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Smith et al.

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(54) **SYNTHETIC APERTURE RADAR SYSTEM AND METHODS**

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(22) Filed: **Jun. 22, 2009**

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Related U.S. Application Data

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G01S 13/90 (2006.01)

(52) **U.S. Cl.**
USPC .... **342/25 F**; 342/75

(58) **Field of Classification Search**
USPC .... 342/25 R–25 F, 75
See application file for complete search history.

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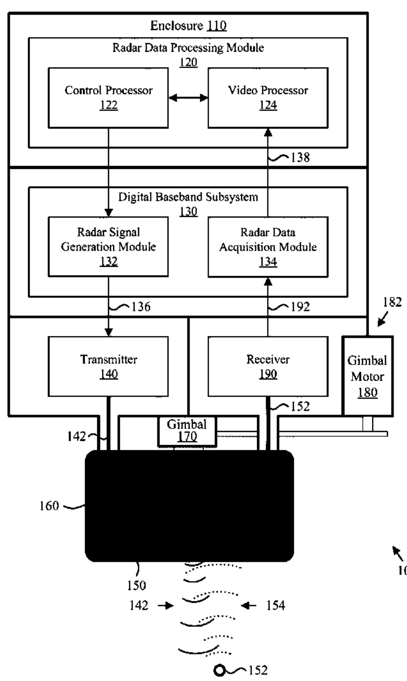
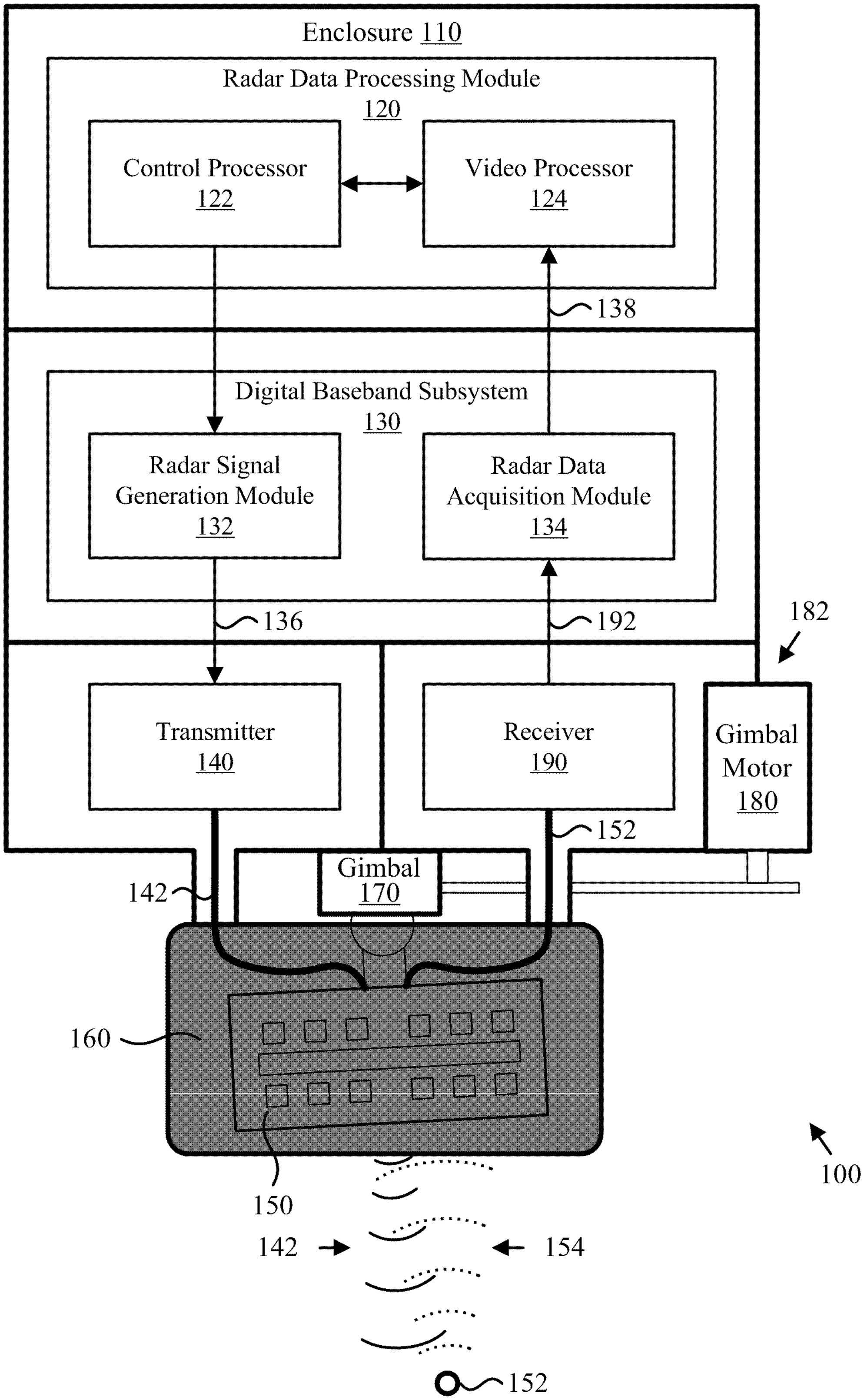
Primary Examiner — Matthew M Barker
(74) *Attorney, Agent, or Firm* — Utah Valley Patent; Steve McDaniel

(57) **ABSTRACT**

A compact synthetic aperture radar system and associated methods are disclosed.

2 Claims, 14 Drawing Sheets





Enclosure 110
Radar Data Processing Module 120
Control Processor 122
Video Processor 124
138
Digital Baseband Subsystem 130
Radar Signal Generation Module 132
Radar Data Acquisition Module 134
136
192
182
Transmitter 140
Receiver 190
Gimbal Motor 180
152
Gimbal 170
142
160
150
142
154
152
100

