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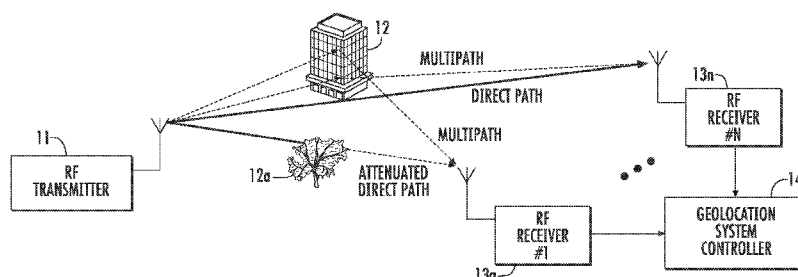


FIG. 1

(57) Abstract: A system for geolocating a radio frequency (RF) transmitter in the presence of multipath interference may include a plurality of RF receivers arranged in spaced relation. The system may also include a controller coupled to the plurality of receivers and configured to generate a plurality of measurements associated with the RF transmitter. The controller may also compute a plurality of ambiguity functions based upon the plurality of measurements and due to the multipath interference, and project the plurality of ambiguity functions onto a common geo-referenced grid. The controller may also detect a peak on the common geo-referenced grid indicative of a geolocation of the RF transmitter.

RF TRANSMITTER GEOLOCATION SYSTEM AND RELATED METHODS

The present invention relates to the field of geolocation of a radio frequency (RF) transmitter, and, more particularly, to geolocation of an RF transmitter
5 in the presence of multipath interference and related methods.

Geolocating an RF transmitter in the presence of multipath interference presents a unique and difficult problem. Signals that do not arrive at a receiver via a direct pathway have an incorrect time, frequency (Doppler), and/or angle of arrival (AOA) compared to those corresponding to the direct path. As a result of this, an
10 erroneous geolocation may be computed using these measurements. Also, errors introduced by multipath interference, for example from buildings, are generally not zero-mean Gaussian random processes and will not necessarily average out over multiple measurements.

Current geolocation systems measure time, frequency, and/or AOA
15 measurements and compute a potential geolocation estimate from these measurements. The potential geolocation may have increased accuracy if the errors are zero-mean Gaussian and all of the transformations are linear.

Unfortunately, the above assumptions are not generally true in the presence of multipath interference. In the presence of multipath interference, the
20 measurement errors are typically not zero-mean or Gaussian, and the transformations from time, frequency, and AOA are typically non-linear.

U.S. Patent No. 5,999,129 to Rose discloses a multiplatform ambiguous phase circle and time difference of arrival protection emitter location system. More particularly, Rose describes determining the geolocation of a stationary
25 RF signal emitter from two or more moving observer aircraft. The observers receive signals from the emitter, and the system measures the phase difference between the signals. The observers perform pulse time of arrival (TOA) measurements over a predetermined clock interval, and calculate the time difference of arrival (TDOA) of corresponding, same-pulse, emitter signals. Based on geometric relationships, the
30 system creates a series of circular lines of position (LOPs) for each observer, and

computes hyperbolic LOPs based on the TDOA calculations. The system determines the emitter location from the intersection of the hyperbolic LOPs and the circular LOPs.

U.S. Patent No. 6,933,888 to Schiffmiller et al. discloses a multi-shop
5 coherent geolocation system. More particularly, TOA measurements at a number of collecting platforms are performed with the positions of the platforms being ascertained. The measurements are sent to a geolocation computer to arrive at the potential location of the emitter.

U.S. Patent No. 7,317,417 to Arikan et al. is directed to a system for
10 detection and tracking of one or more targets. A first slice of a cross-ambiguity function of a transmitted signal and the reflection thereof are calculated.

In view of the foregoing background, it is therefore an object of the present invention to provide increased accuracy in geolocating an RF transmitter in the presence of multipath interference.

15 This and other objects, features, and advantages in accordance with the present invention are provided by a system for geolocating an RF transmitter in the presence of multipath interference. The system may include a plurality of RF receivers arranged in spaced relation. The system may also include a controller coupled to the plurality of receivers and configured to generate a plurality of
20 measurements associated with the RF transmitter, for example. The controller may be configured to compute a plurality of ambiguity functions based upon the plurality of measurements and due to the multipath interference, and project the plurality of ambiguity functions onto a common geo-referenced grid. The controller may also be configured to detect a peak on the common geo-referenced grid indicative of a
25 geolocation of the RF transmitter, for example. Accordingly, the system provides increased accuracy in geolocating an RF transmitter in the presence of multipath interference.

The controller may estimate a weight of each ambiguity function relative to one another for scaling each projected ambiguity function. The controller

may also further be configured to estimate the weight of each ambiguity function relative to one another as a function of noise, for example.

