NASA TECHNICAL MEMORANDUM

NASA TM 78141

(NASA-TM 78141) A TECHNIQUE FOR SIMULATING TURBULENCE FOR AEROSPACE VEHICLE FLIGHT SIMULATION STUDIES (NASA) 22 p HC A02/MF A01 CSCL 01A N78-12014

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G3/02 53602

A TECHNIQUE FOR SIMULATING TURBULENCE FOR AEROSPACE VEHICLE FLIGHT SIMULATION STUDIES

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November 1977

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

MSFC - Form 3190 (Rev June 1971)

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
NASA TM 78141		

4. TITLE AND SUBTITLE	5. REPORT DATE
A Technique for Simulating Turbulence for Aerospace Vehicle Flight Simulation Studies	November 1977
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) George H. Fichtl	8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center, Marshall Space Flight Center, Alabama 35812	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration, Washington, D.C. 20546	13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Space Sciences Laboratory, Science and Engineering

16. ABSTRACT

A technique for simulating atmospheric turbulence that accommodates variability of turbulence properties along an aerospace vehicle trajectory is developed. The technique involves the use of Dryden spectral forms in which the defining parameters are the standard deviations (σ) and integral scales (L) of turbulence. These spectra are expressed as nondimensional functions of the nondimensional frequency $\Omega = \omega L/V$ where ω is dimensional radian frequency and V is the true air speed of the aerospace vehicle. The nondimensional spectra are "factored" by standard techniques to obtain nondimensional linear recursive filters in the time domain whereby band-limited white-like noise can be operated upon to obtain nondimensional longitudinal, lateral, and vertical turbulence velocities, u/σ_u, v/σ_v, and w/σ_w, respectively, as functions of nondimensional time, tV/L, where t is time. Application of the technique to the simulation of the Space Shuttle Orbiter entry flight phase is discussed.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
	George H. Fichtl Unclassified — Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	22	NTIS

MSFC - Form 3292 (Rev December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

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A TECHNIQUE FOR SIMULATING TURBULENCE FOR AEROSPACE VEHICLE FLIGHT SIMULATION STUDIES

INTRODUCTION

The purpose of this document is to describe a technique for simulating atmospheric turbulence which involves a large variability of turbulence properties during the simulation procedure. The technique, which has direct application to Shuttle Orbiter entry and aircraft landing simulation studies, involves extension of recursive filter techniques which have been widely used in the aerospace and aeronautical engineering communities. To apply these filters, a white noise process is passed through a linear filter to generate output processes with statistics that resemble those of atmospheric turbulence [1-3]. In most applications the simulated turbulence velocity components are Gaussian processes with one-dimensional spectra with Dryden or von Karman mathematical forms [4,5]. The defining parameters of these spectra are the turbulence velocity standard deviations and integral scales. These parameters also are the defining parameters of the filters used to process the white noise to generate the turbulence. In fact, the filters are manufactured from the spectral shapes of the turbulence velocity spectra [3]. In many applications the standard deviations and integral scales of turbulence can vary significantly during a flight simulation. For example, from Shuttle Orbiter entry at 120 000 m down to 10 000 m the standard deviations and integral scales of the longitudinal, lateral, and vertical components of turbulence vary by one to two orders of magnitude [6]. Furthermore, from 10 000 m down to 18.3 m these parameters vary by one-half to two orders of magnitude, with the largest variation taking place below 300 m. To apply the linear filters in this situation, the turbulence velocity integral scales and standard deviations are varied during the flight simulation in accordance with *a priori* specified functions of altitude. Thus, during a flight simulation, the flight trajectory and the turbulence simulation procedure are tied together in the sense that the flight trajectory defines altitude which serves to define the turbulence integral scales and standard deviations which determine the simulated turbulence, which, in turn, feeds back to the vehicle and affects the trajectory. Thus, to accommodate the relationship between the flight trajectory and the turbulence simulation model, the turbulence must be simulated during the flight simulation. This can place large demands on the computer facilities available for the flight simulation and could preclude a high fidelity flight simulation. However, this problem can be circumvented by using simulated turbulence generated prior to the actual flight simulation. This can be accomplished via two procedures. One procedure involves the use of a "nominal" trajectory to define the variability of the turbulence standard deviations and integral scales during the flight simulation. The second procedure, the one with which this report is concerned, involves the use of preflight simulated turbulence time histories which are in nondimensional format wherein the turbulence velocity components are scaled with the appropriate standard deviations and the time coordinate is scaled with the appropriate integral scale divided by the true air speed of the vehicle. The central idea here is that the nondimensional turbulence is applicable anywhere along the trajectory. Thus, during the flight simulation, the nondimensional turbulence is placed into the flight simulation computer (via data tape, for example), and the dimensional turbulence as a function of dimensional time is generated by applying the scaling factors (integral scale and standard deviation) and true air speed as a function of time along the trajectory. Application of the scaling factors ties the simulated dimensional turbulence to the flight trajectory with a potentially large saving of flight simulation computer usage. The purpose of this report is to describe this nondimensional turbulence simulation concept and to discuss its application to aerospace and aeronautical flight simulation.

