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Dual-polarization radar processing system using time domain method

Venkatachalam, Chandrasekaran

2014-03-04

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Venkatachalam et al.

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(45) **Date of Patent: Mar. 4, 2014**

(54) **DUAL-POLARIZATION RADAR PROCESSING SYSTEM USING TIME DOMAIN METHOD**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 385 days.

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G01S 13/95 (2006.01)

(52) **U.S. Cl.**
USPC ..... **342/188**; 342/26 R

(58) **Field of Classification Search**
USPC 342/188
See application file for complete search history.

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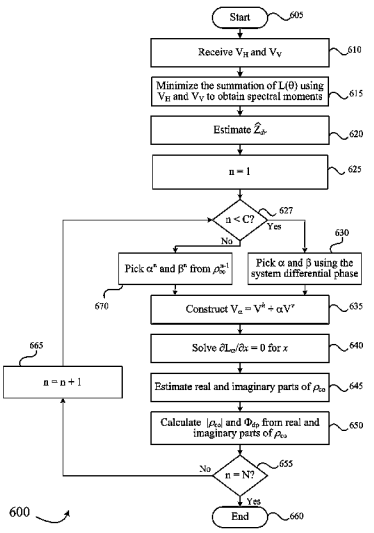
Primary Examiner — Matthew M Barker
(74) *Attorney, Agent, or Firm* — Maschoff Brennan

(57) **ABSTRACT**

Embodiments of the present invention provide for improved estimation of environmental parameters in a dual-polarization radar system. In some embodiments, environmental parameters can be estimated using a linear combination of data received in two orthogonal polarization states. In particular, embodiments of the invention improve ground clutter and noise mitigation in dual polarization radar systems. Moreover, embodiments of the invention also provide for systems to determine the differential reflectivity and/or the magnitude of the co-polar correlation coefficient and the differential phase in a dual polarization radar system.

11 Claims, 12 Drawing Sheets
(3 of 12 Drawing Sheet(s) Filed in Color)



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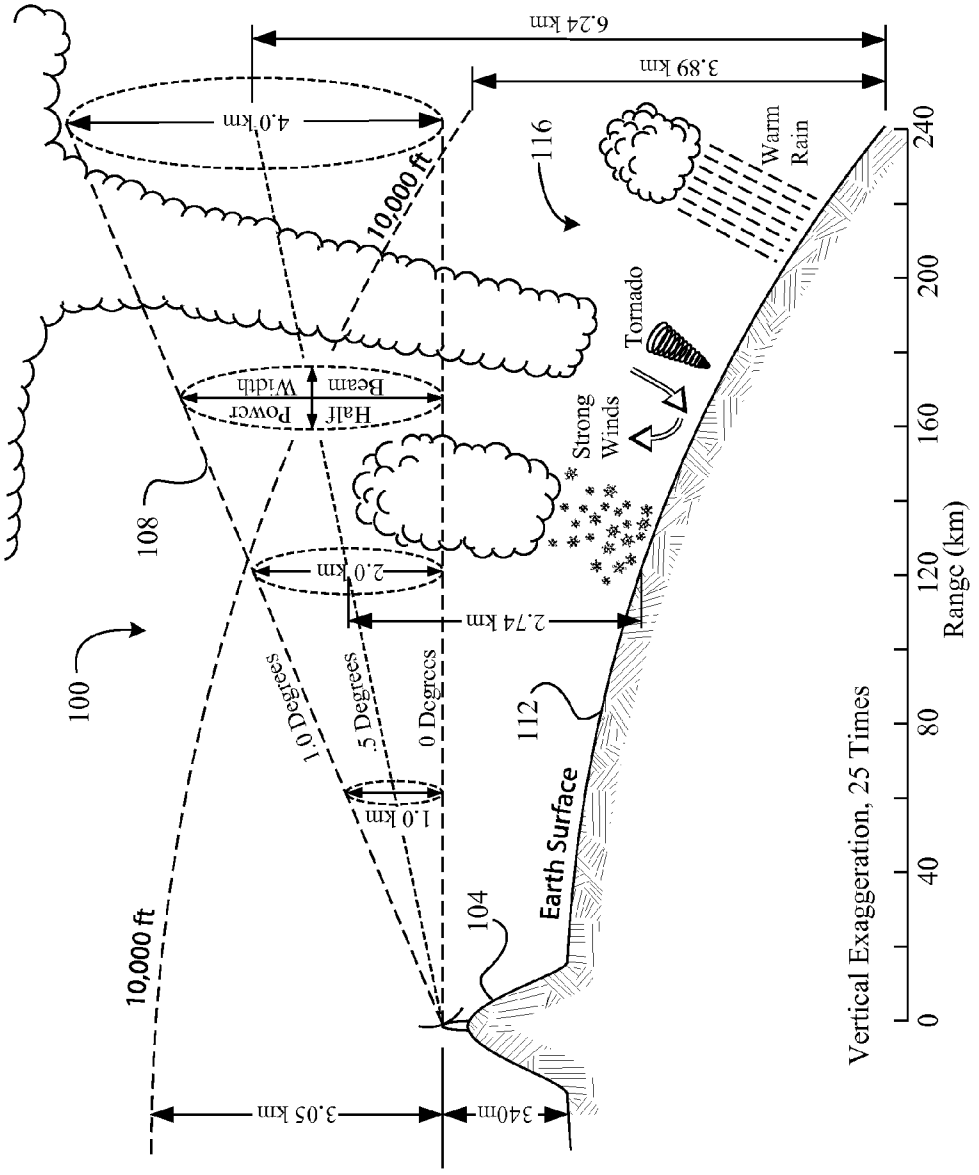

FIG. 1
(prior art)

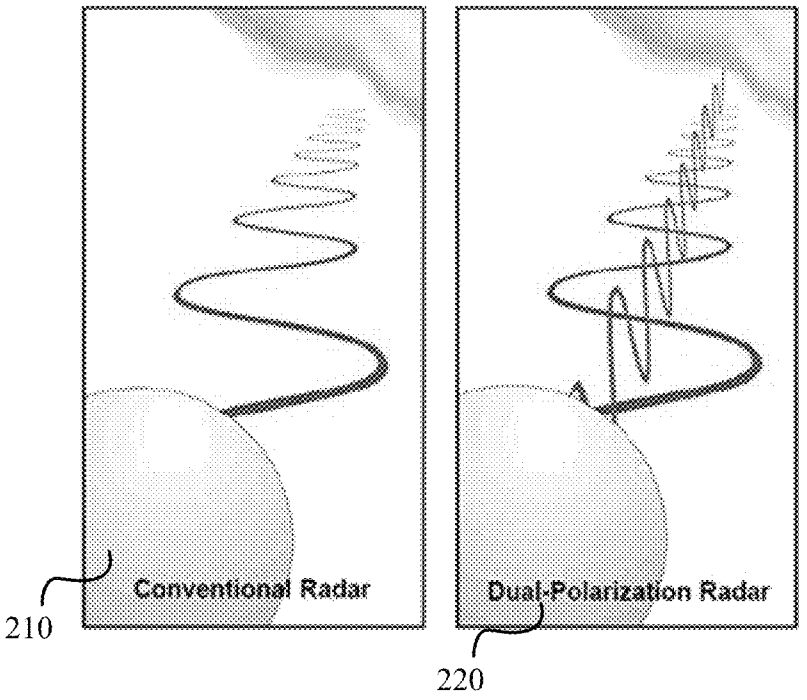

FIG. 2

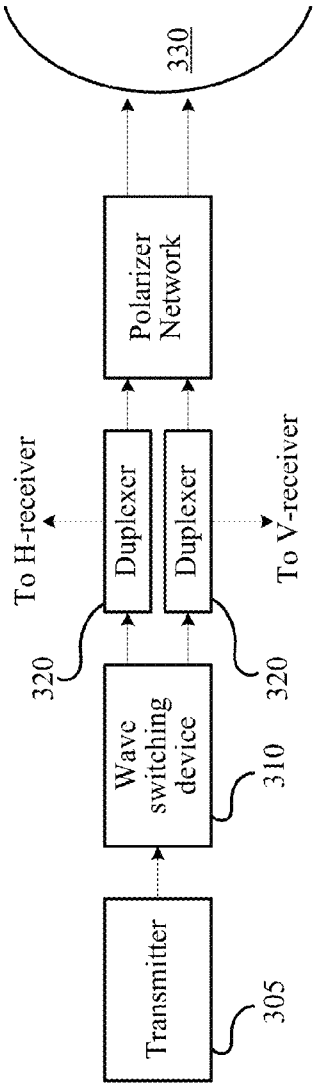
330
Polarizer Network
To H-receiver
Duplexer
Duplexer
To V-receiver
320
320
Wave switching device
310
Transmitter
305
300

