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Gogineni et al.

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[45] **Date of Patent: Feb. 2, 1999**

[54] **SWEPT-STEP RADAR SYSTEM AND DETECTION METHOD USING SAME**

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[21] Appl. No.: **788,355**

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[51] **Int. Cl.^{6}** **G01S 13/88**; G01S 13/04

[52] **U.S. Cl.** **342/22**; 342/128; 342/129; 342/192; 342/196

[58] **Field of Search** 342/22, 27, 127, 342/128, 129, 192, 194, 196

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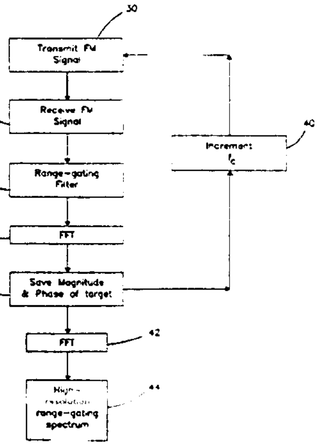
Attorney, Agent, or Firm—Merchant, Gould, Smith, Edell, Welter & Schmidt, P.A.

[57] **ABSTRACT**

An apparatus and method for detecting an object and determining the range of the object is disclosed. A transmitter, coupled to an antenna, transmits a frequency-modulated probe signal at each of a number of center frequency intervals or steps. A receiver, coupled to the antenna when operating in a monostatic mode or, alternatively, to a separate antenna when operating in a bistatic mode, receives a return signal from a target object resulting from the probe signal. Magnitude and phase information corresponding to the object are measured and stored in a memory at each of the center frequency steps. The range to the object is determined using the magnitude and phase information stored in the memory. The present invention provides for high-resolution probing and object detection in short-range applications. The present invention has a wide range of applications including high-resolution probing of geophysical surfaces and ground-penetration applications. The invention may also be used to measure the relative permittivity of materials.

25 Claims, 31 Drawing Sheets

3½ yR mtn fee 02 Aug 02
7½ yR mtn fee 02 Aug 06
11½ yR mtn fee 02 Aug 10



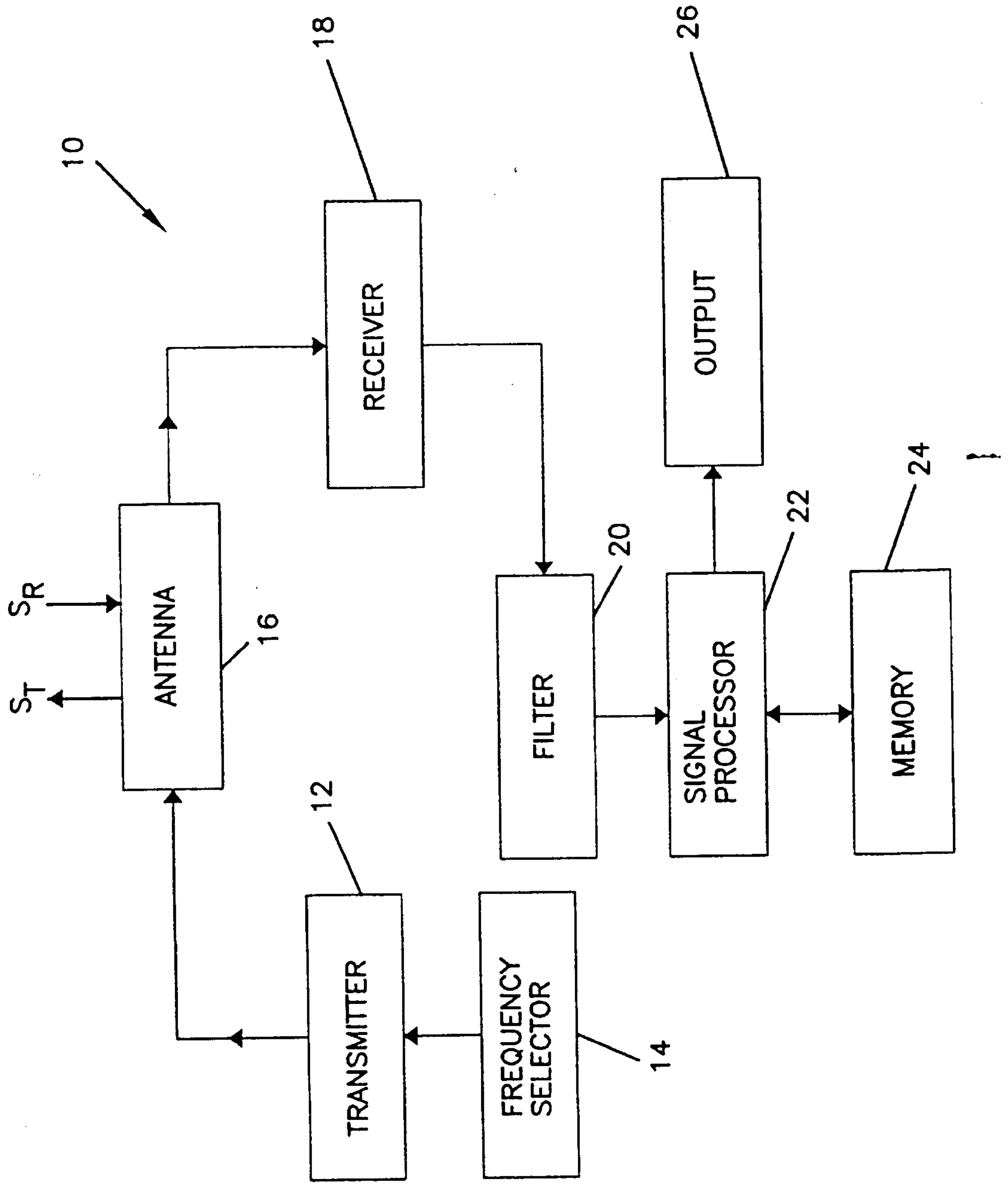

10
18
26
RECEIVER
OUTPUT
S_R
S_T
ANTENNA
16
20
22
24
FILTER
SIGNAL PROCESSOR
MEMORY
12
TRANSMITTER
FREQUENCY SELECTOR
14

FIG. 2

FIG. 4

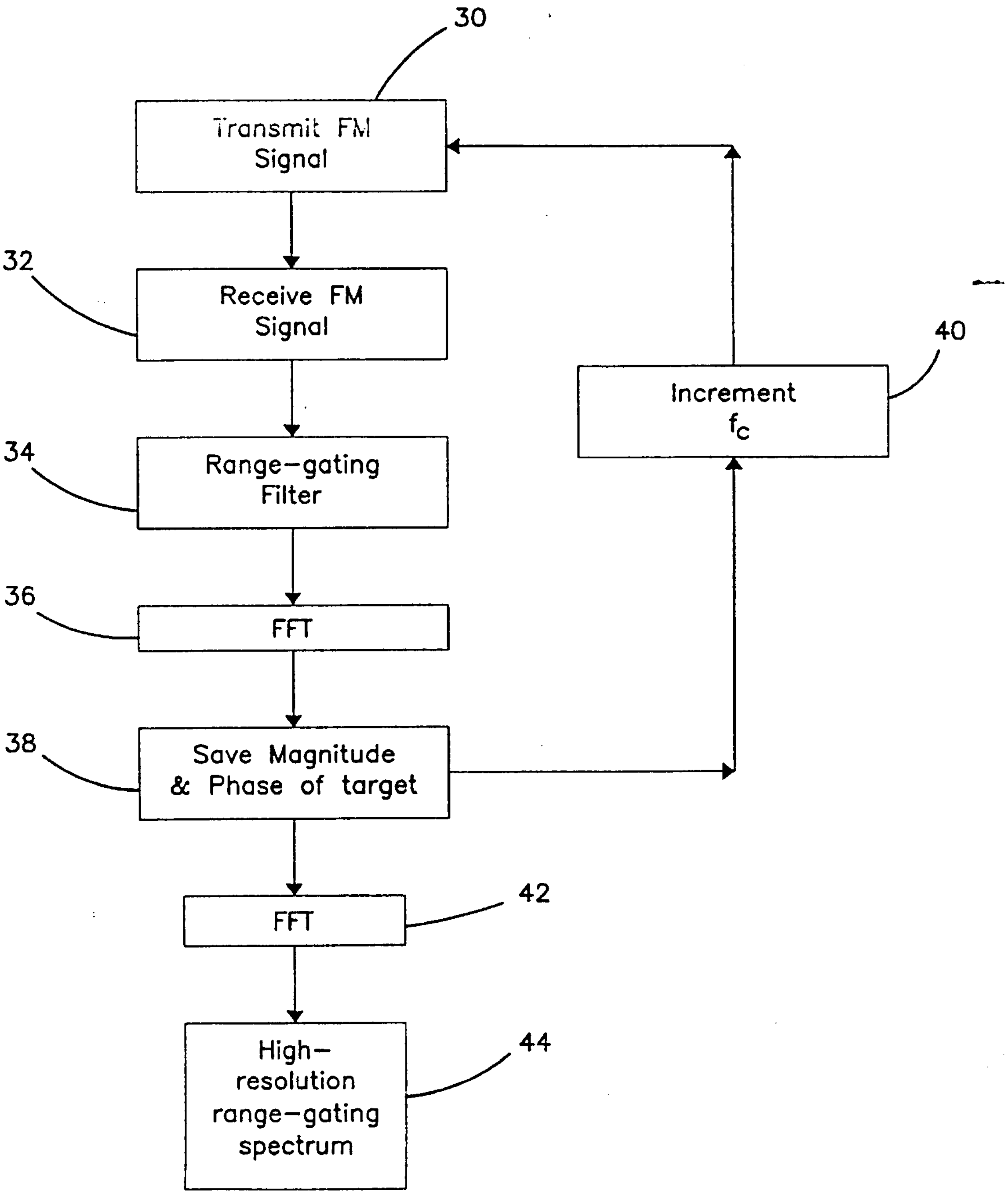

30
Transmit FM Signal
32
Receive FM Signal
34
Range-gating Filter
36
FFT
38
Save Magnitude & Phase of target
40
Increment f_c
42
FFT
44
High-resolution range-gating spectrum

