The Prediction of Cable Drop Position After A Winch Launch Failure at Aston Down

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C1. Introduction

There are many risks when conducting gliding operations from an airfield. One risk, especially to third parties, arises from the use of a winch to launch gliders. At Cotswold Gliding Club, under certain wind conditions, gliders can be launched to heights in excess of 2000ft. If there was a launch failure, for example, and the cable broke near the top of a launch with only sufficient cable remaining attached to the cable's drogue parachute to stabilise its decent, the parachute, weak link and strop assembly could drift in the wind and fall to ground outside the bounds of the airfield causing damage to property or in the worst case injuring or killing a person.

A risk assessment of this possibility has been undertaken and a suitable mitigation strategy has been formulated to ensure that there is a very low probability that the cable or parachute could fall on adjacent property or persons. The principal mitigation will be to site the winch and launch positions after consideration of the prevailing wind conditions. To help the Duty Instructor to determine the best position for the winch and launch positions a computer application has been developed (called **Winch Master**) which is available as an Android application for a mobile phone or tablet and a web page which can be used on the briefing room computer. The application shows on a map the probable drop locations for a range of winch locations.

This document describes the physical/mathematical model underpinning the application and its validation against observed glider launches.

C2. The Winch Launch

For an excellent article on the performance of a winch launch see “Flight on the Winch” by P. J. Goulthorpe[1].

There are three phases to consider during the winch launch failure when computing the probable drop location:

- The initial ground run, acceleration of the glider and initial rotation into the climb;
- The climb in order to compute the height a glider will reach and hence the worst case scenario cable break position over the runway;
- The decent and drift of the parachute assembly.

These will be considered individually in the following sections.

2.1 The Ground Run

I will refer to it as the ground run but it will end with the glider at about 100ft in the air. However, we need a figure for the length of the runway used for this phase.

The glider whilst on the ground is accelerated to flying speed and as soon as the wings start generating lift the glider rises. The pilot controls the initial ascent and will only start to cause a rotation into the climb at a safe height and speed. The pilot then rotates to a climb angle.

A long ground run will reduce the eventual height of the glider. If we are to model a worst case scenario we should choose a short ground run consistent with observations.

This phase was not modelled in detail due to its complexity however we shall consider only a constant acceleration to flying speed and a rotation into the main climb. The ground run r is influenced by the wind speed. The stronger the headwind v the shorter the ground run:

$$r = \frac{(u-v)^2}{2a} + R$$

where u is the flying air speed and a is the acceleration generated by the winch and R is the distance used once flying speed has been reached to rotate into the climb.

The parameters a and R are inputs to the model and can be changed by the user of the application. Initial estimates of a and R from measurements of glider launches are shown in section 3.2 below.

2.2 The Climb

Once in the main climb the winch driver will attempt to control the winch to supply constant tension.

The pilot can control the glider's speed to a limited degree by changing the force applied to the stick i.e. attempting to increase the climb angle to slow the glider or lower it to increase speed.

The forces on the glider from the lift generated by the wings L, the glider drag D, the weight of the glider and of the cable W, the aerodynamic drag of the cable D_c and the tension T generated by the winch will all be balanced so that its speed U is constant.

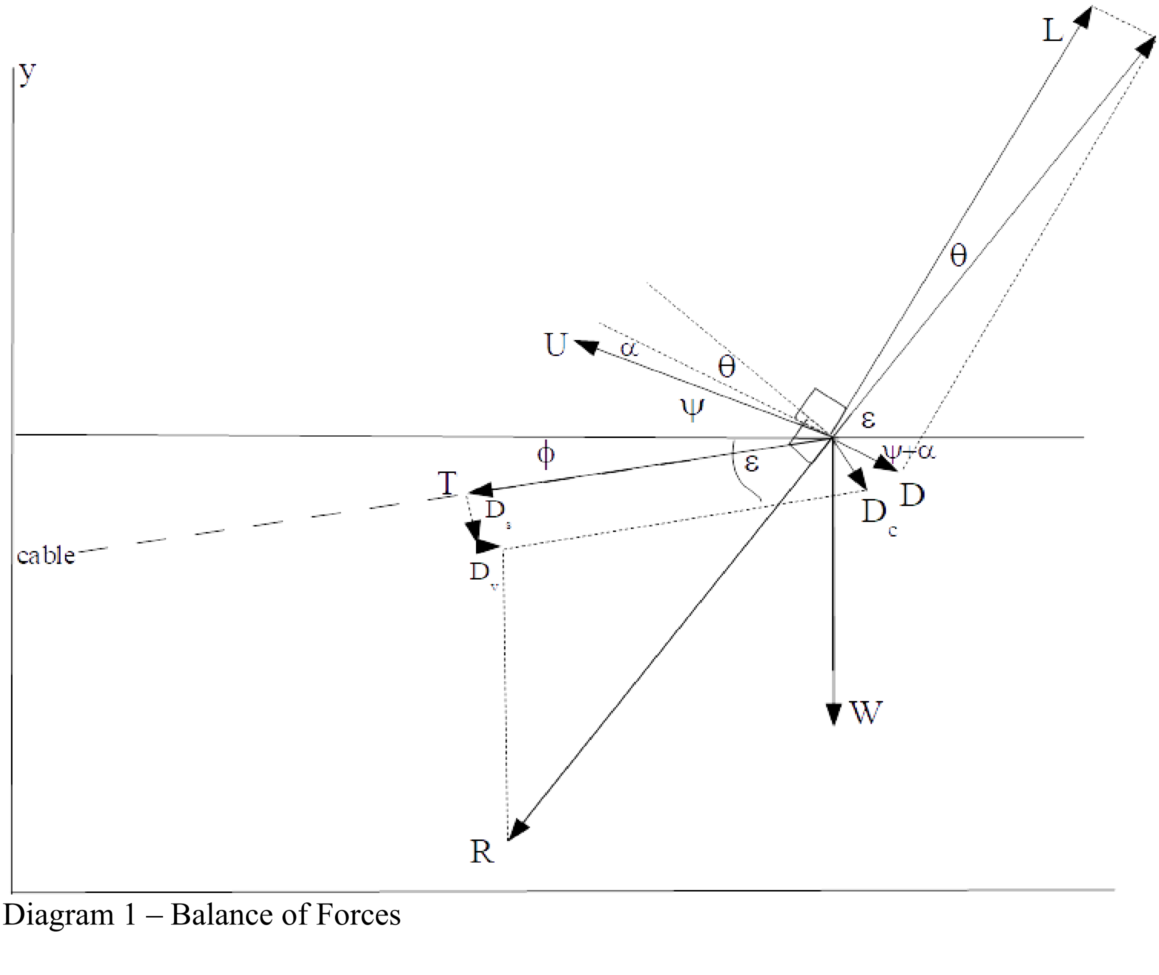


Diagram 1 – Balance of Forces

The motion of the glider will be at the angle of incidence α of the chord of the wings to the fuselage. As the glider rises the angle of the cable changes and so the angle of the climb will change to maintain a balance of forces. The cable is also shortened during the launch and so the glider will follow a curved trajectory which levels out near the top of the launch.

When the angle of the cable to the glider reaches a critical value the back release mechanism of the glider's hook will activate terminating the climb. Typically the winch driver will judge when the glider has reached the top of the launch and will reduce the tension.

This phase is modelled in detail so that the height of the release and its position over the runway can be calculated and used as the starting point for the third phase which is the parachute decent calculation.

The equations for the position of the glider are derived in appendix A where it is shown that there is no simple analytical equation for the system model.

