b) Secondly, that we stop catering to users, because we should leave it to the user to take whatever is available for his personal needs. As a practical example, instead of catering to general aviation, military aviation, or airlines, we are confining ourselves to low, mid- and high-level information, then the user takes whatever he gets from a common data bank.

"THE ELEVENTH MOST SIGNIFICANT EQUATION"

John Houbolt

My impromptu remark deals with some commemorative stamps that were issued a few years ago listing the ten most significant equations of mankind. I don't mean equations to be solved, but equations that state physical reality or physical consequence. Now, somewhat with tongue in cheek, I would like to add the eleventh equation. The substance of the ten most significant equations were these elementary looking equations like $F = ma$; $E = mc^2$ and the like. In the past year, I have been continuing some studies on the response of aircraft in continuous random turbulence, and have come up with a very remarkable result. It is in remarkably simple form and seems to be quite general in nature. This equation is shown as follows:

$$\sigma = \frac{\sigma_1}{\sqrt{\alpha}}$$

To what I can see, the equation is simply stated and applies to all aircraft. The root mean square of vertical acceleration, σ, is equal to a turbulence term, σ_1, divided by the square root of the angle of attack, α, necessary to maintain level flight, and that is all it is. You do not have to include the weight of the airplane, the altitude of flight, the velocity of flight, as it is all inclusive in this one equation. Now, I should make a comment about σ_1. It is actually a combination term that involves the turbulence intensity and the turbulence scale, but it is directly deducible from turbulence data, as a combined form; and you do not have to separate out the intensity and the scale length. It is a natural combined form of the two parameters, directly deducible form turbulence data. So, I submit this as a perfectly general equation which gives you the response of airplanes to turbulence. I won't tell you at the moment how we derived it. I am in the process of writing a paper now to be given at Reno next January; and, at that meeting, if you are interested in how it is derived, I will be presenting it there. Thank you!

"A MODEL OF A DOWNBURST;" A WIND TUNNEL PROGRAM ON PLANETARY BOUNDARY LAYER;" and "AIRSHIP IN TURBULENCE."

Bernard Etkin

Ladies and Gentlemen, before I start describing to you the model of a downburst that we have recently generated, may I, since there is time, philosophize for a moment about the role of analytical models in what we are talking about at this workshop. The meteorologist, of course, has to go out and try to discover what the world is really like, such as drop size distribution; or in the JAWS Program to find the real velocity field in a real microburst. However, what the aeronautical engineering profession needs is something a little different - it needs "engineering models". We need an engineering model of turbulence at high altitude; we need an engineering model of the planetary boundary layer; we need an engineering model of microbursts. What these models must all have in common is that, firstly, they reflect reasonably well the reality of the physics. Secondly, that they have parameters in them that you can vary to adjust the models to suit various circumstances. Last but not least, they must be reasonably easy to use. With that philosophy in mind, I thought that we might be able to make a model of the microburst, or downburst that would be useful.

You have seen a number of diagrams like Figure 1 during this meeting. When you look at it, what you see, (in fact, what Dr. Frost produced in his experiment) is a vertical jet blowing against a plane surface. Well, that did not

