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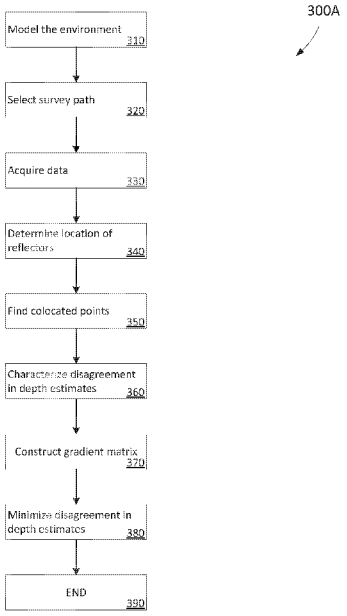
(54) Title: MULTI-PERSPECTIVE ENSONIFICATION SYSTEM AND METHOD

(57) Abstract: A survey system and method to improve one or more of survey quality, efficiency, and utility for example by utilizing a vessel mounted MBES and a selected survey plan to check sound speed(s) via eliciting echoes from reflectors in colocated groups of reflectors using multi -perspective ensonification.

FIG. 3A



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— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

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TITLE: MULTI-PERSPECTIVE ENSONIFICATION SYSTEM AND METHOD

PRIORITY CLAIM, BENEFIT CLAIM AND INCORPORATION BY REFERENCE

[001] This application claims the benefit of U.S. Provisional Pat. Application No. 62/528,354 filed July 3, 2017. This application incorporates by reference, in their entireties and for all purposes, the disclosures of U.S. Pat. Nos. 3,144,631 concerning Mills Cross sonar, 8,305,841 concerning sonar used for mapping seafloor topography, 7,092,440 concerning spread spectrum communications techniques, 5,483,499 concerning Doppler frequency estimation, and 9,244,168 concerning frequency burst sonar.

BACKGROUND OF THE INVENTION

Field of the Invention

[002] The present invention relates to underwater acoustical systems, methods of using underwater acoustical systems, and methods for processing and using the data they produce. In particular, the invention relates to survey systems including multibeam sonar systems capable of obtaining multi-perspective ensonification data.

Discussion of the Related Art

[003] A month after the Titanic struck an iceberg in 1912, English meteorologist Lewis Richardson filed a patent at the British Patent Office for an underwater ranging device. Modern day successors to Richardson's invention are often referred to as SONAR (sound navigation and ranging) devices. Among these devices are ones using transducer arrays to project sound or pressure waves through a liquid medium and transducer arrays to receive corresponding echoes from features that scatter and/or reflect

impinging waves.

[004] Information about these features and their environment can be derived from the echoes. For example, bathymetric surveys provide information about the depth of scattering centers, water column surveys provide information about scattering centers in the water column, and seafloor characterization surveys provide information about scattering centers at the seafloor surface and below the seafloor surface. The diversity and quality of the information returned in echoes may be determined in part by the characteristics of the signal used to excite the projector transducers.

[005] The cost of obtaining this information is strongly influenced by the timeframe during which manpower and equipment is required to acquire the information.

[006] Although some progress towards improving data quality and diversity while reducing the time required to perform an underwater survey has been made, particularly through the use of multibeam echo sounders, long standing technological challenges and risks associated with building and testing costly new survey equipment present significant obstacles to further similar improvements.

SUMMARY OF THE INVENTION

[007] The present invention provides a multi-perspective ensonification system and method. In an embodiment, a multi-perspective ensonification method comprising the steps of: installing a multibeam echo sounder system ("MBES") on a water going vehicle such that one or more transducers in a single MBES projector array and plural transducers in a single MBES hydrophone array are in a Mills Cross arrangement; modeling a waterbody with a plurality of "j" superposed layers (l_1... l_j) having respective layer thicknesses (t_1... t_j), each of the j layers having a layer entry sound speed and a layer exit sound speed such that a set of

(j+1) sound speed values (c_1, c_2... c_{j+1}) characterize the sound speed profile through the layers; designing a vehicle route and traversing the route such that during MBES operation along the route i) plural primary areas are ensonified, ii) plural secondary areas are ensonified, iii) each primary area is overlapped by a respective secondary area, and iv) for each overlap a first echo originating therein traverses a first path to the MBES and a second echo originating therein traverses a second path to the MBES at a location different from the first; via a travel time corresponding to each echo, modeling the propagation of sound through the waterbody to locate in three dimensions a reflector that returned the echo; one of the dimensions indicating a waterbody depth and the other two dimensions indicating coordinates in a reflector plane parallel to the waterbody free surface; selecting a colocation metric and using the metric to identify groups of reflectors that are colocated in the reflector plane; for each group of colocated reflectors, quantifying disagreements in the waterbody depths corresponding to the reflectors in the group; and, determining a set of adjusted sound speed values that tends to simultaneously reduce the disagreement within each group of depth estimates.

BRIEF DESCRIPTION OF THE DRAWINGS

[008] The present invention is described with reference to the accompanying figures. These figures, incorporated herein and forming part of the specification, illustrate embodiments of the invention and, together with the description, further serve to explain its principles enabling a person skilled in the relevant art to make and use the invention.

[009] FIG. 1A shows a survey system including a multibeam echo sounder system ("MBES") of the present invention.

[010] FIG. 1B shows an embodiment of at least portions of the MBES of FIG. 1A.

[011] FIG. 2A shows a vessel equipped with a Mills Cross type arrangement of transducer arrays for use with the MBES of FIG. 1A.

[012] FIG. 2B shows schematically an MBES fan such as a fan resulting from operation of the echo sounder system of FIG. 1A.

[013] FIGS. 2C-D show an antiparallel track survey plan carried out using the MBES of FIG. 1A.

[014] FIGS. 2E-F show a cross track survey plan carried out using the MBES of FIG. 1A.

[015] FIGS. 2G-H show a same track survey plan carried out using the MBES of FIG. 1A.

[016] FIGS. 2I-J show an exemplary waterbody model for use with the surveys of FIGS. 2B-H.

[017] FIGS. 3A-G show a process using the MBES of FIG. 1A for testing sound speeds used in depth estimates.

[018] FIG. 4 shows a method using the MBES of FIG. 1A for synthesizing a sound speed profile using the MBES of FIG. 1A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[019] The disclosure provided in the following pages describes examples of some embodiments of the invention. The designs, figures, and description are non-limiting examples of the embodiments they disclose. For example, other embodiments of the disclosed device and/or method may or may not include the features described herein. Moreover, described features, advantages or benefits may apply to only certain embodiments of the invention and should not be used to limit the disclosed invention.

[020] As used herein, the term "coupled" includes direct and indirect connections. Moreover, where first and second devices are coupled, intervening devices including active devices may be located therebetween.

[021] **Survey System**

[022] FIG. 1A shows a survey system 100A. The survey system includes an echo sounder system such as a multibeam echo sounder system 102 which may be mounted on a surface vehicle or vessel, a remotely operated vehicle, an autonomous underwater vehicle, or the like. As is further described below, echo sounder and/or survey system outputs 114 may be contemporaneous with echo sounder processing of hydrophone data as in some embodiments for bathymetry or non-contemporaneous with processing of hydrophone data as in some embodiments for waterbody bottom classification.

[023] Data acquired by multibeam echo sounder systems 104 includes data from echo sounder listening devices such as hydrophones (e.g., transducers) that receive echoes which are related to the acoustic/pressure waves emanating from the echo sounder projectors but have returned by virtue of an interaction with inhomogeneities of many kinds. The interactions may take the form of reflection or scattering. The inhomogeneities, also known as reflectors and/or scattering centers, represent discontinuities in the physical properties of the medium. Exemplary scattering centers may be found in one or more of i) an ensonified volume of the waterbody such as a water column, ii) upon the ensonified surface of the bottom, or iii) within the ensonified volume of the sub-bottom.

[024] Scattering centers of a biological nature may be present in the water column, as they are a part of the marine life. Scattering centers of a nonbiological nature may be present in the water column in the form of bubbles, dust and sand particles, thermal microstructure, and turbulence of natural or human origin, such as ships' wakes. Scattering centers on the surface of the bottom may be due to the mechanical roughness of the bottom, such as ripples, or be due to the inherent size, shape and physical arrangement of the bottom constituents, such as mud, sand, shell fragments, cobbles and boulders, or due to both factors. Scattering centers in the sub-bottom may be due to bioturbation of the sediments, layering of

different sediment materials within the bottom, or buried manmade structures such as pipelines.

[025] Data processing within the echo sounder system may include contemporaneous processing of hydrophone data 106, for example to obtain bathymetric and/or backscatter data. Data processing may also include non-contemporaneous processing of multibeam echo sounder system data 108, for example to characterize the environment including bottom conditions or the water column.

[026] Data processing may include utilization of complementary or other data. For example, contemporaneous processing of hydrophone data 106 may utilize contemporaneous 110 and/or non-contemporaneous 112 data such as contemporaneously collected global positioning system ("GPS") data, sound speed measurements, attitude, and navigational information. For example, non-contemporaneous processing of echo sounder system data may utilize contemporaneous 110 and/or non-contemporaneous 112 data such as non-contemporaneously collected waterbody bottom composition data and tidal records.

[027] FIG. 1B shows portions of an exemplary multibeam echo sounder system ("MBES") 100B. The echo sounder system includes a transducer section 120 and an acoustic transceiver 122. The echo sounder system may include a transceiver interface such as an interface module 124 and/or a workstation computer 126 for one or more of data processing, data storage, and interfacing man and machine. Exemplary transducers, shown here in a Mills Cross arrangement 120, include a transmitter or projector array 130 and a receiver or hydrophone array 140. Projectors in the projector array may be spaced along a line that is parallel with a keel line or track of a vehicle or vessel to which they are mounted which may be referred to as an along track arrangement. In some embodiments, a receiver of the transceiver 122 has an operating frequency range matched with that of the projectors and/or the hydrophones.

[028] During echo sounder operation, sound or pressure waves emanating

from the projector array travel within a body of water and possibly within the bottom beneath the body of water and in doing so may undergo interactions, such as reflections or scattering, which disturb the propagation trajectory of the pressure waves. Some of the reflections or echoes are "heard" by the hydrophone array. See for example the disclosure of Etal, U.S. Pat. No. 3,144,631, which is included herein by reference, in its entirety and for all purposes.

[029] The acoustic transceiver 122 includes a transmitter section 150 and a receiver section 170. The acoustic transceiver may be configured to transmit to a single projector array 130 and to receive from a single hydrophone array 140. In some embodiments, such a transceiver may be said to operate with a single transmitter array and a single receiver array. Unless otherwise noted, the term transceiver does not require common transmitter and receiver packaging.

[030] In various embodiments, a single projector array ensonifies the entirety of a swath on a single ping. Here, a projector array may be a single projector array regardless of the geometry, arrangement, or quantity of devices employed. For example, where a plurality of projectors forms a plurality of spatially distinct projector groups, the plural projectors are a single projector array if they are operated to ensonify the entirety of a swath on a single ping.

[031] The echo sounder may further include a means such as an interface module 124 for interconnection with the transceiver 122. This interface module may provide, among other things, a power supply for the transceiver, communications with the transceiver, communications with the workstation computer 126, and communications with other sources of data such as a source of contemporaneous GPS data.

[032] The workstation computer 126 may provide for one or more of data processing such as data processing for visualization of survey results, for data storage such as storage of bathymetry data and backscatter data, for user inputs, and for display of any of inputs, system status, and survey

results.

[033] **Mills Cross Transducer Arrangement**

[034] FIGS. 2A-B show an exemplary vessel equipped with a multibeam echo sounder 200A. See for example the echo sounders of FIGS. 1A-B. As seen in FIG. 2A, an MBES array package 204 is affixed to a vessel 202, for example to a bottom of the vessel.

[035] Within the array package 204 is an along track array of projectors 208 and a cross track array of hydrophones 210. The projector array is for excitation by an echo sounder transmitter message. The hydrophone array is for receiving echoes of the transmitted message.

[036] As explained below, a crossed array arrangement such as a Mills Cross arrangement of the projector and hydrophone arrays enables the echo sounder to operate with crossed transmit and receive beams wherein the cross intersection identifies a particular waterbody location, area, or cell. The crossed arrays may be in a perpendicular or a substantially perpendicular arrangement. Substantially perpendicular refers to generally small deviations from perpendicular caused by any of array assembly tolerances, mounting tolerances, adjustment tolerances, and the like.

[037] **Echoes Returned From Particular Locations**

[038] FIG. 2B shows bottom ensonification 200B. In particular, an across track strip or fan of a waterbody bottom 212 is ensonified by the projector array 208. Note the along track projector array 208 ensonifies an across track fan 212. As shown, the projected beam 211 has a wide across track aperture angle θ_{t1} as compared with a relatively narrow along track aperture angle θ_{t2}. Echoes from this ensonified fan are received by the hydrophone array 210.

[039] In various embodiments, MBES receiver beam steering enables subdivision of the fan 212 into a series of zones. This subdivision into zones enables identification of an echo returned from a particular zone or

location 213 on the waterbody bottom 215.

[040] **Survey Perspectives**

[041] Notably, when the fan 212 is ensonified, the vessel is in a particular position relative to the waterbody bottom 215. As such, the echo returned from the waterbody bottom location 213 may be said to have been acquired from a particular perspective with the MBES in a particular position relative to the waterbody bottom location.

[042] As discussed below, when echo data for a particular waterbody bottom location includes data from multiple different perspectives, this data can be used to test assumptions made about the environment that propagates the echoes.

[043] **Echoes From Multiple Perspectives**

[044] Multi-perspective ensonification includes a process of operating MBES projectors at multiple vessel locations such that a site on the waterbody bottom is ensonified multiple times from multiple different perspectives.

[045] For example, when the MBES projectors are operated at location (longitude 1, latitude 1), echo data ed1 from a zone z1 within the ensonified area is acquired. Later in time, when the MBES projectors are operated at location (longitude 2, latitude 2), echo data ed2 from a zone z2 that overlaps zone z1 may be acquired.

[046] Where zones z_1 and z_2 are at least partially superimposed, an overlap is defined. The site may be ensonified from multiple perspectives and echo data may be acquired from multiple perspectives. In some embodiments, different perspectives result when the MBES pitch angles ensonifying zones z_1 and z_2 differ.

[047] Various terminology may be used to refer to this and similar processes. For example, acquiring multiple echoes from the same site may be referred to as a part of a multi-perspective survey, multi-echo ray tracing, multi-look echo sounding, and/or multi-perspective ensonification,

echoes, or queries.

[048] **Survey Plans**

[049] FIGS. 2C-D show an antiparallel track survey plan aimed at acquiring multi-perspective survey data 200C-D.

[050] As shown in FIG. 2C, an MBES transducer plane x-z is at level yt and a waterbody bottom 215 plane x'-z' is at level yb. Survey vessel tracks are located in the upper x-z plane. As shown, the survey vessel movement along a first track Track 1 is parallel to and opposite of survey vessel movement along a second track Track 2. In some embodiments, deviations from parallel tracks arise from vessel instrument measurement inaccuracies, course and or heading errors arising from sea conditions, and the like. In some embodiments similar multi-perspective survey results are provided by non-opposed track directions.

[051] Operation of MBES projectors on a vessel traversing Track 1 may, with a beam angle of $\theta t1$, ensonify a first waterbody bottom fan f1. And, operation of the MBES projectors while traversing Track 2 may, with a beam angle of $\theta t11$, ensonify a second waterbody bottom fan f2. The beam angles may be equal or not.

[052] Notably, when fan f1 overlaps fan f2 a portion of the waterbody bottom is ensonified twice. As explained below, a first ensonification from Track 1 is from a first perspective and a second ensonification from Track 2 is from a second perspective.

