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# A Conceptual Framework for Using Doppler Radar Acquired Atmospheric Data for Flight Simulation

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# A Conceptual Framework for Using Doppler Radar Acquired Atmospheric Data for Flight Simulation

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and Space Administration

**Scientific and Technical
Information Branch**

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# TABLE OF CONTENTS

| | Page |
|---|---|
| INTRODUCTION | 1 |
| SPECTRA OF TURBULENCE | 2 |
| SIMULATION OF TURBULENCE | 4 |
| THE PROPOSED SIMULATION MODEL | 4 |
| GENERATION OF THE FROZEN TURBULENCE DATA BASE | 5 |
| SUMMARY OF THE PROPOSED SIMULATION CONCEPT | 7 |
| POSSIBLE CONCEPT REFINEMENTS | 8 |
| CONCLUSIONS | 10 |
| REFERENCES | 11 |

# LIST OF ILLUSTRATIONS

| Figure | Title | Page |
|---|---|---|
| 1. | Simulation of turbulence | 4 |
| 2. | Simulation volume for a microburst | 5 |
| 3. | Aerospace vehicle flight simulation | 8 |
| 4. | Frozen turbulence data base models | 9 |

TECHNICAL PAPER

# A CONCEPTUAL FRAMEWORK FOR USING DOPPLER RADAR ACQUIRED ATMOSPHERIC DATA FOR FLIGHT SIMULATION

## INTRODUCTION

Simulations of turbulence in the atmosphere in the past [1-8] for the most part involved simulation along the flight path of aerospace vehicles. This procedure, while convenient, has several shortcomings which are described in a later section. The proposed technique would simulate temporal and spatial turbulence variation and would use data provided by sources such as the Joint Airport Weather Studies (JAWS) Project [9,10]. In fact, Doppler radar data is uniquely suited for input into the proposed model which should provide a framework for using the JAWS data for flight simulation.

The three-dimensional model as proposed would simulate turbulent gusts, temporally and spatially varying "mean" winds, and turbulent gust variation over the body of an aircraft, so that all aerodynamic loads and moments could be calculated. In a flight simulator, the actions (i.e., maneuvers, velocity increases, etc.) that a pilot takes in no way invalidate the model. In other words, the pilot is not restricted to flying a particular path. In the past models based on flight recorder data were used; and, if in the simulation, the pilot flew a plane much different from the plane that made the measurements, the simulation became invalid. The pilot was also restricted to fly the same flight path as the original plane. This restriction does not apply to the proposed model.

The effects of gust gradients on flight vehicles has received little attention in the past, but a few researchers have considered the problem [11]. Simulation of gust gradients was described in Reference 5. Currently a NASA program is underway to measure spanwise gust variations in severe turbulence [12]. Early data from NASA's B-57B Gust Gradient program indicate that large spanwise gradients do occur in turbulent gusts. These gradients could be especially significant for today's wide-bodied aircraft. Because gust gradients appear to be significant, a realistic simulation should include them. The proposed model includes spatial gust variation over the body of a vehicle as a natural part of the simulation.

This paper discusses the use of JAWS data as input to the model, but much more general situations can be simulated. For example, during the early stages of reentry, Shuttle velocity is so high that weather systems look like turbulence to the Orbiter. This situation could be simulated. As wind information becomes available, even reentry or flight in planetary atmospheres could be simulated.

A possible disadvantage of the proposed model is that it might require a large data base. Even if a large data base is required, the problem is not devastating since the price of mass storage has decreased dramatically in recent years; and, when new advances such as bubble memory become available, the cost should be reduced even more. Discussions in later sections will show that the size of the data base can be handled readily by minicomputers; and, in a few years, even a microcomputer may be able to run the model. An idea for reducing the data base to a modest size is also discussed.