Figure 1

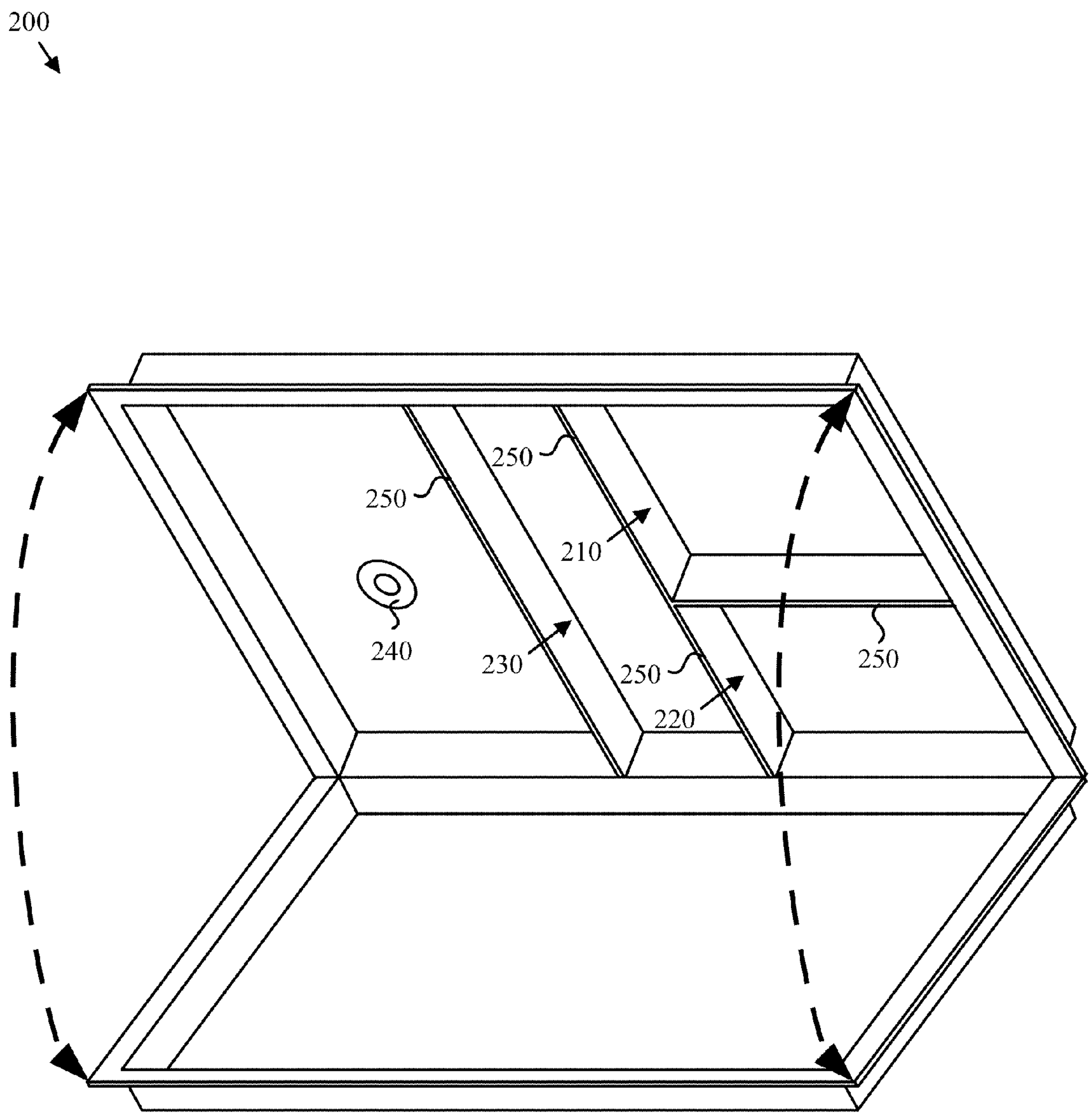


Figure 2

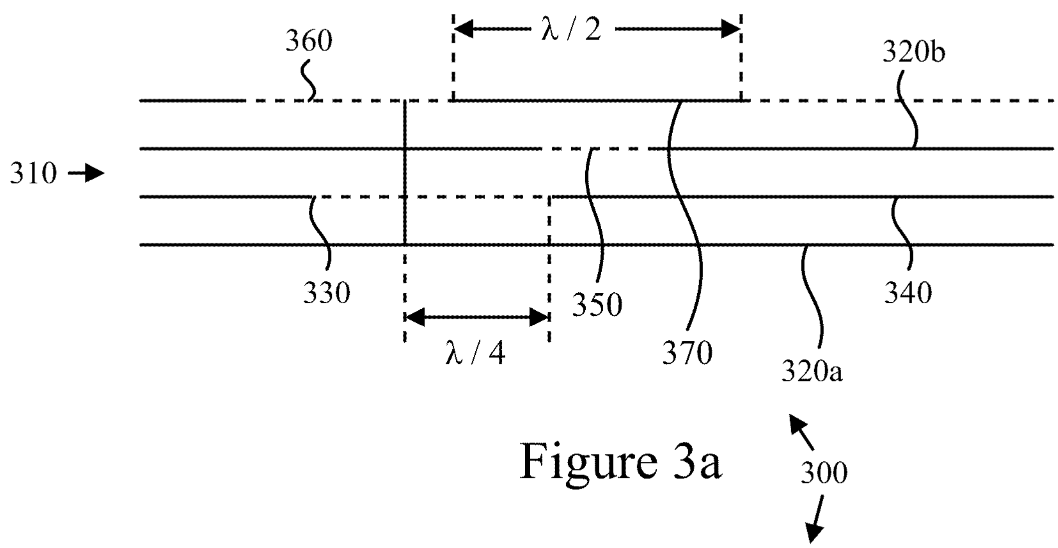


Figure 3a

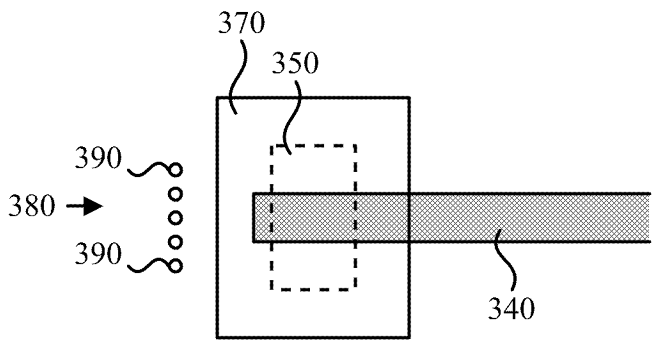


Figure 3b

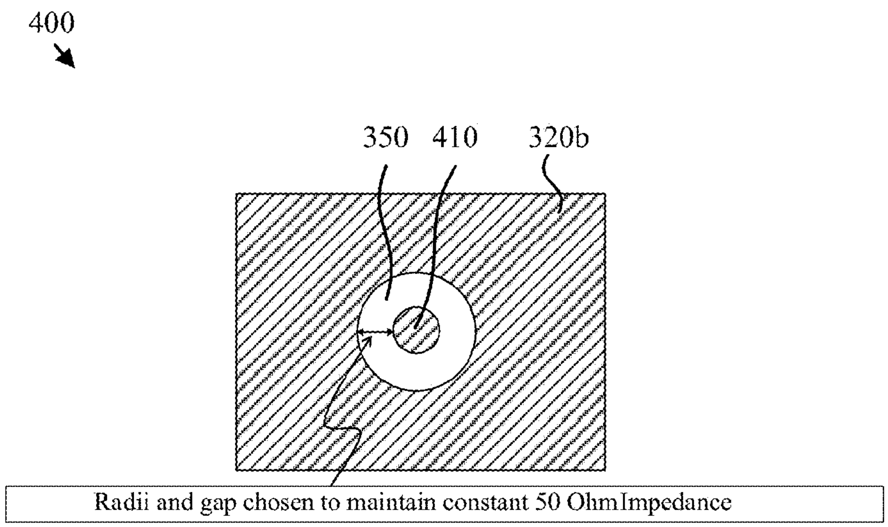


Figure 4a

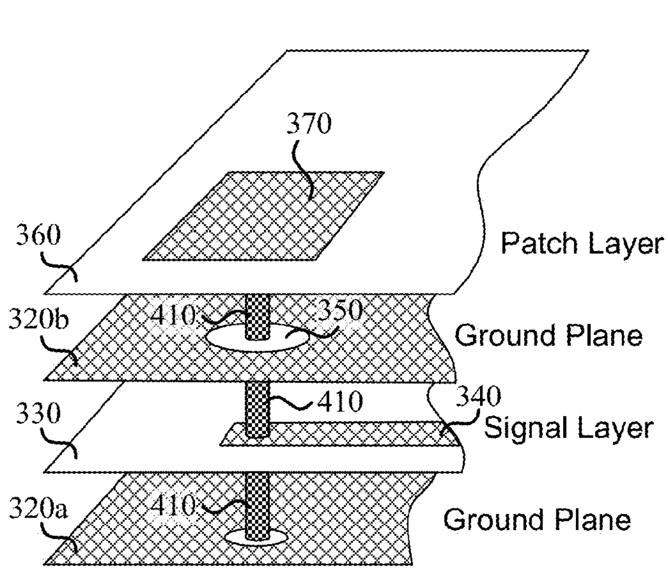


Figure 4b

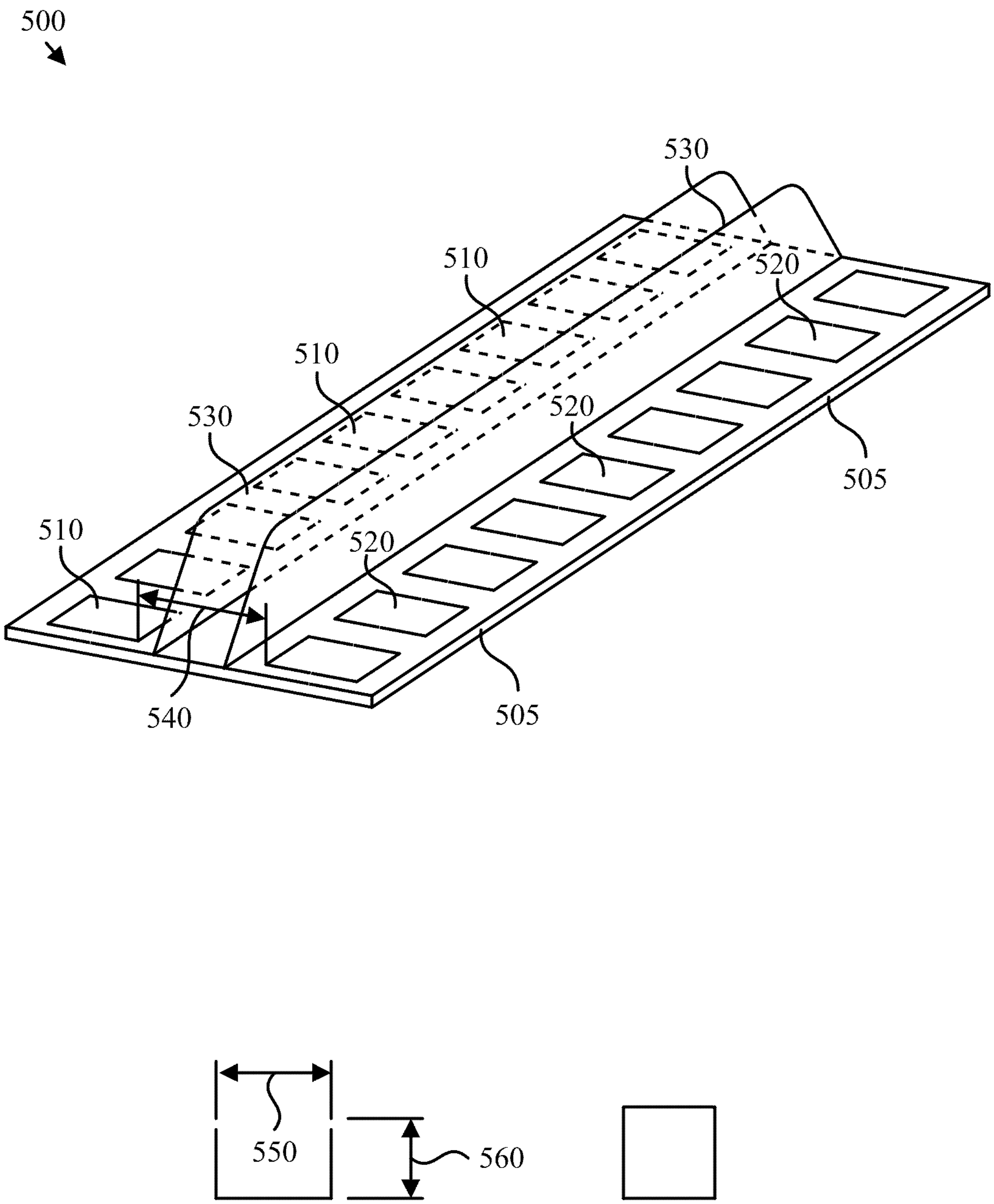


Figure 5

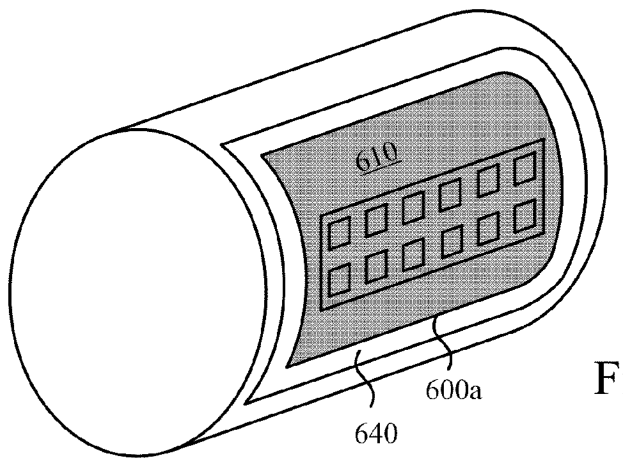


Figure 6a

Figure 6b

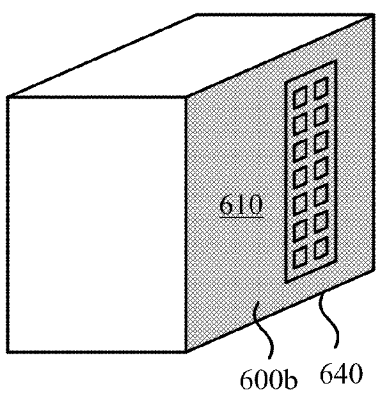
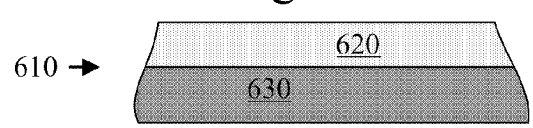


