanners, embodiments enable rapid detection and precise localization of clandestine nuclear and radiological weapons.

20 Claims, 22 Drawing Sheets



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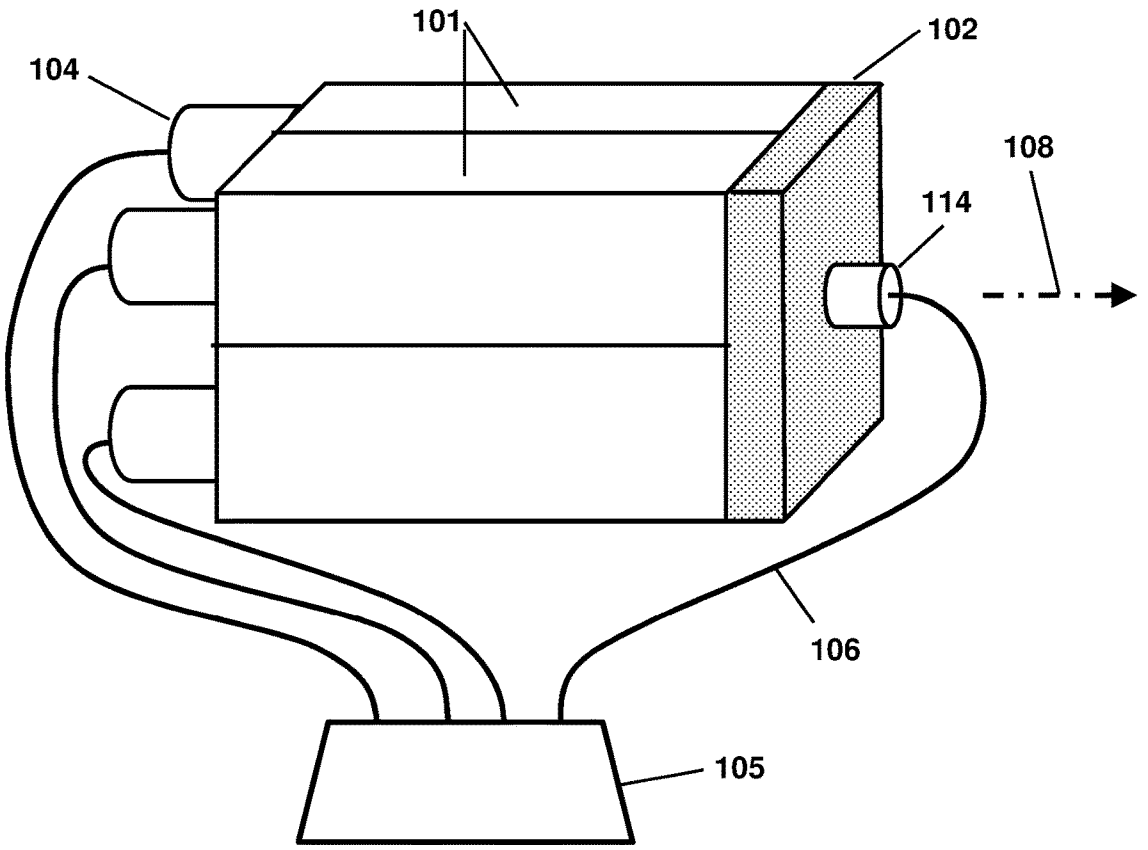
2018/0172853	A1	6/2018	Newman