The basic idea is as follows. Consider a three-dimensional volume fixed in the atmosphere. Later refinements may permit nondimensional simulations such as those described in References 2 and 5. For the present, assume that the volume is in the real atmosphere as opposed to a volume in a transformed dimensionless space. Generate a uniformly spaced, three-dimensional grid in the volume. At each grid point, generate three independent, normal random deviates. Each of the three random number fields are to be transformed to fields of the three components of velocity. The resulting Gaussian white noise-field will have a three-dimensional autocorrelation which is a noisy approximation to the Dirac delta function $\delta(x,y,z)$. Do a three-dimensional Fourier transform on each component of the noise. Point by point, multiply the transformed data by filter functions corresponding to the desired turbulence model; i.e., von Karman, Dryden, Kaimal, etc. For the model used, the turbulent intensity should be set to unity. Transform the result back to the space domain. The result is a simulated field of frozen turbulence. The frozen turbulence is the large data base mentioned earlier. To perform the actual simulation, multiply the frozen turbulence by a model of the temporally and spatially varying turbulent intensity, and add temporally and spatially varying "mean" winds. These ideas are made clearer in the following sections.

## SPECTRA OF TURBULENCE

This section discusses certain aspects of turbulent spectra which are relevant to the proposed model. For clarity the von Karman and Dryden models will be discussed as specific examples, but other models may work equally well. The Dryden and von Karman models are actually continuous or analog turbulence models, whereas all turbulence data analyzed on digital computers are discrete. For simulation purposes, discrete approximations to these models may be used, or a more general discrete model might be useful. Von Karman and others have shown that for isotropic turbulence, the spectrum function of the i and j components of gust velocity in a Cartesian frame can be written in the form:

$$\phi_{ij}(k_1,k_2,k_3) = \frac{E(k)}{4\pi k^2}\left(\delta_{ij} - \frac{k_i k_j}{k^2}\right) , \tag{1}$$

where $k = (k_1{}^2 + K_2{}^2 + k_3{}^2)^{1/2}$, and $k_i$ are the three orthogonal wave number components. For the Dryden and von Karman models of turbulence, E(k) is defined by:

$$E(k) = \frac{8\sigma^2 L}{\pi} \frac{(Lk)^4}{[1 + (Lk)^2]^2} , \tag{2a}$$

$$E(k) = \frac{55\sigma^2 L}{9\pi} \frac{(aLk)^4}{[1 + (aLk)^2]^{17/6}} , \tag{2b}$$

where a = 1.339, L is the length scale of turbulence, and $\sigma$ is the turbulent gust standard deviation. Substituting equation (1) into equations (2a) and (2b) gives the following results when the subscripts are equal:

$$\phi_{ii}(k_i) = \frac{2\sigma^2 L^5}{\pi^2} \frac{(k^2 - k_i{}^2)}{[1 + (Lk)^2]^2} \tag{3a}$$

$$\phi_{ii}(k_i) = \frac{55\sigma^2 a^4 L^5}{36\pi^2} \frac{(k^2 - k_i^2)}{[1 + (aLk)^2]^{17/6}} \quad . \tag{3b}$$

The gust gradient $(\partial u_i/\partial x_j)$ spectra are, by inspection:

$$\phi_{ii,jj} = \frac{2\sigma^2 L^5}{\pi^2} \frac{k_j^2 (k^2 - k_i^2)}{[1 + (Lk)^2]^2} \tag{4a}$$

$$\phi_{ii,jj} = \frac{55\sigma^2 a^4 L^5}{36\pi^2} \frac{k_j^2 (k^2 - k_i)^2}{[1 + (aLk)^2]^{17/6}} \quad . \tag{4b}$$

Many researchers [1-7] have simulated turbulence along the flight path in the following way. $k_2$ and $k_3$ are integrated out of the three-dimensional power spectra.

$$\Phi_{ii}(k_1) = \iint_{-\infty}^{\infty} \phi_{ii}(k_1,k_2,k_3)\, dk_2\, dk_3 \quad . \tag{5}$$

With $\Phi_{ii}(k_1)$ defined, turbulence along the flight path could be simulated. Simulating gust gradients should involve a similar procedure, but unfortunately the integrals blow up for commonly used models; i.e.,

$$\Phi_{ii,jj}(k_1) = \iint_{-\infty}^{\infty} \phi_{ii,jj}(k_1,k_2,k_3)\, dk_2\, dk_3 = \infty \quad . \tag{6}$$