[053] As shown in FIGS. 2C-D, MBES operation on Track 1 results in ensonification of fan f1 which includes ensonification of cell c1 and ensonification Ap of a site within cell c1. In similar fashion, MBES operation on Track 2 results in ensonification of fan f2 which includes ensonification Bp of the same site within cell c2. Temporally, ensonification A_p and its echo A_h may precede ensonification B_p and its echo B_h.

[054] This example shows an antiparallel track survey plan where a site

defined by an overlap (an overlap, site, or overlap site) is ensonified from a first perspective on Track 1 and from a second perspective on Track 2. In particular, the first perspective is the location of g1 on Track 1 relative to the overlap site and the second perspective is the location of g2 on Track 2 relative to the overlapped.

[055] FIGS. 2E-F show a cross track survey plan aimed at acquiring multi-perspective survey data 200E-F.

[056] As shown in FIG. 2E, an MBES transducer plane x-z is at level yt and a waterbody bottom 215 plane x'-z' is at level yb. Survey vessel tracks, Track 1 and Track 2, are located in the upper x-z plane. As shown, the tracks cross at an angle α. In some embodiments, angle α is about a right angle with deviations subject to vessel instrument measurement inaccuracies, course and or heading errors arising from sea conditions, and the like. In various embodiments the survey vessel direction of movement along either track may be reversed.

[057] Operation of MBES projectors on a vessel traversing Track 1 may, with a beam angle of $\theta t1$, ensonify a first waterbody bottom fan f1. And, operation of the MBES projectors while traversing Track 2 may, with a beam angle of $\theta t11$, ensonify a second waterbody bottom fan f2. The beam angles may be equal or not.

[058] Notably, when fan f1 overlaps fan f2 a portion of the waterbody bottom is ensonified twice. As explained below, a first ensonification from Track 1 is from a first perspective and a second ensonification from Track 2 is from a second perspective.

[059] As shown in FIGS. 2E-F, MBES operation on Track 1 results in ensonification of fan f1 which includes ensonification of cell c1 and ensonification Ap of a site within cell c1 and a corresponding echo Ah. In similar fashion, MBES operation on Track 2 results in ensonification of fan f2 which includes ensonification Bp of the same site within cell c2 and a corresponding echo Bh. Temporally, ensonification A_p and its echo A_h may precede ensonification B_p and its echo B_h.

[060] This example shows a cross track survey plan where an overlap site is ensonified from a first perspective on Track 1 and from a second perspective on Track 2. In particular, the first perspective is the location of g1 on Track 1 relative to the overlap site and the second perspective is the location of g2 on Track 2 relative to the overlap site.

[061] FIGS. 2G-H show a same track survey plan aimed at acquiring multi-perspective survey data 200G-H.

[062] As shown in FIG. 2G, an MBES transducer plane x-z is at level yt and a waterbody bottom 215 plane x'-z' is at level yb. Survey vessel Track 1 is located in the upper x-z plane. In some embodiments, Track 1 is a straight line. And, in some embodiments Track 1 deviates from a straight line. For example, where Track 1 is about a straight line, deviations from a straight line path include deviations due to vessel instrument measurement inaccuracies, course and or heading errors arising from sea conditions, and the like. In various embodiments the survey vessel direction of movement along the track may be reversed.

[063] An early operation of MBES projectors on a vessel traversing Track 1 may, with a cross track beam angle of θt1, ensonify a first plurality of waterbody bottom fans f1-f5. As shown, the fans f1-f5 extend between an along track angle βt1.

[064] A later operation of the MBES projectors while traversing Track 1 may, with a beam angle of θt11, ensonify a second plurality of waterbody bottom fans f1'-f5'. As shown, the fans f1'-f5' extend between an along track angle βt11. The angles θt1, θt11 may be equal or not. The angles βt1, βt11 may be equal or not.

[065] As shown, the early MBES projector operation produces a grid of cells located by fan f1-f5 and by zone k1-k4. For example a cell f1, k1 is ensonified by early MBES operation while a cell f5', k1 is ensonified by later MBES operation. These cells do not overlap.

[066] In another example a cell f4, k1 is ensonified by early MBES

operation while the same cell f1', k1 is ensonified by later MBES operation. These cells overlap. As explained below, early MBES operation and later MBES operation provides ensonification of cell f4, k1 from a first perspective at g1 along Track 1 and ensonification of overlapping cell f1', k1 from a second perspective at g2 along Track 1.

[067] As shown in FIG. 2H, early MBES operation on Track 1 at g1 results in ensonification of fans f1-f5 which includes ensonification Ap of cell f4, k1 and a corresponding echo Ah. Later MBES operation on Track 1 at g2 results in ensonification of fans f1'-f5' which includes ensonification Bp of cell f1', k1 and a corresponding echo Bh. Temporally, ensonification A_p and echo A_h may precede ensonification B_p and echo B_h.

[068] This example shows a same track survey plan where a site is ensonified from a first and a second perspective along Track 1. In particular, the first perspective is the location of g1 on Track 1 relative to the overlap site and the second perspective is the location of g2 on Track 1 relative to the overlap site.

[069] **Waterbody Model**

[070] Estimating the propagation path(s) of acoustic energy through a waterbody may be referred to as ray tracing. This ray tracing may involve dividing the waterbody into layers. Tracing sound rays through a body of water may involve dividing the waterbody into layers. With defined layers, physical properties such as the speed of sound may be measured, estimated, or otherwise made available for one or more layers. The value of a particular media property may be held constant or varied, such as linearly varied, within a layer. For example, in a multi-layer media model the speed of sound may be constant within a layer or change with a constant gradient within a layer provided the speed of sound is continuous from layer to layer.

[071] FIGS. 2I-J show an exemplary waterbody model 200I-J. As seen, the waterbody includes three layers (l1, l2, l3), each layer having a corresponding thickness (t1, t2, t3). In each of the figures, four interfaces

with corresponding sound speeds (c1, c2, c3, c4) and (c1', c2', c3', c4') demarcate the layers.

[072] FIG. 2I shows a first echo from a point on a waterbody bottom 283 that is traced with three ray segments. In accordance with Snell's law of refraction (sin θx)/cx = (sin θy)/cy), a first ray segment ra exits layer l3 at an angle θ3, a second ray segment rb exits layer l2 at an angle θ2, and a third ray segment rc exits layer l1 at an angle θ1. In various embodiments, the third ray segment rc leaves layer l1 at or near an MBES hydrophone array.

[073] As skilled artisans will appreciate, ray segments like those of FIGS. 2I-J may travel through a layer and/or be modeled as traveling through a layer with no change in sound speed or with various changes in sound speed. For example, sound may travel through a layer with a constant sound speed and experience no change of ray path angle resulting in a straight ray segment. For example, sound may travel through a layer with a constant sound speed gradient and experience a gradual change of ray path angle resulting in a curved ray segment. Notably, the figures do not attempt to replicate curved ray segments. For example, in some embodiments ray angles at layer interfaces may change abruptly with gradual continuous changes thereafter as in a prior layer. For example, in some embodiments the slopes of adjoining rays at layer interfaces may be equal or about equal, for example within 1 to 10 percent difference.

[074] FIG. 2J shows a second echo from the point 283 on the waterbody bottom. Here, a first ray segment ra' exits layer l3 at an angle θ3', a second ray segment rb' exits layer l2 at an angle θ2', and a third ray segment rc' exits layer l1 at an angle θ1'. In various embodiments, the third ray segment leaves layer l1 at or near an MBES hydrophone array.

[075] As will be noted, the ray segments tracing the first echo are characterized by a more severe slope than those tracing the second echo. This shows, among other things, that the first and second echoes from the point on the waterbody bottom 283 correspond to ensonifications from

different perspectives as discussed above.

[076] It should be noted that FIGS. 2I-J are based on a particular waterbody model and are merely illustrative. For example, the number of layers used in the model may be 2, 3, 4, 5 or more. For example, the value of the speed of sound may vary with depth.

[077] **Testing Sound Speeds**

[078] FIGS. 3A-3G show a process for testing sound speeds used in depth estimates 300A-G.

[079] FIG. 3A provides an overview of the process 300A. In a first step, a model of the waterbody where sound speeds at various depths will be estimated is constructed. See for example the models of FIGS. 2I-J. In a second step, a survey path is selected. See for example the survey paths of FIGS. 2A-H and in particular survey paths that provide multi-perspective ensonifications of individual overlap sites. In the third step 330, survey data is acquired when an MBES is operated on board a vessel that follows the selected survey path. From this data, waterbody bottom reflectors are located in a fourth step.

[080] Because it is unlikely that multiple echoes will emanate from the same reflector, groups of reflectors in relatively small areas on the waterbody bottom are assumed to be colocated and to provide multi-perspective echoes from the same location. For example, the waterbody bottom may be divided using a square grid into colocation areas that are one meter on a side. Notably, grid size may vary with water depth owing to beam footprints that vary with depth.

[081] In step 350, colocated reflectors are identified using a method such as the one just described. Because colocated reflectors are found in a small area on the waterbody bottom, the depth estimate made for each of the reflectors should be closely similar or, perhaps within measurement accuracy, the same. Notably, reducing the grid size reduces the variation in actual depths among a group of colocated reflectors.

[082] With the assumption that depths among colocated reflectors should be the same, in a sixth step 360 disagreements in depth estimates are characterized in a quantitative manner. In step seven 370, the sensitivity in depth disagreements to sound speed perturbations is quantified. In step eight 380, the depth estimate disagreements are reduced or minimized by selecting speed of sound values that achieve this result. In an embodiment, the process ends thereafter at step 390.

[083] FIGS. 3B-3G which follow provide a flowchart with process step details 300B-G.

[084] **Modeling The Environment**

[085] In FIG. 3B, the flowchart starts with modeling the environment in step 310. As shown alongside the flowchart, a waterbody model 312 provides four layers l1-l4 with respective layer thicknesses t1-t4. The sound speeds entering and leaving the waterbody are c1 and c5 while the sound speeds at layer boundaries are c2-c4. Angles of refraction entering each layer are θ1-θ4 and the angle of refraction leaving layer l4 is θ5.

[086] As skilled artisans will appreciate, ray segments like those of the waterbody model 312 may travel through a layer and/or be modeled as traveling through a layer with no change in sound speed or with various changes in sound speed. For example, sound may travel through a layer with a constant sound speed and experience no change of ray path angle resulting in a straight ray segment. For example, sound may travel through a layer with a constant sound speed gradient and experience a gradual change of ray path angle resulting in a curved ray segment. Notably, the figures do not attempt to replicate curved ray segments. For example, in some embodiments ray angles at layer interfaces may change abruptly with gradual continuous changes thereafter as in a prior layer. For example, in some embodiments the slopes of adjoining rays at layer interfaces may be equal or about equal, for example within 1 to 10 percent difference.

[087] A table alongside the flowchart 314 includes selected variables and

their descriptions.

[088] Known variables in the table are travel time tt for an acoustic message emitted by the projectors 208 and received by the hydrophones 210, sound speed at the launch c1, launch angle θ1. User defined variables are the thicknesses t1-t3 of layers of waterbody layers l1-l3.

[089] Initially estimated variables in the table are sound speeds c2-c5 and angles of refraction θ2-θ5. The unknown variable in the table is the thickness of layer l4.

[090] **Selecting Survey Path**

[091] FIG. 3C is a continuation 300C of the flowchart of FIG. 3B as indicated by link f1. In step 320 a survey path is selected. As shown alongside the flowchart, the survey path selected is an antiparallel track path 322. Track B overlaps Track A, the direction of Track B being opposite the direction of Track A.

[092] As discussed above, with this survey path the ensonification of a Track A cell 325 and the subsequent ensonification of an overlapping Track B cell 327 is intended to provide echoes from multiple perspectives. In particular, echoes resulting from the first ensonification of colocated reflectors are from a perspective other than that of echoes resulting from the second ensonification of the colocated reflectors.

[093] Concerning selection of an antiparallel tracks survey path, the discussion above shows any of several survey paths might be selected including parallel tracks in the same or opposed directions, cross tracks in similar or opposed directions, and same track forward and backward look directions. Further, any combinations of these paths may be chosen to provide multiple echoes from differing perspectives from each of plural reflectors.

[094] Notably, while this discussion speaks of echoes from multiple, e.g., two different, perspectives, a group of colocated reflectors may return echoes from many different perspectives.

[095] **Acquiring Data**

[096] An acquired data step 330 includes an ensonification step 332 where multiple "i" areas (Ai, A2... Ai) are ensonified with "i" pings (P1, P2... Pi) to obtain echoes from "i" perspectives. Also included is a receive returns step 334 where waterbody bottom reflectors return echoes from these pings and round trip travel times of those echoes are measured for all beams, fans, and pings.

[097] As shown alongside the flowchart, an example with i = 3 is shown. For illustrative purposes the waterbody bottom areas A1, A2, A3 are shown as circles. Reflectors located in the common area "Z" where the three circles overlap will return echoes from three different perspectives.

[098] Notably, what is presented here is exemplary. For example, just as two areas may provide an intersecting zone z, so too may many more than two or three overlapping areas provide an intersecting zone.

[099] **Ray Tracing To Determine Reflector Locations**

[0100] Given measured travel time information and the modeled sound speed profile, in step 340 acoustic paths through the layers of the waterbody model 312 between the MBES and ensonified reflectors are modeled. Within each of the areas A1, A2, A3 ray tracing to reflectors provides coordinates x, y, z specific to each reflector. As shown, matrices 326 for respective areas PA1, PA2, PA3 provide coordinates for reflectors therein. Here, seven or more sets of reflector coordinates appear in each matrix and indicate returns from corresponding reflectors in each of the areas. Coordinate indicia indicate a reflector number (e.g., 1-7) and an area that confines the reflector (e.g., A1, A2, A3).

[0101] **Finding Colocated Reflectors**

[0102] FIG. 3D is a continuation 300D of the flowchart of FIG. 3C as indicated by link f2. Here, groups of reflectors may be considered as "colocated" or as representative of a single location on a waterbody bottom such as a location having a single or substantially invariant depth such as

a depth that varies within a survey map tolerance, survey instrument tolerance, selected tolerance, or similar industry tolerance.

[0103] A step of finding colocated reflectors 350 includes an identification step 352, a collection step 354, and a rewrite step 356.

[0104] In the identification step 352, colocated reflectors are identified as reflectors having the same or similar x, y coordinates across all three of the matrices PA1, PA2, PA3 are marked 353.

[0105] In particular, as shown by the dotted box outlines, coordinate pairs $x_{2,A1}$, $y_{2,A1}$ and $x_{5,A2}$, $y_{5,A2}$ and $x_{1,A3}$, $y_{1,A3}$ identify a 1st same or similar waterbody bottom location. As shown by dashed box outlines, coordinate pairs $x_{6,A1}$, $y_{6,A1}$ and $x_{7,A2}$, $y_{7,A2}$ and $x_{4,A3}$, $y_{4,A3}$ identify a 2nd same or similar waterbody bottom location. And, as shown by dashed and dotted box outlines, coordinate pairs $x_{4,A1}$, $y_{4,A1}$ and $x_{3,A2}$, $y_{3,A2}$ and $x_{6,A3}$, $y_{6,A3}$ identify a 3rd same or similar waterbody bottom location.

[0106] Reflector coordinates may be said to identify a similar location when they are situated within a selected colocation area, for example within an area of one square meter. Reflector coordinates may be said to identify a similar location when they lie within a colocation circle, for example a circle having a diameter of one meter. Similarly located reflectors may be identified by overlaying and dividing the waterbody bottom with a pattern such as a grid, regular grid, or square grid and designating each area so identified as a colocation area. For example, where a regular grid such as a square grid is used, areas identified within the grid may be colocation areas such that reflectors falling within a particular grid defined area are colocated reflectors with similar x, y coordinates.