Fig. 1A


101
102
104
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114
106
105

Fig. 1B

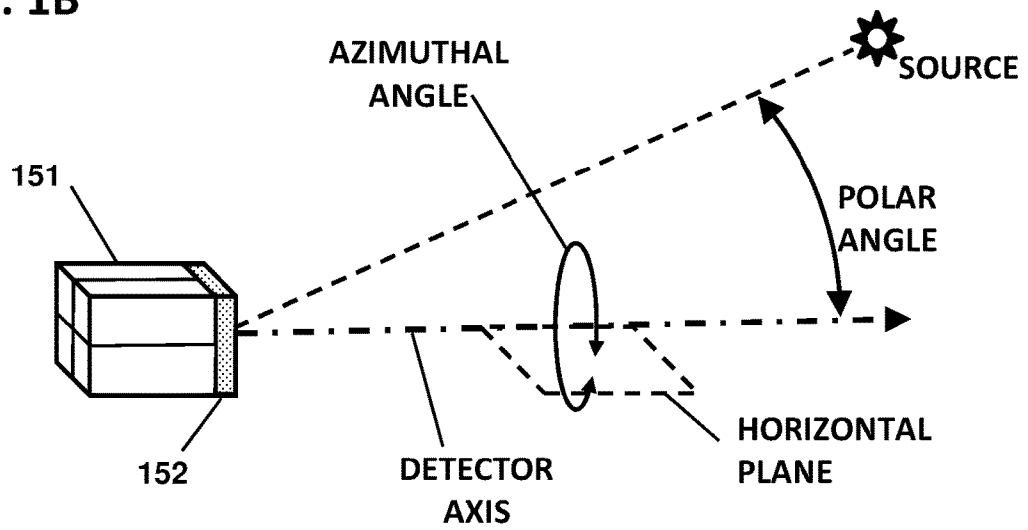

AZIMUTHAL ANGLE
SOURCE
151
POLAR ANGLE
152
DETECTOR AXIS
HORIZONTAL PLANE

Fig. 2A

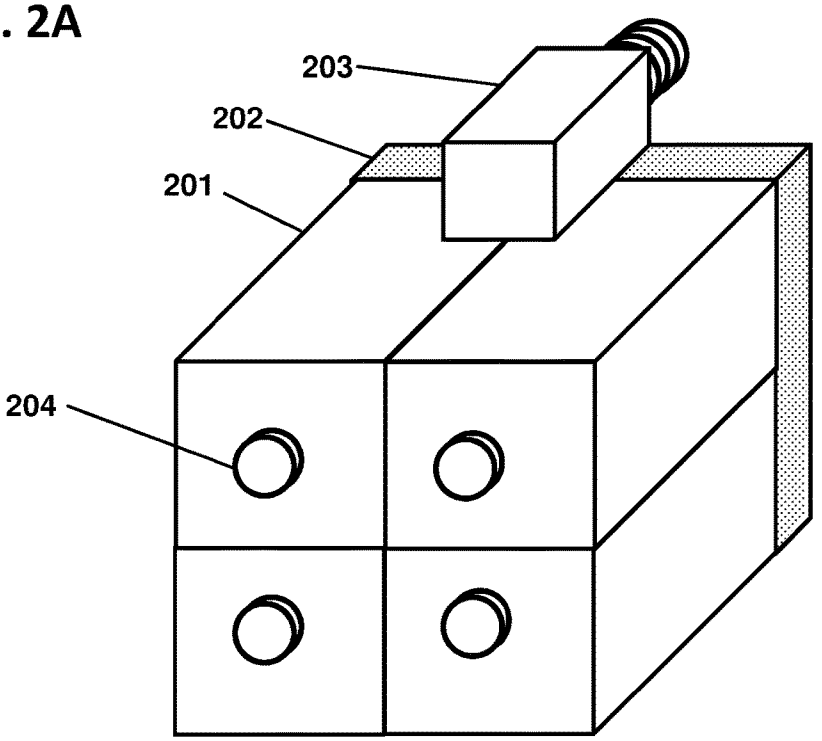


Fig. 2B

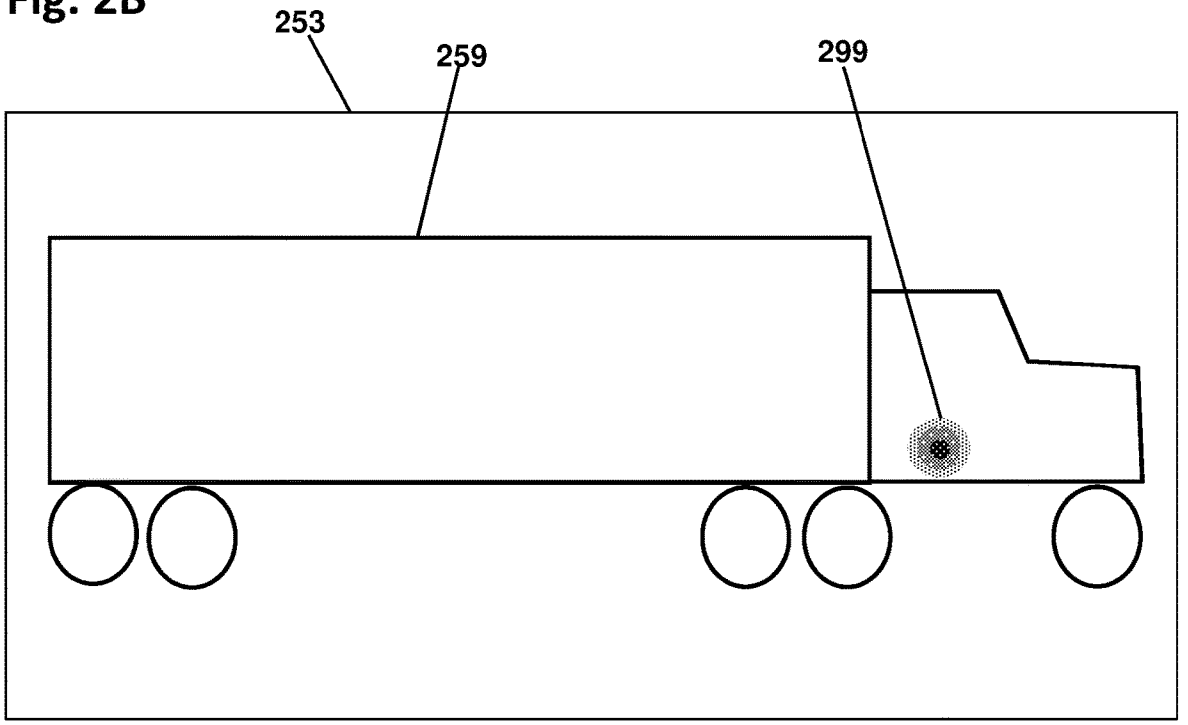


Fig. 3

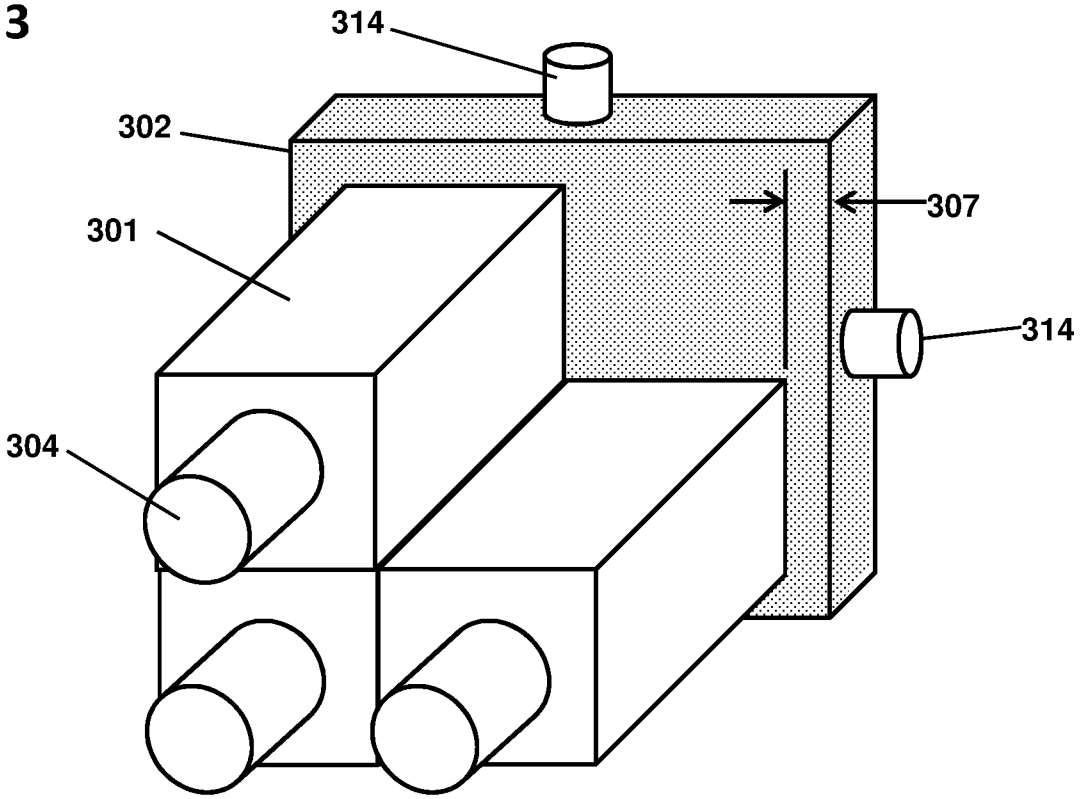


Fig. 4

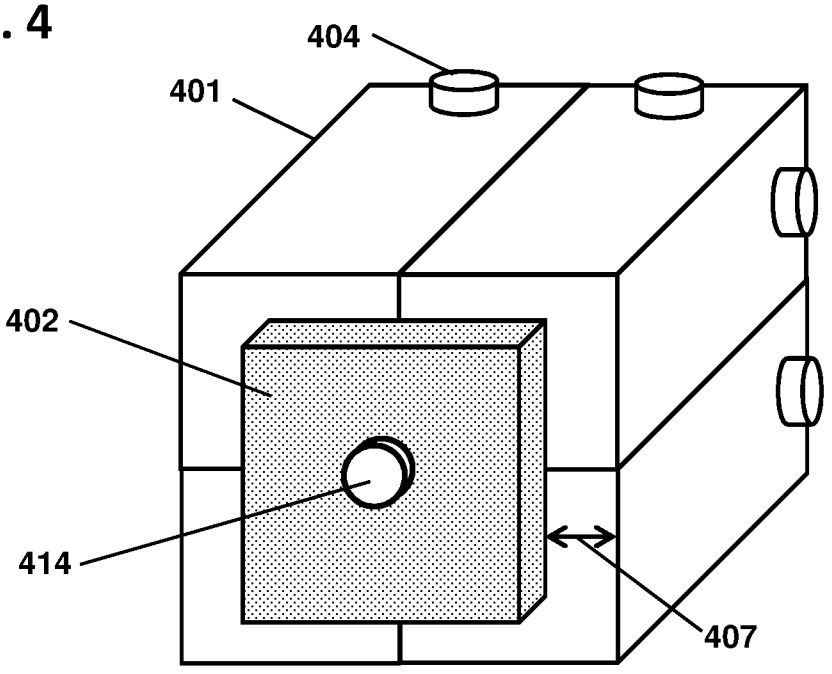


Fig. 5

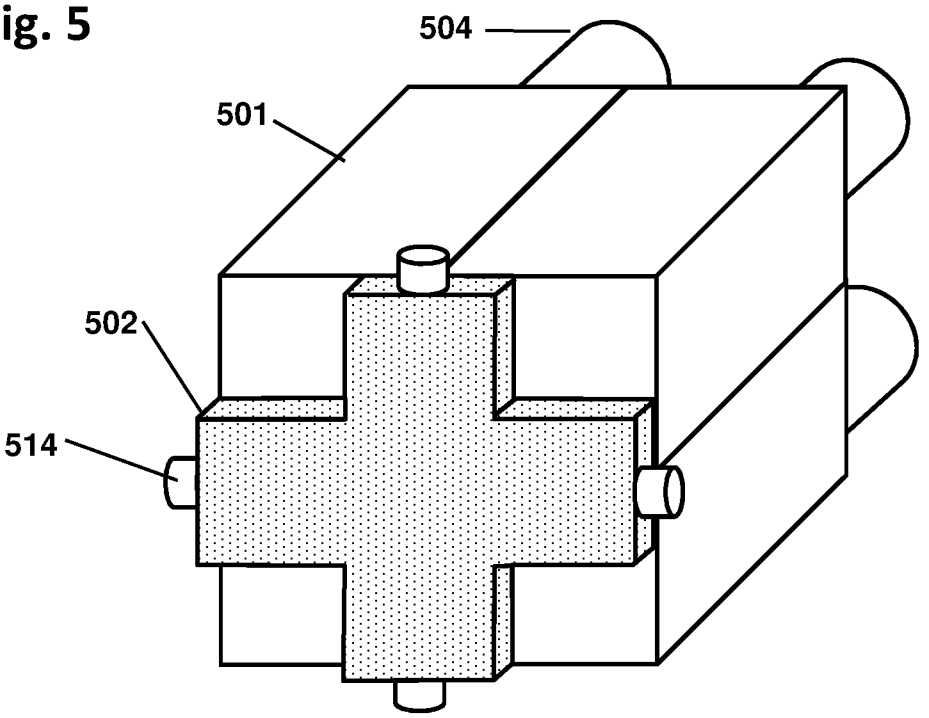


Fig. 6

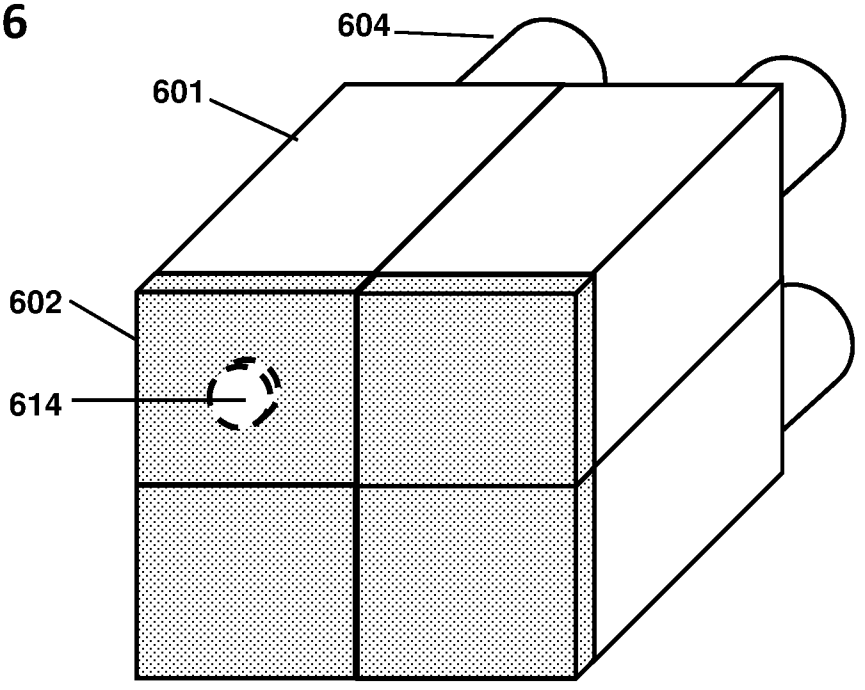


Fig. 7

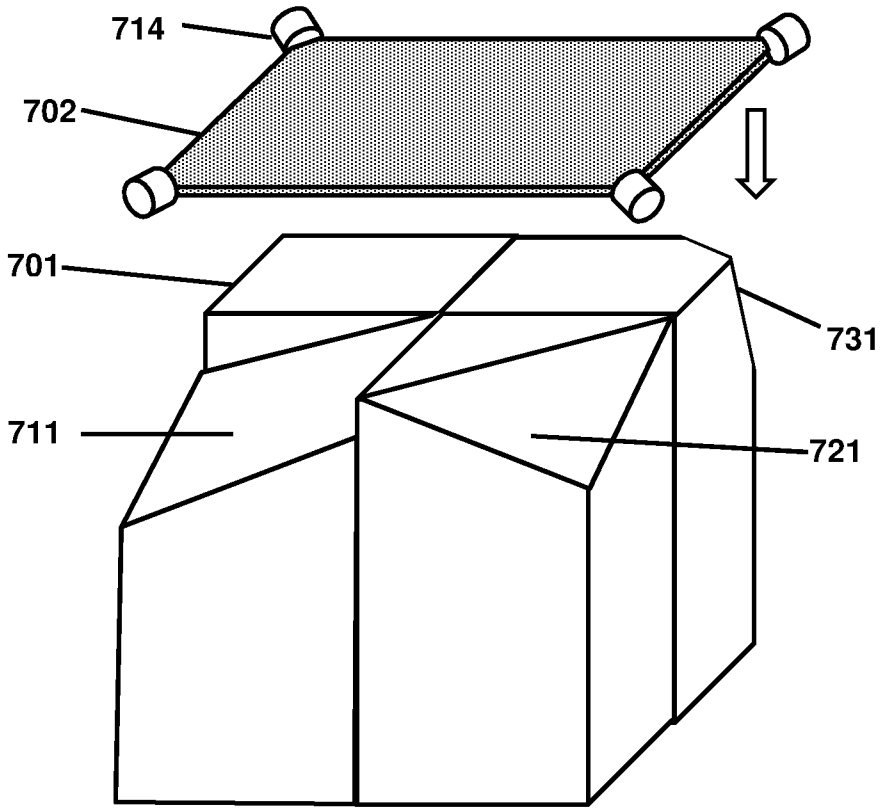


Fig. 8

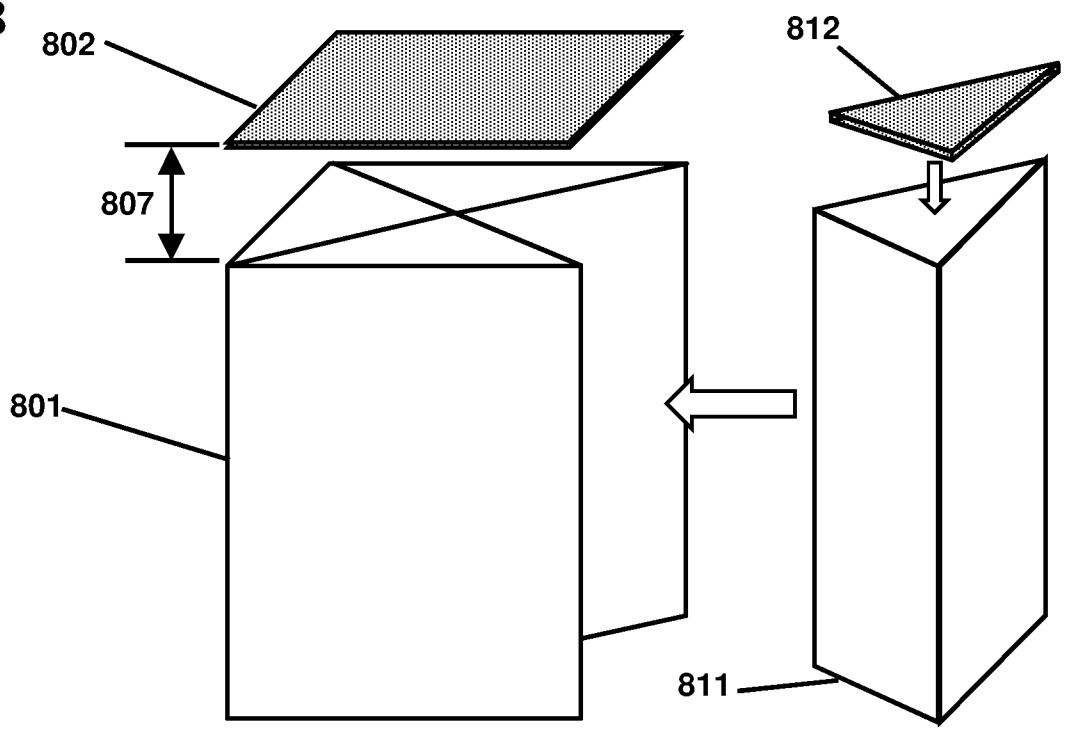


Fig. 9

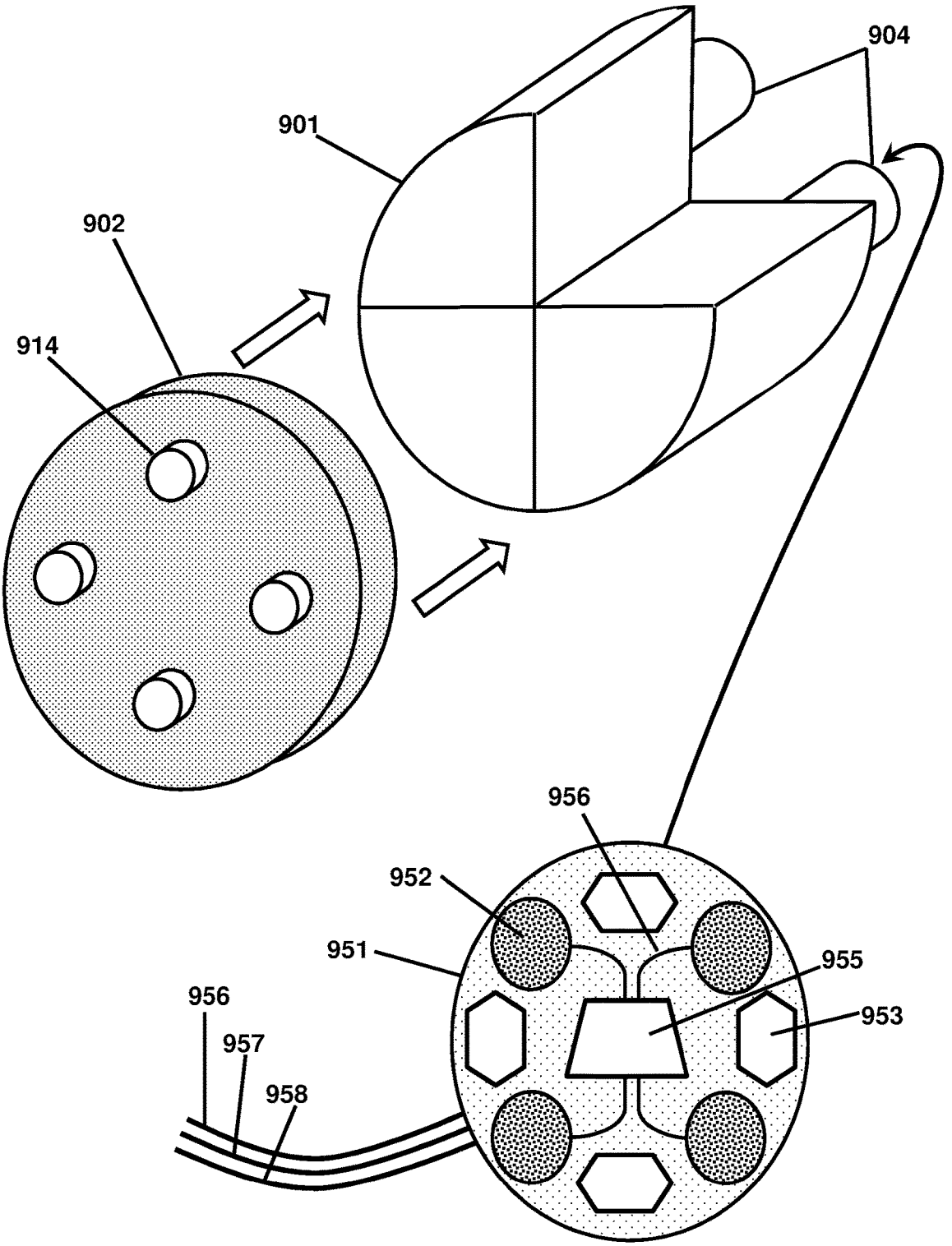


Fig. 10A

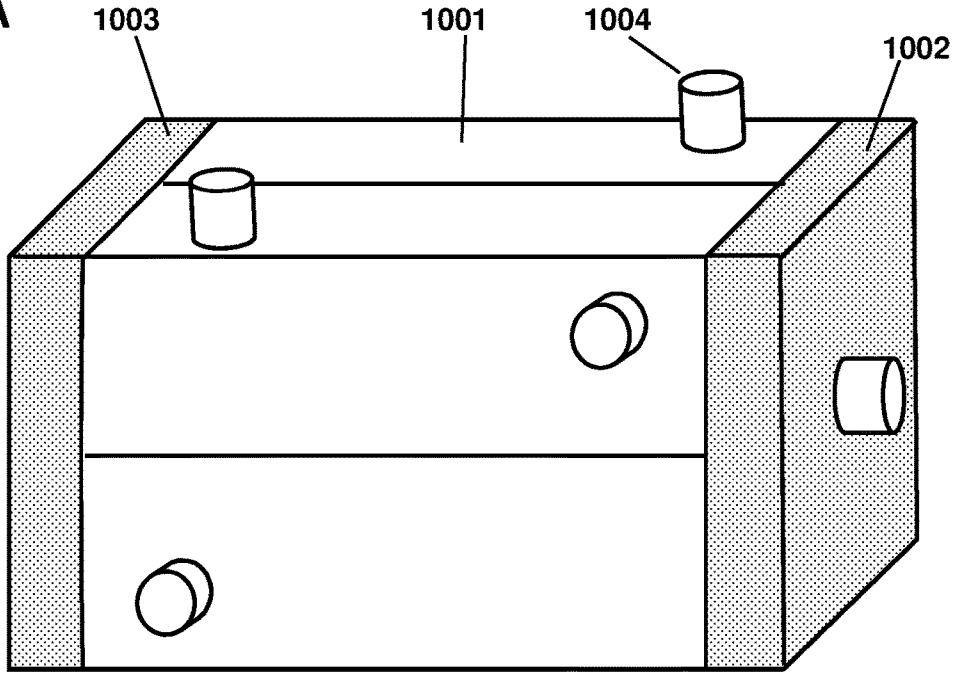


Fig. 10B

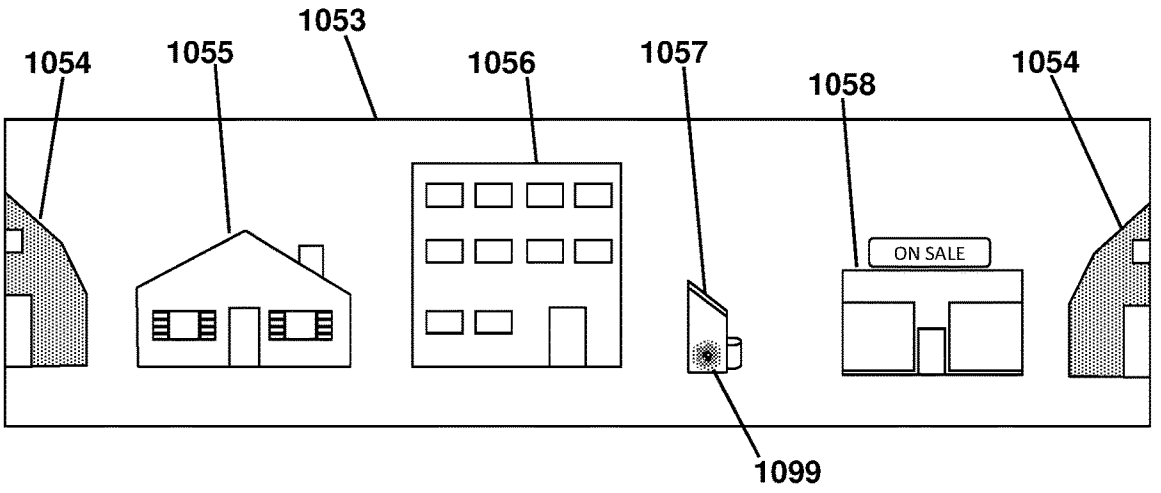


Fig. 11A

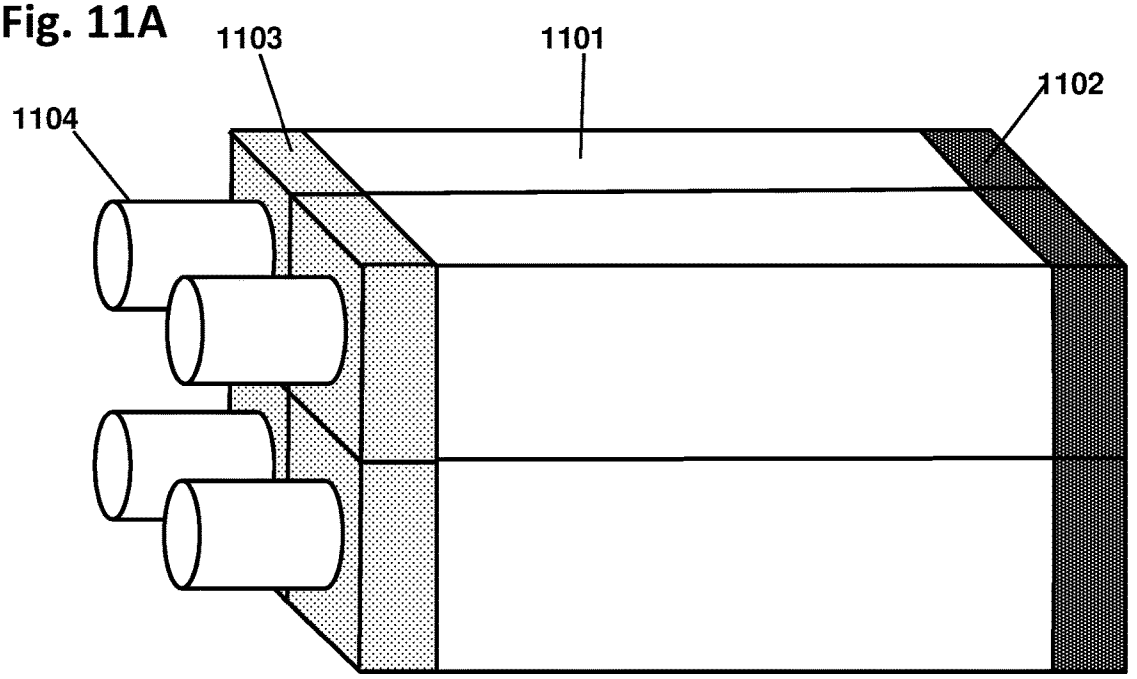


Fig. 11B

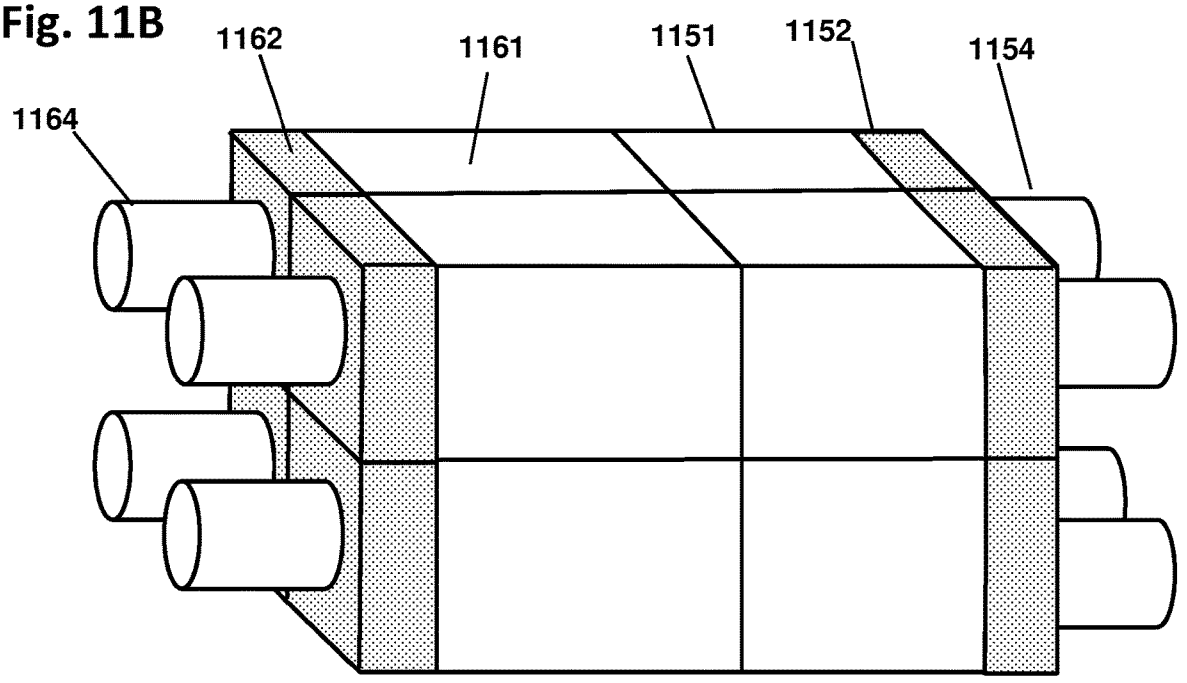


Fig. 12

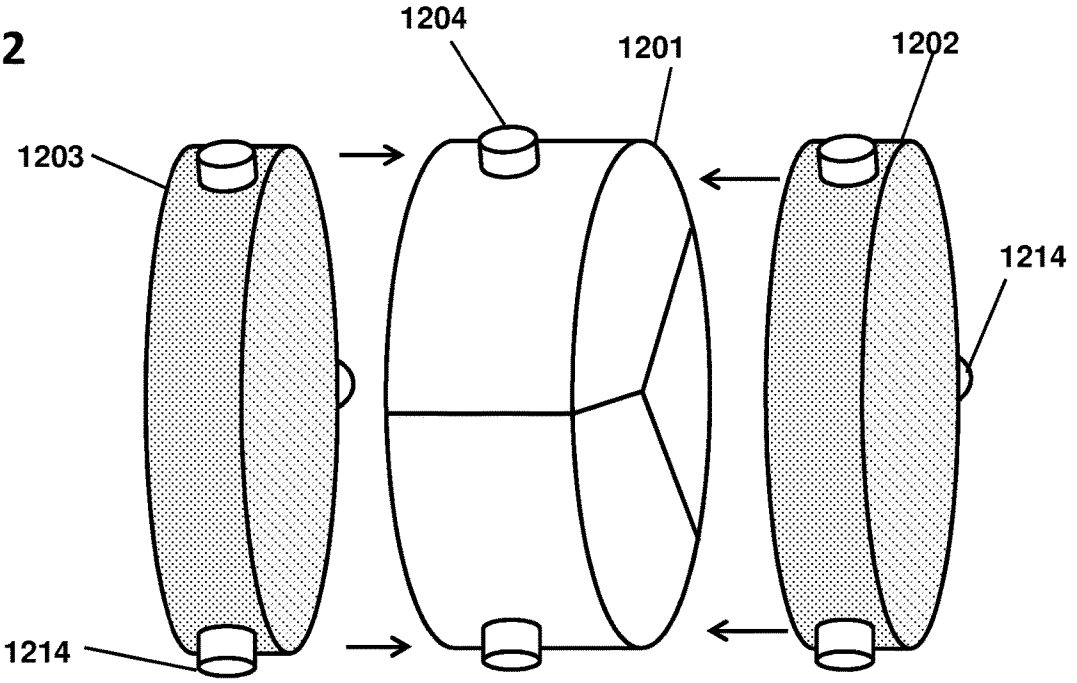


Fig. 13

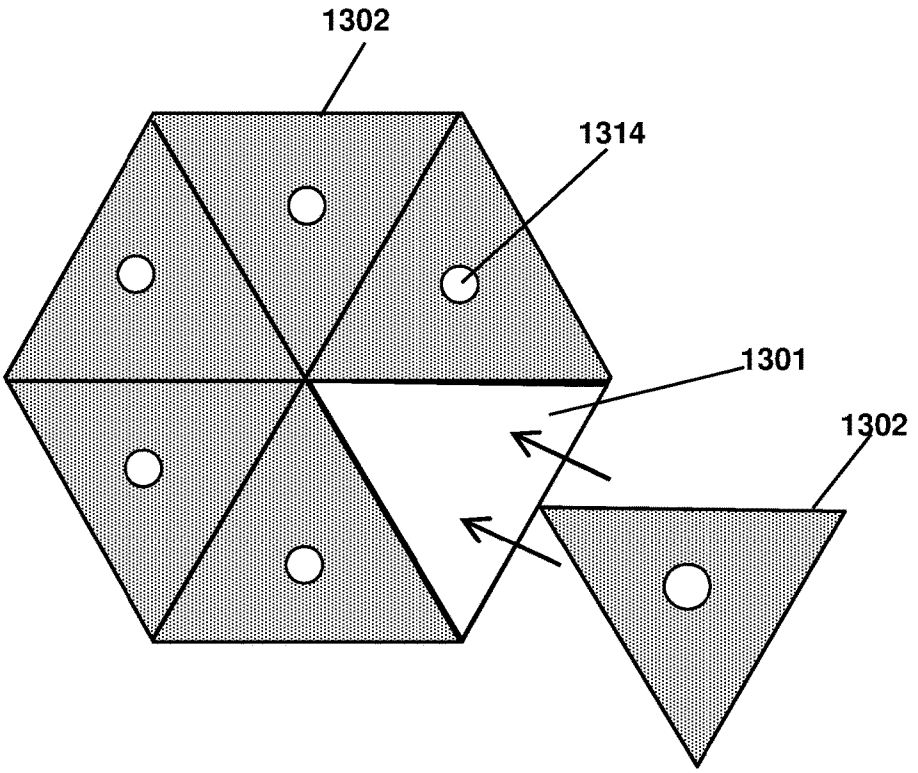


Fig. 14

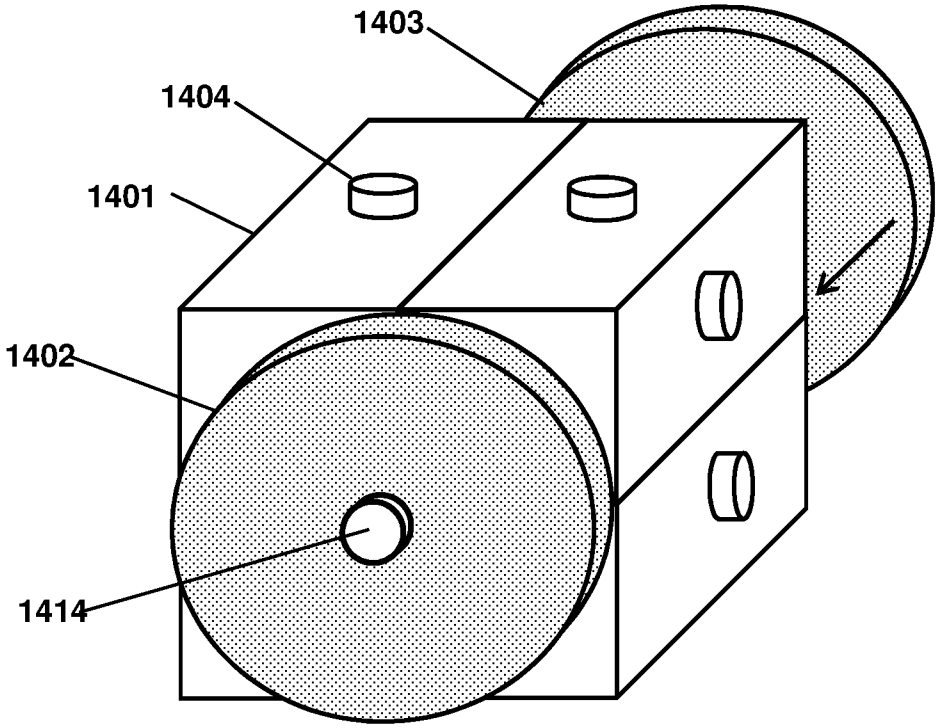


Fig. 15

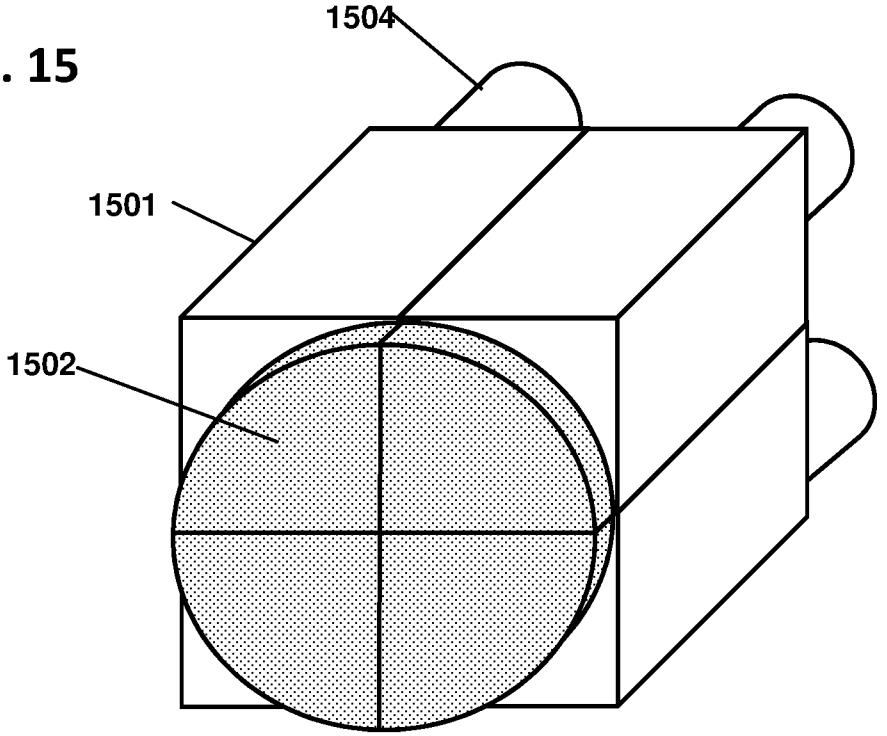


Fig. 16

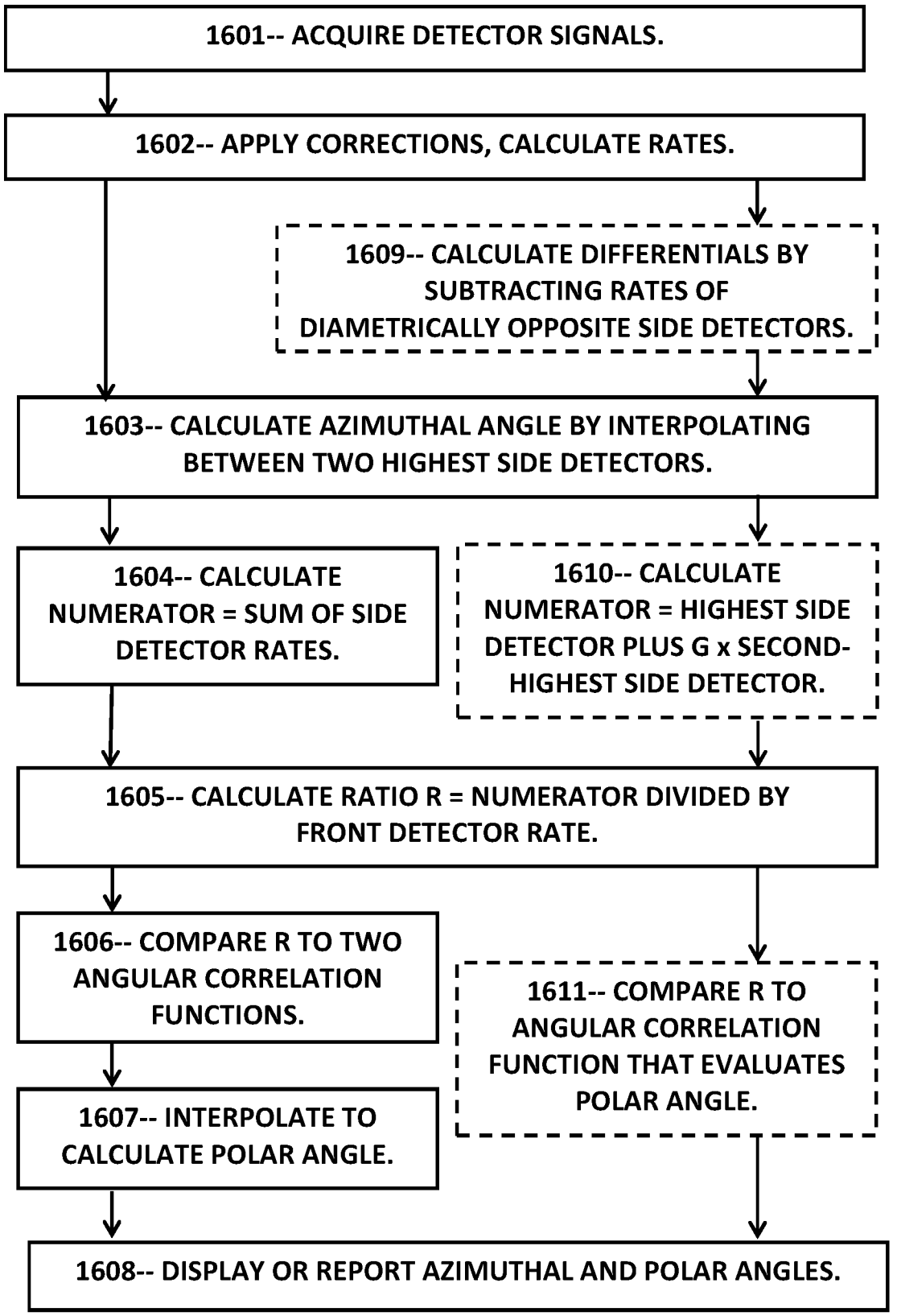

1601-- ACQUIRE DETECTOR SIGNALS.
1602-- APPLY CORRECTIONS, CALCULATE RATES.
1609-- CALCULATE DIFFERENTIALS BY SUBTRACTING RATES OF DIAMETRICALLY OPPOSITE SIDE DETECTORS.
1603-- CALCULATE AZIMUTHAL ANGLE BY INTERPOLATING BETWEEN TWO HIGHEST SIDE DETECTORS.
1604-- CALCULATE NUMERATOR = SUM OF SIDE DETECTOR RATES.
1610-- CALCULATE NUMERATOR = HIGHEST SIDE DETECTOR PLUS G x SECOND-HIGHEST SIDE DETECTOR.