FIG. 6

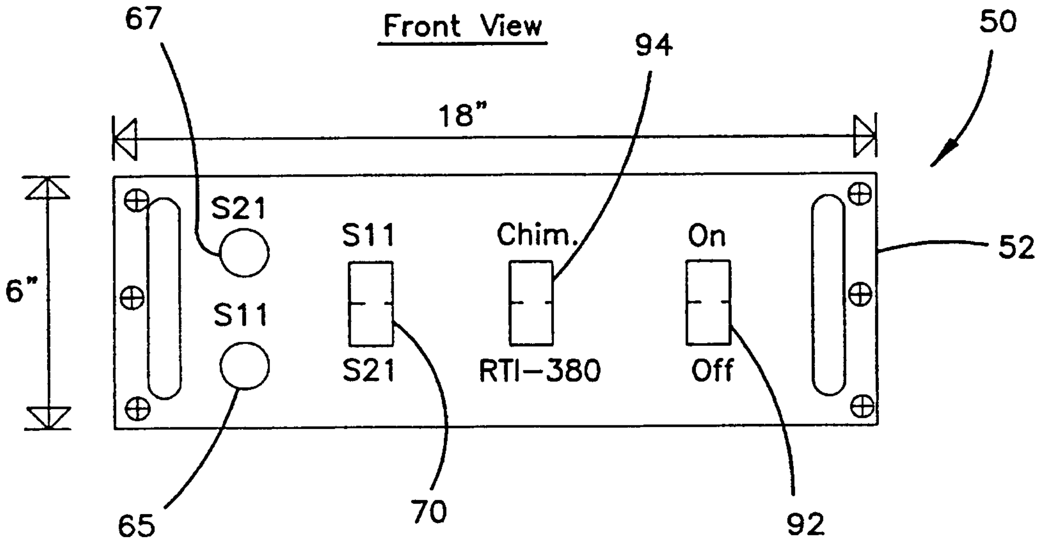

67
Front View
94
50
18"
6"
S21
S11
S11
S21
Chim.
RTI-380
On
Off
52
65
70
92

FIG. 8

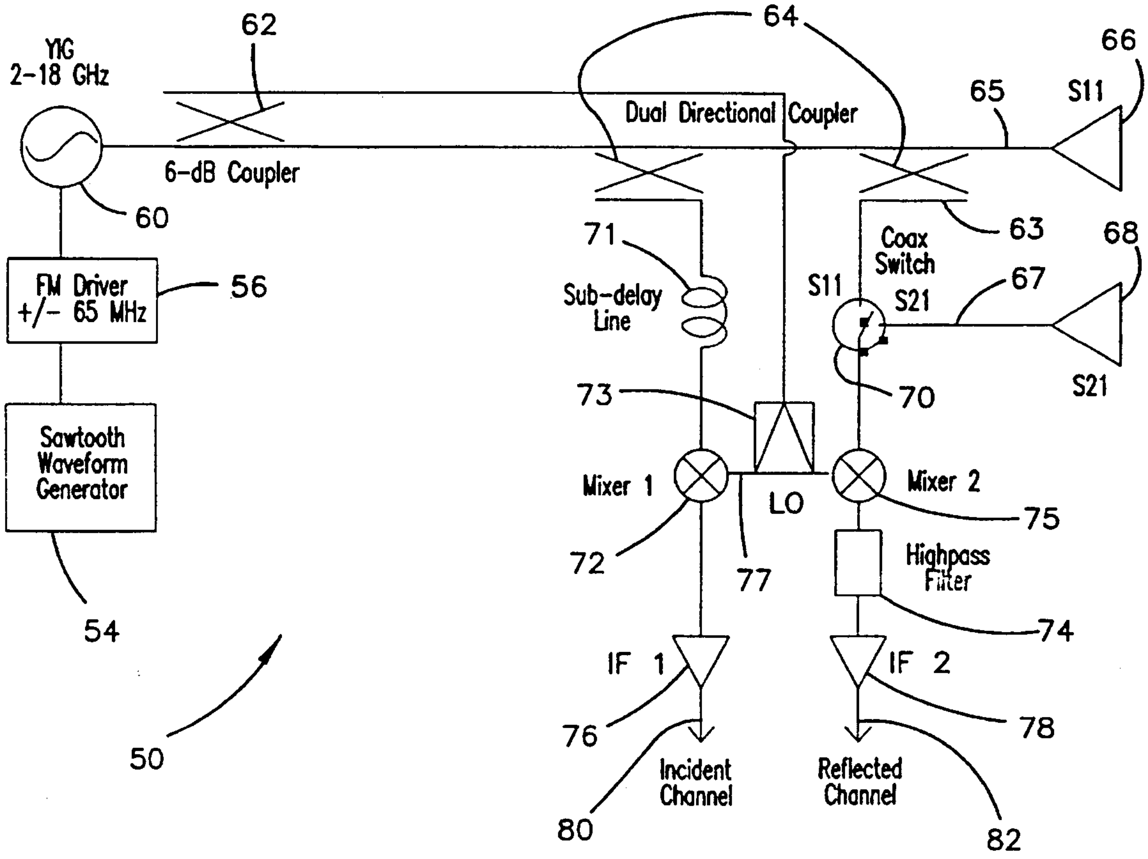

62
64
66
YIG
2-18 GHz
Dual Directional Coupler
65
S11
6-dB Coupler
60
63
68
71
Coax
Switch
S11
S21
67
Sub-delay
Line
FM Driver
+/- 65 MHz
56
73
70
S21
Sawtooth
Waveform
Generator
Mixer 1
LO
Mixer 2
75
72
77
Highpass
Filter
74
54
IF 1
IF 2
76
78
50
Incident
Channel
Reflected
Channel
80
82

FIG. 10

LABEL LIST

Sawtooth	2.00 V	ac voltage
P2	15.00 V	battery
P1	15.00 V	battery
P1	15.00 V	battery
C5	10.00pF	capacitor
L1	2.00μH	inductor
Q2	npn	npn bjt
Q2	npn	npn bjt
AMP2	opamp	opamp
AMP4	opamp	opamp
AMP1	opamp	opamp
AMP3	opamp	opamp
Q1	pnp	pnp bjt
Q1	pnp	pnp bjt
R11	5.60kΩ	resistor
POT3	5.00kΩ	resistor
R4	5.60kΩ	resistor
R6	4.70kΩ	resistor
POT2	10.00kΩ	resistor
POT1	5.00kΩ	resistor
R9	22.00 Ω	resistor
R1	0.50 Ω	resistor
R5	5.60kΩ	resistor
R3	2.70kΩ	resistor
R14	22.00 Ω	resistor
R2	2.70kΩ	resistor
R1	150.00 Ω	resistor
D1	10 V	zener diode

