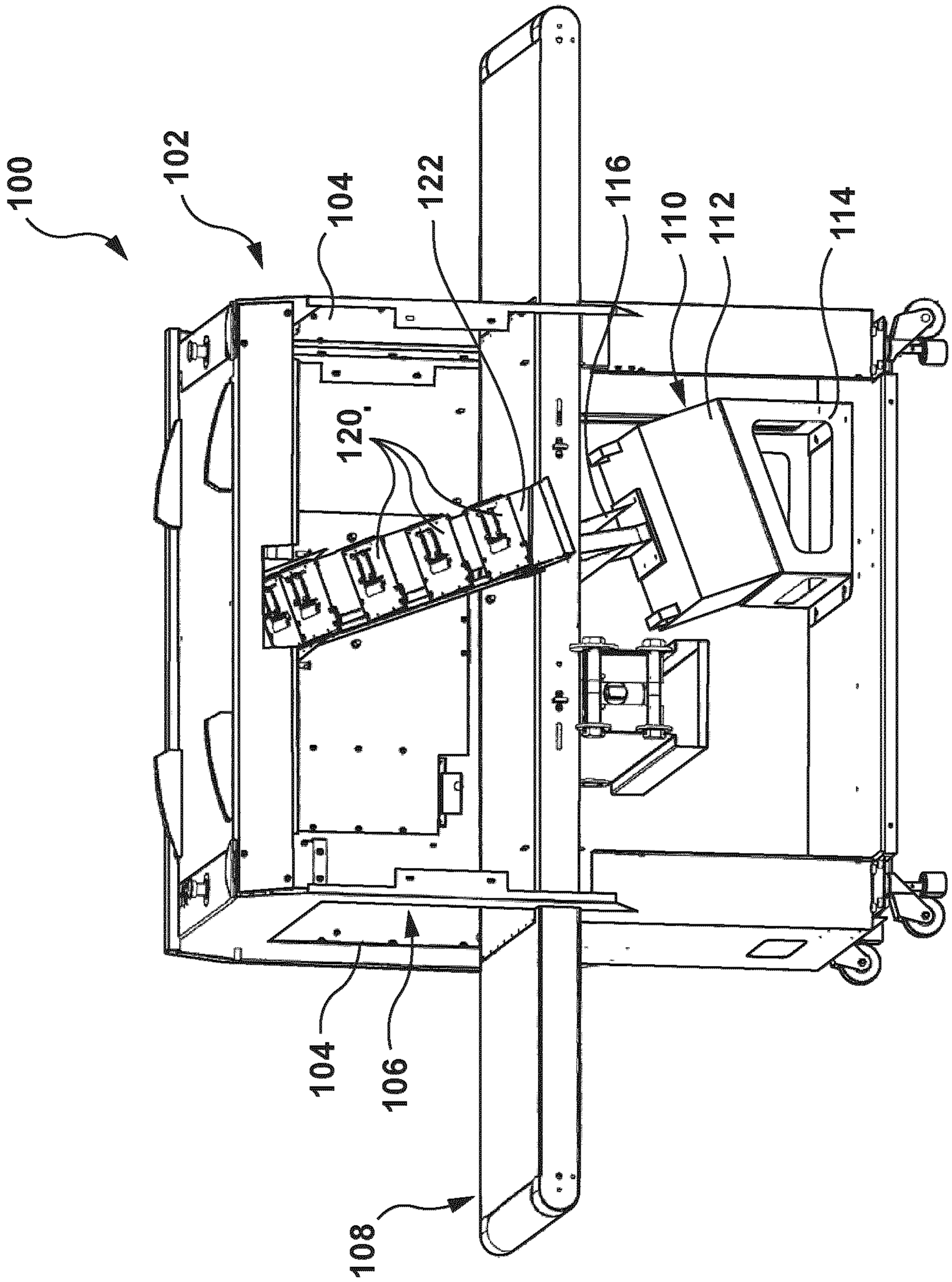

FIG. 1

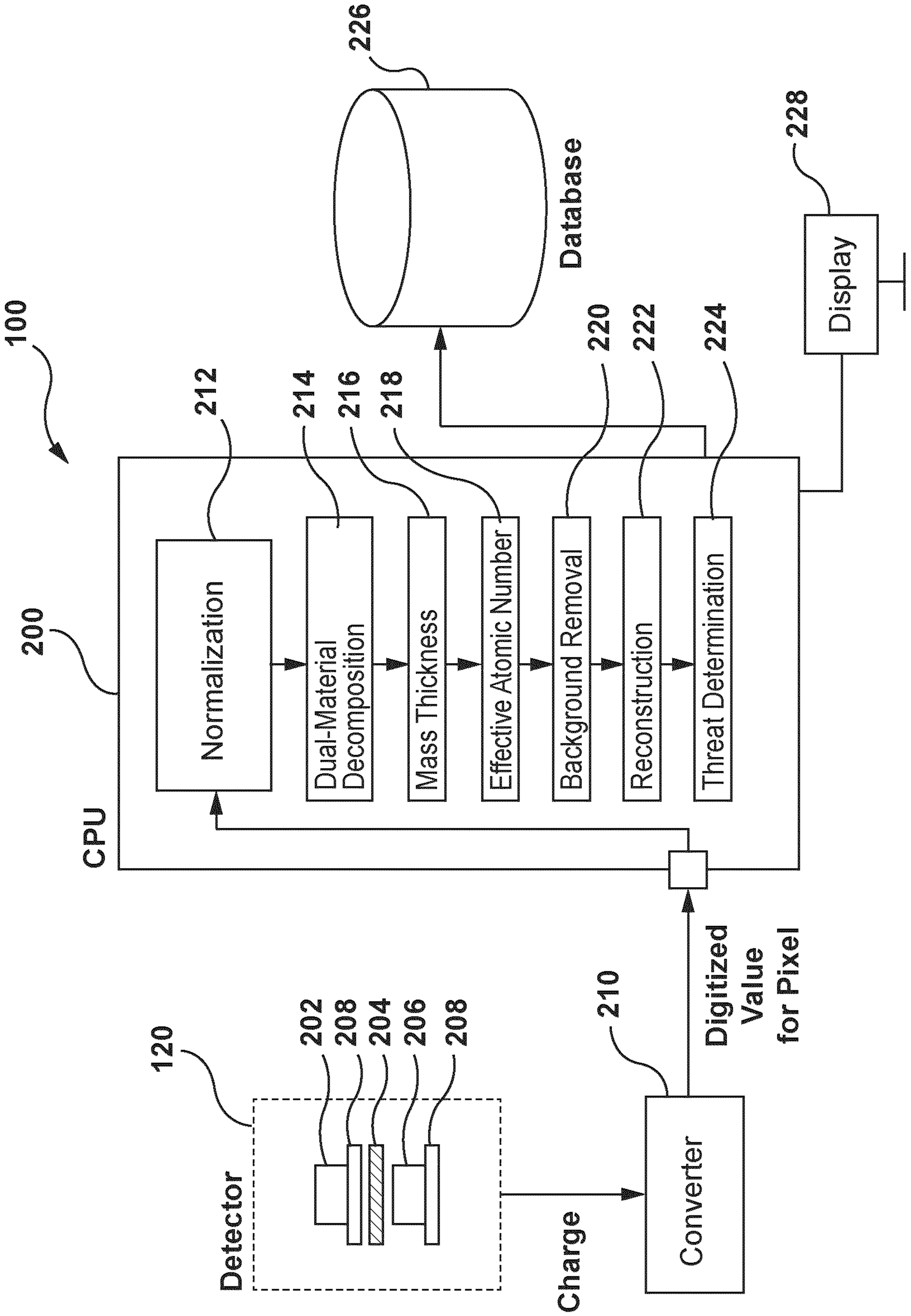
100
226
Database
228
Display
212
214
216
218
220
222
224
Normalization
Dual-Material Decomposition
Mass Thickness
Effective Atomic Number
Background Removal
Reconstruction
Threat Determination
CPU
200
120
202
208
204
206
208
Detector
210
Digitized Value for Pixel
Charge
Converter

FIG. 2

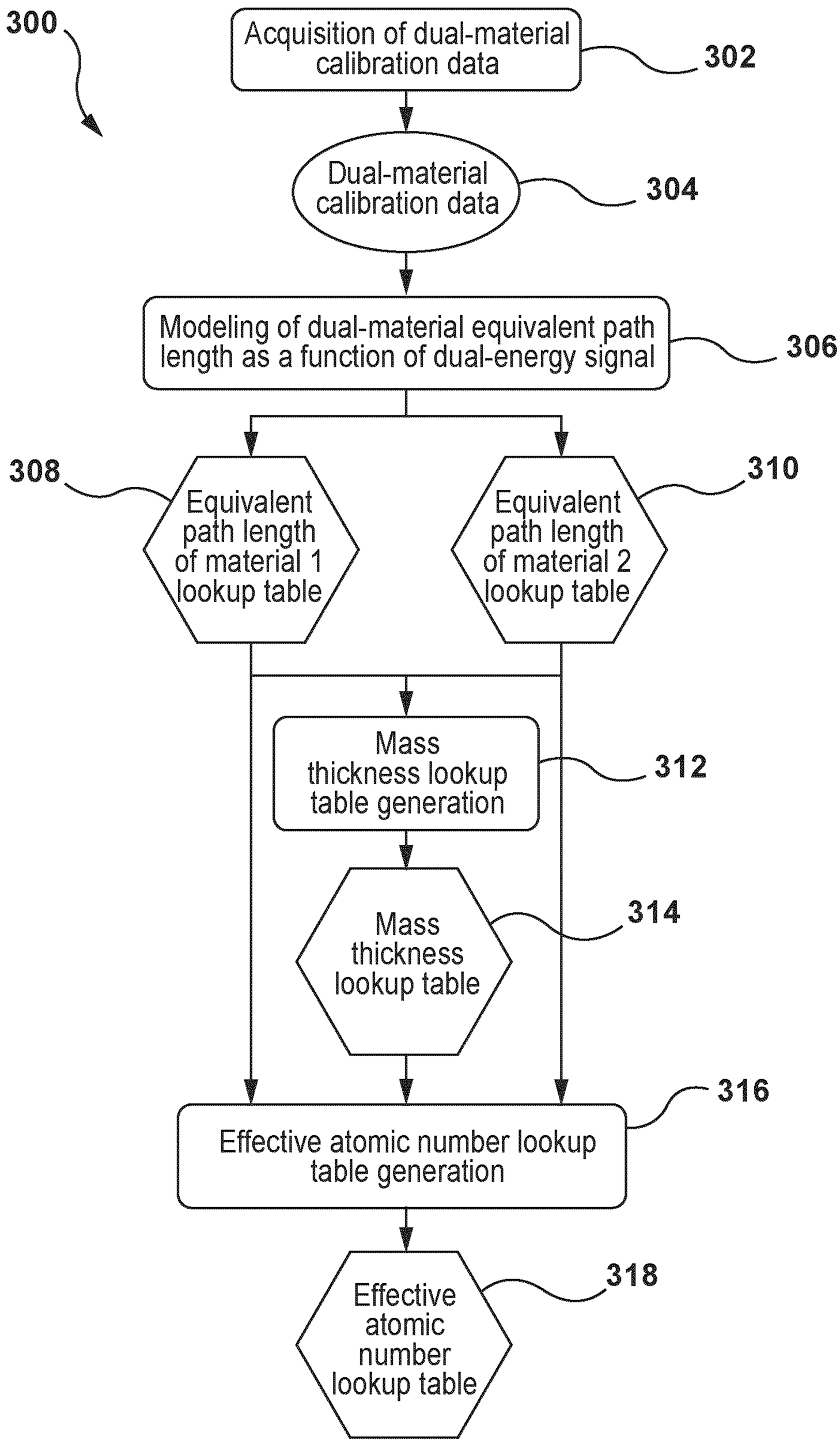
300
Acquisition of dual-material calibration data
302
Dual-material calibration data
304
Modeling of dual-material equivalent path length as a function of dual-energy signal
306
308
Equivalent path length of material 1 lookup table
310
Equivalent path length of material 2 lookup table
Mass thickness lookup table generation
312
Mass thickness lookup table
314
Effective atomic number lookup table generation
316
Effective atomic number lookup table
318

FIG. 3

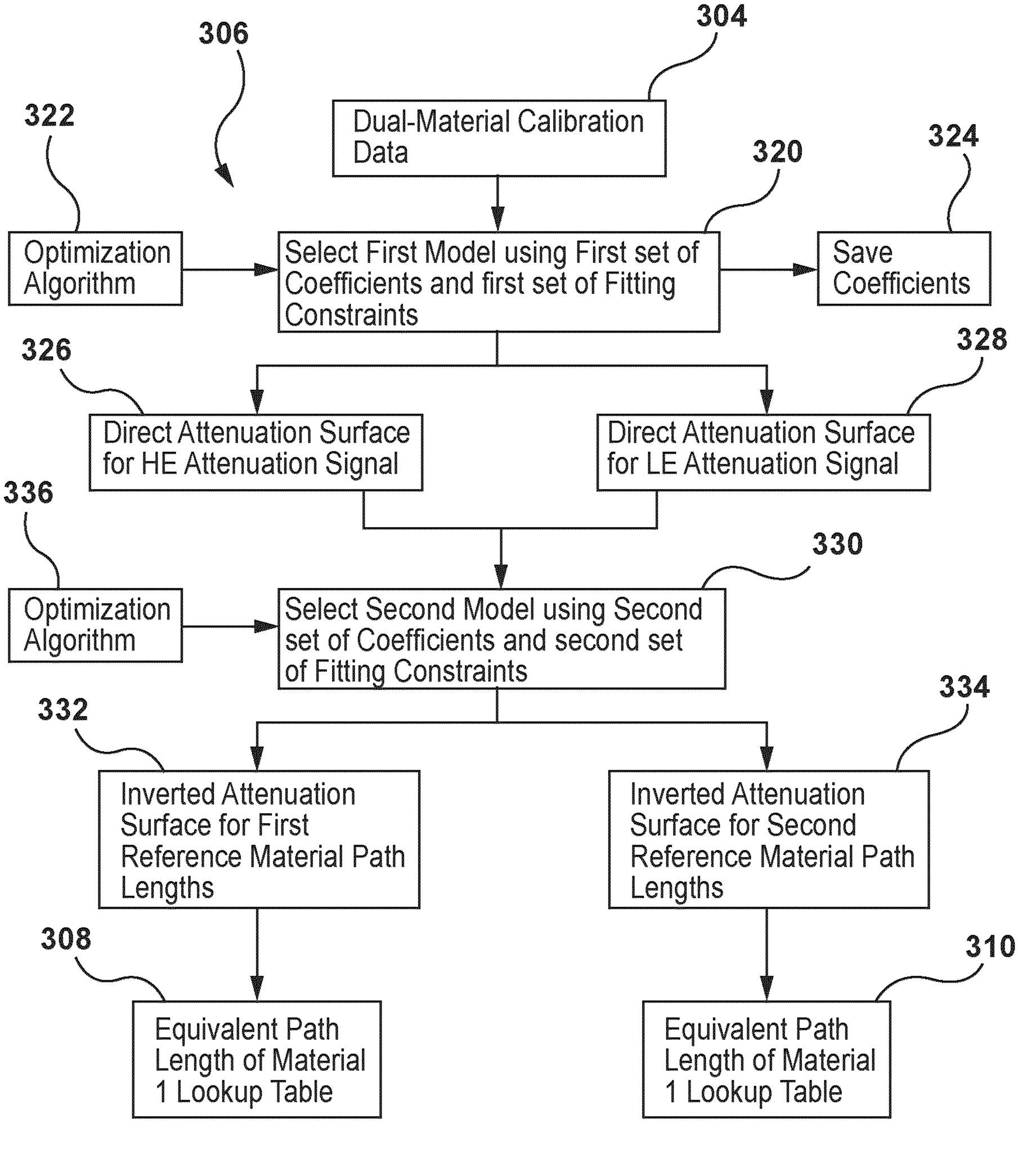
306
304
322
Dual-Material Calibration Data
320
324
Optimization Algorithm
Select First Model using First set of Coefficients and first set of Fitting Constraints
Save Coefficients
326
328
Direct Attenuation Surface for HE Attenuation Signal
Direct Attenuation Surface for LE Attenuation Signal
336
330
Optimization Algorithm
Select Second Model using Second set of Coefficients and second set of Fitting Constraints
332
334
Inverted Attenuation Surface for First Reference Material Path Lengths
Inverted Attenuation Surface for Second Reference Material Path Lengths
308
310
Equivalent Path Length of Material 1 Lookup Table
Equivalent Path Length of Material 1 Lookup Table

