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**Feng et al.**

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(54) **SYSTEM, APPARATUS, AND METHOD USING ADS-B AND TCAS DATA FOR DETERMINING NAVIGATION SOLUTIONS FOR A VEHICLE**

(58) **Field of Classification Search**  
CPC ..... G08G 5/045; G08G 1/162; G08G 5/0008; G08G 5/0039; G08G 5/0078  
USPC ..... 701/1, 120  
See application file for complete search history.

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(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 163 days.

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*Primary Examiner* — Ronnie M Mancho

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(57) **ABSTRACT**

(65) **Prior Publication Data**

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A system using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining navigation solutions for a vehicle is provided. The system has a communal position system (CPS) with a CPS sensor located in the vehicle. The CPS sensor receives ADS-B data and TCAS data from each of one or more proximate vehicles. The system further has a computer system coupled to the CPS. The computer system is configured to perform the steps of: checking the ADS-B data and the TCAS data for data reasonableness; performing data synchronization of the ADS-B data and the TCAS data; and computing a CPS position and a position accuracy based on the ADS-B data and the TCAS data. The navigation solutions include an alternate navigation solution, an independent navigation solution, and a complementary navigation solution.

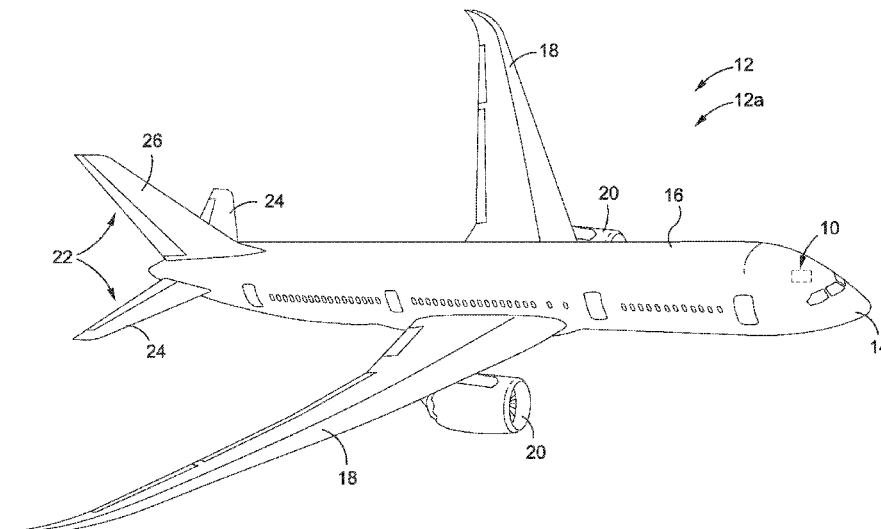
(51) **Int. Cl.**

<b>G06F 19/00</b>	(2018.01)
<b>G08G 5/04</b>	(2006.01)
<b>G08G 5/00</b>	(2006.01)
<b>G01S 19/48</b>	(2010.01)
<b>G01S 5/00</b>	(2006.01)
<b>G01S 13/87</b>	(2006.01)
<b>G01S 13/93</b>	(2006.01)

(52) **U.S. Cl.**

CPC ..... **G08G 5/045** (2013.01); **G01S 5/0072** (2013.01); **G01S 13/878** (2013.01); **G01S 19/48** (2013.01); **G08G 5/0008** (2013.01); **G08G 5/0078** (2013.01); **G01S 13/9303** (2013.01)

