



(12) **United States Patent**
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(54) **WEATHER RADAR SYSTEM AND METHOD FOR DETECTING A HIGH ALTITUDE CRYSTAL CLOUD CONDITION**

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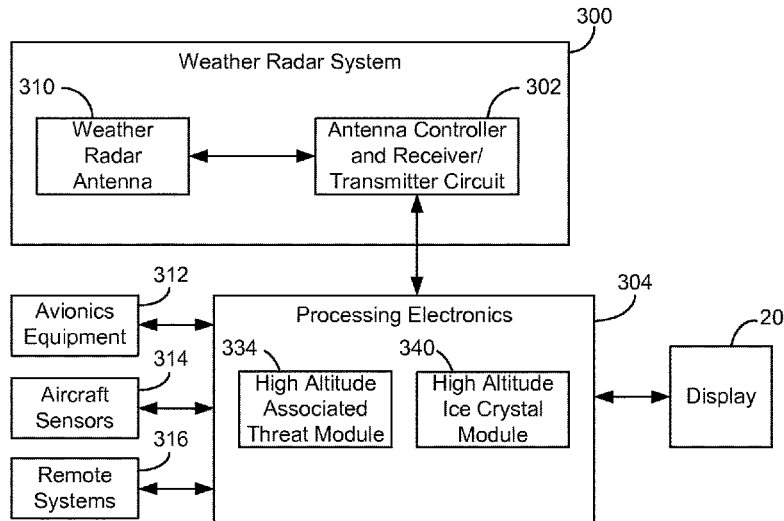
(57) **ABSTRACT**

(52) **U.S. Cl.**
CPC **G01S 13/953** (2013.01); **G01S 13/95** (2013.01); **B64D 15/20** (2013.01)

The hazard warning system that included processing system for detecting a high altitude ice crystal (HAIC) or HAIC cloud (HAIC²) condition. The aircraft warning system can use an inferred detected process or a non-inferred detection process. Warnings of high altitude ice crystal conditions can allow an aircraft to avoid threats posed by HAIC or HAIC² conditions including damage to aircraft equipment and engines.

(58) **Field of Classification Search**
CPC G01S 13/953; G01S 13/95; B64D 15/20; B64C 15/20
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See application file for complete search history.

20 Claims, 5 Drawing Sheets



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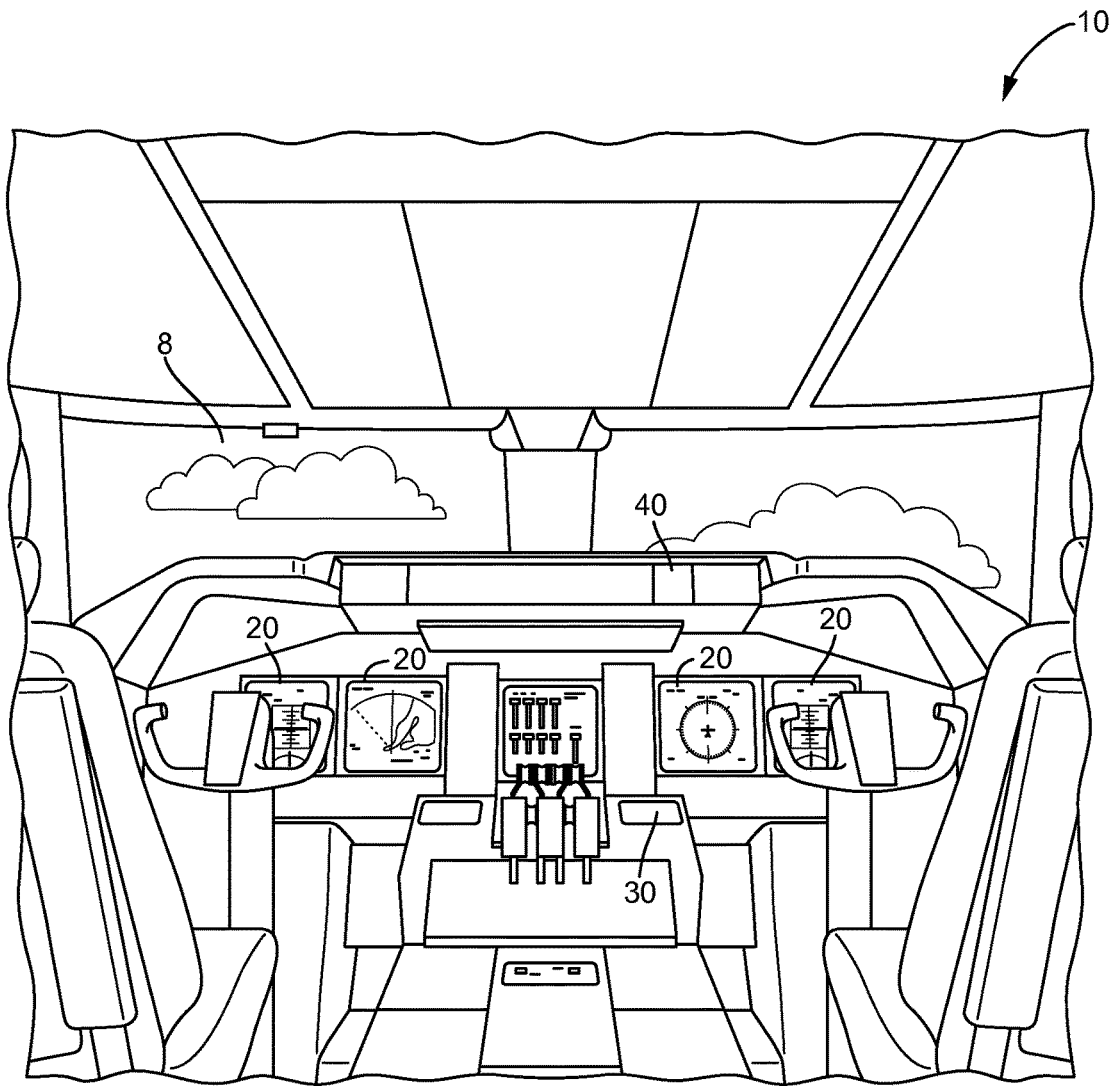


