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ANALYSIS OF MODEL SIMULATIONS OF SPACED ANTENNA USING FULL CORRELATION ANALYSIS

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ABSTRACT: Radar techniques have been used as powerful research tools to study clear air turbulence, cloud physics, and dynamics of consecutive storms and large-scale storms. Several ground-based techniques are used to observe and study turbulent echoes in the MST (Mesosphere Stratosphere Troposphere) region. This paper discusses Spaced Antenna (SA) technique using Full Correlation Analysis (FCA) to estimate wind velocity of simulated moving targets which is one of the important parameter used in various applications. Airglow intensities are recorded for three spaced regions in the sky, and observations of the moving pattern in the middle atmosphere is derived and recorded. The spaced antenna method is applied to model-generated, simulated data in order to extract the typical Full correlation analysis output parameters such as the apparent and true velocity. The quantity of principal interest is the estimate of 'V', the "random velocity parameter". Correlation Analysis is a logical, simple yet effective way to estimate the wind velocity. These ideas are implemented using a mathematical model which can be simulated in any high level language. *C* language has been used to simulate the radar backscatter and '*Origin*' software for further analysis and calculation of useful quantities. The present model incorporates turbulent motions of the pattern under the presence of noise with varying turbulence strength & varying levels of noise.

Keywords: Radar, Spaced Antenna, Wind Velocity, Full Correlation Analysis.

I. RADAR

Radar detects the presence of objects and locates their position in space by transmitting electromagnetic energy and observing the returned echo. The echo not only indicates that the target is present, but the time elapses between transmission of the pulse and the receipt of the echo signal is a measure of the distance to the target [8].

II. SPACED ANTENNA ANALYSIS

A single beam is transmitted vertically, and the back scattered signals are received on three or more separating antennas. The spaced antenna analysis then proceeds by calculating the cross correlation functions for each pair of receiving antennas. The delays at which the correlation functions peak are used to determine the drift velocity of the turbulent structure across the array of receiving antennas [1]. The antenna arrangement and co-ordinate system used for the simulation are shown in Figure1. Other parameters held at fixed values for simulation are given in Table 1. The autocorrelation and cross correlation functions used in the subsequent analysis are obtained by ensemble averaging the results for many samples.

The standard statistical formula for the correlation co-efficient between the values of $f(x,y)$ and of $f(x+\xi, y+\eta)$, i.e. descriptively, between the pattern and the same pattern shifted by a distance ξ in x- direction and η in y-direction is given by equation(1). If regarded as a function of ξ and η it is called the two- dimensional spatial correlation function of the pattern.

$$\rho(\xi,\eta) = \frac{\langle f(x.y)\,.\,f(x+\xi, y+\eta)\rangle}{\langle |f(x,y)|^2\rangle} \qquad (1)$$

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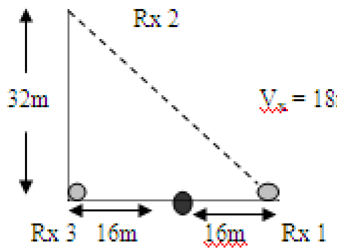

Fig. 1. Receiver Configuration

It is unity when $\xi = \eta = 0$ and decreases as ξ and η increase, eventually tending to zero when the pattern is shifted so far that no correlation exists.

We now consider a pattern which has random changes in time but no tendency to move in any particular direction (rather like the surface of a boiling liquid). Mathematically we now have a dependence on time, and we take the pattern as f(x, y, t). A sensor at a fixed point, say the origin, we would record time variations given by f (0, 0, t) and these could be described by a temporal auto-correlation function defined in the usual way. More generally, spaced sensors could be used to determine the function. By making calculations in which time differences were introduced between the records obtained from the sensors with different separations. [2]

$$\rho(\xi, \eta, \tau) = \frac{\langle f(x, y, t) \,.\, f(x+\xi, y+\eta, t+\tau) \rangle}{\langle |f(x, y, t)|^2 \rangle} \qquad (2)$$

A Wind Velocity measurements

To determine a velocity with two independent components we expect to have to use a minimum of three sensors. We consider first the case in which these form a fight-angled triangle and have separations ξ_0 in the X-direction, and η_0 in the Y-direction. Consider a cross-correlation function for the pair of sensors space along the X-axis. That is, experimentally, we make recordings at these two points, and then compute the correlation between them for values of relative time shift τ.