Figure 7



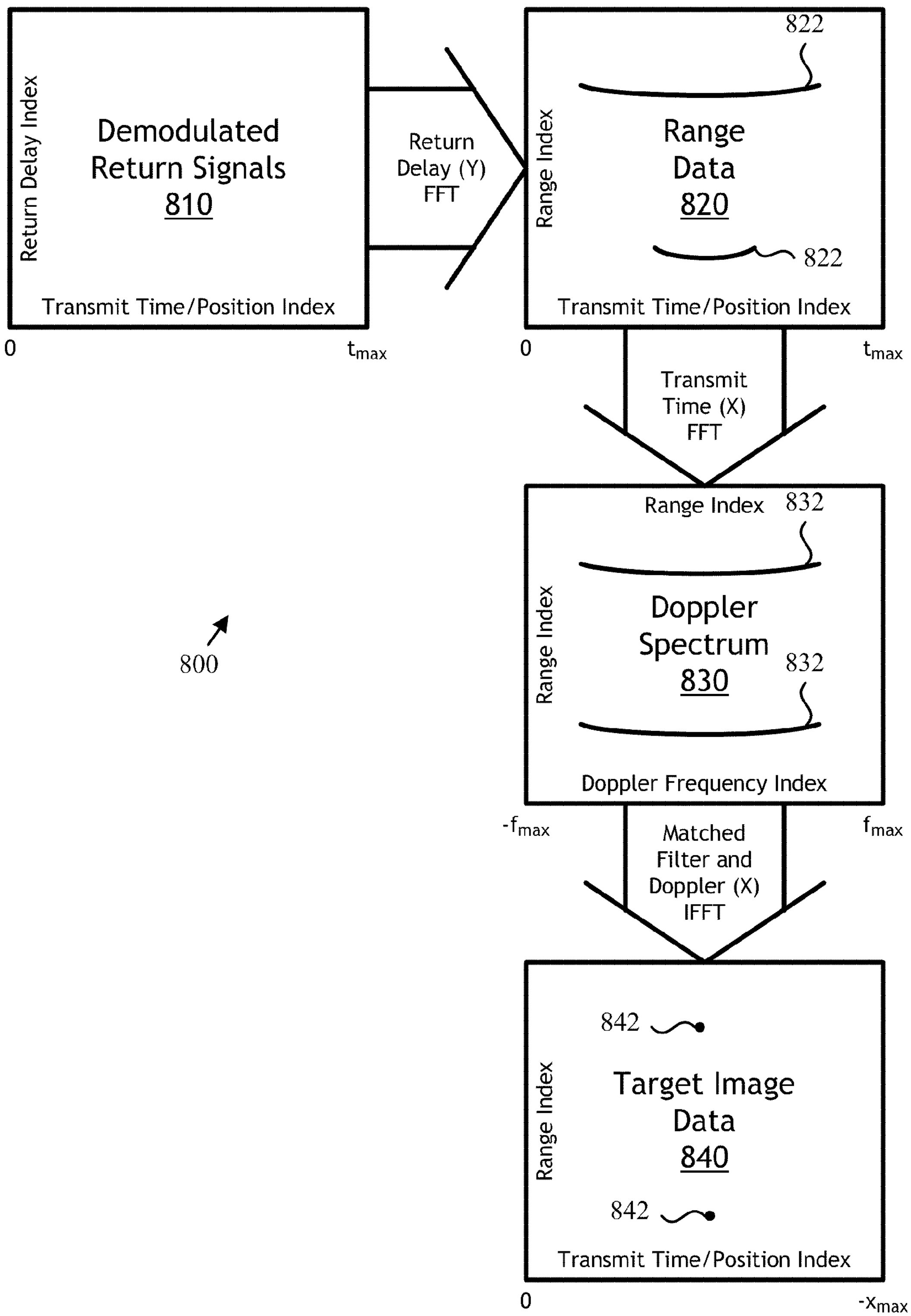

Return Delay Index
Demodulated Return Signals 810
Transmit Time/Position Index
0
tmax
Return Delay (Y) FFT
822
Range Index
Range Data 820
822
Transmit Time/Position Index
0
tmax
Transmit Time (X) FFT
Range Index
832
Range Index
Doppler Spectrum 830
832
Doppler Frequency Index
-fmax
fmax
Matched Filter and Doppler (X) IFFT
842
Range Index
Target Image Data 840
842
Transmit Time/Position Index
0
-xmax
800

Figure 8

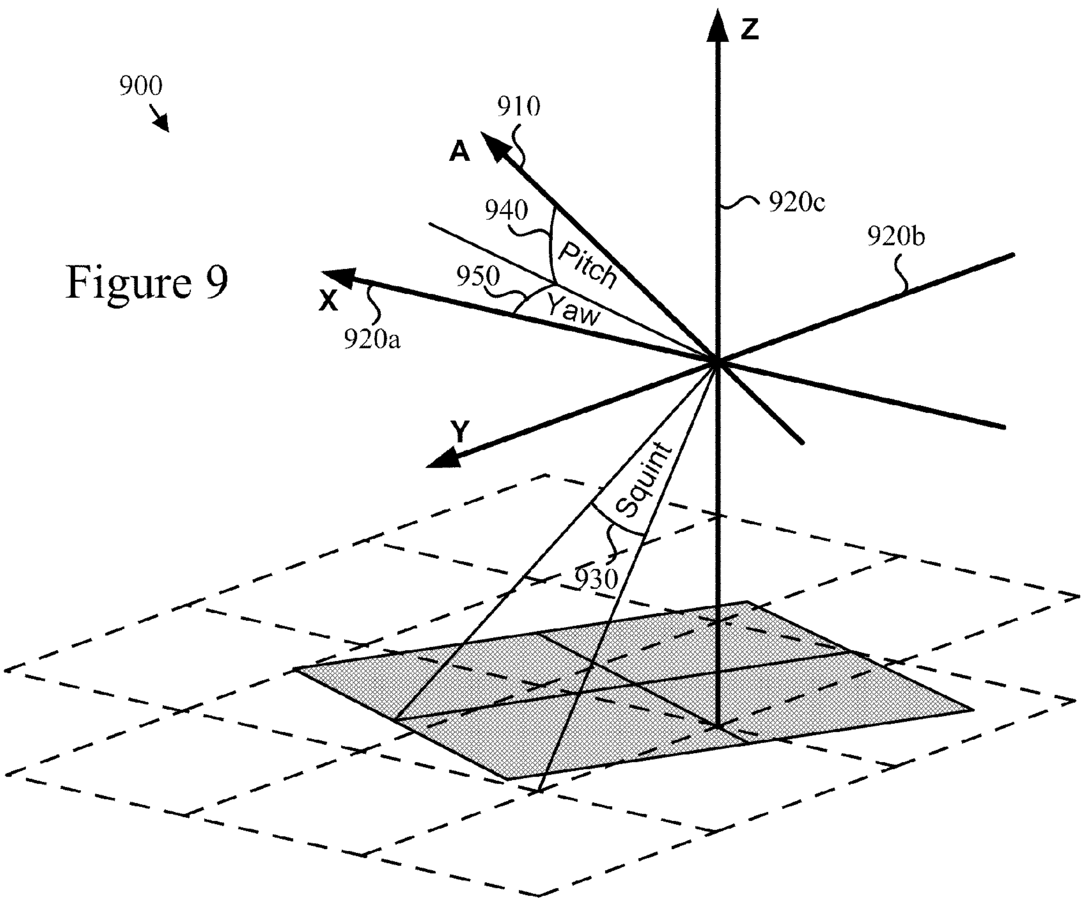


Figure 9

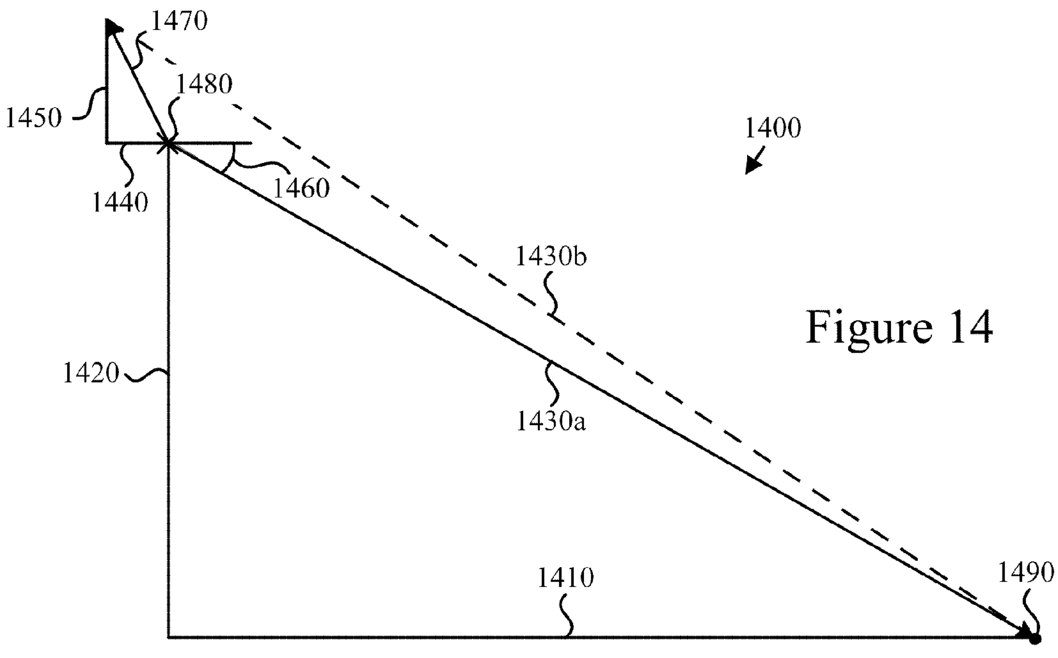


Figure 14

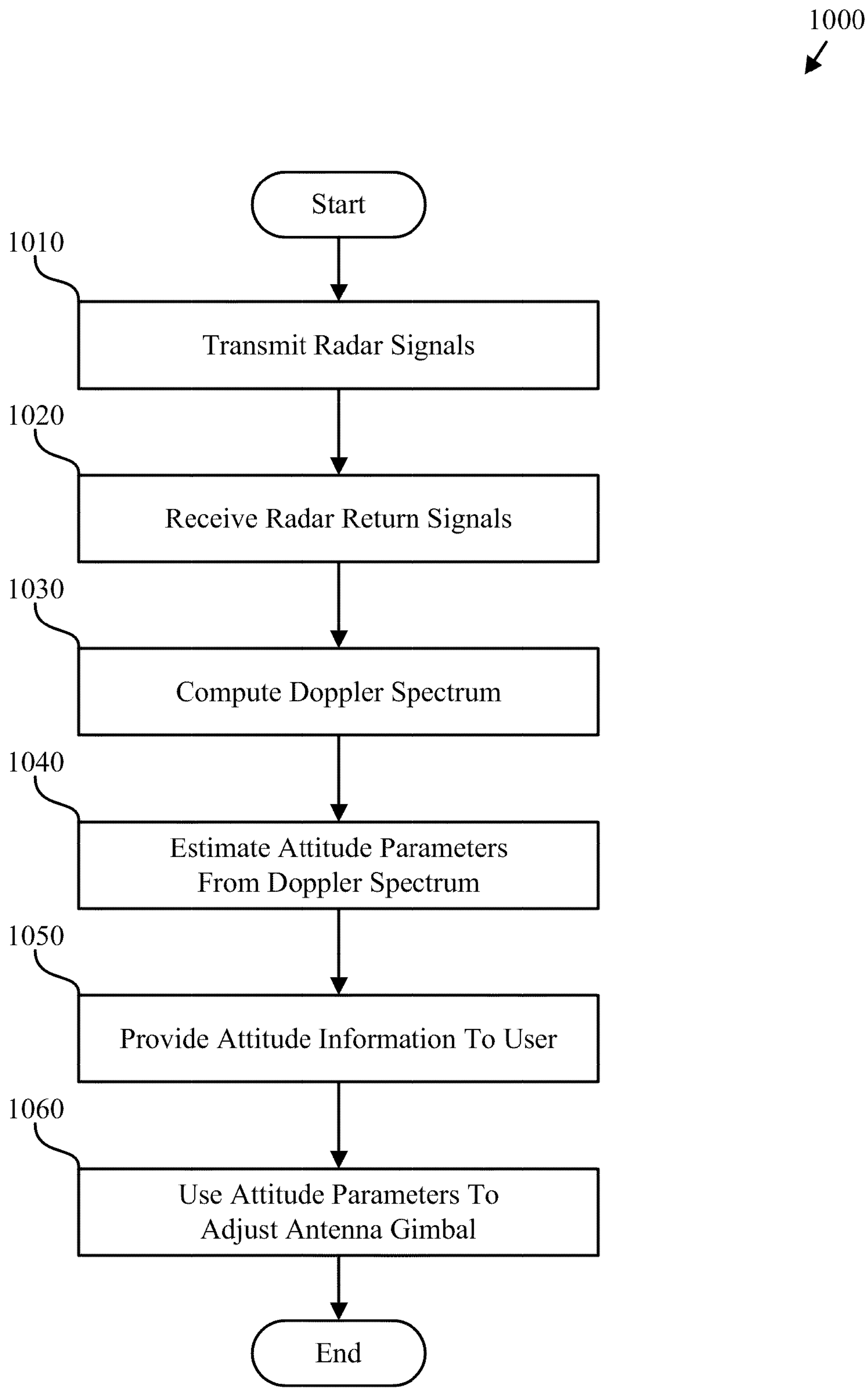

1000
Start
1010
Transmit Radar Signals
1020
Receive Radar Return Signals
1030
Compute Doppler Spectrum
1040
Estimate Attitude Parameters From Doppler Spectrum
1050
Provide Attitude Information To User
1060
Use Attitude Parameters To Adjust Antenna Gimbal
End