FIG. 4

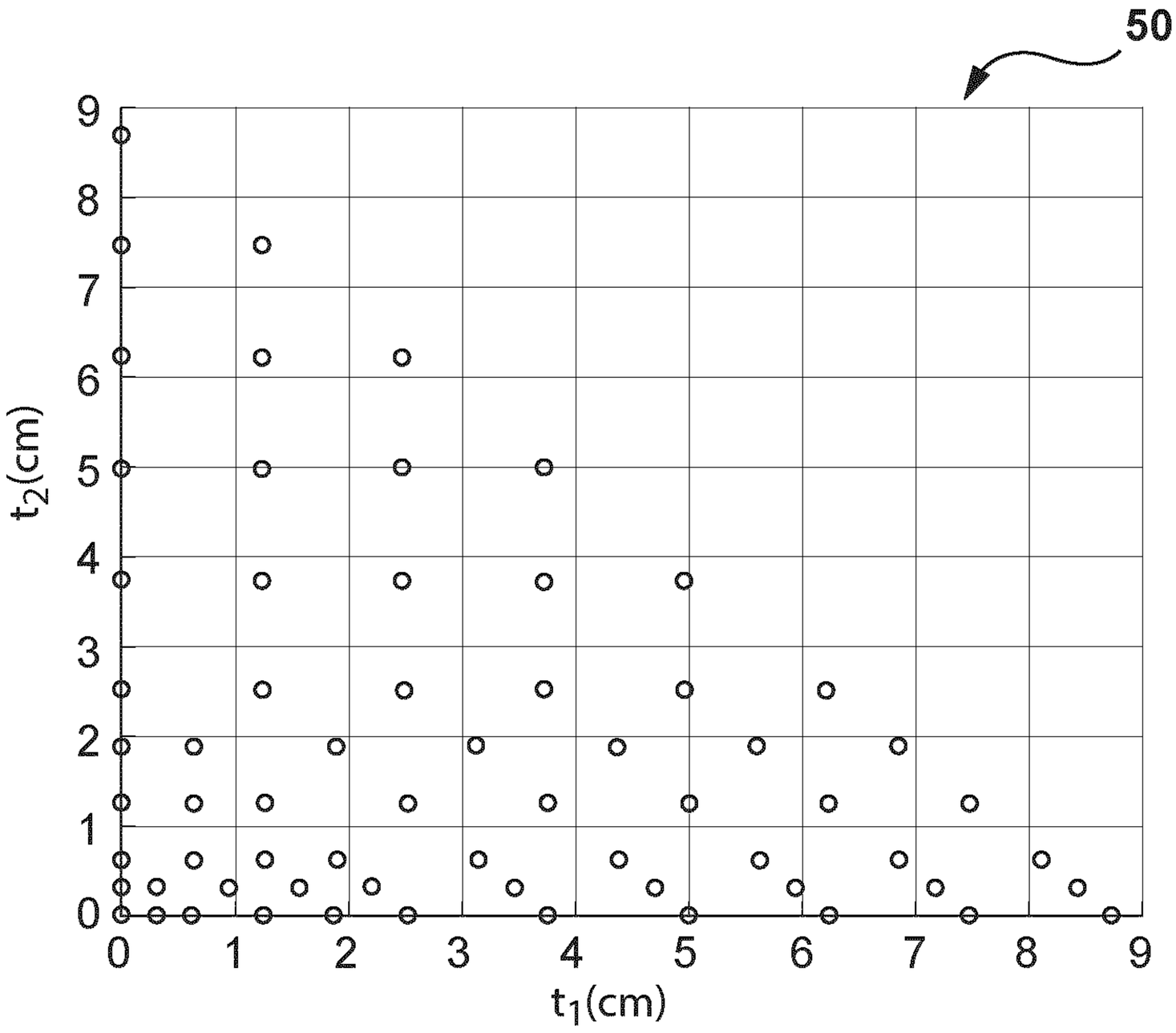
500
9
8
7
6
5
4
3
2
1
0
t_2(cm)
0
1
2
3
4
5
6
7
8
9
t_1(cm)

FIG. 5

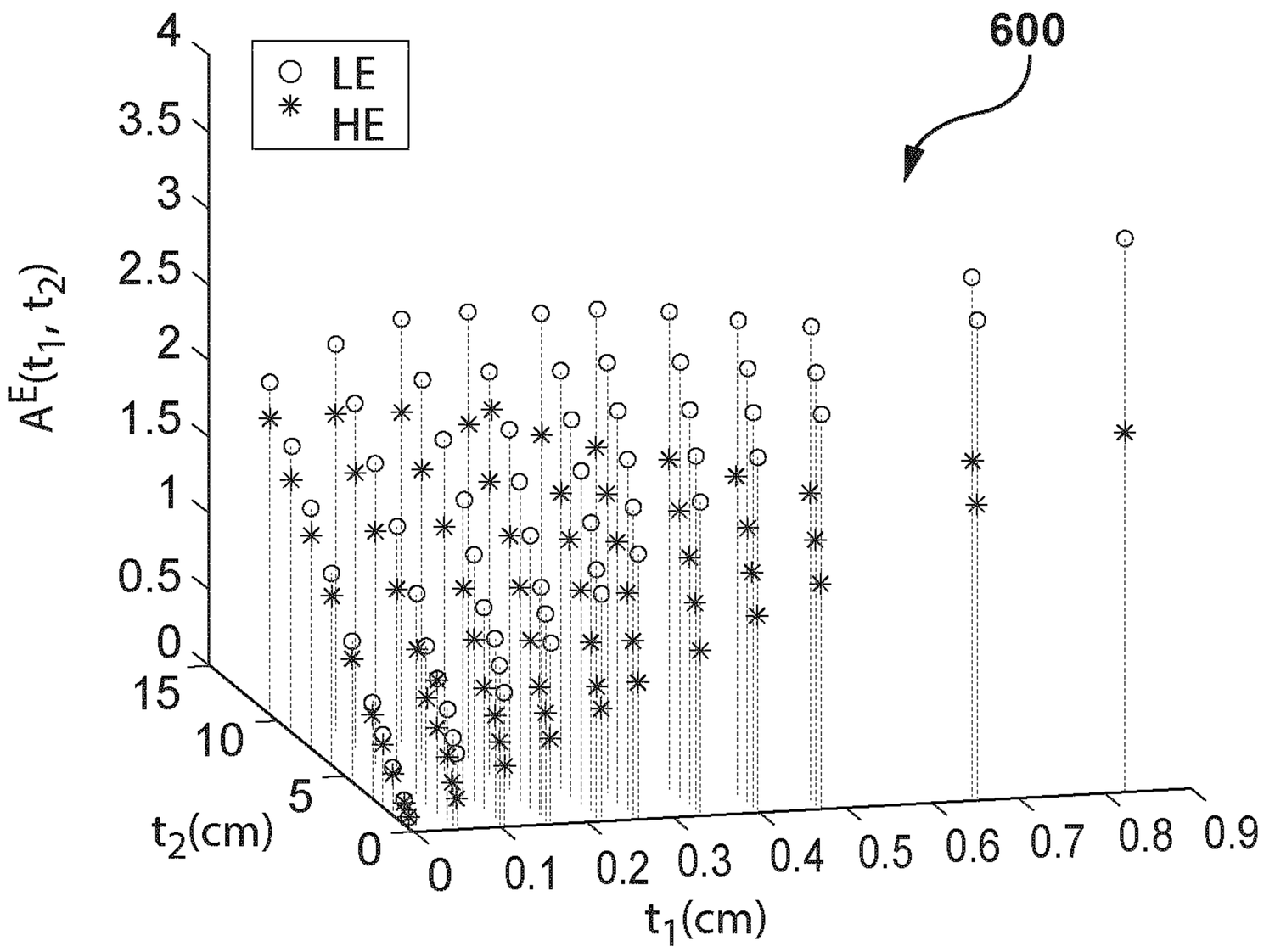
600
LE
HE
$A^E(t_1, t_2)$
4
3.5
3
2.5
2
1.5
1
0.5
0
15
10
5
0
t_2(cm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
t_1(cm)

FIG. 6

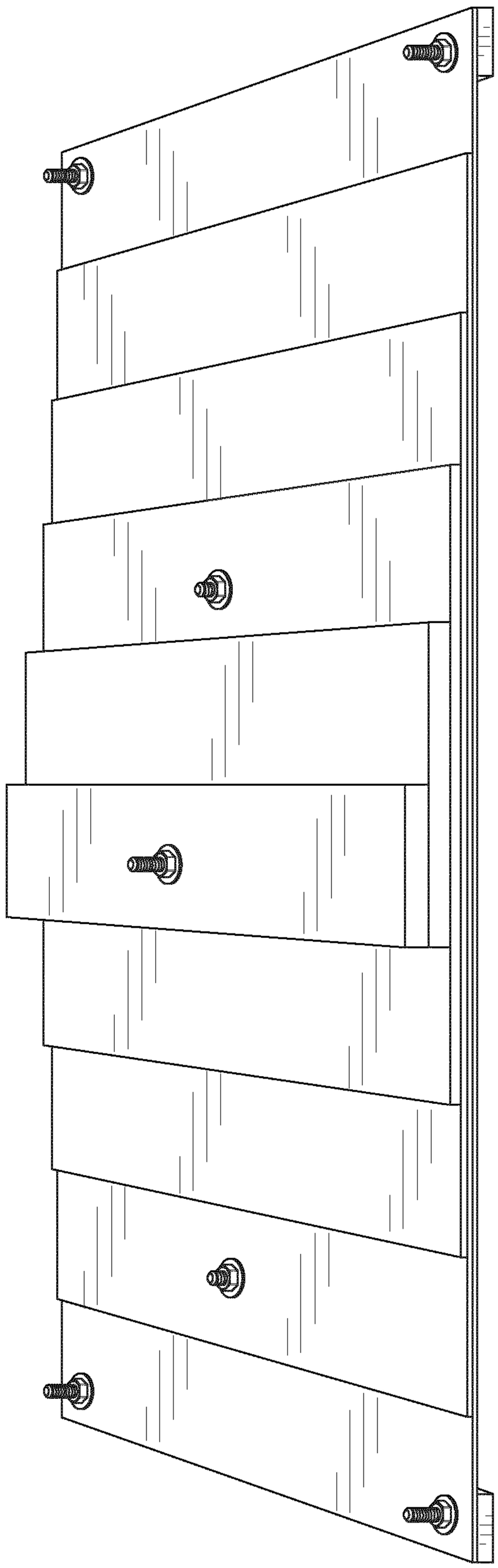

FIG. 7

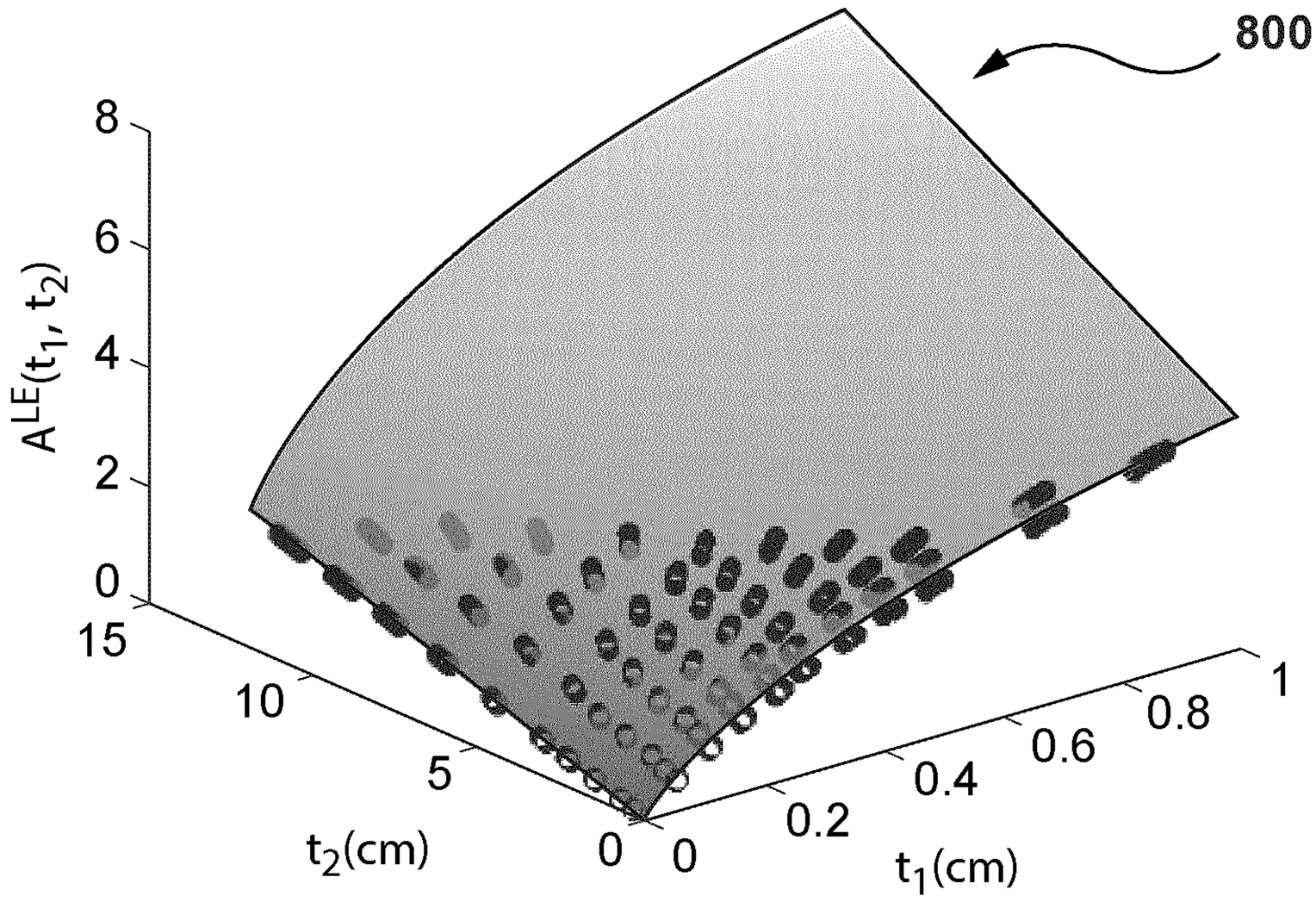
800
8
6
4
2
0
$A^{LE}(t_1, t_2)$
15
10
5
0
t_2(cm)
0
0.2
0.4
0.6
0.8
1
t_1(cm)