**21 Claims, 11 Drawing Sheets**



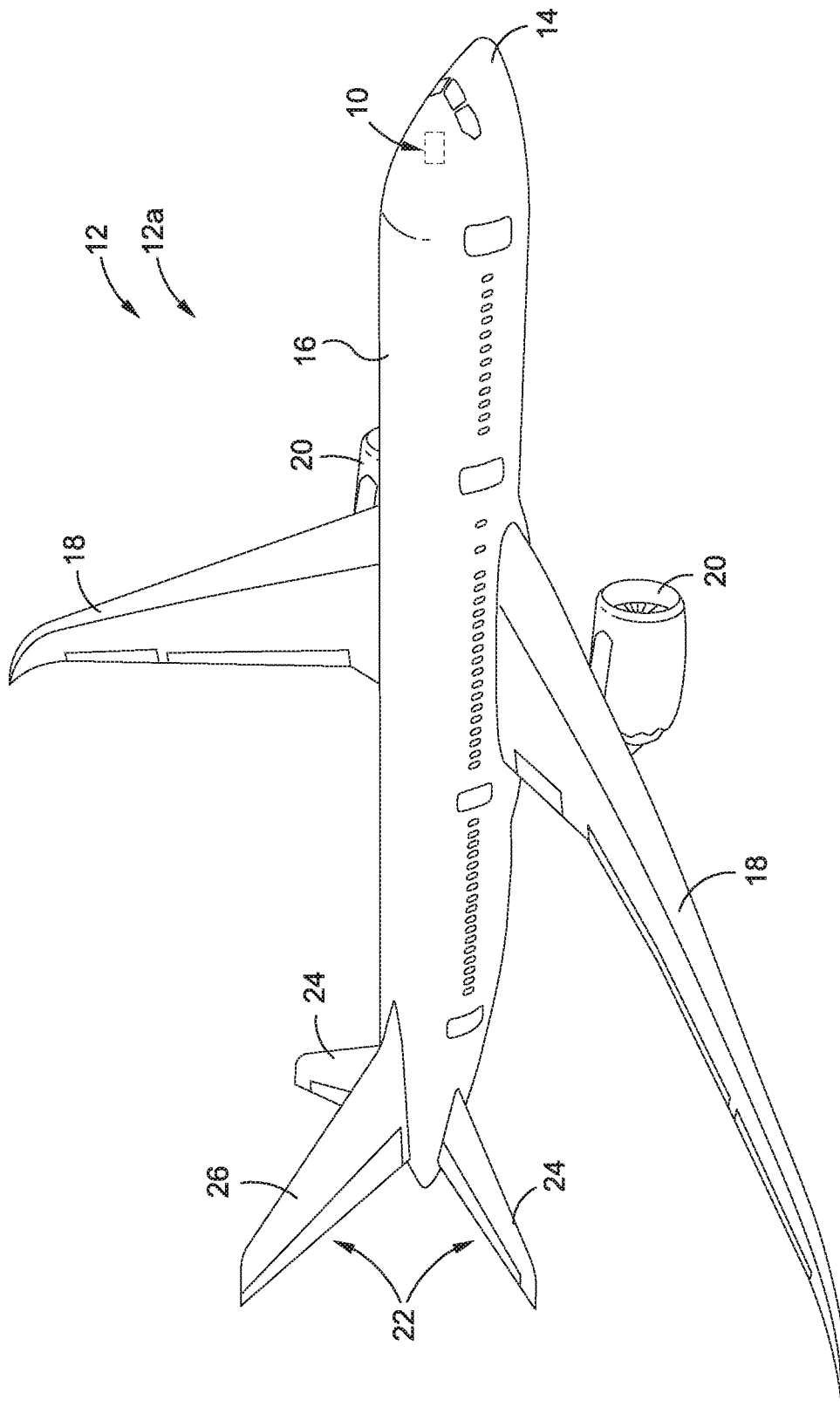


FIG. 1

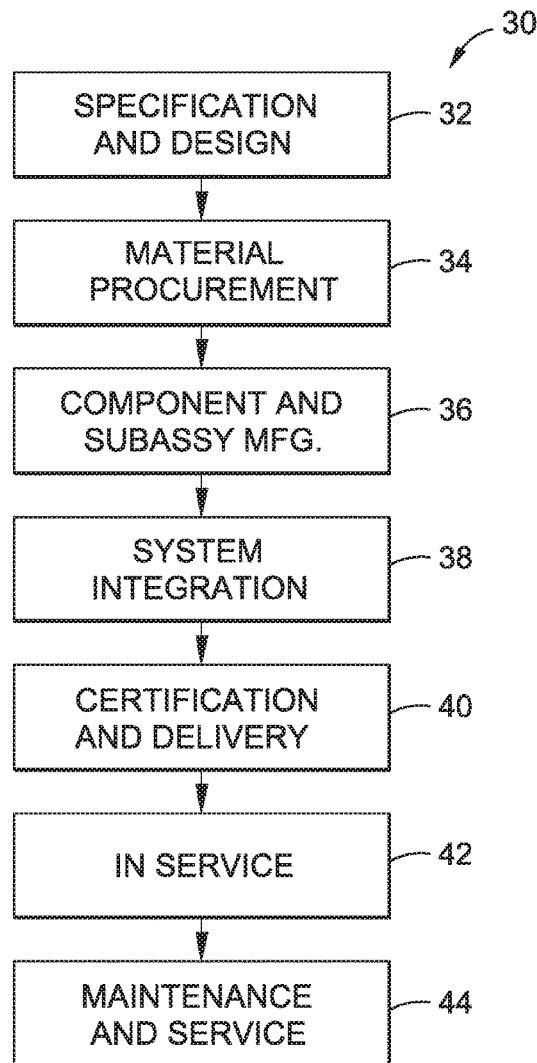


FIG. 2

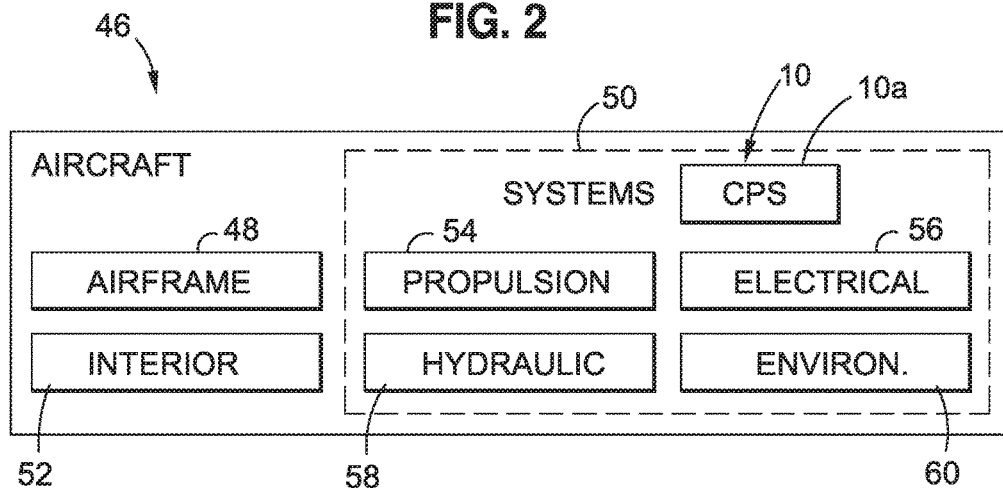


FIG. 3

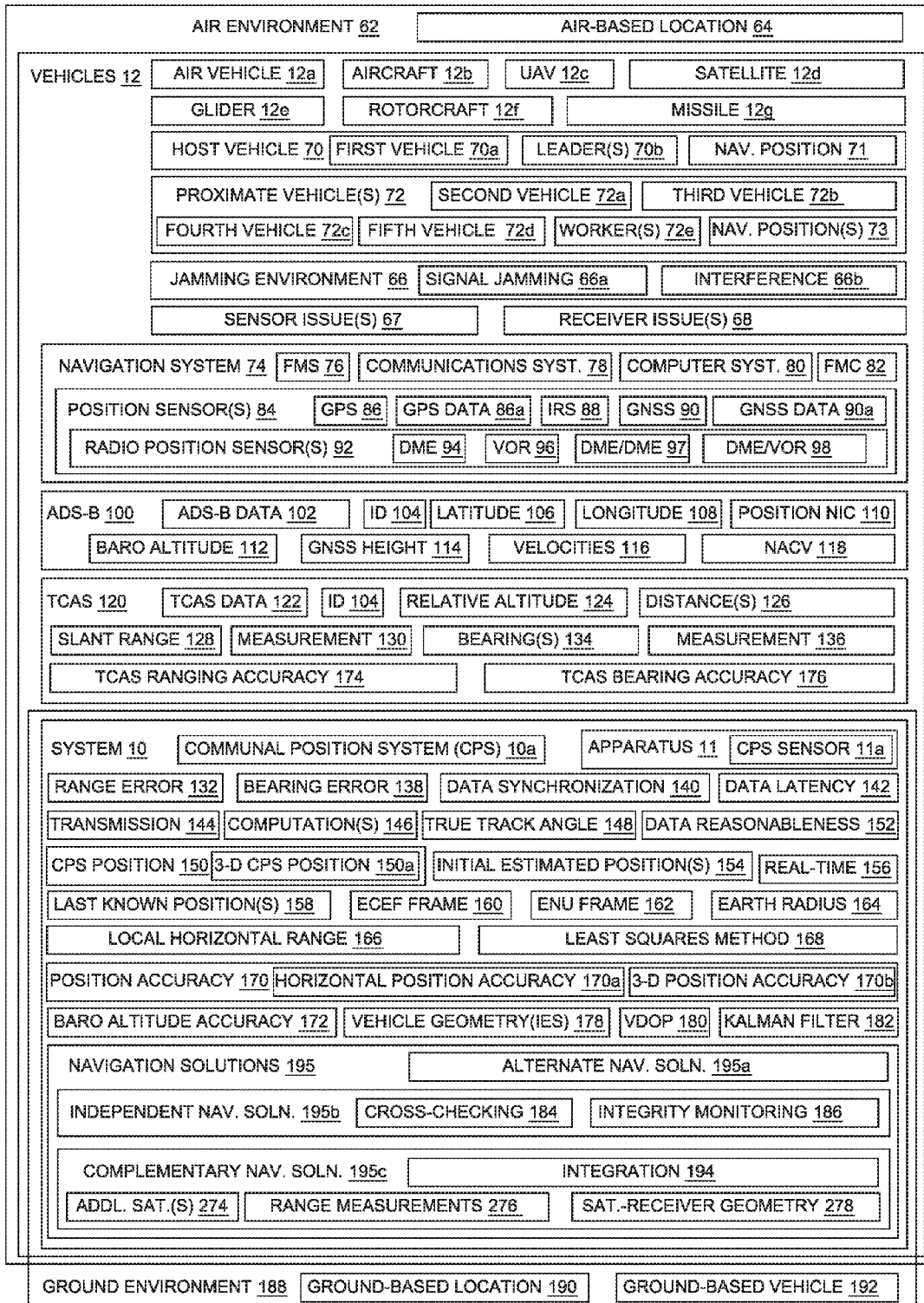


FIG. 4

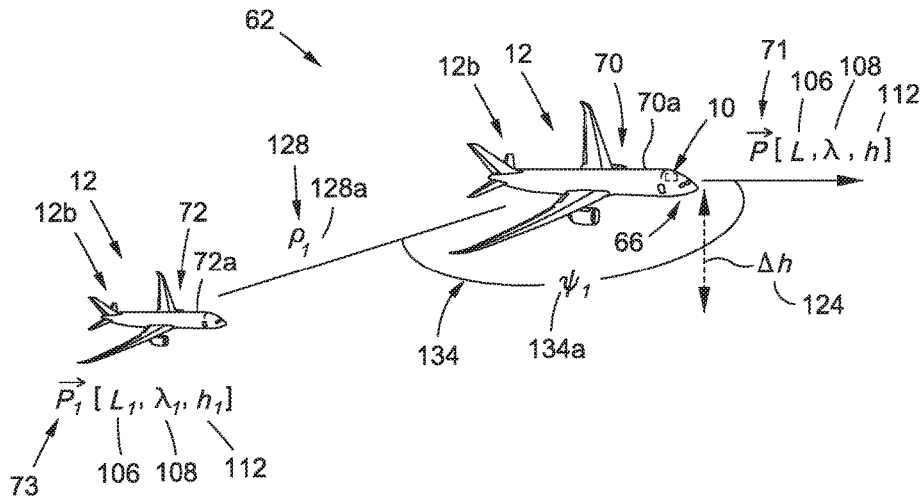


FIG. 5

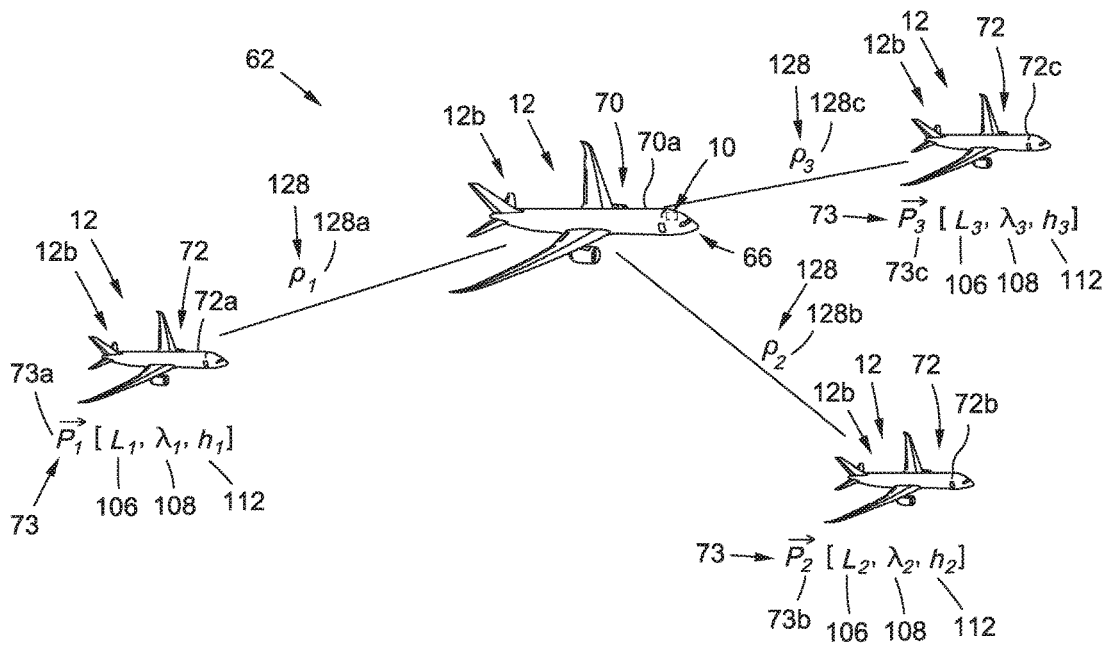


FIG. 6A

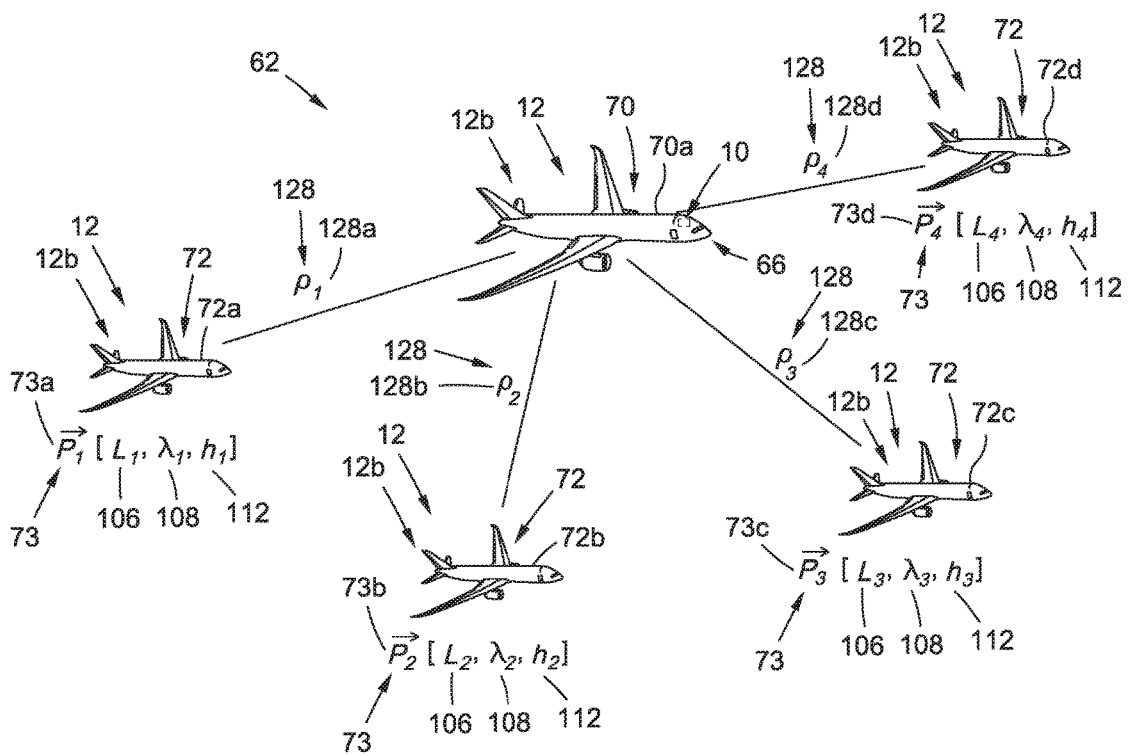
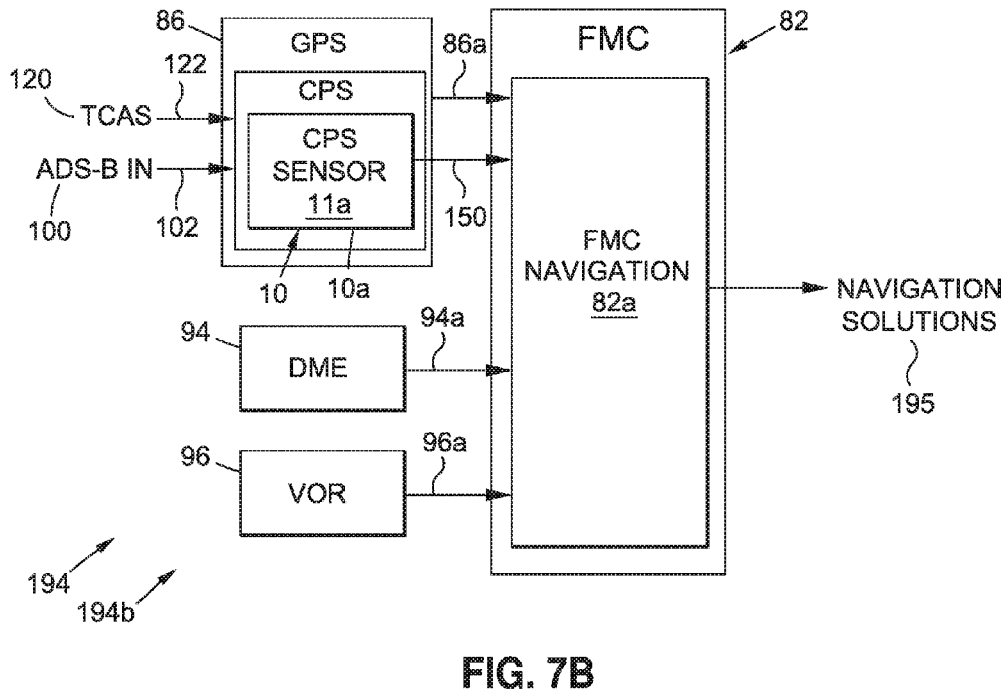
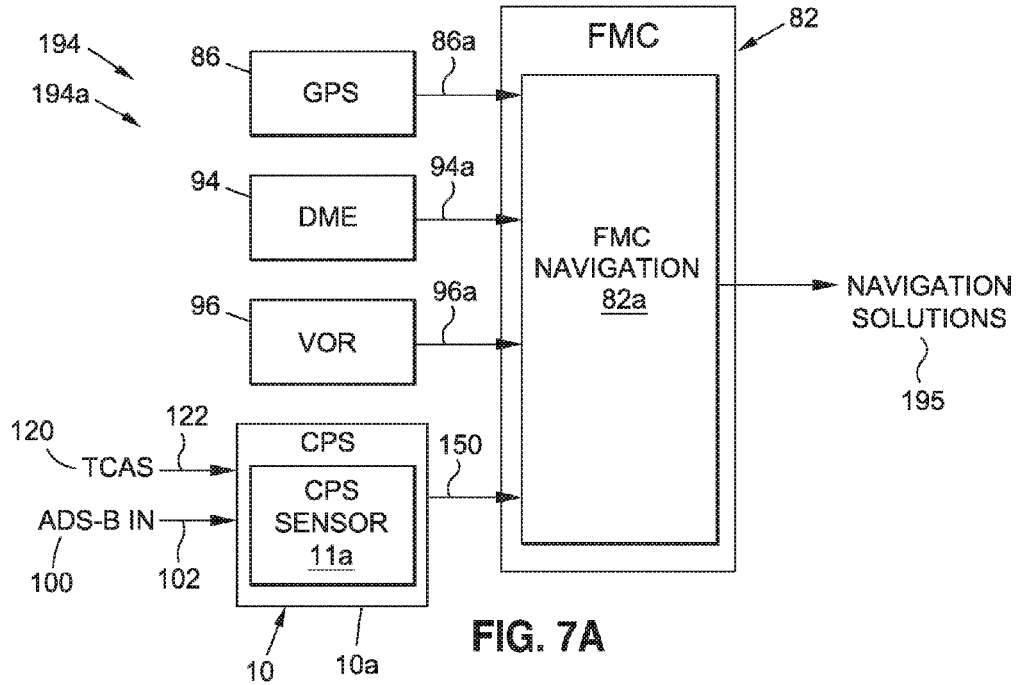