Figure 10

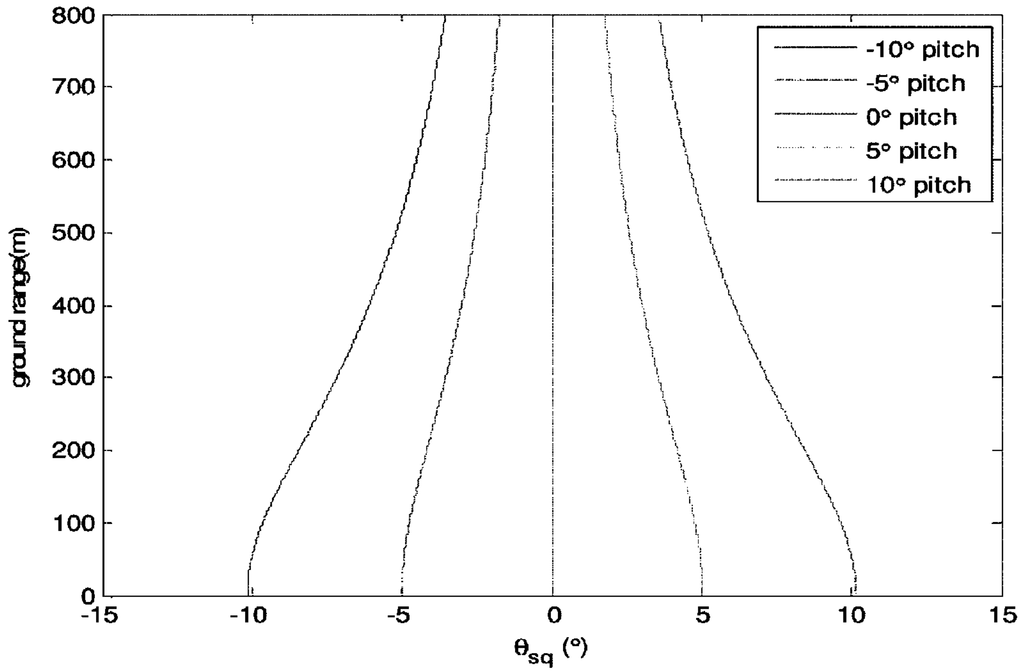


Figure 11a

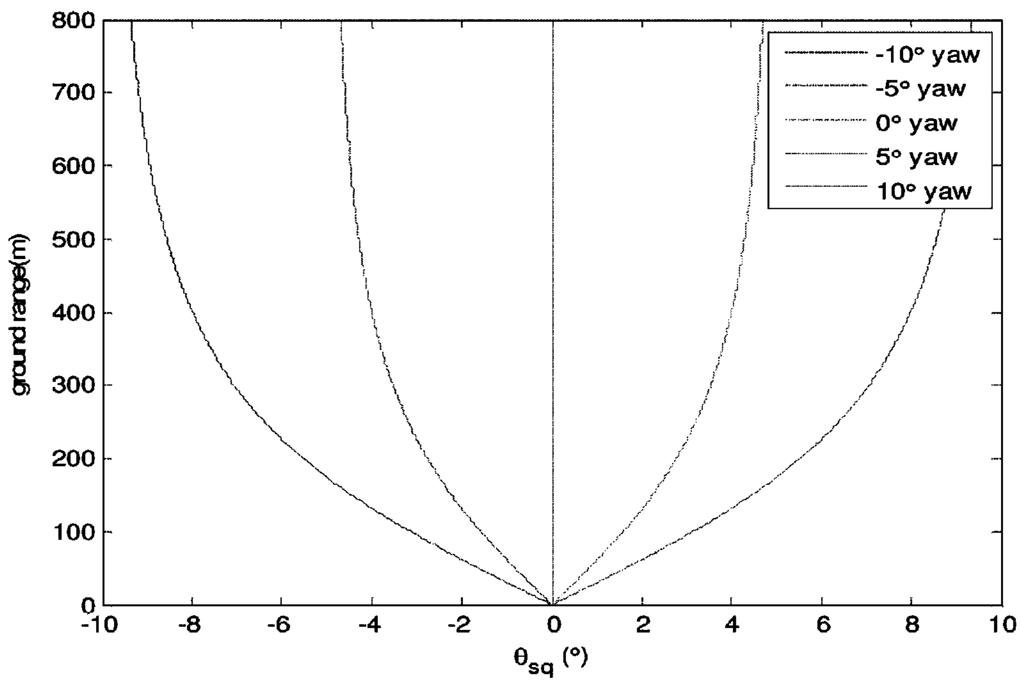


Figure 11b

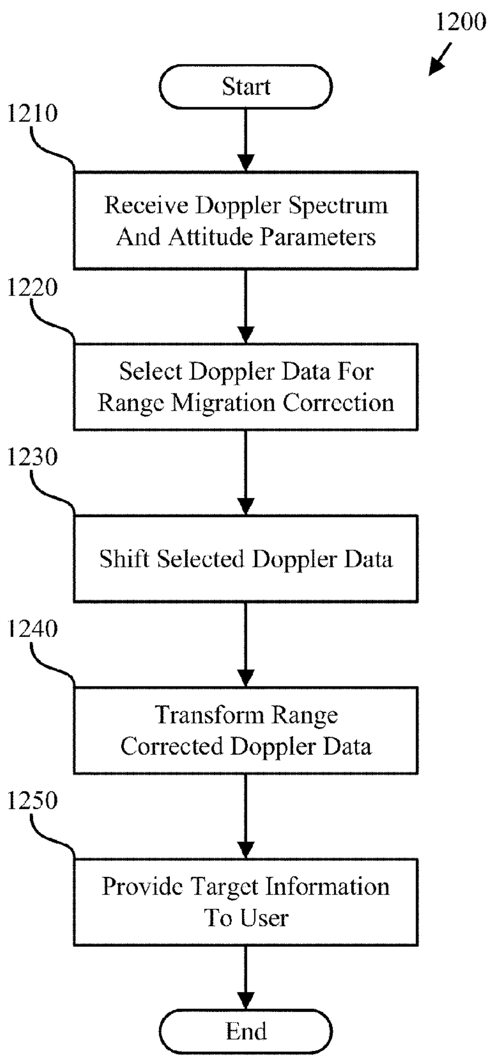


Figure 12a

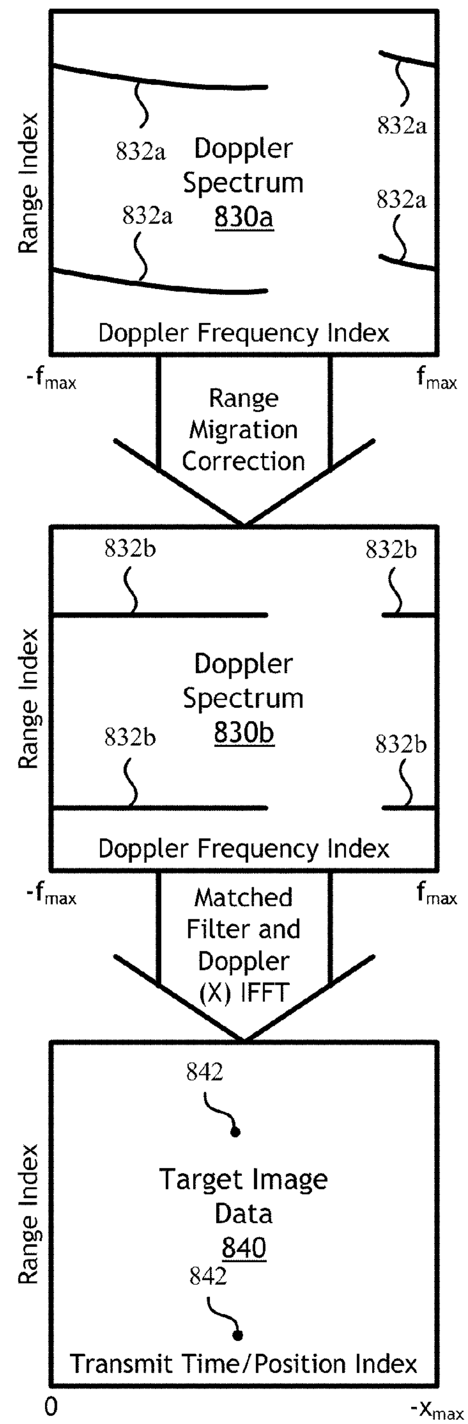


Figure 12b

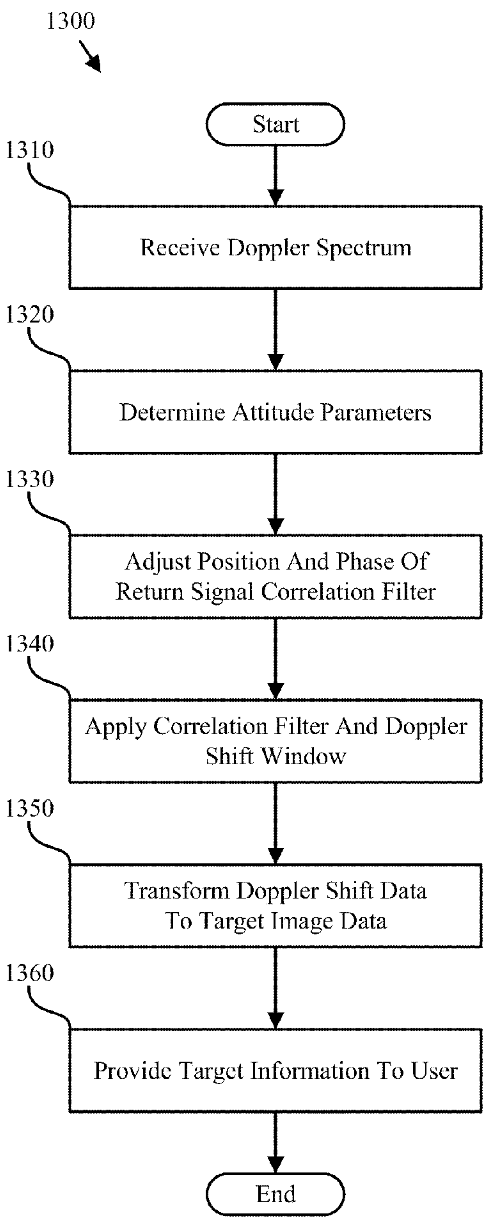


Figure 13

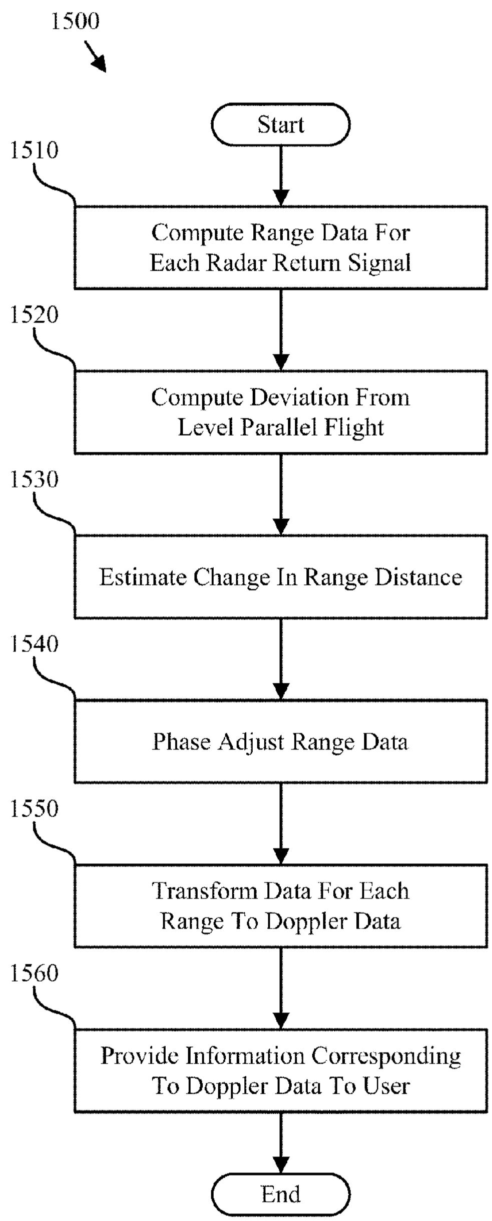


Figure 15

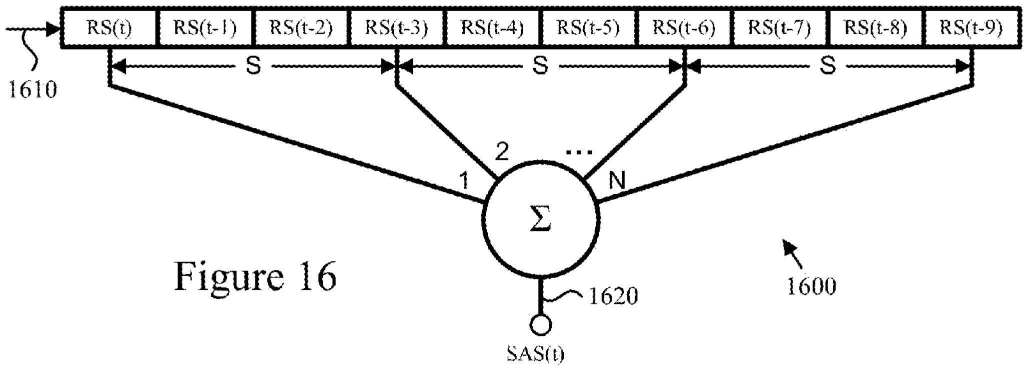


Figure 16

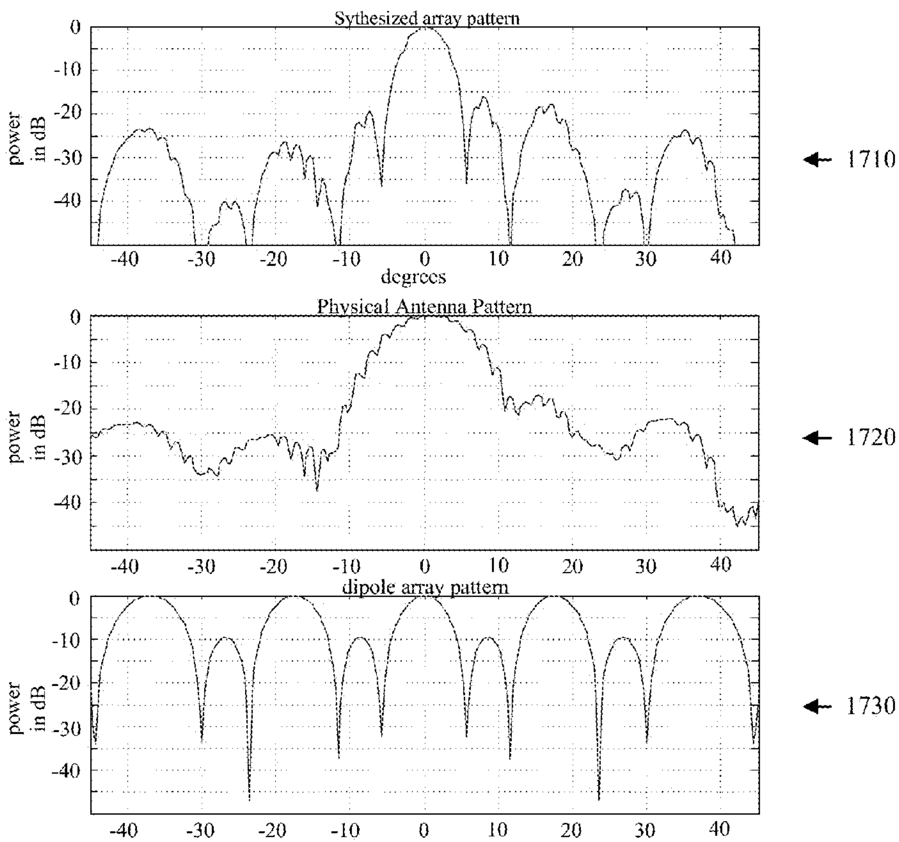


Figure 17

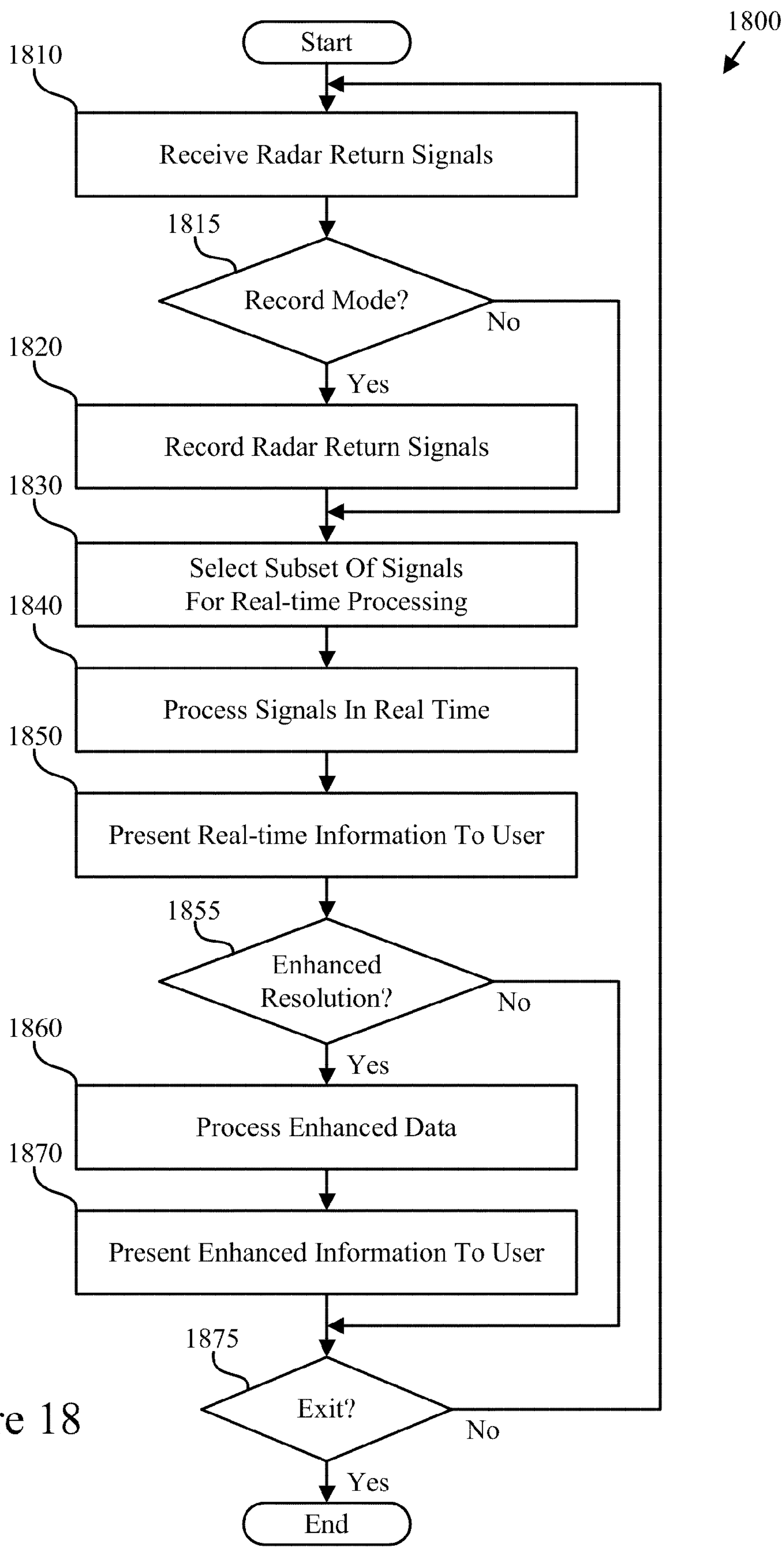

1800
Start
1810
Receive Radar Return Signals
1815
Record Mode?
No
Yes
1820
Record Radar Return Signals
1830
Select Subset Of Signals
For Real-time Processing
1840
Process Signals In Real Time
1850
Present Real-time Information To User
1855
Enhanced
Resolution?
No
Yes
1860
Process Enhanced Data
1870
Present Enhanced Information To User
1875
Exit?
No
Yes
End

Figure 18

SYNTHETIC APERTURE RADAR SYSTEM AND METHODS

RELATED APPLICATIONS

This application claims priority to U.S. Provisional Patent Application 61/154,474 entitled "SYNTHETIC APERTURE RADAR SYSTEM AND METHODS" and filed on 23 Feb. 2009 for Ryan Lee Smith, Logan Carl Harris, David Long, Adam Harper, Britton Quist, and Joshua Hintze. The aforementioned application is hereby incorporated by reference including appendices submitted therewith.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The claimed inventions relate to radar systems and methods.

2. Description of the Related Art

Currently available radar systems typically require expensive bulky components that limit the applications wherein such systems can be deployed. Furthermore, each application of radar technology often requires different processing algorithms. What is needed is a combination of algorithms and methodologies that can be applied to a wide variety of applications using compact, lower-cost components.

BRIEF SUMMARY OF THE INVENTION

The present invention has been developed in response to the present state of the art, and in particular, in response to the problems and needs in the art that have not yet been fully solved by currently available radar systems. Accordingly, the present invention has been developed to provide synthetic aperture radar systems and methods that overcome shortcomings in the art.

In certain embodiments, a system for acquiring and processing radar data includes a multilayer printed circuit board with antenna elements printed thereon including a set of transmit patches and a set of receive patches with an isolation element affixed to the multilayer printed circuit board and placed between the transmit patches and the receive patches. The isolation element increases electromagnetic isolation between the transmit patches and the receive patches.