FIG. 1

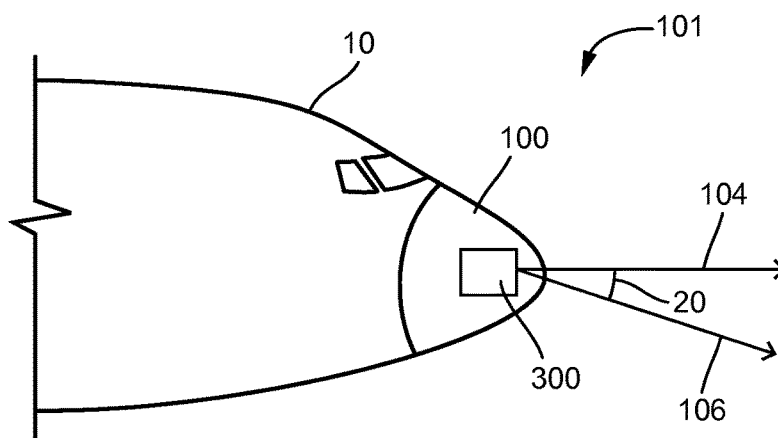


FIG. 2

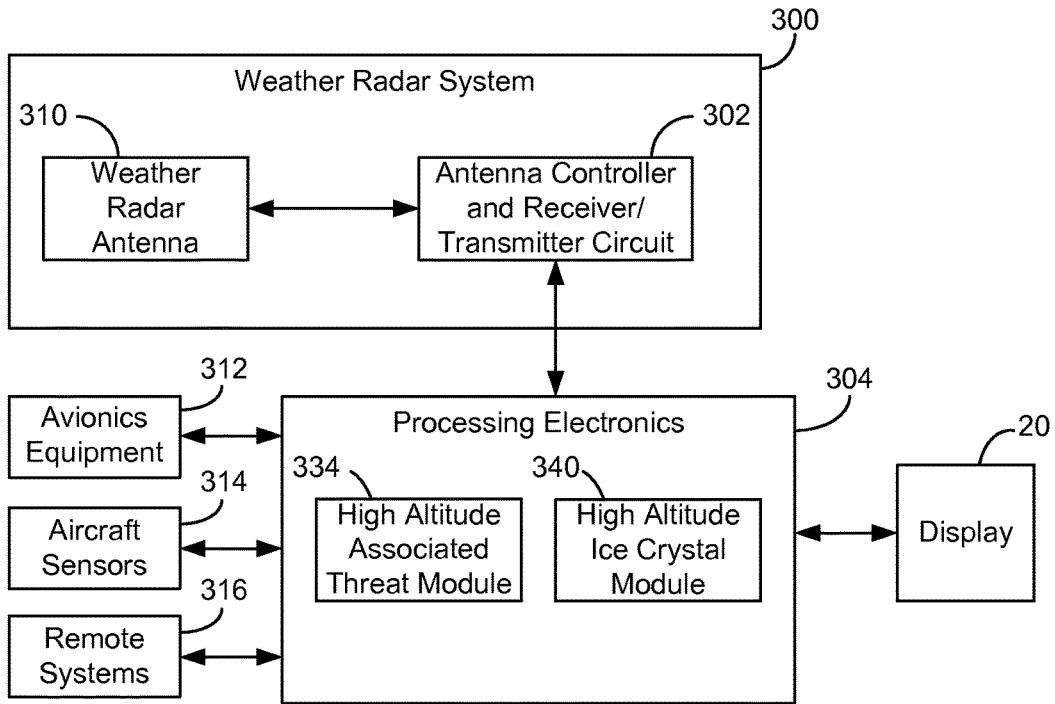


FIG. 3

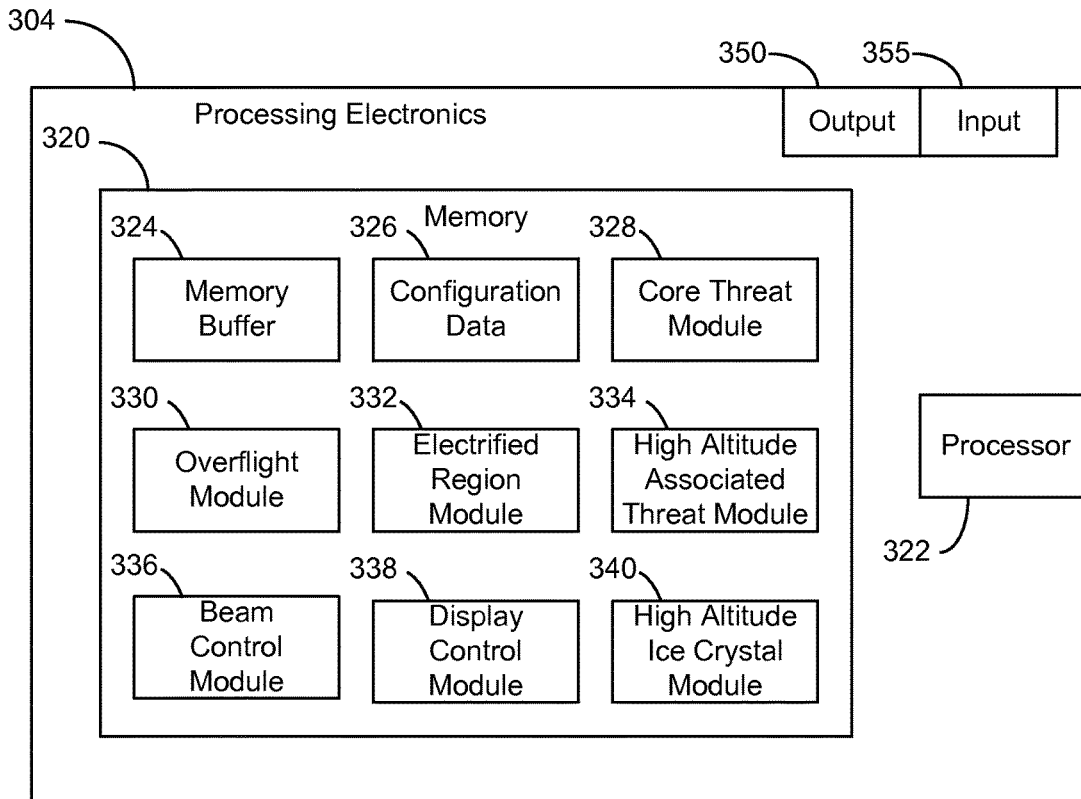


FIG. 4

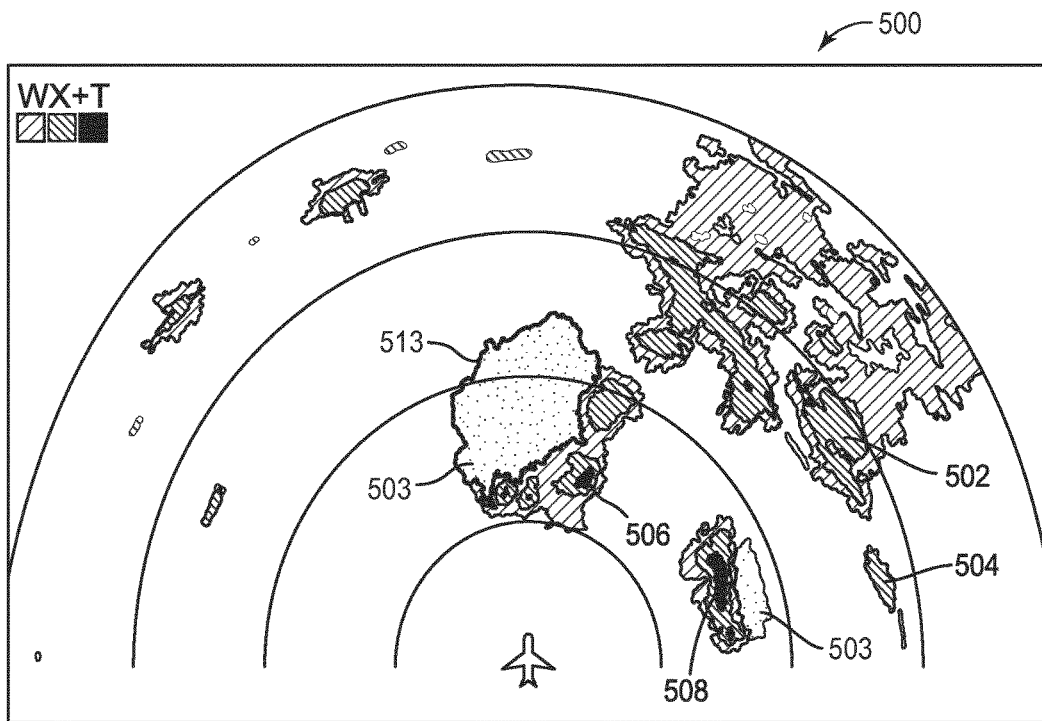


FIG. 5

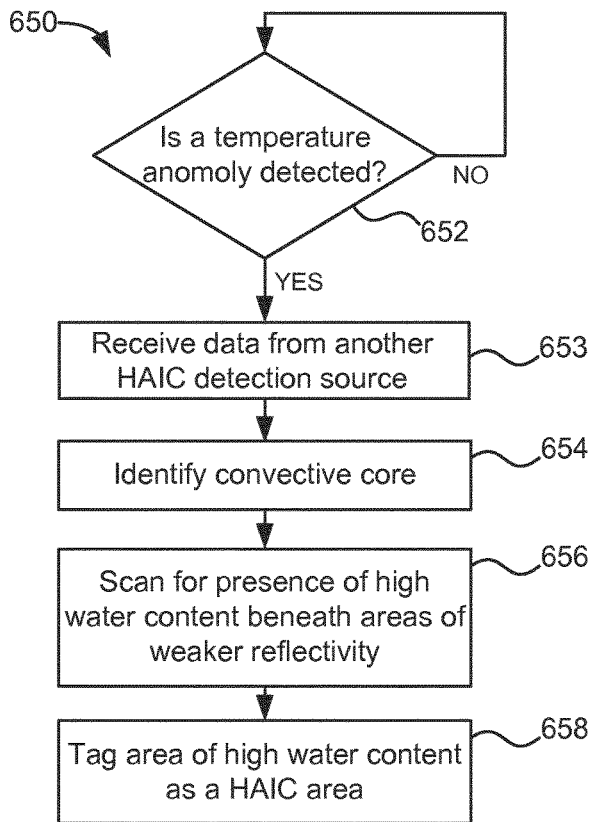


FIG. 6

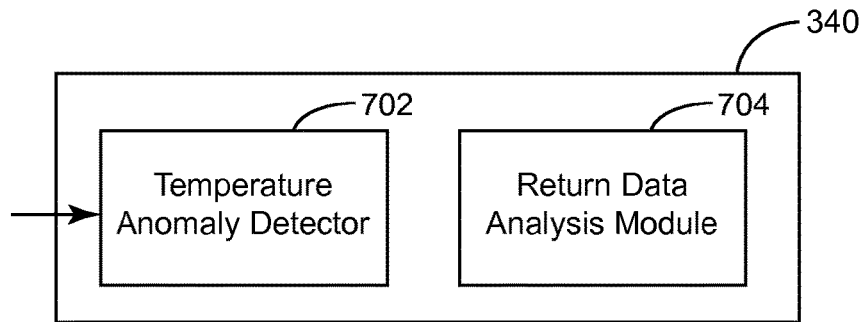


FIG. 7

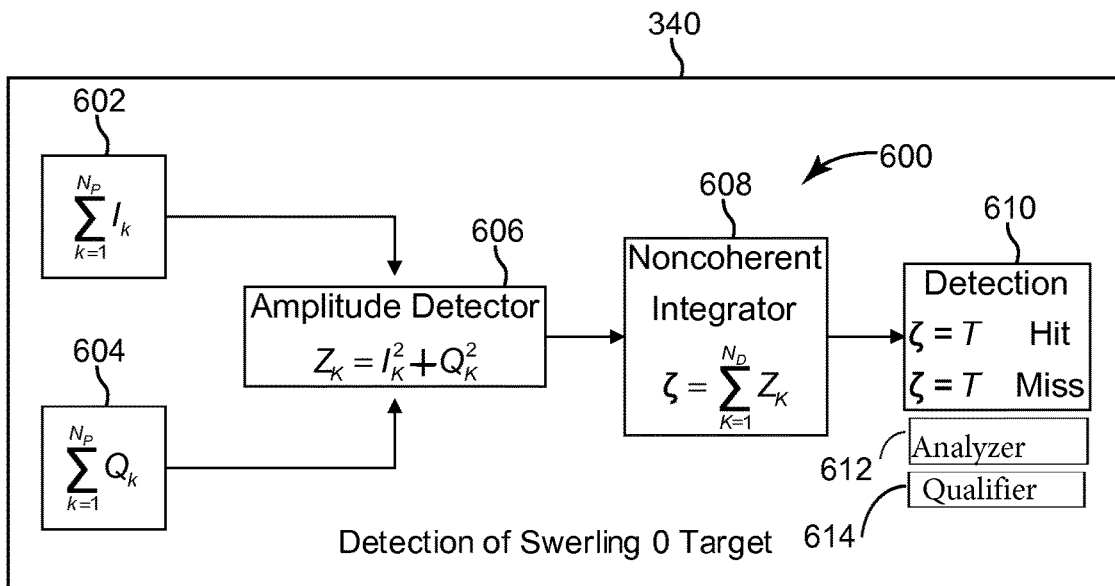


FIG. 8

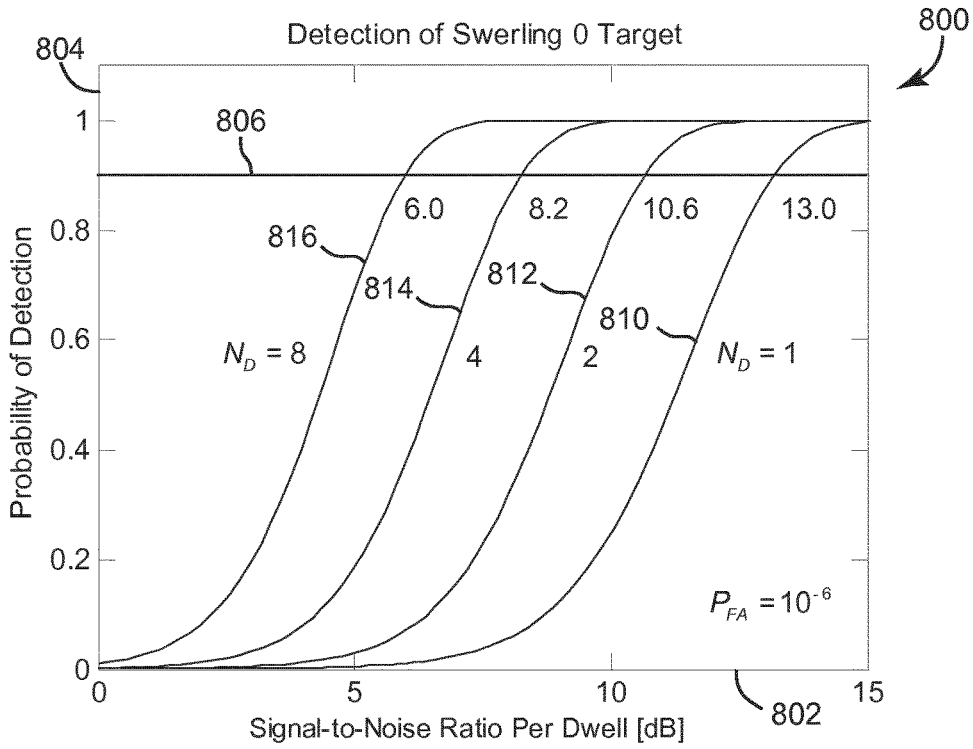


FIG. 9

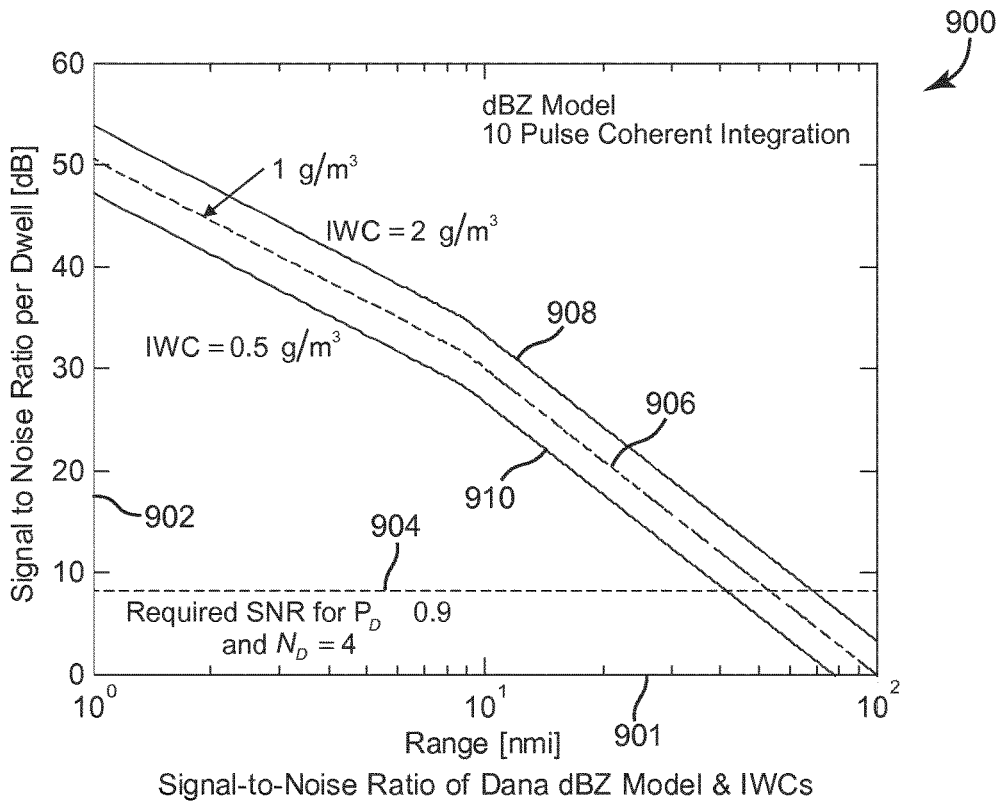


FIG. 10

WEATHER RADAR SYSTEM AND METHOD FOR DETECTING A HIGH ALTITUDE CRYSTAL CLOUD CONDITION

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is related to U.S. patent application Ser. No. 14/086,844 filed on Nov. 21, 2013 (13CR664 (47141-0960)), U.S. application Ser. No. 13/919,406 filed on Jun. 17, 2013 (13CR351 (047141-0923)), U.S. application Ser. No. 13/841,893 filed Mar. 15, 2013 (12CR1778 (047141-0905)), U.S. application Ser. No. 14/207,034 filed on an even date herewith invented by Koenigs, et al. (14CR030 (047141-0978)), U.S. application Ser. No. 13/246,769 filed Sep. 27, 2011 (11CR243 (047141-0802)) and U.S. application Ser. No. 14/206,651 filed on an even date herewith invented by Dana, et al., (14CR048 (047141-0979)), all incorporated herein by reference in their entireties and assigned to the assignee of the present application.

BACKGROUND

This specification relates generally to weather hazard warnings. More particularly, this specification relates to detection of weather hazards related to ice crystals.

Conventional aircraft hazard weather radar systems, such as the WXR 2100 MultiScan™ radar system manufactured by Rockwell Collins, Inc., have Doppler capabilities and are capable of detecting at least four parameters: weather range, weather reflectivity, weather velocity, and weather spectral width or velocity variation. The weather reflectivity is typically scaled to green, yellow, and red color levels that are related to rainfall rate. The radar-detected radial velocity variation can be scaled to a turbulence level and displayed as magenta. Such weather radar systems can conduct vertical sweeps and obtain reflectivity parameters at various altitudes.

Ice crystals pose threats to aircraft and their components. For example, sensors can provide improper readings when clogged by ice. Probes and engines can also be susceptible to damage caused by mixed phase and glaciated ice crystals when operating near areas of deep convection and at higher altitudes. Engine rollback issues are believed to be related to ice crystal accretion, followed by aggregate detachment in solid form before continuing through the aircraft engine. High efficiency engines are believed to be more susceptible to damage caused by ice crystals.

