MODELLING ATMOSPHERIC TURBULENCE FOR A MOTION-BASED SIMULATOR

Status Report
NASA Grant No. NGR 47-005-028

Submitted to:

NASA Scientific and Technical Information Facility
P. O. Box 8757
Baltimore/Washington International Airport
Maryland 21240

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INTRODUCTION

This report documents the background information in establishing several proposed atmospheric turbulence models for use on motion based aircraft simulators. Simulated time histories of aircraft motion in a turbulence environment are required in a variety of engineering applications, and their use appears to be increasing as more intricate and sophisticated design studies are attempted. As an example, the use of flight simulators for the study of airplane handling qualities and ride quality has proven to be more valuable when disturbances in the form of artificially simulated turbulence are introduced into the system. Several methods have been used to generate turbulence signals; each one aimed at realising the actual atmosphere as closely as possible. A realistic representation of turbulence becomes especially important in the simulation of future aircraft with high sensitivity to turbulence, as even light to moderate turbulence may seriously degrade their controllability and ride quality. The low altitude atmospheric turbulence critically effects the evaluation of vehicle handling qualities, pilot work load, ride quality, and other design factors. Several emperical studies (Refs. 1, 2, 3) have shown that low altitude clear air atmospheric turbulence is only locally isotropic i.e. isotropic over a finite range of wavelengths. In order to account for the anisotropy of typical low altitude clean air turbulence, the rms velocities of the gust field are randomly varied in the proposed gust model. The proposed model, in addition to varying turbulence intensity (rms velocity), varies the atmospheric turbulence scale length. The scale lengths predicted by either the Von Karman or the Dryden models (Ref. 5) are large compared to real atmospheric turbulence. The scale length distribution is, therefore, modified to achieve compatibility with real atmospheric turbulence.

With a suitable combination of scale length and intensity distribution, the proposed model will simulate various atmospheric conditions characterized by altitude, stability, and terrain. This new model is mechanized to be included in a flight simulator experiment in order ro determine to what extent the pilots are sensitive to changes in atmospheric conditions and the realism of the model.

The following sections of this report describe the proposed turbulence model and the flight simulator experiment in detail. Briefly the sections consist of:

(a) Literature Survey: Since atmospheric turbulence is a stochastic process, a review of probability and statistics is included in this section. In addition the statistical properties of real atmospheric turbulence is discussed.

(b) Presently Used Techniques: Presently used techniques are inumerated and the need for a new model is demonstrated.

(c) Proposed Model: The proposed turbulence model is discussed and the theoretical results compared with real atmospheric turbulence demonstrating an improved representation of atmospheric turbulence.

(d) Simulation Details: This section describes the details of the flight simulator experiment in which pilots are asked to rate the realism of the various turbulence models.

LIST OF SYMBOLS

$a(t)$	Gaussian Random Process
$b(t)$	Gaussian Random Process
b	Wing Span Process
$c(t)$	Modified Bessel Process
$d(t)$	Gaussian Random Process
f	Frequency in Hz
h	Altitude
I_x, I_y, I_z	Moment of inertia in body axes
L_i	Turbulence scale length in i direction i = u,v,w
M_n	n^{th} central moment
R_{ij}	Cross correlation function i, j = u,v,w
R_{ii}	Auto correlation function i = u,v,w
R	Standard deviation ratio
S	Wing span
T	Time period
u	Longitudinal gust velocity
v	Lateral gust velocity
w	Vertical gust velocity
$\bar{u}$	Mean of u
σ_i	Variance of i = u,v,w
w	Weight
ϕ_{ij}	Cross spectral density
ϕ_i	Power spectra density
ϕ_o	White noise

LITERATURE SURVEY

In this section a review of probability and statistics is followed by a summary of the statistical properties of atmospheric turbulence.

Review of Probability and Statistics (Refs. 8, 13):

Stationarity: A random process is stationary if its statistical properties are not dependent on the time of their measurement. One could, for example, collect an infinite number of time histories, called an ensemble, which are representative of the process. If one takes an average across the ensemble, and if these averages are not a function of time, the process is stationary.

Homogeneity: A random process is homogeneous if its statistical properties are independent of position.

Ergodicity: In turbulence measurements it is impossible to obtain an ensemble from atmospheric measurements. Thus it is necessary to use time averages to get statistical information. If such a time average yields the same statistical properties as the ensemble average the process is called ergodic.

Mean Value: The mean value of a random variable, u, of an ergodic random process is given by

$$\bar{u} = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} u(t)dt$$

In practice the limit is not required and $\bar{u}$ can be approximated by

$$\bar{u} \simeq \frac{1}{T} \int_{0}^{T} u(t)dt, \text{ for T large.}$$

This approximate representation is especially useful for processes such as turbulence. However, the time interval T must be large enough so that the average approaches the asymptotic value one would obtain for a stationary process.

Variance: The variance of u is defined as

$$\sigma_u^2 = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} [(u(t) - \bar{u})^2]dt.$$

as before in practical applications the variance can be approximated by

$$\sigma_u^2 \simeq \frac{1}{T} \int_0^T [u(t) - \bar{u}]^2 dt$$

for sufficiently large T.

Standard Deviation: The standard deviation is defined as the square root of the variance.

Normalized Central Moment: The n^{th} normalized central moment, M of a random process, u(t), is

$$M_n = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} [\frac{u(t) - \bar{u}}{\sigma_u}]^2 dt, \; n = 1,2,3, \ldots$$

which can be approximated by

$$M_n = \frac{1}{T} \int_0^T [\frac{u(t) - \bar{u}}{\sigma_u}]^2 dt, \; n = 1,2,3, \ldots$$

Cumulative Probability Distribution: The cumulative probability distribution of u(t), $P_u(x)$ is defined as the probability that $u \leq x$.

Probability Density Distribution: The probability density distribution of u(t), $P_u(x)$ is defined as the probability that; $x < u \leq x + dx$.

Gaussian Probability Density Distribution: If a random variable, u(t), is Gaussian distributed its probability density is given by

$$P_u(x) = \frac{1}{\sigma_u \sqrt{2\pi}} \exp[-[\frac{1}{2} \frac{(x - \bar{u})}{\sigma_u}]^2]$$

Rayleigh Distribution: Another probability density of interest is the Rayleigh Distribution defined as follows:

$$P(x) = \frac{x}{c^2} \exp(-\frac{1}{2} x^2/c^2)$$

where c^2 is one half the expected value of the random variable x or

$$c^2 = \frac{1}{2} E\{x\}.$$

Cross Correlation Function: The cross correlation function of two random processes u(t), w(t) is defined as

$$R_{uw}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} u(t)w(t + \tau)dt$$

correlations are the measures of the predictability of a signal at some future time $(t + \tau)$ based on the knowledge of a signal at time t.

Autocorrelation Function: The autocorrelation function is a special case of the cross correlation function defined above in which w(t) = u(t), such that,

$$R_{uu}(\tau) = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} u(t)v(t + \tau)dt.$$

Integral Scale Length: A statistical parameter of special importance in atmospheric turbulence is the integral scale length,

$$L_u = \frac{U_0}{\sigma_u^2} \int_{-\infty}^{\infty} R_{uu}(\tau)d\tau.$$

where U_0 is the reference steady state flight speed.

Cross Spectral Density: The cross spectral density of two random processes u(t) and w(t) is defined as the Fourier transform of their cross correlation.

$$\Phi_{vw}(f) = \int_{-\infty}^{\infty} R_{uw}(\tau)\exp(-i2\pi f\tau)d\tau,$$

where f is frequency.

Power Spectral Density: The power spectral density, PSD, of a random process is the Fourier transform of its autocorrelation function, or

$$\phi_u(f) = \int_{-\infty}^{\infty} R_{uu}(\tau)\mathrm{Exp}(i2\pi f\tau)d\tau.$$

The PSD can be interpreted physically as the average contribution to the variable σ_u^2 from the frequency component f. Thus,

$$\phi_u^2 = \int_{-\infty}^{\infty} \phi_u(f)df.$$

White Noise: White noise is a random process for which the PSD is a constant independent of frequency. That is, $\phi_0(f) = k$.

Properties of Atmospheric Turbulence: Atmospheric turbulence simulation studies, in general, begin with the study of the real atmosphere. In Refs. 1, 2, 3, 4, atmospheric data have been reported characterizing various atmospheric conditions in the form of terrain, stability, altitude, temperature, time, season and geographic location. This data has been suitably modified to establish a basis of comparison for the simulated turbulence field.

The following criteria are used for the basis of comparison:

Output Statistics:

Mean

Standard Deviation

Probability Distribution:

Cumulative Probability

Probability Density

Fourth and Sixth Moment

Patchiness of the Field:

Power Spectral Density:

Element of Surprise.

Each of these properties will be discussed from the standpoint of real atmospheric turbulence.

Mean: $\bar{u}$ (mean velocity of longitudinal turbulent gust component)

$$\bar{u} \approx \frac{1}{T} \int_0^T u(t)dt \text{ where T is large.}$$

The mean of a real atmospheric turbulence field is 0 ± 0.1 ft/sec.

Standard Deviation: σ_u (standard deviation of longitudinal turbulence gust component) of a random process is approximated by:

$$\sigma_u^2 \approx \frac{1}{T} \int_0^T (u(t) - \bar{u})^2 dt$$

The standard deviation of the velocity field for low altitude clear air turbulence is 3.0 ± 1.31 ft/sec.

Typical values are also listed in Ref. 5

For clear air turbulence:

σ_u = 2 ft/sec for light turbulence,

σ_u = 4 ft/sec for moderate turbulence,

σ_u = 6 ft/sec for heavy turbulence, and

$\sigma_u = \sigma_v = \sigma_w$ = 21 ft/sec for thunderstorms.

Probability Distribution: (Reference 8).

A typical cumulative probability distribution of atmospheric turbulence indicates a departure from a Gaussian process, showing increased probability of both large and small gusts. The same is true of the probability density function.

A table below compares the normalized fourth and sixth moments of atmospheric turbulence to a Gaussian process.

	M_4	M_6
Atmosphere	3.5	21.7
Gaussian Process	3.0	15.0

Patchiness: It is known that turbulence has a patchy structure, which seems to occur in bursts of relatively intense motion separated by areas of relative calm.

Power Spectral Density (PSD): Analysis of data for about 40 turbulence fields (Ref. 1) characterizing various atmospheric conditions shows that at high frequencies the spectral density varies as ω^{-2}. A constant horizontal asymptote seems to fit best at lower frequencies for the longitudinal and lateral components.

Element of Surprise: More often than not, real atmospheric turbulence, when encountered, presents an element of surprise. It is not easy to formulate a model of this phenomenon in terms applicable to flight simulator work. It seems that a measurement of "sudden jump" in the velocity field can be used as a possible criterion to describe this phenomenon. The relative frequency of "sudden jump" of atmospheric turbulence can be compared to the simulated model. Changes in aircraft orientation angles can also be used to measure this phenomenon.

Presently Used Simulation Techniques: In the preceding pages of this report we have discussed the statistical properties of atmospheric turbulence which are to be modeled by a realistic simulation. In this section several presently used simulation techniques are discussed from the standpoint of their statistical realism and suitability for use in flight simulators.

Measured Turbulence Field: Flight recordings of atmospheric turbulence is perhaps the most obvious method of producing a realistic simulation. There can be little argument as to whether or not these time histories are an accurate and realistic representation. However, it is difficult to adjust the measured time histories to allow for conditions other than those for which it was recorded. No allowances can be made for changes of altitude or different atmospheric conditions. Another serious drawback is that the recorded time histories are fixed in length. Extended run times, therefore, cannot be accommodated without repitition. From the simulation point of view the pilots tend to recognize some of the characteristics of the turbulence field and develop an intuition for predicting the field. This defeats the purpose of an artificially simulated turbulence field, which is to provide unpredictable external disturbances. It can, therefore, be concluded that flight recordings of atmospheric turbulence are not suitable for the simulation of typical turbulence.

Sum of Sine Waves: Reference 8 describes this method in summary form. This technique involves superimposing several sinusoidal waves of different frequencies and amplitudes. The resultant is used to represent time histories of turbulence. One obvious disadvantage of this method is that it contains only a finite range of frequencies whereas actual atmospheric turbulence consists of an infinite number of frequency components.

Results of this simulation are not available but the model can justifiably be discarded on the basis of its inadequacy in matching the frequency content.

Method of Orthogonal Functions: In this method (Ref. 4) the recorded time histories of turbulence are decomposed into eigenfunctions of a covariance matrix. The probabilistic structure of the eigenfunction, and the coefficients of each of the time histories are studied. Simulated time histories are then regenerated by suitably modifying the distribution of the coefficients. The available preliminary results show that this technique adequately models the frequency contents and also presents an element of surprise. However, this model fails to show a patchy non-Gaussian characteristic which is typical of the real atmosphere. In addition to the mathematical complexity of the technique, its application is limited since recorded time histories are needed.

