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Development of a Scale Model Parachute Wind Sensor

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A scale model parachute GPS wind sensor is to be designed that will follow the same trajectory as that of a full size PAD payload. This will allow the wind field to be measured where it is most needed, along the descent path of the payload. In actual operation the scale model sensor would be released shortly before the payload, the wind field calculated in real time during descent, and used in the CARP algorithm to calculate the payload release point. In order for the scale model parachute system to follow the same trajectory as the full size payload system several scaling parameters must be analyzed. A necessary condition that the airflow around scale model system. Since the flow around an object depends upon Reynolds and mach numbers, a change in these parameters could cause the airflow to change and thus the drag coefficients to change between the scale model and full size systems. The mach number will remain the same for the two systems because the systems are designed to maintain the same trajectory. The Reynolds Number however, will be necessity vary because of the difference in the dimensions of the two systems. Thus it must be established whether the variation in Reynolds number over the range that occurs between the full and scaled systems significantly changes the drag coefficient of the systems. Other parameters that may change the relative airflow between the two systems are the porosity of the parachute fabric, the mass of each systems, the length of the tether lines, and the size air passage opening in the center of each parachute. Each of these parameters is addressed in the following analyses.

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Development of Scale Model Parachute Wind Sensor
Progress Report

James K. Luers (UDRI)

A scale model parachute GPS wind sensor is to be designed that will follow the same trajectory as that of a full size PAD payload. This will allow the wind field to be measured where it is most needed, along the descent path of the payload. In actual operation the scale model sensor would be released shortly before the payload, the wind field calculated in real time during descent, and used in the CARP algorithm to calculate the payload release point.

In order for the scale model parachute system to follow the same trajectory as the full size payload system several scaling parameters must be analyzed. A necessary condition that the airflow around scale model and full size systems be similar, is that the geometry of the two systems be proportional. That is; the full size system can be thought of as a photographic enlargement of the scale model system Since the flow around an object depends upon Reynolds and mach numbers, a change in these parameters could cause the airflow to change and thus the drag coefficients to change between the scale model and full size systems. The mach number will remain the same for the two systems because the systems are designed to maintain the same trajectory. The Reynolds Number however, will by necessity vary because of the difference in the dimensions of the two systems. Thus it must be established whether the variation in Reynolds Number over the range that occurs between the full and scaled systems significantly changes the drag coefficient of the systems. Other parameters that may change the relative airflow between the two systems are the porosity of the parachute fabric, the mass of each systems, the length of the tether lines, and the size air passage opening in the center of each parachute. Each of these parameters is addressed in the following analyses.

Reynolds Number:

The Reynolds Number is defined as:

$$Rey = \rho V d / \mu$$

where

ρ = atmospheric density
V = velocity relative to the air
d = reference dimension of the object
μ = viscosity of the air

For the C-9 system typical values of V and d are

V = 8 m/sec at 25,000 ft
V = 7 m/sec at surface
d = 8 meters

Consider two potential diameters for the scale model

d = 1 meter
d = 0.5 meters

The Reynolds Number for each system, evaluated at 25,000 ft, and the surface is;

C-9 (8 meters)

Rey = 2.2×10^6 at 25,000 ft
Rey = 3.8×10^6 at the surface

Scale Model (1 meter)

Rey = 2.8×10^5 at 25,000 ft
Rey = 4.8×10^5 at the surface

Scale Model (0.5 meters)

Rey = 1.4×10^5 at 25,000 ft
Rey = 2.4×10^5 at the surface

The graph of drag coefficient Vs Reynolds No. from Knacke, for a circular flat canopy (C-9) is shown in Figure 1. The drag coefficient is essentially constant for Reynolds numbers greater than about 2.0×10^5. Thus C_D can be considered constant for the 8 m, 1 m, and 0.5 m (sea level) flat circular Parachutes. At altitudes above perhaps 20000 ft the drag Coefficient of the 0.5 m parachute begins to decrease due to Reynolds Number. A geometrically similar scale model (1 meter) parachute, falling at the same mach number as the full size system should not experience any change in drag coefficient (or descent velocity) due to being at a different Reynolds Number than the full size system. For a 0.5 meter parachute a slight change in fall velocity is expected to occur at the higher altitudes due to Reynolds number. This change will increase the fall velocity (via decrease in C_D) in the range of 5% to 10%. To compensate for the Reynolds number effect the Reference Area of the scale model system could be increased by the same percentage as is the decrease in drag coefficient. This is valid because the drag force contains the product of C_D and reference area A.