The controller may generate the common geo-referenced grid based upon at least one of a position, orientation, and relative movement of the plurality of
5 RF receivers, for example.

The controller may generate the plurality of measurements as at least one of a plurality of frequency difference of arrival measurements associated with the RF transmitter, a plurality of time of arrival measurements associated with the RF transmitter, a plurality of time difference of arrival measurements associated with the
10 RF transmitter, a plurality of frequency of arrival measurements associated with the RF transmitter, and a plurality of angle of arrival measurements associated with the RF transmitter, for example.

The controller may sum each projected ambiguity function on the common geo-referenced grid. The controller may detect a peak on the common geo-
15 referenced grid by fitting a probability ellipse thereto.

The controller further may compute the plurality of ambiguity functions based upon calibration data. For example, the calibration data may include at least one of a time offset, a frequency offset, a polarization, and an RF receiver antenna pattern of each of the plurality of RF receivers.

The system may further include a display coupled to the controller to display at least one of the ambiguity functions, and the projected plurality of
20 ambiguity functions, for example.

Another aspect is directed to a method for geolocating an RF transmitter in the presence of multipath interference. The method may include using a
25 controller coupled to a plurality of RF receivers arranged in spaced relation to generate a plurality of measurements associated with the RF transmitter. The controller may also be used to compute a plurality of ambiguity functions based upon the plurality of measurements and due to the multipath interference, and project the plurality of ambiguity functions onto a common geo-referenced grid, for example.

The controller may also detect a peak on the common geo-referenced grid indicative of a geolocation of the RF transmitter.

FIG. 1 is a schematic diagram of a system for geolocating an RF transmitter in the presence of multipath interference in accordance with the present invention.

FIG. 2 is a schematic block diagram of the geolocation system of FIG. 1.

FIGS. 3a and 3b are graphs of an ambiguity function associated with the RF transmitter in accordance with the present invention.

FIG. 4 is a graph of the plurality of ambiguity functions projected onto a common geo-referenced grid in accordance with the present invention.

FIG. 5 is a flow chart illustrating a method for geolocating an RF transmitter in the presence of multipath interference in accordance with the invention.

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout and prime notation is used to indicate similar elements in alternative embodiments.

Referring initially to FIGS. 1 and 2, a system **10** for geolocating an RF transmitter **11** in the presence of multipath interference is now described. The RF transmitter **11** may be a cellular telephone, a handheld walkie-talkie, amateur radio, or other RF transmitter, for example, as will be appreciated by those skilled in the art. The RF transmitter **11** may be stationary or moving. The RF transmitter **11** may also be non-cooperative. In other words, the RF transmitter **11** does not have to send identifying data, location data, or other sensor information, for example, to the receivers **13a-13n**. However, where the RF transmitter **11** is a cellular telephone, for

example, the international mobile equipment identity (IMEI) or electronic serial number (ESN) may be used to further identify the cellular phone.

As will be appreciated by those skilled in the art, multipath interference may be caused by a building **12a**, for example, or any structure or natural feature, such as a tree **12b**, that reflects an RF signal from the RF transmitter **11**. The ionosphere is also another natural feature that may also introduce multipath interference, especially at high frequency (HF) or a lower portion of very high frequency (VHF) bands. As will be appreciated by those skilled in the art, the RF signal path resulting from multipath interference may be stronger than a direct RF signal path, for example, 6-10dB stronger than a direct RF signal path, as the direct path is often attenuated, for example, due to shadowing or blockage.

The system **10** illustratively includes RF receivers **13a-13n** arranged in spaced relation to receive the RF multipath signals. The geolocation, velocity, and orientation of each of the RF receivers **13a-13n** are known, for example, from a GPS or inertial navigation unit (INU) device. This data may be sent by the RF receivers **13a-13n** over a wireless link or stored for later processing. There is also typically relative movement between the RF transmitter **11** and at least one of the RF receivers to provide diversity. As will be appreciated by those skilled in the art, there may not be relative movement between the RF transmitter **11** and at least one of the RF receivers **13a-13n**. The system **10** illustratively includes a controller **14** coupled to the RF receivers **13a-13n**. The controller **14** illustratively includes a measurement generation Block **15** to generate a plurality of measurements associated with the RF transmitter. For example, controller **14** may be configured to generate the plurality of measurements as frequency difference of arrival (FDOA) and time difference of arrival (TDOA) measurements associated with the RF transmitter **11**. As will be appreciated by those skilled in the art, and as noted above, the relative movement between the RF transmitter **11** and at least one of the RF receivers **13a-13n** provides the diversity used for the FDOA measurements, and the relative position change between the RF transmitter **11** and at least one of the RF receivers **13a-13n** provides the diversity used for the TDOA measurements.