Gaussian Turbulence Model: The classical method, most widely used for turbulence simulation, is the linearly filtered white noise technique. Here the turbulence gust field is produced by passing white noise through a linear filter as shown in Figure 1a. The resultant signal is shaped so that the power spectrum and rms intensities match those of real turbulence. A Dryden or Von Karman form (Ref. 5) are normally used to model the power spectrum. This model is remarkably easy to implement and can be adjusted for any general power spectrum. However, this model too falls short of reproducing the non-Gaussian patchy nature of real turbulence. Figure 1b

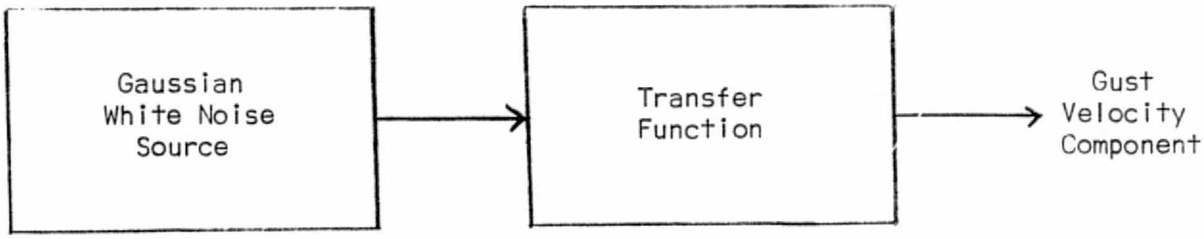
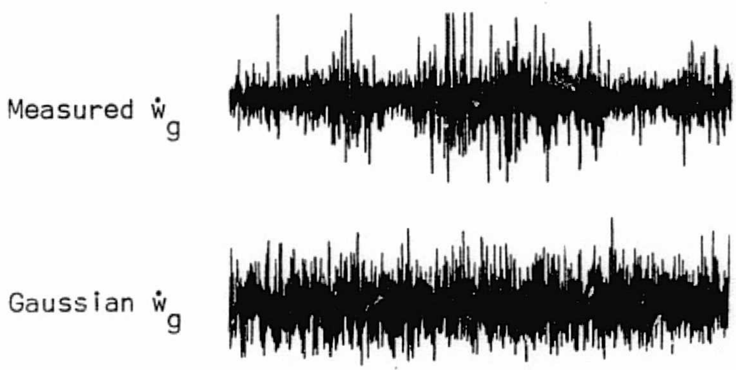


Figure la

Gaussian Turbulence Simulation



40 Sec. Sample

Figure lb

Derivative of Vertical Velocity

compares the artificially simulated gust field using this Gaussian model (with a Dryden spectrum) and real atmospheric turbulence. It may be observed that the intensity for the Gaussian model is nearly constant whereas measured ("real") turbulence exhibits a patchy nature or intensity bursts. Test pilots, when exposed to this model in a flight simulator, rated the realism fair to poor (Ref. 11).

Non-Gaussian Turbulence Model: References 7, 8, 11 present a non-Gaussian turbulence model. Time histories are generated by multiplying two independence random variables, one to represent the turbulence within a patch and the other to represent the variation of intensity with time. Figure 2 shows two independent Gaussian white noise generators and linear filters, which produce Gaussian random variables, a(t) and b(t). These variables are then multiplied to produce gust time histories.

The non-Gaussian model proposed in Ref. 8, a modification of the above, is shown in Figure 3. Here a(t), b(t), and d(t) are independent Gaussian processes. The process c(t) is generated by multiplying a(t) and b(t). The resultant process, c(t), a modified Bessel process, is summed with d(t) to form the output, u(t). The most remarkable achievement of this model is that the patchy characteristic and several statistical parameters of the simulated turbulence field can be varied simultaneously by varying the standard deviation ratio ($R = \sigma_c/\sigma_d$). However, when R is varied to achieve one set of statistical properties, several other statistical parameters of interest do not match real turbulence. In addition, due to the mathematical complexity, the mechanization of this model on a flight simulator is complicated and expensive (Ref. 8).

It can be observed from the review of presently used simulation techniques that there is a need for a new model which adequately matches real atmospheric turbulence and is simple to implement in flight simulator studies. None of the preceeding models have the flexibility of simulating various atmospheric conditions characterized by altitude, stability, and terrain. It is, therefore, necessary to introduce a new turbulence model which is realistic and can flexibly accommodate changes in atmospheric conditions and be easily implemented in flight simulator studies.

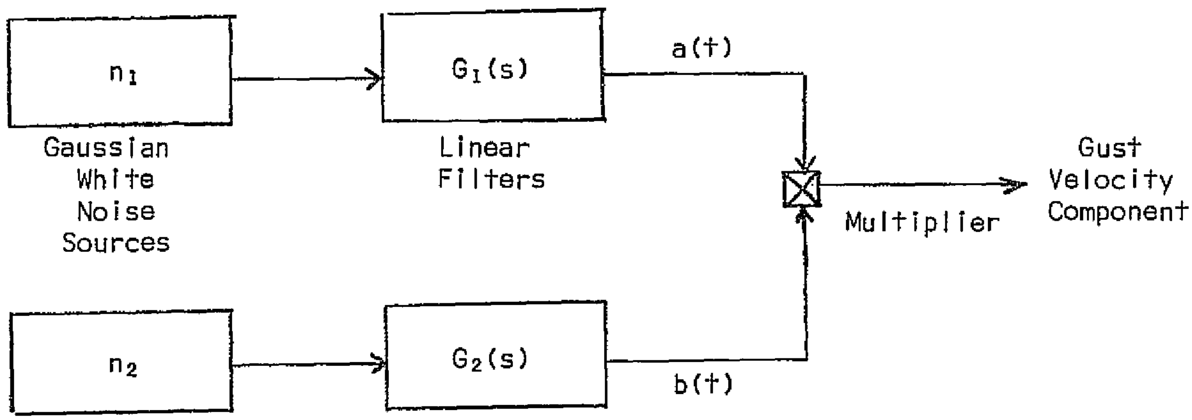


Figure 2

Non-Gaussian Turbulence Model (Reference 1)

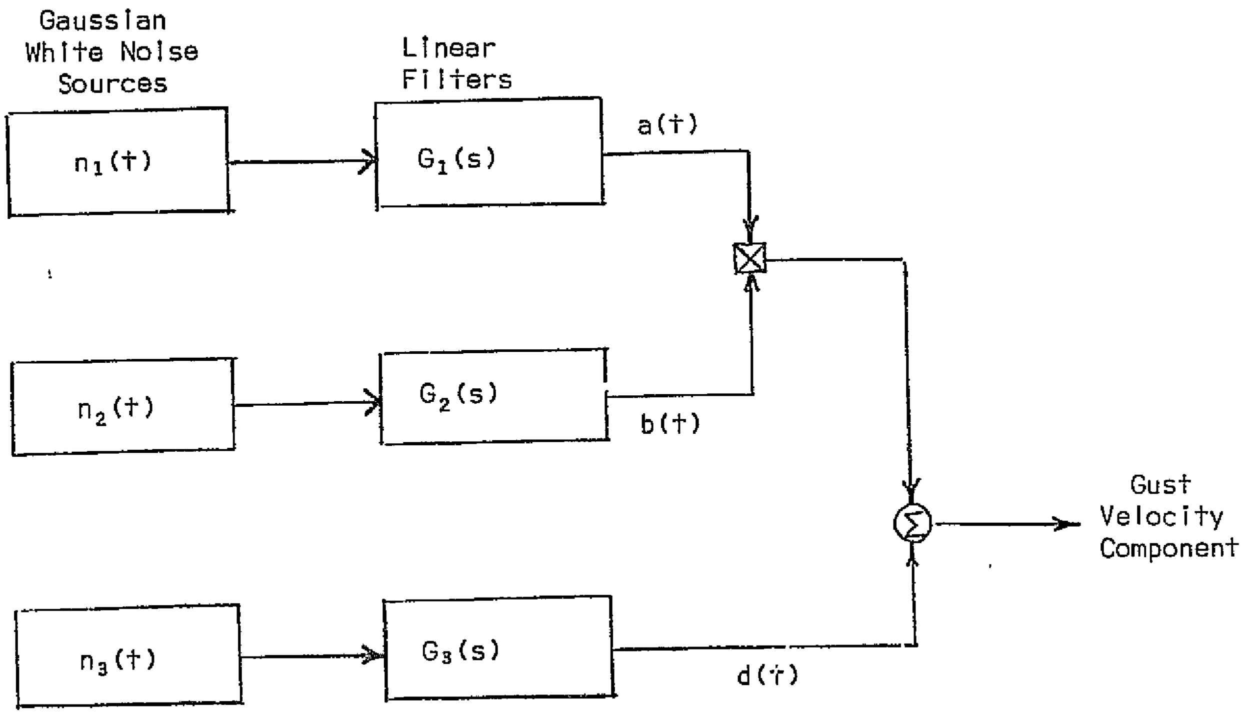


Figure 3

Non-Gaussian Turbulence Simulation (Reference 8)

PROPOSED GUST MODELS

Of the simulation techniques described, the Gaussian turbulence model is the simplest to implement and least expensive computationally. The proposed models, modifications of the Gaussian simulation technique, retain the simplicity of the Gaussian technique while modeling the characteristics of real atmospheric turbulence. In this report three basic models are proposed.

1) Modified Gaussian Model

2) Rayleigh Model

3) UVA Turbulence Model

Modified Gaussian Model: A block diagram of the Modified Gaussian Model is presented in Figure 4a. Gaussian white noise, ϕ_0, is passed through a linear filter, G(S), whose power spectrum is given by a Dryden model. In order to avoid computational complexity the Dryden form is selected in this report over the Von Karman form. The linear filter, G(S), is modified to include random variations of rms intensity. The random number generated by A is passed through a distribution modifier to generate rms intensities. Time histories are then generated by passing Gaussian white noise, ϕ_0, through the linear filter modified by the distribution modifier.

The patchy nature of atmospheric turbulence suggests that the field is composed of two components. One to represent variation of intensity within a patch and the other to represent variation of intensity with time. The distribution modifier in this model, essentially, represents the variation of intensity with time. The level of turbulence within each patch is controlled by the magnitude of the rms intensity.

The Distribution Modifier is the probability density function of the rms intensity. Analysis of several sets of atmospheric data characterized by various atmospheric conditions show that a truncated Gaussian distribution best fits the probability density of rms intensity (Reference 1). In this report two sets of data characterized by terrain, altitude and stability are derived and presented in Table Ia along with the atmospheric conditions. Throughout this report the gust field generated by these two

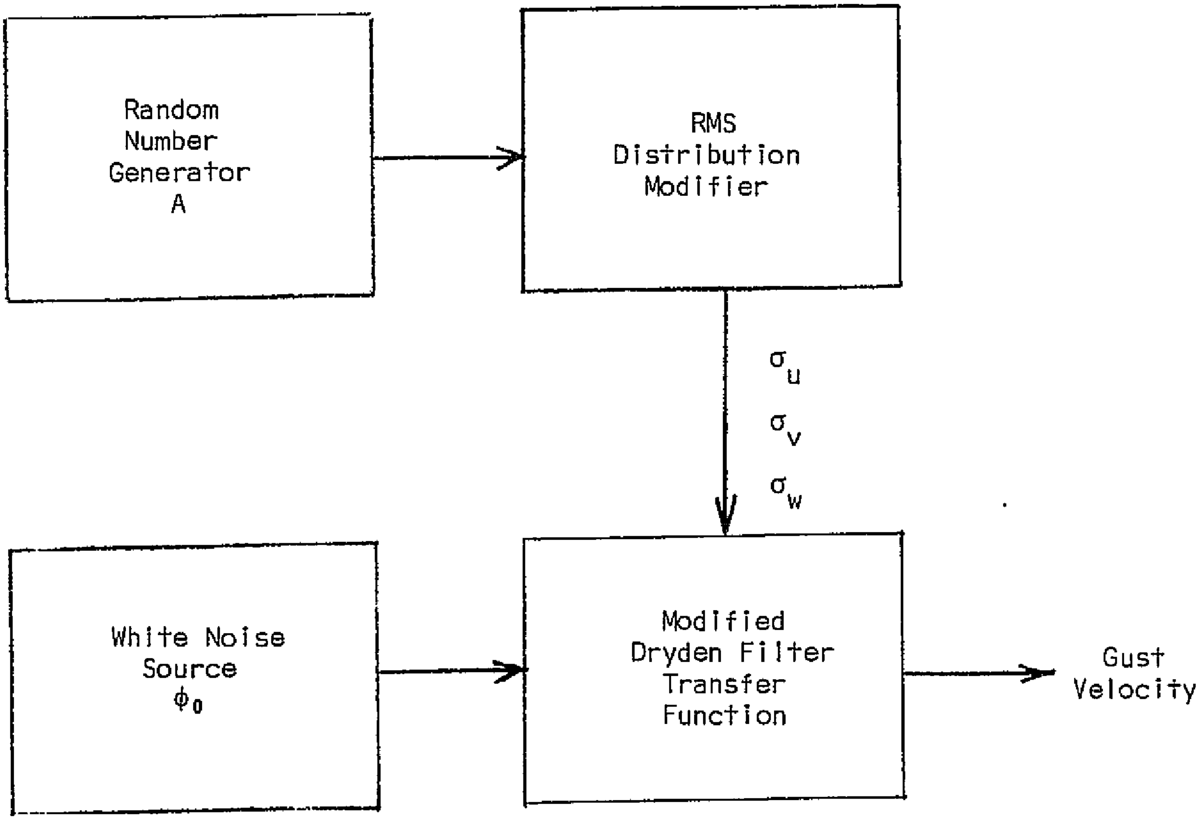


Figure 4a

Modified Gaussian Turbulence Simulation

Table IA

DISTRIBUTION MODIFIERS

		MEAN	VARIANCE
RMS DISTRIBUTION MODIFIER CASE II	σ_u ft/sec	3.1	1.2
	σ_v ft/sec	3.2	1.2
	σ_w ft/sec	2.8	0.9
RMS DISTRIBUTION MODIFIER CASE III	σ_u ft/sec	3.2	0.8
	σ_v ft/sec	3.5	1.0
	σ_w ft/sec	4.1	0.0

CASE II:

ALTITUDE: 250 Ft.

