

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
17 February 2005 (17.02.2005)

PCT

(10) International Publication Number  
WO 2005/015125 A1

(51) International Patent Classification<sup>7</sup>: G01B 21/04, A61B 6/03

(21) International Application Number: PCT/CA2004/001482

(22) International Filing Date: 9 August 2004 (09.08.2004)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data: 60/493,953 8 August 2003 (08.08.2003) US

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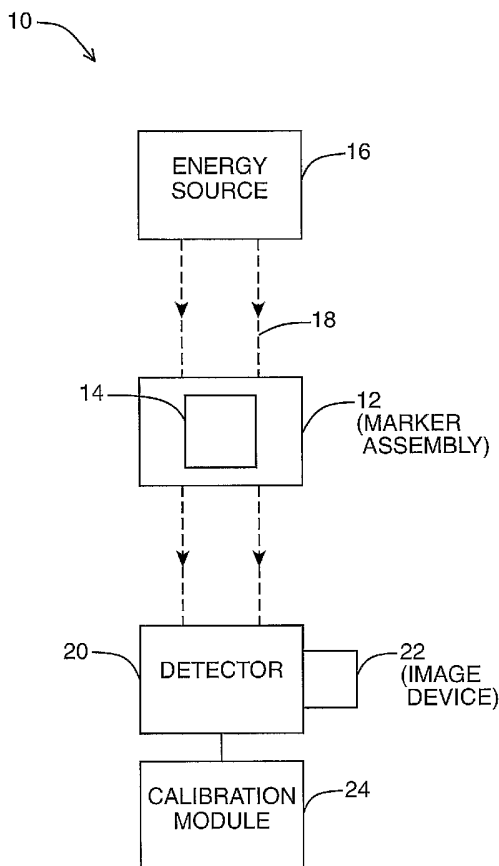
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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

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(54) Title: METHOD AND SYSTEM FOR CALIBRATING A SOURCE AND DETECTOR INSTRUMENT



(57) Abstract: A system for obtaining coordinate data of a source and detector instrument are described. The system includes a marker assembly having a plurality of markers with a particular geometry, and an energy source for targeting the plurality of markers with energy packets. The system further includes a detector for detecting energy packets after the plurality of markers ave interacted therewith, and an image device for forming image data of the plurality of markers from the energy packets detected by the detector. A calibration module for utilizes the particular geometry of the plurality of markers and the image data to non-iteratively determine coordinate data.

WO 2005/015125 A1



(84) **Designated States** (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

**Published:**

— *with international search report*

## **Method and System for Calibrating a Source and Detector Instrument**

### **Field of the invention**

The invention relates to source and detector instruments, and more  
5 specifically to calibrating such instruments.

### **Background of the invention**

Volumetric imaging has become an integral part of modern medicine.  
Such imaging has been widely used to not only diagnose disease but as an  
aid in administering medical treatments. When using diagnostic probes,  
10 operating instruments or radiation therapy, a medical professional can be  
greatly aided by images taken of the patient that can identify target areas, or  
areas to be avoided.

For example, cone-beam computed tomography (CBCT) instruments  
have been coupled to X-ray delivery devices to provide *in situ* clinical imaging  
15 and radiation therapy simultaneously. The Elekta Synergy™ system is an  
example of a commercially available system that combines imaging and  
delivery into one integrated treatment system for precise delivery of radiation  
therapy.

Although the integration of imaging systems with delivery systems has  
20 many advantages, there is at least one drawback. Both imaging systems and  
delivery systems have components that move, typically in a circular motion.  
When imaging and delivery systems are integrated, motion of the components

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is less stable than the separate systems, resulting in perturbations from ideal behavior.

Such perturbations denigrate performance. For example, in cone beam tomography, non-ideal motion, such as tilting or twisting of the image device, can produce severe artifacts, such as loss of detail, poor registration, and streak artifacts. In the delivery system, perturbations can cause inaccurate delivery of energy to a part of the body. Therefore, any system or method that can account for non-ideal motion would be most welcome.

### **Summary of the invention**

This invention is directed to a method and apparatus for obtaining coordinate data of a source and detector system in one configuration captured by one imaging view, or "pose." A source and detector system includes a source of material or wave energy that interacts with a target, and a detector for obtaining image data of the target. Source and detector systems include imaging and treatment delivery systems, and systems combining both.

In one embodiment, the invention employs a device (referred to as a marker assembly) containing a plurality of fiducial markers that are visible in a projection image. Coordinate data associated with a particular pose of the projection system are then computed. The coordinate data can include position and orientation coordinates of the detector, and position coordinates of the source, which if considered to be a point source, is devoid of orientation. The method makes use of analytical expressions relating image data to the known geometry of the plurality of markers to non-iteratively obtain the coordinate data associated with a pose.

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The technique is general to source and detector systems, including systems where the energy source is an X-ray source, a gamma ray source, an atomic/sub-atomic particle source, an optical photon source, or other non-diffracting energy source. It allows determination of pose from a single  
5 projection and may be used to determine pose throughout an arbitrary trajectory of source and detector in which multiple projections are formed -- e.g., the source and detector moving in linear or circular trajectories. Applications in medical imaging in which the invention may be applied include single or multiple view radiography, stereography, bi-plane imaging,  
10 fluoroscopy, tomosynthesis, and cone-beam computed tomography. Example sources in medicine include x-ray tubes, linear accelerators, and radionuclides. Example detectors in medical imaging include film, computed radiography storage phosphors, x-ray image intensifiers, and flat-panel detectors.

15 A direct, non-iterative method is provided herein for determination of pose based on the position of the fiducial markers in a given projection image. The location of markers within the phantom are known with respect to one another. The phantom may be placed arbitrarily with respect to source and detector provided that the fiducial markers are visible in the projection image.  
20 A specific embodiment of the invention involves a phantom containing markers, such as metal ball bearings, arranged in two circles, which project as ellipses. By relating the known geometries of the markers and their projection, the location  $(X_s, Y_s, Z_s)$  of the source as well as the

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location  $(X_d, Y_d, Z_d)$  and orientation  $(\theta, \phi, \eta)$  of the detector may be ascertained using a direct, non-iterative analysis. This analysis is fast, accurate, and general in that it can completely determine pose from a single projection, allowing complete specification of system geometry for a system in which a  
5 single projection is acquired and/or for a system in which the source and detector move in some trajectory about the phantom and acquire one or multiple projections. The resulting pose(s) is completely specified in the reference frame of the phantom, which can in turn be related to other reference frames by appropriate transformations, such as the reference frame  
10 of a medical treatment device or any other system utilizing data from the projection system.

#### **Brief description of the drawings**

For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made, by way  
15 of example, to the accompanying drawings:

Figure 1 shows a box-diagram of a calibration system for calibrating an imaging instrument according to the principles of the present invention;

Figures 2A-E show the marker assembly of Figure 1;

Figure 3 shows the calibration module of Figure 1;

20 Figure 4 illustrates the concept of a converging point used to obtain coordinate data according to the principles of the present invention;

Figure 5 shows coordinate systems used to calibrate a gantry-based, imaging instrument according to the principles of the present invention;

Figures 6A and 6B show coordinate systems used to calibrate a bench-top, turntable imaging instrument according to the principles of the present invention;

Figures 7 and 8 show geometric constructions used for obtaining coordinate data according to the principles of the present invention;

Figure 9 shows the geometry of the virtual and real detector planes to obtain coordinate data according to principles of the present invention;

Figures 10A and 10B show a set of axes in relation to a converging point, as illustrated in Figure 9, arising from detector tilt;

Figure 11 shows a plot for obtaining a pitch angle and a roll angle of the detector of Figure 1;

Figure 12 illustrates a triangulation involving a source to detector distance according to the principles of the present invention;

Figures 13A-D show plots of calibration sensitivity due to uncertainty of the position of the ball bearings shown in Figures 2A-E;

Figures 14A-C show plots testing calibration of the imaging instrument according to the principles of the present invention;

Figures 15A-D show plots of the source and piercing point positions according to the principles of the present invention;

Figure 16A and 16B show axial slices of the cone-beam CT reconstruction of the steel wire in the calibration phantom of Figures 2A-E;

Figures 17A-D show surface plots of axial slice images of a thin steel wire in the calibration phantom of Figures 2A-E;

5 Figure 18 shows a system for obtaining coordinate data of a source and detector instrument according to the principles of the present invention;

Figure 19 shows the trajectory of electrons on a target in the system shown in Figure 18;

Figure 20 shows the nominal gantry angle from the linear accelerator  
10 console and measured gantry angle from the calibration in the system shown in Figure 18;

Figure 21 shows the MV source position and piercing point on the detector in three-dimensional spaces in the system shown in Figure 18;

Figure 22 shows the alignment of collimator rotational axis to the MV  
15 source position in the system shown in Figure 18; and

Figure 23 shows a fluoroscopic C-arm instrument and a marker assembly according to the principles of the present invention.

### **Detailed description of the invention**

Figure 1 shows a box-diagram of a calibration system 10 for calibrating  
20 a source and detector instrument. For example, the source and detector instrument can be an imaging instrument used to image a body part, such as

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a radiography, a stereography, a bi-plane imaging, a fluoroscopy, a tomosynthesis or a tomography instrument.

The calibration system 10 includes a "phantom" or marker assembly 12 having a plurality of markers 14 whose locations with respect to one another is known. The calibration system 10 further includes an energy source 16 that  
5 can emit energy packets 18, a detector 20, an image device 22, and a calibration module 24.

The energy source 16 targets the plurality of markers 14 with energy packets 18. The energy source 16 can include an x-ray, a gamma ray, an  
10 atomic, a sub-atomic, an optical photon, an electromagnetic wave, an x-ray tube, a particle accelerator or a radionuclide source.

The detector 20 detects energy packets after the plurality of markers have interacted therewith. The image device 22 forms image data of the plurality of markers 14 from the energy packets detected by the detector 20.

15 As described in more detail below, the calibration module 24 utilizes the locations of the plurality of markers 14 and the image data to non-iteratively determine coordinate data of at least one of the energy source 16 and the detector 20. The coordinate data allow the imaging instrument to be calibrated. Calibration of a system allows images of a subject to be properly  
20 evaluated.

Figures 2A-E shows the marker assembly 12 of Figure 1. The marker assembly 12 includes a cylindrical plastic phantom 32 having end caps 33. The marker assembly 12 also includes a plurality of markers 14 embedded in

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the phantom 32. The plurality of markers 14, in this case twelve steel ball bearings (BBs), are disposed on two parallel circles at opposite ends of a cylinder of radius  $r$  and length  $l$ . The first circle 34 and the second circle 36 each have a radius of  $r = 50\text{mm}$ . The twelve BBs on each circle 34 and 36 are equally spaced to within a  $25\mu\text{m}$  tolerance. The diameter of each ball bearing is 4.7 mm, and the distance between the two circles 34, 36 is 160 mm. It should be understood that in other embodiments the plurality of markers 14 can take on other shapes and sizes, and can be arranged in a different geometry.

After being emitted from the energy source 16, the energy packets 18 interact with the BBs 14 and then are detected by the detector 20. The image device 22 forms image data of the BBs 14 from the energy packets detected. As described in more detail below, the image data may correspond, for example, to a radiographic image of a first ellipse associated with a first projection of the first circle 34 and a second ellipse associated with a second projection of the second circle 36.

To create a relatively uniform background around the BBs in the radiographic image, and to protect the BBs from mechanical damage, a plastic end cap 33 is provided at each end of the cylindrical plastic phantom 32.

The phantom 32 is large enough to ensure that most of the detector 20 is involved in forming the image. In addition, the diameter of each BB is large enough to include a large number of pixels and to exhibit high contrast, yet

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small enough to avoid overlapping with neighboring BBs when projected to form an image. Preferably, more than ten BBs (five in each circle) should be used in the marker assembly 12 to best employ ellipse parameters associated with the first and second ellipses, which are described below with reference to  
5 equation (8).

The arrangement of BBs in the marker assembly 12 possesses a degree of symmetry that facilitates the subsequent calibration analysis. In particular, the BBs can be divided into groups of four ball bearings such that the positions of the BBs are  $(x, y, z)$ ,  $(-x, -y, z)$ ,  $(x, y, -z)$ , and  $(-x, -y, -z)$  with  
10 respect to a particular set of coordinates axes, the phantom coordinate system. The origin of the phantom coordinate system is the point of intersection of the lines connecting the BBs in Figure 2C. The z-axis of the phantom coordinate system is parallel to the lines connecting the BBs in Figure 2D. Having more than two groups of BBs allows the center of each  
15 circular pattern to be found, as shown in Figure 2E. Since each group consists of four BBs, at least 12 ball BBs are used.

Figure 3 shows the calibration module 24 of Figure 1. The calibration module 24 includes a projection module 42, a marker assembly module 44, an intersection module 46, a scale module 48, and a converging point module  
20 50. These modules 42, 44, 46, 48 and 50 obtain data from which coordinate data of the energy source 16 and detector 20 may be calculated.

In particular, the projection module 42 obtains first ellipse parameters  $a_1, b_1, c_1, u_{01}, v_{01}$  that describe the first ellipse, which is the image projection of the

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first circle 34, and second ellipse parameters  $a_2, b_2, c_2, u_{02}, v_{02}$  that describe the second ellipse, which is the image projection of the second circle 36, according to

$$a(u - u_0)^2 + b(v - v_0)^2 + 2c(u - u_0)(v - v_0) = 1$$

5 where  $(u_0, v_0)$  is the center of the ellipse. The parameters  $a, b, c, u_0$  and  $v_0$  can be found using a linear least square method from projection points of the BBs.

The marker assembly module 44 stores geometric parameters of the marker assembly 12, such as the radius,  $r$ , of, and distance,  $l$ , between the first and second circles 34 and 36.

10 The intersection module 46 determines a location of a piercing or intersection point,  $(U_{\text{offset}}, V_{\text{offset}})$  defined as follows. Each member of the plurality of markers 14 on the first circle 34 has a counterpart on the second circle 36, viz., the member of the plurality of markers 14 on the second circle 36 farthest away. Lines connecting members of the plurality of markers 14 to  
 15 their counterpart on the second circle 36 intersect at a point that coincides with the origin of the phantom coordinate system (see Figure 2C). A BB placed at this point would form an image, as obtained by the imaging instrument, which by definition is the piercing point. In reality, no such BB is placed there. Instead, the piercing point may be obtained by connecting with  
 20 lines the images of BBs on the first and second circles 34 and 36 (which project generally as ellipses) with their counterpart images; where the lines intersect is the piercing point.

To locate the position of the BBs on the image, a signal threshold is chosen such that the edge of each ball bearing is shown clearly. A numerical optimization package, such as `fminsearch` from Matlab<sup>TM</sup> (the MathWorks, Natick, MA), is used to find the center of each ball bearing.

- 5           The scale module 48 obtains a scale factor,  $S_f$ , having dimensions of pixel/length. The scale factor can be used to digitize the image of the plurality of markers 14 according to equations (7A) and (7B) below.

The converging point module 50 obtains the converging point, defined as follows. Referring to Figure 4, one source ( $P_s$ ) and two point objects ( $P_{BB1}$  and  $P_{BB2}$ ) define a plane, called a divergent plane,  $D_1$ . The intersection of the  
10           divergent plane,  $D_1$ , and the detector plane,  $I$ , is the line, which connects the projected BB locations ( $P_{11}$  and  $P_{12}$ ). Another pair of BBs forms another divergent plane in the same way.

$$L_i = I \cap D_i$$

- 15           where  $D_i$  is  $i$ -th divergent plane, and  $L_i$  is the line made by  $I \cap D_i$ . The intersection of all lines ( $L_i$ ) is denoted by the converging point,  $P_c$ :

$$\begin{aligned} P_c &= L_1 \cap L_2 \cap L_3 \cap \dots \\ &= (I \cap D_1) \cap (I \cap D_2) \cap \dots \\ &= I \cap (D_1 \cap D_2 \cap \dots) \end{aligned}$$

- 20           If all the lines connecting a pair of point objects are parallel, the intersection of divergent planes, ( $D_1 \cap D_2 \cap \dots$ ), forms one line,  $L_d$ , denoted by the axis of the divergent planes, which is parallel to the lines. The converging point,  $P_c$ , always exists on the (extended) detector plane except for the special case

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where the axis of divergent planes is parallel to the detector plane. The divergent planes and the axis of the divergent planes are analogous to sheets of paper and the spine of a book. Therefore, the converging point is simply calculated as follows.

5 
$$P_c = I \cap L_d$$

When more than two pairs of point object are available, and the lines connecting a pair of objects in the space are parallel, the converging points formed by the lines connecting pairs of objects in the image can be simply found by the intersection of the axis of the divergent plane,  $L_d$ , and the  
10 detector plane,  $I$ .