In our model we define x as the horizontal position relative to the winch, y is the vertical position above the initial ground run height. The model was simplified by assuming a straight cable between the winch and glider. To model the cable more realistically as a catenary was considered but creates more complexity and introduces more unknowns. The catenary will make the cable slightly longer and hence heavier and increase the angle at the glider resulting in a lower achieved launch height. Ignoring the effect of the catenary will give a worst case solution which is acceptable.

The system of equations in appendix A was solved iteratively using a numerical method described in section 2.4.

2.3 The Parachute Decent

Given the release point in terms of position (Y) along the launch to winch line and a computed height (h) it is reasonable to assume that the chute will then drift with the wind (V) at a decent speed (w) which is characteristic of its design (diameter and drag coefficient) until it hits the ground at position P which we want to find.

$$P = Y + \frac{h}{w} V$$

The rate of descent of a parachute can be calculated by balancing the weight of the chute (plus some cable and strop assembly) with the aerodynamic drag:

$$w = \frac{1}{r}\sqrt{\frac{2mg}{\pi C_D \mu}}$$

where μ is the density of air, C_D is the drag coefficient, r is the radius of the chute, m the mass and g is the acceleration due to gravity. The chute's drag coefficient is modified by cutting slits into the canopy.

2.4 The Algorithm

Set an initial position for the start of the climb which is the winch to launch distance minus an estimate of the distance for the ground run and start of climb.

At a time t and using vector notation we compute:

Cable angle

$$\phi = \tan^{-1}(\frac{P_x}{P_y})$$

Length of cable:

$$s = |P|$$

The tension vector

$$T = \{\tau\cos(\phi), \tau\sin(\phi)\}$$

The weight (force) of the glider and cable

$$W = \{0, -(M + s\rho)\}$$

where ρ is the weight per unit length of the cable,

The cable drag due to its motion:

$$D_s = \frac{1}{6}\mu C_D \delta s (u\sin(\psi+\phi))^2 \vec{v}$$

and the cable drag due to the wind in the horizontal direction

$$D_v = \frac{1}{2}\mu C_D \delta s (v\sin\phi)^2$$

where μ is the density of air, C_D is the drag coefficient dependent upon the shape of the element and δ is the diameter of the cable and $\vec{v}$ is the unit vector in the direction of travel.

Hence the resultant force balance is:

$$R = T + W + D_s + D_v$$

the gliders velocity is

$$U = u \quad orth(R).rotate(\theta)$$

where orth(R) is the unit orthogonal vector to R which is then rotated anti-clockwise by θ. (Note, we have included the angle of incidence α into θ for simplicity because θ is an input to the model.)

The next position in the time step Δt

$$P(t+\Delta t) = P(t) + (U(t) + V)\Delta t$$

The path is computed until the angle of the glider over the winch ϕ is some maximum value.

The position is the release point for the chute and we then determine its trajectory until it hits the ground with equation (1).

2.5 Initial Conditions

In order to start the computations described in section 2.4 we need the initial conditions at the start of the climb.

Because the cable is almost horizontal we set the initial cable angle φ = 0 and ignore cable drag, then the magnitude of the tension resolves to:

$$\tau = |W|\tan(\psi + \tan^{-1}\eta)$$

where η is the drag/lift ratio for the glider under a high wing loading and ψ is the initial angle of the glider to the horizontal. For a 1 to 20 ratio this term is about 3 degrees. Therefore, in order to gain the highest launch a pilot needs to rotate to as high an angle as possible but which is consistent with maintaining a safe launch speed.

The initial position of the glider is the cable length from the winch minus the ground run.

C3. Model Predictions Compared to Observed Launches

Launch profiles were taken from glider data loggers during the launch phase. The logger interval was 1 second but in one case 4 seconds and the altitude was measured with a barometric sensor. An example is shown in figure 1. The others are shown in figures B1 to B3 below. Figure 1 was for a Ventus 2cxa with a mass (including the pilot) of 400kg being launched into a headwind of 20kts. The ground run was measured from the logger. The x,y positions of the glider are normalised to the adjusted cable length (winch to launch distance minus the ground run). The initial glider angle was not measured and so a a range of model angles from 30^0 to 45^0 are shown for comparison. The results indicate that the angle was about 38^0. The profile of the launch then matches the predictions but with some variation which can be explained by variations in tension, and speed changes. The achieved height was 48% of the adjusted cable length.

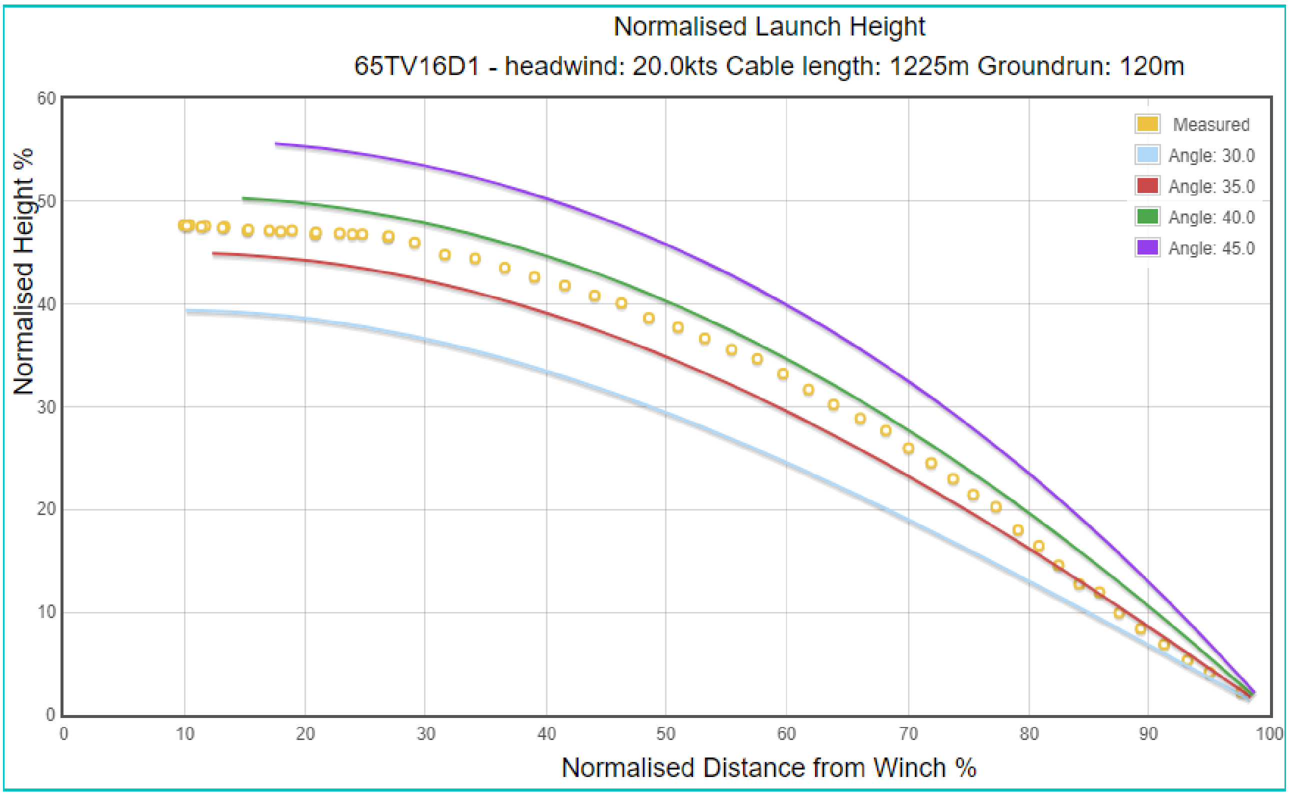


Figure 1 – Ventus 2cxa.

