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METHOD FOR LOCATING A MOBILE OBJECT BASED ON BISTATIC DISTANCE AND SPEED MEASUREMENTS OF SAID OBJECT USING A MULTISTATIC SYSTEM

5 The present invention pertains to a method for locating a mobile object based on bistatic distance and speed measurements of said object, using a multistatic system.

 The technique for locating a mobile object with the aid of multistatic systems conventionally calls upon the joint utilization of bistatic elementary measurements of
10 the distance between each of the transmitters and this object and between this object and respectively each of the receivers. This utilization consists in searching for the intersection of the ambiguity loci corresponding to each elementary measurement, in this instance hyperbolas or ellipses, depending on the time reference used, to locate the position of this object in a unique manner in space.

15 Such a technique is used for example in systems for locating the secondary transponders of aircraft and used in air traffic control.

 This known technique exhibits the following limitations:

- the quasi plane geometry of the layout of the receivers (if they are ground receivers) only allows location in a horizontal plane, without providing the
20 altitude of the object,
- if the signals received from various targets present simultaneously in one and the same space do not have a disjoint temporal support, association of the elementary measurements arising from one and the same target becomes almost impossible, since the combinatorial of possible cases becomes much too big for
25 practical utilization.

 The subject of the present invention is a method of locating a mobile object, in particular a flying object, on the basis of bistatic distance and speed measurements of this object using a multistatic system. The term "location" is understood according to the present invention to mean the 3D position of this object and the determination
30 of its true speed vector in 3D coordinates also. This method must make it possible to locate this object as accurately as possible in space, that is to say by measuring its



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coordinates in a three-dimensional reference frame, even when this object is situated in an environment that may comprise many other mobile objects.

The method in accordance with the invention is a method of locating a mobile object on the basis of bistatic distance and speed measurements of this object using a multistatic system, and it is characterized in that at least two bistatic distance pairs are associated such that for each pair the ellipsoids which determine them have a common focus, that for each pair the intersection of these two ellipses is solved at various altitudes, that the various intersections are optimized with respect to the altitude variable z , that, having found the best value of z , the three-dimensional Cartesian coordinates of this object are calculated, and that, having ascertained the coordinates of the object and at least three bistatic speeds, the direction and the modulus of the true 3D speed vector of the mobile object are deduced.

According to an advantageous characteristic of the invention, the position of the mobile object at the next step of the calculation, and therefore its predicted altitude z , is predicted, and the optimization of the calculation of z about the predicted z is refined by keeping in all said bistatic distance pairs only the n smallest ones, with $n=3$ preferably.

The present invention will be better understood on reading the detailed description of an embodiment, taken by way of nonlimiting example and illustrated by the appended drawing, in which:

- Figure 1 is a simplified diagram of three ellipses resulting from a section through a horizontal plane of the ellipsoids relating to the bistatic distances of a mobile object, such as are used by the method of the invention, and
- Figure 2 is a simplified diagram making explicit the way to determine the direction and the modulus of a flying object on the basis of the knowledge of the ellipsoids of Figure 1.

The present invention is described below with reference to the location in space of an aircraft (here called: airplane), but it is of course understood that it is not limited to this application alone, and that it can be implemented for the location of any mobile object, in particular a flying object, but not exclusively. This location is

implemented using a multistatic system with several transmitters and receivers. The invention consists in jointly utilizing the measurements of bistatic distances and bistatic Doppler speeds of the airplanes to be located, these measurements being performed on a set of several (at least three) "transmitter-receiver" pairs. These pairs
 5 are determined in the following manner.

Represented in Figure 1 is the intersection of a horizontal plane (which here is the plane of the drawing) and of three particular ellipsoids (E1, E2, E3) relating to one and the same airplane to be located, in a multistatic system (not represented in detail in the figure). The plots, in the plane of the drawing, of the ellipsoids, are three
 10 ellipses el1, el2 and el3. These ellipsoids are such that their focuses are, in a manner known per se, the transmitters and the receivers of the bistatic locating system. A system of three equations (defined by the respective equations of the ellipsoids) with three unknowns is thus obtained, which, theoretically, has a solution making it possible to calculate the 3D position of the airplane in question, but no direct
 15 procedure exists for solving it (in fact it involves solving an 8th-degree equation).

According to the invention, the ellipsoids are such that, taken pairwise, they have a common focus. In the example of Figure 1, three such pairs of ellipsoids (E1, E2 and E3) have been taken, but it would be possible to take more. In this example, the multistatic system comprises two transmitters Em1 and Em2 and two receivers
 20 R1 and R2. The ellipsoids E1 and E2 have R1 as common focus, while E1 and E3 have Em1 as common focus. By virtue of this characteristic of the invention, this system of equations can be solved more easily than with said direct procedure. Furthermore, the knowledge of the bistatic speed vectors for each of the three bistatic systems makes it possible to calculate the 3D speed vector of the airplane.