STABILITY: UNSTABLE

TERRAIN: PLAINS

CASE III:

ALTITUDE: 750 Ft.

STABILITY: UNSTABLE

TERRAIN: MOUNTAINS

Distribution Modifiers will be referred to as Case II and III. (Case I is a Gaussian model.)

Rayleigh Model: The Rayleigh model is derived from the previous model by replacing the Distribution Modifier by a Rayleigh probability density function. The Rayleigh probability density function for rms vertical turbulence intensity, σ_w, is given by

$$p(\sigma_w) = \frac{\sigma_w}{c^2} \operatorname{Exp}(- \frac{1}{2} \sigma_w^2/c^2)$$

where c^2 is one half the expected value of σ_w^2.

From the Dryden spectrum models of real atmospheric turbulence the value of c has been estimated in Ref. 5 to . 2.3 ft/sec.

The rms intensities of the longitudinal, u, and the lateral, v, gust components are obtained from the relation:

$$\frac{\sigma_u^2}{L_u} = \frac{\sigma_v^2}{L_v} = \frac{\sigma_w^2}{L_w}$$

The scale lengths are given by:

$$L_u = L_v = L_w \qquad h \geq 1750 \text{ ft.}$$

$$L_u = L_u = 145\, h^{1/3} \qquad h < 1750 \text{ ft.}$$

$$L_w = h.$$

This model will be referred to as Case IV.

UVA Turbulence Model: The UVA Turbulence Model includes in addition to the rms Distribution Modifier, a scale length modifier. A block diagram of this model is presented in Figure 4b. In addition to controlling the patchiness of the turbulence field, the time variations of scale length achieves numerical compatibility with the real atmosphere and further randomizes the simulation.

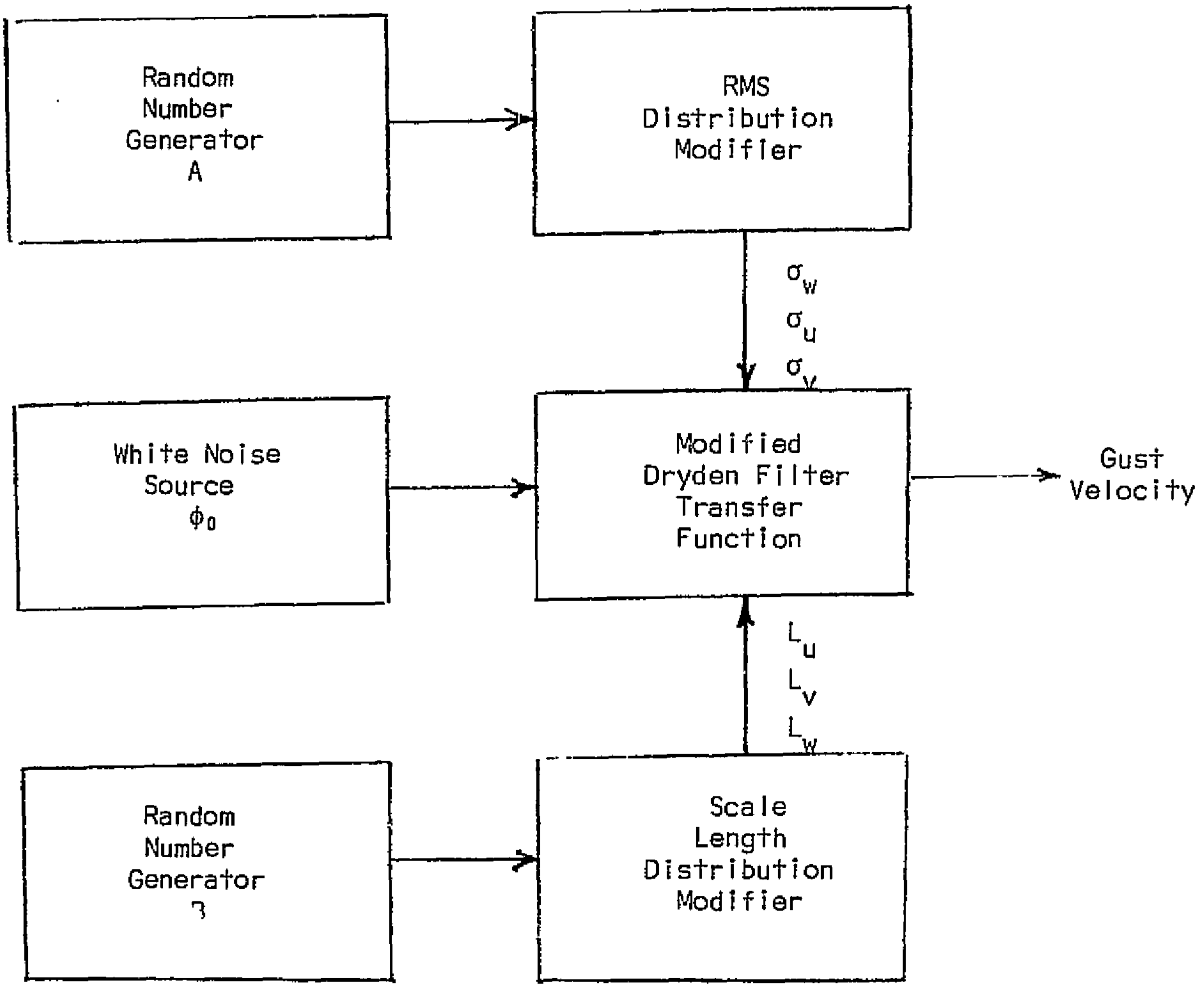


Figure 4b

UVA Gust Model Turbulence Simulation

The Scale Length Distribution Modifier is derived from data collected in the LO-LO-CAT program (Ref. 1) for various combinations of altitude, terrain, stability, temperature and geographic location. Figure 5 shows the Gaussian distribution of scale length derived from the Ref. 1. Of the several atmospheric conditions analyzed, Table 1b presents the scale length modifier along with the corresponding rms modifier. This model will be tested for two separate atmospheric conditions characterized by altitude, terrain and stability. These two cases will be referred to as Cases V and VI.

Attempts are also being made to fit an accurate non-Gaussian distribution for both scale length and rms distribution modifiers.

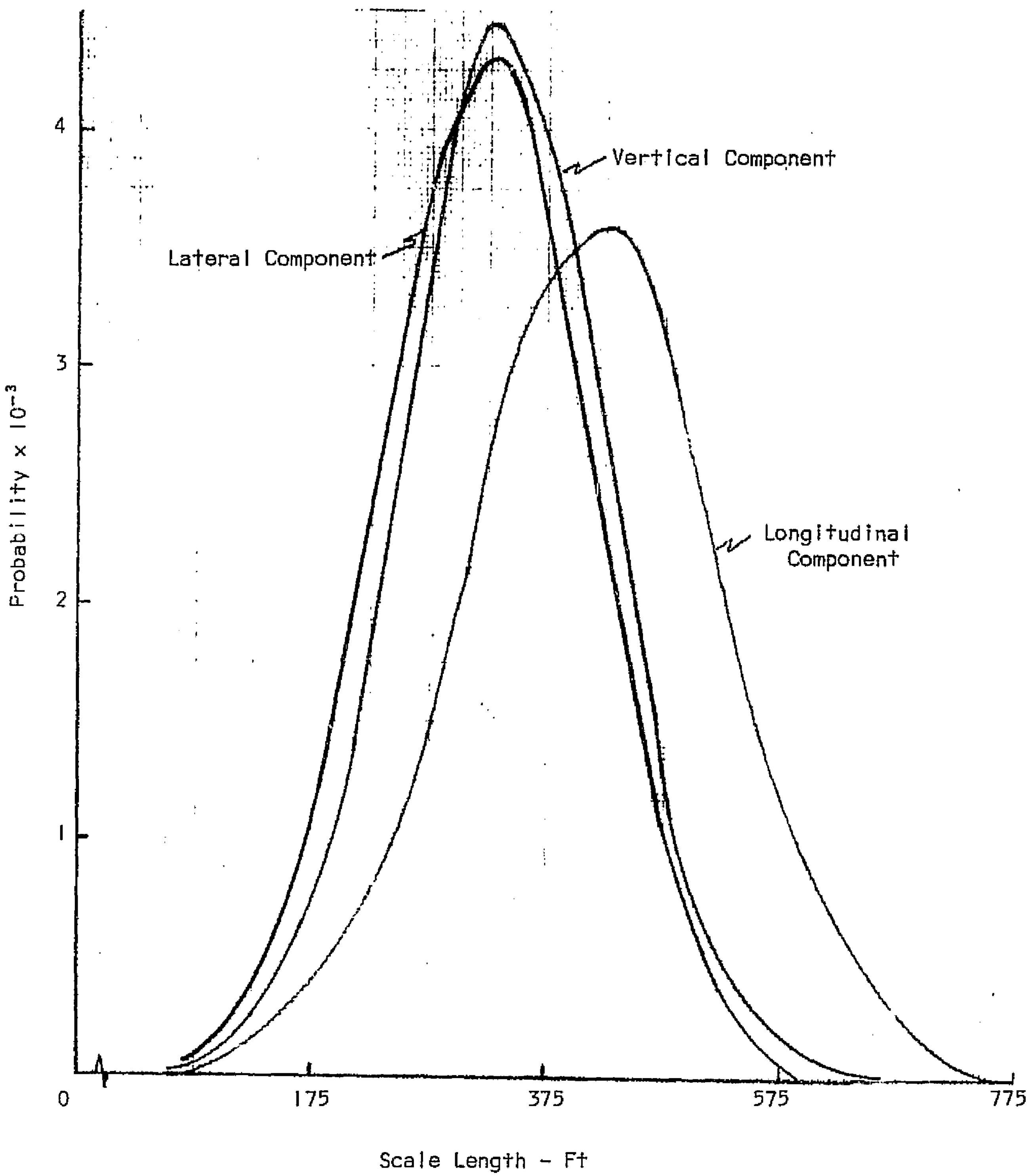


Figure 5

Scale Length Distribution

Table Ib

DISTRIBUTION MODIFIERS

		Case 5		Case 6	
		MEAN	VARIANCE	MEAN	VARIANCE
RMS Distribution Modifier	σ_u ft/sec	3.1	1.2	3.2	0.8
	σ_v ft/sec	3.2	1.2	3.5	1.0
	σ_w ft/sec	2.8	0.9	4.1	0.9
Scale Length Distribution Modifier	L_u ft	415.0	110.0	415.0	116.56
	L_v ft	325.0	86.65	460.0	126.64
	L_w ft	335.0	83.11	425.0	132.98

Case 5

Altitude: 250 ft

Stability: Unstable

Terrain: Plains

Case 6

Altitude: 750 ft

Stability: Unstable

Terrain: Mountains

RESULTS

In this section results obtained by statistical analysis of the gust velocity components for each of the five models will be discussed in view of the properties of real atmospheric turbulence. The statistical results have been obtained in the form of:

1) Mean and standard deviations.

