(54) Title: SATELLITE-BASED COLLISION AVOIDANCE SYSTEM AND METHOD THEREFOR
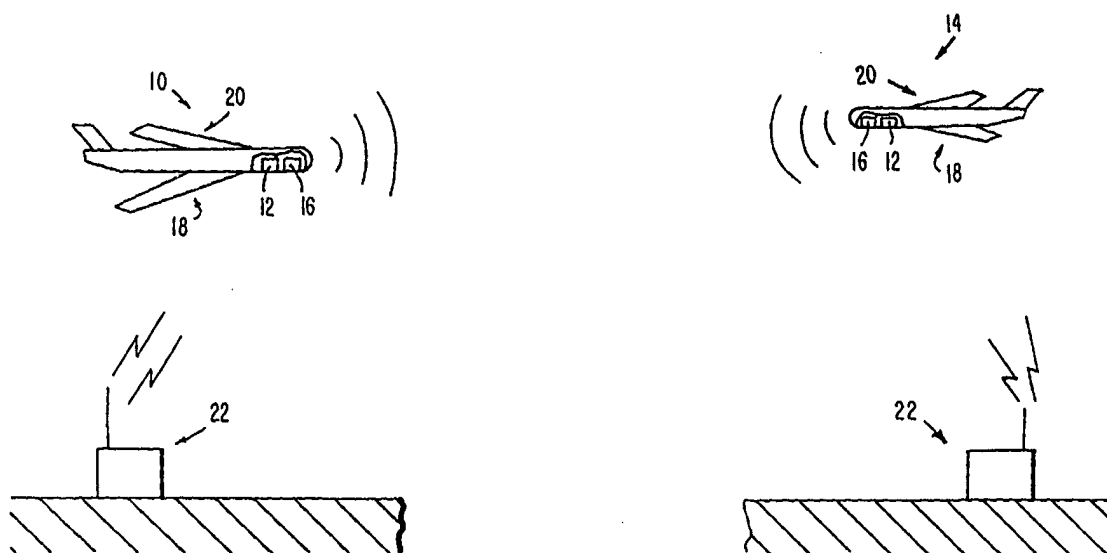
(57) Abstract

An aircraft collision avoidance method, including the steps of determining geopotential heights of a first (10) and a second (14) aircraft at substantially the same instant of time using a satellite-based position determining device disposed on each of the first (10) and second (14) aircraft; pausing for a time period t1, then transmitting data representing the geopotential height of the first aircraft from the first aircraft pausing for a time period t2, then transmitting data representing the geopotential height of the second aircraft from the second aircraft; receiving data from one of the first and second aircraft; estimating a vertical separation distance between the first and second aircraft at substantially the same instant of time using the received data by forming a difference between the geopotential heights of the first and the second aircraft; and reporting a warning to a pilot or an automated flight control computer (22) if the estimated vertical separation distance is below a threshold value.

Satellite-Based Collision Avoidance System And Method Therefor

BACKGROUND OF THE INVENTION

1.   Field of the Invention

The present invention relates to collision avoidance systems and, more particularly, to an aircraft collision avoidance system which utilizes the Global Positioning Satellites and aircraft barometric altimeters.

2.   Description of the Related Art

Recent changes in aircraft flight regulations for flight operations in the North Atlantic Minimum Navigation Performance Specifications (NAT/MNPS) airspace have reduced the minimum allowable vertical distance between two aircraft flying through this airspace from 2,000 feet to 1,000 feet for operation between specified flight levels, currently, Flight Level (FL) 290 and FL 410, inclusive. The Reduced Vertical Separation Minimum, or RVSM, will allow more aircraft to fly more optimal profiles and increase the air traffic capacity through this airspace.

As more aircraft fly through a given airspace, the probability of near misses could also increase due to, for example, inaccurate or malfunctioned altitude control systems. Thus, it is more important than ever that the aircraft flying through the RVSM airspace be equipped with a dynamic collision avoidance system.

Various collision avoidance systems have been developed over the years. An example of such a system is disclosed in U.S. Patent No. 4,293,857 to Baldwin. Baldwin teaches an aircraft avoidance system which utilizes a reference navigational ground station to enable a first aircraft to determine its own location and a reference ground-based air surveillance radar to determine the location, velocity, course and altitude of a second aircraft for potential collision. A disadvantage of this system is that a multitude of expensive navigational ground stations and surveillance radars must be installed along the flight paths of aircraft.