1605-- CALCULATE RATIO R = NUMERATOR DIVIDED BY FRONT DETECTOR RATE.
1606-- COMPARE R TO TWO ANGULAR CORRELATION FUNCTIONS.
1611-- COMPARE R TO ANGULAR CORRELATION FUNCTION THAT EVALUATES POLAR ANGLE.
1607-- INTERPOLATE TO CALCULATE POLAR ANGLE.
1608-- DISPLAY OR REPORT AZIMUTHAL AND POLAR ANGLES.

Fig. 17

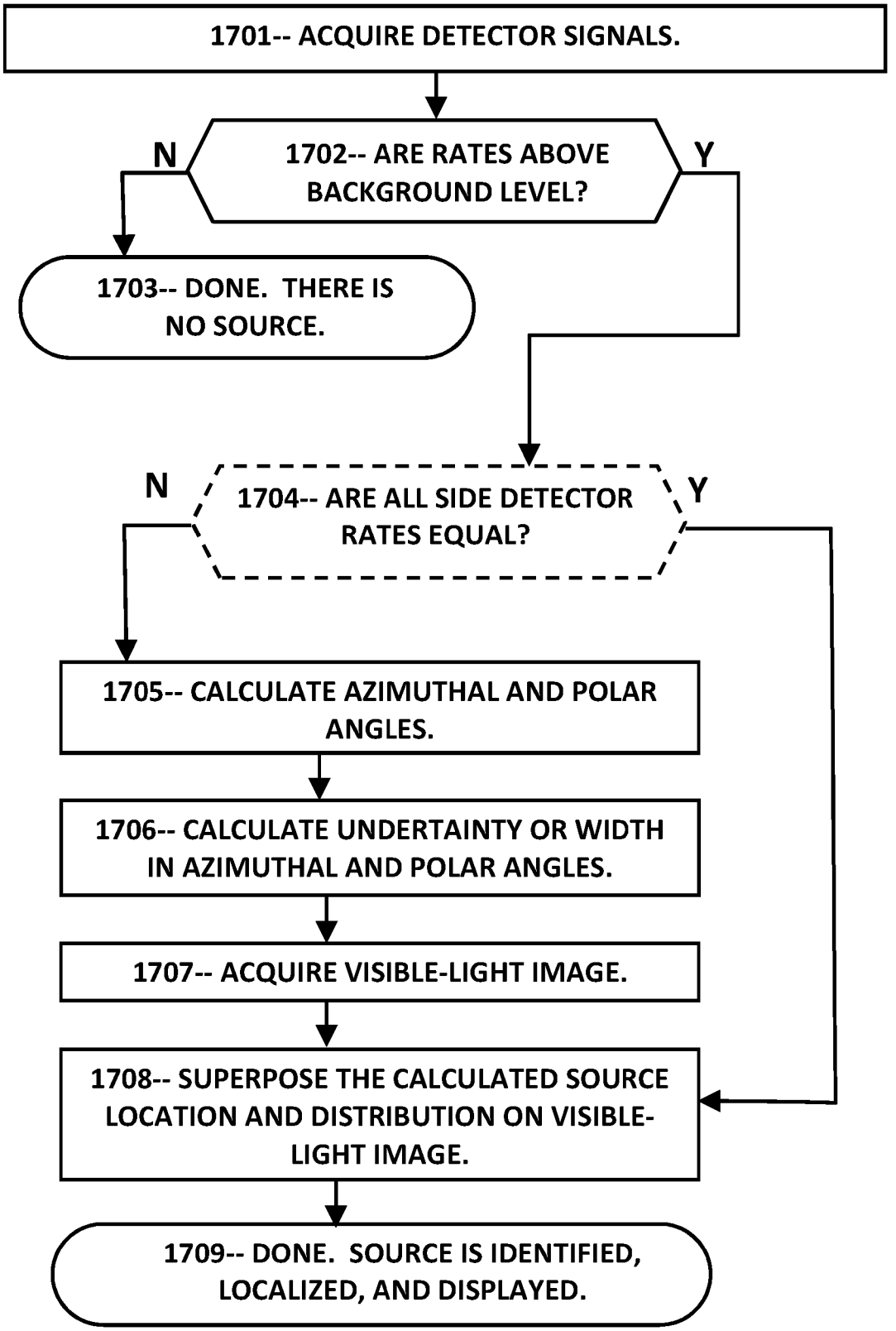

1701-- ACQUIRE DETECTOR SIGNALS.
1702-- ARE RATES ABOVE BACKGROUND LEVEL?
N
Y
1703-- DONE. THERE IS NO SOURCE.
1704-- ARE ALL SIDE DETECTOR RATES EQUAL?
N
Y
1705-- CALCULATE AZIMUTHAL AND POLAR ANGLES.
1706-- CALCULATE UNDERTAINTY OR WIDTH IN AZIMUTHAL AND POLAR ANGLES.
1707-- ACQUIRE VISIBLE-LIGHT IMAGE.
1708-- SUPERPOSE THE CALCULATED SOURCE LOCATION AND DISTRIBUTION ON VISIBLE-LIGHT IMAGE.
1709-- DONE. SOURCE IS IDENTIFIED, LOCALIZED, AND DISPLAYED.

Fig. 18

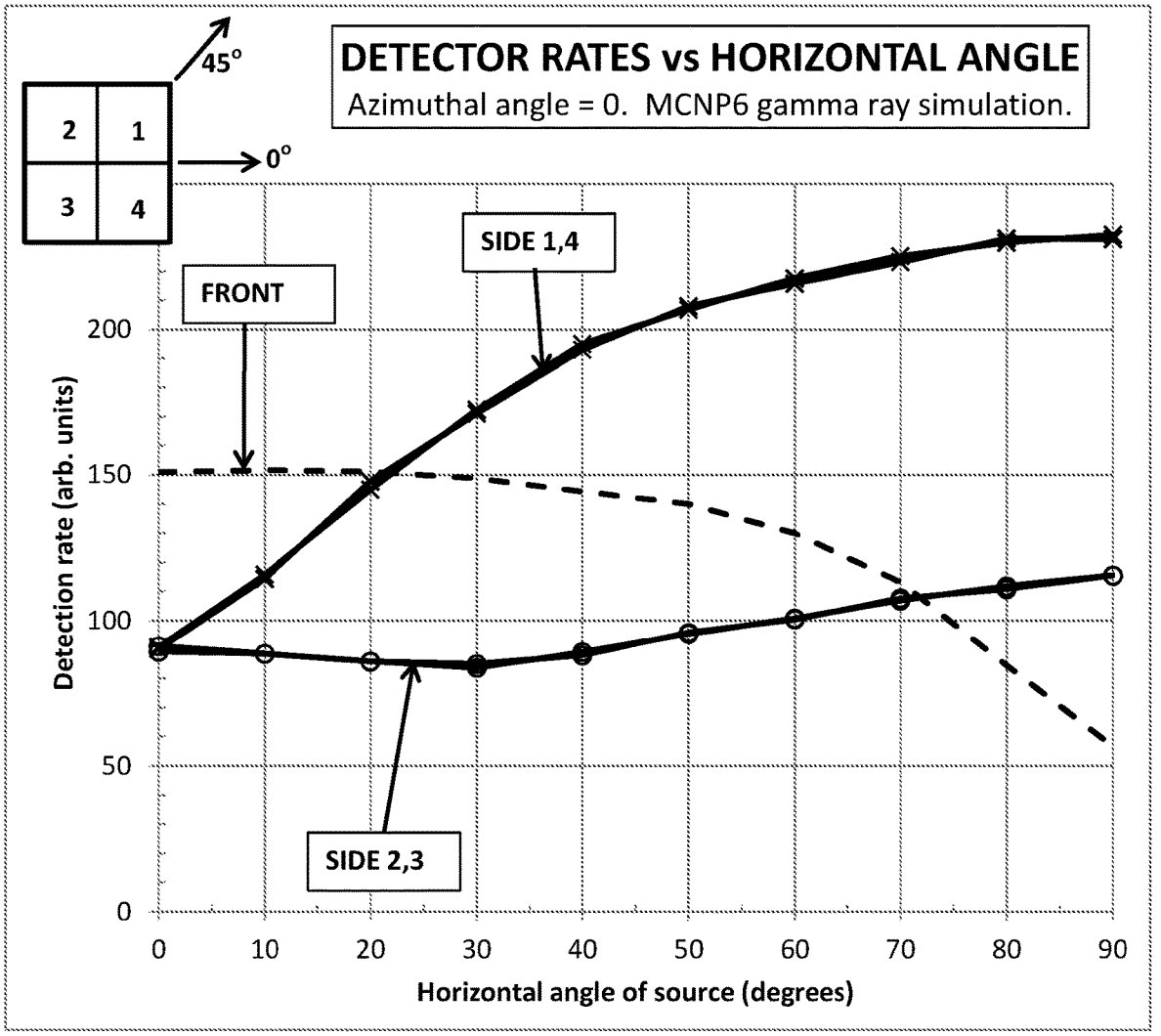

DETECTOR RATES vs HORIZONTAL ANGLE
Azimuthal angle = 0. MCNP6 gamma ray simulation.
45°
0°
2
1
3
4
FRONT
SIDE 1,4
SIDE 2,3
Detection rate (arb. units)
0
50
100
150
200
0
10
20
30
40
50
60
70
80
90
Horizontal angle of source (degrees)

Fig. 19

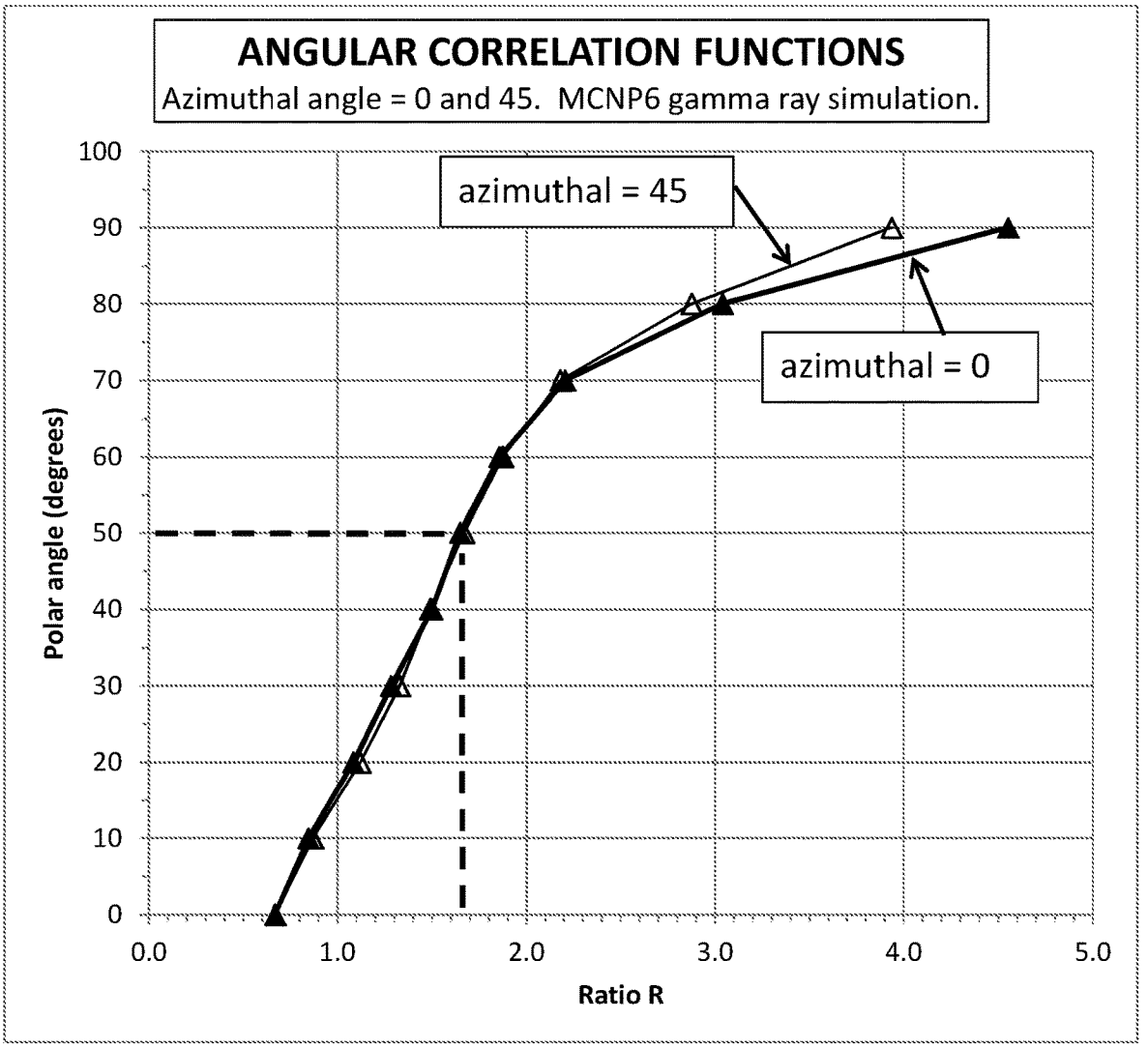
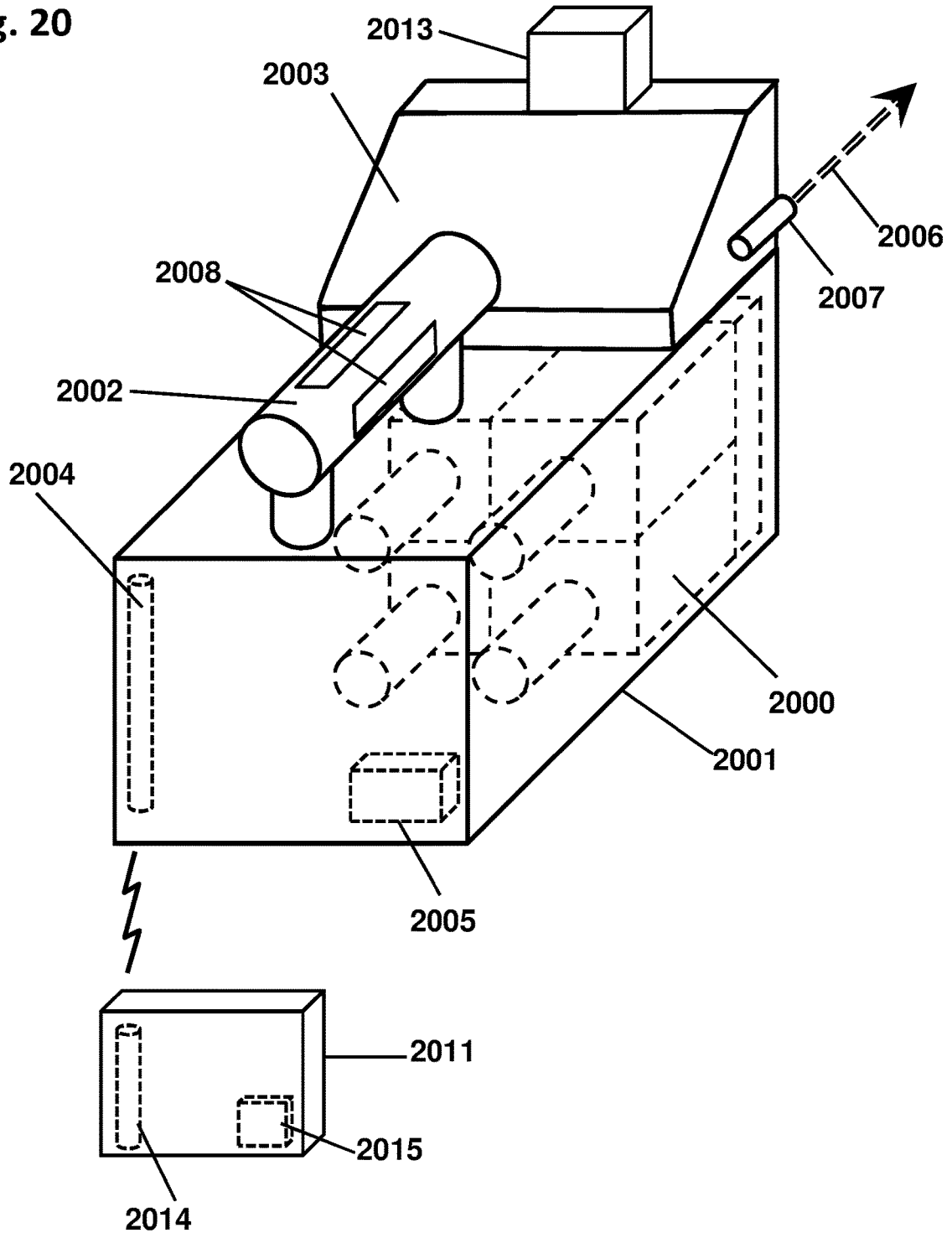

ANGULAR CORRELATION FUNCTIONS
Azimuthal angle = 0 and 45. MCNP6 gamma ray simulation.
azimuthal = 45
azimuthal = 0
Polar angle (degrees)
Ratio R
0
10
20
30
40
50
60
70
80
90
100
0.0
1.0
2.0
3.0
4.0
5.0

Fig. 20


2013
2003
2006
2008
2007
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2004
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2001
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2011
2015
2014