From the ellipse parameters obtained by the projection module 42, the geometric parameters of the marker assembly 12 obtained by the marker assembly module 44, the piercing point obtained by the intersection module 46, the scale factor obtained by the scale module 48, and particular  
15 converging points obtained by the converging point module 50, coordinate data of the energy source 16 and detector 20 may be obtained. In particular, the calibration module 24 determines the coordinate data, which can include three detector orientation coordinates,  $(\theta, \phi, \eta)$  (or pitch, roll, yaw), defining an orientation of the detector, three detector position coordinates,  $(X_d, Y_d, Z_d)$   
20 defining a position of the detector, and three source coordinates,  $(X_s, Y_s, Z_s)$ , defining a position of the energy source.

These coordinate data are obtained non-iteratively, meaning that equations, which are provided below, are used that relate the unknown

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coordinate data to known quantities, such as the ellipse parameters found by the projection module 42 and the geometric parameters of the phantom 32. Specifically,  $\eta_d$  is obtained from equation (16),  $\theta_d$  and  $\phi_d$  from equations (9), (10), (18), and (19),  $Y_d$  and  $Z_d$  from equations (24) and (23), and  $Y_s$  and  $Z_s$  from 5 equations (15) and (17). Positions  $X_d$  and  $X_s$  are zero by construction.

This non-iterative approach should be contrasted with iterative approaches where an initial guess is made of coordinate data that might yield the image obtained. A determination of what type of image would result from the guessed coordinate data is then made, followed by a sequence of other 10 guesses and image determinations. The hope is that the sequence of guesses converges to one that more or less yields the experimentally determined image. Non-iterative methods can be more advantageous than iterative approaches because they can be done more quickly, and because they don't suffer from non-convergence problems.

15 To derive the aforementioned equations and other intermediate equations for deriving the coordinate data of the imaging instrument, three right-handed Cartesian coordinate systems are introduced: a world (w) coordinate system, virtual detector (i) coordinate system, and real detector (l) coordinate system, which are shown in Figures 5 and 6A-B. The phantom 32, 20 and the patient are fixed with respect to the world coordinate system. In Figure 5, a medical linear accelerator/CT imaging instrument having a rotating gantry is shown. In the embodiment shown, a medical linear accelerator, used for the therapeutic delivery of energy packets, is integrated with a cone-

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beam computer tomography (CT) imaging system. For this type of instrument, the world coordinate system is fixed in space. For an instrument composed of a rotating turntable and cone-beam computerized tomography laboratory bench, shown in Figures 6A-B, the world coordinate system is fixed  
5 to the rotating table. The z-axis of the world coordinate system ( $z^w$ ), is along the rotation axis of the gantry for the medical linear accelerator/CT imaging instrument, and along that of the turntable for the laboratory bench instrument. The  $x^w$  axis points to the source at a gantry angle of zero and  $y^w$  points to the source at a gantry angle of 90° degrees. The positive direction of rotation of  
10 the turntable ( $-z^w$ ) is opposite to that of the gantry ( $z^w$ ). Under this convention, the source appears to move around from the x-axis ( $x^w$ ) to y-axis ( $y^w$ ) in both the fixed and rotating world coordinate systems, when the gantry or turntable rotates from 0 degree to 90 degrees. The laboratory cone-beam CT system can be adjusted through three axes of linear motion for the x-ray source and  
15 detector, along with one rotation axis and one linear axis for the phantom 32 and turntable. The resolution of the computer controlled positioning system is 30  $\mu\text{m}$  in all directions and 0.015 ° in rotation.

The origin of the virtual detector system is located at the projection point of the origin of the world coordinate system on the detector plane. This  
20 point is also the piercing point. The y-axis of the virtual detector coordinate system is anti-parallel to the z-axis of world coordinate system. The direction of the  $x^l$  axis is oriented perpendicular to the vector from the piercing point to the source point and the y-axis of the virtual detector. The real detector

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system is used to model possible tilting, specified by a roll angle  $\phi$  and a pitch angle  $\theta$ , and rotation, specified by a rotation angle  $\eta$  about the detector normal axis of the detector from the virtual detector plane as shown in Figure 5.

5           Once the coordinate systems are defined, objects in one coordinate system can be easily referenced to another. The following equation expresses the transformation of a position vector ( $P^w$ ) in the world coordinate system to one ( $P^i$ ) in the virtual coordinate system.

$$P^i = R_w^i P^w + T_w^i \quad (1)$$

10          where  $P \in R^{3 \times 1}$ ,  $R_w^i \in R^{3 \times 3}$ , and  $T_w^i \in R^{3 \times 1}$  are position of object, rotation matrix and translation vector, respectively. The rotation matrix,  $R_w^i$  and translation vector,  $T_w^i$  can be written as follows.

(2)

and

$$15 \quad T_w^i = [X_d \ Y_d \ Z_d] \quad (3)$$

where  $S_t$  and  $C_t$  are sine and cosine of the nominal gantry angle,  $t$ . The translation vector,  $T_w^i$ , is the position vector from the origin of  $i$  to the origin of  $w$ . The subscript  $d$  is used to indicate the position of detector. Since the virtual detector system is defined such that piercing point is perpendicular to the  $x^i$ ,  
 20  $X_d$  is zero and the x-ray source appears in the y-z plane of the virtual detector coordinate system. Therefore, calibration parameters in this transformation are  $t$ ,  $Y_d$ , and  $Z_d$ . Detector rotation and/or tilting information are included in

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the rotation matrix,  $R_i^l$ . This matrix transforms vectors from the virtual detector system ( $i$ ) to the real detector system ( $l$ ) according to

$$P^l = R_i^l P^i \quad (4)$$

where  $P^l = [X^l \ Y^l \ Z^l]^T$  and  $P^i = [X^i \ Y^i \ Z^i]^T$  are position vectors in the real detector  
5 and virtual detector systems, respectively.  $R_i^l$  can be written as follows using the parameters,  $\phi$ ,  $\theta$ , and  $\eta$ :

$$(5)$$

where  $\phi$ ,  $\theta$ , and  $\eta$  are the tilting and rotation of the detector as shown in Figure 5.

10 An x-ray projection of the object onto the detector plane ( $X$ ,  $Y$ ) can be calculated using the trigonometric relations as follows:

$$X = X_s^l - Z_s^l (X_s^l - X^l) / (Z_s^l - Z^l) \quad (6a)$$

$$Y = Y_s^l - Z_s^l (Y_s^l - Y^l) / (Z_s^l - Z^l) \quad (6b)$$

where  $P_s^l = [X_s^l, Y_s^l, Z_s^l]^T$  and  $P^l = [X^l, Y^l, Z^l]^T$  are the position vector of the x-  
15 ray source and the position vector of the object in the real detector coordinate system ( $l$ ), respectively. Finally, the digitization of the image can be modeled as follows:

$$U = -S_f \bullet X + U_{\text{offset}} \quad (7a)$$

$$V = -S_f \bullet Y + V_{\text{offset}} \quad (7b)$$

20 where  $S_f$  is the scale factor [pixel/mm] calculated by the scale module 48, and  $U_{\text{offset}}$  and  $V_{\text{offset}}$  are  $U$  and  $V$  distances separating the detector pixel of the origin of  $U$  and  $V$  from the piercing point, respectively. It is worth noting that the directions of the vectors  $U$  and  $V$  are opposite to the vectors  $X$  and  $Y$ ,

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respectively. The scale factor can be taken from the manufacturer's specification or determined experimentally. Eleven parameters are used to characterize the cone-beam CT geometry: source position  $(X_s, Y_s, Z_s)^t$ , detector position  $(Y_d, Z_d)^t$ , detector tilt  $(\phi, \theta)$ , detector rotation  $(\eta)$ , piercing point  $(U_{\text{offset}}, V_{\text{offset}})$ , and gantry angle,  $t$ . These can be reduced to 9 independent variables by recognizing that (1) the origin of the detector coordinate system is on the line which connects the source and piercing point; therefore, the detector position can be expressed as one independent variable, and (2) the gantry angle is also determined by the source position, bringing the number of independent parameters to a total of nine.

The phantom 32 is placed approximately near the nominal iso-center of the instrument and the longitudinal direction of the phantom 32 is aligned roughly to the axis of rotation of the instrument. This guarantees that the phantom is visible in all projections. Since all measurements are referenced to the phantom, it is not necessary to place the phantom with great accuracy in the world coordinate system.

As described below, it is useful to eliminate the effect of the phantom location in space through determination of an alternative reference frame. For example, in the case of a gantry-based system, the determination of a reference frame that minimizes the discrepancy with respect to a simple circular trajectory permits the results of the calibration to be reported independent of the placement of the phantom (i.e. referenced to the mean circular motion that is expected from the gantry-based system).

As described above, the projection module 42 obtains first ellipse parameters  $a_1, b_1, c_1, u_{01}, v_{01}$  that describe the first ellipse, which is the image projection of the first circle 34, and second ellipse parameters  $a_2, b_2, c_2, u_{02}, v_{02}$  that describe the second ellipse, which is the image projection of the second circle 36, according to

$$a(u-u_0)^2 + b(v-v_0)^2 + 2c(u-u_0)(v-v_0) = 1 \quad (8)$$

where  $(u_0, v_0)$  is the center of the ellipse. Once ellipse parameters are found, the detector angle,  $\phi$ , can be calculated using the following equations:

$$\sin \phi = -c_1 \zeta_1 / (2a_1) - c_2 \zeta_2 / (2a_2) \quad (9)$$

$$\zeta_k = Z_s^1 a_k \sqrt{a_k} / \sqrt{a_k b_k + a_k^2 b_k (Z_s^1)^2 - c_k^2}, \quad k=1,2 \quad (10)$$

where  $\zeta$  is the intermediate parameter used in ellipse parameter calculation and subscript,  $k$ , indicates one of two circular group of ball bearings.

Also described above was the concept of the converging point: if the line  $L_i$  is defined by

$$L_i = I \cap D_i, \quad (11)$$

where  $D_i$  is  $i$ -th divergent plane and  $I$  is the detector plane (see Figure 4), then the converging point is given by

$$P_c = I \cap (D_1 \cap D_2 \cap \dots) \quad (12)$$

$$= I \cap L_d \quad (13)$$

where, if all the lines connecting a pair of point objects are parallel, the intersection of divergent planes,  $(D_1 \cap D_2 \cap \dots)$ , forms the one line,  $L_d$ . The

concept of the piercing point is now used to first obtain the detector rotation angle  $\eta$ .

*Calculation of detector rotation,  $\eta$ :*

The rotation of the detector with respect to its normal axis is referred to as  $\eta$ . By identifying common features in the 3D circular pattern of BBs, and the projected elliptical pattern, it is possible to determine a value for  $\eta$ . The shape of the fitted ellipse on the virtual detector plane ( $X^i$ - $Y^i$ ) depends on the source position with respect to the phantom as shown in Figure 5. By choosing two points at the extreme  $X^i$  dimension on each of the two fitted ellipses, two pairs of points forming two lines parallel to  $X^i$  are identified.

The location of these two points can be found from the numerical model of the ellipse. If the center of ellipse is assumed to be (0,0), then

$$a U^2 + b V^2 + 2cUV = 1$$

or

$$V^2 + (2\frac{c}{b}U) V + (\frac{a}{b}U^2 - \frac{1}{b}) = 0$$

When the discriminant of  $V$  equals to zero, the corresponding  $U$  equals either maximum or minimum value as follows:

$$(\frac{c}{b}U)^2 - (\frac{a}{b}U^2 - \frac{1}{b}) = 0$$

or

$$U = \pm \sqrt{\frac{b}{ab - c^2}}$$

and

$$V = -\frac{c}{b}U$$

Since  $U$  has two real roots, and  $b$  is real positive,  $ab-c^2$  is greater than zero. As shown in Figure 7, the slope of the line passing through the two points found in the equations for  $U$  and  $V$  is determined by ellipse parameters. Two lines from each ellipse are used by the converging point module 50 to find the converging point,  $P_\phi$ .

The last expressions for  $U$  and  $V$  may be generalized for very large detector angle,  $\phi$  and  $\theta$ . (The converging point  $P_\theta$  has an angle of  $\tan\phi \times \sin\theta$  with the axis of  $V$ .) A line, which connects the outmost position of the two ellipses shown as dashed line in Figure 8, may be used instead of using a parallel line to  $V$ -axis. The equation of the line can be written using two parameters,  $A$  and  $B$  as follows.

$$U = A \times V + B$$

The slope of the line,  $A$ , can be approximated using two points from each ellipse:

$$A \approx (U_1 - U_2) / (V_1 - V_2) = (U_1 - U_2) / (U_1 c_1 / b_1 - U_2 c_2 / b_2)$$

The condition of zero discriminant of each ellipse ( $k=1,2$ ) can be found as follows.

$$(c_k^2 - a_k b_k) B_k^2 + (a_k A^2 + b_k + 2c_k A) = 0$$

or

$$B_k = \pm \sqrt{\frac{b_k + a_k A^2 + 2c_k A}{a_k b_k - c_k^2}}$$

where  $B$  has one trivial solution and it can be found easily by comparing the sign with  $(U_1+ U_2)/2$ . The generalizations of  $U$  and  $V$  are therefore

$$V_k = -\frac{a_k A_k B_k + c_k B_k}{a_k A_k^2 + b_k + 2c_k A_k}$$

$$U_k = -A_k \frac{a_k A_k B_k + c_k B_k}{a_k A_k^2 + b_k + 2c_k A_k} + B_k$$

- 5 The previous expressions for  $U$  and  $V$  are recovered from these last two equations when  $A$  is zero.

Referring to Figure 9, lines connecting two pairs of points on the virtual detector plane ( $X^i$  and  $Y^i$ ) are denoted by  $L_1$  and  $L_2$ . When the detector is tilted by  $\phi$  around the axis of  $Y^i$ , these two lines converge to one point. The point is  
 10 the converging point,  $P_\phi$ , due to the detector angle,  $\phi$ , and is the intersection of the axis of the divergent plane, and the real detector plane ( $\alpha$  and  $Y^i$ ) as explained below. If there are BBs in the phantom, shown as a broken circle in Figure 9, the projected image of the BBs forms a line passing through point,  $P_a$ , on the virtual detector plane (i.e., the special case of an ellipse for which  
 15 the length of the short axis is zero). The line,  $L_a$ , passes through the point,  $P_\phi$ , and is parallel to the axis  $\alpha$ . Since the ratio of short axis to long axis of the ellipse,  $\sqrt{a_k/b_k}$  ( $k=1,2$ ), is proportional to the distance from the point,  $P_a$ , to the center of each ellipse,  $P_1$  and  $P_2$ , the location of the point,  $P_a$ , can be found using the following equation,

20 
$$(P_0^a - P_0^2)/(P_0^1 - P_0^a) = \sqrt{a_2/b_2} / \sqrt{a_1/b_1}$$

or

$$P_0^a = (P_0^1 \sqrt{a_1/b_1} + P_0^2 \sqrt{a_2/b_2}) (\sqrt{a_1/b_1} + \sqrt{a_2/b_2}) \quad (14)$$

where  $P_m^n$  is a position vector from point m to point n. The following is true as shown in Figure 9.

$$P_0^a = Y_s^i / \cos(\theta) \quad (15)$$

5 Angles of lines,  $L_1$  and  $L_2$ , with respect to line  $L_a$  are proportional to the distance from the point,  $P_a$ , to the center of each ellipse,  $P_1$  and  $P_2$ . The angle between the line,  $L_a$  and  $X^i$ , or  $\alpha$  and  $X^i$  is the detector angle,  $\eta$ . When the detector rotation angle,  $\eta$ , is not zero, angles of lines in the real detector coordinate system are different by the detector rotation angle,  $\eta$ , as follows.

$$10 \quad P_2^a / P_a^1 = A(\alpha, L_2) / A(\alpha, L_1) \\ = (A(X^i, L_2) - \eta) / (A(X^i, L_1) - \eta)$$

or

$$\eta = (P_a^1 A(X^i, L_1) + P_2^a A(X^i, L_2)) / P_1^2 \quad (16)$$

where  $A(p,q)$  is an angle between line p and line q. Once  $\eta$  is known using the  
 15 equation (16), the effect of  $\eta$  can be corrected by rotating the image by  $\eta$ .  
 Therefore, the remainder of the calibration procedure assumes that the detector rotation angle,  $\eta$ , has been estimated and corrected.