TURBULENCE MODEL

The turbulence simulation technique described in this report is based on a Gaussian turbulence model in which the spectra for the longitudinal, lateral, and vertical components of turbulence are given by

$$\text{Longitudinal:}\quad \phi_u(\omega) = \frac{L_u}{V}\frac{\sigma_u^2}{\pi}\frac{1}{1+(L_u\,\omega/V)^2} \tag{1}$$

$$\text{Lateral:}\quad \phi_v(\omega) = \frac{L_v}{V}\frac{2\sigma_v^2}{\pi}\frac{1+3(L_v\,\omega/V)^2}{[1+(L_v\,\omega/V)^2]^2} \tag{2}$$

$$\text{Vertical:}\quad \phi_w(\omega) = \frac{L_w}{V}\frac{2\sigma_w^2}{\pi}\frac{1+3(L_w\,\omega/V)^2}{[1+(I_w\,\omega/V)^2]^2} \tag{3}$$

where L and σ denote the integral scale and standard deviation of turbulence, ω is the radian frequency, and V is the true air speed of the vehicle. The reader is referred to Section 5.3.14 of Reference 5 for further details. The quantities L, σ, and V are functions of altitude and, hence, time for a non-horizontal flight path; however, they will be treated as being locally constant along the trajectory to generate the turbulence filters and then will be permitted to vary along the trajectory to accommodate the nonstationary character of turbulence resulting from a vehicle traversing a nonhomogeneous turbulence field.

TRANSFORMATIONS

By transforming ω to a nondimensional frequency

$$\Omega = \frac{L\omega}{V} \tag{4}$$

and transforming the dimensional spectral density function $\phi(\omega)$ to a non-dimensional spectral density

$$\Phi(\Omega) = \frac{V}{L\sigma^2}\,\phi\left(\Omega\,\frac{V}{L}\right) \quad , \tag{5}$$

equations (1), (2), and (3) can be written as

$$\Phi_u(\Omega_u) = \frac{1}{\pi}\,\frac{1}{1+\Omega_u^{\,2}} \tag{6}$$

$$\Phi_v(\Omega_v) = \frac{2}{\pi}\,\frac{1+3\Omega_v^{\,2}}{[1+\Omega_v^{\,2}]^2} \tag{7}$$

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$$\Phi_w(\Omega_w) = \frac{2}{\pi}\,\frac{1+3\Omega_w^{\,2}}{[1+\Omega_w^{\,2}]^2} \tag{8}$$

where the subscripts on Ω refer to the fact that $L_u \neq L_v \neq L_w$. The aforementioned spectra imply the existence of Fourier decompositions of the form

$$U(\xi_u) = \int_{-\infty}^{\infty} \hat{U}(\Omega_u)\, e^{i\Omega_u \xi_u}\, d\Omega_u \tag{9}$$

$$V(\xi_v) = \int_{-\infty}^{\infty} \hat{V}(\Omega_v)\, e^{i\Omega_v \xi_v}\, d\Omega_v \tag{10}$$

$$W(\xi_w) = \int_{-\infty}^{\infty} \hat{W}(\Omega_w)\, e^{i\Omega_w \xi_w}\, d\Omega_w \tag{11}$$

where $(\hat{U})$ denotes Fourier decomposition of (U) over the domain $-\infty < \Omega < \infty$. The quantity ξ is a nondimensional coordinate, namely

$$\xi = \frac{tV}{L} \tag{12}$$

where t is dimensional time measured with respect to an arbitrarily selected point on the vehicle entry trajectory. The quantities U, V, and W at the nondimensional longitudinal, lateral, and vertical components of turbulence are defined as