25 For the implementation of the invention, one begins by searching for the intersections of the aforesaid ellipsoid pairs, with common focus for each of these pairs, in a horizontal plane. The following is then carried out:

- the 3D Cartesian coordinates of the airplane to be located are called
 (x, y, z), those of the transmitter Em1 are called (x_{e1} , y_{e1} , z_{e1}) and
 30 those of the receiver R1 are called (x_{r1} , y_{r1} , z_{r1}).

Let:

- d_a be the distance between Em1 and the airplane + the distance between the airplane and R1,
- d_b be the distance between R1 and the airplane + the distance between the airplane and Em2,
- 5 - d_c be the distance between Em1 and the airplane + the distance between the airplane and R2.

The equation of the aforesaid three ellipsoids, respectively E1, E2 and E3, is obtained in a conventional manner:

$$\begin{cases} d_a = \sqrt{(x - x_{e1})^2 + (y - y_{e1})^2 + (z - z_{e1})^2} + \sqrt{(x - x_{r1})^2 + (y - y_{r1})^2 + (z - z_{r1})^2} \\ d_b = \sqrt{(x - x_{r1})^2 + (y - y_{r1})^2 + (z - z_{r1})^2} + \sqrt{(x - x_{e2})^2 + (y - y_{e2})^2 + (z - z_{e2})^2} \\ d_c = \sqrt{(x - x_{e1})^2 + (y - y_{e1})^2 + (z - z_{e1})^2} + \sqrt{(x - x_{r2})^2 + (y - y_{r2})^2 + (z - z_{r2})^2} \end{cases}$$

10 In a so-called initialization phase, that is to say for the first actual measurement of the bistatic distances of the airplane, and for a given altitude z of this airplane, the coordinates of the points of intersection of the ellipsoid pairs are obtained in the following manner, for three horizontal planes cutting these ellipsoids and having the respective altitudes z_1, z_2, z_3 . The present example confines itself to
15 three values of z , which are sufficient for the accuracy sought in the initialization phase. Preferably, in this initialization phase, these three values of z are taken to be very different from one another, for example 0, 500 m and 1000 m in altitude. The following values of these intersection points are then obtained, for the various aforesaid ellipsoid pairs:

20	$E1 \cap E2$	$E1 \cap E3$	$E2 \cap E3$
$z=z_1$	(x_1, y_1)	(x'_1, y'_1)	(x''_1, y''_1)
$z=z_2$	(x_2, y_2)	(x'_2, y'_2)	(x''_2, y''_2)
$z=z_3$	(x_3, y_3)	(x'_3, y'_3)	(x''_3, y''_3)

25 Each coordinate (x_i, y_i) , (x'_i, y'_i) , (x''_i, y''_i) is therefore dependent on z and it is possible to represent all these coordinates by a second-degree polynomial (3 values available per coordinate):

$$\begin{array}{lll}
x=a_x z^2+b_x z+c_x & x'=a'_x z^2+b'_x z+c'_x & x''=a''_x z^2+b''_x z+c''_x \\
y=a_y z^2+b_y z+c_y & y'=a'_y z^2+b'_y z+c'_y & y''=a''_y z^2+b''_y z+c''_y
\end{array}$$

The equations for the various distances D_i , as a function of z , between the intersection points $M(x, y)$, $M'(x', y')$ and $M''(x'', y'')$ are thereafter calculated, then the equations for the various distances $D_i(z)$ are differentiated in z , and they are solved to obtain the minima of these distances $D_i(z)$. These minima correspond to minimum distances between the points M , M' and M'' taken pairwise. According to an advantageous characteristic of the invention, the smallest among these minimum distances is retained. Let z_{airplane} be this smallest distance; it corresponds to a pair of points, for example $M(x, y)$ and $M'(x', y')$, which result from the calculation of the second-degree polynomials mentioned above, in which one takes $z = z_{\text{airplane}}$. The 3D position of the airplane is deduced therefrom:

- along the x axis, it is the barycentre of the two calculated values of x , for example $(x+x')/2$,
- along the y axis, it is the barycentre of the two calculated values of y , for example $(y+y')/2$,
- along the z axis, it is of course z_{airplane} .

Finally, the true 3D speed vector of the airplane is calculated on the basis of the knowledge of the 3D position and of the modulus of the bistatic speed of the airplane in at least three of the aforesaid bistatic systems. This calculation is illustrated by the diagram of Figure 2. In this diagram, which, for reasons of clarity of the drawing, represents only two of the three bistatic systems chosen in a plane cutting two ellipsoids, and which is the plane of the drawing. In this plane, the ellipses $el1$ and $el2$ relating to the transmitters and receivers $Em1$, $Em2$, $R1$, $R2$ have been plotted, the airplane to be located being situated at one of the two intersections of these ellipses whose common focus is $R1$. In a manner known per se, the values of the moduli $v1$ and $v2$ of the bistatic Doppler speeds of the airplane are calculated for the ellipses $el1$ and $el2$, and the corresponding segments are charted on the diagram in such a way that the segment $v1$ is the bisector of the angle formed by the segments (airplane- $Em1$), (airplane- $R1$) and $v2$ the bisector of the angle formed by the

