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(54) **METHOD, APPARATUS, AND SYSTEM TO REMOTELY ACQUIRE INFORMATION FROM VOLUMES IN A SNOWPACK**

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G01S 13/00 (2006.01)

(52) **U.S. Cl.**
USPC .... **342/22**; 342/25 R; 342/25 A

(58) **Field of Classification Search**
USPC .... 342/22, 25 R, 25 A, 25 B, 25 C, 25 D, 342/25 E, 25 F
See application file for complete search history.

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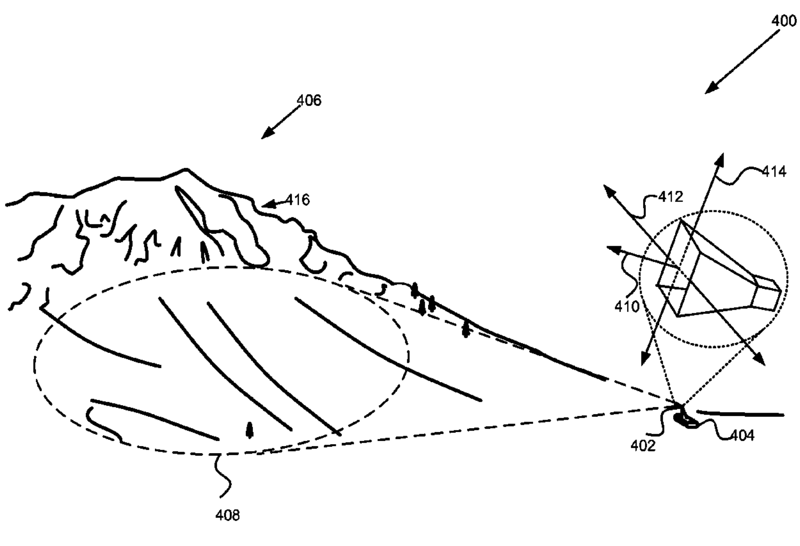
(57) **ABSTRACT**

A method, apparatus, and system to remotely acquire information from volumes in a snowpack and to analyze the information are disclosed. Electromagnetic energy is transmitted remotely to a region of interest in a snowpack and data about reflections are processed to determine reflection values for different volumes within the snowpack. The frequency of the transmit signal is modulated and the positions from which energy is transmitted and received are changed to create a two-dimensional synthetic aperture that allows reflections from three-dimensional volumes to be discriminated and resolved. The electromagnetic energy is transmitted to ensure that it arrives at the snowpack at shallow grazing angles to maximize returns from volumes in the snow and to minimize boundary reflections from the ground.

20 Claims, 17 Drawing Sheets



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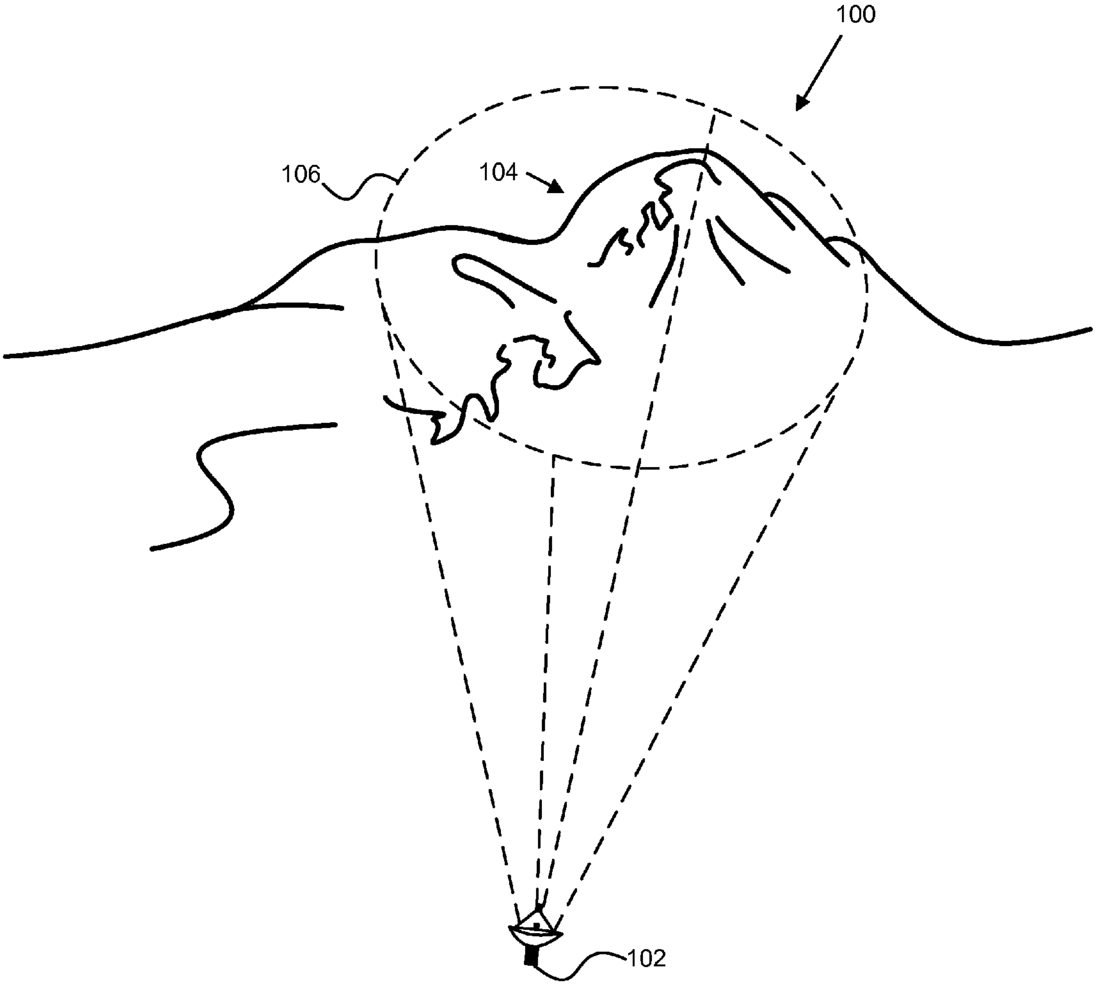

FIG. 1a (Prior art)

$$fp\_diameter = \frac{\lambda R}{d}$$

FIG. 1b

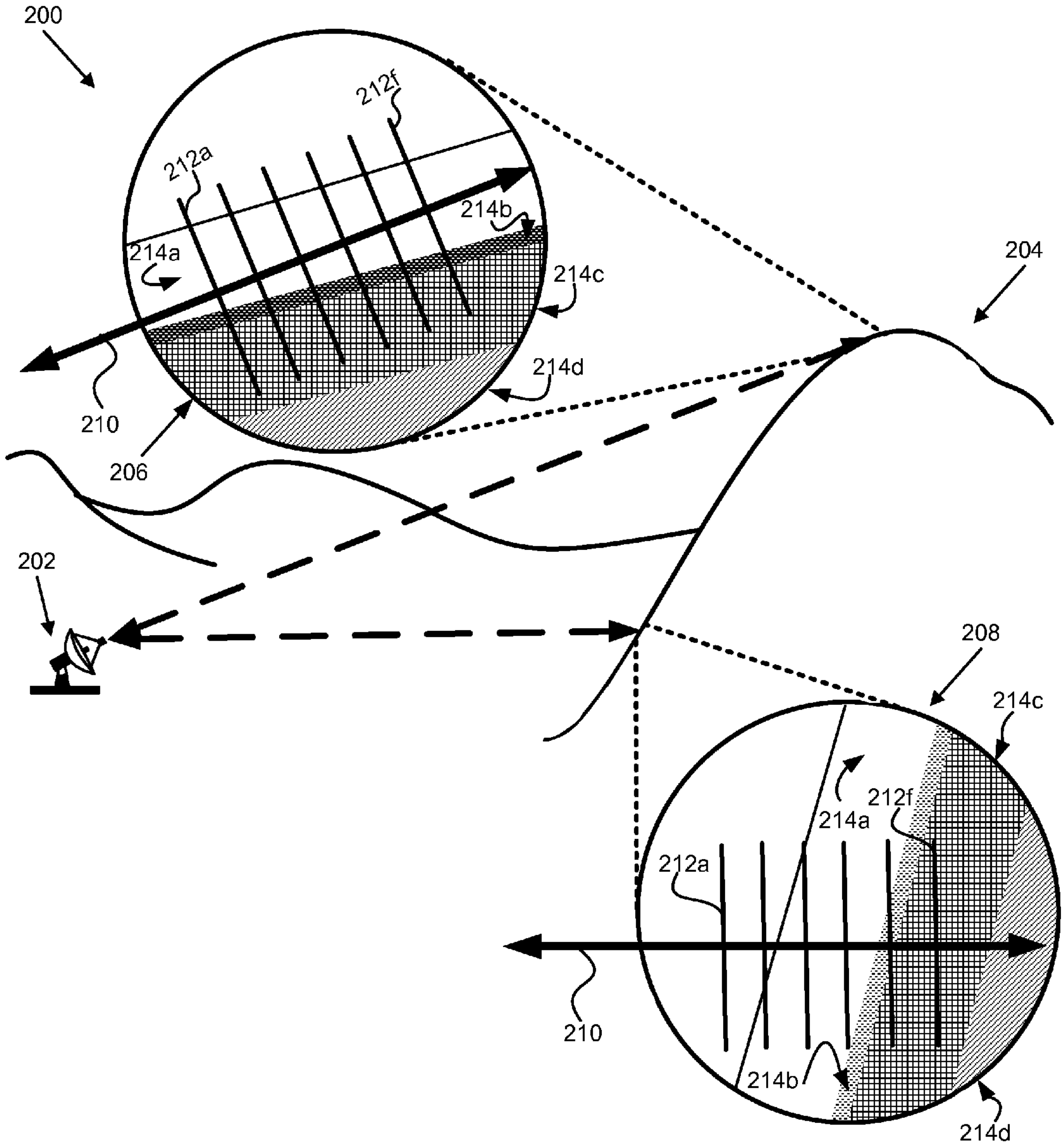

FIG. 2 (Prior art)

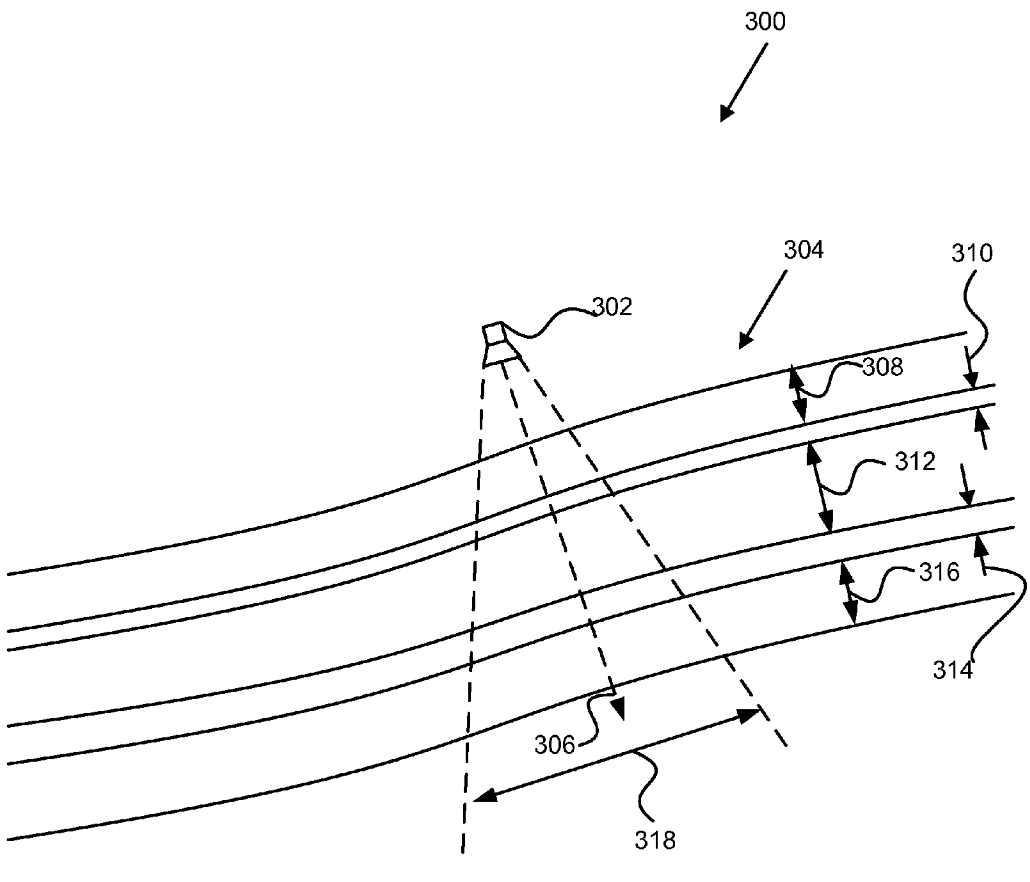

FIG. 3 (Prior art)