U.S. Patent No. 4,317,119 to Alvarez discloses a stand-alone collision avoidance system for installation on a passenger jet. Alvarez's system employs a bistatic radar antenna system

with mechanically driven antennas for scanning the space ahead of the aircraft.   A disadvantage of this system is that the mechanical drive mechanism for the antennas is prone to wear and tear and/or mechanical jamming.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a low-cost, reliable dynamic electronic collision avoidance system for aircraft.

Another object of the invention is to provide a method for dynamically monitoring an RVSM airspace by the aircraft flying therethrough.

In accordance with an embodiment of the present invention, an aircraft collision avoidance method, includes the steps of (1) determining geopotential or absolute geometric heights of a first and a second aircraft at a substantially the same instant of time using a satellite-based position determining device disposed on each of the first and the second aircraft; (2) pausing for a time period t_1 then transmitting data representing the geopotential height of the first aircraft from the first aircraft to the second aircraft; (3) pausing for a time period t_2 then transmitting data representing the geopotential height of the second aircraft from the second aircraft to the second aircraft to the first aircraft; (4) receiving the data from one of the first and second aircraft by another one of the first and second aircraft; (5) estimating a vertical separation distance between the first and the second aircraft at said substantially the same instant of time using the received data by forming a difference between the geopotential heights of the first and the second aircraft; and (6) reporting a warning to a pilot or an automated flight control computer if the estimated vertical separation distance is below a threshold value such as, for example, 1,000 feet.

Other objects and features of the present invention will become apparent from the following detailed description considered in conjunction with the accompanying drawings.   It is to be understood, however, that the drawings are designed solely for purposes of illustration and not as a definition of the limits of

the invention, for which reference should be made to the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, wherein like reference characters denote similar elements throughout the several views:

FIG. 1 illustrates schematically a preferred embodiment of the present invention;

FIG. 2 depicts schematically a flowchart for implementing an embodiment of the early-warning collision avoidance system of the present invention; and

FIG. 3 is a block diagram of an aircraft altimetry monitoring system in accordance with the present invention.

DETAILED DESCRIPTION OF THE PRESENTLY PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown a first aircraft 10 equipped with a satellite-based position-determining device such as, for example, a Global Positioning System (GPS) receiver 12, and a second aircraft 14 also equipped with a satellite-based position-determining device such as, for example, another Global Positioning System receiver 12. Each of the first aircraft 10 and second aircraft 14 further includes a transmitter-receiver 16 for transmitting to and receiving from each other signals representing the position and/or trajectory of each aircraft, an altitude sensor 18 (e.g. a barometric type sensor) for measuring the pressure altitude of the host aircraft, and an airspeed sensor 20 (e.g. an aneroid pressure transducer) for measuring the airspeed of the host aircraft. Pressure altitude, as used herein, refers to the height above sea level as measured by a pressure altimeter such as, for example, altitude sensor 18.

The GPS receiver 12 provides its host aircraft information relating to the location of the host aircraft based on range signals from satellites of the Global Positioning System. The GPS has a network of 24 satellites distributed among six orbits (four satellites in each orbit) but the number of satellites "visible" to a GPS receiver 12 at any location varies with the time of the day. The GPS receiver 12 determines its position at time t_j by obtaining the location of each of the visible GPS satellites and by measuring the range of those satellites on the basis of the propagation time of the range

signals from each of those satellites. Signals from at least four GPS satellites are needed to determine a three-dimensional position (e.g., longitude, latitude and altitude) of the aircraft 10. The position of the GPS receiver is typically expressed in a global coordinate system or the so-called Earth-Centered Earth-Fixed (ECEF) coordinate system wherein the coordinate system origin is at the center of the Earth.

The accuracy of the position estimates of the GPS receiver 12 is affected by a multitude of errors including errors in the satellite position, propagation-induced signal delays, errors from multipath signals, noise in the GPS receiver 12, and intentionally induced errors in the signals by the Department of Defense which maintains the GPS. The geopotential height or the altitude component of the position estimate suffers from the additional problem that its accuracy or resolution is limited by the geometric spatial relationships of the satellites with respect to the GPS receiver. The absolute or geopotential height, as defined herein, is the distance between the center of the Earth and the location of the GPS receiver.