Photographs were taken of four K21 launches and from them the initial angle of the glider in the climb just after rotation was measured with reference to the horizon. An example is shown below.

The observed measured angles varied between 27 and 39 degrees to the horizontal. Analysis of logger data indicates an angle of climb between 35 and 40 degrees.

A more integrated study where the angle from photographs of the launch combined with logger data of the glider launch would be of benefit.

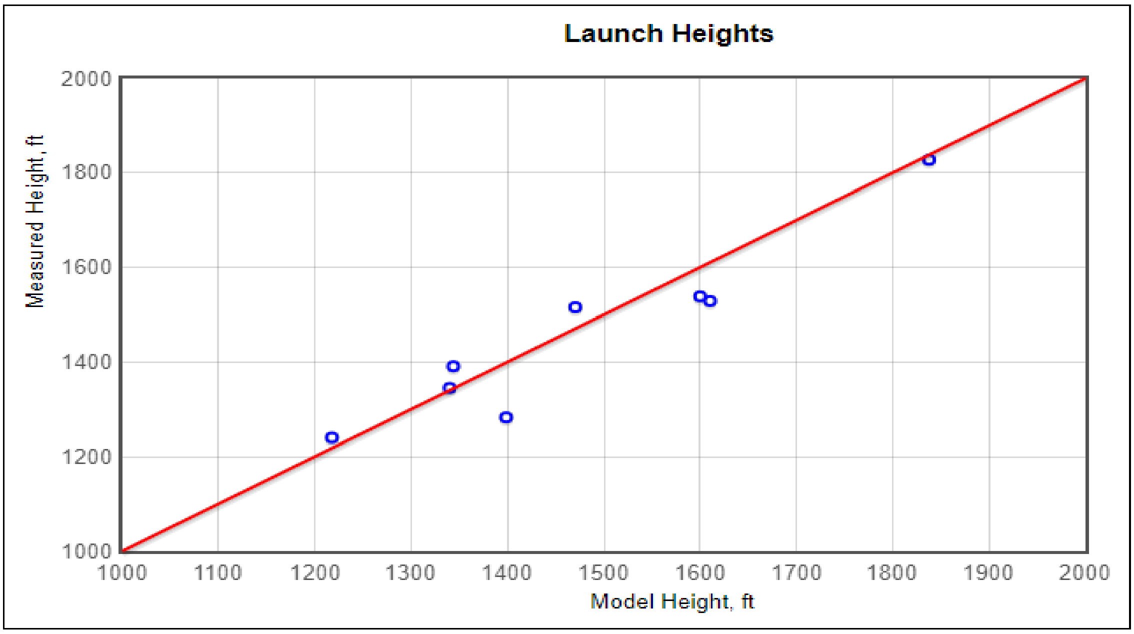


Figure 2 shows the measured launch heights compared to model heights using the best model parameters including the model of the ground run.

3.1 Observations of the Chute Decent Speed

For the worst case scenario we need to know the drop speed of parachutes which are in new or good condition. A worn chute will have a lower drag coefficient and so fall faster. The parachutes used at Aston Down have a diameter of 1.6 metres with slits in the sides and a weight including small length of cable and strop of about 9kg. Manufacturers quote a drag coefficient of 0.7 for the chute design and so the descent rate would be about 10 m/s. However, we do not have specific design data for the drag coefficient, nor design drop speed for the chutes used at Aston Down and so measurements are required.

To measure the chute descent rate for the worst case would require the release of a chute without the cable attached. It would need to be released from sufficient height for it to open fully and to stabilise at its design decent rate so that an accurate time can be measured using either a stopwatch or by filming the descent and analysing the footage. For practical reasons it would need to be released from at least 400 ft above ground and be guaranteed to remain within the airfield boundary. Unfortunately, the facilities to undertake these measurements were not available at the time this report was written however it was possible to let a chute fall under its own weight after a launch with the complete cable attached. With the cable attached the chute descends with a cable weight which decreases as the cable hits the ground and so the speed of descent will decrease during the fall. The equation to derive the drag coefficient from a measurement of the drop height and time to fall is derived in Appendix C:

$$C_D=\frac{T^2\rho^2 g}{2m\pi\mu r^2}\frac{1}{\left(1-\sqrt{\left(\frac{\rho s_0}{m}+1\right)}\right)^2}$$

Where T is the measured time of descent, ρ is the cable mass per unit length, g the acceleration due to gravity, m the mass of the chute assembly, μ the air density, r the radius of the chute when inflated, and s_0 is the drop height.

A measured value for drag coefficient was 0.776. With this value the worst case descent velocity will be 9.6 m/s.

3.2 Observations of Ground Run Length

Fig 3.2 shows measurements of distance taken from the gliders data logger for launches taken on different days with differing head winds.

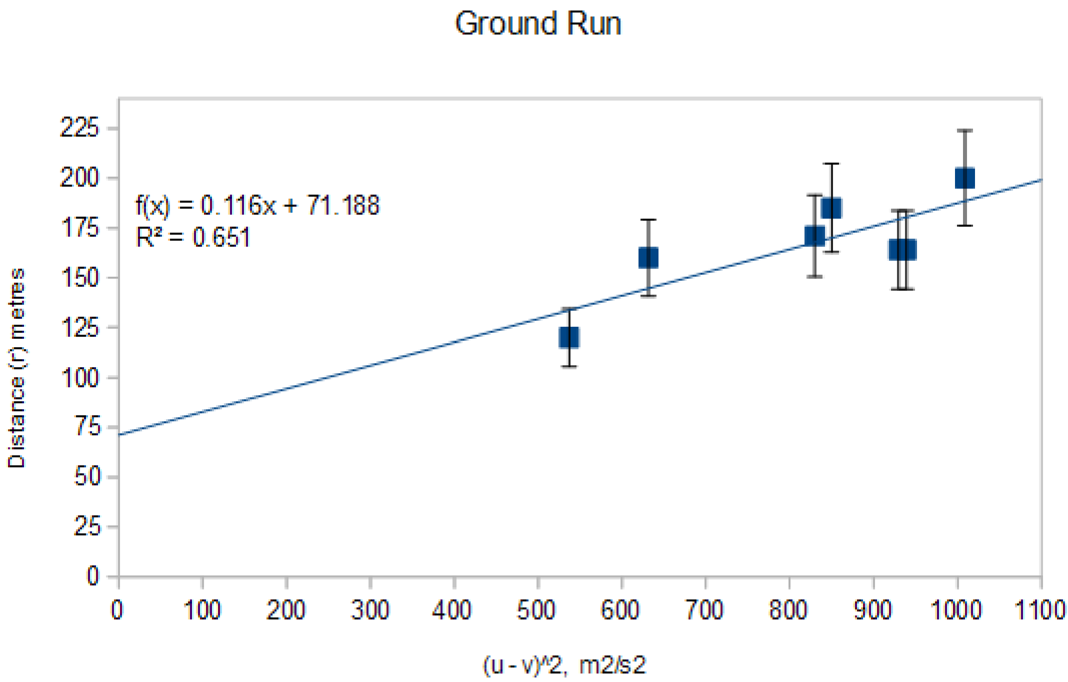


Fig 3.2 Measurement of Ground Run

Using the equation in section 2.1 for the ground run and plot r against $(u\text{-}v)^2$ we can fit a line

$$r = \frac{(u-v)^2}{2a} + R$$

to obtain estimates of a and R for use in the model:

R = 71m and

a = 4.3 ms^{-2}

The estimates will be improved by undertaking a further series of launches with known conditions.