Fig. 21A

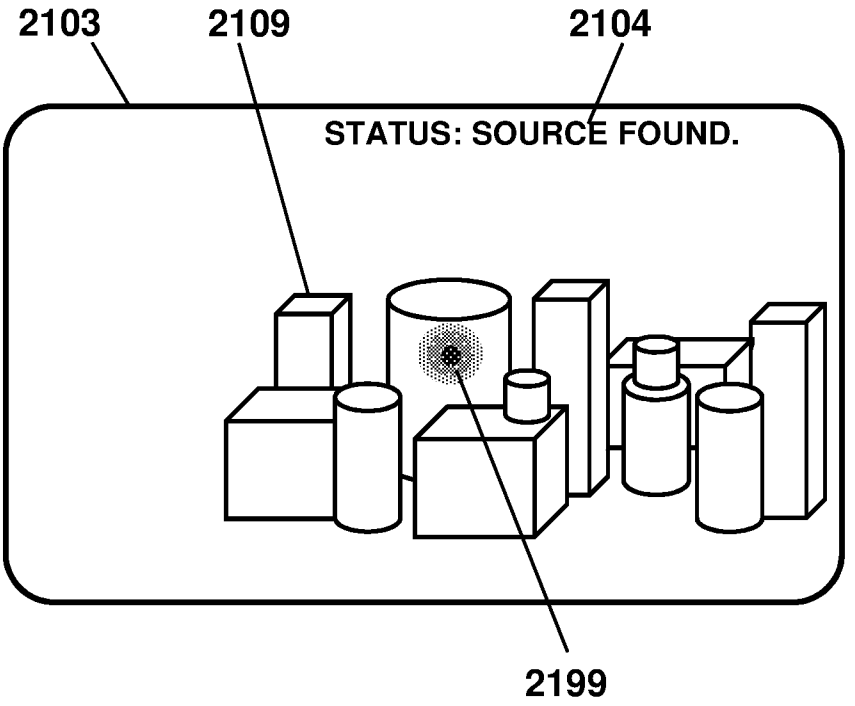


Fig. 21B

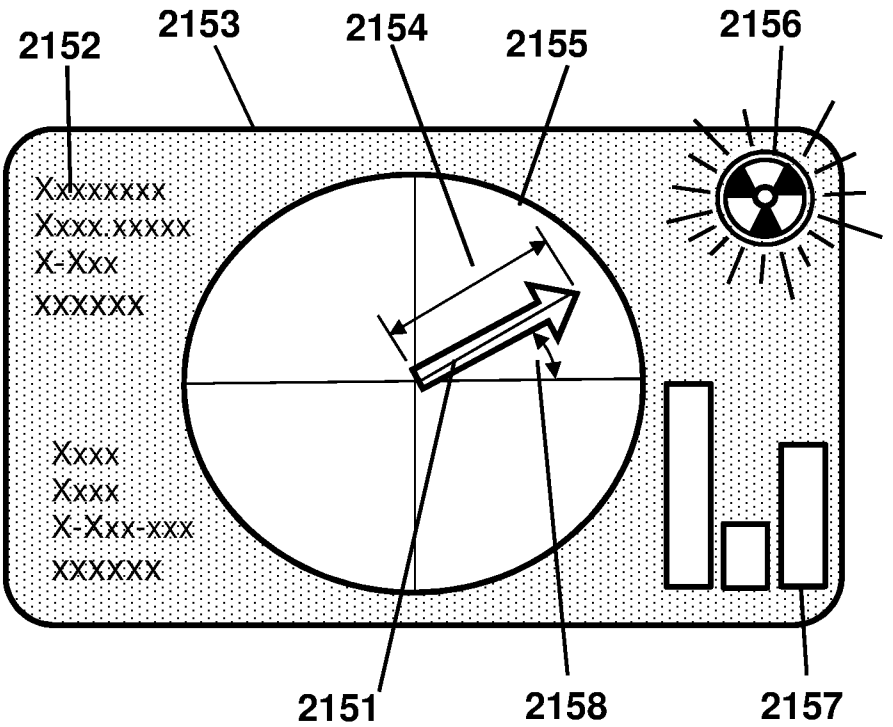


Fig. 22A

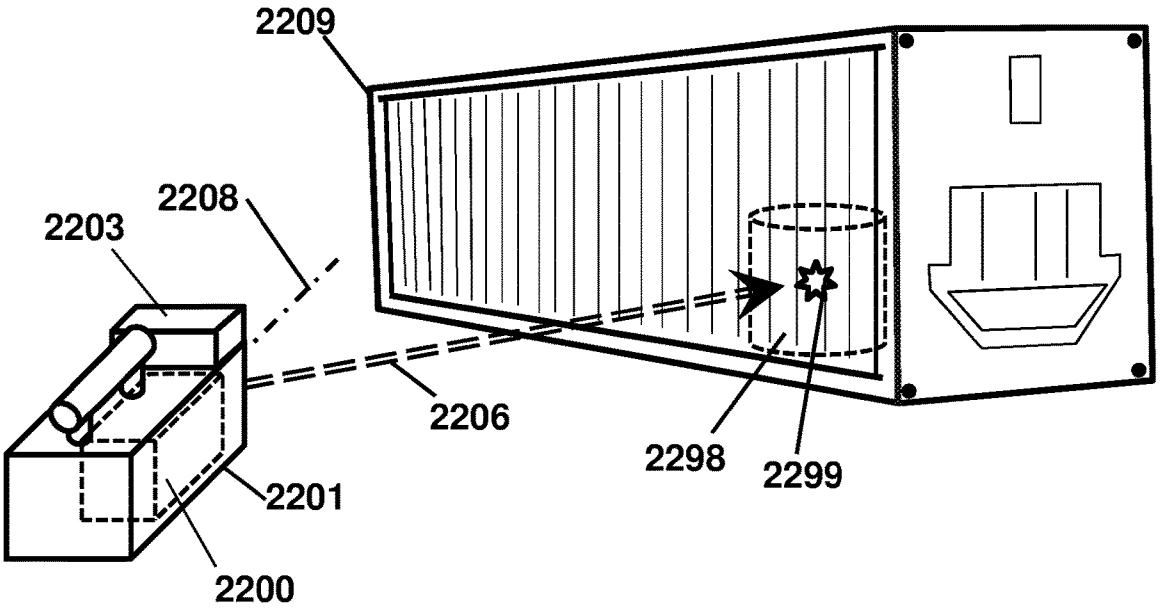


Fig. 22B

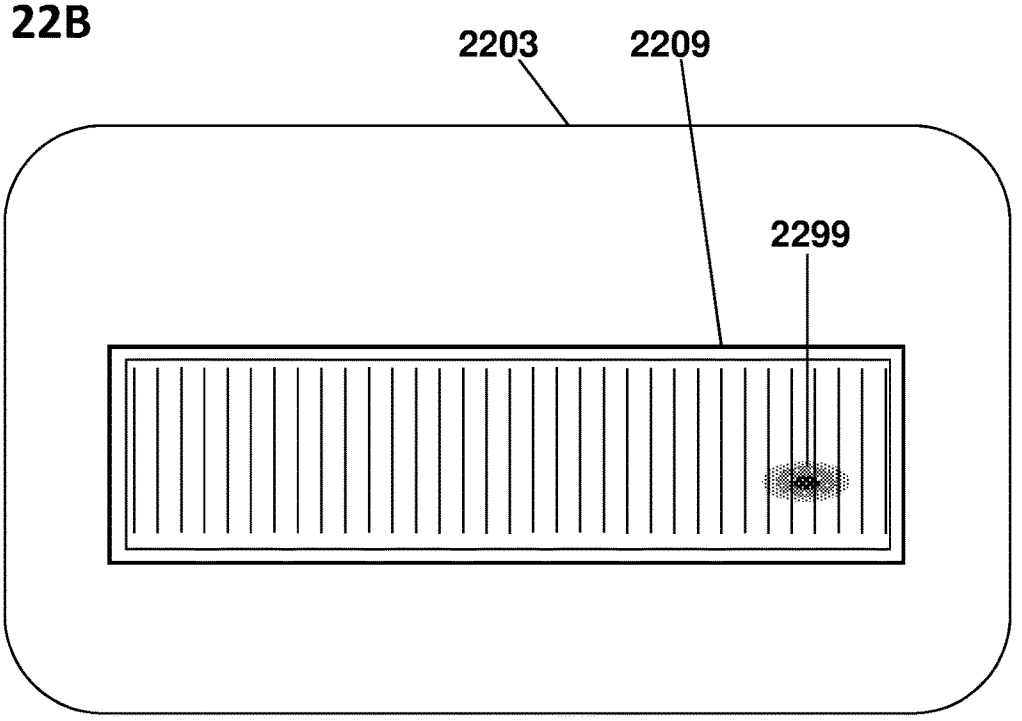


Fig. 23

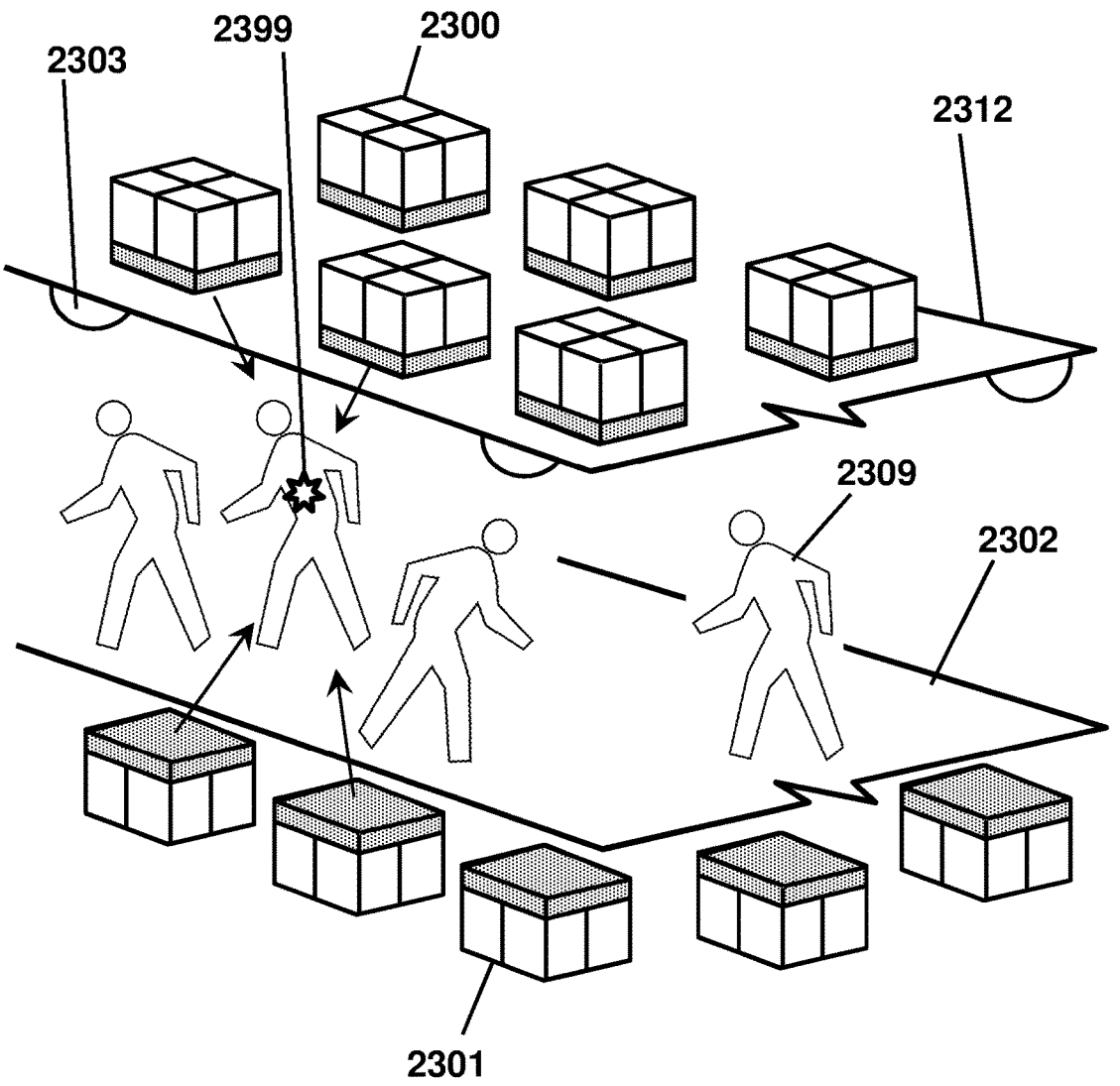


Fig. 24

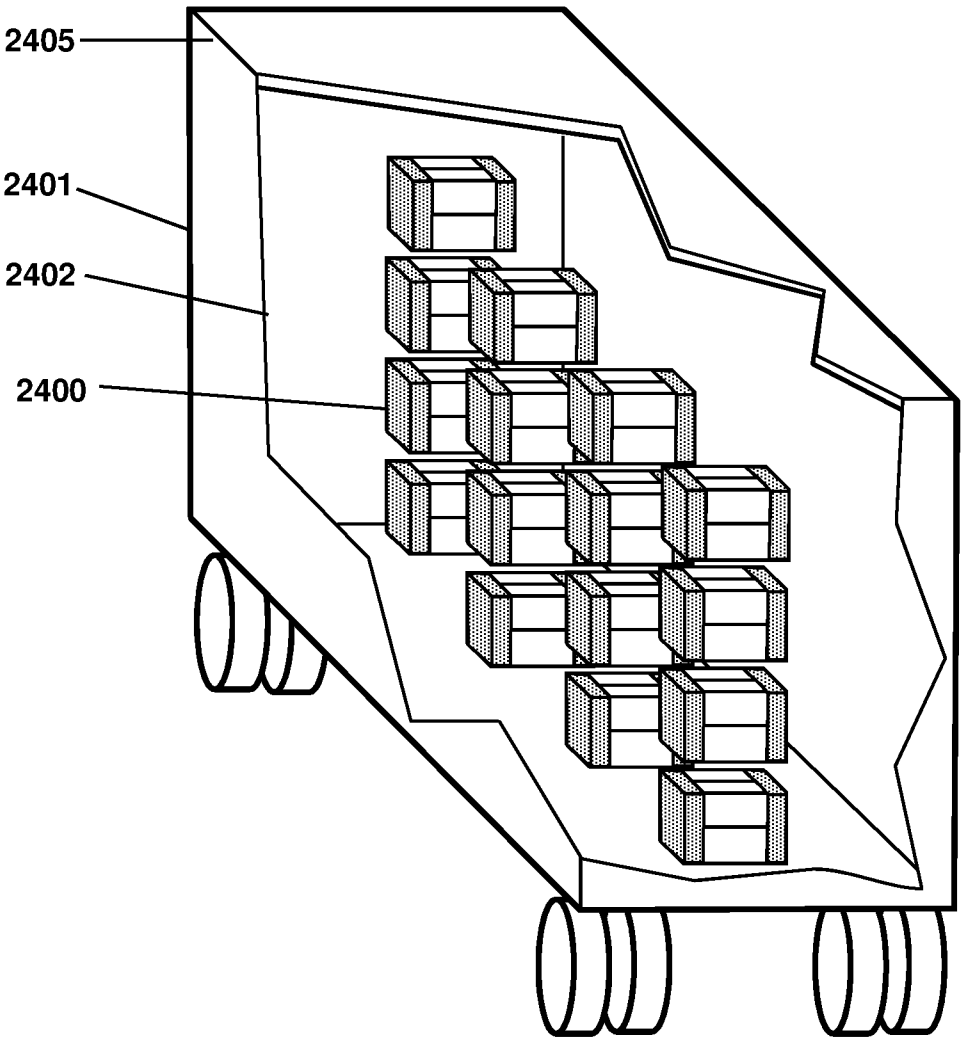


Fig. 25

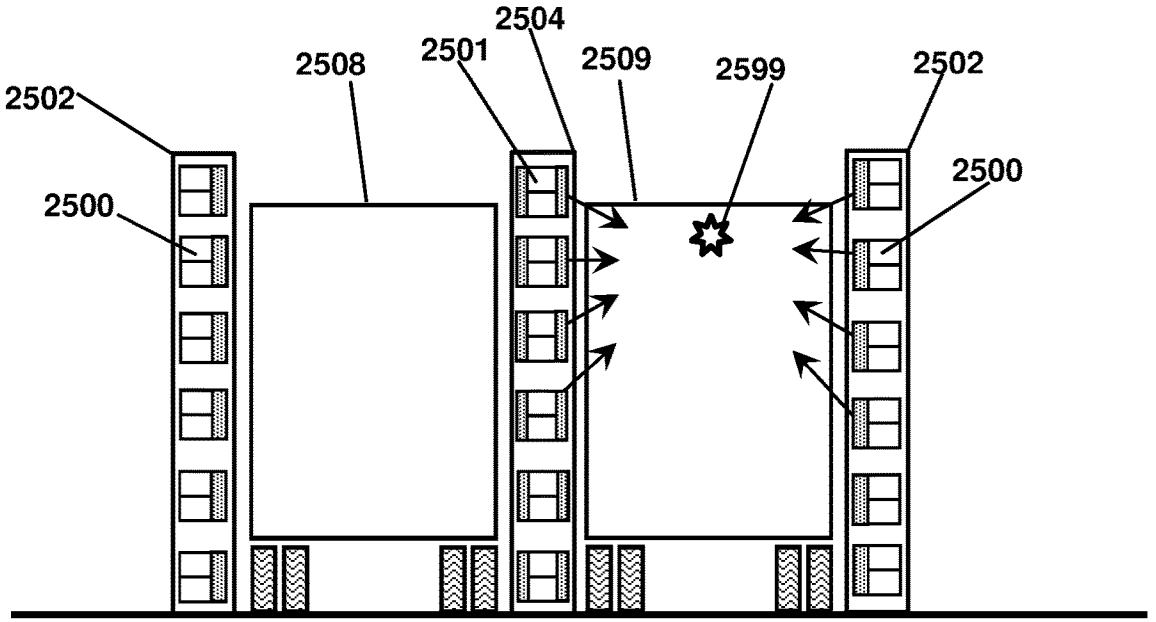

2504
2501
2508
2509
2599
2502
2502
2500
2500

Fig. 26

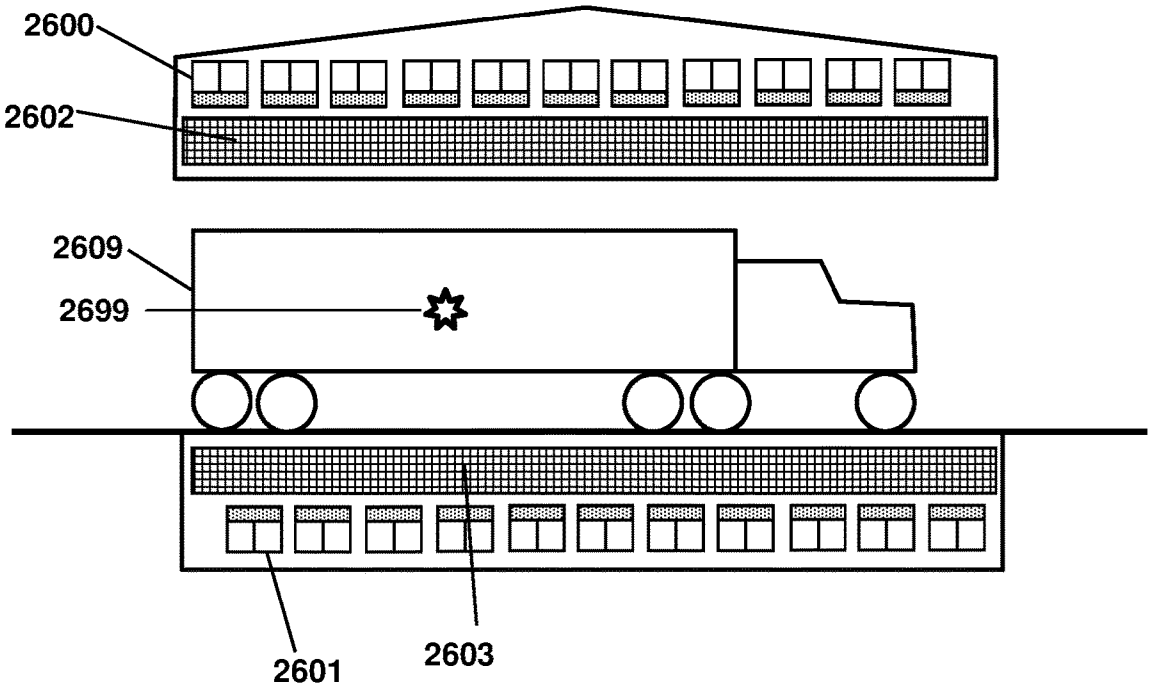

2600
2602
2609
2699
2601
2603

Fig. 27A

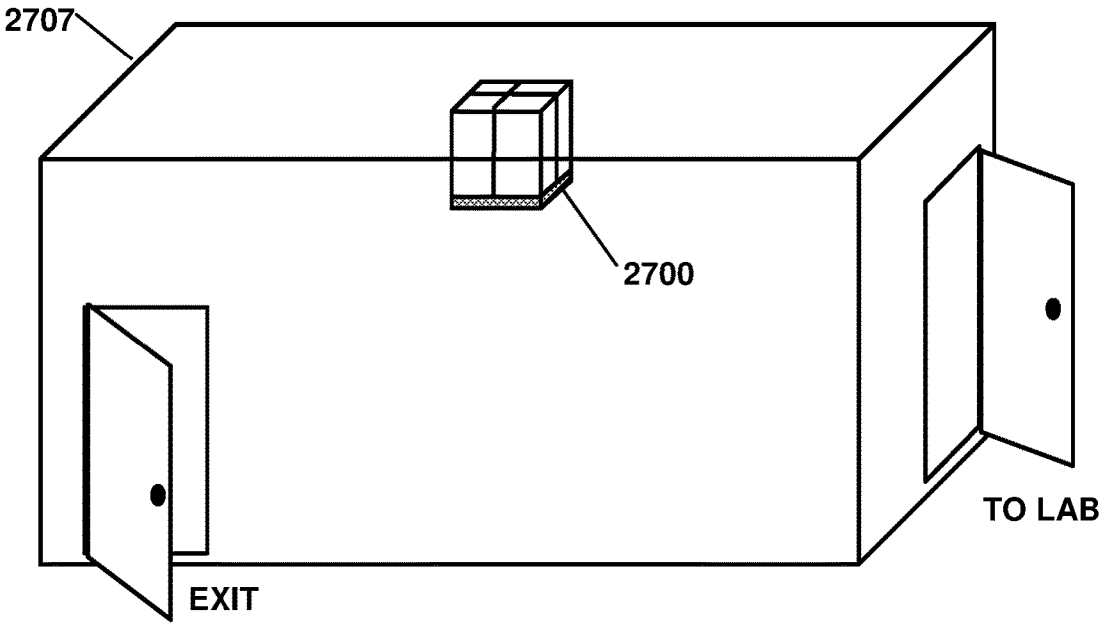


Fig. 27B

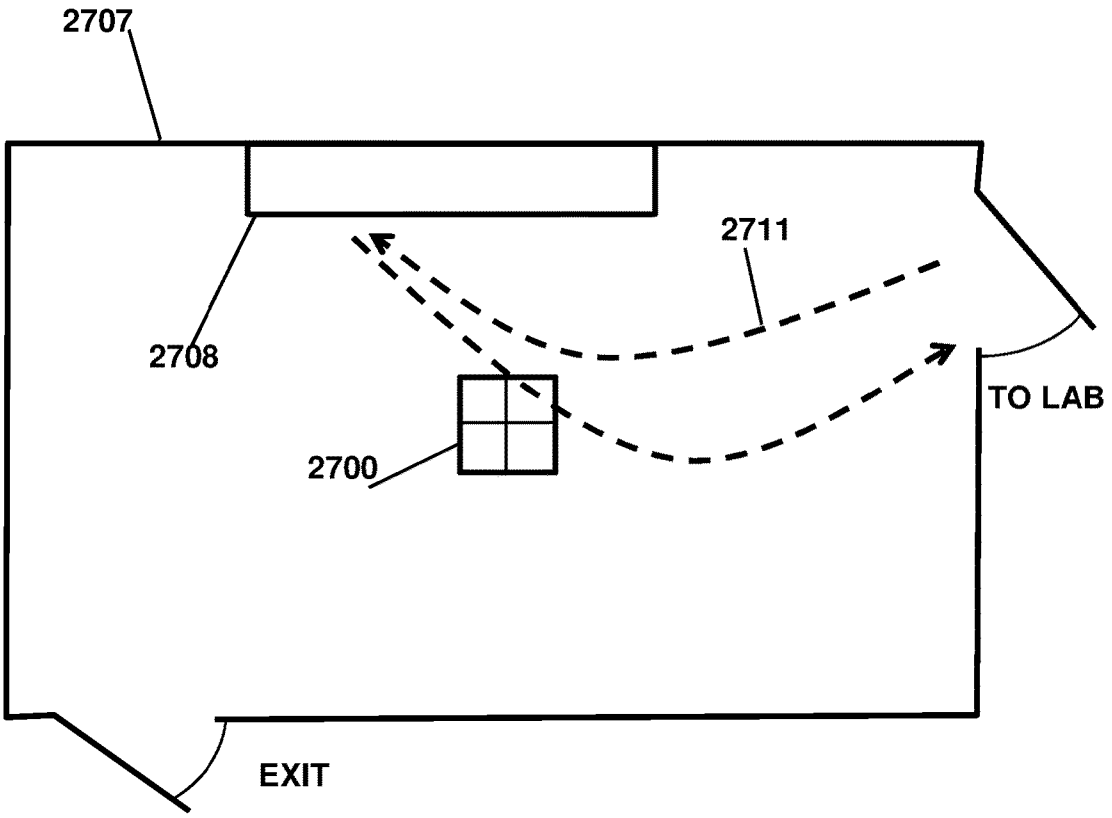


Fig. 28A

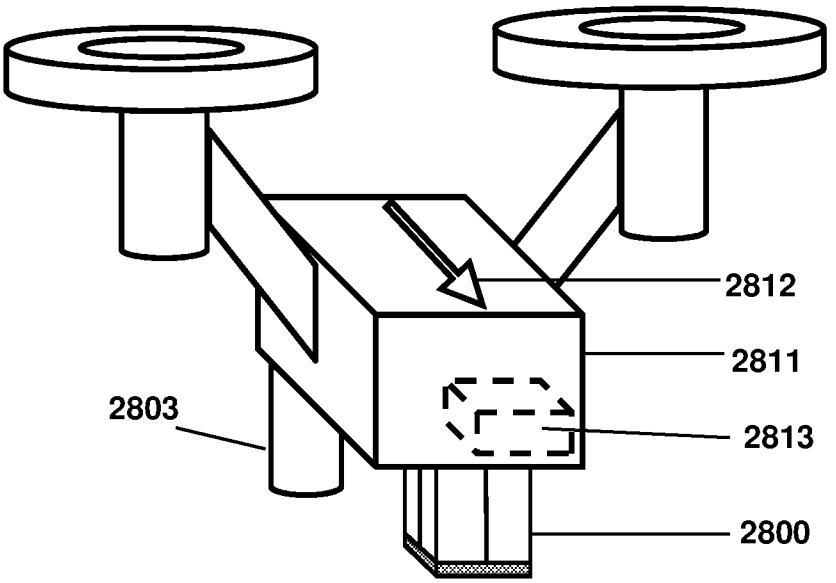
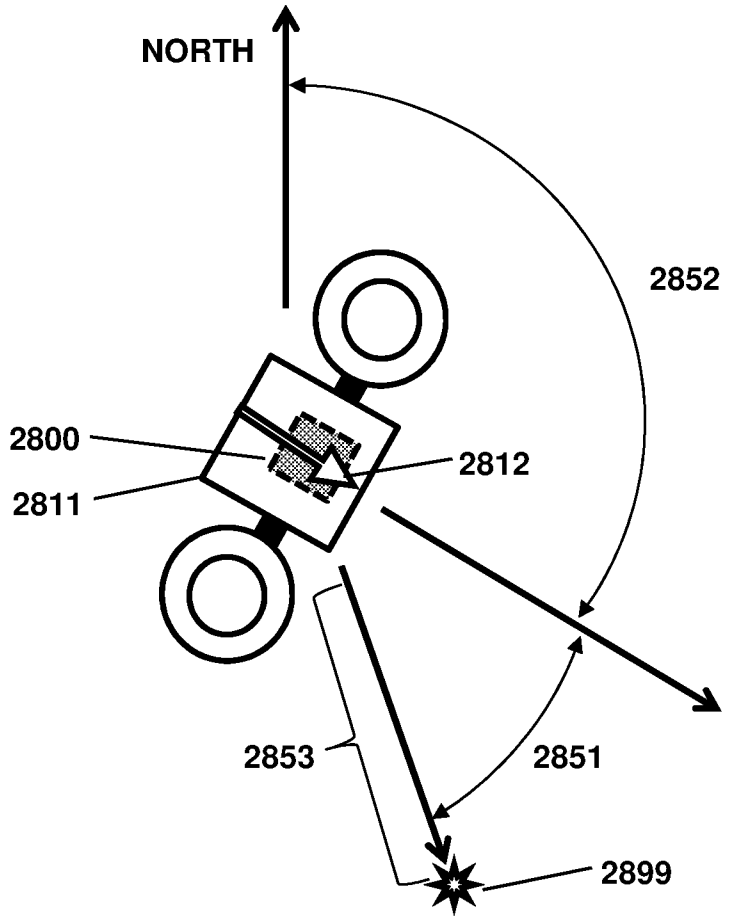


Fig. 28B



COMPACT DIRECTIONAL RADIATION DETECTOR SYSTEM

CROSS REFERENCES TO RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 16/377,195 filed on Apr. 6, 2019, which claims the benefit of U.S. Provisional Patent Application No. 62/661,072 filed on Apr. 22, 2018, and U.S. Provisional Patent Application No. 62/726,295 filed on Sep. 2, 2018, and U.S. Provisional Patent Application No. 62/756,060 filed on Nov. 5, 2018, and U.S. Provisional Patent Application No. 62/830,356 filed on Apr. 5, 2019, the entire disclosures of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to radiation detection. More particularly, the present invention is directed in one exemplary aspect to a particle detector system that determines a two-dimensional location of a radiation source.

BACKGROUND

Clandestine nuclear weapons are an immediate threat to every country and every city in the world. A rogue nation with a nuclear weapon, or a terrorist group that acquires radiological material, could deliver it to a victim city via commercial shipping at low cost and low risk. Nuclear weapons are difficult to detect when shielded. Advanced radiation detectors are necessary to reveal such weapons among backgrounds and benign clutter. An urgent priority of the United States, and indeed of all countries, is the development of radiation detectors that both detect and localize clandestine nuclear material.

A signature of all nuclear and radiological weapons is radiation, principally gamma rays ("gammas") and neutrons. Gamma rays are detected when they interact with matter via photoelectric absorption in which the gamma ray is absorbed and a photoelectron is emitted, Compton scattering which generates a Compton electron and a scattered gamma ray, or electron-positron pair production. In each case, the energetic electron (or positron, treated as an electron herein) can be detected in a charged-particle detector such as a scintillator, semiconductor, or gaseous ionization detector. Neutrons are usually classified according to energy as fast, intermediate, and slow. A fast or high-energy neutron, as used herein, has 100 keV to several MeV of energy. Fast neutrons can be detected by neutron-proton elastic scattering in which the recoil proton passes through a detector such as a scintillator. Slow or low-energy neutrons (1 eV or less, also called thermal or epithermal) can be detected by a capture reaction in a neutron-capture nuclide, usually ^{10}B or ^{6}Li, causing emission of prompt ions such as alpha and triton particles which can be detected in a scintillator or other ionization detector. Intermediate-energy neutrons can be moderated or decelerated by multiple elastic scattering in a hydrogenous material such as HDPE (high-density polyethylene) or PMMA (polymethylmethacrylate), and then detected as slow neutrons.

A directional detector that determines the location of a radiation source would be extremely helpful in detecting and localizing clandestine threats. Even a few gamma rays or neutrons coming from the same location could trigger an alarm. What is needed, then, is a gamma ray or neutron detector system that indicates the direction of the source,

preferably with enough sensitivity to detect a shielded source from a single data set acquired at a single orientation. Preferably such a detector system would be compact, fast, efficient, easy to build, easy to use, and low in cost.

SUMMARY

Disclosed herein is a system for detecting and locating a radioactive source, comprising three or more side detectors positioned symmetrically around a detector axis that extends centrally from the back to the front of the system, each side detector configured to emit signals upon detecting particles from the radioactive source, and to block at least 50% of the particles orthogonally incident thereon; a slab-shaped front detector positioned frontward of the side detectors, orthogonal to the detector axis, and configured to emit signals upon detecting particles from the radioactive source, wherein the thickness of the front detector is at most 0.5 times the average interaction distance of the particles in the front detector, and the lateral dimensions of the front detector are at least 2 times the average interaction distance of the particles in the front detector; and a processor configured to receive the signals and to execute instructions stored in non-transient computer-readable media, wherein the instructions include calculating the azimuthal angle of the radioactive source by interpolating detection data of the side detectors, calculating a numerator according to the detection data of the side detectors, calculating a ratio equal to the numerator divided by detection data of the front detector, and comparing the ratio to a predetermined angular correlation function that provides an estimate of the polar angle of the radioactive source.

These and other embodiments are described in further detail with reference to the figures and accompanying detailed description as provided below.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1**A is a perspective sketch of an exemplary system with four side detectors and a front detector, according to some embodiments.

FIG. **1**B is a perspective sketch showing how the azimuthal and polar angles are related to the detector axis and the source location, according to some embodiments.

FIG. **2**A is a rear-view perspective sketch of an exemplary system with a camera, according to some embodiments.

FIG. **2**B is an exemplary image showing an inspection item and a source location indicator, according to some embodiments.

FIG. **3** is a rear-view perspective sketch of an exemplary system with a large front detector, according to some embodiments.

FIG. **4** is a front-view perspective sketch of an exemplary system with a small front detector, according to some embodiments.

FIG. **5** is a perspective sketch of an exemplary system with a partially-occluding front detector, according to some embodiments.

FIG. **6** is a perspective sketch of an exemplary system with separate front detector portions, according to some embodiments.

FIG. **7** is a perspective sketch, partially exploded, of an exemplary system with beveled side detectors, according to some embodiments.

FIG. **8** is a perspective sketch, partially exploded, of an exemplary system with triangular shaped side detectors, according to some embodiments.

FIG. **9** is a perspective sketch, partially exploded, of an exemplary system with a cylindrical shape, according to some embodiments.

FIG. **10**A is a perspective sketch of an exemplary system with front and back detectors, according to some embodiments.

FIG. **10**B is a sketch of an exemplary image including inspection objects and a source location indicator, according to some embodiments.

FIG. **11**A is a perspective sketch of an exemplary system with front and back detectors divided into portions, according to some embodiments.

FIG. **11**B is a perspective sketch of an exemplary system in which the side detectors are divided at the midplane, according to some embodiments.

FIG. **12** is an exploded perspective sketch of an exemplary system with three side detectors and front and back detectors, according to some embodiments.

FIG. **13** is a cross-section sketch, partially exploded, of an exemplary system with hexagonal symmetry and six side detectors, according to some embodiments.

FIG. **14** is a perspective sketch, partially exploded, of an exemplary system with front and back disk-shaped detectors, according to some embodiments.

FIG. **15** is a perspective sketch of an exemplary system with a disk-shaped front detectors divided into portions, according to some embodiments.

FIG. **16** is a flowchart showing steps of an exemplary method for calculating the polar and azimuthal angles from the detector data without rotations, according to some embodiments.

FIG. **17** is a flowchart showing steps of an exemplary method for producing a composite image indicating the location of the source, according to some embodiments.

FIG. **18** is a graph showing the counting rates for an MCNP6 simulation of a gamma ray detector.

FIG. **19** is a graph showing the angular correlation function that relates the polar angle to the detector counting rates for the simulation of FIG. **18**.

FIG. **20** is a perspective sketch of an exemplary directional hand-held survey meter, according to some embodiments.

FIG. **21**A is a sketch showing an exemplary image including a source location indicator, according to some embodiments.

FIG. **21**B is a sketch showing an exemplary flat-screen display showing the azimuthal angle and polar angle of the source, according to some embodiments.

FIG. **22**A is a notional sketch of a container inspection using a directional system, according to some embodiments.

FIG. **22**B is a sketch of an exemplary image of a cargo container with a source location indicator superposed, according to some embodiments.

FIG. **23** is a notional perspective sketch of an exemplary array of systems arranged to scan passing pedestrians for radioactive material, according to some embodiments.

FIG. **24** shows in perspective an exemplary mobile area scanner, according to some embodiments.

FIG. **25** shows an exemplary vehicle scanner facility, according to some embodiments.

FIG. **26** shows an alternative vehicle scanner facility, according to some embodiments.

FIG. **27**A is a sketch of an exemplary system configured to monitor a room, according to some embodiments.

FIG. **27**B is a top-view sketch of the room of FIG. **27**A including a computed path of a source, according to some embodiments.

FIG. **28**A is a perspective sketch of an exemplary system mounted on a drone, according to some embodiments.

FIG. **28**B is a top-view sketch of a drone including an exemplary system, according to some embodiments.

DETAILED DESCRIPTION OF INVENTION

In the following description, reference is made to the accompanying drawings in which it is shown by way of illustration specific embodiments in which the invention can be practiced. Not all of the described components are necessarily drawn to scale in order to emphasize certain features and to better facilitate the reader's conception of the disclosed embodiments. It is to be understood that other embodiments can be used and structural changes can be made without departing from the scope of the embodiments of disclosed herein.