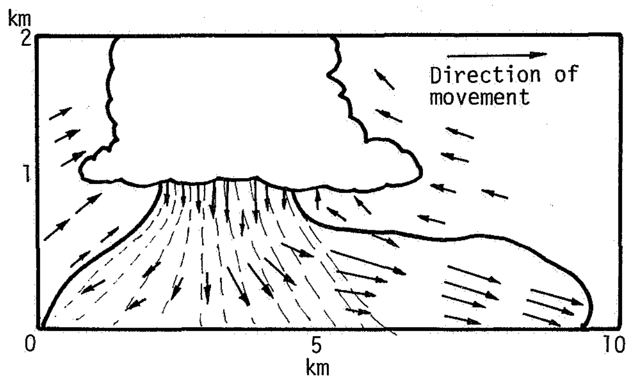

Figure 1a. Section through a thunderstorm in the mature stage

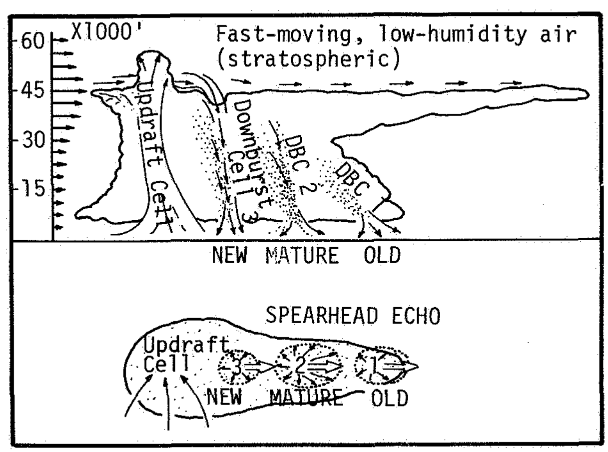

Figure 1b. Imbedded microburst storm characteristics

seem difficult to model. I thought we might try a set of doublets, a doublet surface, or perhaps ring vortices distributed in various ways to produce a flow field that looks somewhat like the downburst. Well, after a few trials, we settled on the one illustrated in Figure 2. What we have here is a circular sheet of doublets that occupies the zone A-A; and, of course, to produce symmetry about the ground plane, there is an image set down below. The figure shows streamline patterns created by such a circular doublet sheet. It

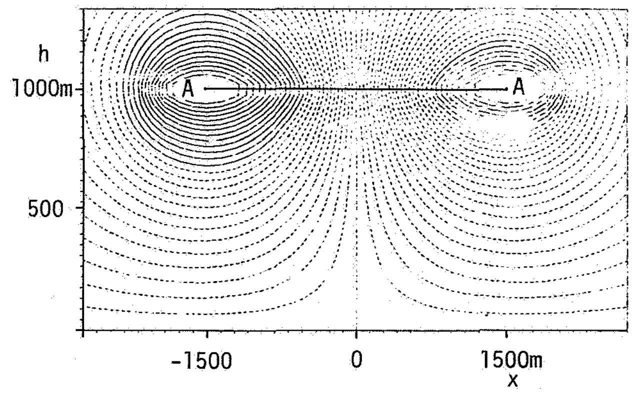

Figure 2. A typical microburst generated by a doublet sheet with cosine intensity distribution

is not a uniform-strength sheet; it has a cosine distribution of intensity. We looked at both uniform and cosine distributions. Figure 3 shows the horizontal wind, W_l, and the vertical wind, W_3, along a vertical plane through the center of the system. This figure demonstrates the main char-

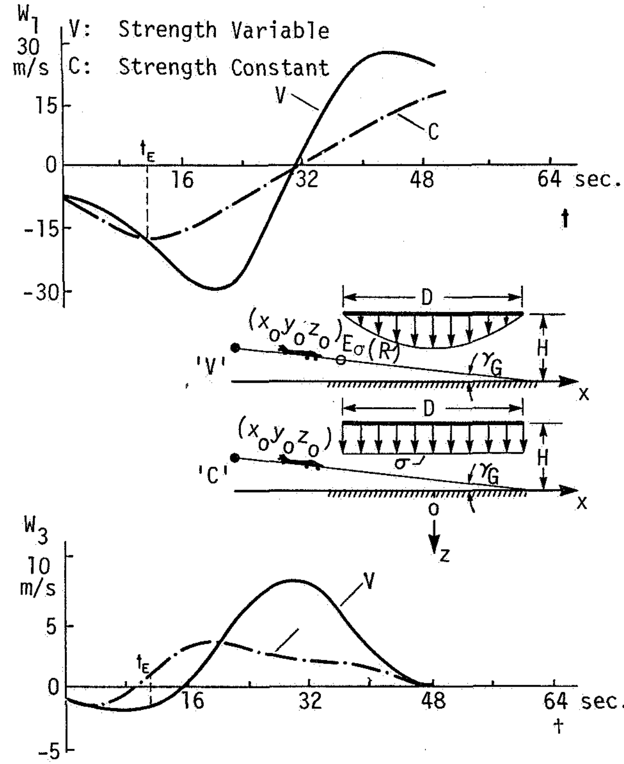

Figure 3. Comparison of 3-D model for different strength distributions:

$\sigma^V_{max} = 100$; $\sigma^C = 93.6$ ($x_0 = 2316$m;

$h_0 = 200$m; $y_0 = 0$; $D/H = 3$;

$D = 3000$m; $\gamma_G = -3°$. Comparison condition: W_1 =18.24 m/s at 'E') acteristics of the downburst. An airplane flying down the glide slope in the sketch initially experiences a head wind that later changes to a tail wind, with a fairly strong gradient. W_3 shows first an upwind, then a downwind, fairly strong to begin with, and then tapering off. One gets slightly different answers if one goes through the field horizontally. Furthermore, with this model, you can just as easily choose a track that does not go through the center, but off to one side, so that you get side wing and gradients in all three directions, simultaneously. The equations that describe such a flow field are quite simple and easy to implement for either a machine computation of flight paths or in real-time on a simulator to give pilots the exercise of flying through a microburst. You can easily change the height at which you put the doublet sheet; you can change its diameter; you can change its strength; and, if you want to, you can play games with the distribution. We ran a couple of exercises of flight through our model using a commercial jet transport (Figures 4 and 5). With fixed controls, the downburst can be seen to be quite severe. On the other hand, with an automatic control system that is tracking the glide slope, the latter is followed quite closely down to the height where a transition would occur. This is a relatively straightforward system operating on height error. That is project number one that I wanted to tell you about.

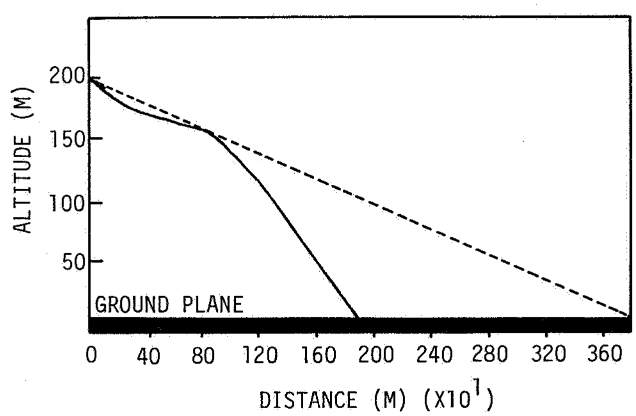

Figure 4. Response to microburst: Controls-fixed; $_G$ = -3°; x_{TD} = D/2; y = 0; h_o = 200m (Flight Path)

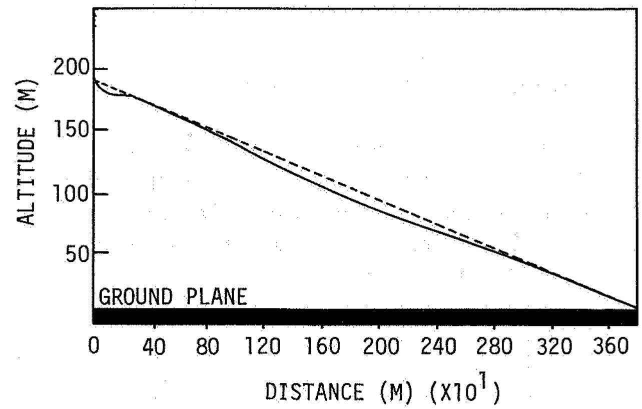

Figure 5. Response to microburst: Automatic Landing; $_G$ = -3°; x_{TD} = D/2; y = 0; h_o = 200m (Flight Path)