C4. Model Predictions and Sensitivities

The numerical model for the prediction of launch height has the following parameters which can vary from launch to launch as an input:

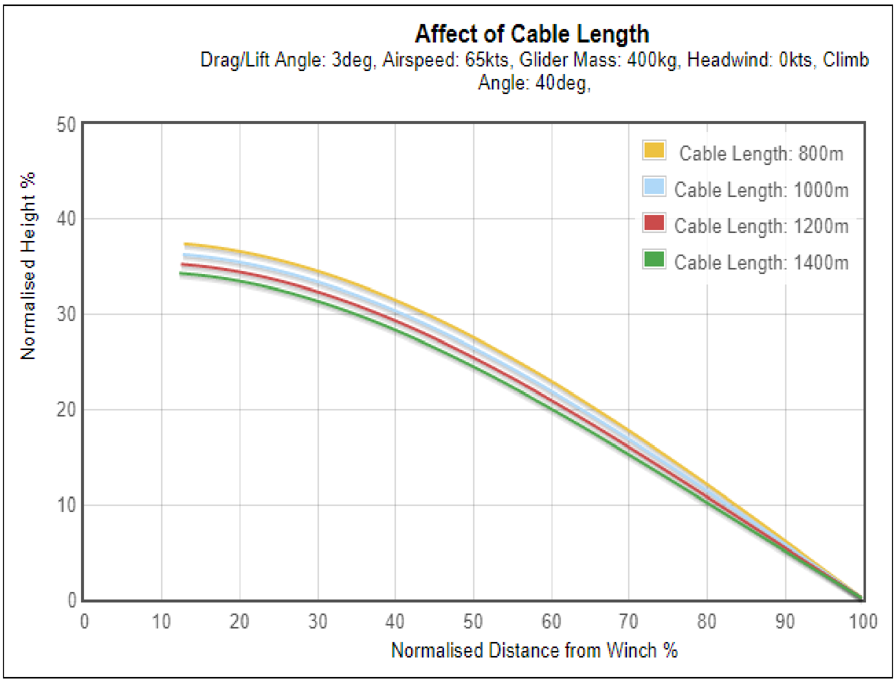
- cable length
- head wind
- glider weight
- glider drag/lift ratio
- initial angle of climb
- ground run
- glider airspeed

Other parameters that are important but which are constant are:

- cable diameter
- cable weight per unit length
- cable drag coefficient
- air density

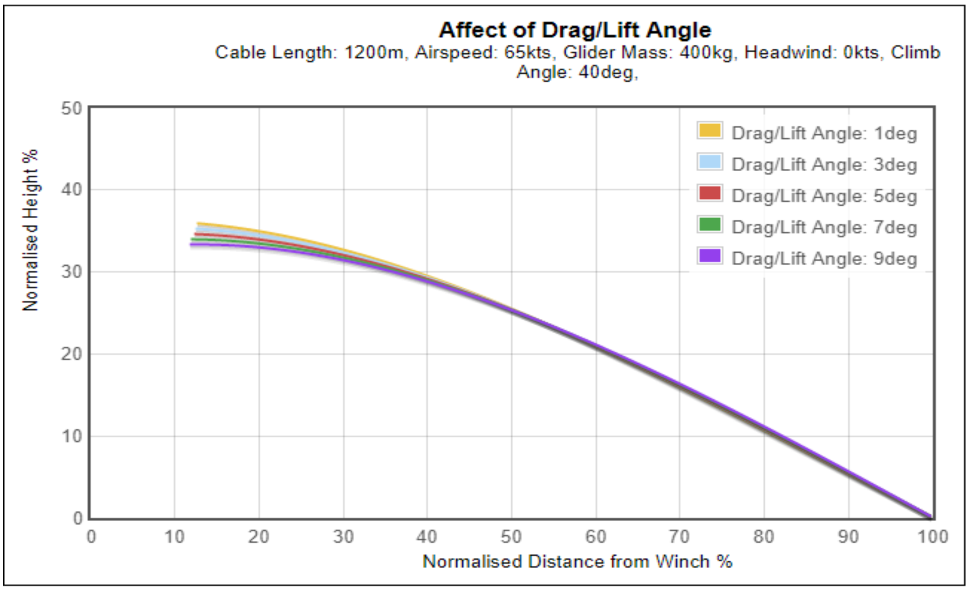
4.1 Cable Length

Figure 2 shows the affect of the cable length for the case with no headwind and ignoring the ground run for a glider with a mass of 400kg and initial climb angle 40 degrees.



The glider has to lift more cable and so will suffer more weight and drag and so will achieve a lower normalised height. However, because the cable is longer the actual height will be higher for a long cable compared to a shorter cable.

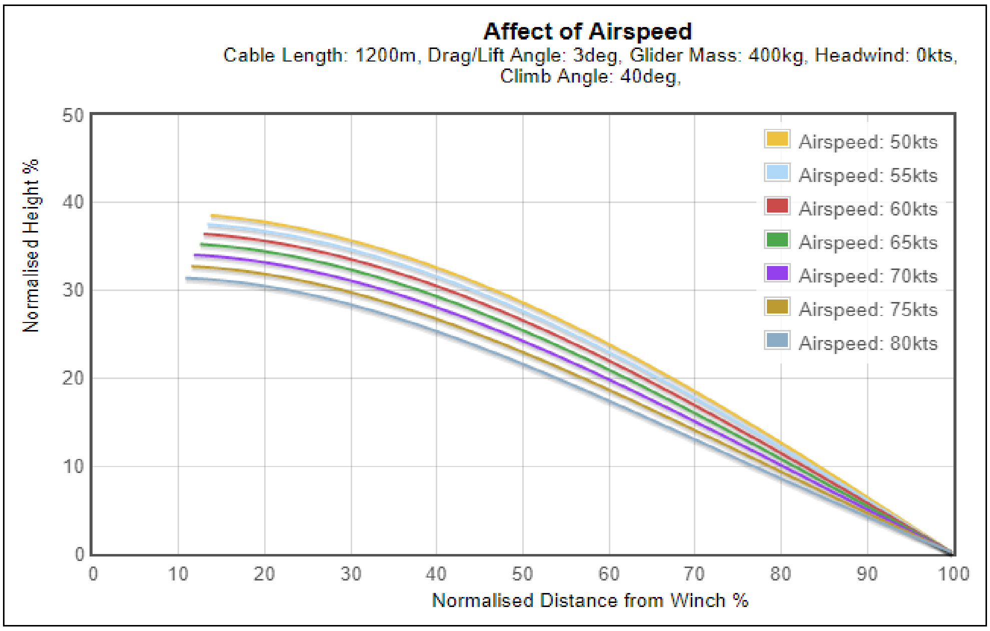
4.2 Drag/Lift Ratio Angle



The drag/lift ratio of the glider only has a significant affect near the top of the launch when the climb angle is small.