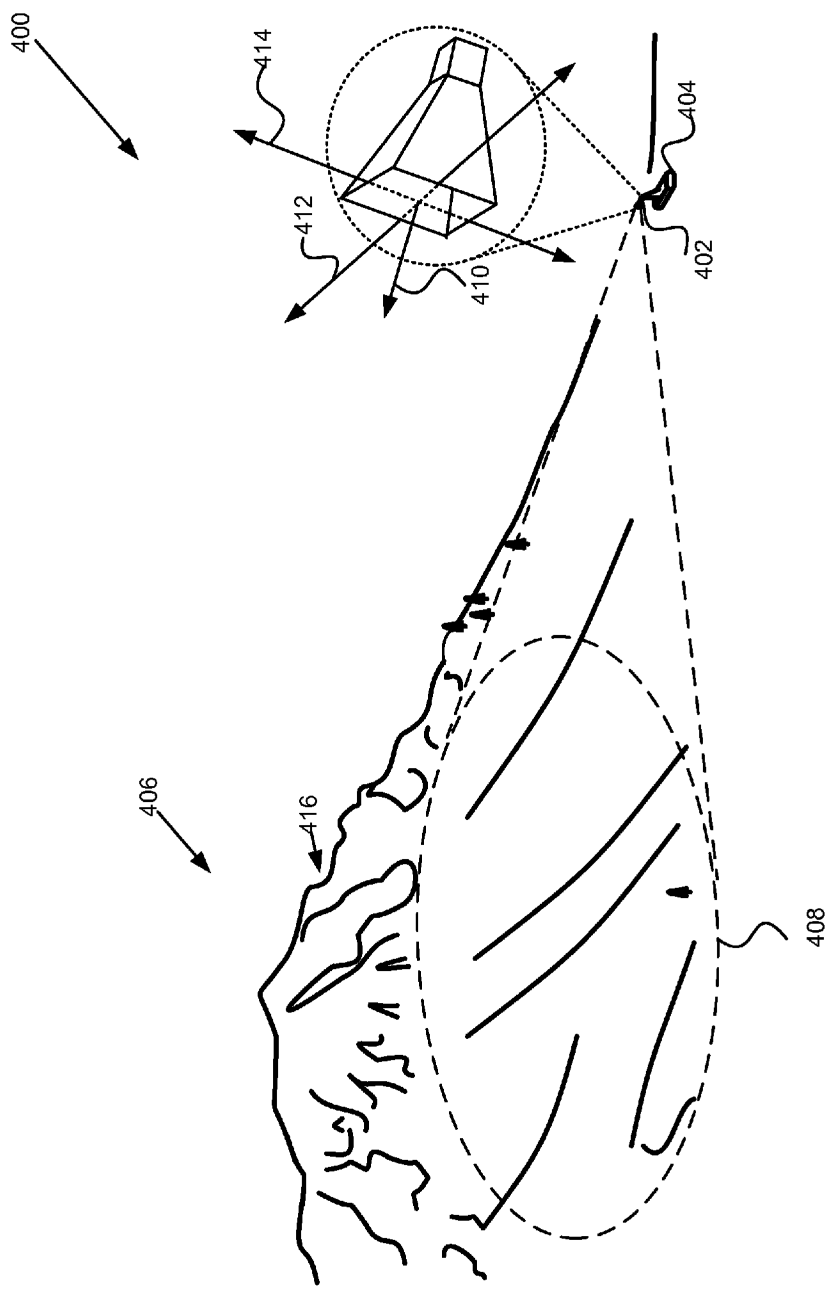

FIG. 4

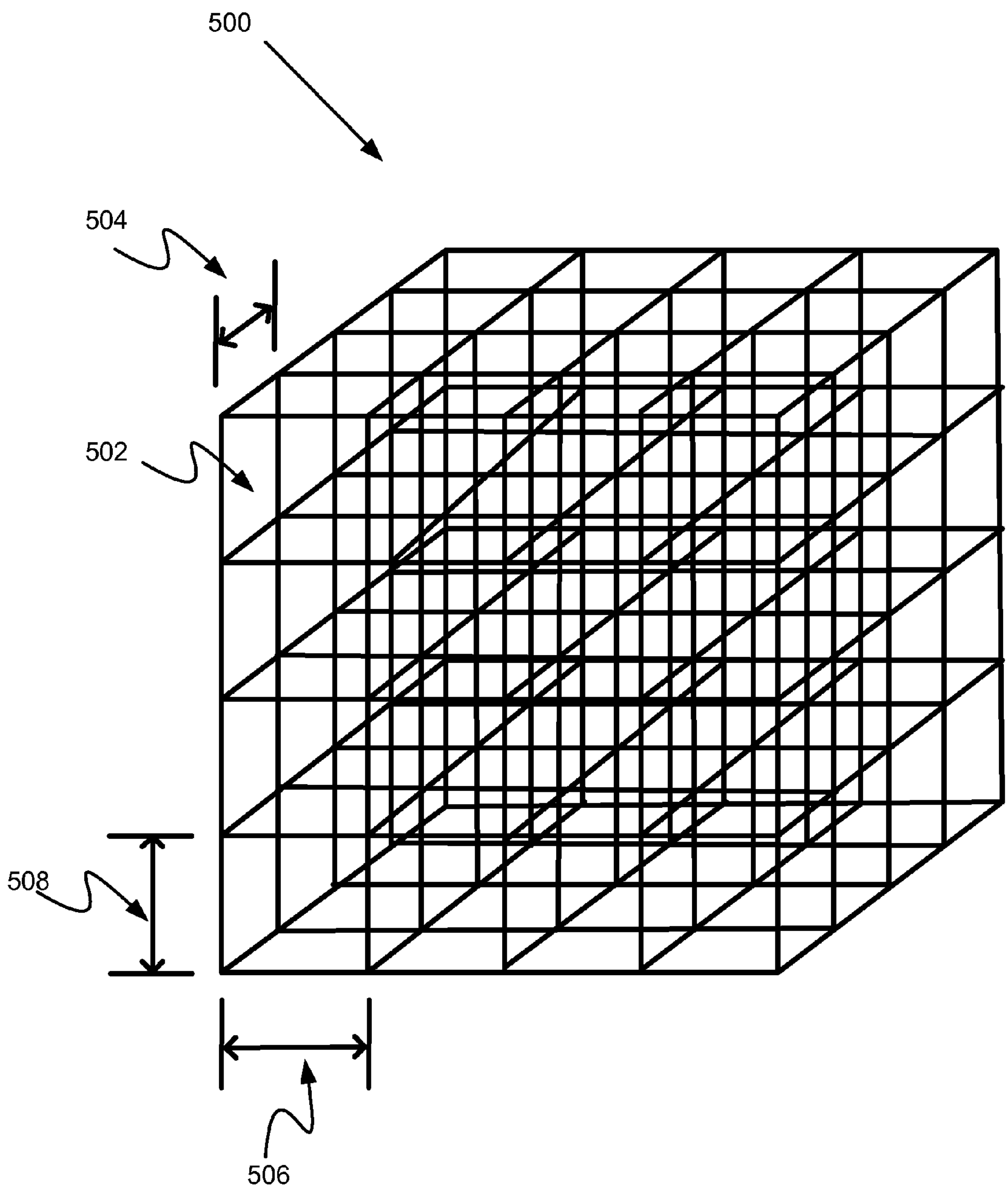

FIG. 5

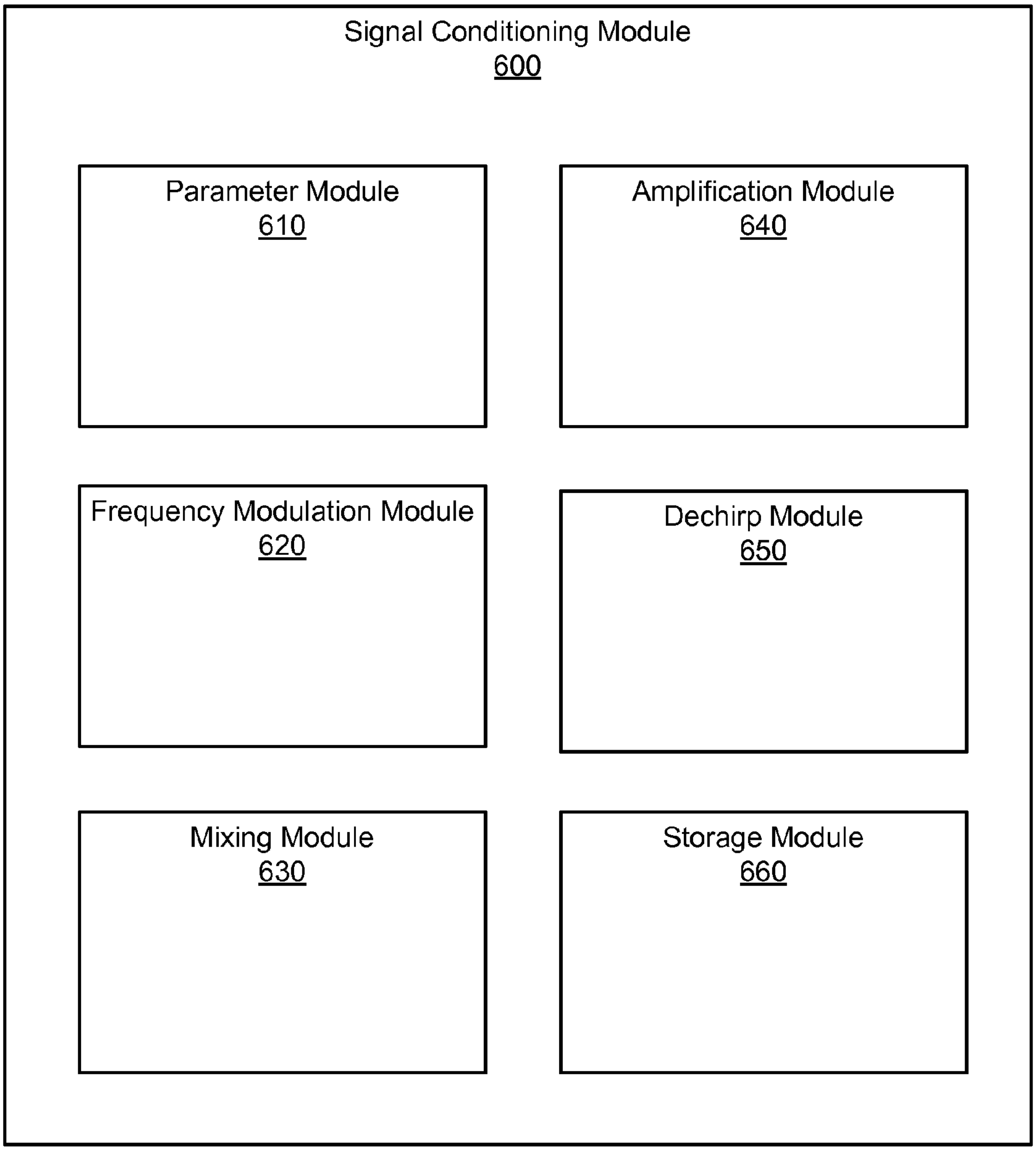

FIG. 6a

$$r = \frac{c}{2B}$$

FIG. 6b

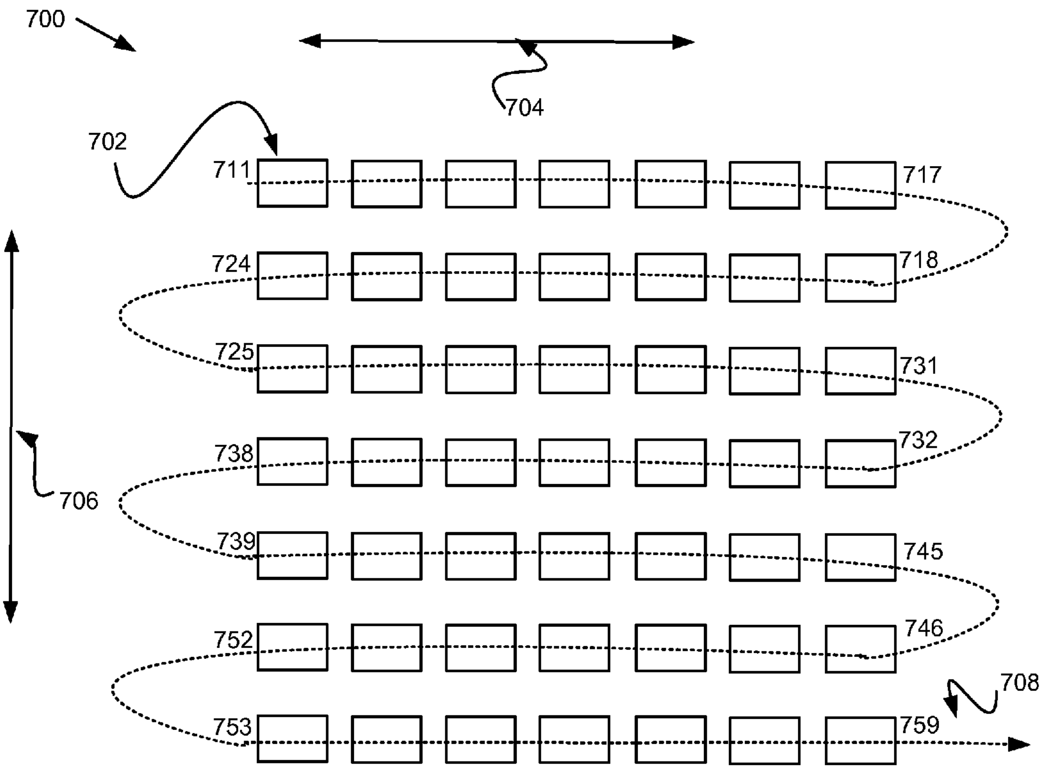

FIG. 7a

$$r = \frac{R\lambda}{2D}$$

FIG. 7b

$$r = \frac{l}{2}$$

FIG. 7c

Freq. (GHz)	Band	50 m Range	100 m Range	300 m Range	500 m Range
15	Ku	5 m	10 m	30 m	50 m
22.25	K	3.37 m	6.74 m	20.2 m	33.71 m
33.75	Ka	2.2 m	4.4 m	13.3 m	22.2 m
40	Ka	1.87 m	3.75 m	11.25 m	18.75 m

FIG. 7d

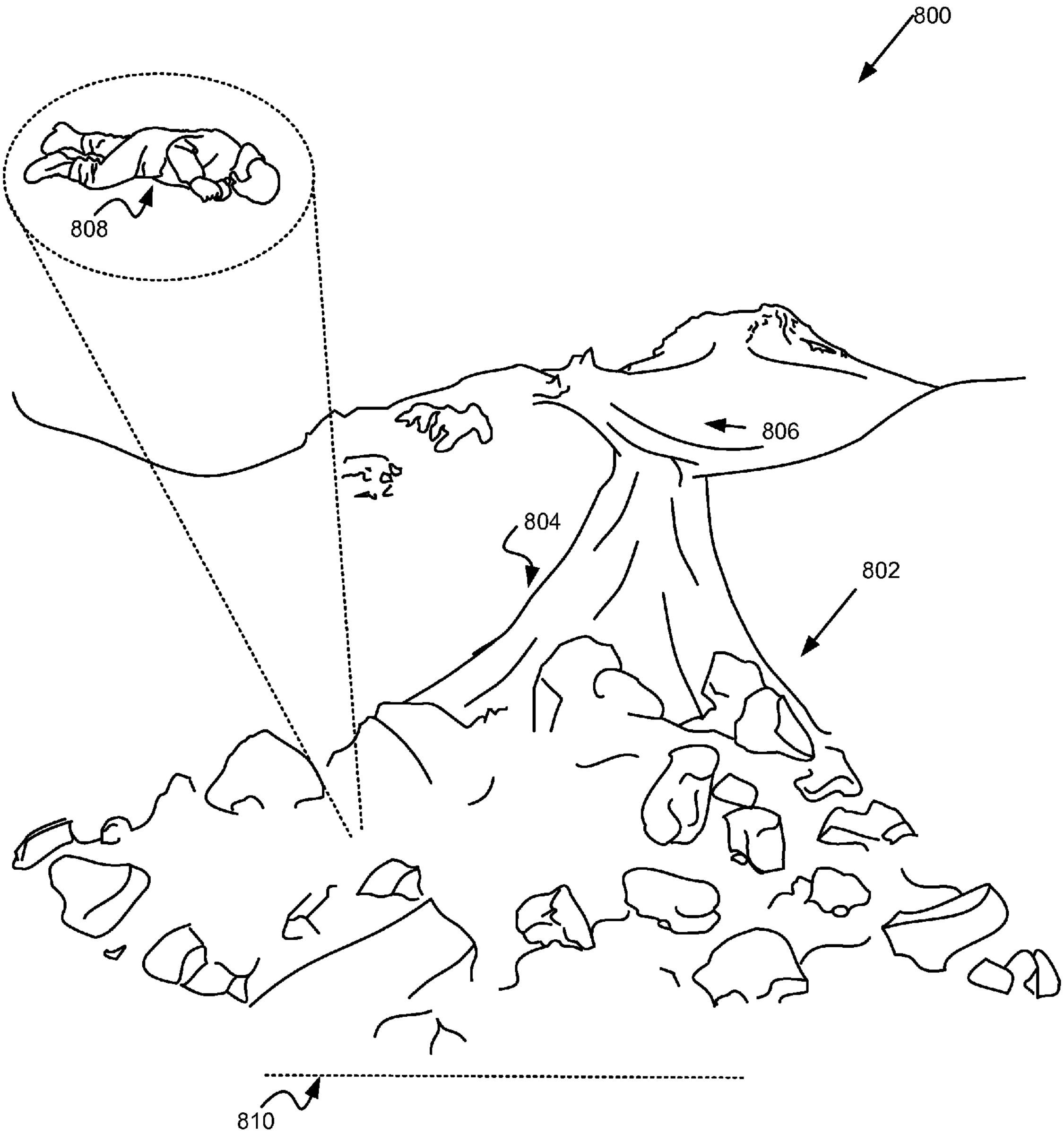

FIG. 8

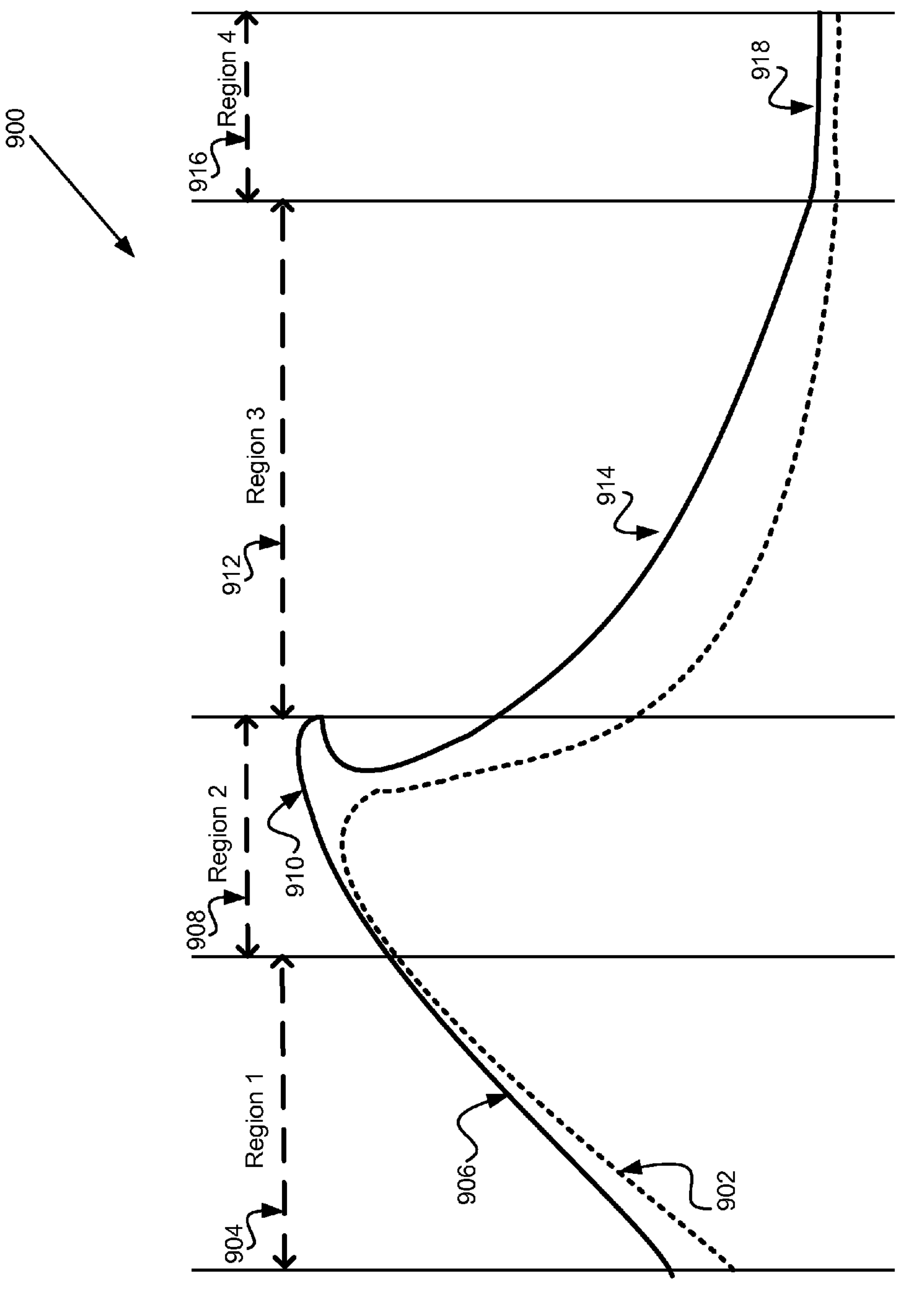
900
Region 1
Region 2
Region 3
Region 4
902
904
906
908
910
912
914
916
918

