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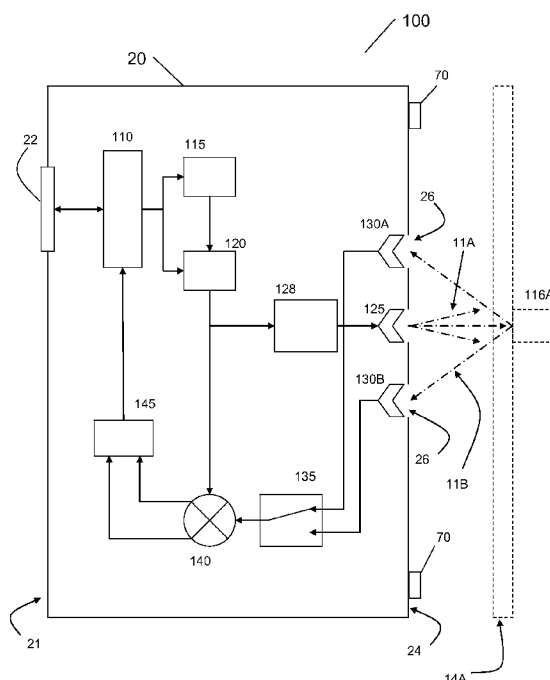


Figure 8

(57) Abstract: A hidden object detector includes a transmission signal source generating a chirped signal whose instantaneous frequency changes linearly during a transmission period. A transmitter is driven by the signal source and transmits a radiating signal away from the detector toward an obstruction capable of hiding a hidden object. At least one receiver in close proximity to the transmitter receives a portion of radiation as reflected back toward the detector from the direction of the obstruction. A signal processing system estimates a signal strength and a time delay of the received signal, where the time delay is measured relative to an internal reference signal. The delay, or phase, information provides an estimation of the distance to the hidden object which is usable as a detection criteria. An indicator signal, usable to drive a user interface, is also generated that indicates the presence or absence of the hidden object.



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## HIDDEN OBJECT DETECTOR

## BACKGROUND

The present invention generally relates to the field of object sensing and more particularly to the field of sensing the presence of objects hidden behind visually obscuring material. The example use of such hidden object detectors is the detection of the location of wall support studs, once the studs have been covered by the wall material, for example plasterboard, in the residential or commercial construction trades. It is desirable to know the location of wall studs when, for example, one is mounting heavy objects to the wall, e.g., shelving, since heavy objects may pull loose from the wall if they are not attached directly to the studs.

When used for stud detection, a hidden object detector ideally has a low false alarm rate. That is, the detector should not indicate the presence of a stud when no stud is present. A second, related use of a hidden object detector is to indicate the presence of utilities (for example, water or drain pipes or electrical wiring) in the hollow cavity behind the wall and between the studs. Generally, when detecting these hidden utilities, a detector ideally has a low miss rate. That is, it should not indicate that it is safe to drill into the wall when, in reality, there is a utility at the tested location. Of the two types of sensing errors, a false alarm is generally preferred to a missed object; a hole in the wall can easily be patched but a damaged utility can mean an expensive repair or even, in the case of electrical wiring, injury or death to the drill operator.

Several different "stud sensors" are commercially available. Typically these sensors are scanned along a wall and are designed to flash an indication when they are in the close proximity of a stud behind the wall. Generally these devices work by sensing either the metal drywall screws used to attach drywall to studs or by sensing a change in capacitance when the dielectric constant beneath the sensor changes due to a stud behind the sheetrock. Typically these sensors perform adequately on new construction, where drywall under a skim coat of plaster is the rule and the location of studs can be confirmed easily by checking at multiples of 16 inches for the presence of neighboring studs. These same sensors are less useful in older construction, where plaster on lath walls might be found or where the 16 inch stud spacing might not hold.

Similarly, these sensors are generally inadequate when used to find utilities behind the finish wall. This shortcoming is not surprising since they were not designed for such a task.

In previous patent applications, the present inventor has described a hidden object imager suitable for identifying objects behind typical drywall construction (U.S. Patent Application No. 11/353,882, now U.S. Patent No. 7,626,400) and a reference target transfer system suitable for aligning objects on two sides of an opaque wall (U.S. Patent Application No. 12/158456). Both of these systems use low power, centimeter wavelength electromagnetic radiation to penetrate typical wall/floor construction material. In particular, the hidden object imager uses a rotating optic/antenna to form a flying spot scanner/reimager system while the reference target transfer system uses an expanding cone of transmitted radiation from a point source that is retro-imaged by the reference target and "tracked" by a rudimentary centroid tracker.

The imager, while performing admirably as a hidden object detector, is more complex than is usually desired for simple drill/no-drill decision making and the reference target transfer system requires access to the far side of the wall in question and only indicates the presence or absence of a stud or utility by inference when the object blocks the signal.

There is, therefore, a need for a hidden object detector that combines the simplicity of the reference target transfer system with the non-inferential, positive identification capability of the imager.

## SUMMARY

In one aspect, the present invention employs a beam of microwave radiation, where, herein, microwave radiation refers to electromagnetic radiation with wavelengths generally longer than 100 microns and shorter than 10 centimeters, to penetrate an obstruction, e.g., a visibly opaque wall, separating two locations to generate a reference between those locations. Many materials typically utilized in construction are transparent to microwave radiation of appropriate frequency. A transmitted reference beam having one or more appropriate frequency components can be projected through a visually opaque obstruction, e.g., a wall, to interact with a positionally and/or angularly sensitive detection device that can sense the transmitted beam. Some embodiments operate in a single-pass mode in which a radiation beam is transmitted once through the obstruction, e.g., a wall, and is sensed by a detection

device (e.g., a plurality of sensors operating in a differential mode). Alternatively, other embodiments operate in a double-pass mode in which a radiation beam (e.g., microwave beam) emitted by a microwave source passes through the obstruction (e.g., a wall), reflects from a reference device, passes back through the obstruction and is positionally sensed.

5 In another aspect, the invention provides a measurement system that includes a source of microwave radiation having one or more wavelengths capable of penetrating through a visibly opaque obstruction, e.g., a wall. The source can be movably positioned on one side of the obstruction for illuminating thereof. The system can further include a microwave reflecting element disposed on another side of the obstruction, where the reflecting element is  
10 capable of reflecting at least a portion of the radiation transmitted through the obstruction. A plurality of radiation sensors are positioned relative to the obstruction so as to detect, e.g., differentially, at least a portion of the reflected radiation transmitted through the obstruction to determine a position of the source relative to the reflective element.

In a related aspect, the radiation source generates radiation with one or more  
15 wavelengths corresponding to a frequency range of about 1 GHz to about 24 GHz (more typically, in a range of about 3 to about 8 GHz) or any other suitable wavelength range. Some examples of suitable microwave sources include, without limitation, Gunn oscillators, magnetrons, IMPATT diodes, Dielectric Resonator Oscillators (DROs), MIMICs or other suitable radio frequency oscillators.

20 In another aspect, the sensors are positioned relative to one another and the source so as to generate a differential null signal when the source, and more particularly the propagating direction of the radiation generated by the source, and the reflective element are substantially aligned. By way of example, the sensors can be positioned to generate a differential null signal when an optical axis of the source is aligned (its extension would intersect) with a  
25 reference location of the reflective element (e.g., its geometrical center).

In another aspect, a measurement system is disclosed that includes an electromagnetic imager adapted to generate images of an interior portion of a visibly opaque obstruction, where the imager comprises a source coupled to a focusing element for focusing radiation directed to a proximal side of the obstruction into an interior portion thereof and a detector for  
30 detecting at least a portion of the radiation propagating back from the obstruction. The system further includes a reflective focusing element disposed on a distal side of the

obstruction for reflecting at least a portion of the radiation propagating through the obstruction. The detector detects at least a portion of the reflected radiation for determining an alignment of the source relative to the reflective element.

In a related aspect, the obstruction comprises a wall, and the reflective focusing element has a focal length of about  $\frac{1}{4}$  of the wall's thickness.

In another aspect, a measurement system is disclosed that comprises a source of microwave radiation adapted to generate a radiation beam having at least one wavelength capable of penetrating an obstruction (e.g., a visibly opaque one), where the source is movably positioned on one side of the obstruction for illuminating thereof with said radiation beam. The system further includes at least two sensors positioned on another side of the obstruction such that each sensor detects at least a portion of radiation transmitted through the obstruction so as to determine a position of said source relative to a reference point on said obstruction.

In a related aspect, in the above system, the sensors are adapted to differentially detect the radiation. For example, the sensors are adapted to generate a null signal when the source is aligned with said reference point.

In another aspect, the radiation source is capable of generating radiation with one or more frequency components in a range of about 1 GHz to about 24 GHz, e.g., in a range of about 10 GHz to about 20 GHz.

In another aspect, the invention provides a measurement method, which comprises movably disposing a radiation source on one side of a visibly opaque obstruction, said source generating radiation having at least one wavelength capable of penetrating through the obstruction. The method further calls for associating a reference element to a location at an opposed side of the obstruction, where the element is reflective to said at least one wavelength. A radiation beam having said wavelength is directed from the source to the obstruction such that at least a portion of said radiation penetrates the obstruction to illuminate said reflective element, and at least a portion of radiation reflected by the element is detected, e.g., differentially, at two or more spatially separate locations so as to determine a position of the source relative to the reflective element.

In yet another aspect, the invention provides a source of microwave radiation movably disposed on one side of a visibly opaque obstruction, the source generating a slowly

expanding beam of radiation, and further providing two radiation detectors disposed to receive radiation scattered in the backward direction (viz., in a direction from the obstruction), allowing measurements along an axis defined by a line connecting the center points of the two radiation detectors. The receiving apertures of the detectors are generally  
5 symmetrically located adjacent to the emitting aperture of the source.

In another aspect, the invention provides a signal processing method, which comprises phase detection of the signals from the two radiation detectors to determine the distance in depth of the scattering object.

In another aspect, the invention provides a radiation source wherein the transmitted  
10 microwave radiation is modulated using the so called Frequency Modulated Continuous Wave (FMCW) technique, also called chirp modulation.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages will be apparent from the  
15 following description of particular embodiments, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of various embodiments.

FIGURE 1A schematically depicts an example measurement system in accordance  
20 with one embodiment;

FIGURE 1B schematically depicts the propagation of radiation from the source in the measurement system of FIGURE 1A via a proximal side of the wall into its interior to be reflected by a reflecting element disposed at a distal side of the wall;

FIGURE 2 schematically depicts an example measurement system in accordance with  
25 another embodiment in which a source and a detector are disposed on the same side of an obstruction;

FIGURE 3 schematically depicts geometrical disposition of a source and four detectors of an example measurement system according to an embodiment relative to one another;

FIGURE 4 schematically depicts a microwave source and four sensor channels suitable for use in some embodiments;

FIGURE 5 schematically depicts the profile of a measurement tool according to one embodiment having an interface providing visual indicators for indicating direction to null;

5       FIGURE 6 schematically depicts an imager incorporating a measurement system according to one embodiment for referencing coordinates on the back of a wall to those on the front, in which the MD reflector has a focal length that is about  $\frac{1}{4}$  of the thickness of the wall;

10       FIGURE 7 schematically depicts another embodiment in which a single pass of microwave radiation through an obstruction, e.g., a wall, is employed to align a radiation beam illuminating the obstruction from one side with a coordinate point on another side of that obstruction;

FIGURE 8 schematically depicts another embodiment in which the radiation beam is used as a probe to identify the location of in-situ, existing, hidden reflective/scattering objects;

15       FIGURE 9 depicts the microwave radiation generation, transmission, reception and processing elements of an embodiment of a stud sensor at a schematic hardware block diagram level;

FIGURE 10 illustrates the microwave radiation generation, transmission, reception and processing elements in a data flow diagram;

20       FIGURE 11 illustrates schematically the frequency difference generated by two identical chirped signals with a specific time delay;

FIGURE 12 illustrates the geometrical relationship between the hidden object, the transmit antenna, and the two receive antennae, for one embodiment; and

FIGURE 13 schematically illustrates the disambiguation scheme.

