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(56) Documents cited
GB 1539522 A GB 1248066 A
**THE MARCONI REVIEW XLVI No. 228, 1st Qtr 1983,
pp1-17, D E RiceHeight measurement by
quadrilateration**

(58) Field of search
UK CL (Edition K) **H4D DPAB DPAC DPX**
INT CL^5 **G01S**

(54) Object locating system

(57) The system comprises a transmitter located at the object and a plurality of receivers (SR1, SR2, SR3, SR4, MS) being precisely located with respect to each other, with one of the receivers (MS) acting as a master receiver. Each receiver comprises a clock synchronisation means which is synchronised by a signal sent from the master receiver, and detection and calculation means which receives a signal from the object's transmitter, determines the time when the signal is received, and sends the determined time to the master receiver (MS) which includes computational means arranged to determine the precise location of the object with respect to the plurality of receivers. The system is particularly relevant to the location of airborne vehicles such as aircraft.

The transmitter may be a secondary surveillance radar (SSR) transponder, and the synchronisation signal may be transmitted from the master in the form of a SSR code. Each receiver may comprise registers which store a SSR code and a time window in which the code is to be detected and the time of arrival of the leading edge of the code measured. The code and time window are set from the master receiver.

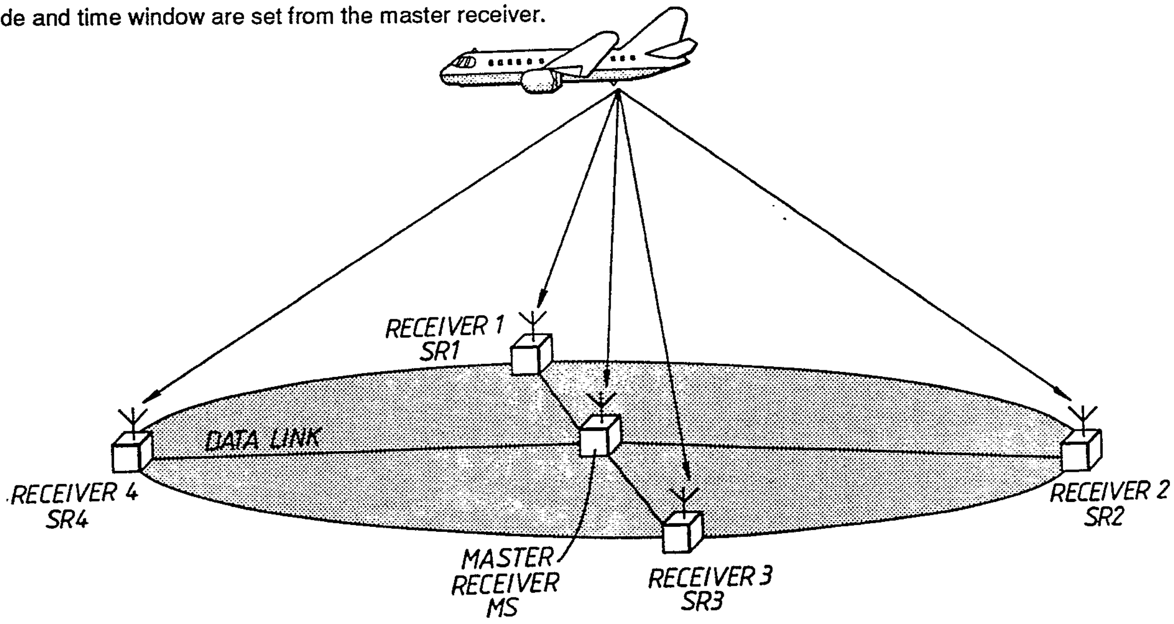

Fig.4.

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

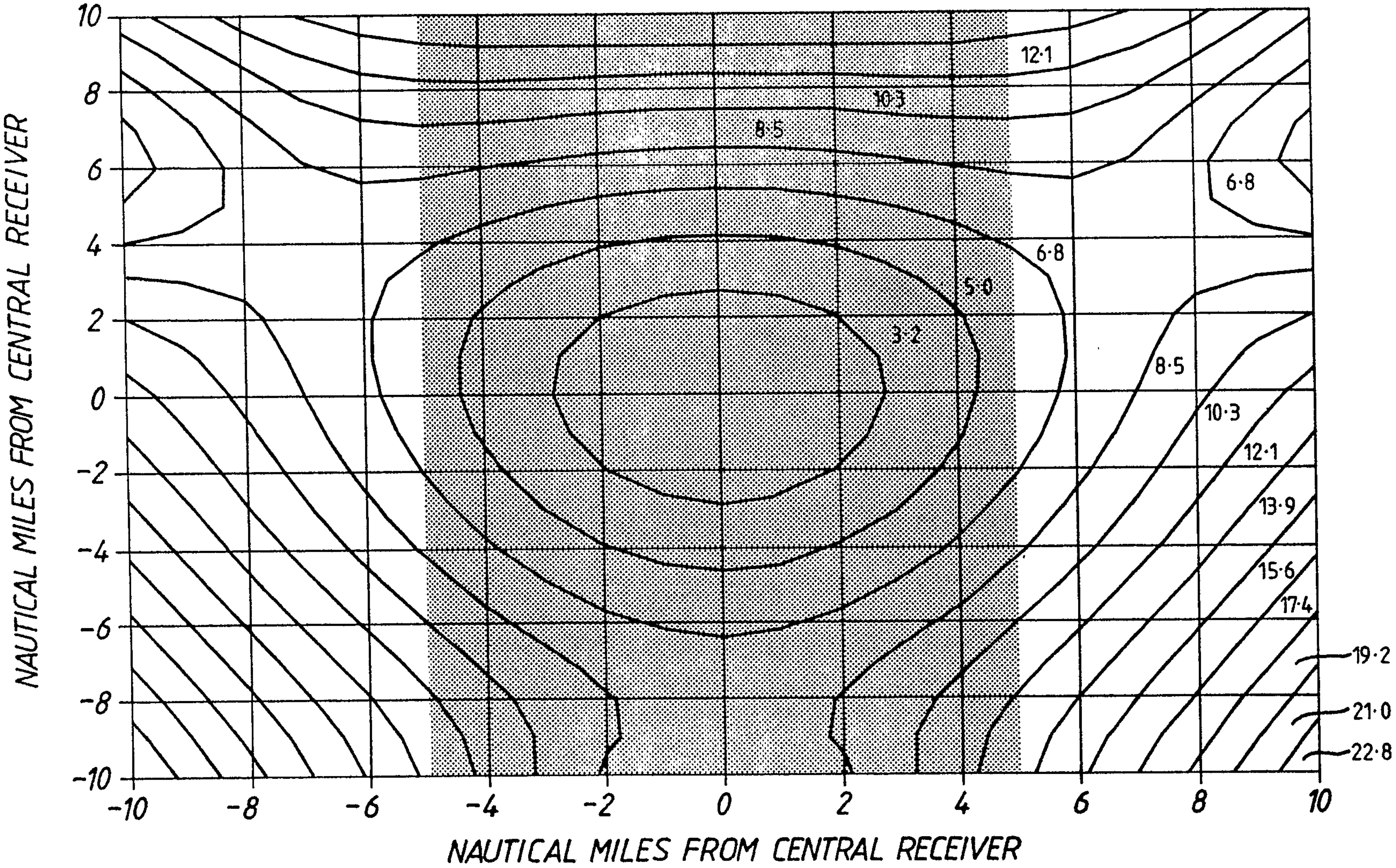
10
8
6
4
2
0
-2
-4
-6
-8
-10
NAUTICAL MILES FROM CENTRAL RECEIVER
-10
-8
-6
-4
-2
0
2
4
6
8
10
NAUTICAL MILES FROM CENTRAL RECEIVER
12·1
10·3
8·5
6·8
6·8
5·0
3·2
8·5
10·3
12·1
13·9
15·6
17·4
19·2
21·0
22·8

Fig. 1.