*Calculation of detector tilt angle,  $\theta$  and  $\phi$ :*

Using the pairs of ball bearings parallel to the  $Z^w$  axis (Figure 2D), the  
 20 converging point,  $P_\theta$ , which is due to the detector angle  $\theta$ , can be found. The axis of divergent planes in this case is parallel to  $Y^i$ , which is parallel to  $Z^w$ , as shown in Figure 10. The axis of divergent planes intersects the detector plane

unless  $\theta$  is zero (regardless to the angle of  $\phi$ ). The converging point,  $P_\theta$ , has the following relationship as shown in Figure 10.

$$\begin{aligned}\alpha_\theta &= Y_\theta^i \tan(\theta) \tan(\phi) \\ \beta_\theta &= Y_\theta^i / \cos(\theta) = Z_s^i \cos(\phi) / \sin(\theta)\end{aligned}\quad (17)$$

5 and

$$\tan(\phi) \sin(\theta) = \alpha_\theta / \beta_\theta \quad (18)$$

The location of the converging point,  $P_\theta = (\alpha_\theta, \beta_\theta)$ , can be found from the point of intersection of all the lines shown in Figure 2C projected on the detector plane. Since the X-axis component of the source position in the virtual  
10 detector coordinate system is zero,  $P_s^i = [0, Y_s^i, Z_s^i]$ , the Z-axis component of the source position in the real detector coordinate system can be found as follows using equations (4) and (5).

$$\begin{aligned}Z_s^i &= Z_s^i \cos(\theta) \cos(\phi) + Y_s^i \sin(\theta) \\ &= \sin(\theta) \cos(\theta) (\beta_\theta + Y_s^i / \cos(\theta))\end{aligned}\quad (19)$$

15 From the ellipse model in equations (9) and (10),  $\phi$  is proportional to  $Z_s^i$ , when  $ab-c^2$  is greater than zero (see Figure 7). Since  $\beta_\theta$  is known from the converging point of  $P_\theta$  and  $Y_s^i / \cos(\theta)$  is known from the converging point of  $P_\phi$ ,  $Z_s^i$  is simply a function of the detector angle of  $\theta$ , and is proportional to  $\theta$  when is less than  $45^\circ$ . Therefore  $\theta$  is proportional to  $\phi$  in ellipse model as  
20 shown in Figure 11. Intersection of two lines, one from equation (18) and the other from the equations (9), (10), and (19) is the solution of  $\phi$  and  $\theta$ . This solution can be found using non-linear root finding method. There is a unique

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solution when the angle of  $\theta$  is less than  $45^\circ$ , in accordance with equation (19).

*Calculation of source position ( $X_s$   $Y_s$   $Z_s$ )<sup>i</sup>:*

Once  $\phi$  and  $\theta$  are known,  $Y_s^i$  and  $Z_s^i$  can be found using equation (15) and (17), respectively. When  $\theta$  is infinitesimally small (e.g. less than 0.001 degrees), however, equation (17) is not stable enough to estimate  $Z_s^i$ . When  $\theta$  is this small, the following methods are used to estimate  $Z_s^i$ . The distance between two ellipses along the  $Y^i$  axis,  $L_1$  and  $L_2$  have the following relations due to the triangulation as shown in Figure 12.

$$10 \quad L_1 / Z_s^i = l / (Z_s^i - Z_d^i + \text{rad}) \quad (20)$$

$$L_2 / Z_s^i = l / (Z_s^i - Z_d^i - \text{rad}) \quad (21)$$

where, rad and  $l$  are the radius of the circular pattern of ball bearing and distance between two circular trajectories, respectively. Combining two equations to calculate  $Z_s^i$  gives,

$$15 \quad Z_s^i = (2 \text{ rad } L_1 L_2) / (l (L_2 - L_1)) \quad (22)$$

Knowing the three detector angles ( $\eta$ ,  $\phi$  and  $\theta$ ) and the source position in the virtual detector coordinate system ( $Y_s^i$  and  $Z_s^i$ ), the source position in the real detector system can be calculated straightforwardly using equations (4) and (5) as follows. (Note:  $X_s^i$  is zero by definition).

$$20 \quad P_s^i = R_i^i P_s^i.$$

*Calculation of detector position ( $Y_d$ ,  $Z_d$ )<sup>i</sup>:*

One of the detector position vectors,  $Z_d^i$ , can be found from equations (20) and (21).

$$Z_d^i = Z_s^i (L_1 - l) / L_1 + r \quad (23)$$

Since the origin of the world coordinate system is on the line connecting the piercing point and the source, the following relationship is true.

$$5 \quad Y_d^i = Y_s^i / Z_s^i Z_d^i \quad (24)$$

*Gantry Angle Determination:*

The nominal gantry angle,  $t$ , can be calculated by the following procedure. Equations (6.a) and (6.b) can be rewritten as follows.

$$(X_s^l - X) / (X_s^l - X^l) = (Y_s^l - Y) / (Y_s^l - Y^l) \quad (25)$$

10 or

$$\begin{aligned} Y_s^l - Y^l &= (X_s^l - X^l) (Y_s^l - Y) / (X_s^l - X) \\ &= p (X_s^l - X^l) \end{aligned} \quad (26)$$

where  $p = (Y_s^l - Y) / (X_s^l - X)$  can be calculated for each object point,  $P^l = [X^l, Y^l, Z^l]^T$ . Since all the other parameters except nominal gantry angle are known,  
15  $X^l$  and  $Z^l$  are functions of nominal gantry angle,  $t$ , only. Rearranging equation (26) gives

$$[b_1 \ b_2] [S t \ C t]^T = A \quad (27)$$

and

$$\begin{aligned} b_1 &= (p r_1 - r_4) x^w + (p r_3 - r_6) y^w \\ 20 \quad b_2 &= (-p r_3 + r_6) x^w + (p r_1 - r_4) y^w \end{aligned} \quad (28)$$

$$A = p X_s^l - Y_s^l - p (r_2 (-z^w + Y_d^i) + r_3 Z_d^i) + r_5 (-z^w + Y_d^i) + r_6 Z_d^i$$

where  $x^w$ ,  $y^w$  and  $z^w$  are the position of the ball bearing in the world coordinate system, and elements of  $R_i^l$  are denoted in the following way for convenience.

The nominal gantry angle can be found from equation (27) using the linear  
25 least squares method.

*Experimental Testing and Validation:*

The calibration algorithm was evaluated on the laboratory cone-beam CT system. Firstly, simple but accurate motions were applied to the x-ray source and detector by a computer controlled positioning system and their  
5 positions were compared to those calculated using the calibration method. In this test, the turntable, which holds the calibration phantom, was not rotated.

Full rotation of the turntable was tested with angular increments of  $1.2^\circ$  and a fixed position of the x-ray source and detector. The calibration phantom was imaged at each angle and the calibration was estimated for every projection.  
10 Once all the calibration parameters were found with respect to the world coordinate system attached to the phantom, a search was performed and another coordinate system was identified which minimized the excursion of the x-ray source trajectory from a simple circle. All the calibration parameters were re-calculated with respect to this coordinate system. This approach  
15 permits inter-comparison of subtle changes in the calibration results independent of the placement of the phantom. Of course, applying this transformation obscures any gross changes in the geometry that can be described by a global rotation and/or translation.

The effect of precise geometric calibration on the quality in cone-beam  
20 CT reconstructions was examined. A thin steel wire (diameter of 0.16 mm) was positioned inside of the calibration phantom. CT compatible markers (two 3mm plastic spheres and two 5mm plastic spheres) were attached on the outside wall of the phantom 32. The calibration phantom 32 with wire and markers was imaged on the laboratory system (300 projections, 120 kVp, 1

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mAs/projection, and  $1.2^\circ$ ) with known perturbations of the system geometry during the collection of the projection data. The projection data was used for both the calibration and the CT reconstruction. The following perturbations were tested: (1) no disturbance, (2) 5 mm sinusoidal displacement of the x-ray  
5 source in y-z plane, (3) 5 mm sinusoidal displacement of the detector in y-z plane and (4) 5 mm sinusoidal displacement of the source and detector in x-y-z direction. The cone-beam CT reconstruction algorithm can accept the variation of source position, detector position, and detector tilt angle at every pose. However, only geometric features such as image scale, and detector tilt  
10 angle, are treated completely. The quality of the cone-beam CT images with and without perturbation correction was compared.

Accurate reconstruction requires accurate estimation of geometric parameters. The most critical geometric parameters on the cone-beam CT reconstruction are the piercing point (or the center of detector) and detector  
15 rotation angle  $\eta$ . The effect of piercing point on the cone-beam CT reconstruction and the correction with single BB were demonstrated. Small detector rotation ( $\eta$ ) has subtle but visibly detrimental effects on the reconstruction image.

The accuracy of the calibration algorithm depends on the detector tilt,  
20 reducing as the detector tilt angles,  $\phi$  and  $\theta$ , increase. The displacement of the phantom from the iso-center of the system did not significantly reduce the accuracy unless BBs appear overlapped in the projection image. The accuracy of piercing point estimation was not reduced due to the detector tilt

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angles. Since the detector tilt angles affect the calibration accuracy the most, the accuracy of the algorithm was analyzed as a function of the detector tilt angles,  $\phi$  and  $\theta$  in the geometry of a medical linear accelerator in which the source-to-detector distance (SDD) is 160cm and the source-to-isocenter distance (SID) is 100cm. The maximum error of the detector angles were found to be less than  $0.05^\circ$  for  $\phi$  and  $\theta$ , and  $0.005^\circ$  for  $\eta$  even at large detector angles ( $\phi = \theta = \pm 40^\circ$ ). In the practical range of the detector tilt angle,  $\phi$  and  $\theta \ll \pm 5^\circ$ , the error of the detector tilt angles,  $\phi$ ,  $\theta$ ,  $\eta$ , and magnification factor were negligible. The magnification factor was determined as the ratio of SDD to SID or  $Z_s^i / (Z_s^i - Z_d^i)$ . Error in the magnification factor was found to be less than 0.05 % at a large detector tilt angle of  $\pm 40^\circ$ . As discussed below, the inaccuracy of the algorithm is less than the uncertainties arising from the imperfections in phantom construction and BB detection. The sensitivity of the algorithm to these uncertainties should be taken into consideration.

The calibration method is an analytic method, which provides exact results when the positions of the BBs are exactly known and the number of BBs is larger than twelve. It is worth exploring the sensitivity of the calibration algorithm due to the uncertainty of the BB position. Although it is possible to derive direct analytic solutions for the sensitivity analysis, a numerical method is often preferred because of its simplicity. Thus, the resulting estimations in this study are approximate. The sensitivity,  $\Delta X$ , in an arbitrary calibration parameter,  $X$ , can be estimated in a root mean square sense as:

(29)

where  $\delta$  is the uncertainty of the ball bearing location, and  $U_i$  and  $V_i$  is the location of the  $i$ -th BB. The uncertainty of the ball bearing location may include manufacturing inaccuracies and uncertainty in the identification of the center of a BB. Instead of calculating direct partial derivatives, the following equation  
5 was used to approximate the sensitivity of the calibration algorithm.

(30)

Table I summarizes the effect of number of ball bearings on the sensitivity for a system as exists on the medical linear accelerator (SDD = 160cm and SID = 100cm). The sensitivity analysis was based on the  
10 assumption that the uncertainty of ball bearing position was 0.1 pixels. This corresponds to the manufacturing inaccuracy of 25  $\mu\text{m}$  or error of 0.1 pixels in the image processing. Since one ball bearing consists of more than 200 pixels in the image in this configuration, this is a reasonable assumption. Larger numbers of BBs reduced the uncertainty as shown in Table I. When the  
15 number of BBs was doubled from 16 to 32, the uncertainty of the source position, detector position, and detector angles were reduced by about 60%, 60% and 90% on average, respectively. Source and detector positions in the direction of beam,  $Z_s^i$  and  $Z_d^i$ , were the most sensitive parameters to the uncertainty of ball bearing position. Although the uncertainty of  $Z_s^i$  and  $Z_d^i$ ,  
20 were about 0.12% (1.2mm at SAD of 1000mm for the phantom with 24 ball bearings), the uncertainty of the magnification factor, the ratio of SDD ( $Z_s^i$ ) to SID ( $Z_s^i - Z_d^i$ ), was relatively small (less than 0.01 %). Therefore, the impact on the reconstructed image quality is expected to be negligible.

TABLE I. Uncertainty in the calibration parameters for different numbers of ball bearings.

Simulation condition is as follows: nominal gantry angle of zero degree, source to detector distance (SDD) of 1600 mm, source to axis of rotation distance (SAD) of 1000 mm, and detector tilting ( $\phi, \theta, \eta$ ) of (0, 0, 0) degree. Uncertainty of ball bearing position is assumed to be 0.1 pixels.

5

N	source position		detector position		detector angle			gantry angle, t [deg]	Magnification $Z_s^i/(Z_s^i-Z_d^i)$ [percent]
	$Y_s^i$ [mm]	$Z_s^i$ [mm]	$Y_d^i$ [mm]	$Z_d^i$ [mm]	$\phi$ [deg]	$\theta$ [deg]	$\eta$ [deg]		
12	0.29	1.89	0.14	1.15	0.09	0.089	0.0080	0.015	0.0093
16	0.17	1.50	0.10	0.92	0.11	0.077	0.0097	0.077	0.0081
20	0.15	1.34	0.09	0.82	0.09	0.069	0.0087	0.068	0.0072
24	0.14	1.23	0.08	0.75	0.09	0.063	0.0078	0.060	0.0066
32	0.12	1.06	0.07	0.65	0.07	0.054	0.0068	0.053	0.0057
40	0.11	0.95	0.07	0.58	0.07	0.049	0.0063	0.049	0.0051
60	0.09	0.78	0.05	0.47	0.06	0.040	0.0053	0.042	0.0042

Figures 13A-D show the sensitivity of the calibration parameters as a function of detector tilt angles,  $\phi$  and  $\theta$ . The sensitivity of the algorithm appears a few times larger than the accuracy of the algorithm. The sensitivity of the algorithm, however, is very small even at very large detector tilt angles as shown in Figures 13A-D.

The performance of the geometric calibration algorithm was evaluated on the laboratory system shown in Figure 6A. A series of accurate displacements in source and detector position were applied and compared to those calculated using the calibration method. Figures 14A and 14B show the applied and measured results when the x-ray source is displaced. Applied movement by the computer-controlled positioning system is shown as a cross and location detected by the calibration algorithm is shown as a circle. Longitudinal, horizontal and vertical directions correspond to X, Y, and Z of the world coordinate system, respectively. Discrepancies in the x-ray source

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positions were found to be 0.08 mm in the direction normal to the beam (Y and Z axis direction) and 0.8 mm in the beam direction (X axis direction). These measured discrepancies are less than those determined through the sensitivity analysis (0.14mm and 1.2mm, respectively as shown in Table I),  
5 due to the conservative estimation of 0.1 pixel error employed in these calculations. Experimental results suggest that the effective pixel error would be about 0.06 to 0.07 pixels. Figure 14C shows the calibration result when the detector position is moved – the discrepancy in the detector position was found to be about 0.06 mm.

10 In the second test, the turntable was rotated for fixed positions of the x-ray source and detector. A total of 300 consecutive images were taken at increments of  $1.2^\circ$ . The piercing point was found as a function of turntable angle. The maximum movement of the piercing point during the turntable rotation was less than 0.1 pixels. The measured gantry (turntable) angle was  
15 compared with the encoder signal reported from the computer controlled positioning system. The maximum error of the turntable angle was about  $0.05^\circ$ . The uncertainty of the nominal gantry angle was about  $0.01^\circ$  and was smaller than the expected,  $0.06^\circ$ , as shown in Table I.

The measured trajectories of the x-ray source and detector are shown  
20 in Figure 15A-D. Even though the angular precision of the turntable in the laboratory cone-beam CT was excellent, a small precession of about  $0.0115^\circ$  at three times per turntable revolution was observed. The wobbling or precession of the turntable generates a “*potato chip*” shaped trajectory for the source and the center of detector in the rotating reference frame. The most

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important detector angle for the precise CT reconstruction,  $\eta$ , was found to be smaller than  $0.01^\circ$  for this system.

The effect of accurate geometric calibration on the quality of reconstructions was examined using a thin steel wire (diameter of 0.16 mm) positioned within the BB phantom at the time of calibration. As described above, four test conditions were explored: (1) circular motion with no disturbance, (2) 5 mm sinusoidal displacement of the x-ray source in y-z plane, (3) 5 mm sinusoidal displacement of the detector in y-z plane and (4) 5mm sinusoidal displacement of the source and detector in x-y-z direction. These results were also compared to the image quality performance achieved using geometric parameters determined through careful mechanical alignment of the laboratory system (including iterative adjustment of the piercing point). Figures 16A-B show the cone-beam CT images using the calibration algorithm (a) and the mechanical calibration (b) for the most complex disturbance. The wire and plastic balls are shown clearly in Figure 16A, but large distortion, artifact and blurring are found in Figure 16B.

Figures 17A-D shows surface plots of the attenuation coefficients reported by the cone-beam CT method for a thin steel wire acquired with (a) the circular motion with the calibration method, (b) complex disturbance with the calibration, (c) circular motion without calibration, and, (d) complex disturbance without calibration. The intensity of the cone-beam CT image of a thin wire was symmetric and the full width at half maximum (FWHM) was 0.78 mm. Improvement in the peak signal was 53 % in the steel wire on average across the four different cases as shown in Table II. The signal from the wire

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was consistent when the calibration method was used regardless of the disturbance applied. Artifact and distortion around the marker was also reduced. On average, improvement in FWHM of the steel wire was 28 %.