FIG. 9

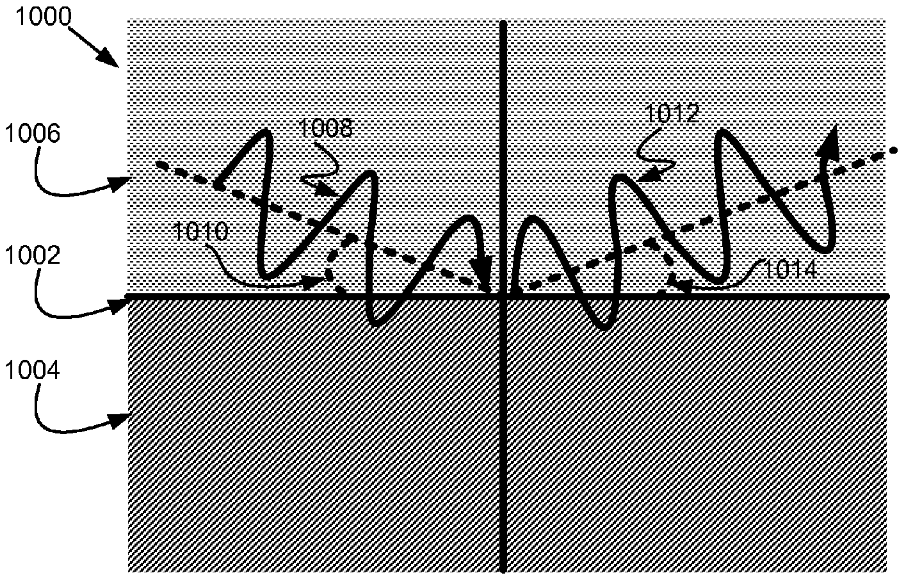

FIG. 10a

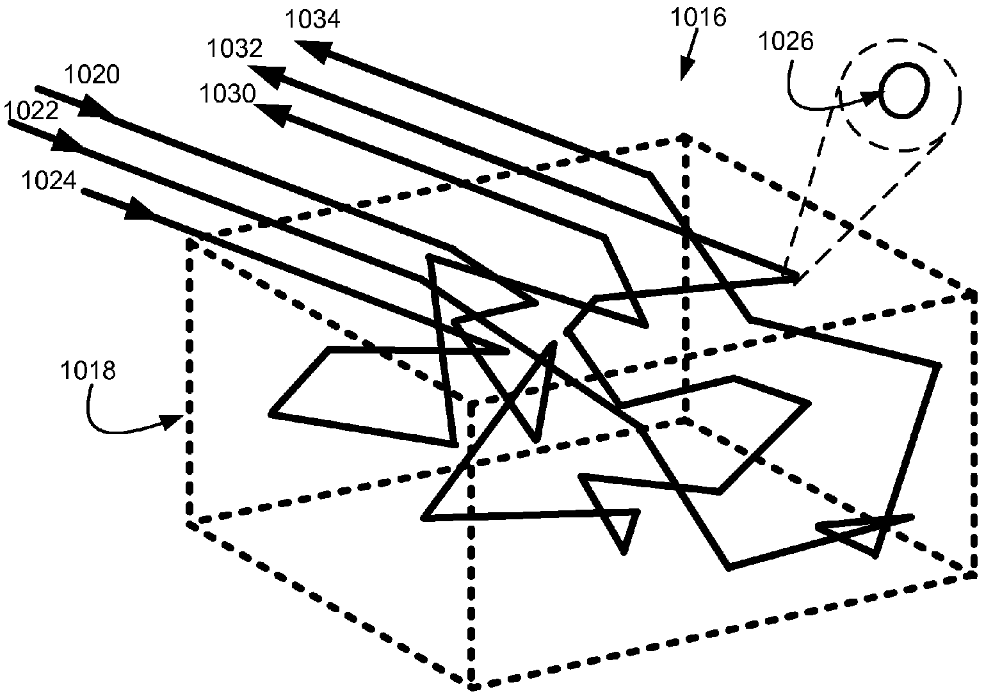

FIG. 10b

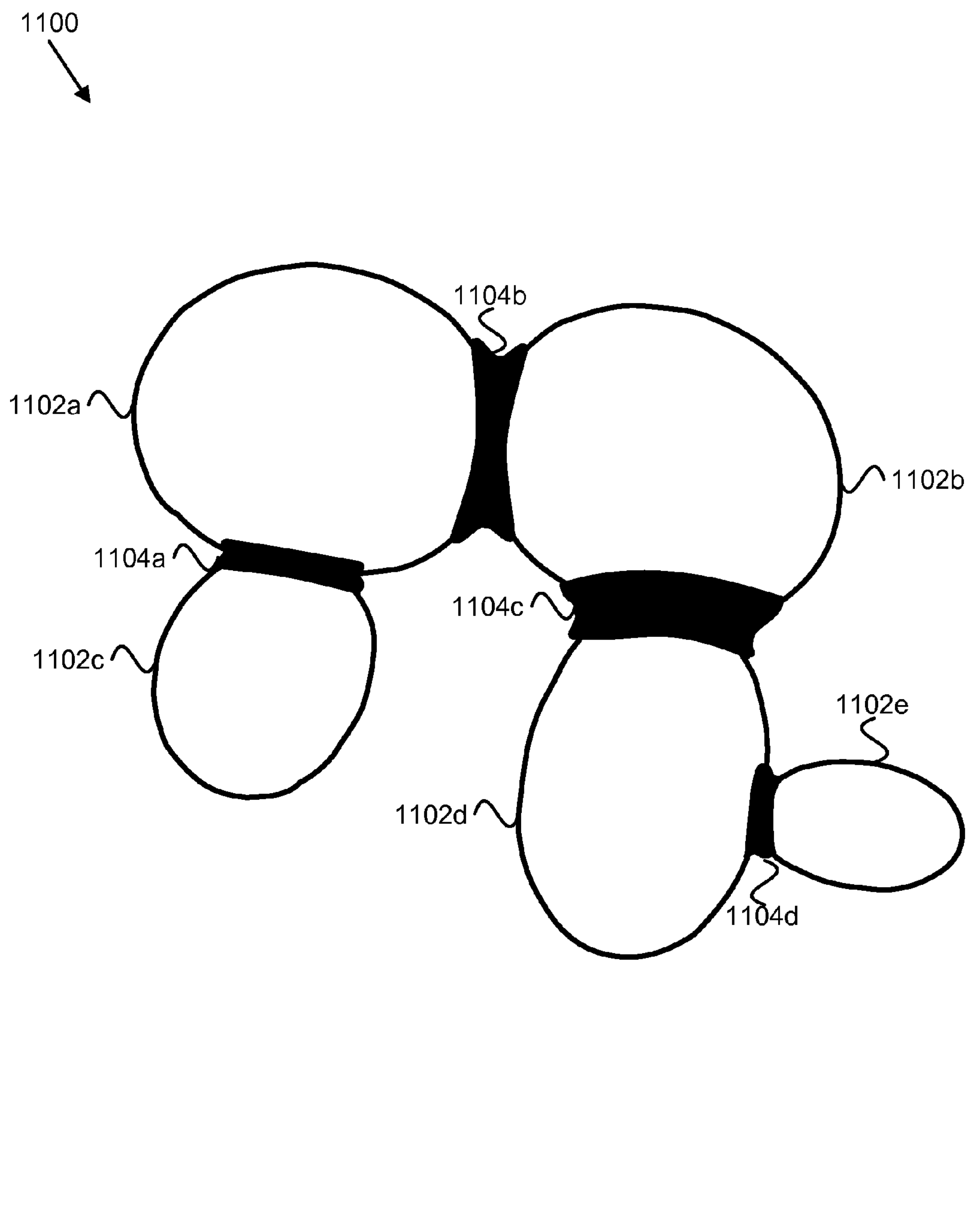

FIG. 11

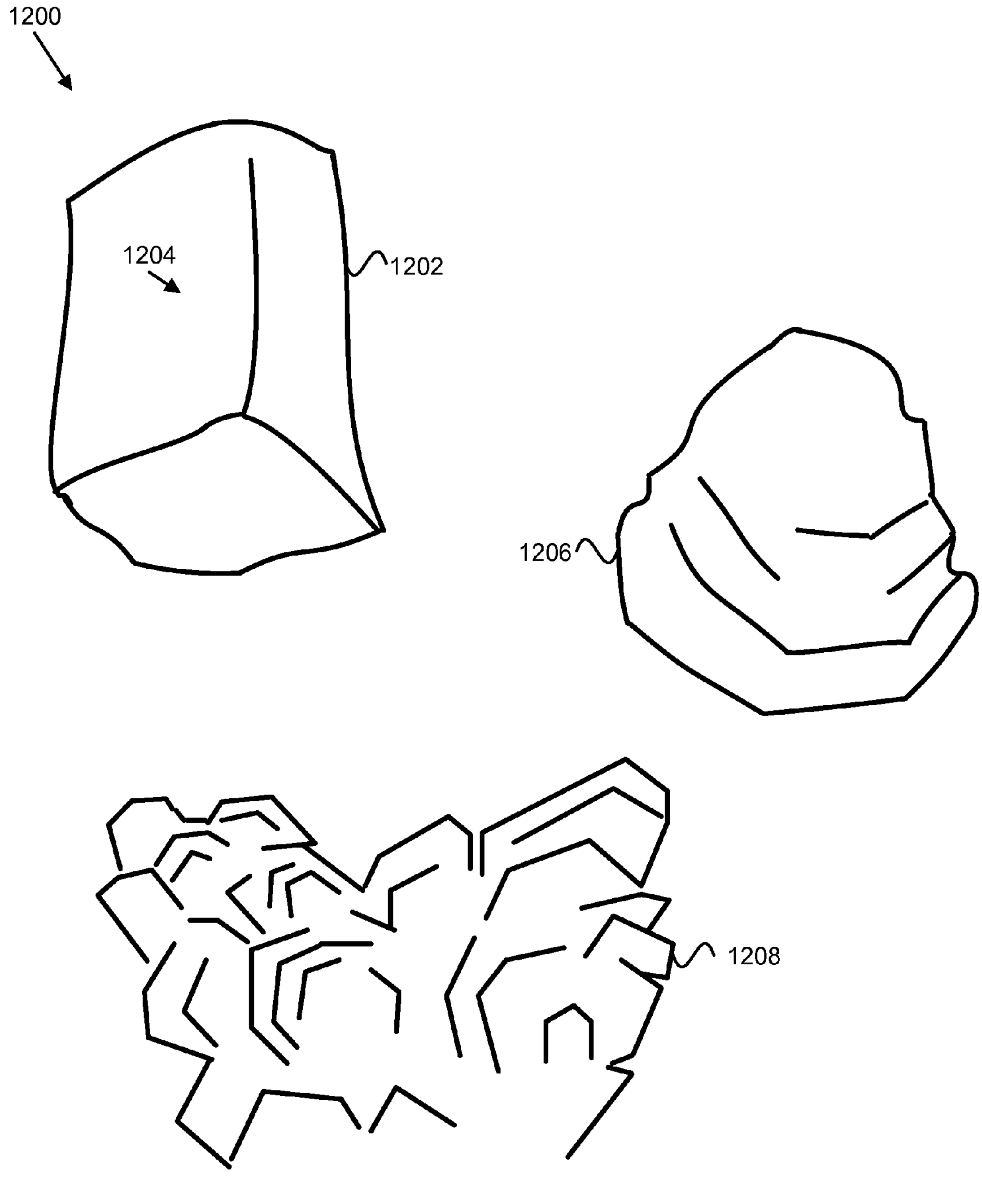

FIG. 12

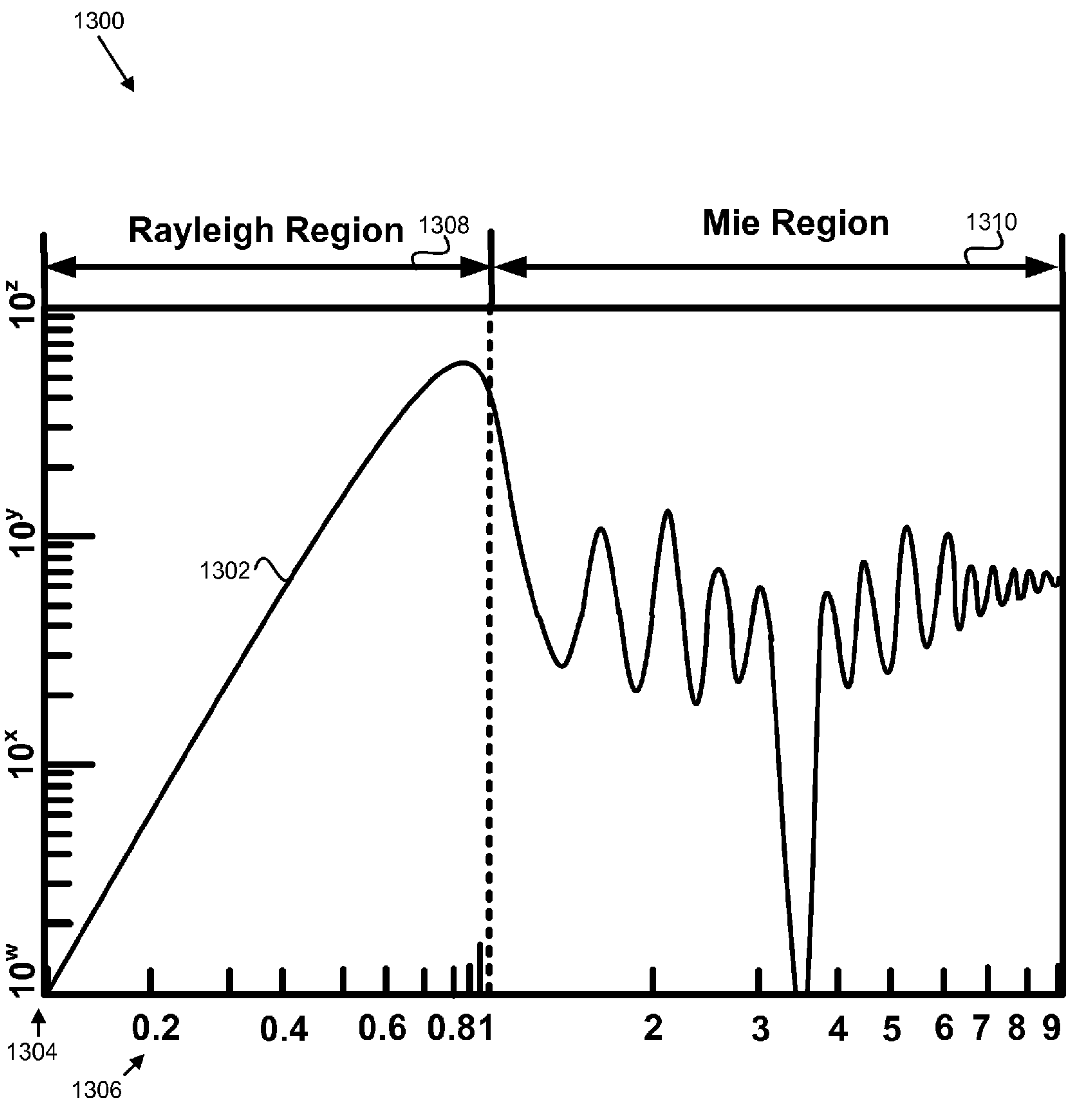
1300
Rayleigh Region
1308
Mie Region
1310
10^z
10^y
10^x
10^w
1302
0.2
0.4
0.6
0.81
2
3
4
5
6
7
8
9
1304
1306

FIG. 13

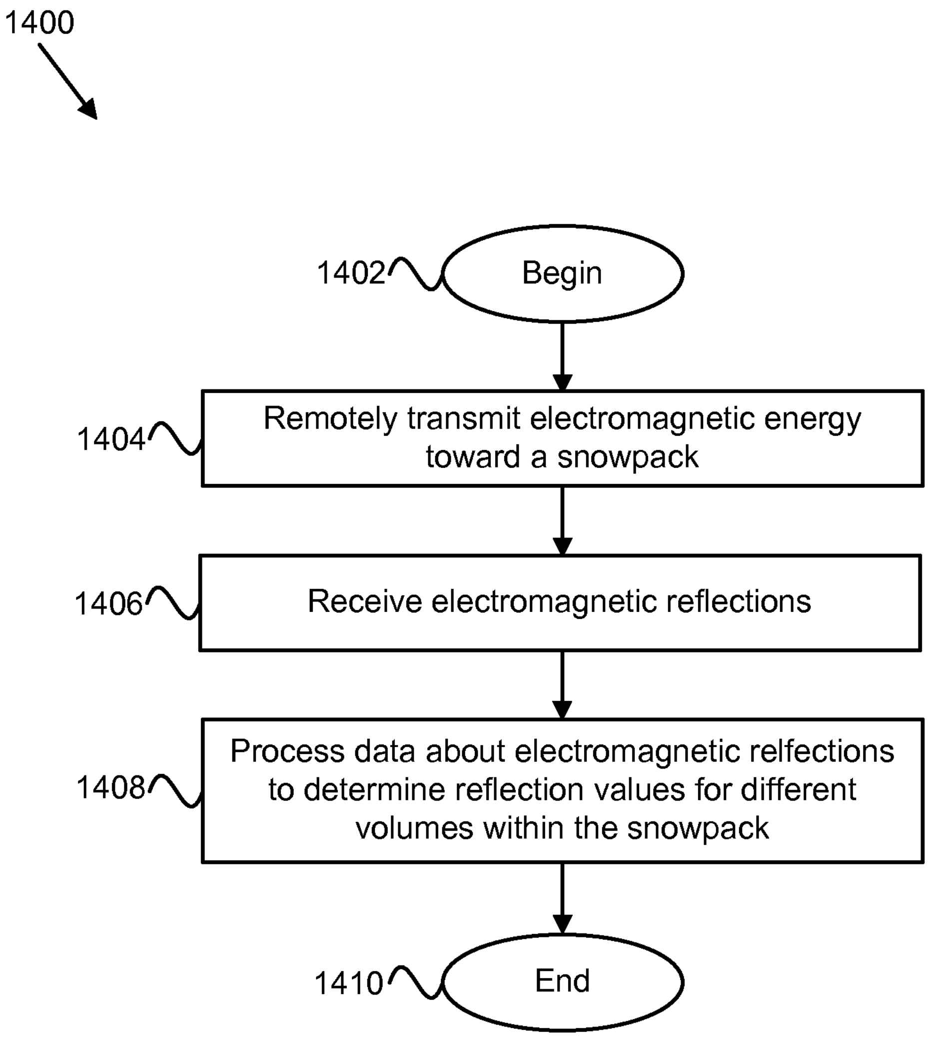
1400
1402
Begin
1404
Remotely transmit electromagnetic energy toward a snowpack
1406
Receive electromagnetic reflections
1408
Process data about electromagnetic relfections to determine reflection values for different volumes within the snowpack
1410
End