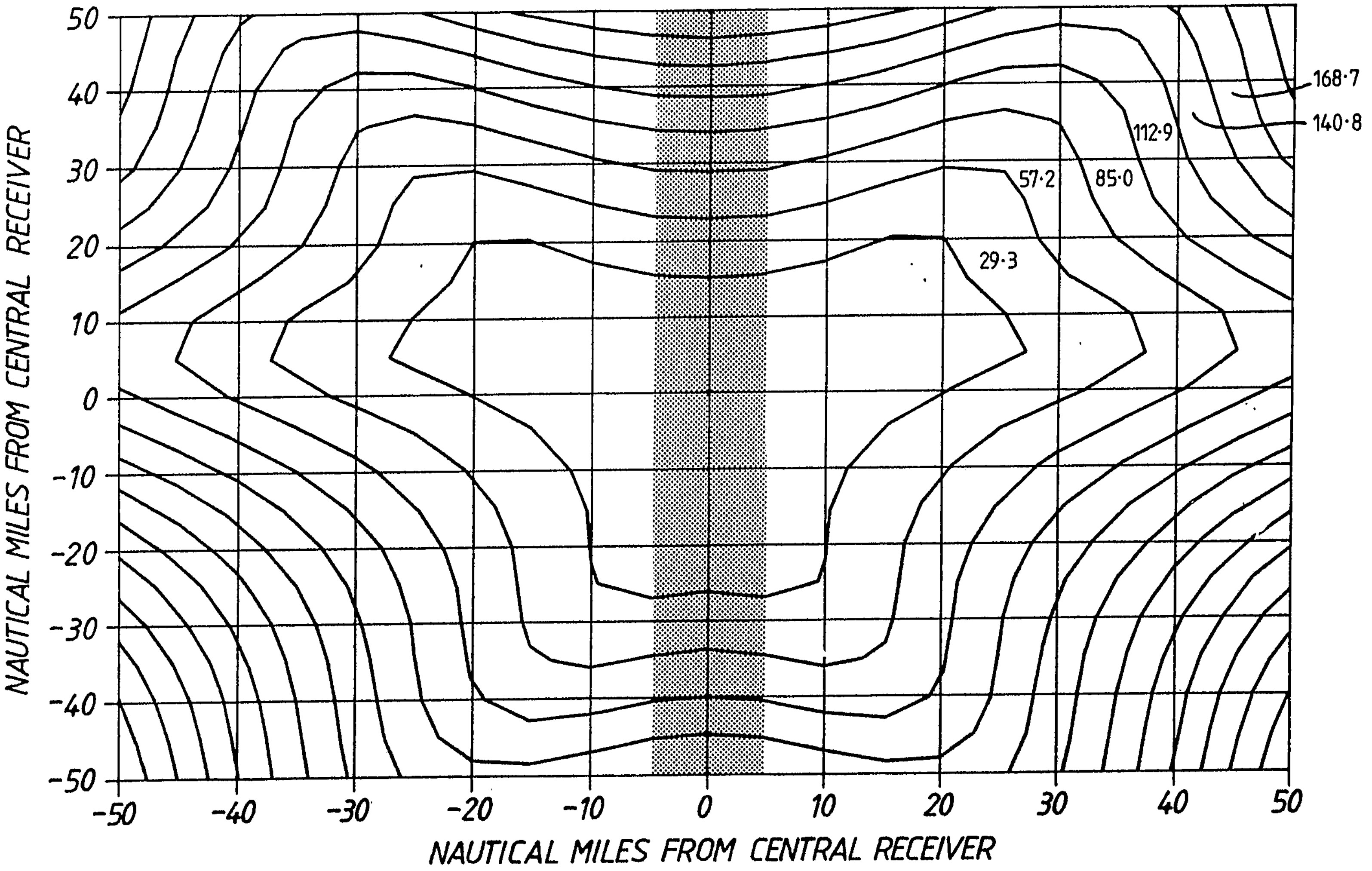
168·7
140·8
112·9
85·0
57·2
29·3
50
40
30
20
10
0
-10
-20
-30
-40
-50
NAUTICAL MILES FROM CENTRAL RECEIVER
-50
-40
-30
-20
-10
0
10
20
30
40
50
NAUTICAL MILES FROM CENTRAL RECEIVER

Fig. 2.

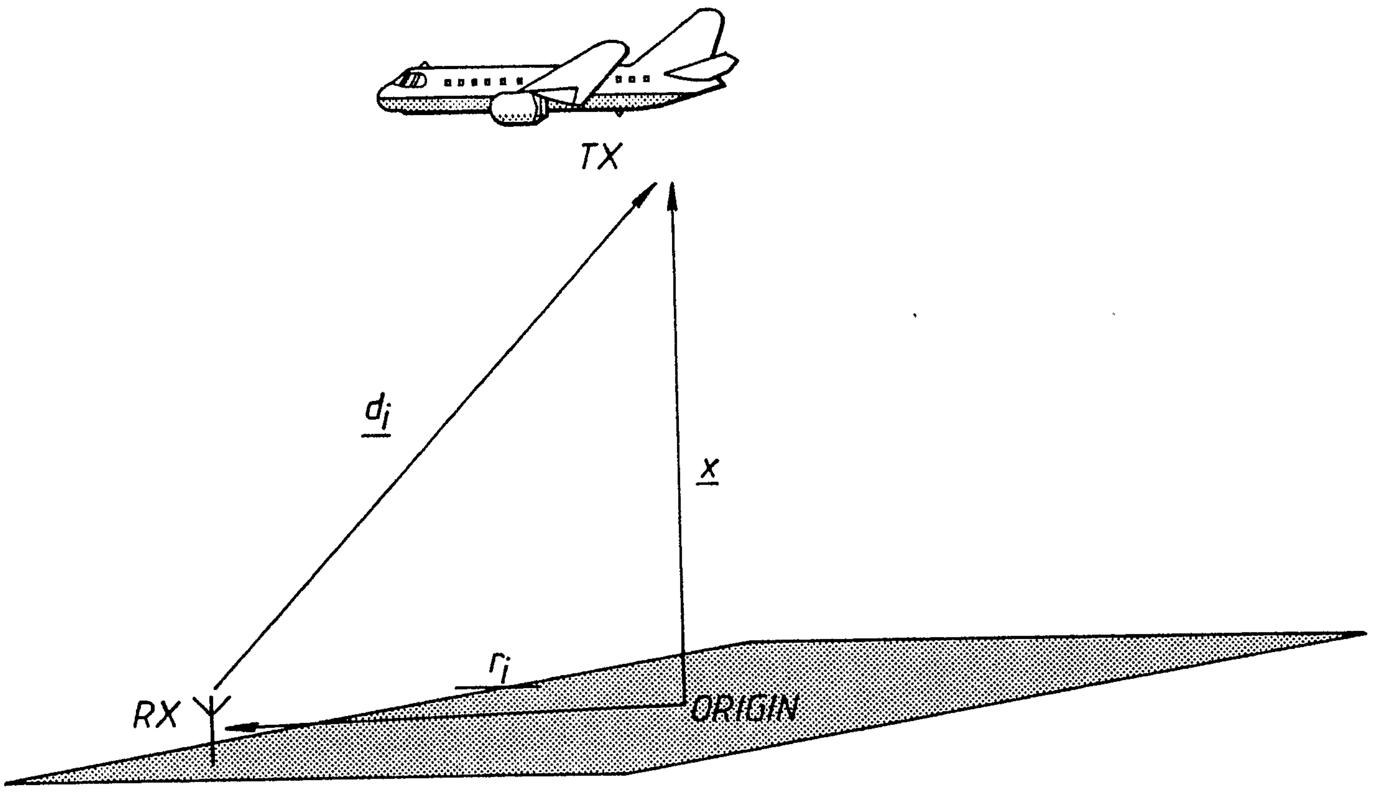

Fig. 3.