FIG. 8

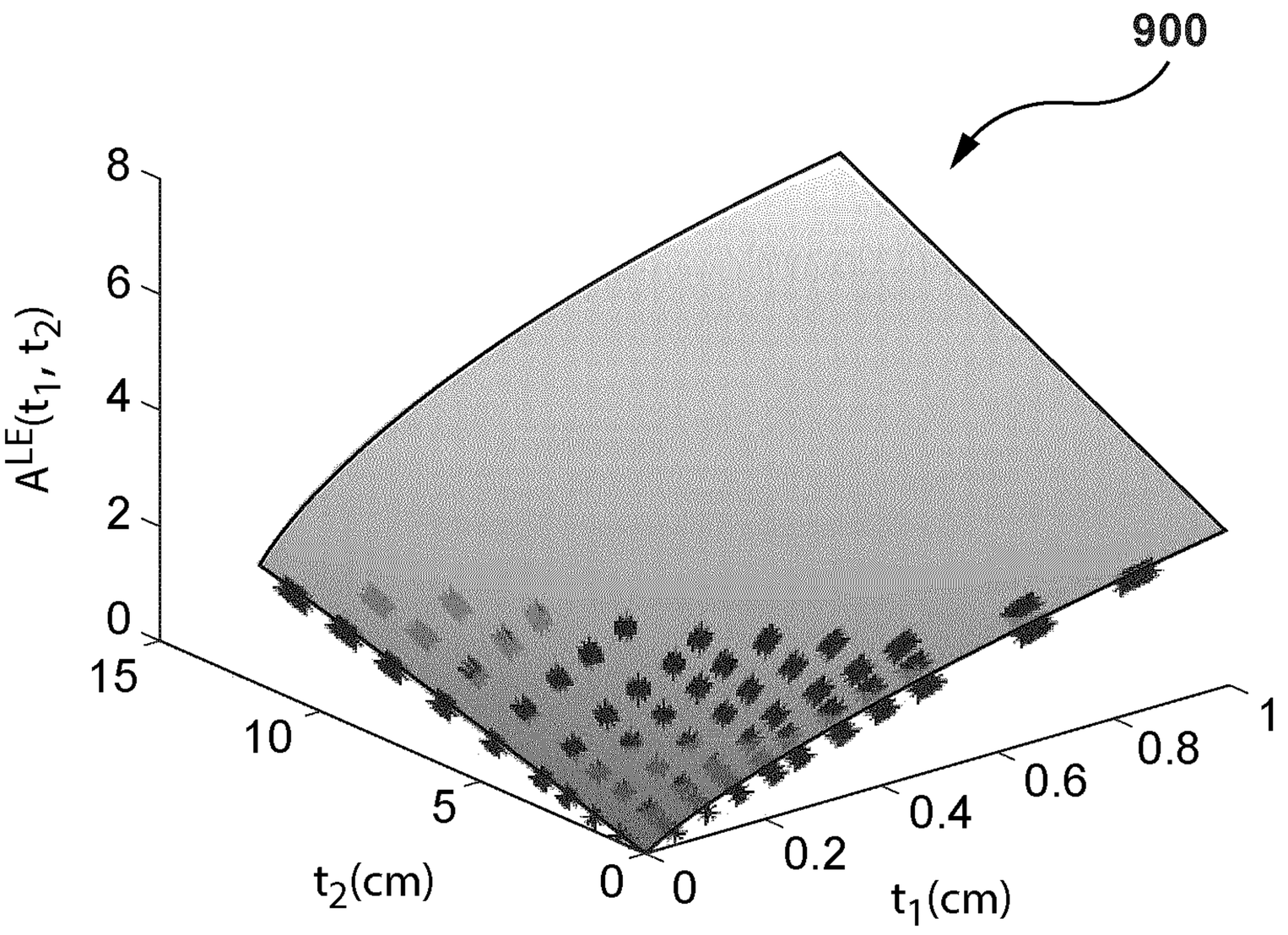
900
8
6
4
2
0
$A^{LE}(t_1, t_2)$
15
10
5
0
t_2(cm)
0
0.2
0.4
0.6
0.8
1
t_1(cm)

FIG. 9

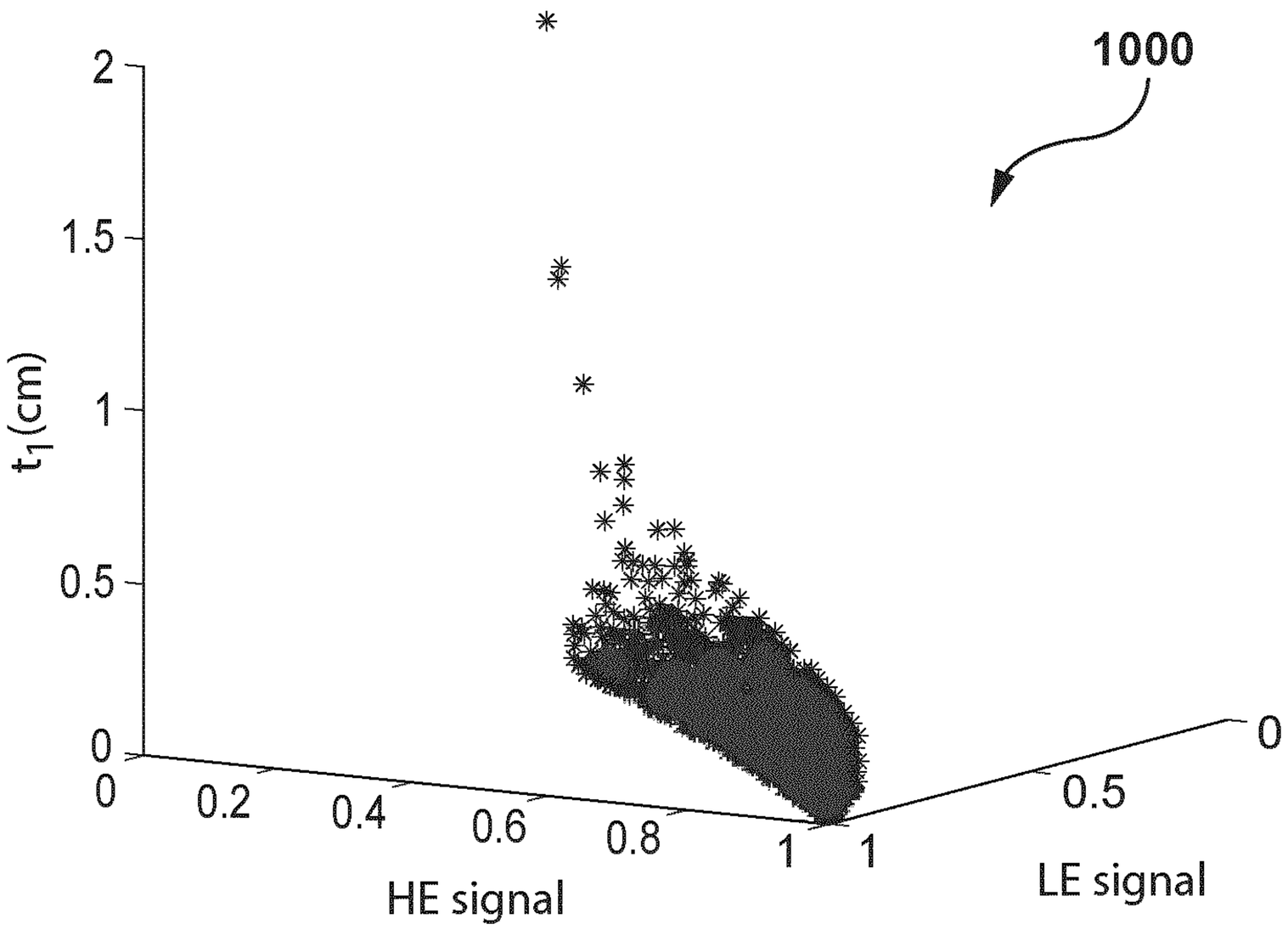

FIG. 10A

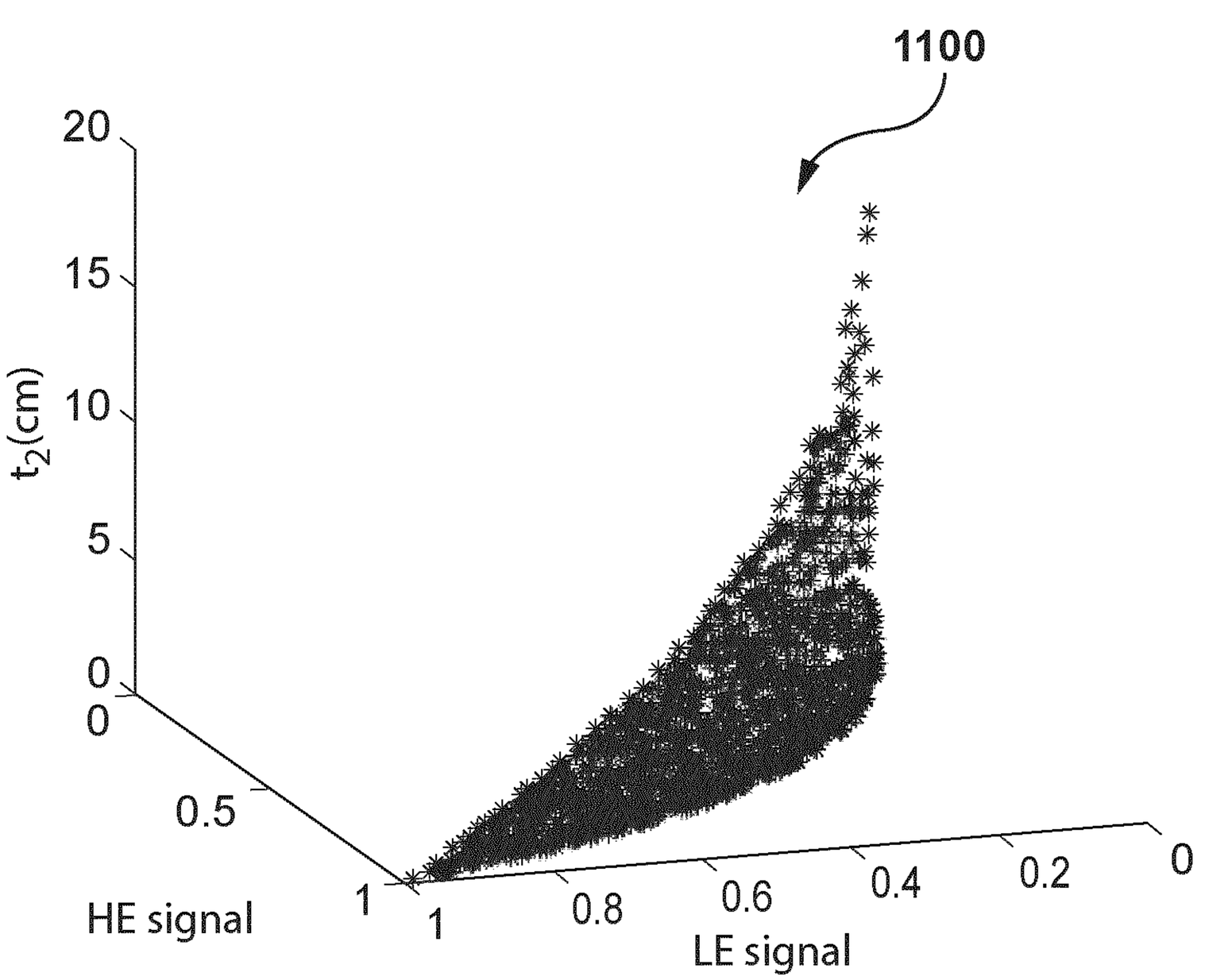

FIG. 10B

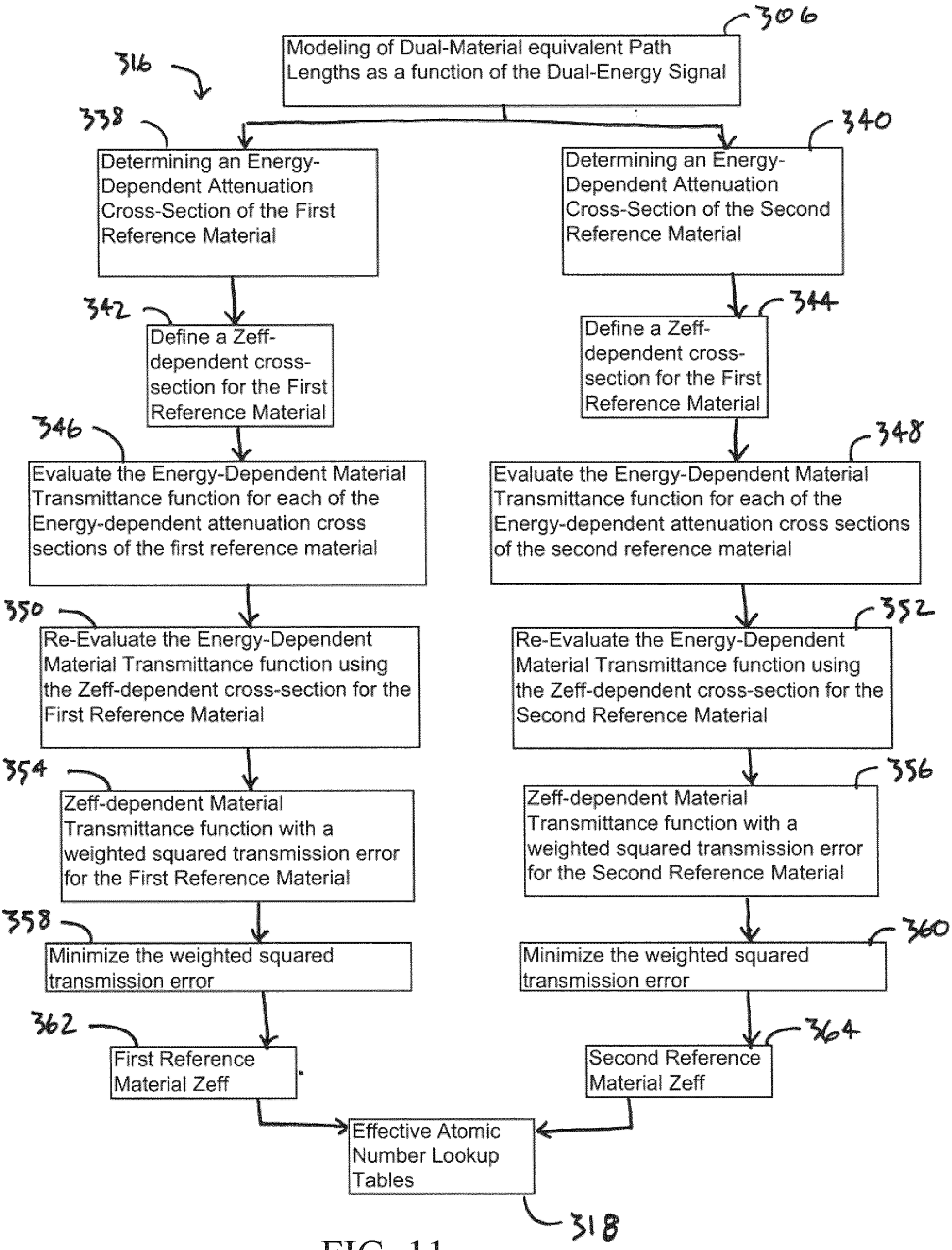
306
Modeling of Dual-Material equivalent Path Lengths as a function of the Dual-Energy Signal
316
338
Determining an Energy-Dependent Attenuation Cross-Section of the First Reference Material
340
Determining an Energy-Dependent Attenuation Cross-Section of the Second Reference Material
342
Define a Zeff-dependent cross-section for the First Reference Material
344
Define a Zeff-dependent cross-section for the First Reference Material
346
Evaluate the Energy-Dependent Material Transmittance function for each of the Energy-dependent attenuation cross sections of the first reference material
348
Evaluate the Energy-Dependent Material Transmittance function for each of the Energy-dependent attenuation cross sections of the second reference material
350
Re-Evaluate the Energy-Dependent Material Transmittance function using the Zeff-dependent cross-section for the First Reference Material
352
Re-Evaluate the Energy-Dependent Material Transmittance function using the Zeff-dependent cross-section for the Second Reference Material
354
Zeff-dependent Material Transmittance function with a weighted squared transmission error for the First Reference Material
356
Zeff-dependent Material Transmittance function with a weighted squared transmission error for the Second Reference Material
358
Minimize the weighted squared transmission error
360
Minimize the weighted squared transmission error
362
First Reference Material Zeff
364
Second Reference Material Zeff
Effective Atomic Number Lookup Tables
318