FIG. 3A

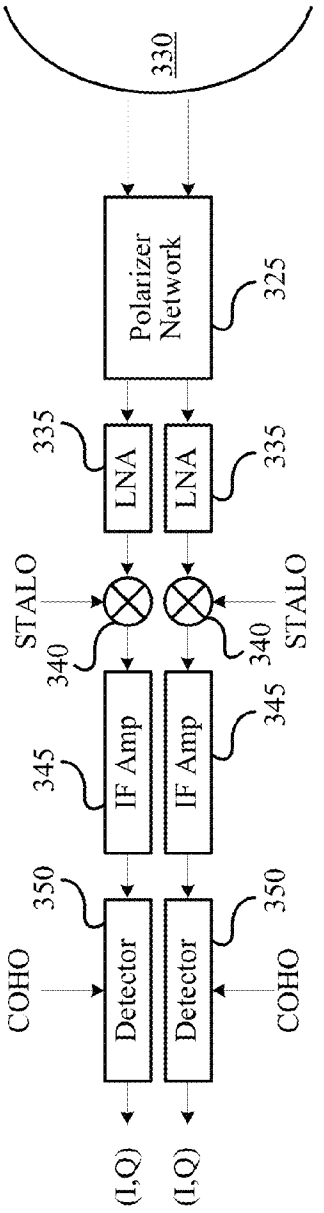
330
Polarizer Network
325
335
LNA
LNA
335
STALO
340
340
STALO
345
IF Amp
IF Amp
345
350
350
COHO
Detector
Detector
COHO
(I,Q)
(I,Q)
360

FIG. 3B

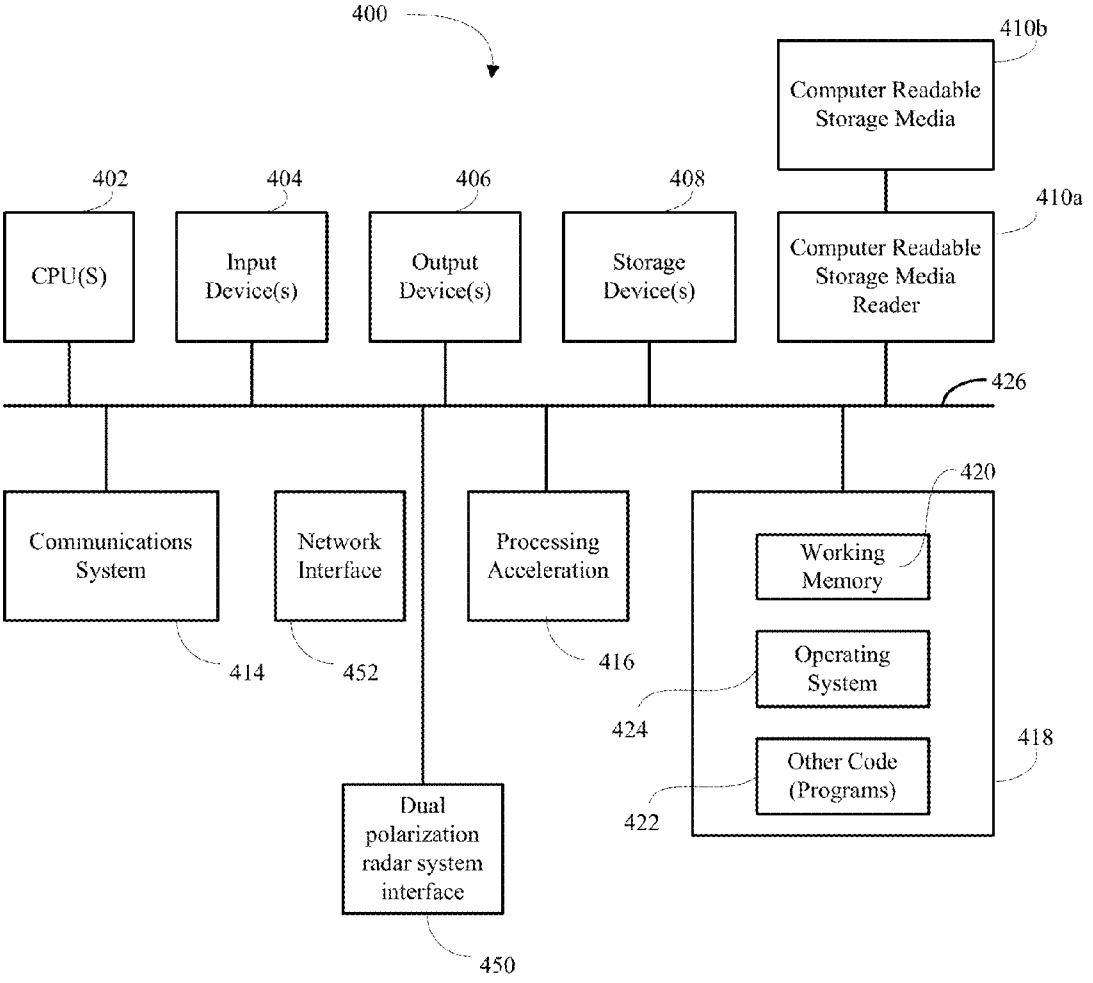
400
410b
Computer Readable Storage Media
402
404
406
408
410a
CPU(S)
Input Device(s)
Output Device(s)
Storage Device(s)
Computer Readable Storage Media Reader
426
420
Communications System
Network Interface
Processing Acceleration
Working Memory
Operating System
Other Code (Programs)
418
414
452
416
424
422
Dual polarization radar system interface
450

FIG. 4

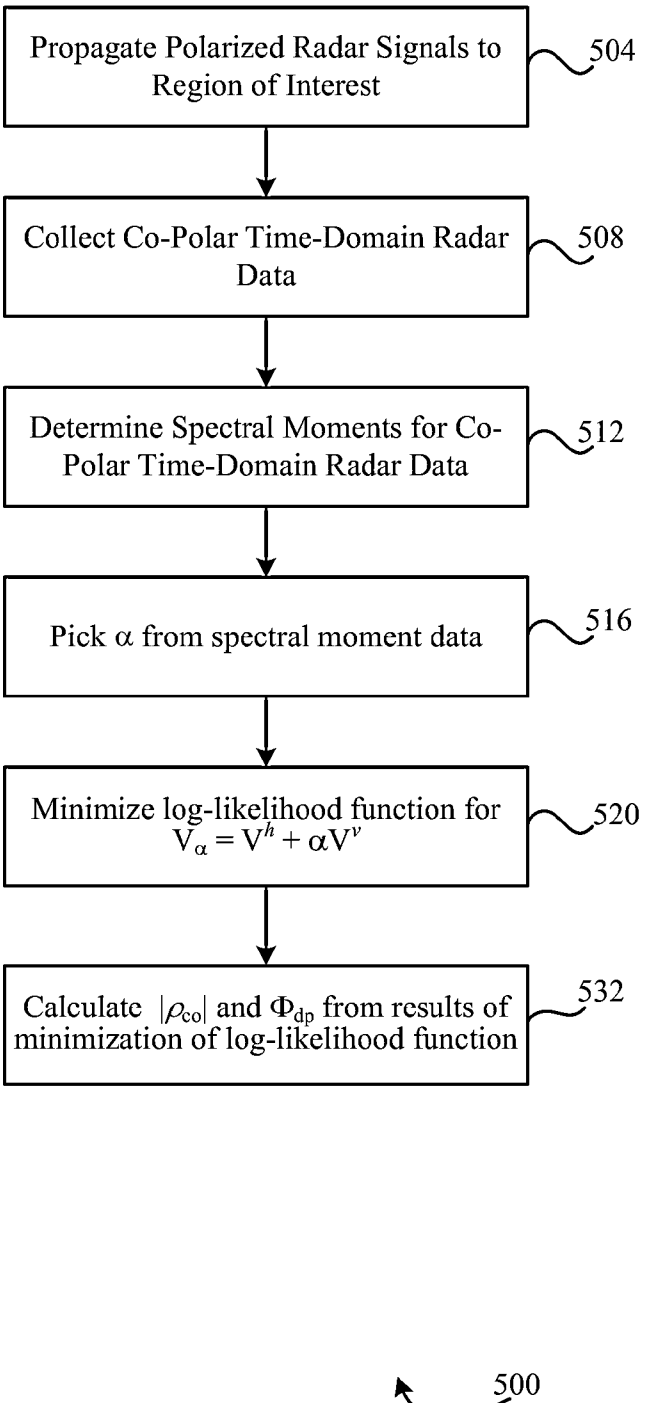
Propagate Polarized Radar Signals to Region of Interest
504
Collect Co-Polar Time-Domain Radar Data
508
Determine Spectral Moments for Co-Polar Time-Domain Radar Data
512
Pick α from spectral moment data
516
Minimize log-likelihood function for $V_\alpha = V^h + \alpha V^v$
520
Calculate $|\rho_{co}|$ and Φ_{dp} from results of minimization of log-likelihood function
532
500