[0107] In the collection step 354, the coordinates of similarly located reflectors are collected 355 in three matrices CP1, CP2, CP3. As suggested by the coordinate indices below the matrices, a simplification in matrix presentation results from rewriting the indices in a manner suggesting that for a given matrix the x,y coordinates are the same or similar.

[0108] In the rewriting step 356 illustrated by three matrices 357, the multiple colocated x and y coordinates of the matrices 355 are assigned a single x and y value to represent the group, for example using an average, grid center or area center. See in particular indices of x, y, z, are rewritten in matrices CPT1, CPT2, CPT3 that correspond to matrices CP1, CP2, CP3. Here, remarking the indices of x and y to be the same within a given matrix emphasizes the equality or similarity of the x, y pairs in the matrix, for example x_1, y_1 for all of the x, y pairs in matrix CPT1.

[0109] Notably, the z coordinates are not necessarily equal or similar. As such, they are remarked as $z_{a,b}$ where "a" is constant in a particular matrix and "b" varies from row to row in the matrix. For example, in the first matrix CPT1 the z coordinates by row are $z_{1,1}$, $z_{1,2}$, $z_{1,3}$.

[0110] In each of the rewritten matrices CPT1, CPT2, CPT3 a respective location x, y corresponds with three different depth estimates. For example, in CPT1 the location x1,y1 corresponds with depth estimates $z_{a,1}$, $z_{a,2}$, $z_{a,3}$.

[0111] **Solution Paradigms**

[0112] In various embodiments, we may assume the depth estimates in each matrix 357 should be the same even though they are not. Equality may be assumed because, for each matrix, the depth estimates correspond with a group of colocated reflectors. As such, the depth estimates in a particular matrix may be viewed as samples or sample values "s" of the same environmental variable at a particular location.

[0113] The goodness of this same matrix/same depth assumption depends on variables including the regularity of the waterbody bottom and the characteristic dimension(s) and/or pattern(s) used to identify colocated reflectors.

[0114] Whatever the case, various methodologies for testing and/or improving depth estimates may manipulate variables such as sound speed(s) to reduce the variability in depth estimates for each group and/or

multiple groups of colocated reflectors.

[0115] **Characterizing Disagreements In Depth Estimates**

[0116] FIG. 3E is a continuation 300E of the flowchart of FIG. 3D as indicated by link f3. Here, a step of characterizing disagreement in depth estimates includes a step establishing a basis to characterize differences 360 and the step of characterizing the disagreement 362.

[0117] In particular, step 360 establishes a basis for characterizing differences in depth estimates. For each group of colocated reflectors a mean value matrix **z** as shown below expresses this basis.

Mean Value Equation	**Variables**	**Variable description**
$\bar{z}_x = (\sum_{y=1}^{s} z_{x,y})/s \Rightarrow \begin{vmatrix} \bar{z}_1 \\ \bar{z}_2 \\ \bar{z}_3 \end{vmatrix}$	$\bar{z}_x$	mean depth for each group x of colocated reflectors
	$z_{x,y}$	depth at y^{th} reflector in group x of colocated reflectors
	s	number of samples

[0118] Given a basis for characterizing differences in depth estimates, step 364 provides for each group of colocated reflectors a measure of the disagreement among depth estimates as expressed by vector **d** shown in the equation below.

Disagreement Equation	**Variables**	**Variable description**
$d_x = (\sum_{y=1}^{s} \lvert \bar{z}_x - z_{x,y} \rvert)/s \Rightarrow \begin{vmatrix} d_1 \\ d_2 \\ d_3 \end{vmatrix}$	d	disagreement in depth estimate for each group x of colocated reflectors (residuals)
	$\bar{z}_x$	mean depth for each group x of colocated reflectors
	$z_{x,y}$	depth at y^{th} reflector in group x of colocated reflectors

	s	number of samples

[0119] **Constructing A Gradient Matrix**

[0120] FIG. 3F is a continuation 300F of the flowchart of FIG. 3E as indicated by link f4. The gradient matrix is a metric of the sensitivity of depth estimates to modeled sound speeds and is constructed by first perturbing the values of sound speed $c_2 \ldots c_p$ by a positive increment and then by a negative increment. Then, for each perturbation, steps are repeated including the steps of determining reflector locations 340, finding colocated reflectors 350, and characterizing disagreements in depth estimates 360 with vectors $\mathbf{d}_+$ and $\mathbf{d}_-$.

[0121] In step 371, a counter p counts from 2 to 5 indicating values of the speed of sound $c_2 \ldots c_5$ consistent with a four layer waterbody model having five corresponding values of the speed of sound $c_1 \ldots c_5$ where c_1 is a known value of the speed of sound at the launch.

[0122] In step 372, a positive perturbation $(+\Delta)$ is applied to a p^{th} sound speed value c_p. Steps 340-364 are repeated and vector $\mathbf{d}_{p+}$ is populated 376. The p^{th} sound speed value c_p is then reset.

[0123] In step 373, a negative perturbation $(-\Delta)$ is applied to the p^{th} sound speed value c_p. Steps 340-364 are repeated and vector $\mathbf{d}_{p-}$ is populated 377. The p^{th} sound speed value c_p is then reset.

[0124] In step 374, a p^{th} row of the gradient matrix $\mathbf{G}$ is populated. In particular, $G_{p,i} = (d_{p+,i} - d_{p-,i})/2 \text{ mag}(\Delta)$ where counter i varies from 1 to n to populate 378 the columns of the matrix $\mathbf{G}$, each value of i representing the i^{th} group of colocated reflectors. When the last column is populated, counter p indexes to the next value in step 375 and steps 372-374 are repeated. When the last row of the matrix $\mathbf{G}$ is populated, the process proceeds to step 382 of the minimize disagreement block 380.

[0125] **Minimizing Depth Estimate Disagreement**

[0126] FIG. 3G is a continuation 300G of the flowchart of FIG. 3F as indicated by link f5. In this figure, disagreements among depth estimates in each group of colocated reflectors are simultaneously minimized utilizing conventional least-squares techniques associated with linear algebra.

[0127] In step 382, an equation utilizing the gradient matrix **G** and disagreement in depth estimates vector **d** provides a vector of corrections **mhat** to be applied to sound speed values to reduce or minimize depth disagreements. The equation presented 382 is a well-known least-squares minimizing solution whose derivation is available in academic texts such as the text by Munk, Walter, et al., *Ocean Acoustic Tomography,* Cambridge University Press, 1995. The equation provides two terms for conveying prior information, if known, about the noise or solutions. The diagonal of matrix **R** can be populated with the relative sizes of noise variance associated with each observation in vector **d**. The diagonal of matrix **S** can be populated with the relative sizes of the elements of **mhat**.

Overdetermined System Equation	**Variables**	**Variable description**
$\hat{m} = (G^T R^{-1} G + S^{-1})^{-1} G^T R^{-1} d$	$\hat{m}$ (**mhat**)	Vector of corrections to be applied to sound speed values $c_2 \ldots c_5$.
	$\mathbf{G}^T$	Transpose of gradient matrix **G** (interchange of rows and columns)
	R	Matrix conveying information about data uncertainty.
	$\mathbf{R}^{-1}$	Inverse of **R** matrix
	G	Gradient matrix.
	S	Matrix conveying information about model parameter sizes.
	$\mathbf{S}^{-1}$	Inverse of **S** matrix
	d	disagreement in depth estimate for each group x of colocated reflectors

		(residuals)

[0128] In step 384, each of the sound speed values c2... c5 is corrected using the correction vector **mhat**.

Sound Speed Estimates	**Variables**	**Variable description**
$c_{2est} = c_2 - \hat{m}_2$ $c_{3est} = c_3 - \hat{m}_3$ $c_{4est} = c_4 - \hat{m}_4$ $c_{5est} = c_5 - \hat{m}_5$	c	sound speed
	mhat	sound speed correction

[0129] **Synthesizing A Sound Speed Profile**

[0130] The above solution procedure is based on a multilayer waterbody model with a known sound speed c_1 at launch and initial estimates or otherwise available values of sound speed at the layer interfaces and at the waterbody bottom.

[0131] Notably, cases may arise where the only available value(s) of sound speed are sound speed value(s) at launch. For example, a survey conducted with equipment malfunction(s) or human error(s) may result in such a case. For example, a survey conducted with the intent to estimate sound speed values after the survey is conducted may result in such a case.

[0132] In some embodiments, the system and method of the present invention may be used to synthesize a sound speed profile. For example, where sound speed at launch is known, the system and method of the present invention may be used to synthesize a sound speed profile through a waterbody modeled with a plurality of layers.

[0133] FIG. 4 shows a method for synthesizing a sound speed profile where

a waterbody is modeled with multiple layers 400. Steps in this synthesis method corresponding to those mentioned above (see e.g., FIGS. 3A-G) may be carried out in a similar manner.

[0134] In a first step 410 the need for synthesizing a sound speed profile is evaluated. Where there is a need, the process proceeds to a second step 420.

[0135] In the second step 420, known variables are identified. In particular, knowns may be sound speed at a Mills Cross transducer array, launch angle, travel time, GPS data, and vessel heading/tilt/roll data. In a third step 430, the environment is modeled. Here, c_1 is known and for j layers the sound speed is set to c_1 such that in each layer the speed of sound is the same.

[0136] With a multilayer model, ray tracing locates reflectors in a fourth step 440. And, finding groups of colocated reflectors follows in a fifth step 450.

[0137] In step 460, i) disagreements in depth estimates are characterized in a manner similar to that described in step 360 above, ii) a gradient matrix is constructed in a manner similar to that described in step 370 above, iii) disagreements among depth estimates in each group of colocated reflectors are reduced in a manner similar to that described in step 380 above, iv) sound speed adjustments are calculated in a manner similar to that described in step 380 above, and v) sound speed adjustments are applied as suggested above. Using the adjusted values of sound speed, a survey may be created in step 470. Following step 470 is an end step 480.

[0138] In an embodiment, a threshold value that when compared to a function of the measured depth disagreements indicates whether the assumed sound speed profile differs from the real environment.

[0139] While various embodiments of the present invention have been described above, it should be understood that they have been presented by

way of example only, and not limitation. It will be apparent to those skilled in the art that various changes in the form and details can be made without departing from the spirit and scope of the invention. As such, the breadth and scope of the present invention should not be limited by the above-described exemplary embodiments, but should be defined only in accordance with the following claims and equivalents thereof.

CLAIMS

What is claimed is:

1. A multi-perspective ensonification method comprising the steps of:

installing a multibeam echo sounder system ("MBES") on a water going vehicle such that plural transducers in a single MBES projector array and plural transducers in a single MBES hydrophone array are in a Mills Cross arrangement;

modeling a waterbody with a plurality of "j" superposed layers (l_1... l_j) having respective layer thicknesses (t_1... t_j), each of the j layers having a layer entry sound speed and a layer exit sound speed such that a set of (j+1) sound speed values (c_1, c_2... c_{j+1}) characterize the sound speed profile through the layers;

designing a vehicle route and traversing the route such that during MBES operation along the route i) plural primary areas are ensonified, ii) plural secondary areas are ensonified, iii) each primary area is overlapped by a respective secondary area, and iv) for each overlap a first echo originating therein traverses a first path to the MBES and a second echo originating therein traverses a second path to the MBES at a location different from the first;

via a travel time corresponding to each echo, modeling the propagation of sound through the waterbody to locate in three dimensions a reflector that returned the echo;

one of the dimensions indicating a waterbody depth and the other two dimensions indicating coordinates in a reflector plane parallel to the waterbody free surface;

selecting a colocation metric and using the metric to identify groups of reflectors that are colocated in the reflector plane;

for each group of colocated reflectors, quantifying disagreements in the waterbody depths corresponding to the reflectors in the group; and,

determining a set of adjusted sound speed values that tends to simultaneously reduce the disagreement within each group of depth estimates.

2. The method of claim 1 wherein the first echo path corresponds to a first beam angle and the second echo path corresponds to a second beam angle.

3. The method of claim 1 wherein the adjusted sound speed values are a function of disagreements in depth estimates evaluated at i) assumed sound speeds $(c_1, c_2 \ldots)$ and at ii) perturbed values of assumed sound speeds $(c_1, c_2 \ldots)_p$.

4. The method of claim 3 wherein non-intersecting first and second survey vessel tracks are chosen such that operating the MBES while traversing the tracks results in (i) at least partially superimposed first and second waterbody bottom fans that overlap at a site and (ii) multiple echoes from multiple colocated reflectors at the site.

5. The method of claim 3 wherein intersecting first and second survey vessel tracks are chosen such that operating the MBES while traversing the tracks results in (i) at least partially superimposed first and second waterbody bottom fans that overlap at a site and (ii) multiple echoes from multiple colocated reflectors at the site.

6. The method of claim 3 wherein MBES operation while traversing a single track results in (i) at least partially superimposed first and second waterbody fans that overlap at a site and (ii) multiple echoes from multiple colocated reflectors at the site.

7. The method of claim 6 wherein the first fan results from a forwardly pitched fan at time1 and the second fan results from rearwardly pitched fan at time2 where time2 > time1.

8. The method of claim 1 further comprising the step of operating the vehicle and the MBES to conduct a bathymetric survey.

9. The method of claim 8 further comprising the step of:

using the colocation metric, assigning each reflector to one of multiple zones that partition the reflector plane; and,

wherein reflectors assigned to the same zone are colocated reflectors.

10. The method of claim 9 wherein each of plural zones includes a respective group of 2 to 100 colocated reflectors.

11. The method of claim 10 wherein the zones have a characteristic dimension that is a function of a beam width and an altitude measured vertically between the MBES and a waterbody bottom.

12. The method of claim 10 wherein the zones have a characteristic dimension that varies proportionally with water depth.

13. The method of claim 8 wherein j = 4, c_1 is measured, and adjusted sound speed values include c_2, c_3, c_4, c_5.

14. The method of claim 9 wherein the quantified disagreements in depth estimates are used to construct a system of simultaneous equations that is overdetermined, plural adjustments to respective sound speed values being indicated by a solution to the equations.

15. The method of claim 3 wherein the sound speed values are corrected using the one or more adjusted sound speed values.

16. The method of claim 3 wherein a portion of a bathymetric survey map is corrected when data used to make the map are used to find adjusted sound speed values and the survey map is recreated by replacing sound speed values in the data with adjusted sound speed values.

17. A synthetic sound speed profile creation method comprising the steps of:

providing MBES bathymetric data from a completed survey, the data including for each of multiple overlapping ensonified areas a first echo originating therein and a second echo originating therein, the first echo traversing a first path and the second echo traversing a second path;

modeling the surveyed waterbody with j superposed layers (l_1... l_j), each of the layers having a layer entry sound speed and a layer exit sound speed such that a set of (j+1) sound speed values (c_1, c_2... c_{j+1}) characterize the sound speed profile through the layers;

setting the value of c_1 to a best estimate of c_1 and setting the values of c_2 through c_{j+1} to c_1;

estimating the three dimensional locations of waterbody bottom reflectors via ray tracing through the layers using the modeled sound speeds and survey data including launch angle, travel time, GPS data, and heading/tilt/roll data;

selecting a colocation metric and using the metric to identify groups of colocated reflectors;

for each group of colocated reflectors and respective reflector depth estimates, quantifying disagreements in the depth estimates;

determining a set of adjusted sound speed values that tends to reduce the depth estimate disagreements within each group of depth estimates; and,

using the adjusted sound speed values and MBES bathymetric survey data, creating a bathymetric survey map.

