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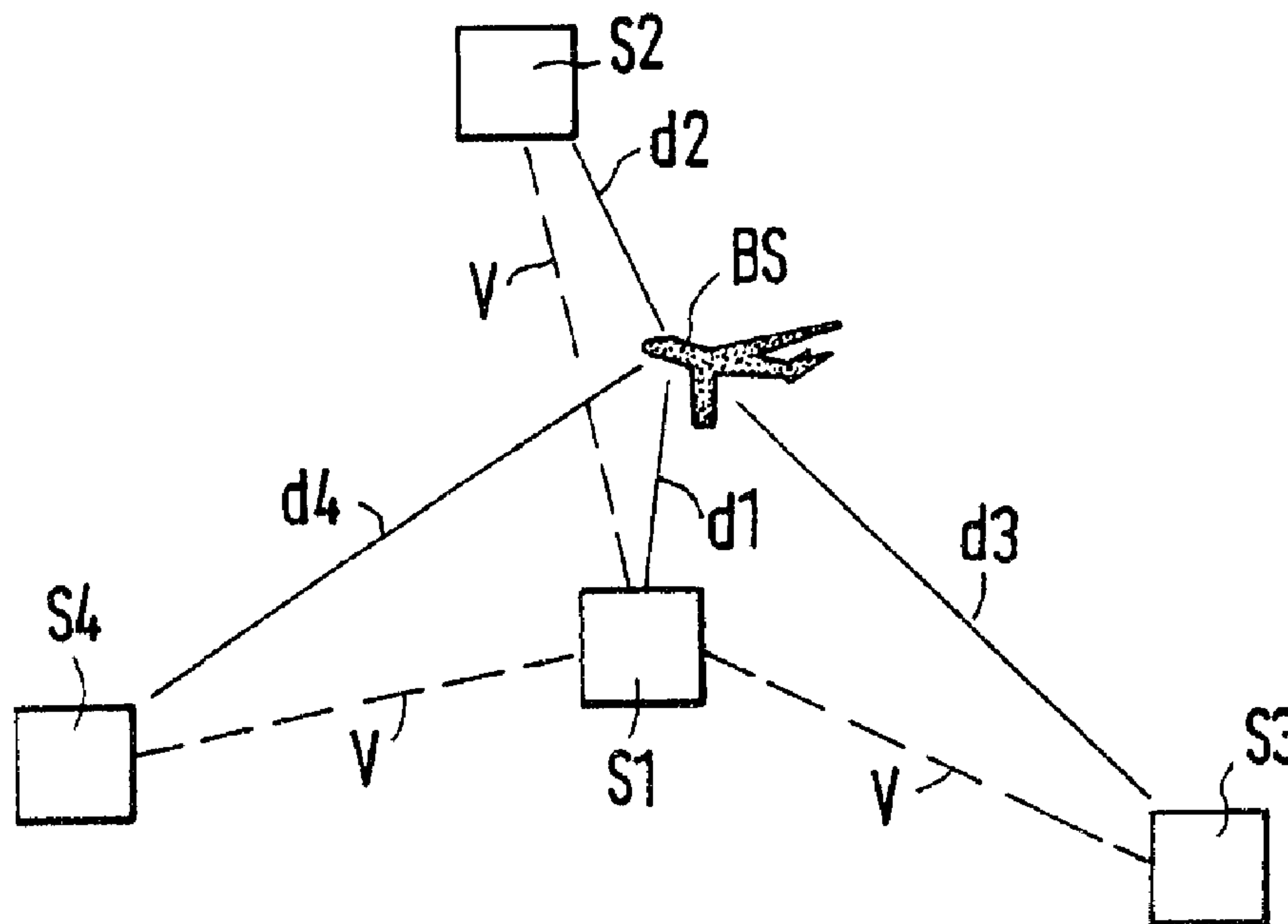
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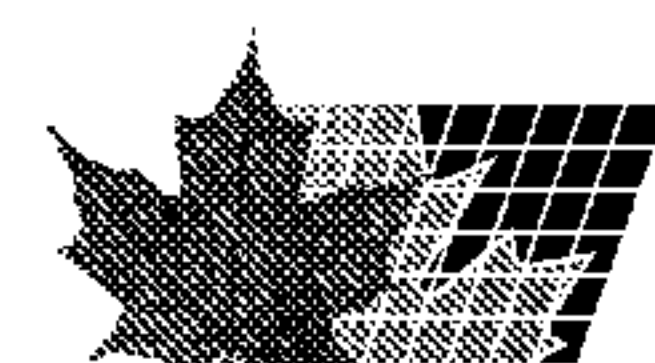
(54) Titre : CORRECTION DES ERREURS DE MESURE ATTRIBUABLES AUX DEVIATIONS DU CADRAN DANS UN
SYSTEME DE RADAR SECONDAIRE

