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Newman

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(54) **IMAGING RADIATION DETECTOR ARRAY**

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

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Related U.S. Application Data

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(51) **Int. Cl.**
G01T 3/06 (2006.01)
G01T 1/20 (2006.01)

(52) **U.S. Cl.**
CPC ***G01T 3/06*** (2013.01); ***G01T 1/20*** (2013.01); *G01T 1/2002* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,037,105	A	7/1977	Laurer	
4,262,202	A	4/1981	Cusano	
5,880,469	A	3/1999	Miller	
6,392,236	B1	5/2002	Maekawa	
6,566,657	B2	5/2003	Odom	
7,638,776	B2	12/2009	Vydrin	
7,745,800	B1	6/2010	McGinnis	
8,030,617	B2	10/2011	Enghardt	
8,121,248	B2 *	2/2012	Ikhlef	A61B 6/032 378/19
8,143,586	B2	3/2012	Inbar	
9,733,367	B1	8/2017	Derzon	
9,958,561	B2	5/2018	Bellinger	
2003/0226971	A1	12/2003	Chandross	
2008/0191140	A1	8/2008	McDevitt	
2009/0166549	A1	7/2009	Czirr	
2010/0090097	A1	4/2010	Koltick	
2010/0090115	A1	4/2010	Lerch	
2010/0258734	A1	10/2010	McCormick	
2011/0101230	A1	5/2011	Inbar	
2015/0301203	A1	10/2015	Lennert	
2018/0136344	A1	5/2018	Nelson	

* cited by examiner

Primary Examiner — Edwin C Gunberg

(57) **ABSTRACT**

An imaging radiation detection system, useful in detecting and localizing radioactive materials, may include a large number of particle detectors stacked in a two-dimensional array. The array may include protruding detectors interleaved with recessed detectors, in which each detector is oriented in a different direction. The array may have a checkerboard-type arrangement of protruding and recessed detectors. Detection data from the recessed detectors may include a radiographic image indicating the distribution of radioactive sources in view. Embodiments with high detection efficiency and large field of view can rapidly detect and localize even well-shielded threat sources at substantial distances.

20 Claims, 10 Drawing Sheets

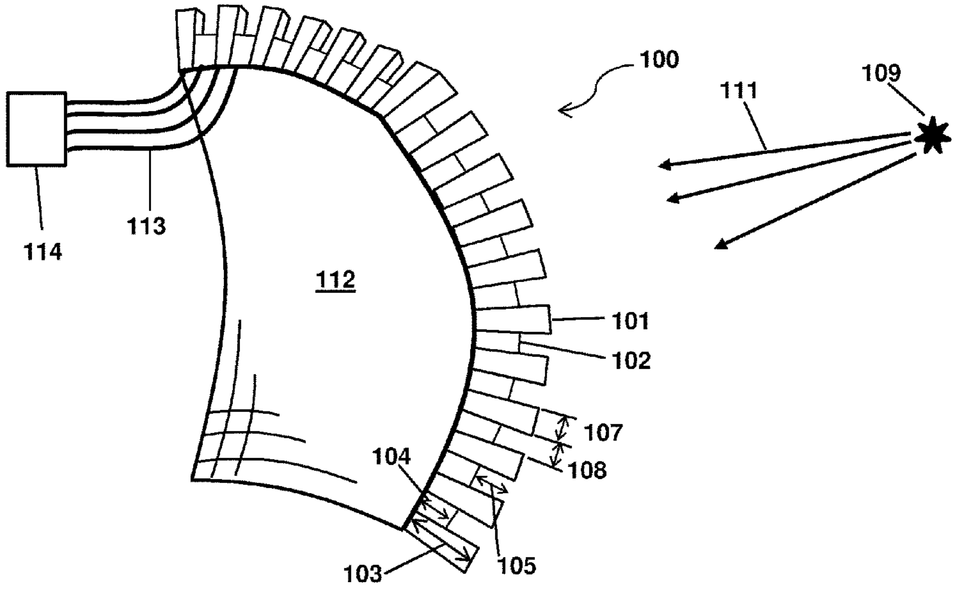
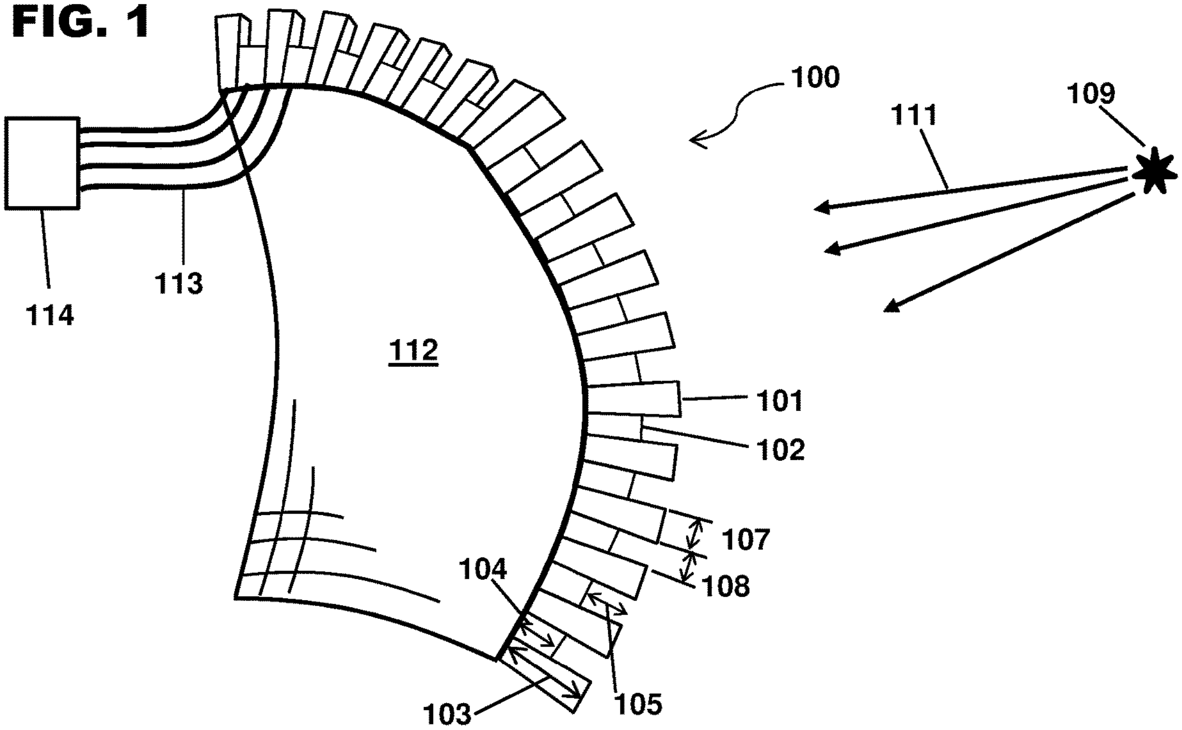


FIG. 1


100
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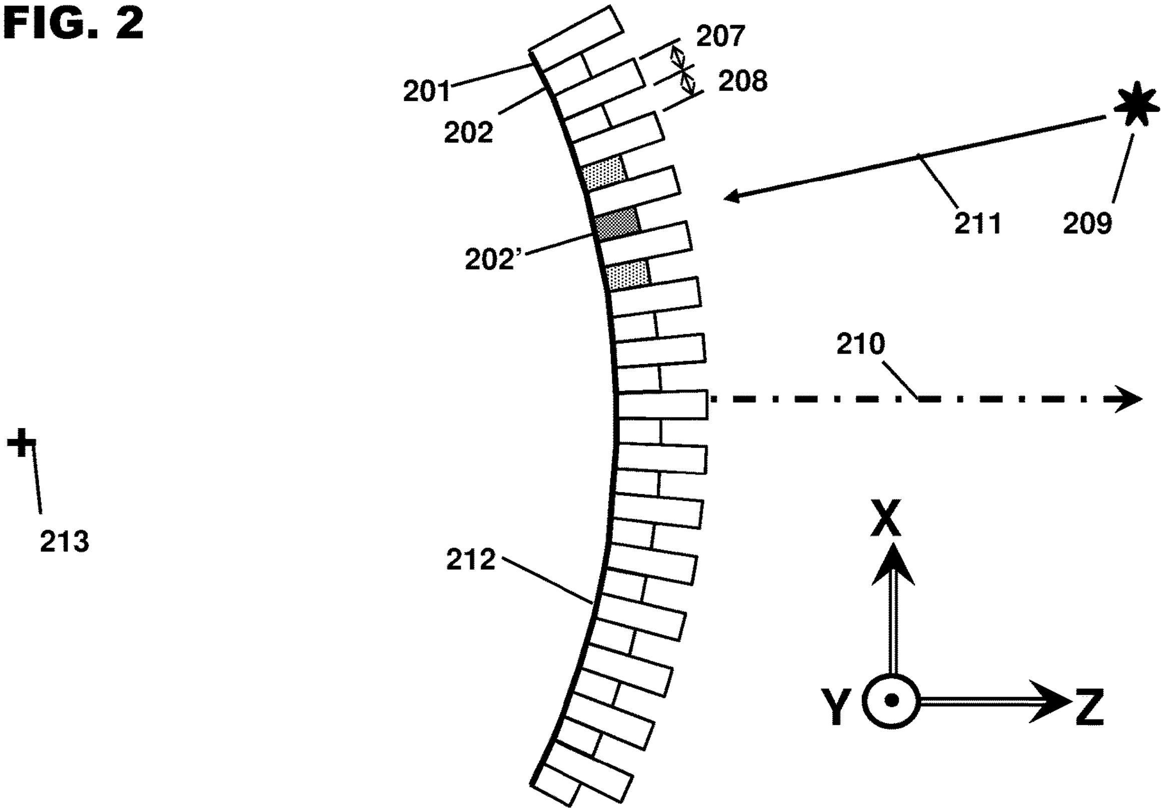
103

FIG. 2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202'
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213
212
X
Y
Z