FIG. 5

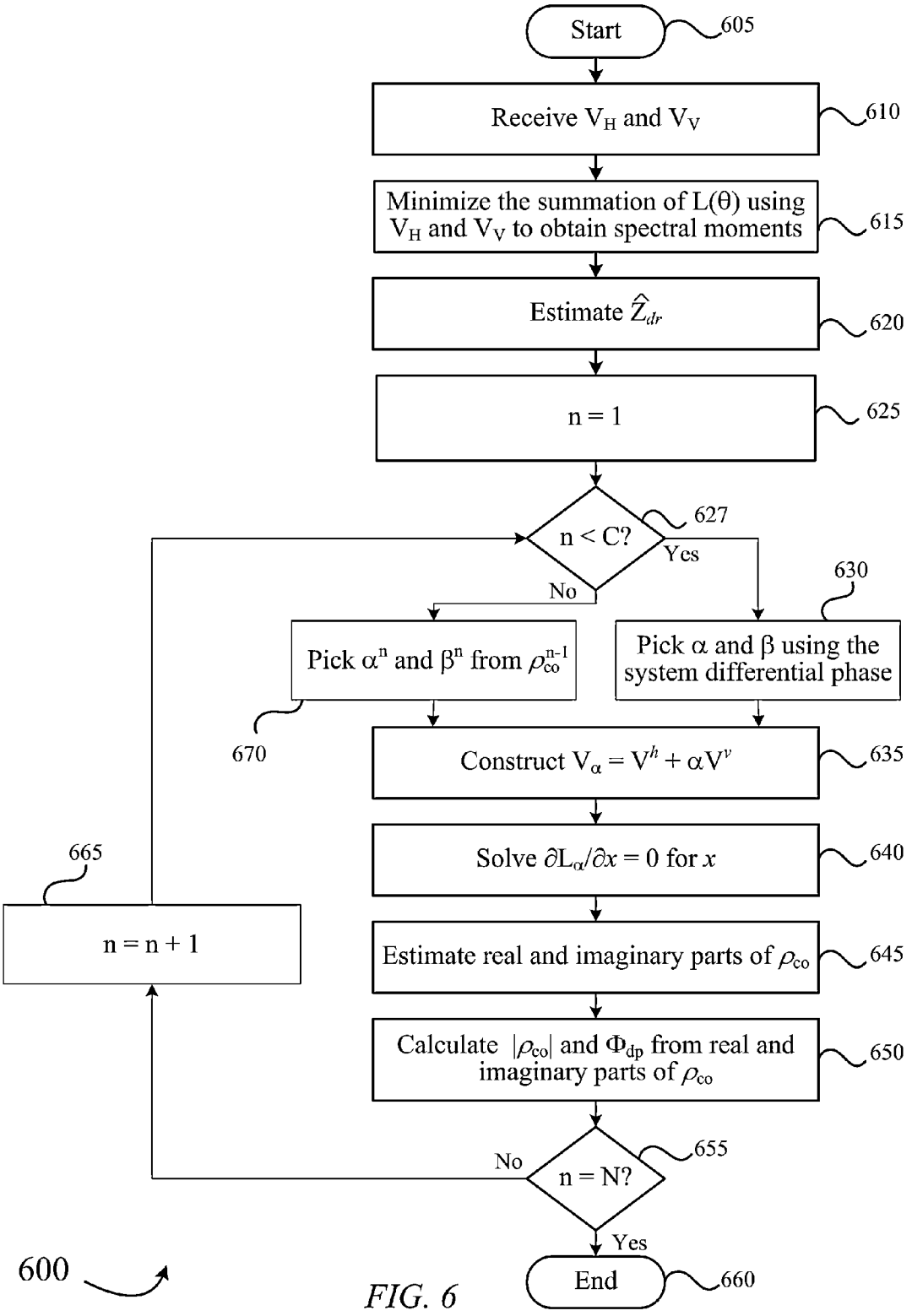
Start
605
Receive V_H and V_V
610
Minimize the summation of L(θ) using V_H and V_V to obtain spectral moments
615
Estimate $\hat{Z}_{dr}$
620
n = 1
625
n < C?
627
Yes
No
630
Pick α^n and β^n from ρ_{co}^{n-1}
670
Pick α and β using the system differential phase
Construct $V_\alpha = V^h + \alpha V^v$
635
Solve $\partial L_\alpha / \partial x = 0$ for x
640
665
n = n + 1
Estimate real and imaginary parts of ρ_{co}
645
Calculate $|\rho_{co}|$ and Φ_{dp} from real and imaginary parts of ρ_{co}
650
No
n = N?
655
Yes
End
660
600

FIG. 6

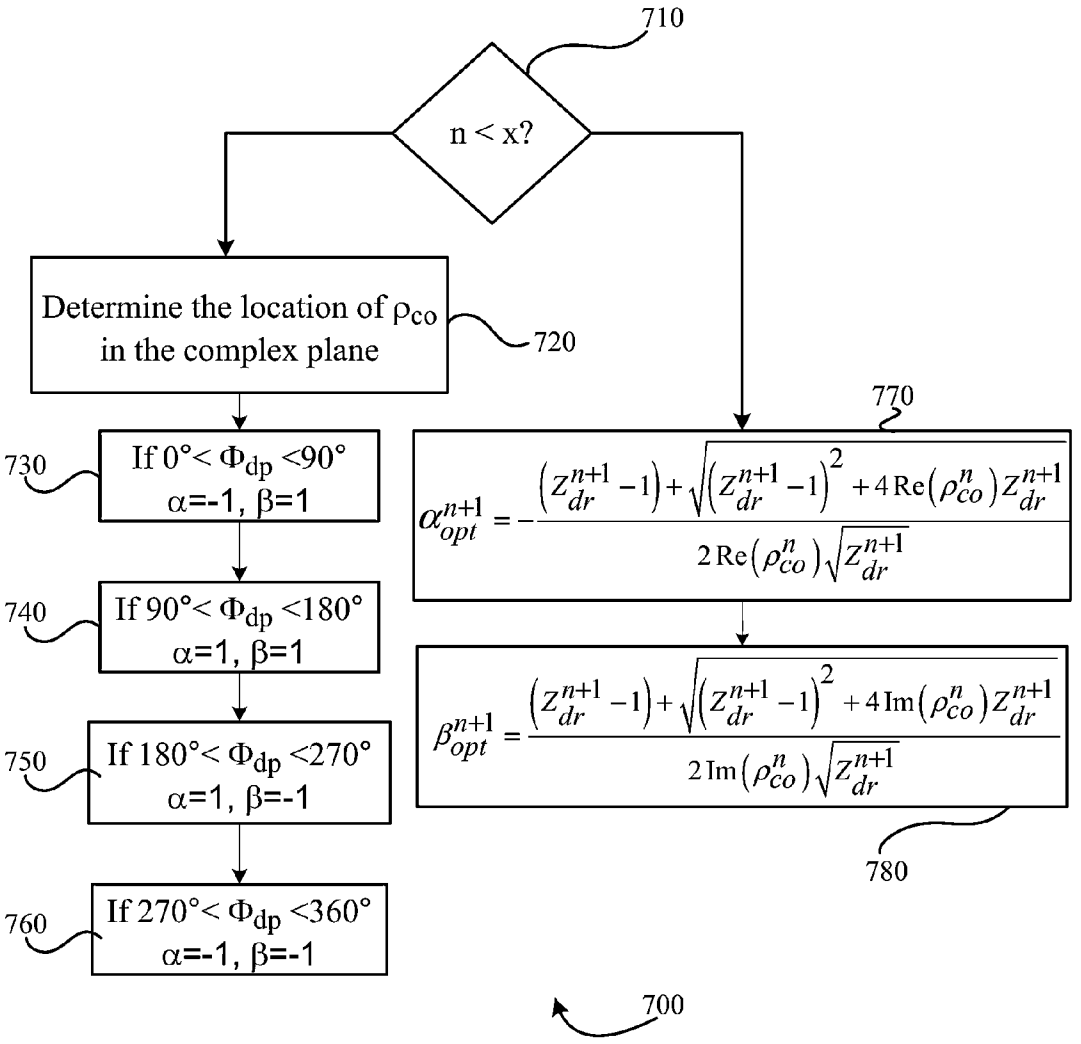
710
n < x?
Determine the location of ρco in the complex plane
720
730
If 0°< Φdp <90°
α=-1, β=1
740
If 90°< Φdp <180°
α=1, β=1
750
If 180°< Φdp <270°
α=1, β=-1
760
If 270°< Φdp <360°
α=-1, β=-1
770
$\alpha_{opt}^{n+1} = -\frac{\left(Z_{dr}^{n+1}-1\right)+\sqrt{\left(Z_{dr}^{n+1}-1\right)^2+4\,\mathrm{Re}\left(\rho_{co}^{n}\right)Z_{dr}^{n+1}}}{2\,\mathrm{Re}\left(\rho_{co}^{n}\right)\sqrt{Z_{dr}^{n+1}}}$
$\beta_{opt}^{n+1} = \frac{\left(Z_{dr}^{n+1}-1\right)+\sqrt{\left(Z_{dr}^{n+1}-1\right)^2+4\,\mathrm{Im}\left(\rho_{co}^{n}\right)Z_{dr}^{n+1}}}{2\,\mathrm{Im}\left(\rho_{co}^{n}\right)\sqrt{Z_{dr}^{n+1}}}$
780
700

FIG. 7

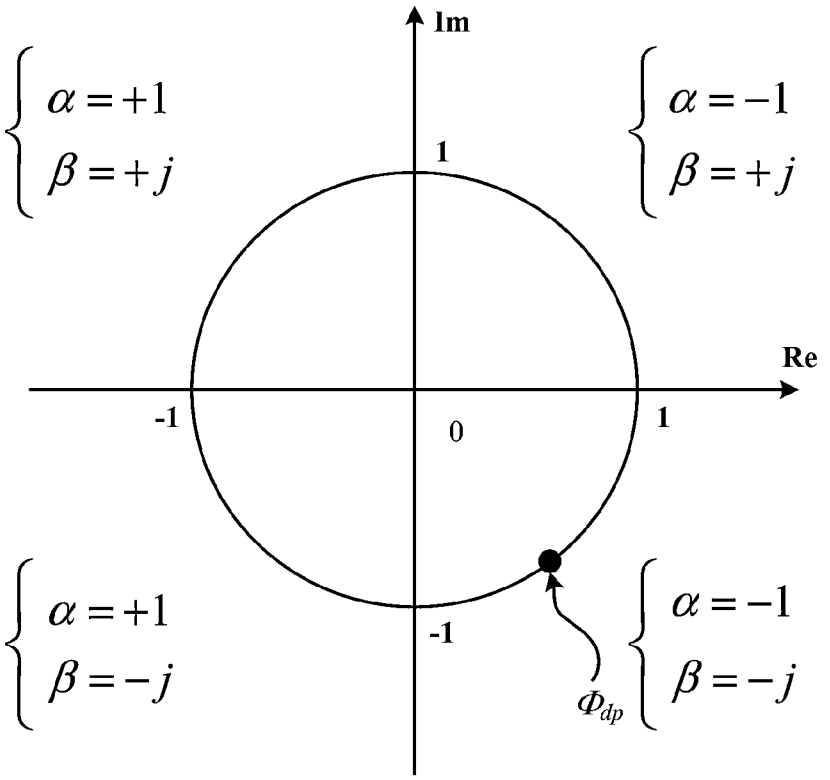
Im
Re
1
-1
0
1
-1
$\alpha = +1$
$\beta = +j$
$\alpha = -1$
$\beta = +j$
$\alpha = +1$
$\beta = -j$
$\alpha = -1$
$\beta = -j$
Φ_{dp}