Disclosed herein are systems for detection, localization, and imaging of radiation sources (the "systems"). In some embodiments, the systems can be configured to detect particles from the radioactive source, determine the direction of the source in two dimensions, such as the azimuthal and polar angles of a spherical coordinate system, relative to a detector axis that runs from the back to the front of the system. Embodiments can also produce a two-dimensional image showing inspection objects with the source location indicated thereon. Examples are given for gamma ray and/or neutron detection, but the systems may be applicable to other particles as well. The system may comprise three or more "side" detectors symmetrically arranged around the detector axis, a "front" detector positioned in front of the side detectors and oriented perpendicular to the detector axis, all providing detection signals to a processor. The side and front detectors (collectively, the "detectors") may be configured to detect the source particles and responsively emit a signal for each particle detected, with each signal being uniquely associated with one of the detectors, respectively. The system may be "compact" in that the detectors may be arranged closely adjacent without interventing shielding or unnecessary air gaps.

In some embodiments, the processor can determine the azimuthal angle of the source according to particle detection data of the side detectors, and can determine the polar angle of the source according to detection data of the front detector. In some embodiments, the processor may calculate the polar angle by comparing a ratio to a predetermined angular correlation function, wherein the ratio may comprise a function of the side detector data divided by a function of the front detector data. The system can thereby determine the source location in two dimensions, using data acquired at a single position and a single orientation of the system. The particle detection data may comprise the number of events in which the signal exceeds a threshold value in a certain time interval, or a measured voltage or current or charge, or a particle detection rate, or other suitable measure of the detected particles. The particle detection rate is the number of times the signals from a detector exceed a threshold, per unit time. In some embodiments, the system can localize the source in the front half-space, which is the angular region spanning the polar angles from 0 to 90 degrees and azimuthal angles from 0 to 360 degrees. With the addition of a "back" detector positioned behind the side detectors, embodiments can detect and localize sources throughout the entire 4π space including azimuthal angles of 0-360 degrees and polar angles of 0-180 degrees, with high angular precision, from data acquired at a single orientation of the system, without rotations or iterations. The resulting

source location can then be superposed as an icon or other indicator on a visible-light or infrared image according to the azimuthal and polar angles so determined, thereby indicating the source position among inspection items. The camera may be configured to adjust the camera viewpoint or aiming direction according to the azimuthal and polar angles of the source, so that the source location is centered in the camera's view and the icon or indicator is centered in the image. The indicator may be an elliptical shape, wherein the axes of the ellipse are configured to indicate the uncertainties in the azimuthal and polar angle determinations, respectively. Such a composite image can then be displayed or transmitted or recorded.

Turning now to the figures, FIG. **1**A is a perspective sketch of an exemplary embodiment of the system, comprising four side detectors **101**, a front detector **102** (in light stipple), and a processor **105**. Each side detector **101** may have a right square prism shape as shown, and may comprise detector material configured to produce a pulsed signal **106** when traversed or partially traversed by an energetic charged particle such as an electron or an ion. The front detector **102** may be a slab-shaped body, also configured to emit a pulsed signal **106** when traversed or partially traversed by an energetic charged particle. The front detector **102** may be oriented perpendicular to the detector axis **108**, and positioned frontward of the side detectors **101**, and centered on the detector axis **108**. The front detector **102** may have a square shape as depicted here, or it may be round or rectangular or triangular or other suitable shape. Each side detector **101** may have a square cross section or other shape, and may be elongate parallel to the detector axis **108**. Thus the side detectors **101** may be oriented perpendicular to the front detector **102**. Sensors **104** are shown connected to each side detector **101**, and a further sensor **114** is shown connected to the front detector **102**. Each sensor **104** or **114** may comprise a transducer or other signal-processing electronics, such as a photomultiplier tube or photodiode or amplifier, configured to tailor the signals **106** so that they can be received by the processor **105**.

In some embodiments, particles from a radioactive source may interact in one of the side detectors **101** or in the front detector **102**. The interaction may produce secondary particles ("secondaries") comprising gamma-generated electrons or neutron-generated ions, for example. The secondary particles may then cause the detector **101-102** to emit a pulse such as an electrical or light pulse, which may be detected by a sensor **104** or **114**, which may then convey signals **106** to the processor **105**. The processor **105** may comprise digital and/or analog electronics, and may include non-transient computer-readable media containing instructions for a method to calculate the azimuthal and polar angles of the source from detection data of the side and front detectors **101-102**. The detection data may comprise the counting rates for each detector **101-102**, such as the number of particle events detected in a time period, or other measure of particle interactions.

In some embodiments, the processor **105** may be configured to calculate the azimuthal angle of the source according to the side detector data. In a first embodiment, the processor **105** may be configured to determine the azimuthal angle of the source by interpolating between the angular positions of the two particular side detectors **101** that have the highest counting rates. In a second embodiment, the processor **105** may be configured to calculate a differential associated with each side detector **101**, wherein each differential is equal to the counting rate of one of the side detectors **101** minus the counting rate of the diametrically opposite side detector **101**, respectively. When the number of side detectors **101** is an odd number, then the differential may equal the counting rate of a respective one of the side detectors **101** minus the average of the two opposing side detectors **101**. The processor **105** may be configured to calculate the azimuthal angle of the source by interpolating between the two highest differentials. In a third embodiment, the processor **105** may be configured to determine the azimuthal angle by performing a fit to the detection data or the differentials of the side detectors **101**. Artisans may devise other methods for calculating the source azimuthal angle from the side detector data.

In some embodiments, the processor **105** may be configured to calculate the polar angle of the source by calculating a ratio R, comprising a numerator based on the side detector **101** detection data, divided by a denominator base on the front detector **102** detection data. The processor **105** may then compare that ratio R to a predetermined angular correlation function that provides an estimate of the polar angle of the source as output. For example, the numerator may be the detection data or counting rate of the highest-counting side detector **101**, while the denominator may be the detection rate of the front detector **102**. In a second embodiment, the numerator may be the highest differential of the side detectors **101**. Alternatively, the numerator may be the sum of the detection data for of the side detectors **101**.

In some embodiments, the predetermined angular correlation function may be a set of data that relates the polar angle of the source to the ratio R. The data may comprise a table of measured or calculated values, an algorithmic form such as a formula or a computer code, a graphical relationship, or other arrangement of data configured to enable the determination of the polar angle from the detection data. The angular correlation function may further include effects, such as adjustments or corrections to the polar angle, based on the azimuthal angle. The predetermined angular correlation function may be prepared by measuring the front and side detector rates while a test source is moved at different polar angles around a system. Alternatively, a simulation program such as MCNP or GEANT may be used to calculate the various detector rates and the ratio R for each of several simulated source angles. The resulting R values, from the measurements or the simulations, may then be fit to an analytic function or programmed in a computer code or otherwise made accessible for determining the source polar angle from the detection data.

In some embodiments, the detectors **101-102** may have different detection efficiencies at different azimuthal angles, and the processor **105** may be configured to cancel such angular anisotropies by analysis. For example, the processor **105** may calculate the numerator as the highest counting rate or differential of the side detectors **101**, plus a geometrical factor G times the second-highest counting rate or differential of the side detectors **101**, wherein G is configured to cancel the angular anisotropies. Angular anisotropies are variations in the angle-dependent detection efficiencies of the side and front detectors **101-102** at various azimuthal angles. The geometrical factor G may largely cancel those anisotropies, so that the same angular correlation function can be used irrespective of the azimuthal angle, a convenience. The processor **105** can then provide the ratio R as input to the predetermined angular correlation function, and thereby obtain an estimate of the polar angle of the source.

As an alternative, the processor **105** may be configured to cancel anisotropies by applying two separate angular correlation functions, rather than using the geometrical factor G. The two angular correlation functions may be prepared at

two predetermined azimuthal angles, and may be used for interpolation to cancel the anisotropies. For example, the two angular correlation functions may correspond to a first plane that passes through the centroid of one of the side detectors **101**, while the second angular correlation function may correspond to a plane that passes between two adjacent side detectors **101**, respectively. In FIG. **1**, for example, the two predetermined angles may be at azimuthal angles of zero degrees and 45 degrees respectively. By symmetry, then the azimuthal angles of 90, 180, and 270 degrees correspond to the zero-degree correlation function, while azimuthal angles of 135, 225, and 315 degrees correspond to the 45-degree function. The processor **105** may then calculate two "candidate values" of the polar angle and interpolate them to obtain a final, corrected polar angle value. For example, the processor **105** may first determine the azimuthal angle according to the side detector data as described, and them may calculate the ratio R as described. The processor **105** may then apply R to each of the two angular correlation functions in turn to obtain the two candidate values, and may interpolate between the two candidate values according to the azimuthal angle of the source, thereby obtaining a value of the polar angle with the anisotropies largely eliminated. By combining the two candidate values according to the source azimuthal angle in this way, the angle-dependent detection efficiencies of the side and front detectors **101-102** may be corrected to high order.