In other embodiments, for example, the measurement generation Block **15** may generate time of arrival measurements (TOA) associated with the RF transmitter. Still, in further embodiments, measurement generation Block **15** may generate time difference of arrival (TDOA) measurements associated with the RF transmitter, frequency of arrival (FOA) measurements associated with the RF transmitter, or angle of arrival (AOA) measurements associated with the RF transmitter. Other measurements may be generated such as azimuth and elevation angle, for example. As will be appreciated by those skilled in the art, any of the above-noted associated measurements may be generated in combination with other associated measurements, for example, FDOA and TDOA, FOA and TOA, and AOA and azimuth angle.

Based on the particular measurements, as noted above, and due to the multipath interference, the controller **14** computes or generates ambiguity functions at the ambiguity function generation Block **16**. Each ambiguity function may be computed in a native coordinate system. In other words, the ambiguity function may be computed at the ambiguity function generation Block **16** based on the measurements generated at the measurement generation Block **15**.

Referring briefly to FIGS. 3a and 3b, the ambiguity functions are illustratively computed based upon frequency and time for FDOA measurements and TDOA measurements. The ambiguity function displayed in FIG. 3a corresponds to a cross-ambiguity function of signals received by two RF receivers at a first time. Of course the ambiguity function may correspond to a cross-ambiguity function of more than two receivers. The first and second RF receivers measure the time and frequency of the RF signal, as FDOA and TDOA measurements, including the multipath interference. The corresponding ambiguity function is displayed. As will be appreciated by those skilled in the art, the peak **28a** of the measured and displayed ambiguity function is at an incorrect location due to the multipath interference. As illustrated, a second peak **28b** is displayed and is at a correct location, for example as would correspond to a direct path.

An additional displayed ambiguity function illustrated in FIG. 3b corresponds to FDOA and TDOA measurements calculated by signals received by the same first and second receivers at a second later time. Stated alternatively, the additional displayed ambiguity function illustrated in FIG. 3b is based upon
5 measurements generated by the first and second receivers at a later time than the displayed ambiguity function illustrated in FIG. 3a. As will be appreciated by those skilled in the art, the first and second receivers have changed their geolocation or position from the first time. Similar to the ambiguity function illustrated in FIG. 3a, the overall peak **28a'** of the measured and displayed ambiguity function is at an
10 incorrect location due to the multipath interference and a second peak **28b'** is displayed and is at a correct location, for example as would correspond to a direct path.

Advantageously, generating a second graphed ambiguity function at a later time generally eliminates the use of a reference RF signal, as is typically used to
15 compute an ambiguity function based on TOA, FOA, and AOA, for example. However, relative movement between the RF transmitter **11** and the RF receiver **13a-13n** supplies diversity to generate the second ambiguity function for each RF receiver **13a-13n** at the ambiguity function generation Block **16** as illustrated in FIG. 3b.

If FDOA measurements are generated at the measurement generation
20 Block **15**, the ambiguity functions, or cross-ambiguity functions, for example, may be computed at the ambiguity function generation Block **16** between the RF signals received by two different RF receivers **13a-13n**. Limited prior knowledge of the RF signal from the RF emitter **11** may be useful in some embodiments. Where the measurements are TDOA measurements, generation of the ambiguity functions at the
25 ambiguity function generation Block **16** may also be between RF signals received from two different RF receivers **13a-13n**, and limited or no prior knowledge of the RF signal from the RF transmitter **11** may be used.

If TOA measurements are generated at the measurement generation
Block **15**, each ambiguity function may be computed at the ambiguity function
30 generation Block **16** by a correlation of the received RF signal with a known

transmitted reference RF signal. For example, an RF signal may include fixed headers or sync sequences to be used as the transmitted reference RF signal, as will be appreciated by those skilled in the art.

If FOA measurements are generated at the measurement generation
5 Block **15**, each ambiguity function may be computed at the ambiguity function generation Block **16** by a correlation of the received RF signal with a known reference RF signal. For example, a demodulation and remodulation of a received RF signal from an RF receiver **13a-13n** may be performed to create the reference RF signal, as will be appreciated by those skilled in the art.

10 If AOA measurements are generated at the measurement generation Block **15**, each ambiguity function may be computed at the ambiguity function generation Block **16** by a correlation of a phase and amplitude of arrival with the RF receivers **13a-13n** with a calibration table of measured or predicted RF receiver responses over frequency, angle of arrival, and/or polarization. Phase difference of
15 arrival and amplitude difference of arrival may also be used in the correlation.

A display **20** is illustratively coupled to the controller **14** downstream from the ambiguity function generation Block **16** for displaying respective ambiguity functions, if desired. For example, a user may wish to display on the display **20**, the graphs shown in FIGS. 3a and 3b.

20 Calibration data may be provided to the ambiguity function generation Block **16** to provide an increased accuracy ambiguity function. The calibration data may include at least one of a time offset, a frequency offset, a polarization, a time drift rate, a frequency drift rate, an amplitude offset, and an RF receiver antenna pattern of each said plurality of RF receivers over frequency, angle of arrival, and/or
25 polarization. Other calibration data may be used, as will be appreciated by those skilled in the art.