FIG. 6B



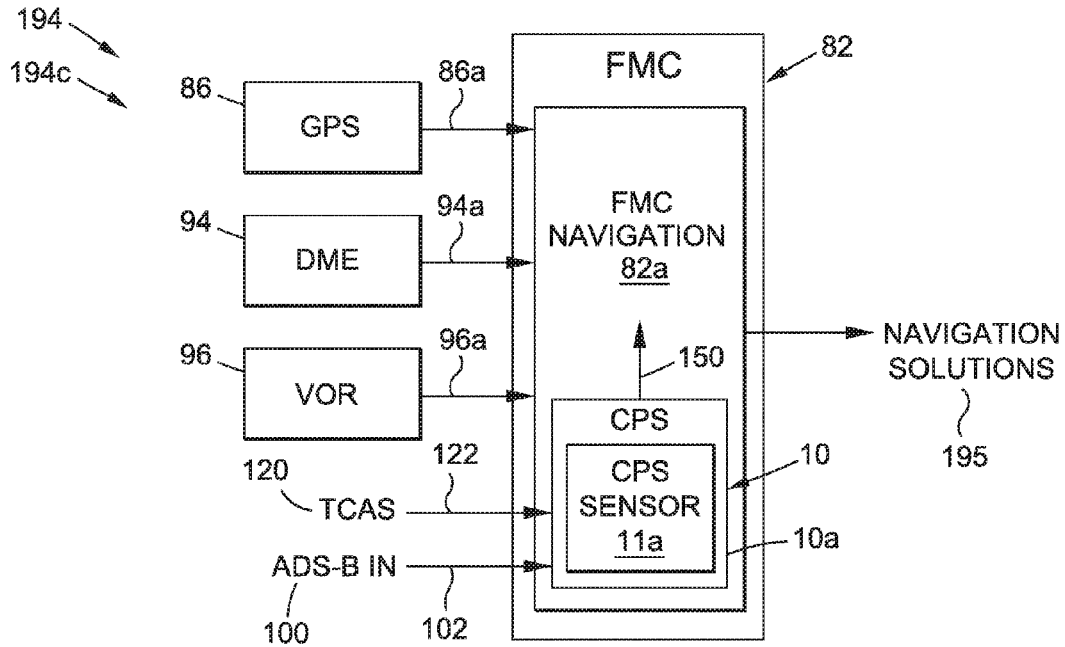


FIG. 7C

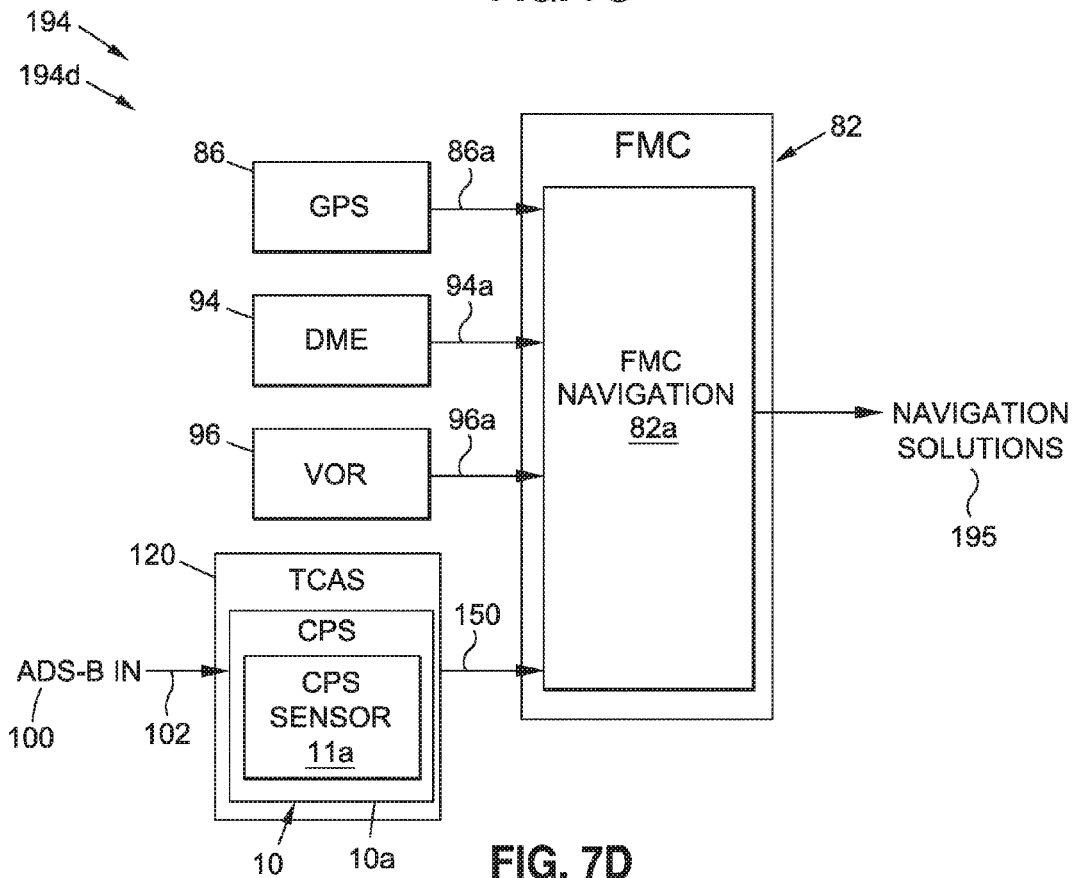


FIG. 7D





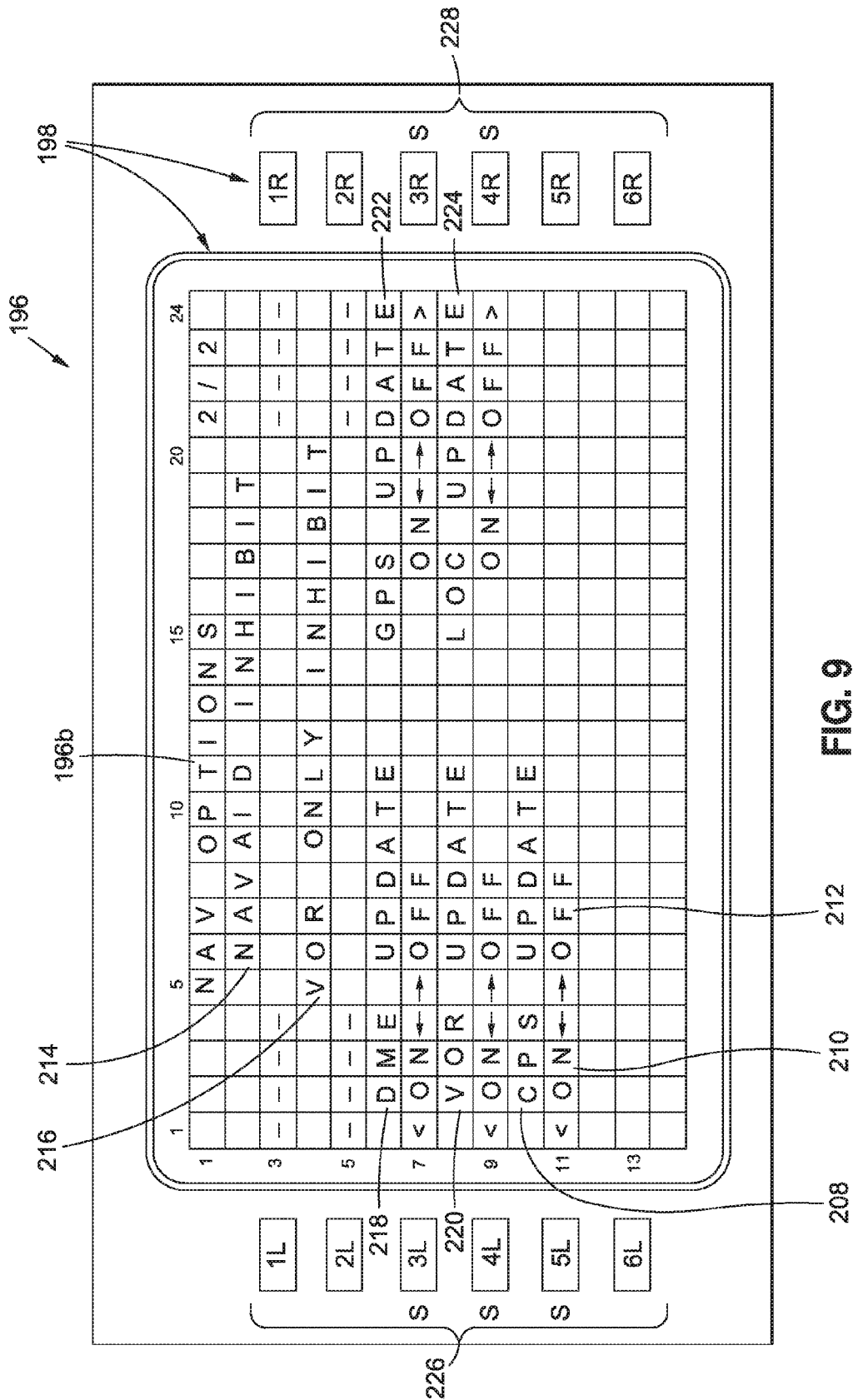


FIG. 9

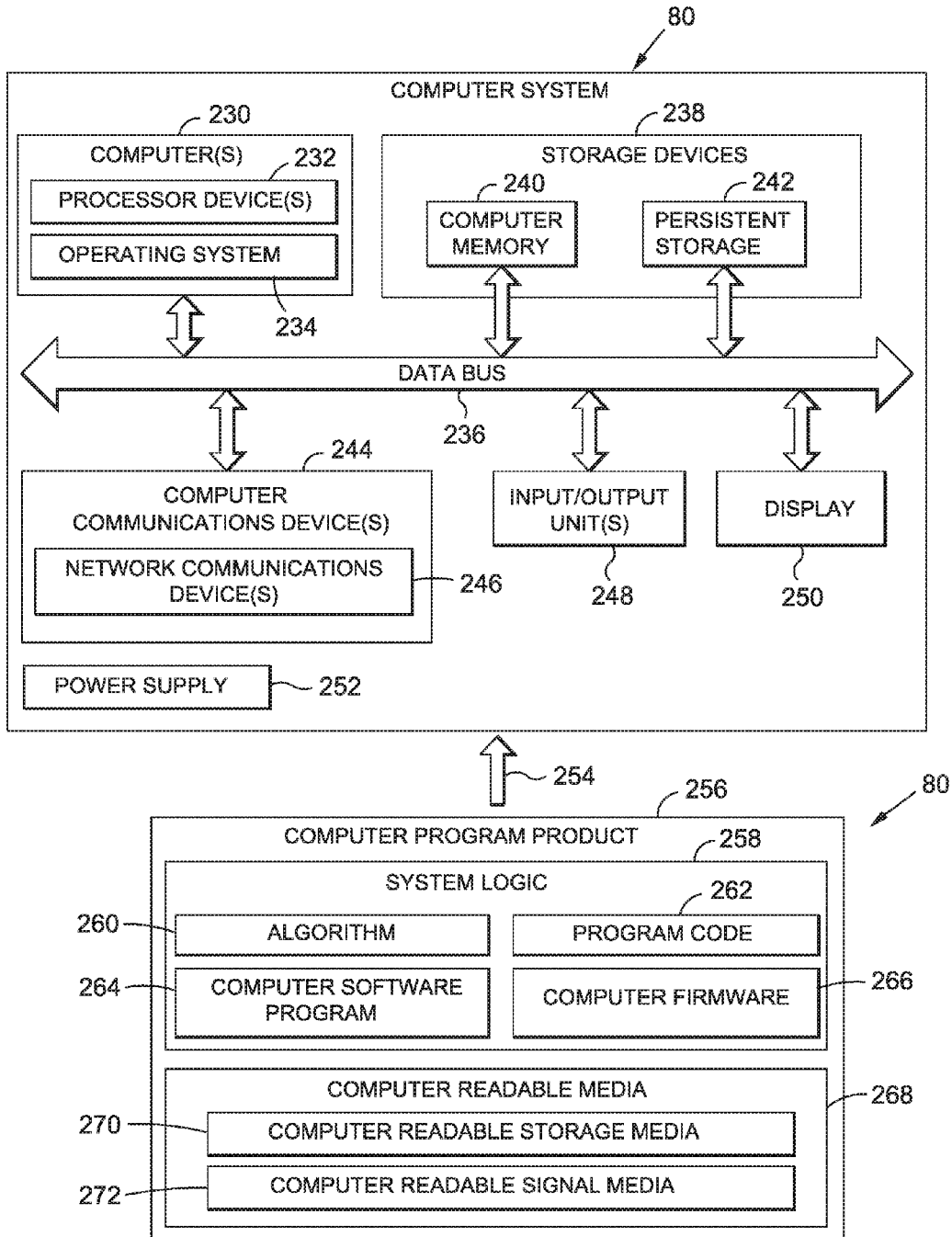


FIG. 10

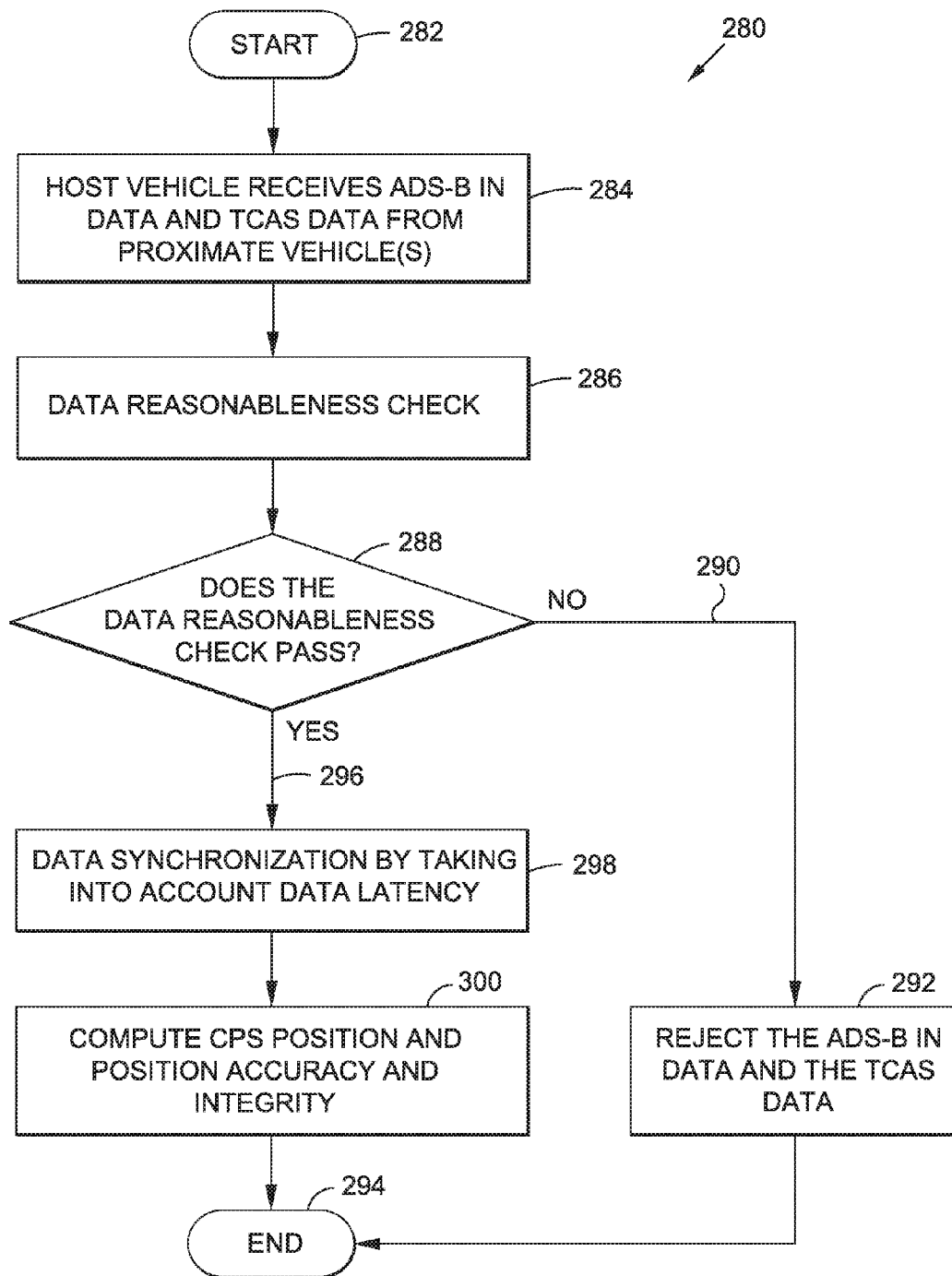


FIG. 11

**SYSTEM, APPARATUS, AND METHOD  
USING ADS-B AND TCAS DATA FOR  
DETERMINING NAVIGATION SOLUTIONS  
FOR A VEHICLE**

BACKGROUND

1) Field of the Disclosure

The disclosure relates generally to vehicle navigation and position determination systems, apparatuses, and methods, and more particularly, to air vehicle navigation and position determination systems, apparatuses, and methods, using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data.

2) Description of Related Art

Vehicles, such as air vehicles, in the form of aircraft or unmanned aerial vehicles (UAVs), typically use navigation and position determination systems, apparatuses, and methods to provide information about the position of the air vehicle during flight, and on take-off and landing. Such air vehicles may commonly be equipped with known onboard position sensors, such as inertial reference system (IRS) sensors, global navigation satellite system (GNSS) sensors, including global positioning system (GPS) sensors, and radio position sensors, for example, those using data from DME (distance measuring equipment) and VOR (very high frequency omnidirectional ranging) receivers. Such onboard position sensors may be used to identify an aircraft's position.

However, such known onboard position sensors may be susceptible to operational and reliability issues, such as sensor receivers becoming nonoperational, may be susceptible to disruption, such as loss of sensor signal, and may be susceptible to interference, such as signal jamming. These may occur unintentionally or deliberately, such as due to outside influences. Such operational issues, signal disruption, and signal jamming may result in lost or inaccurate data, in particular, if there are no similar back-up sensors available. Moreover, while GPS systems, which acquire positioning information from satellites, may provide positioning information to an air vehicle almost anywhere, the availability of such satellite-based systems may be limited due to factors such as satellite geometry. In addition, DME and VOR receivers typically require ground stations or ground infrastructure.

Further, when a group of air vehicles, including UAVs, operate in a relatively close range, either to go from one point to another point, or to perform a single task cooperatively, all of the air vehicles in the group typically need to be equipped with known onboard position sensors, such as IRS sensors, GNSS sensors, and radio position sensors, in order to identify the positions of the air vehicles. Equipping and installing such known onboard position sensors into all of the air vehicles in the group may be expensive, time-consuming, and labor intensive.

In addition, air vehicles are commonly equipped with an automatic position broadcast system, such as automatic dependent surveillance-broadcast ("ADS-B") that may broadcast ADS-B information, such as air vehicle identification, position, velocities, and other information to nearby air vehicles. Air vehicles may also be commonly equipped with traffic alert and collision avoidance system (TCAS) for monitoring the airspace around the vehicle and the position of other air vehicles operating nearby the air vehicle. However, known systems, apparatuses, and methods for air vehicle navigation and position determination do not use data from TCAS and ADS-B, such as receiving information,

as an independent or alternate air vehicle navigation position solution, or as a complementary air vehicle navigation solution for integration with known onboard position sensors.

Accordingly, there is a need in the art for an improved system, apparatus, and method for using data from ADS-B and TCAS for determining navigation and position solutions in vehicles, such as air vehicles, and that provide advantages over known air vehicle navigation and position systems, apparatuses, and methods.

SUMMARY

This need for an improved system, apparatus, and method for using data from ADS-B and TCAS for determining navigation and position solutions in vehicles, such as air vehicles, is satisfied by this disclosure. As discussed in the below detailed description, embodiments of the improved system, apparatus, and method for using data from ADS-B and TCAS for determining navigation and position solutions in vehicles, such as air vehicles, may provide significant advantages over existing systems, apparatuses, and methods.

In an embodiment of the disclosure, there is provided a system using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining one or more navigation solutions for a vehicle. The system comprises a communal position system (CPS).

The CPS comprises a communal position system (CPS) sensor located in the vehicle. The CPS sensor is configured to receive automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data from each of one or more proximate vehicles.

The system further comprises a computer system coupled to the CPS. The computer system is configured to perform the steps of: checking the ADS-B data and the TCAS data for data reasonableness; performing data synchronization of the ADS-B data and the TCAS data; and computing a communal position system (CPS) position and a position accuracy based on the ADS-B data and the TCAS data.

The CPS is used in determining one or more navigation solutions for the vehicle. The one or more navigation solutions comprise one or more of, an alternate navigation solution, an independent navigation solution, and a complementary navigation solution.

In another embodiment of the disclosure, there is provided an apparatus for using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining one or more navigation solutions for a vehicle. The apparatus comprises a communal position system (CPS) sensor located in the vehicle.

The CPS sensor is configured to receive automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data from each of one or more proximate vehicles, and the CPS sensor is used to determine one or more navigation solutions for the vehicle. The one or more navigation solutions comprises one or more of, an alternate navigation solution, an independent navigation solution, and a complementary navigation solution.

The CPS sensor is coupled to a computer system configured to perform the steps of: checking the ADS-B data and the TCAS data for data reasonableness; performing data synchronization of the ADS-B data and the TCAS data; and

computing a communal position system (CPS) position and a position accuracy based on the ADS-B data and the TCAS data.

In another embodiment of the disclosure, there is provided a computer implemented method for using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining one or more navigation solutions for a vehicle. The method comprises the step of receiving, by a communal position system (CPS) in the vehicle, automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data, from each of one or more proximate vehicles.

The method further comprises the step of conducting a data reasonableness check of the ADS-B data and the TCAS data using a computer system coupled to the CPS. The method further comprises the step of rejecting the ADS-B data and the TCAS data, if the data reasonableness check does not pass.

The method further comprises the step of performing, with the computer system, a data synchronization of the ADS-B data and the TCAS data, if the data reasonableness check passes. The data synchronization takes into account a data latency due to a transmission and a computation of the ADS-B data and the TCAS data.

The method further comprises the step of computing, with the computer system, a communal position system (CPS) position and a position accuracy based on the ADS-B data and the TCAS data, and determining one or more navigation solutions for the vehicle. The one or more navigation solutions comprises one or more of, an alternate navigation solution, an independent navigation solution, and a complementary navigation solution.

The features, functions, and advantages that have been discussed can be achieved independently in various embodiments of the disclosure or may be combined in yet other embodiments further details of which can be seen with reference to the following description and drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The disclosure can be better understood with reference to the following detailed description taken in conjunction with the accompanying drawings which illustrate preferred and exemplary embodiments, but which are not necessarily drawn to scale, wherein:

FIG. 1 is a diagrammatic representation of a perspective view of a vehicle that may incorporate an embodiment of a system of the disclosure;

FIG. 2 is a flow diagram of an embodiment of an aircraft manufacturing and service method;

FIG. 3 is an illustration of a functional block diagram of an embodiment of an aircraft;

FIG. 4 is an illustration of a functional block diagram of an embodiment of a system of the disclosure in a vehicle;

FIG. 5 is an illustration of a schematic diagram of an embodiment of a host vehicle with the system of the disclosure using one proximate vehicle;

FIG. 6A is an illustration of a schematic diagram of an embodiment of a host vehicle with the system of the disclosure using multiple proximate vehicles;

FIG. 6B is an illustration of a schematic diagram of another embodiment of a host vehicle with the system of the disclosure using multiple proximate vehicles;

FIG. 7A is schematic diagrams of an embodiment of a sensor integration of the communal position system (CPS) sensor of the disclosure;

FIG. 7B is schematic diagram of an embodiment of a GPS integration with the communal position system (CPS) sensor of the disclosure;

FIG. 7C is schematic diagram of an embodiment of a flight management computer (FMC) integration with the communal position system (CPS) sensor of the disclosure;

FIG. 7D is schematic diagram of an embodiment of a TCAS integration with the communal position system (CPS) sensor of the disclosure;

FIG. 8 is an illustration of a cockpit control display unit (CDU) for a position reference CDU that incorporates a communal position system (CPS) display for the communal position system (CPS) of the disclosure;

FIG. 9 is an illustration of a cockpit control display unit (CDU) for a navigation options control CDU that incorporates a communal position system (CPS) display for the communal position system (CPS) of the disclosure;

FIG. 10 is an illustration of a functional block diagram showing an exemplary embodiment of a computer system that may be used with one or more embodiments of the system, apparatus, and method of the disclosure; and

FIG. 11 is an illustration of a flow diagram showing an embodiment of a method of the disclosure.