FIG. 3

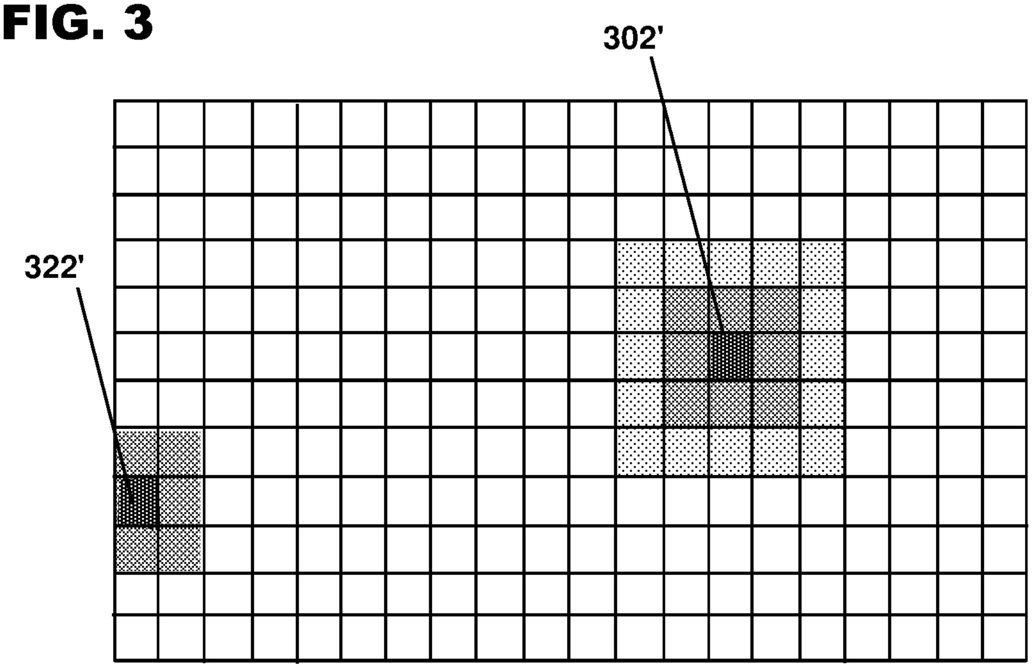


FIG. 4

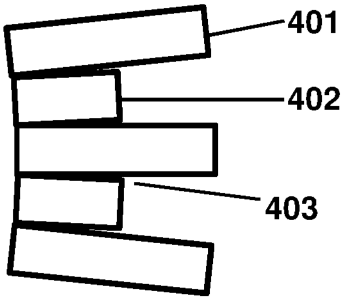


FIG. 5

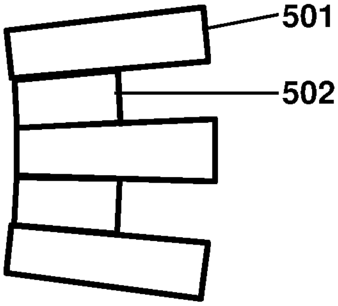


FIG. 6

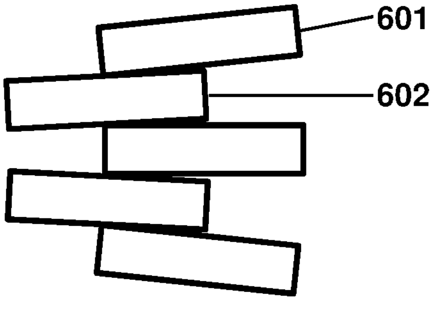


FIG. 7

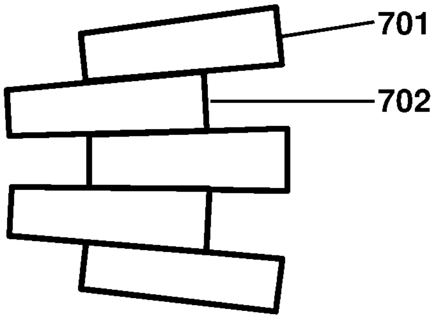


FIG. 8

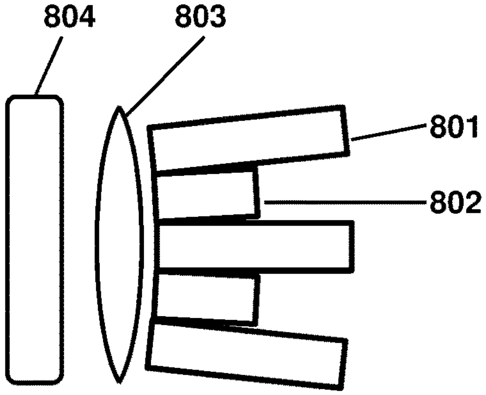


FIG. 9

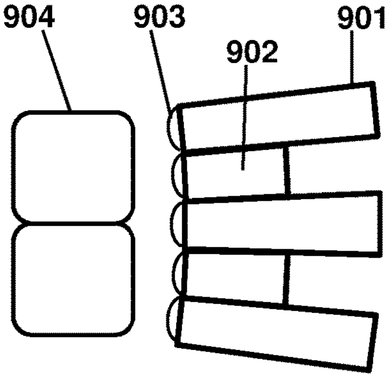
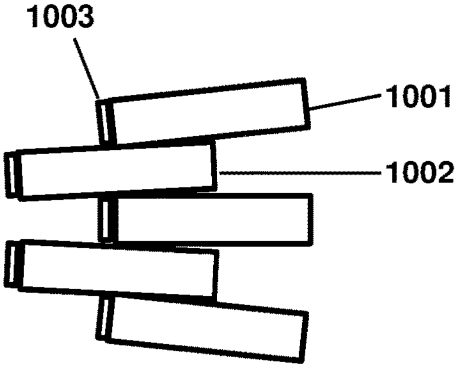


FIG. 10



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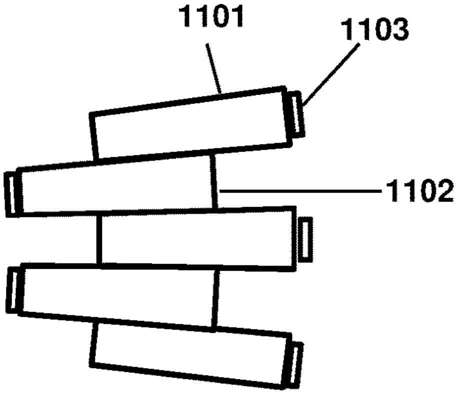