The controller **14** further includes a common grid creation Block **23** to create a common geo-referenced grid. For example, the common-geo-referenced grid created at the common grid creation Block **23** may be a hypercube having a geo-
30 referenced coordinate system. Location data associated with the RF receivers **13a-**

13n is used to create the common geo-referenced grid and provide a geographic area of potential RF transmitter locations. Other RF receiver data may be used in creating the common geo-referenced grid, such as, for example, position, antenna pattern, frequency, orientation, and relative movement of the RF receivers. For example,
5 other dimensions of the hypercube may be used to provide potential RF transmitter velocities and orientations.

The controller **14** illustratively includes a grid projection Block **17** for projecting the ambiguity functions onto the common geo-referenced grid **31**.

The controller **14** also includes a weight estimation Block **22** for
10 estimating a weight of each ambiguity function relative to one another for scaling each projected ambiguity function. More particularly, the weight of each ambiguity function may be estimated relative to one another as a function of noise, for example, a signal to noise ratio. Each weight may also be estimated as a function of a
15 normalized ambiguity function peak, or other metrics. A higher weight may be assigned to those ambiguity functions more likely to identify the geolocation of the RF transmitter **11**, for example. Other weighting metrics may be used, as will be appreciated by those skilled in the art. Respective estimated weights determined at the weight estimation Block **22** are multiplied at the multiplier Block **18** by each
projected ambiguity function projected on the common geo-referenced grid **31**.

20 The controller **14** further illustratively includes a summing Block **19** for summing each projected ambiguity function on the common geo-referenced grid **31**. As illustrated in FIG. 4, the projected and summed ambiguity functions are on the common geo-referenced grid **31**, which may be displayed by the display **20**. The projected ambiguity functions appear “stacked” on the common geo-referenced grid
25 **31**, because of the summing, which contributes to an increase in density of the projected ambiguity functions. Illustratively, the peaks **28a**, **28a’** illustrated in FIGS. 3a and 3b due to multipath interference generally do not align with each other when projected to the common geo-referenced grid **31**. Instead, the peaks **28b**, **28b’** having the correct location align. Accordingly, the contributions to each summed ambiguity
30 function from multipath interference tend to “smear” or “blur” while the contributions

to each summed ambiguity function from direct path tend to “stack,” thus resulting in the overall peak of the summed ambiguity functions on the common geo-referenced grid **31**.

The controller **14** further includes a peak determination Block **21** to
5 detect a peak on the common geo-referenced grid **31**. As noted above, the displayed individual ambiguity functions, as illustrated in FIGS. 3a and 3b, may exhibit a peak in an incorrect geolocation due to the multipath interference. Advantageously, peaks of each of the ambiguity functions, when projected and summed on the common geo-referenced grid **31**, will decorrelate, and the peak of the common geo-referenced grid
10 will likely correspond to the true RF transmitter **11** geolocation. Stated alternatively, the peak of the projected and summed ambiguity functions on the common geo-referenced grid is typically indicative of a geolocation of the RF transmitter **11**.

One advantageous approach to detecting the peak of the projected and summed ambiguity functions on the common geo-referenced grid includes fitting a
15 probability ellipse **32**. The probability ellipse **32** may be fit from the location of the detected peak and a contour level surrounding the detected peak. The probability ellipse **32** may also be fit from a center of mass and an Eigen space fit of vectors from the detected peak to the surrounding surface or through a quadratic ellipsoid fit to the ambiguity surface. The ellipse **32** center corresponds to the geolocation of the RF
20 transmitter **11** and may be output by the controller **14** such as to the display **20** or to another device, for example.

Referring now to FIG. 5, with reference to the flow chart **100**, another aspect is directed to a method for geolocating an RF transmitter **11** in the presence of multipath interference. Starting at Block **102** the method includes using a controller
25 **14** coupled to RF receivers **13a-13n** arranged in spaced relation to generate a plurality of measurements associated with the RF transmitter **11** at Block **104**. The method further includes using the controller **14** to compute a plurality of ambiguity functions based upon the plurality of measurements and due to the multipath interference (Block **106**), and project the plurality of ambiguity functions onto a common geo-
30 referenced grid **31** (Block **108**). The controller **14** is further used at Block **110** to

weight the projected ambiguity functions, and sum at Block **112** the projected ambiguity functions. The method may also include displaying at Block **114**, on a display **20**, the ambiguity functions and the common geo-referenced grid having the projected and summed ambiguity functions thereon. The controller **14** is still further
5 used at Block **116** to detect a peak on the common geo-referenced grid indicative of a geolocation of the RF transmitter **11** before ending at Block **118**.