The figures shown in this disclosure represent various aspects of the embodiments presented, and only differences will be discussed in detail.

#### DETAILED DESCRIPTION

Disclosed embodiments will now be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all of the disclosed embodiments are shown. Indeed, several different embodiments may be provided and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and fully convey the scope of the disclosure to those skilled in the art.

Now referring to the Figures, FIG. 1 is a diagrammatic representation of a perspective view of a vehicle 12, such as in the form of an air vehicle 12a, that may incorporate an embodiment of a system 10 of the disclosure. As further shown in FIG. 1, the vehicle 12, such as in the form of air vehicle 12a, comprises a nose 14, fuselage 16, wings 18, engines 20, and an empennage 22 comprising horizontal stabilizers 24 and a vertical stabilizer 26. The vehicle 12 (see FIGS. 1, 4) may also be in the form of an aircraft 12b (see FIG. 4), an unmanned air vehicle (UAV) 12c (see FIG. 4), a satellite 12d (see FIG. 4), a glider 12e (see FIG. 4), a rotorcraft 12f (see FIG. 4), a missile 12g (see FIG. 4), or another suitable vehicle.

Now referring to FIGS. 2 and 3, FIG. 2 is a flow diagram of an embodiment of an aircraft manufacturing and service method 30, and FIG. 3 is an illustration of a functional block diagram of an embodiment of an aircraft 46. Referring to FIGS. 2-3, embodiments of the disclosure may be described in the context of the aircraft manufacturing and service method 30, as shown in FIG. 2, and the aircraft 46, as shown in FIG. 3. During pre-production, the exemplary aircraft manufacturing and service method 30 (see FIG. 2) may include specification and design 32 (see FIG. 2) of the aircraft 46 (see FIG. 3) and material procurement 34 (see FIG. 2). During manufacturing, component and subassembly manufacturing 36 (see FIG. 2) and system integration 38 (see FIG. 2) of the aircraft 46 (see FIG. 3) takes place. Thereafter, the aircraft 46 (see FIG. 3) may go through certification and delivery 40 (see FIG. 2) in order to be placed in service 42 (see FIG. 2). While in service 42 (see

FIG. 2) by a customer, the aircraft 46 (see FIG. 3) may be scheduled for routine maintenance and service 44 (see FIG. 2), which may also include modification, reconfiguration, refurbishment, and other suitable services.

Each of the processes of the aircraft manufacturing and service method 30 (see FIG. 2) may be performed or carried out by a system integrator, a third party, and/or an operator (e.g., a customer). For the purposes of this description, a system integrator may include, without limitation, any number of aircraft manufacturers and major-system subcontractors; a third party may include, without limitation, any number of vendors, subcontractors, and suppliers; and an operator may include an airline, leasing company, military entity, service organization, and other suitable operators.

As shown in FIG. 3, the aircraft 46 produced by the exemplary aircraft manufacturing and service method 30 may include an airframe 48 with a plurality of systems 50 and an interior 52. As further shown in FIG. 3, examples of the systems 50 may include one or more of a propulsion system 54, an electrical system 56, a hydraulic system 58, an environmental system 60, and the system 10, such as in the form of communal position system (CPS) 10a, disclosed herein. Any number of other systems may be included. Although an aerospace example is shown, the principles of the disclosure may be applied to other industries, such as the automotive industry, including automotive vehicles, the marine industry, including watercraft, ships, and submarines, and other suitable industries.

Methods and systems embodied herein may be employed during any one or more of the stages of the aircraft manufacturing and service method 30 (see FIG. 2). For example, components or subassemblies corresponding to component and subassembly manufacturing 36 (see FIG. 2) may be fabricated or manufactured in a manner similar to components or subassemblies produced while the aircraft 46 (see FIG. 3) is in service 42 (see FIG. 2). Also, one or more apparatus embodiments, method embodiments, or a combination thereof, may be utilized during component and subassembly manufacturing 36 (see FIG. 2) and system integration 38 (see FIG. 2), for example, by substantially expediting assembly of or reducing the cost of the aircraft 46 (see FIG. 3). Similarly, one or more of apparatus embodiments, method embodiments, or a combination thereof, may be utilized while the aircraft 46 (see FIG. 3) is in service 42 (see FIG. 2), for example and without limitation, to maintenance and service 44 (see FIG. 2).

Now referring to FIG. 4, FIG. 4 is an illustration of a functional block diagram of an embodiment of a system 10, such as in the form of communal position system (CPS) 10a, of the disclosure, in the vehicle 12. The system 10, such as in the form of CPS 10a, may be used in an air environment 62, such as in an air-based location 64, for example, in an air vehicle 12a, or may be used in a ground environment 188, such as in a ground-based location 190, for example, in a ground-based vehicle 192. The system 10, such as in the form of CPS 10a, uses automatic dependent surveillance-broadcast (ADS-B) data 102 (see FIG. 4) and traffic alert and collision avoidance system (TCAS) data 122 (see FIG. 4) for determining one or more navigation solutions 195 (see FIG. 4) for the vehicle 12.

The system 10, such as in the form of CPS 10a, comprises an apparatus 11 (see FIG. 4), such as a communal position system (CPS) sensor 11a (see FIG. 4), located in the vehicle 12. The vehicle 12 (see FIG. 4) may comprise a host vehicle 70 (see FIGS. 4, 5), such as a first vehicle 70a (see FIGS. 4, 5), having a navigation position 71 (see FIGS. 4, 5). The vehicle 12 (see FIGS. 4, 6A-6B) may further comprise one

or more proximate vehicles 72 (see FIGS. 4, 6A-6B), such as a second vehicle 72a (see FIGS. 4, 6A-6B), a third vehicle 72b (see FIGS. 4, 6A-6B), a fourth vehicle 72c (see FIGS. 4, 6A-6B), and a fifth vehicle 72d (see FIGS. 4, 6B), each having a navigation position 73 (see FIGS. 4, 6A-6B). The vehicle 12, such as the host vehicle 70 and the one or more proximate vehicles 72, may each comprise an aircraft 12b, an unmanned air vehicle 12c, a satellite 12d, a glider 12e, a rotorcraft 12f, a missile 12g, or another suitable vehicle.

The system 10, such as in the form of CPS 10a, with the CPS sensor 11a, may be used when the vehicle 12 (see FIGS. 4-6B) is in a jamming environment 66 (see FIGS. 4-6B), such as experiencing signal jamming 66a (see FIG. 4) or interference 66b (see FIG. 4). The system 10, such as in the form of CPS 10a, with the CPS sensor 11a, may also be used when the vehicle 12 (see FIG. 4) experiences sensor issues 67 (see FIG. 4) such as non-operation, or experiences receiver issues 68 (see FIG. 4).

As shown in FIG. 4, the vehicle 12 comprises a navigation system 74 comprising a flight management system 76, a communications system 78, a computer system 80 (see also FIG. 10), a flight management computer 82, and a plurality of position sensors 92. As further shown in FIG. 4, the plurality of position sensors 92 may comprise a global positioning system (GPS) 86 that outputs GPS data 86a, an inertial reference system (IRS) 88, a global navigation satellite system (GNSS) 90 that outputs GNSS data 90a, and one or more radio position sensors 92 using data from DME (distance measuring equipment) 94 (see FIG. 4) and VOR (very high frequency omnidirectional ranging) 96 (see FIG. 4) receivers. The radio positions may comprise a DME/DME 97 (see FIG. 4) position and a DME/VOR 98 (see FIG. 4) position determined using data from DME 94 (see FIG. 4) and VOR 96 receivers.

The CPS (10a) may be integrated in one of, the FMC 82 (see FIG. 4) in the host vehicle 70, the GPS 86 (see FIG. 4) in the host vehicle 70, the TCAS 120 in the host vehicle (70), or in another suitable integration 194 (see FIG. 4), apparatus, or device.

The system 10, such as in the form of CPS 10a, with the CPS sensor 11a is configured to receive automatic dependent surveillance-broadcast (ADS-B) data 102 from each of the one or more proximate vehicles 72 in proximity to the host vehicle 70, through an automatic dependent surveillance-broadcast (ADS-B) 100 (see FIG. 4), and is configured to receive traffic alert and collision avoidance system (TCAS) data 122 from each of the one or more proximate vehicles 72, through a traffic alert and collision avoidance system (TCAS) 120 (see FIG. 4).

The CPS sensor 11a receives ADS-B data 102 through ADS-B In (input) data from each of the one or more proximate vehicles 72, which each have ADS-B Out (output). As shown in FIG. 4, the ADS-B data 102 for each of the one or more proximate vehicles 72 comprises one or more of, identification information 104 for each proximate vehicle 72, a latitude 106 for each proximate vehicle 72, a longitude 108 for each proximate vehicle 72, a position navigation integrity category (NIC) 110 for each proximate vehicle 72, a barometric altitude 112 for each proximate vehicle 72, a global navigation satellite system (GNSS) height 114 for each proximate vehicle 72, a plurality of velocities 116 for each proximate vehicle 72, and a navigation accuracy category for velocity (NACv) 118 for each proximate vehicle 72. Based on an existing industry specification, the ADS-B data 102 may be received by the host vehicle 70 (see FIGS. 4-6B) at 2 Hz (Hertz) from the one or more proximate vehicles 72 (see FIGS. 4-6B), the baromet-

ric altitude **112** may be at a 100 ft (foot) increment, and the plurality of velocities **116** may comprise North/South (N/S), East/West (E/W), and vertical velocities.

The CPS sensor **11a** receives TCAS data **122** from each of the one or more proximate vehicles **72**. As shown in FIG. **4**, the TCAS data **122** for each of the one or more proximate vehicles **72** comprises one or more of, identification information **104** for each proximate vehicle **72**, a slant range **128** for each proximate vehicle **72**, a bearing **134** for each proximate vehicle **72**, and a relative altitude **124** for each proximate vehicle **72**. Based on an existing industry specification, the TCAS data **122** may be received by the host vehicle **70** (see FIGS. **4-6B**) with an update rate of 1 Hz (Hertz) from the one or more proximate vehicles **72** (see FIGS. **4-6B**). The slant range **128** (see FIG. **4**) may have a range error **132** (see FIG. **4**) of 50 feet (rms (root mean square)) and 250 feet bias. The bearing **134** (see FIG. **4**) may have a bearing error **138** (see FIG. **4**) of less than 9 degrees (rms), 27 degrees peak from -10 degrees to +10 degrees elevation, and less than 15 degrees (rms), 45 degrees peak from +10 to +20 degrees elevation. The relative altitude **124** (see FIG. **4**) may have a 100 ft (foot) resolution.

By using bearings **134** (see FIG. **4**) and distances **126** (see FIG. **4**) from the one or more proximate vehicles **72** (see FIGS. **4-6B**) through TCAS **120** (see FIG. **4**) and by using the ADS-B data **102** from the one or more proximate vehicles **72** (see FIGS. **4-6B**) through ADS-B **100** (see FIG. **4**), an independent position solution **195b** (see FIG. **4**) can be computed in a ground-based location **190** (see FIG. **4**) or in an air-based location **64** (see FIG. **4**). The CPS **10a** (see FIG. **4**) may be used as an alternate navigation solution **195a**, if a position solution using existing techniques is not available, or one or more onboard position sensors **84** (see FIG. **4**) becomes non-operational. The ADS-B data **102** (see FIG. **4**) and the TCAS data **122** (see FIG. **4**) may be integrated with position sensors **84** on the host vehicle **70** (see FIG. **4**) (e.g., global navigation satellite system (GNSS) **90** (see FIG. **4**) position sensor **84** (see FIG. **4**)), or in the FMS **76** (see FIG. **4**), or the FMC **82** (see FIG. **4**) to determine the navigation solutions **195** (see FIGS. **4, 7A-7D**).

In determining the navigation position **71** (see FIGS. **4-5**) of the host vehicle **70** (see FIGS. **4-5**), the TCAS data **122** (see FIG. **4**) and the ADS-B data **102** (see FIG. **4**) from the proximate vehicle **72** (see FIGS. **4, 5**) are initially synchronized and undergo a data synchronization **140** (see FIG. **4**) by taking into account a data latency **142** (see FIG. **4**) due to a transmission **144** (see FIG. **4**) and one or more computations **146** (see FIG. **4**) (in TCAS **120** (see FIG. **4**) for computing bearing **134** (see FIG. **4**) and slant range **128** (see FIG. **4**)).

The TCAS data **122** (see FIG. **4**) of the slant range **128** (see FIG. **4**) and the bearing **134** (see FIG. **4**) are checked for data reasonableness **152** (see FIG. **4**), by a comparison with initial estimated positions **154** (see FIG. **4**) of the slant range **128** (see FIG. **4**) and the bearing **134** (see FIG. **4**). The initial estimated positions **154** (see FIG. **4**) of the slant range **128** (see FIG. **4**) and the bearing **134** (see FIG. **4**) are computed using last known positions **158** (see FIG. **4**) propagated to real-time **156** (see FIG. **4**) and ADS-B data **102** (see FIG. **4**) of the navigation positions **73** (see FIG. **4**) of the one or more proximate vehicles **72** (see FIG. **4**).

The system **10**, such as the CPS **10a** (see FIG. **4**), is computer implemented. The computer system **80** (see FIGS. **4, 10**) is preferably coupled to the CPS **10a** (see FIG. **4**), including the CPS sensor **11a** (see FIG. **4**). The computer system **80** (see FIGS. **4, 10**) comprises at least one computer

**230** (see FIG. **10**) and a processor device **232** (see FIG. **10**) for executing one or more functions of the at least one computer **230** (see FIG. **10**). The computer system **80** (see FIG. **4, 10**) further comprises a computer software program **264** (see FIG. **10**) adapted to perform via the computer **230** and the processor device **232**, the steps of: checking the ADS-B data **102** and the TCAS data **122** for the data reasonableness **152** (see FIG. **4**); performing the data synchronization **140** (see FIG. **4**) of the ADS-B data **102** and the TCAS data **122**; and computing a communal position system (CPS) position **150** (see FIG. **4**) and a position accuracy **170** (see FIG. **4**) based on the ADS-B data **102** and the TCAS data **122**.

As shown in FIG. **4**, the CPS **10a** is used in determining one or more navigation solutions **195** for the vehicle **12**, where the one or more navigation solutions **195** comprise one or more of, an alternate navigation solution **195a**, an independent navigation solution **195b**, and a complementary navigation solution **195c**. The alternate navigation solution **195a** (see FIG. **4**) is used when one or more position sensors **84** on the host vehicle **70** is or becomes non-operational, experiences signal jamming **66a** (see FIG. **4**), experiences interference **66b** (see FIG. **4**), or experiences another problem or issue. The independent navigation solution **195b** (see FIG. **4**) is used for cross-checking **184** (see FIG. **4**) and integrity monitoring **186** (see FIG. **4**) of one or more of the position sensors **84** (see FIG. **4**) on the host vehicle **70** (see FIG. **4**). The complementary navigation solution **195c** (see FIG. **4**) is used when the ADS-B data **102** and the TCAS data **122** from the one or more proximate vehicles **72** is an integration **194** (see FIG. **4**), and for example, is integrated into the GPS **86** (see FIG. **4**), and the one or more proximate vehicles **72** function as additional satellites **274** (see FIG. **4**) providing additional range measurements **276** (see FIG. **4**), to improve a satellite-receiver geometry **278** (see FIG. **4**).