FIG. 14

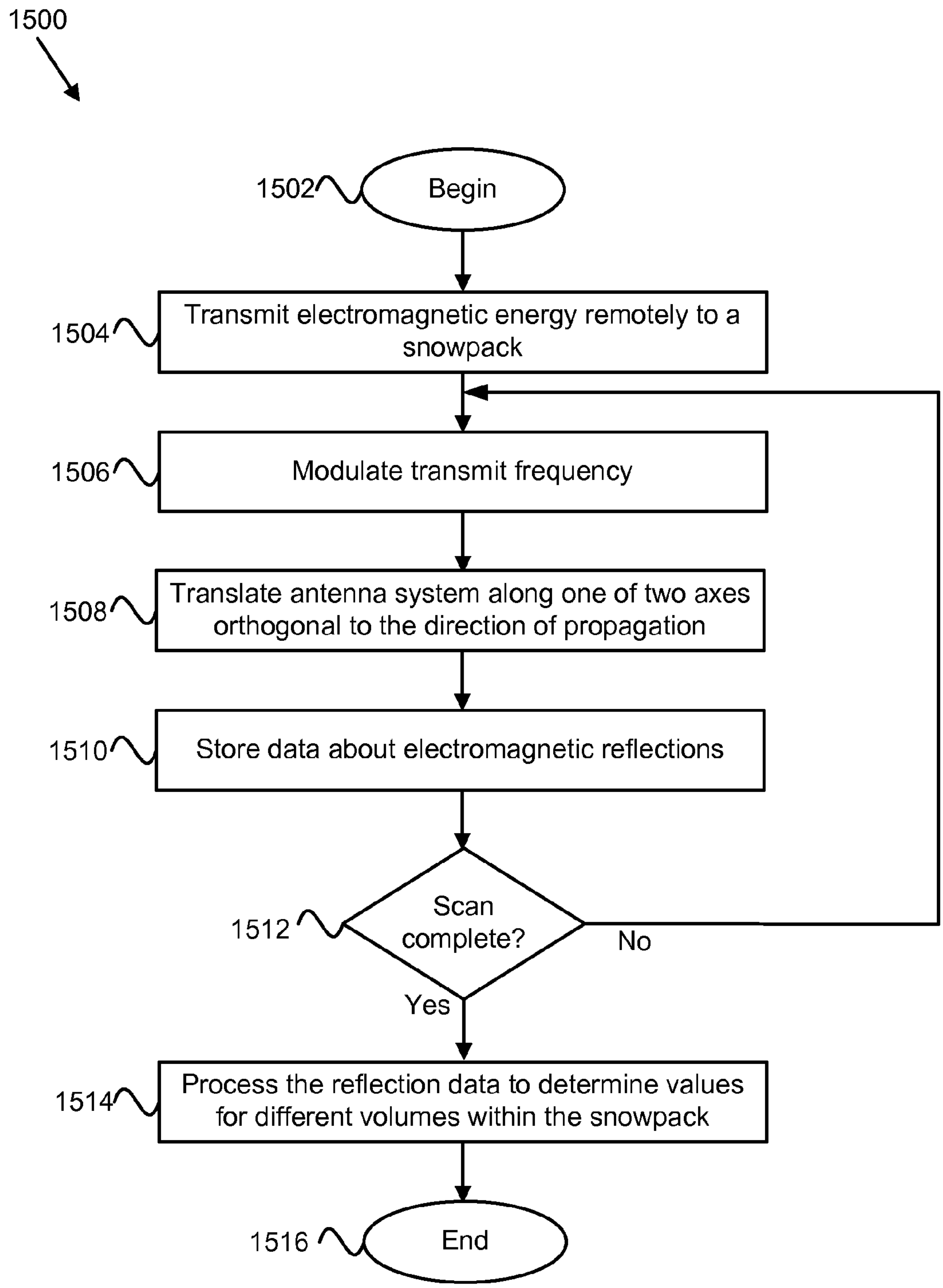
1500
1502
Begin
1504
Transmit electromagnetic energy remotely to a snowpack
1506
Modulate transmit frequency
1508
Translate antenna system along one of two axes orthogonal to the direction of propagation
1510
Store data about electromagnetic reflections
1512
Scan complete?
No
Yes
1514
Process the reflection data to determine values for different volumes within the snowpack
1516
End

FIG. 15

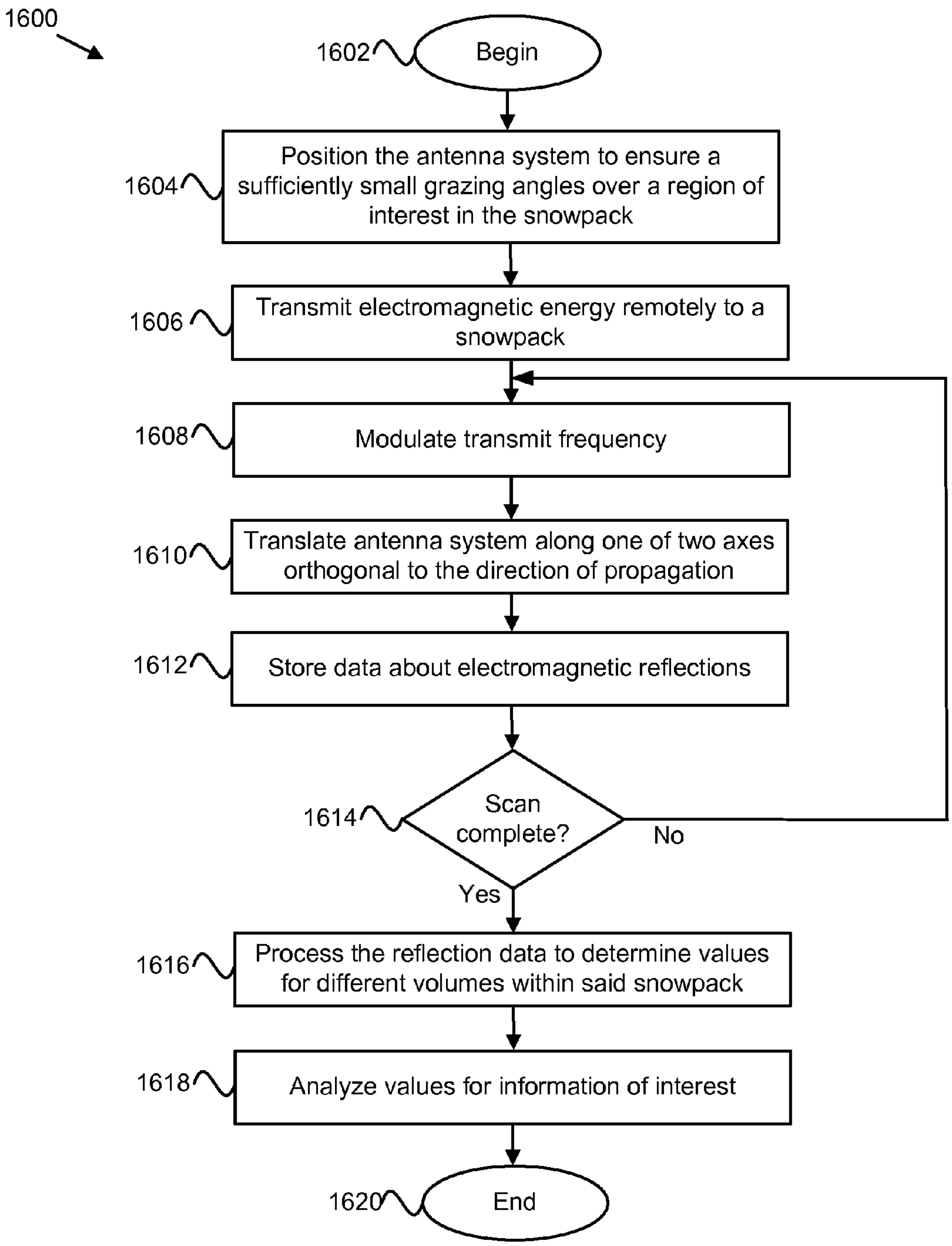
1600
1602
Begin
1604
Position the antenna system to ensure a sufficiently small grazing angles over a region of interest in the snowpack
1606
Transmit electromagnetic energy remotely to a snowpack
1608
Modulate transmit frequency
1610
Translate antenna system along one of two axes orthogonal to the direction of propagation
1612
Store data about electromagnetic reflections
1614
Scan complete?
No
Yes
1616
Process the reflection data to determine values for different volumes within said snowpack
1618
Analyze values for information of interest
1620
End

FIG. 16

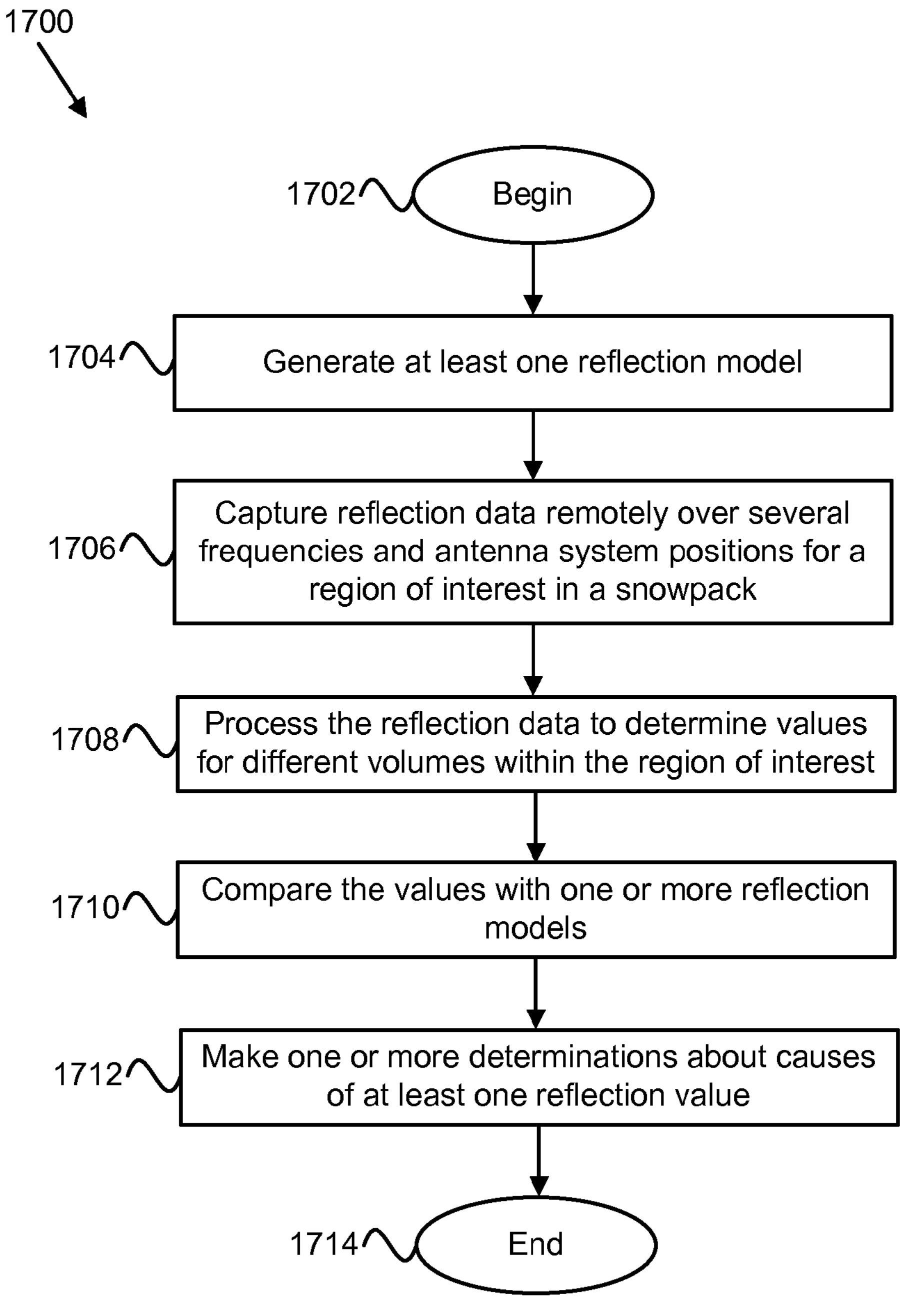
1700
1702
Begin
1704
Generate at least one reflection model
1706
Capture reflection data remotely over several frequencies and antenna system positions for a region of interest in a snowpack
1708
Process the reflection data to determine values for different volumes within the region of interest
1710
Compare the values with one or more reflection models
1712
Make one or more determinations about causes of at least one reflection value
1714
End

FIG. 17

METHOD, APPARATUS, AND SYSTEM TO REMOTELY ACQUIRE INFORMATION FROM VOLUMES IN A SNOWPACK

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims the priority of U.S. Provisional application No. 61/396,920, filed Jun. 4, 2010, the disclosure of which is hereby incorporated by reference herein.

FIELD OF THE INVENTION

This invention relates to approaches to acquiring information from within a snowpack. More particularly, the invention relates to the use of a radar system to remotely acquire information from distinct volumes within a snowpack.

BACKGROUND OF THE INVENTION

The blanket of a snowpack can conceal many different things. For example, a snowpack can conceal the body of an avalanche victim, avalanche debris indicative of the extent and path of an avalanche, layers of weakness that later may become responsible for the formation of an avalanche, and the amount of water contained in the snowpack, among other things. Information about such things can save lives, be helpful in the recovery of human remains, prevent property damage, and provide important information for water-use planning.

Presently, such information is obtained by local investigations of the volume of a snowpack. For example, individuals search for avalanche victims by thrusting probes into the snowpack. Similarly, individuals dig time-consuming snow pits to look for avalanche-prone layers of weakness in a snowpack to predict avalanche danger. Determinations about avalanche flow paths and volumes occupied by avalanche debris are made in similar ways. The snow/water equivalence of a snowpack requires localized and time-consuming measurements about snowpack densities and thicknesses.

These localized investigations and measurements often need to be repeated over large areas to obtain sufficient, or optimal results. For example, the contours for avalanche debris must be determined over several avalanche cycles to assess where structures may safely be built or to determine where to search for an avalanche victim. The stratigraphy of a snowpack, in terms of layers that may contribute to avalanche formation, varies widely over small distances—such as a meter—due to rapidly varying micro-climates in mountainous terrain. A snow pit in a single location, therefore, will often not uncover the weakest portion of a snowpack responsible for the formation of an avalanche in a particular avalanche track. Changes in stratigraphy also have implications for snow/water equivalence, as do changes in snowpack thickness that arise from wind and any number of additional factors, resulting in the need for many measurements.

The time and resources required to make such investigations and measurements are a problem. Where an avalanche victim is involved, every passing minute reduces the probability of finding the victim alive. The investigations and measurements involved in finding an avalanche victim can be so extensive that it is not uncommon to wait for the spring thaw to recover the victim's remains. In terms of avalanche prediction, the number of snow pits required to assess the stratigraphy of a slope in terms of potential for avalanche formation over the region within which an avalanche may form, makes the actual digging of all the snow pits entirely impractical. Educated guesses must be made based on experience, weather, topology, snowpack history, and a wide array of additional factors. The large areas that must be surveyed and the repeated measurements required to assess the flow patterns and regions occupied by avalanche debris also presently require estimations. More objective, less time-consuming, more efficient, and safer methods for acquiring information from volumes in a snowpack over large areas are needed.

The ability of radar to penetrate a snowpack over a large area and to acquire information about varying electromagnetic and geometric properties within the volume of a snowpack that can be correlated to phenomena of interest, makes radar a likely candidate to meet these needs. Prior art demonstrates the ability to harness the impressive range resolution of frequency modulated radar systems to probe a snowpack. Such radar based investigations can be used to discover a body and to reveal properties such as thickness, density, snow-water equivalency, and particular aspects of snowpack stratigraphy by distinguishing between certain layers in the snowpack. The approaches taken in the prior art, however, can only determine the location of reflections from within the snowpack along an axis defined by the direction of propagation, i.e., the range axis.