The system may also include a radar receiver and transmitter operably connected to the radar antenna and a radar data acquisition module that converts a demodulated radar return signal provided by the radar receiver to a digital baseband signal. In addition, the radar data acquisition module interface may mimic a CCD video chip and provide the digital baseband signal as a sequence of scanlines to a video processor that computes Doppler shift data for various ranges, and estimates attitude parameters such as a vehicle pitch and yaw from the Doppler shift data. The system may compensate for the vehicle pitch and yaw and improve data quality by initiating an orientation adjustment of the radar antenna.

The system may also execute a variety of methods described herein including methods that leverage attitude parameters extracted from Doppler shift and power profile data to improve data processing. The described methods may be embodied as a computer program product or computer readable medium comprising computer readable program codes configured to conduct the described methods.

The system may include an enclosure with a gimbal mount integrally formed therein as well as a number of isolation chambers including a transmitter chamber that covers at least a portion of the radar transmitter and a receiver chamber that

covers at least a portion of the radar receiver. The enclosure may be formed from a plastic material (for example using a 3-D printing process) and electroplated to electromagnetically isolate the various subsystems covered by the isolation chambers.

The system may also include a radome formed of a water repellent breathable fabric and configured to cover the radar antenna. The water repellent breathable fabric may comprise a porous membrane capable of passing water vapor without passing liquid water and a fabric backing bonded to the porous membrane. More conventional solid radomes may also be used.

It should be noted that references throughout this specification to features, advantages, or similar language does not imply that all of the features and advantages that may be realized with the present invention should be or are in any single embodiment of the invention. Rather, language referring to the features and advantages is understood to mean that a specific feature, advantage, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, discussion of the features and advantages, and similar language, throughout this specification may, but do not necessarily, refer to the same embodiment.

The described features, advantages, and characteristics of the invention may be combined in any suitable manner in one or more embodiments. One skilled in the relevant art will recognize that the invention may be practiced without one or more of the specific features or advantages of a particular embodiment. In other instances, additional features and advantages may be recognized in certain embodiments that may not be present in all embodiments of the invention.

These features and advantages will become more fully apparent from the following description and appended claims, or may be learned by the practice of the invention as set forth hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the advantages of the invention will be readily understood, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments that are illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

FIG. **1** is a block diagram depicting a synthetic aperture radar system that is consistent with one or more embodiments of the claimed inventions;

FIG. **2** is a perspective view diagram illustrating a radar enclosure that is consistent with one or more embodiments of the claimed inventions;

FIGS. **3***a* and **3***b* are cross-sectional and top view diagrams illustrating an antenna feed structure that is consistent with one or more embodiments of the claimed inventions;

FIGS. **4***a* and **4***b* are top view and perspective view diagrams illustrating a antenna coupling structure that is consistent with one or more embodiments of the claimed inventions;

FIG. **5** is a perspective view diagram illustrating an antenna isolation structure that is consistent with one or more embodiments of the claimed inventions;

FIGS. **6***a* and **6***b* are perspective view diagrams illustrating two implementations of a breathable fabric radome **600** that are consistent with various embodiments of the claimed inventions;

FIG. **7** is a cross sectional view of a water repellant breathable fabric used to construct the breathable fabric radomes depicted in FIGS. **6***a* and **6***b;*

FIG. **8** is a data flow diagram depicting a radar image transformation sequence that is consistent with one or more embodiments of the claimed inventions;

FIG. **9** is a geometric diagram illustrating the relationship between vehicle pitch, yaw, and squint that may leveraged by one or more embodiments of the claimed inventions;

FIG. **10** is a flow chart diagram depicting an attitude estimation and gimballing method that is consistent with one or more embodiments of the claimed inventions;

FIGS. **11***a* and **11***b* are data graphs illustrating the relationship between vehicle pitch and yaw on the Doppler centroid as a function of range that may be leveraged by one or more embodiments of the claimed inventions;

FIG. **12***a* is a flow chart diagram depicting a range migration correction method that is consistent with one or more embodiments of the claimed inventions;

FIG. **12***b* is a data flow diagram depicting a radar image transformation sequence that is consistent with one or more embodiments of the claimed inventions;

FIG. **13** is a flow chart diagram depicting a target image processing method that is consistent with one or more embodiments of the claimed inventions;

FIG. **14** is a geometric diagram depicting certain geometric relationships that may be leveraged in the motion compensation method of FIG. **15**;

FIG. **15** is a flow chart diagram depicting a motion compensation method that is consistent with one or more embodiments of the claimed inventions;

FIG. **16** is a data flow diagram depicting a synthetic aperture processing method that is consistent with one or more embodiments of the claimed inventions;

FIG. **17** is a graphical diagram illustrating the effect of the method of FIG. **16**; and

FIG. **18** is a flow chart diagram depicting an enhanced resolution processing method that is consistent with one or more embodiments of the claimed inventions.

DETAILED DESCRIPTION OF THE INVENTION

Many of the functional units described in this specification have been labeled as modules, in order to more particularly emphasize their implementation independence. For example, a module may be implemented as a hardware circuit comprising custom VLSI circuits or gate arrays, off-the-shelf semiconductors such as logic chips, transistors, or other discrete components. A module may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices or the like.

Modules may also be implemented in software for execution by various types of processors. An identified module of executable code may, for instance, comprise one or more physical or logical blocks of computer instructions which may, for instance, be organized as an object, procedure, or function. Nevertheless, the executables of an identified module need not be physically located together, but may comprise disparate instructions stored in different locations which, when joined logically together, comprise the module and achieve the stated purpose for the module.

Indeed, a module of executable code may be a single instruction, or many instructions, and may even be distributed over several different code segments, among different programs, and across several memory devices. Similarly, operational data may be identified and illustrated herein within modules, and may be embodied in any suitable form and organized within any suitable type of data structure. The operational data may be collected as a single data set, or may be distributed over different locations including over different storage devices, and may exist, at least partially, merely as electronic signals on a system or network.

Reference throughout this specification to "one embodiment," "an embodiment," or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment," "in an embodiment," and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment.

Reference to a computer program product or computer-readable medium may take any form capable of causing execution of a program of machine-readable instructions on a digital processing apparatus. For example, a computer-readable medium may be embodied by a transmission line, a compact disk, digital-video disk, a magnetic tape, a Bernoulli drive, a magnetic disk, a punch card, flash memory, integrated circuits, or other digital processing apparatus memory device.

Furthermore, the described features, structures, or characteristics of the invention may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided, such as examples of programming, software modules, user selections, network transactions, database queries, database structures, hardware modules, hardware circuits, hardware chips, etc., to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the invention may be practiced without one or more of the specific details, or with other methods, components, materials, and so forth. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the invention.

FIG. **1** is a block diagram depicting a synthetic aperture radar system **100** that is consistent with one or more embodiments of the claimed inventions. As depicted, the synthetic aperture radar system **100** includes an enclosure **110**, a radar data processing module **120**, a digital baseband subsystem **130**, a transmitter **140**, an antenna **150**, a radome **160**, a gimbal **170**, a gimbal motor **180**, and a receiver **190**. The synthetic aperture radar system **100** provides high-resolution radar processing in a very compact footprint.

The enclosure **110** provides isolation between various subsystems of the system **100**. In one embodiment, the enclosure **110** is formed of a plastic material by a 3-D printing process. The enclosure may be electroplated to increase the electromagnetic isolation between the between the various subsystems. Electroplating may also increase the mechanical strength of the enclosure. In one embodiment, the enclosure is electroplated to provide mechanical integrity to an acceleration force of at least 25 g. In certain embodiments, a gimbal mount (not shown) is integrally formed into the enclosure **110**. The enclosure **110** may also include a gimbal motor mount **182** integrally formed into the enclosure that mates to the gimbal motor **180**.

The depicted radar data processing module **120** includes a control processor **122** and a video processor **124**. The control processor **122** may configure or direct the digital baseband subsystem **130**, the video processor **124**, the transmitter **140**, the gimbal motor **180**, and the receiver **190**, as well as other modules relevant to transmitting, receiving, and processing radar signals. In one embodiment, the control processor **122** and the video processor **124** are the same processor.

The depicted digital baseband subsystem **130** includes a radar signal generation module **132** and a radar data acquisition module **134**. The radar signal generation module **132** may generate a modulation signal **136**. In one embodiment, the modulation signal **136** is a sawtooth waveform appropriate for frequency modulation. The transmitter **140** may receive the modulation signal **136** and provide a transmission signal **142** to the antenna **150**. The antenna **150** may radiate the transmission signal **142** and receive reflections of that signal from one or more targets **152** as a radar return signal **154**.

The radome **160** may protect the antenna **150** from the environment without significantly attenuating the transmission signal **142** and the radar return signal **152**. In one embodiment, the radome is made from a breathable water repellant fabric. The gimbal **170** enables adjustment of the orientation of the antenna **150** and the viewing angle of the radar system **100** within the radome **160**. The orientation of the antenna **150** may be changed by one or more gimbal motors **180** that are mechanically coupled to the gimbal **170** and/or the antenna **150**.

The radar return signal **152** may be received by the receiver **190** and demodulated to provide a demodulated radar return signal (i.e. analog baseband signal) **192**. The radar data acquisition module **134** may convert the demodulated radar return signal **192** to a digital baseband signal **138**.

In certain embodiments, the radar data acquisition module **134** interface mimics a CCD video chip and provides the digital baseband signal **138** to the video processor as a sequence of scanlines (not shown) where each scanline corresponds to a radar return signal received in response to a transmitted radar signal of a limited duration. The video processor may be configured to interface with a charge coupled device (CCD) video chip and receive and process the sequence of scanlines. See the description of FIGS. **8-14** for additional detail. Mimicking a CCD video chip enables the radar system **100** to use a video processor such as the video processor **124** to process the digital baseband signal **138**. The video processor **124** may be programmed and/or configured to process the sequence of scanlines corresponding to the digital baseband signal **138** and extract target image data and target information therefrom such as magnitude and phase information.

FIG. **2** is a perspective view diagram illustrating a radar enclosure **200** that is consistent with one or more embodiments of the claimed inventions. As depicted, the enclosure includes a transmitter chamber **210**, a receiver chamber **220**, a digital baseband chamber **230**, and may include other chambers as needed. The enclosure **200** may also have a gimbal mount **240** integrally formed therein and dimensioned for directly mounting a gimbal to the enclosure. The radar enclosure **200** is one example of the enclosure **110** depicted in FIG. **1**.

The radar enclosure **200** may be formed of a plastic material and enclose one or more circuit boards with the radar transmitter **140**, the radar receiver **190**, the digital baseband subsystem **130**, and other modules of the radar system **100** assembled thereon. The various chambers on the enclosure **200** correspond to modules of the radar system **100**, as well as physical regions on the enclosed circuit boards (not shown). Due to the electroplating of the enclosure **200**, and a snug (subwavelength) fit between the bottom edges of the chamber ribs **250** and the (ground plane layers on the) enclosed circuit boards, the various chambers function to cover and electromagnetically isolate the covered modules from one another as well as the operating environment in which the enclosure **200** is deployed.

In the depicted embodiment, the transmitter chamber **210** covers at least a portion of the radar transmitter **140**, and the receiver chamber **220** covers at least a portion of the radar receiver **190** sufficient to isolate the receiver chamber from the transmitter chamber by at least 80 dB and the digital baseband subsystem **130** from the radar receiver and transmitter by at least 60 dB. In one embodiment, the provided isolation is greater than 100 dB for the radar receiver and transmitter and 80 dB for the digital baseband subsystem **130**. The combination of elements depicted and described herein increase the compactness of radar system **100**. In one embodiment, the enclosure **110** and the contents contained therein occupy less than 150 cubic inches of volumetric space.