The second project is a study of the landing or takeoff through the planetary boundary layer. To study this problem, we started about ten years ago with the development of a planetary-boundary-layer wind tunnel in which to simulate the shear and turbulence that exists in this situation. We, then make the necessary measurements of the appropriate time-delayed cross correlations down the glide slope, including the gradient terms (rolling gusts, pitching gusts) as well as the U, V and W gust terms. The facility itself is pictured in Figure 6. We have at the upstream end, a grid of jets in eight rows which can be individually controlled row by row and in sets of three across any row, in order to generate the desired velocity profile. We have been working essentially with power-law profiles, but you could use something different. We need a barrier and roughness on the floor in order to get turbulence intensities reasonably simulating those in the atmosphere. Figure 7 shows one particular set of measurements we have made and which have been published recently in one of our reports. It is an example of the time-delayed cross-correlation between the lateral (side) component of wind velocity at two points on the glide slope. In this particular set of experiments, hotwire anemometers were used in pairs, so it was like the NASA B-57 measuring gradients in the air. We had the equivalent measurements at two points that represent the wing tips and we were measuring cross-correlations between data at one point on the glide slope and at a lower point, time-delayed by the interval it takes the airplane to go from the upper point to the lower point. This is only one example out of many correlations. The $(\beta - \alpha)'$ seconds at the bottom is the time-delay.

We have measured the correlations of the various gust gradients, as well as individual velocities.

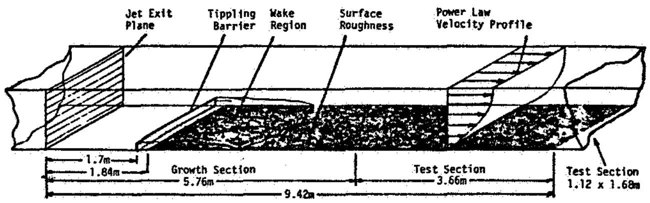

Figure 6. Boundary layer wind tunnel configuration

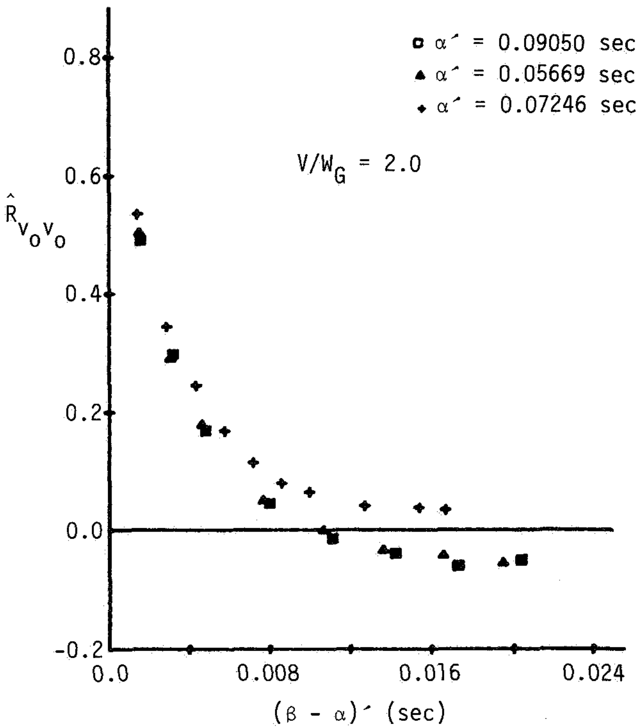

Figure 7. Flight path turbulence correlation-- $\hat{R}_{v_o v_o}$

Figure 8 shows the computed RMS response during the descent. Y_I is the lateral dispersion in an inertial frame of references and the results are for a STOL airplane descending through the boundary layer using the wind tunnel data as inputs, scaled to full scale. The RMS value is of an ensemble of flights. The figure shows how this RMS dispersion increases with distance as you come down from the starting point to the ground. The various curves show what happens when you simplify the calculation by leaving something out in the driving matrix of the system. It turns out that the biggest term is the rolling gust term Pg. If you tried to solve that problem just using side gust alone, you would not get any reasonable answer at all.