FIG. 12

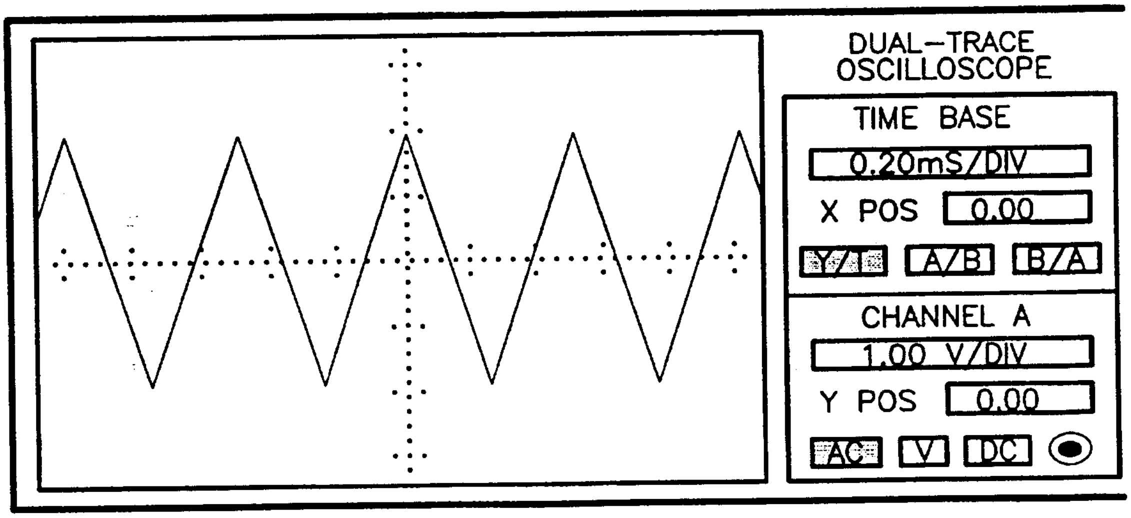

DUAL-TRACE OSCILLOSCOPE
TIME BASE
0.20mS/DIV
X POS
0.00
Y/T
A/B
B/A
CHANNEL A
1.00 V/DIV
Y POS
0.00
AC
V
DC

FIG. 14

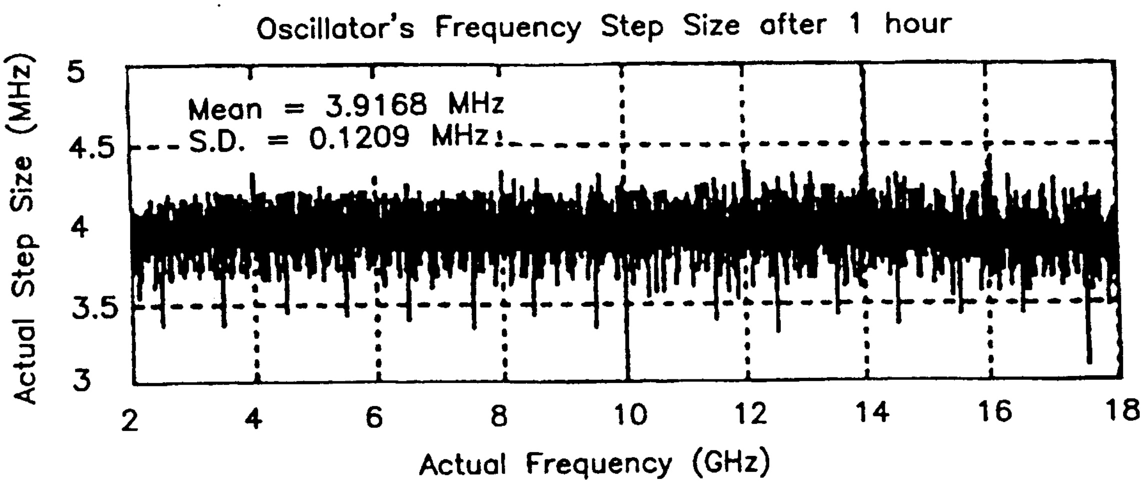

Oscillator's Frequency Step Size after 1 hour
Mean = 3.9168 MHz
S.D. = 0.1209 MHz
Actual Step Size (MHz)
5
4.5
4
3.5
3
2
4
6
8
10
12
14
16
18
Actual Frequency (GHz)

FIG. 16

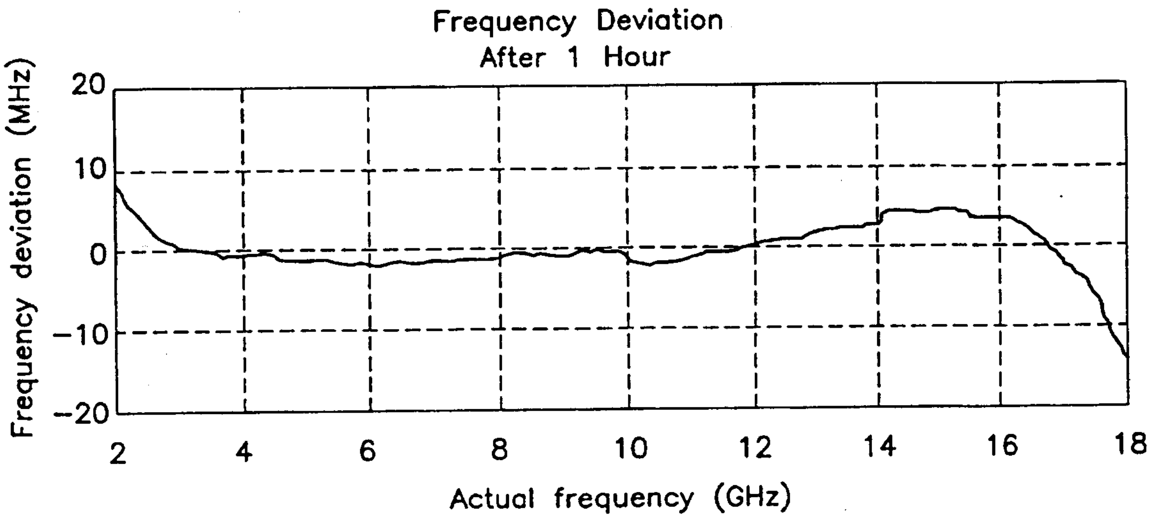

Frequency Deviation
After 1 Hour
Frequency deviation (MHz)
20
10
0
−10
−20
2
4
6
8
10
12
14
16
18
Actual frequency (GHz)

FIG. 18

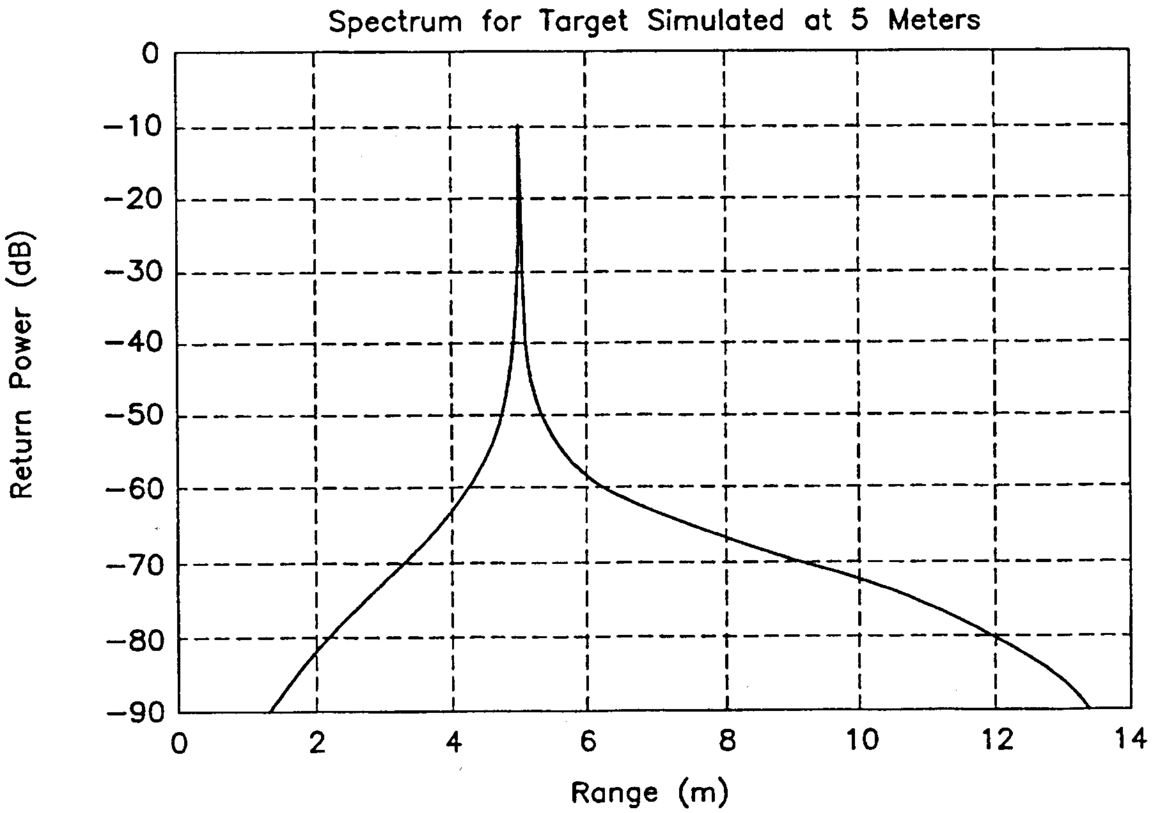

Spectrum for Target Simulated at 5 Meters
Return Power (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
0
2
4
6
8
10
12
14
Range (m)