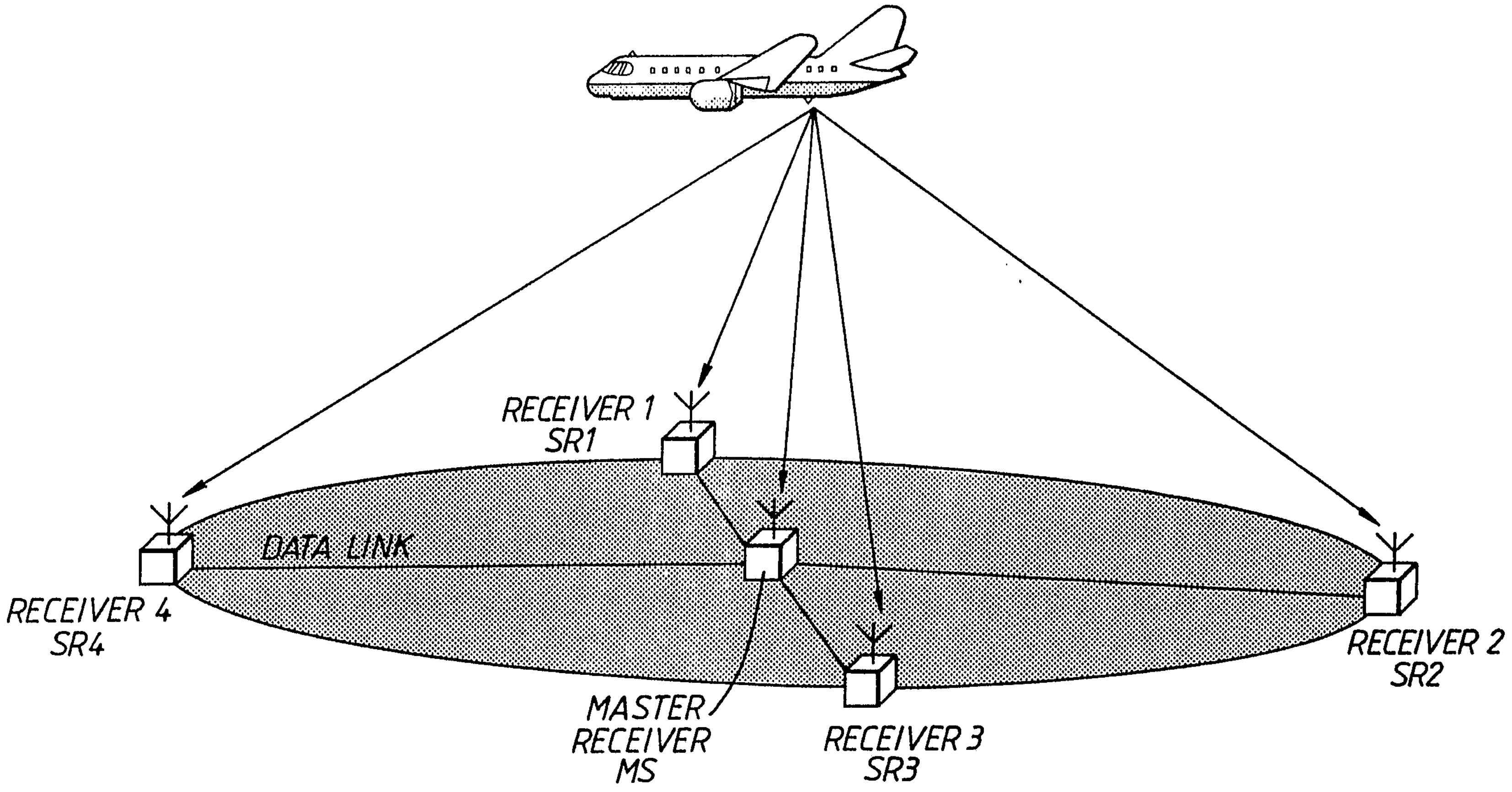
RECEIVER 1
SR1
DATA LINK
RECEIVER 4
SR4
MASTER
RECEIVER
MS
RECEIVER 3
SR3
RECEIVER 2
SR2

Fig. 4.

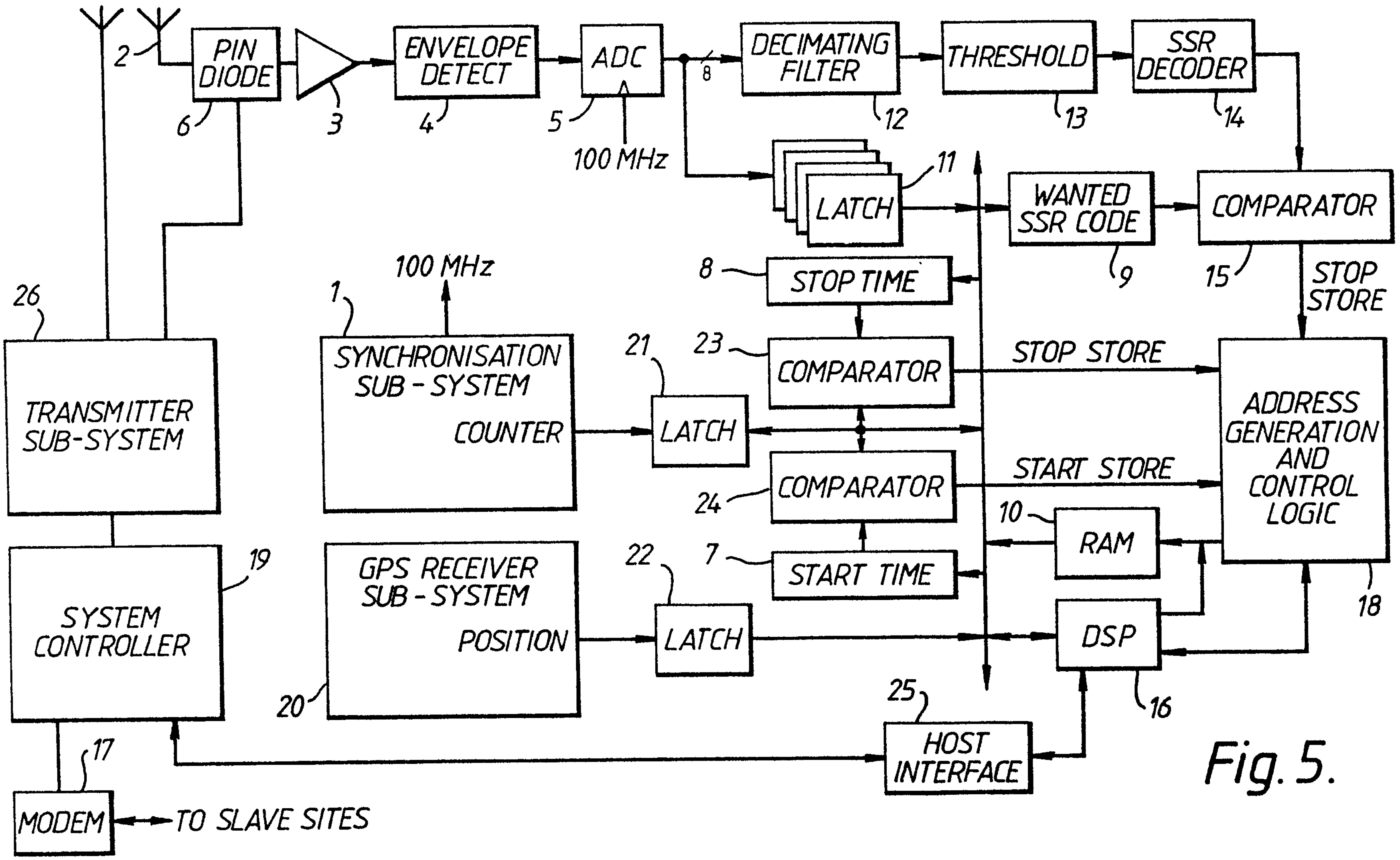
2
PIN DIODE
6
3
ENVELOPE DETECT
4
ADC
5
100 MHz
8
DECIMATING FILTER
12
THRESHOLD
13
SSR DECODER
14
LATCH
11
WANTED SSR CODE
9
COMPARATOR
15
STOP STORE
8
STOP TIME
23
COMPARATOR
STOP STORE
21
LATCH
24
COMPARATOR
START STORE
7
START TIME
22
LATCH
10
RAM
DSP
16
ADDRESS GENERATION AND CONTROL LOGIC
18
26
TRANSMITTER SUB-SYSTEM
1
100 MHz
SYNCHRONISATION SUB - SYSTEM
COUNTER
GPS RECEIVER SUB - SYSTEM
POSITION
20
SYSTEM CONTROLLER
19
17
MODEM
TO SLAVE SITES
25
HOST INTERFACE

Fig. 5.