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#### DETAILED DESCRIPTION

The term “visibly opaque obstruction,” as used herein, generally refers to a piece of material that substantially (or completely) blocks the passage of visible radiation (e.g., radiation having wavelengths in a range of about 400 nm to about 700 nm) therethrough. By

way of example, a beam of light can lose more than about 90% of its intensity as it passes through the obstruction. Without loss of generality, in the following embodiments, the visibly opaque obstruction is assumed to be a wall. It should, however, be understood that the measurement systems and methods can be employed to project reference datums through  
5 other types of obstructions and, in other embodiments, to detect objects hidden behind other types of obstructions, for example, to detect a metal object under a coat or in a suitcase.

Similarly, although some embodiments operate with electromagnetic radiation with wavelengths in the 100 micron to 10,000 micron band- technically millimeter or centimeter waves, this radiation is often called microwave radiation, a term that is used herein.

10 Furthermore, we use the term "light", another wavelength range of electro-magnetic radiation, to describe this radiation when it is convenient herein without intending this terminology to be limiting in any way.

FIGURES 1A and 1B schematically depict an example measurement system that comprises a measurement tool in accordance with one embodiment that can operate in a  
15 double-pass mode. The tool includes a radiation source 10 (a source of microwave radiation in this embodiment) and a radiation detector 12 (shown as sensors 12A and 12B) that can be movably disposed on a proximal side of an obstruction 14, typically referred to herein as a wall. The microwave radiation source projects a beam of microwave radiation through the proximal side of the wall. A reflecting microwave optical device 16 (herein also referred to  
20 as the Microwave Datum or MD) is placed on the distal side of the wall, centered on the measurement point of interest. By way of example, the MD can comprise a reflecting Fresnel Zone Plate (FZP) with a focal distance chosen to be slightly longer than the thickness of the wall. For example, the MD can be a flat sheet typically composed of thin metal foil in a series of concentric zones. An adhesive can be applied to a surface of such a flat MD to  
25 allow it to be readily attached to the wall surface. The measurement tool can then be placed against the proximal surface of the wall and moved along that surface to sense the power reflected from the MD, thus determining the location of the MD on the distal side of the wall, as discussed in more detail below.

Preferably, the MD has a focal length chosen to image the source behind itself, as  
30 illustrated in Figure 1B; that is, the image is at a focal distance slightly longer than the sum of the thickness of the wall and the known distance between the source and the proximal side of

the wall. Generally, the preferred focal length can be calculated using the well known imaging relationship:

$$f = \frac{OI}{(O+I)} \quad (1)$$

where  $f$  is the focal length of a lens and  $O$  and  $I$  are the object and image distances respectively.

For the MD:

$$f_{MD} = \frac{(S+W)(S+W+d)}{(2S+2W+d)} \quad (2)$$

where  $f_{MD}$  is the focal length of the MD,  $S$  is the distance from the source to the proximal side of the wall,  $W$  is the thickness of the wall, and  $d$  is a predetermined distance behind the source at which the source image is to be formed.

In some embodiments, when the measurement tool is centered on the datum, an alert signal is provided to the user. When the source and the datum are not aligned, one or more indicators (e.g., a set of arrows) on the tool indicate the direction of the datum position, that is, the direction in which the source should be moved to align it with the datum. In some embodiments, the relative position of the source and the datum is defined by a vector extending from a fiducial point on the source to a reference point on the datum. By way of example, in some embodiments, the source and the datum are considered aligned when an optical axis of the source (e.g., characterized by a central ray of a beam emitted by the source) is directed towards a reference point (e.g., the geometrical center) of the datum.

In this example embodiment, the measurement system operates by differentially sensing a cone of microwave radiation rays forming a beam that is reflected from the MD. The tool's detector functions as a nulling sensor that provides directional information when off null (i.e., when not exhibiting a null signal) to allow the user to quickly converge on the null position. FIGURE 1B further illustrates the optical geometry in this embodiment. The source emits a cone of radiation that is transmitted through the wall to the MD. The MD retro-focuses the radiation power to a position behind the proximal surface of the wall. Before coming to focus, the power traversing through the space above the source is collected by sensor B's aperture and is sensed. The power below the source is likewise collected and sensed by sensor A. When the MD is located on the optical axis, the power sensed by sensor

B is substantially equal to that sensed by sensor A. In this embodiment, a second pair of sensors (sensors C and D in FIGURE 3) are located in and out of the page (along an axis perpendicular to one along which sensors A and B are disposed), thus resulting in a total of 4 sensors that are differentially connected to sense two degrees of freedom (X and Y). This geometry is illustrated in FIGURE 3, which schematically shows the source and sensor channels as viewed from the distal side of the wall. If only one dimension of measurement is required then a suitable embodiment of the measurement system would comprise only one pair of sensors, i.e., either sensor A and sensor B or sensor C and sensor D.

In this embodiment, the following sensing algorithm can be implemented in an electronic circuit to compute a normalized difference signal:

$$V_{\Delta Y} = k(P_A - P_B) / (P_A + P_B) \quad (3)$$

where:

$P_A$  = power sensed by channel A

$P_B$  = power sensed by channel B

$V_{\Delta Y}$  = the output of the circuit with a given datum misalignment

$K$  = a constant,

and likewise:

$$V_{\Delta X} = k(P_C - P_D) / (P_C + P_D) \quad (4)$$

where C and D represent the sensors into and out of the plane of the page.

The above algorithm produces an output of zero when the tool is aligned on the MD. The output swings from minus to zero and then plus as the tool is scanned across the MD position.

The focal distance and diameter of the MD can be easily tailored to accommodate various wall thicknesses. In general, thicker walls require MDs having longer focal lengths, in accordance with Equation (1). Furthermore, with thicker walls it is preferable for the MDs to have larger diameters. Generally, the diameter of the MD increases in proportion to thickness of the wall to maintain the cone angle of the light forming the image of the source. As measured by well known optical parameter  $f/\#$ , the preferred cone angle is simply:

$$f/\#_{MD} = d / D \quad (5)$$

where  $d$  is the predetermined distance behind the source at which the source image is to be formed and  $D$  is the desired diameter of the beam in the plane of the detectors. In some

embodiments, D is preferably equal to the diameter of the circle that circumscribes the 4 detectors surrounding the source.

In some embodiments, the microwave detection method is a standard microwave technique known as frequency modulated continuous wave (FMCW). A single Gunn oscillator source, for example, including a resonant cavity provides microwave output power. This cavity is also connected to the 4 sensor channels to act as a local oscillator for detection (shown in FIGURE 4). Each of the 4 sensor channels uses, for example, a Schottky diode for detection of the collected microwave power. In some embodiments, the tool is battery powered with a 4.5 to 9 V battery.

In some embodiments the FMCW signal is processed to estimate the magnitude of the return signal in each sensor channel. In other embodiments the FMCW signal is processed in a phase detection processor which yields both the magnitude of the return signal and the range of the reflecting/scattering object from which the return signal is coming, wherein the range of the object is related to the phase delay of the return signal relative to a local reference signal.

In some embodiments, the tool is fairly compact with approximate dimensions of, for example, 3" in diameter by 3" in height (shown in FIGURE 5). Further, in some embodiments, the user interface includes an on/off button and visual indicators, e.g., 4 LEDs which light up to indicate direction to null. Upon reaching a null, the visual indicators provide a selected signal to the user to indicate alignment of the source with the MD, e.g., all 4 LEDs will blink. In some embodiments, the radiation source, the sensors, the user interface and the ancillary electronic circuitry are incorporated in a hand-held housing.

In general, the frequency of operation depends on the type of material from which the obstruction, e.g., a wall, is formed. By way of example, in case of a drywall, some embodiments employ a radiation frequency in a range of about 10 GHz to about 24 GHz, as radiation in that frequency range exhibits good transmission through a drywall. In case of a wall formed of concrete, a lower frequency might be required. Scattering of the microwave beam by inhomogeneities in the concrete is reduced with a lower frequency microwave source (longer wavelength). For example, a radiation frequency in a range of about 1 to about 2 GHz can be employed for obstructions formed of concrete, as radiation in that frequency range transmits better through concrete. Moreover, in the case of concrete (and other cases

when suitable), some embodiments employ a  $\frac{1}{4}$  wavelength thickness of a low index of refraction material (plastic) to impedance match the transition of microwaves between air and (high index) concrete.

In addition, in many embodiments, the intensity of the radiation emitted by the source is selected such that the intensity of the radiation reaching the detectors (e.g., via one or two passages through the obstruction) is sufficient for an adequate signal-to-noise ratio of the detectors' outputs. By way of example, in some embodiments, the power output of the source is in a range of about 10 microwatts to about 10 milliwatts, and the intensity of a radiation beam emitted by the source is in a range of about 10 microwatts per square centimeter to about 10 milliwatts per square centimeter.

With reference to FIGURE 4, in this example embodiment, the geometry of the source and sensor horn antennas is chosen to allow a wide angular admittance of microwave beams without significant attenuation. This results in a small aperture width.

Although the above embodiments are implemented by employing a differential detection system, in other embodiments, a non-differential detection system can be utilized. For example, a source can be aligned with the MD by maximizing the power detected non-differentially by a detector as a function of the detector's position.

With reference to FIGURE 2, in another embodiment, a radiation source 10 is optically coupled to a beam splitter 18 that passes the radiation from the source, through the wall, onto the MD 16. The beam splitter directs the back-propagating radiation, generated via reflection of the incident radiation by the MD, onto a detector 12. By way of example, the detector 12 can include a plurality of detecting modules that differentially detect the reflected radiation, e.g., in a manner discussed above, so as to provide an indication of the relative alignment of the source and the MD. The source, the beam splitter and the detector can be disposed in a portable housing that can be readily moved so as to align the source with the MD.

In some embodiments, the MD reflector is coated with a non-marring adhesive and hence it can be easily relocated on the distal side of the wall so as to function as a reference datum.

In another embodiment, a camera (imager), such as has been disclosed in a U.S. Patent No. 7,626,400 entitled "Electro-Magnetic Scanning Imager, which is herein incorporated by

reference in its entirety, can be utilized in conjunction with the MD to reference coordinates on the back of an obstruction (e.g., a wall) to those on the front. By way of example, in one embodiment, the camera includes a radiation source that generates radiation that is capable of penetrating the wall (e.g., radiation with frequency components in a range of about 1 GHz to about 24 GHz). A focusing element coupled to the radiation source focuses the radiation onto an object plane within the wall, and directs at least a portion of the focused radiation propagating back from that object plane onto a detector of the camera. A scanning mechanism coupled to the focusing element causes scanning of the focused radiation on the object plane (in some embodiments, the mechanism provides scanning along one dimension and the movement of the camera by a user provides scanning in an orthogonal dimension). A processor maps the detected radiation to the scanned locations to generate an image of the object plane, which can then be presented to a user in a display module of the camera. In some embodiments, when utilized in conjunction with the MD, the camera scans the front of the wall and sees where the MD reflector is. In such a case, the focal length of the MD is preferably chosen to be  $\frac{1}{4}$  of the wall thickness so that the MD would provide a 1:1 image of radiation from the camera focused about half way into the wall, as shown schematically in FIGURE 6. In this manner, the coordinates on the back of the wall can be referenced to those on the front.