Simulating gust gradients is not so straightforward. One way of overcoming the difficulty is to integrate over finite limits. Unfortunately, Tatom and King [7] showed that the integral is a strong function of the selected limits. To overcome this problem, scaling arguments based on vehicle size are made which determine the limits of integration. This type of turbulent simulation is vehicle dependent. A simulation can be designed for any vehicle, but one simulation will not serve for two vastly different aircraft. The proposed model will not have this limitation. Since a three-dimensional volume filled with simulated turbulence is generated, the spatial gust gradients are accounted for naturally. This idea is clarified in the following sections.

## SIMULATION OF TURBULENCE

Conceptually, turbulence is frequently simulated as shown in Figure 1. A Gaussian noise source is input to a filter. The filter function is given by:

$$H_i(k_1) = \sqrt{\Phi_{ii}(k_1)} \quad . \tag{7}$$

The phase of $H_i$ does not affect the spectrum and may be set to zero as is indicated in equation (7). $\Phi_{ii}$ is a one-dimensional spectrum from a suitable model. Since the input is white noise, its autocorrelation is a noisy approximation to a Direc delta function and so its power spectrum oscillates randomly about the value of unity. $H_i$ is chosen as in equation (7) so that the output has the desired output spectrum. For the model of Figure 1, the output signal is normally distributed. Other methods [3,4] generate non-Gaussian turbulence, but in each case, the one-dimensional flight path turbulence is simulated.

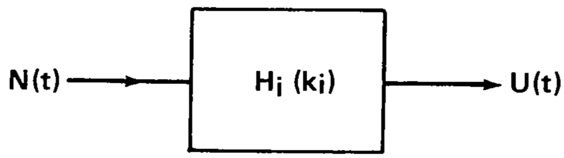



Figure 1. Simulation of turbulence.

## THE PROPOSED SIMULATION MODEL

In a series of papers [13-15], Mark and Mark and Fischer studied a model of turbulence which is modified for the purposes of this paper into the following form:

$$u_i(x,y,z,t) = \overline{U}_i(x,y,z,t) + \sigma_i(x,y,z,t)\, w_i(x,y,z) \quad . \tag{8}$$

Here $u_i$ (x,y,z,t) are the components of total velocity including the spatially and temporally varying effects of a mean wind value, $\overline{U}_i$, and a standard deviation, $\sigma_i$. $w_i$ (x,y,z,t) is a three-dimensional frozen (no time variation) field of simulated turbulence with unit variance, zero mean value, and spectra defined by some suitable model such as given by equation (3). One of the most attractive features of equation (8) is that $\overline{U}_i$ (x,y,z,t) and $\sigma_i$ (x,y,z,t) can be provided by Doppler radar data such as was collected during the JAWS project. $U_i$ are the smoothed or mean winds which could be representative of a microburst or of any other atmospheric phenomenon. $\sigma_i$ are the gust intensities which could be associated with a microburst or other phenomenon and can be deduced from Doppler radar second-moment data. Mark [14] shows several turbulent traces that are modeled well by equation (8). $\overline{U}_i$ and $\sigma_i$ are relatively slowly varying functions compared to $w_i$. Other examples showing equation (8) type behavior are presented in Reference 12. $\overline{U}_i$ and $\sigma_i$ can be provided by many sources, including aircraft measurements or analytical or numerical models.

Multiple Doppler can provide $\overline{U}_i$ directly; but, if only single Doppler radar is available, creation of a reasonable model is still possible. Doppler radar measures only the radial velocity component, but an RHI (vertical) scan through the microburst center or a volume scan of the microburst can provide center plane velocities. The assumption that $U_i$ and $\sigma_i$ are axially symmetric about the microburst center is not unreasonable. Rotation of $\overline{U}_i$ and $\sigma_i$ about a vertical axis through the center of the microburst defines $\overline{U}_i$ and $\sigma_i$ throughout the simulation volume.