18. A method of warning that the assumed sound speed velocity profile is inaccurate, the method comprising the steps of:

installing a multibeam echo sounder system ("MBES") on a water going vehicle such that plural transducers in a single MBES projector array and plural transducers in a single MBES hydrophone array are in a Mills Cross arrangement;

modeling a waterbody with a plurality of "j" superposed layers (l_1... l_j) having respective layer thicknesses (t_1... t_j), each of the j layers having a layer entry sound speed and a layer exit sound speed such that a set of (j+1) sound speed values (c_1, c_2... c_{j+1}) characterize the sound speed profile through the layers;

designing a vehicle route and traversing the route such that during MBES operation along the route i) plural primary areas are ensonified, ii) plural secondary areas are ensonified, iii) each primary area is overlapped by a respective secondary area, and iv) for each overlap a first echo originating therein traverses a first path to the MBES and a second echo originating therein traverses a second path to the MBES at a location different from the first;

via a travel time corresponding to each echo, modeling the propagation of sound through the waterbody to locate in three dimensions a reflector that returned the echo;

one of the dimensions indicating a waterbody depth and the other two dimensions indicating coordinates in a plane parallel to the waterbody free surface;

selecting a colocation metric and using the metric to identify groups of reflectors that are colocated in the reflector plane;

for each group of colocated reflectors, quantifying disagreements in the waterbody depths corresponding to the reflectors in the group; and,

a threshold value that when compared to a function of the measured depth disagreements indicates whether the assumed sound speed profile differs from the real environment.

FIG. 1A

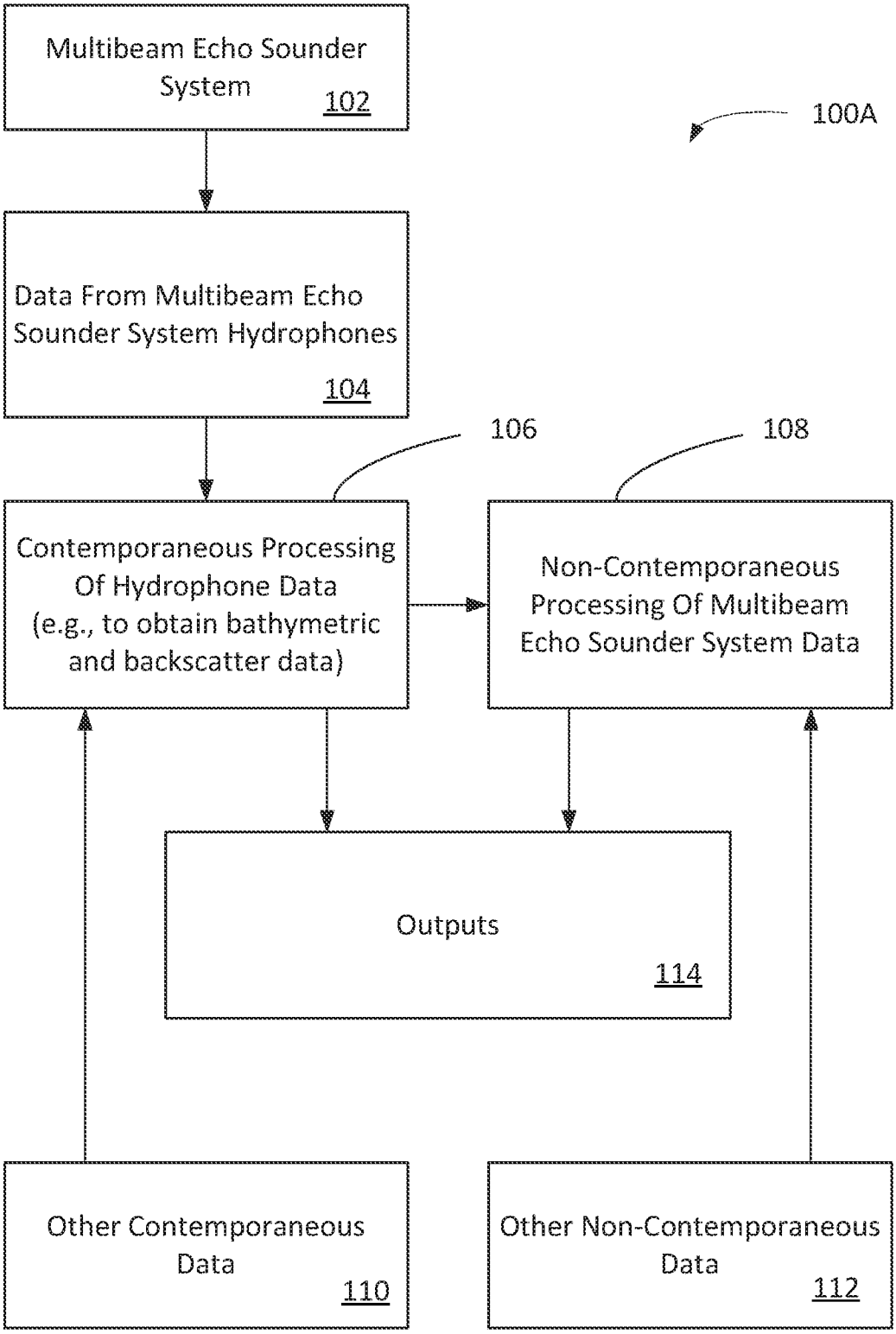

Multibeam Echo Sounder System
102
100A
Data From Multibeam Echo Sounder System Hydrophones
104
106
108
Contemporaneous Processing Of Hydrophone Data (e.g., to obtain bathymetric and backscatter data)
Non-Contemporaneous Processing Of Multibeam Echo Sounder System Data
Outputs
114
Other Contemporaneous Data
110
Other Non-Contemporaneous Data
112

FIG. 1B

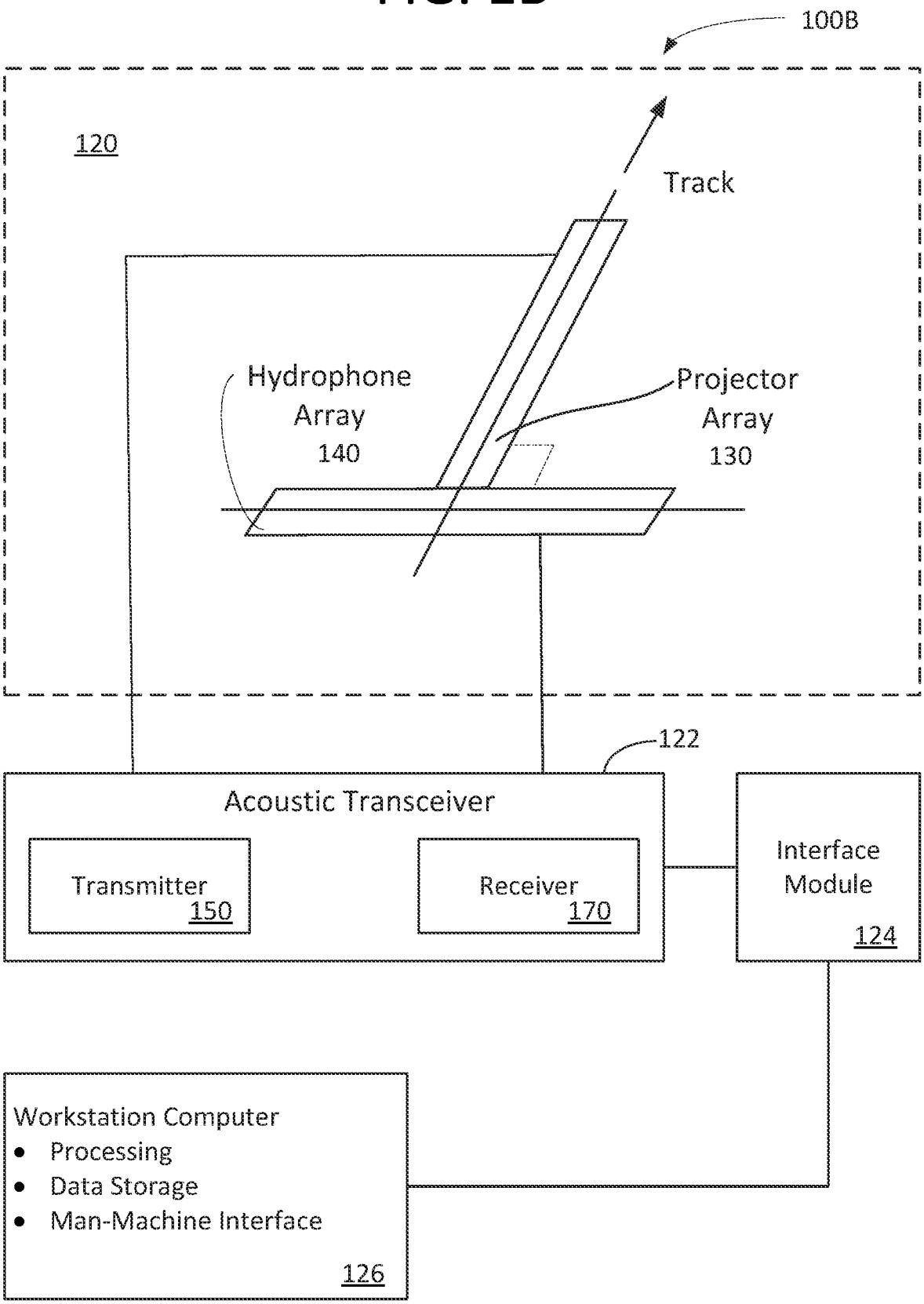

100B
120
Track
Hydrophone
Array
140
Projector
Array
130
122
Acoustic Transceiver
Transmitter
150
Receiver
170
Interface
Module
124
Workstation Computer
• Processing
• Data Storage
• Man-Machine Interface
126