Metals generally reflect or scatter microwave radiation at different frequencies. In some embodiments, the attenuation of microwave radiation through a path can be assessed to determine whether that path is free (or at least substantially free) of metals. For example, in the above double-pass embodiment, the intensity of microwave radiation reflected from the MD and detected by the sensors can be compared with the intensity of the radiation illuminating the wall to determine whether the path of the radiation through the wall is substantially free of metal.

FIGURE 7 schematically depicts another embodiment in which a single pass of microwave radiation through an obstruction, e.g., a wall, is employed to align a radiation beam illuminating the obstruction from one side with a coordinate point on another side of that obstruction. This example embodiment includes a microwave source 10 that generates radiation with wavelengths suitable for penetration through the wall 14. A detector 12, which comprises four sensors (two of which A and B are shown), symmetrically disposed relative to

one another, differentially detects the radiation that has passed through the wall. For example, the detector can be aligned with a coordinate point A on the back surface of the wall by detecting a null signal generated by the detector when the central ray of a cone of diverging microwave radiation from the source illuminating the wall is aligned with that coordinate point.

FIGURE 8 schematically depicts another embodiment in which the radiation beam is used as a probe to identify the location of in-situ, existing, hidden reflective/scattering objects located behind the visually opaque obstruction, generally the proximal panel of a wall, where, for convenience, we assume a “wall” comprises two generally parallel panels enclosing a hollow cavity, wherein further the panels are held in position by a framework of studs, viz., typical stud wall construction. Often these objects are studs and/or plumbing/heating pipes and/or electrical cables. In this embodiment the radiation beam is a probe and a pair of detectors are operated in a differential mode to locate the hidden objects. Typically the configuration of this embodiment is called a “stud sensor” although it may detect other hidden objects, as mentioned above.

The stud sensor embodiment 100 comprises a source and two detectors as in the arrangement of Figure 1, the detectors in some cases being referenced as sensor A and sensor B. The source in this case is a voltage controlled oscillator 120 coupled to a transmitting (“Tx”) antenna 125. As will be explained below, this source may also include a delay line 128. The detectors in this case are receiving (“Rx”) antennas 130A, 130B (generally Rx antenna 130) coupled to a mixer 140. In a preferred embodiment the mixer is an “I-Q” mixer. In the example embodiment of Figure 8 the two Rx antennae are time multiplexed into a single signal path by multiplexing switch 135, whereby only one set of processing electronics, for example, an A/D converter 145 and microprocessor 110, is required.

Typically instrument housing 20 comprises a proximal surface 21, which generally faces a user and which typically comprises a user operating interface 22. Instrument housing 20 further comprises a distal surface 24, which faces the obstructing surface (viz., the proximal panel 14A of a wall) and comprises an exit aperture 25, through which the source transmits an expanding cone or beam of radiation 11a, and one or more entrance apertures 26 through which scattered/reflected radiation 11b passes to reach Rx antenna(e) 130.

In some embodiments, housing 20 further comprises a human manual interface (not illustrated), viz., one or more handles, wherein said manual interface is typically ergonomically designed. In many hand-held, portable tools the one or more handles comprise a battery compartment or a power attachment interface.

5 As further shown in FIGURE 8, receive and transmit antennas 125, 130A, 130B are generally disposed facing outward from distal surface 24 of housing 20 and transmit or receive respectively through exit aperture 25 and entrance apertures 26. Typically, housing 20 is maintained at a small, substantively fixed distance from the proximal panel 14A of obstruction 14 by one or more non-marring feet 70 or pads attached to distal surface 24 of  
10 housing 20. In some embodiments feet 70 may be replaced by wheels or rollers that allow housing 20 to move smoothly along the proximal surface of proximal panel 14A of obstruction 14. In some other embodiments a linear displacement sensing apparatus, for example a track ball, may be disposed between distal surface 24 and proximal surface 14A, either as a replacement of one or more of the non-marring feet or in addition to the feet. In  
15 typical embodiments this displacement sensing apparatus is configured to measure displacement of the housing 20 along only one axis, for example the horizontal axis. More generally the housing 20 will be oriented such that the one measured displacement direction is approximately perpendicular to the expected orientation of an expected hidden object 116A. For example, if object 116A is a framing stud, which runs from the floor to the ceiling, then  
20 the displacement direction is generally horizontal. On the other hand, if the object is a fire stop between studs, then the housing 20 may be rotated in operation of the detector 12 so the displacement direction will be generally along a vertical axis.

FIGURE 9 depicts the microwave radiation generation, transmission, reception and processing elements of an embodiment of a stud sensor at a schematic hardware block  
25 diagram level. FIGURE 10 illustrates the same elements in a data flow diagram.

Referring to FIGURE 9, a user typically operates the stud sensor by interacting with an internal microprocessor 110 via a user interface 22. The microprocessor can contain user-selectable setup and operating routines although herein we show as an example a basic, default system for clarity. In one example embodiment the microprocessor commands a  
30 voltage function generator 115 to generate a 18 microsecond voltage ramp, with a 2 microsecond recovery time, which voltage ramp in turn controls the oscillation frequency of a

voltage-controlled-oscillator 120 (VCO). The voltage range of the ramp generated by function generator 115, for example  $V_0 \leq V \leq V_{\max}$ , has been pre-determined from the component specifications to sweep the oscillation frequency of VCO 120 from, for example, 5.65 gigahertz to 5.85 gigahertz. Preferably, this frequency sweep is substantially linear with time.

5 In one embodiment the VCO is a Hittite HMC431LP4 (available from Hittite Microwave Corporation, 20 Alpha Road, Chelmsford, MA 01824). Any signal at or near the frequencies output by VCO 120 may, for convenience, be called an RF (radio frequency) signal.

In some embodiments the center frequency of VCO 115 may also be controlled by microprocessor 115. In the example embodiment illustrated in FIGURE 9 the central  
10 frequency is nominally 5.75 gigahertz, a design choice determined by FCC regulations and the expected properties of the materials from which proximal panel 14A, typically gypsum drywall in recent residential construction, is fabricated.

In the example stud finder embodiment, the output signal from VCO 120 is conveyed to Tx antenna 125. In a preferred embodiment, a delay line 128 introduces approximately 10  
15 nanoseconds delay into the transmitted signal. This delay, when added to the inherent delay introduced by the round trip the signal takes from Tx antenna 125 to an Rx antenna 130, results in a constant frequency offset,  $\Delta f$ , of approximately 80 kilohertz between the received signal and the local oscillator signal, as will be discussed below.

The electromagnetic signal leaving Tx antenna 125 is formed into a slowly expanding  
20 beam of microwave radiation by the antenna and is directed towards the proximal side of obstruction 14. When the microwave radiation frequency is matched to the properties of proximal panel 14A at least a portion of the beam of transmitted microwave radiation will penetrate panel 14A.

The detector 12 is usable to identify the presence of a hidden object 116B that may be  
25 located on the distal side of panel 14A at an unknown depth behind the panel. When Tx antenna 125 is in approximate alignment with object 116B, at least a portion of the transmitted radiation will be reflected and/or scattered from object 116B when present. The magnitude of the reflected/scattered radiation is determined by the frequency selected by the designer and the material properties of object 116B and panel 14A. Metals, for example as  
30 may be found in wiring, metal studs, and plumbing, generally reflect a high proportion of incident electromagnetic radiation over a wide band of frequency. This high reflectivity of

metals is specifically true for radiation at the example frequency of about 5.75 gigahertz. Further, wood (e.g., studs) and PVC (plumbing) also reflect/scatter well at the example frequency of 5.75 gigahertz.

At least a portion of the reflected/scattered radiation penetrates panel 14A in the reverse direction from the transmitted beam. A portion of this returning radiation is collected by one or more receiving antennas. Two receiving antennas 130A and 130B are illustrated in the example embodiment. As illustrated schematically in FIGURE 9, Rx antennas 130A, 130B are typically disposed symmetrically about transmitting antenna 125.

In other embodiments, not illustrated, the sensor has four Rx antennas, where the four antennas are preferably disposed in a square array centered on the Tx antenna. Preferably the Rx antenna array is oriented with one pair of antennas in the horizontal axis and the other pair in the vertical axis.

Returning to FIGURE 9, in the example embodiment the received signals from Rx antennas 130A and 130B are multiplexed into a single transmission line by multiplexing switch 135. In one embodiment this switch is a Hittite HMC232LP4 (available from Hittite Microwave Corporation, 20 Alpha Road, Chelmsford, MA 01824). The switching rate of multiplexing switch 135 should be well below the repetition rate of function generator 115 (50 kilohertz in the example embodiment) and somewhat greater than the instrument's display update rate, which is a user interface design choice. In the example embodiment the display update rate is about 10 hertz and the multiplexing switching rate is about 1 kilohertz.

For convenience the signal from Rx antenna 130A will henceforth be identified as the Left signal or Left channel whilst the signal from Rx antenna 130B will be identified as the Right signal or Right channel. Furthermore, the time multiplexed output from multiplexing switch 135 will simply be identified as the received signal when its left/right identity is not significant.

As shown in FIGURE 9, the received signal being output from multiplexing switch 135 is sent to I-Q mixer 140 for mixing (that is, multiplying) with a local oscillator (LO) signal derived from VCO 120 in a so-called homodyne configuration. Alternatively, a second signal generator and VCO can be used to generate the reference local oscillator, creating a so-called heterodyne configuration. Delay line 128, in other embodiments, may be inserted in any other portion of the RF signal path, preferably in the transmitted or received signal

path(s). While functionally acceptable, it is generally not preferred to insert the delay line in the local oscillator path since the length of an LO delay line is significantly longer than what is required in the transmit/receive path. In heterodyne configurations the transmitted and local oscillator signals can be a chirped signal, as described herein, or they can be single frequency signals that are offset from each other in frequency .

Returning to FIGURE 9, the received RF signal is combined with the local oscillator signal in I-Q mixer 140 such as model HMC525 (available from Hittite Microwave Corporation, 20 Alpha Road, Chelmsford, MA 01824) to produce an intermediate frequency (IF) signal, as is conventionally done in microwave signal processors. An I-Q mixer uses a phase shifting process so that the input signal is multiplied (mixed) with both the original and a 90 degree-phase-shifted copy of the local oscillator (e.g., reference) signal. The output of an I-Q mixer is the expected “in-phase” IF signal (the “I” of I-Q) and a “quadrature”, or 90 degree phase shifted version of the IF signal (the “Q” of I-Q).

The I and Q IF outputs from mixer 140 are then processed to determine the IF signal’s magnitude and phase, which are both directly related to the magnitude and phase of the RF received signal. As shown in FIGURE 9, the example embodiment preferably performs this processing in a digital signal processor, which can be part of microcontroller 110, requiring an analog-to-digital conversion in an A/D converter 145. Although preferably performed digitally, analog magnitude and phase processing circuits are well known in the art.