In this section it was shown that $\overline{U}_i$ and $\sigma_i$ of equation (8) could represent a variety of atmospheric phenomena. These functions can be provided by Doppler radar or by many other sources. The only other term left undefined in equation (8) is the frozen turbulence term $w_i$ (x,y,z). This function will come from a large data base which is stored in a random access mass storage file. A discussion of the data base generation concept is the topic of the next section.

## GENERATION OF THE FROZEN TURBULENCE DATA BASE

Creation of a data base of simulated, frozen turbulence will probably be the most difficult and time-consuming task in the creation of the proposed model. Simple in concept, in practice several technical issues must be resolved.

The size of the data base may present a problem. Consider the case of an aircraft attempting to land in the vicinity of a microburst contained within a volume 5120 m across. Suppose that a high-resolution simulation is required; i.e., $\Delta x = \Delta y = \Delta z = 10$ m. Since a microburst poses a serious hazard only when encountered at low altitudes, the depth of the volume can be limited to 320 m. Figure 2 illustrates the simulation volume. These numbers indicate that turbulence must be simulated at 512 x 512 x 36 or 8,388,608 grid points. At each grid point three components of velocity must be simulated, which means that 25 million numbers would reside in this data base. If each number consists of 4 bytes (8 bits each), 100 megabytes must be stored; 100 megabytes is a large amount of data but even minicomputers have individual disc units capable of storing more than 100 megabytes. The reason for having a 512 x 512 x 32 grid is that Fast Fourier Transform (FFT) routines are more efficient on arrays of n numbers where n is a power of 2.

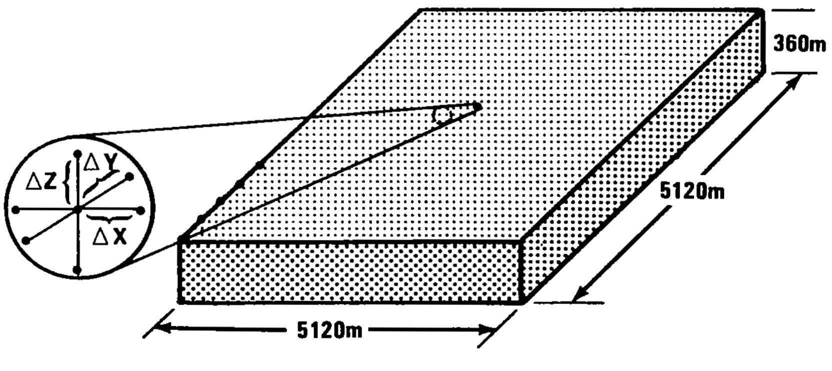



Figure 2. Simulation volume for a microburst.

The numbers mentioned in the previous paragraph are large, but, in recent years, the cost of mass storage has dropped dramatically; and, with bubble memory and other technological advances on the horizon, it is not unreasonable to expect that soon microcomputers will be able to handle a data base this size. A technique for significantly reducing the size of the data base is discussed in a later section.

Generation of the frozen turbulence is simple in concept but in practice is not so simple. The basic idea is similar to that depicted in Figure 1, except that instead of one-dimensional filter functions, three-dimensional functions are used. A set of three independent, normally-distributed random numbers is generated at each grid point. Generation of these random numbers is quite efficient using the method of Box and Muller [16]. Howell and Rheinfurth [17] show that the generation of 1000 random numbers by the method of Box and Muller requires about 1 sec on an unspecified computer. At that rate generation of 25 million values would require 7 hr. On low-cost minicomputers, 7 hr of computation time is not unreasonable.

Once generated, the numbers must be transformed to the wave number domain. The transformation can be accomplished independently for each velocity component. Another problem is that many FFT routines require that all arrays to be transformed be stored in central memory. Fortunately, FFT routines exist that permit blockwise computation of multidimensional data in mass storage [18].