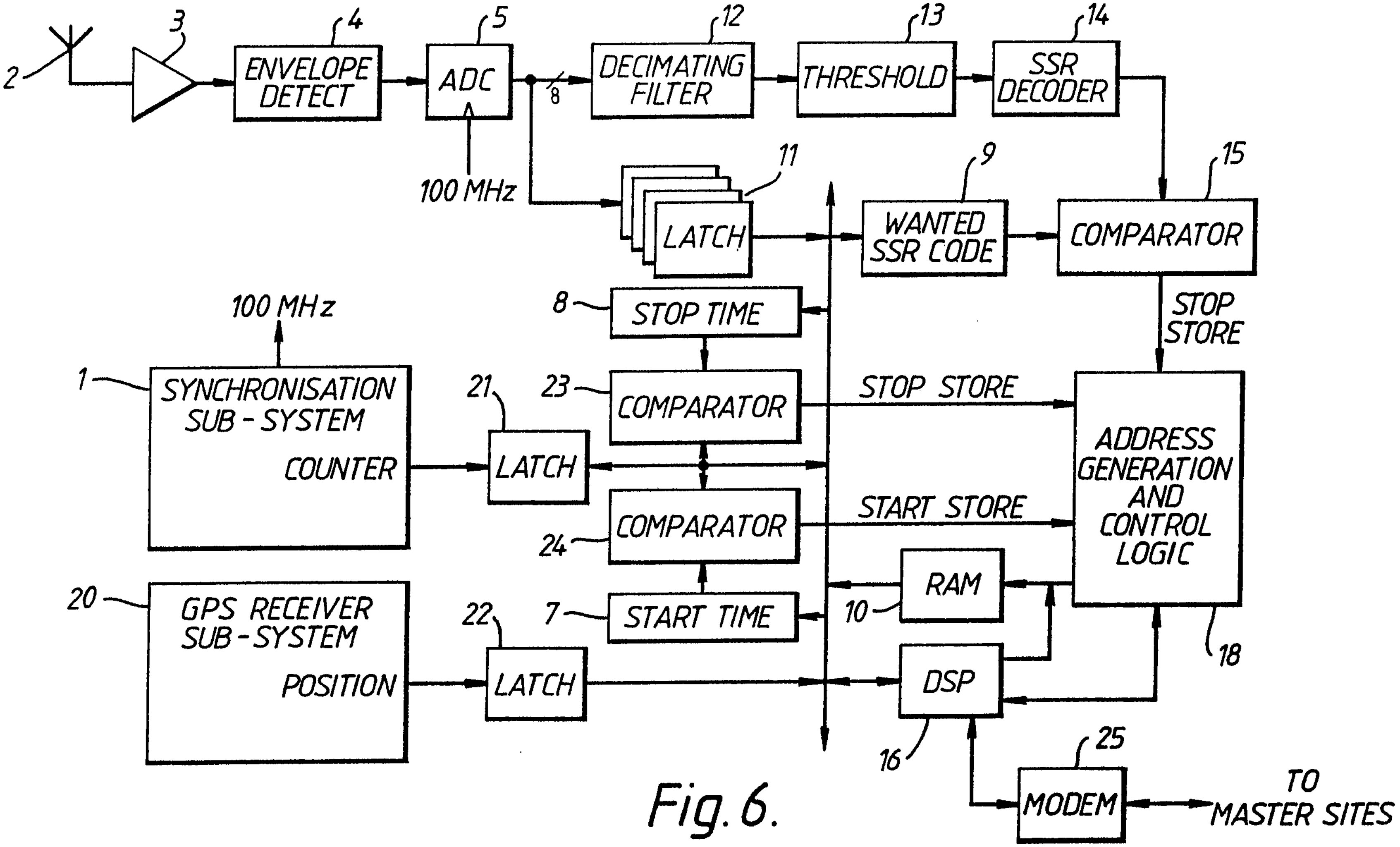
2
3
4
ENVELOPE DETECT
5
ADC
100 MHz
8
12
DECIMATING FILTER
13
THRESHOLD
14
SSR DECODER
11
LATCH
9
WANTED SSR CODE
15
COMPARATOR
STOP STORE
8
STOP TIME
100 MHz
1
SYNCHRONISATION SUB - SYSTEM
COUNTER
21
LATCH
23
COMPARATOR
STOP STORE
ADDRESS GENERATION AND CONTROL LOGIC
24
COMPARATOR
START STORE
RAM
10
20
GPS RECEIVER SUB - SYSTEM
POSITION
22
LATCH
7
START TIME
DSP
16
18
25
MODEM
TO MASTER SITES

Fig. 6.

APPARATUS AND METHOD FOR LOCATING AN OBJECT

The present invention relates to an apparatus and method for locating an object.

The present invention finds particular application in the location of airborne vehicles such as aircraft.

Conventional surveillance radars measure the range and azimuth of a target using a beam that is wide in elevation and narrow in azimuth. Height finding radar however uses a beam that is narrow in elevation but wide in azimuth. The beam is swept in elevation across the target to provide an estimate of target elevation, which in general precludes a simultaneous azimuth search. Such a radar therefore has to be pointed in azimuth at the aircraft using either secondary surveillance radar (SSR) data or a cooperating surveillance radar.

The typical parameters required of such a radar can be determined by considering a height finding radar situated below the centre of a ten nautical miles (10NM) wide airway corridor. For aircraft passing at high elevation it is the range resolution of the radar that determines the height resolution achievable, whilst at low elevation angles it is the elevation resolution that limits the height resolution. At high aircraft elevation the required range resolution of twentyfive feet corresponds to a fifty nanosecond received pulse. Such accuracies are not difficult to achieve for point targets, particularly if X-band frequencies are used, however considering the size of likely targets (perhaps 200 feet in length) fine range detail of the target will be resolved. This would require the range-elevation centroid to be calculated in order to determine the true centre of the aircraft. Since the accuracy of the measured centroid will be dependent on the aspect of the aircraft this is likely to compromise the accuracy with which the aircraft height can be determined. For an aircraft at a low elevation at the edge of the corridor a height resolution of twentyfive feet corresponds to an elevation resolution of 0.06° measured from the radar.

The height finding radar technique does have the advantage that only a single radar site is involved, however, in order to meet the stringent performance requirements any solution is likely to be highly expensive and subject to unquantifiable uncertainties in the height estimation.

By using multistatic radar and triangulation as applied to the ranges from three separate radars to an aircraft, the need for any direct measurement of the aircraft elevation is avoided. It can be shown that for targets at the bottom of the airway corridor (5000 feet) the range measurement from each radar would have to be accurate to approximately five feet in order to triangulate the height to an accuracy of twentyfive feet. The radar range resolution and therefore the pulse length are governed by this worst case requirement and therefore a pulse compression radar would be required to each site. This would result in a costly overall solution.

One possible method for utilising the SSR transmission would be the use of a direction finding (DF) receiver to estimate the azimuth and elevation from which the SSR reply from the aircraft arrives. DF receivers work by comparing either the phase angle or the relative amplitude of the received signal at two antennas separated by a distance of the order of the wavelength.

A phase comparison monopulse method employs the phase difference of a signal received by two antennas separated by a distance similar to the wavelength. There are conflicting requirements for accuracy; a given Off Boresight Azimuth (OBA) will give a bigger phase difference between the antennas when they are further apart. However, when the antenna spacing is increased the measured phase angle and hence the OBA becomes ambiguous.

An alternative, is an amplitude comparison monopulse method which employs either a staring multibeam receiver or a two-beam receiver scanned in elevation. The amplitude of a signal received from the aircraft is compared in adjacent beams in order to interpolate the elevation. Again, such a system may be active or passive by using the SSR replies.

An alternative technique for height finding that utilises the SSR transmission from the aircraft is that of measuring the difference in time of arrival of the SSR code at spatially separated receivers. This technique offers the advantages of the multistatic radar technique in that time-of-arrival is measured rather than angle but it does not suffer the disadvantages of target centroid location. The technique is also significantly less expensive to implement provided some of the technical problems of accurate time measurement can be overcome.

Accordingly, it is an object of the present invention to provide a cost effective and reliable method and apparatus for determining the location of, for example, an aircraft.

According to the present invention there is provided an object location system comprising a transmitting means located at the object and a plurality of receiving means being precisely located with respect to each other, with one of said receiving means being arranged to act as a master receiving means, each receiving means comprising a clock synchronisation means arranged to be synchronised by a signal sent from the master receiving means, and detection and calculation means arranged to receive a signal from the object's transmitting means and determine the time taken to receive said signal from the object, and means for sending the data appertaining to the determination to the master receiving means which includes computational means arranged to determine the precise location of the object with respect of the plurality of receiving means based upon the data received from the plurality of receiving means.

An embodiment of the present invention will now be described with reference to the accompanying drawings in which:-

Figure 1 shows weight vector magnitude contours at an altitude of 10,000 feet, (±10NM by ±10NM),

Figure 2 shows weight vector magnitude contours at 10,000 feet, (±50NM by ±50NM),

Figure 3 shows length definitions in respect of the relationship of an origin, receiver and aircraft,

Figure 4 shows a concept of an altitude monitor system,

Figure 5 shows a block schematic diagram of a master receiver site, and,

Figure 6 shows a block schematic diagram of a slave receiver site.