$$U(\xi_u) = \frac{u(\xi_u L_u/V)}{\sigma_u} \tag{13}$$

$$V(\xi_v) = \frac{v(\xi_v L_v/V)}{\sigma_v} \tag{14}$$

$$W(\xi_w) = \frac{w(\xi_w L_w/V)}{\sigma_w} \tag{15}$$

where u, v, and w are the dimensional longitudinal, lateral, and vertical components of turbulence which are functions of t. Note that after applying the transformation, equation (12), we have expressed nondimensional components of turbulence U, V, W as functions of nondimensional time ξ measured with respect to an arbitrarily selected point on the Orbiter trajectory. In view of the previous developments, it appears reasonable to simulate turbulence in terms of the nondimensional random functions $U(\xi_u)$, $V(\xi_v)$, and $W(\xi_w)$ because the variability in the turbulence simulation resulting from time dependent σ, L, and V has been absorbed into nondimensional random functions $U(\xi_u)$, $V(\xi_v)$, and $W(\xi_w)$ so that σ, L, and V do not appear explicitly in a nondimensional context.

DIGITAL SIMULATION FILTERS

To mechanize the concepts enunciated in the previous sections we shall use the concept of digital recursive filters. We shall use the digital filters associated with Dryden spectra, given in Reference 7. Thus, the components of the digitized turbulence are simulated by passing white noise through the following filters:

$$U_n = C_u U_{n-1} + D_u N_{u,n-1} \tag{16}$$

$$V_n = C_{1,v} V_{n-1} - C_{2,v} V_{n-2} + D_{1,v} N_{v,n-1} + D_{2,v} N_{v,n-2} \tag{17}$$

$$W_n = C_{1,w} W_{n-1} - C_{2,w} W_{n-2} + D_{1,w} N_{w,n-1} + D_{2,w} N_{w,n-2} \tag{18}$$

where subscript n is a running index (i.e., n = 1, 2, . . .), and N_u, N_v, and N_w are independent Gaussian white noise sources. The remaining quantities are defined as

$$C_u = e^{-a_u \Delta\zeta_u} \tag{19}$$

$$D_u = k_u^{1/2} \frac{\left(1 - e^{-a_u \Delta\zeta_u}\right)}{a_u} \tag{20}$$

$$C_{1,v} = 2\,e^{-a_v \Delta\zeta_v} \tag{21}$$

$$C_{2,v} = e^{-2a_v \Delta\zeta_v} \tag{22}$$

$$D_{1,v} = k_v^{1/2} \left\{ \frac{b_v}{a_v^2} + e^{-a_v \Delta\zeta_v} \left(\frac{a_v - b_v}{a_v} \Delta\zeta_v - \frac{b_v}{a_v^2} \right) \right\} \tag{23}$$

$$D_{2,v} = k_v^{1/2} \left\{ \frac{b_v}{a_v^2} \left(e^{-a_v \Delta\zeta_v} - 1 \right) - \frac{a_v - b_v}{a_v} \Delta\zeta_v \right\} e^{-a_v \Delta\zeta_v} \tag{24}$$

$$C_{1,w} = 2e^{-a_w \Delta\zeta_w} \tag{25}$$

$$C_{2,w} = e^{-2a_w \Delta\zeta_w} \tag{26}$$

$$D_{1,w} = k_w^{1/2} \left\{ \frac{b_w}{a_w^2} + e^{-a_w \Delta\zeta_w} \left(\frac{a_w - b_w}{a_w} \Delta\zeta_w - \frac{b_w}{a_w^2} \right) \right\} \tag{27}$$

$$D_{2,w} = k_w^{1/2} \left\{ \frac{b_w}{a_w^2} \left(e^{-a_w \Delta \zeta_w} - 1 \right) - \frac{a_w - b_w}{a_w} \Delta \zeta_w \right\} e^{-a_w \Delta \zeta_w} . \quad (28)$$

The various parameters in equations (19) through (28) are defined as follows:

$$a_u = a_v = a_w = 1 \quad (29)$$

$$b_u = b_v = b_w = 3^{-1/2} \quad (30)$$

$$k_u = \frac{2}{\pi} \quad (31)$$

$$k_v = k_w = \frac{3}{\pi} \quad (32)$$

and $\Delta\zeta_u$, $\Delta\zeta_v$, and $\Delta\zeta_w$ denote the nondimensional time intervals between the digitized values of U, V, and W, respectively.