- 5 TABLE II. Influence of calibration on the reconstruction of a steel wire. The dataset was acquired on the bench top CBCT system with mechanical determination of the imaging geometry assuming a circular trajectory.

	<i>FWHM</i> (mm)	<i>Signal</i> (arbitrary)
Without calibration algorithm	0.99mm	0.27
With calibration algorithm	0.78mm	0.41
Improvement	28%	53%

- 10 As described below in greater detail, similar tests were performed on a medical linear accelerator. In these investigations, an error in geometric scale was identified. The diameter of the phantom was 5 % larger than manufacturing specifications and agreed within 0.2 % when the full calibration method was employed. This large error in the dimensional accuracy in cone-  
15 beam CT on the medical linear accelerator was due to the use of a nominal SDD (160 cm vs 153 cm) in the previous calibration scheme.

- Figure 18 shows a system 100 for obtaining coordinate data of a source and detector instrument. The system 100 includes a marker assembly 12 having a plurality of markers 14 with a particular geometry, the marker  
20 assembly 12 being disposed in a targeting region 102.

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A set of energy sources 104 contains at least one member for bombarding the plurality of markers 14 with energy. In the embodiment shown, two such members 106 and 108 are provided. The energy source 106 is a MV x-ray source for targeting an object, an organism or part thereof.

5 For example, the energy source 106 may be used for radiation therapy to treat a malignant tumor in a human. The other energy source 108 is a kV x-ray source used for imaging the organism to aid in the delivery of radiation from the energy source 106.

The system 100 also includes a set of detectors 110 containing at least one member, wherein energy emitted from any one member of the set of energy sources 104 may be detected by at least one member of the set of detectors 110. In the embodiment shown, the detector 112 detects energy emitted from the source 106, while the detector 114 detects energy from the source 108.

15 In another embodiment, there may be a plurality of sources, but only one detector that detects energy from all these sources. For example, in a triangular arrangement, two sources and one detector can be placed at the corners of a triangle. Conversely, in yet a different embodiment, there may be a plurality of detectors for detecting energy from a single source.

20 An image device 116 includes software and hardware coupled to the set of detectors 110 that processes information captured by the detectors to form image data of the plurality of markers 14. The image device 116 can consist of a central device to which information from the detectors is

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funneled. Alternatively, the device can consist of a plurality of devices, one for each detector, dispersed where each detector is disposed.

A calibration module 118 utilizes information about the particular geometry of the plurality of markers 14 and the image data to determine  
5 coordinate data of at least one of the set of energy sources 104 and the set of detectors 106.

The above-described analytical method for obtaining coordinate data may be applied to the system 100 to obtain location coordinates of the set of sources 104, and position/orientation coordinates of the set of detectors 110,  
10 which data may be used to cross-calibrate the imaging system, which includes the source 106 and detector 112, and the delivery system, which includes the source 108 and the detector 114.

In particular, the position/orientation of the imaging system source 106 and detector 112 may be obtained with respect to the world reference frame.  
15 Likewise, the position/orientation of the delivery system source 108 and detector 114 may be obtained with respect to the same world reference frame. More generally, the position/orientation of the imaging system source 106 and detector 112 may be obtained with respect to a plurality of reference frames, and the position/orientation of the delivery system source 108 and  
20 detector 114 may be obtained with respect to the same plurality of reference frames. Finding these coordinates with respect to a common reference frame(s) affords the opportunity to cross-calibrate the imaging system and the

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delivery system, where cross-calibrating two components involves relating coordinate data of one component to coordinate data of the other component.

It should be emphasized that the principles of the present invention can be used to cross-calibrate any of the components of a source and detector system comprising a plurality of sources and a plurality of detectors. The source and detector system might just comprise components for imaging, and be devoid of any components for therapeutic delivery of energy, and vice versa.

It should be noted that the geometry of the marker assembly 12 permits concurrently disposing a target (not shown), consisting of an object, an organism, or a part thereof, and the plurality of markers 14 within the targeting region 102. The target and the marker assembly 12 in the targeting region 102 may both be bombarded with energy packets simultaneously. This affords the opportunity to simultaneously image the object or organism and determine the pose of the source and detector system. For example, in a system with a non-rigid, irreproducible geometry, where a reproducible geometric calibration cannot be obtained, the invention could be used to simultaneously acquire one or multiple projections of the object or organism along with the source and detector pose for each projection.

The results of experiments applying some of the principles of the present invention to the system 100 of Figure 18 are now provided. First, the sensitivity of the calibration algorithm on the inaccuracy of BB identification due to limitations of image quality or limited accuracy of the phantom

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dimension is analyzed. Table III shows the uncertainty of the calibration parameter due to 0.5 pixel error. The pixel error of the BB position in kV image is less than 0.1 pixels for the marker assembly 12 for system 100. However, the poor quality of the portal image compared to the kV diagnostic image gives poorer estimation, and pixel error seems to be about 0.5 pixels on average. Larger ball bearings and higher monitor units (MU) can be used to make better portal images of the phantom.

Table III. Uncertainty in geometric parameters for different number of ball bearings and 0.5 pixel error in BB localization.

N	source position		detector position		detector angle			gantry angle, t [deg]	Magnification $Z_s^i/(Z_s^i-Z_d^i)$ [percent]
	$Y_s^i$ [mm]	$Z_s^i$ [mm]	$Y_d^i$ [mm]	$Z_d^i$ [mm]	$\phi$ [deg]	$\theta$ [deg]	$\eta$ [deg]		
12	1.1925	9.4450	0.7180	5.7435	0.4515	0.4430	0.0400	0.0760	0.0465
16	0.8545	7.5175	0.5155	4.5890	0.5420	0.3840	0.0485	0.3840	0.0405
20	0.7620	6.7150	0.4595	4.0990	0.4660	0.3435	0.0435	0.3385	0.0360
24	0.6955	6.1295	0.4195	3.7420	0.4425	0.3135	0.0390	0.3020	0.0330
32	0.6025	5.3085	0.3635	3.2405	0.3730	0.2715	0.0340	0.2660	0.0285
40	0.5385	4.7480	0.3250	2.8985	0.3370	0.2430	0.0315	0.2465	0.0255
60	0.4400	3.8770	0.2655	2.3665	0.3015	0.1980	0.0265	0.2110	0.0210

Megavoltage beam stability is tested first. At fixed gantry angle of the source 108, nine images of phantom are taken continuously. The position of the electron beam on the target was found to vary over the first nine images. Figure 19 shows the trajectory of the electrons on the target, where the Z-axis is the direction pointing out from iso-center away from gantry. Since the first couple of images and the last image are extremely poor, those images could not be used. The beam position is controlled very well in the direction of cross

plane (Y axis). Range of motion in Y and Z direction is about 0.3 mm and 1.5 mm, respectively.

The nominal gantry angle and measured gantry were compared. Thirty-six portal images were taken at gantry angles spaced at 10 degrees. Ten MU are given at each gantry angle. Geometric parameters such as source position, detector position and tilt angle, and gantry angle were calculated at each angle. Figure 20 shows the nominal gantry angle reported by the linear accelerator console and measured gantry angle from the calibration. Maximum error of the gantry angle is always less than 0.1 degree as shown in Figure 20.

Figure 21 shows the MV source position and piercing point on the detector in 3 dimensional spaces. Average source to iso-center distance (SAD) is 1003.2mm and source to detector distance is 1600.4mm. The maximum deviation of the beam position from the ideal trajectory of a perfect circle is found at gantry angles of  $-90$  degree and  $90$  degree. The MV source moves toward the gantry by 1.2mm and toward the couch by 1.2mm again at gantry angle of  $-90$  and  $90$  degree, respectively. This movement is also found from the analysis of piercing point movement as a function of gantry angle.

Figure 22 shows the alignment of collimator rotational axis to the MV source position. The collimator rotational axis can be found by attaching the phantom to the collimator. Thirty-six images are taken by rotating collimator with the phantom. Ten MU is given to each image. The source position in the rotating coordinate system fixed in the phantom will stay at a point when the

source is at the axis of collimator rotation. If the source is at distance from the axis of collimator rotation, the source position follows a circular trajectory around the axis of collimator rotation. Thin lines with small circles represent the raw data of source positions in rotating coordinate system of the phantom.

5 The axis of rotation can be found by averaging the source position. The average distance of the source positions from the center indicates the distance between source position and the axis of collimator rotation. Thick lines represent the average motion of the source around collimator axis. It was found to be 0.9mm.

10 It should be understood that various modifications and adaptations could be made to the embodiments described and illustrated herein, without departing from the present invention. For example, many types of imaging devices can benefit from the principles of the present invention. Figure 23, for instance, shows a C-arm instrument 200 used for fluoroscopy in interventional  
15 radiology. A marker assembly 14 is also shown. By imaging the marker assembly 14 and performing the analysis described above, the instrument 200 can be calibrated according to the principles of the present invention.

It should be further understood that the method for calibration can be repeated at as many nominal gantry angles as desired. At each gantry angle,  
20 the geometry of the marker assembly 12 and the image data obtained at that gantry angle yield the nine parameters  $(X_s, Y_s, Z_s)$ ,  $(X_d, Y_d, Z_d)$  and  $(\theta, \phi, \eta)$ . Obtaining coordinate information at several gantry angles affords the opportunity to study motion of the source as a function of time (e.g., MV focal

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spot motion). Thus, a series of subsequent poses and a time-based detector system can be used to track motion, calibrating the coordinate data obtained at each pose according to the principles of the present invention.

The scope of the invention is to be defined in the appended claims.

**Claims**

What is claimed is:

1. A system for obtaining coordinate data of a source and detector instrument, the system comprising
  - 5 a marker assembly having a plurality of markers with a particular geometry;
  - an energy source for targeting the plurality of markers with energy packets;
  - a detector for detecting energy packets after the plurality of markers
  - 10 have interacted therewith;
  - an image device for forming image data of the plurality of markers from the energy packets detected by the detector; and
  - a calibration module for utilizing the particular geometry of the plurality of markers and the image data to non-iteratively determine coordinate data
  - 15 that includes a pitch of the detector.
2. The system of claim 1, wherein the coordinate data is used to calibrate the source and detector instrument.
3. The system of claim 1, wherein the coordinate data includes three source coordinates defining a position of the energy source, three detector
- 20 position coordinates defining a position of the detector and three detector orientation coordinates defining an orientation of the detector, one of the three

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detector orientation coordinates being an angle specifying the pitch of the detector.

4. The system of claim 1, wherein the energy source includes at least one of one of an electromagnetic wave source, a particle accelerator and a  
5 radionuclide source.

5. The system of claim 1, wherein the energy source includes at least one of an x-ray source, a gamma ray source, an atomic source, a sub-atomic source, and an optical photon source.

6. The system of claim 1, wherein the source and detector instrument  
10 includes one of a radiography instrument, a stereography instrument, a bi-plane imaging instrument, a fluoroscopy instrument, a tomosynthesis instrument, and a tomography instrument.

7. The system of claim 1, wherein each of the markers is a metallic sphere.

15 8. The system of claim 7, wherein the plurality of markers describe a first circle and a second circle that are parallel and lie on a cylinder.

9. The system of claim 8, wherein the image data correspond to a first ellipse associated with a first projection of the first circle onto the detector and a second ellipse associated with a second projection of the second circle onto  
20 the detector.

10. The system of claim 9, wherein the calibration module includes

a projection module for obtaining first ellipse parameters that describe the first ellipse and second ellipse parameters that describe the second ellipse; and

a marker assembly module for obtaining geometric parameters of the  
5 marker assembly.

11. The system of claim 10, wherein the calibration module determines the coordinate data from the first ellipse parameters, the second ellipse parameters and the geometric parameters of the marker assembly.

12. The system of claim 11, wherein the calibration module further includes  
10 an intersection module for determining a location of an intersection point where lines connecting points on the first ellipse to opposite points on the second ellipse intersect; and

a scale module for obtaining a scale factor corresponding to the image data, wherein the calibration module determines the coordinate data from the  
15 first ellipse parameters, the second ellipse parameters, the geometric parameters of the marker assembly, the intersection point and the scale factor.

13. A system for obtaining coordinate data of a source and detector instrument, the system comprising

20 a marker assembly having a plurality of markers with a particular geometry;

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an energy source for targeting the plurality of markers with energy packets;

a detector for detecting energy packets after the plurality of markers have interacted therewith;

5 an image device for forming image data of the plurality of markers from the energy packets detected by the detector, the image data associated with a single view of the plurality of markers; and

a calibration module for utilizing the particular geometry of the plurality of markers and the image data to determine coordinate data that includes a  
10 pitch of the detector.

14. The system of claim 13, wherein the coordinate data is used to calibrate the source and detector instrument.

15. The system of claim 13, wherein the coordinate data includes three source coordinates defining a position of the energy source, three detector  
15 position coordinates defining a position of the detector and three detector orientation coordinates defining an orientation of the detector, one of the three detector orientation coordinates being an angle specifying the pitch of the detector.

16. The system of claim 13, wherein the energy source includes at least  
20 one of one of an electromagnetic wave source, a particle accelerator and a radionuclide source.

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17. The system of claim 13, wherein the energy source includes at least one of an x-ray source, a gamma ray source, an atomic source, a sub-atomic source, and an optical photon source.

18. The system of claim 13, wherein the source and detector instrument  
5 includes one of a radiography instrument, a stereography instrument, a bi-plane imaging instrument, a fluoroscopy instrument, a tomosynthesis instrument, and a tomography instrument.

19. The system of claim 13, wherein each of the markers is a metallic sphere.

10 20. The system of claim 19, wherein the plurality of markers describe a first circle and a second circle that are parallel and lie on a cylinder.

21. The system of claim 20, wherein the image data correspond to a first ellipse associated with a first projection of the first circle onto the detector and a second ellipse associated with a second projection of the second circle onto  
15 the detector.

22. The system of claim 21, wherein the calibration module includes  
a projection module for obtaining first ellipse parameters that describe the first ellipse and second ellipse parameters that describe the second ellipse; and

20 a marker assembly module for obtaining geometric parameters of the marker assembly.

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23. The system of claim 22, wherein the calibration module determines the coordinate data from the first ellipse parameters, the second ellipse parameters and the geometric parameters of the marker assembly.

24. The system of claim 23, wherein the calibration module further includes

5 an intersection module for determining a location of an intersection point where lines connecting points on the first ellipse to opposite points on the second ellipse intersect; and

a scale module for obtaining a scale factor corresponding to the image data, wherein the calibration module determines the coordinate data from the  
10 first ellipse parameters, the second ellipse parameters, the geometric parameters of the marker assembly, the intersection point and the scale factor.

25. A method of determining coordinate data of a source and detector instrument, the method comprising

15 providing a marker assembly having a plurality of markers with a particular geometry;

concurrently disposing a target and the plurality of markers within a targeting region;

bombarding the target and the marker assembly in the targeting region  
20 with energy packets from at least one energy source;

forming image data of the plurality of markers with a detector; and

determining coordinate data of at least one of the detector and the at least one energy source using the particular geometry of the plurality of markers and the image data.

26. The method of claim 25, further comprising calibrating the source and  
5 detector instrument with the coordinate data.

27. The method of claim 25, wherein the step of determining includes determining three source coordinates defining a position of the energy source, three detector position coordinates defining a position of the detector and three detector orientation coordinates defining an orientation of the detector.

10 28. The method of claim 25, wherein in the step of providing a marker assembly, each of the markers is a metallic sphere, such that the plurality of markers describe a first circle and a second circle that are parallel and lie on a cylinder, the image data corresponding to a first ellipse associated with a first projection of the first circle onto the detector and a second ellipse associated  
15 with a second projection of the second circle onto the detector.

29. The method of claim 28, further comprising  
obtaining first ellipse parameters that describe the first ellipse and second ellipse parameters that describe the second ellipse; and  
obtaining geometric parameters of the marker assembly.

20 30. The method of claim 29, wherein in the step of determining coordinate data includes using the first ellipse parameters, the second ellipse parameters

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and the geometric parameters of the marker assembly to obtain the coordinate data.

31. A system for obtaining coordinate data of a source and detector instrument, the system comprising

5 a marker assembly having a plurality of markers with a particular geometry;

a set of energy sources containing at least one member for bombarding the plurality of markers with energy;

10 a set of detectors containing at least one member, wherein energy emitted from any one member of the set of energy sources may be detected by at least one member of the set of detectors;

at least one image device for forming image data of the plurality of markers from energy detected by the set of detectors; and

15 a calibration module for utilizing the particular geometry of the plurality of markers and the image data to determine coordinate data of at least one of the set of energy sources and the set of detectors, wherein at least one of the number of members of the set of energy sources and the number of members of the set of detectors is greater than one.