FIG. 20

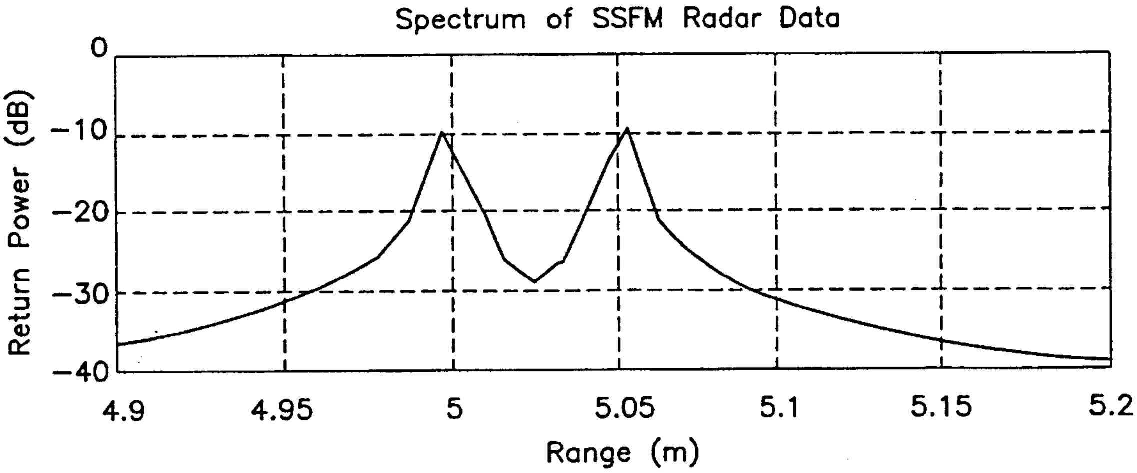

Spectrum of SSFM Radar Data
Return Power (dB)
0
-10
-20
-30
-40
4.9
4.95
5
5.05
5.1
5.15
5.2
Range (m)

FIG. 22

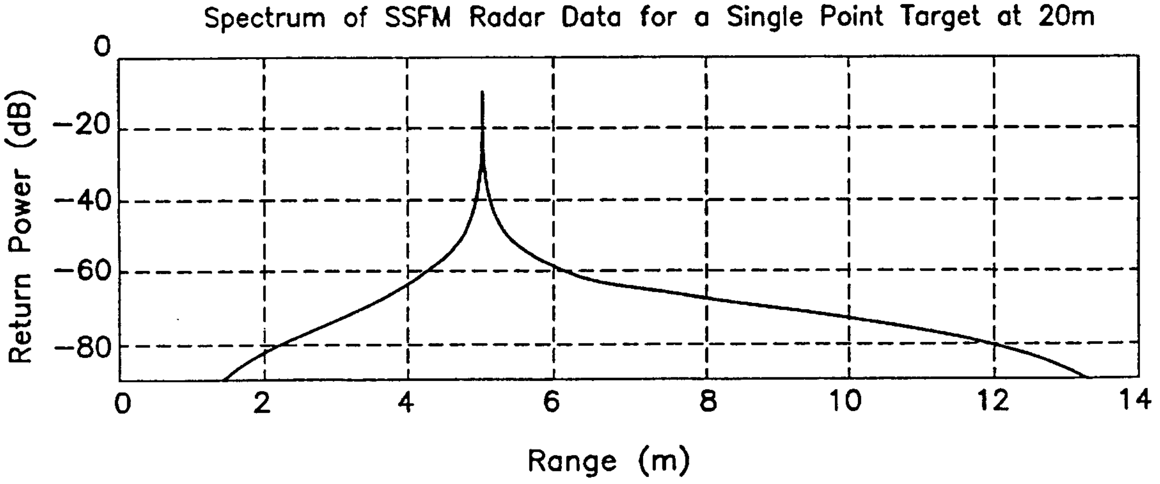

Spectrum of SSFM Radar Data for a Single Point Target at 20m
Return Power (dB)
0
-20
-40
-60
-80
0
2
4
6
8
10
12
14
Range (m)

FIG. 24

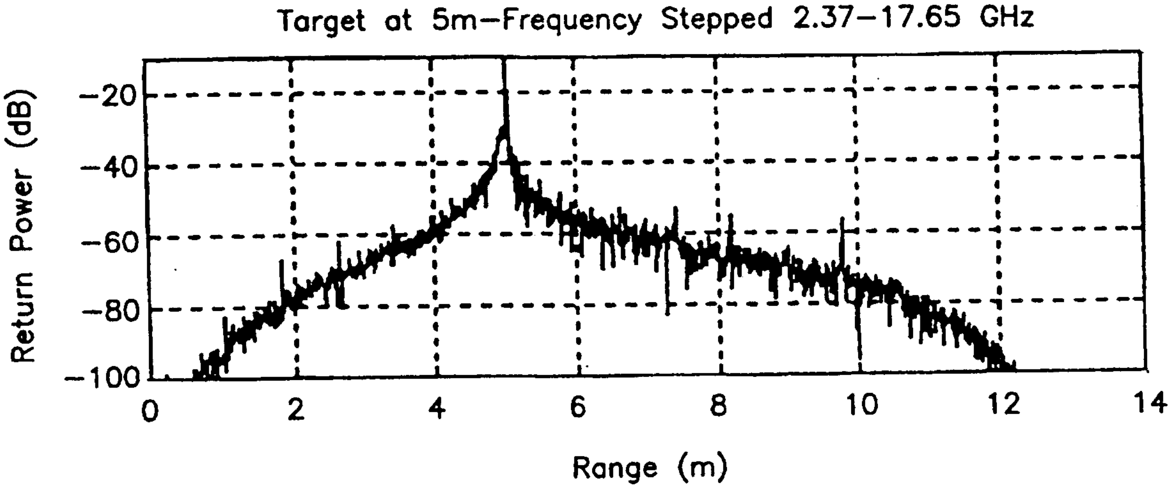

Target at 5m—Frequency Stepped 2.37—17.65 GHz
Return Power (dB)
-20
-40
-60
-80
-100
0
2
4
6
8
10
12
14
Range (m)

FIG. 26

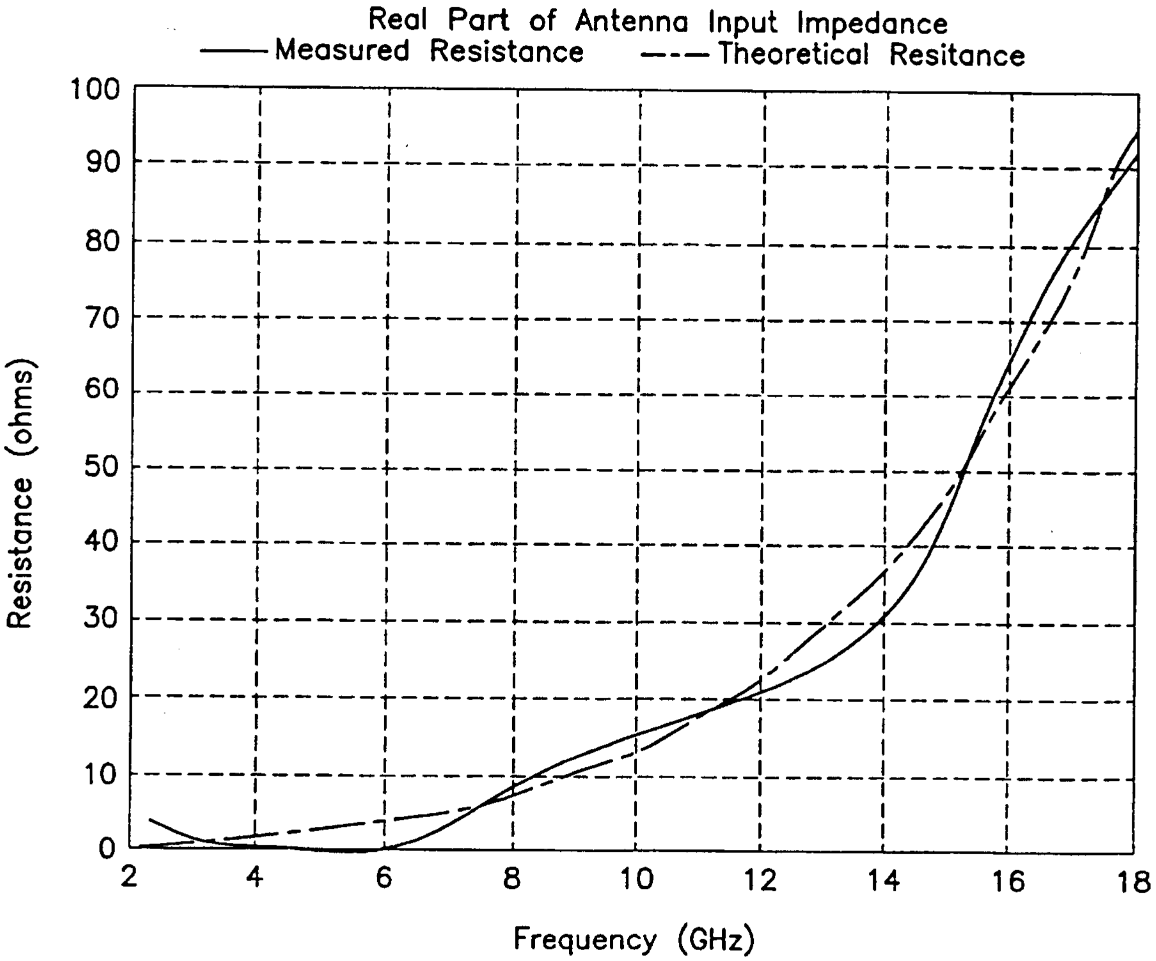

Real Part of Antenna Input Impedance
—— Measured Resistance
––– Theoretical Resitance
Resistance (ohms)
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
Frequency (GHz)