The procedure for simulating turbulence consists of (1) selecting values of U_1, V_1, V_2, W_1, and W_2 (by random selection in the computer, for example), (2) selecting values of $N_{u,1}$, $N_{v,1}$, $N_{v,2}$, $N_{v,1}$, and $N_{v,2}$, (3) substituting results of steps (1) and (2) into equations (16), (17), and (18) to calculate U_2, V_3, W_3, (4) incrementing the subscript n by 1 and repeating steps (1) through (3) a sufficient number of times to generate the desired nondimensional time histories of turbulence, and (5) transforming to dimensional time histories with equations (12) through (15).

The digital simulation of U, V, and W requires specification of the nondimensional intervals $\Delta\zeta_u$, $\Delta\zeta_v$, and $\Delta\zeta_w$ and, of course, three independent Gaussian white noise processes. The dimensional interval Δt can be written as

$$\Delta t = \frac{L}{V} \Delta \zeta \quad . \quad (33)$$

Furthermore, the interval Δt can be written in terms of the local Nyquist frequency ω_N of the data set,

$$\Delta t = \frac{\pi}{\omega_N} \quad . \tag{34}$$

Combining equations (33) and (34) yields

$$\omega_N = \frac{\psi}{\Delta \zeta} \tag{35}$$

where

$$\psi = \frac{\pi V}{L} \quad . \tag{36}$$

During a nondimensional turbulence simulation $\Delta \zeta$ is held constant so that according to equation (35) the Nyquist frequency will vary in direct proportion to ψ. Thus, to encompass all turbulence frequencies of importance during a flight simulation we specify $\Delta \zeta$ by selecting the largest value of ω_N of concern and the smallest value of ψ, $(\omega_N)_o$, and ψ_o. Thus,

$$\Delta \zeta = \frac{\psi_o}{(\omega_N)_o} \quad . \tag{37}$$

APPLICATION TO ORBITER ENTRY

As stated in the previous section, the simulation technique requires specification of $\Delta \zeta$. Let us consider the entry of the Shuttle Orbiter as an example. Figure 1 contains a plot of the Shuttle Orbiter true air speed V during the entry flight phase as a function of altitude above mean sea level (MSL) for the first Operational Flight Test (OFT). Figures 2 and 3 contain plots of the