The mathematical approach about to be described is based on a 'least squares' solution to the aircraft position determined from independent measurements of the time of arrival of the SSR response at an arbitrary number of receiver sites. It is shown that the system can be described by n linear simultaneous equations for the n receiver sites and that these equations can be solved by the 'least squares' technique ($n \geq 4$) to provide target position in three dimensions.

Using the 'least squares' technique, the error in the measured position can also be determined for any arbitrary receiver configuration as a function of transponder location, and the accuracy with which the time of arrival of the SSR code can be determined.

The relationship between measurement error and positional error of the aircraft is expressed as a 'weight vector' which for a given receiver geometry varies with the position of the aircraft. Figures 1 and 2 illustrate the variation of the weight vector as a function of target position for a representative receiver geometry comprising four receivers and an aircraft at a height of 10,000 feet and at distances of ±10NM and ±50NM from the central receiver respectively. Multiplying the weight vector by the time of arrival accuracy, measured in nanoseconds, gives the height error measured in feet.

Also shown in Figures 1 and 2 is a typical 10NM wide flight lane. For an aircraft on the edge of the flight lane and at its point of closest approach to the central receiver, (that is, at position {5,0} or

{0,5}) the weight vector has a value of 5.8, resulting in a required timing accuracy of 4.3 nanoseconds if an accuracy of twentyfive feet is required in the aircraft height estimation.

The accuracy with which the time of arrival can be determined at each receiver site is a function of the accuracy to which clocks running at each site can be synchronised together with the accuracy to which the time of arrival of the SSR code can be determined.

The height error analysis can be applied to an arbitrary configuration and an arbitrary number of receivers ($n \geq 4$). However it is also possible to determine, for an aircraft constrained to within a specified flight land and range of heights, an optimum receiver geometry.

The optimum receiver geometry is that geometry which has the smallest magnitude of weight vector ($\underline{w}$) for the range of transmitter positions of interest. The region of interest is taken as a cylinder of radius 10NM located directly above the origin from a height of 1NM to 13NM.

MATHEMATICAL THEORY FOR DETERMINATION OF THE TIME OF ARRIVAL, DTOA

Figure 1 illustrates the position of the aircraft relative to the ith receiver site. Using vector notation we see that

$$\underline{X} = \underline{r}_i + \underline{d}_i \qquad (1)$$

where

$\underline{X}$ = position vector of the aircraft (transmitter)

$\underline{r}_i$ = position vector of the ith receiver

$\underline{d}_i$ = vector from the ith receiver to the aircraft

If the length of the vector $\underline{d}_i$ is l_i then

$$\underline{d}_i = l_i \underline{e}_i \tag{2}$$

where $\underline{e}_i$ is the unit vector between the ith receiver and the aircraft.

Thus we may rewrite equation (1) as

$$\underline{x} = \underline{r}_i + l_i \underline{e}_i \tag{3}$$

Taking the scalar product of both sides of equation (3) with the unit vector $\underline{e}_i$ gives

$$\underline{e}_i \cdot \underline{x} = \underline{e}_i \cdot \underline{r}_i + l_i \tag{4}$$

Assuming the use of four receivers and receiver number one is arbitrarily chosen as the reference receiver then

$$l_i = l_1 + \Delta_i \tag{5}$$

where

$$\Delta_i = 0 \tag{6}$$

Hence in the four receiver case

$$\Delta_1 = 0$$

$$\Delta_2 = l_2 - l_1$$

$$\Delta_3 = l_3 - l_1$$

$$\Delta_4 = l_4 - l_1$$

substituting equation (5) in equation (4) gives

$$\underline{e}_i \cdot \underline{x} - l_1 = \underline{e}_i \cdot \underline{r}_i + \Delta_i \tag{7}$$

Hence in the general case of an 'n' receiver system (n>=4) then the system is completely described by 'n' equations of the form given in equation (7).

Each equation of the form given in equation (7) contains four unknowns, namely the x, y, z co-ordinates of the transmitter and the distance l_1 from the reference receiver to the transmitter. As stated above, an exact solution may therefore be found using only four equations.

If the measurement errors may be ignored then an exact solution derived from any four arbitrarily chosen receivers will simultaneously satisfy all 'n' equations and will accurately reflect the position of the aircraft. In general due to measurement errors an exact solution derived from any four receivers will not simultaneously satisfy the remaining (n-4) equations and a solution which "best fits" the 'n' equations must be sought.

A common technique applied to the solution of over determined systems is that of "least squares fit" where the optimal solution is the solution which minimises the sum of the squares of the errors in each equation, that is

$$\Sigma\ (\text{error})_i = \text{minimum} \qquad (i = 1 \text{ to } n) \tag{8}$$

where

$$(\text{error})_i = \{\underline{e}_i \cdot \underline{x} - l_1\} - \{\underline{e}_i \cdot \underline{r}_i + \Delta\, i\} \tag{9}$$

and where the summation is taken over all n equations.

The least squares solution is equivalent to centroiding all the possible exact solutions where each exact solution would be calculated by choosing four particular receivers from the 'n'.

Derivation of the least squares solution

The 'n' equations of the form given in equation (7) may be represented by a single equation using matrix notation namely:

$$\underline{e}\,\underline{x} - \underline{l}_1 = \underline{\varepsilon}\ \underline{r} + \underline{\Delta} \qquad (10)$$

where

$$\underline{e} = \begin{array}{l} [\underline{e}_1{}^t] \\ [\underline{e}_2{}^t] \\ [\underline{e}_3{}^t] \\ [\underline{e}_4{}^t] \\ [\underline{e}_2{}^t] \\ [\ldots\ldots] \\ [\underline{e}_n{}^t] \end{array} \qquad \underline{l}_1 = \begin{array}{l} [l_1] \\ [l_1] \\ [l_1] \\ [l_1] \\ [l_1] \\ [\ldots.] \\ [l_1] \end{array}$$

where $\underline{e}_i{}^t$ is a three element row vector made up of the direction cosines of $\underline{e}_i$, for example,

$$\underline{e}_i{}^t = [e_{ix}, e_{iy}, e_{iz}]$$

and where

$$\underline{\Delta} = \begin{array}{l} [\Delta_1] \\ [\Delta_2] \\ [\Delta_3] \\ [\Delta_4] \\ [\ldots..] \end{array}$$

$$[\Delta_n]$$

$$\begin{matrix} \underline{\varepsilon} = & [\underline{e}_1{}^t, \underline{O}, \underline{O}, \underline{O}, \ldots\ldots\ \underline{O}] \\ & [\underline{O}, \underline{e}_2{}^t, \underline{O}, \underline{O}, \ldots\ldots\ \underline{O}] \\ & [\underline{O}, \underline{O}, \underline{e}_3{}^t, \underline{O}, \ldots\ldots\ \underline{O}] \\ & [\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots] \\ & [\underline{O}, \underline{O}, \underline{O}, \underline{O}, \ldots\ldots\ldots\ \underline{O}] \end{matrix}$$

where

$$\underline{O} = [o,o,o]$$

$$\begin{matrix} \underline{r} = & [\underline{r}_1, \underline{0}, \underline{0}, \underline{0}, \ \ldots\ldots\ldots\ldots] \\ & [\underline{0}, \underline{r}_2, \underline{0}, \underline{0}, \ \ldots\ldots\ldots\ldots] \\ & [\underline{0}, \underline{0}, \underline{r}_3, \underline{0}, \ \ldots\ldots\ldots\ldots] \\ & [\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots] \\ & [\underline{0}, \underline{0}, \underline{0}, \underline{0}, \ \ldots\ldots\ldots\ \underline{r}_n] \end{matrix}$$

where

$$\begin{matrix} \underline{0} = & [o] \\ & [o] \\ & [o] \end{matrix}$$

and where r_i is a three element column vector made up of the direction cosines of r_i, for example,

$$\begin{matrix} \underline{r}_i = & [r_{ix}] \\ & [r_{iy}] \\ & [r_{iz}] \end{matrix}$$

The equation may be further simplified by combining the terms on the left hand side into a single matrix product, that is

$$\underline{E}\,\underline{X}' = \underline{\varepsilon}\,\underline{r} + \underline{\Delta} \qquad (11)$$

where

$$\begin{array}{llcl}
\underline{E} = & [\underline{e}1t,\ -1] & = & [e1x,\ e1y,\ e1z,\ -1] \\
 & [\underline{e}2t,\ -1] & = & [e2x,\ e2y,\ e2z,\ -1] \\
 & [\underline{e}3t,\ -1] & = & [e3x,\ e3y,\ e3z,\ -1] \\
 & [\underline{e}4t,\ -1] & = & [e4x,\ e5y,\ e6z,\ -1] \\
 & [\ldots\ldots\ldots\ldots] & = & [\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots] \\
 & [\underline{e}nt,\ -1] & = & [enx,\ eny,\ enz,\ -1]
\end{array}$$

$$\begin{array}{ll}
\underline{X} = & [x] \\
 & [y] \\
 & [z] \\
 & [l_1]
\end{array}$$

where x, y, z is the transmitter position vector $\underline{X}$
Notice that the $\underline{E}$ matrix is made up primarily of the direction cosines from each receiver site to the transmitter and therefore is purely a function of the receiver geometry and transmitter position.