FIGS. **3***a* and **3***b* are cross-sectional and top view diagrams illustrating an antenna feed structure **300** that is consistent with one or more embodiments of the claimed inventions. As depicted, the antenna feed structure **300** includes a multilayer printed circuit board **310** with ground plane layers **320**, a signal layer **330** with a transmission line trace **340**, a coupling aperture **350**, an antenna layer **360** with one or more antenna elements **370**, and a via fence **380**. The antenna feed structure **300** reduces signal crosstalk, reduces the required spacing between antennas, and facilitates providing receive and transmit antennas on a single planer circuit board.

In the depicted arrangement, the signal layer **330** is disposed between the ground plane layers **320***a* and **320***b* and the antenna layer **360** is disposed above ground plane layers. The transmission line trace **340** and associated layer spacings and impedances may be configured to propagate a carrier signal (not shown) that may be provided by a transmitter or the like. The coupling aperture **350** formed on the ground plane layer **320***a* enables the carrier signal propagated by the transmission line trace **340** to couple to the antenna element **370** on the antenna layer **360**.

The via fence **380** may include multiple circuit board vias **390** that electrically connect at least the ground plane layer **320***a* with the ground plane layer **320***b*. The via fence **380** may be disposed near an endpoint of the transmission line trace **340** and configured to inhibit further propagation of the transmission signal between the ground plane layers **320***a* and **320***b*. In the depicted embodiment, the via fence is linear. In another embodiment, the via fence may be curved to at least partially encompass the coupling aperture **350** and/or the antenna element **370**. In one embodiment, a (shortest) distance between the via fence **380** and the transmission line trace **340** is approximately one quarter of a wavelength for the carrier signal. The distance between the via fence **380** and the coupling aperture **350** may also be approximately one quarter of a wavelength for the carrier signal.

FIGS. **4***a* and **4***b* are top and perspective view diagrams illustrating an antenna coupling structure **400** that is consistent with one or more embodiments of the claimed inventions. The antenna coupling structure **400** uses a coupling via **410** within the coupling aperture **350** to essentially form a coaxial waveguide through the ground plane layer **320***b*. The antenna coupling structure **400** may be used in conjunction with the antenna feed structure **300**.

The dimensions of the coupling via **410** and the coupling aperture **350**, as well as the electromagnetic properties of the associated layers, may be selected to provide a desired impedance for the antenna coupling structure **400**. The desired impedance may facilitate waveguiding (i.e. RF coupling) between the transmission line trace and the antenna element **370**. Depending on the desired coupling characteristics, the coupling via **410** may be connected to the transmission line trace **340**, the antenna element **370**, or both. In the depicted embodiment, the coupling via **410** extends from the ground plane layer **320***a* to the antenna element **370** without connecting with the ground plane layers **320**.

FIG. **5** is a perspective view diagram illustrating an antenna isolation structure **500** that is consistent with one or more embodiments of the claimed inventions. The antenna isolation structure **500** may include a printed circuit board **505** with a set of transmit patches **510**, a set of receive patches **520**, and an isolation element **530** affixed to the printed circuit board **505**. The antenna isolation structure **500** electromagnetically isolates the receive patches from the transmit patches.

The transmit patches **510** may be dimensioned and spaced to directionally radiate a transmission signal while the receive patches **520** dimensioned and spaced to receive reflected images of the transmission signal. The isolation element **530** may be partially or fully (electrically) conductive to increase the electromagnetic isolation between the receive patches **520** and the transmit patches **510**.

In one embodiment, the receive patches **520** are electromagnetically isolated from the transmit patches **510** by at least 25 dB. In the depicted embodiment, the transmit patches **510** and the receive patches **520** have a separation distance **540** of less than 2.5 wavelengths and the width **550** of the isolation element **530** is less than the separation distance between the transmit patches and the receive patches and equal to or greater than approximately one quarter of a wavelength for the transmission signal.

The height **560** of the isolation element **530** may be equal to or greater than approximately one quarter of a wavelength for the transmission signal. In the depicted embodiment, the isolation element **530** has a U-shaped cross sectional shape and is made from a partially (electrically) conductive material such as carbon fiber. The isolation element may also be formed from, or plated with, a conductive material.

FIGS. **6***a* and **6***b* are perspective view diagrams illustrating two implementations of a breathable fabric radome **600** that are consistent with various embodiments of the claimed inventions, while FIG. **7** is a cross sectional view of a water repellant breathable fabric **610** used to construct the breathable fabric radomes **600***a* and **600***b* depicted in FIGS. **6***a* and **6***b*. As depicted, the breathable fabric radomes **600***a* and **600***b* include a water repellent breathable fabric **610** with a porous membrane **620** and a fabric backing **630** attached to a frame **640**. The breathable fabric radomes **600** reduce water condensation on a radar antenna and associated electronics while protecting the antenna and electronics from snow and rain.

The porous membrane capable **620** may be capable of passing water vapor without passing liquid water. In certain embodiments, the water repellent breathable fabric **610** is a GoreTex™ fabric with a loss tangent of less than 0.0003 and the porous membrane **620** has a thickness of less than 5 mils. In one embodiment, the water repellent breathable fabric **610** has a thickness equal to or less than 10 mils and the porous membrane **620** has a thickness equal to or less than 3 mils.

The fabric backing **630** may be bonded to the porous membrane **620** and provide strength to the water repellent breathable fabric **610**. The fabric backing **630** may have a camaflouge pattern printed thereon or a color that matches a vehicle exterior. The water repellent breathable fabric **610** may be attached to the frame **640** or other structural member and shaped or formed to cover or encompass a radar antenna and associated electronics. In certain embodiments, the frame **640** and attached fabric **610** may be integrated into a fuselage as shown in FIG. **6***a* or an enclosure as shown in FIG. **6***b*.

FIG. **8** is a data flow diagram depicting a radar image transformation sequence **800** that is consistent with one or more embodiments of the claimed inventions. A radar antenna may project a series of radar transmissions from a vehicle. In certain embodiments, the transmissions may be directionally projected lateral to the movement of the vehicle, for example toward the ground and/or the horizon. A series of radar return signals corresponding to the series of radar transmissions may be received, demodulated, and stored as an array of demodulated return signals **810**.

In certain embodiments, demodulation produces sinusoidal components within each demodulated return signal whose frequency corresponds to a distance to a reflecting object and whose amplitude corresponds to the strength of the reflection from the object. The demodulated radar return signals **810** may be presented to the video processor **124** as a sequence of scanlines where each scanline corresponds to a vertical column in the array **810**. The video processor **124** may execute the various methods presented herein to provide target images and information to a user.

For example, a transform such as a Fourier transform may be conducted on each demodulated return signal to generate range data **820** for each transmission time index. Since the vehicle may be moving, each transmission time index may correspond to a position of the vehicle. The generated range data **820** indicates the relative strength and phase of reflections at each time index. As an object is approached and passed a curved (i.e. 'smile-shaped') ridge **822** may occur in the magnitude of the range data **820** indicating the range of that object from the vehicle over time. Generally speaking, objects that are farther offset from the vehicle in a lateral direction are in view of the radar beam for a longer interval resulting in a longer ridge **822**.

Subsequent to generating range data **820**, a transform may be conducted on each range to provide a Doppler spectrum **830**. The Doppler spectrum **830** indicates the strength of various Doppler shift frequencies for each range and provides considerable information. Approaching objects generate a positive Doppler shift, while receding objects generate a negative Doppler shift. As an object is approached and passed a smile shaped ridge **832** may occur in the Doppler spectrum **830** indicating the Doppler shift frequencies generated by that object. Since the total Doppler shift generated by a passed object is substantially independent of range, each ridge **832** may have essentially the same length in the Doppler spectrum.

The Doppler spectrum may be transformed to target image data **840** with an inverse Fourier transform or the like. In certain embodiments, range migration correction is performed on the Doppler shift data to compensate for the range migration (i.e. smile shaped curvature) that occurs as a target is approached. A return signal correlation (i.e. matched) filter (not shown) may also be applied to the each range of the Doppler spectrum to compensate for the smearing of the objects into ridges. By multiplying each Doppler spectrum range by the frequency domain version of the return signal correlation filter each ridge **832** is effectively deconvolved into a precisely placed object **842**.

FIG. **9** is a geometric diagram illustrating the relationship between vehicle pitch and yaw, and radar squint that may be leveraged by one or more embodiments of the claimed inventions. Due to a variety of factors, the attitude or orientation **910** of a vehicle or craft may be different than the current travel path for the vehicle which is shown in FIG. **9** as the X axis **920***a*. The X axis **920***a* along with a horizontal or Y axis **920***b* and a vertical or Z axis **920***c* define a vehicle relative coordinate system useful for processing data provided by a radar antenna mounted on the vehicle.

The terrain that is seen by a radar antenna may be skewed by the orientation of the vehicle **910** shown in the diagram as vector A. The effective viewing window of the radar antenna, known as antenna squint **930**, may affect the quality of data generated by a radar system. As is shown in FIG. **9**, the antenna squint **930** may be a function of the pitch **940** and yaw **950** of the vehicle. Many of the methods presented herein were developed to determine and account for the attitude related parameters of a vehicle such as vehicle pitch and yaw and antenna squint.

FIG. **10** is a flow chart diagram depicting an attitude estimation and gimballing method **1000** that is consistent with one or more embodiments of the claimed inventions. As depicted, the attitude estimation and gimballing method **1000** includes transmitting **1010** a series of radar signals, receiving **1020** a corresponding series of radar return signals, computing **1030** a Doppler spectrum, estimating **1040** one or more attitude parameters from the Doppler spectrum, providing **1050** attitude information to a user, and adjusting **1060** an antenna gimbal to compensate for the estimated attitude parameters. The depicted method **1000** enables a radar system to leverage information available in a Doppler spectrum to improve radar imaging clarity.

Transmitting **1010** a series of radar signals may include repeatedly transmitting a particular signal such as an FM chirp signal. In one embodiment, an FM chirp signal is repeatedly transmitted by frequency modulating a carrier signal with a sawtooth wave. In response thereto, a radar antenna may receive **1020** a series of radar return signals. The radar return signals may be a superposition of reflections from various objects.

As detailed in the description of FIG. **8**, computing **1030** a Doppler spectrum may include demodulating the return signals with an FM transmission signal or the like to provide a demodulated return signal. The demodulated return signal may comprise a number of sinusoidal components each having a frequency that is proportional to the distance to a reflecting object corresponding to the sinusoidal component in the demodulated return signal. A transform such as a Fourier transform may be conducted on each demodulated return signal to generate range data indicating the relative strength of reflections at each range distance for a particular time/position index. Subsequently, another transform may be conducted on each range over time to provide a Doppler spectrum.

The method **1000** may continue by estimating **1040** one or more attitude parameters from the Doppler spectrum. In certain embodiments, the attitude parameters are estimated by computing a centroid for each range in the Doppler spectrum. The placement of centroids in the Doppler spectrum as a function of range may indicate the attitude of the vehicle. See FIGS. **11***a* and **11***b*. In one particular embodiment, an antenna squint is estimated as function of pitch and yaw with a least squares estimation process using the equation squint=H/R*pitch+yaw*sqrt[1−(H/R)^2], where H is a vehicle height and R is the range from the vehicle. By minimizing the error for the antenna squint, the method **1000** may also provide estimates of the vehicle pitch and yaw.