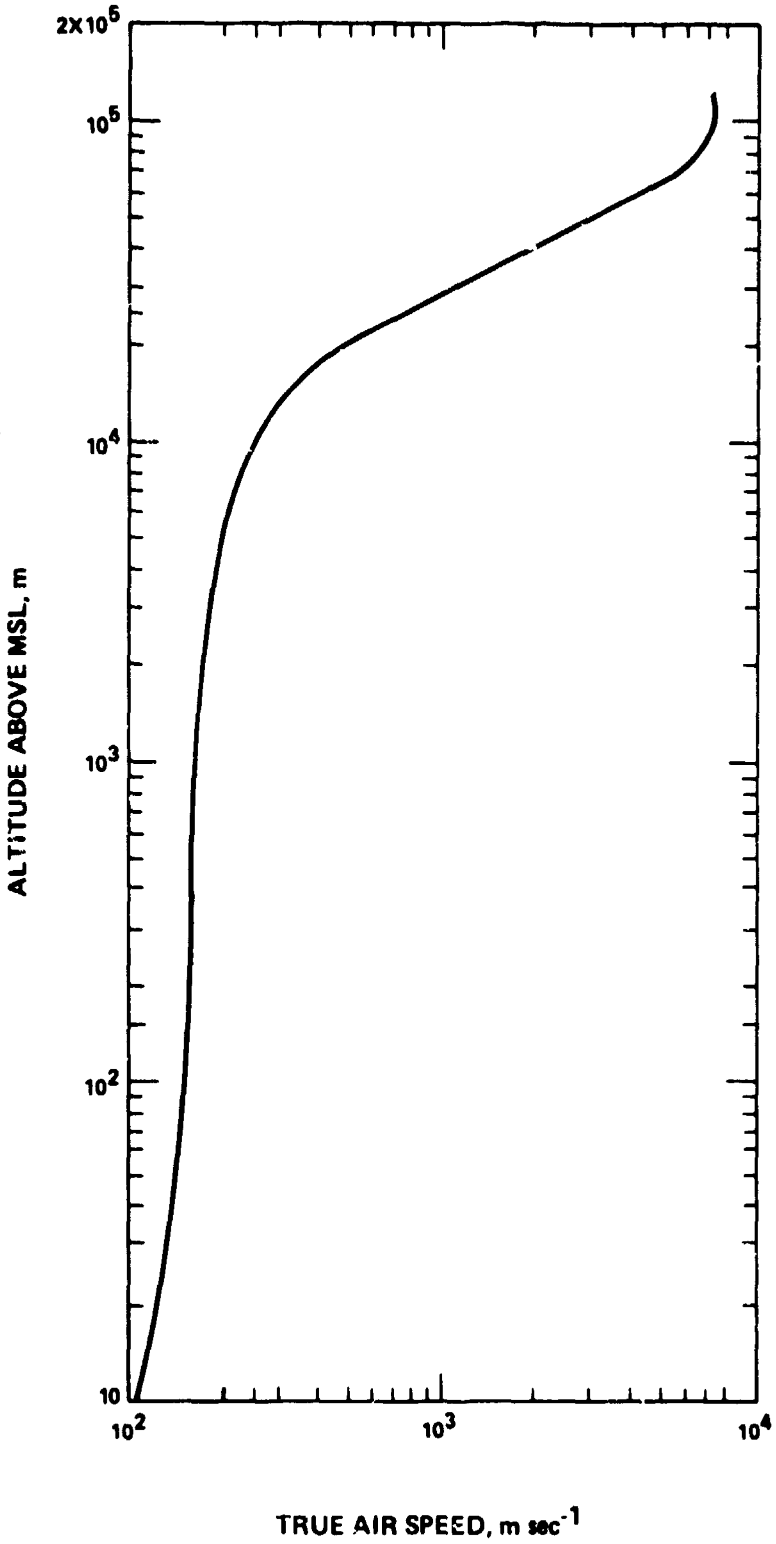

Figure 1. Shuttle Orbiter true air speed as a function of altitude for OFT No. 1.