(54) Title: METHOD OF CORRECTING MEASUREMENT ERRORS CAUSED BY CLOCK DEVIATIONS IN A
SECONDARY RADAR SYSTEM



(57) Abrégé/Abstract:

A method is disclosed for correcting measurement errors caused by clock deviations in a secondary radar system. To determine any deviation of the clocks of two ground stations (S1, S2; ... S1, S4) from each other, two interrogation/reply cycles are performed in direct succession in opposite directions over the same transmission path ($d1 + d2$): - Interrogation by ground station S1, reception of the reply from airborne station BS by ground station S2. - Interrogation by ground station S2, reception of the reply by ground station S1. The two transmission periods differ by twice the deviation of the clocks in the two ground stations S1, S2. The measured deviation is used to correct the measured transit time values and/or to synchronize the clocks. Synchronization of several ground stations with a master station is achieved by successive interrogation/reply cycles between the master station (S1) and all other stations (S2 - S4).



Abstract

A method is disclosed for correcting measurement errors caused by clock deviations in a secondary radar system. To determine any deviation of the clocks of two ground stations (S1, S2; ... S1, S4) from each other, two interrogation/reply cycles are performed in direct succession in opposite directions over the same transmission path ($d1 + d2$):

- Interrogation by ground station S1, reception of the reply from airborne station BS by ground station S2.
- Interrogation by ground station S2, reception of the reply by ground station S1.

The two transmission periods differ by twice the deviation of the clocks in the two ground stations S1, S2. The measured deviation is used to correct the measured transit time values and/or to synchronize the clocks. Synchronization of several ground stations with a master station is achieved by successive interrogation/reply cycles between the master station (S1) and all other stations (S2 - S4).

Method of Correcting Measurement Errors
Caused by Clock Deviations in a Secondary
Radar System

The present invention relates to a method as set forth in the preamble of claim 1.

European Patent Application 92104119.0 discloses a secondary radar system for Mode S operation in which the position of an aircraft is determined from stored arrival times of a reply signal from a station aboard the aircraft, transmitted in response to an interrogation signal from a ground station, at the receivers of at least three ground stations situated at different geographical locations by using hyperbolic position finding techniques.

In such a system, interrogators in the ground stations must operate in strict synchronism so that signal transit times and eventually distances can be calculated from the stored interrogation and arrival times associated with one another.

To maintain synchronism, the above patent application (see claim 6, for example) proposes to synchronize the interrogators in the ground stations with the aid of

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geostationary satellites. Such synchronization therefore requires in all ground stations receivers for the transmitted time signals and antennas for satellite reception.

It is the object of the invention to provide a method of the above kind whereby clock deviations and/or time measurement errors caused thereby can be very accurately corrected without the use of an additional, external device.

According to the present invention, there is provided a
10 method of correcting measurement errors caused by clock deviations in ground stations (S1-S4) of a secondary radar system which determines the positions of aircraft by measuring transit times of interrogation signals addressed to airborne stations (BS) and of reply signals transmitted by said airborne stations and received in at least three ground stations, characterized in that it comprises steps of transmitting, by means of all the ground stations (S1-S4) involved in determining the position on an aircraft, interrogation signal to the airborne station (BS) of the
20 aircraft in a cyclic sequence and at fixed points of time within a time frame predetermined by the clock of a ground station (S1); receiving reply signals from the airborne station by means of all the ground stations, which determine the times of reception, which, by themselves or together with the address of the interrogating ground station, taken from the reply signal of the airborne station, are exchanged among the ground stations or communicated to a master station (S1); calculating in the master station or in one or more of the other ground
30 stations, for changing pairs of ground stations, the elapsed time between the transmission of an interrogation

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signal in one of the ground stations of each pair and the reception in the other ground station of the reply signal transmitted by the airborne station in response to the interrogation for both directions; and interpreting half the absolute value of any difference between the two times as a deviation of the clocks of the two ground stations from each other and taken into account in the position determination to correct the signal transit times.

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The solution uses a principle as is known for performing time comparisons between satellite ground stations used for communication (see, for example, articles by D. Kirchner et al and D.A. Howe in "IEEE Transactions on Instrumentation and Measurement", Vol. 37, No. 3, September 1988, pages 141 et seq. and 418 et seq.).