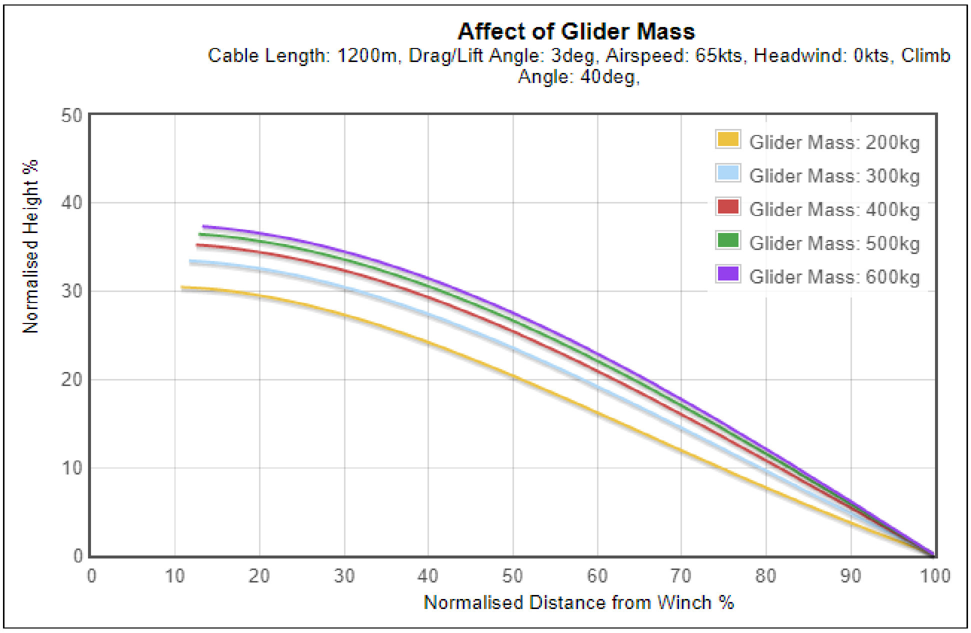
4.3 Airspeed

The reduction in launch height with airspeed is caused by the increase in drag with speed. The drag increases with the square of the speed.



4.4 Glider Mass

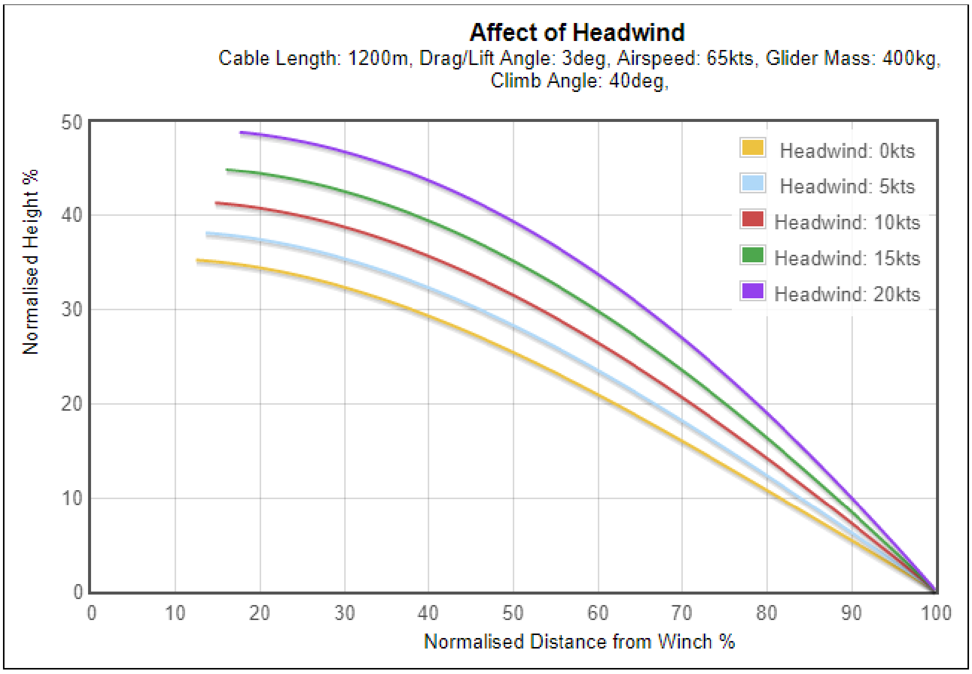
The affect of glider mass shows that the lighter glider will achieve a lower height compared to a heavy glider because the tension in the cable will be lower and so the influence of cable weight and cable drag will be higher.



However, it is normal for a lighter glider to be launched at a lower airspeed and so should achieve a higher launch than indicated here.

4.5 Headwind

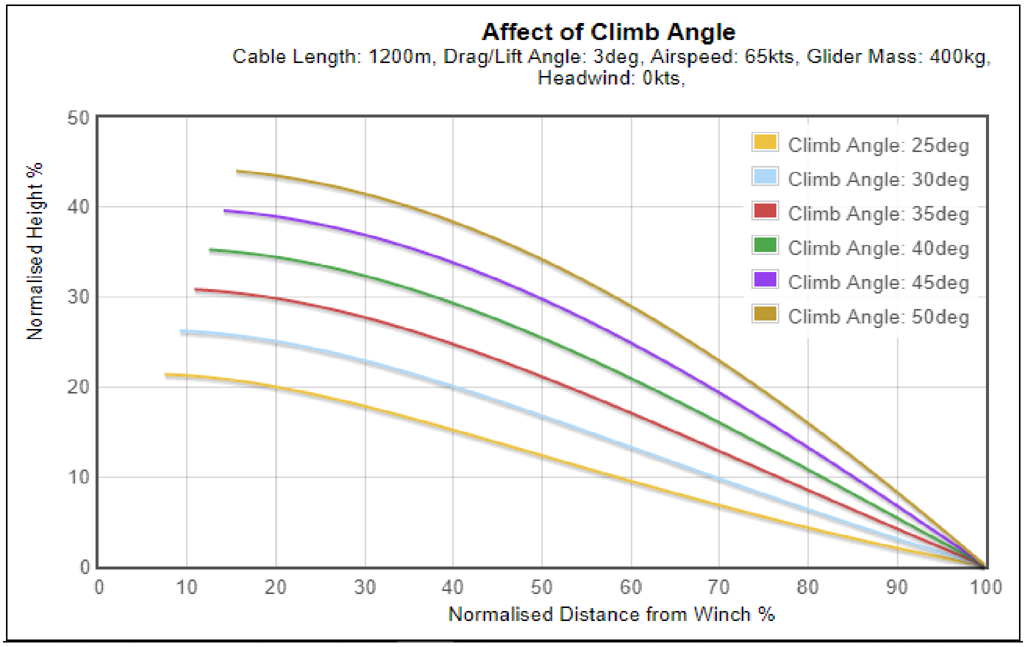
The headwind has the most effect on launch height because some of the energy of the wind is used to assist the launch.



With a 20kt wind a launch height of half the cable length can be achieved.

4.6 Initial Climb Angle

The most directly influential parameter is the initial angle of climb. With all other factors being equal the pilot will achieve a better launch height if he can achieve at least a 40 degree climb.