A dimensionless metric or parameter, known to an ordinary artisan as the position dilution of precision (PDOP), is often used to indicate the accuracy of the geopotential height estimate such that the smaller the PDOP value, the more accurate is the geopotential height estimate. Preferably, the PDOP value is less than 6.0. Typically, the geopotential height estimate computed by a stand-alone GPS receiver has an error in the range of about 100 to 200 feet, which is unacceptable for an aircraft flying through an RVSM airspace.

These errors, however, are substantially eliminated by computing the relative or differential geometric height between two GPS receivers because the aforementioned errors present in the absolute or geopotential height estimates are substantially cancelled in the process of forming their difference, provided the geopotential height estimates are obtained at an instant in time substantially the same or common as time t_j. In such a case, the accuracy of the differential geometric height is quite high, as it has an error of less than about 10 feet.

Advantageously, the present invention provides a collision avoidance system which analyzes the vertical separation distance between two adjacent aircraft to determine the likelihood of collision between the aircraft. The vertical separation

5   distance between two adjacent aircraft is preferably determined by computing the difference between the absolute geometric heights measured -- at substantially the same or common instant of time -- by their respective GPS receivers.

Since the accuracy of the computed vertical separation

10 depends greatly on the relative positions or geometric spatial relationship of the satellites with respect to the GPS receiver 12 at the time of measurement, it is preferable that additional information, such as, for example, the pressure altitude of the aircraft be also transmitted to the adjacent aircraft for

15 comparison. A Kalman filter algorithm may, for example, be employed to determine the most likely vertical separation distance between the first and second aircraft 10 and 14 by assigning appropriate weights to the pressure altitude and geopotential height measurements of the first and second aircraft 10 and 14.

20   The accuracy of the vertical separation estimate can still be further improved by pre-calibrating the barometric altitude sensor 18 of the aircraft during flight prior to the aircraft entering the RVSM airspace. This can be done by predisposing base stations 22 with stored reference pressure-

25 height measurements (i.e. pressure measurements and corresponding geometric height measurements above the base station 22) and communication equipment for transmitting these measurements to the aircraft along the flight path of the aircraft as shown in Fig. 1. Each base station 22 preferably includes a GPS receiver 12 so

30 that the geometric height of the aircraft relative to the base station 22 can be computed by determining the difference between the absolute geometric or geopotential heights of the base station 22 and the aircraft as explained above. The thus-derived geometric height of the aircraft with respect to base station 22

35 and the measured atmospheric pressure outside the aircraft can then be correlated with the reference pressure-height measurements of the base station 22, thereby enabling the aircraft altimetry system to adjust its computed pressure altitude accordingly.

FIG. 2 schematically illustrates the inventive steps of a preferred embodiment of the present invention executed preferably concurrently by aircraft 10 and 14 of FIG. 1. Beginning at step 104, the aircraft altitude sensor 18, airspeed sensor 20, and GPS receiver 12 measure the barometric altitude (through static pressure), airspeed (through impact pressure) and GPS data (e.g. coordinate position of the GPS receiver 12) of the aircraft respectively. The measurements are time stamped at step 106 and stored in, for example, the aircraft on-board digital air data computer (DADC) 30 (as shown in FIG.3). At step 108, the DADC 30 computes pressure altitude, absolute geometric height using the latest or last received GPS data and airspeed (or ground speed) of the aircraft. Preferably, the computed values together with the time-stamp are then stored or recorded in, for example, the DADC 30. The DADC 30 thereafter pauses, at step 110, for a random or pseudo-random time period (as determined by, for example, a pseudo random number generator) prior to their transmission to another similarly equipped aircraft. This pause reduces the possibility that two similarly equipped aircraft operating in the same airspace will communicate at the same time or otherwise interfere with each other. The DADC 30 may, by way of example, pause every 1/100 of a second, every 1/50 of a second, or every second, etc uniformly on non-uniformly. At step 112, the DADC 30 transmits a low power signal that includes, for example, pressure altitude, GPS data such as absolute geometric or geopotential height, airspeed (and/or ground speed), course coordinates, a time stamp indicating the time at which the transmitted data were measured, and data uniquely identifying the transmitting aircraft. In a particularly preferred embodiment, the aircraft 10 or 14 transmits using a low power transmitter at a frequency between approximately 108 MHz and approximately 133 MHz that is not normally used in the RVSM airspace. The DADC 30 may also be provided with the ability to "channel-hop," i.e. to automatically switch transmitting channels (i.e. frequencies) if interference is detected on a particular channel or if the previously-selected channel is currently in use. The DADC 30 can also transmit sequentially at a plurality of frequencies as the