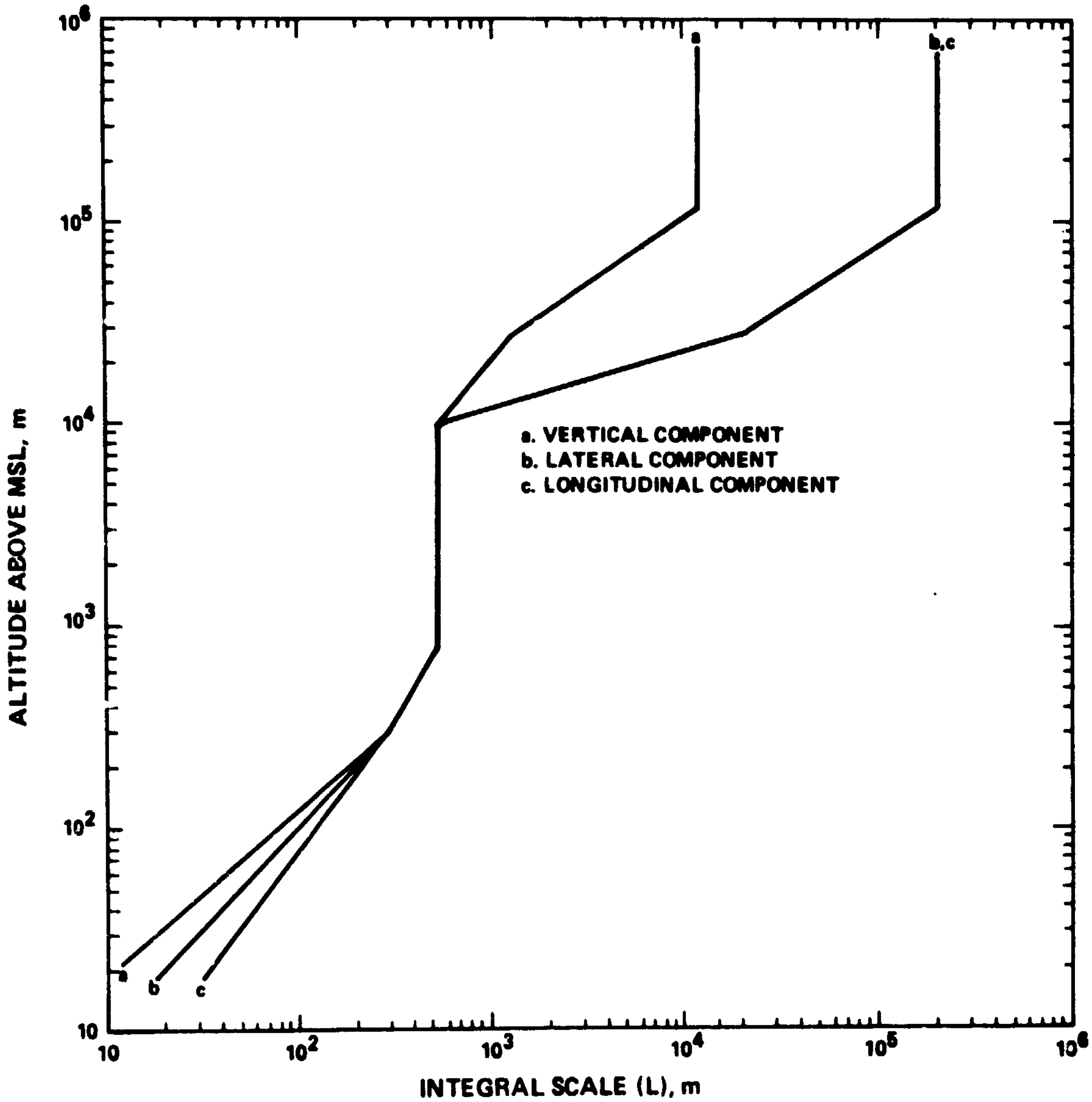

Figure 2. Shuttle program natural environment design integral scales of turbulence (L) as a function of altitude [6].