From equation (11) it follows that **X'** and hence **X** is given by

$$\underline{X}' = \underline{E}^{-I}\,\{\underline{\varepsilon}\,\underline{r} + \underline{\Delta}\} \qquad (12)$$

Where $\underline{E}^{-I}$ is the pseudo inverse to the $\underline{E}$ matrix. It may be shown that the pseudo inverse formulation as given in equation (12) leads directly to the least squares solution.

The pseudo inverse of the $\underline{E}$ matrix is given by

$$\underline{E}^{-1} = [\underline{E}t\,\underline{E}]^{-1}\,\underline{E}t \qquad (13)$$

The existence of the inverse of the matrix product $[\underline{E}t\,\underline{E}]$ is guaranteed provided at least four distinct receivers are used.

The solution of equation (12) requires an iterative solution based on an initial estimate of the transmitter position. One possible iterative technique is based on Gauss's algorithm for over determined systems.

If the required height accuracy was to be obtained using only four receivers then an alternative solution technique would be used which calculates the transmitter position directly without the need for iteration. This technique could be used to derive the initial position estimate for an iterative technique where more than four receivers are used.

The position finding problem can be stated as follows: Solve the set of 'n' non-linear equations represented by equation (12) for the aircraft position vector

$\underline{X}'\ [x, y, z, L1]^{t}$

$$\underline{E}\,\underline{X}' = \underline{\varepsilon}\,\underline{r} + \underline{\Delta} \qquad (12)$$

From equation (12) it follows that

$$\underline{\Delta} = \underline{E}\,\underline{X}' - \underline{\varepsilon}\ \underline{r} \qquad (26)$$

The approach taken here is to expand equation (26) as a Taylor series about the current estimate of the aircraft position ($\underline{P}$) and solve successively for position corrections ($\underline{\mathbf{C}}$) based on the measured values of Δ i.

That is,

$$\underline{\Delta} = \mathbf{f}(\underline{\mathbf{x}}') = \mathbf{f}(\underline{\mathbf{p}} + \underline{\mathbf{c}}) \approx \boldsymbol{\varnothing}\ (\underline{\boldsymbol{\pi}}) + \underline{\mathbf{c}}\mathbf{f}'(\underline{\mathbf{P}}) \qquad (28)$$

Where second and higher order derivatives have been ignored.

Hence a better estimate of the aircraft position can be obtained by adding the position correction to the current estimate of aircraft position, that is:

$$\underline{\mathbf{P}} := \underline{\mathbf{P}} + \underline{\mathbf{c}} \qquad (29)$$

From equation (26) it follows that

$$\mathbf{f}'(\underline{\mathbf{P}}) = \underline{\mathbf{E}}\mathrm{p} \qquad (30)$$

Where $\underline{\mathbf{E}}\mathrm{p}$ is the $\underline{\mathbf{E}}$ matrix formed for the current estimate of the aircraft position.

Now, since

$$\mathbf{f}(\underline{\mathbf{P}}) = \underline{\Delta}\mathrm{p} \qquad (31)$$

Then $\underline{\Delta}\mathrm{p}$ is the $\underline{\Delta}$ matrix according to the current estimate of the aircraft position.

The difference between the measured $\underline{\Delta}$ matrix and the $\underline{\Delta}\mathrm{p}$ matrix is thus an indication of how close the current estimate of aircraft position is to the actual aircraft position. If this difference is denoted by the 'n' element column vector $\underline{\mathbf{d}}$, then

$$\underline{\mathbf{d}} = \underline{\Delta} - \underline{\Delta}\mathrm{p} \qquad (32)$$

Hence from equation (28) it follows that

$$\underline{c} = \underline{E}p^{-I}\underline{d} \qquad (33)$$

Where $\underline{E}P^{-I}$ is the pseudo inverse of the $\underline{E}p$ matrix and is given by

$$\underline{E}p^{-I} = [\underline{E}p^{t}\,\underline{E}p]^{-1}\,\underline{E}p^{t} \qquad (35)$$

Thus the desired position corrections are obtained from equation (33).

In the summary, the suggested algorithm proceeds as follows:-

1. Measure the $\underline{\Delta}$ matrix for the aircraft required
2. Derive an initial estimate of the aircraft position based on only four receivers
3. $\underline{P}$:- initial estimate
4. Given the current estimate of aircraft position $\underline{P}$ calculate $f(\underline{P}) = \underline{\Delta}p$
5. Compute $\underline{d} = \underline{\Delta} - \underline{\Delta}p$
6. Given the current estimate of aircraft position $\underline{P}$ calculate $f'(\underline{P}) = \underline{E}p$
7. Compute $\underline{E}p^{-I} = [\underline{E}pt\,\underline{E}p]^{-1}\,\underline{E}pt$
8. Compute the position correction $\underline{C} = \underline{E}p^{-I}\,\underline{d}$
9 Update the current estimate of aircraft position, that is $\underline{P} := \underline{P} + \underline{C}$
10. If $|\underline{c}|$ was sufficiently small then output the aircraft position vector as being equal to the current estimate $\underline{P}$ and exit otherwise repeat steps 4 to 10.

In order to gain an accurate estimate of aircraft height then the lengths **li** must be measured as accurately as possible. The following analysis considers the effect of measurement errors on the corresponding least squares solution.

From equation (12) it follows that the corresponding error $\delta\underline{\mathbf{X}}'$ in $\underline{\mathbf{X}}'$ due in error $\mathbf{d}\underline{\Delta}$ in $\underline{\Delta}$ is given by

$$\delta\underline{\mathbf{X}}' = \underline{\mathbf{E}}^{-I}\{\delta\,\underline{\Delta}\} \tag{14}$$

If we restrict our interest to the height error component of $\delta\underline{\mathbf{x}}'$ then from (14) we have

$$\delta\mathbf{h} = \underline{\mathbf{w}}\,\{\delta\,\underline{\Delta}\} \tag{15}$$

Where $\delta\mathbf{h}$ is the height error and $\underline{\mathbf{w}}$ corresponds to the third row of the $\underline{\mathbf{E}}^{-I}$ matrix.

Consider the $\delta\,\underline{\Delta}$ matrix:

$$\delta\,\underline{\Delta} = \begin{bmatrix} \delta\,\Delta_1 \\ \delta\,\Delta_2 \\ \delta\,\Delta_3 \\ \delta\,\Delta_4 \\ \dots\dots\dots \\ \delta\,\Delta_n \end{bmatrix}$$

where

$$\delta\,\Delta_i = \delta l_i - \delta l_1 \tag{16}$$

where δl_1 represents error in measurement of the time of arrival of the transmission at the ith receiver. Notice that $\delta\,\Delta_1 = 0$. We may therefore rewrite equation (15) as a summation over 'n-1' terms, that is

$\delta \mathbf{h} = \Sigma\, w_i \Delta_i$ (i=2 to n) (17)

Substituting equation (16) in equation (17) gives

$\delta \mathbf{h} = \Sigma\, w_i \delta l_i - \Sigma\, w_i \delta l_1$ (i=2 to n) (18)

From equations (14) and (15) it follows that if all the δl_i are equal then the errors effectively cancel each other out and the resultant height error is zero, it therefore follows that

$\Sigma\, w_i = 0$ (i=1 to n) (19)

hence

$\Sigma\, w_i = -W_1$ (i=2 to n) (20)

hence substituting equation (20) into equation (18) we arrive at a significant result, namely:

$\delta \mathbf{h} = \Sigma\, w_i \delta l_i$ (i=1 to n) (21)

If we assume that the measurement of the leading edge of the transmission is subject to Gaussian variation then each δl_i has a normal distribution. It can be shown that a weighted sum of independent Gaussian variables is itself a Gaussian variable whose variance $\sigma^2 = \Sigma\, w_i^2 \sigma_i^2$ (i=1 to n) (22)
where σ_i^2 is the variance of δl_i is subjected to the same error mechanisms then each δl_i has the same distribution thus

$\sigma^2 = \sigma'^2\, \Sigma\, w_i^2$ (i=1 to n) (23) where σ^2 is the variance of each δl_i

Hence the standard deviation of height error σ is given by

$$\sigma = \sigma' |\underline{w}| \tag{24}$$

Where $|\underline{w}|$ is the magnitude of the weight vector corresponding to the third row of the $\underline{E}^{-1}$ matrix.