Once the Gaussian white noise is transformed, it is multiplied point by point by three-dimensional filter functions such as the square root of the power spectra defined by equation (3). Another consideration is that the filter functions are continuous filters, whereas the data is digital. Several techniques exist for converting analog filters to digital filters [19]. Care must be taken in the conversion so that aliasing does not occur. Reference 19 describes several methods of conversion including impulse invariance and step invariance. This means that the discrete filter is created so that either the discrete impulse or step response of the digital filter looks like a sample of the continuous impulse or step response of the analog filter. For the desired filters, autocorrelation invariance is desirable. Conversion of the three-dimensional analog filters to corresponding three-dimensional digital filters is a necessary step in the creation of the proposed model.

Once the multiplication is complete, the filtered noise must be transformed back to the space domain; and, if done properly, the result is the desired data base. Fourier transforming back and forth may not be necessary if three-dimensional recursive filters can be developed. For the one-dimensional Dryden spectra, recursive filters significantly reduce the computational effort involved in simulating turbulence.

The procedure described above is time consuming, and some technical issues must be resolved; but, once the frozen turbulence data base is created, regeneration should not be necessary.

At this point, some final comments which may help avoid unnecessary problems are in order. Disc drives are referred to as random access mass storage, but this reference is to each file and not necessarily to data within a file. For example, access to the beginning of a file named DATA may take a millisecond, but access to the one-millionth number in DATA may take seconds. The slow access to the one-millionth number is a result of the fact that the computer must read through 999,999 numbers before it reaches the desired value, because the file DATA was formatted as a sequential access file. Most computers allow either sequential or random access to disc files. On the Hewlett-Packard (HP) 1000 series computers with Real Time Executive (RTE IV) operation systems [20], random access files must have a fixed record length. Sequential access to files would slow the proposed model down to unacceptable levels, so the data base must be stored in random access files.

The data storage must be in unformatted form. Formatted data in many computers such as the HP 1000 series are stored in ASCII format which requires 8 bits per character. ASCII data storage is extremely wasteful of memory. On the other hand, it is useful for data portability. For the previously described data base, the data should be stored in binary or unformatted form. While unformatted data storage creates portability problems from one computer to another because of differing word lengths or differing internal number representation (e.g., binary as opposed to BCD), steps can be taken to minimize the problem.

Another concern is the periodicity in random number generators. Some of the widely accepted random number generators are recursive so that the nth random number generated in a sequence depends only on the n-1st number. If random number n is the same as previously generated random number i, then random number n+1 is the same as number i+1, and the sequence repeats. Investigators design random number generators so that the period is as long as possible. Theoretically, the longest possible period for this type of generator is only as long as the number of different numbers (without consideration of the exponent) that can be represented by the computer. For the HP 1000 series computers, single precision real numbers are stored in 32 bits. Of the 32 bits, 23 are dedicated to the fractional part of the number, while the remaining bits determine the sign of the number, its exponent, and the sign of the exponent. The maximum length of the period is then $2^{23}$ or 8,388,608. If 25 million numbers are to be generated, even with a good random number generator, some repetition is to be expected. On the HP 1000 series computer, more than 1600 million random numbers were generated without a match with the first number generated. The random number generator on the HP computer uses a multiplicative congruence method with asynchronous register shift to achieve long periods and assure that periodicities do not affect simulation results.

The size of the data base can be reduced by several means. To understand how this might be done consider the previous microburst example. Frozen turbulence might be generated for only half of the desired simulation volume. In the simulation, the aircraft enters one side of the simulation volume. At the center of the simulated microburst, the plane would reach a point where it leaves the available simulation volume. Conceptually, the path of the plane could be reflected back into the simulation volume. In real space, this amounts to shifting the block of frozen turbulence each time the plane begins to leave so that it is always entering the available block. Shifting the frozen turbulence around brings to mind a little boy letting a caterpillar crawl on his hands. Each time the caterpillar hangs over the edge of a hand the boy obligingly offers his other hand. After some time the caterpillar thinks that he is going places; but, in fact, he is only retracing his steps. The caterpillar gets his exercise and the little boy has the pleasure of the caterpillar's company.