B. The Atmospheric Radar Backscatter Model

The radar volume is defined according to a beam-pointing angle, an "effective beam width, and a range gate extent. In this model the radar volume is enclosed within a cylindrical volume, also referred to as 'enclosing' volume throughout which a number of scattering locations are initially randomly positioned. These scatterers represent regions of refractive index irregularity, as opposed to physical objects. At each sampling time the complex returns from each scatterer are added, and the scattering positions are updated, based on specified values of the mean background wind, turbulent motions. Scatterers updated to positions outside the enclosing volume are readmitted to maintain a constant number of scatterer [4].

III. MODEL PARAMETERS SIMULATION

Simulation of radar back scatter can be implemented in a mathematical model using any high level language. This project uses 'C' Language for simulation and *origin* software for plotting the results obtained for further analysis and calculation of desired parameters. Initially the simulation of the radar backscatter is implemented neglecting the effects of noise and turbulence. The second step in the simulation is to simulate turbulent motions and observe the effects of turbulence on the simulated radar backscatter model. The turbulent RMS velocity of steady state wind vector is also varied and the effect of varying turbulence strength is observed. Further, we generate noise and add noise with varying strength as noise is inherent during the implementation in real time. Finally, we compare all the results for further analysis. An antenna spacing of D = $\lambda/2$ produces no spatial aliasing. The enclosing volume is chosen to be

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approximately four times the volume of the radar. [4] Although this arrangement of the antennas is not the optimum configuration, this lays a foundation for future scope of the project and analysis. An equilateral triangle is the optimum configuration. [1]. In this case spatial decorrelation will exist between antennas 2 and 3 since each antenna sees a different cut of the diffraction pattern on the ground when the horizontal velocity is in the x direction.

A. Generating the Model Time Series

At each sampling time the complex returns from all scatterers within the radar volume are added. Each scatterer is assigned a reflectivity ratio ρ within the range [0.5 , 1.0] in relation to maximum reflectivity value within the radar volume. The amplitude of the complex return from the *i* th scatterer a_i located at a zenith angle θ_i , is given by

$$a_i = P_i R_i \sqrt{P(\theta i)} \qquad (3)$$

where $P(\theta_i)$ is obtained from (3), and R_i is a triangular range weighting function varying linearly from unity in the middle of the range gate to zero at the edges of the range gate. [2]. The inclusion of the aspect sensitivity and range gate function implies no spurious effects are generated by a scatterer leaving the radar volume, as the amplitude of the complex return from this scatterer is small due to the close proximity of radar volume boundary. The phase of the complex return from the i th scatterer is given by

$$\phi_i = 2\pi (|\overline{r_{ti}}| + |\overline{r_{ti}}|) / \lambda \qquad (4)$$

where $|\overline{r_{ti}}|$ is the distance between the transmitter and the i th scatterer, $|\overline{r_{ri}}|$ is the distance between the relevant receiver and the i th scatterer, and λ is the radar wavelength.

$$P_r = \left[\frac{P_t}{4\pi R^2} \right] \left[\frac{C\tau}{2} \right] \eta \left[\frac{A_r}{R^2} \right] \qquad (5)$$

Where P_t is the transmitter power (W).
C is the velocity of light (3×10^8 m/s)
T is the pulse width (sec)
η is the volume reflectivity (m^2/m^3)
A_r is the receive antenna aperture (m^2)
R is the distance (m).

Thus the Radar equation is simulated. The initial positions for the scatters are selected randomly according to the x, y, and z. For each time increment, positions are updated according to the x, y, and z components of velocity chosen from a Gaussian probability density. The mean value of this density is the average velocity, and the variance is a measure of the turbulence. After each update of the position, a new set of randomly distributed reflectivities can be assigned. The simulation sums scattered voltages at successive time increments to calculate a complex time history of antenna voltage for each of the receiving antennas [7,5].