FIG. 2A

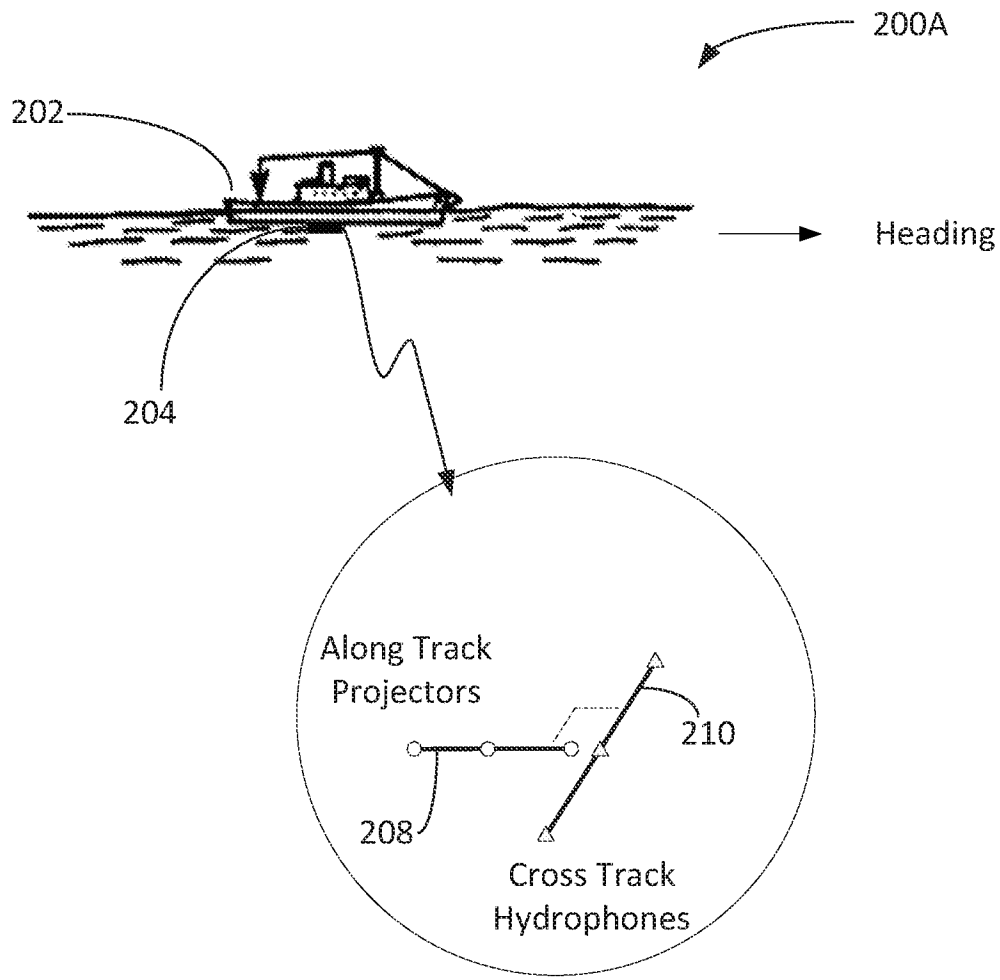

200A
202
Heading
204
Along Track
Projectors
210
208
Cross Track
Hydrophones

FIG. 2B

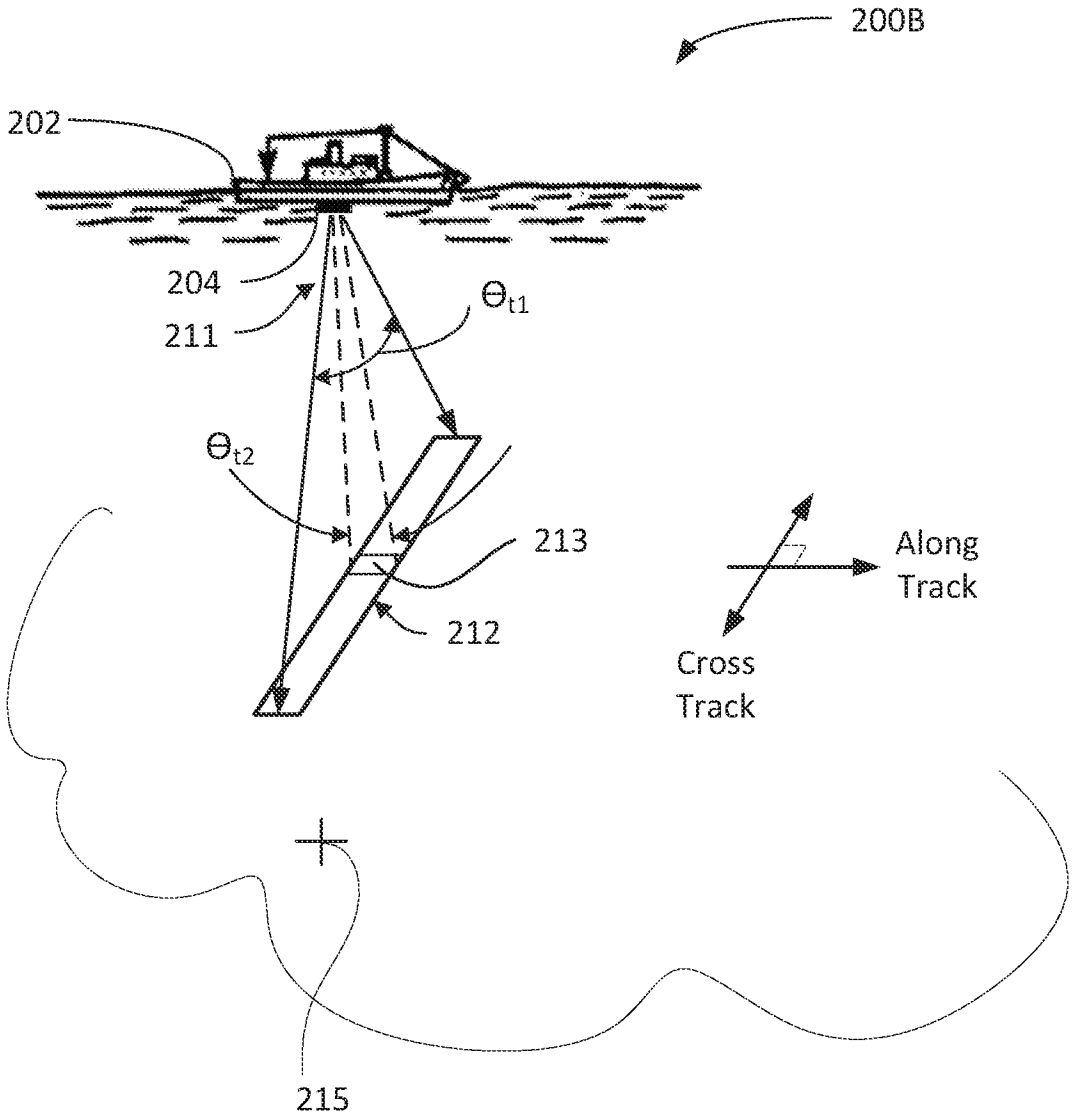

200B
202
204
211
Θ_{t1}
Θ_{t2}
213
212
Along Track
Cross Track
215

FIG. 2C

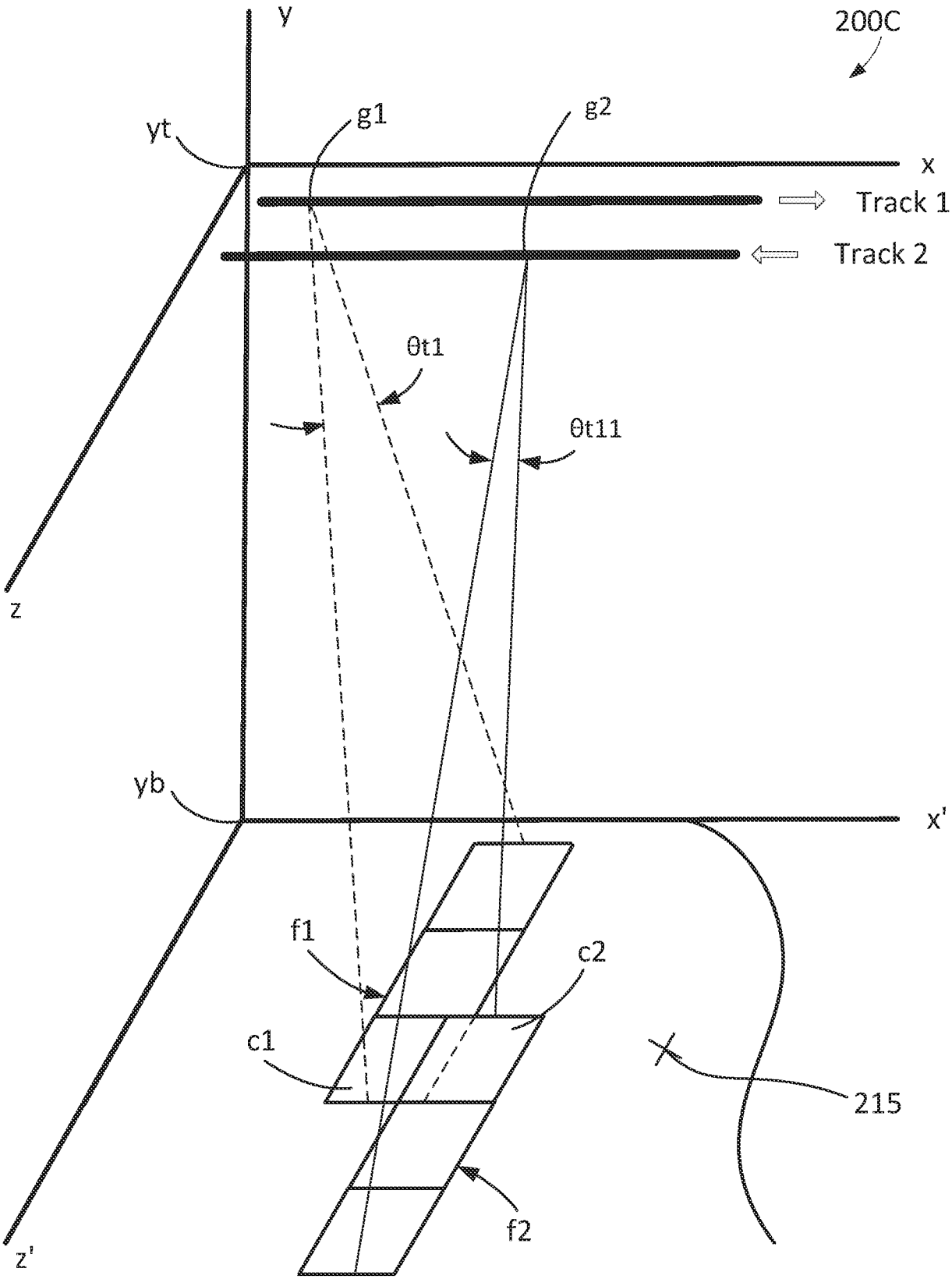


FIG. 2D

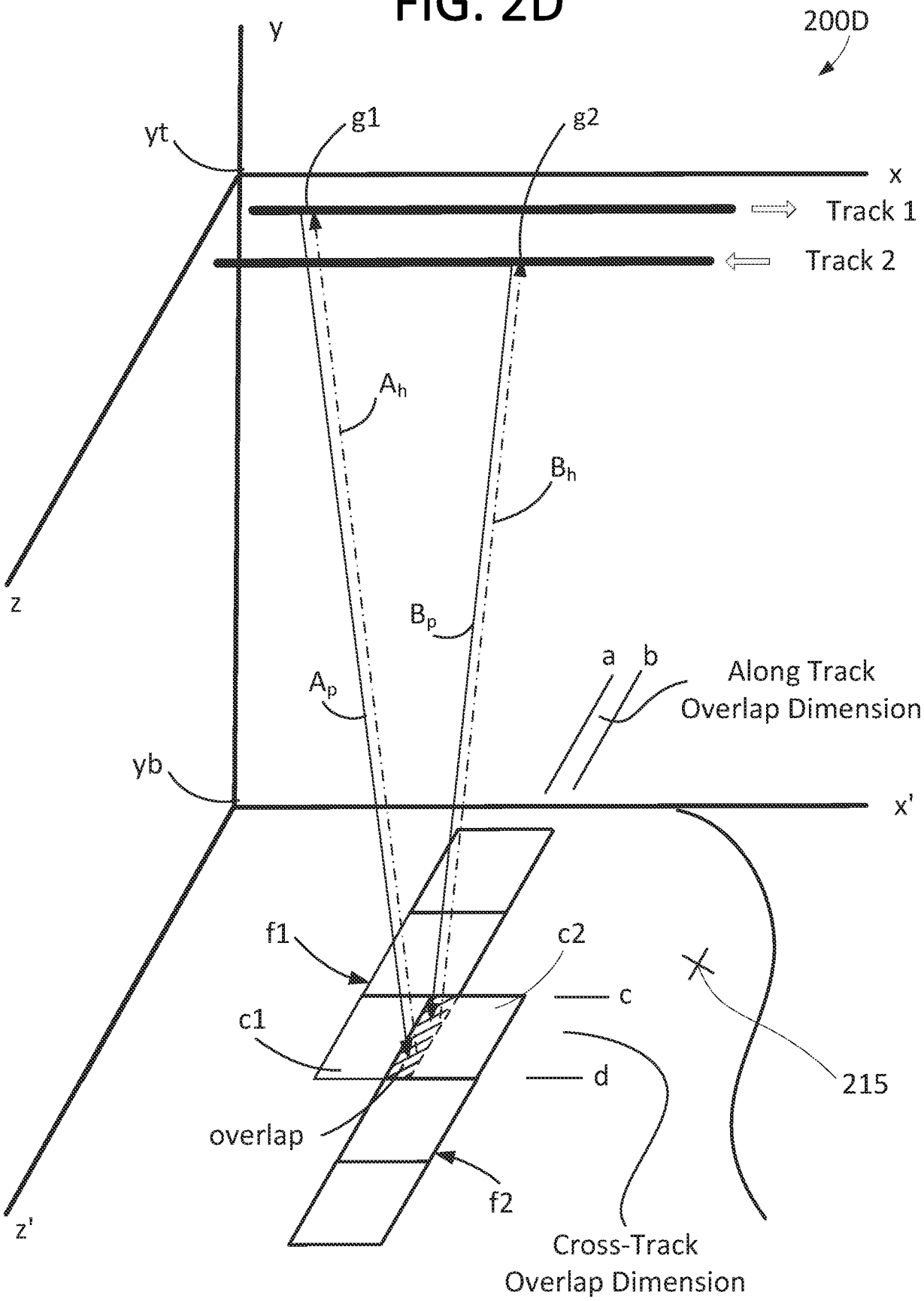

200D
y
yt
g1
g2
x
Track 1
Track 2
A_h
B_h
z
B_p
A_p
a
b
Along Track
Overlap Dimension
yb
x'
f1
c2
c
c1
d
215
overlap
f2
z'
Cross-Track
Overlap Dimension

FIG. 2E

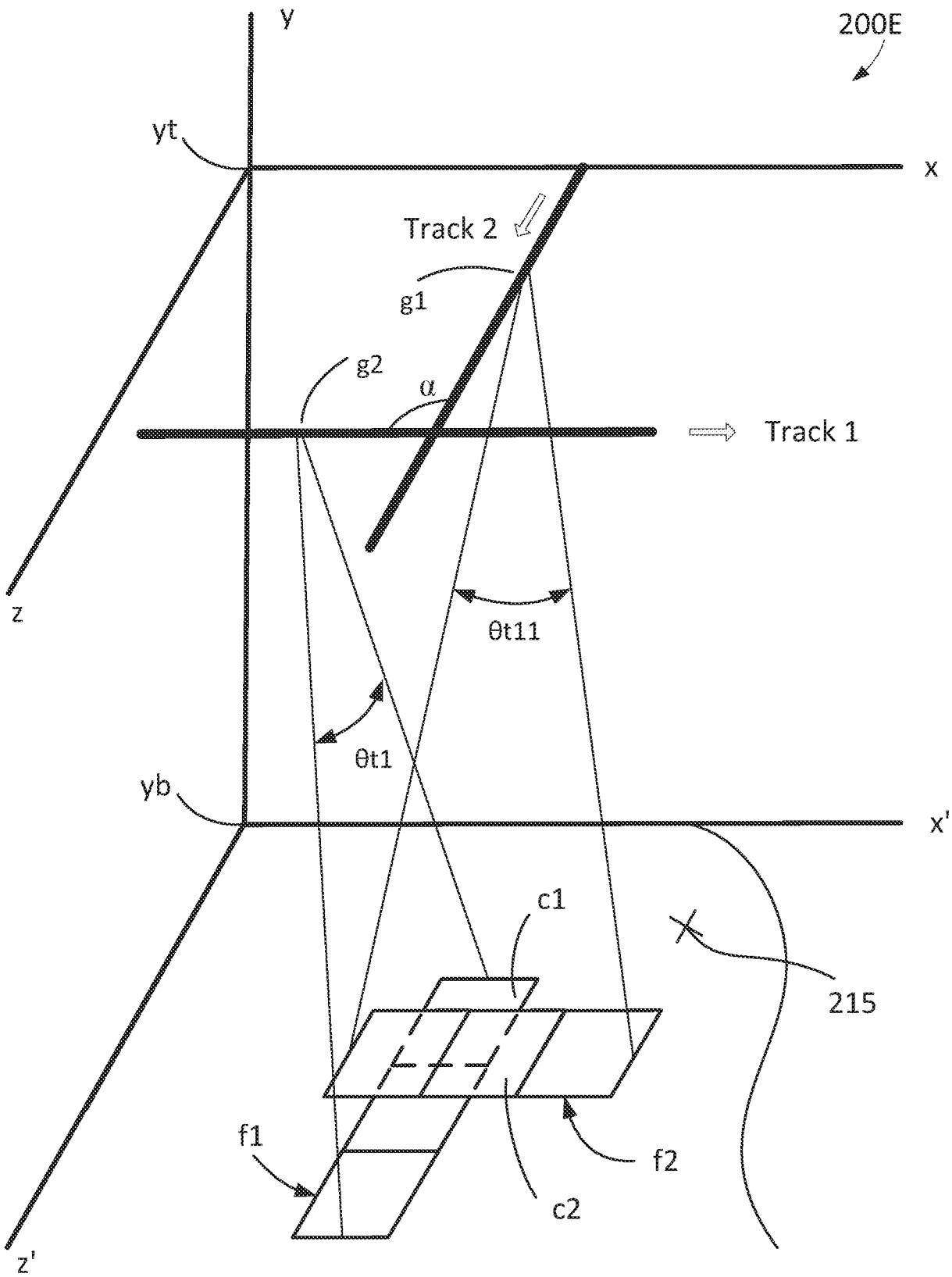


FIG. 2F

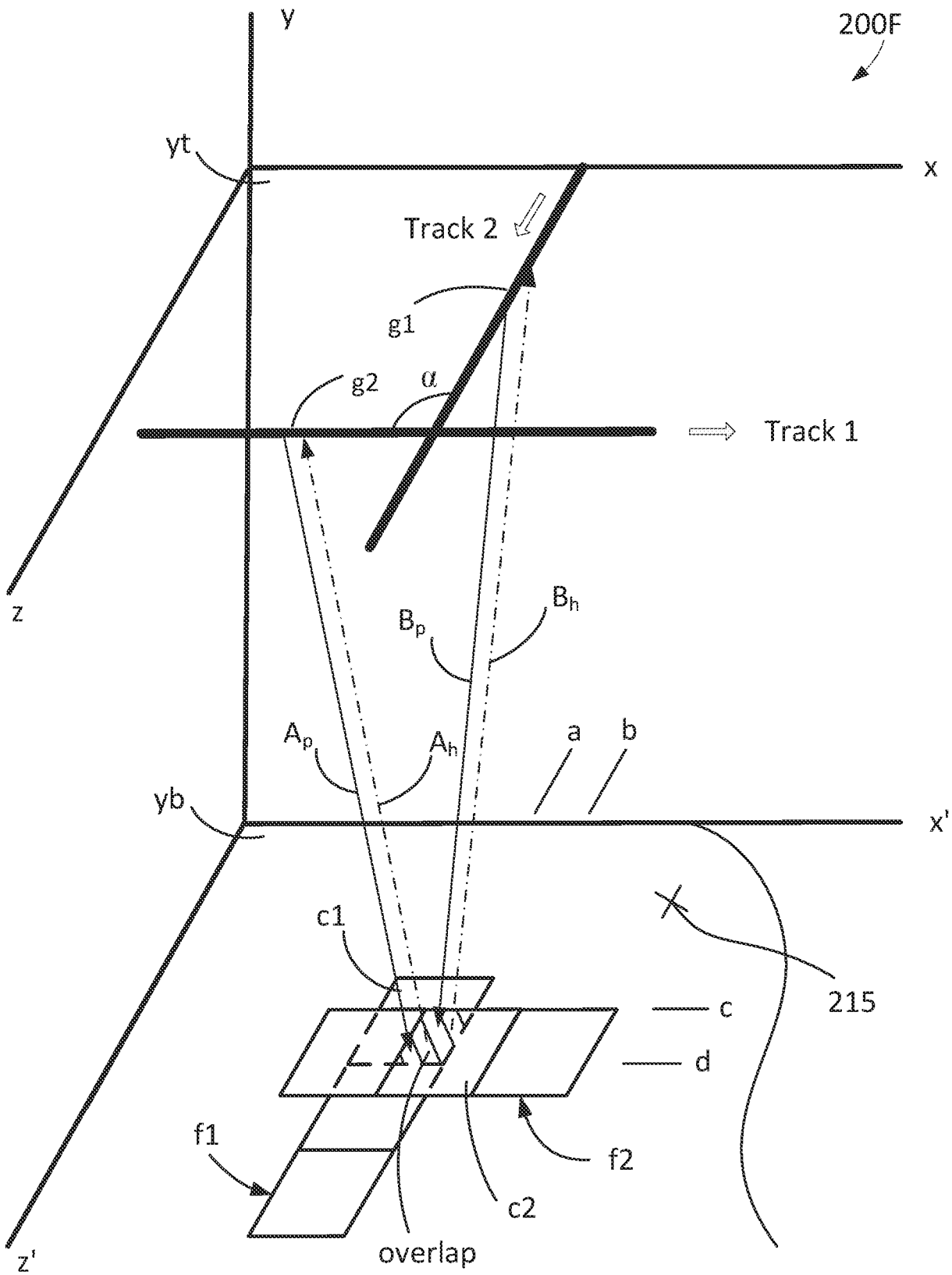

y
200F
yt
x
Track 2
g1
g2
α
Track 1
z
B_h
B_p
A_p
A_h
a
b
yb
x'
c1
215
c
d
f1
f2
c2
overlap
z'