Radar reflectivity levels in and around the convective regions at high altitudes associated with high altitude, thin ice crystal formation have typically been very low and can be difficult to detect. Conventional X-band radar systems provide insufficient energy on the target to detect and discriminate high altitude ice crystal clouds. It is difficult to distinguish low reflectivity precipitation areas from areas of high altitude ice crystal (HAIC) formation and HAIC clouds (HAIC²). Detection and display of high altitude ice crystallization areas is desirous because the icing events caused by HAIC and/or high altitude ice crystal cloud (HAIC²) conditions can have a direct impact on aircraft, crew and passengers depending on the severity of the accretion.

Thus, there is a need for an aircraft hazard warning system and method that senses an inferred or non-inferred high altitude ice crystal (HAIC) or high altitude ice crystal cloud (HAIC²) conditions. There is also a need for a hazard detection system that detects and displays high altitude associated threat (HAIC) or high altitude ice crystal cloud

(HAIC²) conditions. There is also a need for an inferred and/or non-inferred HAIC or HAIC² detection system and method. Still further, there is a need for a signal processing technique for increasing signal-to-noise ratios (SNRs) associated with radar returns for HAIC or HAIC² detection. Yet further, there is a need for an aircraft hazard warning system that alerts a pilot to HAIC or HAIC² conditions.

It would be desirable to provide a system and/or method that provides one or more of these or other advantageous features. Other features and advantages will be made apparent from the present specification. The teachings disclosed extend to those embodiments which fall within the scope of the appended claims, regardless of whether they accomplish one or more of the aforementioned needs.

SUMMARY

An exemplary embodiment relates to an aircraft hazard warning system. The aircraft hazard warning system includes a processing system for detecting a high altitude ice crystal (HAIC) or HAIC clouds (HAIC²) condition.

Another exemplary embodiment relates to a method of providing a high altitude ice crystal (HAIC) or HAIC clouds (HAIC²) warning on an aircraft using an electronic processor. The method includes receiving reflectivity data, and processing the radar reflectivity data to determine a HAIC or HAIC² condition exists.

Another exemplary embodiment relates to an aircraft weather radar system. The aircraft weather radar system includes a radar antenna for receiving radar returns, and a means for determining a high altitude ice crystal (HAIC) or HAIC clouds (HAIC²) condition in response to the radar returns.

Exemplary embodiments can utilize inferred and non-inferred techniques to determine presence of HAIC or HAIC² conditions. Non-inferred techniques can utilize coherent and non-coherent integration to achieve detection at longer ranges according to certain embodiments. Inferred detection techniques can utilize temperature anomalies and radar return analysis to detect a HAIC or HAIC² condition according to various embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments will become more fully understood from the following detailed description, taken in conjunction with the accompanying drawings, wherein like reference numerals refer to like elements, and:

FIG. 1 is a perspective view schematic illustration of an aircraft control center, according to an exemplary embodiment.

FIG. 2 is a side view schematic illustration of the nose of an aircraft including a weather radar system, according to an exemplary embodiment.

FIG. 3 is a block diagram of a weather radar system including a high altitude ice crystal (HAIC) or HAIC clouds (HAIC²) module, according to an exemplary embodiment.

FIG. 4 is a more detailed block diagram of the weather radar system illustrated in FIG. 3 according to another exemplary embodiment.

FIG. 5 is a schematic illustration of an aviation horizontal plan view weather display showing a HAIC or HAIC² warning, according to an exemplary embodiment.

FIG. 6 is a flow diagram showing an inferred process performed by the system illustrated in FIG. 3 according to an exemplary embodiment.

FIG. 7 is a more detailed block diagram of an embodiment of the HAIC or HAIC² module of the weather radar system illustrated in FIG. 3 according to an exemplary embodiment.

FIG. 8 is a more detailed block diagram of a signal processing path for the HAIC or HAIC² module illustrated in FIG. 3 according to another exemplary embodiment.

FIG. 9 is a graph showing signal-to-noise ratio (SIR) per dwell versus probability of detection for the system illustrated in FIG. 3.

FIG. 10 is a graph showing SIR per dwell versus range for the system illustrated in FIG. 3.

DETAILED DESCRIPTION

Referring generally to the FIGURES, systems and methods for indicating a weather threat to an aircraft are described, according to an exemplary embodiment. An airborne weather radar system is generally configured to project radar beams and to receive radar returns relating to the projected radar beams. The projected radar beams generally pass through air and reflect off of precipitation (e.g., rain, snow, etc.), other aircraft, and terrain (e.g., a mountain, a building). Using the reflected return data, processing electronics associated with the weather radar system can distinguish between types of precipitation and terrain. Weather radar systems are typically configured to display the precipitation as measured weather threats in green (light rain or precipitation), yellow (moderate rain or precipitation), and red (severe rain or precipitation). While this “rain gauge” provides valuable information to the crew, more specific indicators of weather threats to the aircraft is helpful to the crew. For example, high altitude associated threat (HAAT) and/or high altitude ice crystal (HAIC) or HAIC cloud (HAIC²) threat warnings advantageously allow pilots to avoid regions detrimental to aircraft and their engines. In one embodiment, the HAIC threat can be a high altitude ice crystal cloud (HAIC²) threat.

Referring now to FIG. 1, an illustration of an aircraft control center or cockpit 10 is shown, according to an exemplary embodiment. Aircraft control center 10 includes flight displays 20 which are generally used to increase visual range and to enhance decision-making abilities. In an exemplary embodiment, flight displays 20 may provide an output from a radar system of the aircraft. For example, flight displays 20 may provide a top-down view, a horizontal view, vertical view/perspective or 3 dimensional view, or any other view of weather and/or terrain detected by a radar system on the aircraft. The views of weather may include monochrome or color graphical representations of the weather. Graphical representations of weather may include an indication of altitude of those objects or the altitude relative to the aircraft. Aircraft control center 10 may further include other user interface elements such as an audio device 30 (e.g., speaker, electro-acoustic transducer, etc.) and illuminating or flashing lamps 40. Weather can be displayed as colored regions on the aircraft according to ARINC standards.

In one embodiment, a HAIC, HAIC² and/or HAAT warning can be provided on any of displays 20 as part of a weather radar display. In one embodiment, the HAAT warning is displayed as a red speckled region, and the HAIC or HAIC² warning is displayed as a yellow speckled region. The red speckled region indicates a higher severity of threat for the HAAT warning as compared to the yellow speckled region for the HAIC or HAIC² warning.

Referring to FIG. 2, the front of an aircraft 101 is shown with aircraft control center 10 and nose 100, according to an

exemplary embodiment. A radar system 300 (e.g., a weather radar system or other radar system) is generally located within nose 100 of aircraft 101 or within aircraft control center 10 of aircraft 101. According to various exemplary embodiments, radar system 300 may be located on the top of aircraft 101 or on the tail of aircraft 101 instead. Radar system 300 may include or be coupled to an antenna system. A variety of different antennas or radar systems may be used as part of system 300 (e.g., a split aperture antenna, a monopulse antenna, a sequential lobbing antenna, etc.).

Radar system 300 generally works by sweeping a radar beam horizontally back and forth across the sky. Some radar systems will conduct a first horizontal sweep 104 directly in front of aircraft 101 and a second horizontal sweep 106 downward at some tilt angle 108 (e.g., 20 degrees down). Returns from different tilt angles can be electronically merged to form a composite image for display on an electronic display 20 shown, for example, in FIG. 1. Returns can also be processed to, for example, distinguish between terrain and weather, to determine the height of terrain, or to determine the height of weather. Radar system 300 can be a WXR-2100 MultiScan™ radar system or similar system manufactured by Rockwell Collins and configured as described herein. According to other embodiments, radar system 300 may be an RDR-4000 system or similar system manufactured by Honeywell International, Inc. configured as described herein. Radar system 300 may be integrated with other avionics equipment and user interface elements in aircraft control center 10 (e.g., flashing lights 40, displays 20, display elements on a weather radar display, display elements on a terrain display, audio alerting devices 30, navigation systems, TAWs equipment, etc.).

Referring to FIG. 3, a block diagram of radar system 300 embodied as a weather radar system is shown, according to an exemplary embodiment. Weather radar system 300 is shown to include a weather radar antenna 310 connected (e.g., directly, indirectly) to an antenna controller and receiver/transmitter circuit 302. Antenna controller and receiver/transmitter circuit 302 may include any number of mechanical or electrical circuitry components or modules for steering a radar beam. For example, circuit 302 may be configured to mechanically tilt the antenna in a first direction while mechanically rotating the antenna in a second direction. In other embodiments, a radar beam may be electronically swept along a first axis and mechanically swept along a second axis. In yet other embodiments, the radar beam may be entirely electronically steered (e.g., by electronically adjusting the phase of signals provided from adjacent antenna apertures, etc.). Circuit 302 may be configured to conduct the actual signal generation that results in a radar beam being provided from weather radar antenna 310 and to conduct the reception of returns received at radar antenna 310. Radar return data is provided from circuit 302 to processing electronics 304 for processing. For example, processing electronics 304 can be configured to interpret the returns for display on display 20.