FIG. 11

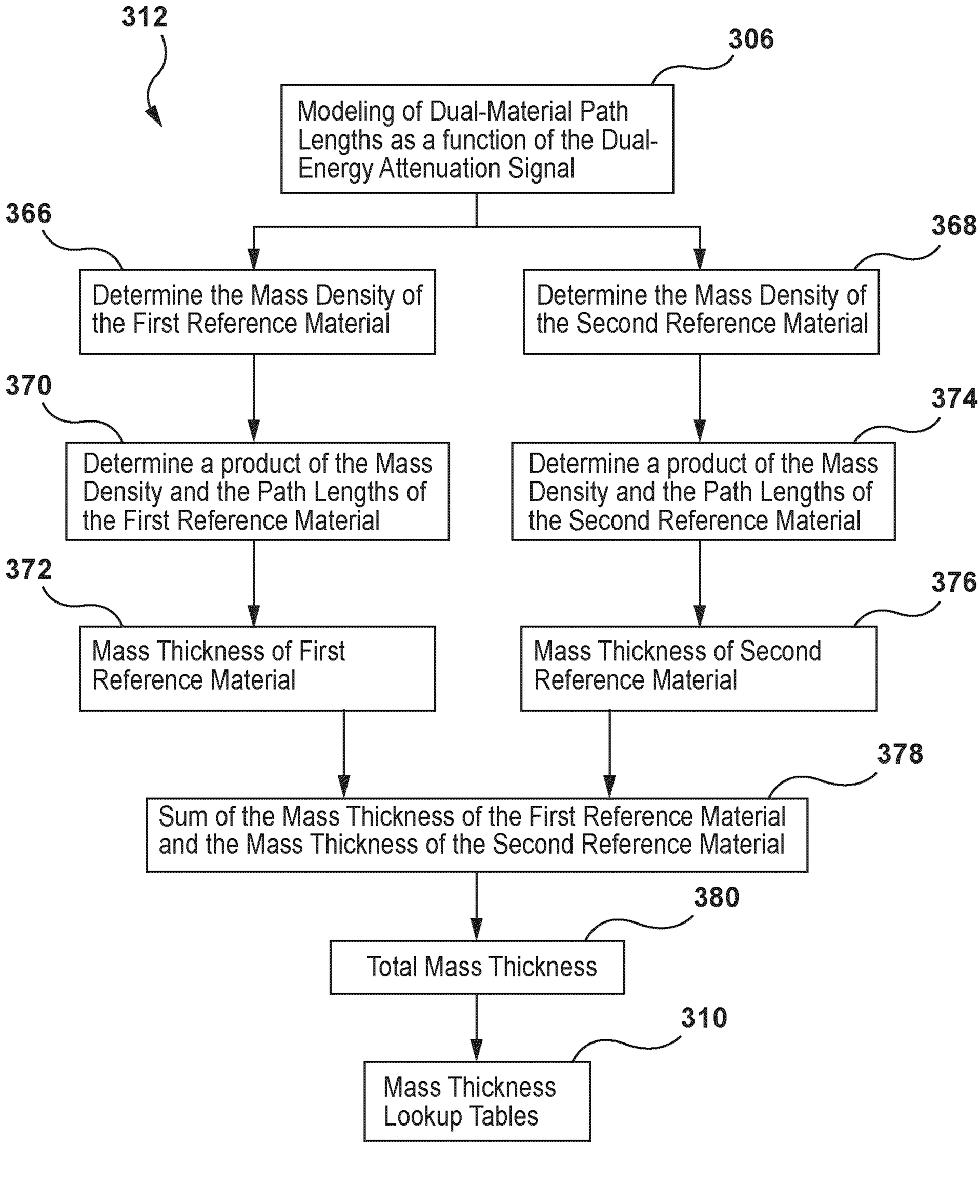
312
306
Modeling of Dual-Material Path Lengths as a function of the Dual-Energy Attenuation Signal
366
Determine the Mass Density of the First Reference Material
368
Determine the Mass Density of the Second Reference Material
370
Determine a product of the Mass Density and the Path Lengths of the First Reference Material
374
Determine a product of the Mass Density and the Path Lengths of the Second Reference Material
372
Mass Thickness of First Reference Material
376
Mass Thickness of Second Reference Material
378
Sum of the Mass Thickness of the First Reference Material and the Mass Thickness of the Second Reference Material
380
Total Mass Thickness
310
Mass Thickness Lookup Tables

FIG. 12

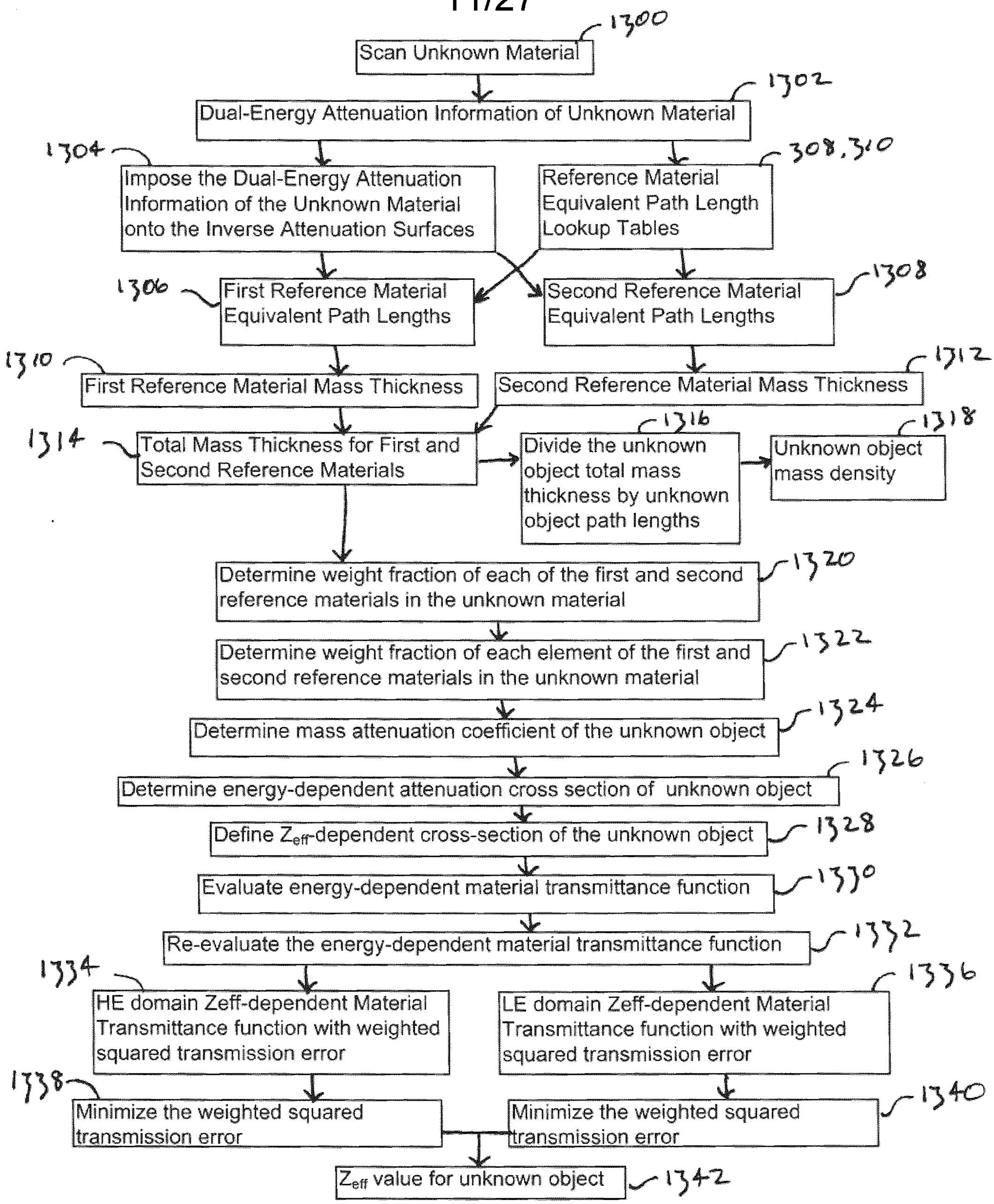
1300
Scan Unknown Material
1302
Dual-Energy Attenuation Information of Unknown Material
1304
Impose the Dual-Energy Attenuation Information of the Unknown Material onto the Inverse Attenuation Surfaces
308, 310
Reference Material Equivalent Path Length Lookup Tables
1306
First Reference Material Equivalent Path Lengths
1308
Second Reference Material Equivalent Path Lengths
1310
First Reference Material Mass Thickness
1312
Second Reference Material Mass Thickness
1314
Total Mass Thickness for First and Second Reference Materials
1316
Divide the unknown object total mass thickness by unknown object path lengths
1318
Unknown object mass density
1320
Determine weight fraction of each of the first and second reference materials in the unknown material
1322
Determine weight fraction of each element of the first and second reference materials in the unknown material
1324
Determine mass attenuation coefficient of the unknown object
1326
Determine energy-dependent attenuation cross section of unknown object
1328
Define Z_{eff}-dependent cross-section of the unknown object
1330
Evaluate energy-dependent material transmittance function
1332
Re-evaluate the energy-dependent material transmittance function
1334
HE domain Zeff-dependent Material Transmittance function with weighted squared transmission error
1336
LE domain Zeff-dependent Material Transmittance function with weighted squared transmission error
1338
Minimize the weighted squared transmission error
1340
Minimize the weighted squared transmission error
Z_{eff} value for unknown object
1342

FIG. 13

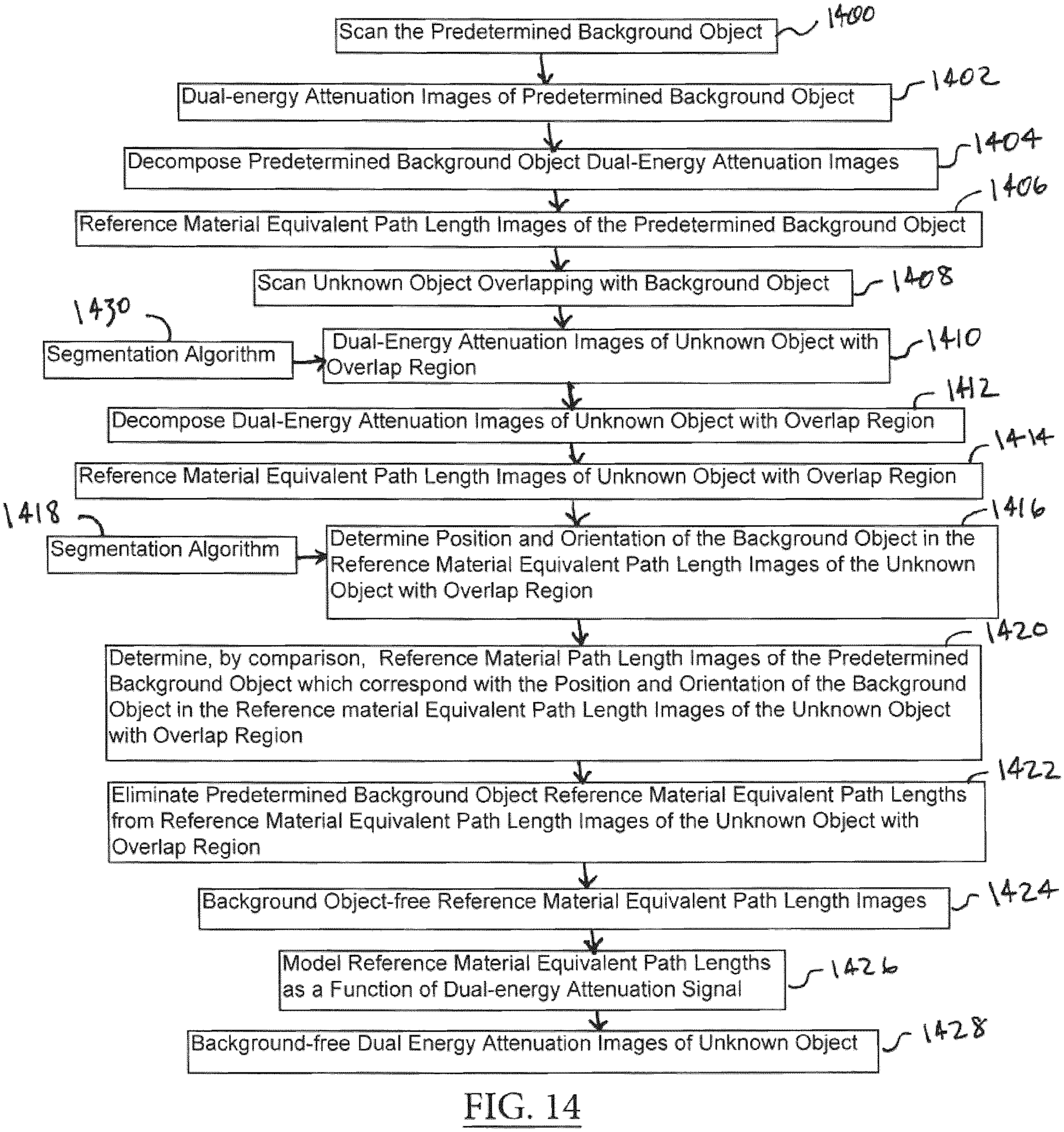
Scan the Predetermined Background Object
1400
Dual-energy Attenuation Images of Predetermined Background Object
1402
Decompose Predetermined Background Object Dual-Energy Attenuation Images
1404
Reference Material Equivalent Path Length Images of the Predetermined Background Object
1406
Scan Unknown Object Overlapping with Background Object
1408
1430
Segmentation Algorithm
Dual-Energy Attenuation Images of Unknown Object with Overlap Region
1410
Decompose Dual-Energy Attenuation Images of Unknown Object with Overlap Region
1412
Reference Material Equivalent Path Length Images of Unknown Object with Overlap Region
1414
1418
Segmentation Algorithm
Determine Position and Orientation of the Background Object in the Reference Material Equivalent Path Length Images of the Unknown Object with Overlap Region
1416
Determine, by comparison, Reference Material Path Length Images of the Predetermined Background Object which correspond with the Position and Orientation of the Background Object in the Reference material Equivalent Path Length Images of the Unknown Object with Overlap Region
1420
Eliminate Predetermined Background Object Reference Material Equivalent Path Lengths from Reference Material Equivalent Path Length Images of the Unknown Object with Overlap Region
1422
Background Object-free Reference Material Equivalent Path Length Images
1424
Model Reference Material Equivalent Path Lengths as a Function of Dual-energy Attenuation Signal
1426
Background-free Dual Energy Attenuation Images of Unknown Object
1428