In general, the magnitude of a received signal(s) (i.e., the received signal strength) is indicative of the presence of an object in front of a hidden object detector whilst the phase of a received signal(s) is a measure of the distance between the reflecting/scattering object and the sensor. In some embodiments the relative magnitude between the left channel and right channel is indicative of the left/right position of the object relative to the center line of the hidden object detector. In the stud sensor embodiment the data must meet three criteria before the sensor will declare that a stud has been sensed. First, the magnitudes of the left and right channel signals must be greater than a pre-determined threshold, to indicate that the hidden object is a stud and not some smaller object; second, the left and right channel magnitudes must be substantially equal, to indicate that the stud is immediately in front of the device; and third, the depth of the object, as calculated from the phases of the left and/or right channels, must be greater than a pre-determined threshold but less than a second pre-

determined threshold. In one embodiment of the stud sensor embodiment, the range of the object must be greater than approximately 12.5 millimeters but less than 25 millimeters, where 12.5 millimeters is assumed to be the minimum thickness of proximal panel 14A. Generally, the minimum and maximum object distance can be a user selectable/settable parameter in the microprocessor.

### RF SIGNAL PROCESSING

As is well known, when two sinusoidal signals of different frequencies are multiplied, the resultant signal has components with frequencies equal to the sum and difference of the frequencies of the two input signals. In the present example embodiment the received signal is mixed with a local oscillator signal derived from the same source as the received signal; that is, the example embodiment uses homodyne signal processing. In a homodyne detector, generally, the two input signals have nominally identical frequencies so the output is comprised of a high frequency signal (at the sum frequency, approximately twice the oscillator frequency) and a baseband signal (at the difference frequency, near zero). In a hidden object detector, neither high frequency nor baseband signals are generally desirable. In particular, in a stud finder embodiment it is desirable to have the received microwave frequency signal converted into a convenient so-called intermediate frequency (IF) signal. In the example embodiment the intermediate frequency is preferably in the range of 50 kilohertz to 100 kilohertz.

Some embodiments of the hidden object detector use a “chirped”, or linearly varying frequency, signal. As shown analytically by Graham M. Brooker in Introduction to Sensors for Ranging and Imaging, Chapter 11, a fixed IF frequency signal is generated by mixing a chirped signal with a time-delayed, equivalently chirped signal, that is, the signal has the form:

$$\cos \left\{ 2\pi S T_D t + \left[ \omega_c T_D - \pi S T_D^2 \right] \right\} \quad (6)$$

where S is the frequency slope (time rate of frequency change) of the RF chirp, in hertz,  $T_D$  is the delay time,  $\omega_c$  is the RF carrier frequency, t is time, and an “equivalently

chirped signal” is one that has the same frequency sweep rate as the signal being measured. Note that that the angular frequency of this cosine is the IF frequency and that

$$IF = 2\pi ST_D \quad (7)$$

Note that the IF frequency is equal to the instantaneous frequency difference between the two swept frequency RF signals, as illustrated schematically in FIGURE 11 for the case of two identical chirped signals with a specific time delay. It should be noted from Equation (7) that the IF frequency depends only on the chirp frequency slope  $S$  times the time delay,  $T_D$ , where the time delay is the sum of the round trip pulse path and the inserted delay line value. Further, the phase of the IF signal is, to first order, simply the product of the carrier frequency  $\omega_c$  times the time delay  $T_D$ .

In one example embodiment of a stud sensor the sweep time of the chirp is 18 microseconds and the frequency sweep range is 200 megahertz, for a frequency sweep ramp rate of  $1.1 \times 10^{13}$  hertz/sec. Thus, a total time delay (internal transmission line delays, round trip travel time, and delay line 128) of 7.2 nanoseconds produces an IF frequency of 80 kilohertz.

In another, preferred, embodiment of a stud sensor two different chirp signals are employed, generally in alternation, said use of two different chirp signals increasing the unambiguous depth measurement, as will be described below. In one example embodiment, for a given total time delay, the first chirp signal produces an IF of 98 kilohertz while the second chirp signal produces an IF of 78 kilohertz. In this embodiment the length of the chirp for both signals is 18 microseconds; only the rate of frequency change is different.

## DIGITAL PROCESSING

Returning to FIGURE 10, wherein one embodiment of the hidden object detector processing is illustrated in a schematic block diagram, the two IF signals, I and Q are digitized by an A/D converter 145 before the magnitude and phase of the received signal are calculated. Typically the IF signals are sampled a short time after they first appear at the output of the mixer, at which time the mixer circuit, by design, has recovered from any transient effects, where said recovery time is a known from the component’s manufacturer’s specification. For example, in one embodiment the IF samples are obtained approximately 5 microseconds after the leading edge. The magnitude is digitally calculated as the root-square-

sum 158 of I and Q, that is  $M = \sqrt{I^2 + Q^2}$ , and the phase is digitally calculated as the arctangent 155 of the ratio I/Q, where the signs of I and Q are tracked to provide a full  $2\pi$  output range. In Figure 10 this full-range arctangent is represent by the ATAN2 function, which is well know in scientific programming. In the example embodiment the time-  
 5 multiplexed left and right channel signals are processed sequentially and independently with their respective magnitude and phase values being demultiplexed within a logic module 168.

The magnitude, M, of the IF signal is quasi-proportional to the size of scattering hidden object behind the obstruction, with the exact relationship being determined by the size, surface profile, and material properties of the object and by the geometric relationship  
 10 between sensor and the object. As will be described below, the magnitude(s) of the left and right signals are used to identify the presence of a hidden object and its lateral location relative to the sensor.

Referring to Equation (6) the non-time dependent phase of the IF signal,:

$$\phi = \omega_c T_D = 2\pi c L_D / \lambda_c, \quad (8)$$

15 where c is the speed of light,  $L_D$  is the total delay path length, and  $\lambda_c$  is the RF wavelength. Examining Equation (8),  $\phi$  is proportional to the product of the round trip path length between the Tx antenna and the Rx antenna and the inverse of the original microwave wavelength (~5 centimeters in the example embodiment). Inverting Equation (8) yields an equation for the round trip path length from transmitter to detector:

$$L_D = \frac{\phi \lambda_c}{2\pi c}. \quad (9)$$

Using basic geometry, shown diagrammatically in Figure 12, it can be shown that, for any given round trip path length, the hidden object must lie substantially on the locus of points forming an ellipse with foci at the Tx and Rx antennas, wherein the ellipse lies in the plane containing the Tx and Rx antennas and the transmission axis of the Tx antenna. When  
 25 both the left and right channel signals are considered, the hidden object can be localized to a unique point in that plane by triangulation. The perpendicular distance from that point to the obstruction is the depth of the object. That is, the path length from the transmitter Tx to a point P1 and then to the first receiver Rx1 is constant for all points on ellipse E1. Similarly, the path length from the transmitter to a point P2 and then to the second receiver Rx2 is also a  
 30 constant for all points on ellipse E2. There are only two locations where ellipses E1 and E2

intersect, only one of which is in the direction of transmission. That point, O, must be where the scattering object is located.

In a basic implementation of the stud finder, a stud is assumed to be present when the left and right signal magnitudes are substantially equal and above a minimum threshold (the threshold can easily be determined experimentally), and when the measured depth is greater  
5 than the expected thickness of the obstruction, but less than, say, 1.5 times that thickness.

In general, a hidden object detector must be calibrated before use to remove the effects of the obstruction. In one embodiment, this calibration comprises operating the detector over a section of the obstruction believed cover a void. During calibration, digitized samples of I  
10 and Q, for both left and right channels, are stored in temporary memory. During normal measurement operations, these stored samples are recalled from memory and subtracted from the data stream before the magnitude and phase calculations are performed. This calibration step not only removes the effect of having a scattered signal coming from the front of the obstruction but also provides a zero phase reference. That is, as shown in Equation (8), the  
15 measured IF phase is proportional to  $L_D$ , the total delay path, which is the sum of all the internal delays plus the delay from the Tx antenna to the Rx antenna, this latter delay being the object depth that is the desired measurement. Applying the calibration measurement described above automatically subtracts all the internal delay induced phase shifts from the subsequent measurements.

It will be noted by those of skill in the art that the measured IF phase of Equation (8)  
20 has a depth ambiguity. Because of the inherent periodicity of a sinusoidal signal, the measured depth repeats with the RF carrier wavelength,  $\lambda_c$ , limiting the unambiguous depth measurement to about  $\frac{1}{2} \lambda_c$ , where the  $\frac{1}{2}$  factor accounts for the round trip measurement. In preferred embodiments additional measurement and processing steps are used to resolve this  
25 ambiguity.

In one preferred embodiment, the IF phase is measured at two sampling times. The first sample time is near the beginning of the IF signal and the second is near the end of the IF signal. For example, the phase can be measured at 5 microseconds and 15 microseconds into the 18 microsecond signal. Returning to Equation (6), the time dependent phase,  $\phi_t$  of the IF  
30 signal is:

$$\phi_t = 2\pi S T_D t, \quad (10)$$

where  $S$  is the slope of the frequency ramp used to create the chirped RF signal. When the two phase measures are compared, the phase difference depends on only one unknown,  $T_D$ , as shown in Equation (11) below:

$$\Delta\phi_t = 2\pi S T_D \Delta t, \quad (11)$$

where  $\Delta t$  is the known sample time difference. In the example embodiment,  $S = 1.1 \times 10^{13}$  hertz/sec,  $T_D \approx 7.2 \times 10^{-9}$  seconds, and  $\Delta t = 1 \times 10^{-6}$  seconds. When the depth of the object changes by  $\frac{1}{2} \lambda_c$ , the delay time changes by approximately  $0.17 \times 10^{-9}$  seconds. Using these values in Equation (11) demonstrates that the measured phase difference,  $\Delta\phi_t$ , will change by about 6 or 7 degrees for each 2.5 centimeter change in depth.

An unambiguous depth measurement can then be calculated by combining the 2.5 centimeter “steps” calculated using Equation (11) and the high resolution (but ambiguous) depth calculated using Equation (8).

In another preferred embodiment, the stud sensor is operated with two slightly different chirped signals. The two chirped signals are processed to increase the unambiguous depth range beyond the 0.5 wave range limit inherent in a single phase angle measurement. The sequence of operations in a two chirp hidden object detector is similar to the one chirp system previously described. In the two chirp system a sequence of transmissions using the first chirp signal is followed by a sequence of transmissions using the second chirp signal. In a two chirp system the starting RF frequencies of the two chirps are offset from one another by a predetermined value, where that predetermined frequency offset value,  $F_{\text{off}}$ , is selected to preferably change the RF carrier frequency by between 2 and 10 percent. In turn, this percentage change in carrier frequency maps into the same percentage change in the carrier wavelength in Equation (8) and hence the same percentage change in the non-time dependent phase of the IF, also shown in Equation (8).

In other words, the two chirp detector makes two independent measurements of the depth using slightly different wavelength signals. It is well known in the interferometer and position encoder arts that two such measurements can be combined to disambiguate the periodic ambiguity of either individual measurement. Horwitz et al. provides an example in U.S. Patent No. 6,366,047 wherein three (or more) such measurements are used to create a very long, unambiguous measurement range using very short wavelength signals.

In one example embodiment, a simple disambiguation scheme may be used. As shown in Figure 13, the response of each phase estimation process with respect to object depth is a sawtooth. That is, the response is a piecewise linear ramp wherein the ramp resets to zero every time the round trip distance to the object increases by one wavelength of the carrier frequency. In the figure, sawtooth 510 is the response of a first chirped signal and sawtooth 520 is the response of a second chirped signal with a longer wavelength. Horizontal lines 511 and 521 represent the measured phase values for the two chirped signals for one object distance. Drawing vertical lines from each intersection of sawtooth 510 and line 511 marks the horizontal axis with the possible distances that could have resulted in the particular phase measurement for the first signal. Of course, these distances are separated by multiples of the wavelength of the first chirp signal. Similarly, drawing vertical lines from each intersection of sawtooth 520 and line 521 marks the horizontal axis with the possible distances that could have resulted in the particular phase measurement for the second chirp signal, again with the distances separated by multiples of the wavelength of the second chirped signal. From the figure it is clear that there is only one distance, point 532, at which it is possible to have the two measured phases simultaneously. That point is the disambiguated object depth.