aircraft approaches a boundary at which a particular frequency
ceases to be unused.

With continued reference to FIG. 2, the DADC 30
preferably, at step 114, checks to see if signals representing GPS
5   data, pressure altitude, geometric height, airspeed (and/or ground
speed), course coordinates, a time stamp indicating the time at
which the transmitted data was measured, have been received from
another adjacent aircraft flying in the same RVSM airspace. If
no data have been received, then the aircraft GPS receiver 12
10   records another, subsequent-in-time measurement beginning at step
104. When the aircraft 10 receives data from another aircraft at
step 114, the DADC 30 compares the received data at step 116 with
its measured and stored data including, for example, GPS derived
geopotential height data, pressure altitude, that were measured
15   at substantially the same instant of time as those of the other
aircraft, as indicated by the time-stamp accompanying the
transmission, and using, for example, a least squares fit method
or a Kalman filter algorithm to determine whether an RVSM
violation has occurred (or about to occur based on the projected
20   trajectory of the approaching aircraft) at step 118, i.e. whether
the vertical separation distance between the two adjacent aircraft
is less than a threshold value such as, for example, 1,000 feet.
If there is no RVSM violation, as determined at step 118, then the
system loops back to step 104 and the GPS receiver 16 records
25   another measurement. If the DADC 30 determines there is a RVSM
violation at step 118, the pilot and/or a flight control computer
is warned or alerted at step 120 to take corrective actions at
step 122, including contacting the approaching aircraft. These
steps are repeated as shown in Fig. 2 and data are updated and
30   transmitted at the next randomly selected time period.

Thus, in accordance with the present invention, aircraft
operating in RVSM airspace can continuously monitor the airspace
for approaching aircraft and alert the pilots (and/or automated
aircraft flight control and signalling systems) of RVSM violations
35   by the approaching aircraft. Corrective action can thereby be
initiated well in advance of any real danger, and travelling
through an RVSM airspace is rendered safer and more automated as
the present invention enables the DADC 30 to assume the task of

dynamically monitoring and reporting a RVSM violation by, for example, warning or alerting the crew or automated flight computer of the approaching aircraft.

Referring now to FIG. 3, a DADC 30, pilot airspeed indicator/altimeter 60 and copilot airspeed indicator/altimeter 70 are separately connected to pairs of pressure inputs: 42 and 44, 62 and 64, and 72 and 74, respectively. Static source error data is collected using known methods and apparatus for each device and communicated via lines 46, 66, 76 to and stored in an EEPROM 52, which, in a preferred embodiment, is located in a connector 50. These data comprise static source error (SSE) data for a specific aircraft and provide a more accurate representation of the condition of the pressure input ports than normally provided by the manufacturer-preset SSE data. The SSE data can be used to automatically adjust or calibrate the raw measurement data so as to render more accurate computation of the pressure altitude, airspeed or other air data for a specific aircraft. The connector 50 is removably affixed to the DADC 30 and communicates SSE data over line 54. As the aircraft ages, new SSE data can be measured and stored in the EEPROM 52 (during flight or on the ground) to reflect the actual condition of the static pressure ports. The present invention thereby more accurately measures and monitors the condition of the static pressure ports which, in turn, provides a more accurate altimetry system. Although most preferably employed for RVSM operation, this feature of the present invention is equally useful for aircraft flying in traditional airspace.

Thus, while there have shown and described and pointed out fundamental novel features of the invention as applied to preferred embodiments thereof, it will be understood that various omissions and substitutions and changes in the form and details of the devices illustrated, and in their operation, may be made by those skilled in the art without departing from the spirit of the invention. For example, it is expressly intended that all combinations of those elements and/or method steps which perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention.