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A particular advantage of the method according to the invention is that, apart from the devices required for secondary radar Mode S operation, no further devices are needed for the correction. The necessary calculations and data transmissions are performed by existing processors and transmission equipment, respectively.

Further advantageous aspects of the method according to the invention are defined below.

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Preferably, signal transit times from a master station to one other ground station and back are calculated. This makes the synchronization of the clocks of all ground stations with the clock of the master station particularly simple.

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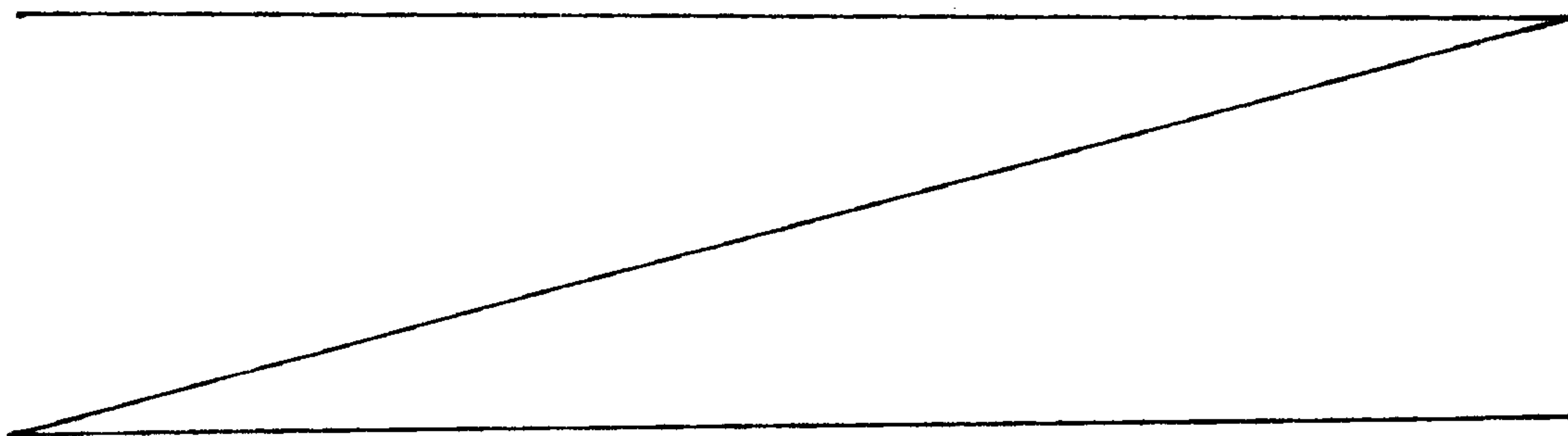
According to preferred embodiments, the method according to present invention prevents the clocks of the ground stations from deviating from each other too much during times in which no airborne station is available for interrogation and from transmitting a reply signal, i.e., in which the method described above cannot be carried out.

10 The method according to the invention will now be described in detail with reference to the accompanying drawing, in which:

Fig. 1 shows the principle of the invention in a system with two ground stations, and

Fig. 2 shows a secondary radar system with several ground stations with synchronized clocks.

20 Fig. 1 shows two ground stations S1, S2 with interrogators which are interconnected by a data link V. Located within the coverages of both interrogators is an aircraft with an airborne station BS which, after a fixed delay following the reception of an interrogation signal transmitted by one of the interrogators, transmits a reply signal which is received by both interrogators. The distance from the airborne station BS to the interrogator of the ground station S1 is d_1 , and that to the interrogator of the ground station S2 is d_2 .



The interrogators of both ground stations are equipped with highly accurate clocks which operate synchronously in a fixed system time frame. These clocks serve as a time standard for measurements of the transit times of interrogation and reply signals. With them, the time of transmission of a predetermined pulse edge of an interrogation signal and the time of reception of a likewise predetermined pulse edge of a reply signal transmitted by the airborne station after a fixed delay can be precisely measured in relation to a synchronization mark of the system time frame. The time elapsed between the transmission of an interrogation signal and the arrival time of an associated reply signal can then be calculated at the interrogating ground station. If the receiving station is not the interrogating station, the arrival time must be transmitted to the interrogating station.