For a remotely disposed radar system, however, large areas of a snowpack are included within the beam pattern from the radar system. FIG. **1***a* depicts a system **100** exemplary of this situation in the prior art. In FIG. **1***a*, a remotely disposed antenna **102** is orientated to transmit toward a snowpack **104** that reposes in mountainous terrain. The remote location of the antenna **102** results in large ranges to locations in the snowpack **104**. The footprint **106** illuminated by the antenna **102** becomes larger and larger as range increases according to Equation 1, as provided in FIG. **1***b*, where 'λ' denotes wavelength, 'R' denotes range, and 'd' denotes the diameter of a circular antenna aperture **102**. As appreciated, according to Equation 1, the footprint **106** increases with increasing range. For a particular range, the footprint **106** in FIG. **1***a* would actually describe an arched shape. However, for simplification of the illustration, the footprint **106** is depicted in a plane normal to the direction of propagation.

The ability to differentiate locations only with respect to the range axis results in ambiguities about the location from which reflections to the radar system originate from within the beam pattern, despite the fine range resolution. As depicted in FIG. **1***a*, the footprint **106** includes large portions of the snowpack **104**. Although the reflections from the same range will not include reflections from the entire snowpack **104**, the reflections from large areas of the snowpack **104** will be combined.

Where information about snowpack stratigraphy is sought, changes in the orientation of layers in the snowpack relative to the range axis are particularly problematic for radar systems solely capable of determining locations with respect to the range axis. On the mountainous slopes on which a snowpack reposes, the orientation of a snowpack relative to a remotely disposed radar system can vary widely. FIG. **2** depicts a system **200** exemplifying this additional complication to the situation in the prior art.

In FIG. **2**, a remotely disposed radar **202** transmits to a snowpack **204** that reposes in mountainous terrain. The sloping nature of mountainous terrain greatly changes the relative orientation of the range axis **210** from one location to another as seen in the first expanded view **206** and the second expanded view **208**. Additionally, mountainous terrain is rugged, and the surface of the bed on which a snowpack reposes undulates and varies widely from location to location.

In the expanded views **206**, **208** of the relative orientations of the range axis **210** to the snowpack layers **214***a*-**212***d*, the hash marks **121***a*-**121***f*, disposed along the range axis **210**, indicate regions that are distinctly resolvable for the radar **202** with its ultra-high-range resolution. However, even with ultra-high-range resolution, at least three distinct problems arise.

First, where the range axis **210** is close to parallel with the snowpack layers **214***a*-**214***d*, reflections from adjacent layers **214***a*-**214***d* in the snowpack **204** become confused and become adulterated. However, where the orientation of the range axis **210** becomes more normal, as in the second expanded view **208**, the resolvable regions **212***a*-**212***f* are better oriented to distinguish reflections relative to adjacent strata/layers **214***a*-**214***d*.

Second, the differing orientations of the range axis **210** relative to the snowpack layers **214***a*-**214***d* in the first **206** and the second **208** expanded views indicate that reflections travel different distances along the range axis **210** from different layers **214***a*-**214***d* depending on the orientation of the range axis **210**, making it difficult to determine the relative location and thicknesses of the layers **214***a*-**214***d* in the snowpack. In the first expanded view **206**, where the range axis **210** is almost parallel, great distances must be traveled before boundaries between layers **214***a*-**214***d* are traversed, making the snowpack **204** and its layers **214***a*-**214***d* appear very thick. In the second expanded view **208**, where the range axis **210** is almost normal to the snowpack **204**, the distances traveled more accurately indicate the actual locations and thicknesses of layers **214***a*-**214***d* within the snowpack **204**.

For reasons discussed with respect to FIG. **1** and FIG. **2**, and for additional reasons, the radar systems in the prior art must remain close to a snowpack which they probe for information. Also, radar systems in the prior art must maintain the orientation of their range axis relative to snowpack stratigraphy constant along the contour of the snowpack to determine the location from which reflections originate relative to snowpack stratigraphy. For this reason, radar systems are positioned in the prior art directly on top of the snowpack on a sled or beneath a low-hovering helicopter.

FIG. **3** depicts a system **300** exemplary of additional aspects of the situation in the prior art. An antenna **302** depicted in FIG. **3** transmits electromagnetic energy from a prior-art radar system (not shown) to a snowpack **304** that is disposed close to the antenna **302**—directly underneath the antenna **302**. The antenna **302** is oriented so that the direction of propagation **306**, of the waves it transmits, is substantially normal to the contour of the snowpack **304** and the various layers **310**-**316** that make up the stratigraphy of the snowpack **304**.

Since the antenna **302** is maintained close to the snowpack **304**, the size of the footprint **318** allows reflections from different portions of the snowpack **304** to be resolved. Additionally, since the direction of propagation **306** is maintained normal to the snowpack **304**, the relative location of layers **310**-**316** in the snowpack **304** and the thicknesses of those layers **310**-**316** can be determined by the distances traveled by reflections from those layers **310**-**316**.

Unfortunately, such radar systems **300** lose the principal benefits of radar. Such benefits include the ability to scan large areas remotely. These benefits could be employed in the service of meeting the needs of more-objective, less-time-consuming, more-efficient, and safer approaches to acquiring information from volumes in a snowpack **304** over large areas. A radar system **300** that must be maintained close to the snowpack **304** and maintained so that the orientation of the direction of propagation **306** relative to the snowpack **304** is known, cannot meet these needs.

What are needed are a method, an apparatus, and a system capable of scanning large regions of a snowpack to acquire information from within the snowpack from a distance. Such information should be relevant to addressing questions such as, but not limited to, the location of an avalanche victim, the flow patterns of avalanches, regions occupied by avalanche debris, the stratigraphy of a snowpack as it relates to avalanche formation, and the snow/water equivalence of a snowpack. To achieve these ends, such approaches should be capable of remotely pinpointing the location from which reflections back to the radar system originate in three-dimensional space with high resolution.

SUMMARY

The 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 methods, apparatus, and systems. Accordingly, the invention has been developed to provide an improved method, apparatus, and system to remotely acquire information from volumes in a snowpack. The features and advantages of the invention will become more fully apparent from the following description and appended claims, or may be learned by practice of the invention as set forth hereinafter.

Consistent with the foregoing, a method to remotely acquire information from volumes in a snowpack is disclosed herein. In certain embodiments, such a method may include transmitting electromagnetic energy toward a snowpack from a remote location. This electromagnetic energy results in reflections from the snowpack. Data about these reflections are processed to determine reflection values for different volumes within the snowpack.

The method may further include modulating the transmit frequency. The frequency is modulated over a sufficient bandwidth, or group of bandwidths to resolve distinct volumes within the snowpack with respect to a first axis. The first axis may be considered in certain embodiments, but not necessarily all embodiments, as the range axis. In certain embodiments, the transmit frequency may be modulated across multiple different frequency spans to acquire information about responses from different portions of the electromagnetic spectrum so that, for example and without limitation, information about the response of a snowpack to frequencies in C-band, X-band, and/or any of the K-bands, or different portions of these bands can be acquired.

Additionally, the method may further include translating an antenna system, for transmitting and receiving the electromagnetic energy over an area to create a synthetic aperture capable of discriminating and resolving reflections with respect to a second axis and a third axis. These second and third axes should be substantially orthogonal to the first axis and to one another. The antenna system is translated, whether linearly, or along a curving path, over an area with dimensions sufficient to resolve distinct volumes within the snowpack with respect to the second and third axes. The second axis and the third axis may be considered in certain embodiments, but not necessarily all embodiments, as the azimuth and elevation axes respectively. In certain embodiments, the bandwidth or bandwidths, and the dimensions of the area of the synthetic aperture with respect to the second and third axes are sufficient to achieve resolution commensurate with thicknesses for different layers of interest in the stratigraphy of the snowpack. In some embodiments, the area of the synthetic aperture

can be curved so that the antenna positions are also defined with respect to the direction-of-propagation axis.

Also, the method may involve positioning the antenna system to maintain a relative orientation to a region of interest within said snowpack that ensures that electromagnetic energy incident upon said snowpack arrives at a sufficiently shallow grazing angle or angles. The sufficiently shallow grazing angle maximizes the ratio of returns from volume scattering within the snowpack to returns from reflections from the ground underneath. The regions of interest may comprise, without limitation, a region of the snowpack wherein a victim of an avalanche may be buried, a region with the potential for including avalanche debris, a region important to determining snow-water equivalencies for a watershed, a region from which avalanche formation may occur, and a slope that may be skied.

Reflection values may be analyzed to determine, without limitation, a location for an avalanche victim, to determine a three-dimensional distribution for avalanche derbies, to determine snow-water equivalencies for a watershed; to determine snow densities associated with high-quality snow for powder skiing, and for properties relevant to avalanche prediction. Analysis may involve comparison to reflection models developed from empirical sampling and/or computer modeling over one or more sets of frequencies. Such reflection models may be informed by, without limitation, snow density, average ice grain size, average ice grain shape, water content, and expected resonance profiles for particular sizes and/or shapes.

An apparatus/system for remotely retrieving information from a snowpack may include a signal conditioning module that generates electromagnetic energy at various frequencies within a bandwidth, or multiple bandwidths across different spans of frequencies in the electromagnetic spectrum, with sufficient power to transmit the energy to a snowpack from a remote location through an antenna system. The signal conditioning module receives reflections through the antenna system.

The apparatus/system, in certain embodiments, further comprises infrastructure for translating the antenna system over an area to create a synthetic aperture capable of discriminating and resolving reflections with respect to a second axis and a third axis that are substantially orthogonal to one another. The infrastructure translates the antenna system over an area with sufficient dimensions with respect to the second and third axis sufficient to create a synthetic aperture that can resolve distinct volumes within the snowpack with respect to these two axes. The signal conditioning module stores data about the reflections and the locations of the antenna system, at which transmissions are made and reflections are received, in a memory device communicatively coupled to the signal conditioning module. A processor communicatively coupled to the memory device determines reflection values for different volumes within the snowpack by running an algorithm, such as, but not limited to, the backprojection algorithm, embedded in software. Additionally, the apparatus/system maintains an orientation of the antenna system relative to the snowpack to maximize returns from volume scattering within the snowpack and to minimize returns from the ground.

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 illustrated in the appended drawings. To better understand the advantages of the present invention, the drawings depicting the present invention can be compared against drawings of existing technologies in the prior art. Understanding that these drawings depict only typical embodiments of the invention and are not, therefore, to be considered limiting of its scope, the invention will be described and explained with additional specificity and detail through use of the accompanying drawings, in which:

FIG. **1***a* exemplifies the situation in the prior art by depicting a footprint from a remotely disposed radar as it would occupy a snowpack;

FIG. **1***b* provides an equation that defines the relationship between the diameter of a footprint illuminated by an antenna and the range of the footprint;

FIG. **2** exemplifies the situation in the prior art by depicting changes in the orientation of the range axis relative to a remotely disposed snowpack;

FIG. **3** exemplifies the situation in the prior art by depicting a system in which an antenna must be maintained directly above a snowpack and follow the contour of the snowpack in its orientation relative to the snowpack;

FIG. **4** depicts one embodiment in accordance with the present invention;

FIG. **5** depicts a collection of empty voxels corresponding to different volumes in a snowpack;

FIG. **6***a* provides a schematic depiction of a signal conditioning module as employed in one embodiment in accordance with the present invention;

FIG. **6***b* provides an equation that defines the relationship between range-resolution and bandwidth;

FIG. **7***a* depicts a synthetic aperture generated from an antenna system that is translated over an area in accordance with the present invention;

FIG. **7***b* provides an equation that defines the relationship between resolution along an axis of a synthetic aperture and the distance traversed by the antenna system within the area of the synthetic aperture along that axis;

FIG. **7***c* provides an equation that defines the relationship between the maximum achievable resolution of a synthetic aperture and the length of a constitutive antenna used to create that synthetic aperture;

FIG. **7***d* provides a table with the dimensions that a synthetic aperture must obtain in two dimensions to provide 10 cm resolution, with respect to two dimensions, at different frequencies and ranges;

FIG. **8** depicts different possible regions of interest within a snowpack to which electromagnetic energy is transmitted in accordance with the present invention;

FIG. **9** depicts a typical snowpack of varying depths that reposes in mountainous terrain;

FIG. **10***a* depicts a boundary reflection at the boundary between the ground and the snowpack for an incident wave arriving at a shallow grazing angle;

FIG. **10***b* depicts the volume scattering that occurs within a snowpack;

FIG. **11** depicts a cluster of ice grains **1102** and a water content distribution typical of a layer common to alpine snowpacks;

FIG. **12** depicts a collection of faceted ice grains and crystals;

FIG. **13** depicts a characterization of reflection values for an imagined ice grain of a particular size and shape as a function of wavelength;

FIG. **14** is a flow chart illustrating one embodiment of a method to remotely acquire information from volumes in a snowpack in accordance with the present invention;

FIG. **15** is a flow chart illustrating one embodiment of a method to remotely acquire information from volumes in a snowpack by employing frequency modulation and creating a synthetic aperture in accordance with the present invention;

FIG. **16** is a flow chart illustrating one embodiment of a method to remotely acquire information from volumes in a snowpack by maximizing the ratio of returns from within the snowpack to returns from the ground underneath in accordance with the present invention; and

FIG. **17** is a flow chart illustrating one embodiment of a method to remotely acquire and analyze information from volumes in a snowpack in accordance with the present invention.

DETAILED DESCRIPTION

The components of the present invention, as described with reference to the Figures herein, could be arranged and designed in a wide variety of different configurations. Thus, the detailed description of the embodiments of the invention that follows is not intended to limit the scope of the invention, but rather to provide certain examples of presently contemplated embodiments in accordance with the invention. The presently described embodiments will be best understood by reference to the drawings.

As will be appreciated by one skilled in the art, the present invention may be embodied as an apparatus, system, of method. Elements of the present invention may combine hardware and software components (including firmware, resident software, micro-code, etc.) in their embodiment that may all generally be referred to herein as a "module." A module may be realized on a combination of one or more computer-usable or computer-readable medium(s). Without limitation, the computer-usable or computer-readable medium may be an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium.

The module may also embody computer program code for carrying out operations. The code may be written in any combination of one or more programming languages, including an object-oriented programming language such as Java, Smalltalk, C++, or the like, and conventional procedural programming languages, such as the "C" programming language, or similar programming languages.

The present invention is described below with reference to flowchart illustrations and/or block diagrams of a method, apparatus, and systems according to embodiments of the invention. Each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, may be implemented by computer program instructions or code. These computer program instructions may be implemented on a processor or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create infrastructure for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

FIG. **4** depicts aspects of one embodiment **400** in accordance with the present invention. In the illustrated embodiment **400**, an antenna system **402** and supporting infrastructure **404** are depicted transmitting electromagnetic energy toward a snowpack **406** that reposes on a remotely disposed mountain. The transmitted electromagnetic energy illuminates a region of interest **408** within the alpine snowpack **406**. Electromagnetic reflections from the snowpack are received by the antenna system **402** and supporting infrastructure **404**. For the embodiment depicted in FIG. **4**, reflections come primarily from the region of interest **408**. The supporting infrastructure **404** includes a memory device (not shown) for storing data about received reflections. The supporting infrastructure **404** may include memory and a processor (not shown) necessary to process the data to determine reflection values for different volumes within said snowpack. The processing of data will be discussed in greater detail below.

Although the antenna system **402** depicted in FIG. **4** is a horn antenna, those of ordinary skill in the art will recognize that multiple horn antennas, one or more dish antennas, an antenna array, a patch antenna, or any other device for coupling electromagnetic energy into the air for transmission may also be employed. The antenna system **402** causes plane waves of electromagnetic energy to propagate along a first axis **410** that can be, but does not need to be, referred to as the range axis. As discussed with relation to FIG. **6**, the location from which reflections originate with respect to the range axis may be determined by modulating the frequency of the transmitted electromagnetic energy, as has been done in the prior art to probe snowpacks for information at close range.

However, as depicted in FIG. **4**, the embodiment **400** seeks to probe a snowpack remotely at a distance that for all but impracticality large antenna apertures result in unacceptable beam widths. The remote distance is crucial because it preserves the benefits of radar to acquire quantitative data from large areas relatively quickly, efficiently, and safely. Information is acquired over large areas because the regions of interest **408** comprise integral wholes over large area.

To successfully probe a snowpack for information remotely, the ability to discriminate and resolve reflections from within the beam width of an antenna with respect to additional axes is required. Since the contours of a snowpack and/or avalanche debris, strata within the snowpack, or a victim or object of interest within the snowpack may be located in three dimensional space, the location from which reflections of interest originate needs to be determinable in three dimensional space.

One way in which reflections may be discriminated and resolved along an axis is by creating a synthetic aperture along that axis. To discriminate and resolve locations from which reflections originate in three dimensional space, according to one embodiment, the antenna system **402** is translated along a second axis **412** that is substantially orthogonal to the first axis **410** and along a third axis **414** that is substantially orthogonal to the first axis **410** and to the second axis **412**. In some embodiments, the antenna system **402** may also follow curved and/or diagonal paths to occupy different positions with respect to the second axis **412** and the third axis **414**. In certain embodiments, the antenna system **402** may even also occupy different positions with respect to the first axis **410** while occupying different positions with respect to the second axis **412** and the third axis **414**.

By translating the antenna system **402** along the second axis **412** and along the third axis **414** a synthetic aperture can be generated along the second axis **412** and along the third axis **414** that can be used to discriminate and resolve locations from which reflections originate with respect to the second axis **412** and the third axis **414**. The second axis **412** and the third axis **414** may be referred to, but need not be referred to, as the azimuth axis and the elevation axis respectively.