CLAIMS

1. A system for geolocating a radio frequency (RF) transmitter in the presence of multipath interference, the system comprising:
- 5 a plurality of RF receivers arranged in spaced relation; and
a controller coupled to said plurality of receivers configured to generate a plurality of measurements associated with the RF transmitter,
- 10 compute a plurality of ambiguity functions based upon the plurality of measurements and due to the multipath interference,
project the plurality of ambiguity functions onto a common geo-referenced grid, and
detect a peak on the common geo-referenced grid indicative of a geolocation of the RF transmitter.
- 15
2. The system according to Claim 1 wherein said controller is further configured to estimate a weight of each ambiguity function relative to one another for scaling each projected ambiguity function.
- 20
3. The system according to Claim 2 wherein said controller is further configured to estimate the weight of each ambiguity function relative to one another as a function of noise.
- 25
4. The system according to Claim 1 wherein said controller is further configured to generate the common geo-referenced grid based upon at least one of a position, orientation, and relative movement of said plurality of RF receivers.
- 30
5. The system according to Claim 1 wherein said controller is further configured to generate the plurality of measurements as at least one of a plurality of frequency difference of arrival measurements associated with the RF

transmitter, a plurality of time of arrival measurements associated with the RF transmitter, a plurality of time difference of arrival measurements associated with the RF transmitter, a plurality of frequency of arrival measurements associated with the RF transmitter, and a plurality of angle of arrival measurements associated with the
5 RF transmitter.

6. The system according to Claim 1 wherein said controller is further configured to sum each projected ambiguity function on the common geo-referenced grid.
10

7. The system according to Claim 1 wherein said controller is further configured to detect a peak on the common geo-referenced grid by fitting a probability ellipse thereto.

8. A method for geolocating a radio frequency (RF) transmitter in the presence of multipath interference comprising:

using a controller coupled to a plurality of RF receivers arranged in spaced relation to at least

generate a plurality of measurements associated with the RF
20 transmitter,

compute a plurality of ambiguity functions based upon the plurality of measurements and due to the multipath interference,

project the plurality of ambiguity functions onto a common geo-referenced grid, and

25 detect a peak on the common geo-referenced grid indicative of a geolocation of the RF transmitter.

9. The method according to Claim 8 further comprising using the controller to generate the common geo-referenced grid based upon at least one of a
30 position, orientation, and relative movement of the plurality of RF receivers.

10. The method according to Claim 8 further comprising using the controller to generate the plurality of measurements further comprises using the controller to generate the plurality of measurements as at least one of a plurality of frequency difference of arrival measurements associated with the RF transmitter, a
- 5 plurality time of arrival measurements associated with the RF transmitter, a plurality of time difference of arrival measurements associated with the RF transmitter, a plurality of frequency of arrival measurements associated with the RF transmitter, and a plurality of angle of arrival measurements associated with the RF transmitter.

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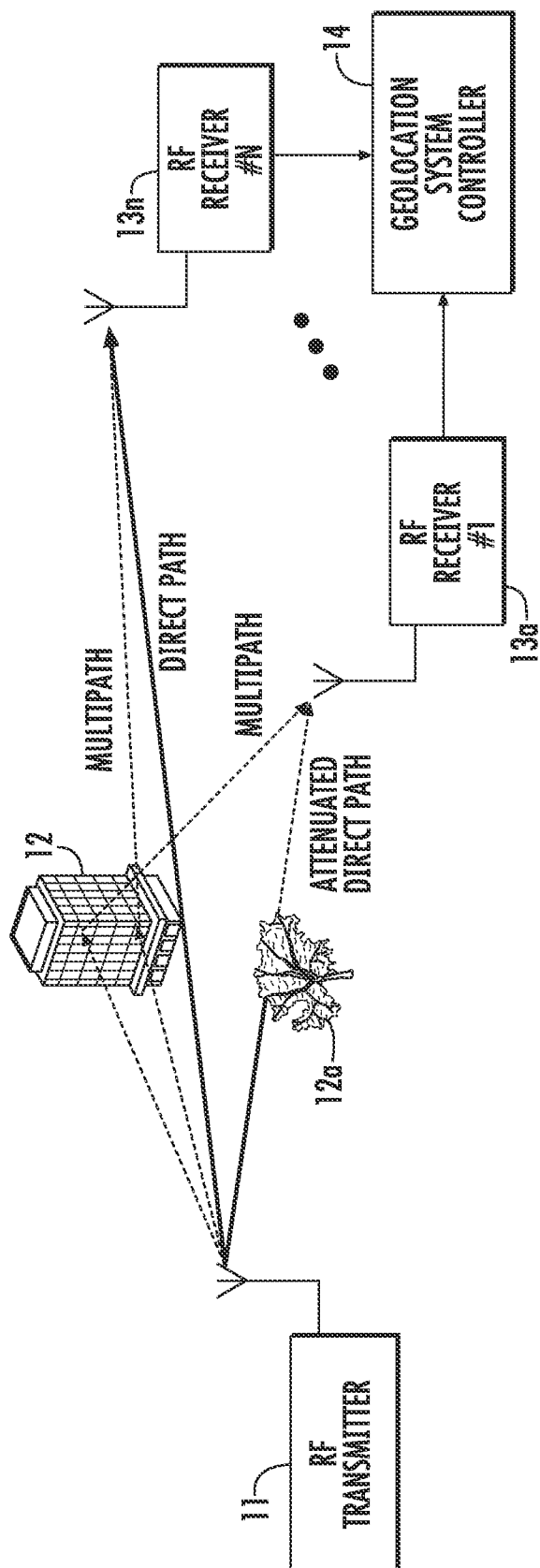