In an example embodiment of the two chirp detector the nominal RF frequency is about 5.75 gigahertz and the frequency offset,  $F_{\text{off}}$ , between the two chirps is  $\sim 100$  megahertz, resulting in a percentage wavelength change of about 1.7 percent. Therefore, each change in the delay path of  $\sim 5$  centimeters (nominal wavelength) results in a  $\sim 6$  degree phase difference between the two IF phase measurements.

Finally, as is often the case, there are applications of the hidden object detector where the signal-to-noise ratio of the return signal is less than optimum. In some embodiments, therefore, perform an average on the I and Q IF signals immediately after these signals are digitized.

## USER INTERFACE

In many embodiments the hidden object detector is employed as a stud finder. Many substantially equivalent user interfaces can be developed to communicate the presence of a stud behind a wall. As shown in Figure 10, in one embodiment the user interface comprises a graphical display 190 having three variable length vertical bars, the bars being disposed in a

horizontal row. The lengths of the two outer bars are adjusted by the processing electronics to represent the magnitude of the returns in the left and right channels respectively. The central bar is the stud-present indicator. In one embodiment this bar will only illuminate when a stud is in front of the detector. In another embodiment this bar will only be illuminate to, say, one  
5 half its maximum length when a stud is in front of the detector.

As has been mentioned, the detector “declares” a stud to be present based on a set of a priori logic rules applied to the measured data by logic module 168. In one example  
embodiment the rule for declaring a stud to be present in front of the detector comprises three  
10 parts: first, the left and right channels must have substantially equal magnitude returns;  
second, the left and right channels must both have returns substantially greater than a pre-determined clutter level; third, the depth of the scattering object must be approximately equal to typical wallboard thickness.

As has been described, the hidden object detector is capable of sensing the presence of objects other than studs. Additional logic rules may be implemented in logic module 168 to  
15 determine that a non-stud object has been detected. For example, a simple modification of the three part “stud-detected” rule may entail: first, the left and right channels must have substantially equal magnitude returns; second, the left and right channels must both have returns substantially greater than a pre-determined clutter level; and third, the depth of the scattering object is greater than typical wallboard thickness by a pre-determined threshold.  
20 Similarly, the graphical interface can be programmed to communicate the presence of a non-stud object by modifying the display used when a stud is present. For example, the lengths of the two outer bars may be adjusted by the processing electronics to represent the magnitude of the returns in the left and right channels respectively, as with a stud but the central bar will be illuminate to, say, its maximum length when a non-stud is in front of the detector, the longer  
25 bar representing the fact that the object is further away from the detector.

Although the detector 12 is described as using electromagnetic radiation directed at and received from a hidden object for sensing it presence, in the most general sense this form of radiation is not strictly necessary. Potentially other types of radiating signals, such as acoustic signals for example, could be used. Generally, the technique includes directing a  
30 transmitted radiating signal in a direction of an obstruction capable of hiding a hidden object, where the transmitted radiating signal includes a chirped signal whose instantaneous

frequency increases or decreases substantially linearly during a transmission period, and the instantaneous frequency having a minimum frequency and a maximum frequency. The technique further includes receiving at least one received radiating signal from the direction of the obstruction and using the received radiating signal to generate a received signal for processing, and using a signal processing system to estimate a signal strength and a time delay of the received signal and to generate an indicator signal to drive a user interface, where the time delay is measured relative to an internal reference signal and where the indicator signal is indicative of presence or absence of the hidden object. The time delay, or phase, is used to obtain an accurate estimate of the depth (or distance to) the object, and this information along with signal strength information enable very accurate and useful object detection capability.

While various embodiments have been particularly shown and described, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope as defined by the appended claims.

## CLAIMS

What is claimed is:

1. A hidden object detector comprising:

a transmission signal source, the transmission signal comprising a chirped signal wherein the instantaneous frequency of the signal increases or decreases substantially linearly during a transmission period, the instantaneous frequency having a minimum frequency and a maximum frequency;

a transmitter of electromagnetic radiation, the transmitter being driven by the signal source, the transmitter transmitting the electromagnetic radiation away from the detector, towards an obstruction capable of hiding a hidden object;

at least one receiver of electromagnetic radiation, the receiver disposed in close lateral proximity to the transmitter, the receiver further disposed to receive at least a portion of the electromagnetic radiation as reflected back towards the detector from the direction of the obstruction, the receiver producing a received signal; and

a signal processing system, the signal processing system configured to estimate a signal strength and a time delay of the received signal from the at least one receiver, the time delay being measured relative to an internal reference signal, the signal processing system further configured to generate an indicator signal to drive a user interface, the indicator signal being indicative of presence or absence of the hidden object.

2. The detector of claim 1, wherein the nominal frequency,  $f_c$ , is in a range between 1 gigahertz and 50 gigahertz.

3. The detector of claim 1, wherein the nominal frequency,  $f_c$ , is in a range between 4 gigahertz and 6 gigahertz.

4. The detector of claim 3, wherein the instantaneous frequency has a minimum frequency of approximately  $0.9825 \cdot f_c$  and a maximum frequency of approximately  $1.0175 \cdot f_c$ .

5. The detector of claim 1, comprising two receivers of electromagnetic radiation wherein the two receivers are disposed in close lateral proximity to the transmitter, wherein the receivers are disposed with the transmitter between them.
6. The detector of claim 1, wherein the signal processing system includes at least one electronic mixer wherein the mixer produces at least one output signal having an intermediate frequency (IF).
7. The detector of claim 6, wherein the signal processing system includes a homodyne mixer and a local oscillator signal source wherein the mixer comprises a reference input and a signal input, wherein further the internal reference signal is obtained from the transmission signal source.
8. The detector of claim 7, wherein the signal processing system includes a delay line wherein the delay line delays the signal on the signal input of the mixer relative to the signal on the reference input of the mixer.
9. The detector of claim 6, wherein the signal processing system includes a heterodyne mixer and a local oscillator signal source, wherein the mixer comprises a reference input and a signal input, wherein further the internal reference signal is obtained from the local oscillator signal source, the local oscillator signal comprises a chirped signal wherein the minimum instantaneous frequency, maximum instantaneous frequency and transmission period are substantially equal to corresponding frequencies and period of the transmission signal.
10. The detector of claim 6, wherein the electronic mixer is an I-Q mixer configured to produce two IF output signals in quadrature.
11. The detector of claim 10, wherein the signal processing system includes a subsystem for estimating instantaneous phase and magnitude of the two IF signals, the estimating including an arctangent operation using the two IF signals.

12. The detector of claim 6, wherein the signal processing system includes a subsystem for estimating the instantaneous phase and magnitude of the at least one output IF signal, the subsystem operative to perform a Fourier transformation operation.

13. The detector of claim 1, wherein the signal processing system includes a decision logic module operative to apply a pre-determined set of rules to the measured phases and magnitudes of the signals from the at least one receiver to determine whether the received signal is indicative of the presence of the hidden object.

14. The detector of claim 1, wherein the rules include first, second and third rules, the first rule requiring substantially equal magnitudes for return signals from different receivers, the second rule requiring magnitudes for the return signals above a threshold noise or clutter level, and a third rule requiring a calculated depth of the hidden object to be substantially equal to a thickness of a the obstruction.

15. The detector of claim 1, further comprising four receivers of radiation, the four receivers disposed in close lateral proximity to the transmitter, wherein the receivers are disposed substantially in a square array, the receivers further disposed with the transmitter centered in the square array.

16. The detector of claim 1 wherein the user interface is part of the detector and includes a graphical display for displaying a graphical indicator based on the indicator signal.

17. The detector of claim 1 for use with a wall panel as the obstruction, wherein the electromagnetic radiation is in a frequency range for which there is substantial transmission through the wall panel and substantial reflection from the hidden object.

18. The detector of claim 17, wherein the wall panel is a sheet of gypsum-based drywall.

19. The detector of claim 17, wherein the hidden object is a wooden framing member.

20. The detector of claim 1, wherein the electromagnetic radiation from the transmitter has a power level in the range of 10 microwatts to 10 milliwatts.

21. The detector of claim 1, wherein the signal processing system is operative when generating the indicator signal to calculate an estimated depth of the hidden object behind the obstruction based on the estimated time delay.

22. The detector of claim 21, wherein calculating the estimated depth includes removing a depth ambiguity arising from periodicity of the electromagnetic radiation.

23. The detector of claim 22, wherein removing the depth ambiguity includes (1) making multiple measurements of phase at respective times during the transmission period to obtain a non-ambiguous coarse depth measure, and (2) combining the non-ambiguous coarse depth measure with a finer depth measure.

24. The detector of claim 22, wherein removing the depth ambiguity includes (1) a second chirped signal transmitted by the detector in the direction of the obstruction and received by the receiver as electromagnetic radiation reflected back towards the detector, and (2) combining a first depth measurement with a second depth measurement based on the second chirped signal.

25. The detector of claim 1, wherein respective values of the sweep time of the chirped signal and the minimum and maximum frequencies are effective to enable the signal processing system to generate an intermediate-frequency signal of a known frequency from the received signal when the time delay is on the order of 10 nanoseconds or less.

26. The detector of claim 25, wherein (1) the sweep time of the chirped signal is on the order of 18 microseconds, (2) the minimum and maximum frequencies are separated by on the order of 200 MHz, and (3) the signal processing system includes a mixer operative to

generate the intermediate-frequency signal on the order of 80 KHz from the received signal when the time delay is on the order of 7 nanoseconds.

27. A method of sensing a hidden object using the detector of claim 1, comprising the steps of:

moving the detector at a surface of the obstruction while monitoring the user interface for an indication of presence of the hidden object, the indication being generated by the detector using the indicator signal from the signal processing system.

28. The method of claim 27, wherein the obstruction is a wall and the hidden object is a framing member to which the wall is attached, and wherein the detector is moved in a general area of the wall where the framing member is believed to be located.

29. The method of claim 27, further including a calibration operation in which (1) the detector is placed at a known area of the same or similar wall where no hidden object is located, and (2) calibration measurement values are obtained and stored while the detector is placed at the known area, and wherein the signal processing system is operative to subtract the calibration measurement values from operational measurement values to generate the indicator signal.

30. A method, comprising:

directing a transmitted radiating signal in a direction of an obstruction capable of hiding a hidden object, the transmitted radiating signal comprising a chirped signal whose instantaneous frequency increases or decreases substantially linearly during a transmission period, the instantaneous frequency having a minimum frequency and a maximum frequency;

receiving at least one received radiating signal from the direction of the obstruction and using the received radiating signal to generate a received signal for processing; and

using a signal processing system to estimate a signal strength and a time delay of the received signal and to generate an indicator signal to drive a user interface, the time delay

being measured relative to an internal reference signal, the indicator signal being indicative of presence or absence of the hidden object.