2) Normalized fourth and sixth moments.

3) Probability density functions.

4) Power spectral densities.

5) Patchiness.

6) Relative frequency of element of surprise.

Table 2 tabulates the mean and standard deviation of gust components of each of the six cases to be simulated. It can be observed that the standard deviation varies from 2.6 to 5.2 ft/sec which is typical of low altitude clear air (light to moderate) turbulence.

Fourth and sixth moment characteristics are tabulated in Table 3. Within the limits of experimental error these characteristics are in fairly good agreement with the real atmospheric data obtained in the LO-LO-CAT experiments (Ref. 1).

Since the cumulative probability and the probability density function essentially contains identical information, only probability density functions will be analyzed. Figures 6 to 10 are plots of probability density functions for the simulated cases. In order to compare with atmospheric turbulence, a Gaussian distribution is plotted on the same scale. It has been established (Ref. 8) that real atmospheric turbulence exhibits a higher probability of both smaller and larger gust velocities than the Gaussian distribution. A careful study of the probability density of the simulated field reveals a higher probability of larger gust velocities compared to a Gaussian distribution, however, the distributions do not show higher probability of lower gust velocities.

Table 2

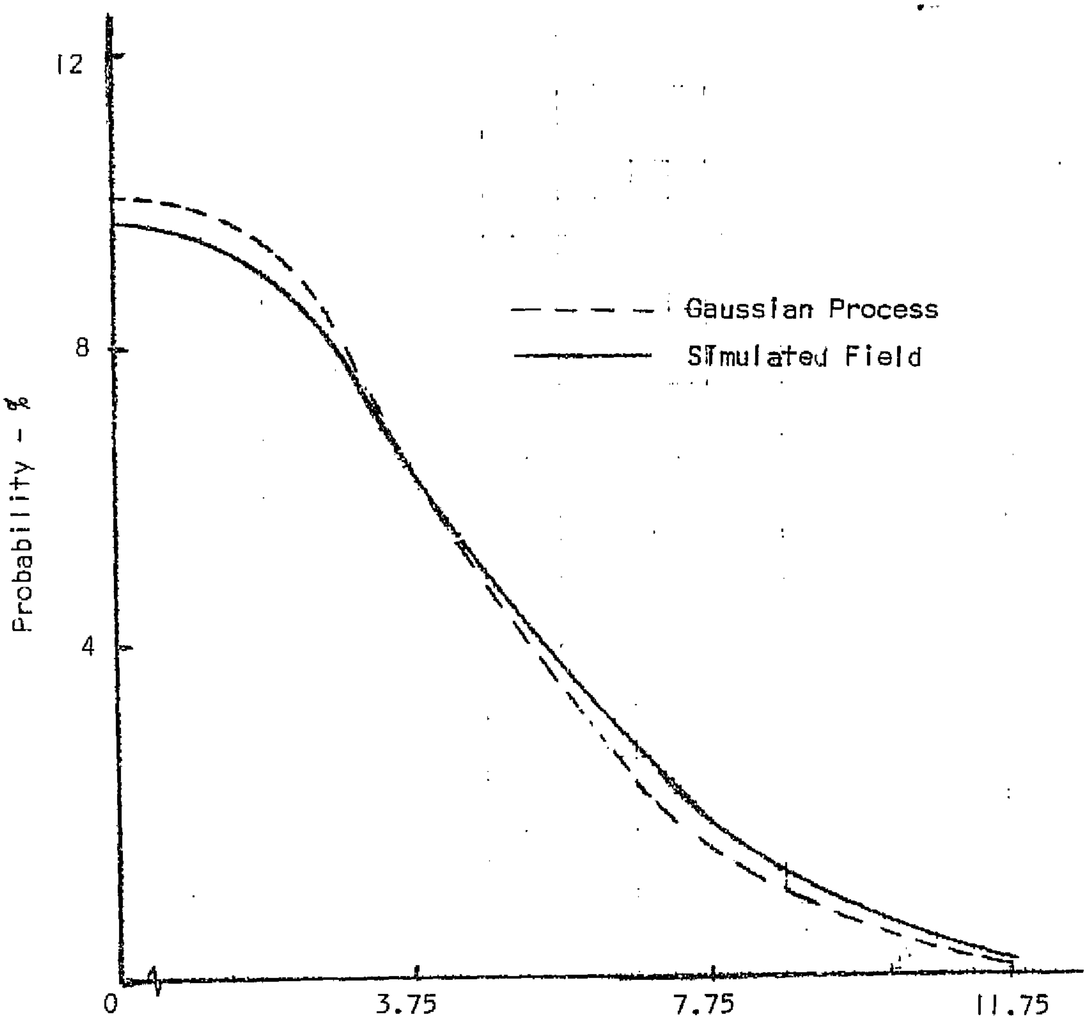
MEAN AND STANDARD DEVIATION OF
GUST COMPONENTS FOR PROPOSED SIMULATION
(over a 2 mile segment)

CASE	OUTPUT STATISTICS	GUST COMPONENT			MODEL
		UG	VG	WG	
1	MEAN	0.086	0.063	-0.031	GAUSSIAN
	STANDARD DEVIATION	3.97	3.90	4.43	
2	MEAN	0.83	-0.32	-0.15	MODIFIED GAUSSIAN
	STANDARD DEVIATION	3.9	3.5	2.6	
3	MEAN	0.88	-0.40	0.06	MODIFIED GAUSSIAN
	STANDARD DEVIATION	3.9	3.9	3.8	
4	MEAN	-0.36564	-0.1663	-0.2256	RAYLEIGH
	STANDARD DEVIATION	5.1998	4.8406	4.4880	
5	MEAN	0.27621	-0.3604	-0.2080	U. Va. MODEL
	STANDARD DEVIATION	3.6644	3.5022	2.6756	
6	MEAN	0.2010	-0.1017	-0.3261	U. Va. MODEL
	STANDARD DEVIATION	3.5680	3.9064	3.8100	

Table 3

FOURTH AND SIXTH MOMENT DATA OF
REAL AND SIMULATED TURBULENCE FIELDS
(over a 2 mile segment)

REAL ATM.	FOURTH SIXTH	3.5 21.7	3.5 21.7	3.5 21.7	
		GUST VELOCITY COMPONENTS			
	MOMENT	UG	VG	WG	MODEL
1	FOURTH 3. SIXTH	3.0 15.0	3.86 15.60	3.00 15.00	GAUSSIAN
2	FOURTH SIXTH	5.864 61.076	3.546 22.323	3.176 16.846	MODIFIED GAUSSIAN
3	FOURTH SIXTH	5.129 46.698	3.224 18.976	2.853 11.985	MODIFIED GAUSSIAN
4	FOURTH SIXTH	3.738 21.726	3.200 18.075	3.3085 19.887	RAYLEIGH
5	FOURTH SIXTH	3.494 20.838	3.236 16.012	3.467 21.803	U. Va.
6	FOURTH SIXTH	3.065 14.006	3.145 16.12	3.856 21.473	U. Va.



Gust Velocity Component

w_g - Ft/Sec

Figure 6

Probability Density (Case II)

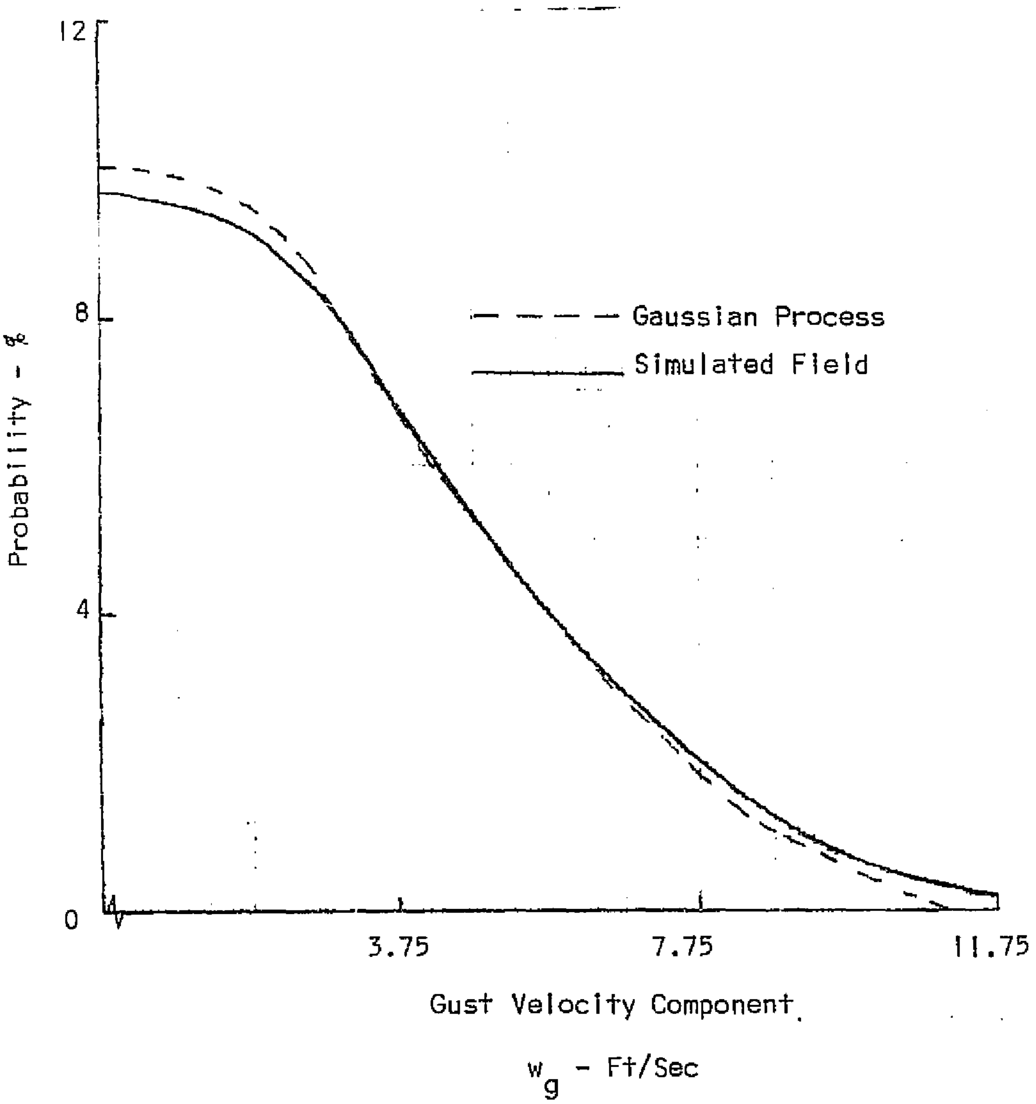
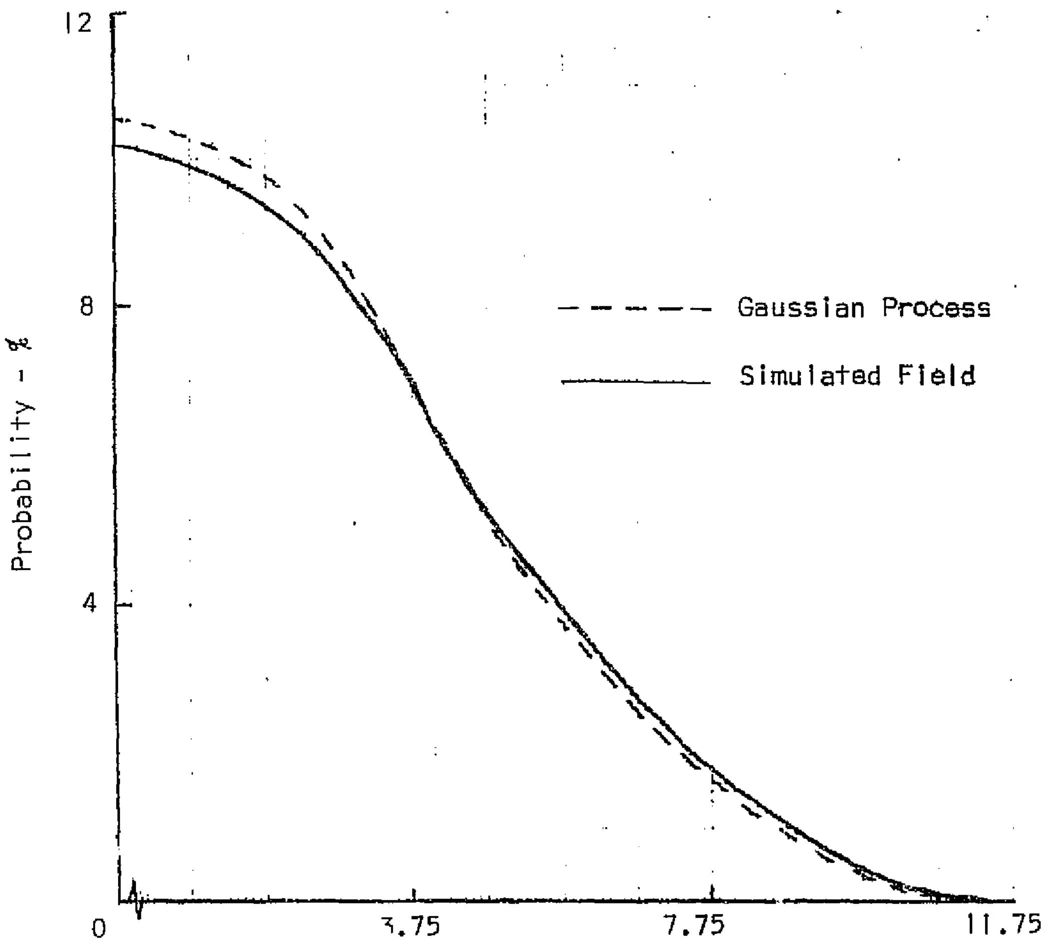