FIG. 28

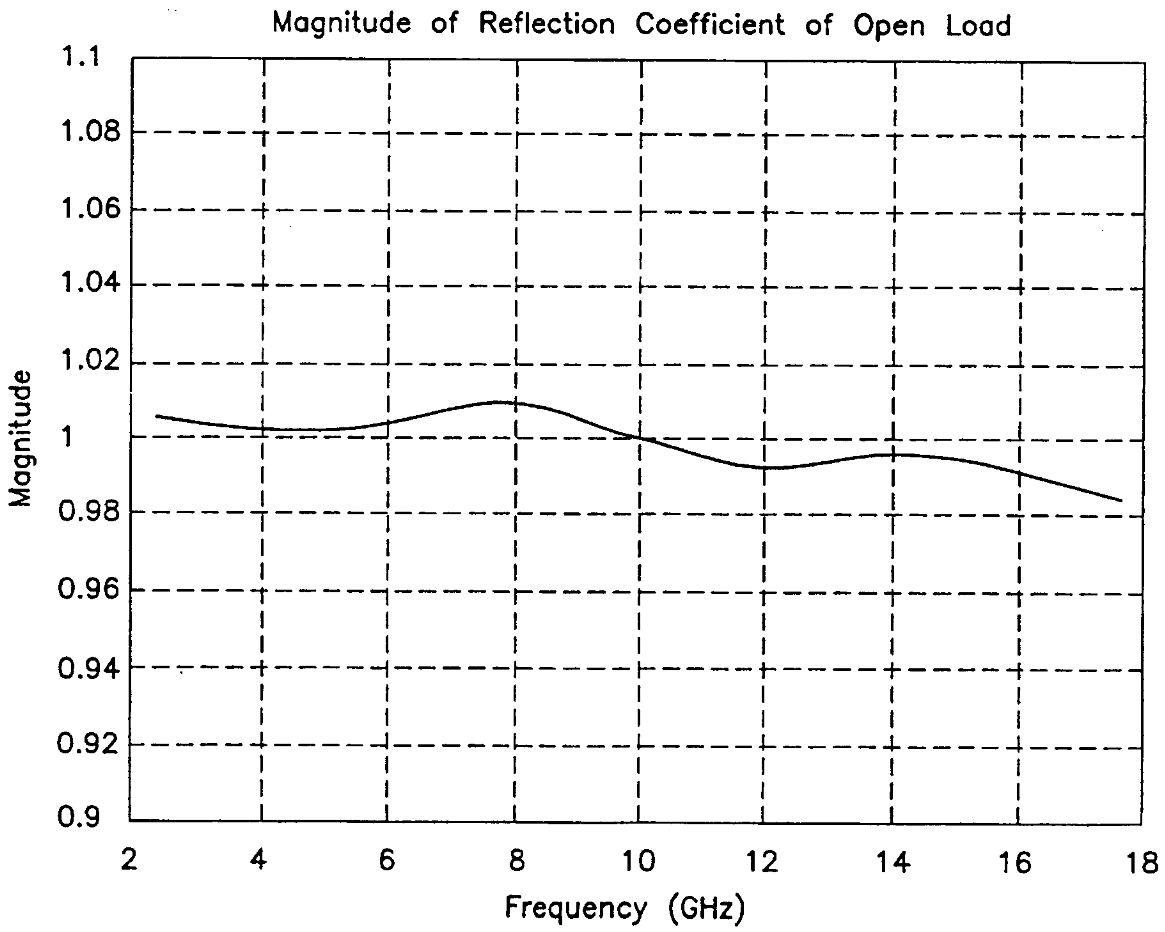
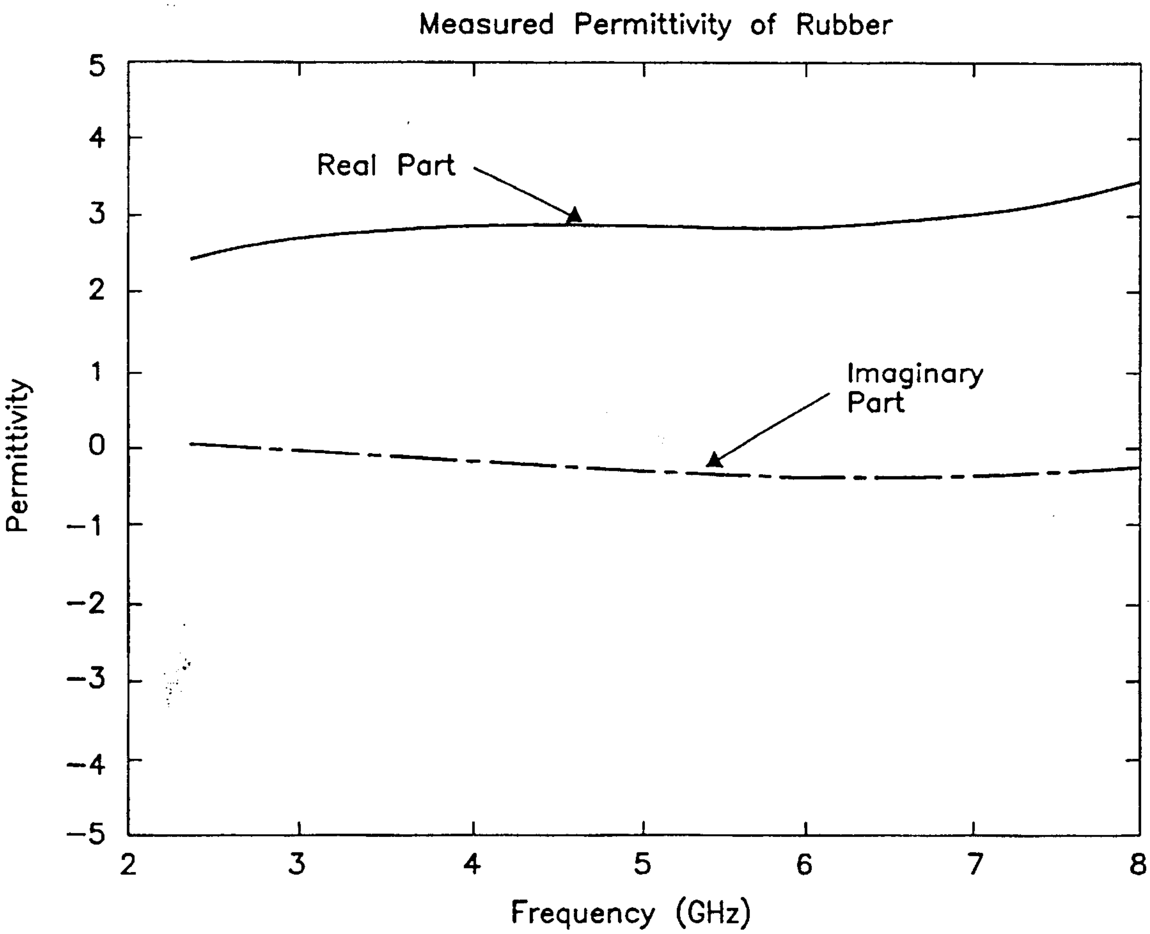

Magnitude of Reflection Coefficient of Open Load
Magnitude
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
2
4
6
8
10
12
14
16
18
Frequency (GHz)

FIG. 30


Measured Permittivity of Rubber
Real Part
Imaginary Part
Permittivity
5
4
3
2
1
0
−1
−2
−3
−4
−5
2
3
4
5
6
7
8
Frequency (GHz)

SWEPT-STEP RADAR SYSTEM AND DETECTION METHOD USING SAME

FIELD OF THE INVENTION

The present invention relates generally to detection systems and methods, and, more particularly, to radar systems and detection methods.

BACKGROUND OF THE INVENTION

Various types of radar systems and target detection techniques are known. Two radar systems capable of detecting a target object at a relatively short-range include the step-frequency radar and the frequency-modulated, continuous-wave radar.

A step-frequency radar produces a carrier signal having a frequency that is stepped by predetermined interval frequencies. Return signals are processed at each of the intervals or steps from which range information is determined. Two significant limitations associated with the use of a step-frequency radar in short-range applications are its limited unambiguous ranging capability and the significant difficulty of implementing range gating for short-range applications. Range gating, in general terms, is a technique that improves the sensitivity of a short-range radar by suppressing reflections up to the point of the antenna reflection. Such undesirable reflections, if left unabated, would generally render undetectable the relatively low energy return signals received from a short-range target object.