31. The method of claim 30, wherein the transmitted and received radiating signals are electromagnetic signals.

FIG. 1A

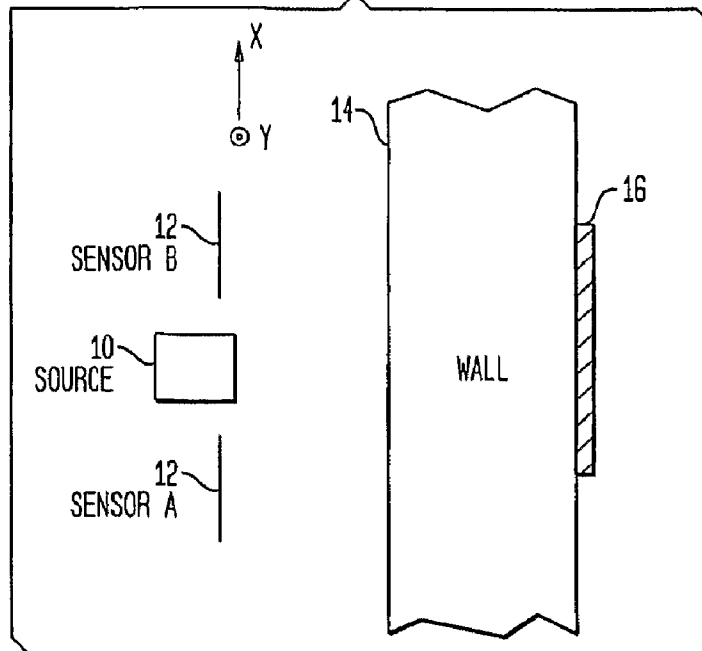
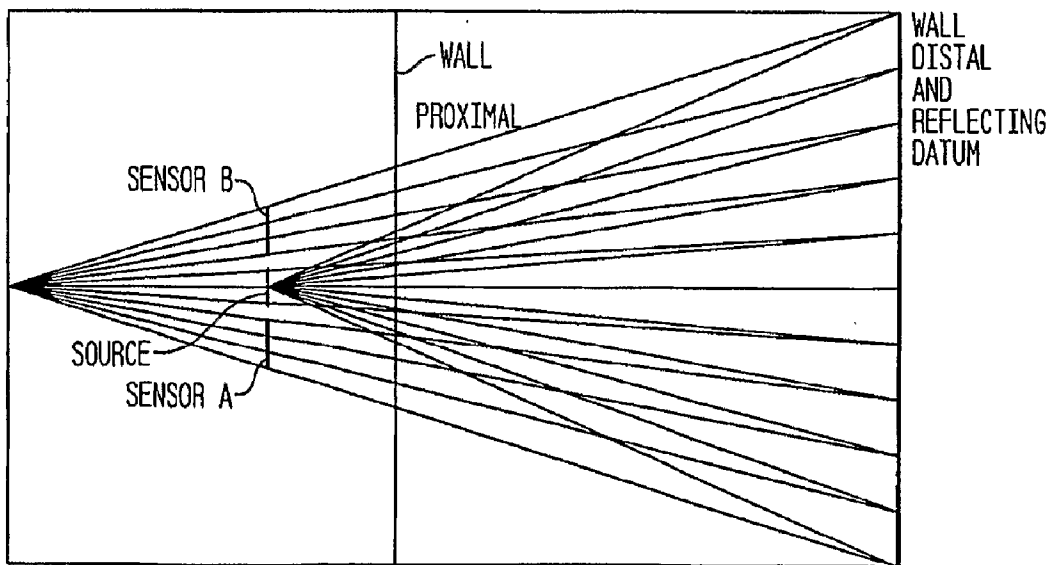


FIG. 1B



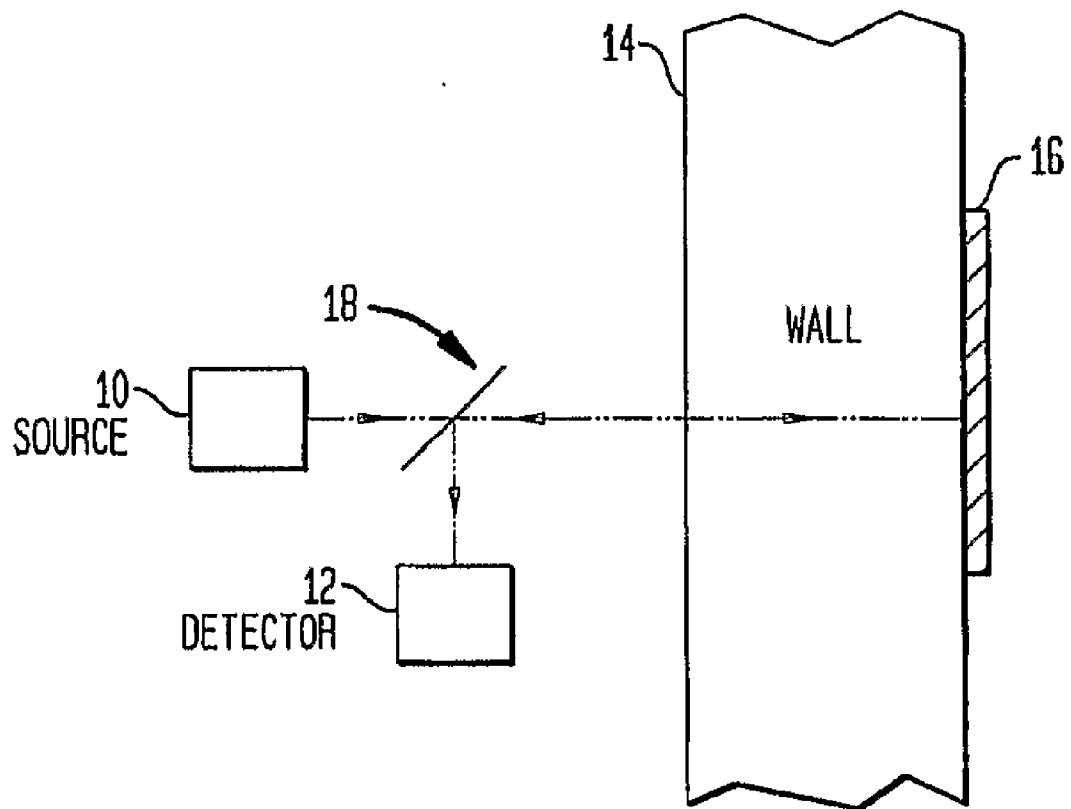
**FIG. 2**

FIG. 3

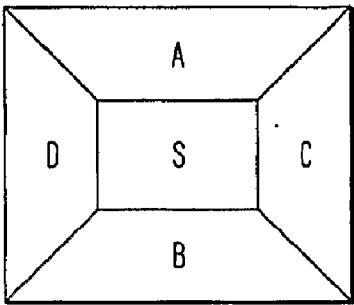


FIG. 4

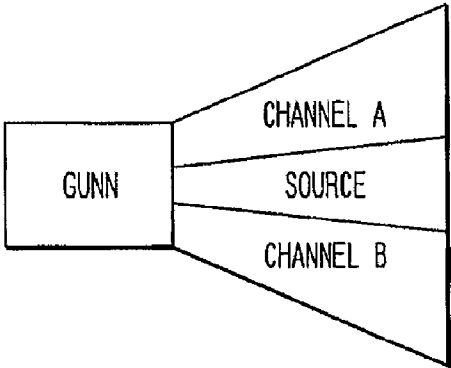
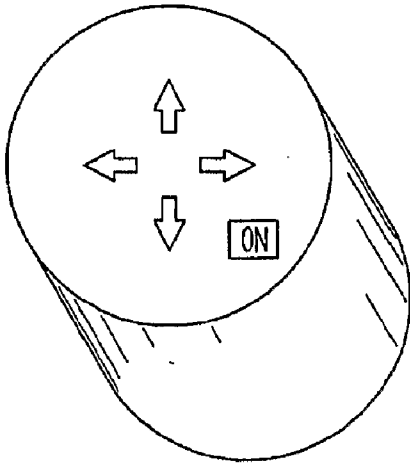
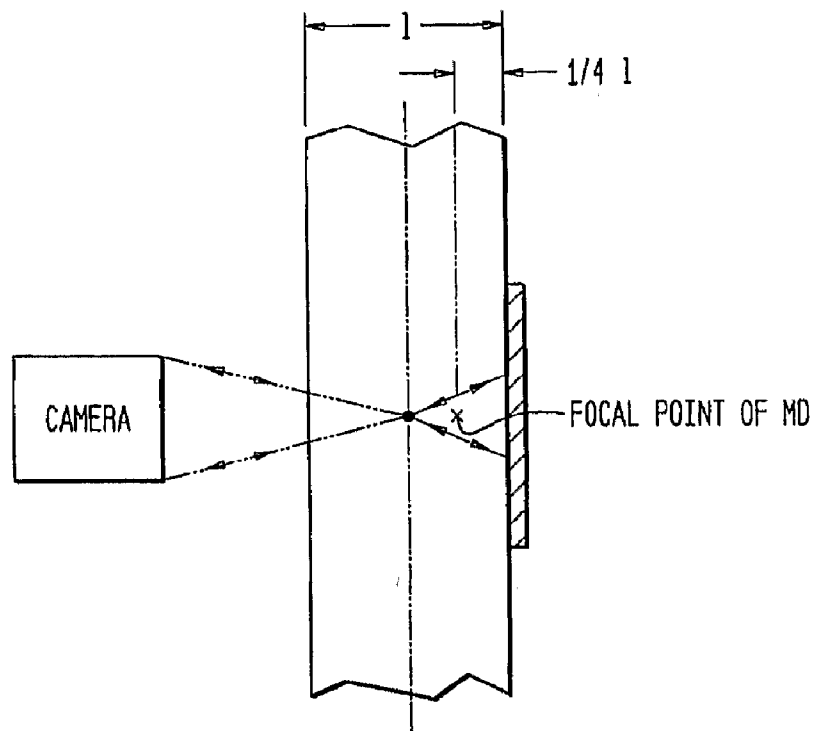