FIG. 8

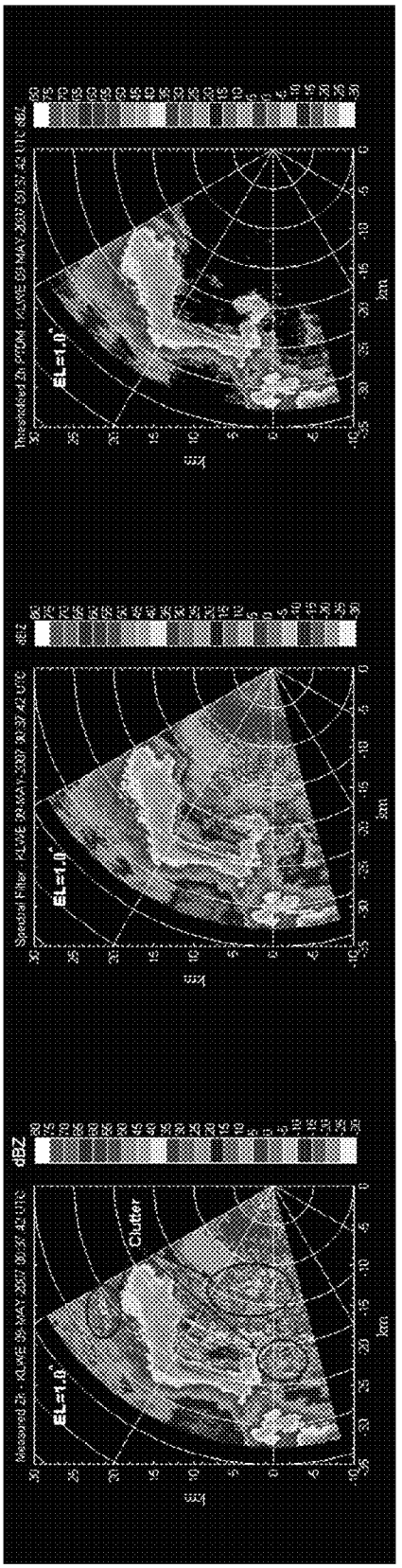

FIG. 9A

FIG. 9B

FIG. 9C

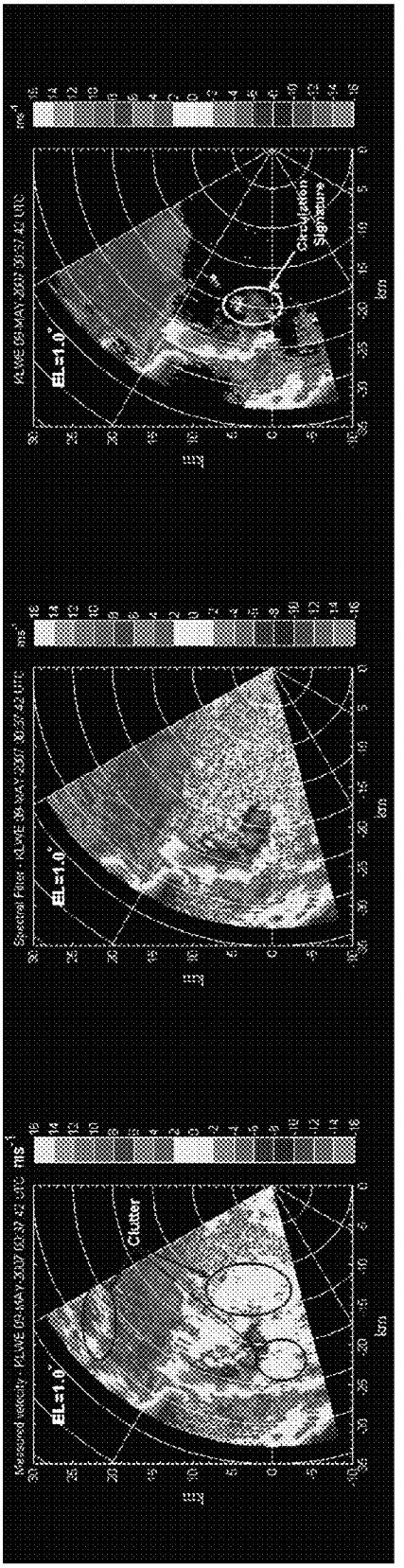

FIG. 9D

FIG. 9E

FIG. 9F

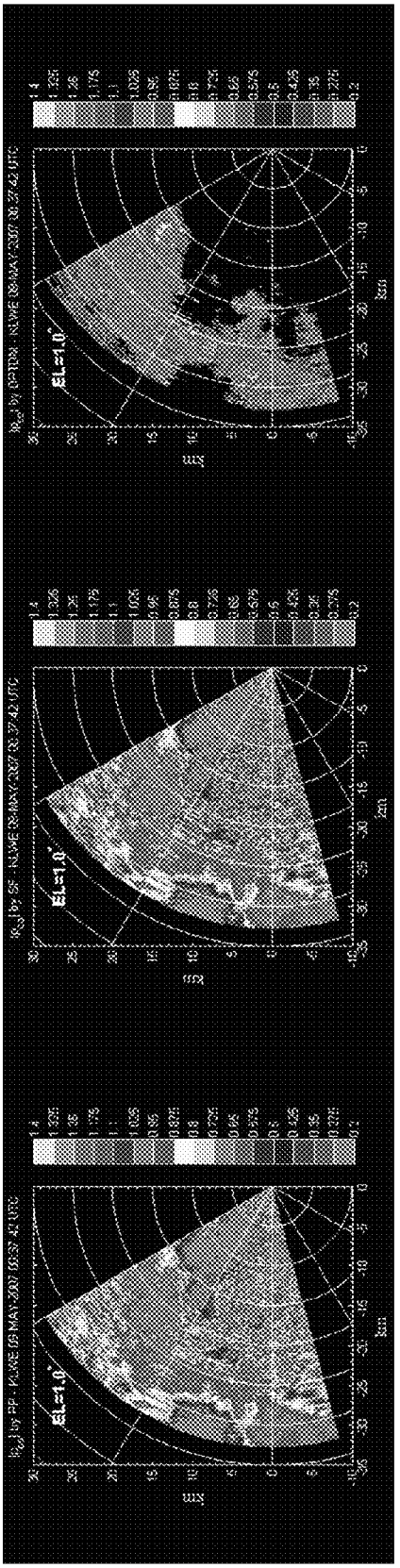

FIG. 10A

FIG. 10B

FIG. 10C

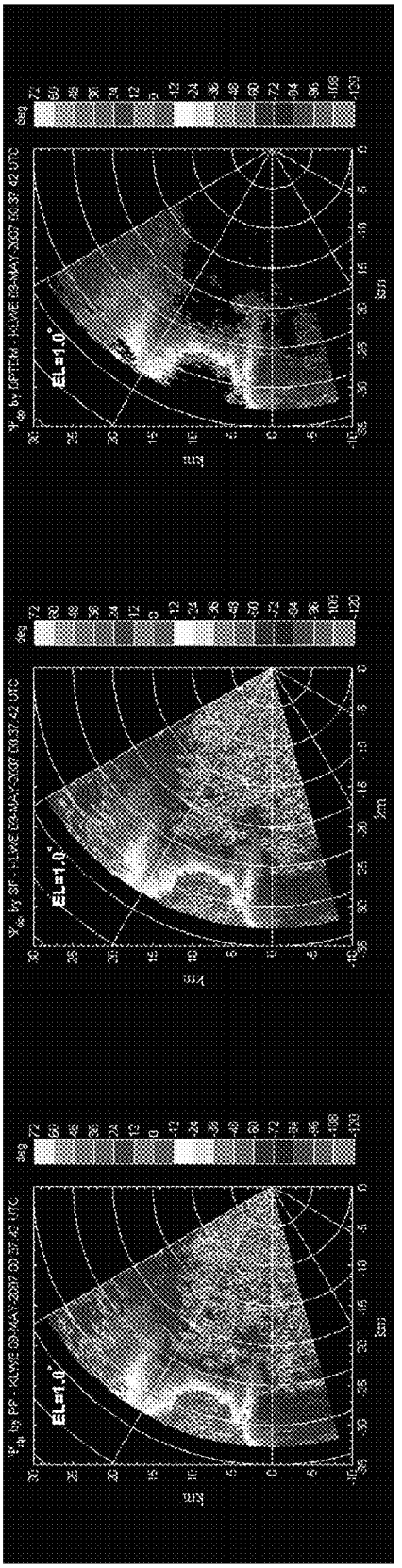

FIG. 10D

FIG. 10E

FIG. 10F

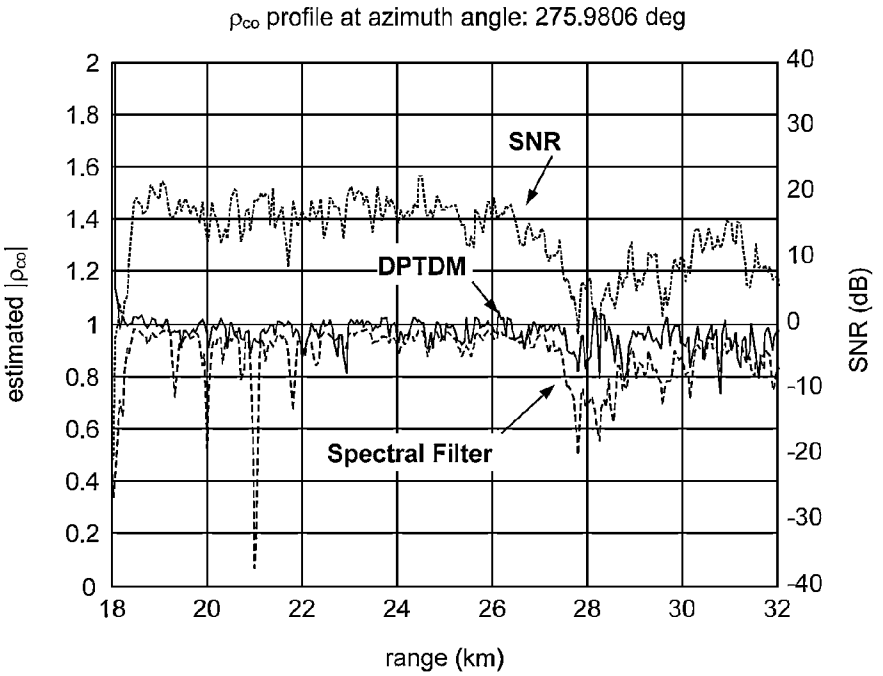

FIG. 11A

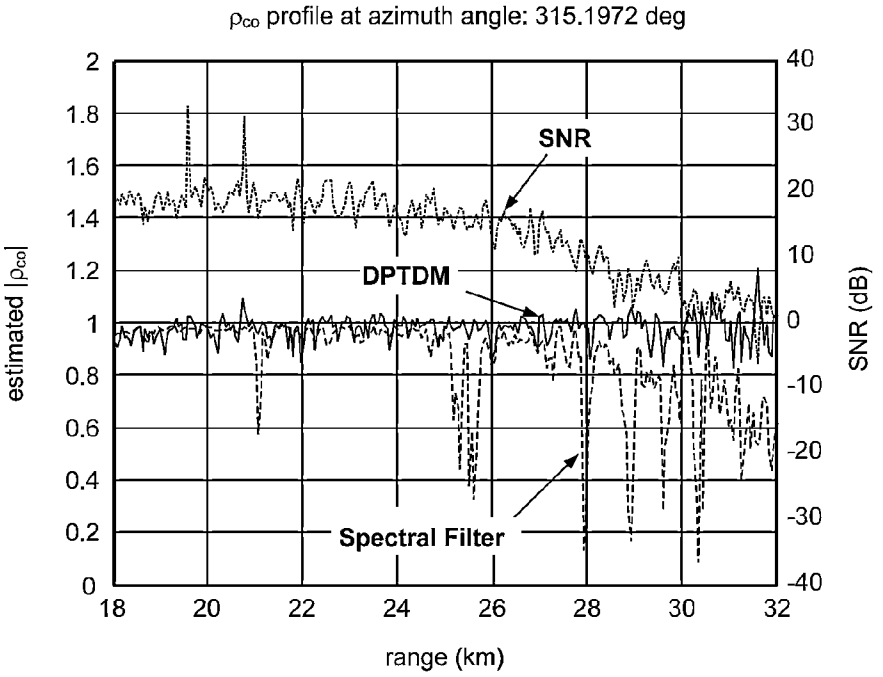

FIG. 11B

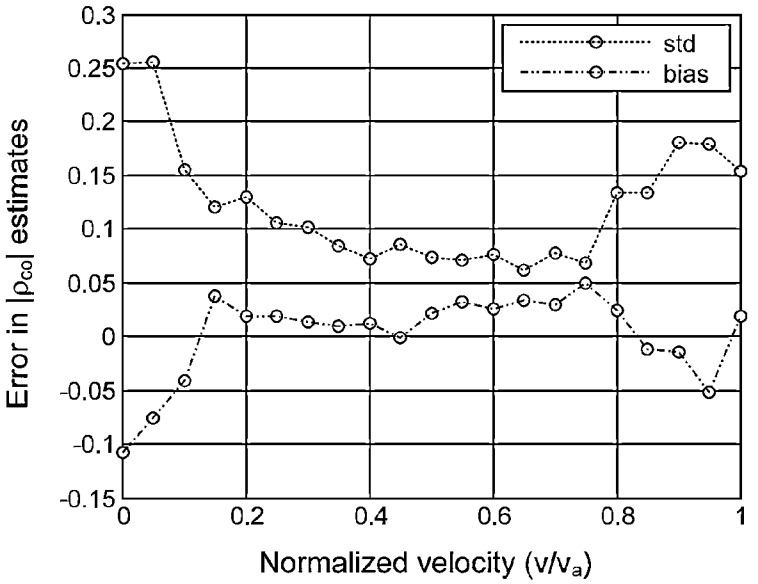

FIG. 12A

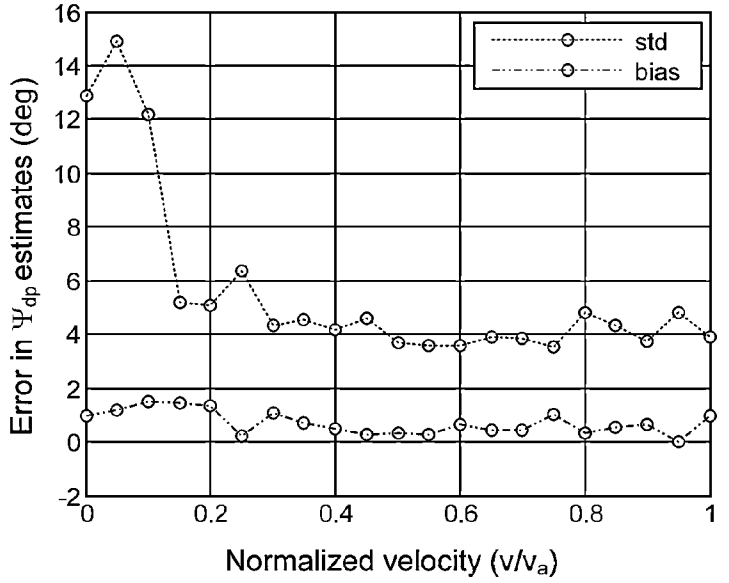

FIG. 12B

DUAL-POLARIZATION RADAR PROCESSING SYSTEM USING TIME DOMAIN METHOD

CROSS-REFERENCES TO RELATED APPLICATIONS

This application is a non-provisional of, and claims the benefit of, U.S. Provisional Patent Application Ser. No. 61/051,123, entitled "DUAL-POL SYSTEM," filed May 7, 2008, the entire disclosure of which is incorporated herein by reference for all purposes.

FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support through the National Science Foundation, Grant No. ERC0313747.

BACKGROUND

One of the fundamental objectives of meteorological radar systems is to sample the atmosphere surrounding the Earth to provide a quantitative measure of precipitation. Conventional meteorological radars provide coverage over long ranges, often on the order of hundreds of kilometers. A general schematic of how such conventional radar systems function is provided in FIG. **1**. In this illustration, a radar is disposed at the peak of a raised geographical feature such as a hill or mountain **104**. The radar generates an electromagnetic beam **108** that disperses approximately linearly with distance, with the drawing showing how the width of the beam **108** thus increases with distance from the radar. Various examples of weather patterns **116** that might exist, and which the system **100** attempts to sample, are shown in different positions above the surface **112** of the Earth.