FIG. 12

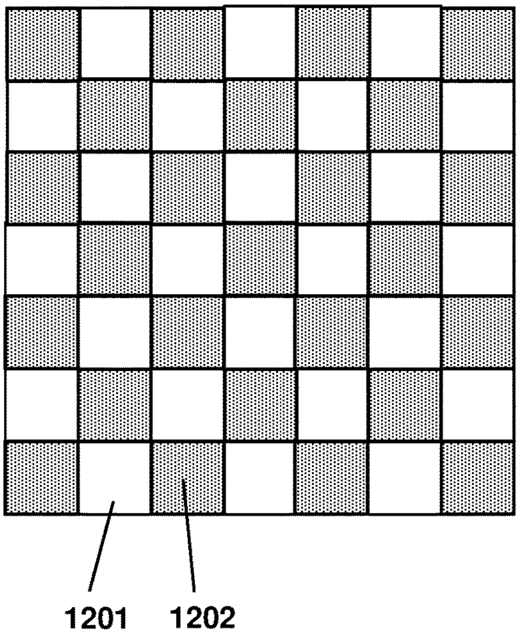


FIG. 13

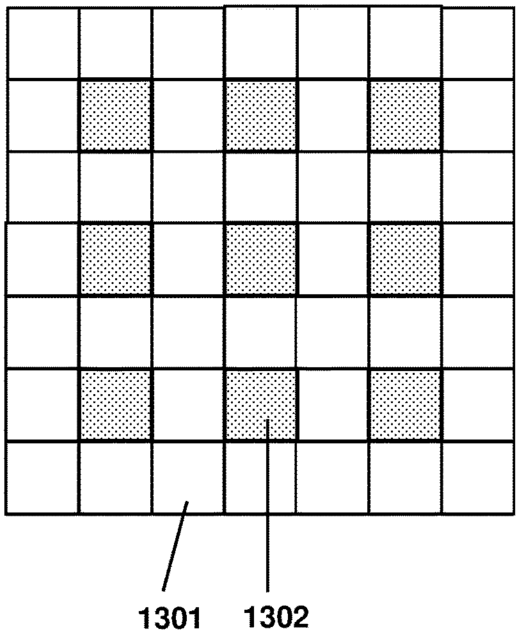


FIG. 14

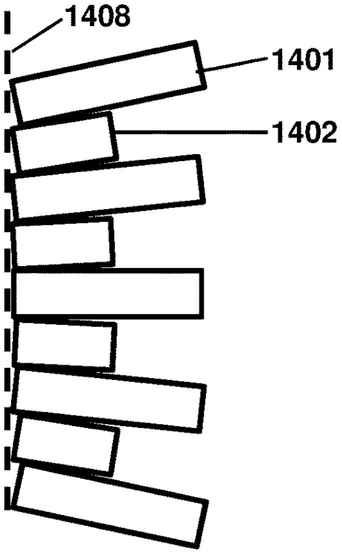


FIG. 15

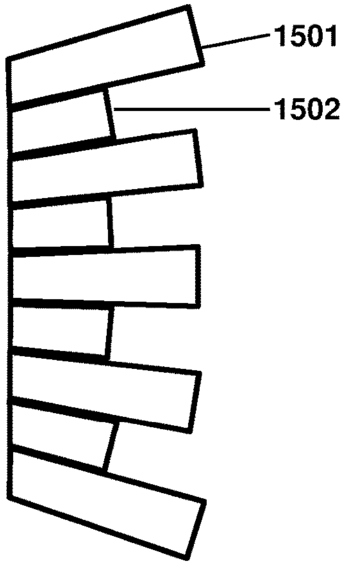


FIG. 16

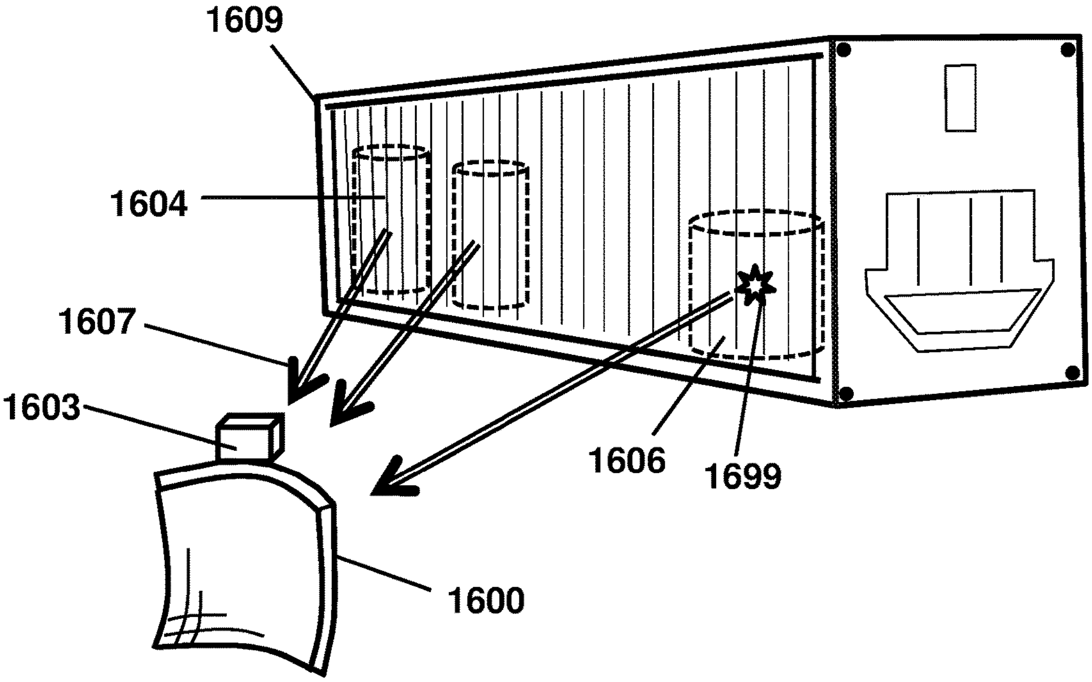


FIG. 17

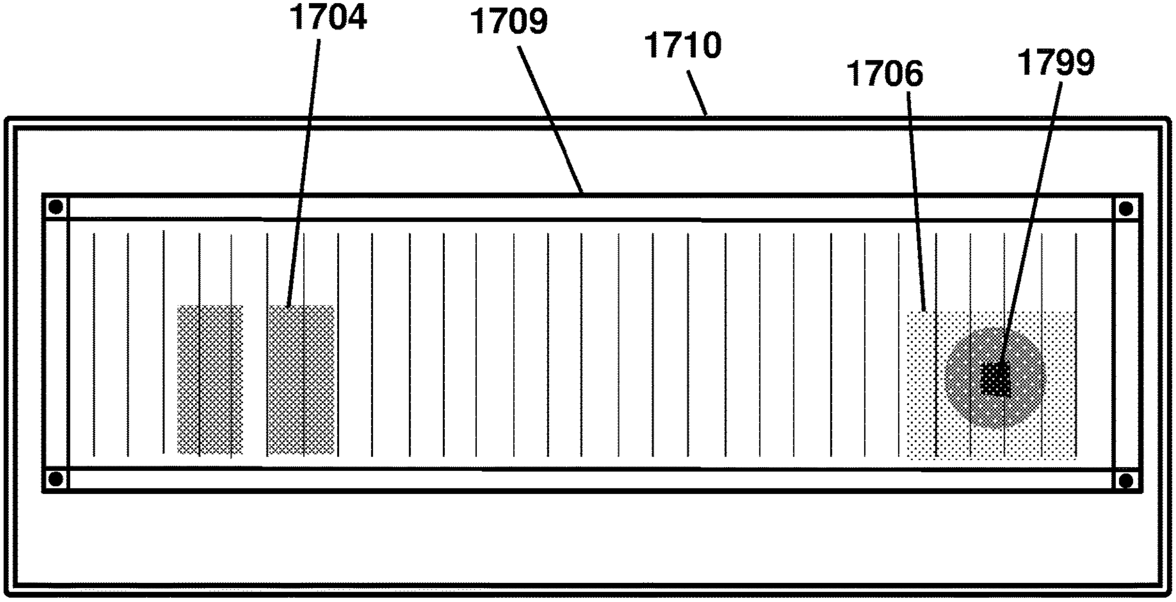


FIG. 18

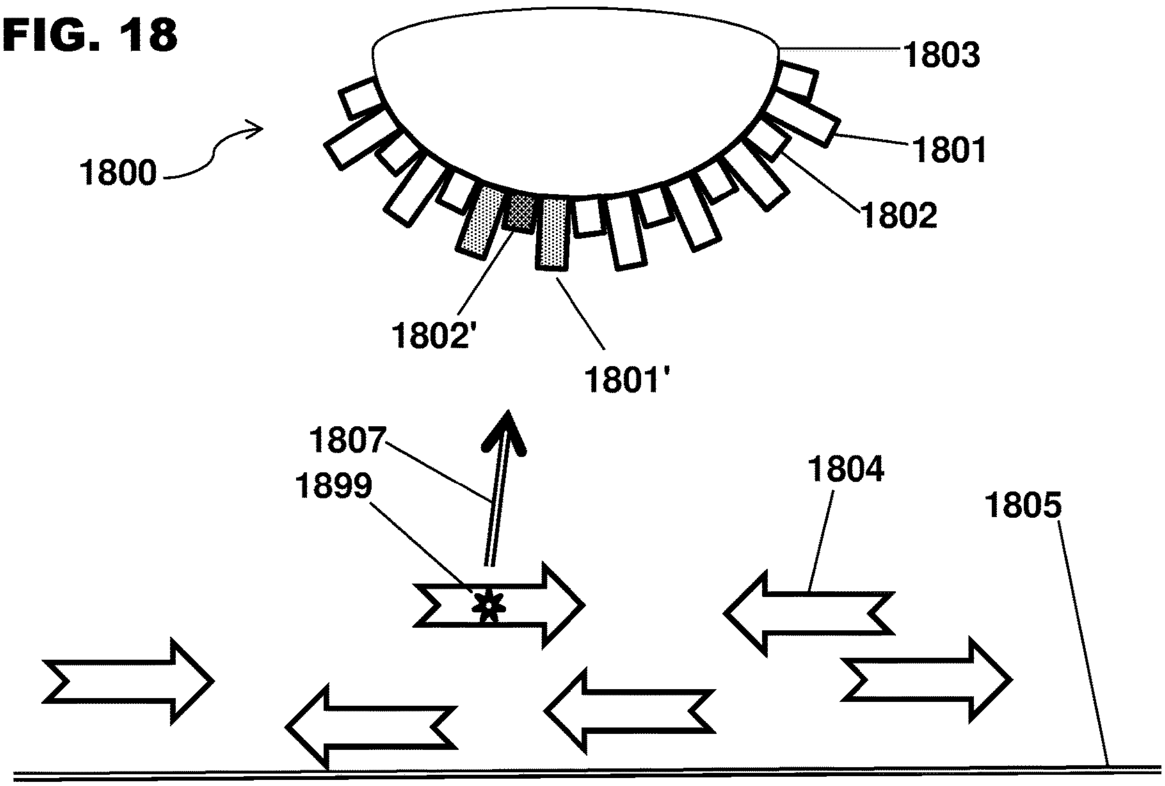


FIG. 19

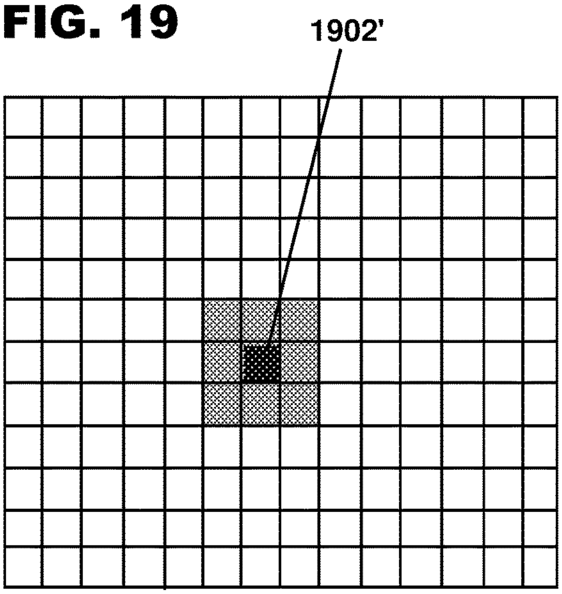


FIG. 20

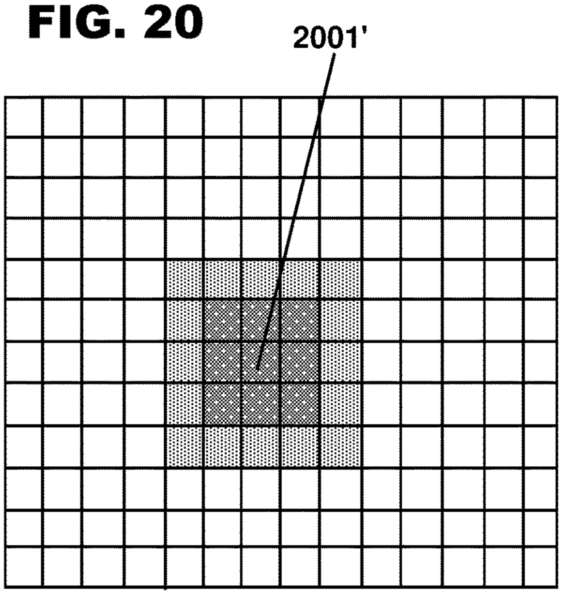


FIG. 21

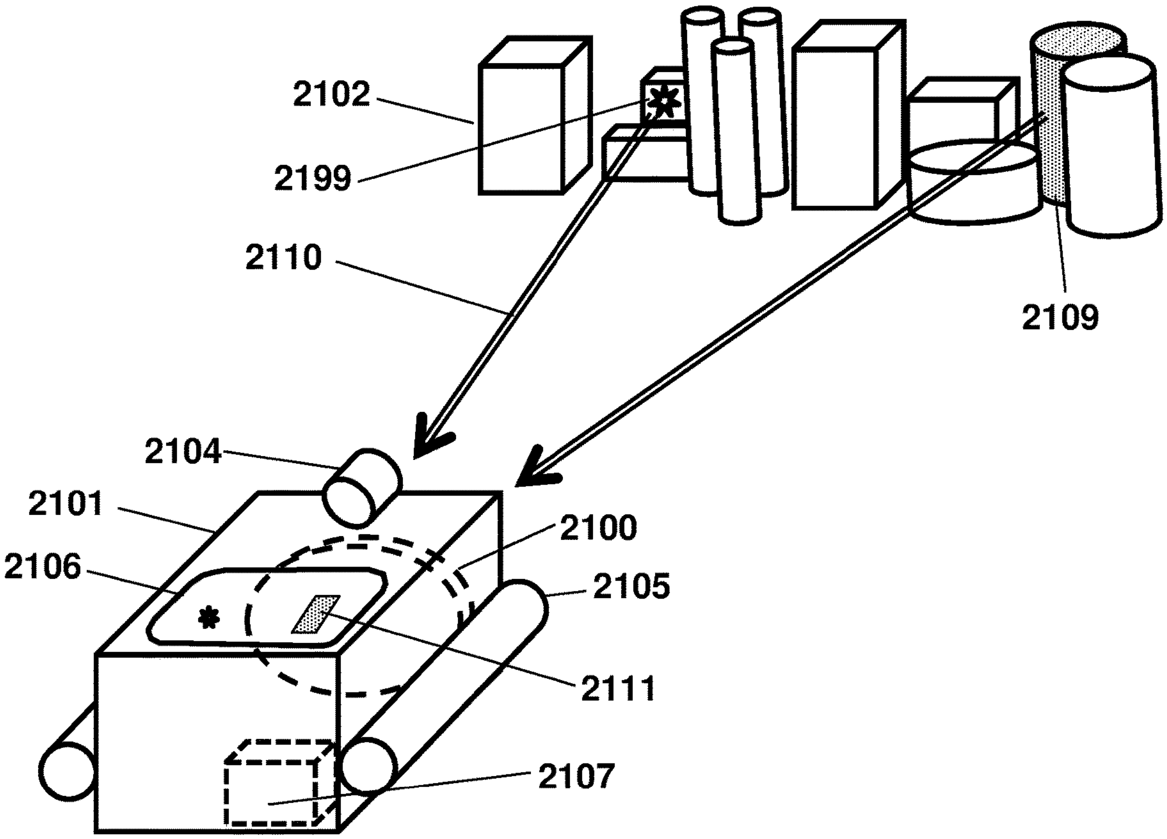


FIG. 22

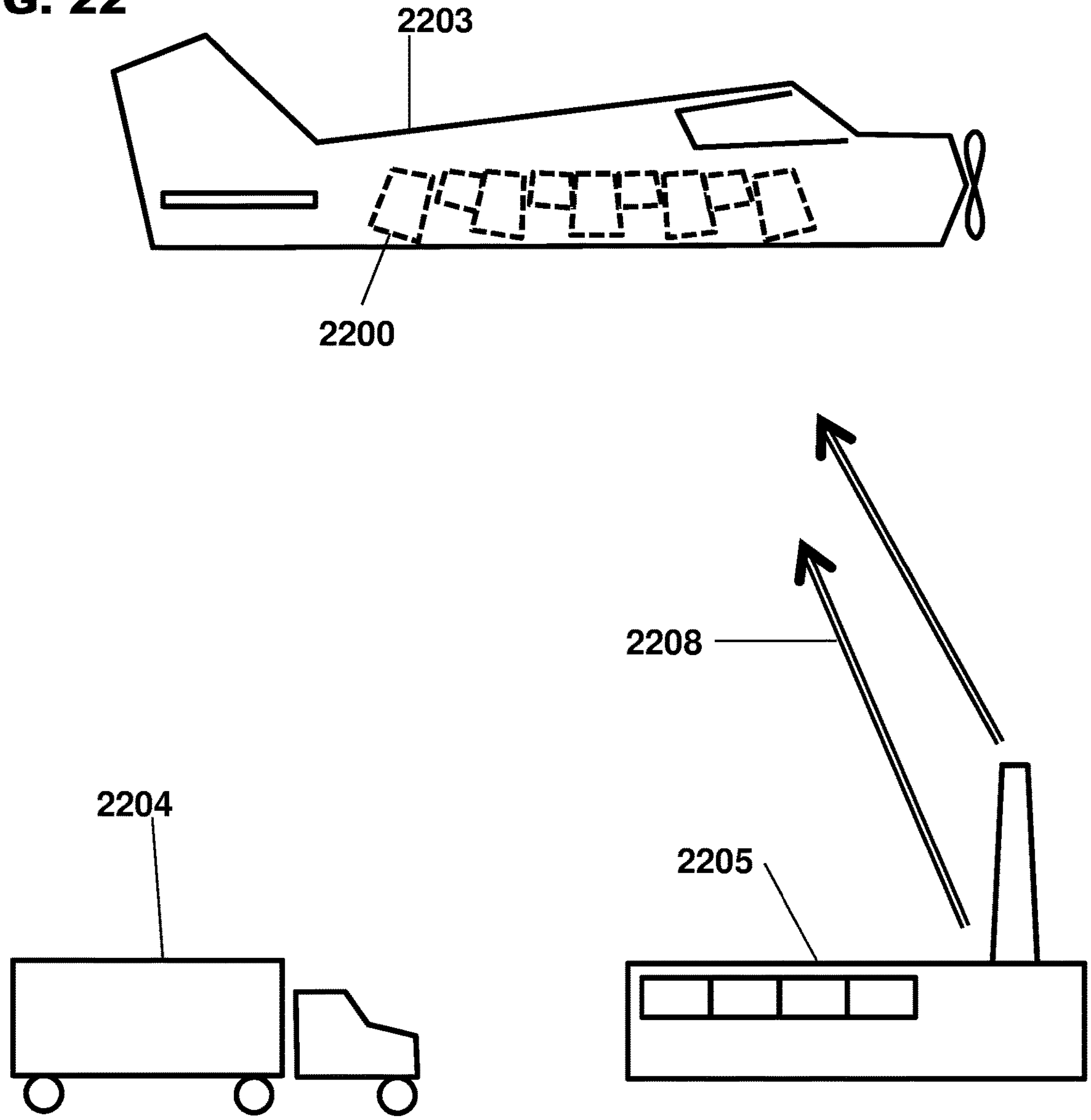


FIG. 23

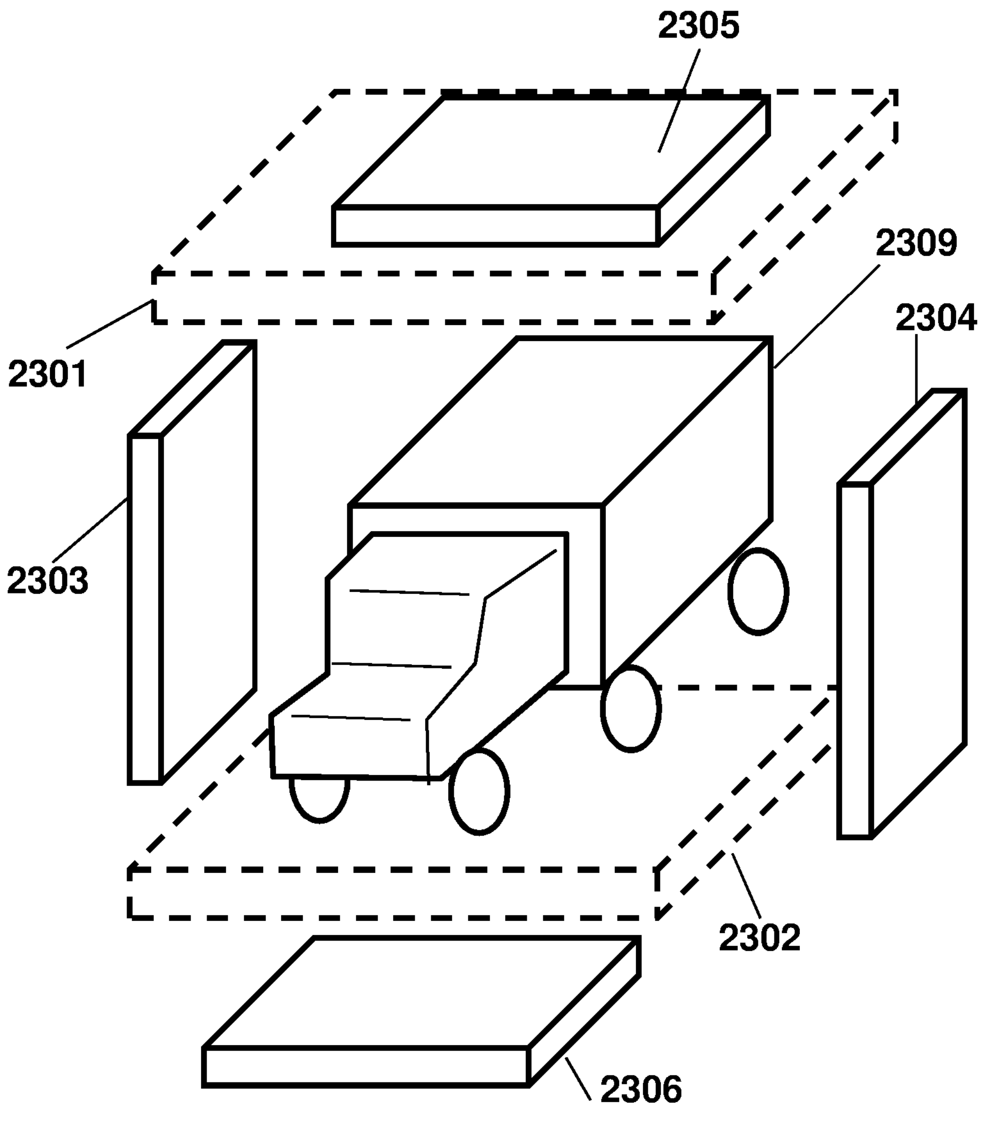
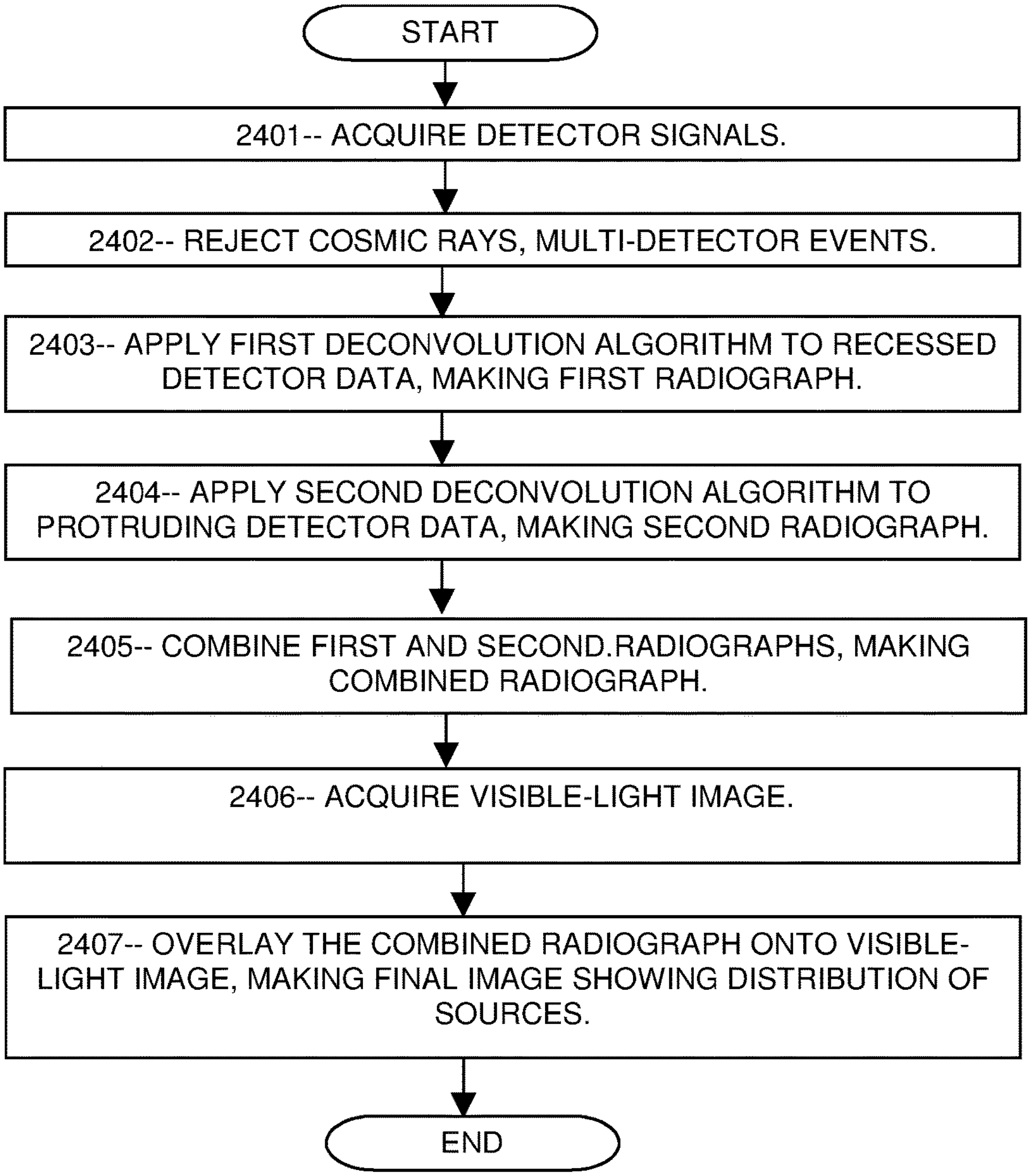


FIG. 24


START
2401-- ACQUIRE DETECTOR SIGNALS.
2402-- REJECT COSMIC RAYS, MULTI-DETECTOR EVENTS.
2403-- APPLY FIRST DECONVOLUTION ALGORITHM TO RECESSED DETECTOR DATA, MAKING FIRST RADIOGRAPH.
2404-- APPLY SECOND DECONVOLUTION ALGORITHM TO PROTRUDING DETECTOR DATA, MAKING SECOND RADIOGRAPH.
2405-- COMBINE FIRST AND SECOND.RADIOGRAPHS, MAKING COMBINED RADIOGRAPH.
2406-- ACQUIRE VISIBLE-LIGHT IMAGE.
2407-- OVERLAY THE COMBINED RADIOGRAPH ONTO VISIBLE-LIGHT IMAGE, MAKING FINAL IMAGE SHOWING DISTRIBUTION OF SOURCES.
END

IMAGING RADIATION DETECTOR ARRAY

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Patent Application No. 62/726,295 filed on Sep. 2, 2018, and U.S. Provisional Patent Application No. 62/787,694 filed on Jan. 2, 2019, and U.S. Provisional Patent Application No. 62/839,673 filed on Apr. 27, 2019, the entire disclosures of which are incorporated by reference as part of the specification of this application.

FIELD OF THE INVENTION

The present invention relates generally to detecting radiation sources. More particularly, the present invention is directed in one exemplary aspect to a radiation detection system that produces an image of radiation sources.

BACKGROUND

The U.S. Congress has ordered that all cargo entering the country must be inspected for clandestine radiological and nuclear materials. Unfortunately, this is still not feasible. Although threat materials emit radiation (principally gamma rays and/or neutrons), sufficient shielding can greatly reduce the amount of escaping radiation. In addition, natural radiation (cosmic rays and radioactive materials in the environment) further complicate detection. In the short time allocated for an entry scan at a shipping port (typically less than 2 minutes and often less than 1 minute), current detectors cannot detect a well-shielded nuclear weapon.

Advanced detectors with large solid angle acceptance and high detection efficiency are needed. In addition, detectors are needed that can determine the spatial distribution of radiation sources so that they can be distinguished from backgrounds. What is needed is an advanced detector or detector array capable of efficiently detecting even a well-shielded source, separating neutrons and gamma rays of various energies, and determining the spatial distribution of radiation sources present. Preferably the detection and imaging may be completed rapidly and automatically, without using expensive or rare materials, and preferably at low cost.

SUMMARY

A system for detecting and imaging radiation sources, includes a detector array with at least 40 detectors, each detector configured to detect particles from the radiation sources and responsively emit a signal, wherein the at least 40 detectors include protruding detectors interleaved with recessed detectors, each recessed detector being adjacent to a plurality of protruding detectors, and each protruding detector protruding beyond the adjacent recessed detectors by an offset distance that is at least equal to the thickness of the recessed detectors; a camera configured to acquire a photographic image of an inspection region; and non-transient computer-readable media containing instructions for a method that includes preparing a first radiographic image according to detection data of the recessed detectors, preparing a second radiographic image according to detection data of the protruding detectors, acquiring the photographic image of the inspection region, and producing a composite image showing the spatial distribution of the radiation sources in the inspection region by combining the first and second radiographic images with the photographic image.