FIG. 5

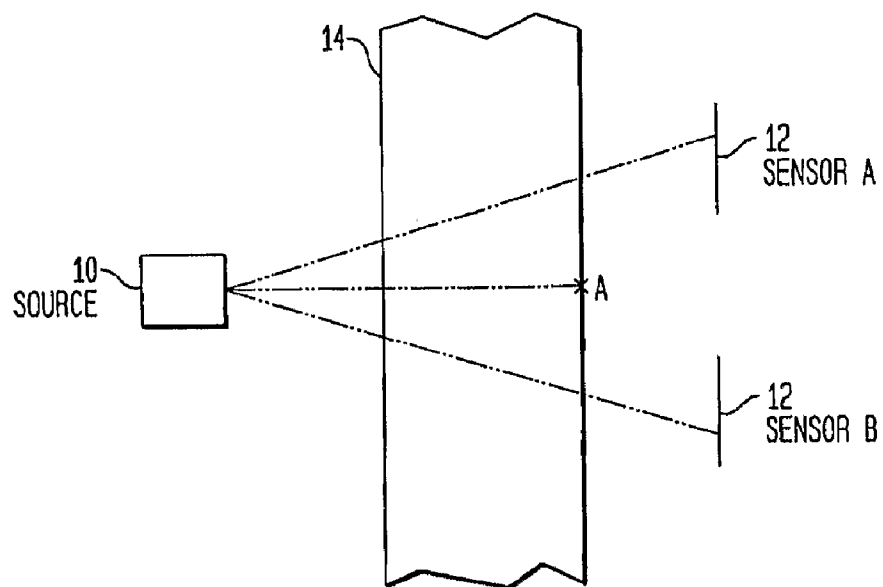


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**FIG. 6**



**FIG. 7**



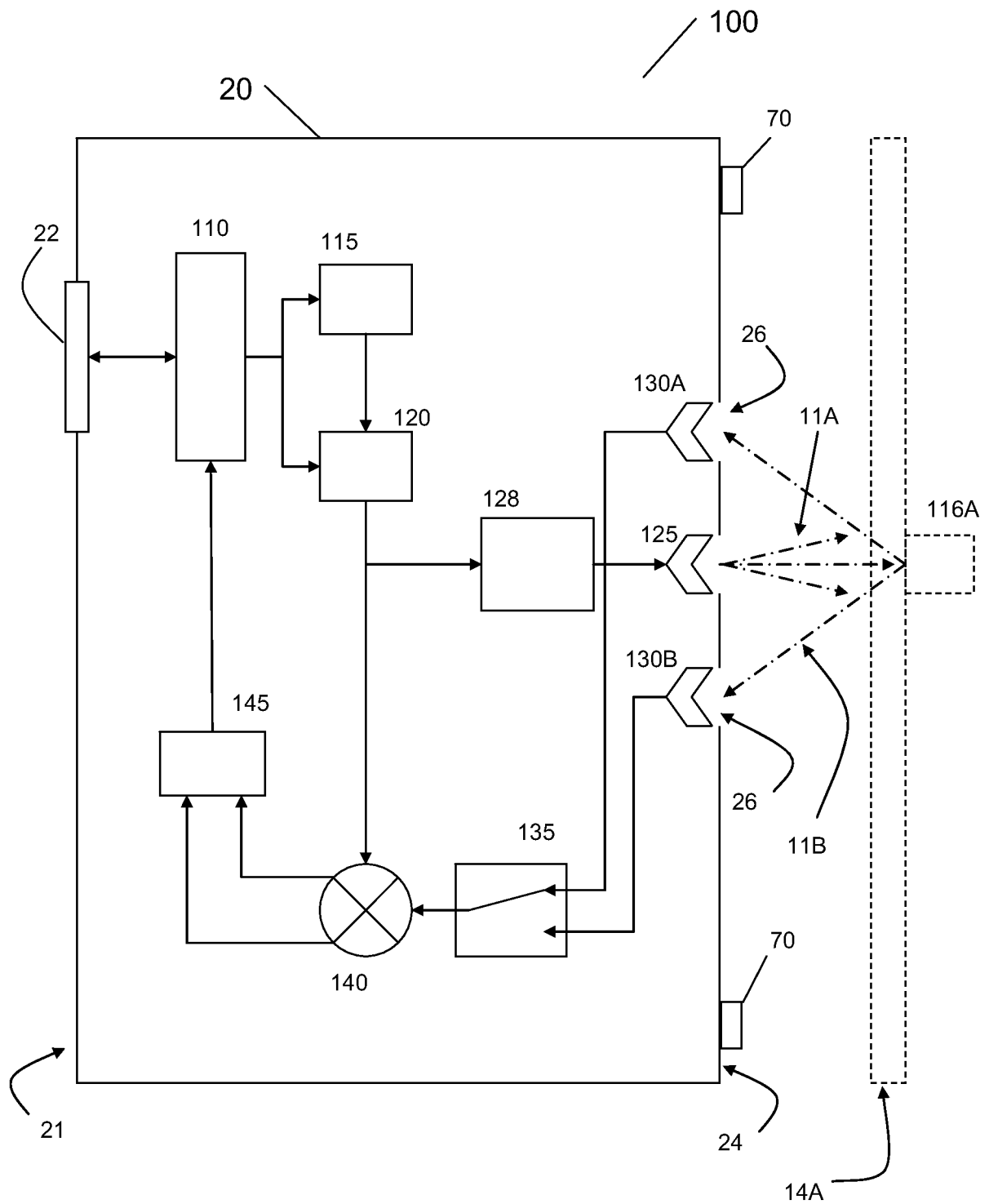


Figure 8

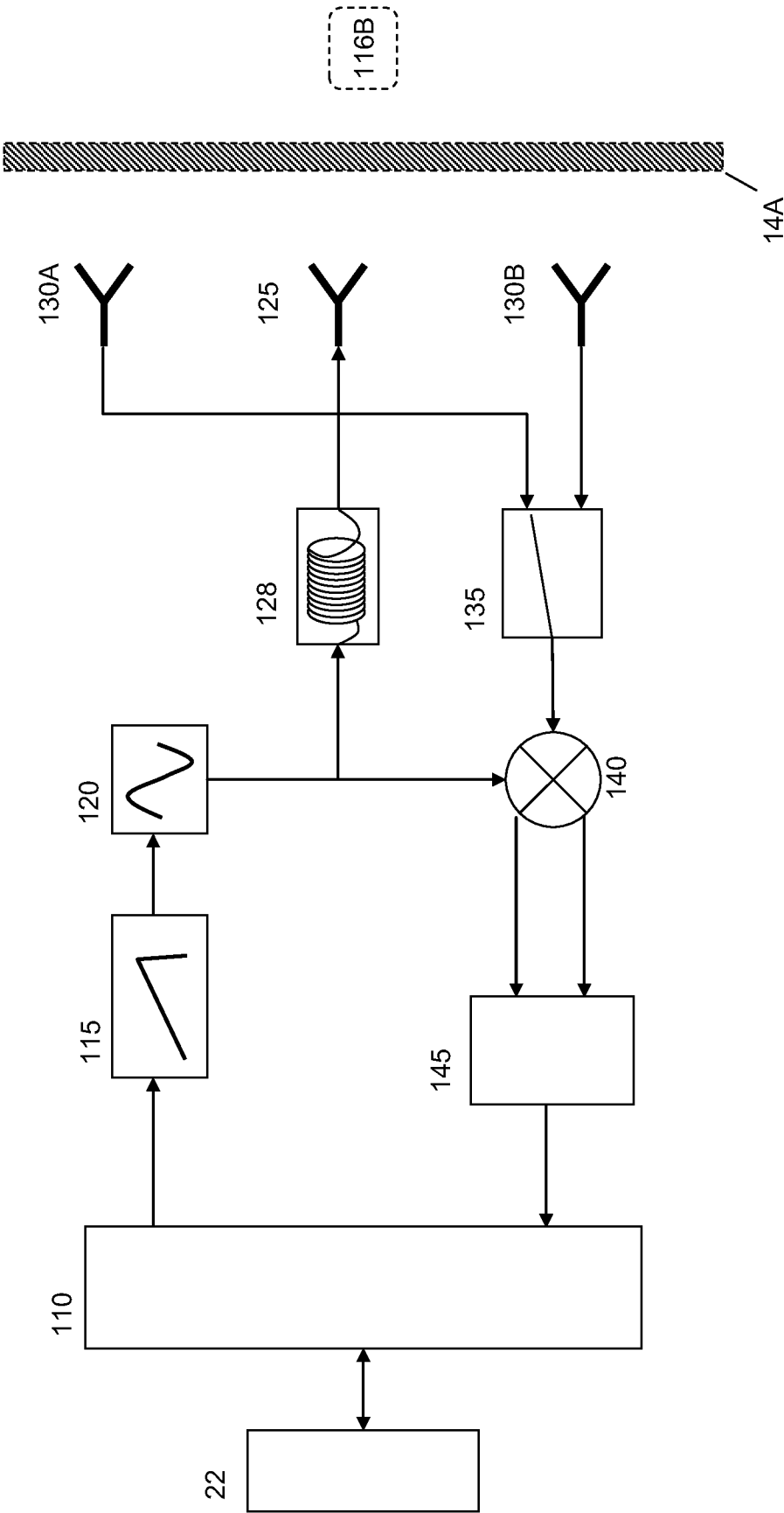


Figure 9

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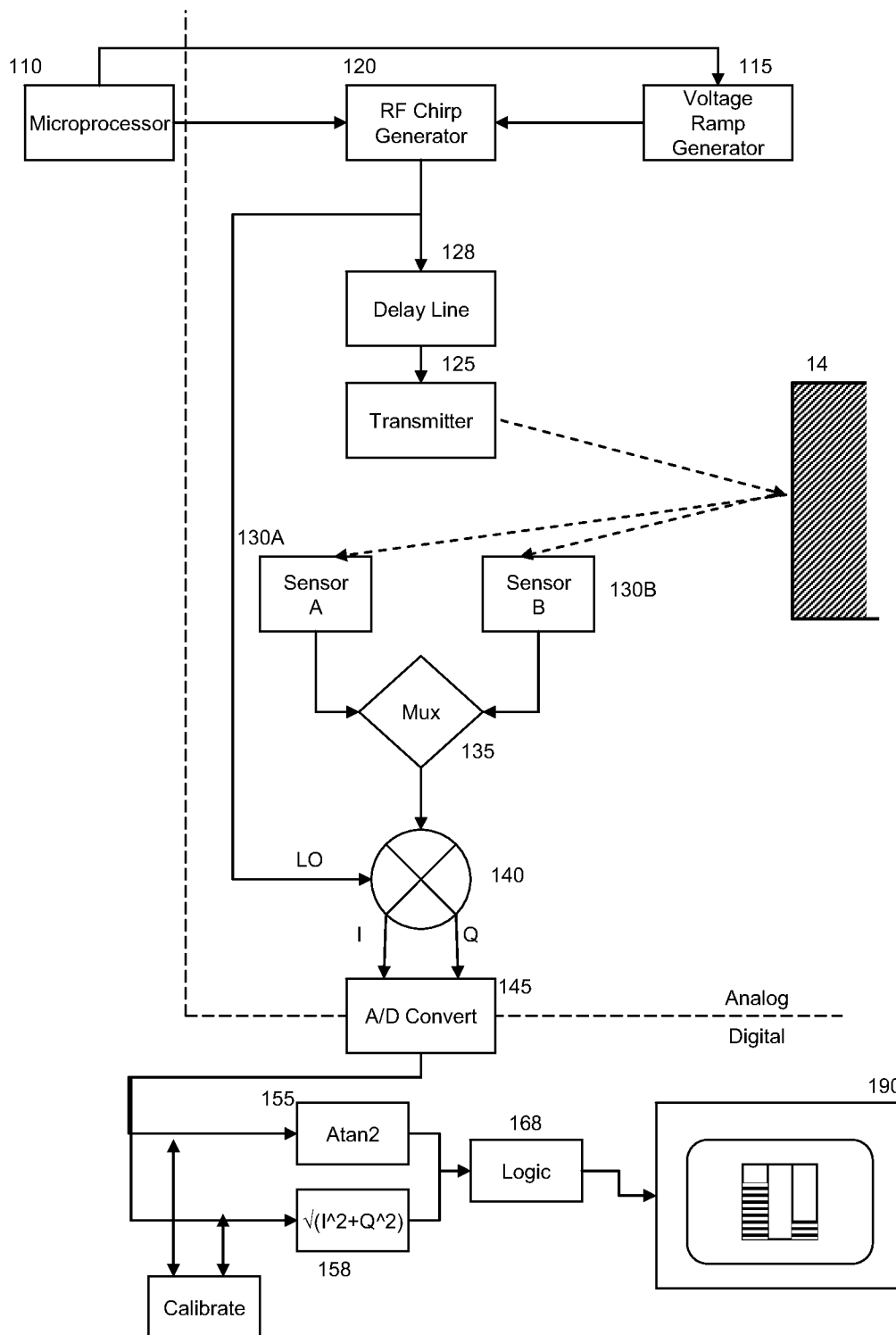