It is the intention, therefore, to be limited only as indicated by the scope of the claims appended hereto.

CLAIMS

I claim:

1.   An aircraft collision avoidance method, comprising the steps of:

determining geopotential heights of a first and a second aircraft at substantially a common instant of time using a satellite-based position determining device disposed on each of the first and the second aircraft;

pausing for a first time period then transmitting data representing the geopotential height of the first aircraft from the first aircraft;

pausing for a second time period then transmitting data representing the geopotential height of the second aircraft from the second aircraft;

receiving the data from one of the first and the second aircraft by another one of the first and the second aircraft;

estimating a vertical separation distance between the first and the second aircraft at said substantially common instant of time using the received data by forming a difference between the geopotential heights of the first and the second aircraft; and

reporting a warning if the estimated vertical separation distance is below a threshold value.

2.   The method of claim 1, including randomly selecting the first and the second time periods.

3.   The method of claim 1, further comprising the steps of determining pressure altitudes of the first and the second aircraft, transmitting data representing the pressure altitudes together with the data representing geopotential heights of corresponding said first and the second aircraft, and estimating the vertical separation distance between the first and the second aircraft based on the pressure altitudes and the geopotential heights of the first and the second aircraft using a Kalman filter algorithm.

4.   The method of claim 3, further comprising the step of storing the data representing the geopotential heights and the data representing the pressure altitudes of the first and the second aircraft at the respective aircraft.