FIG. 14

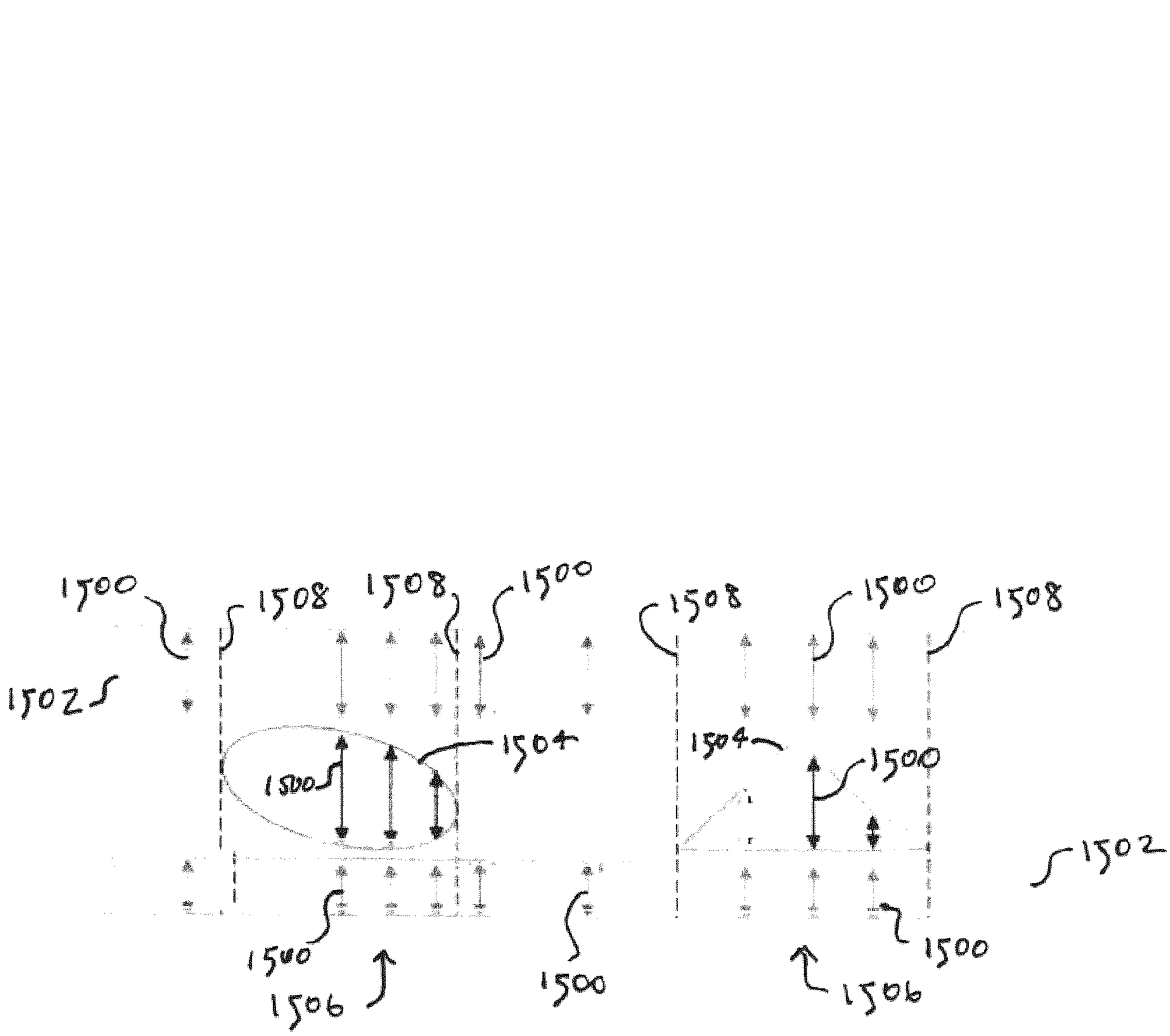
1500
1508
1508
1500
1502
1504
1500
1500
1506
1500
1508
1500
1508
1504
1500
1500
1506
1502

FIG. 15

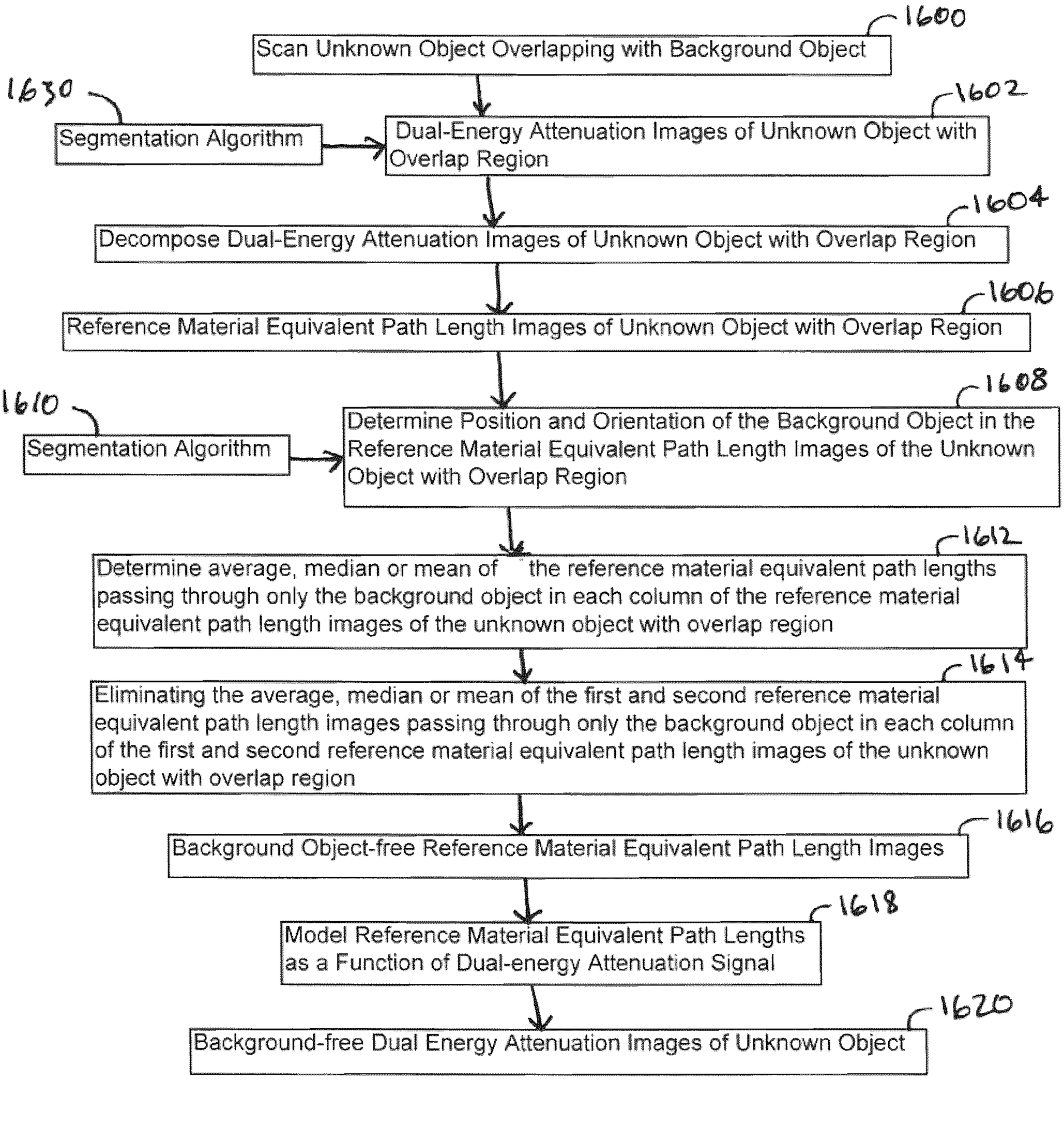
1600
Scan Unknown Object Overlapping with Background Object
1630
Segmentation Algorithm
1602
Dual-Energy Attenuation Images of Unknown Object with Overlap Region
1604
Decompose Dual-Energy Attenuation Images of Unknown Object with Overlap Region
1606
Reference Material Equivalent Path Length Images of Unknown Object with Overlap Region
1610
Segmentation Algorithm
1608
Determine Position and Orientation of the Background Object in the Reference Material Equivalent Path Length Images of the Unknown Object with Overlap Region
1612
Determine average, median or mean of the reference material equivalent path lengths passing through only the background object in each column of the reference material equivalent path length images of the unknown object with overlap region
1614
Eliminating the average, median or mean of the first and second reference material equivalent path length images passing through only the background object in each column of the first and second reference material equivalent path length images of the unknown object with overlap region
1616
Background Object-free Reference Material Equivalent Path Length Images
1618
Model Reference Material Equivalent Path Lengths as a Function of Dual-energy Attenuation Signal
1620
Background-free Dual Energy Attenuation Images of Unknown Object

FIG. 16

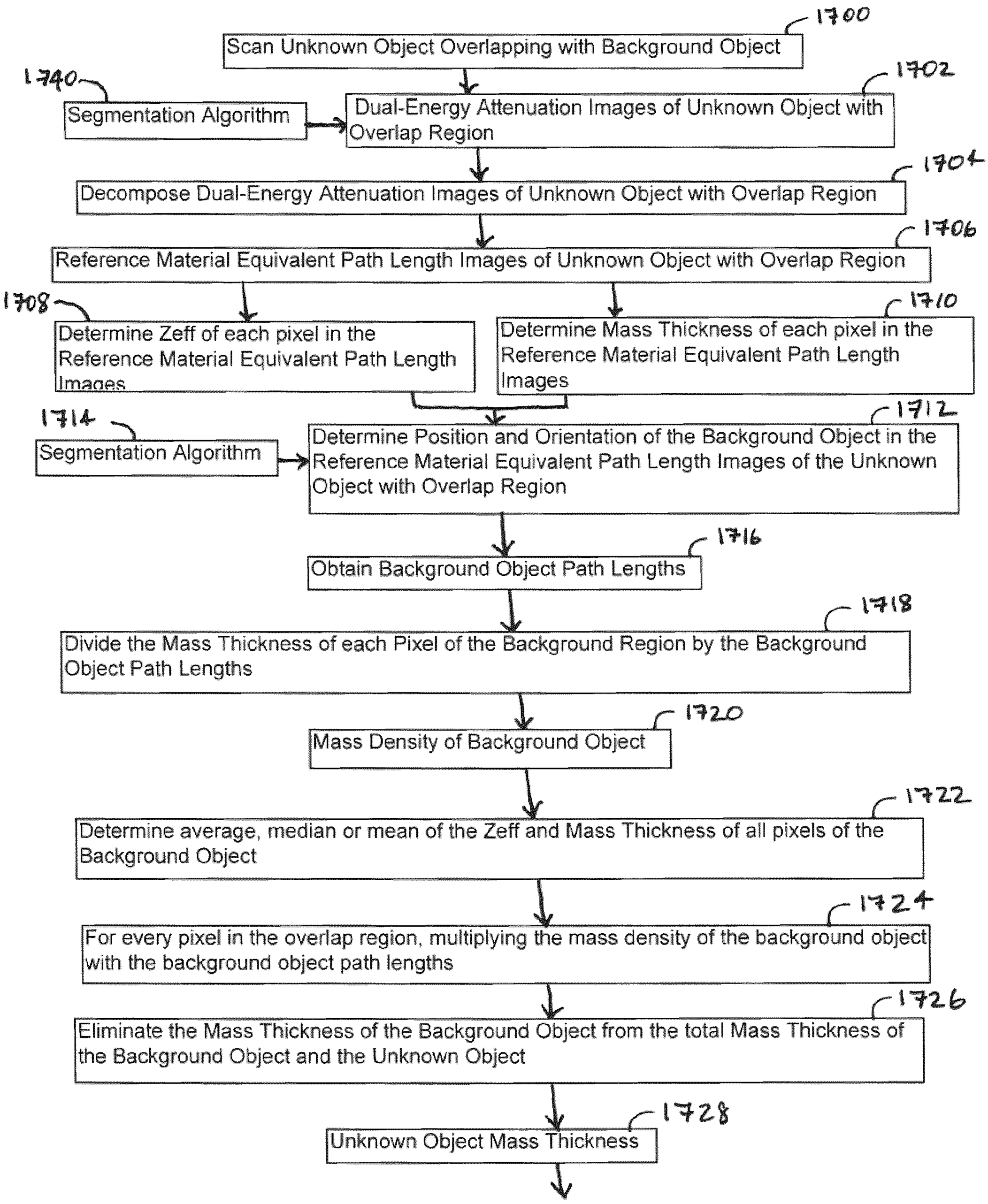
1700
Scan Unknown Object Overlapping with Background Object
1740
Segmentation Algorithm
1702
Dual-Energy Attenuation Images of Unknown Object with Overlap Region
1704
Decompose Dual-Energy Attenuation Images of Unknown Object with Overlap Region
1706
Reference Material Equivalent Path Length Images of Unknown Object with Overlap Region
1708
Determine Zeff of each pixel in the Reference Material Equivalent Path Length Images
1710
Determine Mass Thickness of each pixel in the Reference Material Equivalent Path Length Images
1714
Segmentation Algorithm
1712
Determine Position and Orientation of the Background Object in the Reference Material Equivalent Path Length Images of the Unknown Object with Overlap Region
1716
Obtain Background Object Path Lengths
1718
Divide the Mass Thickness of each Pixel of the Background Region by the Background Object Path Lengths
1720
Mass Density of Background Object
1722
Determine average, median or mean of the Zeff and Mass Thickness of all pixels of the Background Object
1724
For every pixel in the overlap region, multiplying the mass density of the background object with the background object path lengths
1726
Eliminate the Mass Thickness of the Background Object from the total Mass Thickness of the Background Object and the Unknown Object
1728
Unknown Object Mass Thickness

FIG. 17A

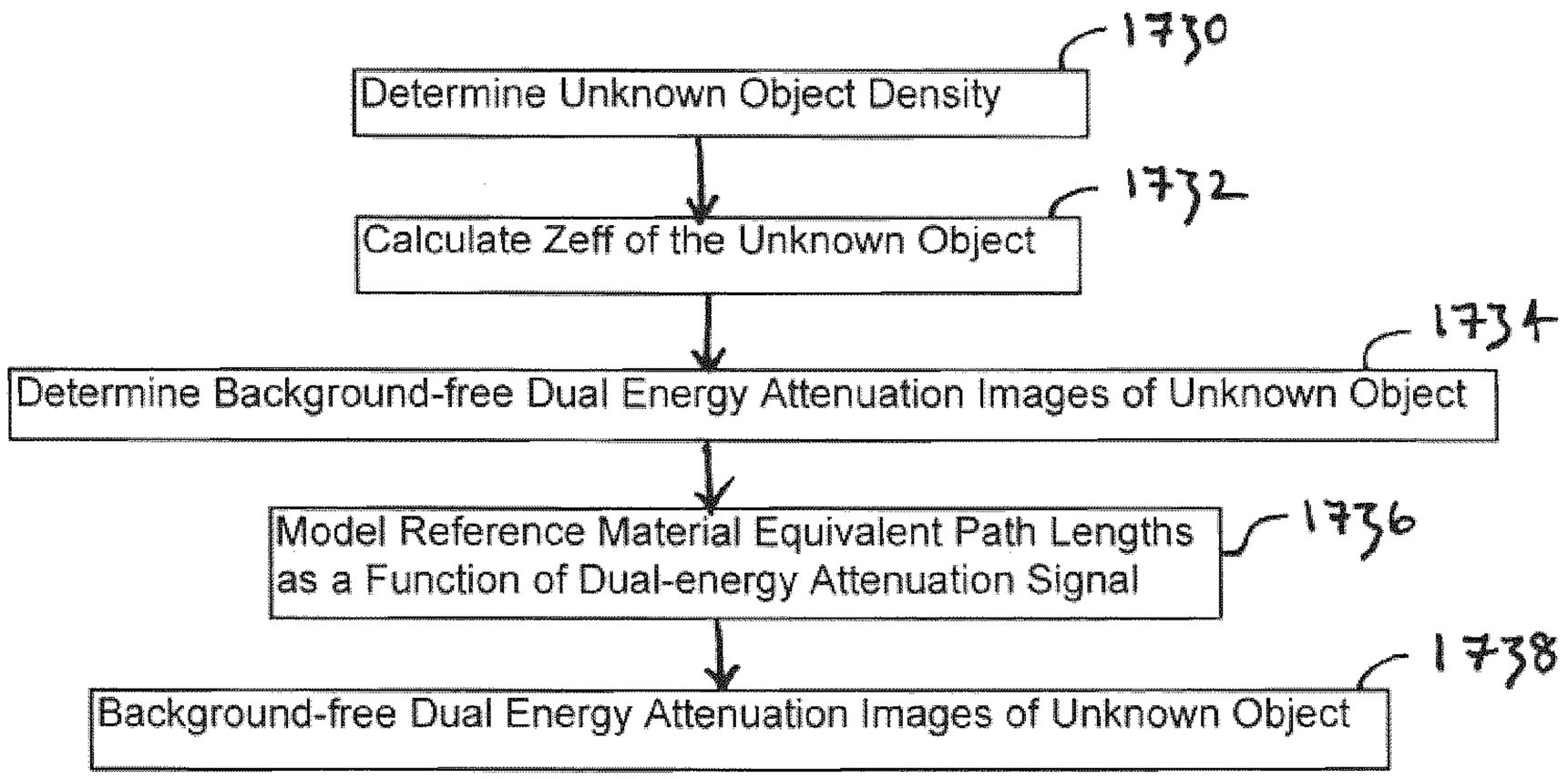
1730
Determine Unknown Object Density
1732
Calculate Zeff of the Unknown Object
1734
Determine Background-free Dual Energy Attenuation Images of Unknown Object
1736
Model Reference Material Equivalent Path Lengths as a Function of Dual-energy Attenuation Signal
1738
Background-free Dual Energy Attenuation Images of Unknown Object