For weather radars, the signal coming from ground targets represents clutter. It is generally desirable to mitigate the contribution of clutter to the overall radar signal to improve the quality of the radar signal and for quantitative applications. Such mitigation is conventionally achieved by applying a notch filter around zero Doppler frequency. The main disadvantage of such an approach is the signal loss, especially in cases where weather echoes have small radial velocities. Recent developments in radar signal processors allow for improvement in clutter suppression. For example, one approach compensates for the effect of notching by using advanced spectral filter that interpolates over notched spectral lines. The limitation of spectral filtering techniques is the effect of spectral leakage, caused by finite sample length, on the spectral moments estimates. As a result, spectral processing limits successful clutter suppression to cases of moderate clutter-to-signal ratios.

BRIEF SUMMARY

Embodiments of the invention make use of a dual-polarization parametric time-domain method ("DPTDM") for mitigating ground clutter and/or noise in radar observations. Such embodiments accordingly provide a method of investigating a region of interest with a dual-polarization radar. A radar signal is propagated into the region of interest in two polarization states and backscatter data is received in the two polarization states. In some embodiments, the two polarization states are orthogonal. The spectral moments of the time series data can be calculated for each of the two polarization states. A new time series that linearly combines the data in the two polarization states can be constructed. In some embodiments, the linear combination of the data in the two polarization states can be a complex value. The magnitude and phase of the co-polar correlation coefficient can then be determined by maximizing the likelihood function of the linear combination time series.