FIG. 7

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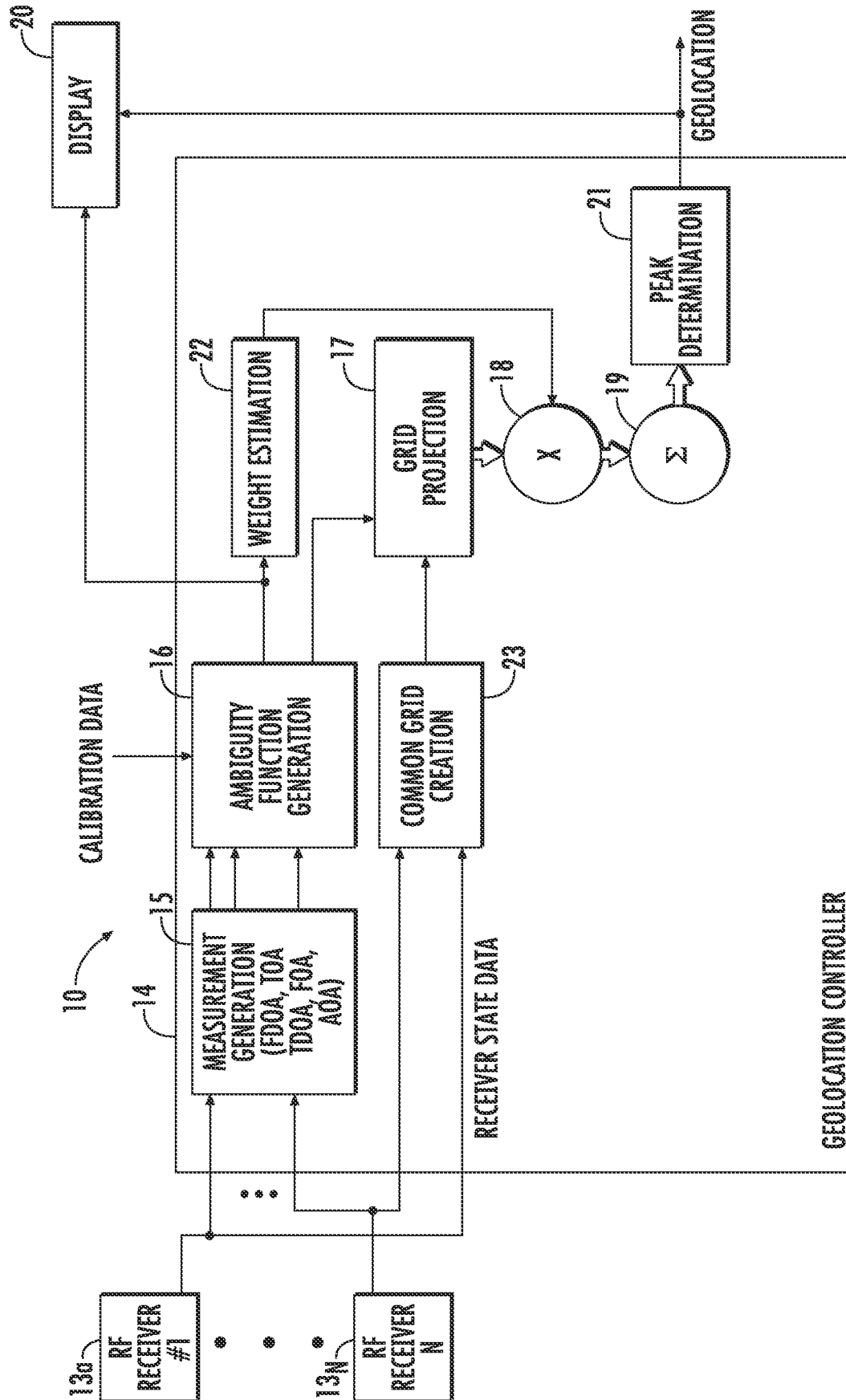