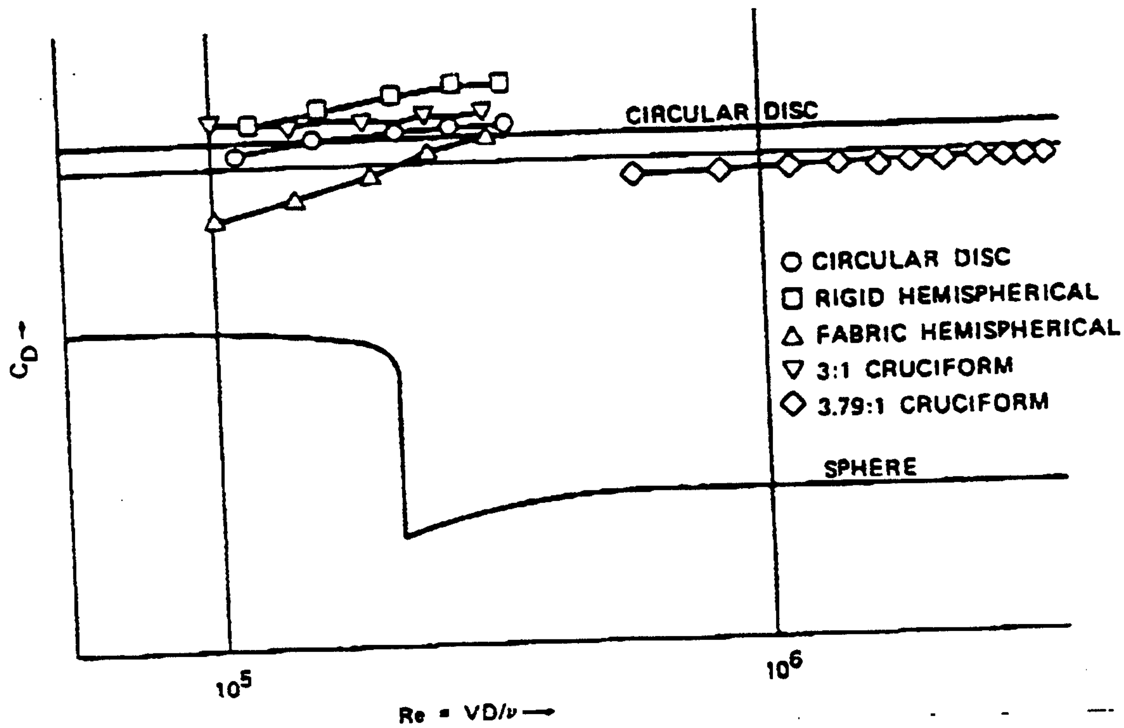

Figure 1; Drag Coefficient as a function of Reynolds Number for a Flat Circular Canopy (from Knacke)

<u>Diameter of Scale Model Parachute</u>

The equations of motion in two dimensions for a parachute, considered as a point mass is given by;

Full Size

$$m\ddot{Z} = 0.5\rho C_{Dz} A_z V\dot{Z} - mg \qquad \text{vertical}$$

$$m\ddot{X} = 0.5\rho C_{Dx} A_x V(\dot{X} - W_x) \qquad \text{horizontal} \qquad (1)$$

Scale Model

$$m^*\ddot{Z} = 0.5\rho C_{Dz} A_z{}^* V\dot{Z} - m^* g$$

$$m^*\ddot{X} = 0.5\rho C_{Dx} A_x{}^* V(\dot{X} - W_x)$$

where;

$m.m^*$ = mass of full-size and Scale model systems respectively
$\dot{Z},\ddot{Z}$ = vertical velocity and acceleration
$\dot{X},\ddot{X}$ = horizontal velocity and acceleration
W_x = horizontal wind speed
g = gravitational acceleration

$$V = \left((\dot{X} - W_x)^2 + (\dot{Y} - W_y)^2 + \dot{Z}^2\right)^{1/2}$$

The full size and scale parachute systems will follow the same trajectory if their horizontal and vertical acceleration profiles are identical. Thus the left size of each equation is divided by mass, and the right sides of the respective component equations are set equal. Because of geometric similarity in shape and Reynolds number, the full and scale systems have the same component drag coefficients. Thus an equality condition exists if :

$$A/m = A^*/m^*.$$

That is; the scale model will follow the same trajectory as the full size if the two systems have the same area to mass ratio.

It should be noted that the above equation represent the parachute /payload system as a point mass. This is a first order approximation to a system which contains motion and angle of attack between the payload and parachute. Nevertheless this simplified approximation is reasonable for design of a scale model system.

Typical Values of Area and mass for each system are:

C-9 Parachute

$A = 50\ m^2$

$m = 200\text{-}300$ lb. (90 -135 Kg)

$A/m = 0.55 - 0.37\ m^2/Kg$

1 meter Scale

$A = 0.78\ m^2$

Thus

$m^* = 3.1 - 4.6$ lb. (1.43-2.10 Kg)

0.5 meter Scale

$A = 0.20\ m^2$

Thus

$m^* = 0.78 - 1.2$ lb. (0.36-0.53 Kg)

G-12 Parachute

$A = 314\ m^2$

$m = 1200\text{-}2200$ lb. (550 -1000 Kg)

$A/m = 0.57 - 0.32\ m^2/Kg$

1 meter Scale

$A = 0.78\ m^2$

Thus

$m^* = 3.0 - 5.5$ lb. (1.37-2.48 Kg)

0.5 meter Scale

$A = 0.20\ m^2$

Thus

$m^* = 0.76 - 1.27$ lb. (0.34-0.58 Kg)

The mass of a GPS radiosonde is about 0.4 Kg (Vaisala) and 0.25 Kg (AIR). The mass of a 1 meter parachute is less than 30 grams. Thus either a 1 meter or a 0.5 meter scale model parachute would have sufficient allowable mass to carry a GPS sonde.

Diameter of Parachute Opening

The circular flat canopy may have a circular opening in its center to allow restricted airflow through the inflated canopy. A question of concern is what the relative size of the opening should be in the scale model parachute.