In some embodiments, the linear combination of the data in the two polarization states can be written as $V_\alpha = V^h + \alpha V^v$ and the likelihood function can be written as:

$$L_\alpha = \ln(|(R_{cN}) + xR_p^h|) + tr\left(((R_{cN}) + xR_p^h)^{-1}\hat{R}_{V_\alpha}\right) \quad (1)$$

where $R_{cN} = R_c^h + R_N^h + |\alpha|^2(R_c^v + R_N^v)$ Extremum of the likelihood function can be determined by solving the differential of L_α with respect to x. In some embodiments, the real and imaginary parts of the co-polar correlation coefficient can be determined from

$$x = 1 + \frac{\alpha^2}{\hat{Z}_{dr}} + \frac{2\alpha \mathrm{Re}(\rho_{co})}{\sqrt{\hat{Z}_{dr}}}, \text{ where } \alpha \text{ is real and} \quad (2)$$

$$x = 1 + \frac{\beta^2}{\hat{Z}_{dr}} - \frac{2\beta \mathrm{Im}(\rho_{co})}{\sqrt{\hat{Z}_{dr}}}, \text{ where } \alpha = j\beta \quad (3)$$

In some embodiments, the initial values of α and β can be set to ± 1, and subsequent values of α and β can be determined from

$$\alpha^n = \frac{(\hat{Z}_{dr}^n - 1) + \sqrt{(\hat{Z}_{dr}^n - 1)^2 + 4\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\hat{Z}_{dr}^n}}{2\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^{(n)}}} \quad (4)$$

$$\beta^n = \frac{(\hat{Z}_{dr}^n - 1) + \sqrt{(\hat{Z}_{dr}^n - 1)^2 + 4\mathrm{Im}(\hat{\rho}_{co}^n)\hat{Z}_{dr}^n}}{2\mathrm{Im}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^n}}$$

Thus, various embodiments of the invention provide for the determination of environmental factors using a linear combination of radar data received in orthogonally polarized states. In particular, ground clutter and noise mitigation can be increased using embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

FIG. **1** provides a schematic illustration of the operation of a conventional radar system (reproduced from the National Academy of Sciences Report, "Flash flood forecasting over complex terrain").

FIG. **2** shows an illustration of a conventional radar system compared with a dual-polarization radar system.

FIG. **3** shows a simplified block diagram of the transmission side of a dual-polarization radar system according to some embodiments.

FIG. **4** shows a simplified block diagram of the receiver side of a dual-polarization radar system according to some embodiments.

FIG. **5** shows a flowchart of a process for defining the state of a region of interest using dual-polarization radar according to some embodiments.

FIG. **6** shows a flowchart for a process for determining the differential reflectivity, the co-polar correlation coefficient ($|\rho_{co}|$) and/or the differential propagation phase (Φ_{dp}) according to some embodiments.

FIG. **7** shows a flowchart for estimating the coefficient in the linear combination data α according to some embodiments.

FIG. **8** depicts a correspondence between the location of an estimated differential propagation phase (Φ_{dp}) and the initial choices of α.

FIGS. **9**A-**9**C show a comparison of reflectivity over a region of interest using pulse pair processing (**9**A), spectral filtering (**9**B), and dual-polarization parametric time domain method as described throughout this disclosure (**9**C).

FIGS. **9**D-**9**F show a comparison of velocity measurements over a region of interest using pulse pair processing (**9**D), spectral filtering (**9**E), and dual-polarization parametric time domain method as described throughout this disclosure (**9**F).

FIGS. **10**A-**10**C show a comparison of differential propagation phase (Φ_{dp}) measurements over a region of interest using pulse pair processing (**10**A), spectral filtering (**10**B), and dual-polarization parametric time domain method as described throughout this disclosure (**10**C).

FIGS. **10**D-**10**F show a comparison of co-polar correlation coefficient (ρ_{co}) measurements over a region of interest using pulse pair processing (**10**D), spectral filtering (**10**E), and dual-polarization parametric time domain method as described throughout this disclosure (**10**F).

FIGS. **11**A and **11**B show range profiles for estimated ρ_{co} at azimuth angles 275 degree and 315 degree using embodiments described herein.

FIGS. **12**A and **12**B show errors in $|\rho_{co}|$ and ϕ_{dp} estimates using embodiments described herein.

DETAILED DESCRIPTION

Some embodiments of the invention provide a system for determining environmental parameters within a region of interest using a dual polarization parametric time domain method. Previous work has provided parametric time domain methods (PTDM) that can estimate various parameters in single-polarization and/or dual-polarization radar data. Such methods and/or systems are described in U.S. patent application Ser. No. 11/83,0574, titled "Ground Clutter Mitigation Using a Parametric Time Domain Method," filed Jul. 30, 2007, the entire disclosure of which is incorporated by reference for all purposes. PTDM provides a good model for clutter, precipitation and noise in the received radar data for each polarization. However, PTDM does not consider any correlation between the polarized data. Some embodiments of the invention provide a model and estimator to explore the correlation between the two polarization channels.

FIG. **2** shows an illustration of a conventional radar system **210** with a single polarization state compared with a dual-polarization radar system **220** (or polarimetric radar system). Dual-polarization radar systems **220** can transmit and receive two orthogonal polarization states, often at vertical polarization and horizontal polarization as shown in the figure. Dual-polarization radar systems can provide many important parameters for meteorologists including differential reflectivity, co-polar correlation coefficients, linear depolarization ratio and/or specific differential phase.

FIG. **3**A shows a simplified block diagram **300** of the transmission side of a dual-polarization radar system according to some embodiments. Such a transmitter can change the polarization state between any two orthogonal polarization states on a pulse-to-pulse basis. Transmitter **305** can produce and/or send signals and/or waveforms to waveguide switching device **310**. Wave switching device **310** can be a high power waveguide switch. Wave switching device **310** can switch between transmission from transmitter **305** to duplexer **320** based on the desired polarization of waveform. Wave switching device **310**, for example, can include a mechanical motor-driven rotary vane switch and/or an electronically controlled ferrite circulator switch.

Duplexer **320** can isolate the received signals from the transmitter waveform. As noted, received signals can be sent to the proper polarization receiver. Microwave polarizer network **325** can include a variable ratio power dived and/or variable phase shifter which can be used to synthesize the proper input waveform to antenna **330**.

FIG. **3**B shows a simplified block diagram **360** of the receiver side of a dual-polarization radar system according to some embodiments. Such receivers can measure the various terms (both real and imaginary) that are part of the data covariance matrix (the covariance matrix is discussed below). Microwave polarizer network **325** receives the backscatter radar signal from antenna **330** and the received signals are duplexed from the transmitter signals by duplexers **320**. Low noise amplifiers **335** can be employed for signal filtering. Mixers **340** for each polarization channel can be employed to mix the received signal with a stable local oscillator (STALO). Intermediate frequencies can be amplified using intermediate frequency amplifiers **345**; and the backscatter signal can be detected for both polarizations at detectors **350**.

FIG. **4** shows a block diagram of a computer system **400** that can be coupled with a dual polarization radar system for computation of environmental parameters using various embodiments of the invention. Computer system **400** can be used to perform any or all the computations shown in FIG. **2** and/or FIG. **3**. The drawing illustrates how individual system elements can be implemented in a separated or more integrated manner. The computer **400** is shown having hardware elements that are electrically coupled via bus **426**. Network interface **452** can communicatively couple the computational device **400** with another computer, for example, through a network such as the Internet. The hardware elements can include a processor **402**, an input device **404**, an output device **406**, a storage device **408**, a computer-readable storage media reader **410***a*, a communications system **414**, a processing acceleration unit **416** such as a DSP or special-purpose processor, and memory **418**. The computer-readable storage media reader **410***a* can be further connected to a computer-readable storage medium **410***b*, the combination comprehensively representing remote, local, fixed, and/or removable storage devices plus storage media for temporarily and/or more permanently containing computer-readable information.

Dual polarization radar system interface **450** is coupled with bus **426**. In some embodiments, dual polarization radar system interface **450** can be any type of communication interface. For example, dual polarization radar system interface **450** can be a USB interface, UART interface, serial interface, parallel interface, etc. Dual polarization radar system interface **450** can be configured to couple directly with a dual polarization radar system.

The computer system **400** also comprises software elements, shown as being currently located within working memory **420**, including an operating system **424** and other

code **422**, such as a program designed to implement methods and/or processes described herein. In some embodiments, other code **422** can include software that provides instructions for receiving user input from a dual polarization radar system and manipulating the data according to various embodiments disclosed herein. In some embodiments, other code **422** can include software that can predict or forecast weather events, and/or provide real time weather reporting and/or warnings. It will be apparent to those skilled in the art that substantial variations can be used in accordance with specific requirements. For example, customized hardware might also be used and/or particular elements might be implemented in hardware, software (including portable software, such as applets), or both. Further, connection to other computing devices such as network input/output devices can be employed.

While FIGS. **3**A, **3**B and **4** are described herein with reference to particular blocks, it is to be understood that the blocks are defined for convenience of description and are not intended to imply a particular physical arrangement of component parts. Further, the blocks need not correspond to physically distinct components.