Figure 7

Probability Density (Case III)



Gust Velocity Component

w_g - Ft/Sec

Figure 8

Probability Density (Case IV)

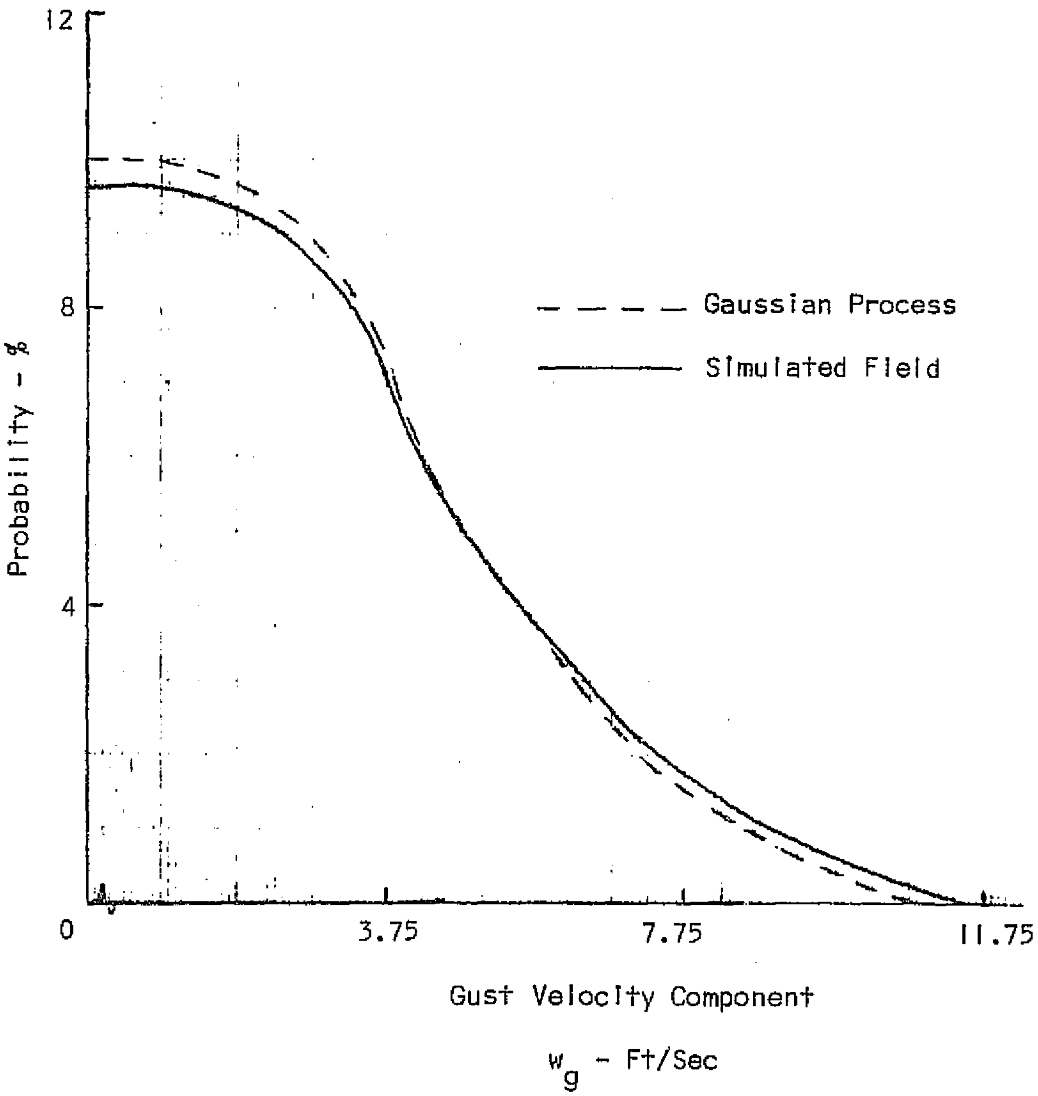


Figure 9

Probability Density (Case V)

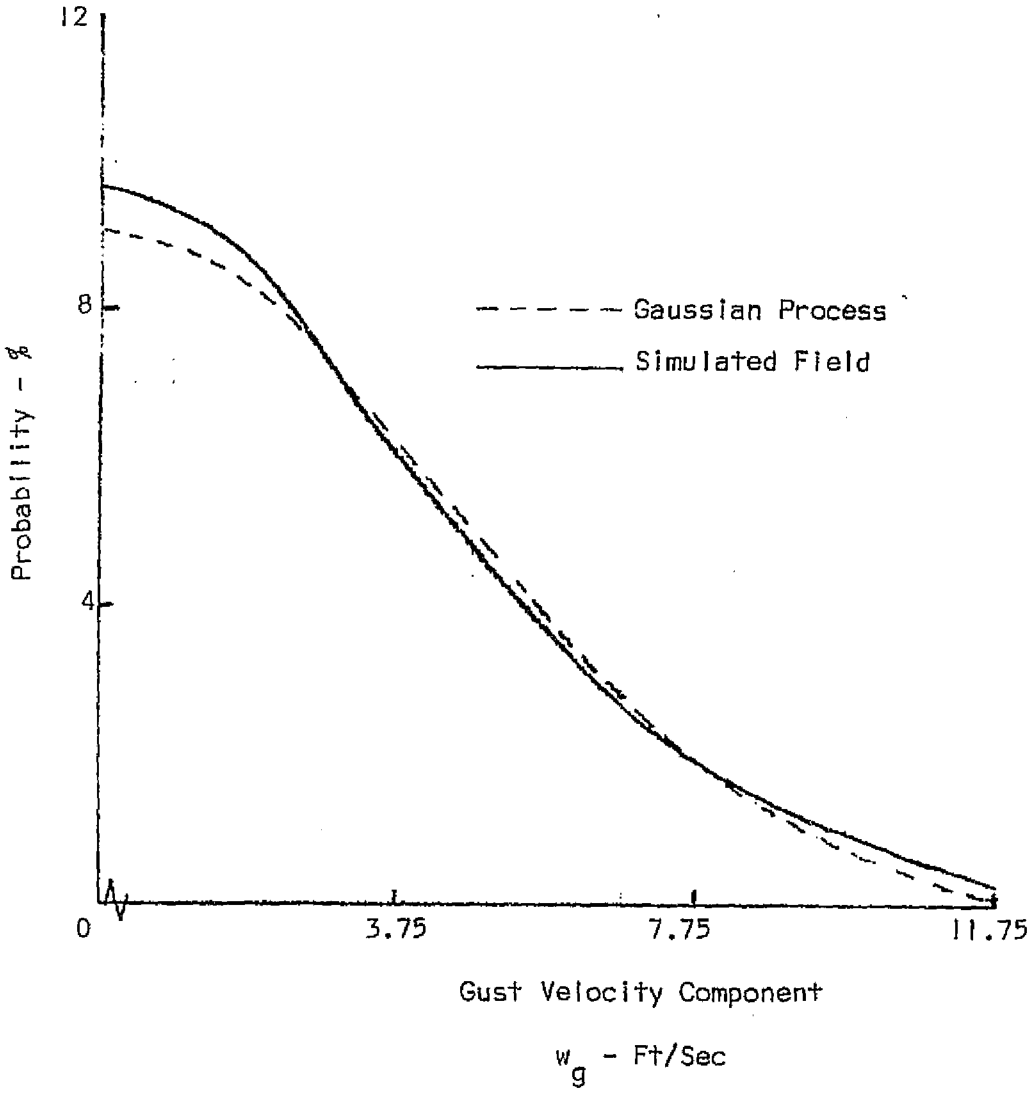


Figure 10

Probability Density (Case VI)

Power spectral densities of the simulated turbulence fields are presented in Figures 11 to 15. The high frequency contents are compared with a line of slope -2. It is observed that the power spectrum at high frequency varies as ω^{-2} (-2 logarithmic slope). At low frequencies a constant asymptote fits best. The power spectrum in the entire frequency range within the limit of experimental error, is in fairly good agreement with the assumed Dryden form (Figure 16).

The patchiness of each of the cases is presented in Figures 17 to 19. The derivative of the vertical gust component is plotted illustrating a varying intensity of patchiness. Case IV presents patchy characteristics which closely matches real atmospheric turbulence.

Element of surprise is tabulated in Table 4. The presently used criterion, "sudden jump in velocity field," does not adequately quantize this phenomenon. For future work an alternative criterion namely, changes in aircraft orientation angles, may be used to measure this phenomenon quantitatively.

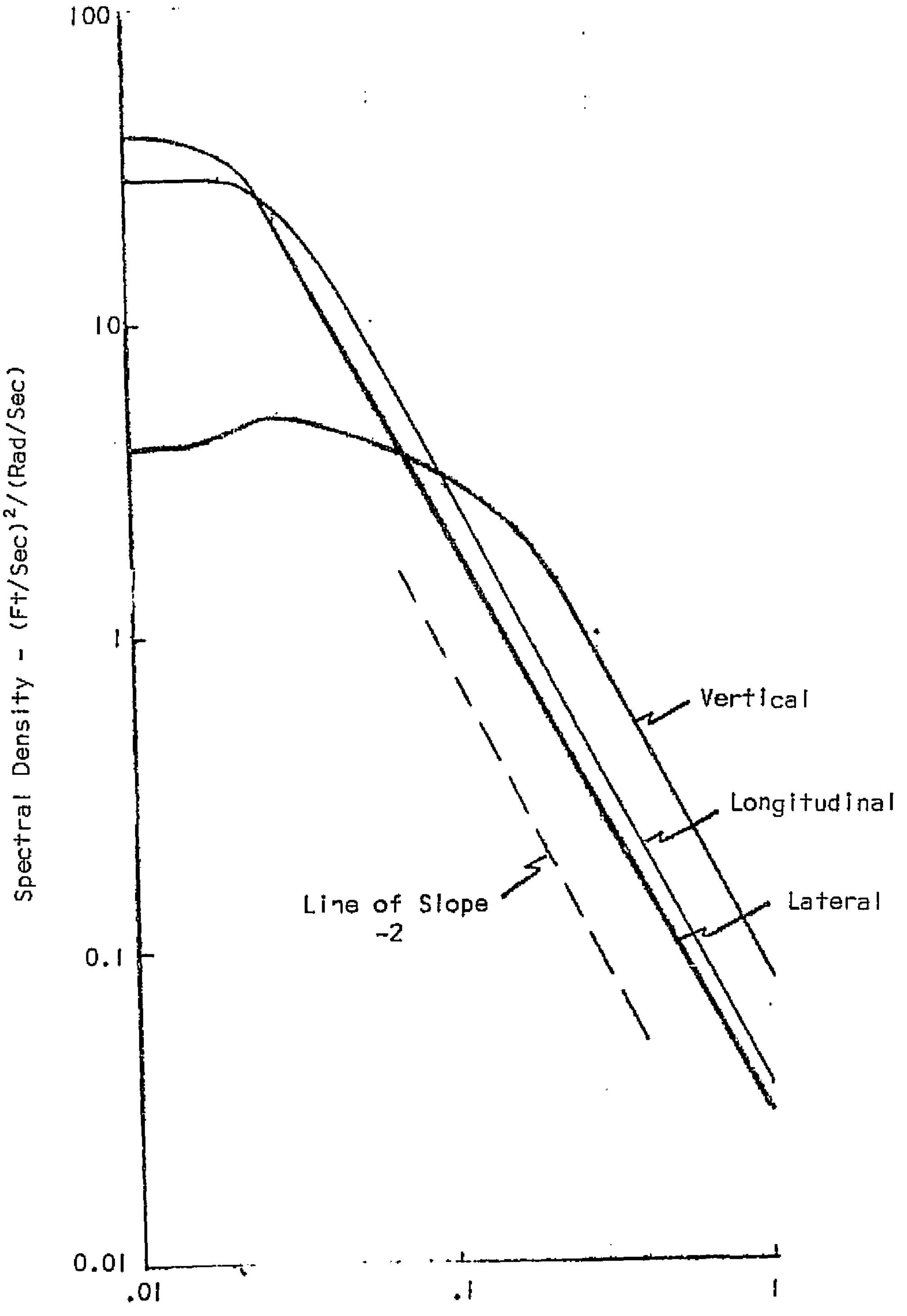


Figure 11

Power Spectral Density of Simulated Field (Case II)