B. Updating the scattering positions with no noise and turbulence

The position of the ith scatterer is updated and if the updated position for a particular scatterer lies outside the enclosing volume the scatterer is readmitted at the opposite horizontal position to that occupied at the previous sampling time. On re-admission of a scatterer, both the random reflectivity and the turbulent velocity V associated with the scatterer are regenerated, as the readmitted scatterer is considered to be a different scatterer to that leaving the enclosing volume [2]. For the simulation results presented, the input parameters which were varied include the velocity and velocity variance in the x direction. All the scatterers were given a 18m/s horizontal velocity with zero variance parallel to the x-axis. Also, scatter amplitudes, once assigned, were held constant thereafter. The mean auto and cross-correlation functions are shown in the results. The three auto- and cross-covariance functions are calculated from the three-receiver time series. The auto-covariance at zero lag includes the effects of noise. This is removed using an interpolation over zero-

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lag and by fitting a least squares Gaussian fit to the auto & cross correlation functions the wind velocity parameters are calculated.

C. Turbulent motion simulation & updating the scattering positions

The position of the i^{th} scatterer after the $(n+1)^{th}$ update of position $\overline{r}_{i,n+1}$ is given by

$$\overline{r}_{i,n+1} = \overline{r}_{i,n} + \{\overline{V} + \overline{V}_{turb}(\overline{r}_{i,n})\}\nabla t \qquad (6)$$

where $\overline{V}$ is the mean background wind velocity, $\overline{r}_{i,n}$ is the position of i^{th} scatterer after n updates, $\overline{V}_{turb}(r_{i,n})$ is the turbulent velocity at $\overline{r}_{i,n}$, and ∇t is the sampling time.

Turbulent motions are simulated as follows:

A three-dimensional vector V is generated for each scatterer, with components generated according to Gaussian distributions with specified horizontal and vertical root-mean-square (RMS) values. The Turbulent velocity for the i^{th} scatterer is then given by

$$\overline{V}_{turb}(\overline{r}_{i,n}) = \sum_{j=0}^{N-1} V_j \exp -\left(\frac{|\overline{r}_{i,n} - \overline{r}_{i,n}|}{\overline{S}_{turb}}\right) \qquad (7)$$

where S_{turb} is the " turbulent scale-factor"[3]. This simulation allows the turbulent motions to evolve so that no abrupt changes are seen. If the density within the radar volume is assumed constant, the continuity equation is satisfied to within 2% when using a rectangular volume of the scale of the inter-scatterer spacing about each scattering position.

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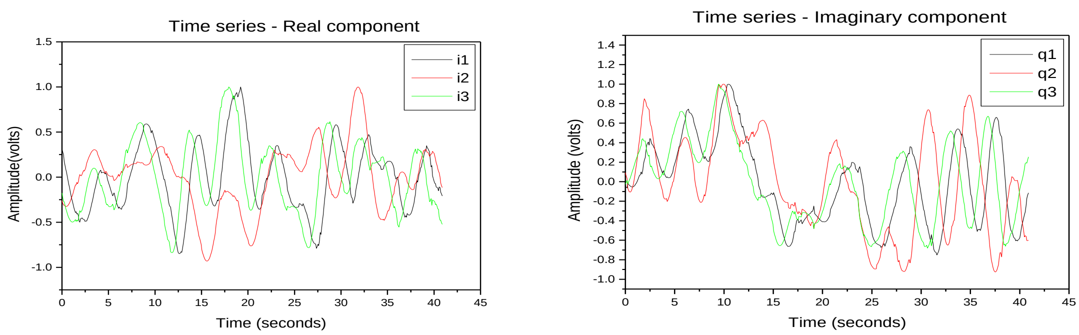

Fig. 2 Real and imaginary components of model-produced time series using the VHF simulation parameters for Receivers 1, 2 & 3

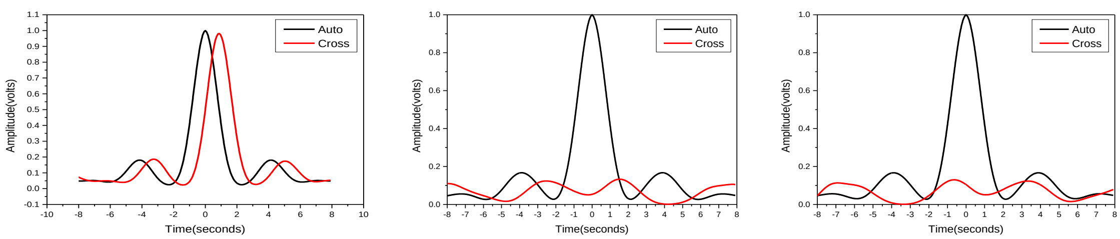

Fig. 3 Auto and cross correlation function for the Rx pair 1-3, 1-2, 2-3 respectively.