Processing electronics 304 can also be configured to provide control signals or control logic to circuit 302. For example, depending on pilot or situational inputs, processing electronics 304 may be configured to cause circuit 302 to change behavior or radar beam patterns. In other words, processing electronics 304 may include the processing logic for operating weather radar system 300. It should be noted that processing electronics 304 may be integrated into radar system 300 or located remotely from radar system 300, for example, in aircraft control center 10.

Processing electronics **304** are further shown as connected to aircraft sensors **314** which may generally include any number of sensors configured to provide data to processing electronics **304**. For example, sensors **314** could include temperature sensors, humidity sensors, infrared sensors, altitude sensors, a gyroscope, a global positioning system (GPS), or any other aircraft-mounted sensors that may be used to provide data to processing electronics **304**. It should be appreciated that sensors **314** (or any other component shown connected to processing electronics **304**) may be indirectly or directly connected to processing electronics **304**. Processing electronics **304** are further shown as connected to avionics equipment **312** and include a high altitude ice crystal (HAIC) or HAIC cloud (HAIC²) module **340** and a high altitude associated threat (HAAT) module **334**. Modules **340** and **334** advantageously detect and locate HAIC, HAIC² and HAAT conditions and cause display **20** to provide a visual and/or audio warning of such conditions. Modules **334** and **340** process data associated with weather radar reflectivity levels and/or data from other sensors (e.g., temperature, altitude, etc.) to determine HAIC, HAIC² and HAAT conditions. Avionics equipment **312** can be or include a flight management system, a navigation system, a backup navigation system, or another aircraft system configured to provide inputs to processing electronics **304**. The HAIC or HAIC² condition can be sensed via an inferred or non-inferred process as explained below according to various exemplary embodiments. Processing electronics **304** are further shown as connected to remote systems **316** which may generally include any number of sensors located off the aircraft and configured to transmit data wirelessly to processing electronics **304**. For example, remote systems **316** could include ground radars, satellites, other aircraft or any other remote system that may be used to provide data to processing electronics **304**. Processing electronics **304** can use data from remote systems to determine HAAT, HAIC, and HAIC² conditions.

Referring to FIG. 4, a detailed block diagram of processing electronics **304** of FIG. 3 is shown, according to an exemplary embodiment. Processing electronics **304** includes a memory **320** and processor **322**. Processor **322** may be or include one or more microprocessors, digital signal processors, an application specific integrated circuit (ASIC), a circuit containing one or more processing components, a group of distributed processing components, circuitry for supporting a microprocessor, or other hardware configured for processing. According to an exemplary embodiment, processor **322** is configured to execute computer code stored in memory **320** to complete and facilitate the activities described herein. Memory **320** can be any volatile or non-volatile memory device capable of storing data or computer code relating to the activities described herein. For example, memory **320** is shown to include modules **328-340** which are computer code modules (e.g., executable code, object code, source code, script code, machine code, etc.) configured for execution by processor **322**. When executed by processor **322**, processing electronics **304** is configured to complete the activities described herein. Processing electronics **304** includes hardware circuitry for supporting the execution of the computer code of modules **328-340**. For example, processing electronics **304** includes hardware interfaces (e.g., output **350**) for communicating control signals (e.g., analog, digital) from processing electronics **304** to circuit **302** or to display **20**. Processing electronics **304** may also include an input **355** for receiving, for

example, radar return data from circuit **302**, feedback signals from circuit **302** or for receiving data or signals from other systems or devices.

Memory **320** includes a memory buffer **324** for receiving radar return data. The radar return data may be stored in memory buffer **324** until buffer **324** is accessed for data. For example, a core threat module **328**, overflight module **330**, electrified region module **332**, HAAT module **334**, display control module **338**, HAIC or HAIC² module **340** or another process that utilizes radar return data may access buffer **324**. The radar return data stored in memory **320** may be stored according to a variety of schemes or formats. For example, the radar return data may be stored in an x,y or x,y,z format, a heading-up format, a north-up format, a latitude-longitude format, a radial format, or any other suitable format for storing spatial-relative information.

Memory **320** further includes configuration data **326**. Configuration data **326** includes data relating to weather radar system **300**. For example, configuration data **326** may include beam pattern data which may be data that a beam control module **336** can interpret to determine how to command circuit **302** to sweep a radar beam. For example, configuration data **326** may include information regarding maximum and minimum azimuth angles of horizontal radar beam sweeps, azimuth angles at which to conduct vertical radar beam sweeps, timing information, speed of movement information, and the like. Configuration data **326** may also include data, such as threshold values, model information, look up tables, and the like used by modules **328-340** to identify and assess threats to aircraft **101**.

Memory **320** is further shown to include a core threat module **328** which includes logic for using radar returns in memory buffer **324** to make one or more determinations or inferences relating to core threats to aircraft **101**. For example, core threat module **328** may use temperature and radar return values at various altitudes to calculate a probability that lightning, hail, and/or strong vertical shearing exists within a weather cell. Core threat module **328** may be configured to compare the probability and/or severity of the core threat to a threshold value stored, for example, in core threat module **328** or configuration data **326**. Core threat module **328** may further be configured to output a signal to display control module **338** indicative of the probability of the core threat, of the inferred threat level within the weather cell, or of the inferred threat level within the weather cell being greater than the measured threat due to radar returns from rainfall. The signal may further cause a change in a color on aviation display **20** associated to the threat level to aircraft **101**.

Memory **320** is further shown to include an overflight module **330** which includes logic for using radar returns in memory buffer **324** to make one or more determinations or inferences based on weather below aircraft **101**. For example, overflight module **330** may be configured to determine the growth rate of a weather cell and/or the change in altitude of an echo top of a weather cell over time. Overflight module **330** may further be configured to calculate a probability that a weather cell will grow into the flight path of aircraft **101**. Overflight module **330** may be configured to output a signal to display control module **338** indicating the threat of the growing weather cell in relation to the flight path of aircraft **101**. For example, the signal may indicate predicted intersection of the flight path of aircraft **101** and the weather cell, rate of growth of the weather cell, or predicted growth of the weather cell to within a threshold distance of the flight path of aircraft **101**. For example, the signal may cause an icon to be displayed on aviation display

20 in a location corresponding to the growing cell, wherein the size of the icon may represent the size, amount, or probability of threat to the aircraft. Overflight module **330** may be configured to inhibit display of weather far below, and thus not a threat to, aircraft **101**.

Memory **320** is further shown to include an electrified region module **332** which includes logic for using radar returns in memory buffer **324** to make one or more determinations or inferences regarding potentially electrified regions around the weather cell. For example, electrified region module **332** may be configured to use temperature and reflectivity to determine whether a region around a weather cell is likely to produce lightning. Electrified region module **332** may be configured to determine a probability of aircraft **101** producing a lightning strike if the aircraft flies through a particular region based on the reflectivity around a convective cell near the freezing layer. Electrified region module **332** may further be configured to cause a pattern to be displayed on aviation display **20**. For example, electrified region module **332** may be configured to output a signal to display control module **338** indicating the existence, location, and/or severity of risk of the electrified region.

Memory **320** is further shown to include HAAT module **334** which includes logic for using radar returns (e.g., data) in memory buffer **324** to make one or more determinations or inferences regarding high altitude associated threats (e.g., threats related to a blow off or anvil region of a weather cell). HAAT conditions can be associated with high severity threat conditions such as hail, lightning, turbulence, etc. For example, HAAT module **334** may be configured to use wind speed, wind direction, and size of a weather cell to predict the presence of an anvil region downwind of a weather cell that may contain lightning, hail, and/or turbulence. HAAT module **334** may be configured to cause a pattern (e.g., a red speckled region) to be displayed on an aviation display **20**. For example, HAAT module **334** and module **338** can be configured to output a signal to display control module **338** indicating the existence, location, and severity or risk of the anvil region. HAAT module **334** can detect a HAAT condition based upon the presence of convective cells reaching high altitudes and having anvil shapes. Such conditions can be sensed using the techniques described in U.S. application Ser. Nos. 13/919,406 and 13/841,893. Ice crystals may be present in a HAAT region. A HAAT condition generally is a more significant threat than a HAIC or HAIC² condition.

Memory **320** is further shown to include HAIC or HAIC² module **340** which includes logic for using radar returns in memory buffer **324** to make one or more determinations or inferences regarding threats related to a HAIC or HAIC² condition. Module **340** can be combined with module **338**, be a hard wired ASIC, or programmable logic circuit in one embodiment. HAIC module **340** and weather radar system **300** can be configured to use coherent and non-coherent integration processes to detect presence of the HAIC or HAIC² condition and its location in one embodiment. Alternatively, module **340** and weather radar system **300** can utilize a dual frequency or dual polarization process discussed in related U.S. patent application Ser. No. 14/206,651 (047141-0979) incorporated herein by reference in one embodiment. In one embodiment, HAIC or HAIC² module receives data associated with weather returns at high altitude and processes the data to determine existence of a HAIC or HAIC² condition. The data can be processed by comparing the data to known ice crystal return characteristics to determine a match and therefore a HAIC or HAIC² condition. In one embodiment, module **340** senses only one of a HAIC or HAIC² condition.