As shown in FIG. **4**, the system **10**, such as in the form of CPS **10a**, includes the apparatus **11**, such as the CPS sensor **11a**. In another embodiment, there is provided the apparatus **11** (see FIG. **4**) for using ADS-B data **102** (see FIG. **4**) and TCAS data **122** (see FIG. **4**) for determining one or more navigation solutions **195** (see FIG. **4**) for a vehicle **12**. The apparatus **11** comprises the communal position system (CPS) sensor **11a** located in the vehicle **12** comprising a host vehicle **70**. The CPS sensor **11a** is configured to receive ADS-B data **102** from each of the one or more proximate vehicles **72** in proximity to the host vehicle **70**, through the ADS-B **100** (see FIG. **4**), and is further configured to receive TCAS data **122** from each of the one or more proximate vehicles **72**, through the TCAS **120**. The CPS sensor **11a** is used to determine one or more navigation solutions **195** (see FIG. **4**) for the vehicle **12**. The one or more navigation solutions **195** comprises one or more of, the alternate navigation solution **195a** (see FIG. **4**), the independent navigation solution **195b** (see FIG. **4**), and the complementary navigation solution **195c** (see FIG. **4**).

The apparatus **11**, such as the CPS sensor **11a**, is computer implemented. The CPS sensor **11a** is coupled to the computer system **80** (see FIGS. **4, 10**) comprising at least one computer **230** (see FIG. **10**) and a processor device **232** (see FIG. **10**) for executing one or more functions of the at least one computer **230** (see FIG. **10**), and further comprising a computer software program **264** (see FIG. **10**) adapted to perform via the computer **230** (see FIG. **10**) and the processor device **232** (see FIG. **10**), the steps, as discussed above, of: checking the ADS-B data **102** and the TCAS data **122** for data reasonableness **152** (see FIG. **4**); performing data synchronization **140** (see FIG. **4**) of the ADS-B data



102 and the TCAS data 122; and computing the communal position system (CPS) position 150 (see FIG. 4) and the position accuracy 170 (see FIG. 4) based on the ADS-B data 102 and the TCAS data 122. The CPS sensor 11a may be integrated in one of, the FMC 82 (see FIG. 4) in the host vehicle 70, the GPS 86 (see FIG. 4) in the host vehicle 70, the TCAS 120 (see FIG. 4) in the host vehicle 70, or another suitable integration 194 (see FIG. 4).

FIG. 5 is an illustration of a schematic diagram of an embodiment of the host vehicle 70, such as the first vehicle 70a, with the system 10 of the disclosure using one proximate vehicle 72, such as the second vehicle 72a to determine a navigation position  $\vec{P}_1$  71 of the host vehicle 70. As shown in FIG. 5, the host vehicle 70 and the proximate vehicle 72 are preferably vehicles 12, such as in the form of aircraft 12b in an air environment 62. As shown in FIG. 5, the host vehicle 70 comprises the first vehicle 70a in a jamming environment 66, and the proximate vehicle 72 comprises the second vehicle 72a. The host vehicle 70 (see FIG. 5) has a bearing ( $\psi$ ) 134 (see FIG. 5), such as a magnetic bearing ( $\psi_1$ ) 134a (see FIG. 5). As further shown in FIG. 5, the navigation position  $\vec{P}_1$  71 of the host vehicle 70 includes [L,  $\lambda$ , h], which is latitude L 106, longitude  $\lambda$  108, and baro (barometric) altitude h 112.

In determining the navigation position  $\vec{P}_1$  71 (see FIGS. 4-5) of the host vehicle 70 (see FIGS. 4-5), the TCAS data 122 (see FIG. 4) and the ADS-B data 102 (see FIG. 4) from the proximate vehicle 72 (see FIGS. 4, 5), as discussed above, are initially synchronized by taking into account data latency 142 (see FIG. 4) due to transmission 144 (see FIG. 4) and computation 146 (see FIG. 4) (in TCAS 120 (see FIG. 4) for computing bearing 134 (see FIG. 4) and slant range 128 (see FIG. 4)). The TCAS data 122 (see FIG. 4) of the slant range 128 (see FIG. 4) and the bearing 134 (see FIG. 4) are checked for data reasonableness 152 (see FIG. 4), by a comparison with initial estimated positions 154 (see FIG. 4) of the slant range 128 (see FIG. 4) and the bearing 134 (see FIG. 4) of the slant range 128 (see FIG. 4) and the bearing 134 (see FIG. 4) are computed using the last known positions 158 (see FIG. 4) propagated to real-time 156 (see FIG. 4) and ADS-B data 102 (see FIG. 4) of the proximate vehicle position  $\vec{P}_1$  73. For example, based on existing TCAS 120 (see FIG. 4) industry specifications, if a range error 132 (see FIG. 4) is within 350 ft (feet) (250 ft (feet) bias+2\*50 rms (root mean square)), a range measurement 130 (see FIG. 4) is considered reasonable; and if a bearing error 138 (see FIG. 4) is within 18 degrees (2\*9 rms), a bearing measurement 136 (see FIG. 4) is considered reasonable. The position navigation integrity category (NIC) 110 (see FIG. 4) of ADS-B data 102 (see FIG. 4) is also checked to ensure it is acceptable.

Examples of computing navigation positions 71 (see FIG. 4), such as a CPS position 150 (see FIG. 4) or a 3-D (three-dimensional) CPS position 150a (see FIG. 4), of the host vehicle 70, are discussed below.

EXAMPLE 1

In determining the navigation position  $\vec{P}_1$  71 (see FIGS. 4-5), such as the CPS position 150 (see FIG. 4), of the host vehicle 70 using one proximate vehicle 72, as shown in FIG. 5, the following steps were taken and computations 146 (see FIG. 4) were made:

(a) It was assumed that the proximate vehicle 72 (see FIG. 5) had a known slant range  $\rho$  128 (see FIG. 5), such as a known first slant range  $\rho_1$  128a (see FIG. 5), from the host vehicle 70 (see FIG. 5), a known bearing  $\psi$  134 (see FIG. 5), such as a magnetic bearing  $\psi_1$  134a (see FIG. 5), from the host vehicle 70, and a known relative altitude  $\Delta h$  124 (see FIG. 5) from TCAS 120 (see FIG. 4). It was also assumed that the proximate vehicle 72 (see FIG. 5) had a known latitude  $L_1$  106 (see FIG. 5), a known longitude  $\lambda_1$  108 (see FIG. 5), and a known baro (barometric) altitude  $h_1$  112 (see FIG. 5) from the ADS-B 100 (see FIG. 4). It was also assumed the baro (barometric) altitude 112 (see FIG. 5) and true track angles 148 (see FIG. 4) of the host vehicle 70 (see FIGS. 4, 5) were available.

(b) The navigation position  $\vec{P}_1$  73 (see FIG. 5) of the proximate vehicle 72 (see FIG. 5) was converted to an Earth Centered Earth Fixed (ECEF) frame 160 (see FIG. 4), which becomes  $\vec{P}_{1,e}$ .

(c) With the first slant range  $\rho_1$  128a (see FIG. 5) and the bearing  $\psi_1$  134a (see FIG. 5) and the true track angle 148 (see FIG. 4) of the host vehicle 70 (see FIG. 5), a navigation position  $\vec{P}_1$  71 (see FIGS. 4-5) of the host vehicle 70 (see FIGS. 4-5) was computed in ECEF frame 160 (see FIG. 4) as follows:

$$\vec{P}_{h,e} = \vec{P}_{1,e} + C_n^e \begin{bmatrix} \rho_{11} \sin(\psi_{1T} + \varphi) \\ \rho_{11} \cos(\psi_{1T} + \varphi) \\ h_1' \end{bmatrix}$$

Where:

$\psi_{1T}$  is the true bearing by adding magnetic variation to the magnetic bearing  $\psi_1$ .

$C_n^e$  is the direction cosine matrix that transforms the vector from a navigation ENU (East-North-Up) frame 162 (see FIG. 4) to an ECEF frame 160 (see FIG. 4).

$\rho_{11}$  is the horizontal range from the proximate vehicle 72 in the ENU (East-North-Up) frame 162,  $\rho_{11} = \sqrt{\rho_1^2 - h_1'^2}$ .

$h_1'$  is the host vehicle height in the navigation ENU frame 162 (see FIG. 4).

$$h_1' = \frac{\Delta h^2 + 2r\Delta h - \rho_1^2}{2r}$$

r is the earth radius 164 (see FIG. 4) at the host vehicle 70,

$$r = \frac{a}{\sqrt{1 - e^2 \sin^2 L_1}} + h.$$

The latitude 106 of the proximate vehicle 72 was used instead, as the resulting error in the earth radius 164 (see FIG. 4) is negligible.

h is the baro (barometric) altitude 112 of the host vehicle 70 in meters.

a=6378137.0 m, semi-major axis of elliptical earth.

e<sup>2</sup>=0.006694379991013, square of earth eccentricity.

$\Delta h = h - h_1$ , is a relative altitude 124 (see FIG. 4), which is the difference between the host vehicle 70 altitude and the proximate vehicle 72 altitude in meters (m).

For the host vehicle 70 (see FIG. 5) with the system 10 (see FIG. 5) using one proximate vehicle 72 (see FIG. 5), the

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resulting position accuracy **170** (see FIG. 4) of the navigation position  $\vec{P}$  **71** (see FIGS. 4-5) of the host vehicle **70** was a function of a baro (barometric) altitude accuracy **172** (see FIG. 4), a TCAS ranging accuracy **174** (see FIG. 4) and a TCAS bearing accuracy **176** (see FIG. 4), and the position NIC **110** (see FIG. 4) of the proximate vehicle **72** (see FIGS. 4, 5). The main contributor to the position accuracy **170** (see FIG. 4) was the bearing **134** (see FIG. 4) of the proximate vehicle **72** (see FIGS. 4, 5). For example, with a TCAS bearing accuracy **176** (see FIG. 4) of 9 degrees, the position accuracy **170** (see FIG. 4) was a function of distance **126** (see FIG. 4) to the proximate vehicle **72** (see FIGS. 4, 5). For example, of a 10 nm (nautical miles) distance, the position accuracy **170** (see FIG. 4) was about 1.5 nm (nautical mile).

FIG. 6A is an illustration of a schematic diagram of an embodiment of a host vehicle **70**, such as a first vehicle **70a**, with the system **10** of the disclosure, using three proximate vehicles **72**, such as in the form of the second vehicle **72a**, the third vehicle **72b**, and the fourth vehicle **72c**, to determine the navigation position  $\vec{P}$  **71** (see FIG. 4) of the host vehicle **70** (see FIG. 6A). As shown in FIG. 6A, the host vehicle **70** and the proximate vehicles **72** are preferably vehicles **12**, such as in the form of aircraft **12b**, in an air environment **62**. As shown in FIG. 6A, the host vehicle **70** comprises the first vehicle **70a** in a jamming environment **66**, and the proximate vehicles **72** comprise the second vehicle **72a**, the third vehicle **72b**, and the fourth vehicle **72c**.

As further shown in FIG. 6A, the proximate vehicle **72**, such as the second vehicle **72a**, in relation to the host vehicle **70**, has a known slant range  $\rho$  **128**, such as a known first slant range  $\rho_1$  **128a**, from the TCAS **120** (see FIG. 4), and the proximate vehicle **72**, such as the second vehicle **72a**, has navigation position  $\vec{P}_1$  **73**, such as first navigation position **73a**, with a known latitude  $L_1$  **106**, a known longitude  $\lambda_1$  **108**, and a known baro (barometric) altitude  $h_1$  **112** from the ADS-B **100** (see FIG. 4). As further shown in FIG. 6A, the proximate vehicle **72**, such as the third vehicle **72b**, in relation to the host vehicle **70**, has a known slant range  $\rho$  **128**, such as a known second slant range  $\rho_2$  **128b**, from the TCAS **120** (see FIG. 4), and the proximate vehicle **72**, such as the third vehicle **72b**, has navigation position  $\vec{P}_2$  **73**, such as second navigation position **73b**, with a known latitude  $L_2$  **106**, a known longitude  $\lambda_2$  **108**, and a known baro (barometric) altitude  $h_2$  **112** from the ADS-B **100** (see FIG. 4). As further shown in FIG. 6A, the proximate vehicle **72**, such as the fourth vehicle **72c**, in relation to the host vehicle **70**, has a known slant range  $\rho$  **128**, such as a known third slant range  $\rho_3$  **128b**, from the TCAS **120** (see FIG. 4), and the proximate vehicle **72**, such as the fourth vehicle **72c**, has navigation position  $\vec{P}_3$  **73**, such as third navigation position **73c**, with a known latitude  $L_3$  **106**, a known longitude  $\lambda_3$  **108**, and a known baro (barometric) altitude  $h_3$  **112** from the ADS-B **100** (see FIG. 4).

EXAMPLE 2

In determining the navigation position  $\vec{P}$  **71** (see FIG. 4), such as a CPS position **150** (see FIG. 4), of the host vehicle **70** using two or more proximate vehicles **72**, for example, three proximate vehicles **72**, as shown in FIG. 6A, instead of using the bearing **134** (see FIG. 4), only the slant ranges **128** (see FIGS. 4, 6A) to the proximate vehicles **72** (see FIG. 6A) were used. It was assumed the baro (barometric) altitude **112** of the host vehicle **70** ( $h_{h0}$ ) was available. It was assumed

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there were three (3) proximate vehicles **72**, such as the second vehicle **72a** (see FIG. 6A), the third vehicle **72b** (see FIG. 6A), and the fourth vehicle **72c** (see FIG. 6A). The navigation position  $\vec{P}$  **71**, such as the CPS position **150** (see FIG. 4), of the host vehicle **70** (see FIGS. 4, 6A), was computed iteratively and the following steps were taken:

(a) Started from the initial estimated position **154** (see FIG. 4) or the last known position **158** (see FIG. 4) of the host vehicle **70** (see FIG. 6A),  $\vec{P}_{h0} = [L_{h0}, \lambda_{h0}, h_{h0}]$ .

(b) Converted  $\vec{P}_{h0}$ ,  $\vec{P}_1$ ,  $\vec{P}_2$ , and  $\vec{P}_3$  to ECEF (Earth Centered Earth Fixed) frame **160** (see FIG. 4), and obtained  $\vec{P}_{h0,e}$ ,  $\vec{P}_{1,e}$ ,  $\vec{P}_{2,e}$ , and  $\vec{P}_{3,e}$ .

(c) Converted the slant ranges **128** (see FIG. 4)  $\rho_1$ ,  $\rho_2$ , and  $\rho_3$  to local horizontal ranges **166** (see FIG. 4)  $\rho_{11}$ ,  $\tau_{12}$ , and  $\rho_{13}$  in a local horizontal plane of the ENU (East-North-UP) frame **162** (see FIG. 4):

$$\rho_{1i} = \sqrt{\rho_i^2 - h_{li}^2}$$

Where:

$$h_{li} = \frac{\Delta h_i^2 + 2r\Delta h_i - \rho_i^2}{2r}$$

$$\Delta h_i = h_i - h_{h0} (i=1,2,3).$$

$r$  is the earth radius **164** (see FIG. 4) at  $\vec{P}_{h0}$ .

$$r = \frac{a}{\sqrt{1 - e^2 \sin^2 L_{h0}}} + h_{h0}.$$

(d) The navigation positions **73** (see FIGS. 4, 6A) of the three proximate vehicles **72** (see FIGS. 4, 6A) were converted to a local navigation frame relative to  $\vec{P}_{h0}$  and their coordinates are  $[e_1, n_1, u_1]$ ,  $[e_2, n_2, u_2]$ , and  $[e_3, n_3, u_3]$ . Formed the direction cosine matrix relative to  $\vec{P}_{h0}$ :

$$H = \begin{bmatrix} \frac{e_1}{\sqrt{e_1^2 + n_1^2}} & \frac{n_1}{\sqrt{e_1^2 + n_1^2}} \\ \frac{e_2}{\sqrt{e_2^2 + n_2^2}} & \frac{n_2}{\sqrt{e_2^2 + n_2^2}} \\ \frac{e_3}{\sqrt{e_3^2 + n_3^2}} & \frac{n_3}{\sqrt{e_3^2 + n_3^2}} \end{bmatrix}$$

(e) The local horizontal range **166** (see FIG. 4) was computed in ENU frame **162**:

$$\rho_{11c} = \sqrt{e_1^2 + n_1^2}, \rho_{12c} = \sqrt{e_2^2 + n_2^2}, \rho_{13c} = \sqrt{e_3^2 + n_3^2}.$$

(f) Obtained delta horizontal range:  $\Delta \rho_{11} = \rho_{11c} - \rho_{11}$ ,  $\Delta \rho_{12} = \rho_{12c} - \rho_{12}$ ,  $\Delta \rho_{13} = \rho_{13c} - \rho_{13}$ .