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** is a perspective sketch of an exemplary detector array including protruding and recessed detectors, according to some embodiments.

FIG. **2** is a cross-section sketch of an exemplary detector array including recessed and protruding detectors and a radioactive source, according to some embodiments.

FIG. **3** is a notional sketch of an exemplary image produced by two radioactive sources, according to some embodiments.

FIG. **4** is a cross-section sketch showing how an exemplary detector array can be assembled from rectangular detectors, according to some embodiments.

FIG. **5** is a cross-section sketch showing how an exemplary detector array can be assembled from trapezoidal detectors, according to some embodiments.

FIG. **6** is a cross-section sketch showing how an exemplary detector array can be assembled by displacing two sets of rectangular detectors radially, according to some embodiments.

FIG. **7** is a cross-section sketch showing how an exemplary detector array can be assembled by displacing two sets of trapezoidal detectors radially, according to some embodiments.

FIG. **8** is a cross-section sketch showing how an exemplary detector array can be read out using optics, according to some embodiments.

FIG. **9** is a cross-section sketch showing how an exemplary detector array can be read out using phototubes, according to some embodiments.

FIG. **10** is a cross-section sketch showing how an exemplary detector array can be read out using solid-state sensors on the back of each detector, according to some embodiments.

FIG. **11** is a cross-section sketch showing how an exemplary detector array can be read out using solid-state sensors on both front and back sides, according to some embodiments.

FIG. **12** is a notional front-view sketch of an exemplary detector array showing recessed and protruding detectors in a checkerboard pattern, according to some embodiments.

FIG. **13** is a notional front-view sketch of an exemplary detector array showing recessed and protruding detectors in a centered pattern, according to some embodiments.

FIG. **14** is a cross-section sketch of a portion of an exemplary detector array with a flat or planar shape.

FIG. **15** is a cross-section sketch of a portion of another exemplary detector array with a flat or planar shape.

FIG. **16** is a perspective sketch showing how an exemplary detector array can scan a shipping container, according to some embodiments.

FIG. **17** is a notional sketch of an exemplary image showing multiple radiation sources, according to some embodiments.

FIG. **18** is a notional sketch of an exemplary detector array mounted on a ceiling to scan passing pedestrians for radiation, according to some embodiments.

FIG. **19** is a notional sketch showing an exemplary distribution of detection data in recessed detectors, according to some embodiments.

FIG. **20** is a notional sketch showing an exemplary distribution of detection data in protruding detectors, according to some embodiments.

FIG. **21** is a notional sketch of an exemplary portable radiation imager scanning cargo for radiation, according to some embodiments.

FIG. **22** is a sketch showing an exemplary detector array mounted in an aircraft, according to some embodiments.

FIG. **23** is a perspective sketch showing a vehicle being scanned by multiple exemplary detector arrays, according to some embodiments.

FIG. **24** is a flowchart of an exemplary method of producing a composite image showing the distribution of sources among items in view, according to some embodiments.