Memory **320** is further shown to include a beam control module **336**. Beam control module **336** may be an algorithm for commanding circuit **302** to sweep a radar beam. Beam control module **336** may be used, for example, to send one or more analog or digital control signals to circuit **302**. The control signals may be, for example, an instruction to move the antenna mechanically, an instruction to conduct an electronic beam sweep in a certain way, an instruction to move the radar beam to the left by five degrees, etc. Beam control module **336** may be configured to control timing of the beam sweeps or movements relative to aircraft speed, flight path information, transmission or reception characteristics from weather radar system **300** or otherwise. Beam control module **336** may receive data from configuration data **326** for configuring the movement of the radar beam.

Memory **320** is further shown to include a display control module **338** which includes logic for displaying weather information on aviation display **20**. For example, display control module **338** may be configured to display radar return information received from memory buffer **324** and to determine a gain level or other display setting for display of an inferred threat to aircraft **101** on a weather radar display. Display control module **338** may be configured to receive signals relating to threats to aircraft **101** from core threat module **328**, overflight module **330**, electrified region module **332**, HAAT module **334**, and HAIC or HAIC² module **340**. Display control module **338** may further be configured to cause, in response to one or more signals received from threat modules **328-334** and **340** and threshold values from configuration data **326**, a change in color of a portion of an image on aviation display **20**, a pattern (e.g., a speckled region) to be overlaid on an image on aviation display **20**, and an icon to be shown on aviation display **20**. Display control module **338** may be configured to cause a change in size, location, shape, or color of the colored regions, patterns, symbols, and/or icons in response to updated signals received from modules **328-336** and **340**. Further, display control module can provide a pattern or symbol to indicate an inferred HAIC or HAIC² warning and to indicate a non-inferred HAIC or HAIC² warning.

Processing electronics **304** may be configured to use none, some, or all of the threat modules **328-334** and **340** described above. For example, processing electronics **304** may have an automatic mode, in which weather radar antenna **310** is automatically controlled (e.g., direction, gain, etc.) and core threat module **328**, overflight module **330**, electrified region module **332**, HAAT module **334** and HAIC or HAIC² module **340** are all processing information looking for inferred threats. Processing electronics **304** can have a manual mode, in which one or more of core threat module **328**, overflight module **330**, electrified region module **332**, HAAT module **334** and HAIC or HAIC² module **340** are disabled, for example, for diagnostic purposes.

Referring now to FIG. **5**, a schematic illustration of aviation display **20** showing a weather radar display **500** including precipitative (or weather) regions **502**, **504**, **506** and **508** corresponding to radar returns according to an exemplary embodiment. Processing electronics **304** may be configured to cause aviation display **20** to show measured threats to aircraft **101** using symbology, icons, or text. In FIG. **5**, light rain is shown as a slanted down left to right cross hatched area region, which is often indicated with a green color on display **20**. A moderate rain is shown as a slanted down right to left cross hatched region in FIG. **5** often colored yellow on display **20** to indicate caution to the crew. Solid black regions in FIG. **5** correspond to heavy rain, and are usually colored red on display **20** to indicate warning

to the crew. Region **502**, **504**, **506**, and **508** can be shown in accordance with Federal Aviation Administration (FAA) standards.

As described above, processing electronics **304** uses avionics and radar return information to infer or detect existence of a HAIC or HAIC² condition via module **340**. The HAIC or HAIC² condition can be symbolized as a stippled region **503** on display **20**. Region **503** can be stippled using yellow dots to signify caution. Alternatively, cross hatching or other dot colors can be utilized to show region **503**. Region **503** can have a border **513** in yellow or other color. Underlying weather can be viewable through stippled region **503** in one embodiment.

In one embodiment, inferred HAIC or HAIC² conditions can be displayed in a first format (speckling) and directly sensed or non-inferred HAIC or HAIC² conditions can be displayed in a second format (e.g., cross hatching). Alternatively, a text symbol or can be used to differentiate an inferred and non-inferred detection of a HAIC or HAIC² condition. In one embodiment, a HAIC condition can be displayed in one format and a HAIC² condition can be displayed in another formula.

In one embodiment, the HAIC and HAIC² condition or region shown on the display **20** may be a composite threat display showing on the same display the HAIC and HAIC² threats detected by system **300** and the HAIC and HAIC² threats detected or inferred by other HAIC detection sources, including other on-board systems (infrared, LIDAR, etc.), or remote systems (e.g., ground-based radar, satellites, etc.). At any given location, the most significant threat from any of the possible sources may be displayed.

In one embodiment, with reference to FIGS. **4** and **6**, HAIC or HAIC² module **340** can use an inferential process **650** to detect a HAIC or HAIC² condition. In one embodiment, the HAIC or HAIC² condition can be inferred by sensing temperature anomalies and reflectivity characteristics associated with core threats. In process **650**, if radar system **300** detects temperature anomalies at a step **652**, module **340** advances to step **653**. In one embodiment, system **300** can skip step **653** and proceed to step **654**.

A temperature anomaly can be a condition where temperature detected by system **300** (e.g., a temperature sensor (e.g., Full Authority Digital Engine Control (FADEC) saturated temperature input) of sensors **314**) is different than a predicted (e.g. expected) or baseline atmospheric temperature. The temperature can be a saturated temperature value in one embodiment. The temperature value can be adjusted for heating caused by the movement of aircraft **101** through the atmosphere in one embodiment. The predictive or baseline temperature can be from satellite trip information. A large discrepancy (e.g., 15 degrees or more) between the actual temperature and the predicted temperature at the altitude of the aircraft **101** can indicate a potential icing condition according to one embodiment. In one embodiment, a local temperature reading more than 15 degrees warmer than the expected temperature indicates an anomaly. A low pass filter or averaging technique can be used to prevent a spurious reading from improperly causing a temperature anomaly to be detected.

At a step **653**, weather radar system **300** may optionally receive data from another on-board HAIC detection source (e.g., infrared, LIDAR, etc.) or a remote systems HAIC detection source (e.g., ground-based radar, satellites, etc.) in one embodiment. After step **653**, system **300** can advance to step **653** and skip step **654**.

System **300** identifies convective cells or cores at step **654**. Convective cores can be identified using cell height,

cell growth, and other analysis techniques. Generally, cores in front of or along the flight path of the aircraft are identified at step **654** for further analysis in process **600**, according to one embodiment. Cores can be identified using core threat module **328**. Identification of cores is discussed in U.S. application Ser. No. 13/841,893 incorporated herein by reference. Cores can be identified by analyzing spectral characteristics in areas of higher reflectivity in one embodiment. In one embodiment, the information from step **653** can be used to identify cores or increase confidence in the cores identified using radar parameters.

At a step **656**, system **300** scans the environment and identifies large areas (e.g. more than a square nm, several square nms, ten square nm, etc.) of weaker reflectivity in the vicinity of a convective core. Areas for scanning are chosen based upon a presence of core cells. In one embodiment, if core cells are not present, system **300** returns to step **652**. In one embodiment, cores are not identified in step **654**, and the information provided in step **653** associated with an HAIC or HAIC² condition or potential thereof is used to identify areas for scanning.

In one embodiment, HAIC detection assessment or inference may also be performed by other sensors on board the aircraft (infrared, LIDAR, etc.) or off the aircraft by ground radars or satellites. The HAIC detection assessment or inference information may be optionally input to system **300** for identification of the HAIC or HAIC² region in step **653** in one embodiment. When the HAIC detection assessment or inference information is input into system **300**, the scanning region or location of the radar beams may be directed to scan that region and a higher confidence of the HAIC threat can be determined. The radar may advantageously apply the detection technique described with reference to FIG. **8** to those regions.

HAIC and HAIC² conditions are caused by strong updrafts that also created turbulence. The Doppler processing of the radar returns or off-aircraft wind information can provide additional information for detection of HAIC and HAIC² regions. If a HAIC or HAIC² region is detected, it may be qualified by a turbulence (spectral width) or vertical wind speed as qualifier to determine if HAIC or HAIC² are present.

In one embodiment, vertical scans and/or auxiliary horizontal scans can be commanded at step **656** via module **336** to look for the presence of high water content (high reflectivity) beneath the areas that were depicted as weaker reflectivity (green or black). If such a scenario is identified using the vertical and horizontal beams, the area is tagged or identified as a potential area for ice crystal icing or a HAIC or HAIC² condition by module **340** at a step **658** in one embodiment. The area can be identified on display **20** with a HAIC or HAIC² warning. High water content can be identified by using a vertical integrated liquid (VIL) measurement or a reflectivity measurement in one embodiment. VIL measurement techniques are discussed in U.S. patent application Ser. No. 14/086,844 filed Nov. 21, 2013 and incorporated herein by reference in its entirety. In one embodiment, system **300** is restricted from executing process **600** at altitude, below cruise altitudes.