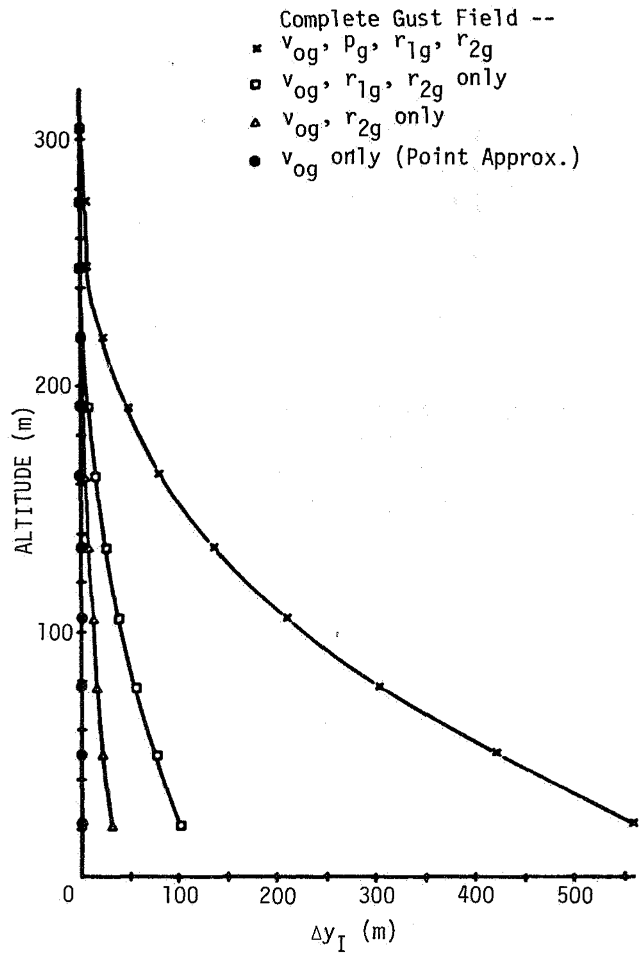

Figure 8. Aircraft RMS response -- Δy_I

I turn now to the third project, an airship in turbulence. Figure 9 shows the same wind tunnel again but set up a little differently to study a somewhat different problem. The setup here uses the grid of jets all blowing uniformly to produce an essentially constant field, and a very coarse turbulence grid to produce quasi-isotropic large-scale intense turbulence at the location of the model, which, in this case, is an airship. The aim of this investigation was to find whether the most commonly used theory for the turbulence-induced forces on a body like an airship was any good. That theory is the "slender-body/strip theory". I suspected that it wasn't much good. There doesn't exist in the literature any really good data for use in comparison, so we undertook this experiment. The model was instrumented so that it had two degrees of freedom, heave and pitch. We have two force sensors on it measuring the aerodynamic load at two positions so that through calibrations we can deduce the lift and pitching moment, which would be the same, if you rotate the system 90^0, as side

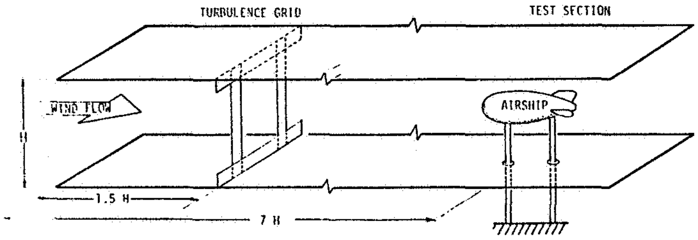

Figure 9. Wind tunnel layout for airship study

force and yawing moment, because it is axially symmetric. The main result we got is shown in Figure 10. Plotted are the transfer function from up-gust to normal force and from up-gust to pitching moment. Also shown are the corresponding predictions of the slender-body theory, and they are quite different. So, as a quantitative means of finding out what the hull contributes, the slender-body theory is certainly inadequate. We almost didn't do the experiment with fins. I told the student doing the experiment that we knew what the