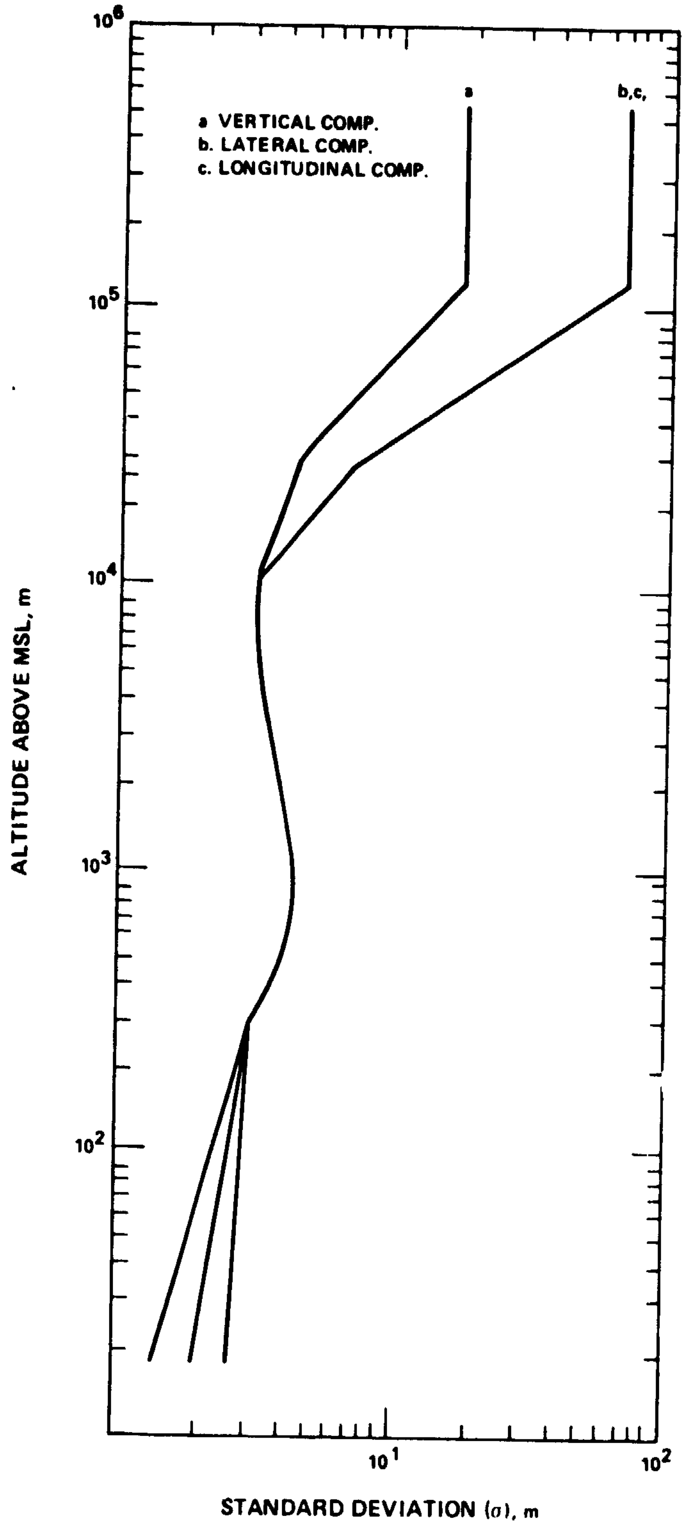

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Figure 3. Shuttle program natural environment design standard deviations of turbulence (σ) as a function of altitude [6].

integral scale of turbulence (L) and the standard deviation (σ) for each component of turbulence as specified by the Shuttle Level II requirements document [6]. As stated earlier, σ serves as velocity scale and L/V serves as a time scale to nondimensionalize the turbulence velocity time histories. Combination of the data in Figures 1 and 2 yields the calculated values of ψ [equation (36)] in Table 1 for each component of turbulence. As discussed in the previous section, we require the lowest value of ψ and the largest value of ω_N to encompass all turbulence frequencies of concern.

TABLE 1. VALUES OF ψ DERIVED FOR OFT No. 1 MISSION

Altitude (m)	ψ_w	ψ_v	ψ_u
120 000	1.884956	0.113097	0.113097
90 000	2.748894	0.169163	0.169163
70 000	3.257948	0.204569	0.204569
50 000	3.337942	0.205412	0.205412
30 000	2.094395	0.142800	0.142800
20 000	1.636246	0.261799	0.261799
18 000	1.570796	0.329119	0.329119
16 000	1.374447	0.407243	0.407243
14 000	1.308997	0.496041	0.496041
12 000	1.393448	0.863938	0.863938
10 000	1.481883	1.481883	1.481883
7 000	1.274420	1.274420	1.274420
5 000	1.185507	1.185507	1.185507
2 000	1.037318	1.037318	1.037318
1 000	0.978043	1.978043	0.978043
500	1.2566	1.2566	1.2566
300	1.6232	1.6232	1.6232
50	12.5664	8.7965	6.1087
18.3	37.6991	20.9440	11.7810

According to Table 1, the values of ψ_o listed in Table 2 can be used for the Shuttle Orbiter mission. Table 1 shows that ψ is very nearly equal to a constant for the vertical component of turbulence for the entry mission except in the vicinity of the ground where ψ increases rapidly with decreasing altitude. However, for the longitudinal and lateral components of turbulence, ψ varies by one order of magnitude from 120 000 m down to 10 000 m and remains constant until, in the vicinity of the ground, ψ increases rapidly with decreasing altitude. The actual Nyquist frequency for each component of turbulence in the data set will vary with altitude according to the formula

$$\omega_N = (\omega_N)_o \frac{\psi}{\psi_o} \tag{38}$$

so that any variability of ψ with altitude will be reflected in ω_N. Thus, for the vertical component of turbulence, ω_N is very nearly constant with altitude except near the ground, where ψ and, hence, ω_N increase by nearly one order of magnitude. For the longitudinal and lateral components, the respective values of ω_N increase by one order of magnitude in the altitude band from 120 000 to 10 000 m, as well as near the ground.