Since the $\underline{E}$ matrix is a function of the direction cosines from each receiver site to the transmitter, the weight vector $|\underline{w}|$ can be determined as a function of the receiver geometry and transmitter position. Figures 3 and 4 illustrate the magnitude of the weight vector for a typical receiver geometry suitable for the desired application for an aircraft flying at a height of 1NM.

Figure 5 shows a preferred layout of an altitude monitoring system. Four slave receivers SR 1-4 are disposed about a single master receiver MS. The master receiver MS is disposed in the centre of a circle with the slave receivers SL1-4 disposed upon the circumference. The diameter of the circle is approximately 10NM. Each receiver includes means for receiving a coded message transmitted from an aircraft, and each slave receiver can communicate with the master station over a data link.

Clock Synchronisation

Two possible schemes have been considered for achieving inter-site clock synchronisation.

SSR Synchronisation

The first technique assumes that each receiver site has an atomic clock driving a free running counter that can be read on reception of a signal transmitted from one of the other receiver sites. It is proposed that this signal should be produced by use of an SSR transmitter generating a unique code which would be received at the other sites. Since this code would be received at a high signal-to-noise ratio and could have a large number of bits set, averaging the times of each leading edge would result in very accurate synchronisation (<1 nanosecond) provided the same algorithm was employed at each receiver site. The technique also has the advantage that the same receiving circuit could be used for the synchronisation signal as for the SSR codes from the aircraft. This would therefore remove any uncertainty in the time of arrival due to antenna feeds, phase distortion in the RF pre-amplifier stage or signal processing delays. The rate at which resynchronisation would occur is dependent on the stability of the atomic clock at each site. If a rubidium atomic frequency secondary standard was used then a drift of one nanosecond in one hundred seconds could readily be achieved.

Use of the Global Positioning System (GPS)

The alternative technique is to use GPS at each of the receiver sites in order to provide both accurate location and intersite clock synchronisation.

The GPS system is well known and currently consists of six satellites any four of which may be used to give a position fix. At present these six satellites only provide coverage for three hours a day. When the system is fully operational, GPS will consist of between twentyone and twentyfour satellites giving twentyfour hours a day coverage. By repetitive measurements over a time scale of hours, the static user can achieve positional accuracy comparable to the ephemeris accuracies. Once an accurate position fix has been obtained subsequent position fixes would only be required to maintain synchronisation with GPS time for which only one satellite is required. Given that the position of each receiver site is already accurately known, it should be possible to maintain GPS time accurate to within ten nanoseconds by performing each synchronisation position fix over a time scale of minutes rather than hours.

Receiver Site Location

Both the SSR code synchronisation and the GPS synchronisation techniques require the relative location of each of the receiver sites to be accurately determined (to approximately one metre) if the aircraft height is to be measured to within the twentyfive feet requirement. Since GPS is able to provide the required accuracy it is proposed that either the receiver sites are pre-surveyed using GPS or that a GPS receiver is available at each site. The latter option would enable the system to be rapidly redeployed or reconfigured.

To this end, each site is provided with a GPS receiver subsystem 20.

Referring to Figures 5 and 6, each receiver site contains an SSR receiver and decoder sub-system, allowing all receiver sites to examine all the SSR traffic in the operating region. The master site initially selects particular SSR codes of interest and instructs the slave sites via a communications link to make time of arrival measurements of particular SSR codes within a pre-defined time window. Once the measurements are made the slave sites reply to the master site with the measured times of arrival for these codes which are then compared with the time of arrival measurements performed at the master site. The function of the time window is to ensure that all receiver sites measure the time of arrival of the same SSR reply. The master site would instruct the slave sites when to start and stop looking for each particular SSR code. If a slave site fails to detect the SSR code within that code's allotted observation time span then that slave site will send a default time of arrival for the SSR code back to the master site. The master site then reschedules an observation time interval for that SSR code. A similar scheme would be implemented if the master site fails to observe the SSR code.

When a complete set of time of arrival measurements has arrived at the master site then the master site calculates the position of each SSR code resulting in a compiled 'picture' of the aircraft traffic within the operating region. By decoding the mode 'C' SSR replies and extracting the pressure altimeter height indication, the master site associates the Mode 'C' data with particular known aircraft positions. This data is then stored locally or transferred to a remote centre for further statistical analysis. The data analysis function includes the capability to track each aircraft so that the measured height and the Mode 'C' height could be correlated over a period of time.

The master site is required to perform the following functions:-

1. System initialisation
2. Maintaining synchronisation between all receiver sites.
3. Monitoring all SSR traffic within the operating region.

4. Selecting SSR codes of interest.
5. Communicating the list of SSR codes of interest to selected slave sites.
6. Communicating the observation time interval (that is, start and stop time) for each SSR code of interest to the selected slave sites.
7. Making time of arrival measurements for the selected SSR codes.
8. Receiving the time of arrival measurements from the selected slave sites.
9. Check that each selected slave site has managed to observe each selected SSR code within that code's allotted observation time span.
10. Reschedule observation time when any selected slave site fails to observe a given SSR code of interest within the allotted observation time interval.
11. Perform the aircraft position location calculation for each code.
12. Estimate position error bounds for each aircraft position.
13. Decode SSR mode 'A' and mode 'C' replies
14. Associated decoded SSR mode 'C' and mode 'A' information with the known aircraft positions.
15. Log results to either a bulk storage medium or to a remote host.
16. System BITE

System initialisation would include the following:

i) Establish communications channels to all available slave sites.

ii) Determine the location of each slave receiver site relative to the master site.
iii) Establish synchronisation between all receiver sites.

The system BITE functions could include:

i) Monitoring the performance of the communications channels between the master and slave sites by transmission of test patterns.
ii) Monitor the performance of individual slave sites by using redundant slave sites to cross check position fix calculations.

Each slave site would be required to perform the following functions:

1) Receive control/instructions from the master site.
2) Make time-of-arrival measurements for selected SSR codes.
3) Transmit time-of-arrival and control information to master site.
4) Local BITE.

The architecture of both the master and slave receiver sites is illustrated in Figures 5 and 6 and will now be described. The method of operation assumes that each site is capable of continuously receiving SSR signals from aircraft and that these signals are continuously digitised and stored directly into a high speed Random Access Memory (RAM) which has sufficient capacity to contain at least one complete SSR code. Simultaneously the received SSR signal is filtered and decimated and the SSR code extracted. This code is then compared with the 'wanted' code that has previously been passed from the master site controller. If the codes match the counter value is read and if the counter value is within the time of validity of the SSR code the storage process is terminated. The Digital Signal Processor (DSP) then accesses the stored data and uses an edge detection algorithm to locate the leading edge of each bit of the SSR code and its precise address within the RAM. Using this address and the counter value at the time the storage process ended the equivalent counter value for each bit leading edge can be determined.

A synchronisation process is required to provide a common counter reference between all receiver sites. This is achieved by the master site transmitting a special SSR code as a precursor to the measurement of a group of wanted SSR codes. Measurement of this special code is performed as described above and the value of the counter at each leading edge determined and an average taken across all edges. The resulting average counter value is then used as the reference zero count for all subsequent measurements and stored in the DSP. Using a 32 bit ECL counter at 100 MHz would mean that measurements could be made within a time epoch of 42.9 seconds before the counter value 'folded over'.

Each receiver site comprises a number of sub-systems which are described below. Most of the sub-systems which are described below. Most of the sub-systems are common to both the Master and Slave sites, however some of the sub-systems are unique to the Master site. The main sub-systems are:-

i) Synchronisation sub-system

ii) SSR Receiver sub-system

iii) Data Acquisition sub-system
iv) SSR Decoder sub-system
v) Data processing sub-system
vi) Address Generation and control logic
vii) Communications sub-system
viiii) System Controller and Data storage sub-system

Synchronisation Sub-system 1

The synchronisation sub-system 1 comprises a 32 bit ECL free running counter driven at 100 MHz from an atomic clock. The stability of the atomic clock is required to meet the requirement of <1 nanosecond error within the maximum count period of the counter which is 42.9 seconds. A clock stable to one part in 10^{11} would be adequate. The 100 MHz signal is also used to drive the data acquisition and the address generation and control logic sub-systems. The counter is read by the data processing sub-system via ECL latches and if the counter value is within the correct time epoch the data storage process is terminated and the counter value stored.