20 32. The system of claim 31, wherein the number of members of the set of energy sources is greater than one, and wherein the coordinate data include position coordinates of the members of the set of energy sources with respect to at least one common reference frame, the calibration module cross-

calibrating the members of the set of energy sources using the position coordinates.

33. The system of claim 31, wherein the number of members of the set of detectors is greater than one, and wherein the coordinate data include  
5 coordinates of the members of the set of detectors with respect to at least one common reference frame, the calibration module cross-calibrating the members of the set of detectors using the coordinates.

34. The system of claim 31, wherein the number of members of the set of detectors is greater than one and the number of members of the set of  
10 detectors is greater than one, and wherein the coordinate data include coordinates of the members of the set of detectors with respect to at least one common reference frame, and coordinates of the members of the set of sources with respect to the one reference frame, which are used by the calibration module to cross-calibrate the members of the set of detectors with  
15 the members of the set of sources.

35. A marker assembly for calibrating a source and detector system, the marker assembly comprising a first set of at least two markers and a second set of at least two markers, the first set of markers disposed substantially on a first plane, and the second set of markers disposed substantially on a second  
20 plane.

36. The marker assembly of claim 35, wherein the first set is arranged on a first circle and the second set is arranged on a second circle, the first and second circles being parallel and lying on a cylinder.

37. The marker assembly of claim 36, wherein the first set and the second set include ball bearings.

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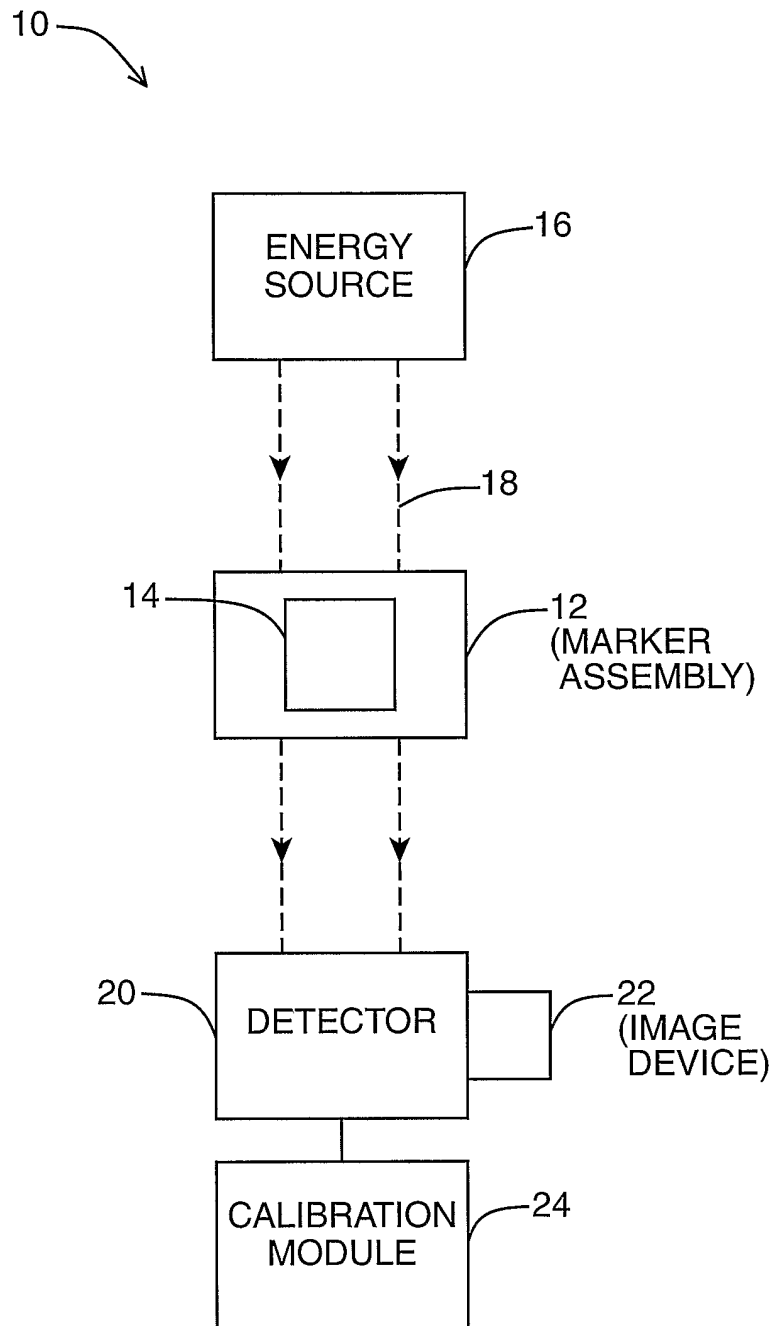


FIG. 1

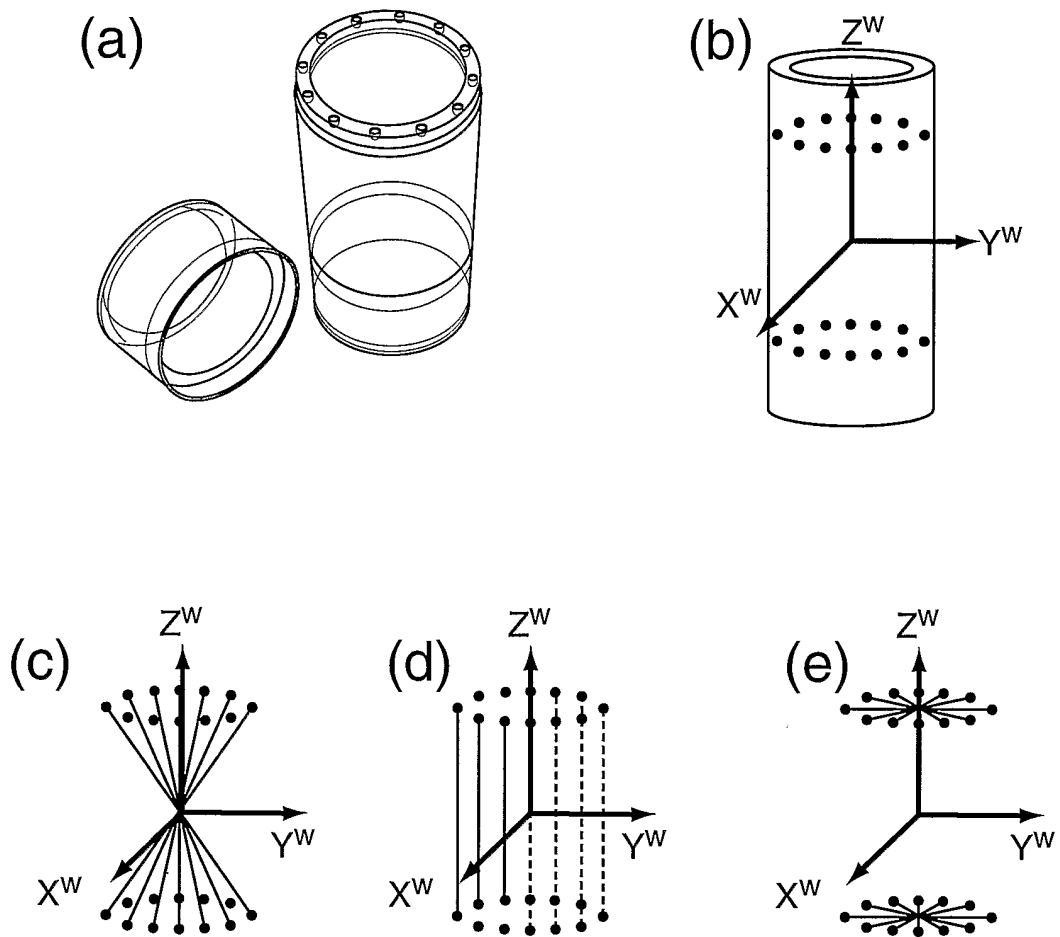


FIG. 2

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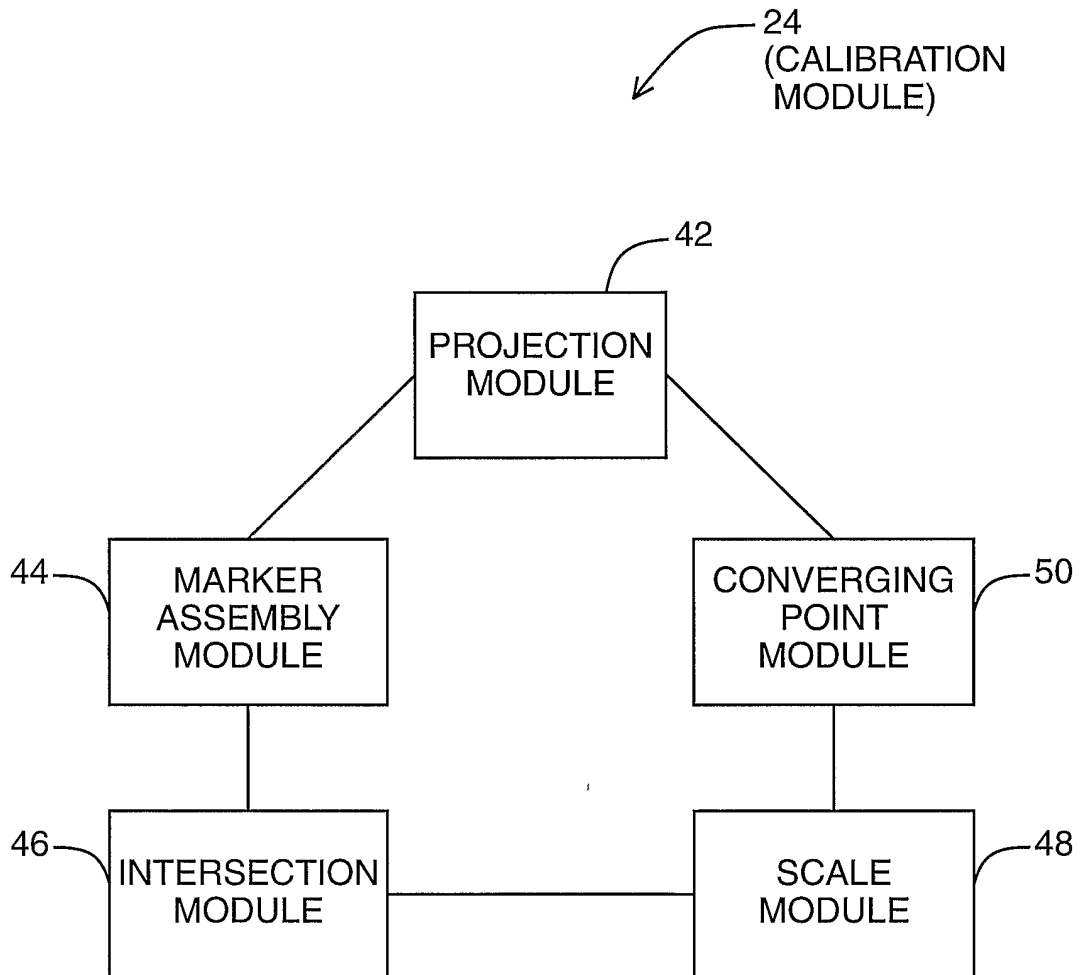


FIG. 3

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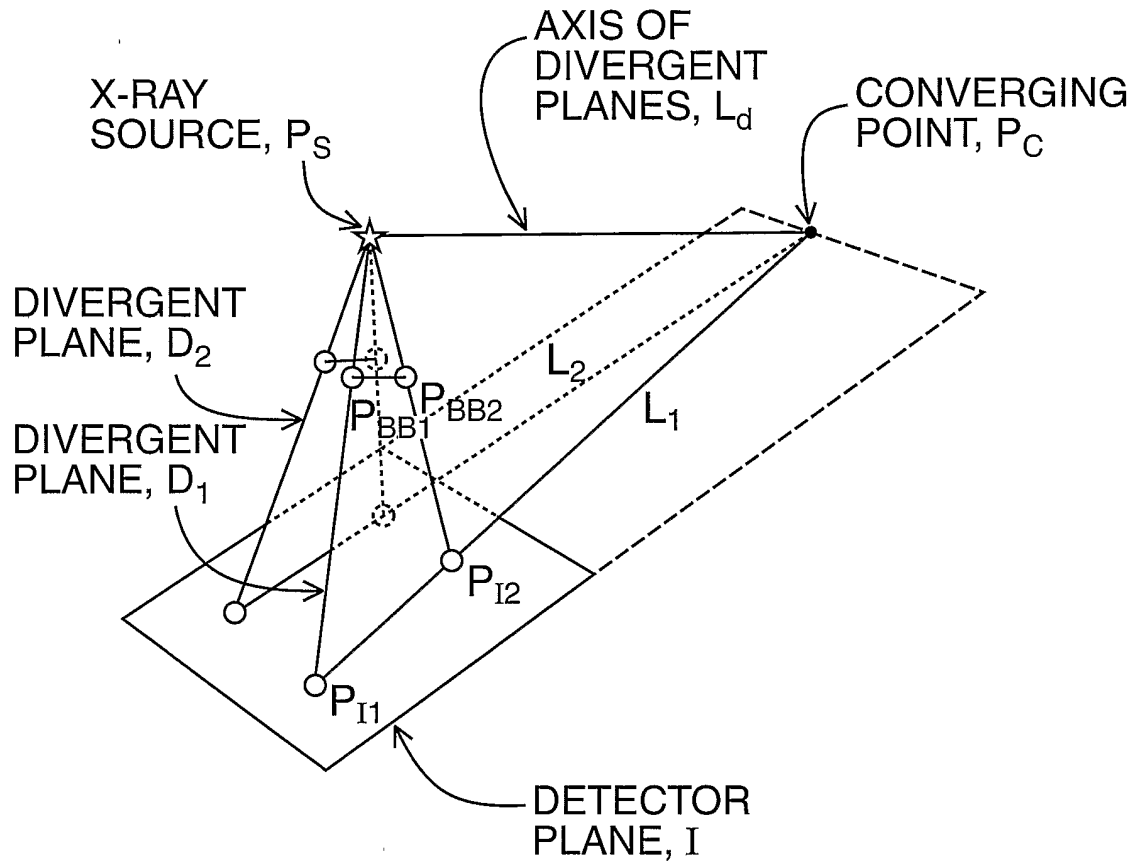