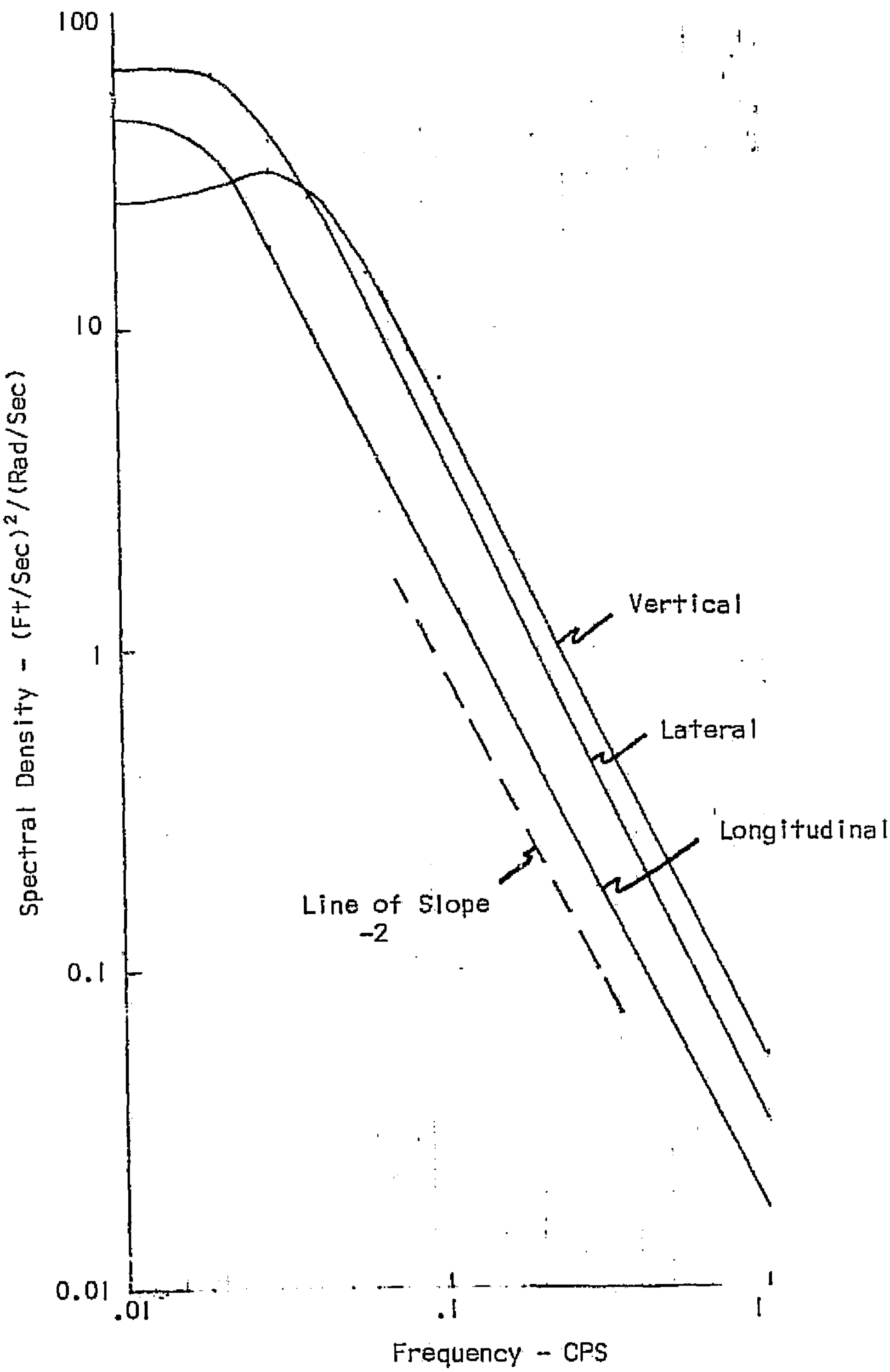


Figure 12

Power Spectral Density of Simulated Field (Case III)

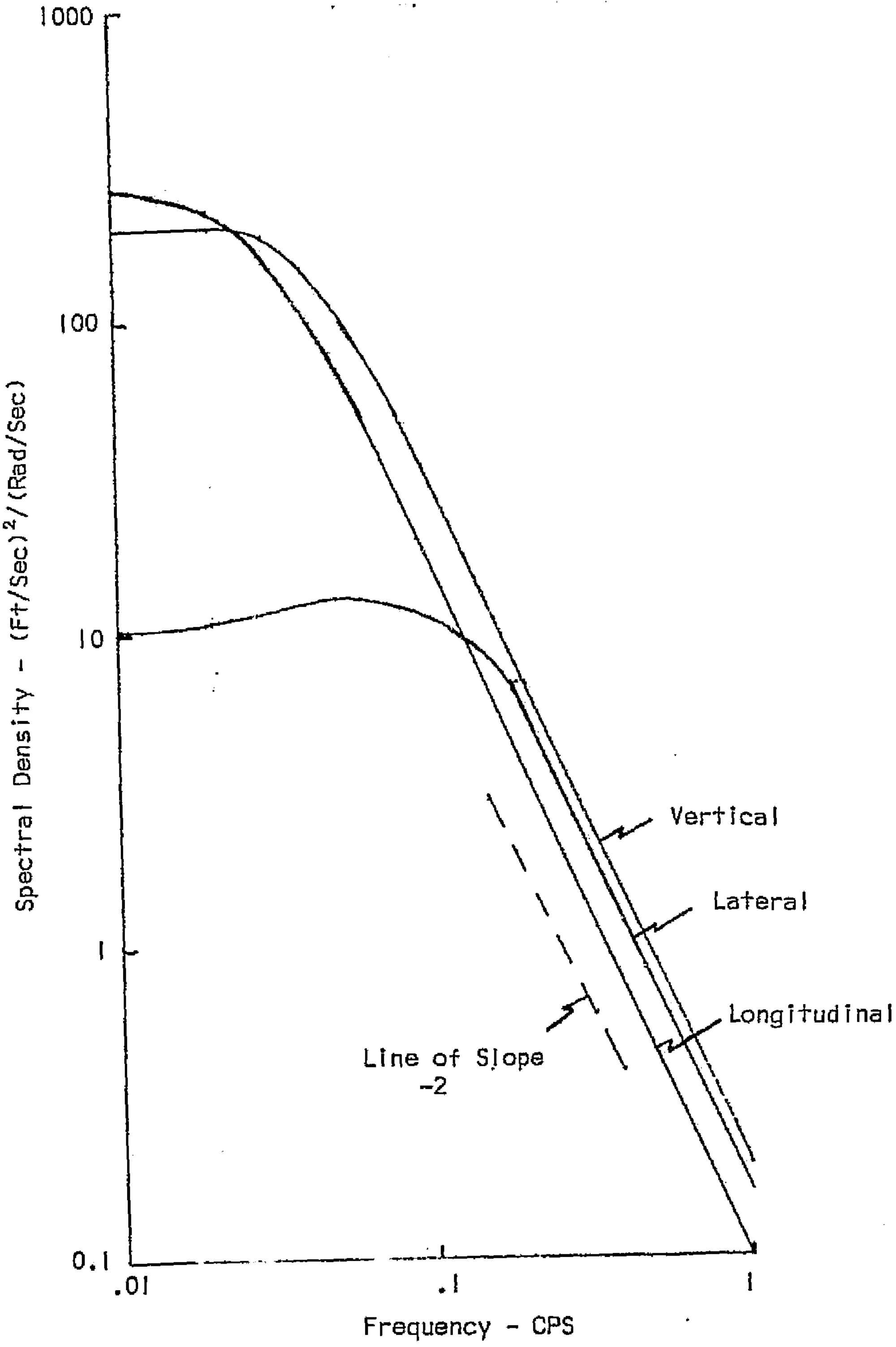


Figure 13

Power Spectral Density of Simulated Field (Case IV)

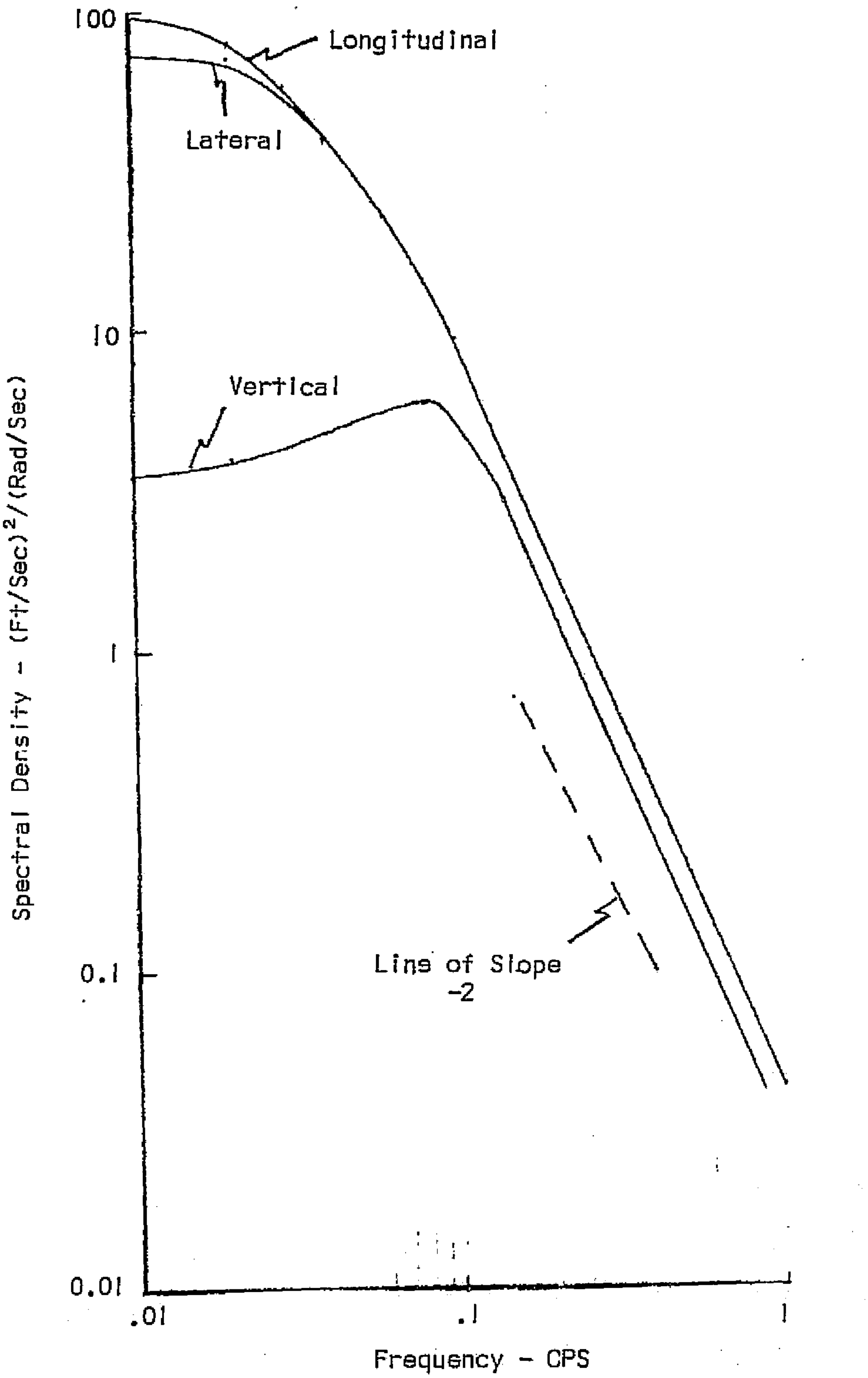


Figure 14

Power Spectral Density of the Simulated Field (Case V)