SSR Receiver Sub-system

The SSR receiver sub-system comprises four sections:

i) The antenna 2.
ii) An RF linear amplifier 3.
iii) An envelope detector 4.
iv) An analogue to digital converter (ADC) 5.
v) A PIN switch (Master site only) 6.

The ADC 5 is required to digitise to eight bits at a rate of 100 MHz allowing accurate characterisation of the leading edge of the SSR transmission. To ensure that the noise samples at the output of the ADC 5 are uncorrelated the bandwidth of the envelope detector 4 (low pass filter) is required to be at least 100 MHz. Since both the synchronisation signal and wanted SSR signals use the same receiver circuitry no matching of the amplifiers or RF path lengths are required in order to satisfy the timing accuracies required.

Data Acquisition Sub-system

The data acquisition sub-system consists of:-

i) The start time register 7.
ii) The stop time register 8.
iii) The wanted SSR code register 9.
iv) The RAM store 10.

The wanted SSR code is captured by writing the output of the ADC 5 to a RAM store 10. To reduce the size of RAM required, the RAM is configured as a cyclic buffer when acquiring data. The buffer size is sufficiently large to store an entire twenty micro-second SSR transmission (that is, a transmission of more than two thousand samples). In order to determine when the wanted SSR code has been captured the output of the ADC 5 is also processed by a 'wanted code detection sub-system' which prevents the RAM store from being over written once the wanted code has been detected. In order to reduce the RAM speed requirements and avoid the need for an ECL RAM, the RAM is implemented by four banks, each bank being eight bits wide. Each data sample output from the ADC 5 is latched into one of four eight bit latches 11, every fourth data sample, the contents of all four latches would be written to the thirty-two bit wide memory

SSR Decoder

Raw SSR binary video data is derived from the envelope of the transmission by decimation 12 and comparing against a threshold 13. The decimation functional block 12 averages each block of eight samples output by the ADC 5, thus reducing the sample rate from 100 MHz to 12.5MHz. Each twenty microsecond SSR code is then represented by approximately twohundred and fiftysix bits. This over-sampled representation can then be converted to the thirteen bit SSR code by the SSR decoder 14. The wanted code may then be detected by comparing the output of the decoder with the wanted code by comparator 15.

Data Processor Sub-system

The data processor sub-system consists of:-

i) Digital Signal Processor (DSP) 16.
ii) A RAM store 10.
iii) Modem 17.

The various registers are memory mapped into the DSP 16 address space. This will allow the processor to set up the data acquisition sub-system prior to attempting to capture any data. the output of the counter sub-system is also memory mapped into the processor's address space allowing the processor to determine the current counter value.

Once an SSR transmission of interest has been captured in the RAM store 10, the DSP processor 16 performs the time-of-arrival measurement for each leading edge within the transmission. by performing the time-of-arrival measurement in software many different measurement techniques could be compared and contrasted. When the measurements have been made the time-of-arrival for each leading edge would be sent to the master site via the communications sub-system.

Address Generation and Control Logic 18

The address generation and control logic performs the following functions:-

i) Generate the cyclic address to the RAM store 10 when performing data acquisition.

ii) Arbitrate the use of the RAM store 10 between the DSP 16 and the data acquisition sub-system.

iii) Perform the address decoding for the memory mapped registers.

The logic is driven by the 100 MHz signal derived from the atomic clock and also used to drive the ADCs and ECL counters.

Each receiver site also includes a latch 21, 22 for respectively latching the counter output from the synchronisation sub-system 1, and the position output from the GPS receiver sub-system 20. Comparators 23, 24 respectively compare the latched count from the synchronisation sub-system 1 with the value stored in the stop time register 8 and start time register 7.

In the master site, a host interface 25 handles the data flow between the DSP 16 and the system controller 19. The master site also inclosed a transmitter sub-system 26 for transmitting the synchronisation codes to all the slave receiver sites.

Communications Sub-system

A bi-directional data communications channel is required between the master and each slave receiver. The bandwidth requirement for each master to slave channel is dependent on the expected SSR traffic within the operating region and the number of position fixes required per aircraft. For the position location of a single SSR code it is unlikely that more than a few hundred bits of information will need to be communicated thus making the bandwidth requirement modest (≈4800 baud). The communication may be performed by a land line of a dedicated VHF communications system, for example.

System Controller and Data Storage Sub-system

The functions of the system controller, which is based at the master site, are to

i) Determine which SSR codes are to be located.

ii) Instruct each receiver site which SSR codes to measure and over what time validity period relative to the synchronisation time.

ii) Initiate the transmission of the synchronisation signal.

iv) Receive the time-of-arrival data from each of the receiver sites and calculate the position of each SSR code.

v) Correlate the SSR code positions and to determine which codes are mode A and which are mode C.

vi) Produce a recognised air picture (RAP) for each aircraft within pre-defined flight lanes and to compute the error in the height estimation as a function of aircraft position.

vii) Store the mode A, mode C and aircraft height and error and to compute statistical data on the relation between indicated mode C height and actual height.

The controller will also initially configure the system by either receiving the various receiver site locations via the communications sub-system or by having this data supplied independently. The controller and data storage sub-system could readily be implemented using a microcomputer.

CLAIMS:-

1. An object location system comprising a transmitting means located at the object and a plurality of receiving means being precisely located with respect to each other, with one of said receiving means being arranged to act as a master receiving means, each receiving means comprising a clock synchronisation means arranged to be synchronised by a signal sent from the master receiving means, and detection and calculation means arranged to receive a signal from the object's transmitting means and determine the time taken to receive said signal from the object, and means for sending he data appertaining to the determination to the master receiving means which includes computational means arranged to determine the precise location of the object with respect to the plurality of receiving means based upon the data received from the plurality of receiving means.

2. An object location system as claimed in Claim 1, wherein the object's transmitting means is a secondary surveillance radar transponder.

3. An object location system as claimed in Claim 2, wherein the object is an aircraft.

4. An object location system as claimed in Claim 1, wherein the master station includes a transmitter arranged to send the synchronisation signal to all receiving means, said signal being in the form of a secondary surveillance radar code.

5. An object location system as claimed in Claim 2, wherein the detection and calculation means includes a first register, in which is

stored data indicative of a start time, a second register in which is stored data indicative of a stop time and a third register in which is stored data indicative of a required secondary surveillance radar code, said first and second registers data content define a time period in which the detection and calculation means is primed to look for said code.

6. An object location system as claimed in Claim 5, wherein the third register receives the wanted code, which is transferred from and to a random access memory which stores all code values which the system is required to detect, under the control of a digital signal processor.

7. An object location system as claimed in Claim 5, wherein a first comparator is connected to an output of the third register, and to an output of a decoder circuit which decodes the received secondary surveillance radar signal, and arranged to compare the output of the decoder with the output of the third register, and if a match is found, the value of the clock at detection is downloaded into a latch.

8. An object location system as claimed in Claim 7, wherein a second and third comparator are respectively arranged to compare the data value of the start time stored in the first register, and the data value of the stop time stored in the second register with the value stored in the latch, and the comparator output signals are passed to the digital signal processor which is arrange to calculate a value indicative of an elapsed time period for the code to be received, and to pass said value to the master receiver which includes further processing means arranged to operate upon all

values received from the receivers and to compute the aircraft's position.

9. An object location system substantially as hereinbefore described, with reference to any one of the accompanying drawings.

10. A method of locating an object substantially as hereinbefore described.

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Relevant Technical fields

(i) UK Cl (Edition K) H4D (DPAB,DPAC,DPX)

(ii) Int Cl (Edition 5) G01S

Databases (see over)

(i) UK Patent Office

(ii)

Search Examiner

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18 January 1991

Documents considered relevant following a search in respect of claims
1-10

Category (see over)	Identity of document and relevant passages	Relevant to claim(s)
X,Y	GB 1539522 (MARCONI)	1
X,Y	GB 1248066 (CHISHOLM)	1
Y	THE MORCONI REVIEW, VOL XLV1, No 228 First Quarter 1983, pages 1-17, D.E.Rice, Height measurement by quadrilateration	2,3

	Identity of document and relevant passages	Relevant to claim(s)

Categories of documents

X: Document indicating lack of novelty or of inventive step.

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