FIG. 2G

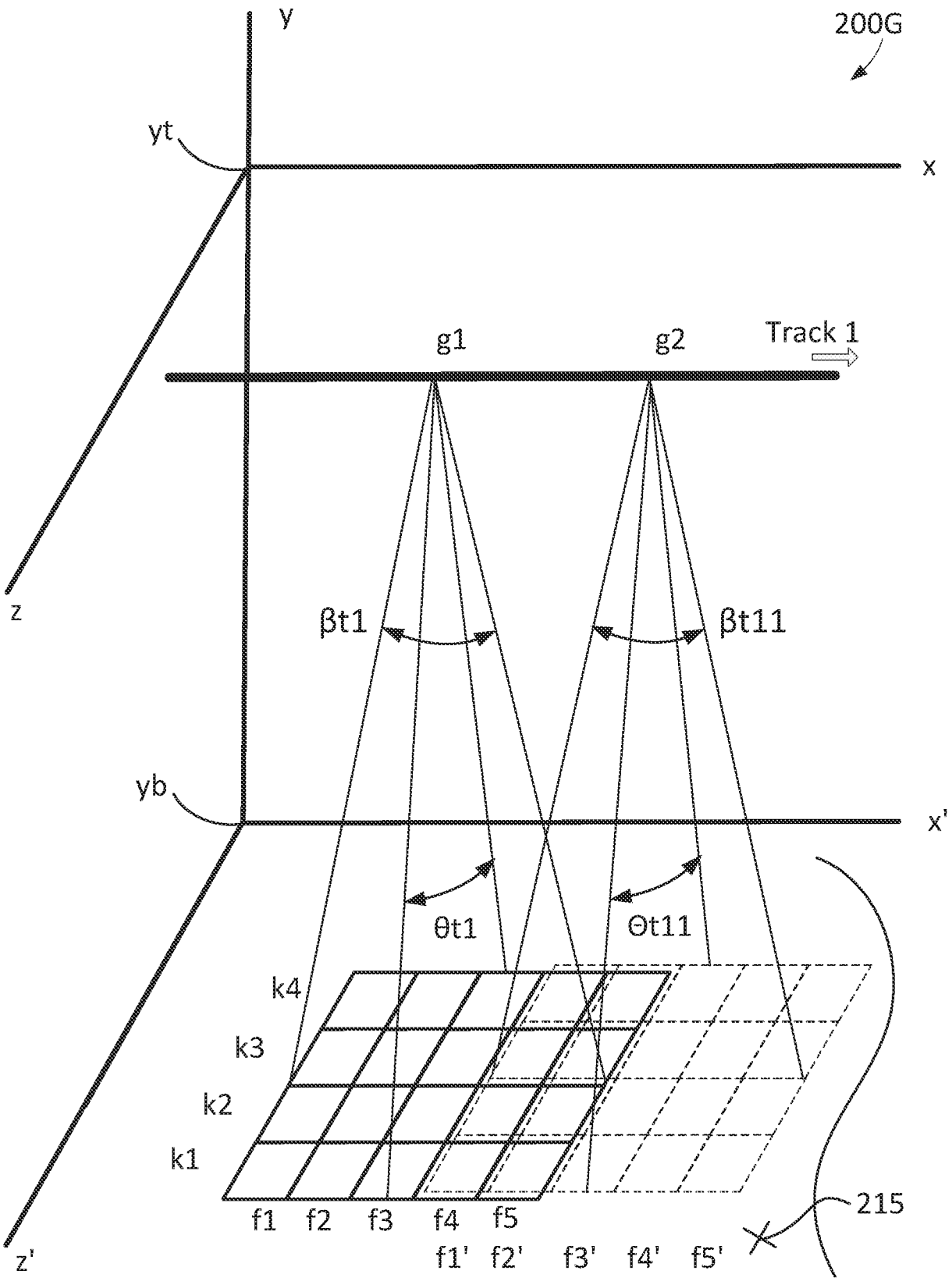

y
200G
yt
x
g1
g2
Track 1
z
βt1
βt11
yb
x'
θt1
Θt11
k4
k3
k2
k1
f1
f2
f3
f4
f5
f1'
f2'
f3'
f4'
f5'
215
z'

FIG. 2H

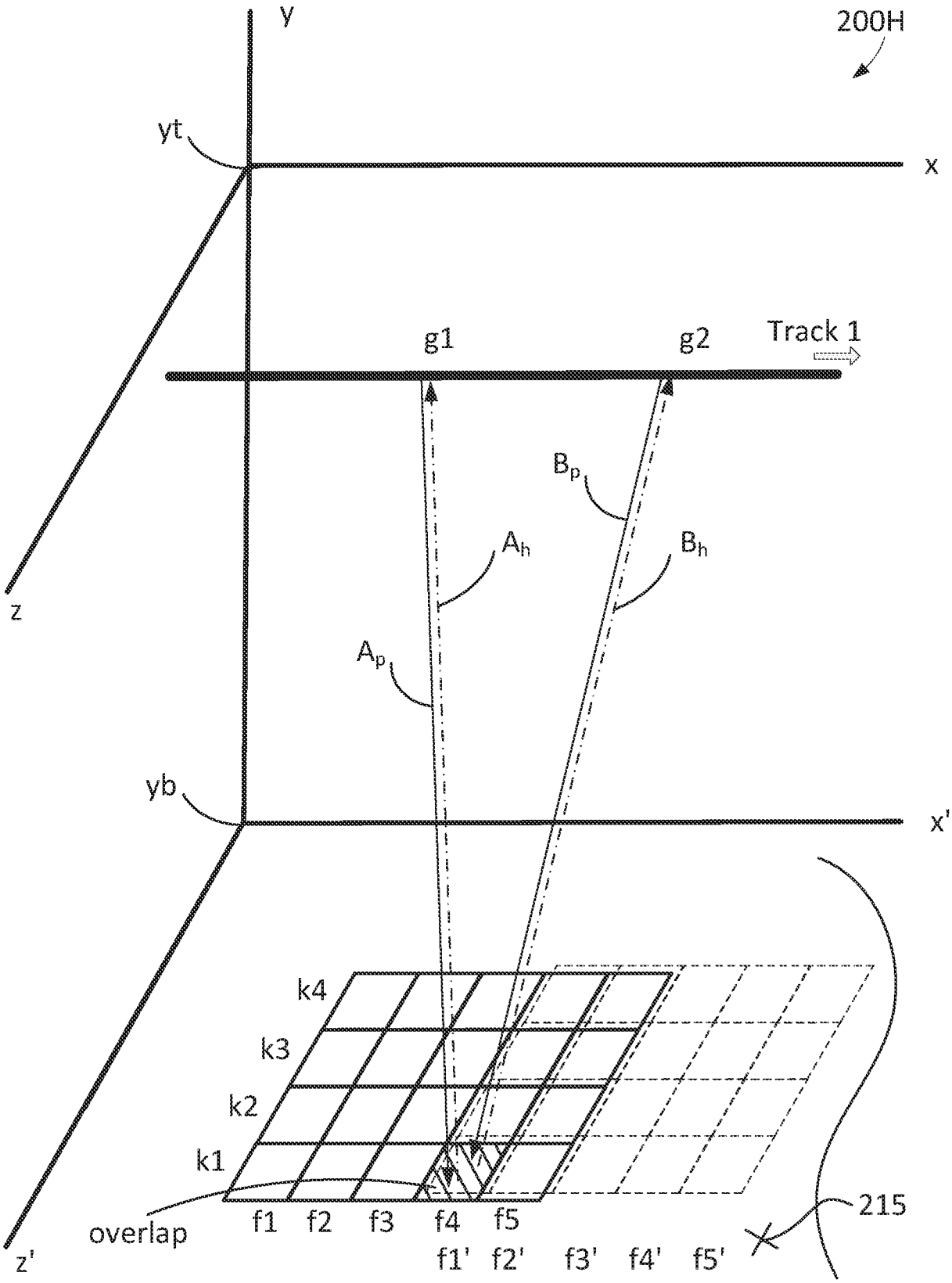

y
200H
yt
x
g1
g2
Track 1
B_p
A_h
B_h
z
A_p
yb
x'
k4
k3
k2
k1
overlap
f1 f2 f3 f4 f5
f1' f2' f3' f4' f5'
215
z'

FIG. 2I

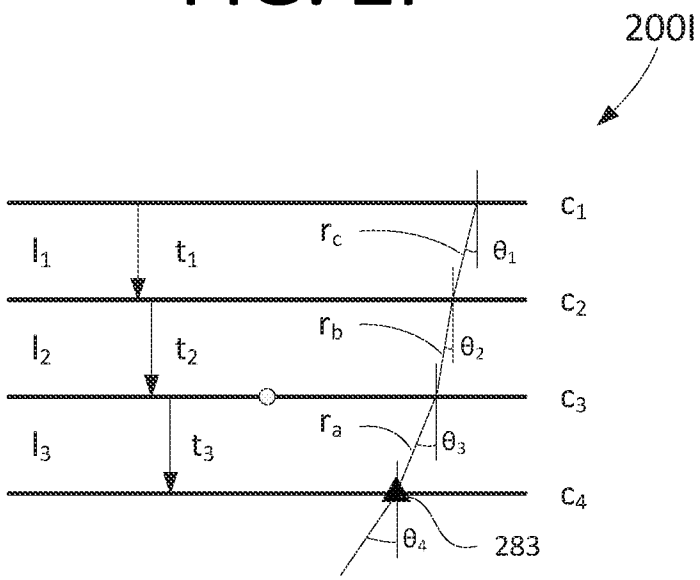

200I
c1
c2
c3
c4
l1
t1
rc
θ1
l2
t2
rb
θ2
l3
t3
ra
θ3
θ4
283

FIG. 2J

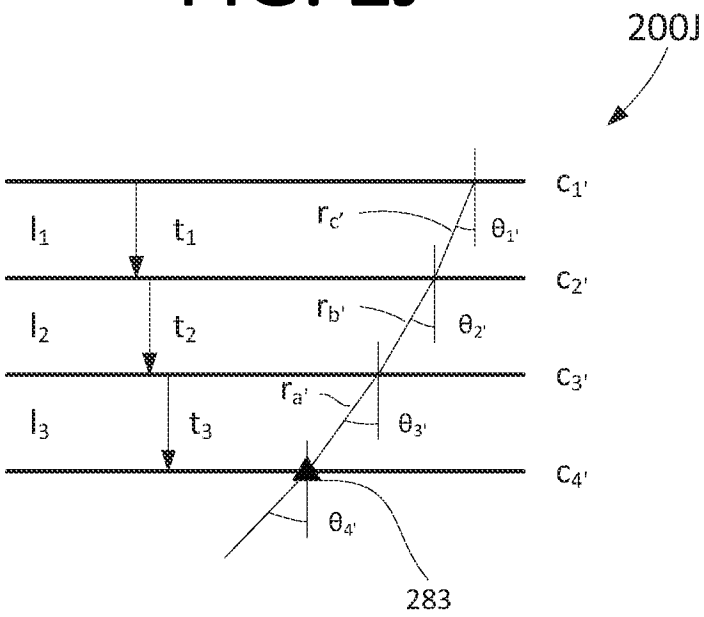

200J
c1'
c2'
c3'
c4'
l1
t1
rc'
θ1'
l2
t2
rb'
θ2'
l3
t3
ra'
θ3'
θ4'
283

FIG. 3A

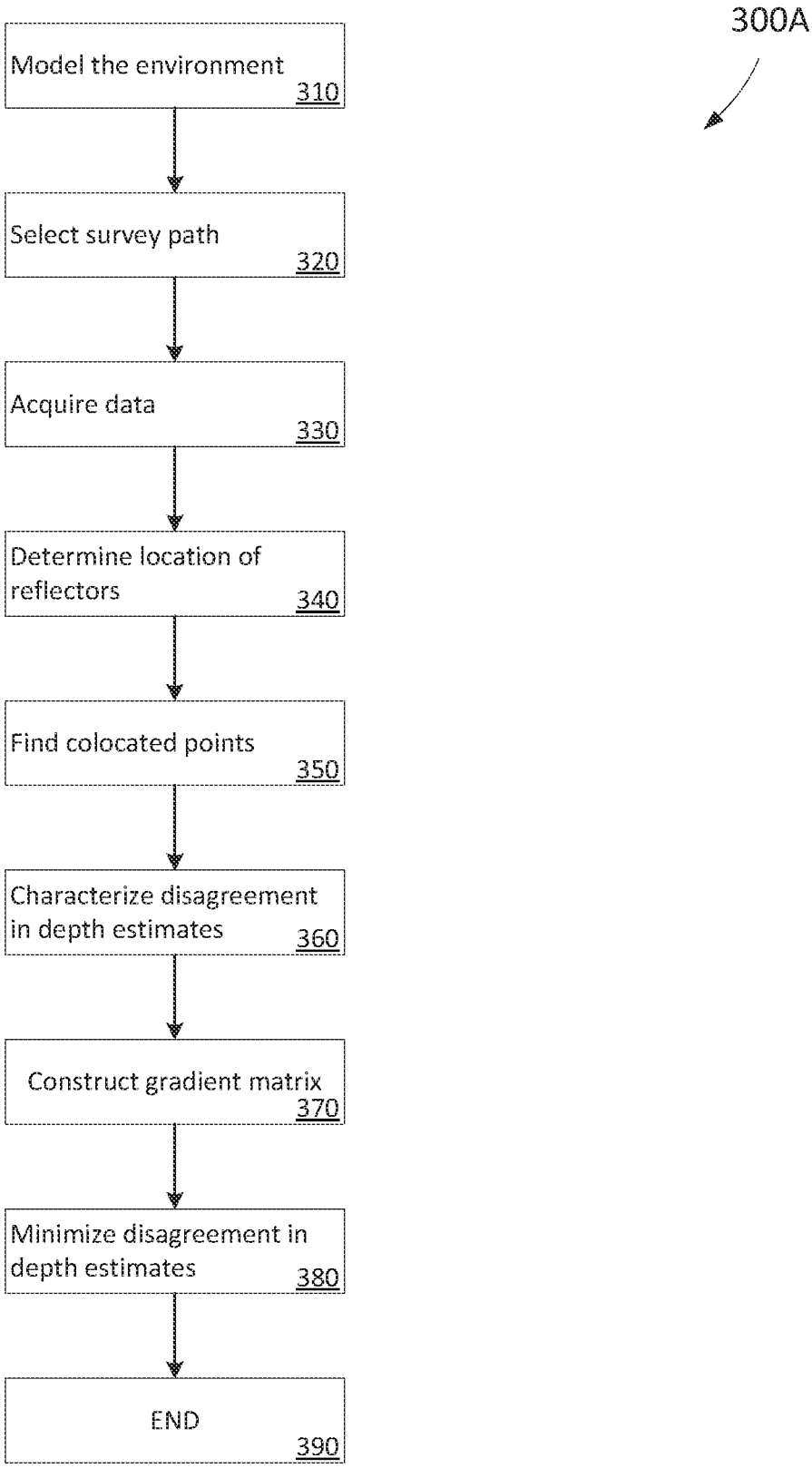
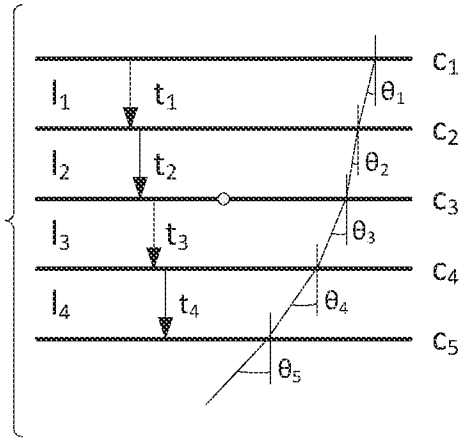