FIG. 4

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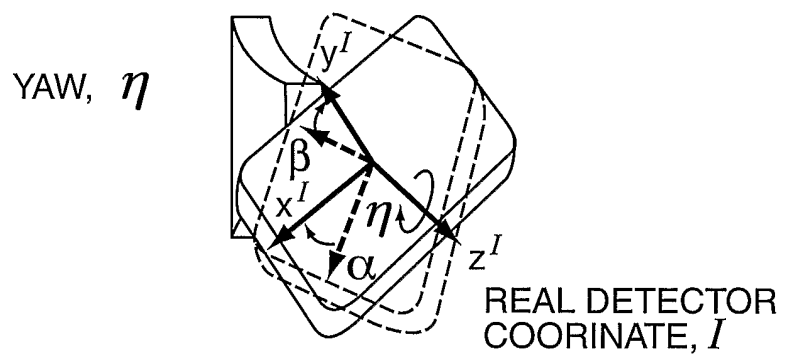
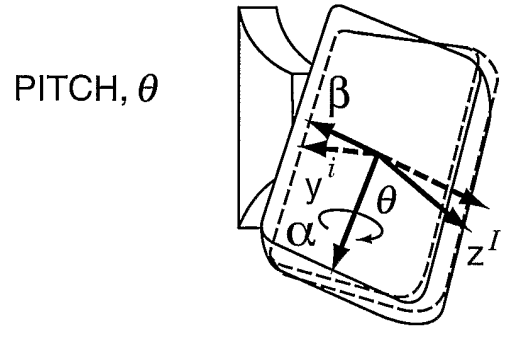
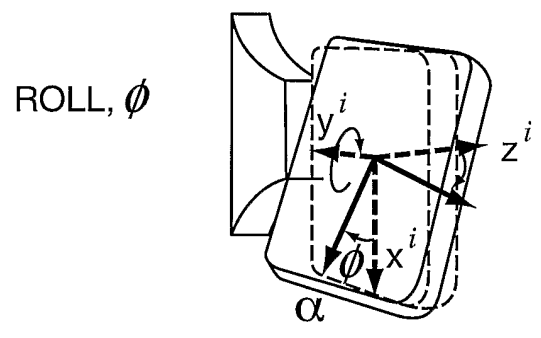
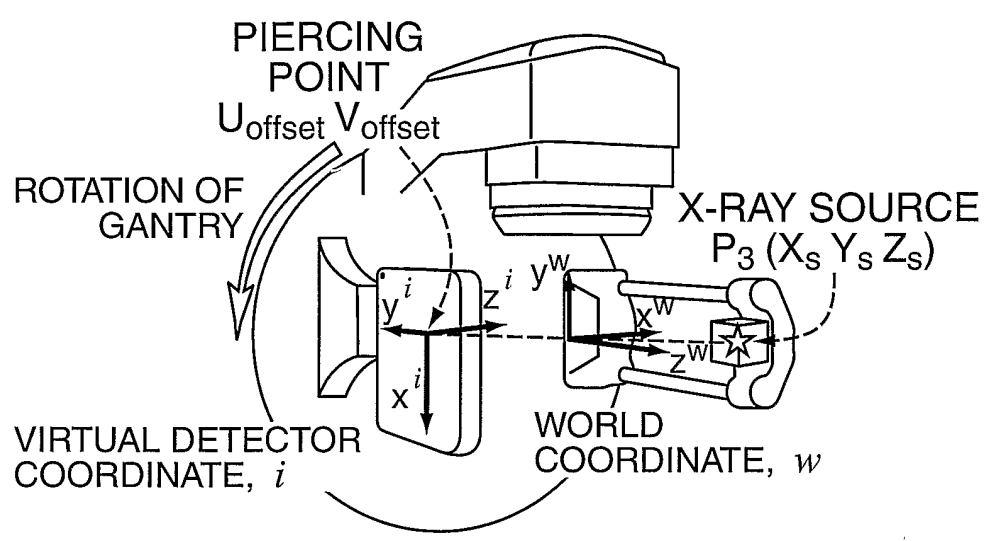
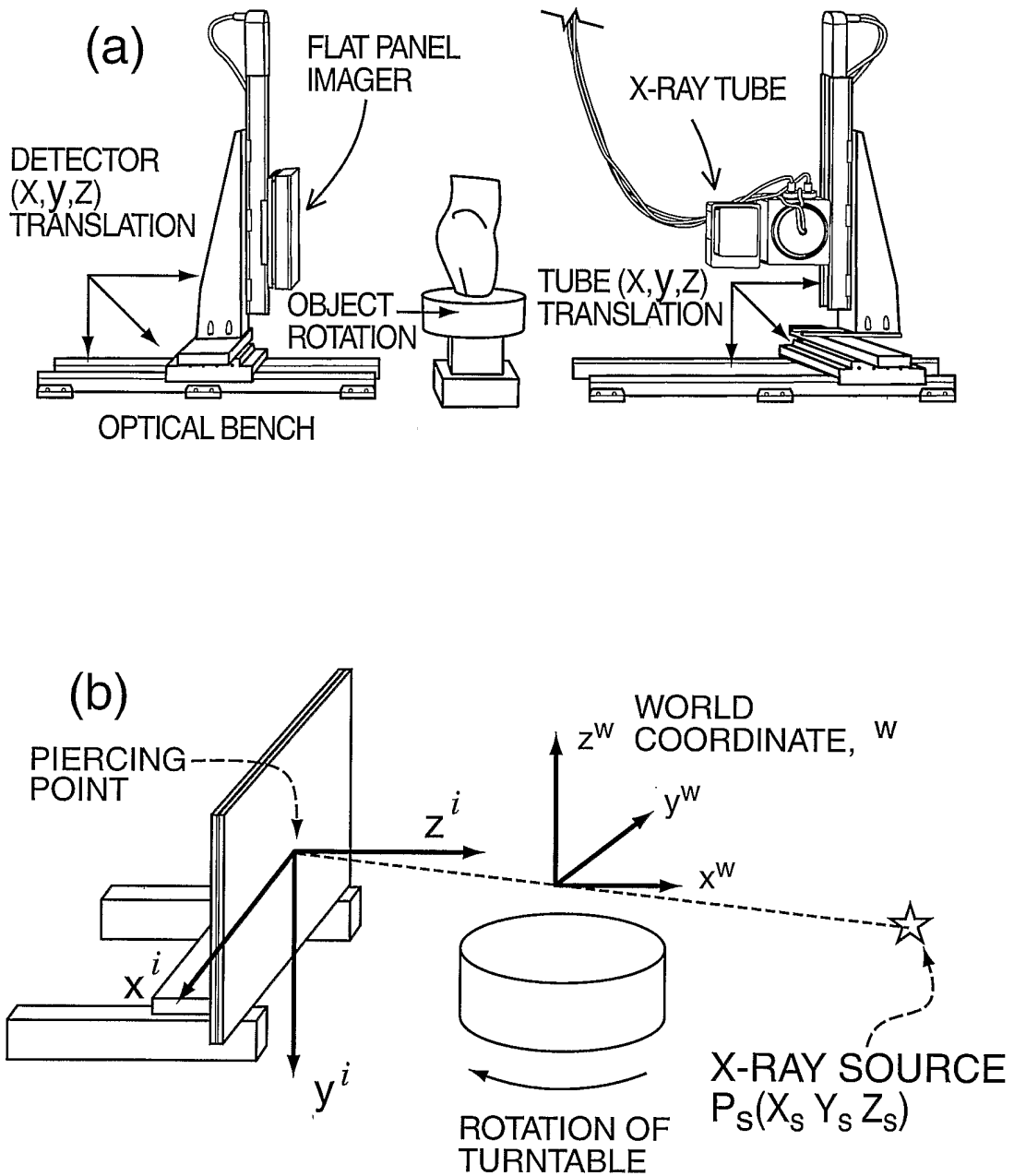


FIG. 5

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**FIG. 6**

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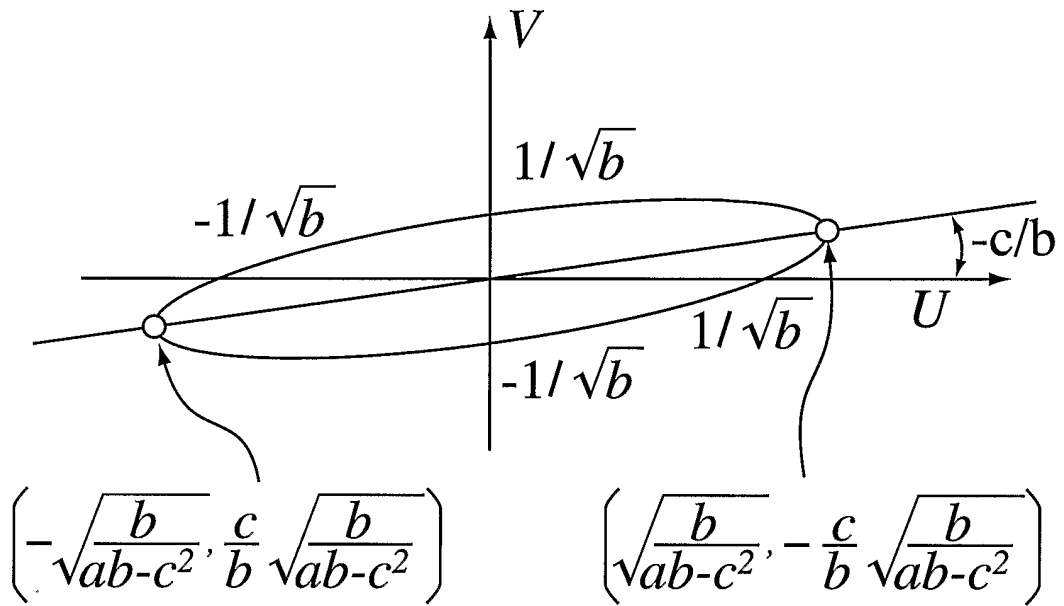


FIG. 7

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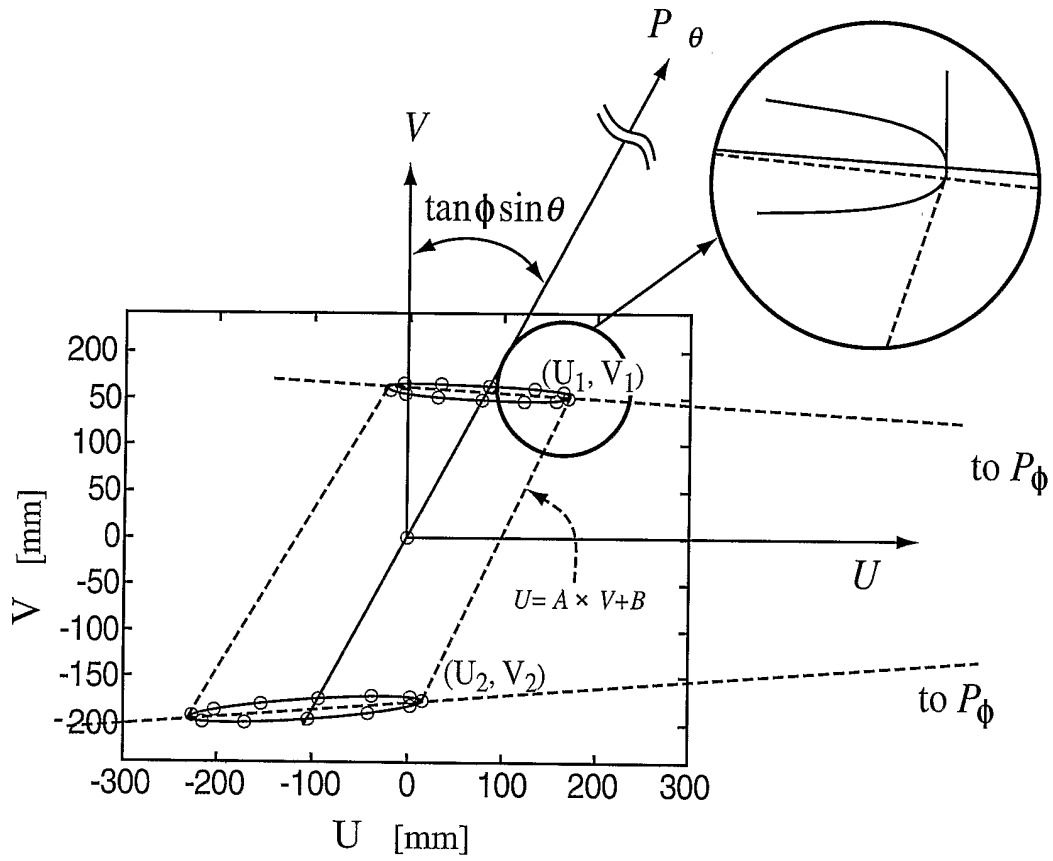


FIG. 8

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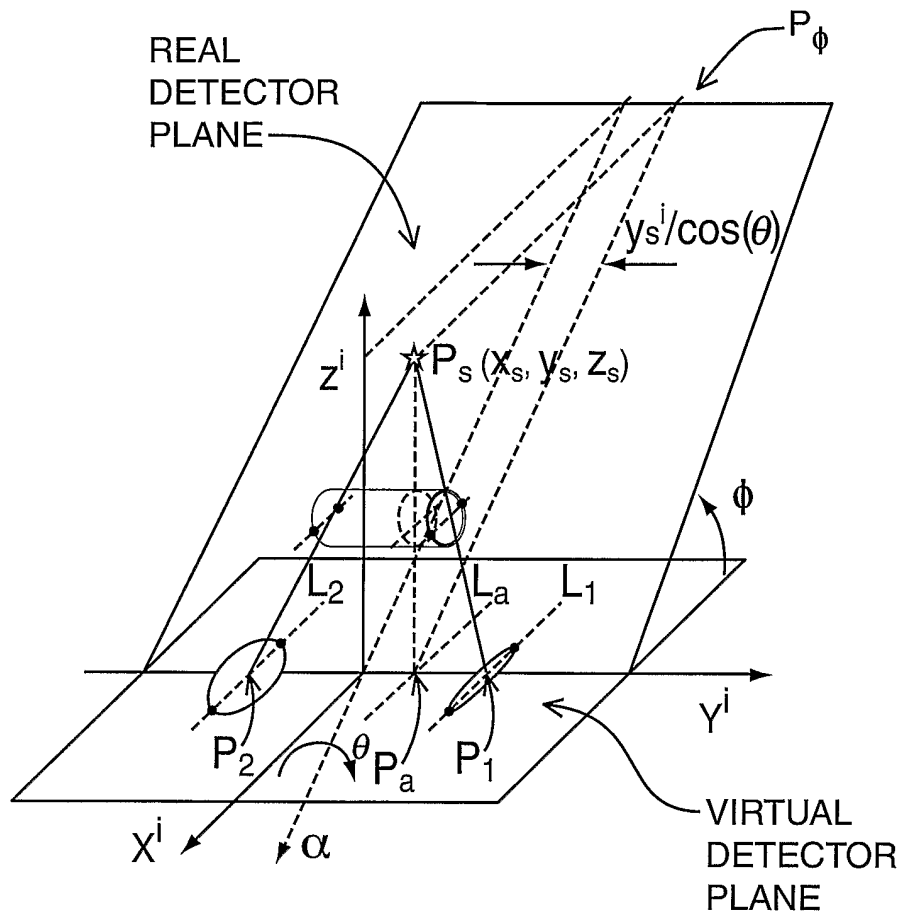


FIG. 9

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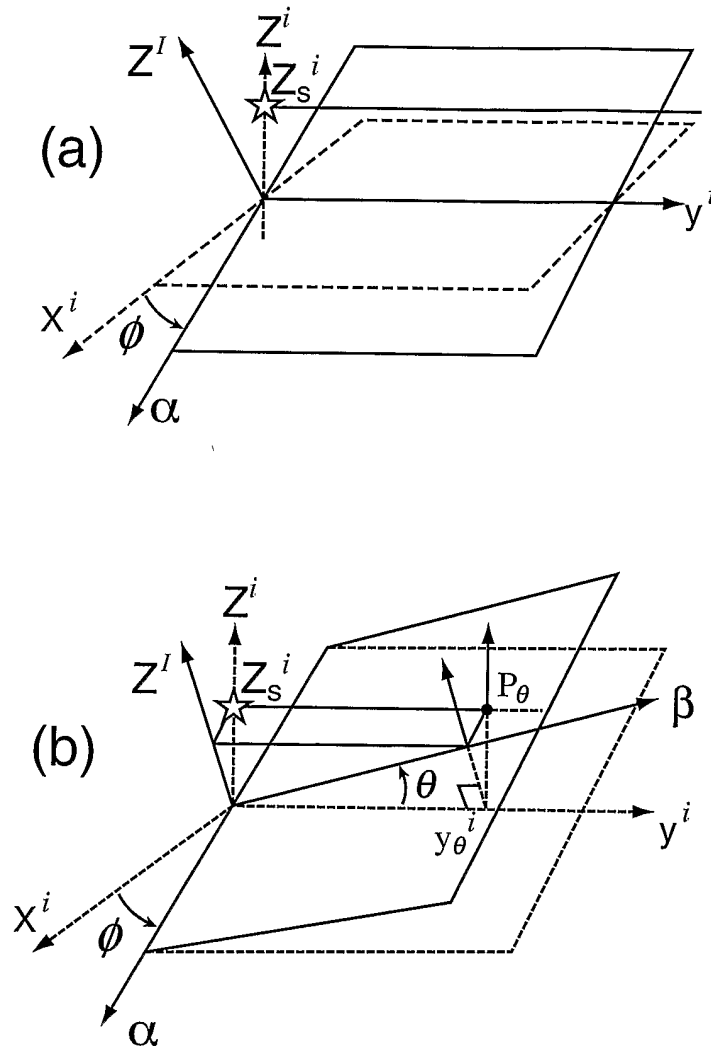
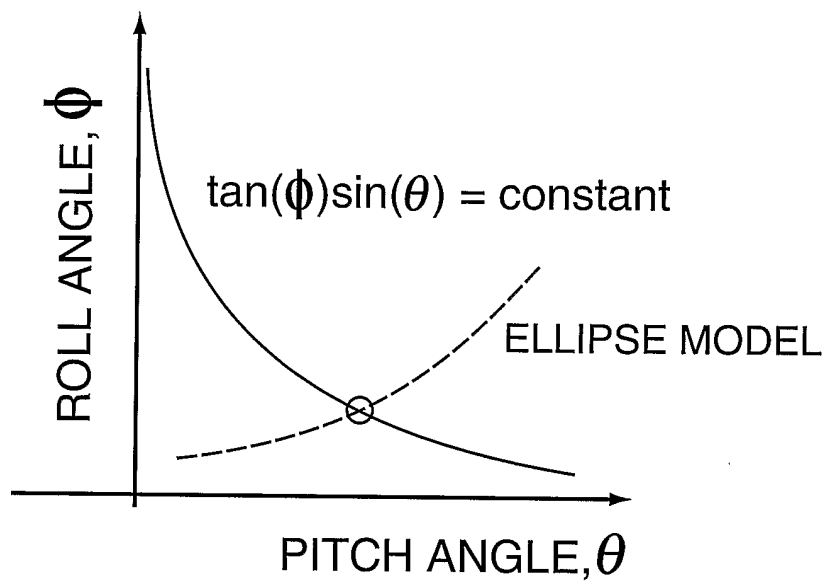