For the caterpillar model, the block of frozen turbulence can be considerably smaller than half a microburst in size. While the block is periodically shifted, the mean and standard deviation are not so that only the rapidly varying turbulence component is repeated. The final result is that the caterpillar model allows the use of a much smaller data base. By the technique of block shifting, the entire data base could be held in the central memory of some computers. A very significant advantage of the caterpillar model is that simulations of any extent in the atmosphere can be done. In theory, a flight around the world could be simulated.

## SUMMARY OF THE PROPOSED SIMULATION CONCEPT

Figure 3 summarizes flight simulation with the proposed model. Block 1 in the diagram represents the frozen turbulence data base. Block 2 contains the positive definite function representing the temporally and spatially varying rms gust intensity. Block 3 represents the mean winds. The specific atmospheric phenomenon simulated is determined by blocks 2 and 3 containing $\overline{U}_i$ and $\sigma_i$. These blocks may represent data bases or numerical or analytical models.

In Figure 3 the proposed Monte Carlo wind simulation model is contained within the dashed-line box. Block 4 represents a model of any aerospace vehicle. The feedback loop for vehicle position shown in the figure is important because it will probably enable the use of the proposed model by flight simulators. Calculation of forces and moments on the aircraft only requires the winds in the immediate vicinity of the aircraft. With the feedback loop, the turbulence model will "know" the aircraft location and supply only winds at surrounding grid points at each time step. From this information, the winds over the body of the vehicle are known, and aerodynamic loads and moments can be calculated.