300A
Model the environment
310
Select survey path
320
Acquire data
330
Determine location of reflectors
340
Find colocated points
350
Characterize disagreement in depth estimates
360
Construct gradient matrix
370
Minimize disagreement in depth estimates
380
END
390

FIG. 3B

300B

Model the environment 310



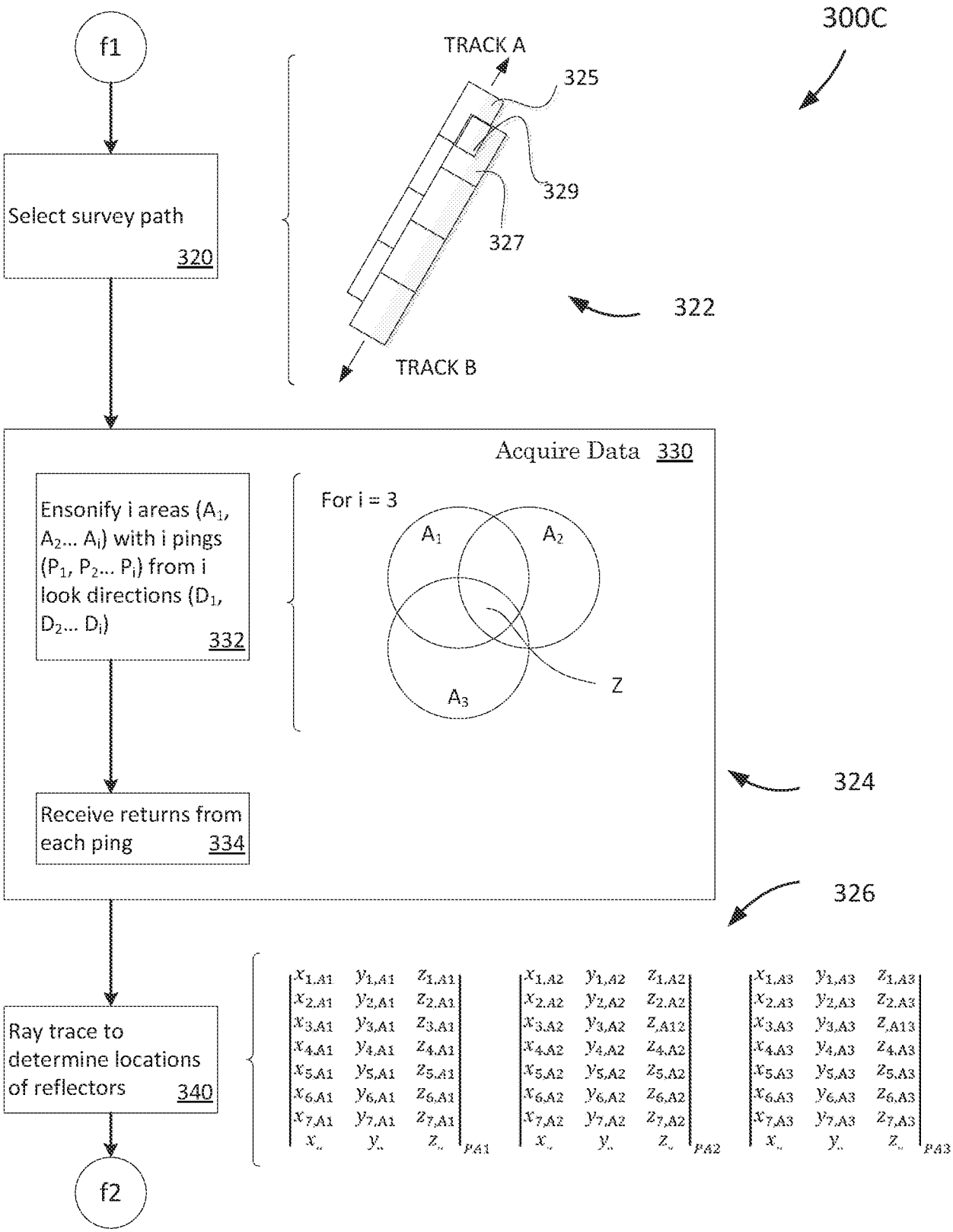
312

314

Variable	Description	Known	Defined	Initially Estimated	Unknown
tt	travel time	X			
c_1	launch soundspeed	X			
θ_1	launch angle	X			
t_1	thickness of layer l_1		X		
c_2	soundspeed at l_2 entry			X	
θ_2	angle at l_2 entry			$\theta_2 = f(c_1, c_2, \theta_1)$	
t_2	thickness of layer l_2		X		
c_3	soundspeed at l_3 entry			X	
θ_3	angle at l_3 entry			$\theta_3 = f(c_2, c_3, \theta_2)$	
t_3	thickness of layer l_3		X		
c_4	soundspeed at l_4 entry			X	
θ_4	angle at l_4 entry			$\theta_4 = f(c_3, c_4, \theta_3)$	
t_4	thickness of layer l_4				X
c_5	soundspeed at l_5 entry			X	
θ_5	angle at l_5 entry			$\theta_5 = f(c_4, c_5, \theta_4)$	

f1

FIG. 3C



$$\begin{vmatrix} x_{1,A1} & y_{1,A1} & z_{1,A1} \\ x_{2,A1} & y_{2,A1} & z_{2,A1} \\ x_{3,A1} & y_{3,A1} & z_{3,A1} \\ x_{4,A1} & y_{4,A1} & z_{4,A1} \\ x_{5,A1} & y_{5,A1} & z_{5,A1} \\ x_{6,A1} & y_{6,A1} & z_{6,A1} \\ x_{7,A1} & y_{7,A1} & z_{7,A1} \\ x_{..} & y_{..} & z_{..} \end{vmatrix}_{PA1} \quad \begin{vmatrix} x_{1,A2} & y_{1,A2} & z_{1,A2} \\ x_{2,A2} & y_{2,A2} & z_{2,A2} \\ x_{3,A2} & y_{3,A2} & z_{,A12} \\ x_{4,A2} & y_{4,A2} & z_{4,A2} \\ x_{5,A2} & y_{5,A2} & z_{5,A2} \\ x_{6,A2} & y_{6,A2} & z_{6,A2} \\ x_{7,A2} & y_{7,A2} & z_{7,A2} \\ x_{..} & y_{..} & z_{..} \end{vmatrix}_{PA2} \quad \begin{vmatrix} x_{1,A3} & y_{1,A3} & z_{1,A3} \\ x_{2,A3} & y_{2,A3} & z_{2,A3} \\ x_{3,A3} & y_{3,A3} & z_{,A13} \\ x_{4,A3} & y_{4,A3} & z_{4,A3} \\ x_{5,A3} & y_{5,A3} & z_{5,A3} \\ x_{6,A3} & y_{6,A3} & z_{6,A3} \\ x_{7,A3} & y_{7,A3} & z_{7,A3} \\ x_{..} & y_{..} & z_{..} \end{vmatrix}_{PA3}$$

FIG. 3D

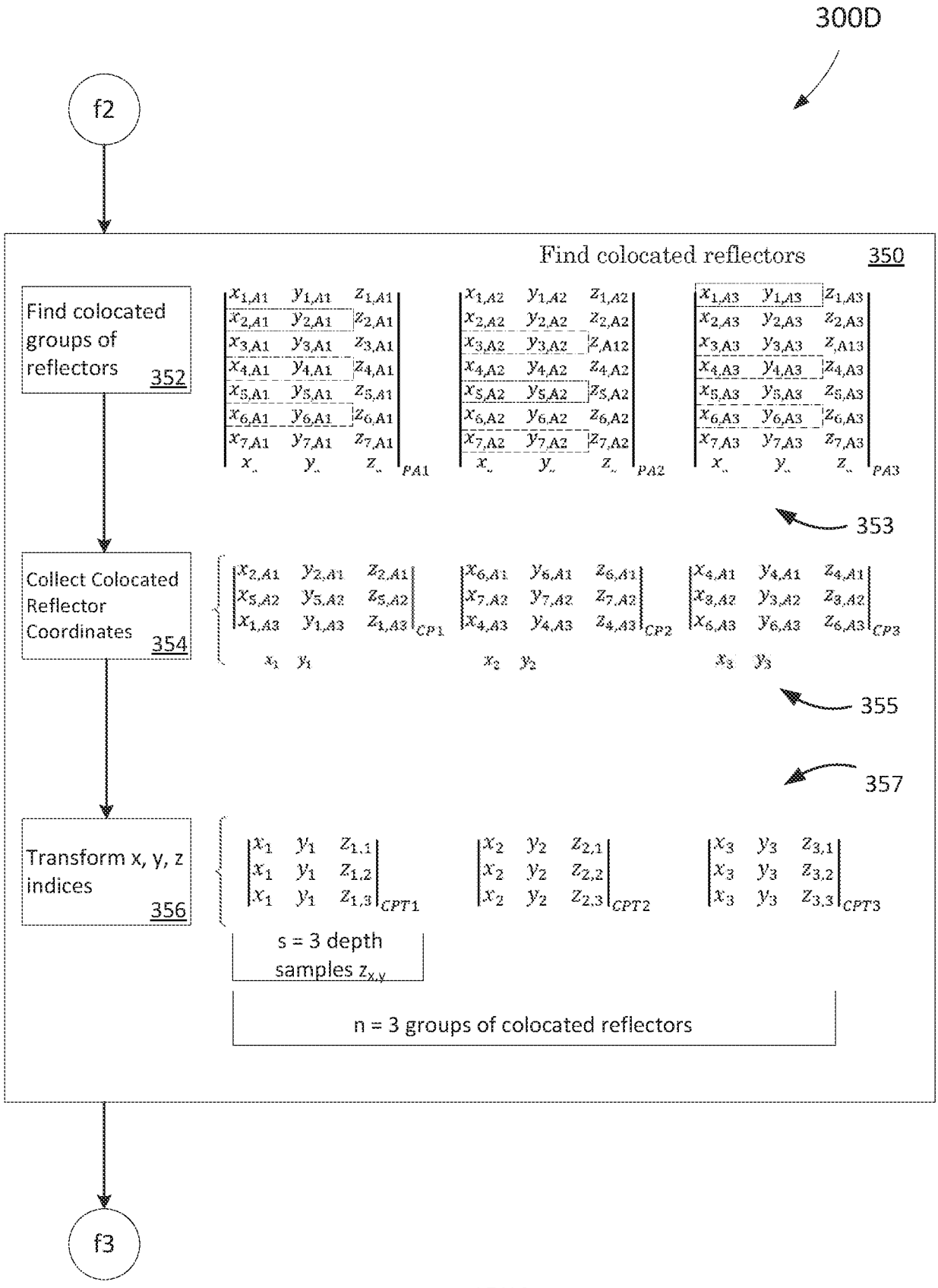

300D
f2
Find colocated reflectors 350
Find colocated groups of reflectors 352
Collect Colocated Reflector Coordinates 354
Transform x, y, z indices 356
353
355
357
s = 3 depth samples $z_{x,y}$
n = 3 groups of colocated reflectors
f3

FIG. 3E

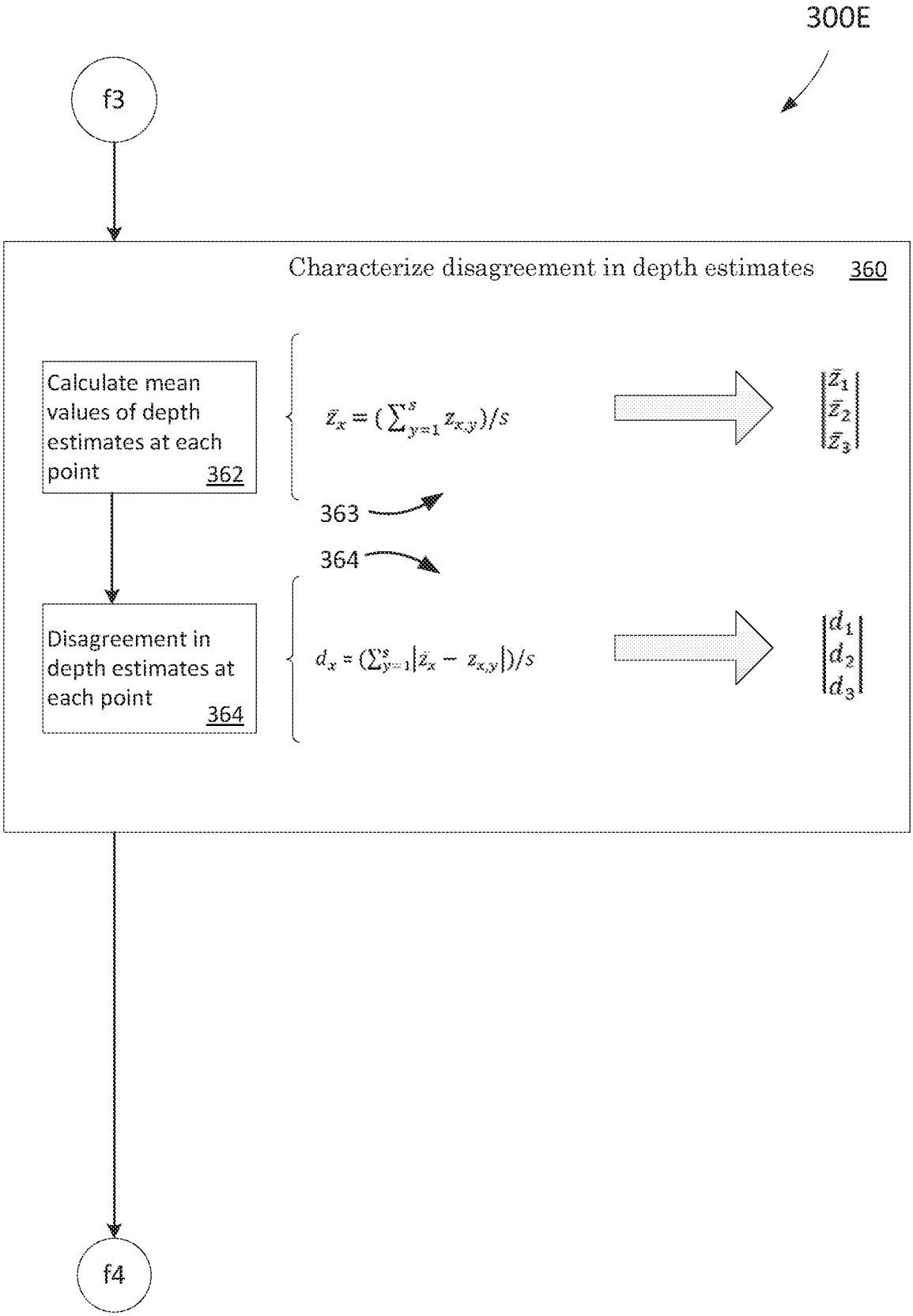

300E
f3
Characterize disagreement in depth estimates 360
Calculate mean values of depth estimates at each point 362
$\bar{z}_x = (\sum_{y=1}^{s} z_{x,y})/s$
$\begin{vmatrix} \bar{z}_1 \\ \bar{z}_2 \\ \bar{z}_3 \end{vmatrix}$
363
364
Disagreement in depth estimates at each point 364
$d_x = (\sum_{y=1}^{s} |\bar{z}_x - z_{x,y}|)/s$
$\begin{vmatrix} d_1 \\ d_2 \\ d_3 \end{vmatrix}$
f4