With reference to FIG. **7**, module **340** includes an inferential detection path which uses a temperature anomaly detector **702**, and a return data analysis module **704**. Path **340** can execute process **650** in one embodiment. Module **704** can receive core threat indications from module **328**. Temperature anomaly detector **702** compares the sensed outside temperature at or near the altitude of aircraft **101** with the expected temperature at the altitude in accordance

with the atmosphere conditions. The expected temperatures can be provided by or derived from data received real time or received during flight preparation. Temperature readings in NEXRAD data can be utilized by detector 702 for expected temperature values.

Once a temperature anomaly is detected, module 340 can provide vertical and horizontal radar returns to an area in the vicinity of a weather cell core as detected by core module 328 according to one embodiment. Various algorithms and techniques can analyze radar returns to determine a HAIC or HAIC² condition. In one embodiment, if return data analyzer 704 determines that a yellow or higher region is directly in front of aircraft 101 when temperature anomaly detector 702 detects the temperature anomaly, system 300 identifies a HAIC or HAIC² condition in front of aircraft 101. Alternatively, module 704 can analyze radar returns for a HAIC or HAIC² condition in accordance with steps 656 and 658 described above with reference to FIG. 6. Beam control module 336 under control of module 340 can have antenna 310 provide beams to the areas in the vicinity of cores found by core threat module 328. When reflectivities from these areas indicate that higher reflectivity is located at a location below the freezing level, module 340 provides an indicator of the presence of a HAIC or HAIC² condition in one embodiment. For example, if precipitation rates associated with a red or yellow region are detected below the freezing level, a HAIC or HAIC² condition is present.

HAIC or HAIC² module 340 and module 338 can be configured to cause a pattern (e.g., a yellow speckled region) to be displayed on an aviation display 20 to indicate a HAIC or HAIC² warning in one embodiment. HAIC or HAIC² module 340 is configured to output a signal or data to display control module 338 indicating the existence, location, and severity or risk of the HAIC or HAIC² condition or region in one embodiment. Module 338 can cause the appropriate video signal to be provided to display 20. An indication that the HAIC or HAIC² warning is based on an inferred processing can be utilized in one embodiment. Module 340 and module 338 can operate to provide the displays described in U.S. patent application Ser. No. 14/207,034 (47141-0978), incorporated herein by reference in one embodiment.

In one embodiment, areas tagged as potential for icing (a HAIC or HAIC² condition) could be enhanced in color to depict the threat (a green echo could be enhanced to amber) since these icing conditions have weaker reflectivity. Module 338 and configuration data 326 can be used to make the threshold adjustment and appropriately provide for the HAIC or HAIC² condition on display 20.

With reference to FIG. 8, HAIC or HAIC² module 340 can directly detect a HAIC or HAIC² condition using a combination of coherent and non-coherent integration path 600. Path 600 receives a series of inphase I signals associated with an IQ demodulated signal from radar returns and a series of quadrature phase Q signals associated with the IQ data from radar returns from coherent integrators 602 and 604, respectively. Integrator 602 provides a value I_K according to the equation

$$\sum_{k=1}^{N_P} I_k$$

in one embodiment. Integrator 604 provides the value Q_K according to the equation

$$\sum_{k=1}^{N_P} Q_k$$

in one embodiment. N_P is the number of pulses in the coherent integrator, and these coherent sums are updated at a rate R_{PRF}/N_P, where R_{PRF} is the pulse repetition frequency. In one embodiment, system 300 provides multiple rapid pulses on target. If the radar cross section (RCS) is coherent, the signal to noise ratio (SNR) increases linearly with the number of pulses.

An amplitude detector 606 determines the amplitude associated with each combination of I_K and Q_K according to the equation Z_K=I_K²+Q_K² in one embodiment. I_K and Q_K represent voltage values at the output of the coherent integrators 602 and 604 associated with return data. These sums can be implemented with a Fourier transform that also will provide Doppler information. Detector 606 can be any monotonic function of the input I_K²+Q_K², e.g., a logarithm or a square root.

A non-coherent integrator 608 non-coherently sums the values of Z according to the equation

$$\zeta = \sum_{k=1}^{N_D} Z_k$$

N_D is the number of dwells over which non-coherent integration is performed, and the update rate of is R_{PRF}/(N_PN_D). Non-coherent integration after the amplitude detector 606 is less efficient than coherent integration, but does not require signal coherence from dwell to dwell (both in phase and amplitude). A detector 610 determines if the value from integrator 608 is greater than a threshold value T. If so, the data is further processed to determine if a HAIC or HAIC² condition is detected.

Various algorithms or techniques can be utilized to discriminate a HAIC or HAIC² condition from the radar return data. Module 340 can compare the characteristics of the radar data to known ice crystal reflectivity characteristics to determine a HAIC or HAIC² condition. For example, a HAIC² condition can be determined when reflectivity levels are above a level zero or nominal level and less than a level associated with liquid precipitation. According to another example, the algorithm can utilize temperature and reflectivity to determine the presence of a HAIC or HAIC² condition. According to another embodiment, a HAIC or HAIC² condition can be determined if the appropriate reflectivity level is provided across a significant area (e.g., many range bins). According to yet another embodiment, temperature, combined with reflectivity level or area and reflectivity level can be utilized to determine the presence of a HAIC or HAIC² condition. In another embodiment, the radar returns are processed to determine whether the radar returns indicate spherical targets which are more likely water or non-spherical targets which are more likely ice crystals.

In one embodiment, if the temperature is below temperature threshold (e.g. -20 degrees Celsius), the reflectivity level is consistent with ice crystal levels and the altitude is above a threshold (e.g. 10,000 feet), a HAIC or HAIC² condition is detected. In one embodiment, modern fuzzy logic techniques can be utilized to detect and discriminate HAIC² conditions. The reflectivity characteristics of known HAIC and HAIC² can be stored and used for comparisons.

In one embodiment, HAIC and HAIC² can be stored with respect to particular locations or locations types (e.g., continental, maritime, etc.) and/or seasons and the comparisons can be made with consideration of location and/or season.

If detector **610** detects that the value from non-coherent integrator **608** is less than the value T, a HAIC or HAIC² condition is not detected. The value T represents a threshold power value for a HAIC or HAIC² evaluation. Evaluation can be performed by analyzer **612** to identify regions of HAIC or HAIC² conditions in one embodiment. A qualifier **614** can use detection of turbulence to qualify the regions of HAIC or HAIC² conditions in one embodiment. Doppler processing or off-aircraft wind information can be used to qualify the regions in one embodiment. Advantageously, module **340** allows ice crystals to be detected across a longer distance.

Path **600** advantageously serves to coherently integrate the pulses within a dwell using integrator **602** and **604** and non-coherently integrating the energy from each dwell using amplitude detector **606** and non-coherent integrator **608**. The combination of coherent and non-coherent integration allows for HAIC or HAIC² decorrelation over the integration period in one embodiment. Integration is done over time scales shorter than the radar scan time in one embodiment. Path **600** advantageously increases detection range to a point where discrimination and avoidance of HAIC regions are feasible for aircraft **101**. Advantageously, path **600** can use the same pulses as used for X band weather radar to avoid disruption of other radar-sensing operations in one embodiment. Although the integration period degrades angular resolution of the data, it is an acceptable tradeoff to determine HAIC or HAIC² conditions.

With reference to FIG. 9, a chart **800** represents a Swerling 0 radar cross section (RCS) model and includes an X axis **802** representing a signal-to-noise ratio (SNR) per dwell in decibels (dB) and a Y axis **804** showing a probability of detection from varying from 0 to 1. A probability of false alarm (P_{FA}) on thermal noise alone is assumed to be $P_{FA} = 10^{-6}$. An SNR threshold **806** is provided at a probability of detection of 0.9. With N_D equal to 1, a probability of detection at 0.9 requires a signal-to-noise ratio of approximately 13 dB as given by curve **810** in one embodiment. With N_D equal to 4, a probability of detection at 0.9 requires a signal-to-noise ratio of 8.2 dB as given by a curve **814**. The curve **812** shows that the required signal-to-noise ratio for N_D equal to 2 is 10.6 dB. The required signal-to-noise ratio for N_D equal to 6 is shown by a curve **816** to be approximately 6.0 dB. In one embodiment, N_D equal 4 is chosen giving a 8.2 dB decibel per dwell signal-to-noise ratio requirement.

With reference to FIG. 10, a chart **900** for a Swerling 0 target model ($P_{FA} = 10^{-6}$) using 40 pulses integrated includes an X axis **901** representing range in nautical miles (nm) and a Y axis **902** representing signal-to-noise ratio (SNR) per dwell. A line **904** represents the required signal-to-noise ratio for a probability of 0.9 with N_D equal to 4. As shown in FIG. 10, the coherent/non-coherent process can provide detection ranges of 41.4 nautical miles for an ice water content (IWC) of 0.5 grams per meter cubed as shown by a curve **910**, a range of 53.4 nautical miles for an IWC of 1 gram per meter cubed as shown by curve **906** and a range of 68.8 nautical miles for an IWC of two grams per meter cubed as shown by curve **908** using 10 pulse coherent integration according to one embodiment.