FIG. 17B

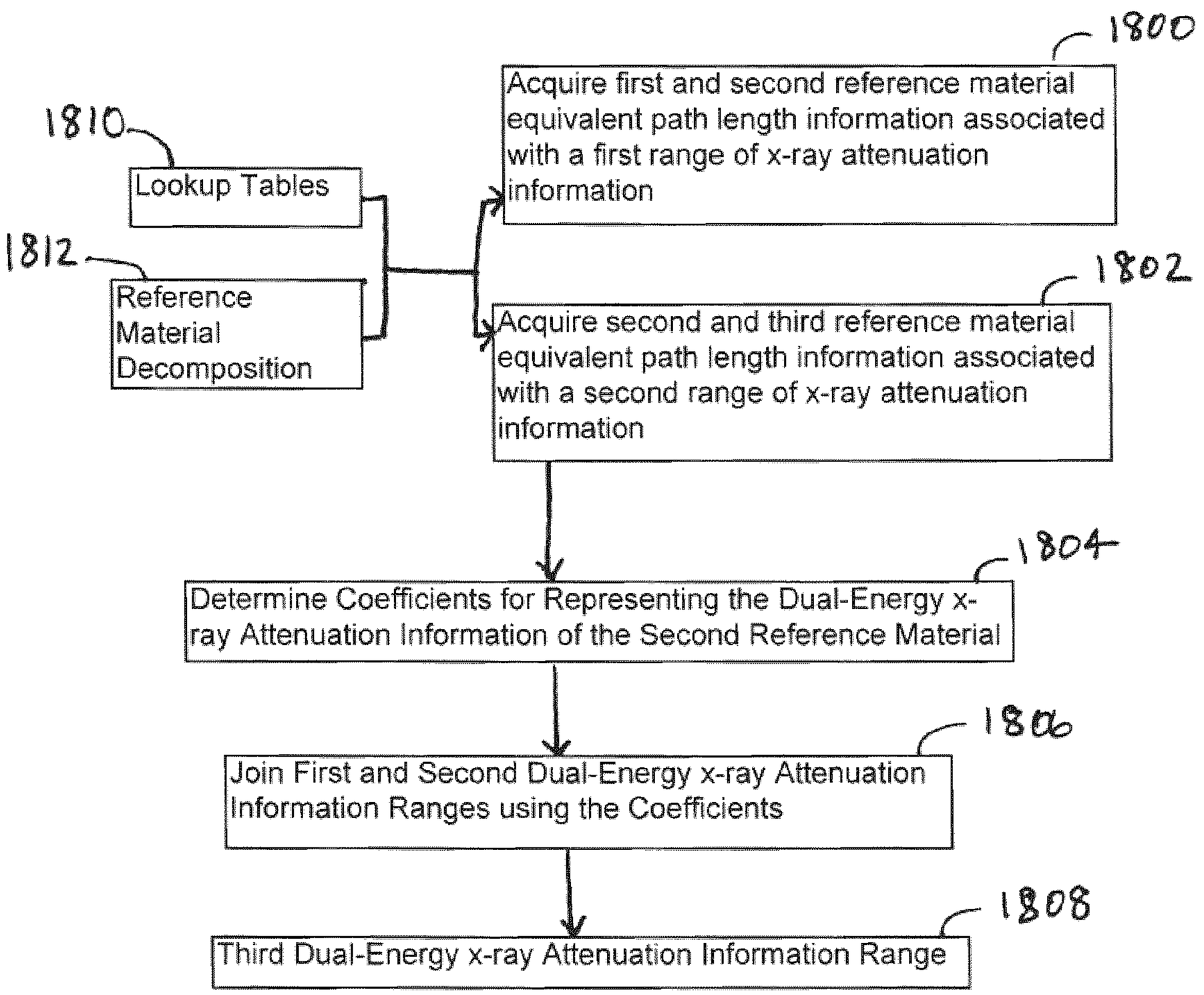
1800
Acquire first and second reference material equivalent path length information associated with a first range of x-ray attenuation information
1810
Lookup Tables
1812
Reference Material Decomposition
1802
Acquire second and third reference material equivalent path length information associated with a second range of x-ray attenuation information
1804
Determine Coefficients for Representing the Dual-Energy x-ray Attenuation Information of the Second Reference Material
1806
Join First and Second Dual-Energy x-ray Attenuation Information Ranges using the Coefficients
1808
Third Dual-Energy x-ray Attenuation Information Range

FIG. 18

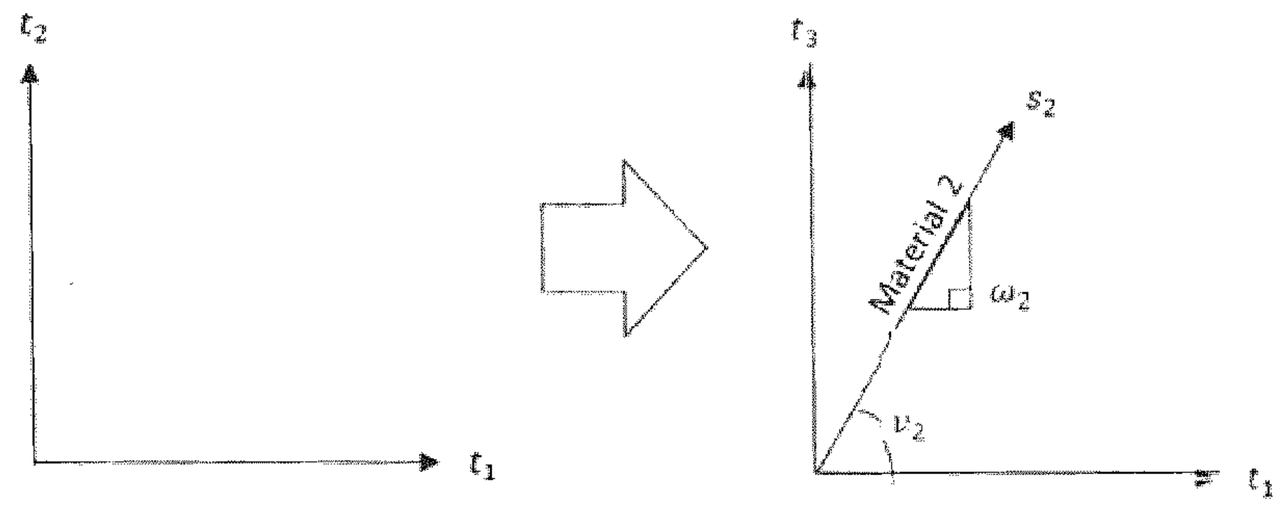

FIG. 19

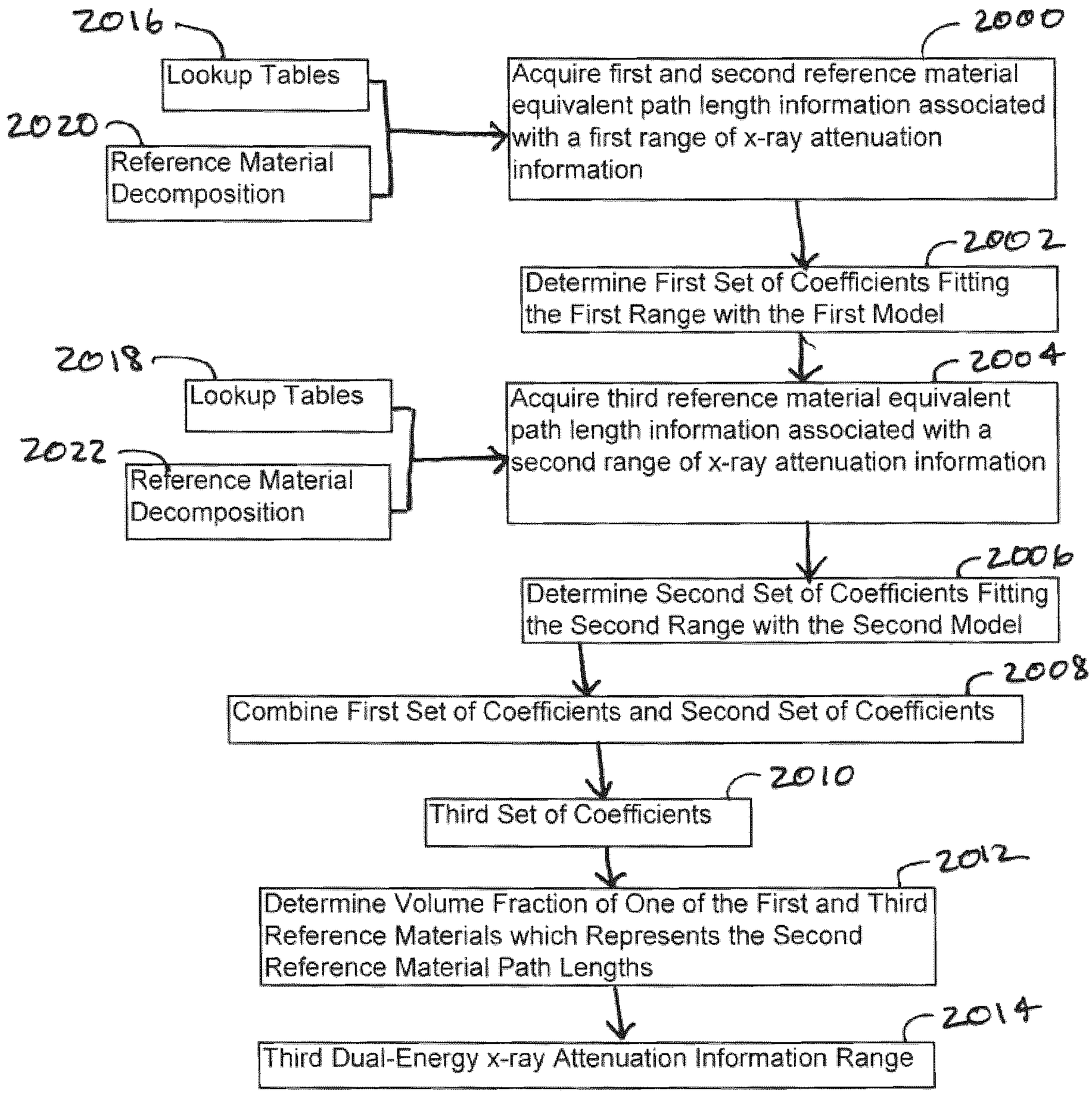
2016
Lookup Tables
2020
Reference Material Decomposition
2000
Acquire first and second reference material equivalent path length information associated with a first range of x-ray attenuation information
2002
Determine First Set of Coefficients Fitting the First Range with the First Model
2018
Lookup Tables
2022
Reference Material Decomposition
2004
Acquire third reference material equivalent path length information associated with a second range of x-ray attenuation information
2006
Determine Second Set of Coefficients Fitting the Second Range with the Second Model
2008
Combine First Set of Coefficients and Second Set of Coefficients
2010
Third Set of Coefficients
2012
Determine Volume Fraction of One of the First and Third Reference Materials which Represents the Second Reference Material Path Lengths
2014
Third Dual-Energy x-ray Attenuation Information Range

FIG. 20

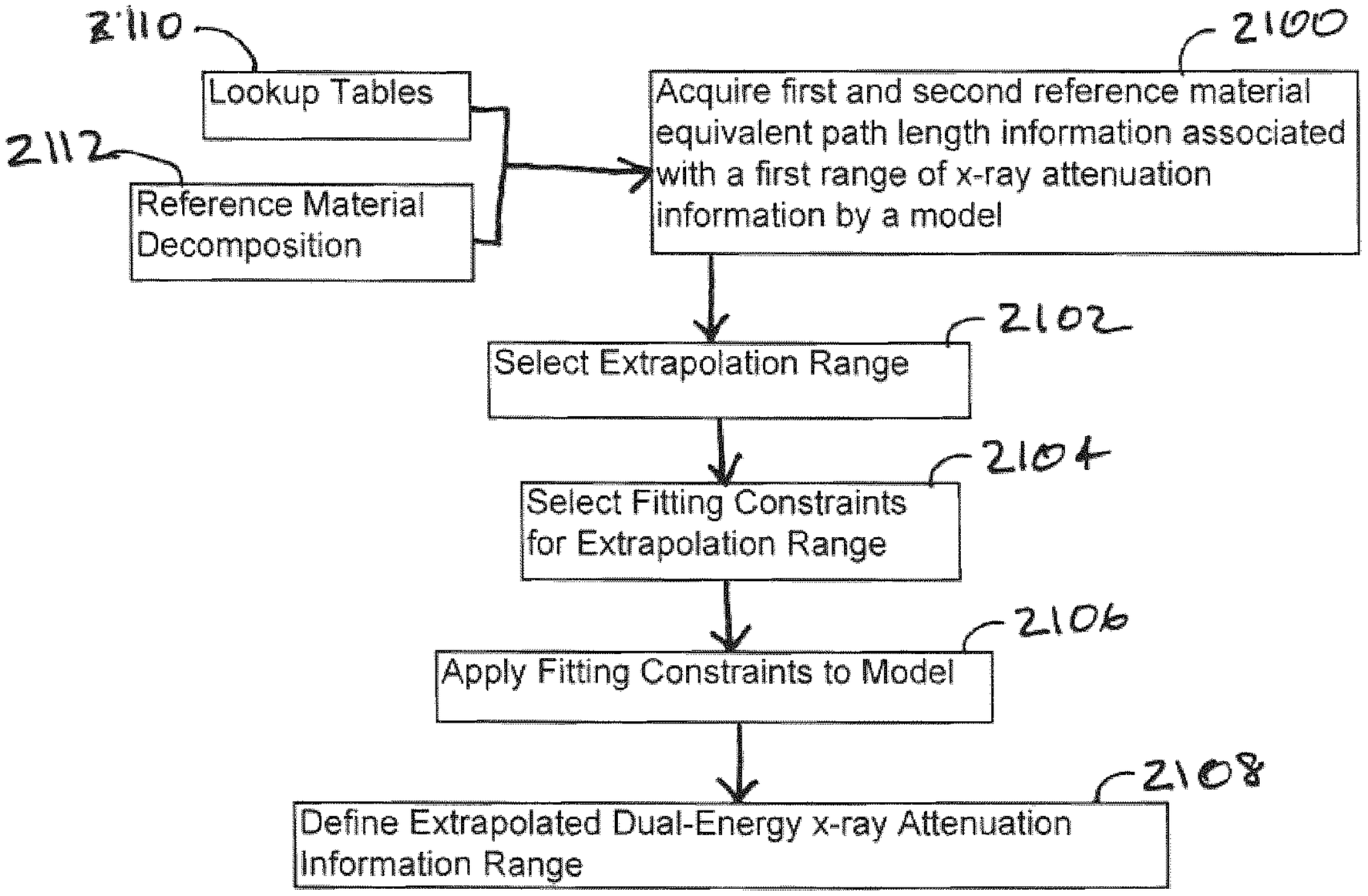
2110
Lookup Tables
2112
Reference Material Decomposition
2100
Acquire first and second reference material equivalent path length information associated with a first range of x-ray attenuation information by a model
2102
Select Extrapolation Range
2104
Select Fitting Constraints for Extrapolation Range
2106
Apply Fitting Constraints to Model
2108
Define Extrapolated Dual-Energy x-ray Attenuation Information Range