DETAILED DESCRIPTION

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 is a system for imaging radiation (the "system"). The system may include an array of detectors (the "detector array") configured to detect gamma rays or neutrons or both (the "particles") from one or more sources of radiation (the "sources") in a spatial or angular region (the "inspection region"), and to responsively transmit signals such as electrical pulses to a processor. The system may further include a camera configured to produce a photographic image of the inspection region, using visible or infrared light (or both) to show items in the inspection region. The processor may be configured to receive the signals from the detectors and produce a radiographic image of the sources, such as a two-dimensional image or rendition showing the distribution of radiation detected from sources in the inspection region. The system may be configured to combine the photographic image and the radiographic image, thereby producing a "composite" image that shows items in the inspection region as well as the distribution of radiation in the inspection region.

In some embodiments, the detector array may have no passive collimators or shields ("passive" meaning material that blocks a substantial fraction of incident particles, such as 5% or 10% of incident particles, and does not emit signals). The detector array may have a front surface and an opposite back surface, and may be configured to produce an image of radiation sources in front of the detector array. Hence, the "inspection region" may be a region in front of the detector array that is viewed by the detectors and by the camera. The detector array may include "protruding" detectors interleaved with "recessed" detectors, wherein the front surface of each protruding detector may be offset toward the front, relative to the front surfaces of the adjacent recessed detectors. Likewise, the front surface of each recessed detector may be recessed toward the back relative to the front surfaces of the adjacent protruding detectors. Each recessed detector may be surrounded by a plurality of adjacent protruding detectors which act as active (i.e., particle-detecting) collimators by blocking particles that arrive from various angles, thereby restricting the field of view of the adjacent recessed detector. For example, the protruding detectors may block particles that arrive at angles higher than a predetermined angle (termed a "cutoff angle") relative to the orientation direction of the adjacent protruding detectors. However, the protruding detectors may allow particles that arrive at lower angles to reach the adjacent recessed detector unhindered, so that the recessed detector's field of view is determined by the surrounding protruding detectors. For example, the tangent of the cutoff angle may be the thickness of the recessed detectors divided by the offset distance. Due to the active collimation, each recessed detector may have an unobstructed view of sources in a limited part of the inspection region, and may be blocked from detecting other particles arriving at angles above the cutoff angle. The processor may be configured to form a radiographic image showing the distribution of radiation sources in the inspection region, in which each pixel is based on the detection data of a corresponding one of the recessed detectors. "Detection data" may include a number or rate of detection events in which the signal exceeds a predetermined threshold, or a current or voltage, or other measure of the interactions of the particles with the detectors. The "composite image" may be an image formed by combining the photographic and radiographic images, such as by overlaying the radiographic data onto the photographic data, or by adding color or brightening or other parameter to the photographic pixels, or otherwise arranging to display the items in the inspection region together with the distribution of radiation detected.

In some embodiments, each protruding detector may have a different orientation direction, wherein the "orientation direction" of a protruding detector is the direction of its longest dimension. The various protruding detectors may have orientation directions that vary in both lateral directions, thereby spanning the inspection region in two dimensions. Each recessed detector may have a different "viewing direction," or field of view, which is determined by the orientation directions of the adjacent protruding detectors. The "offset distance" is the distance between the front surfaces of adjacent protruding and recessed detectors. The "length" of a detector is its longest dimension. The "thickness" of a detector is its smallest dimension, and the "width" is the intermediate dimension. The "central axis" of the detector array is a vector centered in both lateral directions of the detector array, and oriented in the back-to-front direction. A "source angle" is the angle between the central axis and a vector toward a particular source. The "angular sensitivity distribution" of a detector is the range of angles over which the detector is able to receive and detect incoming particles. An "edgemost" detector is a protruding or recessed detector at an edge of the detector array. "Secondaries" are charged particles resulting from an interaction of the particles from the source, such as Compton electrons or photoelectrons or electron-positron pairs from gamma ray interactions, or alpha particles or tritons or other ions from low-energy neutron capture reactions, or recoil protons from high-energy neutron scattering. The "lateral directions" are the two mutually-orthogonal directions perpendicular to the central axis. A "detection peak" is a set of detectors that have high detection rates, usually due to a source being positioned in alignment with those detectors.

In some embodiments, the protruding and recessed detectors may be stacked or assembled or positioned face-to-face in a two-dimensional array. The protruding and recessed detectors may be alternated in a checkerboard pattern, wherein in some embodiments, the "white" squares represent protruding detectors and the "black" squares represent recessed detectors, while in other embodiments the "white" squares represent recessed detectors and the "black" squares represent protruding detectors; other patterns are presented below. The detector array may be arranged in rows and columns along the two lateral directions. In some embodiments, the detector array may include at least 20 protruding and 20 recessed detectors (at least 40 in all), and may have at least 5 rows and at least 8 columns of detectors. In another embodiment, the detectors may be arranged in a hexagonal or honeycomb pattern, in which each recessed detector may be surrounded by 6 protruding detectors. The shape of the detector array may be flat, or curved ("arc-shaped") in one lateral direction such as the surface of a cylinder, or curved in both lateral directions such as the surface of a sphere, or other shape having curvature. The orientation directions of the protruding detectors may span the inspection region in both lateral directions. Accordingly, the recessed detectors, collimated by the protruding detectors, may view the inspection region two-dimensionally, and the processor may form a radiographic image based on the recessed detector data, showing the distribution of sources in the inspection region. In addition, the processor may form a second radiographic image based on the protruding detector data, and may combine the photographic image with one or both radiographic images to produce a composite image that shows the radiation distribution along with items in the inspection region.

Examples are presented for detecting gamma rays and neutrons, but the principles disclosed herein are readily applicable to other particle types as well. In applications involving clandestine radioactive threats, the ability to rapidly determine the distribution of radioactive sources in an inspection region is a major benefit.

FIG. **1** is a perspective sketch of an exemplary detector array **100** according to some embodiments, including protruding **101** and recessed **102** detectors. Each detector **101-102** may be configured to produce signals **113** upon detecting particles **111** from a radiation source **109**, and to covey those signals **113** to a processor **114**. The detectors **101-102** are shown positioned with their adjacent faces substantially in contact; other arrangements are described below. Each detector **101-102** is mounted on a curved surface **112**, which in this case is a portion of a spherical surface with a generally square outline, viewed at an oblique angle from the rear. The protruding detectors **101** are oriented in a variety of directions. The front surfaces of the protruding detectors **101** are offset toward the front (to the right in the drawing) relative to the recessed detectors **102**. Likewise, the front surfaces of the recessed detectors **102** are recessed toward the back by that offset distance **105**. Thus, the offset distance **105** is the distance between the front surfaces of adjacent protruding and recessed detectors **101-102**. Also indicated is the length **104** of the recessed detectors **102** and the length **103** of the protruding detectors **101**. Also indicated is the thickness **107** of the protruding detectors **101**, and the thickness **108** of the recessed detectors **102**. As shown, the detectors **101-102** may have right prism shapes according to various embodiments, where each detector's width and thickness are the same. In other embodiments, each detector **101-102** may have a rectangular, tetragonal, hexagonal, circular, or other type of shape, and the recessed and protruding detectors **101**, **102** may have different thicknesses and widths.

In some embodiments, the protruding and recessed detectors **101-102** may be interleaved, or otherwise placed successively in a two-dimensional pattern, so that each recessed detector **102** is at least partially surrounded by protruding detectors **101**. In the depicted embodiment, the pattern is a checkerboard pattern in which each recessed detector **102** is surrounded by four adjacent protruding detectors **101**, except for the edgemost detectors which are only partially surrounded. Each recessed detector **102** is collimated by the adjacent protruding detectors **101**, since the protruding detectors block or at least partially block particles **111** that arrive from various directions, and in particular, particles that arrive at angles above the cutoff angle relative to the orientation direction of the adjacent protruding detectors **101**. In this case, the cutoff angle is the arctangent of the width **108** of the recessed detectors **102** divided by the offset distance **105**. Each recessed detector **102** has a relatively narrow field of view between the adjacent protruding detectors **101**. Particles from a source that is positioned in alignment with a particular recessed detector may pass between the protruding detectors **101** and may be detected by the particular recessed detector. Particles arriving at larger angles, but less than the cutoff angle, may be partially obscured. Particles arriving at angles larger than the cutoff angle, relative to the orientation direction of the surrounding protruding detectors, are blocked. Thus, each recessed detector **102** views only, or primarily, whichever radiation sources are located within a restricted field of view, which is centered on the orientation direction of the surrounding protruding detectors and has a width determined by the cutoff angle. The amount of radiation detected by each particular recessed detector **102** is therefore related to (usually proportional to) the intensity of radioactive sources in that particular recessed detector's field of view. Taken together, the set of recessed detectors **102** thereby provides detection data spanning the inspection region in two lateral directions, thereby facilitating the generation of a two-dimensional radiographic image showing the distribution of sources in the inspection region.

In some embodiments, the back surface of each protruding detector **101** may be substantially coplanar with the back surfaces of the adjacent recessed detectors **102**, as shown in the figure. "Substantially coplanar" means that the back surfaces of adjacent recessed **102** and protruding **101** detectors are at the same radial position to within a small distance such as 0.1 or 0.2 times the thickness **108** of the recessed detectors **102**.

In other embodiments, the protruding and recessed detectors may be offset from each other in both front and back. For example, the protruding and recessed detectors may have the same length and shape, and the recessed detectors may be simply displaced toward the back relative to the protruding detectors. In that case, the distance between the back surfaces of the protruding and recessed detectors may be equal to the distance between their respective front surfaces, and the offset distance is the same in front and back. Examples are provided below.

In some embodiments, the detectors **101-102** may include a material suitable for detecting the particles and/or their charged secondaries. For example, the detectors **101-102** may include scintillators, semiconductors, and/or gaseous ionization types of detectors. Scintillators may include organic types such as organic crystalline (stilbene or anthracene, for example) or polymer (polyvinyltoluene PVT, for example) or liquid (based on mineral oil or other organic liquid, for example), or inorganic types such as NaI, BGO, LYSO, CsI, $CdWO_4$, $LaBr_3$, and scintillating glass among many other possibilities. For detecting neutrons, the detectors **101-102** may include a transparent matrix such as polycarbonate or polystyrene or acrylic or glass, which may be coated or loaded with a neutron-specific scintillator such as layered ZnS or scintillator microbeads, for example. The ZnS or the scintillator microbeads may contain or be adjacent to a neutron-capture nuclide such as lithium or boron, and may include lithium glass or borosilicate scintillator. Semiconductor detectors may include n-type or p-type reverse-biased junctions such as Si or CZT, optionally including a converter layer of hydrogenous material for neutron scattering, or a neutron-capture material such as boron or lithium, or a high-Z material for gamma conversion (Z being the atomic number). Gaseous ionization detectors may include proportional counters, Geiger tubes, or other gas-filled enclosures configured to collect ionization charges generated by the particles and/or their secondaries. The gaseous ionization detectors may include a converter material, such as a layer or coating of a high-Z material for Compton scattering of gamma rays, or a lithium or boron layer (or BF_3 or ^{3}He gas fill) for neutron capture reactions, or a hydrogenous layer for scattering of fast neutrons, for example. Responsive to detecting the particles, the detectors **101-102** may emit signals **113** such as electronic pulses which may be conveyed to the processor **114** for analysis. The processor **114** may be configured to receive the signals **113** and produce a radiograph or other two-dimensional image showing where the sources of radiation are distributed in the inspection region. The image may further include a visible-light or infrared photographic image showing the items being inspected. An icon or radiation map or other indicator may be added to the photographic image to indicate where the radioactive material is located among objects in the image. Alternatively, the items in the image may be modified by coloration or brightness, for example, to indicate which items are radioactive. The indicator and/or the modification may be configured to indicate the intensity of radiation detected for each direction or each item. For example, it may be colored or shaded according to the detection rate in the particular recessed detectors that view each direction or item. In addition, the indicator and/or modification may indicate the type of particle detected, such as one color for gamma radiation, a second color for low-energy neutron detection, and a third color for high-energy neutrons. The detectors **101-102** and/or the processor **114** may include optical and/or analog electronics to tailor the signals **113** for analysis, such as light sensors for scintillator detectors, amplifiers for semiconductor detectors, as well as transducers, filters, and the like.

In some embodiments, the detectors **101-102** may be configured to detect one particle type and to not detect another particle type, such as detecting neutrons but not gamma rays, or vice-versa. For example, ZnS scintillator is mainly sensitive to the dense tracks of neutron-capture ions and proton-recoil events, and is relatively insensitive to lightly-ionizing particles such as Compton electrons. For gamma detection, many inorganic scintillators such as NaI and BGO are efficient gamma detectors but nearly neutron-blind due to the low neutron-capture rates for the nuclides involved and the lack of recoil protons.