When a step-frequency radar is operated monostatically, for example, the return signal is corrupted by reflections from the antenna feed, which significantly degrades the sensitivity of the system. Although range gating for a step-frequency radar is technically implementable, very fast switches must be employed on the transmit and receive channels to gate out undesired antenna reflections. Because switching times must be on the order of nanoseconds in typical short-range applications, a range gating implementation for a step-frequency radar which utilizes such switches is complex, costly, and is often unable to reliably provide for relatively large unambiguous step frequency ranges. It is noted that the range of the step-frequency radar is limited by the number of its frequency steps.

Several of the problems associated with the step-frequency radar may be overcome by using a frequency-modulated, continuous-wave radar system, although this approach has associated with it a number of deficiencies and limitations that negatively impact the efficacy of such radars in short-range applications. Although a frequency-modulated, continuous-wave radar approach offers the opportunity to implement range gating in a generally straightforward manner and typically provides for an unambiguous ranging capability superior to that of a step-frequency radar, the resolution of the frequency-modulated, continuous-wave radar is significantly poorer than that of a step-frequency radar.

There exists a need for a radar system and detection method that overcomes these and other limitations associated with step-frequency and frequency-modulated, continuous-wave radars. There exists a further need for such a system and method that provides for accurate target detection and range determination in short-range applications. The present invention fulfills these and other needs.

SUMMARY OF THE INVENTION

The present invention is directed to an apparatus and method for detecting an object and determining the range of the object. In accordance with the general principles of the present invention, a transmitter, coupled to an antenna, transmits a frequency-modulated probe signal at each of a number of center frequency intervals or steps. A receiver, coupled to the antenna when operating in a monostatic mode or, alternatively, to a separate receive antenna when operating in a bistatic mode, receives a return signal from a target object resulting from the probe signal. Magnitude and phase information corresponding to the object are measured and stored in a memory at each of the center frequency steps. The range to the object is determined using the magnitude and phase information stored in the memory.

The present invention provides for high-resolution probing and object detection in short-range applications. The present invention has a wide range of applications including high-resolution probing of geophysical surfaces and ground-penetration applications. The invention may also be used to measure the relative permittivity of materials.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagrammatic representation of a transmit and receive signal associated with a point target detected by a frequency-modulated, continuous-wave radar;

FIG. **2** is a block diagram illustrating a radar system in accordance with the principles of the present invention;

FIG. **3** is a showing of center frequency shifting in accordance with a swept-step radar technique of the present invention;

FIG. **4** illustrates in flow diagram form a swept-step radar detection methodology in accordance with the principles of the present invention;

FIG. **5** is a top plan view of a swept-step radar system disposed in a housing in accordance with an embodiment of the present invention;

FIG. **6** is a front plan view of the swept-step radar system housing shown in FIG. **5**;

FIG. **7** is a rear plan view of the swept-step radar system housing shown in FIG. **5**;

FIG. **8** is an illustration of various components and interconnections of a swept-step radar system in accordance with an embodiment of the present invention;

FIG. **9** is a schematic illustration of one embodiment of the frequency-modulated (FM) driver shown in FIG. **8**;

FIG. **10** is a table of component identification and value information for the components illustrated in FIG. **9**;

FIGS. **11** and **12** illustrate an input waveform and an output waveform respectively processed by the FM driver shown in FIG. **9**;

FIGS. **13–16** illustrate various performance characteristics of the oscillator shown in FIG. **8** upon start-up and after one hour of operation;

FIG. **17** is a block diagram of the IF section of a swept-step radar system in accordance with an embodiment of the present invention;

FIG. **18** is a graphical representation of a spectrum for a target simulated at a distance of 5 meters (m) from a swept-step radar system operating in a linear sweep mode from 2 to 18 GHz;

FIG. **19** graphically illustrates the spectrum of data for a conventional frequency-modulated, continuous-wave radar when attempting to resolve two targets simulated at 5 m and 5.05 m from the frequency-modulated, continuous-wave radar, respectively;

FIG. **20** graphically illustrates the capability of a swept-step radar system to accurately resolve two targets simulated at 5 m and 5.05 m from the swept-step radar system, respectively;

size (i.e., the smaller the step size, the greater the maximum range). From Equation [11], it can be seen that for the same frequency step size, a higher resolution may be obtained by increasing the sweep bandwidth, which may be accomplished by increasing the number of frequency steps. As will be described in detail hereinbelow, the swept-step radar of the present invention provides for extended range determinations beyond the maximum range defined for a step-frequency radar having equivalent operational characteristics, yet maintains the same resolution.

Typically, more than one scatterer will be present in a given volume subjected to radar probing. For purposes of example, it is assumed that there are K number of scatterers. Using Equation [7] above, it follows that:

$$V_r(f_n) = \sum_{k=0}^{K-1} E_{ok}\Gamma_k \exp j\left(\frac{4\pi(f_o + n\Delta f)d_k}{c}\right) \qquad [12]$$

From Equation [12], it can be seen that for each frequency, f_n, there are K number of sinusoids with differing periods, assuming that no two scatterers are located within the same range resolution, ΔR. In order to resolve all of the scatterers, a constraint must be imposed that only N number of scatterers are present. Hence, the maximum value for K is N. The fast Fourier transform (FFT) of $V_r(f_n)$ with respect to n provides the spectral distribution of all the scatterers with their associated amplitude and phase values as given by the following equations:

$$\text{Amplitude} = E_{ok}|\Gamma_k| \qquad [13]$$

$$\text{Phase} = \frac{4\pi f_o d_k}{c} + arg(\Gamma_k) \qquad [14]$$

The complex reflection coefficient of a target can be determined by calibrating the return signal with a target of known reflection coefficient. The complex reflection coefficient as a function of frequency for a target can be obtained by centering a bandpass filter over the target of interest and taking the inverse fast Fourier transform (IFFT) of the gated signal.

Having discussed the general operational characteristics of a typical step-frequency radar, a brief description of the operational characteristics of a frequency-modulated, continuous-wave radar will now be provided, with reference being made to FIG. 1. In general, a frequency-modulated, continuous-wave radar frequency modulates a signal, S_T, over some bandwidth. The bandwidth of the transmit or probe signal, S_T, determines the range resolution. The larger the bandwidth of the probe signal, S_T, the higher the range resolution. The return signal, S_R, from a target is compared to the transmitted probe signal, S_T, to extract the range, amplitude, and phase information associated with the target. The difference between the return signal, S_R, and the probe signal, S_T, is referred to as the intermediate frequency (IF) signal or beat signal.

FIG. 1 is an illustration of a typical transmit and receive waveform associated with a point target for a typical frequency-modulated, continuous-wave radar. The amount of time, τ, required for the signal to travel the two-way distance between the target and the radar, commonly referred to as flight time, is given by the following equation:

$$\tau = \frac{2R}{c} \qquad [15]$$

Based on the geometry of the transmit and receive waveforms, S_T and S_R, illustrated in FIG. 1, a relationship may be derived between the beat frequency, f_b, and the range, R. The beat frequency, f_b, represents the instantaneous difference frequency between the transmitted and received signals, S_T and S_R, respectively. For the sawtooth modulated waveform depicted in FIG. 1, the following relationship is given:

$$\frac{\tau}{T_m} = \frac{f_b}{B} \qquad [16]$$

Substituting for τ of Equation [15] into Equation [16], the following equation results:

$$f_b = \frac{2RBf_m}{c} \qquad [17]$$

where, R represents the range to the target, B represents the FM sweep bandwidth, f_m represents the modulation frequency of the sawtooth waveform, c represents the speed of light, and f_b represents the beat frequency.

For multiple targets, the beat signal will consist of several frequencies. The Fourier transform of the beat signal provides the spectral components of each of these targets. The minimum two-way travel time, τ_{min}, for the signal is given by:

$$\tau_{min} = \frac{1}{B} \qquad [18]$$

Substituting Equation [18] into Equation [15], it can be seen that the range resolution, ΔR, for the frequency-modulated, continuous-wave radar is given as:

$$\Delta R = \frac{c}{2B} \qquad [19]$$

From Equation [19], it can be observed that the range resolution, ΔR, is dependent on the sweep bandwidth.

It is generally understood that frequency-modulated, continuous-wave radars provide for broad-band measurements which, in turn, provide for high-resolution probing. This understanding is verified by Fourier transform theory, which defines the inverse relationship between the frequency domain and time domain: the wider the sweep bandwidth, the higher the time resolution, hence the better resolving capabilities. The target resolving capabilities of currently available frequency-modulated, continuous-wave radars, as with any conventional short-range single-antenna radar system, however, are negatively impacted by a number of limitations.

By way of example, typical frequency-modulated, continuous-wave radars produce many interference and leakage signals that are usually much higher in strength than the return signal, S_R, received from a target. Antenna reflection, for example, is a primary source of interference that severely limits the sensitivity of conventional frequency-modulated, continuous-wave radar systems when used in short-range applications. Also, undesirable reflections from impedance mismatches between RF components contribute to an overall reduction in target detection sensitivity and resolution. Additionally, there exists the problem of limited isolation when the oscillator signal leaks into the receive path. These undesirable operational characteristics severely limit the sensitivity and resolution capabilities of conventional frequency-modulated, continuous-wave radars when utilized in short-range probing applications.