FIG. 10

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FIG. 11

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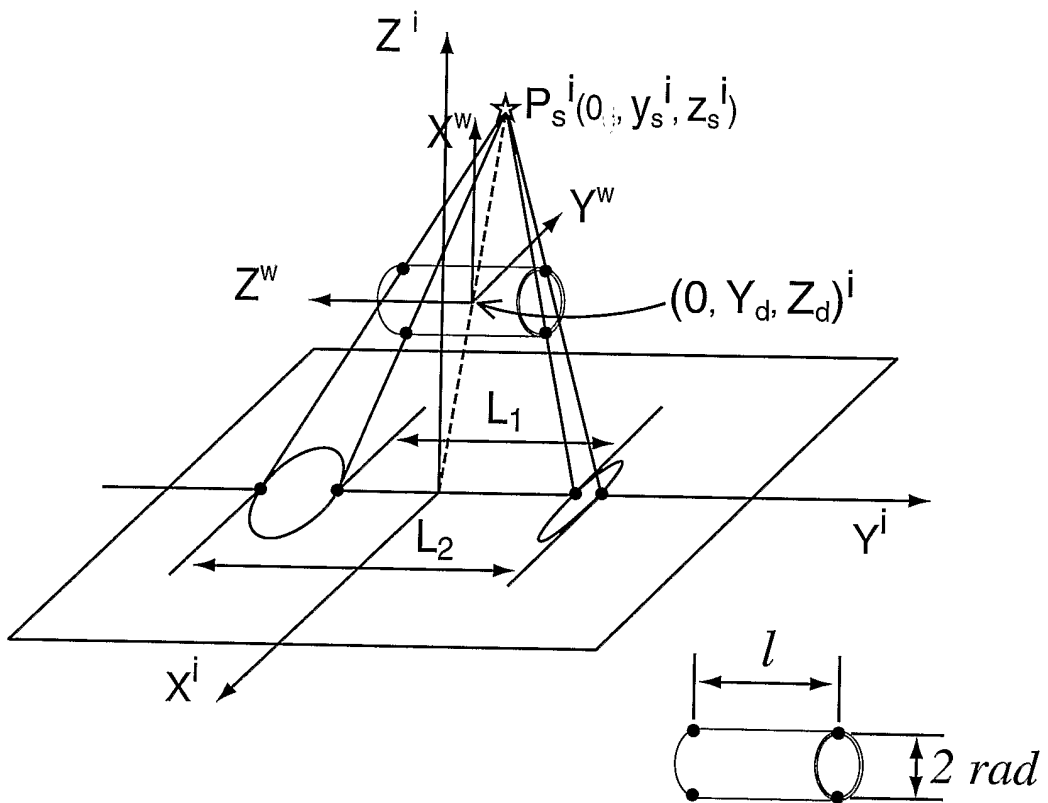
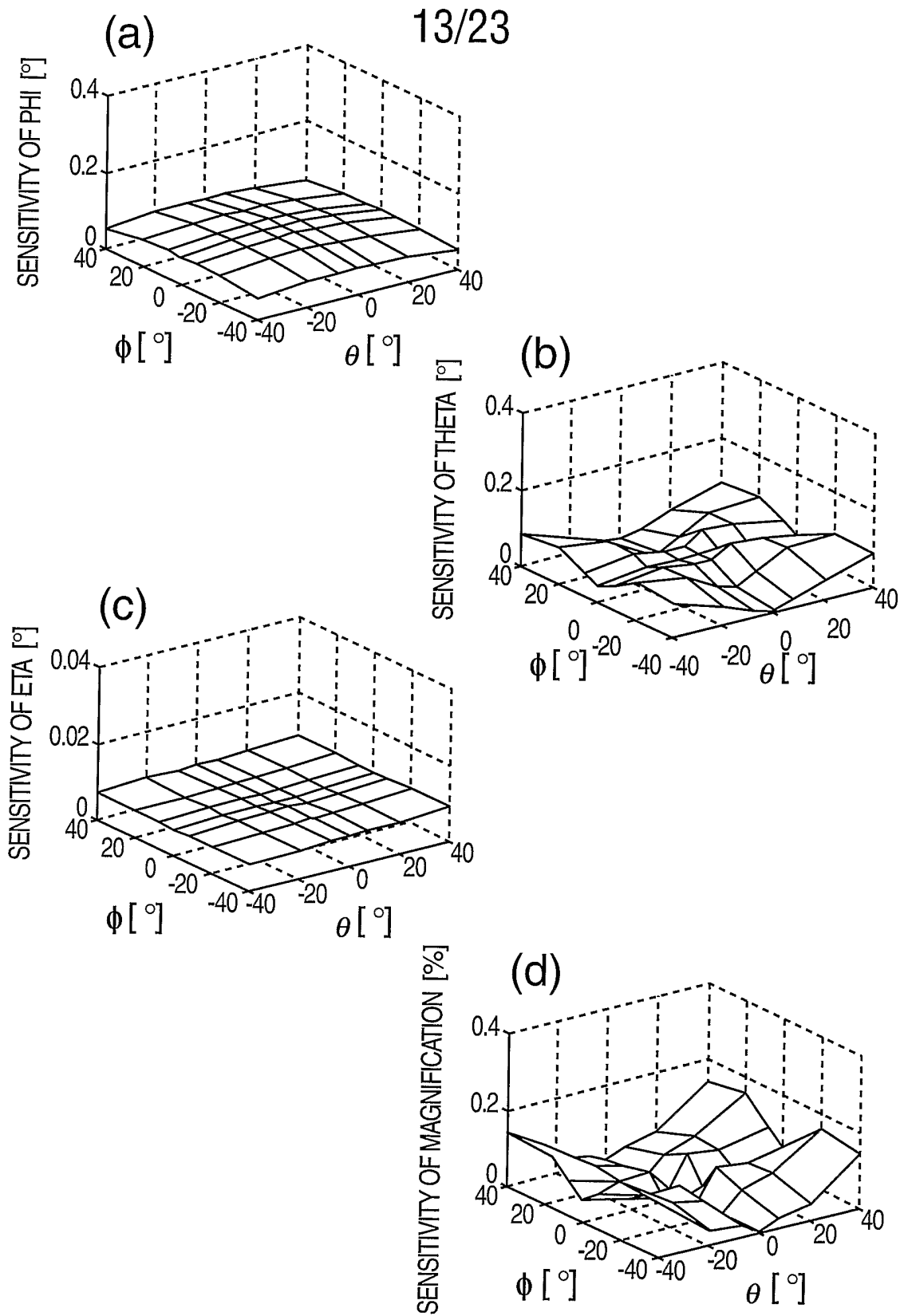
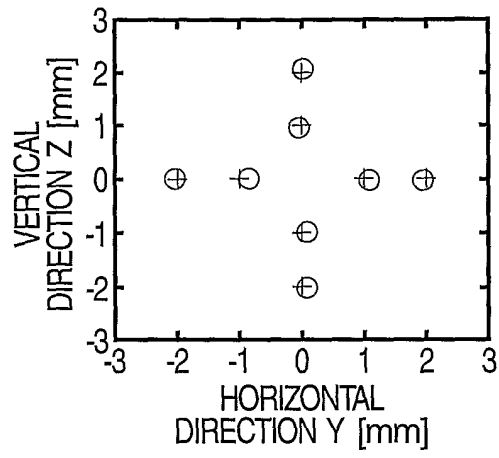


FIG. 12

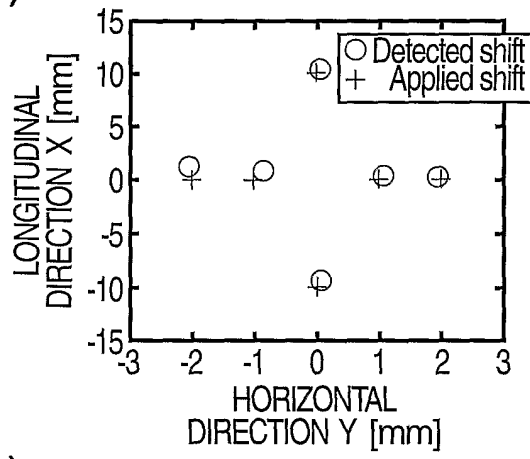


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(a)



(b)



(c)

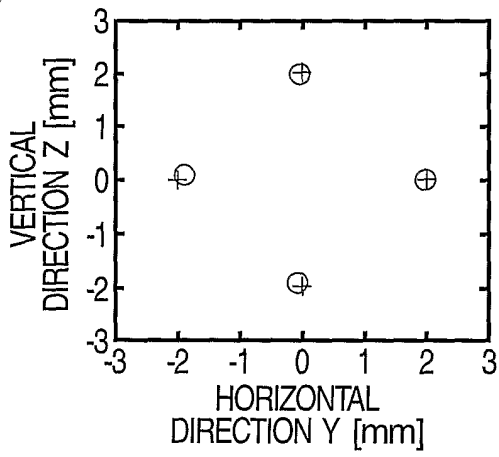


FIG. 14

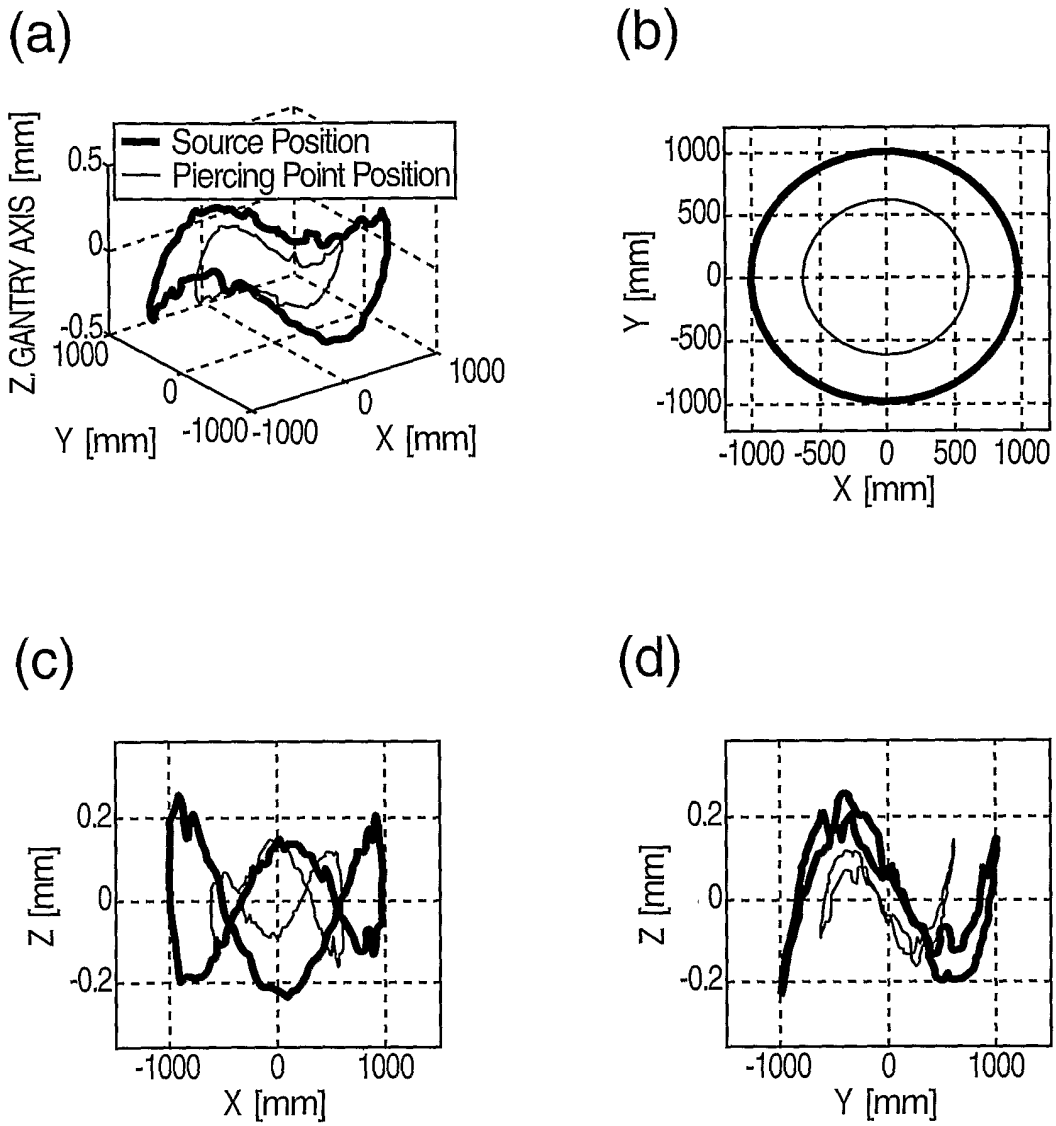
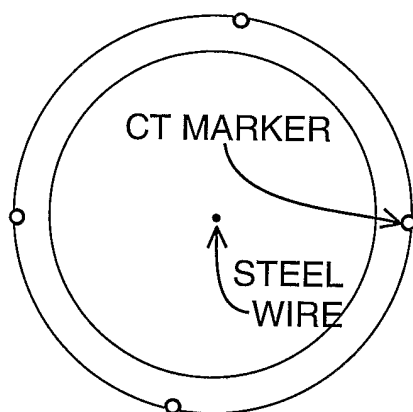


FIG. 15

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(a)



PLASTIC TUBE OF  
CALIBRATION PHANTOM

(b)

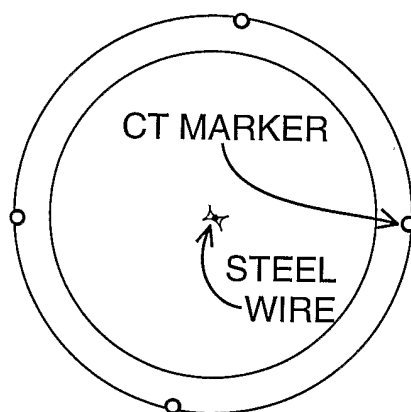
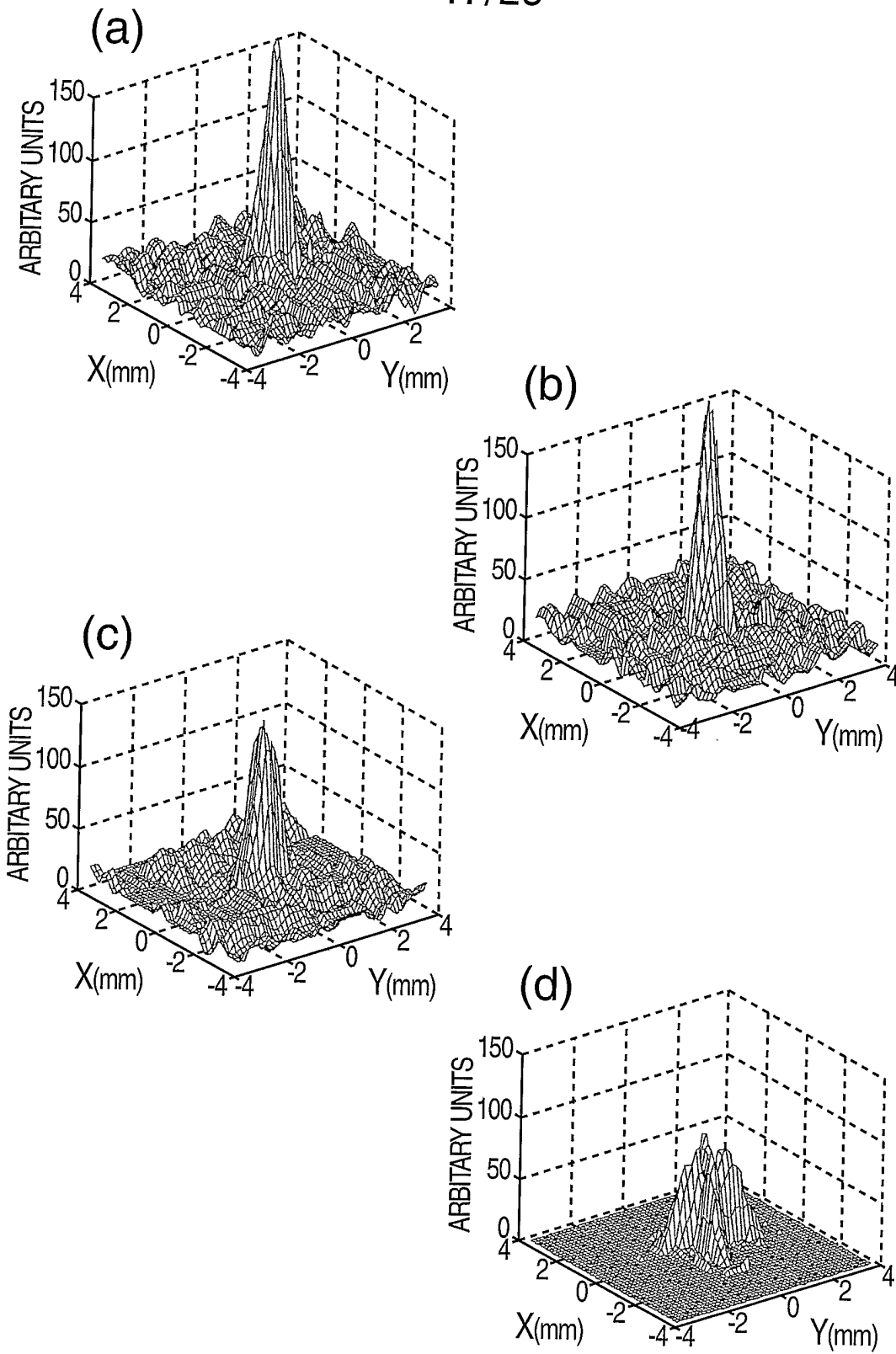