(g) Solved for the navigation positions **73** (see FIGS. 4, 6A) using a weighted Least Squares method **168** (see FIG. 4):

$$\begin{bmatrix} \Delta e_{h1} \\ \Delta n_{h1} \end{bmatrix} = (H^T W H)^{-1} H^T W \begin{bmatrix} \Delta \rho_{11} \\ \Delta \rho_{12} \\ \Delta \rho_{13} \end{bmatrix}$$

Where:

$$W = \begin{bmatrix} \frac{1}{\sigma_1^2} & 0 & 0 \\ 0 & \frac{1}{\sigma_2^2} & 0 \\ 0 & 0 & \frac{1}{\sigma_3^2} \end{bmatrix}$$

is a weighting matrix,  $\sigma_i$  ( $i=1, 2, 3$ ) is proportional to the position NIC 110 (see FIG. 4) in the ADS-B data 102 (see FIG. 4) from the three proximate vehicles 72 (see FIGS. 4, 6A).

(h) If  $\sqrt{\Delta e_{h1}^2 + \Delta n_{h1}^2} < 1e^{-3}$ , the iteration was stopped, and the navigation position 71 (see FIGS. 4, 6A) of the host vehicle 70 (see FIGS. 4, 6A) in the ECEF frame 160 (see FIG. 4) was:

$$\vec{P}_{h1,e} = \vec{P}_{h0,e} + C_n^e \begin{bmatrix} \Delta e_{h1} \\ \Delta n_{h1} \\ 0 \end{bmatrix}$$

Otherwise, let  $\vec{P}_{h0,e} = \vec{P}_{h1,e}$ , and returned to step (c) for the next iteration.

For the host vehicle 70 (see FIG. 6A) with the system 10 (see FIG. 6A) using the three proximate vehicles 72 (see FIG. 6A), the resulting position accuracy 170 (see FIG. 4), such as a horizontal position accuracy 170a (see FIG. 4), was a function of the baro (barometric) altitude accuracy 172 (see FIG. 4), a TCAS ranging accuracy 174 (see FIG. 4), vehicle geometries 178 (see FIG. 4) of the host vehicle 70 (see FIGS. 4, 6A) and the proximate vehicles 72 (see FIGS. 4, 6A), and the position NIC 110 (see FIG. 4) of the proximate vehicles 72 (see FIGS. 4, 6A). A vertical dilution of precision (VDOP) 180 (see FIG. 4) was assumed due to vehicle geometry 178 (see FIG. 4) of 1.5, and a given baro (barometric) altitude accuracy 172 (see FIG. 4) of 50 ft (feet), a TCAS ranging accuracy 174 (see FIG. 4) with a range error 132 (see FIG. 4) of 50 ft (feet) rms (root mean square) and 250 ft (feet) bias, and the position accuracy 170 (see FIG. 4) of the proximate vehicles 72 (see FIGS. 4, 6A) of 30 ft (feet) ( $1\sigma$ ) (see FIG. 4), the resulting position accuracy 170 (see FIG. 4), such as the horizontal position accuracy 170a (see FIG. 4), of 95% of the host vehicle 70 (see FIGS. 4, 6A) was about:

$$2 * 1.5 * \sqrt{250^2 + 2 * 50^2 + 30^2} \approx 785 \text{ ft} \approx 239 \text{ m} \approx 0.13 \text{ nm (nautical mile)}$$

FIG. 6B is an illustration of a schematic diagram of another embodiment of a host vehicle 70, such as a first vehicle 70a, with the system 10 of the disclosure, using three or more proximate vehicles 72, for example, using four proximate vehicles 72, such as in the form of second vehicle 72a, third vehicle 72b, fourth vehicle 72c, and a fifth vehicle 72d, to determine the navigation position  $\vec{P}$  71 (see FIG. 4), such as a 3-D (three-dimensional) CPS position 150a (see FIG. 4) of the host vehicle 70 (see FIGS. 4, 6B). As shown in FIG. 6B, the host vehicle 70 and the proximate vehicles 72 are preferably vehicles 12, such as in the form of aircraft 12b, in an air environment 62. As shown in FIG. 6B, the host vehicle 70 comprises the first vehicle 70a in a jamming environment 66, and the proximate vehicles 72 comprise the

second vehicle 72a, the third vehicle 72b, the fourth vehicle 72c, and the fifth vehicle 72d.

As further shown in FIG. 6B, the proximate vehicle 72, such as the second vehicle 72a, in relation to the host vehicle 70, has a known slant range  $\rho$  128, such as a known first slant range  $\rho_1$  128a, from the TCAS 120 (see FIG. 4), and the proximate vehicle 72, such as the second vehicle 72a, has navigation position  $\vec{P}_1$  73, such as first navigation position 73a, with a known latitude  $L_1$  106, a known longitude  $\lambda_1$  108, and a known baro (barometric) altitude  $h_1$  112 from the ADS-B 100 (see FIG. 4). As further shown in FIG. 6B, the proximate vehicle 72, such as the third vehicle 72b, in relation to the host vehicle 70, has a known slant range  $\rho$  128, such as a known second slant range  $\rho_2$  128b, from the TCAS 120 (see FIG. 4), and the proximate vehicle 72, such as the third vehicle 72b, has navigation position  $\vec{P}_2$  73, such as second navigation position 73b, with a known latitude  $L_2$  106, a known longitude  $\lambda_2$  108, and a known baro (barometric) altitude  $h_2$  112 from the ADS-B 100 (see FIG. 4). As further shown in FIG. 6B, the proximate vehicle 72, such as the fourth vehicle 72c, in relation to the host vehicle 70, has a known slant range  $\rho$  128, such as a known third slant range  $\rho_3$  128c, from the TCAS 120 (see FIG. 4), and the proximate vehicle 72, such as the fourth vehicle 72c, has navigation position  $\vec{P}_3$  73, such as third navigation position 73c, with a known latitude  $L_3$  106, a known longitude  $\lambda_3$  108, and a known baro (barometric) altitude  $h_3$  112 from the ADS-B 100 (see FIG. 4). As further shown in FIG. 6B, the proximate vehicle 72, such as the fifth vehicle 72d, in relation to the host vehicle 70, has a known slant range  $\rho$  128, such as a known fourth slant range  $\rho_4$  128d, from the TCAS 120 (see FIG. 4), and the proximate vehicle 72, such as the fifth vehicle 72d, has navigation position  $\vec{P}_4$  73, such as fourth navigation position 73d, with a known latitude  $L_4$  106, a known longitude  $\lambda_4$  108, and a known baro (barometric) altitude  $h_4$  112 from the ADS-B 100 (see FIG. 4).

EXAMPLE 3

In determining the navigation position  $\vec{P}$  71 (see FIG. 4), such as the 3-D (three-dimensional) CPS position 150a (see FIG. 4), of the host vehicle 70 using three or more proximate vehicles 72, for example, four proximate vehicles 72, as shown in FIG. 6B, it was assumed there were four (4) proximate vehicles 72, such as the second vehicle 72a (see FIG. 6B), the third vehicle 72b (see FIG. 6B), the fourth vehicle 72c (see FIG. 6B), and the fifth vehicle 72d (see FIG. 6B). The navigation position  $\vec{P}$  71, such as the 3-D (three-dimensional) CPS position 150a (see FIG. 4), of the host vehicle 70 (see FIGS. 4, 6B) was computed iteratively, and the following steps were taken:

(a) Started from the initial estimated position 154 (see FIG. 4) or the last known position 158 (see FIG. 4) of the host vehicle 70 (see FIG. 6B),  $\vec{P}_{h0} = [L_{h0}, \lambda_{h0}, h_{h0}]$ .

(b) Converted  $\vec{P}_{h0}$ ,  $\vec{P}_1$ ,  $\vec{P}_2$ ,  $\vec{P}_3$  and  $\vec{P}_4$  to ECEF (Earth Centered Earth Fixed) frame 160 (see FIG. 4), and obtained:

$$\vec{P}_{h0,e} [x_{h0,e} \ y_{h0,e} \ z_{h0,e}], \vec{P}_{1,e} [x_{1,e} \ y_{1,e} \ z_{1,e}], \vec{P}_{2,e} [x_{2,e} \ y_{2,e} \ z_{2,e}], \vec{P}_{3,e} [x_{3,e} \ y_{3,e} \ z_{3,e}], \text{ and } \vec{P}_{4,e} [x_{4,e} \ y_{4,e} \ z_{4,e}].$$

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(c) Formed the direction cosine matrix relative to  $\vec{P}_{h0}$ :  
The  $i^{th}$  row:

$$H[i, :] = \begin{bmatrix} \frac{x_{h0,e} - x_{i,e}}{\sqrt{(x_{h0,e} - x_{i,e})^2 + (y_{h0,e} - y_{i,e})^2 + (z_{h0,e} - z_{i,e})^2}} \\ \frac{y_{h0,e} - y_{i,e}}{\sqrt{(x_{h0,e} - x_{i,e})^2 + (y_{h0,e} - y_{i,e})^2 + (z_{h0,e} - z_{i,e})^2}} \\ \frac{z_{h0,e} - z_{i,e}}{\sqrt{(x_{h0,e} - x_{i,e})^2 + (y_{h0,e} - y_{i,e})^2 + (z_{h0,e} - z_{i,e})^2}} \end{bmatrix}^T$$

(d) Computed the slant ranges **128** (see FIG. 6B)  $\rho_1, \rho_2, \rho_3$  and  $\rho_4$  of the proximate vehicles **72a, 72b, 72c, 72d** (see FIG. 6B), respectively:

$$\rho_{ic} = \sqrt{(x_{h0,e} - x_{i,e})^2 + (y_{h0,e} - y_{i,e})^2 + (z_{h0,e} - z_{i,e})^2}$$

(e) Obtained delta horizontal range:  $\Delta\rho_i = \rho - \rho_{ic}$ .

(f) Solved for the navigation positions **73** (see FIGS. 4, 6B), such as the 3-D CPS positions **150a** (see FIG. 4), using the weighted Least Squares method **168** (see FIG. 4):

$$\begin{bmatrix} \Delta x_{h0,e} \\ \Delta y_{h0,e} \\ \Delta z_{h0,e} \end{bmatrix} = (H^T W H)^{-1} H^T W \begin{bmatrix} \Delta\rho_1 \\ \Delta\rho_2 \\ \Delta\rho_3 \\ \Delta\rho_4 \end{bmatrix}$$

Where the weighting matrix W is a diagonal matrix and its  $i^{th}$  diagonal element

$$W[i, i] = \frac{1}{\sigma_i^2}, \sigma_i (i = 1, 2, 3, 4)$$

is proportional to the position NIC **110** (see FIG. 4) in the ADS-B data **102** (see FIG. 4) from the proximate vehicles **72**.

(g) If  $\sqrt{\Delta x_{h0,e}^2 + \Delta y_{h0,e}^2 + \Delta z_{h0,e}^2} < 1e^{-3}$ , the iteration was stopped, and the navigation position **71** (see FIGS. 4, 6B), such as the 3-D CPS position **150a** (see FIG. 4), of the host vehicle **70** (see FIGS. 4, 6B) in the ECEF frame **160** (see FIG. 4) was:

$$\vec{P}_{h1,e} = \vec{P}_{h0,e} + \begin{bmatrix} \Delta x_{h0,e} \\ \Delta y_{h0,e} \\ \Delta z_{h0,e} \end{bmatrix}$$

Otherwise, let  $\vec{P}_{h0,e} = \vec{P}_{h1,e}$ , and returned to step (c) for the next iteration.

For the host vehicle **70** (see FIG. 6B) with the system **10** (see FIG. 6B) using the four proximate vehicles **72** (see FIG. 6B), a resulting 3-D (three-dimensional) position accuracy **170b** (see FIG. 4) was a function of TCAS ranging accuracy **174** (see FIG. 4), vehicle geometries **178** (see FIG. 4) of the host vehicle **70** (see FIGS. 4, 6B) and the proximate vehicles **72** (see FIGS. 4, 6B), and the position NIC **110** (see FIG. 4) of the proximate vehicles **72** (see FIGS. 4, 6B). A vertical dilution of precision (VDOP) **180** (see FIG. 4) was assumed due to vehicle geometry **178** (see FIG. 4) of 1.5, a TCAS ranging accuracy **174** (see FIG. 4) with a range error **132** (see FIG. 4) of 50 ft (feet) rms (root mean square) and 250

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ft bias, and the 3-D position accuracy **170b** (see FIG. 4) of the proximate vehicles **72** (see FIGS. 4, 6B) of 30 ft (feet) ( $1\sigma$ ) (see FIG. 4), the resulting position accuracy **170** (see FIG. 4) of 95% of the host vehicle **70** (see FIGS. 4, 6B) was about:

$$2 * 1.5 * \sqrt{250^2 + 50^2 + 30^2} \approx 770 \text{ ft} \approx 235 \text{ m} \approx 0.13 \text{ nm (nautical mile)}$$

Thus, the 3-D (three-dimensional) CPS position **150a** of the host vehicle **70** (see FIG. 6B) was computed iteratively using TCAS range measurements **130** and ADS-B data **102** from the four (4) proximate vehicles **72**, which is similar to a GPS **86** receiver computing a three-dimensional (3-D) position.

The slant ranges **128** (see FIGS. 4-6B) and distances **126** (see FIG. 4) from the one or more proximate vehicles **72** (see FIG. 4) may be integrated into GPS **86** (see FIG. 4) receivers and used as additional satellite(s) **274** (see FIG. 4). The range measurement **130** (see FIG. 4) can be weighted based on a known TCAS ranging accuracy **172** (see FIG. 4) and its existence may improve a satellite-receiver geometry **278** (see FIG. 4), in particular, a vertical dilution of precision (VDOP) **180** (see FIG. 4), if the one or more proximate vehicle(s) **72** (see FIGS. 4-6B) is/are below the host vehicle **70** (see FIGS. 4-6B). Similarly, the slant ranges **128** (see FIG. 4) and distances **126** (see FIG. 4) from the proximate vehicles **72** (see FIGS. 4-6B) may be integrated into an FMC (flight management computer) navigation **82a** (see FIGS. 7A-7D) of the FMC **82** (see FIG. 4) using a Kalman filter **182** (see FIG. 4).

The CPS position **150** (see FIG. 4) and the 3-D CPS position **150a** (see FIG. 4), as computed above, may be integrated into the FMC **82** (see FIGS. 4, 7A) with existing inertial position sensors (IRS) **88** (see FIG. 4) and/or radio position sensors **92** (see FIG. 4), such as the DME/DME **97** position or the DME/VOR **98** position using the Kalman filter **182** (see FIG. 4), or another suitable complementary filter. The DME/DME **97** position and the DME/VOR **98** positions are based on DME (distance measuring equipment), which is a ground navigational aid that may be at a ground-based location **190** (see FIG. 4) that can provide display of distance **126** (see FIG. 4) to a selected ground navigational radio transmitter. The VOR (very high frequency omnidirectional ranging) **96** (see FIG. 4) is a ground navigational aid that may be at a ground-based location **190** (see FIG. 4) that can provide display of a vehicle position relative to a course through a selected ground navigational radio transmitter.

Further, when a group of vehicles **12**, such as autonomous unmanned air vehicles (UAVs) **12c** (see FIG. 4) operates in a relatively close range, either to go from one location to another location, or to perform a single task cooperatively, the system **10** (see FIG. 4), such as the CPS **10a** (see FIG. 4) with the CPS sensor **11a** (see FIG. 4) eliminates the need for all vehicles **12**, such as aircraft **12b** (see FIG. 4) or UAVs **12c** (see FIG. 4), to have position sensors **84** (see FIG. 4), such as inertial reference system (IRS) sensors **88** (see FIG. 4), global navigation satellite system (GNSS) **90** (see FIG. 4) sensors, and radio position sensors **92** (see FIG. 4).