For the full size and scale parachutes to have the same fall velocity, the percentage of the air flowing through the opening relative to the total airflow in the path of the parachute must be the same in the full and scale systems.

Let

- A = presented area of the full size parachute in the direction of airflow
- A* = presented area of the scale parachute in the direction of airflow
- V = free stream velocity of air relative to each parachute (fall velocity)
- D = Diameter of the opening in the full size parachute
- D* = Diameter of the opining in the scale parachute

Then the flow through the full size parachute is:

$$V k \pi D^2 / 4$$

and through the scaled parachute is:

$$V k^* \pi D^{2*} / 4$$

where:

k = the capture efficiency of the parachute for passing air through the opening

By the geometric similarity of the two parachutes when the parachutes are falling at the same velocity, the streamlines around each parachute are similar so that k must equal k*. Equating the ratio of flow through the opening to total approaching flow for the two systems gives:

$$V k \pi D^2 / 4 V A = V k \pi D^{*2} / 4 V A^*$$

or:

$$A^* / A = D^{*2} / D^2.$$

Thus the Diameters squared ratio of the scale and full size systems equates to the presented area ratio. This relationship will hold if the ratio of the diameter of the openings of the two parachutes is the same as the ratio of the diameters of the flat circular canopies of the respective parachutes. In essence this relationship merely verifies the geometric similarity of the two parachute shapes, including the center opening.

<u>Length of Suspension line</u>

With geometric similarity between full and scale parachutes systems the length of the suspension lines should be in the same proportion as the other dimensions. It should be determined however, if the suspension lines are truly scaleable; that is, whether factors such as fabric rigidity, and friction drag may result in a somewhat different inflated geometry of the two systems even though all component dimensions are proportional. Figure 2 from Knacke shows the drag coefficient as a function of the ratio of suspension line length to parachute diameter for different sized and type canopies. Solid flat circular parachutes with diameters 3.8, 6.5 and 28 ft show less than a 2% change in C_D for a given L/D. The direction of change indicates that the smaller diameter canopy should have slightly longer suspension lines to provide the same drag coefficient. However, for the small drag effect observed, the expected change is not sufficient to warrant a change in the suspension line length from that of geometric similarity.

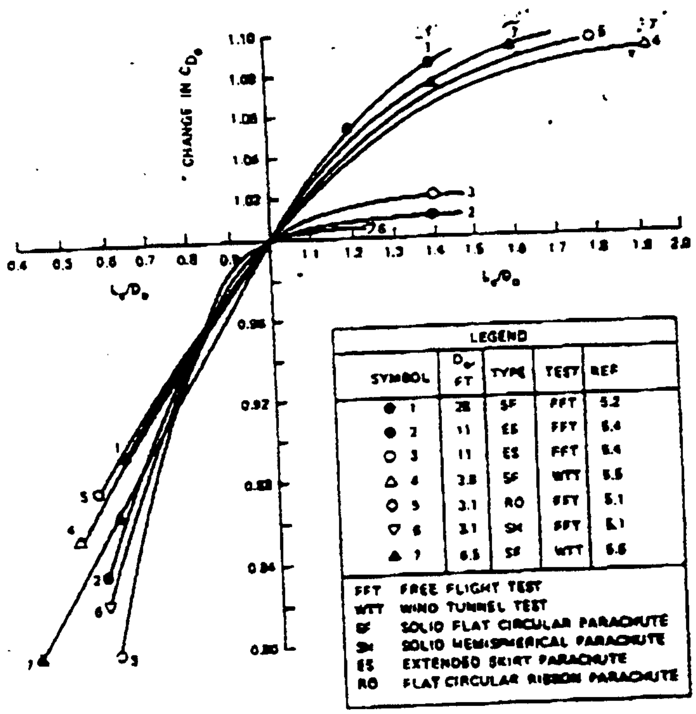

Figure 2: Influence of Suspension Lines on Drag Coefficient (from Knacke)

Porosity of Parachute Material:

The porosity of the full and scale model parachutes should be such that there should be no change in the vertical velocity of the scale and full size systems because of a difference in porosity of the canopy fabrics.

Let

G = the average flow rate per unit presented area through the full size parachute canopy in steady state descent, in its inflated configuration.

G* = the average flow rate per unit presented area through the scale parachute canopy in steady state descent, in its inflated configuration

Because the inflated configuration of both the full size and scaled canopies is similar, the proportion of surface area facing a given direction is the same in both systems. Thus, if the full and scaled parachutes were made from the same fabric , the average flow rate per unit area, would be the same for both systems.

The ratio of the airflow through the fabric to the total air in the path of the each parachute is:

$$G A / V A \quad \text{full size}$$

$$G^* A^* / V A^* \quad \text{scale}$$

These ratios will be equal it G = G*. Thus the porosity of the full and scale parachutes should be the same to provide the same vertical velocity profile. The same fabric can thus be used for both parachute systems. It should be noted that geometric similarity would imply that spacing of holes in the fabric of the scale parachute be smaller than the full size by the scaling factor. However, the fabric elements must also be smaller by the scaling factor. Thus the ratio of open area to fabric would be the same.