The radar probing apparatus and technique of the present invention overcomes the deficiencies identified hereinabove and other known limitations associated with conventional short-range radar probing approaches, yet exploits the advantageous attributes of step-frequency and frequency-modulated, continuous-wave radar systems. A radar system

$$H(i)=|\Gamma_{tar}| \exp\{j(2\pi f_o\tau_{tar}+2\pi\Delta f\tau_{tar}i+\phi_{tar})\} \quad [25]$$

Taking the fast Fourier transform of H(i) with respect to i provides the high-resolution spectral response of the target.

The range, R, to the target may be computed in the following manner. The time resolution (Δt) associated with a step-frequency probing technique is given by:

$$\Delta t=\frac{1}{N\Delta f} \quad [26]$$

where, N represents the number of frequency steps. Substituting Δt for τ and ΔR for R in Equation [15] provided hereinabove, the relationship between the range resolution and time resolution is given by:

$$\Delta R=\frac{\Delta t\times c}{2} \quad [27]$$

It can be seen that the index location of the target, i, is equal to $\Delta f\tau_{tar}$, which varies from 0 to N−1, where N represents the number of frequency steps. Thus, the range, R, to the target may be computed as:

$$R=\Delta R\Delta f\tau_{tar} \quad [28]$$

Referring now to FIGS. **5–8**, there is illustrated an embodiment of a swept-step radar apparatus that operates in accordance with the radar probing methodology depicted in FIG. 4 and the principles represented in mathematical terms in Equations [20] through [28]. The swept-step radar **50** includes a waveform generator **54** and an FM driver **56** coupled to the waveform generator **54**. The RF section **58** of the swept-step radar **50** includes a YIG oscillator **60** coupled to both the FM driver **56** and a 6-dB coupler **62**, a dual directional coupler **64** coupled to the 6-dB coupler **62**, a phase trimmer (not shown), a dual mixer **77**, and a coaxial switch **70** that selectively couples a single antenna **66** or a dual antenna apparatus **66/68** to an input of the dual mixer **77**.

An IF section includes two IF amplifiers **76** and **78** which are respectively coupled to first and second mixers **72** and **75** of the dual mixer **77**. The first and second IF amplifiers **76** and **78** are respectively coupled to an incident channel **80** and a reflected channel **82**. As will later be described in detail, a highpass filter **74** is placed in the reflected channel **82** between the second IF amplifier **78** and the second mixer **75** of the dual mixer **77** to effectively eliminate undesirable antenna reflection.

The waveform generator **54**, in accordance with one embodiment of the present invention, produces a sawtooth waveform, such as that illustrated in FIG. **1**. A MAX038 High-Frequency Waveform Generator, manufactured by Maxim Integrated Products, produces a sawtooth waveform of a type suitable for use in this embodiment of the present invention. The MAX038 waveform generator is a high-frequency function generator capable of producing accurate triangle, sine, and square waveforms by configuring the appropriate jumper settings. The sawtooth waveform may be generated by changing the duty cycle of the triangular waveform. The MAX038 waveform generator, as assembled in the factory, generates waveforms from 325 kHz to 10 MHz.

The frequency range for the generated waveform may be set by selecting the appropriate capacitor (C1) value from the table provided on page 4 of the MAX038 1994 data sheet. The frequency of the generated waveform may then

be set by adjusting the potentiometers, IIN or FADJ. The modulation frequency was chosen based on the range of operation. In accordance with this embodiment, a 1-kHz modulation was selected to enable operation at ranges up to 29 m with a maximum beat frequency of 25 kHz and a sweep bandwidth of 130 MHz (see Equation [17] above).

The center frequency, f_c, of the YIG oscillator **60** may be deviated as much as +/−70 MHz by pumping current into the FM coil of the YIG oscillator. The sensitivity of the FM coil is given as 450 kHz/mA. Theoretically, in order to achieve a sweep bandwidth of 140 MHz, as much as +/−155.6 mA of current must flow into the FM coil. This amount of current is well within the maximum current rating threshold of +/−200 mA specified by the manufacturer.

The FM driver **56** was initially designed to produce a current of +/−155.6 mA. However, upon testing the FM driver **56** with the spectrum analyzer, it was found that this amount of current produced center frequency deviations of only +/−55 MHz. The current flow into the FM coil was then increased to +/−190 mA to deviate the center frequency of the YIG oscillator **60** by +/−65 MHz. Hence, a range resolution of 1.15 m is obtained for a sweep bandwidth of 130 MHz.

The schematic diagram of FIG. **9** is a depiction of an exemplary FM driver **56** for use in the embodiment of the swept-step radar **50** illustrated in FIGS. **5–8**. In the diagram of FIG. **9**, resistor R_1 and inductor L_1 represent the input impedance of the FM port coupled to the YIG oscillator **60**. Transistors Q_1 are configured as a PNP Darlington transistor pair that supplies current from 0 to 380 mA to the FM port. The Q_1 Darlington transistor pair is designed to supply 380 mA of current in response to an input voltage of +2 V, and 0 mA of current in response to an input voltage of −2 V. This is accomplished by selecting appropriate values for resistors R_2 and R_5 of the difference amplifier AMP_1. The variable resistor, POT_1, is used to fine tune the current range to be 380 mA. As such, the bandwidth of the FM sweep of the YIG oscillator **60** may be adjusted using POT_1.

Amplifier AMP_4 acts as a buffer that drives the Q_1 Darlington transistor pair. The voltage appearing at the positive terminal of AMP_1 may be adjusted using the variable resistor POT_2 in order to accurately control the current within the range of 0 to 380 mA. Hence, POT_2 operates as an FM bandwidth offset adjuster. Diode D_1 is a 10 V zener diode that provides a stable +10 V supply. This voltage is used as a reference voltage for POT_2 to set the offset voltage at the positive terminal of AMP_1, and is also used as the input voltage to AMP_2 for setting the reference voltage at resistor R_{14}.

Transistors Q_2 are configured as an NPN Darlington transistor pair that pulls a constant +190 mA current out of the FM port. This effectively supplies +/−190 mA to the FM port. To achieve this, the voltage across the 22 ohm resistor R_{14} is designed to be about 4.2 V. This voltage drop across resistor R_{14} will result in 190 mA of current in the emitter of the Q_2 transistor pair. Since the common-emitter current gain for the Darlington configuration is very large (e.g., β=2,500), the current in the collector of Q_2 can also be assumed to be about 190 mA. Because of the large wattage generated across resistors R_9 and R_{14}, which is about 1 W, 3 W rated resistors are suitable for withstanding this high wattage.

The op-amp AMP_2 is an inverting amplifier that provides the reference voltage across the resistor R_{14}. The values of the resistors R_6 and R_{11} are selected to obtain the required voltage at R_{14}, and POT_3 is a variable resistor that can be used to fine tune the reference voltage at R_{14}. Operational amplifier AMP_3 is a buffer amplifier that drives the base of

The IF amplifier **101** comprises three stages to amplify the signal to the required gain level. The first stage is a single-pole high-pass filter **104** with a fixed gain of 30 dB implemented with an op-amp. The second stage is a programmable gain amplifier **106** with gains of 0, 20, 40, and 60 dB. The gain of the amplifier **106** is set by sending the appropriate gain control bits from a processor or from a computer to the programmable gain amplifier **106** via a CIODIO-24 I/O board, for example. The final stage is a unity-gain buffer **108** used to boost the output current of the programmable gain amplifier **106** to a level sufficient for driving a 50 ohm load.

In accordance with one embodiment of the present invention, data acquisition is performed by digitizing the IF signal at the output of the IF amplifier **101** using a high-speed analog-to-digital convertor (A/D) board. A suitable A/D board to digitize the IF signal is model RTI-860 manufactured by Analog Devices. The RTI-860 A/D board is capable of sampling at a frequency of 250 kHz with 12-bit resolution in single-channel mode, and up to 200 kHz in a multi-channel mode. Sampling rates of up to 330 kHz in single-channel mode and 250 kHz in multi-channel mode can be achieved using 8-bits of resolution. For N-bit resolution, the maximum signal-to-noise ratio (SNR) that can be measured is given by the following equation:

$$SNR_{max}=6\times(N-1)-1.25\ (dB) \qquad [30]$$

Hence, for 8-bit resolution, the maximum SNR that can be measured is 40.75 dB, and for 12-bit resolution, the maximum measurable SNR is 64.75 dB.

An input voltage range of either +/−5 V or 10 V may be selected using the appropriate jumper. The digitized data can be stored in either on-board memory or system memory. The RTI-860 has 256K×12 bits of dynamic RAM (DRAM) for storing the acquired data without being interrupted by the computer's CPU. Three methods of triggering A/D conversion with the RTI-860 are available. These include digital, analog, and software triggering.