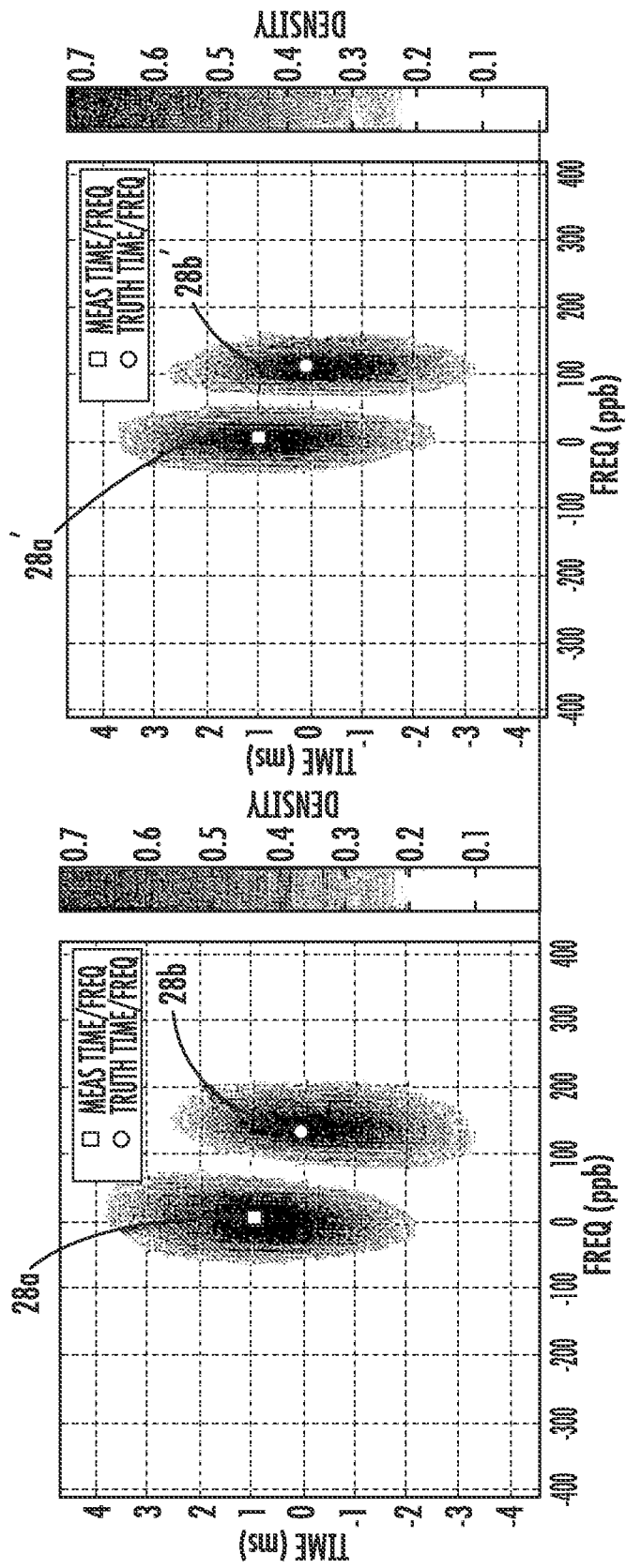
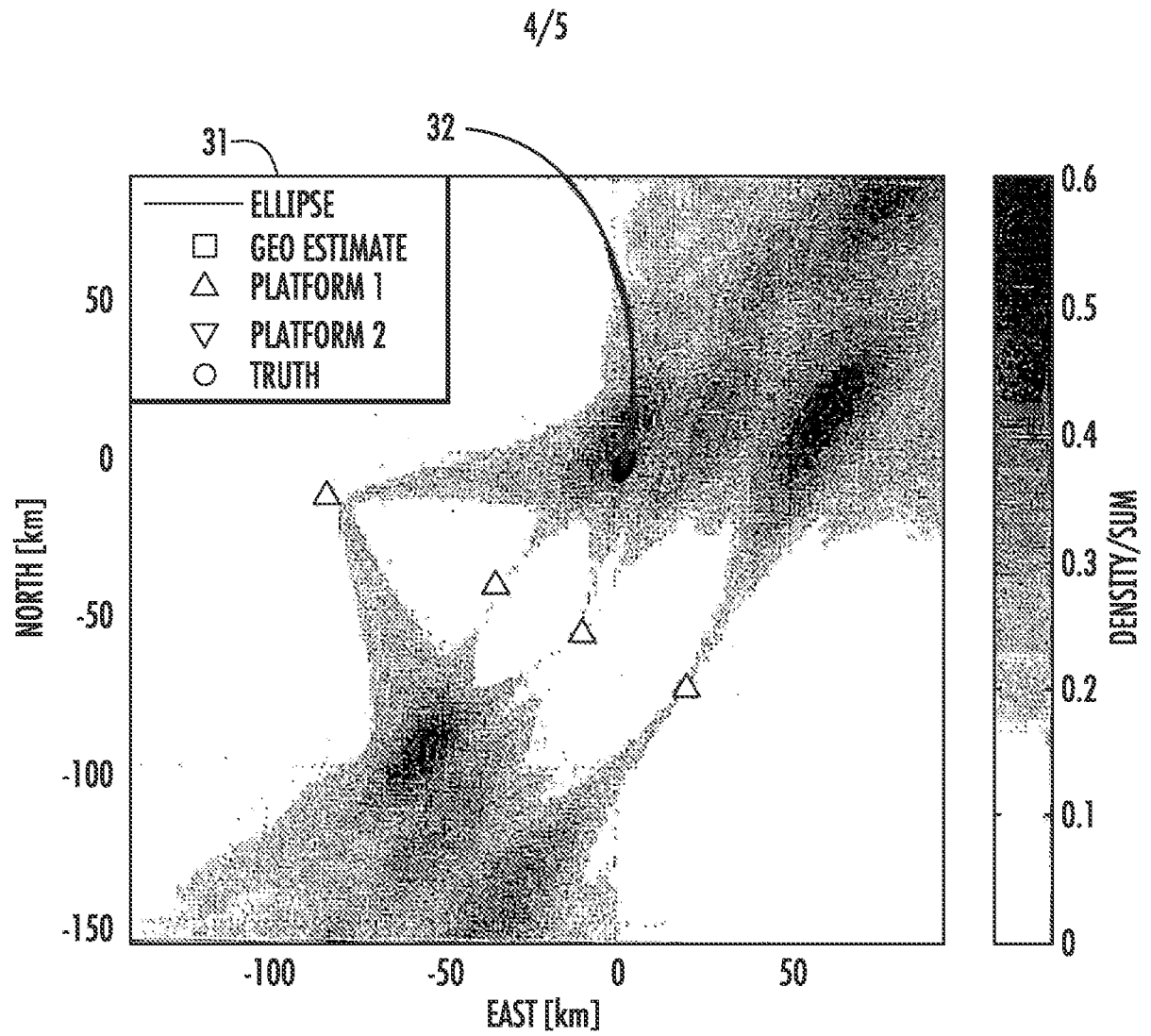