The calculated time is composed of the signal transit times between the interrogating ground station and the airborne station, t_1 , and between the airborne station and the receiving ground station, t_2 , and the fixed delay t_0 in the airborne station. Depending on which ground station is interrogating and in which ground station the time of reception of the reply signal is being determined, the signal transit time is composed of the fixed delay t_0 and twice the distance d_1 (interrogation and reply evaluation by ground station S1), the distance $d_1 + d_2$ (interrogation by ground station S1, reply evaluation by ground station S2) or twice the distance d_2 (interrogation and reply evaluation by ground station S2). If the reply signal is evaluated by the interrogators of both ground stations, and the measured signal transit times are exchanged via the

data link V , the distances d_1 and d_2 can be calculated, since the wave velocity (speed of light c) is known. To determine the position of the aircraft using a hyperbolic system, at least one additional ground station is necessary whose clock must also be synchronized with the system time frame.

Mutual synchronization of the interrogators necessitates measuring the existing clock deviation and, to this end, two successive interrogation/reply cycles with signal transmissions taking place over the same distances in opposite directions. For example, the reception at the station S_2 of a reply signal from the airborne station BS which was elicited by the interrogator S_1 is followed, after a predetermined waiting time, by an interrogation from the station S_2 and the reception of the reply signal from the airborne station BS by the ground station S_1 . The time measured between the transmission of the interrogation signal and the reception of the associated reply signal is the same in both directions provided the interrogators operate in exact synchronism and the interrogations follow in such rapid succession that any distance meanwhile traveled by the airborne station will be of no consequence. If the synchronization is not correct, a time error will be measured for both directions of transmission. The measured error is the same for both directions of transmission but has a different sign for each direction.

If t_1 is the signal transit time over the distance d_1 in Fig. 1, t_2 the signal transit time over the distance t_2 ,

and t_0 the delay in the airborne station, the total time for an interrogation/reply cycle directed from ground station 1 to ground station 2 or oppositely is

$$T_{1,2} = T_{2,1} = t_1 + t_0 + t_2$$

In the presence of a synchronization error t_f (e.g., lag of the clock of the ground station S2), a total time of

$$T_{1,2} = t_1 + t_0 + t_2 - t_f$$

will be measured for the interrogation/reply cycle initiated by the station S1, while a total time of

$$T_{2,1} = t_2 + t_0 + t_1 + t_f$$

will be measured for the interrogation/reply cycle in the opposite direction. The two total times thus differ by $2 t_f$. Accordingly, the deviation of the clock in the ground station S2 from the clock in the ground station S1 is t_f , half the measured difference.

If it is possible to readjust the clock in the ground station S2, this can be done after transmission of the magnitude and sign of the detected time error t_f to the station S2. Exact synchronization of the two clocks is thus restored. The deviation can also be stored and taken into account as a correction value in calculating distance for the purpose of locating the position of the aircraft. Thus, the erroneous measured value need not be discarded.

The delay in the airborne station does not enter into the measured total time. It is therefore inconsequential if the delays in the airborne station of different aircraft are not exactly equal. The delay in a single airborne station, however, should be so constant that it does not measurably change during two successive interrogation/reply cycles.

In practice, this requirement cannot always be met. Delay jitter occurs which, according to the regulations of the ICAO for secondary radar systems, must not exceed 50 nanoseconds. In addition, randomly distributed measurement inaccuracies are also likely when measuring the times of reception in the interrogators of the ground stations. These randomly distributed transit-time and measurement errors can be reduced by making multiple measurements and averaging the measured values.

Errors in the measured total times may also result from the motion of the airborne station and the resulting signal-path change during the time between two successive interrogation/reply cycles. Such errors will remain small if the waiting time between the successive interrogation/reply cycles is very short, e.g., on the order of 1 millisecond. Time-measurement errors will then remain below 1 nanosecond even with an unfavourable spatial constellation of the ground stations and the airborne station (airborne station vertically above one of the ground stations).

Fig. 2 shows a group of ground stations S1 ... S4 of a cellular network. In such a secondary radar network,

the position of an aircraft (airborne station BS) is determined by measuring the times required for a reply signal transmitted by the aircraft in response to an interrogation signal from one of the ground stations to travel to at least three of the ground stations. If, according to an embodiment of the system described in the European patent application referred to above, the flight altitude is to be additionally determined by evaluating the transit times of the reply signal, a fourth, synchronously operating ground station is required. To be able to synchronize the interrogators of all required ground stations as described above or to correct measurement errors caused by deviations of the clocks, it is necessary to organize the interrogation/reply mode of these ground stations in such a manner that all ground stations send interrogations to the same airborne station in as even a distribution as possible, and that this does not result in intersections of signals at the receivers or in signals arriving at the airborne receiver when the latter is off during the transmission of a reply signal.