Failure to acquire information from the integral whole that is the region of interest **408** could result in a failure to answer the question. For example, the avalanche victim may not be found. The region of interest **408** comprises a substantially indivisible region of a snowpack that should be probed to garner sufficient information to address questions about a snowpack or what resides therein. Examples of such questions may include, without limitation, questions about the location of an avalanche victim (whether for a rescue or for a recovery), the extent of the region occupied by avalanche debris and/or and the path of an avalanche, the risk of avalanche formation presented by certain weaknesses in the snowpack in a region from within which avalanche formation occurs for a particular avalanche track, the snow/water equivalence of the snowpack for purposes of measuring a watershed, and snow depths across a ski slope.

The region of interest **408** in FIG. **4** exemplifies regions of interest that should be scanned to acquire information necessary to address several questions presented in the preceding paragraph. For example, the region of interest may circumscribe the region that could be occupied by avalanche debris and flow paths from the chutes found in the band of rocks **416** near the summit of the mountain. The region of interest **408** may also circumscribe the region in which an avalanche victim, from an avalanche forming in the chutes in the rock band **416**, may be buried. Alternatively, the region of interest **408** may circumscribe a bowl where avalanches form for an avalanche track (not shown) below the region of interest **408**. Since an avalanche may be triggered from any location in the region of interest **408** where the snowpack **406** is the weakest, the entire region of interest **408** needs to be scanned. Another possibility for the region of interest **408** is that it may circumscribe a bowl that makes a significant contribution to a watershed. Additional possibilities are contemplated.

As appreciated, the region of interest **408** in FIG. **4** spans a large area. To make localized, physical measurements, or close-range measurements with a radar system whose range-axis orientation relative to the snowpack must be maintained would either place large demands on time and resources, or impractical demands. The embodiment **400** in FIG. **4** collects information over the large area of the region of interest **408** from a single remote location, reducing demands on time, resources, and avoiding safety issues that could arise from taking measurements in avalanche terrain. In certain embodiments, the region of interest **408** may be scanned from more than one remote location. However, the remoteness of these multiple locations, from which the orientation of the range axis need not follow the contour of the snowpack, allows the scan to be performed in a manageable amount of time with manageable demands placed on resources.

The remote location from which the antenna system **402** and supporting infrastructure **404** illuminate the region of interest **408** is selected to insure that the waves of electromagnetic energy incident upon the region of interest arrive a shallow grazing angle, or shallow grazing angles. For the purposes of the present invention, a grazing angle of 45° or less is considered to be a shallow grazing angle.

The ability to discriminate and resolve locations from which reflections originate in three dimensions, as discussed with respect to FIG. **4**, creates the possibility to image the volume of a snowpack in three dimensions. FIG. **5** depicts a collection of empty voxels **500**—a voxel is the three-dimensional analog to a pixel—that describes the structure of a three-dimensional, volume image. In certain embodiments, the reflection values for different volumes in the snowpack are aggregated to form such three-dimensional volume images for purposes of analysis. Regardless of the embodiment, however, the structure of the three dimensional image in FIG. **5** is instructive insofar as the distinct volumes in the image correspond to distinct volumes in the snowpack. Limitations and possibilities that exist for the distinct volumes in the image correspond to limitations and possibilities for acquiring information about distinct volumes in a snowpack.

In FIG. **5**, the upper, left-most voxel **502**, or unit of distinct volume, serves as a representative voxel. The voxel **502**, as with all other voxels in the collection of voxels **500**, is assigned a reflection value by the processing algorithm to be discussed below. The value may be real or complex, depending on the embodiment. Real values represent the magnitude of returns from reflections within the volume of the voxel **502**, with the imaginary component in embodiments with complex values being reserved for phase information.

Each voxel **502** is defined by a range length **504**, an azimuth length **506**, and an elevation length **508**. The axes along which the range length **504**, azimuth length **506**, and elevation length **508** are defined correspond to the first axis **410**, second axis **412**, and third axis **414** discussed above with respect to FIG. **4**. Depending on the embodiment, the range length **504**, azimuth length **506**, and elevation length **508** may be the same lengths, or may differ in length from one another. The lengths may correspond to the resolution limit along a particular axis, as defined below in the discussions of FIG. **6** and FIG. **7**; the lengths may be larger than the resolution units; or, they may be smaller, where interpolation is involved.

Every voxel **502** in the collection of empty voxels **500** corresponds to a specific physical volume within the snowpack, where the dimensions of the physical volume correspond to the range length **504**, azimuth length **506**, and elevation length **508** of the corresponding voxel. The collection of voxels **500**, therefore, provides information from within the volume of the snowpack.

In several important embodiments, the a collection of voxels **500** is not aggregated to form a three-dimensional, volume image, but rather, a reflection value for a region of space that corresponds to an actual physical volume and would correspond to a voxel **502** is considered independently, or in conjunction with additional reflection values, for analysis, as discussed in more detail below with respect to FIG. **17**.

FIG. **6***a* provides a schematic depiction of a signal conditioning module **600**. In certain embodiments, the signal conditioning module **600** is part of the supporting infrastructure **404** depicted in FIG. **4** that makes the remote transmission of electromagnetic energy to a snowpack possible in such a way that reflection values can be determined for different volumes within the snowpack. The signal conditioning module **600** in FIG. **6***a* is only representative of certain embodiments—not all embodiments—and is provided only to teach one embodiment of the present invention, without limiting alternative embodiments of the invention to elements of the signal conditioning module **600** in FIG. **6***a*.

In FIG. **6***a*, the signal conditioning module **600** comprises a parameter module **610**, a frequency modulation module **620**, a mixing module **630**, an amplification module **640**, a dechirp module **650**, and a storage module **660**. Alternative embodiments may have additional, fewer, or different elements. The parameter module **610** provides information about the parameters necessary to generate a transmit signal capable of producing reflections from which reflection values for different volumes in a snowpack can be calculated.

Such parameters may include a start frequency for a linear chirp, a stop frequency, and/or a bandwidth. Depending on the embodiment, multiple start and stop frequencies may be included to acquire response information from multiple portions of the electromagnetic spectrum. Although the use of linear frequency modulation greatly reduces the complexity of processing, the frequency modulation need not be linear. In certain embodiments, the signal conditioning module **600** may produce a transmit signal that is a frequency modulated continuous wave. In alternative embodiments, the signal conditioning module **600** may produce a transmit signal that is pulsed. In such embodiments, the parameter module **610** includes information necessary to control the pulse sequence, such as a pulse repetition frequency (PRF) and a ramp rate. In certain embodiments, the parameter module **610** may be a field programmable gate array, but several other possibilities may also be employed, such as a custom chip. The parameter module **610** may be communicatively coupled with the frequency modulation module **620**.

The frequency modulation module **620** generates the range of frequencies necessary to discriminate and resolve reflections with respect to the first axis **410** discussed above with respect to FIG. **4**. The bandwidth over which the transmit frequency is modulated determines the degree to which reflections may be resolved with respect to the first axis **410**, according to Equation 2, as provided in FIG. **6***b*, where resolution 'r' is equal to the speed of light 'c' divided by twice the bandwidth 'B.' According to Equation 2, a bandwidth of 1.5 GHz allows 10 cm resolution, a value sufficiently fine to resolve many of the layers of weakness important to avalanche formation within a snowpack. In other embodiments, coarser resolutions with smaller bandwidths are sufficient. In certain embodiments, larger bandwidths with finer resolution may be employed.

The frequency modulation module **620** may include a voltage controlled oscillator capable of creating an analogue transmit signal that spans one or more predetermined bandwidths. The frequency module may also include a Stable Local Oscillator (STALO) and one or more Direct Digital Synthesizer (DDS) chips to synthesize discrete frequency steps to span one or more predetermined bandwidths from the stable frequency provided by the STALO. In embodiments that employ discrete frequencies, the demands of the Nyquist theorem must be satisfied to prevent aliasing. Several alternative arrangements of hardware and software can also be employed to create the requisite frequencies.

A snowpack, its constitutive layers, snow types, grain and crystal sizes and shapes, water contents and distributions, densities, objects buried therein (such as an avalanche victim) respond differently to different wavelengths and portions of the electromagnetic spectrum. In some embodiments, it is desirable to acquire information about how the snowpack responds to more than one portion of the electromagnetic spectrum. Therefore, in some embodiments, the frequency modulation module **620** creates frequencies that span multiple bandwidths from different portions of the electromagnetic spectrum. In such embodiments, enough frequencies are produced for each portion of interest in the electromagnetic spectrum to allow for discrimination and resolution of reflections with respect to the first axis **410** without recourse to the frequencies generated for other portions of interest in the electromagnetic spectrum. As a result, for example, information about the response of a snowpack to different spans of frequencies/wavelengths in C-band, X-band, and/or any of the K-bands, or different portions of these bands, can be acquired and compared. Information from frequency bands not listed may also be acquired.

In certain, but not necessarily all embodiments, the signal created by the frequency modulation module **620** becomes the input to a mixing module **630**. The mixing module **630** mixes an input signal with a carrier frequency provided by the mixing module. The input signal may be mixed with the carrier frequency directly or through intermediate stages. The source for the carrier frequency may come from a variety of oscillators or may itself be the product of mixing. Several configurations of hardware and software are possible. The carrier frequency may belong to any number of bandwidths from the radio and microwave spectrums.

Carrier frequencies in C-band are useful for penetrating very dense snow, such as that is often found in avalanche debris. Frequencies from higher bands, such as those in X-band, Ku-band, K-band, and Ka-band have potential for providing more refined information about properties of snow stratigraphy. The invention may also be practiced with carrier frequencies outside of these enumerated bands.

The output of the mixing module may, in certain embodiments, be amplified by the amplification module **640**. In certain embodiments, amplification may take place elsewhere. The amplification module **640** gives the transmit signal sufficient power to transmit remotely to a snowpack and to produce the reflections used in processing to create reflection values for different volumes in the snowpack. Since the signal conditioning module **600** modulates the frequency of the transmit signal it generates, the power necessary to create reflections can be spread over large durations of time without compromising range resolution. Therefore, the power requirements of the signal conditioning module **600** may be measured in Watts to fractions of a Watt, allowing the signal conditioning module to be small, light-weight, and portable within the mountainous terrain where avalanches occur. In certain embodiments, the amplification module **640** may have stages and/or may be adjustable.

In certain embodiments, the signal conditioning module **600** includes a dechirp module **650** configured to receive reflections from a snowpack. The dechirp module **650** includes a variety of mixers, filters, and other hardware necessary to mix the transmit signal with a signal comprised of reflections from a snowpack. After mixing, a sum signal and a difference signal result. The sum signal has a frequency equal to the sum of the frequency of the transmit signal and the frequency of the receive signal. The difference signal has a frequency equal to the difference of the frequency of the transmit signal and the frequency of the receive signal. The sum signal is filtered by a low pass filter. The frequency of the difference signal can be correlated with the distance with respect to the first axis **410** from which the reflections responsible for the difference signal originate by referencing the ramp rate of the linear chirp of the transmit signal. Innumerable variations on this concept are possible.

The dechirp module **650** may be communicatively coupled with a storage module **660**. The storage module **660** records data about received reflections, whether processed in a manner akin to that described with respect to the dechirp module **650** or not. In some embodiments, reflections from several transmission pulses are stored together. Reflections from multiple pulses are aggregated to improve Signal to Noise Ratio (SNR). The data is recorded in a manner so that it can be processed to create reflection values for different volumes in the snowpack. For example, the data may be indexed by frequency and the position of an antenna system **402** similar to the one depicted in FIG. **4**. The position information indicates the position of the antenna system **402** from which transmissions are made and reflections received. The data may be saved on a compact flash card, flash drive, hard drive, writable disc, magnetic tape, or any other medium capable of recording data.

Several alternative embodiments may create the requisite transmit signal according to different configurations. For example, in one creative embodiment, the transmit signal may be generated by a network analyzer that has been modified to serve as a radar. In many embodiments, commercially available systems can be employed as-is, or with modification, to produce the requisite transmit signal.

Frequency modulation in the transmit signal can be used to determine the location, with respect to the first axis **410** depicted in FIG. **4**, from which reflections originate. To create data from which reflection values for different volumes in a snowpack may be generated, the location from which reflections originate with respect to a second axis **412** and a third axis **414** must also be determinable. Data from which such determinations can be made, as discussed, can be generated by creating a synthetic aperture extending along the second axis **412** (azimuth axis) and the third axis **414** (elevation axis) depicted in FIG. **4**.

FIG. **7***a* depicts a synthetic aperture **700** generated from an antenna system **702** that is translated over and area with respect to an azimuth axis **704** and an elevation axis **706**. In the particular embodiment depicted in FIG. **7***a*, the antenna system **702** is translated over time along a path **708** within a plane depicted by the surface of the page. As the antenna system **702** traverses the path **708**, the antenna system **702** occupies a number of positions **711-759** that create a grid of rows along the azimuth axis **704** and columns along the elevation axis **706**.

The path **708** traversed to create the synthetic aperture **700** in FIG. **7***a* begins in the upper, left corner, follows the azimuth axis **704** from position **711** to position **717** before dropping down with respect to the elevation axis **706** to return to the left side at position **724**. The path **708** continues in a serpentine manner until position **759** is achieved in the bottom right corner. Innumerable different possibilities for paths **708** exist. The path **708** could begin in any corner and could start by moving up, down, left, or right.

The path need not be rectilinear, but may include diagonal and/or curved elements. The path may even have circular components as it fills out different positions with respect to the azimuth axis **704** and the elevation axis **706**. As discussed above with respect to FIG. **4**, in some embodiments, the antenna system **702** may also follow curved and/or diagonal paths (not shown) to occupy different positions with respect to the azimuth axis **704** and the elevation axis **706**. In certain embodiments, the antenna system **702** may even also occupy different positions with respect to the direction of propagation while occupying different positions with respect to the azimuth axis **704** and the elevation axis **706**.

In some embodiments, the antenna system **702** transmits and receives from each of the positions **711-759**. In certain embodiments, the antenna system **702** continually transmits and receives, but data is only recorded at the positions **711-759**. In other embodiments, the antenna system **702** continually transmits and receives and data is continuously recorded

The processing algorithm uses the progression in phase that accumulates between different positions **711-759** to determine locations with respect to the axes of the synthetic aperture **700**. Therefore, to preserve the necessary phase information, the positions **711-759** from which transmissions are made and from which reflections are received must be known accurately and indexed with the data to preserve phase information. As a reference, position information is sufficiently accurate where positions **711-759** are known relative to a first position **711** to within a tenth of the wavelength of the carrier frequency of the transmit signal. However, this standard may be adjusted either up or down while still practicing the invention.

The resolution with which reflections may be resolved with respect to the azimuth axis **704** and the elevation axis **706** are a function of the distances between the furthest most positions occupied by the antenna system **702** along these axes. For a particular axis **704**, **706**, the resolution is defined by Equation 3, as provided in FIG. **7***b*, where 'R' denotes range, 'λ' denotes wavelength, and 'D' represents the distance traversed along the axis for which range is defined.

For reasons discussed in the prior art on synthetic apertures, the dimension of the aperture of the antenna system **702** place an upper limit on resolution with respect to the axis of the synthetic aperture parallel to the dimension of the aperture. Equation 4, as provided in FIG. **7***c*, defines this upper limit in terms of a length, 'l,' describing the dimension of the antenna system **702** aperture. Equation 3 can be used to calculate the dimensions that would be required of a synthetic aperture **700** for a desired resolution. Table 1, as provided in FIG. **7***d*, gives a dimension that would be required of the synthetic aperture **700** with respect two orthogonal axes to achieve 10 cm resolution, with respect to these axes, at various ranges and frequencies. The invention can be practiced at different resolutions, different frequencies, and different ranges. The large dimensions indicated in Table 1 can by drastically reduced by practicing the invention with multiple remote scans.

Additionally, to prevent aliasing, the positions **711-759** need to be spaced sufficiently close together along each axis **704**, **706** of the synthetic aperture **700** to satisfy the Nyquist requirement. As a reference, a spacing of a quarter of the aperture dimension of the antenna system **702** is sufficient. However, the invention may be practiced with different standards.

The supporting infrastructure necessary to create a synthetic aperture of sufficient dimensions can take a variety of different forms. The infrastructure (not shown) may comprise a ground based system of step motors, optical encoders, lead screws, and tracks arrayed on a frame. In embodiments that make use of a frame, the frame may take a variety of shapes, including an "inverted T" shape, where the central post moves from side to side as is common with near field scanners. The frame may have a rectangular shape, or any other shape necessary to provide support for the tracks. The infrastructure may include belts and/or chains, servo motors, pulleys, or any other device that can be used to translate the antenna system **702** and provide accurate information about antenna system **702** positions **711-759**. The infrastructure may translate multiple antenna systems **702** at the same time, each transmitting and receiving reflections at the same time, or at different times. Alternatively, the infrastructure may comprise a system of cables. To provide an example of the range of forms the infrastructure used to create the synthetic aperture **700** can take, the infrastructure may comprise a group of robotic helicopters coordinated and oriented by laser triangulation. The range of possibilities is large.

In FIG. **7***a*, the synthetic aperture **700** resides in a plane and the antenna system **702** always faces so that the direction of propagation is out of the page for all of positions **711-759**. In alternative embodiments, however, the antenna system **702** may be rotated in two dimensions to focus on a target location from individual positions **711-759**, as would be done in one dimension in a method for synthetic aperture formation commonly referred to as the steered spotlight method. Additionally, in certain embodiments, the positions **711-759** of the antenna system may occupy locations in a surface curved in two dimensions, as opposed to a plane, as would be done in one dimension in a method for synthetic aperture formation commonly referred to as the geometric spotlight method.