Figure 10

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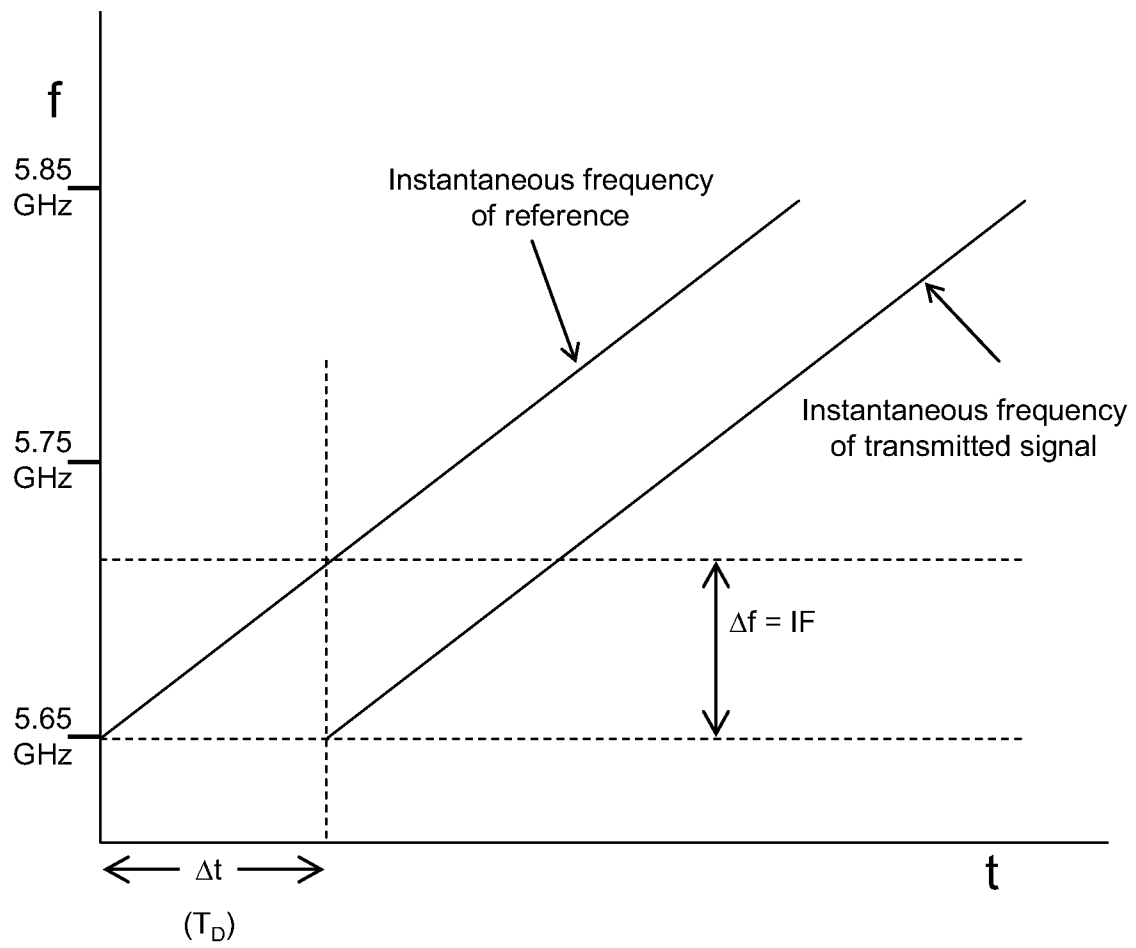


Figure 11

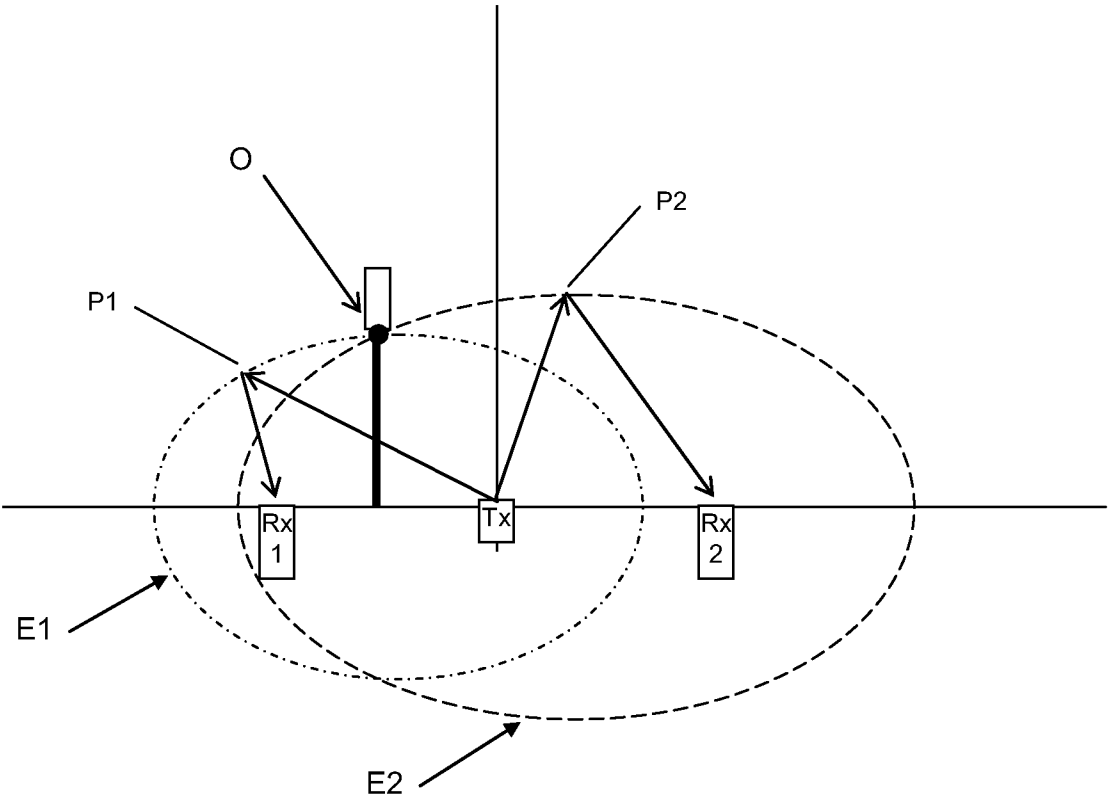


Figure 12

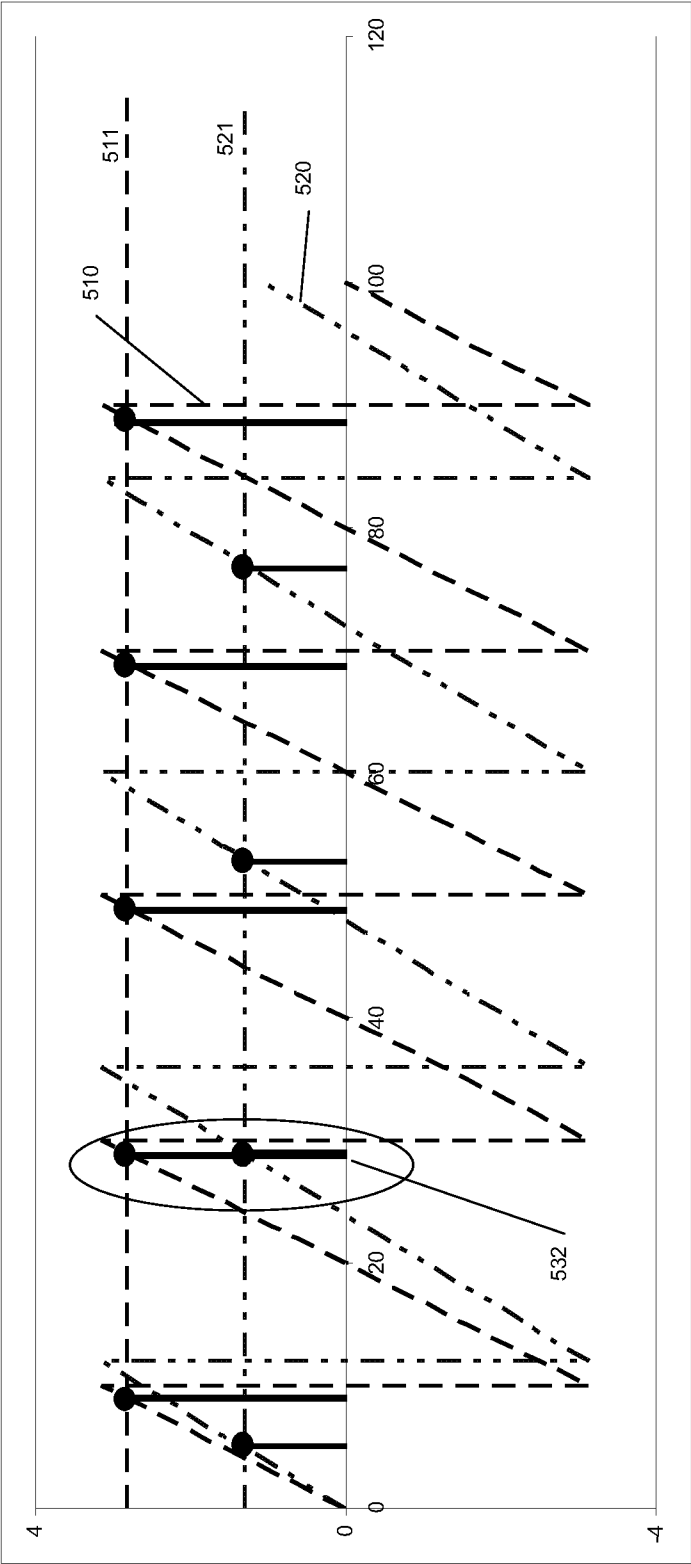


Figure 13

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 2012/024317

A. CLASSIFICATION OF SUBJECT MATTER **G01N 22/02 (2006.01)**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01V 3/12, G01N 22/00-22/02, G01S 13/88

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

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

RUPAT, RUABRU, RUPAT-OLD, RUABU1, Esp@cenet, PAJ, USPTO DB, PatSearch

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                                                    | Relevant to claim No.       |
|-----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|
| Y         | RU 2121671 C1 (OTKRYTOE AKTSIONERNOE OBSHESTVO "TSENTRALNY NAUCHNO-ISSLEDOVATELSKY INSTITUT RADIOELEKTRONNYKH SISTEM") 10.11.1998                                     | 1-3, 5-10, 15-21, 25, 27-31 |
| Y         | RU 2234694 C2 (ZARENKOV VYACHESLAV ADAMOVICH et al.) 20.08.2004                                                                                                       | 1, 27, 30                   |
| Y         | US 7592943 B2 (QINETIQ LIMITED) 22.09.2009                                                                                                                            | 1, 27, 30                   |
| Y         | US 2009/0212990 A1 (PAUL A.CLOUTIER) 01.03.2011                                                                                                                       | 5, 15                       |
| Y         | RU 2375729 C1 (GOSUDARSTVENNOE OBRAZOVATELNOE UCHREZHDENIE VYSSCEGO PROFESSIONALNOGO OBRAZOVANIYA VOENNO-KOSMICHEESKAYA AKADEMIYA IMENI A. F. MOZHAISKOGO) 10.12.2009 | 21                          |



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See patent family annex.

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

13 April 2012 (13.04.2012)

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