Subsequent to estimating **1040** one or more attitude parameters from the Doppler spectrum, the method may continue by leveraging the attitude parameters. In the depicted embodiment, the method continues by providing **1050** attitude information to a user, and adjusting **1060** an antenna gimbal to compensate for the estimated attitude parameters. Adjusting **1060** an antenna gimbal may improve the quality of data collected with a radar system by aligning the antenna with the actual travel path of the vehicle. As is subsequently disclosed, the attitude parameters may be used to improve the processing of radar data and the quality of the information extracted therefrom.

FIGS. **11***a* and **11***b* are data graphs illustrating one example of the relationship between vehicle pitch and yaw on the location of the Doppler centroid as a function of range. FIG. **11***a* illustrates the effect of pitch on the position of the Doppler centroid, while FIG. **11***b* illustrates the effect of yaw on the position of the Doppler centroid. The illustrated relationships may be leveraged by the methods described herein to estimate one or more attitude parameters such as vehicle pitch and yaw and antenna squint.

FIG. **12***a* is a flow chart diagram depicting a range migration correction method **1200** that is consistent with one or more embodiments of the claimed inventions, while FIG. **12***b* is a data flow diagram depicting a radar image transformation sequence that is consistent with the range migration correction method **1200**. As depicted, the range migration correction method **1200** includes receiving **1210** a Doppler spectrum **830***a* and corresponding attitude parameters, selecting **1220** Doppler data for range migration correction, shifting **1230** the selected Doppler data, transforming **1240** the Doppler data, and providing **1250** target information to a user.

Receiving **1210** may include receiving attitude parameters that were extracted from the Doppler spectrum **830***a*. The attitude parameters may correspond to the shifting and/or skewing of range data **832***a* that may occur due to radar squint or the like. Selecting **1220** Doppler data for range migration correction selects that data which could benefit from migration correction previous to forming a target image. In the example depicted in FIG. **12***b*, the data that could benefit from migration correction includes the columns of data corresponding to the curved ridges **832***a* in general and the sloped portions of the curved ridges **832***a* in particular.

The method proceeds by shifting **1230** the selected Doppler data to correct for range migration in order to align data corresponding to a reflecting object into the same or nearly the same range. In certain embodiments, shifting **1230** the selected Doppler data occurs by conducting a frequency scaling algorithm. In one embodiment, Doppler data is shifted (vertically in the Doppler spectrum **830**) a discrete number of cells where the number of cells is a function of the Doppler frequency. In other embodiments, shifting may involve interpolating, summing, or spatially filtering data from multiple cells.

Subsequent to shifting **1230** the selected Doppler data, the method **1200** is completed by transforming **1240** the Doppler data to target image data and providing **1250** target information corresponding to the target image data to a user. Transforming **1240** the Doppler data to target image data may produce a target object **842** at a position corresponding to the lowest point along each curved ridge **832***a*.

FIG. **13** is a flow chart diagram depicting a target image processing method **1300** that is consistent with one or more embodiments of the claimed inventions. As depicted, the target image processing method **1300** includes receiving **1310** a Doppler spectrum, determining **1320** one or more attitude parameters, adjusting **1330** a return signal correlation filter, applying **1340** the return signal correlation filter and a Doppler shift window along each range, transforming **1350** the Doppler shift data to target image data, and providing **1360** target information to a user. The target image processing method **1300** improves the quality of the target image data and information extracted therefrom.

Receiving **1310** a Doppler spectrum and determining **1320** one or more attitude parameters may be accomplished in a manner that is consistent with steps **1030** and **1040** of the attitude estimation and gimballing method **1000** or similar methods disclosed herein. Adjusting **1330** a return signal correlation filter may include adjusting the location and phase of the return signal correlation filter (i.e. matched filter) and location of a corresponding windowing function.

The location or Doppler frequency interval of the return signal correlation filter and the windowing function may correspond to the Doppler frequency interval of the ridges **832**. The placement of the ridges **832** may be due to the attitude of the vehicle and/or the orientation of the transmitting antenna and correlate to the attitude parameters determined in step **1320**. Therefore, the Doppler frequency interval to which the return signal correlation filter and the windowing function are applied may be the same or essentially the same for each ridge within a particular Doppler spectrum. In certain embodiments, the phase of the return signal correlation filter and the location or Doppler frequency interval the filter is applied to, is determined by the received attitude parameters. In one embodiment, the phase of the return signal correlation filter may be calculated for each ridge in the Doppler spectrum according to the formula MF[I,J]=(2*pi*F0/c)*(J*V)^2/R[I] where F0 is the carrier frequency of the radar signal, J is the index of the Doppler spectrum column, V is the velocity of the vehicle, and R[I] is the range distance of the Doppler spectrum row.

Applying **1340** a return signal correlation filter and a Doppler shift window along each range of the Doppler spectrum facilitates generation of more precise target image data. Subsequently, transforming **1350** the Doppler shift data to target image data enables extraction of target information and providing **1360** the target information to a user.

FIG. **14** is a geometric diagram depicting certain geometric relationships **1400** that may be leveraged in the motion compensation method of FIG. **15** described below. [Note: FIG. **14** is shown on the same drawing sheet as FIG. **9**.] As depicted, the geometrical relationships **1400** include a ground range **1410**, an altitude **1420**, a slant distance or range distance **1430**, a horizontal displacement **1440**, a vertical displacement **1450**, a depression angle **1460**, and a total displacement **1470**. The geometrical relationships **1400** enable the detection of deviations from a level parallel flight **1480** (into the page) relative to a target **1490**, and correction of an old range distance estimate **1430*a*** to a new range distance estimate **1430*b***.

FIG. **15** is a flow chart diagram depicting a motion compensation method **1500** that is consistent with one or more embodiments of the claimed inventions. As depicted, the motion compensation method includes computing **1510** range data for each radar return signal, computing **1520** a deviation from a level parallel flight, estimating **1530** a change in range distance, phase adjusting **1540** range data, transforming **1550** data for each range to Doppler data, and providing **1560** information corresponding to Doppler data to the user.

Computing **1510** range data for each radar return signal may occur in a manner that is consistent with the description of FIG. **8**. Computing **1520** a deviation from a level parallel flight may include computing the horizontal displacement **1440**, the vertical displacement **1450**, and the depression angle **1460**. Estimating **1530** a change in range distance may include using the geometrical relationships shown in FIG. **14** to compute a difference between the new range distance **1430*b*** and the old range distance **1430*a***. In one embodiment, a change in range distance DR is estimated as dR=cos(DA)*VD+sin(DA)*HD where DA is the depression angle **1460**, VD is the vertical deviation or displacement **1450**, and HD is the horizontal deviation or displacement **1440**.

The depicted method may be completed by phase adjusting **1540** range data according to the change in range distance, transforming **1550** data for each range to Doppler data, and providing **1560** information corresponding to the Doppler data to the user.

FIG. **16** is a data flow diagram depicting a synthetic aperture processing method **1600** that is consistent with one or more embodiments of the claimed inventions. As depicted, the synthetic aperture processing method **1600** includes buffering a series of radar return signals **1610** provided by the radar data acquisition module or the like, and summing N non-adjacent radar return signals to provide a synthetic aperture return signal **1620**.

Summing the N non-adjacent return signals may include applying a taper to the N non-adjacent return signals to provide a weighted sum of the non-adjacent return signals. The N non-adjacent radar return signals may be separated by a pseudo aperture spacing S. In the depicted embodiment, N is equal to 4 and S is equal to 3. By selecting N and S to be relatively prime (i.e. with no common factors), the effective radar transmission pattern may be significantly narrowed.

FIG. **17** is a graphical diagram illustrating one example of the effect of the method of FIG. **16**. By selecting N and S to be relatively prime, an effective radar transmission pattern **1710** may be the product of the actual transmission pattern **1720** and the synthetic dipole pattern **1730**.

FIG. **18** is a flow chart diagram depicting an enhanced resolution processing method **1800** that is consistent with one or more embodiments of the claimed inventions. As depicted, the enhanced resolution processing method **1800** includes, receiving **1810** a series of radar return signals, determining **1815** whether a record mode is active, recording **1820** the radar return signals, selecting **1830** a subset of return signals for real-time processing, processing **1840** the return signals in real-time, presenting **1850** real-time information to a user, determining **1855** whether an enhanced resolution is active, processing **1860** the enhanced data, and presenting **1870** advanced information to a user. The enhanced resolution processing method **1800** enables a radar system to provide standard radar information in real-time, while providing enhanced information at a deferred time.

Receiving **1810** a series of radar return signals may include receiving return signals from a radar antenna. If the record mode is active, the method may continue by recording **1820** the radar return signals for subsequent enhanced resolution use. Selecting **1830** a subset of return signals for real-time processing enables a radar system to process **1840** the selected return signals and present **1850** corresponding information to a user in real-time.

The method continues by determining **1855** whether an enhanced resolution mode is active. If the enhanced resolution mode is active, the method processes **1860** the enhanced data and presents **1870** enhanced information such as enhanced resolution data to a user. The enhanced resolution data may be presented at a deferred time instead of real-time. Subsequently, the method determines **1875** whether a user desires to exit the method **1800**. If the user does not desire to exit the method **1800**, the method loops to step **1810**, otherwise the method terminates.

The present invention may be embodied in other specific forms without departing from its spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed is:

1. An apparatus for acquiring and processing radar data, the apparatus comprising:

a radar antenna comprising a multilayer printed circuit board, the multilayer printed circuit board comprising a plurality of antenna elements including a plurality of transmit patches configured to directionally radiate a transmission signal and a plurality of receive patches configured to receive reflected images of the transmission signal;

the radar antenna further comprising an isolation element affixed to the multilayer printed circuit board and disposed between the transmit patches and the receive patches, the isolation element configured to electromagnetically isolate the receive patches from the transmit patches;

a radar transmitter operably connected to the radar antenna;

a radar receiver operably connected to the radar antenna;

an enclosure formed from a plastic material with a gimbal mount integrally formed therein, the enclosure comprising a transmitter chamber configured to cover at least a portion of the radar transmitter and a receiver chamber configured to cover at least a portion of the radar receiver, the enclosure formed from a 3-D printing process and electroplated to electromagnetically isolate the receiver chamber from the transmitter chamber;

a radome formed of a water repellent breathable fabric and configured to cover the radar antenna, the water repellent breathable fabric comprising a porous membrane capable of passing water vapor without passing liquid water and a fabric backing bonded to the porous membrane;

a radar data acquisition module configured to convert a demodulated radar return signal provided by the radar receiver to a digital baseband signal;

the radar data acquisition module configured to provide the digital baseband signal as a sequence of scanlines;

a radar data processing module comprising a video processor configured to receive the sequence of scanlines and programmed to compute Doppler shift data for a plurality of ranges from the sequence of scanlines, and estimate a vehicle pitch and yaw from the Doppler shift data;

the radar data processing module further configured to initiate an orientation adjustment of the radar antenna to compensate for the vehicle pitch and yaw.

2. The apparatus of claim **1**, wherein the target information comprises magnitude and phase information corresponding to at least one target.

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