5.   The method of claim 1, wherein the threshold value is about 1,000 feet.
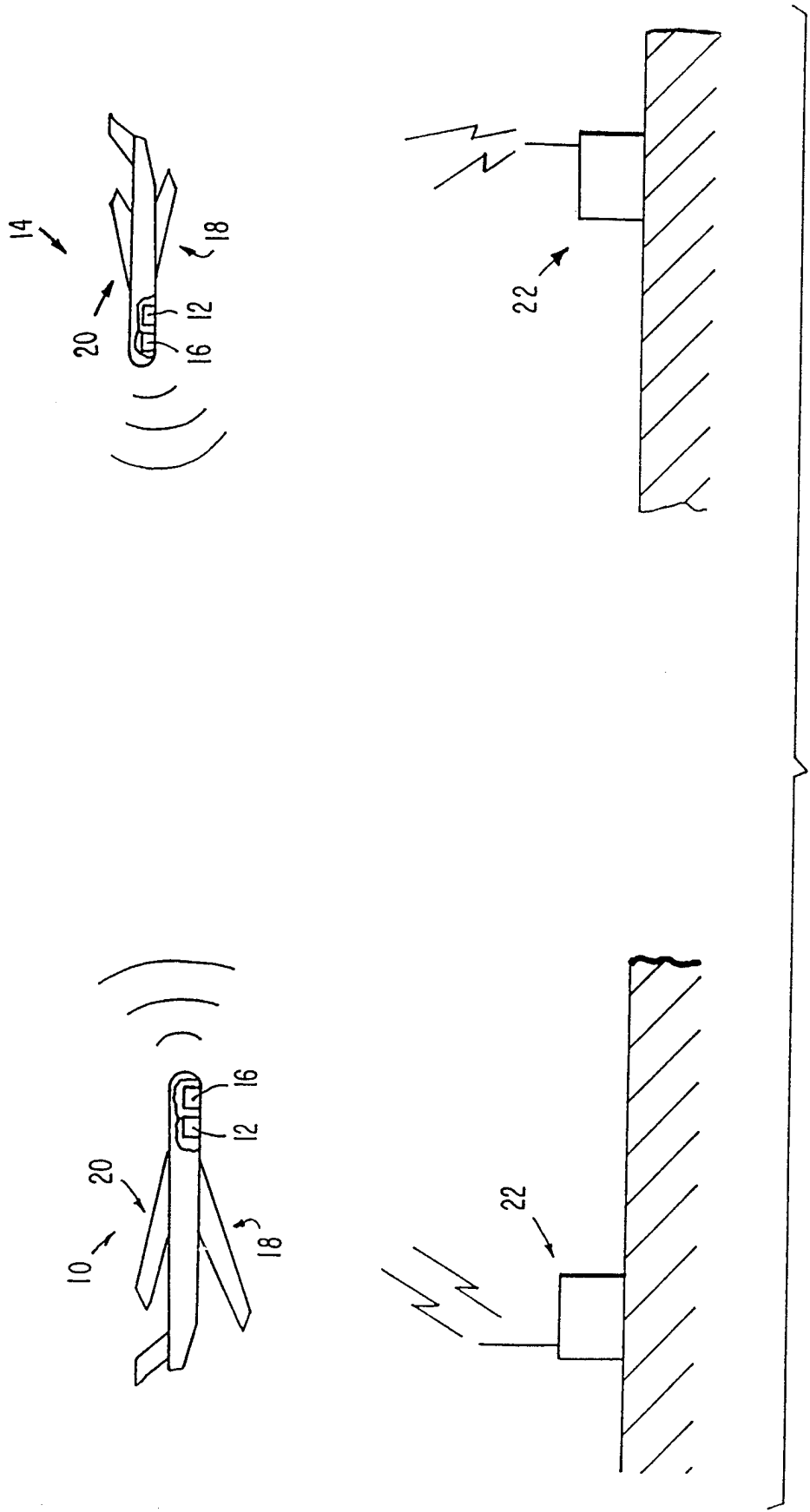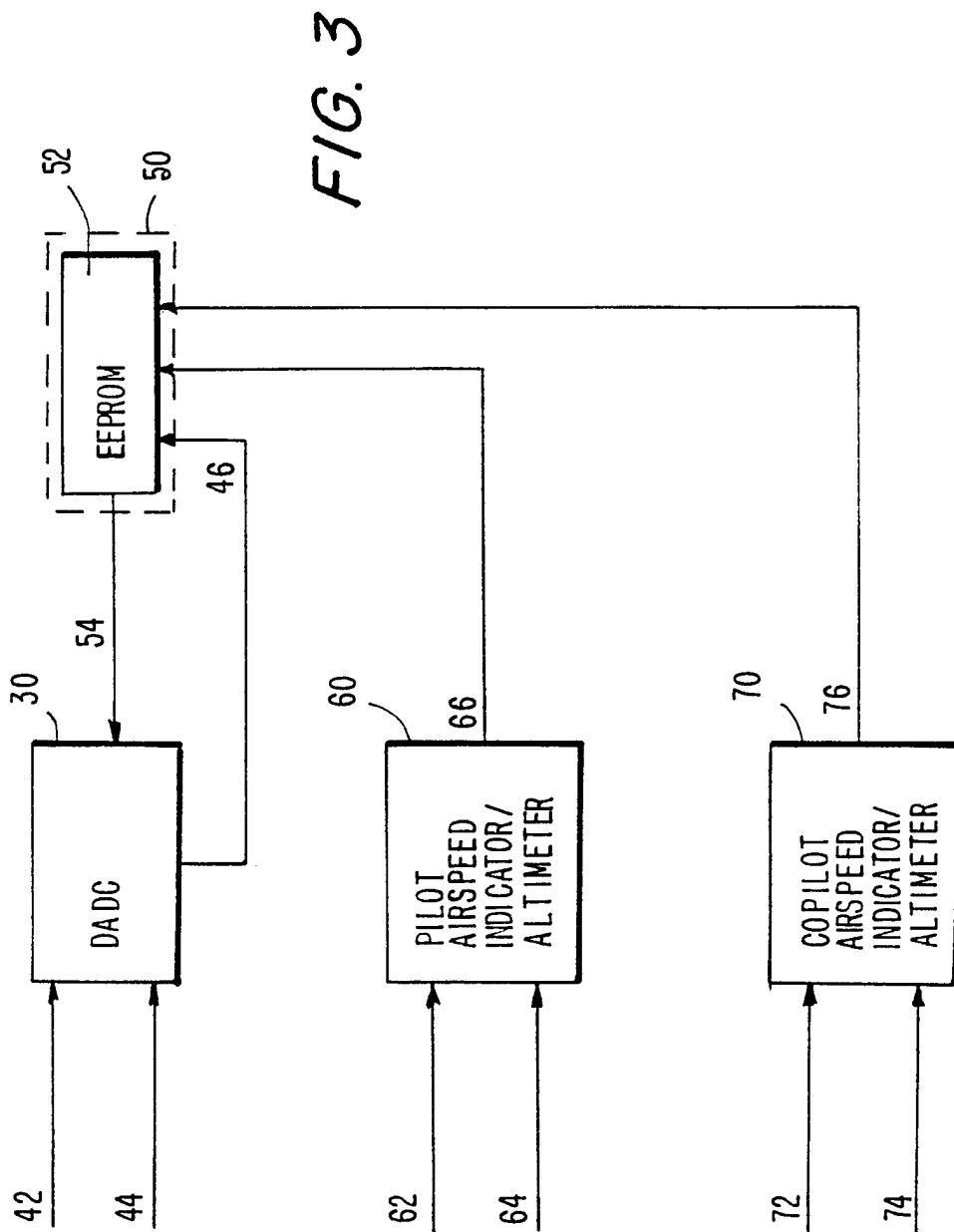
1 / 3