A general overview of methods of the invention is provided with the flow diagram **500** of FIG. **5**. The method **500** begins by propagating dual-polarization radar signals to a region of interest as indicated at block **504**. Sampled time series data are collected at block **508** in two polarizations and used in determining dual-polarization parameters for a time-domain parametric model of the region of interest. A specific model is described below but alternative embodiments of the invention may use other dual-polarization parametric models.

At block **512**, spectral moments for co-polar time domain data can be estimated. For example, spectral moments can be estimated using PTDM and/or GMAP methods that are known in the art. In some embodiments, the summation of the log-likelihood function for co-polar data can be minimized and solved for die spectral moments. In other embodiments, the summation of the log-likelihood function for co-polar data can be maximized and solved for the spectral moments. In some embodiments, the differential reflectivity can also be estimated from the spectral moments of two polarizations. At block **516**, α and $\beta=j\alpha$ can be determined using estimated dual-polarization parameters from previous range gates. At block **520**, a log-likelihood function for the linear combination of the two polarization vectors, for example, $V_\alpha=V^h+\alpha V^v$, can be minimized. In other embodiments, a log-likelihood function can be maximized. From this minimization (or maximization) the magnitude and/or the phase of the co-polar correlation coefficient can be determined at block **532**.

Some embodiments of the invention can estimate the magnitude and the phase of the co-polar correlation coefficient from a linear combination of two polarization radar data. Such estimations, for example, can be performed using computer system **400**. FIG. **6** shows a flowchart of such process **600** that can be followed to determine the magnitude of the co-polar correlation coefficient (ρ_{co}) and the differential propagation phase (Φ_{dp}), which is the angle of ρ_{co} in the complex plane. Process **600** starts at block **605** and can receive voltage readings from the backscatter of a region of interest for two polarizations at block **610**. For example, the voltage readings can include data from vertically polarized and horizontally polarized signals.

At block **615**, a summation of the likelihood functions for both V^H and V^V can be minimized to obtain the horizontal and vertical spectral moments. The likelihood function for each polarization (h,v) can be written as

$$L(\theta)^{h,v}=\ln(|R(\theta)^{h,v}|)+tr\left(R^{h,v-1}(\theta)\hat{R}_v^{h,v}\right), \tag{5}$$

where $R^{h,v}$ is the covariance matrix of measures signal at sampling rate T_S and can be given by

$$R^{h,v}[k,l]=P_p^{h,v}\exp\left(-\frac{8\pi^2\sigma_p^{h,v2}(k-l)^2T_s^2}{\lambda^2}\right)\exp\left(-j\frac{4\pi\bar{v}^{h,v}(k-l)T_s}{\lambda}\right)+ P_c^{h,v}\exp\left(-\frac{8\pi^2\sigma_c^{h,v2}(k-l)^2T_s^2}{\lambda^2}\right)+\sigma_N^{2h,v}\delta(k-l); \tag{6}$$

$$k,l=1,\ldots,N,$$

and $\hat{R}_v^h=V^hV^{hH}$ is the sample covariance matrix for H signal and $\hat{R}_v^v=V^vV^{vH}$ is the sample covariance matrix for V signal. The spectral moments can be

$$\theta=[\sigma_c^h,P_c^h,\sigma_c^v,P_c^v,\bar{v},\sigma,P_p^h,P_p^v,\sigma_N^{2h},\sigma_N^{2v}], \tag{7}$$

where $P_p^{h,v}$ is the precipitation signal power, $\sigma_p^{h,v}$ is the precipitation spectrum width, $\bar{v}$ is the mean velocity of precipitation, $P_c^{h,v}$ is the clutter power, $\sigma_c^{h,v}$ is the clutter spectrum width, $\sigma_N^{2h,v}$ is the noise power, and λ denotes the radar wavelength; j is $\sqrt{-1}$ and δ is a Kronecker function.

The precipitation spectral moments for the two polarizations can be obtained by minimizing the log-likelihood function

$$\hat{\theta}=\underset{\theta}{\operatorname{argmin}}(L(\theta)). \tag{8}$$

Once the spectral moments have been determined, at block **620**, $\hat{Z}_{dr}$ can be determined from

$$\hat{Z}_{dr}(dB)=\hat{P}^h(dB)-\hat{P}^v(dB). \tag{9}$$

The counter n is initialized to one starting at the first range bin at block **625**. At block **627**, it can be determined whether n is less than some predetermined and/or user defined constant C. In some embodiments, C can be 2, 3, 4, 5, 6, 7, 8, 9, 10, etc. If n is less than C, then α and β can be determined from the angle of Φ_{dp} in the complex plane at block **630**. The values for the first range bins (bin numbers less than C) of α and β can be estimated as being +1 or −1 as shown in FIG. **8**. In some embodiments, the angle of Φ_{dp} for the firsts bins can be estimated using estimation technique. For example, for the first few bins, if $0°<\Phi_{dp}<90°$, then $\alpha=-1$ and $\beta=1$. If $90°<\Phi_{dp}<180°$, then $\alpha=1$ and $\beta=1$. If $180°<\Phi_{dp}<270°$, then $\alpha=1$ and $\beta=-1$. If $270°<\Phi_{dp}<360°$, then $\alpha=-1$ and $\beta=-1$. Process **600** can then move on to block **635**.

If n is greater than C at block **627**, then α and $\alpha=j\beta$ can be estimated using

$$\alpha^n=-\frac{(\hat{Z}_{dr}^n-1)+\sqrt{(\hat{Z}_{dr}^n-1)^2+4\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\hat{Z}_{dr}^n}}{2\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^{(n)}}} \tag{10}$$

-continued

$$\beta^n = -\frac{\left(\hat{Z}_{dr}^n - 1\right) + \sqrt{\left(\hat{Z}_{dr}^n - 1\right)^2 + 4\mathrm{Im}(\hat{\rho}_{co}^n)\hat{Z}_{dr}^n}}{2\mathrm{Im}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^n}}.$$

In equation 10, ρ_{co}^{n-1} is the co-polar correlation coefficient for the previous range bin.

At block **635**, a linear combination of the two polarization vectors can be constructed as

$$V_\alpha = V^h + \alpha V^v \tag{11}$$

where V^h is the sampled voltage data for the horizontally polarized signal and V^v is the sample voltage data for the vertically polarized signal.

A log-likelihood function for dual polarization data can be written as:

$$L_\alpha = \ln(|(R_{cN}) + xR_p^h|) + tr\left\{((R_{cN}) + xR_p^h)^{-1}\hat{R}_{V_\alpha}\right\}, \tag{1}$$

where R_c is the covariance matrix for clutter, R_N is the covariance matrix for noise, R_p^h is the horizontally polarized covariance matrix for precipitation, R_p^v is the vertically polarized covariance matrix for precipitation, and $\hat{R}_{v_\alpha}$ is the covariance matrix of sampled data for V_α.

In some embodiments, L_α can be minimized by setting the derivative of the likelihood function with respect to x to zero:

$$\frac{\partial L_\alpha}{\partial x} = tr\left\{(xR_p^h + R_{cN})^{-1}R_p^h\left(I - (xR_p^h + R_{cN})^{-1}\hat{R}_{V_\alpha}\right)\right\} = 0, \tag{13}$$

where

$$R_{cN} = R_c^h + R_N^h + |\alpha|^2(R_c^v + R_N^v). \tag{14}$$

The results of minimizing the likelihood function L_α can produce values for the real and the imaginary parts of the co-polar correlation coefficient.

At block **645**, if α is real, then we can determine the real parts of ρ_{co} from the following,

$$x = 1 + \frac{\alpha^2}{\hat{Z}_{dr}} + \frac{2\alpha\mathrm{Re}(\rho_{co})}{\sqrt{\hat{Z}_{dr}}}; \tag{15}$$

and if α is imaginary, $\alpha = j\beta$ where β is real, then we can determine the imaginary part of ρ_{co} from the following,

$$x = 1 + \frac{\beta^2}{\hat{Z}_{dr}} - \frac{2\beta\mathrm{Im}(\rho_{co})}{\sqrt{\hat{Z}_{dr}}}. \tag{16}$$

Using the values for α, β, and estimated value of Z_{dr}, and estimated x as determined in blocks **630**, **620** and **640**, we can solve equations 15 and 16 for the real and imaginary parts of ρ_{co} at block **645**. At block **650**, the magnitude and angle (Φ_{dp}) of ρ_{co} can be determined from the real and absolute values of ρ_{co} for the n^{th} range bin.

If n equals the number of range gates, N, in the data set, at block **655**, then process **600** ends at block **660**, where N is the number of range gates. If, however, n is less than the number of range gates, then n can be incremented at block **665** and process **600** returns to block **627**.

FIG. **7** shows a method **700** for estimating the optimal values of α and β according to some embodiments. At block **710**, process **700** determines whether bin number n is less than a preset value x, which, for example, can be less than 10. In some embodiments, x can equal 1, 2, 3, 4, 5, 6, 7, 8, 9, etc. If n is less than x, then we are looking at data in the first few bins, and we can estimate ρ_{co} from the location of Φ_{dp} in the complex plan at block **720**. If $0° < \Phi_{dp} < 90°$, then $\alpha = -1$ and $\beta = 1$, as shown in block **730**. If $90° < \Phi_{dp} < 180°$, then $\alpha = 1$ and $\beta = 1$, as shown in block **740**. If $180° < \Phi_{dp} < 270°$, then $\alpha = 1$ and $\beta = -1$, as shown in block **750**. If $270° < \Phi_{dp} < 360°$, then $\alpha = -1$ and $\beta = -1$, as shown in block **760**. If bin number n is greater than a preset value x, then the optimal values of α and β can be determined as shown in blocks **770** and **780**.