Mass, C_D, and A_i vs Miss Distance

The mass, drag coefficient and reference area of the scale parachute system are designed so that both systems experience the same fall velocity and trajectory profiles. In practice however, the mass of payload systems may vary somewhat from payload to payload. Also because of various container dimensions for the payload, the influence of payload on the drag coefficient and reference area may not be the same for each parachute/payload systems. Thus the question arises concerning how the impact point may vary with small changes in each of these parameters.

The equation for the vertical component (Eq. 1) can be simplified by assuming steady state descent (no vertical acceleration) and that the parachute is a good wind sensor (i.e. the horizontal parachute velocity equals the horizontal wind velocity). The drag force can then be equated to the gravitational force and the resulting equation solved for the vertical velocity as:

$$\dot{Z} \approx (mg / 0.5\rho C_{Dz} A_Z)^{1/2} \qquad (2)$$

Typical descent times for a C-9 parachute/payload from 25000 ft is 1330 sec, and from 10000 ft is 500 sec. Consider the deviation in impact point, or miss distance that would result if the mass were changed by 10%. The change in impact point occurs because a change in mass, C_{Dz}, or A_z changes the vertical velocity allowing the wind field to carry the parachute/payload over a longer or shorter period of time. Using Equation 2 to estimate changes in the descent time for a parachute/payload system, the following results have been calculated for a 25000 ft and 10000 ft release under the influence of a constant 10 m/sec horizontal wind.

25000 ft release:

if: $m = 1.1\ m$

then:

$\dot{Z} = 1.05\dot{Z}$

$\Delta t = 62$ sec

$\Delta X = 620$ m

10000 ft release:

if: $m = 1.1\ m$

then:

$\dot{Z} = 1.05\dot{Z}$

$\Delta t = 23$ sec

$\Delta X = 230$ m

A 5% change in mass would produce one half of the 10% miss distances Similarly a 10% change in C_{Dz}, or A_z would have the same magnitude effect on miss distance, but in the opposite direction.

As an example consider an acceptable miss distance to be 100 meters for a 10000 ft release in a 10 m/sec average horizontal wind field. An accuracy of $\approx 4\%$ is required in $m/C_{Dz}\ A_z$. This equates to an acceptable error tolerance for typical C-9 and G-12 parameters as follows:

Parachute/Payload Weight = 2000 lb., $\varepsilon_w = 80$ lb.

Weight = 50 lb., $\varepsilon_W = 2$ lb.

$C_{Dz} = 1.10$, $\varepsilon_{CDz} = 0.044$

$A_z = 50\ m^2$, $\varepsilon_{Az} = 2\ m^2$

$A_z = 314\ m^2$, $\varepsilon_{Az} = 12.5\ m^2$

TRAJECTORY SIMULATIONS

A two dimensional falling sphere trajectory simulation code was modified to simulate the trajectory of a parachute released from a moving airplane, under the influence of a one dimensional wind field. The trajectory code assumes the parachute/payload system to be a point mass, and thus does not account for motion between the payload and the parachute, nor the angle of attack of the parachute. The trajectory simulations were designed to establish the order of magnitude influence of the wind field, and other parameters on the trajectory of a parachute/payload system. As such, the two dimensional trajectory code provides results that are in agreement with more elaborate codes, and thus is adequate for the sensitivities analyses performed.

Figure 3 shows vertical velocity profiles for a 10000 ft release of a C-9 payload/parachute system as a function of the drag coefficient of the system. The vertical velocity for each scenario decreases by about 3 m/sec between 10000 ft and the surface. The change in drag coefficient from 0.70 to 0.95 only changes the vertical velocity by about 3 ft/sec. Thus the vertical velocity of the C-9 system is only mildly sensitive to changes in drag coefficient, and to changes in atmospheric density (altitude).