FIG. 2



**FIG. 4**

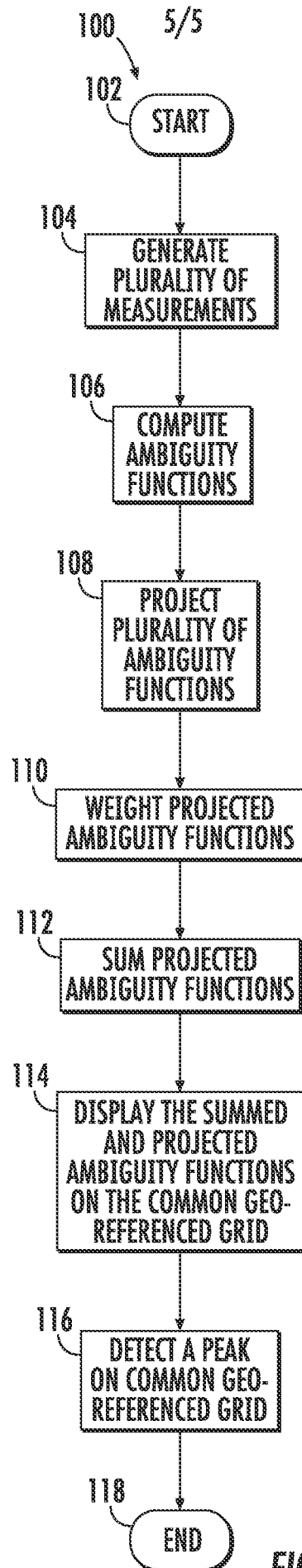


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/025377

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01S3/74
ADD.

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

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2008/186235 A1 (STRUCKMAN KEITH A [US] ET AL) 7 August 2008 (2008-08-07) fig. 1-11 par. 1, 13-22, 24, 25, 40, 47-75 -----	1-10
X	GULDOGAN M B ET AL: "Comparison of the CAF-DF and SAGE algorithms in multipath channel parameter estimation" SENSOR ARRAY AND MULTICHANNEL SIGNAL PROCESSING WORKSHOP, 2008. SAM 2008. 5TH IEEE, IEEE, PISCATAWAY, NJ, USA LNKD-DOI:10.1109/SAM.2008.4606818, 21 July 2008 (2008-07-21), pages 33-36, XP031312280 ISBN: 978-1-4244-2240-1 "introduction", "signal and channel model" and "CAF-DF algorithm" sections ----- -/--	1,8

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

☒ See patent family annex.

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Date of the actual completion of the international search

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González Moreno, J

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/025377

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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