As a further alternative, the angular correlation function may include values or functional forms that take, as input, both the R value and the azimuthal angle, and may thereby apply the anisotropy corrections internally using precalibrated data from the measurements or the simulations. In this way, the angular correlation function may provide a value of the polar angle with the anisotropies largely cancelled.

In some embodiments, the detectors **101-102** may comprise detector material suitable for detecting the particles. In an embodiment for detecting gamma rays, for example, the side and front detectors **101-102** may include an organic or inorganic scintillator, or a semiconductor detector comprising a back-biased junction, or a gaseous ionization detector such as a proportional or Geiger counter, or other suitable medium for producing a signal **106** responsive to gamma-generated electrons. In an embodiment for detecting fast neutrons, the detectors **101-102** may comprise a hydrogenous scintillator, such as a liquid or plastic scintillator, configured to detect recoil protons from elastic neutron scattering, or a scintillator with an ionization-dependent fluor that emits different pulses or pulse shapes for gamma-generated electrons versus recoil protons. For detecting low-energy neutrons, the detectors **101-102** may comprise PMMA or other transparent matrix loaded with microbeads of scintillator and a neutron-capture nuclide such as boron or lithium, configured so that the capture ions excite the scintillator microbeads strongly, while gamma-generated electrons hardly interact with the microbeads due to the electrons' low ionization density. Alternatively, recoil protons or capture ions can be detected in a threshold scintillator such as ZnS, coupled to a wavelength-shifted transparent medium. Capture ions can also be detected in a semiconductor detector or a gaseous ionization detector coated with a capture nuclide. A hydrogenous moderator may be included to enhance the detection efficiency of neutrons. As a further alternative, a material that produces different signals for highly-ionizing particles (recoil protons or reaction ions for example) than for lightly-ionizing particles (such as photoelectrons, Compton electrons, or pair-produced electrons and positrons). PSD (pulse-shape discriminating) scintillators are an example.

In some embodiments, the side or front detectors **101-102** may comprise an energy-resolving detector material, such as NaI scintillator, that emits a signal **106** proportional to the amount of energy deposited therein. Preferably the material can provide sufficient energy resolution to identify the source composition, for example by having an energy uncertainty of at most 10%, where the energy uncertainty may comprise the full width at half maximum of a total energy peak, divided by the total energy. NaI(Tl) and many other scintillators, as well as many solid-state detectors and some gaseous ionization detectors, can provide such a measurement of the particle energy, or of the energy deposited by secondaries. In some embodiments, the processor **105** may be configured to calculate the total particle energy by adding together the signals **106** emitted by each of the respective side detectors **101**, or the energies derived therefrom. In other embodiments, the processor **105** may be configured to calculate a total energy by adding together the signals **106** or energies of the side detectors **101** plus the front detector **102**. Such a total energy sum may have higher detection efficiency, higher detection rate, and comparable or lower energy uncertainty than obtainable in each of the detectors separately. To minimize energy losses in non-scintillating material, the side detectors **101** may be separated by thin reflective separators with little or no other intervening material. Also, when the side detectors **101** are hygroscopic, such as NaI, all of the side detectors **101** may be enclosed in a single hermetic enclosure, thereby avoiding having any enclosure walls between the side detectors **101**. In addition, the front detector **102** may be enclosed in the same enclosure, regardless of whether the front detector **102** is the same type of scintillator as the side detectors **101**. For example, the enclosure may enclose the side detectors **101** comprising NaI, and may also enclose the front detector **102** comprising CsI which has a different pulse width. The processor **105** may then be configured to add the energies corresponding to the signals **106** from each of the detectors **101-102** to obtain a full-energy value for the incident particle, and may thereby identify the source composition isotopically. The front and side detectors **101-102** may be separated by an opaque reflective barrier and viewed by separate light sensors from opposite sides. Alternatively, the front and side detectors **101-102** may be viewed by common light sensors with the signals from each detector being separated according to shape or other parameter.

In some embodiments, the size or thickness of the side detectors **101** may be sufficient to prevent a fraction (the "blocking fraction") of incident particles or their secondaries from reaching the other side detectors **101**. For example, the side detectors **101** may be thick enough to block 30% or 50% or 90% or more of the particles that are orthogonally incident from the side (that is, incident with a polar angle of 90 degrees). Typically the detection of a particle occurs when the particle or its secondaries deposit sufficient energy in the detector **101-102** to produce a signal **106** exceeding a predetermined threshold. The threshold may be 10% of the incident particle energy, or other value depending on design. Thicker side detectors **101** generally provide higher detection efficiency and higher blocking fractions, and thereby higher contrast between side detectors **101** for various azimuthal angles of the source. Thinner side detectors **101** generally have lower cost and weight. Therefore the design of the side detectors **101** may be selected according to the

relative importance of the detection efficiency and lateral contrast of the side detectors **101**, versus the cost and weight of the system.

In some embodiments, the front detector **102** may be thick enough to detect all or substantially all of the orthogonally incident particles. The side detectors **101** can then detect particles that pass beside the front detector **102**, as well as particles that scatter in the front detector **102** and then continue through to the side detectors **101**. In other embodiments, the front detector **102** may be thin enough to allow a fraction of the incident particles to pass through without interacting in the front detector **102**, thereby allowing more detections in the side detectors **101**. Preferably the front detector **102** is thick enough to detect a sufficient number of the incident particles to provide a definite polar angle determination, but not so thick that it significantly shadows the side detectors **101**. In some embodiments, the thickness of the front detector **102** may be sufficient to detect 30% or 50% or 90% of the orthogonally incident particles, with the rest traveling through the front detector **102** undetected. For detecting gamma rays or fast neutrons, the incident particles that scatter in the front detector **102** have a high probability of continuing in about the same direction, so that they can then be detected in one of the side detectors **101**, in which case both the front and side detectors **101-102** are triggered simultaneously. These are valid events.

Low-energy neutrons, on the other hand, generate reaction products comprising heavy ions such as alpha particles, tritons, and recoil nuclei which have extremely short ranges. Therefore, low-energy neutrons generally cannot trigger both the front detector **102** and a side detector **101** simultaneously. If the capture nuclide is ^{10}B, then usually it produces a de-excitation gamma ray which may be detected in one of the side detectors **101**, however the gamma is emitted isotropically and therefore may be detected by any one of the side detectors **101** regardless of the direction of the initial particle. For these reasons, events in which the front and side detectors **101-102** are triggered simultaneously by low-energy neutrons may be rejected.

In some embodiments, the front detector **102** may have an angular sensitivity distribution that is substantially opposite to the angular sensitivity distribution of the side detectors **101**. For example, the detection rate in the front detector **102** may be higher when the source is in front, while the detection efficiency of the side detectors **101** may be lowest when the source is in front. This difference in angular detection efficiencies may be employed by the processor **105** to calculate the source polar angle from the detection data. To accentuate this difference in detection efficiencies, the lateral dimensions of the front detector **102** may be at least two times, and more preferably three to five times, and possibly 10 or 20 times, the thickness of the front detector **102**. The lateral dimensions of the front detector **101** are its dimensions perpendicular to the detector axis **108**, while the thickness of the front detector **102** is the dimension parallel to the detector axis **108**. The front detector **102**, with a thickness that is substantially less than its lateral dimensions, may be mainly sensitive to particles arriving from the front, due to the larger area of the front surface than the side surfaces of the front detector **102**. On the other hand, the side detectors **101** may be mainly sensitive to particles arriving from one side, due to the blocking effect of the front detector **102**. In addition, the side detectors **101** may have an elongate shape that further enhances the side detection efficiency geometrically. The angular correlation function relates the polar angle to the difference in the angular sensitivities of the side and front detectors **101-102**. The angular correlation function may thereby relate each value of the ratio R to the corresponding polar angle.

In some embodiments, the thickness of the front detector **102** may be substantially less than an average interaction distance of the particles in the material of the front detector **102**, which thereby allows many particles to pass directly through the front detector **102**. Those particles may then be detected in the side detectors **101**. Also, the lateral dimensions of the front detector **102** may be substantially greater than the average interaction distance, so that most particles arriving from the side are likely to interact before traveling all the way through the front detector **102**. Due to the small thickness of the front detector **102**, the detection rate of the front detector **102** may be higher for particles arriving from the front than from the side. The "average interaction distance" is the distance that the particle can travel in a particular material, on average, before interacting in a way that would cause the particle to be detected. For gamma rays, the average interaction distance is the mean free path for Compton scattering or photoelectric absorption or pair-production, or alternatively is the inverse of the mass attenuation factor which includes all those interactions. For fast neutrons, the average interaction distance is the mean free path for neutron-proton scattering. For slow neutrons, the average interaction distance is the (projected) mean free path for neutron capture. In some embodiments, the front detector may be configured so that each lateral dimension of the front detector is at least two times the average interaction distance, while the thickness is at most 0.5 times the average interaction distance.

In some embodiments, the lateral dimensions of the front detector **102** may be substantially equal to the lateral dimensions of the array of side detectors **101**, as depicted in the figure. In other embodiments, the front detector **102** may extend laterally beyond the array of side detectors **101**, thereby providing additional detection area of the front detector **102**. In other embodiments, the lateral dimensions of the front detector **102** may be smaller than the lateral dimensions of the array of side detectors **101** (or equivalently, the side detectors **101** may extend laterally beyond the front detector **102**) thereby exposing part of the front surface of each side detector **101** to the particles without being unobscured by the front detector **102**. In systems that include a back detector (discussed below), the back detector may have the same shape and size as the front detector **102**, and thus may be laterally coterminous with the side detectors **101**, or may extend laterally beyond the side detectors **101**, or the side detectors **101** may extend laterally beyond the back detector, according to various embodiments.

FIG. **1**B is a perspective sketch showing the spherical angles measured by an exemplary directional detector comprising side detectors **151** and a front detector **152**. The detector axis, shown as a dot-dash line, is the central symmetry axis of the system. The source is indicated by a star, and the angles by arrowed arcs. The azimuthal angle is a rotational angle measured around the detector axis, with zero degrees at the right-side horizontal plane (shown in dash) as viewed from behind the system. The polar angle is the overall angle between the detector axis and the source. The polar and azimuthal angles thus localize the source direction in two dimensions.

FIG. **2**A is a rear-view perspective sketch of an exemplary system comprising four side detectors **201**, a front detector **202** frontward of the side detectors **201**, and sensors **204** such as photodiodes viewing the side detectors **201**. Further light sensors (not visible) may be mounted on the front

detector **202**. A camera **203** is mounted above the detectors **201**-**202** and configured to produce images of an inspection scene frontward of the system. In other embodiments, the camera **203** may be configured to record wide-angle images such as images that cover most or substantially all of the front half-space, including polar angles of 0-90 degrees. The system may be configured to determine a direction of a source or, using images from the camera **203**, a composite image that shows the inspection scene and the source location together.

Alternatively, instead of using separate light sensors **204**, the side detectors **201** can be viewed by a single planar photocathode, followed by a multichannel plate charge amplifier, all mounted across the back of the system. The charge amplifier can be configured with four separate anodes, thereby providing four separate electrical pulse signals corresponding to each of the side detectors **201** separately. Likewise, the front detector **202** can be viewed by a similar planar photocathode-multichannel amplifier, but with a single anode spanning the front detector. Such planar light sensors can be made thin enough to avoid blocking a significant fraction of the incoming particles, according to some embodiments.

FIG. **2**B shows an exemplary image **253** derived with the system of FIG. **2**A for example. An inspection item comprising a truck **259** is being inspected. The trailer is clean, but a radioactive source has been hidden in the driver's sleeping compartment, as indicated by a detected radiation source distribution **299**, which is superposed on the visible-light image. With this composite image **253**, inspectors would know where to search to find the contraband **299**.

FIG. **3** is a rear-view perspective sketch of an exemplary system with four side detectors **301** (only three are shown) and a front detector **302** that extends laterally beyond the side detectors **301** by a distance **307**. Thus the lateral dimensions of the front detector **302** are larger than the lateral dimensions of the array of side detectors **301**, in contrast to the system of FIG. **1**A in which the lateral dimensions of the front detector **102** are substantially the same as the lateral dimensions of the array of side detectors **101**. The additional area of the front detector **302** can provide additional detection efficiency, and can also tailor the angular correlation function in various ways. Also shown are light sensors **304** such as photomultiplier tubes on the side detectors **301**, and small light sensors **314** such as photodiodes positioned on the edges of the front detector **302** to avoid blocking incoming particles.

FIG. **4** is a front-view perspective sketch of an exemplary system comprising four side detectors **401**, a front detector **402**, compact sensors **404** on the lateral surfaces of the side detectors toward the back, and another compact sensor **414** centered on the front detector **402**. The sensors **404** and **414** thus comprise two separate sets, a first set of sensors **404** on the side detectors **401** and a second, separate set of (one or more) sensors **414** on the front detector **402**. The lateral dimensions of the front detector **402** are smaller than the lateral dimensions of the side detector **401** array as shown, thereby leaving an open space **407** in which the side detectors **401** are directly exposed to incoming particles from the front, unobscured by the front detector **402**.

In some embodiments, the sensors **404** on the side detectors **401** may be positioned rearward, as shown, to minimize blocking of particles that arrive from the front half-space. Also, two sensors **404** are shown on each side detector **401** to ensure sufficient signal collection. The front sensor **414** is shown in the center of the front detector **402** so that any obscuration effects from the front sensor **414** are symmetrically distributed across the front detector **402** and the four side detectors **401**. As an alternative, the front sensor **414** may be mounted on the back surface of the front detector **402**, by spacing the front detector frontward away from the side detectors **401**.

FIG. **5** is a front-view perspective sketch of an exemplary system comprising four side detectors **501**, a front detector **502**, four sensors **504** attached to the side detectors **501**, and four small sensors **514** attached to the front detector **502**. The front detector **502** is shown configured as a cross shape, thereby leaving part of the frontal area of the side detectors **501** unobscured. Also, the front sensors **514** are shown mounted exteriorly on the ends of the arms of the front detector **502**, to avoid shadowing the side detectors **501** when the system is aligned with the radioactive source. As an alternative, the front detector **502** could be shaped differently, such as an octagon or diamond shape for example, to allow a portion of each side detector **501** to view particles unobscured from the front. In some embodiments, including the depicted embodiment, the front detector **502** may be configured to obscure the same fraction of each of the side detectors **501** respectively, thereby simplifying analysis.

FIG. **6** is a front-view perspective sketch of an exemplary system comprising four side detectors **601**, four sensors **604** attached to the side detectors **601**, and a front detector comprising four front detector portions **602**. In some embodiments, if N is the number of side detectors **601**, then there are also N front detector portions **602**, N being any integer of 3 or greater. Thus the system may include one front detector portion **602** for each side detector **601**, and likewise one side detector **601** for each front detector portion **602**. In some embodiments, a first set of sensors **604** may be coupled to the side detectors **601** respectively, and a second separate set of sensors **614** (one shown, in dash) may be coupled to the front detector portions **602** respectively, in which case the side and front detectors **601**-**602** each produce separate signals.

In other embodiments, the front and side detectors **601**-**602** may be viewed by a shared sensor **604**. In that case, the second set of sensors **614** may be eliminated, saving costs. For example, the front detector portions **602** may be coupled to the respective adjacent side detectors **601**, with both being read out by a respective one of the sensors **604**. The signals from the front detector portions **602** may be detectably different from the signals of the side detectors **601** so that they can be separated in analysis. More specifically, each front detector portion **602** may be coupled to exactly one of the side detectors **601** respectively, and each side detector **601** may be coupled to exactly one of the front detector portions **602** respectively, and each set of coupled detectors may be read out by its attached sensor **604**. The processor may be configured to determine which of the detectors, side **601** or front **602**, has detected each particle according to a parameter of the signals that distinguishes the two coupled detectors. For example, the side detectors **601** may be made of a different material than the front detector portions **602**, so that each side detector **601** may emit detectably different signals or pulses from those of the front detector portions **602**. In some embodiments, the front detector portions **602** may comprise scintillators such as CaF_2 with a 900 ns pulse width, and the side detectors **601** may be NaI with a 230 ns pulse width, while a shared photomultiplier tube sensor **604** may view each side detector **601** and its coupled front detector portion **602** together. Each sensor **604** may then receive light pulses or other signals from the side detector **601** to which the sensor **604** is coupled, as well as signals

from the front detector portion **602** that is coupled to that side detector **601**. The signals from the side detectors **601** can then be separated from signals of the front detector portions **602** by suitable signal processing means, such as pulse shape discrimination which is well known in the field. One advantage of this configuration may be economy, since only one sensor **604** is needed per quadrant. Other advantages may be reduced weight and reduced power consumption by avoiding separate sensors on the front detector portions **602**. In addition, the blocking of particles by a frontward sensor is avoided, and the entire system may be made more compact. The depicted system may be fabricated conveniently in separate quadrants, with each quadrant comprising one front detector portion **602**, one side detector **601**, and one sensor **604**, all bound together as a unit. Each quadrant can be tested separately before being assembled into the final system, thereby allowing the quadrants to be matched in efficiency. Separate quadrant assembly may also simplify repairs when needed.

The various signals from the four front detector portions **602** may be added together and the combined detection data may be used in the polar angle calculation. For example, the detection data of the four front detector portions **602** may be combined using electronics or software for example, and may thereby form an effectively undivided front detector that spans across the entire assembly. Combining the detection data from the four front detector portions **602** may simplify analysis since the combined data can be used as if the system had a single spanning front detector. Combining the data in this way may also cancel a variety of effects such as the blocking of one of the front detector portions **602** by another front detector portion **602**, particularly at high polar angles. The combined front detector detection rate may then be used as the denominator in the ratio R for determining the polar angle. Although the angular response of each individual front detector portion **602** may be asymmetric due to its off-center placement, the combined data from all four front detector portions **602** is overall symmetric, just as if there were a single undivided monolithic front detector.

FIG. **7** is a perspective sketch, partially exploded, of an exemplary system comprising four side detectors, each shown with a different shape to illustrate examples. The side detectors are beveled in various ways to sharpen the angular resolution, by avoiding detecting particles that arrive from certain angles. For example, a particle may arrive at an oblique polar angle such as 45 degrees, pass over the nearest side detectors, and then strike the farther or downstream side detectors. Each such "wrong" or downstream side detector event reduces the contrast and the angular resolution achievable with limited data. To avoid such events, the side detectors may be beveled or trimmed in various ways.

In the figure, four exemplary side detector shapes labeled **701**, **711**, **721**, and **731** are shown, plus a front detector **702** with sensors **714** attached to the corners. A first side detector **701** has a regular right square prism shape, similar to those shown in the previous drawings. A second side detector **711** has a bevel or slope covering its entire front surface. Particles that arrive from the front at large angles may pass by the beveled front surface without being detected, which thereby avoids counting those errant particles in the downstream detector. A third side detector **721** is shown with an alternative bevel, that extends across half the front area of the side detector. A fourth side detector **731** has a steeper bevel cut, which removes a smaller fraction of the front surface area. In each case, the bevel is on the outside corner of the respective detector. Each of the bevel shapes shown has a different effect on the side detector angular efficiency. Four different shapes are shown together in the sketch to illustrate alternative options; in a practical system, all four of the side detectors are preferably made with the same shape to simplify analysis.

FIG. **8** is a partially exploded perspective sketch of an exemplary system with four triangular-prism-shaped side detectors **801** and a monolithic front detector **802** that is mounted spaced apart from the front edge of the side detectors **801** by the distance **807**. The spaced-apart distance **807** may provide room for sensors or electronics. The spaced-apart distance **807** may also be adjusted to tailor the shape of the angular correlation function, by allowing particles from some angles to pass under the front detector **802**, and thereby strike the side detectors **801** without the partial blocking caused by the front detector **802**. Also shown is an alternative embodiment, in which four separate front detector portions **812** (one shown) may be prepared with one portion **812** attached to each side detector **811** respectively. Each such assembly may advantageously be bench-tested in separate quadrants, and then mounted together to form the complete system as shown.

FIG. **9** is an exploded front-view perspective sketch of an exemplary system configured as a cylindrical assembly including four side detectors **901** (only three shown), each side detector **901** being shaped as a 90-degree pie-section prism and viewed by a sensor **904**. Also shown is a disk-shaped front detector **902** which includes four solid-state sensors **914**. The configuration may be advantageous when spatial constraints require a cylindrical shape, such as a tubular shell constraint. Also shown is a highly notional sketch of an exemplary circuit board **951** which may be mounted onto the sensors **904**. In some embodiments, the circuit board **951** may include power control circuits **952** such as resistor dividers for photomultiplier tubes or voltage regulators and isolators for amplifier type sensors, a processor **955**, connected to the powering circuits **952** by signal-carrying traces **956**, and other circuit elements **953** such as voltage converters, analog signal-processing circuits, and the like. When mounted to the sensors **904**, the circuit board **951** may also provide some mechanical stabilization to the system. The processor **955** may be programmed remotely or locally using JTAG pins or the like, thereby allowing firmware updates without disassembling the system. The circuit board **951** may be powered and read out by a simple 3-wire connection comprising power **956**, serial data **957**, and ground **958** in some embodiments. In other embodiments, a 4-wire protocol such as USB may be implemented. Together, the front detector **902**, the side detector **901** array, the sensors **904**, and the circuit board **951** may comprise a compact and easily mounted light-weight directional detector system with many applications.