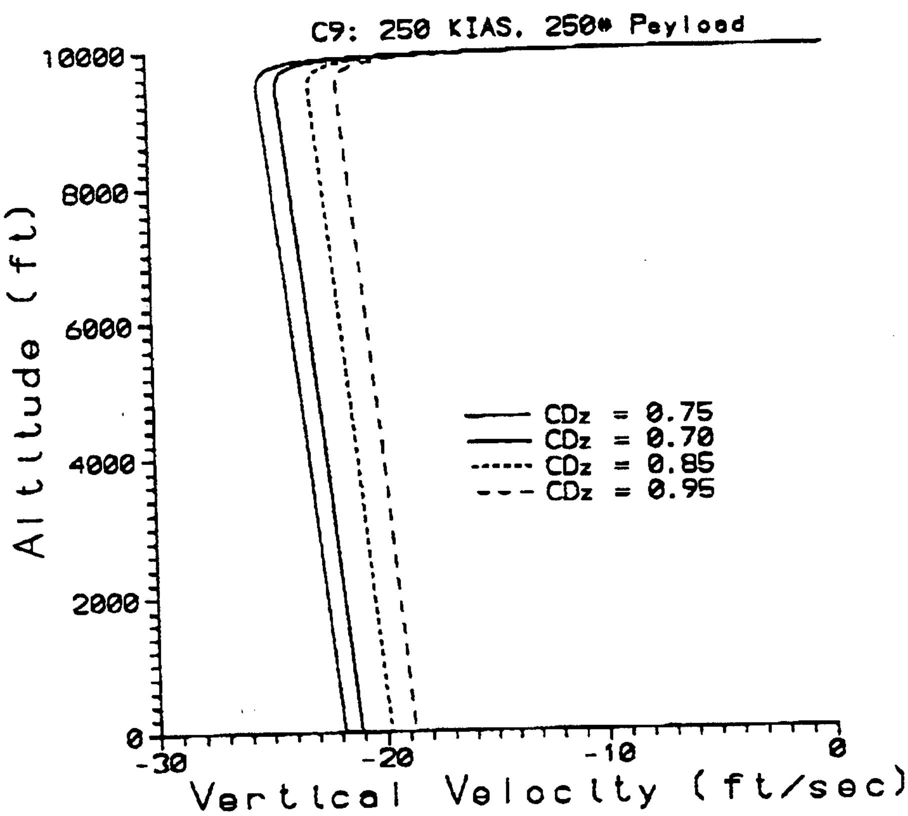

Figure 3: Vertical Velocity as a Function of Drag Coefficient for the C-9 System

Figure 4 compares the vertical velocity profile for a C-9 system with a high altitude release of a G-12 parachute/payload system. The G-12 system experiences a faster descent rate decreasing from 42 m/sec at about 1000 ft below release altitude to 29 ft/sec at the surface. The change in atmospheric density causes the decrease in descent rate as the parachute/payload approaches the surface. The more rapid fall rate at the higher altitudes will result in a proportional decrease in responsiveness of the system to a horizontal wind field.

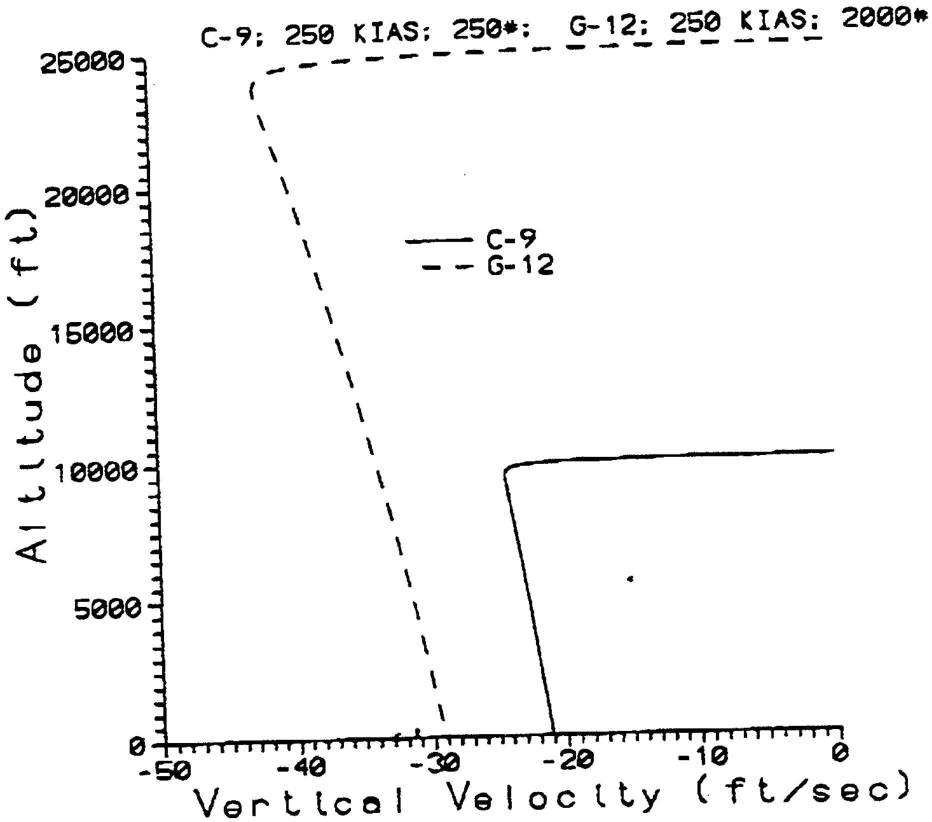

Figure 4: Vertical Velocity of a C-9, and high Altitude G-12 Release

Figure 5 shows a 10000 and 1000 ft release of the C-9 system at airplane speeds of 150 and 250 KIAS. The affect of airplane speed is only seen in the first few hundred feet of descent. After this distance the initial horizontal velocity is bled off, and the horizontal parachute descent is influenced only by the wind field. A deviation in impact point of less than 100 ft occurs as a result of the 100 KIAS difference in airplane speed.