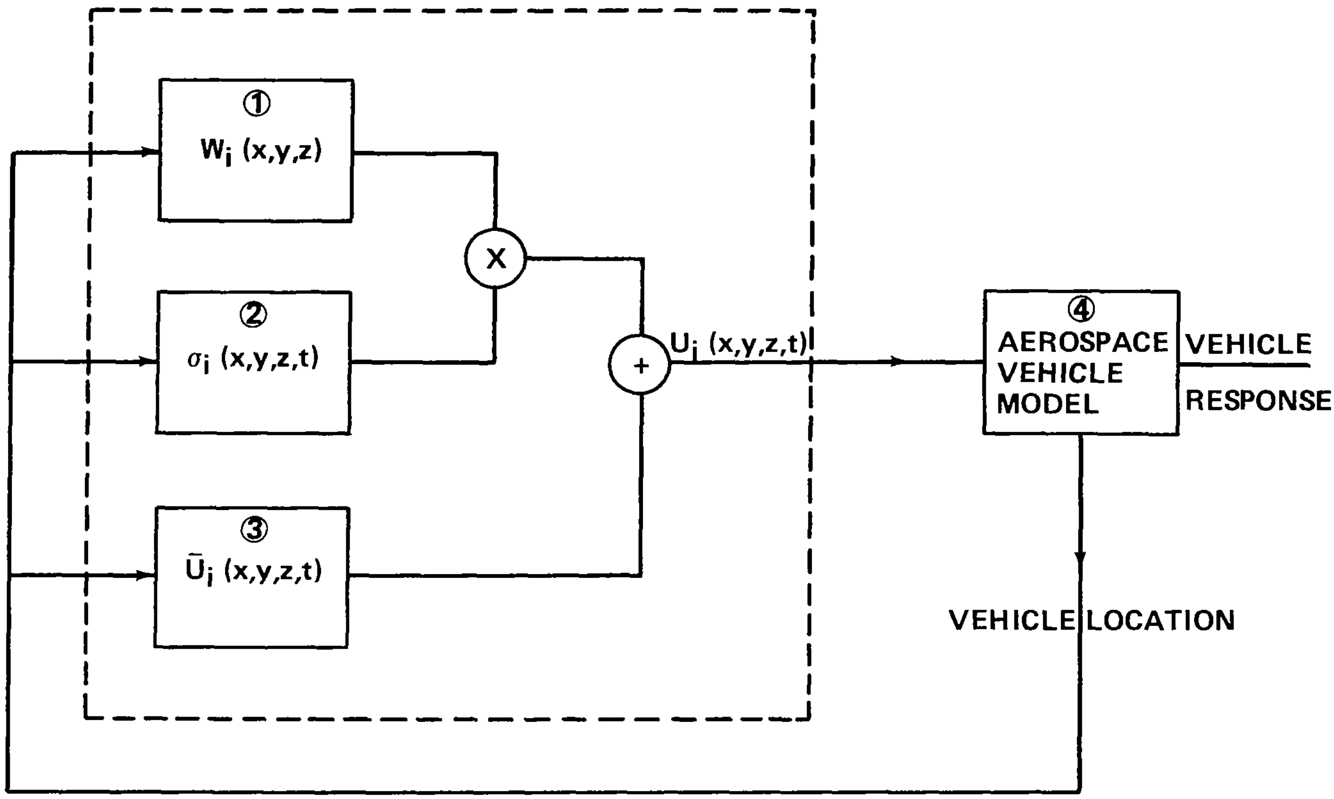



Figure 3. Aerospace vehicle flight simulation.

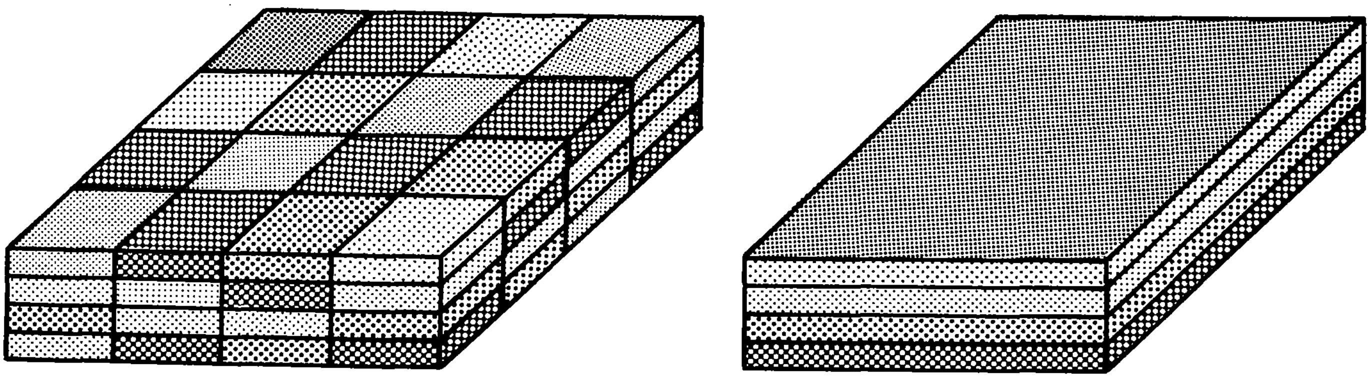
Finally it should be mentioned that the resulting winds are non-Gaussian even without the mean values added. As is pointed out by Reeves and others in References 3 and 4, atmospheric turbulence is non-Gaussian, and the non-normal behavior of the simulation is considered an advantage rather than a disadvantage. With the mean winds added, the wind simulation will be extremely non-Gaussian with possibly more than one mode. Reference 12 presents data with roughly bimodal probability densities.

## POSSIBLE CONCEPT REFINEMENTS

For simplicity, the proposed concept was described in terms of a grid fixed in real space with equal grid spacing $\Delta x = \Delta y = \Delta z$. In addition, dimensional filter functions were described. While the model permits the realistic variation of turbulent intensity, the length scales of turbulence are constant. References 2 and 5 describe the generation of nondimensional turbulence. To perform simulations, simple scaling multiplications are made, and the result is dimensional turbulence. Nondimensionalizing the data base may be possible so that grid spacing is uniform in dimensionless space but varies in nondimensional space. Nondimensionalizing the data base may permit turbulent length scale variation in dimensional space. While useful simulations can be performed with nonvarying representative values of turbulent length scales, variation of the length scales would certainly improve realism.

Nondimensionalization could be used in conjunction with the caterpillar model. The grid spacing would be uniform in the shifting block which would be defined in nondimensional space. At each shift of the block, the nondimensional turbulence could be dimensionalized with different length scales. In effect, the physical size of the block and its two aspect ratios would change with each shift.