In some embodiments, the detectors **101-102** may be configured to detect two particle types, generating distinct signals. For example, such a detector could emit a first signal upon detecting the ions from a neutron interaction, and a second signal different from the first signal upon detecting electrons from a gamma ray interaction. The detectors may be configured to emit signals indicative of the particle type, such as PSD (pulse-shape discriminating) organic scintillators, or certain inorganic scintillators such as CsI and elpasolites that emit differently shaped pulses for gamma-generated electrons and neutron-generated ions. Alternatively, the processor **114** may be configured to identify neutron capture events in which two separate pulses occur in succession, corresponding to thermalization of the incident neutron, followed microseconds later by emission of neutron-capture ions.

In some embodiments, the processor **114** may be configured to reject events in which a signal **113** corresponds to an energy deposition greater than the maximum energy of the particles being sought. For example, most gamma rays and neutrons from nuclear materials have energies in the range of 1-3 MeV. A cosmic ray, on the other hand, traveling at nearly the speed of light, generally deposits energy at a rate of 2 MeV per gram of material in its path. In a plastic scintillator detector with a thickness **107** of 20 cm and density of 1 g/cm^3, cosmic rays deposit about 40 MeV and thus generate huge pulses, which can be eliminated by an energy cutoff.

In some embodiments, the processor **114** may be configured to reject events in which adjacent detectors fire at the same time or within a time window of, typically, 10-200 nsec depending on the time resolution of the detectors. Rejecting such coincident signals may reduce or eliminate events in which a particle scatters in one detector and then interacts in an adjacent detector.

In some embodiments, the thickness **107** of the protruding detectors **101** may be related to the average interaction distance of the particles **111** in the detector material. The average interaction distance is the distance that the particle **111** travels, on average, before being scattered or absorbed or otherwise interacting detectably with the material. For gammas, the average interaction distance is an inverse mass-attenuation factor. For energetic neutrons, the average interaction distance is an elastic scattering distance. For thermal or epithermal neutrons, the average interaction distance is a (projected) neutron-capture mean free path. In some embodiments, the protruding detector thickness **107** may be at least equal to the average interaction distance of the particles in the detector material. Alternatively, the protruding detector thickness **107** may be 2 or 3 or more times the average interaction distance, for greater blocking of particles and thus higher contrast in the final image.

In some embodiments, the offset distance **105** may be related to the recessed detector thickness **108**. For example, the offset distance **105** may be at least equal to the thickness **108** of the recessed detectors **102**, thereby providing a sufficiently narrow angular field of view of the recessed detectors **102**. In other embodiments, the offset distance **105** may be 2 or 3 or 5 times the recessed detector thickness **108** or more, for improved angular resolution. A higher ratio results in a narrower angular field of view for each recessed detector **102** and therefore a better angular resolution.

The cutoff angle may be determined by the recessed detector width **108** divided by the offset distance **105**. For example, the cutoff angle may equal the arctangent of the width **108** divided by the offset **105**. In a particular case, when the offset **105** is three times the width **108**, the cutoff angle is about 18 degrees. A particular recessed detector **102** is likely to detect particles that arrive at an angle of less than the cutoff angle (relative to the orientation of the surrounding protruding detectors **101**), since those particles are likely to pass between the protruding detectors **101** and may thereby reach the particular recessed detector **102**. In contrast, those particles that arrive at angles larger than the cutoff angle relative to the adjacent protruding detectors are likely to be blocked by the adjacent protruding detectors **101**. Due to the collimation effect of the protruding detectors **101**, the angular field of view of each recessed detector **102** is limited to directions that are within the cutoff angle or less, relative to the elongation direction of the surrounding protruding detectors **101**.

In some embodiments, the lateral dimensions of the detector array **100** may be 0.1 to 0.5 meter to intercept a sufficient fraction of the emitted particles **111**; in other embodiments the detector array lateral dimensions may be 1 meter for a greater solid angle, or 2 or 3 or 5 or 10 or 20 meters or more when needed to scan large objects. In some embodiments, the number of detectors may total at least 25 to provide sufficient spatial resolution, and more preferably at least 40 detectors for a larger total field of view, and may be 200 or 500 or 1000 or more detectors in a large inspection installation. Four exemplary embodiments are presented below for detecting particular particle types.

In a first exemplary embodiment, intended for imaging gamma rays, the detectors **101-102** may include an organic scintillator, such as liquid scintillator or PVT-based plastic scintillator, configured to detect 1-2 MeV gamma rays by Compton scattering. High-energy neutrons may also be detected by elastic n-p scattering. The detector array lateral dimensions may be 2.4 meters by 15 meters, the detector thicknesses **107-108** may be 15 cm, the total number of detectors may be 1600. The offset distance **105** may be 25 cm, thereby providing a detection area of 36 square meters and a weight (not including accessories discussed below) of about 19 tons.

In a second exemplary embodiment, intended for detection of 100-500 keV gamma rays but not neutrons, the detectors **101-102** may include BGO scintillator. The detector array lateral size may be 0.25 meter square, the detector thickness **107-108** may be 1 cm, the total number of detectors may be 625, and the offset distance **105** may be 1 cm, thereby providing a detection area of 625 square cm and a total weight of about 8 kg.

In a third exemplary embodiment, for detection of neutrons, the detectors **101-102** may include a PMMA (polymethylmethacrylate) matrix loaded with scintillating microbeads containing ZnS or other scintillator, along with lithium or boron neutron-capture targets, and configured to detect slow neutrons by capture as well as fast neutrons by moderation and capture. Alternatively, the detectors **101-102** may include a PSD organic scintillator with a fluor that produces different pulse shapes for electrons and ions, thereby selecting neutron interactions. In either case, the detector array lateral size may be 4×20 meters, the detector thickness **107-108** may be 10 cm, the total number of detectors may be 8000, the offset distance **105** may be 20 cm, with a detection area of 80 square meters and a weight of about 20 tons.

In a fourth exemplary embodiment, for detection of low-energy neutrons, the detectors **101-102** may include gaseous ionization detectors with enclosures containing a neutron-capture nuclide, a wire grid at high positive voltage, and a gas that promotes electron drift toward the wire grid when ionized by an energetic particle. For example, the gas may include ^{3}He or BF_3, thereby including neutron-capture nuclides. Alternatively, the walls of the enclosure may be coated with LiF, B_4C, boron metal, or another neutron-capture compound. Other surfaces, such as electrodes including aluminum or a different conductor may be coated on one or both sides with neutron-capture compounds. Preferably such coatings are thin enough to allow neutron-capture ions (such as tritons and alpha particles) to escape through the coating into the gas, thereby generating an ionization pulse that indicates the detection of a low-energy neutron. The detector array may have a lateral size of 3×12 meters and an overall longitudinal dimension of 1 meter, thereby providing a detection surface area of 36 square meters and a weight of about 1 ton, assuming aluminum/plastic construction.

FIG. **2** is a cross-section sketch of an exemplary detector array showing protruding detectors **201** alternating with recessed detectors **202** mounted on a curved surface **212** and aligned radially relative to a focal point **213** behind the detector array. The thickness of the protruding detectors **201** is labeled **207** and the thickness of the recessed detectors **202** is labeled as **208**. The recessed detectors **202** are shorter than the protruding detectors **201** by a distance at least equal to the thickness **208** of the recessed detectors **202**. A source **209** is shown in front (to the right) and is emitting particles **211**. A particular recessed detector **202'** is directly aligned with the source **209**, and therefore detects the particles **211** unobscured by the protruding detectors **201**. The particular recessed detector **202'** therefore has a high detection rate as indicated by the dark stipple fill. The other recessed detectors **202** are either partially or completely blocked by the protruding detectors **201**, and therefore have lower detection rates as shown in medium stipple or clear. The distribution of detections in the various recessed detectors **202** thus exhibits a narrow detection peak, or region of enhanced detection, with a maximum detection rate in the particular recessed detector **202'** that is directly aligned with the source **209**. The lateral position of the detection peak in the recessed detectors **202** thereby indicates the direction or angle of the source **209**. If multiple sources are present, the corresponding recessed detectors that are directly aligned with the respective sources exhibit high counting rates according to the radioactivity of each source or source region in view. If the source is distributed across an area, the detection rate in each recessed detector **202** is related to, or proportional to, the amount of radioactivity in each recessed detector's field of view. In this way the recessed detector detection rates reveal the distribution of radiation, including the locations and shapes of various sources in the inspection region. For example, if radioactive material is distributed across an area, such as a barrel filled with radwaste for example, then the various recessed detectors that are aligned with portions of the barrel have high counting rates, whereas the other recessed detectors aimed elsewhere are partially or totally obscured relative to particles emitted from the barrels. The processor can thus form a radiation image, radiograph, or radiation density map according to the detection rates of the corresponding recessed detectors.

The protruding detectors **201** also detect the particles **211**, but unlike the recessed detectors **202**, the protruding detectors **201** generally have a much broader detection distribution since the protruding detectors **201** directly face the source **209** without collimation according to some embodiments. In general, each protruding detector **201** may have a detection rate proportional to its geometrical area as viewed by the source **209**, and consequently the detection distribution of the protruding detectors **201** may be much wider than the narrow detection peak of the recessed detectors **202**. On the other hand, the protruding detectors **201** generally have higher detection efficiency than the recessed detectors **202** due to the greater angular field of view of the protruding detectors **201**. Therefore, the distribution of detections in the protruding detectors **201** may provide valuable information about the source distribution, which may be used to enhance or augment an image based on the recessed detector **202** detection rates. For example, the processor may be configured to determine the angle or direction or distribution or image of the source or sources according to the detection rates in the recessed detectors, and may also prepare an additional distribution or image according to the detection rates in the protruding detectors. The processor may prepare an image in which the detection data of the recessed and protruding detectors are combined, such as by weighted averaging to emphasize the recessed detector data over the broader protruding detector data. Additionally, a deconvolution algorithm may be applied to the protruding detector distribution, and optionally to the recessed detector data as well, thereby extracting a sharper image of the source distribution. The processor may also correct for certain distortions such as edge effects using, for example, a predetermined correction function related to the position of each recessed or protruding detector.

If a source is located outside the direct field of view of the array (that is, the source is located so far from the central axis **210** that none of the recessed detectors **202** is aligned with the source), then an edgemost detection peak is generally produced, yielding enhanced detections in whichever detectors are at the edge of the detector array (that is, "edgemost" detectors) closest to the source. For example, if the source is located beyond one edge of the detector array field of view, then the detectors **201-202** at that edge of the array, closest to the source position, generally receive most of the particles, or at least more counts than the adjacent detectors **201-202** which are shielded by that edgemost detector or detectors. The high-counting edgemost detector may be either the protruding or recessed type, depending on the construction of the particular detector array. The processor may determine that a source is present when the high-counting detector is an edgemost detector, and may further determine that the source is outside the field of view of the detector array, and also that the location of the high-counting edgemost detector indicates the general direction of the source (although not the specific location of the source).

FIG. **3** is a notional front-view sketch of the recessed detectors of an exemplary detector array, showing only the recessed detectors, and with the curvature suppressed. Dark stipple fill indicates a particular recessed detector **302'** that is directly aligned with a source, has a high detection rate, and thereby indicates the source direction. A second recessed detector **322'** is an edgemost detector with a high detection rate. This second high-counting recessed detector **322'** indicates that a second source is present and is located somewhere to the left side of the array as viewed here. The two-dimensional distribution of counting rates of the various recessed detectors thus yields a radiograph that shows the two-dimensional distribution of particle emitters in the direct field of view of the recessed detectors, and also indicates the presence and general direction of other sources that are not in the direct field of view. Alternatively, an edgemost protruding detector with a detection rate higher than its neighbors can also indicate the presence of a source outside the direct field of view of the detector array. For example, if the edgemost detectors are protruding detectors, then particles from the source may interact primarily with the edgemost protruding detector that is closest to the source, and the recessed detectors may be shielded by the protruding detectors. In that case, the processor may be configured to add the high-counting protruding detector data to the composite image, or otherwise indicate that another source is present off the corresponding edge, even though the recessed detectors failed to see it.

Although the drawing is in black and white, the composite image can be configured to convey a variety of information using colors, according to some embodiments. Besides the lightness or darkness, the pixels can be colored to indicate radiation intensity, or the detected particle type, or the particle energy, or other information. In addition, the radiation indicators can be caused to flicker or otherwise be temporally modulated to convey further information, such as indicating that the radiation levels from the flickering source have reached a hazardous level, or that a source indicated in red is a neutron emitter, for example.