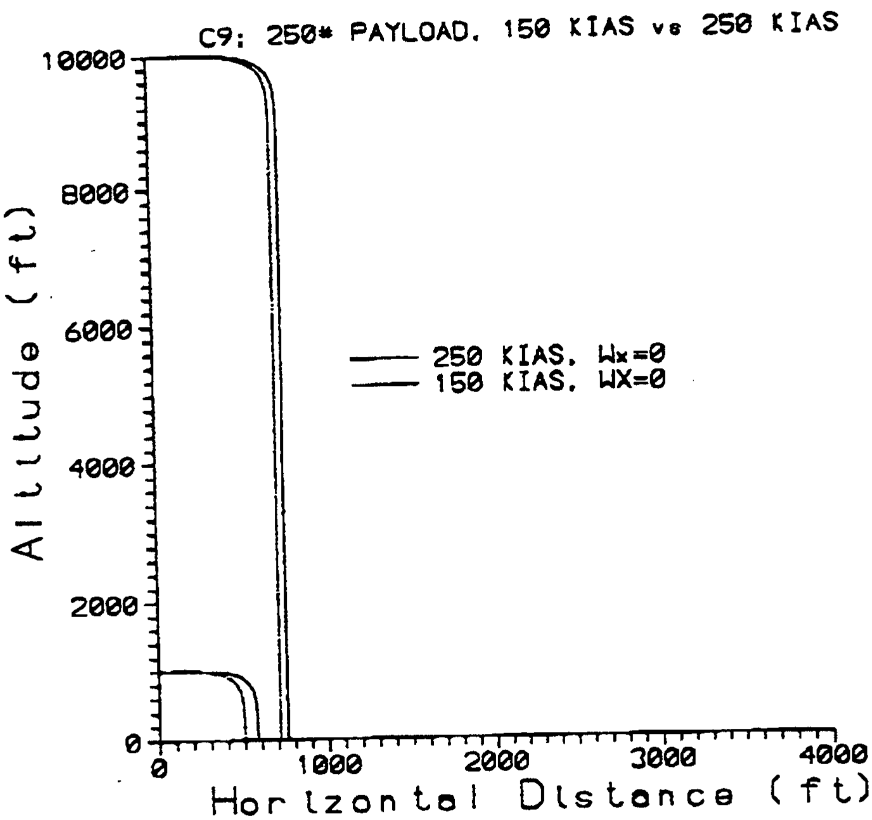

Figure 5: Horizontal Trajectories of C-9 Releases at Different Airspeeds

Figure 6 shows the horizontal trajectory of the C-9 system under the influence of no wind, and 4 different wind fields. For the 10000 ft release the 20 m/sec wind field carries the parachute/payload system 30000 ft downrange. The lighter wind fields produce less downrange distance. The influence of the wind field on downrange distance is only slightly less at the higher altitudes, as observed from the trajectory in the sinusoidal wind field This is also consistent with the fact that the vertical velocity of the system varies only slightly with altitude. Thus the exposure time to the wind field is nearly constant at all altitudes. It is clearly evident from Figure 6 that the wind field strongly influences the parachute/payload trajectory and therefore must be known accurately in order to predict the impact location of any parachute/payload system.

Figure 7 shows the same wind field simulations for the C-9 system with two different payload weights; 200 lb. and 300 lb. A deviation in impact point of several hundred feet for a 100 lb. change in mass under strong wind conditions is possible.

The response of a parachute system to the wind field depends upon the horizontal drag coefficient and reference area of the parachute/payload system. For a parachute, the drag coefficient is usually only known in its vertical direction, since this determines its fall velocity. Thus in solving for the horizontal components in the two dimensional drag equation a value for the horizontal drag coefficient and reference area in the horizontal plane is also needed. This value was estimated from the literature, based upon wind tunnel measurements of drag for a open semi-sphere with the opening perpendicular to the direction of flow. The drag coefficient for this geometry is referenced to the cross-sectional area of the sphere. The nominal C_{Dx} value used in the trajectory equations is $C_{Dx}=0.3$ and the reference area is for that of a sphere with diameter equal to 0.7 times the diameter of a flat circular canopy parachute