If a small subset of vehicles **12**, such as aircraft **12b** (see FIG. 4), and tagged as leaders **70b** (see FIG. 4), have the positions sensors **84** (see FIG. 4), the remaining vehicles **12**, such as aircraft **12b** (see FIG. 4), and tagged as workers **72e** (see FIG. 4), may compute their independent navigation solutions **195** (see FIGS. 7A-7D) using only their ADS-B **100** (see FIG. 4) and TCAS **120** (see FIG. 4). Thus, this may reduce or minimize navigation sensor installation costs to

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operate a group of vehicles **12**, such as aircraft **12b** (see FIG. 4). Also, it may accommodate different operational objectives where the leaders **70b** (see FIG. 4) may be located either in a ground environment **188** (see FIG. 4) at a ground-based location **190** (see FIG. 4) or on a ground-based vehicle **192** (see FIG. 4), or in an air environment **62** (see FIG. 4) on an air-based location **64** (see FIG. 4), with the workers **72e** (see FIG. 4).

Now referring to FIG. 7A, FIG. 7A shows a schematic diagram of an embodiment of an integration **194**, such as a sensor integration **194a** of the communal position system (CPS) sensor **11a** of the system **10**, such as the communal position system (CPS) **10a**, of the disclosure. As shown in FIG. 7A, the system **10**, such as the CPS **10a**, comprising the CPS sensor **11a**, is a separate module or box external to and used with a flight management computer (FMC) **82**, that includes a flight management computer (FMC) navigation **82a**. As further shown in FIG. 7A, the TCAS data **122** from the TCAS **120** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B), and the ADS-B data **102** from the ADS-B **100** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B) are transmitted to, and received by, the system **10**, such as the CPS **10a**, comprising the CPS sensor **11a**. The CPS position **150** determined in the system **10**, such as the CPS **10a**, is input to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7A, global positioning system (GPS) data **86a** from the GPS **86** is input to the FMC navigation **82a** of the FMC **82**, distance measuring equipment (DME) data **94a** from the DME **94** is input to the FMC navigation **82a** of the FMC **82**, and very high frequency omnidirectional ranging (VOR) data **96a** from the VOR **96** is input to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7A, navigation solutions **195** result from and are output from the FMC navigation **82a** of the FMC **82**.

Now referring to FIG. 7B, FIG. 7B shows a schematic diagram of an embodiment of an integration **194**, such as a GPS integration **194b** with the communal position system (CPS) sensor **11a** of the system **10**, such as the communal position system (CPS) **10a**. As shown in FIG. 7B, TCAS data **122** from the TCAS **120** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B), and the ADS-B data **102** from the ADS-B **100** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B) are transmitted to, and received by, the GPS **86** and the system **10**, such as the CPS **10a**, comprising the CPS sensor **11a**. The GPS data **86a** and the CPS position **150** are input to the FMC navigation **82a** of the FMC **82**. In addition, as further shown in FIG. 7B, DME data **94a** from the DME **94** is input to the FMC navigation **82a** of the FMC **82**, and VOR data **96a** from the VOR **96** is input to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7B, navigation solutions **195** result from and are output from the FMC navigation **82a** of the FMC **82**.

Now referring to FIG. 7C, FIG. 7C is a schematic diagram of an embodiment of an integration **194**, such as a flight management computer (FMC) integration **194c** with the communal position system (CPS) sensor **11a** of the system **10**, such as the communal position system (CPS) **10a**. As shown in FIG. 7C, TCAS data **122** from the TCAS **120** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B), and ADS-B data **102** from the ADS-B **100** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B) are transmitted to, and received by, the system **10**, such as the CPS **10a**, comprising the CPS sensor **11a**, within the FMC navigation **82** of the FMC **82**. The CPS position **150** determined in the system **10**, such as the CPS **10a**, and is

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output from the CPS **10a** to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7C, the GPS data **86a** from the GPS **86** is input to the FMC navigation **82a** of the FMC **82**, the DME data **94a** from the DME **94** is input to the FMC navigation **82a** of the FMC **82**, and the VOR data **96a** from the VOR **96** is input to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7C, navigation solutions **195** result from and are output from the FMC navigation **82a** of the FMC **82**.

Now referring to FIG. 7D, FIG. 7D is a schematic diagram of an embodiment of an integration **194**, such as a TCAS integration **194d**, with the communal position system (CPS) sensor **11a** of the system **10**, such as the CPS **10a**. As shown in FIG. 7D, the system **10**, such as CPS **10a**, with the CPS sensor **11a**, is hosted in the TCAS **120** with additional input from the ADS-B data **102** from the ADS-B **100**, from the one or more of the proximate vehicles **72** (see FIGS. 4-6B), before being used in the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7D, the ADS-B data **102** from the ADS-B **100** of the one or more of the proximate vehicles **72** (see FIGS. 4-6B) is transmitted to, and received by, the system **10**, such as CPS **10a**, comprising the CPS sensor **11a**. As further shown in FIG. 7D, the CPS position **150** from the system **10**, such as CPS **10a**, is output from the CPS **10a** to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7D, GPS data **86a** from the GPS **86** is input to the FMC navigation **82a** of the FMC **82**, DME data **94a** from the DME **94** is input to the FMC navigation **82a** of the FMC **82**, and VOR data **96a** from the VOR **96** is input to the FMC navigation **82a** of the FMC **82**. As further shown in FIG. 7D, navigation solutions **195** result from and are output from the FMC navigation **82a** of the FMC **82**.

Now referring to FIG. 8, FIG. 8 is an illustration of a first cockpit control display unit (CDU) **196** for a position reference CDU **196a** that incorporates a communal position system (CPS) display **200** for the CPS **10a** (see FIG. 4) with the CPS sensor **11a** (see FIG. 4) of the disclosure. As shown in FIG. 8, the position reference CDU **196a** comprises a user interface **198** showing the CPS display **200** with, for example, a bearing **134** of 253° and a distance **126** of 0.5 NM (nautical miles), with, for example, displays (270°/0.1 NM (nautical miles), 263°/1.1 NM, 85°/1.2 NM) for the inertial reference system (IRS) **88**, and with, for example, displays (5 KT (knots), 13 KT, 9 KT) for ground speed (GS) **202**. The position reference CDU **196a** (see FIG. 8) may be controlled with left controls **204** (see FIG. 8) and right controls **206** (see FIG. 8).

Now referring to FIG. 9, FIG. 9 is an illustration of a second cockpit control display unit (CDU) **197** for a navigation options control CDU **197a** that incorporates a CPS display such as a CPS UPDATE display **208**, for the CPS **10a** (see FIG. 4) with the CPS sensor **11a** (see FIG. 4) of the disclosure. As shown in FIG. 9, the navigation options control CDU **197a** comprises a user interface **198** showing the CPS UPDATE display **208** with an ON control **210** and an OFF control **212**, showing a NAV (navigational) AID INHIBIT display **214**, a VOR (very high frequency omnidirectional ranging) ONLY INHIBIT display **216**, a DME (distance measuring equipment) UPDATE display **218**, a VOR (very high frequency omnidirectional ranging) UPDATE display **220**, a GPS (global positioning system) UPDATE display **222**, and a LOC (localizer) UPDATE display **224**. The navigation options control CDU **197a** (see FIG. 9) may be controlled with left controls **226** (see FIG. 9) and right controls **228** (see FIG. 9).

Now referring to FIG. 10, FIG. 10 is an illustration of a functional block diagram showing an exemplary embodi-

ment of the computer system **80** that may be used in one or more embodiments of the computer implemented system **10** (see FIG. **4**), computer implemented apparatus **11** (see FIG. **4**), and computer implemented method **280** (see FIG. **11**) of the disclosure. As shown in FIG. **10**, the computer system **80** comprises one or more computers **230**, which may include one or more processor device(s) **232** and an operating system **234**. The computer system **80** (see FIG. **10**) may be used to implement the one or more computer(s) **230** (see FIG. **10**).

The one or more computer(s) **230** (see FIG. **10**) or one or more processor device(s) **232** (see FIG. **10**) may be configured to control one or more functions of one or more elements of the system **10** (see FIG. **4**), such as CPS **10a** (see FIG. **4**) through computer program instructions, such as computer software **264** (see FIG. **10**) stored on a computer memory **240** (see FIG. **10**), accessible to the one or more computer(s) **230** (see FIG. **10**), or one or more processor device(s) **232** (see FIG. **10**).

As shown in FIG. **10**, the computer system **80** further comprises a data bus **236** that transfers data between the one or more computers **230**, storage devices **238**, one or more computer communications devices **244**, one or more input/output units **248**, and a display **250**. The data bus **236** (see FIG. **10**) may include hardware components such as wires, optical fibers, and other hardware devices, and may include software components such as communications protocols or other software devices.

As shown in FIG. **10**, the computer system **80** further comprises storage devices **238**, such as computer memory **240** and persistent storage **242**. The computer memory **240** (see FIG. **10**) may comprise one or more of a random access memory (RAM), including dynamic and/or static RAM, on-chip or off-chip cache memory, or other suitable computer memory **240** (see FIG. **2**). The persistent storage **242** (see FIG. **10**) may comprise one or more of a flash memory, a hard drive, Read-Only Memory (ROM), magnetic storage devices such as hard disks, floppy disk drives, and rewritable magnetic tape, rewritable optical disk drives and/or media, non-volatile random access memory (NVRAM), or other suitable persistent storage **242** (see FIG. **10**).

As shown in FIG. **10**, the computer system **80** may further comprise one or more computer communications device(s) **244**, such as one or more networking communications device(s) **247**, for linking the computer implemented system **10** (see FIG. **4**), for example, to one or more separate systems. The one or more networking communications device(s) **246** (see FIG. **10**) may comprise network links between various computers and devices connected together within a network data processing system via wire connections, wireless communication links, fiber optic cables, or other suitable network connections, and that may connect to a network, a server, the Internet, or another system or device.

The one or more computer communications device(s) **244** (see FIG. **10**) may be configured to provide for communications in accordance with any of a number of wired or wireless communication standards. The one or more computer(s) **230** (see FIG. **10**) or one or more processor device(s) **232** (see FIG. **10**) may also be configured to facilitate communications via the one or more computer communications device(s) **244** (see FIG. **10**) by, for example, controlling hardware included within the one or more computer communications device(s) **244** (see FIG. **10**). The one or more computer communications device(s) **244** (see FIG. **10**) may include, for example, one or more

antennas, a transmitter, a receiver, a transceiver and/or supporting hardware, including, for example, a processor for enabling communications.

As shown in FIG. **10**, the computer system **80** further comprises one or more input/output unit(s) **248**, a display **250**, and a power supply **252**. The one or more input/output unit(s) **248** (see FIG. **10**) provide for the input and output of data with other devices connected to the computer system **80** (see FIG. **10**), such as computer interfaces. The one or more input/output unit(s) **248** (see FIG. **10**) may comprise such devices as a keyboard, a mouse, a joystick, or other input/output devices. For example, the one or more input/output unit(s) **248** (see FIG. **10**) may provide a connection for user input through a keyboard and mouse, or may send output to a printer or other device.

The display **250** (see FIG. **10**) provides the means to display data or information to a user such as a pilot, one or more separate automated systems, automated computer programs, automated apparatuses, or automated devices, or another suitable separate system, program, or device. The power supply **252** (see FIG. **10**) of the computer system **80** (see FIG. **10**) may comprise batteries, electricity, or other power supply elements.

As shown in FIG. **10**, a computer program product **256** may be used in the computer system **80** by loading the computer program product **256** into the computer system **80** via a loading mechanism **254** or other suitable mechanism. The computer program product **256** (see FIG. **10**) may comprise a system logic **258** (see FIG. **10**). As shown in FIG. **10**, the system logic **258** may comprise an algorithm **260**, a program code **262**, a computer software **264**, a computer firmware **266**, or another suitable system logic **258**. As shown in FIG. **10**, the computer program product **256** may comprise a computer readable medium **268**. The computer readable medium **268** (see FIG. **10**) may comprise a computer readable storage media **270** (see FIG. **10**), a computer readable signal media **272** (see FIG. **10**), or another suitable computer readable medium **268** (see FIG. **10**).

The system logic **258** (see FIG. **10**), such as the algorithm **260** (see FIG. **10**), the program code **262** (see FIG. **10**), the computer software **264** (see FIG. **10**), the computer firmware **266** (see FIG. **10**), or another suitable system logic **258** (see FIG. **10**), may be stored in and retrieved from the computer readable storage media **270** (see FIG. **10**) and loaded into the one or more computer(s) **230** (see FIG. **10**), the one or more processor device(s) **232**, or other programmable device, to configure and direct the one or more computer(s) **230**, the one or more processor device(s) **232**, or other programmable device to execute operations to be performed on or by the one or more computer(s) **230**, the one or more processor device(s) **232**, or other programmable device, and to function in a particular way to generate a particular apparatus or article of manufacture. Execution of the system logic **258** (see FIG. **10**), such as the algorithm **260** (see FIG. **10**), the program code **262** (see FIG. **10**), the computer software **264** (see FIG. **10**), the computer firmware **266** (see FIG. **10**), or another suitable system logic **258** (see FIG. **10**), may produce a computer-implemented system, process or method, such that the system logic **258** (see FIG. **10**), such as the algorithm **260** (see FIG. **10**), the program code **262** (see FIG. **10**), the computer software **264** (see FIG. **10**), the computer firmware **266** (see FIG. **10**), or another suitable system logic **258** (see FIG. **10**), executed by the one or more computer(s) **230** (see FIG. **10**), one or more processor device(s) **232** (see FIG. **10**), or other programmable device, provide operations for implementing the functions disclosed herein.

Now referring to FIG. 11, in another embodiment of the disclosure, there is provided a computer implemented method 280 for using automatic dependent surveillance-broadcast (ADS-B) data 102 (see FIG. 4) and traffic alert and collision avoidance system (TCAS) data 122 (see FIG. 4) for determining one or more navigation solutions 195 (see FIG. 4) for a vehicle 12 (see FIG. 4). FIG. 11 is an illustration of a flow diagram showing an embodiment of the method 280 of the disclosure. The method 280 may be performed in one of, an air-based location 64 (see FIG. 4), and a ground-based location 190 (see FIG. 4).

FIG. 11 shows a START step 282. FIG. 11 further shows step 284 of receiving, by a communal position system (CPS) 10a (see FIG. 4) in the vehicle 12 (see FIG. 4), preferably comprising a host vehicle 70 (see FIG. 4), automatic dependent surveillance-broadcast (ADS-B) data 102 (see FIG. 4) and traffic alert and collision avoidance system (TCAS) data 122 (see FIG. 4) from one or more proximate vehicles 72. The ADS-B data 102 is preferably received from each of one or more proximate vehicles 72 (see FIG. 4) in proximity to the host vehicle 70, through an automatic dependent surveillance-broadcast (ADS-B) 100 (see FIG. 4). The TCAS data 122 (see FIG. 4) is preferably received from each of the one or more proximate vehicles 72, through a traffic alert and collision avoidance system (TCAS) 120 (see FIG. 4).

In the receiving 284 step (see FIG. 11), the receiving the ADS-B data 102 from each of the one or more proximate vehicles 72 comprises receiving the ADS-B data 102 comprising one or more of, identification information 104 (see FIG. 4) for each proximate vehicle 72, a latitude 106 (see FIG. 4) for each proximate vehicle 72, a longitude 108 (see FIG. 4) for each proximate vehicle 72, a position navigation integrity category (NIC) 110 (see FIG. 4) for each proximate vehicle 72, a barometric altitude 112 (see FIG. 4) for each proximate vehicle 72, a global navigation satellite system (GNSS) height 114 (see FIG. 4) for each proximate vehicle 72, a plurality of velocities 116 (see FIG. 4) for each proximate vehicle 72, and a navigation accuracy category for velocity (NACv) 118 (see FIG. 4) for each proximate vehicle 72. In the receiving 284 step, the TCAS data 122 from each of the one or more proximate vehicles 72 comprises receiving the TCAS data 122 comprising one or more of, identification information 104 (see FIG. 4) for each proximate vehicle 72, a slant range 128 (see FIG. 4) for each proximate vehicle 72, a bearing 134 (see FIG. 4) for each proximate vehicle 72, and a relative altitude 124 (see FIG. 4) for each proximate vehicle 72.

In one embodiment, the receiving 284 by the host vehicle 70, of the ADS-B data 102 and the TCAS data 122, comprises receiving the ADS-B data 102 and the TCAS data 122 from one proximate vehicle 72 having TCAS data 122 comprising a slant range 128, a bearing 134, and a relative altitude 124, and having ADS-B data 102 comprising a latitude 106, a longitude 108, and a barometric altitude 112. In another embodiment, the receiving 284 by the host vehicle 70, of the ADS-B data 102 and the TCAS data 122, comprises receiving the ADS-B data 102 and the TCAS data 122 from multiple proximate vehicles 72, for example, three proximate vehicles 72 (see FIG. 6A), each proximate vehicle having TCAS data 122 comprising a slant range 128, and having ADS-B data 102 comprising a latitude 106, a longitude 108, and a barometric altitude 112.