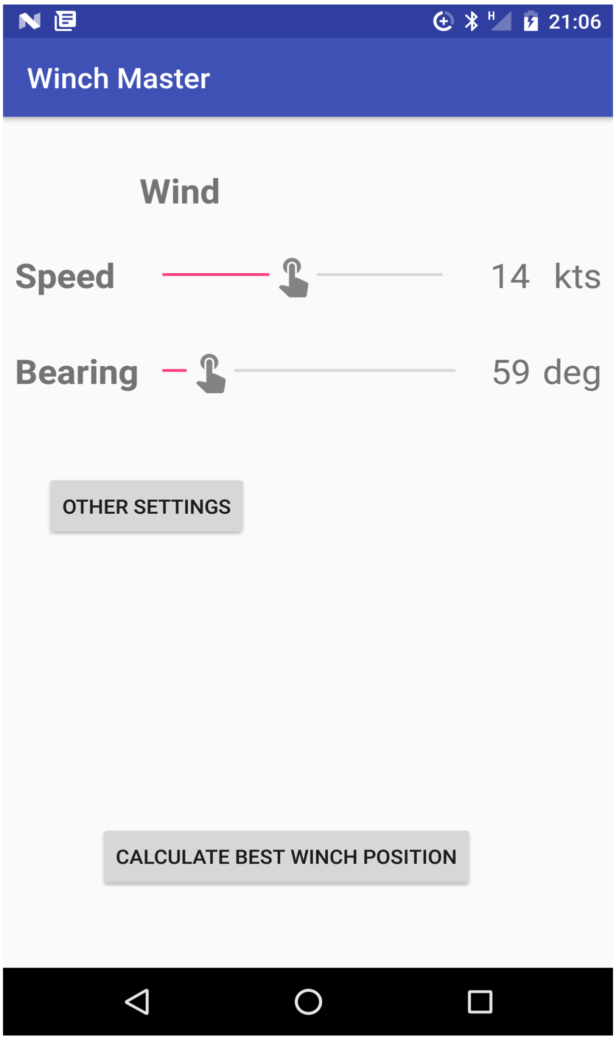
4.7 Cross Wind

A cross wind component to the direction of launch will if not corrected will cause the glider to drift downwind. If the cable broke then the final drop position will be even further downwind risking landing beyond the boundary. If no correction is applied by the pilot then normal mitigation would be for the winch driver to terminate the launch at a lower height. Normally, the pilot will correct for the cross wind by rolling the into-wind wing down and climbing with an angle of roll. With a roll angle applied the glider wing has to generate more lift and hence drag and so a lower launch height will be obtained.

This effect has not been modeled bacause we are only interested in the worst case and an overprediction of the launch height is acceptable. In the worst case the glider is released vertically above the runway.

C5. The Android Application

An application to calculate the likely drop position has been developed for the Android platform. Geographic information about the runway layout and the bounds of the airfield at Aston Down have been coded. Other airfields can be configured.



The first screen invites the user to input the wind direction and speed. If there is an internet connection then the initial values will be obtained from the weather station at Aston Down http://www.cotswoldgliding.co.uk/weather/clientraw.txt There is a button to view the main settings page where the standard parameters (parachute descent speed, cable mass per unit length, etc.) can be set.

From the initial page the user clicks on the "Calculate Best Winch Position" button to display a map of the airfield showing the launch and winch positions on the runway normally used for the selected wind and then the likely drop positions if the winch is moved in steps of 100 metres towards the launch position. In the example shown above, the first four winch positions would be unacceptable because if there was a worst case cable break the chute assembly would drop onto the glider trailers. The winch should be sited at position 5, The expected launch heights are shown as the list of figures at the top of the screen. In this example, at position 5 in the best case we would expect to get a 1500ft launch.

Appendix A – Derivation of Formulae

In a small time interval dt the distance moved by the glider in vertical plane at P (x,y), where x is horizontal and y is vertical, is:

$$dx=(u\cos\psi\ -v)\,dt \qquad dy=u\sin\psi\,dt \quad ....(1)$$

hence

$$\frac{dy}{dx}=\frac{\sin\psi}{\cos\psi-\frac{v}{u}} \quad ...(2)$$

where the angles are shown in diagram 1 (section 2.2), in particular ψ is the climb angle, u is the glider's airspeed and v is the headwind.

In diagram 1 the weight W comprises the weight of the glider and the cable:

$$W=(M+s\rho)\,g$$

where g is the acceleration due to gravity, M is the mass of the glider, ρ is the mass per unit length of the cable and s is the length of the cable.

Resolving the forces onto the x and y axes:

$$E\cos\varepsilon\ -T\cos\phi+D_s\sin\phi+D_v=0 \quad ...\ (3)$$

$$E\sin\varepsilon\ -T\sin\phi\ -D_s\cos\phi\ -(M+s\rho)\,g=0 \quad ...(4)$$

now

$$\varepsilon+\psi+\theta=\frac{\pi}{2} \quad ...(5)$$

The angle θ is given by the lift to drag coefficient η and for simplicity we include the angle of incidence α:

$$\theta=\tan^{-1}\frac{D}{L}+\alpha=\tan^{-1}\eta+\alpha \quad ...\ (6)$$

because

$$\cos(A-B)=\cos A\cos B-\sin A\sin B \quad ...(7)$$

rearranging (3) and substituting for ε and applying (7) we get the lift force in terms of the winch tension:

$$E=\frac{T\cos\phi-D_s\sin\phi-D_v}{\sin(\psi+\theta)} \quad ...(8)$$

and subtituting back into (4)

$$\frac{T\cos\phi-D_s\sin\phi-D_v}{\tan(\psi+\theta)}\ -T\sin\phi\ -D_s\cos\phi\ -(M+s\rho)\,g=0 \quad ...(9)$$

The cable from the winch to the glider will follow the shape of a catenary as shown in diagram 2.

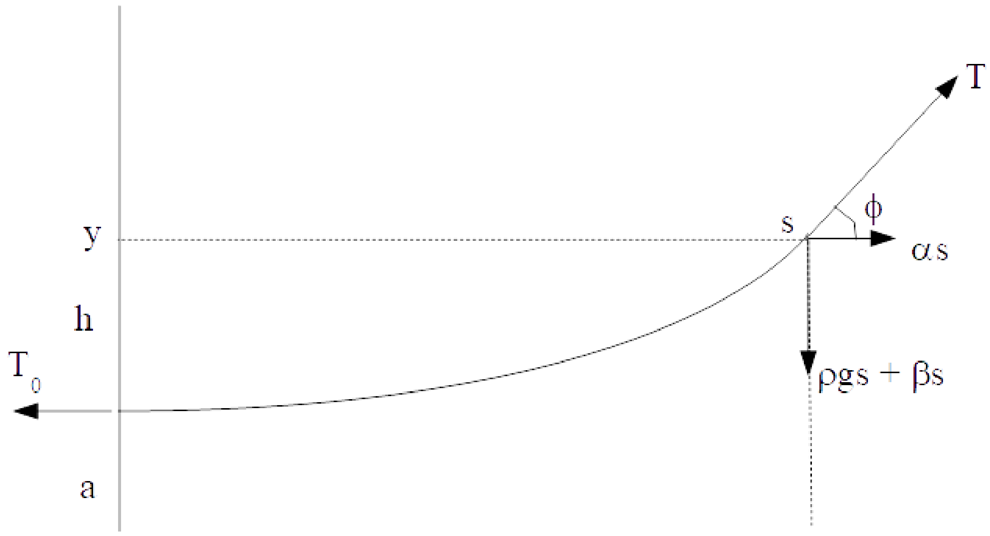


Diagram 2 - Catenary

The coordinate system for a catenary is usually defined to be vertically below the lowest point where h is the sag and a is a constant. The wind drag is represented by the horizontal (α s) and vertical (β s) components.

Considering only the cable the balance of forces are:

$$T\cos\phi - T_0 - \alpha s = 0 \quad ...(10)$$

and

$$T\sin\phi - \rho g s - \beta s = 0 \quad ...(11)$$

T will be the tension due to the weight and wind loading on the cable up to the position s.

Rearranging and dividing gives

$$\tan\phi = \frac{dy}{dx} = \frac{\rho g s - \beta s}{T_0 - \alpha s} \quad ....(12)$$

It is convenient to set

$$a = \frac{T_0}{\rho g - \beta} \qquad b = \frac{\alpha}{\rho g - \beta} \quad ...(13)$$

then

$$\frac{dy}{dx} = \frac{s}{a - bs} \quad ...(14)$$

The formula for an arc gives

$$\frac{ds}{dx} = \sqrt{1 + \left(\frac{dy}{dx}\right)^2} = \sqrt{1 + \left(\frac{s}{a - bs}\right)^2} \quad ...(15)$$

then

$$\frac{dx}{ds} = \frac{1}{\sqrt{1 + \left(\frac{s}{a - bs}\right)^2}} \quad ...(16)$$

and

$$\frac{dy}{ds}=\frac{dy}{dx}\frac{dx}{ds}=\frac{s}{a-bs}\frac{1}{\sqrt{1+(\frac{s}{a-bs})^2}} \quad ...(17)$$

Integrating

$$x=\int_0^s \frac{1}{\sqrt{1+(\frac{s}{a-bs})^2}}ds \quad ....(18)$$

$$y=\int_0^s \frac{s}{\sqrt{(a-bs)^2+s^2}}ds \quad ...(19)$$

Given x and y, s is found by using the inverse of the integrals but we must remember that the zero of the x and y coordinates are with reference to the lowest point on the catenary. In our case the cable will be shortened progressively for a constant tension and so the lowest point will be continuously changing.