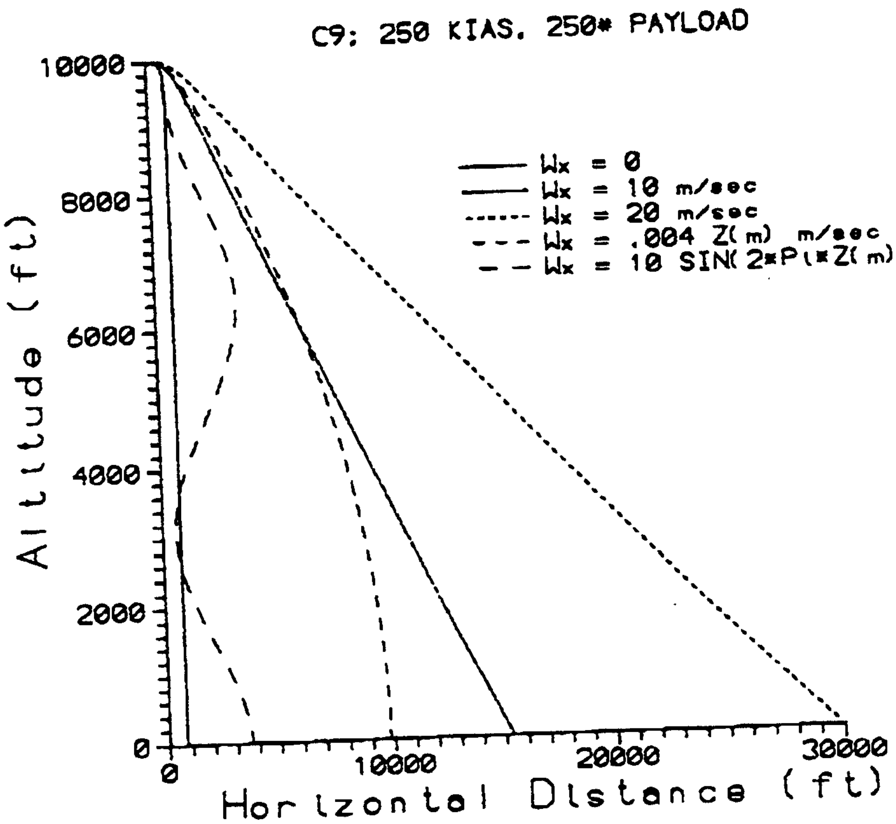

Figure 6: Horizontal Trajectories of C-9 Systems through Various Wind Fields

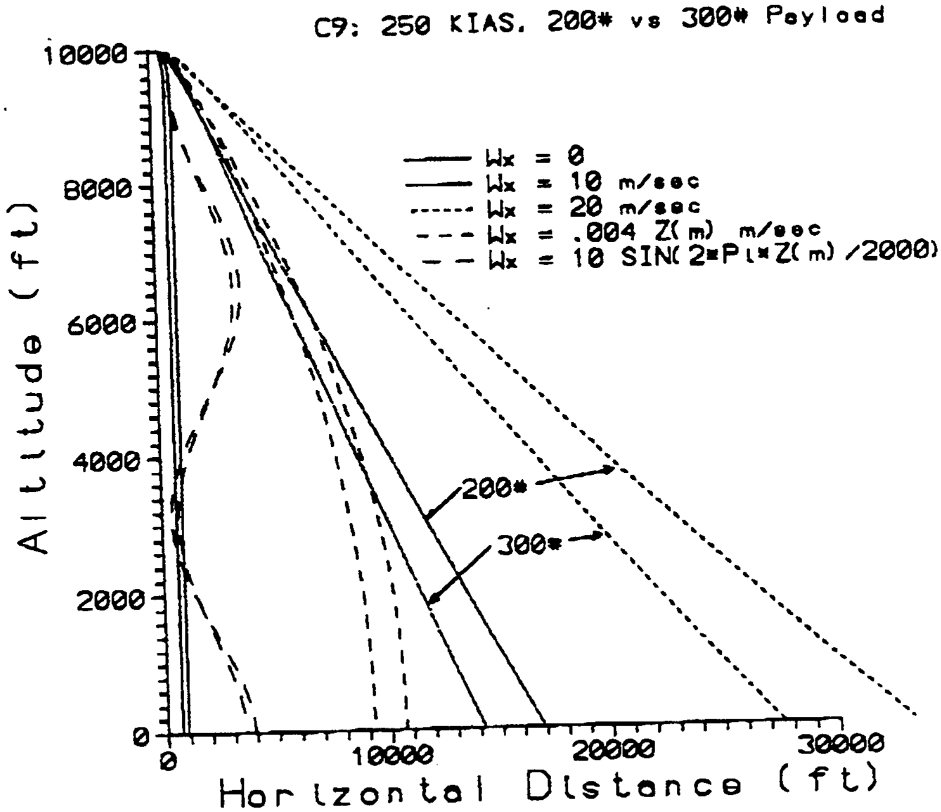

Figure 7: Horizontal Trajectories of C-9 Systems with Different Payload Weights

To establish the sensitivity of the horizontal trajectory of the parachute to the accuracy of the horizontal drag coefficient, simulations were made using increased and decreased values for C_{Dx}. An upper limit of 0.5, and a lower limit of 0.1 were used in the simulations. The results for a C-9 release from 10000 ft. and a G-12 release from 25000 ft are shown for two different wind fields in Figures 8 and 9. For both systems the deviation in impact point due to changes in C_{Dx} occurs primarily because of the slowing down of the parachute system during the first 200 to 500 ft after release from the airplane. After the initial airplane induced velocity is bled off, each parachute system becomes a good wind sensor. The low horizontal drag system (C_{Dx} = 0.1) follows nearly the same path as that of a high horizontal drag system. In the G-12 system slightly less wind responsiveness can be seen in the low drag trajectory through the sinusoidal wind field at the higher altitudes; but this is a relatively minor effect.