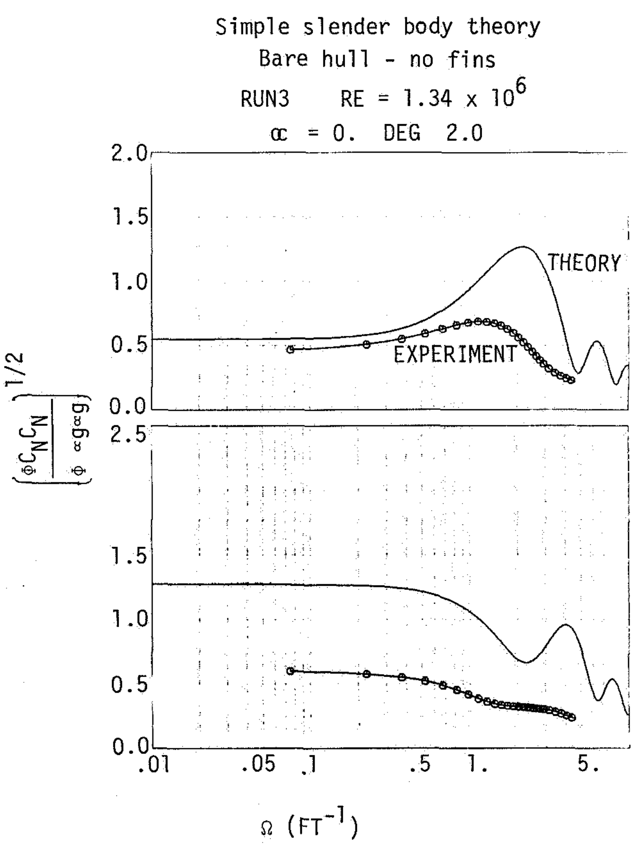

Figure 10. Experimental results vs. simulation

fins were going to do. They are just some little airfoils at the back and we can calculate that, so why should we bother to do it? The real question was the hull. It turns out that the most interesting result we got was after we put the fins on! (Figure 11)

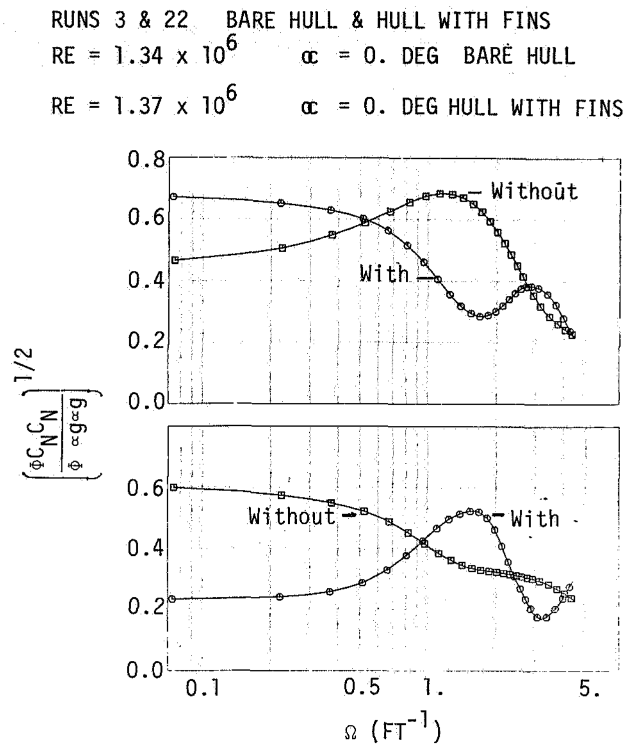

Figure 11. System gust response comparison

Figure 11 shows the transfer functions with and without fins. Now, it is perfectly obvious that at zero frequency or wave number, you have the steady state case, and adding fins must add lift. Indeed, this is what we see. However, as the frequency goes up, the effect of the fins is to diminish the lift! The maximum reduction occurs at a wavelength about twice the hull length.