As shown in FIG. 11, the method 280 further comprises step 286 of conducting a data reasonableness 152 (see FIG. 4) check of the ADS-B data 102 and the TCAS data 122 using a computer system 80 (see FIG. 4) coupled to the CPS 10a (see FIG. 4). The computer system 80 (see FIGS. 4, 10)

preferably comprises at least one computer 230 (see FIG. 10) and a processor device 232 (see FIG. 10) for executing one or more functions of the at least one computer 230. The computer system 80 (see FIG. 10) further preferably comprises a computer software program 264 (see FIG. 10) adapted to perform via the computer 230 and the processor device 232, the data reasonableness 152 (see FIG. 4) check. In the conducting 286 step, the data reasonableness 152 (see FIG. 4) check of the ADS-B data 102 and the TCAS data 122 comprises checking the data reasonableness 152 (see FIG. 4) for the slant range 128 and the bearing 134 using a last known position 158 (see FIG. 4) of each of the one or more proximate vehicles 72 propagated to real-time 156 (see FIG. 4) and the ADS-B data 102 (see FIG. 4).

As shown in FIG. 11, the method 280 further comprises step 288 of asking the question of, "Does the data reasonableness 152 check pass"? As shown in FIG. 11, if a "NO" answer 290 is the answer to the question in step 288, then the method 280 proceeds to step 292, where the ADS-B data 102 and the TCAS data 122 are rejected, if the data reasonableness 152 check does not pass.

As shown in FIG. 11, if a "YES" answer 296 is the answer to the question in step 288, then the method 280 proceeds to step 298. As shown in FIG. 11, step 298 comprises performing, with the computer system 80 (see FIG. 10), preferably comprising at least one computer 230 (see FIG. 10) and the processor device 232 (see FIG. 10) and the computer software program 264 (see FIG. 10), a data synchronization 140 (see FIG. 4) of the ADS-B data 102 (see FIG. 4) and the TCAS data 122 (see FIG. 4), if the data reasonableness 152 (see FIG. 4) check passes. The data synchronization 140 (see FIG. 4) takes into account a data latency 142 (see FIG. 4) due to a transmission 144 (see FIG. 4) and a computation 146 (see FIG. 4) of the ADS-B data 102 and the TCAS data 122.

As shown in FIG. 11, the method 280 further comprises step 300 of computing, with the computer system 80 (see FIG. 10), preferably comprising at least one computer 230 (see FIG. 10) and the processor device 232 (see FIG. 10) and the computer software program 264 (see FIG. 10), a communal position system (CPS) position 150 (see FIG. 4) and a position accuracy 170 (see FIG. 4) based on the ADS-B data 102 (see FIG. 4) and the TCAS data 122 (see FIG. 4), and determining one or more navigation solutions 195 (see FIG. 4) for the vehicle 12 (see FIG. 4). The one or more navigation solutions 195 (see FIG. 4) comprise one or more of, an alternate navigation solution 195a (see FIG. 4), an independent navigation solution 195b (see FIG. 4), and a complementary navigation solution 195c (see FIG. 4).

The method 280 may further comprise integrating the CPS 10a (see FIG. 4) in one of, a flight management computer (FMC) 82 (see FIGS. 4, 7C) in the host vehicle 70, a global positioning system (GPS) 86 (see FIGS. 4, 7B) in the host vehicle 70, and a traffic alert and collision avoidance system (TCAS) 120 (see FIGS. 4, 7D) in the host vehicle 70.

Disclosed embodiments of the system 10 (see FIG. 4) such as the CPS 10a (see FIG. 4), the apparatus 11 (see FIG. 4) such as the CPS sensor 11a (see FIG. 4), and the method 280 (see FIG. 11) provide an innovative way to determine vehicle 12 (see FIG. 4), such as aircraft 12b (see FIG. 4), navigation solutions 195 (see FIG. 4) by using automatic dependent surveillance-broadcast (ADS-B) data 102 (see FIG. 4) and traffic alert and collision avoidance system (TCAS) data 122 (see FIG. 4). By using bearings 134 (see FIG. 4) and distances 126 (see FIG. 4) from one or more proximate vehicles 72 (see FIGS. 4-6B) through TCAS 120 (see FIG. 4), and the navigation positions 73 from the one or

more proximate vehicles **72** (see FIGS. 4-6B) through ADS-B **100** (see FIG. 4), a CPS position **150** (see FIG. 4) and a navigation position **71** (see FIG. 4) of the host vehicle **70** (see FIG. 4) may be computed in an air environment **62** (see FIG. 4) or on a ground environment **188** (see FIG. 4). Further, disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) provide an alternate navigation solution **195a** (see FIG. 4), if a position solution using existing techniques is not available, or one or more position sensors **84** (see FIG. 4) onboard the vehicle **12** (see FIG. 4) become non-operational or fail. For example, disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) may solve various issues and provide an alternate navigation solution **195a** (see FIG. 4), when the global navigation satellite system (GNSS) data **90a** (see FIG. 11) is lost due to GNSS **90** (see FIG. 4) receiver failures, or signal jamming **66a** (see FIG. 4) of GPS **86** (see FIG. 4), provided the ADS-B data **102** from the one or more proximate vehicles **72** (see FIG. 4) is not affected by the signal jamming **66a** (see FIG. 4). Further, disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) provide an independent navigation solution **195b** (see FIG. 4) for cross-checking **184** (see FIG. 4) and integrity monitoring **186** (see FIG. 4) of other position solutions, e.g., FMC **82** (see FIG. 4) or GPS **86** (see FIG. 4) positions.

Moreover, disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) provide a complementary navigation solution **195c** for integrating with existing or known position sensors **84** (see FIG. 4). The ADS-B data **102** (see FIG. 4) and the TCAS data **122** (see FIG. 4) from proximate vehicles **72** (see FIG. 4) may be integrated into a GPS **86** (see FIG. 4) receiver. The proximate vehicles **72** (see FIG. 4) may be treated as additional satellites **274** (see FIG. 4), which provide additional range measurements **276** (see FIG. 4), and which may be weighted based on known position accuracy **170** (see FIG. 4), which, in turn, may be used to improve a satellite-receiver geometry **278** (see FIG. 4), especially in a vertical dilution of precision (VDOP) **180** (see FIG. 4), if one or more of the proximate vehicles **72** (see FIGS. 4-6B) is/are below the host vehicle **70** (see FIGS. 4-6B). Thus, the CPS **10a** and the CPS sensor **11a** may be integrated with existing or known position sensors **84** (see FIG. 4). Similarly, the slant ranges **128** (see FIG. 4) and distances **126** (see FIG. 4) or bearings **134** (see FIG. 4) of the one or more the proximate vehicles **72** (see FIGS. 4-6B) may be integrated into the FMC **82** (see FIGS. 7A-7D) with existing IRS **88** (see FIG. 4) position sensors and/or radio position sensors **92** (see FIG. 4) using the Kalman filter **182** (see FIG. 4).

In addition, disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) may reduce navigation sensor installation costs associated with operating a group of air vehicles **12a** (see FIG. 4), including unmanned air vehicles **12c** (see FIG. 4), as the use of the CPS **10a** with the CPS sensor **11a** (see FIG. 4) may eliminate the need for all of the air vehicles **12a** (see FIG. 4) in the group to have position sensors **84** (see FIG. 4), such as IRS **88** (see FIG. 4) sensors,

GNSS **90** (see FIG. 4) sensors, and radio position sensors **92** (see FIG. 4). If a small subset of air vehicles **12a**, referred to as leaders **70b** (see FIG. 4) have the position sensors **84** (see FIG. 4), the remaining air vehicles **12a**, referred to as workers **72e** (see FIG. 4), may be able to compute their independent navigation solutions using only their ADS-B **100** and TCAS **120**. Not having to equip and install known onboard position sensors into all of the air vehicles **12** in the group may thus decrease the costs, installation time, and labor to install. Moreover, different operational objectives may also be accommodated, where the leader **70b** (see FIG. 4) may be located either on the ground or in the air, with the workers **72e** (see FIG. 4).

Further, disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) provide a communal position navigation solution that uses ADS-B data **102** and TCAS data **122** from nearby or proximate air vehicles **72** to compute a navigation position **71** of a host vehicle **70** should one or more position sensors **84** become nonoperational onboard the host vehicle **70** or should the host vehicle **70** experience signal jamming **66a** (see FIG. 4). The use of disclosed embodiments of the system **10** (see FIG. 4) such as the CPS **10a** (see FIG. 4), the apparatus **11** (see FIG. 4) such as the CPS sensor **11a** (see FIG. 4), and the method **280** (see FIG. 11) in vehicles **12** may result in an overall cost savings and cost avoidance.

Many modifications and other embodiments of the disclosure will come to mind to one skilled in the art to which this disclosure pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. The embodiments described herein are meant to be illustrative and are not intended to be limiting or exhaustive. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

1. A system using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining one or more navigation solutions for a vehicle, the system comprising:
  - a communal position system (CPS) comprising:
    - a communal position system (CPS) sensor located in the vehicle, the CPS sensor configured to receive automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data from each of one or more proximate vehicles, wherein the ADS-B data comprises a latitude, a longitude, and a barometric altitude for each proximate vehicle, and wherein the TCAS data comprises one of, a slant range for each proximate vehicle, or a slant range, a bearing, and a relative altitude for each proximate vehicle;
  - a computer system coupled to the CPS, the computer system configured to perform the steps of:
    - checking the ADS-B data and the TCAS data for data reasonableness;
    - performing data synchronization of the ADS-B data and the TCAS data; and
    - computing a communal position system (CPS) position and a position accuracy based on the ADS-B data and the TCAS data,
- wherein the CPS is used in determining one or more navigation solutions for the vehicle, the one or more navigation solutions comprising one or more of, an



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alternate navigation solution, an independent navigation solution, and a complementary navigation solution.

2. The system of claim 1 wherein the CPS is integrated in one of, a flight management computer (FMC) in the vehicle, a global positioning system (GPS) in the vehicle, and a traffic alert and collision avoidance system (TCAS) in the vehicle.

3. The system of claim 1 wherein the automatic dependent surveillance-broadcast (ADS-B) data for each of the one or more proximate vehicles further comprises one or more of, identification information for each proximate vehicle, a position navigation integrity category (NIC) for each proximate vehicle, a global navigation satellite system (GNSS) height for each proximate vehicle, a plurality of velocities for each proximate vehicle, and a navigation accuracy category for velocity (NACv) for each proximate vehicle.

4. The system of claim 1 wherein the traffic alert and collision avoidance system (TCAS) data for each of the one or more proximate vehicles further comprises identification information for each proximate vehicle.

5. The system of claim 1 wherein the data reasonableness for the slant range and the bearing is checked using a last known position of each of the one or more proximate vehicles propagated to real-time and the ADS-B data.

6. The system of claim 1 wherein the data synchronization takes into account a data latency due to a transmission and a computation of the ADS-B data and the TCAS data.

7. The system of claim 1 wherein the alternate navigation solution is used when one or more position sensors on the vehicle experiences one of, being non-operational, signal jamming, and interference.

8. The system of claim 1 wherein the independent navigation solution is used for cross-checking and integrity monitoring of one or more position sensors on the vehicle.

9. The system of claim 1 wherein the complementary navigation solution is used when the ADS-B data and the TCAS data from the one or more proximate vehicles is integrated into a global positioning system (GPS), and the one or more proximate vehicles function as additional satellites providing additional range measurements, to improve a satellite-receiver geometry.

10. The system of claim 1 wherein the vehicle is a host vehicle comprising an air vehicle, including one of, an aircraft, an unmanned air vehicle, a satellite, a glider, a rotorcraft, and a missile.

11. An apparatus for using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining one or more navigation solutions for a vehicle, the apparatus comprising: a communal position system (CPS) sensor located in the vehicle, the CPS sensor configured to receive automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data from each of one or more proximate vehicles, wherein the ADS-B data comprises a latitude, a longitude, and a barometric altitude for each proximate vehicle, and wherein the TCAS data comprises one of, a slant range for each proximate vehicle, or a slant range, a bearing, and a relative altitude for each proximate vehicle, and the CPS sensor being used to determine one or more navigation solutions for the vehicle, the one or more navigation solutions comprising one or more of, an alternate navigation solution, an independent navigation solution, and a complementary navigation solution,

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wherein the CPS sensor is coupled to a computer system configured to perform the steps of: checking the ADS-B data and the TCAS data for data reasonableness;

performing data synchronization of the ADS-B data and the TCAS data; and

computing a communal position system (CPS) position and a position accuracy based on the ADS-B data and the TCAS data.

12. The apparatus of claim 11 wherein the CPS sensor is integrated in one of, a flight management computer (FMC) in the vehicle, a global positioning system (GPS) in the vehicle, and a traffic alert and collision avoidance system (TCAS) in the vehicle.

13. The apparatus of claim 11 wherein the CPS sensor receives ADS-B data further comprising one or more of, identification information for each proximate vehicle, a position navigation integrity category (NIC) for each proximate vehicle, a global navigation satellite system (GNSS) height for each proximate vehicle, a plurality of velocities for each proximate vehicle, and a navigation accuracy category for velocity (NACv) for each proximate vehicle, and wherein the CPS sensor receives TCAS data further comprising identification information for each proximate vehicle.

14. A computer implemented method for using automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data for determining one or more navigation solutions for a vehicle, the method comprising the steps of:

receiving, by a communal position system (CPS) in the vehicle, automatic dependent surveillance-broadcast (ADS-B) data and traffic alert and collision avoidance system (TCAS) data, from each of one or more proximate vehicles, wherein the ADS-B data comprises a latitude, a longitude, and a barometric altitude for each proximate vehicle, and wherein the TCAS data comprises one of, a slant range for each proximate vehicle, or a slant range, a bearing, and a relative altitude for each proximate vehicle;

conducting a data reasonableness check of the ADS-B data and the TCAS data using a computer system coupled to the CPS;

rejecting the ADS-B data and the TCAS data, if the data reasonableness check does not pass;

performing, with the computer system, a data synchronization of the ADS-B data and the TCAS data, if the data reasonableness check passes, the data synchronization taking into account a data latency due to a transmission and a computation of the ADS-B data and the TCAS data; and

computing, with the computer system, a communal position system (CPS) position and a position accuracy based on the ADS-B data and the TCAS data, and determining one or more navigation solutions for the vehicle, the one or more navigation solutions comprising one or more of, an alternate navigation solution, an independent navigation solution, and a complementary navigation solution.

15. The method of claim 14 further comprising integrating the CPS in one of, a flight management computer (FMC) in the vehicle, a global positioning system (GPS) in the vehicle, and a traffic alert and collision avoidance system (TCAS) in the vehicle.

16. The method of claim 14 wherein the receiving the ADS-B data from each of the one or more proximate vehicles comprises receiving the ADS-B data further com-

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prising one or more of, identification information for each proximate vehicle, a position navigation integrity category (NIC) for each proximate vehicle, a global navigation satellite system (GNSS) height for each proximate vehicle, a plurality of velocities for each proximate vehicle, and a navigation accuracy category for velocity (NACv) for each proximate vehicle.

17. The method of claim 14 wherein the receiving the TCAS data from each of the one or more proximate vehicles comprises receiving the TCAS data further comprising identification information for each proximate vehicle.

18. The method of claim 14 wherein conducting the data reasonableness check of the ADS-B data and the TCAS data comprises checking the data reasonableness for the slant range and the bearing using a last known position of each of the one or more proximate vehicles propagated to real-time and the ADS-B data.

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19. The method of claim 14 wherein the receiving by the vehicle, of the ADS-B data and the TCAS data, comprises receiving the ADS-B data and the TCAS data from one proximate vehicle having TCAS data comprising the slant range, the bearing, and the relative altitude, and having ADS-B data comprising the latitude, the longitude, and the barometric altitude.

20. The method of claim 14 wherein the receiving by the vehicle, of the ADS-B data and the TCAS data, comprises receiving the ADS-B data and the TCAS data from three proximate vehicles, each proximate vehicle having TCAS data comprising the slant range, and having ADS-B data comprising the latitude, the longitude, and the barometric altitude.

21. The method of claim 14 wherein the method is performed in one of, an air-based location, and a ground-based location.

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