FIG. 21

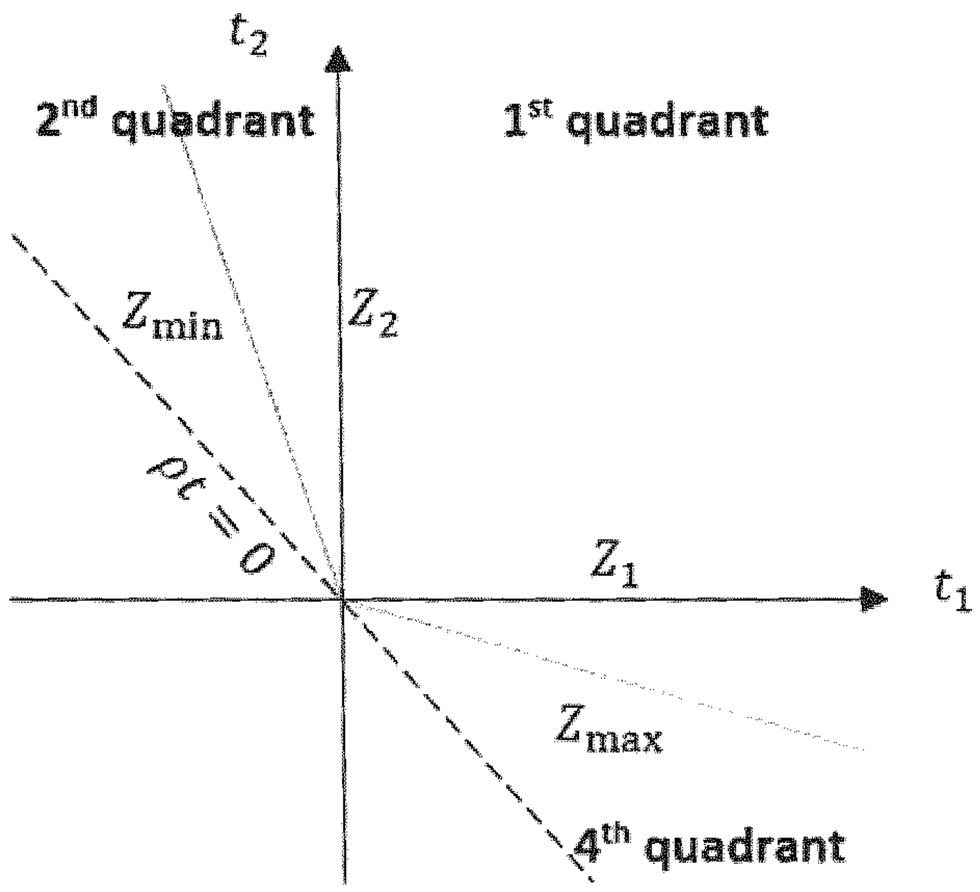
t_2
2nd quadrant
1st quadrant
Z_{min}
Z_2
$\rho t = 0$
Z_1
t_1
Z_{max}
4th quadrant

FIG. 22

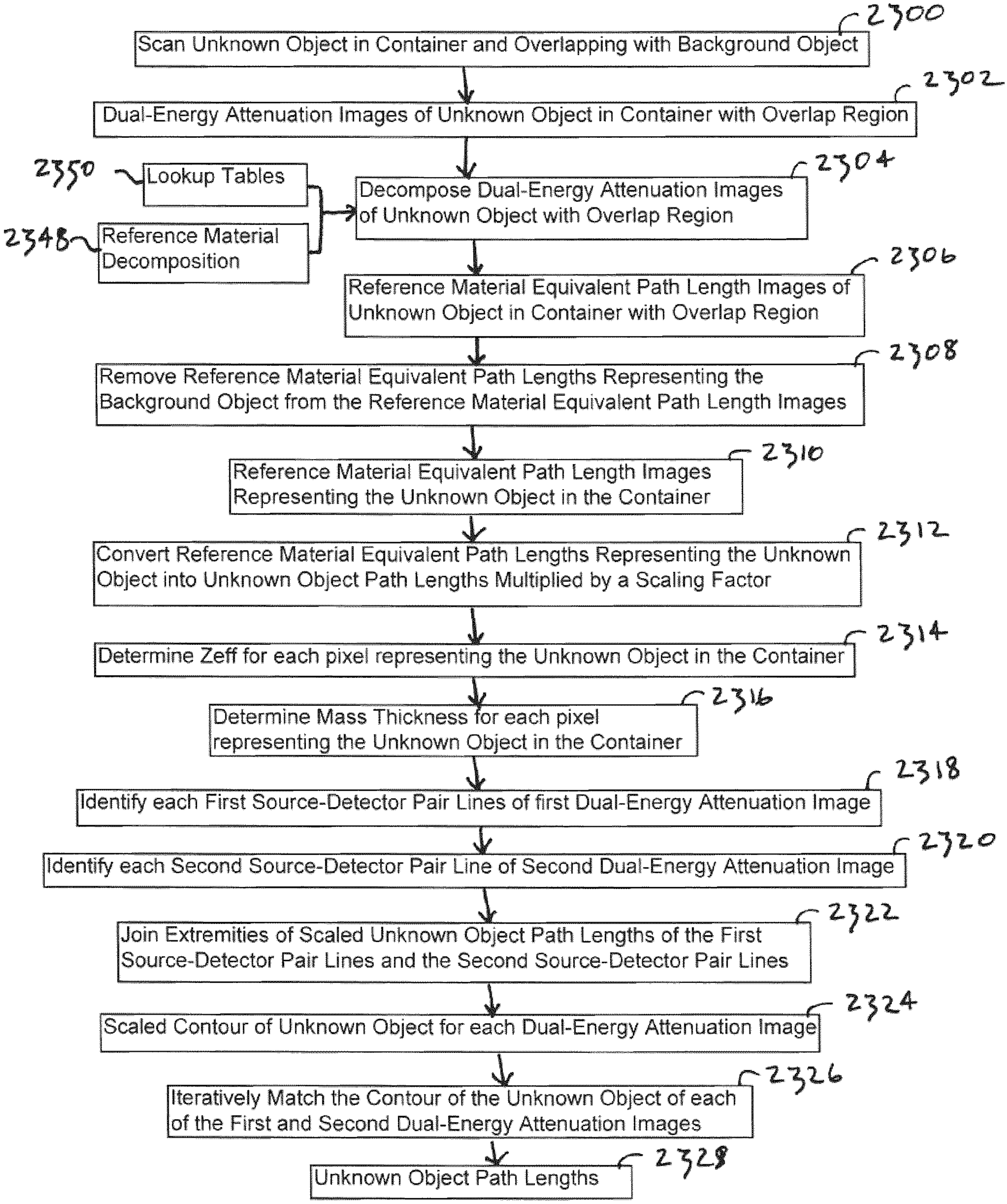
2300
Scan Unknown Object in Container and Overlapping with Background Object
2302
Dual-Energy Attenuation Images of Unknown Object in Container with Overlap Region
2350
Lookup Tables
2348
Reference Material Decomposition
2304
Decompose Dual-Energy Attenuation Images of Unknown Object with Overlap Region
2306
Reference Material Equivalent Path Length Images of Unknown Object in Container with Overlap Region
2308
Remove Reference Material Equivalent Path Lengths Representing the Background Object from the Reference Material Equivalent Path Length Images
2310
Reference Material Equivalent Path Length Images Representing the Unknown Object in the Container
2312
Convert Reference Material Equivalent Path Lengths Representing the Unknown Object into Unknown Object Path Lengths Multiplied by a Scaling Factor
2314
Determine Zeff for each pixel representing the Unknown Object in the Container
2316
Determine Mass Thickness for each pixel representing the Unknown Object in the Container
2318
Identify each First Source-Detector Pair Lines of first Dual-Energy Attenuation Image
2320
Identify each Second Source-Detector Pair Line of Second Dual-Energy Attenuation Image
2322
Join Extremities of Scaled Unknown Object Path Lengths of the First Source-Detector Pair Lines and the Second Source-Detector Pair Lines
2324
Scaled Contour of Unknown Object for each Dual-Energy Attenuation Image
2326
Iteratively Match the Contour of the Unknown Object of each of the First and Second Dual-Energy Attenuation Images
2328
Unknown Object Path Lengths

FIG.23A

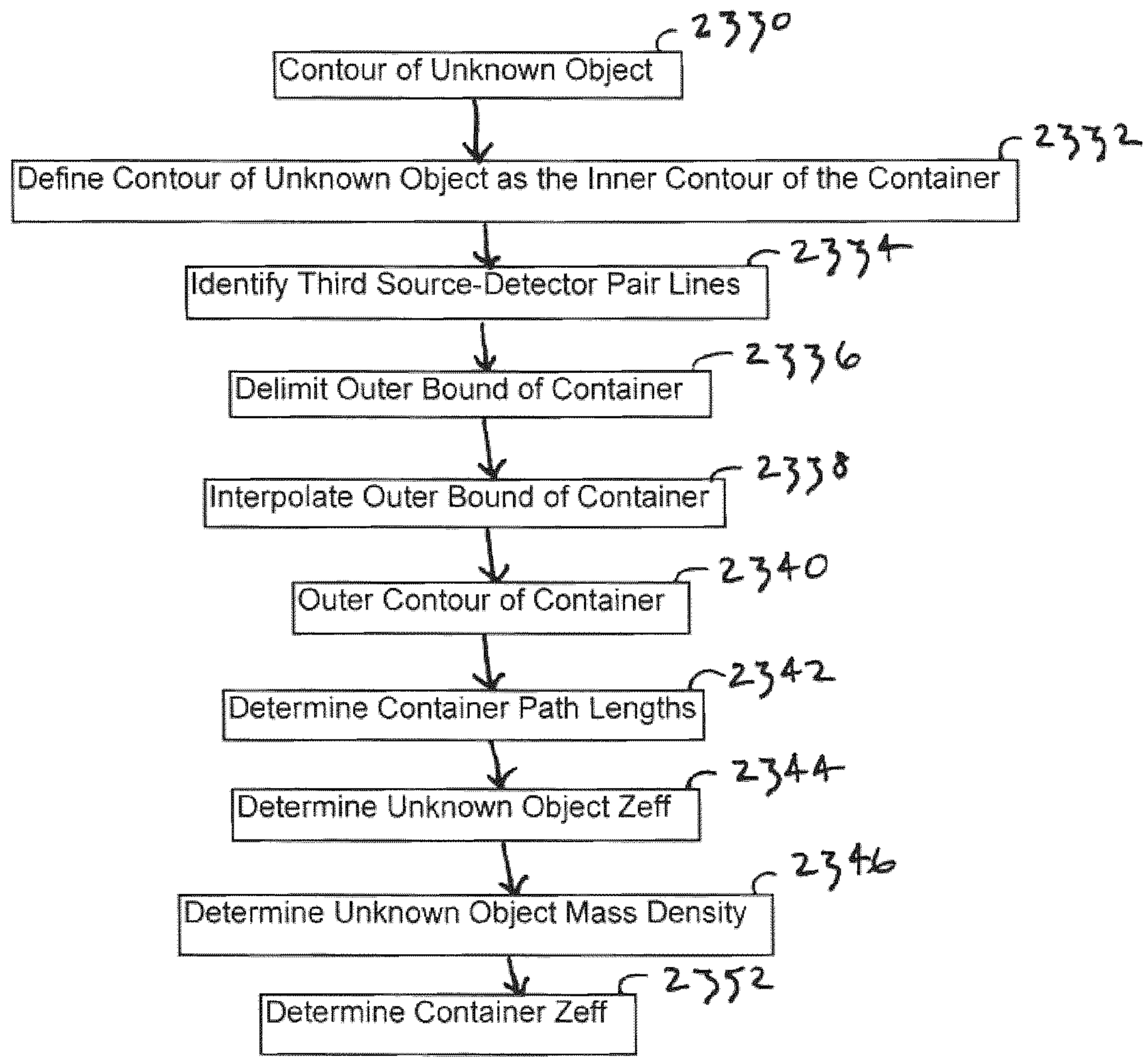
2330
Contour of Unknown Object
2332
Define Contour of Unknown Object as the Inner Contour of the Container
2334
Identify Third Source-Detector Pair Lines
2336
Delimit Outer Bound of Container
2338
Interpolate Outer Bound of Container
2340
Outer Contour of Container
2342
Determine Container Path Lengths
2344
Determine Unknown Object Zeff
2346
Determine Unknown Object Mass Density
2352
Determine Container Zeff

FIG. 23B

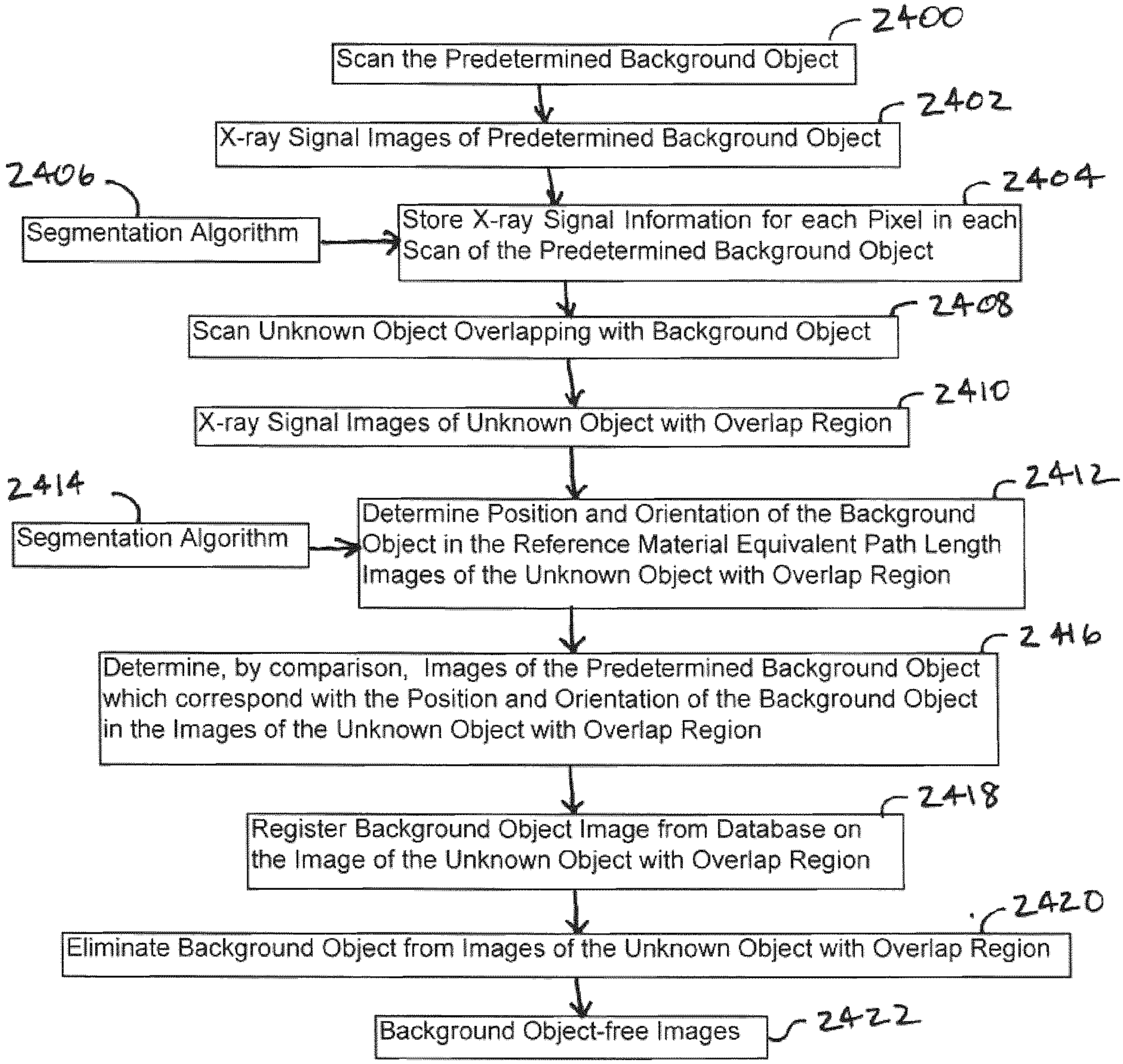
2400
Scan the Predetermined Background Object
X-ray Signal Images of Predetermined Background Object
2402
2406
Segmentation Algorithm
Store X-ray Signal Information for each Pixel in each Scan of the Predetermined Background Object
2404
Scan Unknown Object Overlapping with Background Object
2408
X-ray Signal Images of Unknown Object with Overlap Region
2410
2414
Segmentation Algorithm
Determine Position and Orientation of the Background Object in the Reference Material Equivalent Path Length Images of the Unknown Object with Overlap Region
2412
Determine, by comparison, Images of the Predetermined Background Object which correspond with the Position and Orientation of the Background Object in the Images of the Unknown Object with Overlap Region
2416
Register Background Object Image from Database on the Image of the Unknown Object with Overlap Region
2418
Eliminate Background Object from Images of the Unknown Object with Overlap Region
2420
Background Object-free Images
2422