To practice the invention, the synthetic aperture **700** depicted in FIG. **7** is deployed remotely. Remote deployment allows the synthetic aperture **700** to transmit to a large area of a snowpack similar to the region of interest **408** depicted in FIG. **4**. As discussed in the background section, information from within a snowpack must be acquired over a large area to be useful in answering questions that arise with a snowpack. Such questions may include, without limitation: the potential for avalanche formation within a region where avalanches form; the location of an avalanche victim for purposes of recovery or rescue; the course of an avalanche flow pattern and the extent of an area occupied by avalanche debris to determine where property, trails, ski slopes, and activities can safely be located, or the location of an avalanche victim; the snow/water equivalence of a region important to a watershed; and the depth of snow over ski slope. Additional regions of interest are contemplated.

Data needs to be collected from a snowpack in a way that reflection values for three dimensional volumes can be calculated. Embodiments discussed provide examples of how the transmit signal can be modulated in frequency and modulated in space to form a synthetic aperture that allows data to be collected in this way. At this point, a discussion is provided of the ways in which data is processed to render the required reflection values for different snow volumes.

The different frequencies and angles from different positions in the synthetic aperture produce different magnitudes and phases for the backscatter from the same volume of space. Without these changes in frequency and angle, only a single magnitude and phase would be present. These differing magnitudes and phases are responsible for the data that is captured by the radar. In certain embodiments, the data is indexed by antenna position and transmit frequency. Processing this data involves taking the different magnitude and phase information and reconstructing the volumes from which different reflections originate.

The reflections from volumes are recorded in the data for each antenna position. Moving from data to reflection values for those volumes requires the gathering up of energy corresponding to the various volumes as received at various antenna positions and determining the location of those volumes from that energy. Various algorithms, tailored to different deployment modes for the antenna positions in the synthetic aperture, can achieve this goal. All of these algorithms must know where to look in the data for the energy associated with each volume.

The Point Spread Response (PSR) for a particular antenna, antenna deployment mode and signal processing scheme, provides the requisite information about where in the data energy for a given location can be found. A wide variety of algorithms make use of the PSR for a particular antenna deployment to determine reflection values for different volumes in a snowpack. The most general algorithms include a simple matched filter and the backprojection algorithm. The backprojection algorithm is used widely in synthetic aperture radar signal processing because of its improved efficiency. Those of ordinary skill in the art will recognize additional algorithms and variations on those mentioned that are best suited to particular embodiments.

Where the backprojection algorithm is employed, and with different algorithms and variations, the data from a signal conditioning module **600** with a dechirp module **650** similar to the one depicted in FIG. **6***a* is first range compressed. Often range compression is performed by executing a Fast Fourier Transform (FFT) on frequency and position indexed data. Range compression enhances the data by improving the range-resolution of the data.

The processing algorithms may be implemented in a wide variety of languages ranging from C to MATLAB scripts. The processing can take place on a wide variety of computing systems with memory and a processor. In many embodiments, a common laptop will suffice.

FIG. **8** depicts features in mountainous terrain **800** typical of the terrain in which an alpine snowpack resides. FIG. **8** can be used to further discuss potential regions of interest. In FIG. **8**, avalanche debris **802** strewn across an avalanche flow path **804** is depicted underneath the bowl/slope **806** where the avalanche formed.

In certain embodiments, the region of interest **408**, as depicted in FIG. **4**, is a bowl/slope **806** similar to the one depicted in FIG. **8**, where avalanche formation occurs. Avalanche formation starts where the cohesion within or between the layers **308**-**316**, similar to those depicted in FIG. **3**, breaks down. As discussed in more detail below with respect to FIG. **11** and FIG. **12**, certain commonly occurring layers in a snowpack, such as, without limitation, wind deposited snow, faceted snow, buried surface hoar, depth hoar, and crusts, are known for their weakness. These layers make up the stratigraphy of the snowpack, which is notorious for varying widely over distances as small as a meter.

The stratigraphy of a snowpack varies widely due to changes in aspect, elevation, wind pattern, terrain, and a variety of additional factors. Since avalanche formation occurs at the weakest point within the stratigraphy of the snowpack residing in the bowl/slope **806**, improved avalanche prediction requires the extraction of information about snowpack stratigraphy across the entire bowl/slope **806**.

In embodiments that acquire information about the potential of avalanche formation, information is sought about snowpack stratigraphy, layers of weakness, and the properties of such layers, as discussed in more detail below. To acquire this information, resolution along the range length **504**, azimuth length **506**, and elevation length **508** depicted in FIG. **5** should be fine. Considering the thicknesses of important layers of interest and practical limitations, resolutions around **10** cm are suggested, but finer and courser resolutions easily fall within the ambit of the invention.

As discussed in more detail with respect to FIG. **13**, frequencies in the X-, Ku-, K, and Ka-bands have the most potential for acquiring information about stratigraphy. At the upper frequencies from the K-bands and at higher frequencies the potential for high attenuations in the transmit signal become a factor. However, higher and lower frequency bands may also be used. In important embodiments, frequencies from different bands and/or form different portions of a particular band may be used to acquire information about the different responses in the snowpack to wavelengths from different portions of the electromagnetic spectrum.

In an important class of embodiments pertaining to the present invention, an entire region of interest that can include an avalanche path **804** and avalanche debris **802** must be scanned to determine the location of an avalanche victim **808**. The avalanche victim **808** may be found in any location within the avalanche path **804**—often a large area. Reflection values are analyzed for indications of the presence of the avalanche victim **808**.

The location of the victim **808** may be determined by the unique electromagnetic properties of the victim's body. These unique electromagnetic properties result in marked differences in reflection values at the location of the victim **808**. This is especially true in a rescue operation where the body is still warm and has a high liquid content. Different reflection values may be the result of volume scattering caused by the victim's unique electromagnetic properties or by boundary reflections between the snow and materials that make up the victim's body.

Additional embodiments transmit to a region of interest to determine the flow path **804** and the extent of avalanche debris **802**. Since avalanches commonly reoccur in common locations, this information is important for determining where property may be developed and where activities can be engaged in safely. Sometimes this information can help to find an avalanche victim **808**.

To determine the flow path **804** and the outer boundary **810** that an avalanche could reach with sufficient probability in the future, a region where an avalanche flow path **804** and avalanche debris **802** can be found must be scanned with regularity to account for multiple flows. Often an avalanche flow path **804** and avalanche debris **802** can be buried in a snowpack, even by the storm that triggers them. Avalanche debris **802** can be distinguished from the snowpack in which it is buried by the variation in density from the surrounding snowpack. In such embodiments, where densities are high, the density of avalanche debris **802** suggests the use of C-band frequencies, but additional frequency bands are also within the ambit of the invention.

In certain embodiments, the bowl/slope **806** comprises a region of interest for purposes of determining the snow/water equivalence of the snowpack, as the bowl/slope **806** may be an important contributor to a watershed. In such embodiments, the snow/water equivalence may simply be estimated from the volume of the snowpack, as discussed in more detail with respect to FIG. **9**. In more sophisticated embodiments, reflection values may be analyzed to determine snow properties such as, without limitation, density and water content, within different portions of the snowpack, where higher densities and water contents correlate with higher reflection values.

In a similar embodiment, the depth of the snow may be assessed across the bowl/slope **806** to determine if the bowl/slope **806** is in condition for helicopter skiing, or if, at a ski resort, the bowl/slope **806** requires additional man-made snow. As an example of a previously un-suggested region of interest, in certain embodiments, several slopes similar to the bowl/slope **806** in FIG. **8** could be assessed for their snow density to determine the slope with the lightest-density, "powder" snow for purposes of determining where to deposit helicopter-skiing clients, or which slopes would most desirably be accessed by skiers of all types.

FIG. **9** depicts a snowpack **900** of varying depths that reposes in mountainous terrain **902**. In embodiments, such as those that seek to determine snow/water equivalence, changes in snow depth, such as those shown in FIG. **9** are important. FIG. **9** is segmented into three distinct regions, a first region **904** that contains wind-swept snow **906** on the windward side of a wind-swept slope, a second region **908** that includes a cornice **910**, a third region **912** that includes snow accumulations **914** in a bowl, and a forth region **916** that includes unaltered snow depths **918**. An assumption that the snowpack **900** has a depth equal to that of the unaffected snow **918** in the fourth region **916**, evenly distributed across the mountainous terrain **902**, would have disastrous consequences when determining the volume of the snowpack **900** or a depth at a particular location.

As suggested from FIG. **9**, a region of interest can cover a large area. To acquire information about these large areas efficiently, the antenna system **402** and supporting infrastructure **404** are disposed remotely from the area of interest **408**, as depicted in FIG. **4**. As also discussed with respect to FIG. **4**, the antenna system **402** is oriented so that electromagnetic energy incident upon the region of interest **408** arrives at shallow grazing angles. Grazing angles for incident wavelengths that are sufficiently shallow maximize returns from volume scattering in volumes of said snowpack compared to reflections from the boundary between the snowpack and the ground underneath. The way in which shallow grazing angles, where the term "shallow" refers to angles at or less than 45°, achieve these goals can be explained with reference to FIG. **10***a* and FIG. **10***b*.

FIG. **10***a* depicts a boundary reflection **1000** at the boundary **1002** between the ground **1004** and the snowpack **1006** for an incident wave **1008** arriving at a shallow grazing angle **1010**. According to Snell's law, a portion of the incident wave **1008** is reflected away in a reflected wave **1012** at a reflection angle **1014**. Also in accordance with Snell's law, the reflection angle **1014** and the shallow grazing angle **1010** are equal.

The electromagnetic energy transmitted to the ground boundary **1002** in FIG. **10***a* is reflected away in the reflected wave **1012**. The boundary reflection **1000** at the ground boundary **1002** does not produce reflections back to an antenna system **402** similar to that depicted in FIG. **4**. Therefore, returns from the ground are minimized together with their contributions to reflection values generated from processing the reflection data. Minimizing these contributions is highly desirable so that returns from the snowpack **1006** do not become confused with returns from the ground **1004**.

FIG. **10***b* depicts the volume scattering **1016** that occurs within a volume of snow **1018**. In FIG. **10***b*, the trajectory of three transmitted waves **1020**, **1022**, **1024** as they ricochet off of ice grains (represented by the ice grain **1026** depicted in the expanded view) are charted within a volume of snow **1018**. Eventually, these transmitted waves **1020**, **1022**, **1024** become reoriented back as reflections **1028**, **1030**, **1032**. The reflections **1028**, **1030**, **1032** are oriented in their trajectories so that they are substantially parallel to the trajectories of the transmitted waves **1020**, **1022**, **1024**. The reflections **1028**, **1030**, **1032** return to an antenna system **402** similar to the one depicted in FIG. **4**.

Obviously not all the electromagnetic energy transmitted to the snow volume **1018** becomes reflected back to its source. Admittedly, FIG. **10***b* is highly idealized. Nevertheless, the ricocheting that takes place in volume scattering **1016** is much more likely to produce reflections the return to the source of transmission. Consequently, reflections **1028**, **1030**, **1032** from volume scattering **1016** predominate among the reflections from which reflection values are calculated during processing. The predominance of returns from volume scattering **1016** allows information from within a snowpack **1006** to be acquired without becoming confused with reflections from the ground **1004** underneath. Experimentation shows that grazing angles below 25° are sufficiently shallow for frequencies in C-band. Nevertheless the invention may be practiced with smaller or larger grazing angles in C-band and other frequency bands. As stated, for purposes of the present invention shallow grazing angles shall mean angles at 45° or less.

The volume scattering **1016** described in FIG. **10***b* relies on ice grains **1026** and water content from a volume of snow **1018**. As indicated by the presence of different layers **308**-**316** in a snowpack **304**, as depicted in FIG. **3**, a snowpack comprises ice grains and crystals of different sizes shapes and possibly different water-content distributions at different layers in the snowpack. Additionally, different layers may represent different clustering behaviors among ice grains. These differing shapes, sizes, clustering behaviors, and possibly differing water distributions result in different reflection values for different volumes corresponding to different layers.

FIG. **11** depicts a cluster **1100** of ice grains **1102** and a water content distribution typical of a layer common to alpine snowpacks. As appreciated, the ice grains **1102** are rounded. Such rounded grains are commonly associated with layers of strength in an alpine snowpack. The cluster includes a large ice grain **1102***a* and a small ice grain **1102***e* for purposes of discussion. Typically, within a snowpack, ice grains **1102** of the same or similar sizes are found in the same layer. Different ice grain **1102** sizes contribute to different reflection values for different wavelengths.

Within a snowpack, ice grains **1102** grow in size as water vapor present in the snowpack freezes to ice grains **1102**. Commonly, rounded grains **1102** worn down from snowflake fragments maintain their rounded shape as they grow from a small ice grain **1102***e* to a large ice grain **1102***a*. However, when a strong temperature gradient is present in the snowpack, the physics of the scenario dictate that the ice grains **1102** take on a sharp angular structure as discussed with reference to FIG. **12**.

Snow completely devoid of water content is known as a dry. Initially, as water begins to manifest in the snow, it congregates at points of connection between ice grains in Pendular rings **1104**, which receive their name from the Pendular regime in which such rings form, where water content is between about 0% and 8%. For higher water contents, the water inclusions start to flow together, being found wherever ice grains are not present, as is typical of the Funicular regime. The water content and its distribution also contribute to reflection values for different wavelengths.

FIG. **12** depicts a collection **1200** of faceted ice grains and crystals. The collection includes a faceted grain **1202**, with its angular shape, as it may grow in a snowpack in the presence of a strong temperature gradient. Layers of faceted snow are known for being cohesively very weak and are the layers in which many avalanches originate. Since they must grow in the snowpack, faceted grains **1202** are typically larger than other ice grains in a snowpack.

The structure of the faceted grain is characterized by the planner region **1204** depicted, as contrasted to the rounded shape of the ice grains **1102** in FIG. **11**. The planner regions **1204** and angular shape, in contrast to the rounded shapes of the round ice grains **1102**, contribute to different reflection values for layers comprised of these different types of ice grains across different wavelengths. Additionally, the shape of faceted grains **1202** can alter the distribution of water content, which in turn would affect reflection values. The angular and pyramidal structure of depth hoar **1206** also presents characteristic shapes that contribute to reflection values. Depth hoar **1206**, which is also associated with weak layers forms at the base of the snowpack, creating the potential for large avalanches.

Also among the collection **1200** of faceted forms is a depiction of the hexagonal crystalline shapes that grow on the surface of a snowpack in the presence of temperature gradients and are known as surface hoar **1208**. These plate-like structures, also characterized with weakness when they become buried, can grow to become very large. Surface hoar **1208** is often measured in centimeters, as opposed to the millimeters and fractions of a millimeter used to measure other types of ices grains. These large sizes open the possibility for increased reflection values due to the surface roughness of the surface hoar **1208** when the wavelengths involved are sufficiently small.

Additional types of snow layers have characteristics that should represent themselves in reflection values. For example, the smooth surfaces of crusts can cause specular reflections away from a radar system at shallow grazing angles. Additionally, the high density of wind deposited snow should increase reflection values. Wind-deposited snow is infamous for increasing the load on a snowpack to the fracture point. It is also infamous for being undetected in its rapid accumulations during inclement weather. The ability of radar to scan large areas quickly provides an ideal solution for detecting and assessing this hazard.

The volume scattering **1016** discussed with respect to FIG. **10***b* caused by various ice grains **1026**, as explored in FIG. **11** and FIG. **12**, can be characterized by size, shape and the wavelengths involved, among other things. Two major divisions to characterize reflection behavior based on the ratio of the circumference of the ice grains involved to the size of the wavelengths reflected. These major divisions comprise the Rayleigh region and the Mie region.

FIG. **13** depicts a characterization **1300** of reflection values for an imagined ice grain of a particular size and shape (not shown). The characterization includes a plot **1302** of reflection values **1304** from the imagined ice grain as a function of the ratio **1306** of the circumference of the ice grain to the transmitted wavelength. The reflection values axis **1304** and the ratio axis **1306** are plotted on a logarithmic scale. Place holders are used for the magnitudes on the reflection value axis **1304** as magnitude is based on a large number of variables, including the number of transmit pulses that may be summed during processing.

The plot **1302** is characterized by two distinct regions, the Rayleigh region **1308** and the Mie region **1310**. The Rayleigh region **1308** is characterized by an exponential increase in reflection values **1304** as the ratio **1306** of circumference to wavelength increases. Therefore, in the Rayleigh region **1308**, information about the size of the ice grain can be obtained by comparing the reflection values **1304** from different frequencies/wavelengths that result in different ratios **1306** with those expected for a particular size. Considering the sizes of ice grains typical of a snowpack, frequencies in X-band are best suited for acquiring information about size in the Rayleigh Region **1308**. However, the invention can be practiced to acquire this information in alternate frequency bands.

After the ratio **1306** of circumference to wavelength reaches values of about 1 and greater, the plot **1302** enters the Mie region **1310**. The Mie region **1310** is characterized by a resonance profile that is a function of both size and shape. Therefore, in the Mie region **1308**, information about the size and shape of the ice grains can be obtained by comparing the reflection values **1304** from different frequencies/wavelengths with those expected for a particular size or shape. Considering the sizes of ice grains typical of a snowpack, frequencies in the K-bands are best suited for acquiring information about size and shape in the Mie Region **1310**. However, the invention can be practiced to acquire this information in alternate frequency bands. To determine size and size and shape information from the Rayleigh region **308** and Mie region **1310** respectively, embodiments that transmit frequencies from different portions of the electromagnetic spectrum as discussed above with respect to FIG. **2** are required.