FIG. 3F

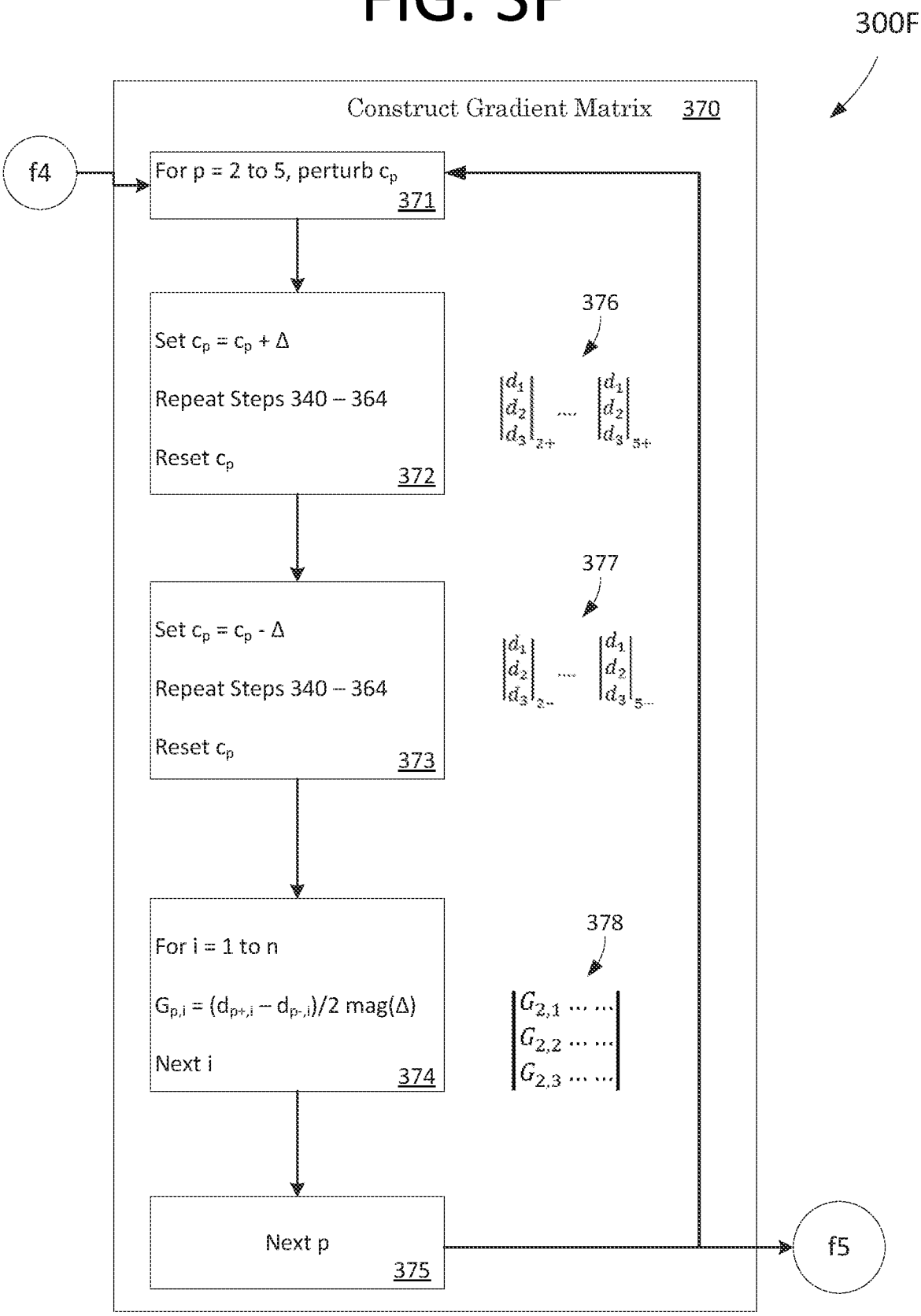

300F
Construct Gradient Matrix 370
f4
For p = 2 to 5, perturb c_p
371
Set $c_p = c_p + \Delta$
Repeat Steps 340 – 364
Reset c_p
372
376
$\begin{vmatrix} d_1 \\ d_2 \\ d_3 \end{vmatrix}_{2+}$ .... $\begin{vmatrix} d_1 \\ d_2 \\ d_3 \end{vmatrix}_{5+}$
Set $c_p = c_p - \Delta$
Repeat Steps 340 – 364
Reset c_p
373
377
$\begin{vmatrix} d_1 \\ d_2 \\ d_3 \end{vmatrix}_{2-}$ .... $\begin{vmatrix} d_1 \\ d_2 \\ d_3 \end{vmatrix}_{5-}$
For i = 1 to n
$G_{p,i} = (d_{p+,i} - d_{p-,i})/2\ mag(\Delta)$
Next i
374
378
$\begin{vmatrix} G_{2,1} \dots \dots \\ G_{2,2} \dots \dots \\ G_{2,3} \dots \dots \end{vmatrix}$
Next p
375
f5

FIG. 3G

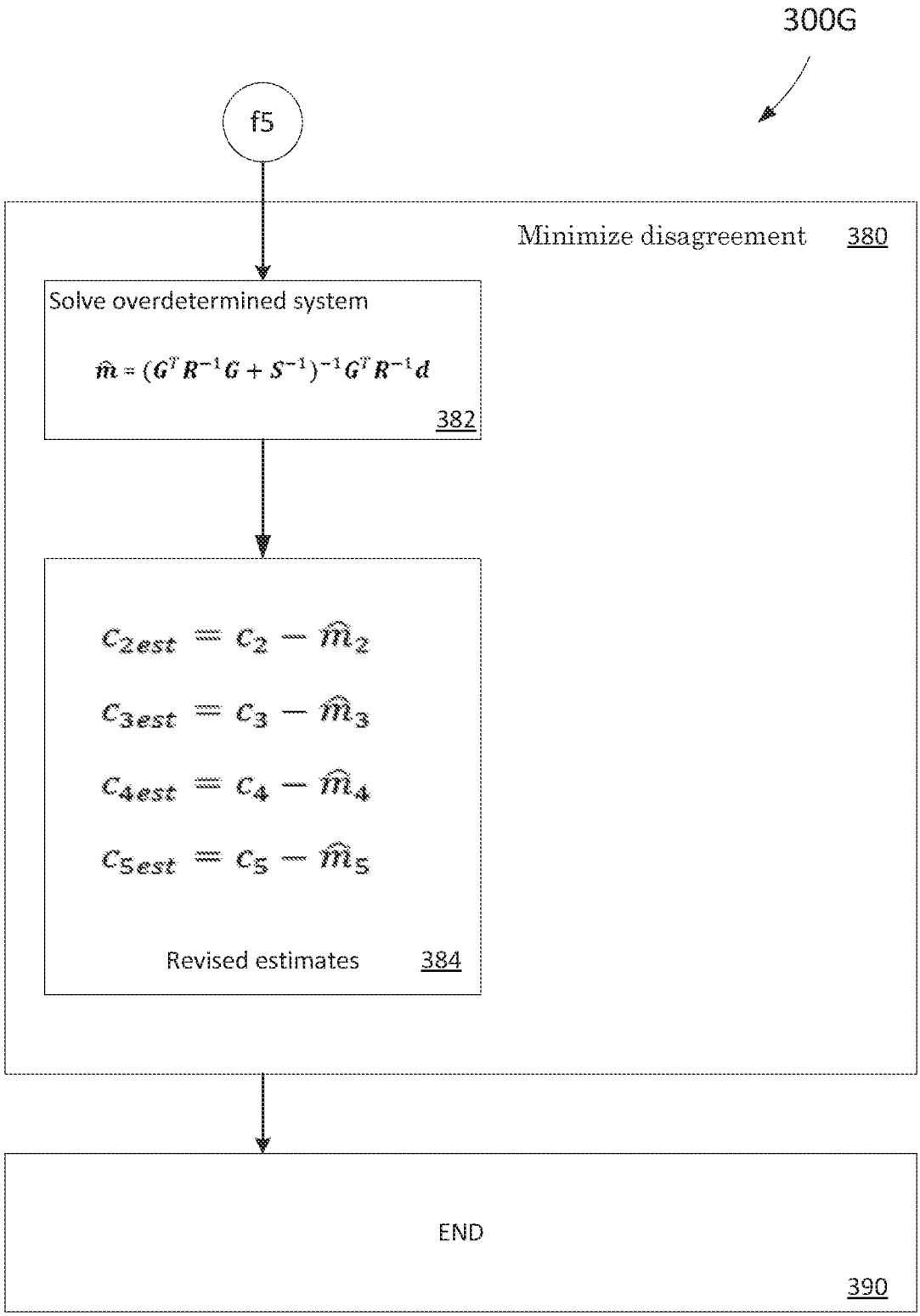
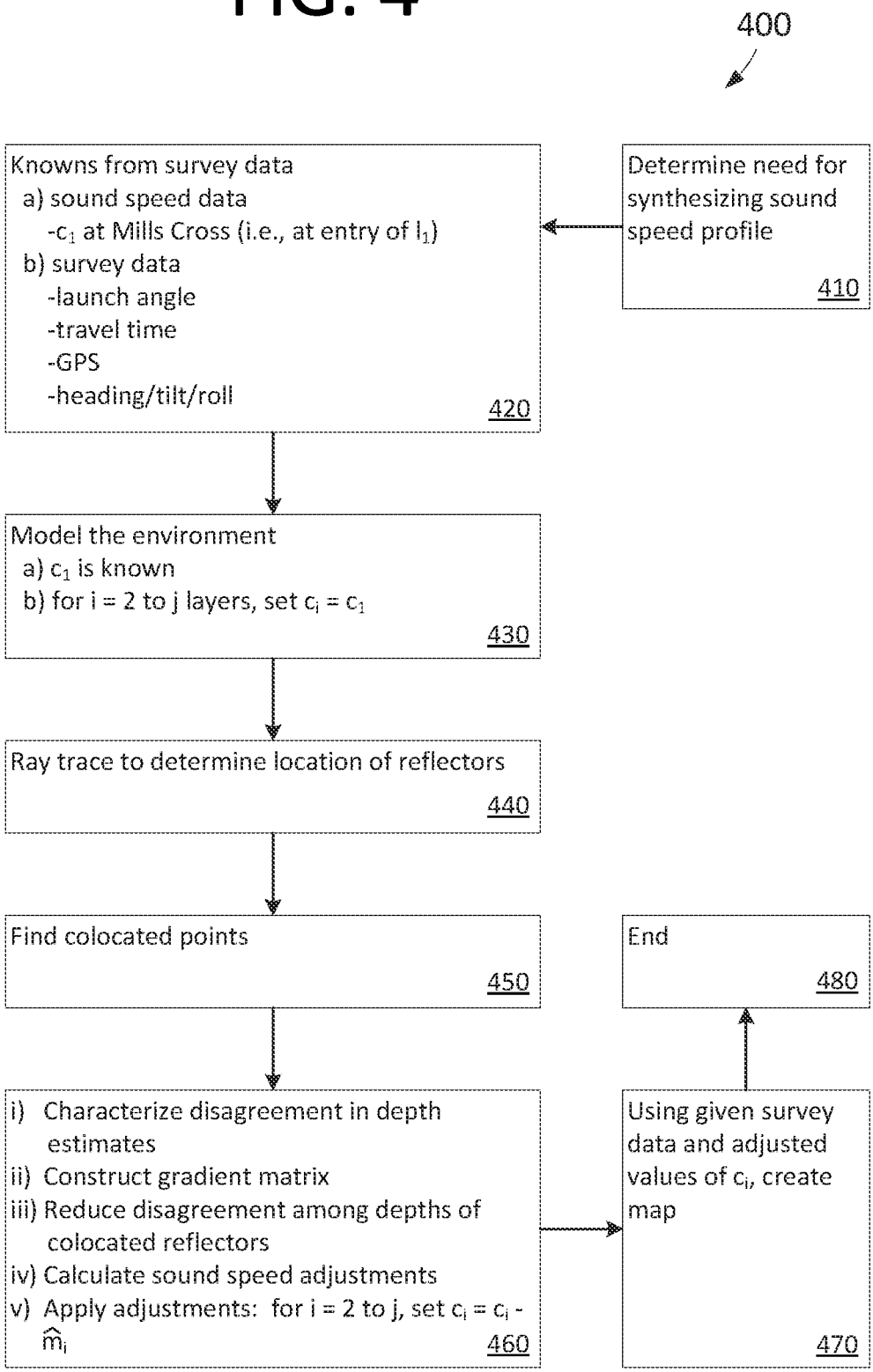

300G
f5
Minimize disagreement 380
Solve overdetermined system
$\hat{m} = (G^T R^{-1} G + S^{-1})^{-1} G^T R^{-1} d$
382
$c_{2est} = c_2 - \hat{m}_2$
$c_{3est} = c_3 - \hat{m}_3$
$c_{4est} = c_4 - \hat{m}_4$
$c_{5est} = c_5 - \hat{m}_5$
Revised estimates 384
END
390

FIG. 4


400
Knowns from survey data
a) sound speed data
-c_1 at Mills Cross (i.e., at entry of l_1)
b) survey data
-launch angle
-travel time
-GPS
-heading/tilt/roll
420
Determine need for synthesizing sound speed profile
410
Model the environment
a) c_1 is known
b) for i = 2 to j layers, set $c_i = c_1$
430
Ray trace to determine location of reflectors
440
Find colocated points
450
i) Characterize disagreement in depth estimates
ii) Construct gradient matrix
iii) Reduce disagreement among depths of colocated reflectors
iv) Calculate sound speed adjustments
v) Apply adjustments: for i = 2 to j, set $c_i = c_i - \hat{m}_i$
460
Using given survey data and adjusted values of c_i, create map
470
End
480

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2018/039189

A. CLASSIFICATION OF SUBJECT MATTER

G01S 15/88(2006.01)i, B63C 11/38(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01S 15/88; G01S 15/00; G01S 15/89; G01S 15/93; G01S 7/00; G01S 7/52; G01V 1/38; B63C 11/38

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: MBES(multibeam echo sounder system), SONAR, modeling, speed

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008-0137483 A1 (SAWRIE) 12 June 2008 See paragraphs [0002], [0014], [0024], [0034]-[0035]; and figure 1.	1-18
A	US 2012-0327741 A1 (PEARCE) 27 December 2012 See paragraphs [0009]-[0015], [0044], [0066]; and figures 1-4.	1-18
A	US 2016-0011326 A1 (AIRMAR TECHNOLOGY CORPORATION) 14 January 2016 See paragraphs [0005]-[0011], [0102]; and figures 1-3.	1-18
A	US 6438071 B1 (HANSEN et al.) 20 August 2002 See claim 1; and figures 1-3.	1-18
A	US 2007-0025183 A1 (ZIMMERMAN et al.) 01 February 2007 See figures 1-5.	1-18

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"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
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 October 2018 (26.10.2018)	**26 October 2018 (26.10.2018)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/039189

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		NO 307014 B1	24/01/2000
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		NO 982891 D0	19/06/1998
		WO 99-66343 A1	23/12/1999
US 2007-0025183 A1	01/02/2007	AU 2002-345848 A1	08/01/2003
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		WO 2005-047930 A1	26/05/2005

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2018/039189

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		WO 2007-127271 A3	11/12/2008