With the pitching moment, we get the opposite result—when you add fins, it reduces the low-frequency value; at higher wave numbers, it goes up above the value without fins. Although the slender-body theory was quite inadequate to predict quantitatively the transfer functions of lift and moment, nevertheless, if it is used to compute the phase angle between the hull lift and the fin lift, it turns out that it explains this peculiar behavior very well.

That concludes my presentations of these three projects. We have done some others that relate to automatic control of vehicles on landing, and our conclusion reinforces what has already been said at this workshop - i.e. that where a microburst is concerned, or, indeed, a strong wind shear of any kind, an automatic pilot will do the right thing in terms of pitch attitude; whereas a human pilot may well be inclined to do the wrong thing, such as putting the nose down when it should come back up. What is fundamental to this is that when landing at an approach speed of 1.3 V_s, there is a 69% lift margin available. Consequently, when there is a loss of air speed, so long as you are still safely below stalling angle of attack, the correct thing to do is to pull the wheel back and compensate with additional angle of attack for the loss in lift associated with the loss in air speed. Automatic controls have no trouble doing that as you saw in Figure 1.

We did a similar study of an automatic abort system that had no trouble carrying out aborts through very strong wind shears, that included both downdrafts and horizontal shears.

Thank you for your kind attention.

GENERAL DISCUSSION SUBSEQUENT TO IMPROMPTU PRESENTATIONS

QUESTION FROM THE FLOOR:
Dr. Etkin, could you please explain the relationship of NASA's Gust Gradient Program with that of Canada's study?

ANSWER: DR. BERNARD ETKIN
As a matter of fact, I only learned about the NASA work a couple of days ago when I read the report of last year's meeting here and found that somebody had made a report on it here. There has not been an opportunity to make a comparison yet; but our data implicitly contains some things that were measured in the NASA Program. So, when we see your report and you see our report, somebody can see if the numbers come out the same. I would guess that they do. Just let me say this, because I think it is significant. The work that I reported today on this gradient data was done a couple of years ago and it was published in the Journal of Aircraft in a paper by Dr. Lloyd Reid, one of my colleagues. What Dr. Reid found, and I think this is a very important finding that somehow has been overlooked by the aeronautical engineering community, is you can use the von Karman model of turbulence in the planetary boundary layer with reasonable accuracy for these landing and takeoff problems providing you make a few empirical adjustments in choosing the correct intermediate value of L and sigma that relates to the upper and lower points. The student who did the work that I reported here intends to carry on and look at gradients and see if they fit the von Karman model. My guess is that they will probably be very close, and that the ones measured in flight by NASA will be, too.

COMMENT: DR. FROST
We have found in analyzing the NASA B-57 data for flying both near thunderstorms and doing touch-and-go's, (i.e., boundary layer turbulence) that the von Karman is generally valid. We have also looked at the data from the array of towers at NASA/MSFC; in that case, if you get too close to the ground (that is about 70 feet), you begin to get into some trouble using von Karman. However, around the top of the towers, von Karman looks pretty good.

QUESTION: K. H. HUANG, FWG ASSOCIATES, INC.
Dr. Etkin, which control laws did you use when you simulated airplane trajectory flying through your doublet wind shear?

ANSWER: DR. BERNARD ETKIN
The automatic control law used in flight through the microburst is given in detail in the report. I do not recall the exact details, but if you see me afterwards, we can look it up. I do not recall the exact algorithm we used, but I can show it to you. It basically operates on height and speed error and tracks the glide slope.

QUESTION: DR. FROST
Is it ground speed control or air speed control?

ANSWER: DR. ETKIN
It uses airspeed feedback.