TABLE 2. VALUES OF ψ_o FOR TURBULENCE SIMULATION DERIVED FOR THE ORBITER OFT No. 1 MISSION

Component	ψ_o
Longitudinal	0.113
Lateral	0.113
Vertical	0.978

A value of $\omega_N/(\omega_N)_o > 1$ implies that the digital rate at which turbulence is provided in the simulation is greater than the rate which would actually be necessary. Thus, if data tapes are used to store the digital simulations of turbulence, values of $\psi/\psi_o > 1$ and, hence, $\omega_N/(\omega_N)_o > 1$ near the ground do not appear to pose data storage problems for the vertical component of turbulence because the length of the trajectory near the ground, over which the data rate would be too large, is relatively short. However, in the case of the longitudinal and lateral components of turbulence, ω_N varies by an order of magnitude over a significantly large portion of the entry mission, i.e., 120 000 to 10 000 m (Table 1). Thus, $\psi_o = 0.113$ corresponds to a digital simulation rate which is too large by a factor of 10 below 10 000 m down to 50 m and by a factor of 100 below 50 m. To remedy this situation two values of ψ could be used for the longitudinal and lateral turbulence simulation (Table 3). The increase in ψ/ψ_o, and hence $\omega_N/(\omega_N)_o$, by an order of magnitude below 500 m does not appear to pose data storage problems for the same reason that the vertical component does not appear to pose data storage problems relative to simulated turbulence near the ground, as previously stated.

TABLE 3. VALUES OF ψ_o FOR LONGITUDINAL AND LATERAL TURBULENCE SIMULATION AS A FUNCTION OF ALTITUDE DERIVED FOR THE ORBITER OFT No. 1 MISSION

Altitude > 10 km	
Component	ψ_o
Longitudinal	0.113
Lateral	0.113
Vertical	0.978
Altitude ≤ 10 km	
Component	ψ_o
Longitudinal	0.978
Lateral	0.978
Vertical	0.978

TURBULENCE DATA TAPE CONCEPT

To provide nondimensional turbulence for flight simulation of the Shuttle Orbiter, a data tape with nondimensional turbulence for at least two sets of ψ_o values would be required. First, an upper bound Nyquist frequency $(\omega_N)_o$ would be required. This upper bound frequency should be a factor of 10 greater than any turbulence frequency ω_E of concern, in an engineering context, to insure that all Fourier components of the turbulence with frequency $\omega < \omega_E$ have 100 percent (or very nearly so) spectral energy. The spectral densities $\phi_s(\omega)$ of the simulated turbulence for $\omega > \omega_E$ will tend to zero as $\omega \rightarrow (\omega_N)_o$ and are related to the spectral densities of the turbulence model [equations (1), (2), and (3)] $\phi(\omega)$ as follows:

$$\frac{\phi_s(\omega)}{\phi(\omega)} = \frac{\sin^2\left(\frac{\pi\omega}{\omega_E}\right)}{\left(\frac{\pi\omega}{\omega_E}\right)^2} \quad . \tag{39}$$

Once the upper bond Nyquist frequency $(\omega_N)_o$ and ψ_o are specified, the non-dimensional time intervals $\Delta\xi$ [equation (37)] are known and equations (16), (17), and (18) can be applied.

To provide nondimensional turbulence data tapes to encompass the total Shuttle Orbiter entry mission, the tapes could consist of two parts in sequence, or more parts if required for more detailed definition of the turbulence with respect to altitude. The first set of nondimensional simulated turbulence velocities is applicable to altitudes above 10 000 m and is generated with the values of ψ_o given in Table 2. The second set is applicable to altitudes below 10 000 m and is generated with $\psi_o = 0.978$ for each turbulence component. Thus, during a flight simulation, nondimensional turbulence from the first turbulence set on the data tapes would be used down to 10 000 m whereupon the data tape could provide for a number of different simulations by entering sets 1 and 2 at different locations with the actual number of different simulations available depending on the relative magnitudes of ψ_o and $(\omega_N)_o$.

In each data tape set the nondimensional time between the simulated nondimensional turbulence velocities for each component of turbulence is a constant. In view of equation (33), the dimensional time Δt between the dimensional simulated winds will vary with altitude to the degree that L/V varies with altitude. Furthermore, Δt for the various components of turbulence will not necessarily be equal. Above 10 000 m $(\Delta t)_u = (\Delta t)_v \neq (\Delta t)_w$. Below 10 000 m and above 304.8 m $(\Delta t)_u = (\Delta t)_v = (\Delta t)_w$, and below 304.8 m $(\Delta t)_u \neq (\Delta t)_v \neq (\Delta t)_w$. However, this variation of Δt from component to component and from altitude to altitude can be easily accommodated during the flight simulation process.

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APPROVAL

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By George H. Fichtl

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for t chnical accuracy.

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Director, Space Sciences Laboratory

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