The construction and arrangement of the systems and methods as shown in the various exemplary embodiments are illustrative only. Although only a few embodiments have

been described in detail in this disclosure, many modifications are possible (e.g., variations in sizes, dimensions, structures, shapes and proportions of the various elements, values of parameters, mounting arrangements, use of materials, colors, orientations, etc.). For example, the position of elements may be reversed or otherwise varied and the nature or number of discrete elements or positions may be altered or varied. Accordingly, all such modifications are intended to be included within the scope of the present disclosure. The order or sequence of any process or method steps may be varied or re-sequenced according to alternative embodiments. Other substitutions, modifications, changes, and omissions may be made in the design, operating conditions and arrangement of the exemplary embodiments without departing from the scope of the present disclosure.

According to various exemplary embodiments, electronics **304** may be embodied as hardware and/or software. In exemplary embodiments where the processes are embodied as software, the processes may be executed as computer code on any processing or hardware architecture (e.g., a computing platform that can receive reflectivity data from a weather radar system) or in any weather radar system such as the WXR-2100 system available from Rockwell Collins, Inc. or an RDR-400 system available from Honeywell, Inc. The processes can be performed separately, simultaneously, sequentially or independently with respect to each other.

While the detailed drawings, specific examples, detailed algorithms and particular configurations given describe preferred and exemplary embodiments, they serve the purpose of illustration only. The inventions disclosed are not limited to the specific forms and equations shown. For example, the methods may be performed in any of a variety of sequence of steps or according to any of a variety of mathematical formulas. The hardware and software configurations shown and described may differ depending on the chosen performance characteristics and physical characteristics of the weather radar and processing devices. For example, the type of system components and their interconnections may differ. The systems and methods depicted and described are not limited to the precise details and conditions disclosed. The flow charts show preferred exemplary operations only. The specific data types and operations are shown in a non-limiting fashion. Further, the term HAIC condition as used in the claims and related applications can refer to a HAIC condition and/or HAIC² condition, unless explicitly limited to a HAIC² condition. Furthermore, other substitutions, modifications, changes, and omissions may be made in the design, operating conditions, and arrangement of the exemplary embodiments without departing from the scope of the invention as expressed in the appended claims.

Some embodiments within the scope of the present disclosure may include program products comprising machine-readable storage media for carrying or having machine-executable instructions or data structures stored thereon. Such machine-readable storage media can be any available media which can be accessed by a general purpose or special purpose computer or other machine with a processor. By way of example, such machine-readable storage media can include RAM, ROM, EPROM, EEPROM, CD ROM or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures and which can be accessed by a general purpose or special purpose computer or other machine with a processor. Combinations of the above are also included within the scope of machine-readable storage media. Machine-executable

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instructions include, for example, instructions and data which cause a general purpose computer, special purpose computer, or special purpose processing machine to perform a certain function or group of functions. Machine or computer-readable storage media, as referenced herein, do not include transitory media (i.e., signals in space).

What is claimed is:

1. An aircraft hazard warning system, comprising:
 - a processing system for detecting a presence of at least one of a high altitude ice crystal (HAIC) or HAIC cloud (HAIC²) condition, the processing system being configured to cause a radar antenna to produce radar beams and receive radar returns associated with a region at high altitude, the processing system being configured to process radar return data associated with the radar returns and to detect the presence of the at least one of the HAIC or HAIC² condition, wherein the processing system further comprises a first coherent integrator, a second coherent integrator, an amplitude detector, and a non-coherent integrator, wherein the processing system performs:
 - a coherent and non-coherent integration process to detect the presence, wherein the coherent and non-coherent integration process coherently integrates I return values associated with the radar return data in the first coherent integrator and Q return values associated with the radar return data in the second coherent integrator to produce integrated I values and integrated Q values, wherein combined amplitude values for a combination of the integrated I values and the integrated Q values are provided by the amplitude detector, wherein the combined amplitude values are non-coherently integrated by the non-coherent integrator to provide non-coherent integration values that are compared to a threshold, wherein if the non-coherent integration values are below the threshold, an HAIC or HAIC² condition is not detected and if the non-coherent integration values are above the threshold, further processing is performed to detect the HAIC or HAIC² condition.
2. The aircraft hazard warning system of claim 1, wherein the processing system is configured to receive sensor data from at least one sensor and the processing system uses inferred detection of the at least one of the HAIC or HAIC² condition using the radar return data and the sensor data.
3. The aircraft hazard warning system of claim 2, wherein the inferred detection of the at least one of the HAIC or HAIC² condition comprises detecting temperature anomalies and large areas of weaker convection in a vicinity of a convective core.
4. The aircraft hazard warning system of claim 3, wherein the inferred detection comprises additional scans of the radar beams in the large areas to sense areas of high water content beneath areas of lower reflectivity.
5. The aircraft hazard warning system of claim 1, wherein the processing system receives information from sensors on board an aircraft associated with the aircraft hazard warning system or from a source remote from the aircraft, the information indicating an area of the HAIC or HAIC² condition or a potential HAIC or HAIC² condition, wherein the processing system directs a weather radar system on board the aircraft to scan the area.
6. The aircraft hazard warning system of claim 1, wherein the processing system determines the at least one of the HAIC or HAIC² condition using a pulse detection process and the pulse detection process uses the coherent and non-coherent integration process.

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7. The aircraft hazard warning system of claim 5, wherein the processing system comprises an IQ demodulator.

8. The aircraft hazard warning system of claim 1, wherein the processing system is configured to cause the HAIC or HAIC² condition to be displayed on a weather radar display.

9. The aircraft hazard warning system of claim 8, wherein the processing system is configured to cause a warning of the HAIC or HAIC² condition to be provided corresponding to its size and location correlated on the weather radar display.

10. The aircraft hazard warning system of claim 9, wherein the warning of the HAIC or HAIC² condition is provided as a speckled region.

11. A method of providing at least one of a high altitude ice crystal (HAIC) or HAIC cloud (HAIC²) information on an aircraft using an electronic processor, the method comprising:

receiving radar reflectivity data;

processing the radar reflectivity data to detect a presence of the at least one of the HAIC or HAIC² condition by using a coherent and non-coherent integration process, wherein the coherent and non-coherent integration process coherently integrates I return values associated with the radar reflectivity data in a first coherent integrator and Q return values associated with the radar reflectivity data in a second coherent integrator to produce integrated I values and integrated Q values, wherein combined amplitude values for a combination of the integrated I values and the integrated Q values are provided by an amplitude detector, wherein the combined amplitude values are non-coherently integrated by a non-coherent integrator to provide non-coherent integration values that are compared to a threshold, wherein if the non-coherent integration values are below the threshold, an HAIC or HAIC² condition is not detected and if the non-coherent integration values are above the threshold, further processing is performed to detect the HAIC or HAIC² condition; and

providing at least one of the HAIC or HAIC² information to a pilot.

12. The method of claim 11, wherein the information of the HAIC condition is provided on a weather radar display.

13. The method of claim 12, wherein the electronic processor is part of an avionic weather radar system and the HAIC² information is provided on the weather radar display.

14. The method of claim 11, wherein an update rate for the non-coherent integrator is a pulse repetition frequency divided by a number of pulses over which coherent integration is performed by the first and second coherent integrators multiplied by the number of dwells over which non-coherent integration is performed by the non-coherent integrator.

15. The method of claim 11, wherein the radar reflectivity data is processed to identify a region of high water content beneath a region of low radar reflectivity in a vicinity of a core cell to detect the presence of at least one of the HAIC or HAIC² condition.

16. The method of claim 15, wherein the information of the at least one of the HAIC or HAIC² condition is provided as a speckled region on a plan view display or a vertical situation display.

17. An aircraft weather radar system, comprising:

a radar antenna for receiving radar returns; and

means for determining a high altitude ice crystal (HAIC) or HAIC cloud (HAIC²) condition in response to the radar returns by a coherent and non-coherent integration process, wherein the coherent and non-coherent integration process coherently integrates I return values

associated with the radar returns in a first coherent integrator and Q return values associated with the radar returns in a second coherent integrator to produce integrated I values and integrated Q values, wherein combined amplitude values for a combination of the integrated I values and the integrated Q values are provided by an amplitude detector, wherein the combined amplitude values are non-coherently integrated by a non-coherent integrator to provide non-coherent integration values that are compared to a threshold, wherein if the non-coherent integration values are below the threshold, an HAIC or HAIC² condition is not detected and if the non-coherent integration values are above the threshold, further processing is performed to detect the HAIC or HAIC² condition.

18. The aircraft weather radar system of claim **17**, further comprising:

a display for providing weather images, the display providing a warning of the HAIC or HAIC² condition.

19. The aircraft weather radar system of claim **17**, wherein a high altitude associated threat (HAAT) is sensed and a warning of the HAAT condition is displayed.

20. The aircraft weather radar system of claim **19**, wherein the warning of the HAIC or HAIC² condition is provided in response to an inferred process using temperature anomalies or a non-inferred process using non-coherent integration.

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