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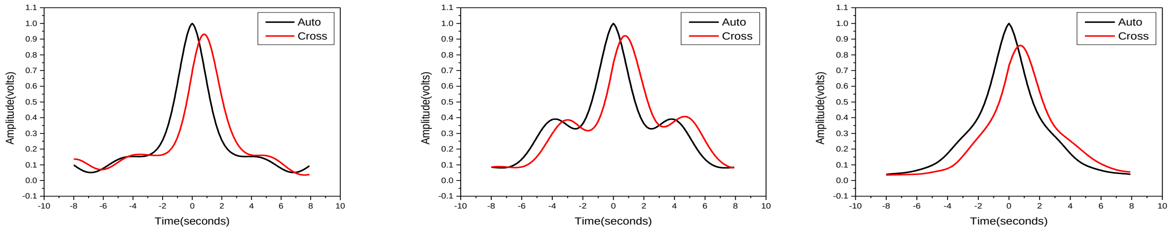

Fig. 4 Auto and Cross correlation function for the receiver pair 1-3 with turbulent RMS velocity of 10%, 15% and 20% respectively of steady state wind vector.

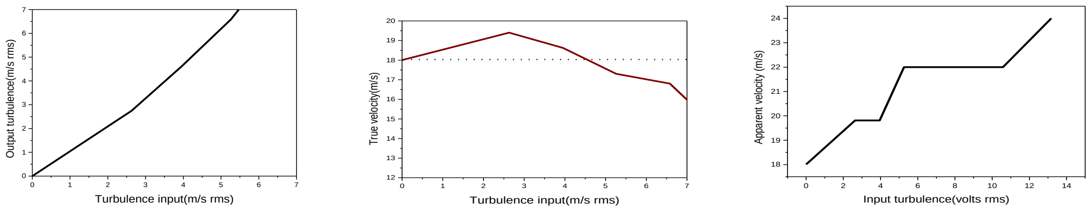

Fig. 5 Input turbulence Vs detected output turbulence from turbulence simulation.

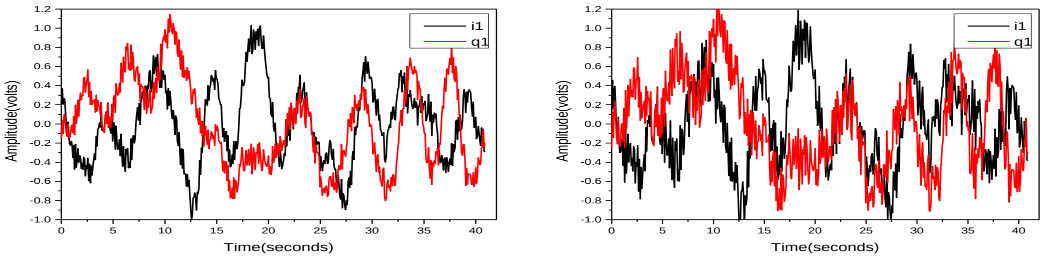

Fig. 6 Real and imaginary components of model-produced time series using the VHF simulation Parameters for first receiver with added noise level of 20% and 40%.

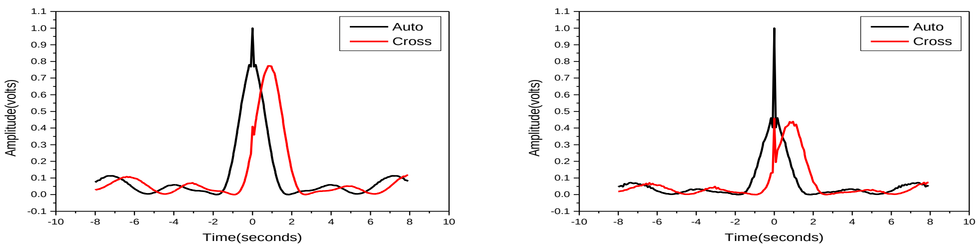

Fig. 7 Auto and cross correlation function for the Rx pair 1-3 with noise level of 20% and 40% respectively.