FIG. **14** through FIG. **17** provide flow charts that set forth the logical structure of the method of the present invention. The orders depicted in the flow charts are only indicative of particular embodiments of the present invention. The orders need not be observed in all embodiments of the invention and are included only for the purposes of illustrating these particular embodiments. The ordering is also ambiguous with respect to time in the sense that steps may occur concurrently or after a wait period. Additional steps may be added that are in keeping with the overall logical structure of the invention. With different wording, fewer steps may be employed.

FIG. **14** is a flow chart illustrating one embodiment of a method **1400** to remotely acquire information from volumes in a snowpack. The method **1400** begins **1402** by transmitting **1404** electromagnetic energy to a remote snowpack. The method **1400** continues by receiving **1406** electromagnetic reflections from the snowpack. The method **1400** involves processing **1408** data about electromagnetic reflections to determine reflection values for different volumes within the snowpack. After processing the data, the method **1400** comes to an end **1410**.

FIG. **15** is a flow chart illustrating one embodiment of a method **1500** to remotely acquire information from volumes in a snowpack by employing frequency modulation and creating a synthetic aperture. The method **1500** begins **1502** by transmitting **1504** electromagnetic energy to a remote snowpack. The step of modulating **1506** a transmit signal is involved.

Modulation **1506** may be performed by a frequency modulation module **620** similar to the one discussed with respect to the signal conditioning module **600** in FIG. **6***a*. Frequency modulation may or may not be linear. Frequency modulation may occur across a single bandwidth.

In certain embodiments, frequency modulation is performed across multiple different bands. In such embodiments, frequency modulation is performed across different bandwidths over a sufficient range so that reflections can be discriminated with respect to range with sufficient resolution for different sets of frequencies/wavelengths from different portions of the electromagnetic spectrum. These different sets of frequencies/wavelengths interact differently within a snowpack to provide different types of information about the snowpack. In other words, the invention is practiced multiple times across different spans of frequency to acquire more information from the different responses of the snowpack to different wavelengths. As a result, for example, information about the response of a snowpack to different spans of frequencies/wavelengths in C-band, X-band, and/or any of the K-bands, or different portions of these bands, can be acquired and compared. Information from frequency bands not listed may also be acquired.

In certain embodiments, a range of frequencies pertaining to a bandwidth over which the frequencies are modulated may be stitched together from multiple, non-continuous blocks of frequencies to discriminate and resolve reflections with respect to range for a single span of the electromagnetic spectrum. Stitching together frequencies from non-continuous blocks of frequencies is different than acquiring information from different spans of the electromagnetic spectrum as discussed in the preceding paragraph, where sufficient bandwidth is achieved at different spans of the spectrum to discriminate and resolve reflections with respect to range at different from different spans of the electromagnetic spectrum. Frequency modulation may be continuous, or performed in discrete steps. Where frequency modulation is performed in discrete steps, the Nyquist rate should be observed to avoid aliasing.

To allow return values to be calculated for complete volumes defined in three dimensions, the method **1500** involves translating **1508** an antenna system to occupy different positions with respect two axes substantially orthogonal to the direction of propagation and to each other. Reflections from the snowpack result in storing **1510** data about electromagnetic reflections indexed to positions of the antenna system. These reflections are received by the antenna system, which may be attached to a signal conditioning module **600** similar to the one depicted in FIG. **6**. In certain embodiments, storing **1510** data about electromagnetic reflections may also involve de-chirping as discussed with respect to the dechirp module **650** discussed with reference to FIG. **6**. The storing of data may or may not be facilitated by a storage module **650** similar to the one discussed with respect to FIG. **6**. In certain embodiments, data is stored by indexing reflection returns to frequencies and antenna system positions.

After the storing **1510** of data, a determination **1512** is made as to whether a scan is complete. A scan is complete when the antenna has been translated sufficiently with respect to both axes over an area to create a synthetic aperture, as discussed with respect to FIG. **7**. If the answer to the determination **1512** is no, the method **1500** returns to modulating **1506** the transmit frequency.

At each position occupied by the antenna system during the creation of the synthetic aperture, the frequency of the transmit signal needs to be substantially modulated over the entire bandwidth needed to discriminate reflections with respect to range with sufficient resolution for a particular set of frequencies. Where the invention involves the acquisition of information from multiple sets of frequencies, the sets of frequencies may be traversed during a single scan or multiple scans. Where the antenna system is translated continuously, and not incrementally, the frequencies may not all be transmitted **1504** and received **1510** from the same position, but discrepancies can be accounted for during processing **1514**.

After modulating **1504** the frequency again, the antenna system is again translated. The antenna system is translated in a path, whether linear, diagonal, curved, circular, or any other trajectory to occupy different positions with respect to the two axes. The two axes should be substantially orthogonal to one another and to the direction of propagation. In some embodiments, the different positions may also differ from one another with respect to the direction-of-propagation axis, as when a synthetic aperture is formed in accordance with the geometric spotlight method for creating a synthetic aperture. Additionally, the line of sight of the antenna system may be rotated at individual positions in accordance with the steered spotlight method for creating a synthetic aperture.

The scan is complete when the synthetic aperture is of sufficient dimensions to acquire the requisite range resolution pursuant to the equation in FIG. **7***b* and when a sufficient spatial sampling frequency is achieved. At this point, processing **1514** is performed on the reflection data to determine reflection values for different volumes within the snowpack. A discussion of different approaches to processing **1514** reflection data follows the discussion of FIG. **7**. After processing **1514** the data, the method **1500** comes to an end **1516**.

FIG. **16** is a flow chart illustrating one embodiment of a method **1600** to remotely acquire information from volumes in a snowpack by maximizing the ratio of returns from within the snowpack to returns from the ground underneath. The method includes steps of: transmitting **1606** electromagnetic energy remotely to a snowpack; modulating **1608** a transmit frequency; translating **1610** an antenna system; storing **1612** data about electromagnetic reflections; determining **1614** the completeness of a scan; and processing **1616** data that are substantially similar respectively to step **1504**, step **1506**, step **1508**, step **1510**, determination **1512**, and step **1514** as discussed in reference to FIG. **15**. The method **1600** discussed with reference to FIG. **16** includes the additional steps of positioning **1604** the antenna system to ensure sufficiently small grazing angles over a region of interest in the snowpack and analyzing **1618** reflection values for information of interest.

The method **1600** begins **1602** and the position **1604** of the antenna system is oriented to ensure small grazing angles. Small grazing angles are achieved where the direction of propagation of transmitted electromagnetic energy at a remotely disposed region of interest describes a shallow angle relative to the plane of the snowpack with its constitutive layers. One example of this situation is depicted in FIG. **4**. At sufficiently small grazing angles, reflections from the snowpack are not overcome by reflections from the ground, as explained with reference to FIG. **10***a* and FIG. **10***b*.

Before the method **1600** comes to an end **1620**, a step of analyzing **1618** reflection values for information of interest is involved. The step of analyzing **1618** may be as simple as determining the volume of snow in the snowpack by determining which volumes have sufficient reflection values to indicate the presence of snow. In more complicated embodiments, analyzing **1618** reflection values may involve looking for relatively strong or weak (depending on the set of frequencies transmitted) return values to determine the location of an avalanche victim. The strength of return values may also be used to determine densities and/or water content and to determine the presence of avalanche debris. In some embodiments, reflection values may be aggregated into an image that is reviewed to determine snowpack properties.

The properties discussed above do not limit the properties for which reflection returns may be analyzed **1618**. As examples of some of the additional properties for which returns may be analyzed, reflection returns may be analyzed **1618** for properties important to snowpack stratigraphy, some of which may be important to avalanche prediction. Analysis for such properties may proceed according to the method **1700** discussed with respect to FIG. **17**.

FIG. **17** is a flow chart illustrating one embodiment of a method **1700** to remotely acquire and analyze information from volumes in a snowpack. The method **1700** begins **1702** by generating **1704** at least one reflection model. A reflection model provides an expected reflection value for a particular volume that might be found in a snowpack for at least one frequency. A reflection model is similar to a volume scattering coefficient, but provides reflection values for predetermined volumes. In certain embodiments, volume scattering coefficients can be relied upon in the analysis process.

The subject of reflection volumes can vary widely from snow generally to the body of an avalanche victim, whether frozen or warm. A reflection model can model expected returns for high density avalanche debris, low-density, "powder" snow, snow of various water contents and distributions, and different layers important to avalanche formation. Such layers may include, without restriction, layers with rounded grains **1102** (see FIG. **11**) faceted grains **1202**, depth hoar **1206**, buried surface hoar **1208** (see FIG. **12**), crusts, and wind deposited snow. Reflection models may be created for different sizes and/or shapes of ice grains generally or for different sizes and/or shapes within the categories enumerated above. Different reflection models within these categories may also be generated based on additional properties not enumerated.

Reflection models may be generated by empirical methods and/or by computer modeling. Empirical models may be generated from returns from several samples of a particular type of snow, or other subject of interest, with calculated variances and standard deviations. In certain embodiments only a single sample may be used.

Computer models may be generated from three-dimensional volume models of the different electromagnetic properties associated with the subject of interest. For example, three-dimensional volume maps of snow structures may be generated based on the typical sizes, shapes, and distributions of ice grains pertaining to a layer of interest in a snowpack. The three-dimensional models may include water distributions. More sophisticated volume maps of microstructure may be generated from x-ray diffraction of actual samples of snow types.

Volume maps can then be imported into electromagnetic computational software. A wide variety of software packages (both proprietary and open source) are available based on the Finite Difference Time Domain (FDTD), Method of Moments (MOM), and Finite Element Method (FEM), algorithms, among others. The particular software package selected should be tailored to the particular model and selected by those of ordinary skill in the art. High Frequency Structural Simulator (HFSS), based on the FEM algorithm, is an example of such software packages that can be used in certain embodiments.

In certain embodiments, reflection models are calculated for several different sets of frequencies. Reflection models for reflection values at several different sets of frequencies can be used to generate an expected plot for a volume similar to the plot **1302** for the imagined ice grain discussed with reference to FIG. **13**. Such an expected volume plot for different sizes in the Rayleigh regime **1308** and sizes and shapes in the Mie regime can be compared against actual returns at the actual sets of frequencies transmitted.

The method **1700** continues by capturing **1706** reflection data remotely over several frequencies and antenna system positions for a region of interest in a snowpack. Additionally, the method **1700** involves processing **1708** the reflection data to determine values for different volumes within the region of interest. The steps of capturing **1706** reflection data and of processing **1708** the reflection data may be performed by methods substantially similar to those discussed with reference to FIG. **14**, FIG. **15**, and FIG. **16**.

Once the reflection values are determined for various volumes, they are compared **1710** with one or more reflection models. Determinations **1712** are then made as to whether reflection values resemble a particular reflection model or which model the actual reflection values most resemble, whether at a single set of frequencies or over multiple sets of frequencies. The determination **1712** may be based on modern theories of estimation and detection. Once the determinations **1712** have been made, the method **1700** ends **1714**.

The invention claimed is:

1. A method for remotely acquiring information from volumes in a snowpack comprising:

transmitting electromagnetic energy to a snowpack from a remote location at a shallow grazing angle;

receiving electromagnetic reflections from said snowpack; and

processing data about said electromagnetic reflections with an electronic computer processor to determine reflection values for different volumes within said snowpack.

2. The method of claim **1**, further comprising:

modulating a frequency of said transmitted electromagnetic energy over a sufficient bandwidth to resolve distinct volumes within said snowpack with respect to a first axis;

translating an antenna system transmitting said transmitted electromagnetic energy and receiving said electromagnetic reflections to occupy different positions with respect to a second axis substantially orthogonal to said first axis over a first distance sufficient to resolve different volumes within said snowpack with respect to said second axis; and

translating said antenna system to occupy different positions with respect to a third axis, substantially orthogonal to said first axis and said second axis over a second distance sufficient to resolve different volumes within said snowpack with respect to said third axis, wherein said positions cover an area of dimensions defined by said first distance and said second distance.

3. The method of claim 2, further comprising positioning said antenna system to maintain a relative orientation to a region of interest within said snowpack that ensures that electromagnetic energy incident upon said region of interest arrives at a grazing angle sufficiently shallow to maximize returns from volume scattering in volumes of said snowpack compared to reflections from a boundary between said snowpack and ground underneath.

4. The method of claim 2, further comprising:
transmitting electromagnetic energy from at least one additional span of the electromagnetic spectrum capable of producing a different response from said snowpack over a sufficient bandwidth to resolve distinct volumes within said snowpack with respect to said first axis; and
processing data about said different response to determine reflection values for different volumes within said snowpack.

5. The method of claim 2, wherein said reflection values are compared against expected reflection values from a reflection model for a volume comprised of a particular subject of interest.

6. The method of claim 5, wherein said reflection model takes into account a density for said volume.

7. The method of claim 5, wherein said reflection model takes into account a general shape for an average ice grain in said volume.

8. The method of claim 5, wherein said reflection model takes into account a general size for an average ice grain in said volume.

9. The method of claim 5, wherein said reflection model provides an expected response profile as a function of wavelength.

10. The method of claim 5, wherein said reflection model takes into account a water content distribution.

11. The method of claim 2, further comprising:
transmitting electromagnetic energy to a region of interest of said snowpack wherein a victim of an avalanche may be buried; and
analyzing said reflection values to determine a location for said victim.

12. The method of claim 2, further comprising:
transmitting electromagnetic energy to a region of interest of said snowpack with a potential for including avalanche debris; and
analyzing said reflection values to determine a three-dimensional distribution for said avalanche debris.

13. The method of claim 2, further comprising:
transmitting electromagnetic energy to a region of interest of said snowpack important to determining snow-water equivalencies for a watershed; and
analyzing said reflection values to determine snow-water equivalencies.

14. The method of claim 2, further comprising:
transmitting electromagnetic energy to a region of interest of said snowpack from which avalanche formation may occur; and
analyzing said reflection values for properties relevant to avalanche prediction.

15. The method of claim 14, wherein said bandwidth, and said first distance and said second distance with respect to said second and said third axes are sufficient to achieve a resolution commensurate with a thickness for a layer of interest to avalanche prediction in said snowpack regardless of a direction of propagation relative to said snowpack.

16. An apparatus for remotely acquiring information from a snowpack comprising:
a signal conditioning module modulating electromagnetic energy across various frequencies within at least one bandwidth sufficiently large to resolve different volumes within said snowpack with respect to a first axis, defined by a direction of propagation directed along a shallow grazing angle relative to the snowpack, and with sufficient power to transmit said electromagnetic energy to a remote area of interest in a snowpack and to produce detectible reflections;
an antenna system electrically coupled to said signal conditioning module, wherein said antenna system transmits said electromagnetic energy, to arrive at a shallow grazing angle relative to the snowpack, and receives said reflections from said snowpack;
a memory coupled to said signal conditioning module, wherein said memory stores data about values for said reflections generated by said signal conditioning module; and
a processor communicatively coupled to said memory, wherein said processor determines reflection values for different volumes within said snowpack.

17. The apparatus of claim 16, further comprising infrastructure for translating said antenna system substantially orthogonal to said first axis, wherein said infrastructure translates said antenna system to occupy different positions with respect to a second axis and with respect to a third axis substantially orthogonal to said first axis and substantially orthogonal to one another over an area sufficient to resolve different volumes within said snowpack.

18. The apparatus of claim 16, wherein an orientation of said antenna system relative to said snowpack is maintained to ensure that electromagnetic energy incident upon said region of interest of said snowpack arrives at a grazing angle sufficiently shallow to maximize returns from volume scattering in volumes of said snowpack compared to reflections from a boundary between said snowpack and ground underneath.

19. A system for remotely retrieving information from a snowpack comprising:
a signal conditioning module modulating electromagnetic energy across various frequencies within at least one bandwidth sufficiently large to resolve different volumes within said snowpack with respect to a first axis, defined by a direction of propagation directed along a shallow grazing angle relative to the snowpack, and with sufficient power to transmit said electromagnetic energy to a remote area of interest in a snowpack and to produce detectible reflections;
an antenna system electrically coupled to said signal conditioning module transmitting said electromagnetic energy, to arrive at the shallow grazing angle relative to the snowpack, and receiving said reflections from said snowpack;
infrastructure for translating said antenna system substantially orthogonal to said first axis, wherein said infrastructure translates said antenna system to occupy different positions with respect to a second axis and with respect to a third axis substantially orthogonal to said first axis and substantially orthogonal to one another over an area sufficient to resolve different volumes within said snowpack, and wherein said infrastructure maintains an orientation of said antenna system relative to said area of interest to ensure that electromagnetic energy incident upon said snowpack arrives at a grazing angle sufficiently shallow to maximize returns from vol-

ume scattering in volumes of said snowpack compared to reflections from a boundary between said snowpack and ground underneath;

a memory coupled to said signal conditioning module storing reflection data indexed to reflection frequencies and positions of said antenna system at which reflections are received; and

a processor communicatively coupled to said memory determining reflection values for different volumes within said snowpack.

20. The system of claim **19**, wherein:

said memory also stores at least one volume scattering coefficient that provides an expected reflection value for a particular volume that potentially exists in the snowpack; and

said processor compares the at least one volume scattering coefficient to the reflection data to determine the presence of the particular volume in the snowpack.

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