Rather than modelling the catenary we will simplify the model by keeping the cable straight and rotating it about the winch as the glider climbs.

The cable length then has a simple relationship to the glider position:

$$s=\sqrt{x^2+y^2} \quad ...(20)$$

and

$$\sin\phi=(\frac{y}{s}) \quad ...(21)$$

$$\cos\phi=\frac{x}{s} \quad ... (22)$$

and equation (9) becomes

$$\frac{T\,x\;-D_s y\;-D_v\sqrt{x^2+y^2}}{\tan(\psi+\theta)}\;-T\,y\;-D_s x\;-Mg\sqrt{x^2+y^2}-\rho\,g=0 \quad ...(23)$$

The cable drag can be decomposed into a component perpendicular to the cable due to the motion of the cable through the air as the glider rises and a horizontal force due to the wind over the cable.

$$D_c=D_s+D_v \quad ...(24)$$

The aerodynamic drag on an object moving in a fluid is :

$$D=(\frac{1}{2}\mu\,v^2 C_D A)\;\;\mathbf{v} \;...(25)$$

where μ is the density of air, v the velocity of air relative to the element, A the area normal to the motion relative to the air and C_D is the drag coefficient dependent upon the shape of the element and **v** is the unit vector. For a cylinder in a high Reynolds number flow C_D is approximately 1.2.

For the cable A = δ per unit length where δ is the diameter of the cable and so the drag per unit length is:

$$\gamma \;=\; (\frac{1}{2}\mu\,v^2 C_D\delta) \quad ...(26)$$

For a straight cable rotating about the winch the velocity is the wind plus the angular velocity of the wire the drag due to the velocity of the cable:

$$D_s = \int_0^s \gamma\, dr \;=\; \frac{1}{2}\mu C_D \delta \omega^2 \int_0^s r^2\, dr \quad \text{...(27)}$$

where

$$\omega = \frac{u \sin(\psi+\phi)}{s} \quad \text{...(28) at the point P,}$$

hence the drag on a cable of length s perpendicuar to the cable will be:

$$D_s \;=\; \frac{1}{6}\mu C_D \delta s \left(u \sin(\psi+\phi)\right)^2 \quad \text{...(29)}$$

The drag of the wind moving over the cable at an angle φ is:

$$D_v = \frac{1}{2}\mu C_D \delta s \left(v \sin\phi\right)^2 \quad \text{...(30)}$$

We now have all the relationships we need for a numerical soution to the motion of the glider being launched by winch.