FIG. 1

2 / 3

FIG. 2

```
┌─────────────────────┐
│ OBTAIN STATIC IMPACT │
│ PRESSURES AND GPS    │──104 ◄─────────┐
│ DATA                 │                │
└─────────┬───────────┘                │
          │                            │
          ▼                            │
┌─────────────────────┐                │
│ STORE AND TIME STAMP │──106          │
│ GPS DATA             │               │
└─────────┬───────────┘                │
          │                            │
          ▼                            │
┌─────────────────────┐                │
│ COMPUTE PRESSURE     │               │
│ ALTITUDE, AIRSPEED   │──108          │
│ AND GEOMETRIC HEIGHT │               │
└─────────┬───────────┘                │
          │                            │
          ▼                            │
┌─────────────────────┐                │
│ PAUSE FOR A          │               │
│ PSEUDO-RANDOM        │──110          │
│ TIME PERIOD, ti      │               │
└─────────┬───────────┘                │
          │                            │
          ▼                            │
┌─────────────────────┐                │
│ TRANSMIT PRESSURE    │               │
│ ALTITUDE, AIRSPEED,  │──112          │
│ TIME STAMPED GPS     │               │
│ DATA                 │               │
└─────────┬───────────┘                │
          │                            │
          ▼                            │
        114                            │
```
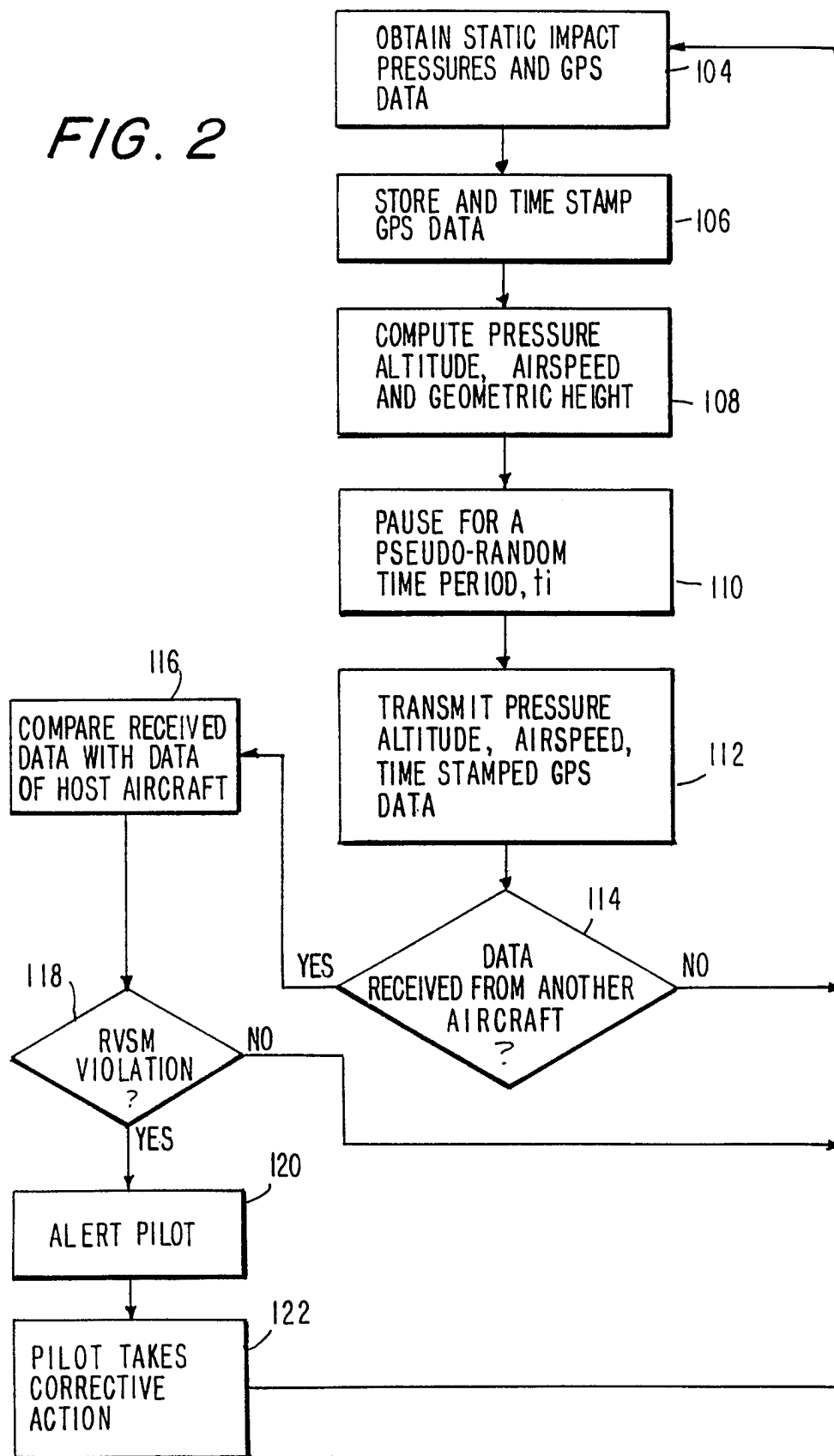
COMPARE RECEIVED DATA WITH DATA OF HOST AIRCRAFT — 116