FIG. 24

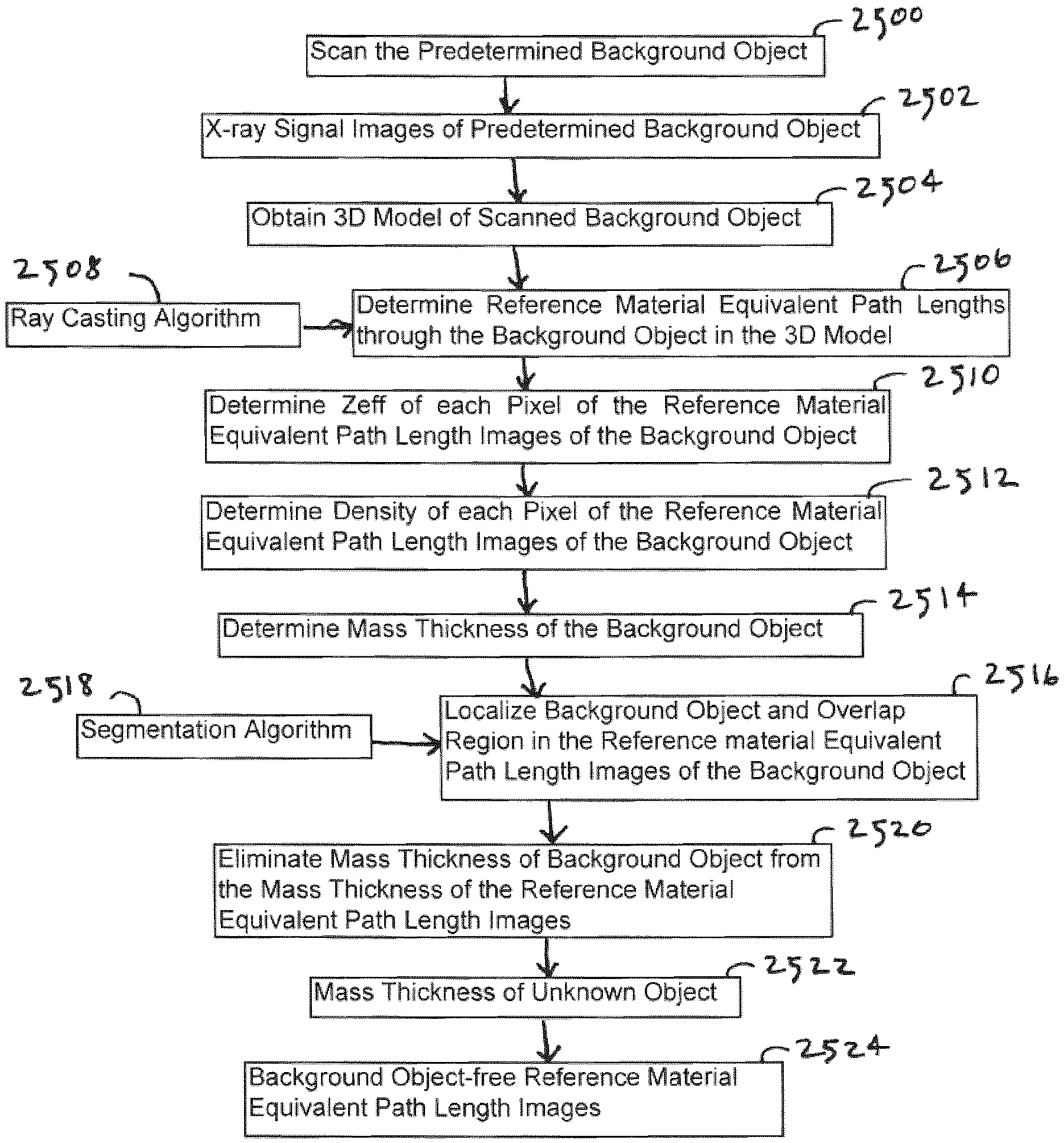
Scan the Predetermined Background Object
2500
X-ray Signal Images of Predetermined Background Object
2502
Obtain 3D Model of Scanned Background Object
2504
2508
Ray Casting Algorithm
Determine Reference Material Equivalent Path Lengths through the Background Object in the 3D Model
2506
Determine Zeff of each Pixel of the Reference Material Equivalent Path Length Images of the Background Object
2510
Determine Density of each Pixel of the Reference Material Equivalent Path Length Images of the Background Object
2512
Determine Mass Thickness of the Background Object
2514
2518
Segmentation Algorithm
Localize Background Object and Overlap Region in the Reference material Equivalent Path Length Images of the Background Object
2516
Eliminate Mass Thickness of Background Object from the Mass Thickness of the Reference Material Equivalent Path Length Images
2520
Mass Thickness of Unknown Object
2522
Background Object-free Reference Material Equivalent Path Length Images
2524

FIG. 25

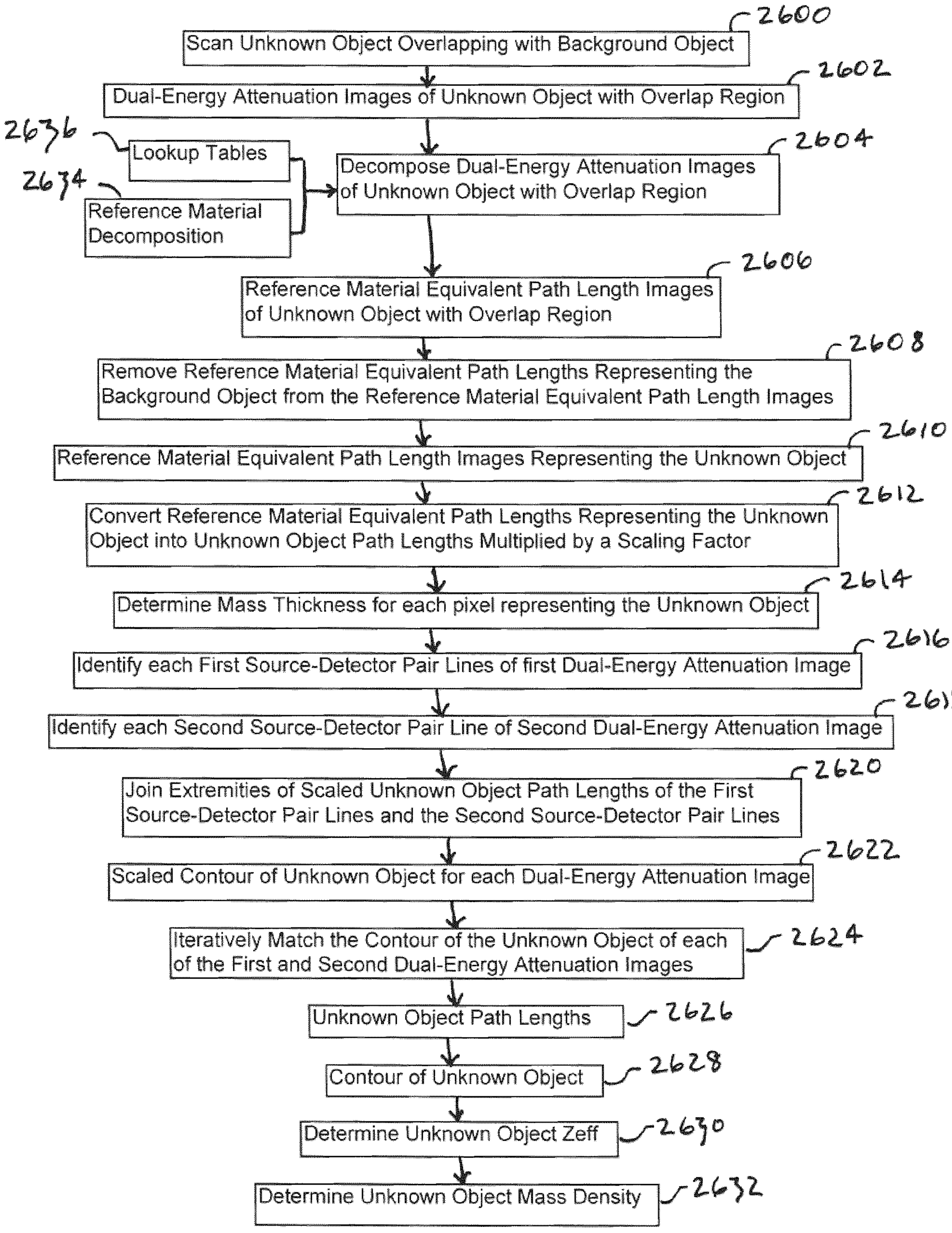
2600
Scan Unknown Object Overlapping with Background Object
2602
Dual-Energy Attenuation Images of Unknown Object with Overlap Region
2636
Lookup Tables
2634
Reference Material Decomposition
2604
Decompose Dual-Energy Attenuation Images of Unknown Object with Overlap Region
2606
Reference Material Equivalent Path Length Images of Unknown Object with Overlap Region
2608
Remove Reference Material Equivalent Path Lengths Representing the Background Object from the Reference Material Equivalent Path Length Images
2610
Reference Material Equivalent Path Length Images Representing the Unknown Object
2612
Convert Reference Material Equivalent Path Lengths Representing the Unknown Object into Unknown Object Path Lengths Multiplied by a Scaling Factor
2614
Determine Mass Thickness for each pixel representing the Unknown Object
2616
Identify each First Source-Detector Pair Lines of first Dual-Energy Attenuation Image
2618
Identify each Second Source-Detector Pair Line of Second Dual-Energy Attenuation Image
2620
Join Extremities of Scaled Unknown Object Path Lengths of the First Source-Detector Pair Lines and the Second Source-Detector Pair Lines
2622
Scaled Contour of Unknown Object for each Dual-Energy Attenuation Image
2624
Iteratively Match the Contour of the Unknown Object of each of the First and Second Dual-Energy Attenuation Images
2626
Unknown Object Path Lengths
2628
Contour of Unknown Object
2630
Determine Unknown Object Zeff
2632
Determine Unknown Object Mass Density

FIG. 26

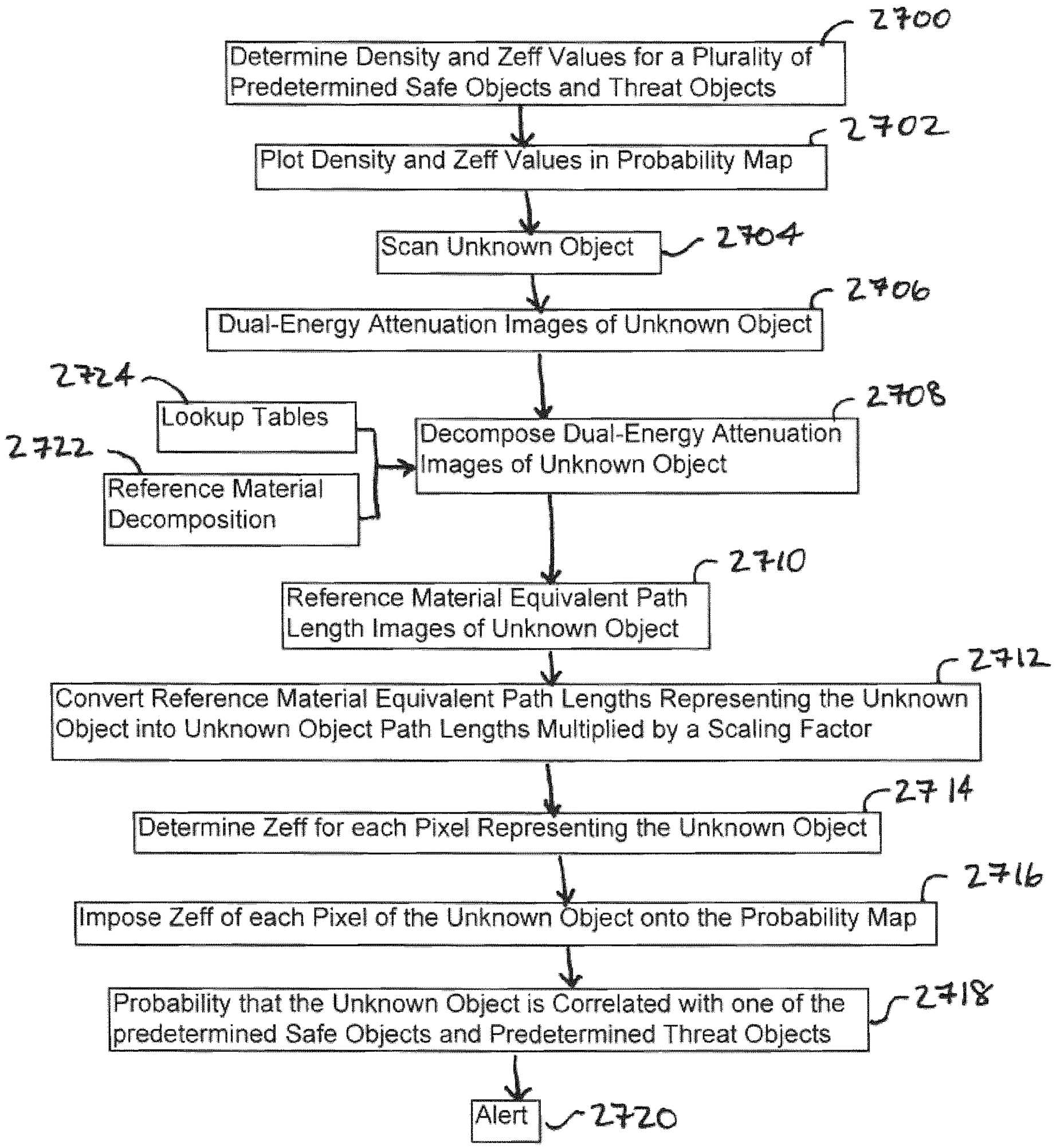
2700
Determine Density and Zeff Values for a Plurality of Predetermined Safe Objects and Threat Objects
2702
Plot Density and Zeff Values in Probability Map
2704
Scan Unknown Object
2706
Dual-Energy Attenuation Images of Unknown Object
2724
Lookup Tables
2722
Reference Material Decomposition
2708
Decompose Dual-Energy Attenuation Images of Unknown Object
2710
Reference Material Equivalent Path Length Images of Unknown Object
2712
Convert Reference Material Equivalent Path Lengths Representing the Unknown Object into Unknown Object Path Lengths Multiplied by a Scaling Factor
2714
Determine Zeff for each Pixel Representing the Unknown Object
2716
Impose Zeff of each Pixel of the Unknown Object onto the Probability Map
2718
Probability that the Unknown Object is Correlated with one of the predetermined Safe Objects and Predetermined Threat Objects
Alert
2720

FIG. 27