Digital signal triggering is a type of edge triggering that uses an external digital signal. The RTI-860 can be configured to trigger via software on either the falling edge or on the rising edge of the external digital signal. Analog triggering is accomplished by comparing an external analog input signal with a software-specified threshold voltage. The RTI-860 can be configured via software to trigger when the analog signal is above or below the specified threshold voltage. Software triggering initiates the A/D conversion process as soon as the user or host requests data.

In one embodiment, a sampling rate of 200 kHz with 12-bit resolution in multi-channel mode is selected, which effectively provides for a 50 kHz per channel sampling rate since there are a total of four channels. The trigger mechanism is a rising-edge digital-signal trigger that is synchronized to the sawtooth waveform. The digitized data are first stored in on-board DRAM and then transferred to system memory. The data acquisition program may be written in C language and, if desirable, interfaced with MATLAB software for purposes of performing data processing.

The advantages of the swept-step radar probing apparatus and method in accordance with the present invention and as described herein were demonstrated and verified by use of a MATLAB simulation approach. For purposes of concept verification, several operating scenarios were simulated, as are described below in Examples 1 through 5.

EXAMPLE 1

FIG. 18 is a graphical representation of a spectrum for a target simulated at a distance of 5 m from the swept-step radar operating in a linear sweep mode from 2 to 18 GHz. The plot of the spectrum data in FIG. 18 demonstrates unambiguous and accurate detection of the simulated target located at 5 m from the swept-step radar.

EXAMPLE 2

FIGS. **19** and **20** dramatically illustrate the high-resolution capability of the swept-step radar operating in accordance with the principles of the present invention in comparison to that provided by a conventional frequency-modulated, continuous-wave radar. FIG. **19** graphically illustrates the spectrum of data for a conventional frequency-modulated, continuous-wave radar when attempting to resolve two targets simulated at 5 m and 5.05 m from the radar, respectively. It can be seen from the plot in FIG. **19** that the conventional frequency-modulated, continuous-wave radar was unable to accurately resolve the two, closely spaced targets. Rather, the frequency-modulated, continuous-wave radar data suggests the presence of only a single target.

In stark contrast, as is illustrated in FIG. **20**, the plot of spectrum data demonstrates that the swept-step radar clearly resolves the two targets simulated at 5 m and 5.05 m from the swept-step radar, which represents a separation distance of only 5 cm. It is noted that both the frequency-modulated, continuous-wave and swept-step radars were simulated so as to operate in a linear sweep mode from 2 to 18 GHz.

EXAMPLE 3

The data graphically presented in FIGS. **21** and **22** demonstrate that the range of the swept-step radar is co-extensive with that of a conventional frequency-modulated, continuous-wave radar. FIG. **21** illustrates the spectrum of data for a simulated single point target located 20 m from a conventional frequency-modulated, continuous-wave radar. FIG. **22** illustrates that the range of the swept-step radar is equivalent to that of the frequency-modulated, continuous-wave radar.

Previously, by using a network analyzer as a step-frequency radar, targets beyond 15 m could not be detected, which is a range limit determined by the number of points and the sweep bandwidth. As such, the spectrum obtained by the swept-step radar is simply wrapped around, and the corrected range, or actual range, can be determined from the plot shown in FIG. **22** by adding 15 m to the displayed range. As such, the swept-step radar, taking into account the additional 15 m offset (15 m+5 m=20 m), accurately detects the presence of the target located 20 m from the swept-step radar.

EXAMPLES 4 & 5

FIGS. **23** and **24** provide comparison data demonstrating swept-step radar performance when the frequency of the oscillator **60** is swept the entire frequency span of 2 to 18 GHz (FIG. **23**), and when the oscillator **60** is swept in the linear region of operation from 2.37 to 17.65 GHz (FIG. **24**). It can be seen in these figures that degradation in the performance of the radar results when the frequency steps of the oscillator **60** are not uniform. The linearity of the sweep was determined by measuring the oscillator's actual frequency and removing the straight-line fit from these frequencies. The results of these measurements were discussed previously in connection with the description of the YIG oscillator.

An advantageous feature of the swept step radar in accordance with the embodiment of the invention shown in FIGS.

calibration factor, H(f), is obtained by dividing the true reflection of the short circuit load, which is −1, by S(f). This function, H(f), is multiplied by the measured reflection from the medium to obtain the true reflection from the medium, $\Gamma_M(f)$. FIGS. **28** and **29** demonstrate the accuracy of this calibration technique. Using this technique, the reflection coefficient of an open load ($\Gamma_{open}=1$) with less than 2% error in magnitude (FIG. **28**) and less than 3% error in phase (FIG. **29**) across the frequency range may be obtained.

FIG. **30** shows the relative permittivity of a rubber sample obtained using a monopole antenna in accordance with the above-discussed procedure. The theoretical relative permittivity is given as 3 for the real part and 0 for the imaginary part. FIG. **30** demonstrates close agreement between the empirically determined permittivity of the rubber sample through use of the monopole antenna **120** and the theoretically derived permittivity value. It is noted that FIG. **31** illustrates the results of a delay line measurement made in the S_{21} mode of operation with 0-dB gain.

It is believed that the performance of the swept-step radar may be further improved by linearizing the frequency steps by using a direct digital synthesizer (DDS). It is further believed that the IF spectrum can be further improved if the IF signal is weighted by a window, such as a Hamming window, before it is input into the range gating filter to reduce the effects of ringing.

It will, of course, be understood that various modifications and additions can be made to the various embodiments discussed hereinabove without departing from the scope or spirit of the present invention. Accordingly, the scope of the present invention should not be limited by the particular embodiments described above, but should be defined only by the claims set forth below and equivalents thereof.

We claim:

1. A method of detecting an object, comprising the steps of:

(a) transmitting a frequency-modulated probe signal having a center frequency and a sweep bandwidth using an antenna;

(b) receiving a return signal resulting from the probe signal using the antenna;

(c) producing a difference signal using a reference signal related to the probe signal and the return signal;

(d) filtering the difference signal so as to suppress reflections from the antenna;

(e) storing magnitude and phase information of the difference signal corresponding to the object;

(f) shifting the center frequency;

(g) repeating steps (a) through (f) a predetermined number of times; and

(h) determining a range to the object using the stored magnitude and phase information.

2. A method according to claim **1**, including the additional step of performing Fourier transformation on the difference signal prior to the storing step.

3. A method according to claim **1**, wherein the determining step includes the further step of performing a Fourier transformation on the stored magnitude and phase information to produce a spectral response of the object.

4. A method according to claim **1**, wherein the shifting step includes the further step of shifting the center frequency of the probe signal between approximately 2 GHz and 18 GHz.

5. A method according to claim **1**, wherein:

the transmitting step includes the step of transmitting the probe signal using a transmit antenna; and

the receiving step includes the step of receiving the return signal using a receive antenna.

6. A method according to claim **1**, wherein the determining step includes the step of determining the range to the object when the object has a range of less than approximately 3 meters.

7. A method according to claim **1**, wherein the object is an underground object.

8. A method according to claim **1**, wherein shifting the center frequency includes changing the sweep bandwidth.

9. A method according to claim **1**, wherein the difference signal includes a beat frequency determined by a difference in frequency between the reference signal and the return signal.

10. A method of detecting an object, comprising the steps of:

(a) transmitting a frequency-modulated probe signal having a center frequency and a sweep bandwidth;

(b) receiving a return signal resulting from the probe signal;

(c) storing magnitude and phase information corresponding to the object derived by using the return signal;

(d) shifting the center frequency;

(e) repeating steps (a) through (d) a number of times; and

(f) determining a range to the object using the stored magnitude and phase information.

11. A method according to claim **10**, including the further step of filtering the return signal.

12. A method according to claim **10**, wherein:

the transmitting step includes the step of transmitting the probe signal using a transmit antenna; and

the receiving step includes the step of receiving the return signal using a receive antenna.

13. A method according to claim **10**, wherein the determining step includes the step of determining the range to the object when the object has a range of less than approximately 3 meters.

14. A method according to claim **10**, wherein the object is an underground object.

15. A method according to claim **10**, wherein shifting the center frequency includes changing the sweep bandwidth.

16. A system for detecting a object, comprising:

a transmitter, coupled to an antenna, that transmits a frequency-modulated probe signal having a center frequency and a sweep bandwidth;

a receiver, coupled to the antenna, that receives a return signal resulting from the probe signal;

a frequency selector that controls shifting of the probe signal center frequency to a number of center frequency values;

a memory that stores magnitude and phase data of the return signal resulting from transmission of the probe signal at each of the center frequency values; and

a processor, coupled to the memory, that computes a range to the object using the magnitude and phase data stored in the memory.

17. A system according to claim **16**, wherein:

the transmitter is coupled to a transmit antenna; and

the receiver is coupled to a receive antenna.

18. A system according to claim **16**, further comprising a filter coupled to the antenna and the receiver for suppressing reflections from the antenna.

19. A system according to claim **16**, wherein the range of the object is detectable by the system when the object is situated less than approximately 3 meters from the system.