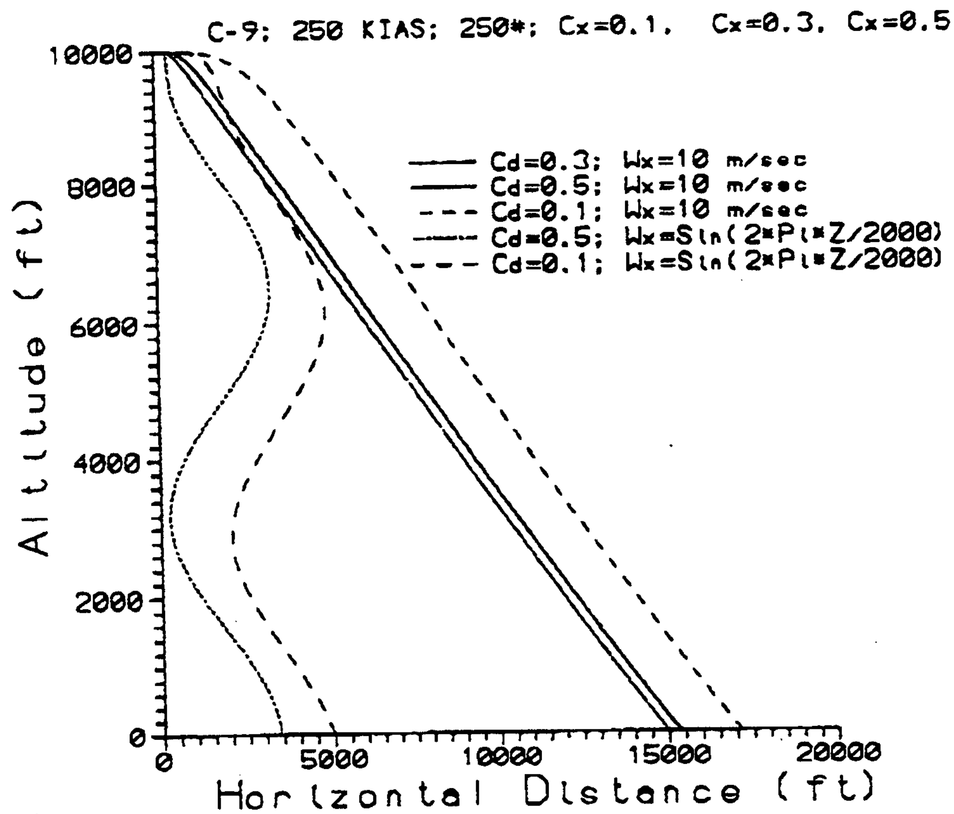

Figure 8: Influence of the Horizontal Drag Coefficient on Path of C-9 System

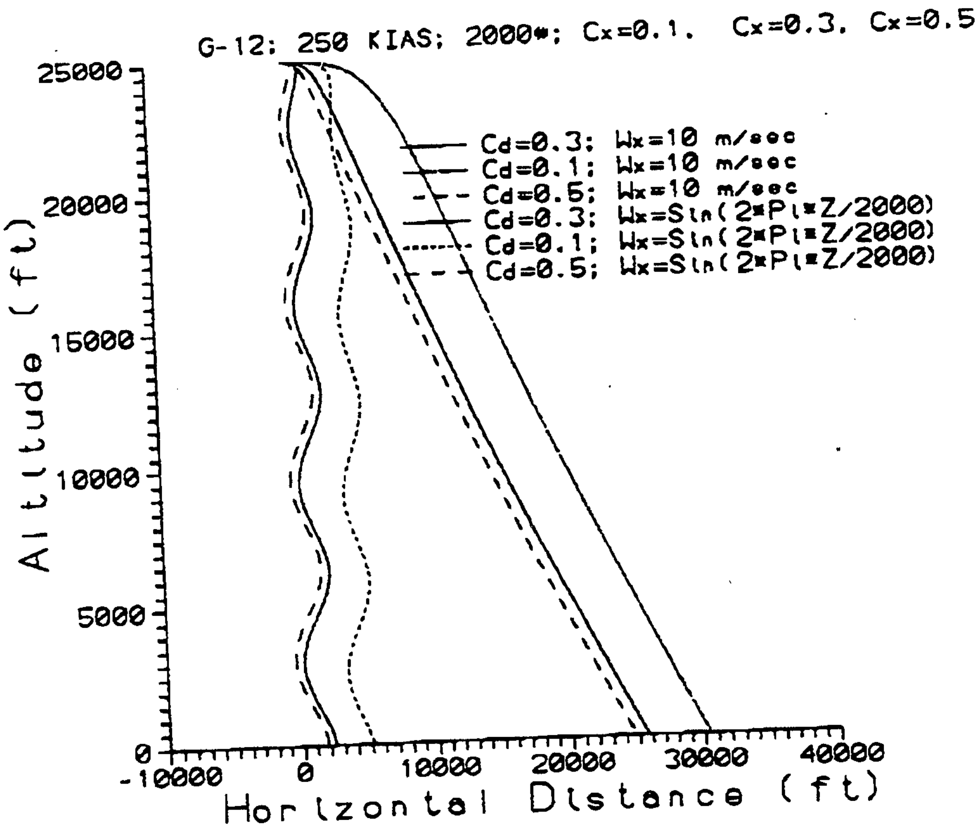

Figure 9: Influence of the Horizontal Drag Coefficient on Path of G-12 System

SUMMARY AND CONCLUSIONS

The wind field must be known accurately at all altitudes to predict parachute/payload impact point. Because the fall velocity of a parachute system decreases somewhat with altitude, the parachute is slightly less responsive to the wind field at the higher altitudes. However this influence is not of sufficient magnitude to alleviate the need for accurate wind information at all altitudes, even to 25000 ft.

The C-9 and G-12 parachute/payloads are good wind sensors, and after a few hundred feet of descent (from release), they closely follow the wind field. The speed of the airplane at release, and the horizontal drag coefficient of the parachute are of secondary importance and primarily affect the trajectory of the parachute/payload system during its initial segment of descent until it becomes wind sensitive.

Either a 1 meter or a 0.5 m diameter flat circular scale model parachute can be fabricated to provide the same trajectory as that of a full size C-9 or G-12 systems. The scaled system should be geometrically similar to the full size system. The scaled and full size systems should be fabricated from the same material, so as to have the same porosity. The scaled system will carry a GPS receiver as part of its payload to obtain tracking data. Additional ballast mass will be added to the scaled system to make its descent trajectory the same as that of the full scale system. The length of the suspension lines should be in the same geometric proportion as the rest of the scaled system.