FIG. 16



**FIG. 17**

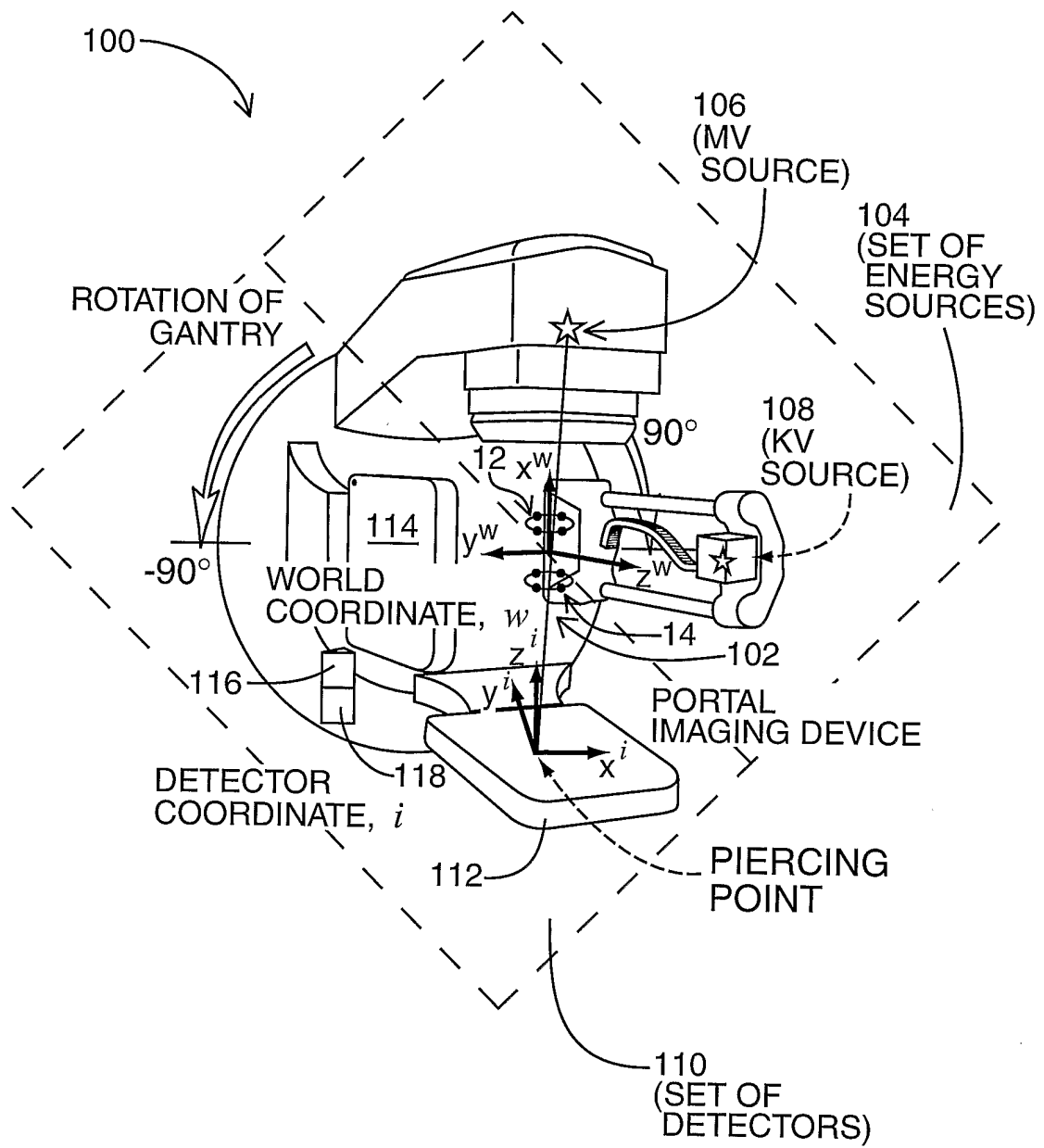


FIG. 18

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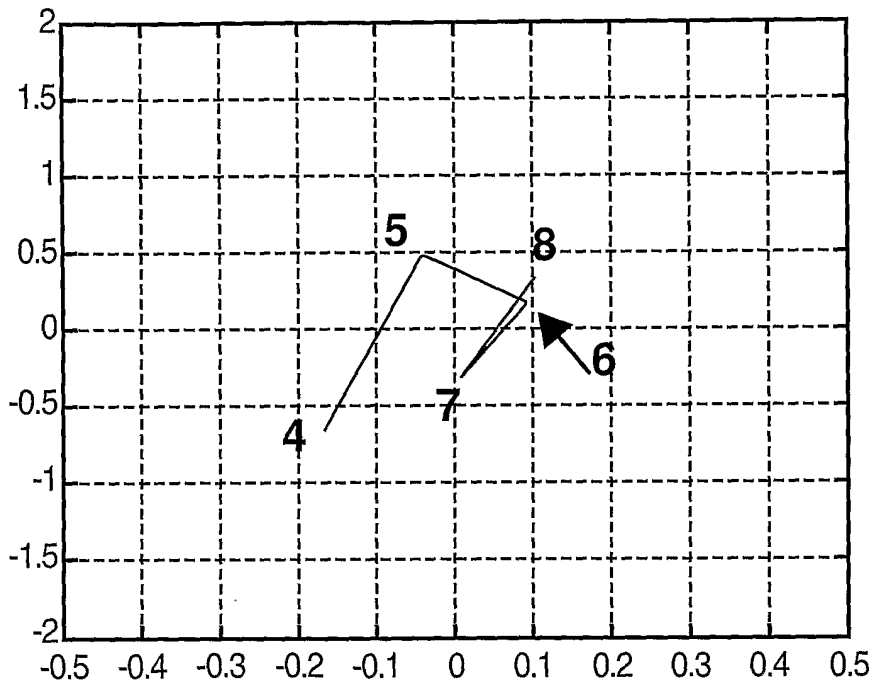


FIG. 19

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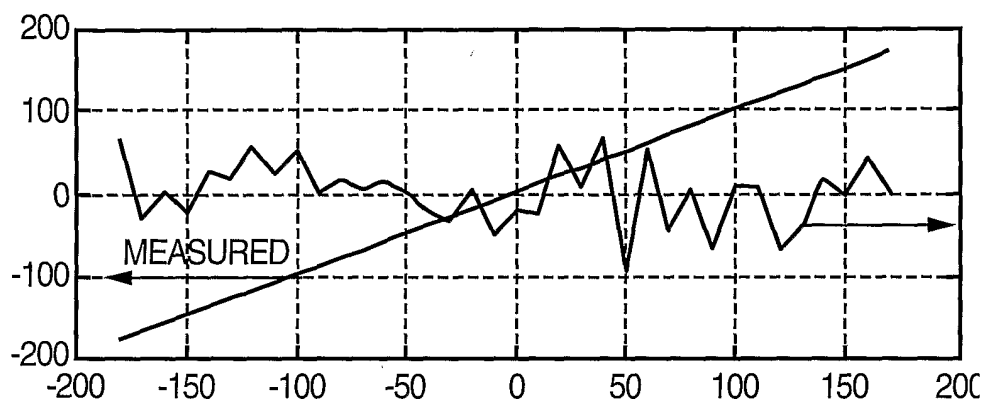


FIG. 20

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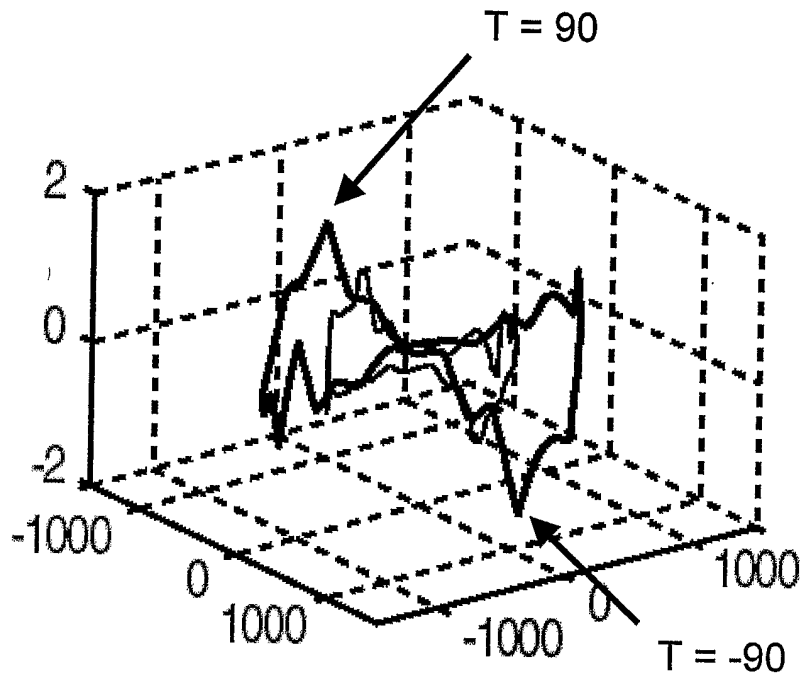


FIG. 21

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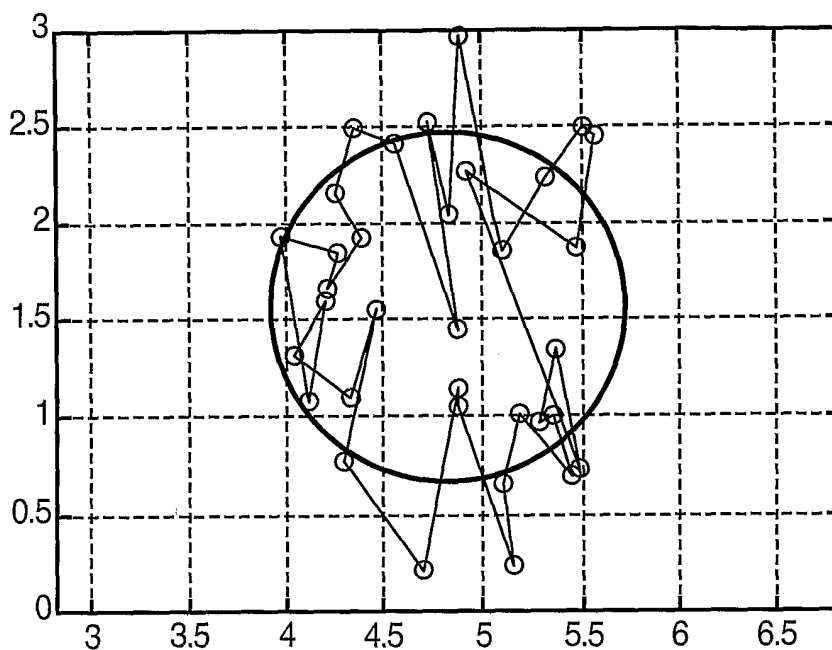


FIG. 22

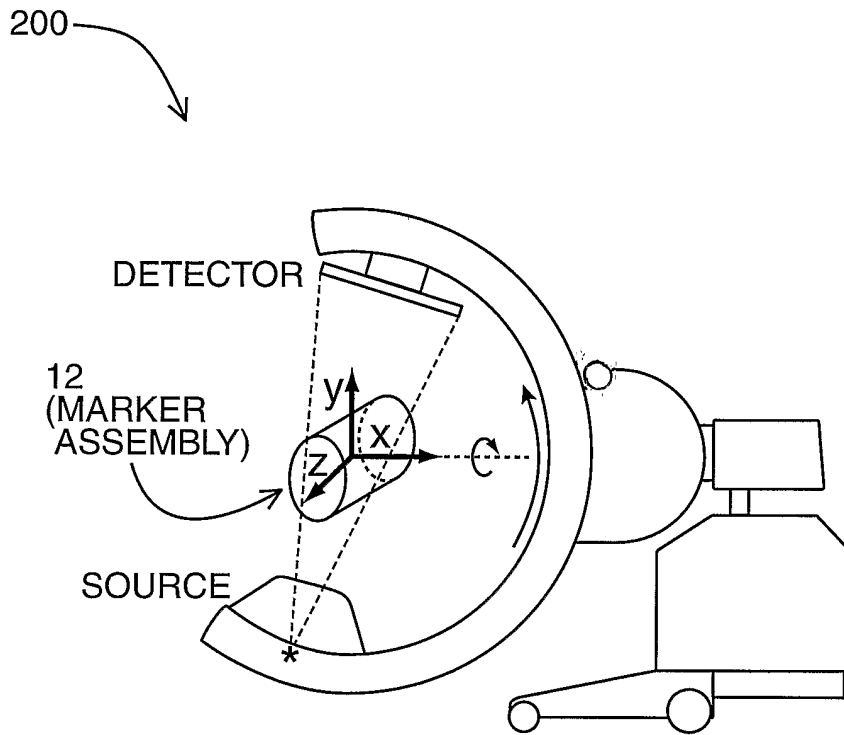


FIG. 23

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/CA2004/001482

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(7): G01B 21/04; A61B 6/03

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(7): G01B 21/04; A61B 6/03;;

US: 378/207; 378/205; 378/4; 378/20; 378/21; 378/98; 600/449; 73/1.79; 73/1.81

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base, and, where practicable, search terms used)

Canadian Patent Database, USPTO, Espacenet, Delphion

keywords: source, detector, marker, coordinate, data, calibration

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	<b>US2003/0058999</b> Publ. Appl. Mar. 27, 2003 <b>Mitschke et al.</b> (col. 5, lines 25-40, Fig. 1)	1, 2, 5-7, 13, 14, 17-19, 25, 26 37
X Y	<b>US2002/0131559</b> Publ. Appl. Sept. 19, 2002 <b>Launay et al.</b> (abstract, col. 1, line 65 - col. 2, line 10; col. 2, line 45- col. 3, line 14, Fig. 2)	1, 2, 3, 5-7, 13, 14, 17-19, 25, 26 37
Y	<b>US5835561</b> 10 Nov. 1998 <b>Moorman et al.</b> (abstract)	31
X	<b>US6044132</b> 28 March 2000 <b>Navab</b> (abstract, col. 3, lines 23-32, Fig. 12)	35-37
A	<b>WO03/020114</b> 13 March 2003 <b>Lai</b> (abstract, page 2 line 27 - page 3, line 20, Fig. 1)	1, 2, 5-7, 13, 14, 17-19, 25, 26

[X] Further documents are listed in the continuation of Box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international-type search  
25 October 2004 (25-10-2004)Date of mailing of the international-type search report  
24 December 2004 (24-12-2004)Name and mailing address of the ISA/  
*Commissioner of Patents*  
*Canadian Patent Office*  
*Box PCT, Ottawa/Gatineau K1A 0C9*  
Facsimile No.

Authorized officer

Goran Basic

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/CA2004/001482

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US5442674 15 August 1995 Picard et al. (col. 4, line 55- col. 5, line 10, Fig. 3; col.5, lines16-20)	1, 2, 5-7, 13, 14, 17-19, 25, 26,37

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/CA2004/001482**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons :

- 1  Claims Nos. :  
because they relate to subject matter not required to be searched by this Authority; namely:
- 2  Claims Nos. :  
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically :
- 3  Claims Nos. :  
because they are dependant claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box III Observation where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows :

Claims 1-34 are directed to a system for obtaining coordinate data of a source and detector instrument comprising a marker assembly, an energy source, a detector, an image device and a calibration module.

Claims 35-37 are directed to a marker assembly comprising two sets of markers, each set having at least two markers and being disposed in different coordinate planes.

Claims 35-37 do not form a proper subcombination since additional features such as "... comprising a first set of at least two markers and a second set of at least two markers, the first set of markers disposed substantially on a first plane, and the second set of markers disposed substantially on a second plane" are not found in independent claims 1, 13, 25 and 31 and therefore claims 35-37 represent a different set of special technical features.

- 1  As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
- 2  As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
- 3  As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos. :
- 4  No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos. :

**Remark on Protest**  The additional search fees were accompanied by the applicant's protest.  
 No protest accompanied the payment of additional search fees.

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