FIGS. **9**A-**9**C show a comparison of reflectivity over a region of interest using pulse pair processing (**9**A), spectral filtering (**9**B), and dual-polarization parametric time domain method as described throughout this disclosure (**9**C). As can be seen in FIG. **9**C, ground clutter and/or noise has been greatly mitigated.

FIGS. **9**D-**9**F show a comparison of velocity measurements over a region of interest using pulse pair processing (**9**D), spectral filtering (**9**E), and dual-polarization parametric time domain method as described throughout this disclosure (**9**F). As can be seen in FIG. **9**F, ground clutter and/or noise has been greatly mitigated. Moreover, FIG. **9**F shows characteristics of a circular signature indicative of tornadoes and/or hurricanes. This circular signature is difficult (or impossible) to visualize in FIGS. **9**D and **9**E.

FIGS. **10**A-**10**C show a comparison of co-polar correlation coefficient (ρ_{co}) measurements over a region of interest using pulse pair processing (**10**A), spectral filtering (**10**B), and dual-polarization parametric time domain method as described throughout this disclosure (**10**C). As can bee seen in FIG. **10**C, by using embodiments of the invention, the ground clutter and/or noise has been mitigated.

FIGS. **10**D-**10**F show a comparison of differential propagation phase (Φ_{dp}) measurements over a region of interest using pulse pair processing (**10**D), spectral filtering (**10**E), and dual-polarization parametric time domain method as described throughout this disclosure (**10**F). Again, as can be seen in FIG. **10**F, by using embodiments of the invention, the ground clutter and/or noise has been mitigated.

FIGS. **11**A and **11**B show range profiles for an estimated $|\rho_{co}|$ using both embodiments described herein and GMAP methods at azimuth angles of 275 degree and 315 degree using embodiments described herein. It is shown that GMAP $|\rho_{co}|$ is low where the signal is weak, i.e., SNR is small. Moreover, using both reflectivity and correlation coefficient thresholding, GMAP does not provide a good classification between weather echoes and clutter. In the region where clutter presents, standard deviation of GMAP $|\rho_{co}|$ is pretty high. It is explained by can be the leakage spectral points of clutter. Because some embodiments described herein operate in the time domain, these embodiments are not affected by this leakage problem. Moreover, embodiments described herein can estimate noisefloor better than GMAP does. When noise is not subtracted properly from signal, it can provide more accurate estimated $|\rho_{co}|$.

FIGS. **12**A and **12**B show errors in ρ_{co} and Φ_{dp} estimates for only 16-sample data using embodiments described herein. As can be seen, such estimate errors is acceptable.

Circuits, logic modules, processors, and/or other components may be described herein as being "configured" to perform various operations. Those skilled in the art will recog-

nize that, depending on implementation, such configuration can be accomplished through design, setup, interconnection, and/or programming of the particular components and that, again depending on implementation, a configured component might or might not be reconfigurable for a different operation. For example, a programmable processor can be configured by providing suitable executable code, a dedicated logic circuit can be configured by suitably connecting logic gates and other circuit elements, and so on.

While the embodiments described above may make reference to specific hardware and software components, those skilled in the art will appreciate that different combinations of hardware and/or software components may also be used and that particular operations described as being implemented in hardware might also be implemented in software or vice versa.

Computer programs incorporating various features of the present invention may be encoded on various computer-readable storage media; suitable media include magnetic disk or tape, optical storage media such as compact disk (CD) or digital versatile disk (DVD), flash memory, and the like. Computer-readable storage media encoded with the program code may be packaged with a compatible device or provided separately from other devices. In addition program code may be encoded and transmitted via wired optical, and/or wireless networks conforming to a variety of protocols, including the Internet, thereby allowing distribution, e.g., via Internet download.

What is claimed is:

1. A method comprising:

propagating polarized radar signals to a region of interest using a dual-polarization radar transmitter;

collecting sampled co-polar time series radar data scattered within the region of interest with the dual-polarization radar transmitter, wherein the co-polar time series radar data includes vertically polarized data and horizontally polarized data;

creating, using a computer system, a summed likelihood function by adding a likelihood function for the first time series radar data and a likelihood function for the second time series radar data;

maximizing, using the computer system, the summed likelihood function to estimate the spectral moments of the first time series radar data and the second time series radar data; and

determining, using the computer system, at least one of the differential propagation phase and the co-polar correlation coefficient between the horizontally polarized data and the vertically polarized data from a complex linear combination of the vertically polarized data and horizontally polarized data.

2. The method according to claim **1**, wherein the linear combination of the horizontally polarized data and the vertically polarized data is expressed as $V_\alpha = V^H + \alpha V^V$.

3. The method according to claim **2**, wherein an optimal value for α for the n^{th} range gate measurement is estimated as

$$\alpha_{opt}^{(n)} = -\frac{(\hat{Z}_{dr}^{(n)} - 1) + \sqrt{(\hat{Z}_{dr}^{(n)} - 1)^2 + 4\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\hat{Z}_{dr}^{(n)}}}{2\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^{(n)}}}.$$

4. The method according to claim **2**, wherein an optimal value for $\alpha = j\beta$ for the n^{th} range gate measurement is estimated as

$$\beta_{opt}^{(n)} = -\frac{(\hat{Z}_{dr}^{(n)} - 1) + \sqrt{(\hat{Z}_{dr}^{(n)} - 1)^2 + 4\mathrm{Im}(\hat{\rho}_{co}^{(n-1)})\hat{Z}_{dr}^{(n)}}}{2\mathrm{Im}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^{(n)}}}.$$

5. A method of investigating a region of interest with a radar, the method comprising:

propagating polarized radar signals to the region of interest using a dual-polarization radar system;

collecting a first time series radar data scattered within the region of interest with a first polarization using a radar;

collecting a second time series radar data scattered within the region of interest with a second polarization using a radar, wherein the first polarization and the second polarization are substantially orthogonal;

creating, using a computer system, a summed likelihood function by adding a likelihood function for the first time series radar data and a likelihood function for the second time series radar data;

maximizing, using a computer system, the summed likelihood function to estimate the spectral moments of the first time series radar data and the second time series radar data; and

estimating, using a computer system, at least one of the differential propagation phase, the magnitude of the co-polar correlation coefficient, and the phase of the co-polar correlation coefficient using a linear combination of the first time series radar data and the second time series radar data.

6. The method according to claim **5**, wherein at least one of the magnitude of the co-polar correlation coefficient and the phase of the co-polar correlation coefficient are estimated using the first time series radar data and the second time series radar data.

7. The method according to claim **5**, wherein the linear combination of the first time series radar data and the second time series radar data comprises

$$\alpha_{opt}^{(n)} = -\frac{(\hat{Z}_{dr}^{(n)} - 1) + \sqrt{(\hat{Z}_{dr}^{(n)} - 1)^2 + 4\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\hat{Z}_{dr}^{(n)}}}{2\mathrm{Re}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^{(n)}}}$$

and

$$\beta_{opt}^{(n)} = -\frac{(\hat{Z}_{dr}^{(n)} - 1) + \sqrt{(\hat{Z}_{dr}^{(n)} - 1)^2 + 4\mathrm{Im}(\hat{\rho}_{co}^{(n-1)})\hat{Z}_{dr}^{(n)}}}{2\mathrm{Im}(\hat{\rho}_{co}^{(n-1)})\sqrt{\hat{Z}_{dr}^{(n)}}}$$

where $\alpha = j\beta$.

8. The method according to claim **5**, wherein the estimating a magnitude and a phase of the co-polar correlation coefficient includes minimizing a log-likelihood function for the linear combination of the first time series radar data and the second time series radar data.

9. A radar system comprising:

a dual-polarization transmitter configured to transmit a signal in two substantially orthogonal polarizations;

a dual-polarization receiver configured to receive a first signal in first polarization and a second signal in a second polarization, wherein the first polarization and the second polarization are substantially orthogonal;

a computer system coupled at least with the dual polarization receiver, the computer system being configured to:

create a summed likelihood function by adding a likelihood function for the first signal and a likelihood function for the second signal;

maximize the summed likelihood function to estimate the spectral moments of the first signal and the second signal; and,

estimate at least one of the differential propagation phase, the magnitude of the co-polar correlation coefficient, and the phase of the co-polar correlation coefficient using a linear combination of the first signal and the second signal.

10. The radar system according to claim **9**, wherein the computer system is further configured to estimate at least one of the magnitude of the co-polar correlation coefficient and the phase of the co-polar correlation coefficient using the first signal and the second signal.

11. A radar system comprising:

propagation means for propagating radar into a region of interest;

receiving means for receiving radar backscatter in a first polarization state and radar back scatter in a second polarization state from the region of interest; and

computation means for estimating the spectral moments of the radar backscatter in a first polarization state and the radar backscatter in a second polarization state, for minimizing a log-likelihood function of a linear combination of the radar backscatter in the first polarization state and the radar backscatter in the second polarization state, and for estimating at least one of the differential propagation phase, the magnitude of the co-polar correlation coefficient, and the phase of the co-polar correlation coefficient using the minimization of the log-likelihood function of the linear combination of the radar backscatter in the first polarization state and the radar backscatter in the second polarization state.

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