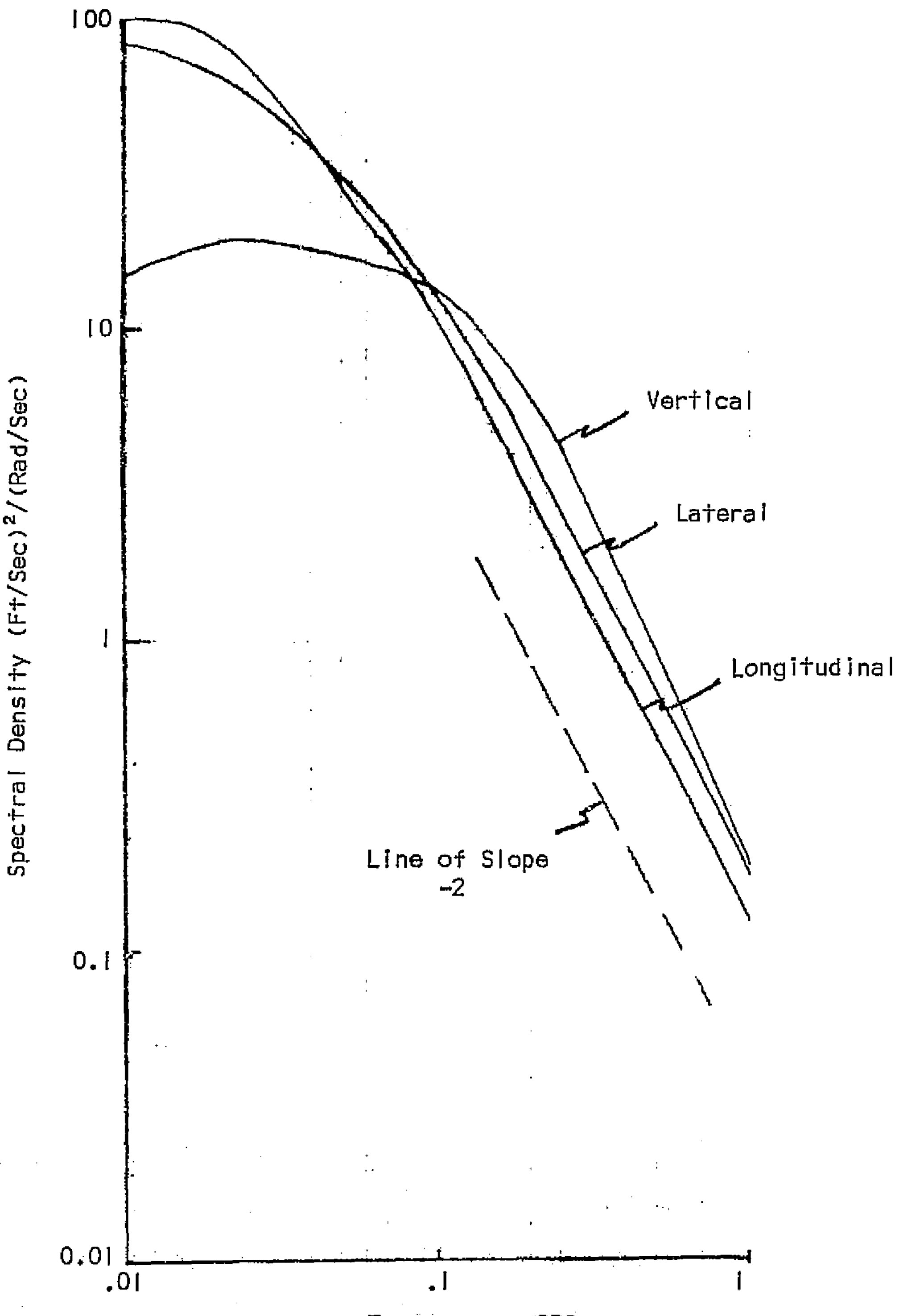


Figure 15

Power Spectral Density of Simulated Field (Case VI)