FIG. **10**A is a perspective sketch of an exemplary bi-directional or double-ended system, with side detectors **1001**, a front detector **1002** and a back detector **1003**. The back detector **1003** may be a slab-shaped detector configured to detect the particles from the source and emit signals, and may be oriented perpendicular to the detector axis and positioned behind, or to the back of, the side detectors **1001**. The back detector **1003** may have the same shape and/or composition as the front detector **1002**. The lateral dimensions of the back detector **1003** may be at least four times the thickness of the back detector **1003**. The thickness of the back detector **1003** may be at most 0.5 times the particle interaction distance therein, and the lateral dimensions of the back detector **1003** may be at least 2 times the particle interaction distance. Sensors **1004** are also shown. The front and back detectors **1002** and **1003** can receive particles from

the front and back half-space regions respectively, thereby covering a full 4π solid angle of view. The system can determine whether the source is in front or behind by comparing the detection rates of the front and back detectors **1002-1003**. The system can then analyze the side detector **1001** detection data to determine the azimuthal angle of the source, and calculate a ratio R according to the side detector **1001** data divided by the detection data of whichever front or back detector **1002-1003** has the higher detection rate. Then that ratio can be compared (or provided as input) to a predetermined angular correlation function that directly indicates the polar angle of the source. In some embodiments, both the ratio R and the calculated azimuthal angle may be provided as inputs to the angular correlation function, which then determines the polar angle with anisotropies canceled. Alternatively, two angular correlation functions, corresponding to different azimuthal angles, can be used and interpolated to obtain a polar angle value that corrects for anisotropies of the detectors **1001-1003**.

In some embodiments, the bi-directional or double-ended version of FIG. **10**A may be useful in applications where a source could be located anywhere around the system, such as a mobile area scanner that searches for hidden weapon material throughout a wide area on both sides. The bi-directional system may also be useful in a vehicle inspection station in which multiple parallel lanes are active, since the bi-directional system can inspect two vehicles on opposite sides of the system at the same time.

FIG. **10**B is an exemplary image of a 360-degree scene surrounding a double-ended detector such as that of FIG. **10**A. The image **1053** includes a barn **1054**, a house **1055**, an apartment building **1056**, a small shed **1057**, and a store **1058** which are being scanned by a vehicle-mounted double-ended directional detector such as that of FIG. **10**A. The barn **1054** appears on both sides of the image **1053** since the image **1053** extends around 360 degrees.

The image **1053** further also shows a radiation indicator **1099**, which in this case is a map or distribution of the detected radiation. Apparently an adversary has concealed some stolen nuclear material in the otherwise innocent-looking shed **1057**. With this data, officials can retrieve the lost radioactive material, and perhaps the adversary as well.

FIG. **11**A is a perspective sketch of an exemplary bi-directional detector such as that of FIG. **10**A, but now the front and back detectors are divided into portions labeled **1102** and **1103** respectively. Also, the front detector **1102** is made of a different material, with different signal properties, than the back detector **1103**. Each front or back detector portion **1102** or **1103** may be optically coupled to the intervening side detector **1101**, and that combination may be viewed by one of the sensors **1104**, respectively. For example, each front detector portion **1102** may be optically coupled to exactly one of the side detectors **1101** respectively, and each back detector portion **1103** may be optically coupled to exactly one of the side detector portions **1101** respectively, and each such combination may be optically coupled to exactly one of the sensors **1104** respectively. Thus each sensor **1104** may collect pulses or signals from one of the front detector portions **1102**, and one of the side detectors **1101**, and one of the back detector portions **1103**, respectively, all together. To differentiate the various pulses or signals, the front detector portions **1102** may comprise a first material, the side detectors **1101** may comprise a second material different from the first material, and the back detector portions **1103** may comprise a third material different from the first two materials, wherein each of the materials is configured to emit a detectably different signal or pulse. For example, the front, side, and back detectors **1101-1103** may comprise three different scintillators producing three differently shaped light pulses that can be separated in analysis. In an embodiment, the side detectors **1101** may be PVT scintillator with a 5 ns pulse width, the front detector portions **1102** may be BGO with a 300 ns pulse width, and the back detector portions **1103** may be CaF_2 with a 900 ns pulse width. An advantage of coupling the detectors in this way may be economy, since only N sensors **1104** may be needed, N being the number of side detectors **1101**. It may be noted that some particles from the back are blocked by the sensors **1104**; however, this asymmetry may be accounted for in the angular correlation function.

FIG. **11**B is a perspective sketch of an exemplary double-ended system which is split symmetrically at the midplane. The midplane is a centrally positioned plane perpendicular to the detector axis. A first set of side detectors **1151** are coupled to front detector portions **1152** which are coupled to sensors **1154** that view both the attached front detector portion **1152** and the coupled side detector **1151**. A second set of side detectors **1161** is coupled to back detectors **1162** which are viewed by back sensors **1164**. The depicted embodiment may detect radiation from a source located at an arbitrary position throughout the 4π solid angle, that is, 0-180 degrees in polar angle, 0-360 degrees in azimuthal angle, from a single position and a single orientation, according to some embodiments.

FIG. **12** is an exploded perspective sketch of an exemplary system with three-fold symmetry, having three pie-sector-shaped side detectors **1201**. The depicted system also includes a disk-shaped front detector **1202** and a disk-shaped back detector **1203** covering the front and back of the system respectively, and sensors **1204** on the three side detectors **1201**, with additional sensors **1214** on the front and back detectors **1202-1203**. Each side detector **1201** is a prism with an extrusion direction in the longitudinal direction. The extrusion dimension of the side detectors **1201** is the shortest dimension of the side detectors **1201** in the depicted embodiment. Nevertheless, each side detector **1201** may be sensitive primarily to particles from the side, due to the blocking effect of the other side detectors **1201** and the front and back detectors **1202-1203**. The front and back detectors **1202-1203**, on the other hand, may be mainly sensitive to particles from the front or back respectively. These contrasting sensitivity distributions may allow the polar angle to be determined from detection data, specifically by comparing detection rates in the side detectors **1201** with whichever of the front or back detectors **1202** or **1203** has the higher counting rate. Sensors **1204** can be connected to the side detectors **1201**, and other sensors **1214** can be connected to the front and back detectors **1202-1203**.

FIG. **13** is a transverse cross-section view of a hexagonal embodiment of the system with six triangular side detectors **1301** (only one visible) and six separate front detector portions **1302** matching the shape of each side detector **1301**. A small sensor **1314** such as photodiode light sensor or an amplifier circuit may view each front detector portion **1302**. As an alternative, instead of the separate front detectors **1302**, a single hexagonal monolithic front detector may be used.

FIG. **14** is a partially exploded perspective view of an exemplary system comprising four side detectors **1401**, a disk-shaped front detector **1402**, and a disk-shaped back detector **1403**. Sensors **1414** are centrally positioned on the front and back detectors **1402-1403** and further sensors **1404** are positioned around the midplane of the side detectors

1401. The midplane position of the sensors 1404 on the side detectors 1401 may improve the front-back symmetry and thereby simplify analysis.

The disk-shaped front and back detectors 1402-1403 may have a detection efficiency that is independent of the azimuthal angle due to their symmetry. This may further reduce nonlinearities and azimuthal anisotropy effects in the angular correlation function. Also, the disk-shaped front and back detectors 1402-1403 leave a portion of the front surface of each side detector 1401 unobscured, thereby enabling the side detectors 1401 to detect particles from a source aligned with the detector axis.

FIG. 15 is a perspective sketch of an exemplary system comprising four side detectors 1501 viewed by four sensors 1504 from the back, and coupled to four front detector portions 1502 that together comprise a disk shape. Thus each sensor 1504 may be configured to receive signals (such as light pulses or electrical pulses) from one of the side detectors 1501 and the associated front detector portion 1502, respectively. The front detector portions 1502 may comprise a different material than the side detectors 1501 and may be configured to emit detectably different signals such as different pulse shapes, thereby enabling the various detector signals to be separated in analysis.

FIG. 16 is a flowchart showing steps of an exemplary method for calculating the azimuthal and polar angles from the detector signals, including several options shown in dash. In some embodiments, the sequence of steps may follow the arrows on the left side of the page, starting with 1601, acquisition of detector signals at a particular orientation of the system, including side detector and front detector detection data. After accumulating detection data for a predetermined integration time, or at any time, the data can be corrected 1602 for the different efficiencies of each detector, for example to compensate for manufacturing variations or different threshold settings. Also, any events in which more than one side detector registers a signal at the same time may be rejected, either at this point 1602 or during acquisition 1601. Then 1603 the azimuthal angle can be calculated by interpolating between the two side detectors that have the highest detection rates (or the highest differentials), or by fitting the detection rates (or differentials) of all the side detectors to a source location model, or by another formula that relates the source azimuthal angle to the side detector data.

The polar angle can then be calculated. At 1604, the numerator of a ratio R can be calculated as the sum of the detection rates of all the side detectors as shown, or using another formula according to the side detector data. At 1605, the ratio R can be calculated as the numerator from step 1604 divided by the front detector rate as shown, or using another formula for the denominator according to the front detector data. Optionally, the result may be further modified for calculational convenience or for improved accuracy in particular embodiments, such as by squaring or taking the square root or other function of R.

Then at 1606, R is compared to two different angular correlation functions, one corresponding to an azimuthal angle of zero degrees and the other at an azimuthal angle of 180/N where N is the number of side detectors. When N=4, the second angular correlation function is at an azimuthal angle of 45 degrees, and for N=6, the second azimuthal angle is 30 degrees, for example. Thus one of the angular correlation functions corresponds to a plane passing through the centroid of one of the side detectors, and the other angular correlation function corresponds to a plane passing through the interface between two side detectors. The two angular correlation functions are generally different due to azimuthal anisotropies, or different detection efficiencies for sources at different azimuthal angles. As mentioned, the angular correlation functions may be prepared by measuring the front and side detector rates of a prototype system while a test source is moved around various polar angles. For one of the angular correlation functions, the test source may be placed at various polar angles with the azimuthal angle aligned with the center of one of the side detectors, and for the other angular correlation function, the test source may be placed at various polar angles in a plane aligned with the interface between two of the side detectors. Alternatively, a simulation program such as MCNP or GEANT may be used to calculate the individual detector response when a simulated source is placed at various polar angles, with an azimuthal angle of either zero degrees or 45 degrees (for a four-side-detector system). The front and side detector rates are noted, and the ratio R is calculated from those detection rates. The angular correlation function may then be the set of values of R along with the corresponding source polar angle.

When the ratio R is compared to the two angular correlation functions separately at step 1606, each angular correlation function provides a separate "candidate" value of the polar angle. The processor can then 1607 interpolate between those two candidate values according to the azimuthal angle of the source, which was already determined at step 1603. The resulting polar angle determination thereby eliminates the detection anisotropies of the detectors to high order. Therefore, the interpolation may provide a polar angle determination in this way that may be accurate throughout the azimuthal range of 0-360 degrees and polar range of 0-90 degrees, according to some embodiments. Finally at step 1608, the azimuthal and polar angles may be displayed, transmitted elsewhere, stored locally, used to redirect a light beam or a camera image, emblazoned upon that camera image at the source location, or otherwise reported according to the application requirements.

The method includes several optional variations shown in dash. At 1609, after determining the detection rates of the side detectors, a set of differentials can be calculated, each differential equaling the detection rate of one side detector minus the detection rate of the diametrically opposite side detector, thereby obtaining a zero-based differential. (Using a differential instead of the actual detector rates may enhance the contrast between side detector signals, in some cases.) If the number of side detectors is odd, then the differential may equal the difference between one side detector rate and the average of the two nearly-opposing side detector rates, respectively. Then the differentials may be used in the interpolation step 1603 to evaluate the azimuthal angle. (However, the differentials are preferably NOT used in step 1604, calculation of the sum of the side detector data, since the sum of differentials is necessarily zero.) The option of using differentials for the azimuthal angle determination is generally beneficial when the blocking fraction is high, such as greater than about 60%. However if the blocking fraction is low, such as below about 40%, the penetration of particles through to the opposite side detector may affect the angular response; hence in designs with low blocking fractions, the side detector rates may preferably be used instead of the differentials for calculating the azimuthal and polar angles.

After determining the azimuthal angle in step 1603, as an option, the numerator may be calculated 1610 by taking the highest side detector rate (or the highest side detector differential), and adding the second-highest rate or differential times a geometrical factor G. The geometrical factor

is a first-order correction for the detection anisotropies, and usually is optimal in the range of 0.05 to 0.20, with values in the range of 0.10-0.12 being most common. Artisans can determine the value of G for a particular system design by measuring the detector rates and calculating R with a test source positioned at azimuthal angles of zero and then at 45 degrees, and adjusting G so that the resulting two values of R are equal. With the detector anisotropies thus canceled, the resulting value of R is substantially independent of the azimuthal angle, and therefore a single angular correlation function may be sufficient to localize a source irrespective of the azimuthal angle, at step **1611**.

Alternatively, the angular correlation function may include polar angle values corresponding to various values of R and various values of the azimuthal angle. Then, after determining the azimuthal angle from the side detector data, the polar angle can be determined from the angular correlation function with the anisotropies largely canceled, since the azimuthal effects are already included in the function.

To summarize the flowchart of FIG. **16**, the azimuthal angle can be calculated by interpolating between the side detector rates or their corresponding differentials; the numerator can be calculated as the sum of all the side detector rates, or as the highest rate plus G times the second-highest rate to cancel anisotropies, or as the highest differential plus G times the second-highest differential, with G being adjusted so that the zero-degree and 45-degree values are equal. In the polar angle determination, the numerator can be the sum of the side detector rates or other function of the side detector data, while the two angular correlation functions (corresponding to azimuthal angles of zero and 45 degrees when N=4) may be interpolated to obtain the final, anisotropy-corrected polar angle. Alternatively, a single angular correlation function can be used to determine the polar angle, optionally using G to correct anisotropies as mentioned. Or a comprehensive angular correlation function can be used that includes both the ratio R and the azimuthal angle to determine the polar angle. For most system designs and most source angles, the various options shown in FIG. **16** produce similar results. Artisans can select the analysis options that are most convenient for their particular system.

FIG. **17** is a flowchart showing steps of an exemplary method for preparing an image that indicates where a source is located in an inspection scene. First **1701** detection signals from the side and front detectors are acquired. The rates may be checked against the expected or normal background levels **1702**, for example by adding the detection rates of all the detectors and comparing to a predetermined background rate. If the total rate is normal, there is no source present, or at least no source has yet been detected, and the method is done at **1703**. If the rates are above background, then optionally (in dash, **1704**), the side detector rates can be checked to determine if they are all equal to within expected statistical variations. If the are not equal, the system can then **1705** calculate the azimuthal angle of the source according to the distribution of side detector rates, and the polar angle according to the front detector rates, as discussed above. The system can also calculate **1706** the uncertainty in each angular determination according to the number of counts in each detector using, for example, Poisson statistics if the number of counts is low such as less than about 30, or Gaussian statistics if the number is higher than 30 (or other threshold value).

Then **1707**, or earlier, an image of the scene may be acquired, using for example visible light or infrared or other wavelength range. If a source is detected, its calculated direction can be indicated **1708** on the image by, for example, placing an icon overlay or a density map or contours on the image, or other graphical means for indicating where the source was observed. Thus the position of the icon on the image corresponds to the polar and azimuthal angles calculated from the detector rates, so that the icon appears correctly registered relative to other items in the image. In addition, the uncertainties in the azimuthal and polar angles may be determined according to the detection data, and these uncertainties can be displayed on the image, for example by adjusting the width and height of the source overlay according to the uncertainties. For example, the source location may be indicated as an ellipse overlay, which is centered at the calculated source direction on the image, and the ellipse axes may be set according to the uncertainties in the polar and azimuthal angles. In a similar way, if the source is indicated as a density map or contour overlay, then its dimensions may be scaled according to the angular uncertainties, thereby informing an operator of the range of directions in which the source is likely to be found. As a further option, the source indicator may be colored or otherwise varied according to the rate of detections, or the type of particle detected, or other criterion.

Returning to the interrogator at **1704**, if all the side detectors exhibit the same counting rates within statistical uncertainties, then the flow can proceed directly to the image processing step at **1708** since the source is then known to be aligned with the detector axis, that is, the polar angle is zero degrees and the azimuthal angle is irrelevant. Then **1709**, after the composite image has been prepared and displayed (or stored or transmitted elsewhere), the task is done.

In some embodiments, the flow may return to acquire further detector data at **1701**, and to update the polar and azimuthal angle determinations incrementally. For example, new detection data may be combined with earlier data by weighted averaging or a ring buffer calculation or other means for updating the angles with new detection data. Also, the uncertainties in the source angles can be adjusted, usually downward, as further counts are accumulated, and the source icon or the radiation distribution, shown on the image display, can be adjusted likewise. The scene image may also be updated whenever the operator moves the system, so as to continuously track rotations or other motions of the system. When the scene does shift, the direction of the source may be corrected automatically (that is, without waiting for more detection data) by moving the source icon overlay on the image, in the opposite direction to the perceived system rotation. The icon may thereby continue to be centered on the calculated source location after the system is rotated. In some embodiments, a compass or other direction-sensitive sensor can be included, and the source icon can be moved in response to changes in the system orientation as revealed by the compass or other sensor. Alternatively, without such a sensor, the processor may be configured to perform image analysis on items in the scene and thereby determine when and how far the system orientation has changed, and can then adjust the position of the source icon on the image accordingly to keep the source indicator centered on the detected source direction. As further detection data is accumulated, the source icon can then be adjusted accordingly, irrespective of any prior orientation changes in the system.

FIG. **18** is a graph showing the results of an MCNP6 simulation of an exemplary system to detect 1 MeV gamma rays from an isotropic source at a distance of 3 meters. The system was modeled after FIG. **1**, with four side detectors of NaI measuring 5×5×16 cm and a BGO front detector mea-

suring 10×10×1 cm. Each detector had a detection energy threshold of 100 keV. The simulated source was moved in the horizontal plane around the simulated detector, acquiring data at horizontal angles every 10 degrees from 0 to 90 degrees relative to the detector axis, with an elevation angle of zero. In spherical coordinates, this corresponds to a polar angle ranging from zero to 90 degrees, and the azimuthal angle of zero. The graph shows the counting rates, in arbitrary units, of the four side detectors according to the numbering shown in the inset drawing. The counting rates in side detectors **1** and **4**, shown as the lines with "x" data points, have high detection rates since the source is on the same side of the system. Side detectors **2** and **3**, shown as the lines with "o" markings, have lower rates since the source is on the opposite side. The dashed curve shows the front detector counting rate, which is maximum when the source is in front of the system and declines at high angles. The shape of the front detector curve is due to the front detector width-to-thickness ratio, which was 10 in the simulation.

The two side detectors numbered **2** and **3** have nearly the same counting rate since they are equally exposed to the source when the azimuthal angle is zero. Likewise, the two side detectors **1** and **4** show statistically the same response for the same reason. At a polar angle of zero degrees, all four side detectors show nearly the same detection rate, since the system is directly aimed at the source in that case. As the source is moved horizontally away from the detector axis, the near-side detectors (**1** and **4**) increased in detection rate as expected, while the far-side detectors (**2** and **3**) remained substantially lower. At the highest polar angles, the far-side detectors do not drop to a very low detection rate in this case, because the simulated system was intentionally made compact, with a blocking fraction of only about 50%. Nevertheless, the contrast is sufficient to determine the azimuthal and polar angles of the source.

FIG. **19** is a graph showing the angular correlation function, derived from the data of FIG. **18**, as the heavy curve labeled azimuthal=0. The graph shows how the polar angle is related to the ratio R, calculated in this case as the sum of side detector rates divided by the front detector detection rate, for a source at an azimuthal angle of zero degrees. The correlation is smooth and monotonic, and therefore allows the polar angle of the source to be determined from the ratio R directly. Since the curve is monotonic throughout the 0-90 degree range, it provides a unique correlation between R and the polar angle for sources at an azimuthal angle of zero degrees, and also at 90, 180, and 270 degrees by symmetry.

To check for anisotropies, the simulation was repeated but with the source at an azimuthal angle of 45 degrees, or diagonally relative to the detectors as indicated in the inset of FIG. **18**. The thin-line curve of FIG. **19** labeled azimuthal=45 is the angular correlation function for sources positioned, at various polar angles, with an azimuthal angle of 45 degrees. The 45-degree curve also applies at azimuthal angles of 135, 225, and 315 degrees by symmetry. The two curves (azimuthal of zero and 45 degrees) are closely in agreement below about 80 degrees polar, but they diverge at the highest polar angles due to the anisotropic shape of the side and front detectors. In terms of R, the two curves diverge when R is greater than about 3.0. The corrected polar angle can be obtained at any azimuthal angle by interpolation between the two "candidate" values from the two curves shown. The interpolation is performed according to the known azimuthal angle of the source, which was already determined from the side detector data. In this way, the polar angle can be obtained at all angles, with the detector anisotropies corrected to high order.

To consider a specific example, a value of R=1.65, shown by a vertical dashed line, corresponds to a polar angle of 50 degrees as indicated, and is the same for both curves. At polar angles of zero to about 75 degrees, the angular correlation is independent of the azimuthal angle and no correction is needed. At high polar angles of 80-90 degrees, the anisotropy between the two curves is still relatively small, due to the low slope of the curves in that region, and results in at most a 4-degree variation in polar angle as the azimuthal angle is changed, which is sufficient for many applications. For other applications requiring higher precision, the anisotropy can be corrected by weighted averaging between the two curves according to the previously-calculated azimuthal angle. The weighted average thereby provides a precise value for the polar angle throughout the range of 0 to 90 degrees polar. Furthermore, with the addition of a back detector, the same method can locate a source in a full 4π solid angle coverage (azimuthal=0-360, polar=0-180), from data acquired at a single orientation of the system.

FIG. **20** is a perspective sketch, partly hidden, of an exemplary hand-held survey meter **2001** that can determine the direction of a source in two dimensions. The meter **2001** may include a system **2000** (hidden lines in dash) such as that of FIG. **1**, and a handle **2002** and a display **2003** controlled by a processor **2005**. A camera **2013** is shown mounted on the meter **2001** and configured to generate images of the inspection scene. Typically, the operator holds the meter **2001** at some orientation, waits for a brief integration time, and then views the display **2003** which indicates the source location. In a first embodiment, the display **2003** can graphically show the calculated azimuthal and polar angles of the source (if present), and the operator can then rotate the meter **2001** into alignment with the source if desired. The operator can rotate the meter **2001** in the azimuthal direction as indicated in the display **2003**, and can rotating more quickly or farther if the polar angle is large. The operator can stop rotating when the display **2003** indicates that the meter **2001** is aimed directly at the source. Thus the meter **2001** can enable rapid convergence to a source location by determining, and displaying, both the azimuthal and polar angles of the source in real time.

In a second embodiment, the display **2003** shows an image acquired by the camera **2013**, with the source location indicated by an overlay for example, or a heat map or other graphical indicator positioned on the image according to the azimuthal and polar angles, so as to be correctly registered relative to items in the image. The image **1003** can thereby show which item in view contains the source. As before, the operator may wish to rotate the meter **2001** until aimed directly at the source, by rotating in the direction indicated by the icon on the image **2003**.