FIG. **4** is a cross-section sketch of a portion of an exemplary detector array including protruding **401** and recessed **402** detectors. Each detector **401-402** is a right square prism shape with parallel sides, elongated in an extrusion direction, and therefore appears rectangular in this cross-section view. Adjacent detectors are rotated by a small angle relative to each other, so that each detector **401-402** is oriented in a different direction. Due to the small angular difference between adjacent detectors, they are not in face-to-face contact, but are separated by a small triangular air gap **403**. In most embodiments, the relative angle between adjacent detectors is small and the air gap **403** has no significant effect on performance.

FIG. **5** is a cross-section sketch of a portion of an exemplary detector array including protruding **501** and recessed **502** detectors which are slightly tapered or trapezoidal shaped, so that they fit together face-to-face without a triangular air gap. The tapered shape may make it easier to assemble and support the detectors **501-502** since they can be stacked together. In a practical implementation, the detectors **501-502** may be separated by inert materials such as foil, tape, insulators, chamber walls, or the like, all of which will be disregarded herein.

FIG. **6** is a cross-section view of a portion of an exemplary detector array including protruding detectors **601** and recessed detectors **602**, each of which is a non-tapered (parallel-sided) prism shape shown as a rectangle. The protruding and recessed detectors **601-602** have the same size and shape in this case, in contrast to the previous examples in which the recessed detectors were shorter than the protruding detectors. In the embodiment of FIG. **6**, the protruding detectors **601** are displaced toward the front and the recessed detectors **602** are displaced toward the back, thereby providing an offset between the protruding and recessed detectors **601-602**. The offset distance in the back is the same as the offset in the front. Such a detector array can be built from detectors **601-602** all having the same dimensions, a potential simplification.

FIG. **7** is a cross-section view of a portion of an exemplary detector array including protruding detectors **701** and recessed detectors **702**, each of which has the same size and shape such as a tapered or trapezoidal in shape. The recessed detectors **702** are displaced rearward relative to the protruding detectors **701**. The detectors **701-702** may fit together face-to-face, simplifying assembly and support.

FIG. **8** is a cross-section view of a portion of an exemplary detector array including protruding detectors **801** and recessed detectors **802** which, in this embodiment, include scintillators. To convert scintillation light into an electrical signal, the embodiment includes a position-dependent light sensor **804** such as a multi-anode microchannel plate or a CCD, either of which may also include a light amplifier. The embodiment further includes an optical system **803**, represented as a lens, configured to collect scintillation light from each detector **801-802** and focus it on the light sensor **804**. The light sensor **804** then produces an electrical signal or a series of signals that indicate which of the detectors **801-802** detected a particle.

FIG. **9** is a cross-section view of a portion of an exemplary detector array including protruding detectors **901** and recessed detectors **902** which in this embodiment include scintillators. Small optical elements such as lenses **903** mounted on each detector **901-902** focus scintillation light onto two conventional (that is, NOT position-sensitive) photomultiplier tubes **904**, which are configured to produce electrical signals proportional to the amount of light that each respective tube **904** receives. Each photomultiplier tube **904** is positioned to receive a different amount of light from each of the detectors **901-902**, so that the ratio of light received by the two tubes **904** indicates which of the detectors **901-902** was active. In analysis, the signals from the two photomultiplier tubes **904** may be compared and the ratio of signals determined, which thereby indicates which of the detectors **901-902** detected a particle.

FIG. **10** is a cross-section view of a portion of an exemplary detector array including protruding detectors **1001** and recessed detectors **1002** along with sensors **1003** attached to each detector **1001-1002**. The sensors **1003** are configured to produce signals that the processor can receive. For example, if the detectors **1001-1002** are scintillators, the sensors **1003** may be solid-state light sensors such as avalanche photodiodes or the like. If the detectors **1001-1002** are semiconductor detectors or gaseous ionization type detectors, then the sensors **1003** may be amplifiers, filters, and/or related electronics. In the depicted embodiment, the sensors **1003** are shown mounted at the back surface of each detector **1001-1002**, which thereby avoids blocking incoming particles from the front (to the right in the sketch).

FIG. **11** is a cross-section view of a portion of an exemplary detector array including tapered protruding detectors **1101** and recessed detectors **1102** along with sensors **1103**. In this embodiment, each sensor **1103** is mounted on the respective front surface of each protruding detector **1101** or on the back surface of each recessed detector **1102**. With such mounting, the sensors **1103** may be more easily accessible for assembly, maintenance, etc. Some sensors **1103** can be made small enough and thin enough that they intercept negligible incoming particles.

FIG. **12** is a notional front-view sketch showing an exemplary detector array with protruding **1201** and recessed **1202** detectors in a checkerboard pattern. Each recessed detector **1202** is surrounded on four sides by protruding detectors **1201** (other than the edgemost detectors which are only partially surrounded). Thus, the protruding detectors **1201** serve as active collimators for the recessed detectors **1202**, thereby limiting the field of view of each of the recessed detectors **1202**. Due to that collimation, the detection data of the recessed detectors **1202** indicates the distribution of radiation sources in front of the detector array.

FIG. **13** is a notional front-view sketch showing an exemplary detector array with protruding **1301** and recessed **1302** detectors in a "centered" type of arrangement, in which each recessed **1302** detector is surrounded by eight of the protruding detectors **1301**, thereby providing even greater collimation.

As another alternative, the detectors may be in a hexagonal pattern in which each recessed detector is surrounded on 6 sides by protruding detectors. The hexagonal arrangement generally provides greater collimation, but with a reduction in the number of recessed detectors in the array.

FIG. **14** is a cross-section sketch of an exemplary detector array in which the protruding **1401** and recessed **1402** detectors are right regular prism shapes and are positioned abutting a planar surface **1408** in back. This is in contrast to the foregoing examples in which the overall shape of the detector array was arc-shaped. Each detector **1401-1402** is oriented at a slightly different angle, and therefore each recessed detector **1402** has an unobstructed view of a different region of space in the inspection region, which is to the right. The flat-back design as depicted may be simpler to build and/or more compact than a curved design.

FIG. **15** is a cross-section sketch of another exemplary detector array with a flat back surface. Here the protruding **1501** and recessed **1502** detectors are tapered, and their back surfaces are shaped and positioned so that their back surfaces are coplanar. The configuration of FIG. **15** may be easier to build and support since the detectors are tapered and shaped to fit face-to-face.

FIG. **16** is a perspective sketch of an inspection scenario in which an exemplary detector array **1600** is shown inspecting a shipping container **1609** for radioactive material. The shipping container **1609** contains two barrels **1604** of radwaste, which were legally declared on a manifest. However, in an attempt to get past the inspection, an adversary has also hidden a clandestine nuclear weapon **1699**, encased in a heavy shield **1606**. The adversary assumed that radiation detectors would detect the declared material **1604** and would miss the weapon **1699** entirely. Fortunately, the inspection uses an imaging detector array **1600** which detects particles **1607** from the radwaste **1604** and also separately detects those from the weapon **1699**. The detector array **1600** then produces a radiation image that shows all the sources in view. At the same time, a camera **1603** mounted on the detector array **1600** records the scene in visible light, to document the locations of any sources detected. Although the shield **1606** greatly reduces the amount of radiation from the weapon **1699**, the large surface area and high detection efficiency of the detector array **1600**, and the inherent directionality of the recessed detectors of the detector array **1600**, reveal the weapon **1699**. The resulting image is further illustrated in FIG. **17**.

FIG. **17** is a sketch of an exemplary composite image **1710** produced from the inspection scenario of FIG. **16**, in which the radiation distribution is overlain onto the visible-light photographic image. The composite image **1710** thereby shows where each source is located in the shipping container **1709**. Depending the size of a source and the angular resolution of the recessed detectors, the image **1710** may also indicate the shape and distribution of each source. The two radwaste barrels **1704** show up clearly in the shipping container **1709**. In addition, the clandestine weapon **1799** appears as a point-like source, as indicated by a sharp detection peak in the particular recessed detector that is directly aligned with the weapon **1799**. The shield **1706** also shows up, due to scattered radiation. Thus the composite image **1710** reveals the weapon **1799**, and the detector array **1600** has successfully defeated an adversary's attempt to transport clandestine radioactive material.

As an option, the type of particle detected may be rendered as a color or other feature of the radiation overlay on the composite image **1710**. For example, the radiation from radwaste is usually gamma rays, whereas most weapons emit neutrons. Accordingly, the radiation overlay corresponding to gammas from the barrels **1704** may be rendered in yellow to indicate gamma detection, while the weapon **1799** overlay may be rendered in red to indicate neutrons.

FIG. **18** is a notional sketch of an exemplary detector array **1800** mounted over a passageway **1805** and configured to scan passing entities **1804** (indicated by arrows) such as pedestrians, vehicles, cargo, baggage, or the like, and to image the detected radiation sources in real-time. The detector array **1800**, shown in cross-section, is mounted over the passing entities **1804**, for example mounted on a ceiling, gantry, overpass, or other overhead structure. Alternatively, the detector array **1800** may be mounted on or under the passageway **1805**, or on a side wall or other mounting structure. The detector array **1800** includes protruding **1801** and recessed **1802** detectors interleaved or alternated, and mounted on a hemispherical mounting surface **1803** with each detector **1801-1802** being oriented perpendicular to the local surface of the hemispherical mounting surface **1803**, so that each protruding detector **1801** is oriented in a different direction including both lateral directions. Each recessed detector **1802** is thereby collimated to view a different region of space, and an image of the radiation distribution can be formed from the detection rates of the recessed detectors **1802**. In addition, by acquiring and processing the detection data in real-time, a moving image of the radiation field can also be formed, thereby detecting a moving source, as is expected for entities **1804** in motion.

One of the moving entities **1804** is carrying concealed radioactive material **1899** which is emitting particles **1807**. At the particular moment depicted, a particular recessed detector **1802'** is aligned with the radioactive material **1899** and therefore has an unobstructed view of the arriving particles **1807**. The particular recessed detector **1802'** therefore has a higher counting rate than the other detectors as indicated by a dark stipple fill. An image formed from the detection rates of the recessed detectors **1802** can thus detect the radioactive material **1899**, and can also indicate its location at a particular moment. When analyzed with radiation images acquired at different times, the direction of travel and speed of the entity **1804** carrying the radioactive material **1899** can be determined.

The sketch also shows which particular protruding detectors **1801'** register high detection rates since they have a direct view of the particles **1807**, whereas the other protruding detectors **1801** are partially or almost completely shielded by their neighbors due to the curvature of the mounting surface **1803**. Accordingly, a second radiation image can be prepared based on the detection rates of the protruding detectors **1801**. The second radiation image can indicate the presence, speed, and direction of travel of the radioactive materials **1899**, thereby confirming the results of the recessed detectors **1802**. The radiation image of the protruding detectors **1801** is expected to have substantially lower (broader) spatial resolution than the radiation image of the recessed detectors **1802**, due to the lack of active collimation among the protruding detectors **1801**. On the other hand, the statistical power of the protruding-detector image can be quite high due to the larger number of protruding detectors **1801** positioned to detect the particles **1807**. Therefore both the recessed-detector data and the protruding-detector data may be useful in detecting and localizing the radioactive material **1899**.

FIG. **19** is a notional front view sketch of the detector array **1800** of FIG. **18**, with the curvature suppressed and the protruding detectors averaged over so that only the recessed detector rates are shown. A particular element **1902'** is shown heavily stippled, corresponding to the particular recessed detector **1802'** that is directly aligned with the radioactive materials **1899**. Thus the distribution of detection rates in the recessed detectors **1802** can form the basis for a two-dimensional radiographic image showing the distribution of radiation sources in view of the detector array **1800**.

FIG. **20** is a notional front view of the detector array **1800** of FIG. **18**, but this time with the recessed detectors averaged over so that only the protruding detector rates are shown. A particular set of elements **2001'** are shown darkened, corresponding to the particular protruding detectors **1801'** that are most exposed to the particles **1807** from the radioactive materials **1899**. Thus the distribution of detection rates in the protruding detectors **1801** can form the basis for a two-dimensional radiographic image showing the distribution of radiation sources in view of the detector array **1800**. As is apparent, the spatial resolution of the protruding detectors **1801** is much less (that is, wider) than that of the recessed detectors **1802**. The protruding detector resolution is due to the overall curvature of the mounting surface **1803**, whereas the recessed detector resolution is due to the collimation from the adjacent protruding detectors, which limit the field of view of each recessed detector. On the other hand, the number of protruding detectors that contribute to the detection distribution of FIG. **20** is larger than the number of recessed detectors contributing to the detection distribution of FIG. **19**. Therefore the detection data of the protruding detectors may be statistically significant, particularly when the source is weak.