If the data base cannot be nondimensionalized, another idea offers an attractive alternative. This idea will be referred to as the concrete block model. Briefly, the data base would be formed block by block and then stacked together in the form of a concrete wall. Figure 4a depicts the concrete block model. Each block would have different values of the turbulent length scales as is represented by the different shadings in the figure. The concrete model has the advantage that each block could be created piece by piece. If simulation over a larger volume is required, generation of a larger data base is not necessary. All that is required is that more blocks be constructed and added to the appropriate part of the simulation volume.



a. CONCRETE BLOCK MODEL

b. CONCRETE SLAB MODEL

Figure 4. Frozen turbulence data base models.

A slightly simpler alternative to the concrete block model will be referred to as the concrete slab model and is depicted in Figure 4b. Instead of blocks, large horizontal slabs would be stacked to create the volume. The slab model would account for the pronounced vertical variation of turbulent length scales.

One possible criticism of block or slab models concerns the abrupt change in turbulent characteristics across the interface between the blocks and slabs. This is not believed to be a major problem. The variation across contiguous blocks is smoothed by the physical size of the aircraft. While one part of the vehicle experiences turbulence in one block, the other part of the aircraft feels turbulence in the adjoining block. The response of the aircraft is smoothed by its physical size. While the aircraft would not respond to the high-frequency components at a single interface, the repeated change across a sequence of interfaces could conceivably excite vehicle resonant frequencies such as the phugoid oscillation. This possibility should be tested; and, if it does pose a problem, then the blocks could be created in different sizes to avoid a particular resonant frequency.

Block and slab models are not totally without precedent. Tatom and others [5] used a one-dimensional equivalent for a turbulence simulation model.

## CONCLUSIONS

A concept was formulated which provides a framework for utilizing JAWS and other Doppler radar data for realistic flight simulation. Because the simulation is done over a three-dimensional volume in the atmosphere, any maneuver a pilot in a flight simulator might make would not lessen the realism of the simulation as long as he did not fly out of the simulation volume.

Although this paper dealt with the use of data from JAWS for flight simulation, the model is quite general and can accept data from many sources. For any atmospheric situation for which spatially and temporally varying means and gust standard deviations are known, the proposed model can be used to simulate flight in the phenomenon. As an example, the model is general enough to simulate reentry and flight in the terrestrial or planetary atmospheres.

Procedures for generating the frozen turbulence data base were discussed. Generation of this data base is the only major obstacle to the creation of the proposed technique.

The speed of the model should be such that flight simulators could use it for pilot training. The speed is achieved because at each time step, only the winds in the immediate vicinity of the aircraft position are required.

Finally, some possible model refinements were suggested. These included nondimensionalization of the frozen turbulence data base to permit smooth variation of the length scales of turbulence. A possibility of a simpler nondimensionalization performed in conjunction with the caterpillar model offered the possibility of varying turbulent length scales while at the same time making a large reduction in the size of the data base. Other possibilities offered some advantages over nondimensionalization. These were the concrete block and slab models which permit construction of the large data base in independent pieces. With block or slab models, expansion of the data base after the initial generation would not require complete regeneration of the larger data base. Instead, independent blocks and slabs would be generated and simply added to the existing data base.

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16. ABSTRACT

A concept is presented which will permit turbulence simulation in the vicinity of microbursts. The method involves a large data base, but should be fast enough for use with flight simulators. The model will permit any pilot to simulate any flight maneuver in any aircraft. The model will simulate a wind field with three-component mean winds and three-component turbulent gusts, and gust variation over the body of an aircraft so that all aerodynamic loads and moments can be calculated. The time and space variation of mean winds and turbulent intensities associated with a particular atmospheric phenomenon such as a microburst is used in the model. In fact, Doppler radar data such as provided by JAWS is uniquely suited for use with the proposed model. The concept is completely general and is not restricted to microburst studies. Reentry and flight in terrestrial or planetary atmospheres could be realistically simulated if supporting data of sufficient resolution were available.

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