In a third embodiment, the camera **2013** may be configured to redirect its viewpoint so that the calculated source location is centered in the image **2003**. This option may be most convenient for fixed-site inspections as opposed to portable applications. With the image **2003** so adjusted, the camera **2013** can zoom in or out, producing either magnified or wide-angle views of the scene, while remaining centered on the calculated source location.

In some embodiments, the meter **2001** may have a light emitter **2007** that can emit a light beam **2006**, which can be configured to indicate the azimuthal and polar angles visually as well. In a first version, the light beam **2006** may be aligned with the detector axis, thereby indicating where the meter **2001** is aimed. When the meter **2001** has been rotated into alignment with a source, the light beam **2006** thereby indicates where the source is found. The beam shape may be

modified to indicate where the source is located, such as a wedge-shaped or arrow-shaped beam spot pointing toward the source. Alternatively, the beam **2006** may be redirected, using an optical beam deflector for example, to shine in the direction of the source according to the calculated polar and azimuthal angles. In that case, the beam spot may illuminate the source location, thereby visually showing the operator where the source is located. In addition, the beam **2006** may be caused to dwell persistently on the source location, regardless of any changes in the orientation of the meter **2001**, by sensing those changes (using a compass for example) and correcting the beam direction accordingly. Thus the light beam **2006** may seem to be "locked on" to the source, thereby providing inspectors with a compelling visual indication of the source location. In addition, the light beam **2006** may also be flickered or otherwise modulated to further enhance visibility. The azimuthal and polar angles, and therefore the location of the beam spot, can be updated continuously or periodically as the meter **2001** is moved around. The shape of the beam **2006** may be adjusted, using further optical elements for example, to indicate the uncertainties in the polar and azimuthal angles.

In some embodiments, the meter **2001** may have four haptic indicators **2008** (two showing) mounted on the handle **2002**. The haptic indicators **2008** may be activated according to the calculated azimuthal angle, thereby indicating to the operator tactically in what direction the source is located (for example, the right-side haptic indicator **2008** may be activated if the source is to the right). The haptic indicators **2008** may also be modulated so as to indicate the magnitude of the polar angle (for example, being modulated faster if the polar angle is large, and more slowly if the polar angle is small, or vice-versa). Also, when the detector axis is brought into alignment with the source, the haptic indicators **2008** may be activated in a characteristic way, such as all four haptic indicators **2008** being pulsed at once, or in a circular sequence, or otherwise indicate that the detector axis is aligned with the source. This would inform the operator of the source direction and the source alignment without the operator having to look away from the scene.

In some embodiments, the meter **2001** may include a wearable personal safety device **2011** comprising a multi-axis accelerometer **2015** and a radio transmitter **2014** which may be in communication with a transceiver **2004** in the meter **2001**, or with an external receiver for example. The operator may wear the personal safety device **2011** using, for example, a belt clip or lanyard or other demountable attachment. Then, if the operator falls or otherwise is in trouble, the multi-axis accelerometer **2015** may detect a change in orientation and cause the transmitter **2014** to send a help request message. Thus the personal safety device **2011** is configured to transmit a message when an operator of the meter **2001** falls down.

FIG. **21**A schematically shows an exemplary flat-screen display **2103**, such as the display **2003** of FIG. **20**. The exemplary display **2103** may be configured to show the visible-light or infrared image of the inspection scene, which in this case assorted cargo **2109**, with the source location indicated by an overlay **2199** as described above. The camera in this case is configured to adjust its aiming direction or view, so as to center the image **2103** on the source location (when a source is present). Therefore the cargo **2109** is shown off-center and the source location indicator **2199** is shown at the center of the image **2103**. When no source is present, a different overlay, or other indicator, or no indicator, may be displayed. Alternatively, or in addition, the image **2103** may include peripheral text or data **2104** indicating, for example, whether a source has been detected as well as other information.

FIG. **21**B shows a second exemplary display **2153** in which the source angles are indicated explicitly. The display **2153** can include a rotatable asymmetric icon **2151** (such as an arrow or wedge icon) which points at an angle **2158** corresponding to the azimuthal direction of the source relative to the detector axis. The icon **2151** may also be configured with a length **2154** or other feature that indicates the size of the polar angle. The operator can then see from the shape and orientation of the icon **2151** where the source is located, and also how to move the system to bring the detector axis into alignment with the source. In addition, when the detector axis is aligned with the source, a non-directional icon **2155** (such as a circle) can be displayed or prominently modulated instead of the directional icon **2151**. Two other widgets **2156** and **2157**, such as bar displays and graphical alarms, can indicate other information such as the current radiation level or the integrated dose received or the presence of neutrons in the detected radiation. Further numerical or text information **2152** may also be displayed, such as the GPS coordinates, the accumulated dose, numerical values of the source angles, and the like.

As a further option, a portable system may have a plurality of LED's or other lamps arranged in a shape, such as a circle, and illuminated according to the azimuthal angle of the source, thereby indicating to the operator in what direction the source is located. The LED's can be flickered or their intensity adjusted to indicate the size of the polar angle, for example. And when the system is aligned with the source, the LED's may be illuminated in a characteristic way, such as all-on. If no source is detected, they may be all-off.

FIG. **22**A is a perspective sketch showing how an exemplary survey meter **2201**, such as that of FIG. **20**, containing a directional detector system **2200** such as that of FIG. **1**, may detect and expose a nuclear weapon **2299** within a shield **2298** within a refrigerated steel shipping container **2209**. An adversary has selected a refrigerated container **2209** to avoid detection since the frozen food that fills the container **2209** provides additional shielding, and also the thermal insulation of the container **2209** can conceal additional radiation shielding. In addition, any secondary inspection would be very difficult to perform when the container **2209** is tightly packed with frozen stuff. Despite these evasions, the meter **2201** has successfully detected the small amount of gamma ray or neutron radiation that escaped from the shield **2298**, and has calculated the azimuthal and polar angles of the source **2299** relative to the detector axis **2208**, and has indicated the source location on the display **2203**, and has projected a light beam **2206** directly at the source direction, thereby exposing the threat.

FIG. **22**B is an exemplary sketch of the display **2203** of FIG. **22**A. Shown is the inspection container **2209** with the detected source indicator **2299** shown as an elliptical density map. The processor in this case is configured to calculate the uncertainties in the azimuthal and polar angles, based for example on the number of counts in the various detectors and/or on prior calibrations of the system. At the position of the source, the polar angle corresponds to the horizontal direction and the azimuthal angle corresponds to the vertical direction. The processor is further configured to render the source indicator ellipse **2299** with axes proportional to the uncertainties in the azimuthal and polar angles. The uncertainty in the polar angle is larger than the uncertainty in the azimuthal angle in this case, due perhaps to having fewer counts in the front detector. Accordingly, the horizontal axis

of the ellipse **2299** is shown larger than the vertical axis, thereby indicating to an operator the region over which the source is likely to be found, as well as the uncertainties in the source angles. As further data are accumulated, the uncertainties may be reduced, and the displayed ellipse **2299** may be adjusted in position and reduced in size accordingly.

FIG. **23** is a notional sketch in perspective and partially cut-away, of an exemplary pedestrian scanner array to scan people **2309** passing through a walkway or hallway or other passageway, such as an airport or border crossing, where large numbers of people are to be scanned continuously for radiation sources. The walkway is demarked by a floor **2302** and a ceiling **2312**. Above the ceiling **2312**, numerous copies of the present system **2300** may be arranged pointing downward, while another set of the systems **2301** can be arrayed below the floor **2302** and pointing upward. One of the people **2309** has foolishly swallowed a source **2399** comprising a piece of SNM (special nuclear material) for clandestine transport, using his body as a neutron shield. However, the systems **2300** and **2301** have detected and localized the source **2399** as indicated by arrows. While each system **2300** or **2301** may detect just one or two extra particles, the combined data from all the systems **2300** and **2301** can detect and localize the source **2399**, and determine the direction and speed of travel. Security cameras **2303** can simultaneously record the scene so that the person carrying the source **2399** can be uniquely identified by correlating the images with the directional data from the systems **2300** and **2301**. For example, the location of the source **2399** can be determined according to the azimuthal and polar angles observed by the various systems **2300-2301**, and can be superposed on images from the cameras **2303** to indicate which pedestrian **2309** is carrying the source **2399**. The systems **2300-2301** may be configured to acquire detection data periodically, such as once per second, and to calculate a direction toward the source including the polar and azimuthal angles periodically, and to thereby determine the location of the source at a succession of times. Alternatively, the data from each of the side and front detectors of each of the systems **2300-2301** may be routed to a central computer and analyzed together using, for example, a maximum-likelihood moving-source model with variable speed and direction. Such a global fit may achieve greater sensitivity and accuracy than provided by each system **2300-2301** individually.

FIG. **24** is a notional sketch in perspective, partly cut-away **2402**, of an exemplary mobile area radiation scanner **2401** such as a trailer or van, incorporating an array of the present systems **2400**, according to some embodiments. Preferably the systems **2400** are of the double-ended type as shown in FIG. **10**, which simultaneously scan for hidden sources on both the left and right side while the mobile area scanner **2401** is either stationary or in motion. The systems **2400** may be spaced apart to minimize mutual shadowing, although this may not be a major concern because a hidden source is unlikely to be buried in the road in front of the mobile area scanner **2401**. However, if a weapon really is hidden in the roadway, the lowest rank of systems **2400** can detect the threat when the mobile scanner **2401** passes over it.

The systems **2400** may be configured for gamma ray detection or neutron detection according to some embodiments. Alternatively, some of the systems **2400** may be of each type for simultaneous scanning of both gammas and neutrons, using pulse-shape discrimination for example. Very high sensitivity can be obtained by analyzing the several systems **2400** together, so that a weak or well-shielded source can be detected even when each individual system **2400** detects only one or two particles above background. The array as a whole can yield a statistically significant increase, consistent with a particular source direction. The motion of the area scanner **2401** can provide a range of viewpoints as it travels through the area, so that a source can be localized in three dimensions by triangulation, or alternatively by fitting the detection data to a source model, or other suitable analysis. Optionally, a sheet of scintillator **2405** (such as plastic scintillator) may be mounted on the ceiling to reject cosmic rays according to some embodiments.

FIG. **25** is a sketch of an exemplary drive-through vehicle inspection station comprising two side columns **2502** and a central column **2504** according to some embodiments. Each side column **2502** may contain an array of systems **2500** such as that of FIG. **1**, while the central column **2504** may contain an array of the double-ended detection systems **2501** such as that of FIG. **10**, to scan both sides simultaneously. A first truck **2508**, which does not contain a threat, and a second truck **2509**, which contains a shielded nuclear weapon **2599** mounted near the ceiling, are being scanned simultaneously. Radiation escaping from the shielded weapon **2599** is detected in the systems **2500** and **2501**, which then calculate the direction of the weapon **2599** relative to each system **2500** and **2501**. The calculated directions are indicated by arrows. Using data from the entire array, a central computer can use triangulation to determine the exact three-dimensional location of the weapon **2599**.

FIG. **26** is a sketch of an exemplary drive-through vehicle and cargo scanner configured to detect nuclear material both by radiation detection and by cosmic ray scattering. Cosmic rays, primarily GeV-level muons from the sky, scatter in a characteristic way in the high-Z material of a nuclear pit and its high-density shielding. Thus the facility includes an overhead muon tracking chamber **2602** and an underground tracking chamber **2603** that, together, detect high-angle scattering of cosmic rays, and thereby detect nuclear weapon materials. The upper chamber **2602** measures the track of a cosmic ray before it enters the inspection zone, and the lower chamber **2603** measures the track after passing through the inspection zone. Thus the tracking chambers **2603** and **2602** can detect a weapon or its shield by measuring the difference in track directions above and below the inspection zone.

The facility further includes an array of directional systems **2600**, such as that of FIG. **1**, above the upper cosmic ray tracker **2602**, and second array of the directional systems **2601** under the lower cosmic ray tracker **2603** and pointing up. The detector systems **2600-2501** can detect and localize a threat **2699** in a truck **2609** by radiation detection, while the cosmic ray trackers **2602-2603** detect the threat **2699** by scattering. Advantageously, the detector systems **2600** and **2601** may be positioned outside the cosmic ray tracking chambers **2602-2603** to avoid causing additional scattering of the cosmic rays. In addition, the cosmic ray tracking chambers **2602-2603** generally comprise light, thin, low-Z materials such as aluminum tubing, through which gamma rays and neutrons readily pass. Thus the two inspection systems avoid interfering with each other, while both systems scan for nuclear contraband.

Synergy is a big advantage of the combined inspection. If an adversary tries to reduce the emitted radiation signature by adding more shielding around the weapon **2699**, the cosmic ray scattering signature is increased and the weapon can be more easily detected by the tracking chambers

2602-2603. And if the adversary tries to reduce the cosmic ray scattering signature by reducing the amount of shielding, the directional systems **2600-2601** can more easily pick up the radiation. Thus the combination of the two detection modes leaves an adversary with no design space for avoiding detection.

FIG. **27**A is a sketch in perspective of a room containing an exemplary directional radiation monitor **2700** according to the present disclosure, mounted on the ceiling of the room **2707**. The monitoring is necessary because the room **2707** is a passage between a laboratory doing nuclear research and the outside world, as indicated by two doors labeled "to lab" and "exit" respectively. The room **2707** thus comprises a passageway that people can pass through to go into and out of the laboratory. The monitor **2700** may be configured to detect radioactive contamination, pilfering, and other problems by detecting a radioactive source nearby and measuring its location versus time.

FIG. **27**B is a top-view sketch of the room **2707** of FIG. **27**A, showing the "to lab" and "exit" doors as well as the directional monitor **2700** from the top. Also shown is a shelf **2708** containing tools that workers can access. In the depicted example, a radiation event has occurred involving an unexpected radiation signature in which the detection rates increased and then decreased, just as if someone had taken a source from the lab to the exit door. If a non-directional detector had reported this incident, it would have appeared to be pilferage. But with the directional monitor **2700**, an entirely different explanation emerged. The dashed lines **2711** show the trajectory of the source as measured by the directional monitor **2700**, as a worker moved through the room **2707**. The monitor **2700** was configured to detect radiation and to calculate the azimuthal and polar angles of the source of radiation periodically and to record those values in non-transient memory, thereby localizing the source in two dimensions at a large number successive times. From that data, the correct interpretation of the event was determined. A worker came into the room **2707** from the lab, selected a tool from the shelf **2708**, and returned to the lab. Thus no pilferage occurred at all. Instead, a more serious problem was exposed, namely that the worker had been contaminated by radioactive material, and that is why the directional monitor **2700** registered radiation. By recording source directional information in real-time, the directional monitor **2700** enabled inspectors to determine the correct cause instead of a false alarm, and more importantly to assist the contaminated worker.

FIG. **28**A is a sketch of an exemplary drone-mounted directional radiation inspection system. A drone is a remotely-operated or autonomous or semi-autonomous unoccupied airborne vehicle such as a gasoline-powered model airplane, a battery-powered multi-rotor helicopter, a propeller-driven or jet-powered airplane, a hovercraft, a balloon or blimp or other lighter-than-air vehicle, or other unoccupied airborne craft. A directional detector system **2800** according to the present disclosure is mounted under a small battery-operated radio-controlled aircraft or drone **2811**. An arrow **2812** indicates a frontward direction. A down-facing camera **2803** is also shown. Inside the drone **2811** is an electronics package **2813** comprising a GPS receiver or an electronic compass or an altimeter or a 3-axis accelerometer or a digital processor or other electronics. The directional detector system **2800** is configured to detect radiation from a source in an inspection region which is generally below the drone **2811**, such as on the ground, on a roof, in a smokestack, or on a ground vehicle (such as a car, truck, train, boat, etc.) and to measure the polar and azimuthal angles of the source relative to the drone **2811**, and to determine a direction toward the source in two dimensions such as the polar angle relative to the vertical, and an azimuthal angle relative to the frontward direction **2812**. The drone **2811** may be further configured to acquire an image of the inspection region using the camera **2803**, and the electronics package **2813** may be configured to add an icon to the image according to the azimuthal and polar angles as determined by the directional detector system **2800**, thereby indicating where in the inspection region the source is located. The image, including the source location icon, may be transmitted wirelessly to a receiver elsewhere.

In addition, the electronics package **2813** may be configured to determine the location of the source in geographical coordinates. First, the electronics package **2813** may determine the frontward direction **2812** of the drone **2811** relative to magnetic north or true north or other external coordinate system, using a compass for example, and the altitude of the drone above the ground using a laser altimeter for example. The electronics package **2813** may be further configured to add the orientation angle of the drone **2811** to the azimuthal angle determined by the directional detector **2800**, and thereby calculate the angle of the source relative to the external coordinate system. The electronics package **2813** may be further configured to determine the altitude of the drone **2811**, and to calculate the horizontal distance of the source from the drone according to the altitude and the polar angle as determined by the directional detector system **2800**. Then, using the drone coordinates (from GPS for example), and the horizontal distance of the source, and the angle of the source relative to the geographical coordinates, the electronics package **2813** may calculate the coordinates of the source, and transmit them to a ground-based receiver. Thus the drone-mounted directional detector can indicate the location of the source both pictorially in an image and numerically in geographical coordinates.

FIG. **28**B is a notional top-view sketch of an exemplary drone **2811** including a directional detector system **2800** (under, in dash) and a source **2899**. The azimuthal angle of the source **2899** relative to the frontward direction **2812** of the drone **2811** is indicated as **2851**, and the orientation angle (or bearing) of the drone **2811** relative to north is indicated is the angle **2852**. The directional detector system **2800** may determine the azimuthal angle **2851** and the polar angle (not visible since this is a top view) of the source **2899**, relative to the drone **2811**. The drone **2811** may then determine the angle of the source **2899** relative to true north by adding the orientation angle **2852** to the azimuthal angle **2851**. The drone **2811** may also calculate the horizontal distance **2853** of the source **2899** from the drone **2811** according to the altitude of the drone **2811** and the tangent of the polar angle. Then, using the GPS coordinates of the drone **2811**, the true bearing of the source, and the distance **2853** of the source **2899**, the drone **2811** can thereby determine the geographical coordinates of the source.

Embodiments of the systems disclosed herein can provide many advantages for rapid detection and localization of radiation sources. Embodiments can: (a) determine both the azimuthal angle and polar angle of the source relative to the system, thereby locating the source in two dimensions; (b) determine the source direction using only a single acquisition of detector data at a single orientation of the system, thereby avoiding extensive iteration and rotations; (c) provide high-resolution azimuthal and polar angle determinations for source angles throughout the front half-sphere from the detector axis to the midplane and, with the addition of a back detector, can cover the entire 4π sphere; (d) determine

when the detector axis is aligned with the source by comparing the side detector signals; (e) provide high detection efficiency at low system weight due to the lack of shields and collimators; (f) detect gamma rays, fast neutrons, or slow neutrons by substituting appropriate detector materials; (g) acquire images of the inspection scene and overlay an icon on the image at the source location; and (h) be compact, economical, easy to build, easy to use, and require no exotic/rare/expensive materials. Embodiments may be well-suited for critically important security applications including as a portable survey instrument, a walk-through portal, a fixed-site cargo and vehicle scanner, a mobile area scanner for concealed weapons, an airborne directional radiation sensor, and a two-dimensional room monitor for radiation as well as many others. Advanced radiation detection systems like those disclosed herein will be needed in the coming decades to protect innocent people from the threat of nuclear and radiological terrorism.

The embodiments and examples provided herein illustrate the principles of the invention and its practical application, thereby enabling one of ordinary skill in the art to best utilize the invention. Many other variations and modifications and other uses will become apparent to those skilled in the art, without departing from the scope of the invention, which is defined by the appended claims.

What is claimed is:

1. A system for detecting and locating a radioactive source, comprising:

three or more side detectors positioned symmetrically around a detector axis that extends centrally from the back to the front of the system, each side detector configured to emit signals upon detecting particles from the radioactive source;

a front detector positioned frontward of the side detectors and configured to emit signals upon detecting particles from the radioactive source; and

a processor configured to receive the signals and to execute instructions stored in non-transient computer-readable media, wherein the instructions include calculating the azimuthal angle of the radioactive source based at least in part on detection data of the side detectors, and calculating the polar angle of the radioactive source based at least in part on detection data of the front detector.

2. The system of claim **1**, wherein the instructions further include comparing the front detector detection data, or a function thereof, to the side detector detection data, or a function thereof.

3. The system of claim **1**, wherein the instructions further include subtracting detection data of each of the side detectors from detection data of an oppositely positioned side detector, respectively.

4. The system of claim **1**, wherein the instructions further include calculating a ratio based at least in part on the front detector detection data and at least in part on the side detector detection data, and comparing the ratio to a predetermined angular correlation function that determines the polar angle of the radioactive source.

5. The system of claim **1**, further comprising a back detector, positioned behind the side detectors, and configured to emit signals upon detecting the particles.

6. The system of claim **5**, wherein the instructions further include comparing detection data of the front detector to detection data of the back detector.

7. The system of claim **1**, wherein each side detector is a right prism shape having a triangular cross section.

8. The system of claim **1**, wherein the front surface of each respective side detector is beveled.

9. The system of claim **1**, further comprising a camera configured to indicate the location of the radioactive source relative to one or more objects imaged by the camera.

10. The system of claim **9**, wherein the processor is configured to calculate an azimuthal angle uncertainty and a polar angle uncertainty, and the camera is configured to graphically indicate the azimuthal angle uncertainty and the polar angle uncertainty on an image.

11. The system of claim **1**, further comprising a light beam emitter configured to direct a light beam toward the calculated location of the radioactive source.

12. The system of claim **1**, further comprising a wearable personal safety device configured to transmit a message indicating a health or safety emergency.

13. The system of claim **1**, wherein the personal safety device comprises an accelerometer configured to determine an orientation of the personal safety device relative to gravity, and to determine, based at least in part on the orientation, whether a health or safety emergency exists.

14. The system of claim **1**, further comprising a portable enclosure comprising a handle and a display, wherein the display is configured to graphically indicate the location of the radioactive source.

15. The system of claim **14**, wherein the display is configured to show an image of an inspection region with the location of the radioactive source superposed thereon.

16. The system of claim **14**, wherein the handle includes one or more haptic panels.

17. The system of claim **16**, wherein the haptic panels are configured to produce haptic indications related to the location of the radioactive source.

18. The system of claim **16**, wherein the haptic panels are configured to indicate when the radioactive source is detected.

19. The system of claim **1**, further including at least two cosmic ray detection chambers, each cosmic ray detection chamber being configured to determine a cosmic ray track direction, respectively.

20. The system of claim **19**, further including one or more processors configured to determine a region of enhanced scattering based at least in part on data from the cosmic ray detection chambers, and to compare the region of enhanced scattering to the radioactive source location.

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