In some embodiments, the processor may be configured to exploit the detection data from both types of detectors, recessed and protruding. The processor may be configured to combine the data from the recessed and protruding detectors respectively, and thereby produce a more informative composite image than obtainable from each type of detector separately. The processor may also be configured to apply a deconvolution algorithm to each set of data, thereby sharpening the resulting radiographic image, using deconvolution technology well known in image processing fields. Due to the different properties of the recessed and protruding detector data, the processor may use a different deconvolution template for the two data sets. The processor may be further configured to combine the deconvoluted distribution of the recessed detectors with the deconvoluted distribution of the protruding detectors, and thereby prepare a radiographic image with better sensitivity and lower noise than could be obtained with either distribution alone.

In some embodiments, the deconvolution template may be based on the angular sensitivity distribution of the recessed detectors. The angular sensitivity distribution is a function that corresponds to the distribution of detections among the recessed (or protruding) detectors when exposed to a single isolated point-like source of radiation. The angular sensitivity distributions of the respective recessed and protruding detectors may be determined by placing a test source in front of a detector array and recording the distribution of detection rates in the two types of detectors. Alternatively, the angular sensitivity distributions may be determined by simulation, for example using software such as MCNP or GEANT, with a simulated isotropic point source. The distribution of detections in the recessed detectors is determined primarily by the offset distance and the width of each recessed detector, due to the active collimation provided by the protruding detectors. If the angular sensitivity distribution of each recessed detector is known, then the recessed detector radiographic image can generally be sharpened by applying a deconvolution algorithm. Likewise, the angular sensitivity distribution of the protruding detectors is primarily determined by the exposed area of each protruding detector as viewed by the source. Many deconvolution algorithms are known, usually based on two-dimensional Fourier transformations, particularly in the field of image processing. The recessed detector radiographic image may then indicate the distribution of sources more clearly after the deconvolution algorithm is applied to the recessed detector data, and likewise for the protruding detector radiographic image.

In some embodiments, the recessed detector radiographic image (optionally with deconvolution) and the protruding detector radiographic image (optionally with deconvolution) may be combined to obtain an even sharper and/or more nuanced total radiographic image with higher quality than either component alone. In addition, the total radiographic image can be overlaid, or otherwise combined, with a visible-light (or infrared) image of the inspection scene, so that the final combined two-dimensional image can show where the radioactive sources are located. For example, in an inspection involving numerous items such as mixed cargo, or numerous separate items such as passing vehicles, and in many other cases, the combined image can indicate which of the items contains radioactive material.

FIG. **21** is a perspective sketch of an exemplary portable imaging radiation detector **2101** inspecting some cargo **2102** for radioactive contraband. The depicted imaging radiation detector **2101** includes an imaging detector array **2100** (hidden, dashed), a visible-light and/or infrared camera **2104**, carrying handles **2105**, a flat-screen display **2106**, and a processor **2107** (hidden, dashed). The cargo **2102** includes a radiological weapon **2109** and the core of a plutonium weapon **2199**, both of which produce particles **2110** such as gamma rays and/or neutrons, which the detector array **2100** is configured to detect.

The processor **2107** in the depicted embodiment is configured to prepare a composite image that includes both the cargo items **2102** and the distribution of sources **2109**, **2199** in the inspection region. The flat-screen display **2106** is configured to show the composite image, including the scene as observed by the camera **2104**, overlain or otherwise combined with a radiation distribution based on data from the imaging detector array **2100**. The imaging radiation detector **2101** thereby provides an image **2111** indicating which of the cargo items **2102** includes a radiological weapon **2109** and a nuclear pit **2199**. In addition, the processor **2107** is configured to calculate a total detection rate by adding detection data from all of the detectors in the detector array **2100**. The processor **2107** may be further configured to compare that total detection rate to a predetermined background rate, to calculate the statistical uncertainty of the total detection rate, and to thereby determine whether a source is present according to a formula. For example, the formula may include a ratio in which the numerator is the total counting rate minus a previously-determined background rate, and the denominator is the statistical uncertainty in the total counting rate. The uncertainty may be equal to the square root of the number of detections in the detector array **2100**, divided by the amount of time, in seconds, over which those detections are accumulated. Alternatively, and equivalently, the numerator may be the total number of detections minus the expected background (which is equal to the number of seconds times the predetermined background rate), and the denominator may be the square root of the number of detections. In either case, the display **2106** may indicate the ratio so calculated, or it may show an alarm if the ratio exceeds a predetermined threshold such as 1 or 2 or 3 (that is, the detection rate exceeds the expected background by 1 or 2 or 3 standard deviations), or other information indicating whether a source is present based on the total detection rate of the detector array **2100**.

FIG. **22** is a sketch of an exemplary imaging detector array **2200** mounted in or on an aircraft **2203** such as a drone, helicopter, hovercraft, or airplane for example. As the aircraft **2203** flies over an inspection region, the detector array **2200** acquires directional data on sources below the aircraft **2203**, including vehicles **2204** and fixed sites such as factories **2205** and warehouses, and the like. The system can acquire a radiographic image that shows the distribution of radiation coming from sources in the inspection region. The system may also record detection data in real-time, along with geographical data such as the GPS coordinates and compass heading and altitude of the aircraft. A radiation map can then be prepared from that time-stamped data by calculating the ground location corresponding to each recorded particle **2208** in each detector of the detector array **2200**. The radiation map may then be combined with a visible-light or infrared image acquired concurrently, so that the composite image indicates which items on the ground are radioactive. Alternatively, the radiation map can be superposed on a satellite image of the area scanned, or a road map for example, thereby localizing the radiation sources geographically.

FIG. **23** is a perspective sketch of an exemplary vehicle inspection station that uses both radiation detection and cosmic ray scattering to detect clandestine weapons. Cosmic rays are mainly GeV-energy muons which readily pass through large amounts of material. Here a truck **2309** is being scanned by an upper **2301** and lower **2302** cosmic ray tracking chamber (in dash). When cosmic rays pass through high-Z materials such as a nuclear weapon or dense shielding, the cosmic rays scatter in a characteristic way. The tracking chambers **2301-2302** compare the cosmic ray track directions above and below the inspection object **2309**, thereby detecting the nuclear material or massive shield according to the scattering patterns. In addition, two imaging detector arrays **2303**, **2304** are positioned on both sides of the inspection object **2309** to detect and localize radioactive sources that the cosmic ray tracking chambers **2301**, **2302** may miss, such as a radiological weapon that may contain no high-Z material. By remaining outside the field of view of the tracking chambers, the imaging detector arrays **2303**, **2304** thereby avoid causing additional scattering of the cosmic rays, or otherwise interfering with the cosmic ray measurement. In addition, two more detector arrays **2305**, **2306** are shown above the upper tracking chamber **2301** and below the lower tracking chamber **2302**, to image sources in the inspection object **2309** from orthogonal directions. Often an adversary will make the shielding thicker on the sides and thinner at the top and bottom, since many vehicle inspection stations have radiation detectors only on the sides. But with the additional detector arrays **2305**, **2306**, the contraband is readily detected.

FIG. **24** is a flowchart of an exemplary method of producing a composite image showing the distribution of radiation sources in an inspection region. The method may be encoded in instructions on computer-readable non-transient media and executed by the processor or other processor to produce the composite image, thereby showing both the items in the inspection region and the radiation distribution detected in the inspection region.

At block **2401**, the signals from the detector array may be accumulated for a predetermined time. Defective events such as cosmic rays and multi-detector events may be rejected **2402** in real-time or later. At block **2403**, the processor may apply a deconvolution algorithm to the recessed detector data to sharpen the resolution, resulting in a first radiographic image. At block **2404**, the processor may apply a different deconvolution algorithm to process the protruding detector data. At block **2405**, the processed (or raw) radiographic images may be combined, producing an improved radiographic image with improved signal-to-noise ratio and/or sharper resolution. At block **2406**, a visible-light photographic image (or infrared or other spatial image) may be acquired, and the radiographic image may be overlaid at block **2407** or otherwise combined with the visible-light image to produce a composite image that shows the distribution of radiation among items in view. Alternatively, one or both of the radiographic images may be combined with the photographic image without first combining the two radiographic images.

Embodiments of the imaging detector array described herein can provide many advantages over conventional detectors and can economically solve important security inspection problems. Embodiments can: (a) detect a source with high sensitivity, due to the large area and high intrinsic efficiency of detector arrays as described, (b) produce a two-dimensional radiographic image showing the distribution of radiation sources in the inspection region, (c) scan trucks, cargo containers, railcars, airplanes, vans, automobiles, boats, pedestrians, baggage, cargo, mail, conveyorized matter, fluid in pipes, and many other things to detect and localize radioactive materials, (d) detect a plurality of radioactive sources simultaneously and indicate their respective locations, (e) cooperate with a cosmic ray scattering inspection system, thereby providing two contrasting detection modes for detecting nuclear materials, (f) scan across a wide area and detect nuclear materials in regions such as an urban environment, (g) be assembled from available detector types including gamma-blind neutron detectors, neutron-blind gamma detectors, PSD or ionization-dependent scintillators that separately detect both neutrons and gammas, gaseous ionization type detectors, and low-cost liquid scintillators, according to some embodiments.

The ability to localize a clandestine radioactive source rapidly is a key enabling factor in nuclear and radiological threat detection. Advanced radiation detection, localization, and imaging 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 imaging radiation sources, comprising:

a detector array comprising at least 40 detectors, each detector configured to detect particles from the radiation sources and responsively emit a signal, wherein the at least 40 detectors comprise protruding detectors interleaved with recessed detectors, each recessed detector being adjacent to a plurality of protruding detectors, and each protruding detector protruding beyond the adjacent recessed detectors by an offset distance that is at least equal to the thickness of the recessed detectors;

a camera configured to acquire a photographic image of an inspection region; and

non-transient computer-readable media containing instructions for a method that includes preparing a first radiographic image according to detection data of the recessed detectors, preparing a second radiographic image according to detection data of the protruding detectors, acquiring the photographic image of the inspection region, and producing a composite image showing the spatial distribution of the radiation sources in the inspection region by combining the first and second radiographic images with the photographic image.

2. The system of claim **1**, wherein each recessed detector is surrounded by protruding detectors which are configured to block particles arriving at angles above a predetermined angle and to admit particles arriving at angles below the predetermined angle, relative to the orientation direction of the adjacent protruding detectors.

3. The system of claim **1**, wherein each detector has a prism shape with parallel sides.

4. The system of claim **1**, wherein each detector is tapered, and adjacent detectors are positioned face to face.

5. The system of claim **1**, wherein the thickness of the protruding detectors is at least equal to the average interaction distance of the particles therein.

6. The system of claim **1**, wherein the recessed detectors are shorter than the protruding detectors by a distance at least equal to the thickness of the recessed detectors.

7. The system of claim **1**, wherein the recessed detectors and the protruding detectors have substantially the same size and shape, and wherein the recessed detectors are displaced toward the back of the detector array by the offset distance.

8. The system of claim **1**, wherein each protruding detector is oriented radially from a focal point that is located behind the detector array.

9. The system of claim **1**, wherein the back of the detector array is a portion of a spherical surface.

10. The system of claim **1**, wherein the protruding and recessed detectors are arranged in a checkerboard pattern.

11. The system of claim **1**, wherein the detector array includes no passive collimators and no passive shields.

12. The system of claim **1**, wherein the photographic image represents both visible and infrared light.

13. The system of claim **1**, wherein the type of radiation detected from each source is indicated in the composite image by colors.

14. The system of claim **1**, further including a processor configured to determine, when an edgemost detector has a higher detection rate than the adjacent detectors, that a radiation source is located outside the field of view of the detector array.

15. The system of claim **1**, further including a processor configured to apply a first deconvolution algorithm to the detection data of the recessed detectors, and a second deconvolution algorithm to the detection data of the protruding detectors.

16. The system of claim **15** wherein the first deconvolution algorithm is based on an angular sensitivity distribution of the recessed detectors, and the second deconvolution algorithm is based on an angular sensitivity distribution of the protruding detectors.

17. The system of claim **1**, further comprising a portable enclosure, at least one carrying handle, and a flat-screen display configured to show the composite image.

18. The system of claim **1**, wherein the system is mounted in or on an aircraft and is configured to image sources below the aircraft.

19. The system of claim **1**, further comprising a passageway through which pedestrians can pass, wherein the system is configured to image the sources periodically and to determine a velocity and a direction of travel for each source.

20. The system of claim **1**, further comprising an upper tracking chamber and a lower tracking chamber configured to measure cosmic ray scattering within the inspection region.

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