segments (airplane-R1), (airplane-Em2). The straight line D1 (which is the plot, visible only in the plane of the drawing, of the plane PL1 perpendicular to the segment v1 and passing through the end of the latter) is plotted thereafter, followed by the straight line D2 (which is the plot, visible only in the plane of the drawing, of the plane PL2 perpendicular to the segment v2 and passing through the end of the latter). The straight lines D1 and D2 cut one another at a point P. These two planes PL1 and PL2, which pass respectively through D1 and D2, are the geometric loci of the potential positions of the end of the true speed vector of the airplane (and with this airplane as origin) and cut one another along a straight line $D_{1,2}$ passing through the point P and perpendicular to the plane of the drawing. The same is done for another pair of bistatic speeds (for example v2 and a third speed v3), and a first plane PL2 passing through D2 and another plane PL3 (which is not in the plane of the drawing) are obtained. These two planes PL2 and PL3 cut one another along another straight line $D_{2,3}$ (not visible in the drawing) which, itself, cuts $D_{1,2}$ at a point P1 (not visible in the drawing). The end of the true speed vector is thus this point P1.

After this initialization phase, when the airplane has been located and its speed vector determined, the airplane tracking process is maintained so as to be able to determine the position and the speed of the airplane as accurately and as easily as possible at each instant.

In practice, a multistatic system generally comprises a large number of transmitters and receivers, and the higher this number, the more intrinsic bistatic systems there are, and therefore yet higher is the number of bistatic distances calculated. This results in a yet more rapidly increasing complexity of the locating method of the invention. To solve this problem, another characteristic of the invention makes it possible to simplify the maintenance calculation method by virtue of the prediction of the position of the airplane. This prediction is done in the following manner. On the basis of the knowledge of the 3D position of the airplane and of its speed vector at the instant t, the position of the airplane is calculated at the instant $t+\Delta t$ (the value of Δt depending in particular on the speed and trajectory of the airplane and the accuracy of the measurements, so as not to take Δt too high to avoid too approximate a prediction, or too small so as not to do unnecessary intermediate

calculations). The altitude of the airplane is thus calculated, as set forth above, at the instant $t+\Delta t$, namely $z_{\text{predicted}}$. Knowing $z_{\text{predicted}}$, all the previous calculations are redone (from the first step of calculating the points of intersection of ellipsoid pairs up to the calculation of the 3D speed vector), taking at the first step a bracket of values of z (z_1, z_2, z_3) that is much narrower than that mentioned above by example, and staying centered about $z_{\text{predicted}}$, for example $0.8 z_{\text{predicted}}$, $z_{\text{predicted}}$ and $1.2 z_{\text{predicted}}$. The calculations are simplified by taking preferably the three lowest (exhibiting the best signal/noise ratio) from among all the available bistatic distance values.

Among the possible applications of the invention may be cited its use, in a multistatic system for detecting and locating targets at low cost, intended for detecting in a surveillance zone, for example in the neighborhood of the approach zone of an airport, intruders with low radar cross section, or intended for protecting a sensitive site. The device making it possible to perform measurements of bistatic distance and of bistatic Doppler speed is based on the utilization of one or more receivers, associated, simultaneously or not, with:

- a set of cooperative transmitters (transmitting a deterministic and controlled waveform),
- a set of conventional frequency-modulation broadcasting transmitters,
- a set of broadcasting transmitters with OFDM waveforms (such as DAB or DVBT transmitters),
- a set of broadcasting transmitters whose transmitted signals comprise spectral lines with deterministic position, for example analog television transmitters.

In conclusion, the invention makes it possible, including in a situation in which multiple flying objects are to be detected, to obtain a practically instantaneous measurement of the position of the objects to be located in 3D (in coordinates in a horizontal plane and in altitude) and of their speed vector in modulus and in direction (in 3D). The accuracy obtained by virtue of the method of the invention is directly related to the accuracy with which the bistatic distances are measured. In the case of typical configurations of geometric distribution (that is to say configurations for

which the transmitters and receivers are disposed at the vertices of simple geometric figures, such as rectangles), an elementary bistatic distance accuracy of a few meters makes it possible to achieve accuracies of a few meters in a horizontal plane, and accuracies of the order of magnitude of about ten meters in altitude.

CLAIMS

1. A method for locating a mobile object on the basis of bistatic distance
5 and speed measurements of this object using a multistatic system,
characterized in that at least two bistatic distance pairs are associated
such that for each pair the ellipsoids which determine them have a
common focus, that for each pair the intersection of these two ellipses
is solved at various altitudes, that the various intersections are
10 optimized with respect to the altitude variable z , that having found
the best value of z , the three-dimensional Cartesian coordinates of
this object are calculated, that, having ascertained the coordinates of
the object and at least three bistatic speeds, the direction and the
modulus of the true 3D speed vector of the mobile object are
15 deduced.
2. The method as claimed in claim 1, characterized in that the position
of the mobile object at the next step of the calculation, and therefore
its predicted altitude z , is predicted, and that the optimization of the
calculation of z about the predicted z is refined by keeping in all said
20 bistatic distance pairs only the n smallest ones.
3. The method as claimed in claim 2, characterized in that n is taken
equal to 3.