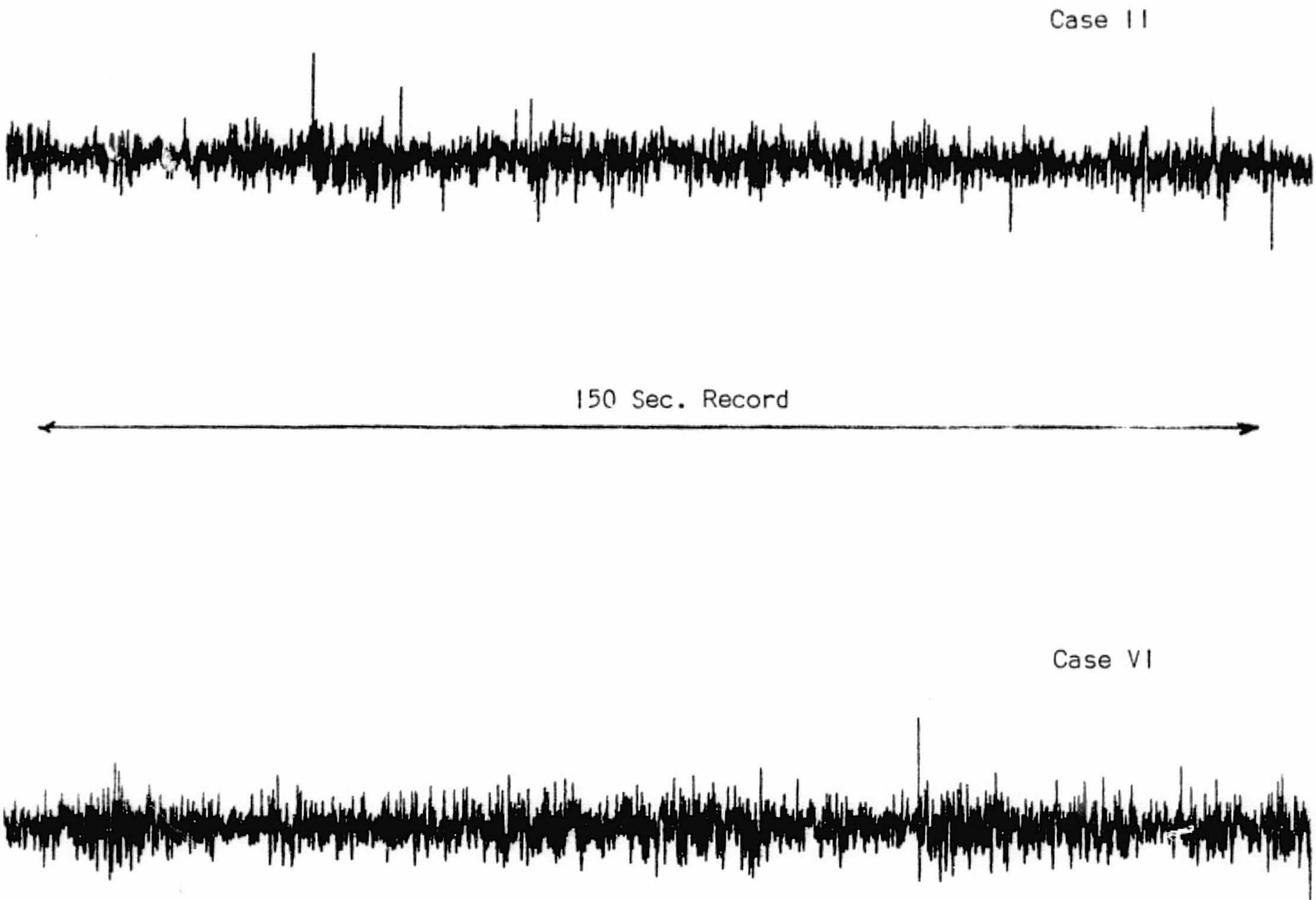


Figure 16

Patchiness of Simulated Field

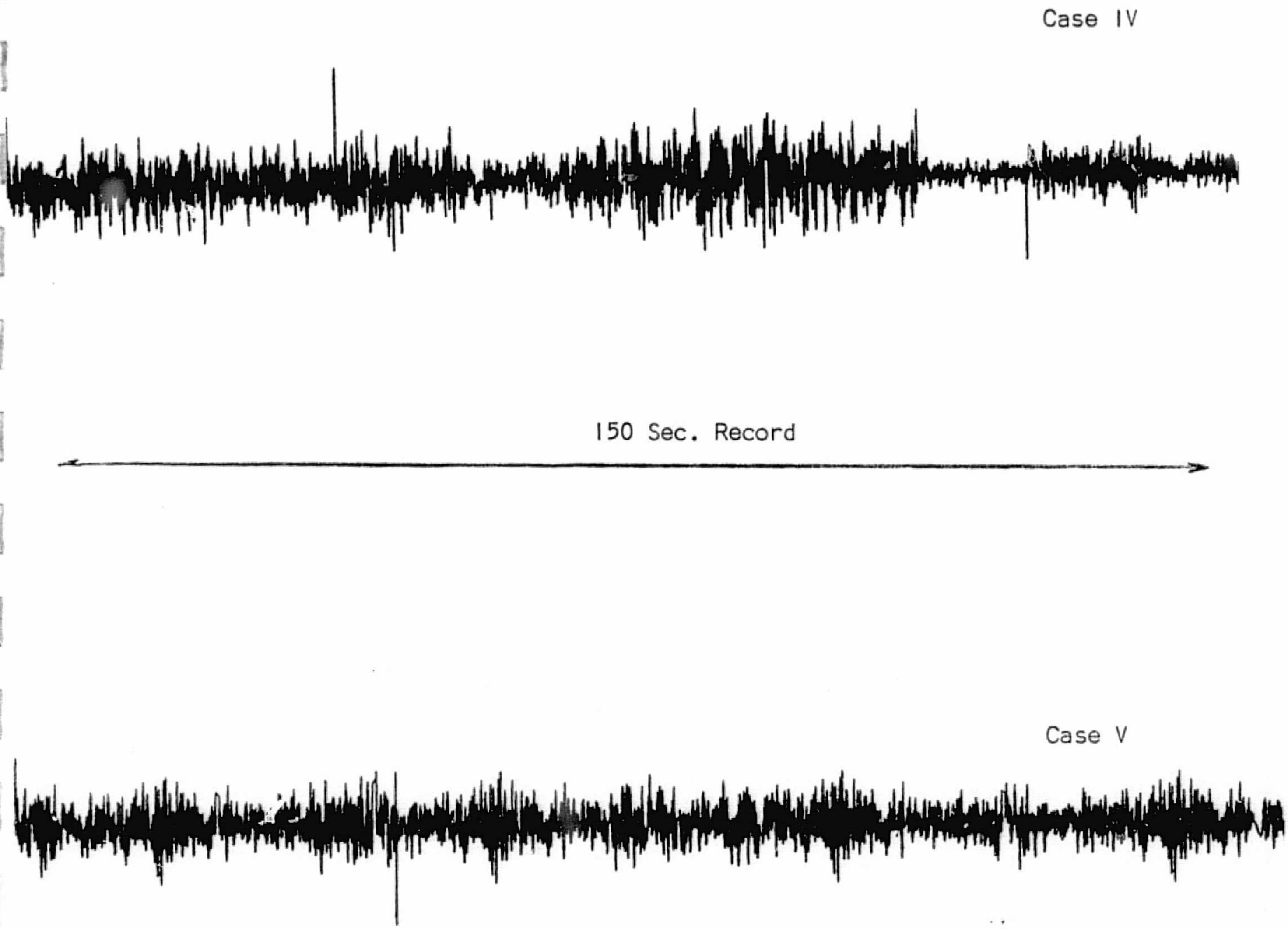


Figure 17

Patchiness of Simulated Field

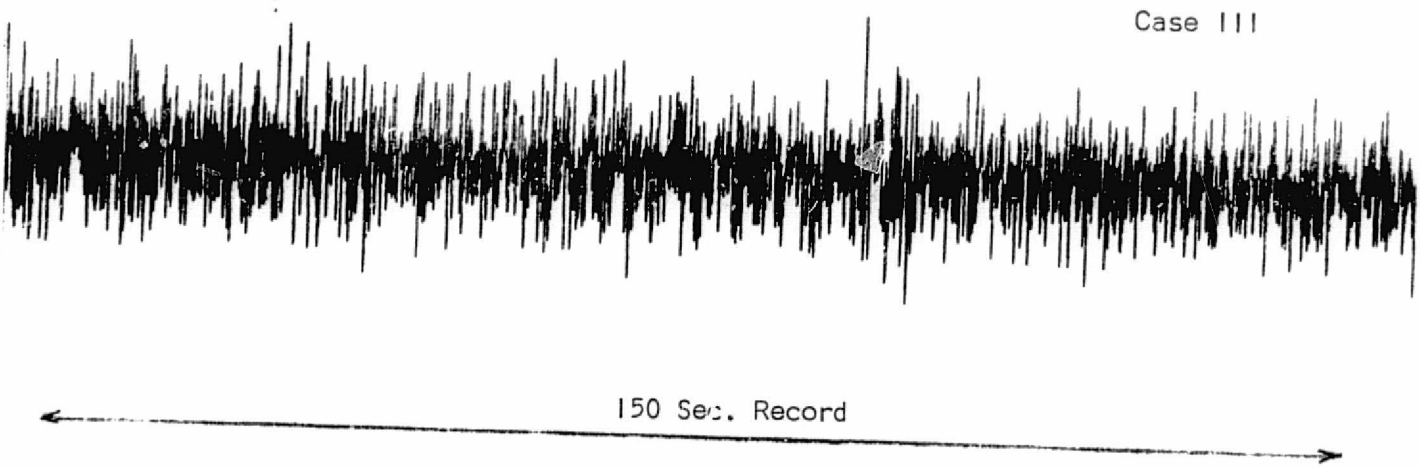


Figure 18

Patchiness of Simulated Field

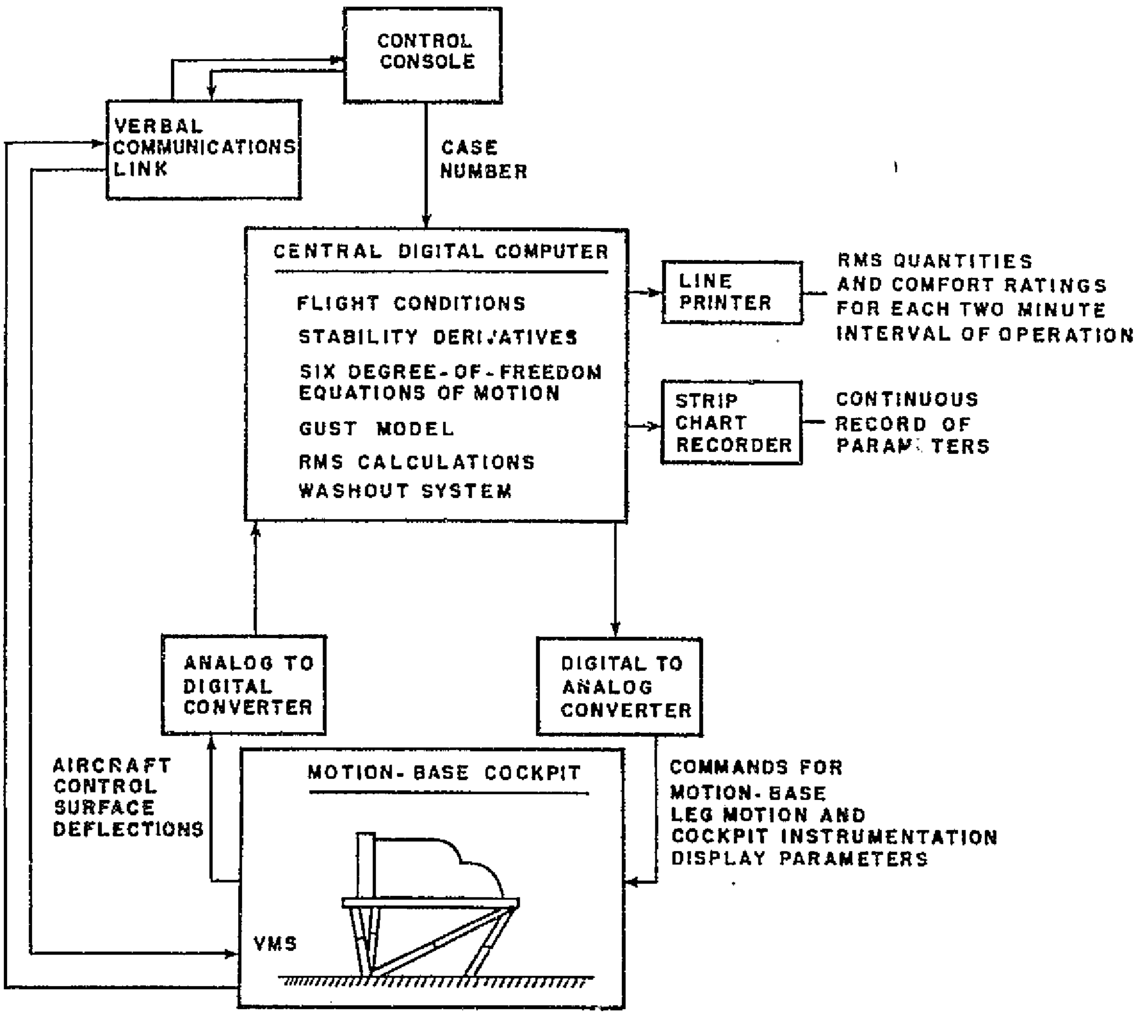


Figure 19

Block Diagram of Motion Based Simulator (Reference 15)

Table 4

FREQUENCY OF ELEMENT OF SURPRISE
OF SIMULATED FIELD

Case	FREQUENCY OF ELEMENT OF SURPRISE %		
	UG	VG	WG
2	0.0666	0.0666	0.0
3	0.0333	0.0	0.0
4	0.0	0.0	0.233
5	0.0333	0.0333	0.0
6	0.2666	0.400	0.0

SIMULATION DETAILS

This section describes the flight simulator experiment, including details of the aircraft simulated, the flight simulator and the pilot task performance. The purpose of the experiment is to determine to what extent pilots are sensitive to changes in atmospheric conditions and realism of the simulation.

The aircraft simulated in this study is the Canadian de Havilland DHC-6 Twin Otter. This particular aircraft is chosen because it is a typical STOL aircraft and its flying characteristics are well known. In addition, there are many pilots available with flying experience in the Twin Otter to valididate the simulation. Table 5 tabulates typical aircraft parameters (Ref. 15).

The simulator used in this study is the six degree of freedom visual motion simulator (rms) at the NASA Langley Research Center. This is a motion based simulator with the basic interior and instrumentation of a jet transport cockpit. Figure 19 presents a block diagram of the simulator reproduced from Ref. 15.

Table 5

AIRCRAFT PARAMETER (Ref. 15)

$w = 11500$ lb	$I_z = 40600$ slug-ft^2
$u_o = 256.67$ ft/sec	$F_{x_z} = 1400$ slug-ft^2
$c_T = 0.045$	$\alpha_o = -1.3°$
$h^* = 0.2$	$\bar{c} = 6.5$ ft
$I_x = 16900$ slug-ft^2	$b = 65$ ft
$I_y = 27600$ slug-ft^2	$s = 420$ ft^2

PILOT POSITION WITH RESPECT TO C.G.

$x = 8.8$ ft $\quad$ $y = -1.6$ ft $\quad$ $z = 0$

DESCRIPTION OF THE EXPERIMENT

The tests will be conducted for six cases composed of Gaussian turbulence and five models. Table 6 presents preliminary planning of the test runs along with the duration and purpose of each run. The pilots will fly each of the six runs in random order for ten minutes achieving a composite flight task. Initially the pilot, in cruise, will be required to achieve a constant altitude tracking task. After each run the pilot will be given a flight questionnaire (see Appendix A) to determine sensitivity to the various models and realism of the simulation. The entire experiment will be repeated with a higher level of turbulence intensity.

Table 6

PRELIMINARY PLANNING OF SIMULATOR EXPERIMENT

SUB MODEL	RMS DISTRIBUTION MODIFIER	SCALE LENGTH DISTRIBUTION MODIFIER	ATMOSPHERIC CONDITION	PURPOSE OF RUN	DURATION OF RUN
1	DETERMINISTIC $\sigma_u = 4.0$ $\sigma_v = 4.0$ $\sigma_w = 4.5$	DETERMINISTIC $L_u = 1317.41$ $L_v = 1317.41$ $L_w = 750$	AVERAGE	TO EXPOSE THE PILOT TO GAUSSIAN MODEL	10 Min
2	GAUSSIAN DISTRIBUTION MEAN ST. DEVIATION U: 3.1 1.2 V: 3.2 1.2 W: 2.8 0.9	DETERMINISTIC $L_u = 913.44$ $L_v = 913.44$ $L_w = 250$	250 FT, UNSTABLE PLAINS	TO EXPOSE THE PILOT TO EXTREME ATMOSPHERIC CONDITIONS	10 Min
3	GAUSSIAN MEAN ST. DEVIATION U: 3.2 0.8 V: 3.5 1.0 W: 4.1 0.9	$L_u = 1317.41$ $L_v = 1317.41$ $L_w = 750$	750 FT, UNSTABLE MOUNTAINS	TO EXPOSE THE PILOT TO EXTREME ATMOSPHERIC CONDITIONS	10 Min

4	RAYLEIGH C = 2.3	DETERMINISTIC L_u = 913.44 L_v = 913.44 L_w = 750	UNKNOWN	TO PROVIDE FEEL FOR PATHINESS	10 Min
5	GAUSSIAN MEAN ST. DEVIATION U 3.1 1.2 V 3.2 1.2 W 2.8 0.9	GAUSSIAN MEAN ST. DEVIATION U 415 110.0 V 325 86.65 W 335 83.11	250 FT, UNSTABLE PLAINS	TO EXPOSE THE PILOT TO EXTREME ATMOSPHERIC CONDITIONS	10 Min
6	GAUSSIAN	GAUSSIAN	250 FT, UNSTABLE MOUNTAIN	TO EXPOSE THE PILOT TO EXTREME ATMOSPHERIC CONDITIONS	10 Min

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APPENDIX A

FLIGHT QUESTIONNAIRE:

Flight Number ________ Date ________________

Pilot: ____________________________________

1. Turbulence Intensity:

   Light ____ Moderate ____ Severe ____ Extreme ____

2. Realism of Turbulence:

   Very Good ____ Good ____ Fair ____ Poor ____ Very Poor ____

3. Correctness of Relative Amplitude of Disturbances:

	Not Enough	About Right	Too Much	No Comments
Roll	____	____	____	____
Pitch	____	____	____	____
Yaw	____	____	____	____
Heave	____	____	____	____
Side Force	____	____	____	____

4. Patchy Characteristics (Variation of Intensity Bursts)

   Much Too Continuous ___ A Little Too Continuous ___ About Right ___

   A Little Too Patchy ___ No Comments ___

5. Frequency Contents of Turbulence:

	Not Enough	About Right	Too Much	No Comments
Low FRQ:	____	____	____	____
High FRQ:	____	____	____	____

6. Element of Surprise in the Simulated Turbulence Field:

   a. Quite Often ____ Sometimes ____ Never ____

   b. Realism of 6a:

      Very Good ____ Good ____ Fair ____ Poor ____ Very Poor ____

7. Atmospheric Conditions:

   a. Altitude: 0 - 1,000 Ft ____ 1,000 - 10,000 Ft ____

      Over 10,000 Ft ____ Unable to Judge ____

8. Pilot Estimate of the Work Load:

Very Easy ____ Easy ____ Average ____ Difficult ____ Very Difficult ____

9. Pilot Estimate of Task Performance: (Integral Squared Error for ILS Tracking Task)

Very Good ____ Good ____ Average ____ Poor ____ Very Poor ____

10. Realism of This Model Compared to Previously Flown Model:

Very Good ____ Good ____ About the Same ____ Poor ____ Very Poor ____

11. Did You Observe a Repetitive Pattern in the Turbulence Field?

Yes ____ No ____

12. Cooper-Harper Rating: ________________

13. Additional Comments About Realism of Turbulence and Aircraft Simulation:

____

____

____

____

PILOT EXPERIENCE:

1. Name ______________________________ Date __________

2. What Type of Flying Experience Have You Had?

   Military ________ Civil ________

3. Main Types of Aircrafts Flown: ______________________________

   ____

4. Total Number of Hours Flown: __________

5. Hours of Instrument Flying: __________

6. Hours in Simulators: __________

7. Hours in VMS: __________

8. Hours in Twin Otter: __________

9. a. Estimate the % of Time Flown in Turbulence: __________

   b. Of This Time What % Was Flown in

Light Turbulence	Moderate Turbulence	Severe Turbulence	Extreme Turbulence
________	________	________	________

10. What Characteristic of Turbulence Interferes Most with Your Ability to Control the Aircraft? ______________________________

    ____

11. Describe the Most Critical Case of Turbulence Encountered During Your Flying Experience:

    a. Day ______ Night ______

    b. Terrain: ________ Altitude: ________

    c. Atmospheric Stability:

       Stable _____ Neutral _____ Unstable _____ Unable to Judge _____

    d. What Was the Task You Were Attempting Before Turbulence Was Encountered: (e.g. ILS Approach, Cruise, etc.) ______________________________

    e. Any Additional Comments: ______________________________

       ____