DATA RECEIVED FROM ANOTHER AIRCRAFT ? — 114

YES / NO

RVSM VIOLATION ? — 118

NO / YES

ALERT PILOT — 120

PILOT TAKES CORRECTIVE ACTION — 122

3 / 3

FIG. 3

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(6) :G01S 3/02, 13/00; H04B 7/185
US CL :342/455, 357, 29
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)
U.S. : 342/455, 357, 29

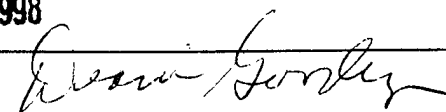| Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched |
|---|
| |

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,596,332 A (COLES et al) 21 January 1997 (21/01/97), col. 3, lines 15-52, col. 9, lines 9-19, col. 10, lines 55-63	1-5
X	US 5,450,329 A (TANNER) 12 September 1995 (12/09/95), Figs. 1-2, col. 5, lines 1-43	1-5
X	US 5,325,302 A (IZIDON et al) 28 June 1994 (28/06/94), Fig. 1, col. 2, lines 43-52, col. 4, lines 12-34	1-5
X,P	US 5,636,123 A (RICH et al) 03 June 1997 (03/06/97), entire document	1-5
X	US 5,153,836 A (FRAUGHTON et al) 06 October 1992 (06/10/92), Figure 3	1-5

X	Further documents are listed in the continuation of Box C.		See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
"O"	document referring to an oral disclosure, use, exhibition or other means	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10 JUNE 1998	1 6 JUL 1998

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks	
Box PCT	
Washington, D.C. 20231	GREGORY C. ISSING
Facsimile No. (703) 305-3230	Telephone No. (703) 306-4156

Form PCT/ISA/210 (second sheet)(July 1992)★

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,570,095 A (DROUILHET, Jr. et al), 29 October 1996 (29/10/96), col. 2, lines 1-9	1-5
A	US 5,506,587 A (LANS) 09 April 1996 (09/04/96) col. 8, lines 30-67	1-5
A	US 4,835,537 A (MANION) 30 May 1989 (30/05/89), Figure 1	