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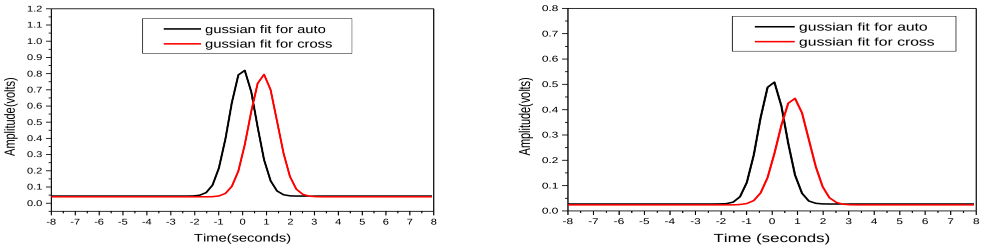

Fig. 8 Least squares Gaussian fit for the auto and cross correlation function for the Rx pair 1-3 with noise level of 20% and 40% respectively

IV. RESULTS

The horizontal velocity is estimated for 3 simulation runs for the following cases:
Case 1: No noise & no turbulence
Case 2: With a turbulent RMS velocity of 10%, 15% & 20% of steady state wind vector.
Case 3: With noise strength of 20 % & 40% added.
Corresponding velocity estimates are given in Table 2 for all the cases for comparison.

V. CONCLUSION

Spaced Antenna method is a logical, simple yet effective method for studying moving patterns in the atmosphere. This configuration of antennae arranged in a right angled triangle may not appear ideal since the FCA true velocity is biased toward the direction of the largest side of the triangle of antennae. However, this effect is eliminated if receiver noise is properly accounted for in the FCA. From the results, it is evident that this method of estimating wind velocity is quite effective method. In the presence of turbulence and noise also, this model is applicable and accurate results are obtained. The analysis also suggests that the effective scattering positions approach the zenith as the magnitude of the turbulent motions increases. As a result, the horizontal wind velocity component inferred from the radial velocity must increase as the magnitude of the turbulent motions increases.

Table I Simulation Parameters Employed for Model Data Generation

Sr.No	Model Parameter	Value
1	Radar frequency, MHz	53
2	Range, Km	8
3	Range gate size, Range resolution, m	150
4	Transmitter beam width, deg	4.5
5	Receiver beam width, deg	9
6	Receiver spacing, m	32
7	Sampling time, s	0.08
8	Time series elements	512
9	Number of scatterers	250
10	Mean horizontal wind speed, m s^{-1}	18
11	Wind direction (E of N), deg	0
12	Turbulent rms velocity, m s^{-1}	7

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Table II Comparison of the Results

Parameter	τ (Time delay)	Velocity (m/s) (Theoritical)	Velocity (m/s (Calculated)
Turbulence Strength (10%)	0.82186	18	19.468
Turbulence Strength (15%)	0.8052	18	19.87084
Turbulence Strength (20%)	0.82186	18	19.468
Noise Level of 20% (without Gaussian fit)	0.8	18	20
Noise Level of 20% (with Gaussian fit)	0.8999	18	17.7975
Noise Level of 40% (without Gaussian fit)	0.96	18	16.6667
Noise Level of 40% (with Gaussian fit)	O.89999	18	17.7975

VI. FUTURE WORK

The use of more than four antennas multiple receivers and, therefore more spacings (and directions), might be expected to improve considerably the determination of all quantities, and over a still greater range of observing wavelengths [6]. Given the notorious variability of the ionosphere itself, and the wide range of radio wave lengths required to observe this mechanism. We conclude that observations at a moderate number (e.g., between 4 and 20) of spaced antenna and data analysis by rigorous statistical estimation procedures, comprise the necessary and sufficient conditions to obtain meaningful results. This can be a scope for future work.

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