In a group of ground stations as shown in Fig. 2, it is therefore advantageous to operate one of the ground stations as a master station (or to provide an additional master station), to regard the timing signal of the latter as the system timing, and to synchronize the clocks of the other interrogators with the system time of the master station. The calculation of the various distances and the hyperbolic position finding method are then carried out in a computing device in the master station after all measured values have been transmitted to this station.

In Fig. 2, the ground stations S1 to S4 belong together. The ground station S1 is the master station, in which the signal transit times needed for position determination are determined from the measured values of all stations, and in which position determination is performed. The clocks of all stations are first coarsely synchronized with a system time which is provided by the master station to the stations S2-S4, e.g., via data links V existing between the stations. Synchronization with the aid of a public time standard transmitter or with the aid of a GPS timing signal is also possible. Starting from a point 0 of the system time or any agreed point of the public time standard, the ground stations transmit interrogation signals at fixed instants which are 1 millisecond apart, for example. If the master station S1, for example, transmits at the instant 0, the ground station S2 will follow at instant $0+1$, the ground station S3 at the instant $0+2$, and finally, after 3 ms, the ground station S4. After a fixed waiting time (e.g., 1 s), the master station begins a new interrogation cycle. In this case, the coarse synchronization of the ground stations must be at least so good that the sequence of the stations in the interrogation cycle will be preserved and no overlapping of the interrogations will occur.

If an aircraft whose airborne station (transponder) is on comes near to the stations S1 to S4, the stations will receive squitter signals from the airborne station. From these squitter signals, they take the identification of the aircraft, which is used to

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selectively address the airborne station.

Also, a first coarse determination of the position of the aircraft can be performed with the aid of the arrival times of the squitter signals, which are registered in the ground stations.

If the airborne station can be addressed on a selective basis, it will, after a fixed delay t_0 , transmit in response to each interrogation signal containing its identification a reply signal whose respective arrival times in the individual ground stations are registered and transmitted to the master station. It is then possible to carry out the method of determining time errors and correcting the synchronization of the ground stations, described above for two ground stations, for the station pairs S1/S2, S1/S3, and S1/S4, but also for the three other possible pairs S2/S3, S2/S4, and S3/S4. The initially possibly large synchronization error can thus be reduced step by step, so that after a few seconds, all ground stations involved, even if the ground stations S1 to S4 are used without connection with an areawide network, e.g., for air space surveillance, will be very accurately synchronized with the system time provided by the master station S1.

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WHAT IS CLAIMED IS:

1. A method of correcting measurement errors caused by clock deviations in ground stations (S1-S4) of a secondary radar system which determines the positions of aircraft by measuring transit times of interrogation signals addressed to airborne stations (BS) and of reply signals transmitted by said airborne stations and received in at least three ground stations, characterized in that it comprises steps of transmitting, by means of all the ground stations (S1-
10 S4) involved in determining the position on an aircraft, interrogation signal to the airborne station (BS) of the aircraft in a cyclic sequence and at fixed points of time within a time frame predetermined by the clock of a ground station (S1); receiving reply signals from the airborne station by means of all the ground stations, which determine the times of reception, which, by themselves or together with the address of the interrogating ground station, taken from the reply signal of the airborne station, are exchanged among the ground stations or
20 communicated to a master station (S1); calculating in the master station or in one or more of the other ground stations, for changing pairs of ground stations, the elapsed time between the transmission of an interrogation signal in one of the ground stations of each pair and the reception in the other ground station of the reply signal transmitted by the airborne station in response to the interrogation for both directions; and interpreting half the absolute value of any difference between the two times as a deviation of the clocks of the two ground stations

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from each other and taken into account in the position determination to correct the signal transit times.

2. A method as claimed in claim 1, characterized in that pairs of ground stations (S1, S2; S1, S3; S1, S4) are formed in which one (S1) of the ground stations is the master station, and that any deviation of the clocks of a pair of ground stations from each other which is determined in the master station is communicated to the respective other ground station (S2, S3, S4) and used there to correct the clock.

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3. A method of coarsely synchronizing clock generators of ground stations in a secondary radar system suitable for carrying out the method claimed in claim 1 or 2, characterized in that the clock signal of one of the ground stations is transmitted over the data links (V) to all the other ground stations.

4. A method of coarsely synchronizing clock generators of ground stations in a secondary radar system suitable for carrying out the method claimed in claim 1 or 2, characterized in that all ground stations receive the time standard signal from a public time standard transmitter and adjust their clocks to said time standard signal.

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