Appendix B – Measured Launch Profiles

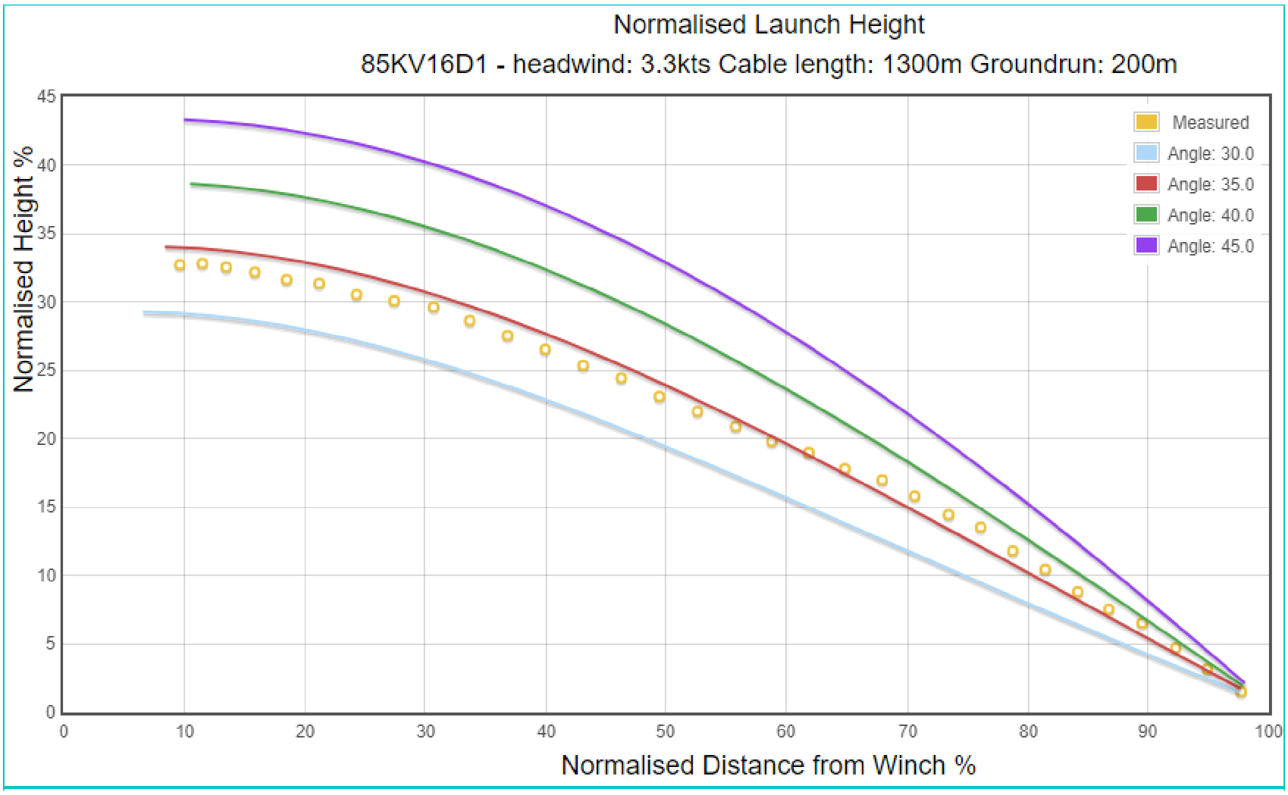


Figure B1 – Ventus 2cxa

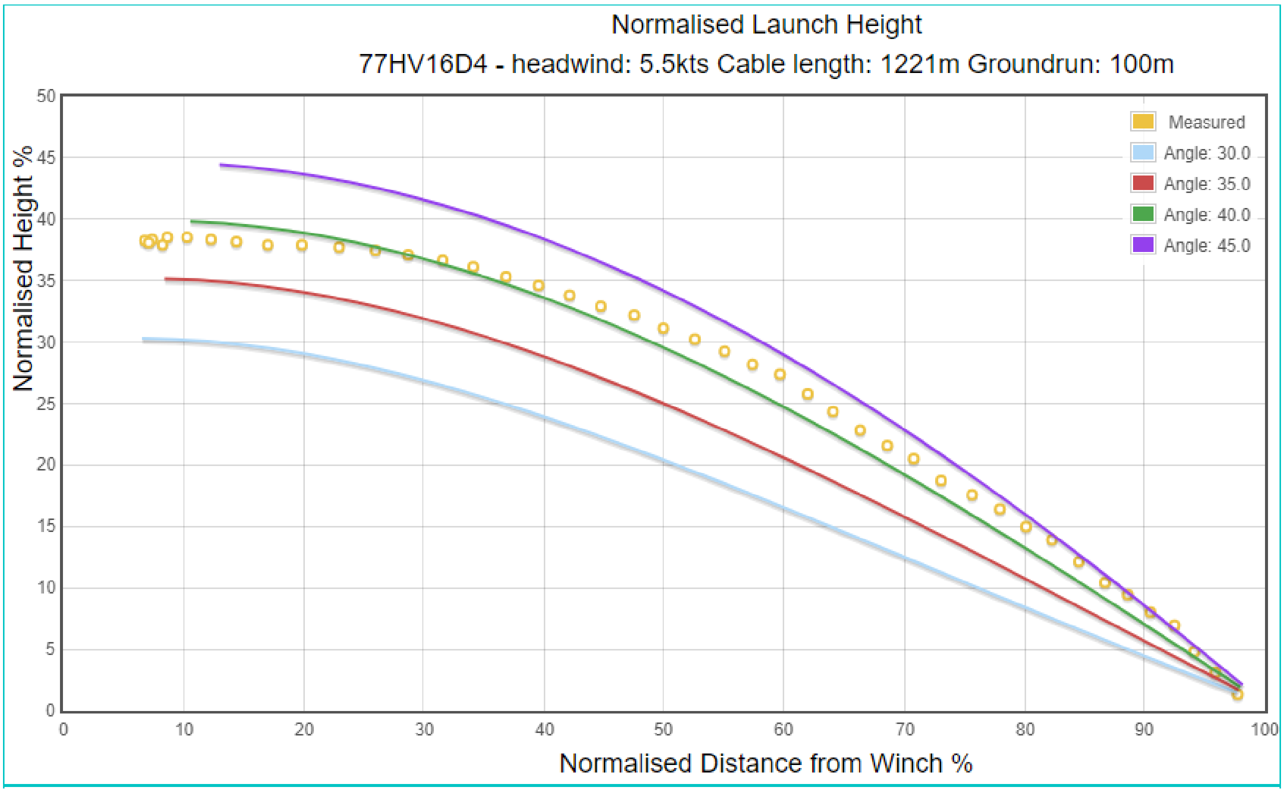


Figure B2 – Ventus 2cxa

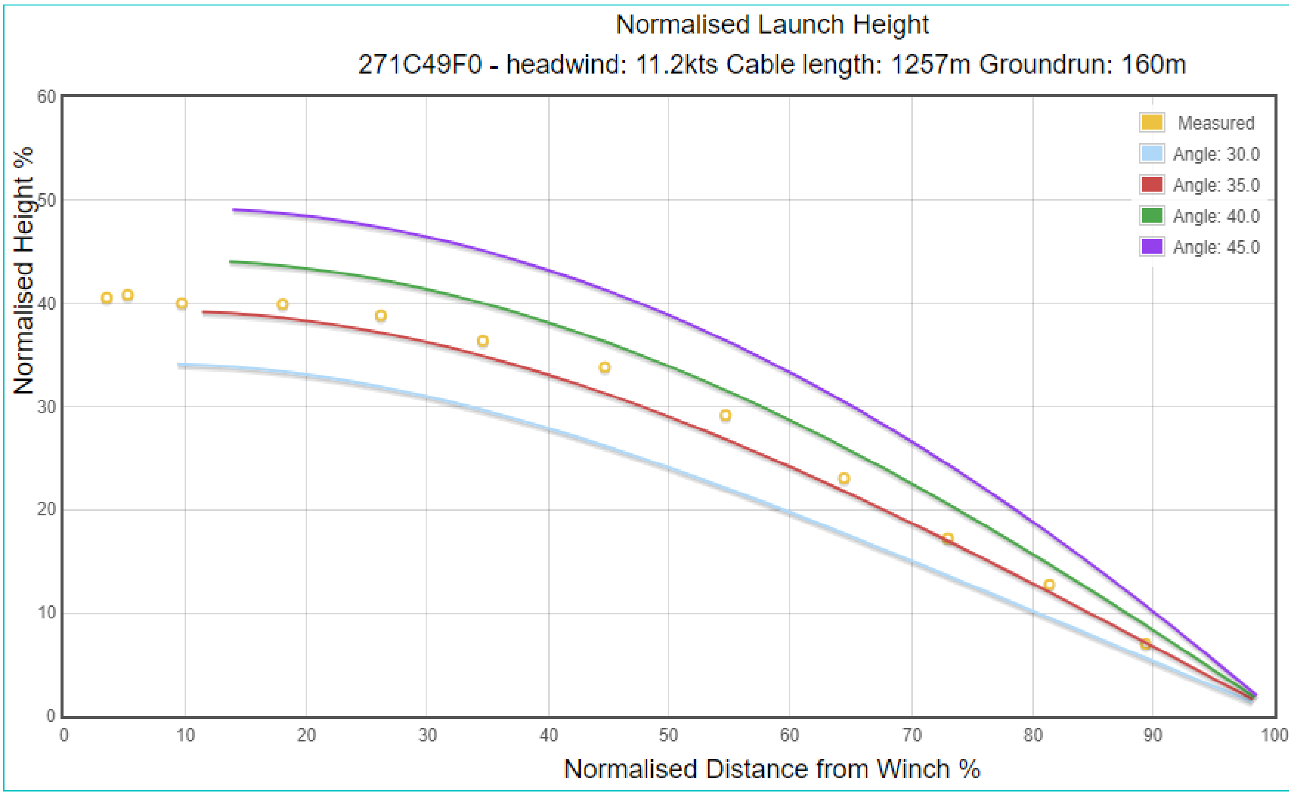


Figure A3 – Discus B

Appendix C – Chute Drag Coefficient Measurement

The average chute descent speed with complete cable attached was measured so that the chute's drag goefficient could be derived. This section derives the equations used for the measurements.

The drag force on the chute is balanced by the weight of the chute and cable attached:

$$mg+\rho g s=\frac{1}{2}C_D\mu\pi r^2 w^2 \quad \text{...c1}$$

but as the cable length s is reducing from an initial length s_0 the descent velocity w will decrease because the weight on the chute is decreasing. The velocity can be expressed as the change in distance with time (negative because the chute is decending):

$$w=-\frac{ds}{dt} \quad \text{...c2}$$

therefore we have a first order separable ordinary differential equation to solve:

$$\left(\frac{ds}{dt}\right)^2=a(\rho s+m) \quad \text{...c3}$$

where

$$a=\frac{C_D\mu\pi r^2}{2\mathrm{g}} \quad \text{...c4}$$

in the form of a first irder ODE where we gather the terms in s on the left:

so c3 becomes

$$\sqrt{a}(\rho s+m)^{-\frac{1}{2}}\frac{ds}{dt}=1 \quad \text{...c5}$$

integrating

$$\sqrt{a}\int_0^{s_0}(\rho s+m)^{-\frac{1}{2}}ds=\int_0^T 1\,dt \quad \text{...c6}$$

becomes

$$\sqrt{a}\left[\frac{2}{\rho}\sqrt{\rho s+m}\right]_0^{s_0}=[t]_0^T \quad \text{...c7}$$

resolves to:

$$\sqrt{a}\frac{2}{\rho}\sqrt{m}\left(\sqrt{\frac{\rho s_0}{m}+1}\ -1\right)=T \quad \text{...c8}$$

Let

$$X=\sqrt{\frac{\rho s_0}{m}+1}\ -1 \quad \text{...c9}$$

and

$$M=\frac{2}{\rho}\sqrt{\frac{C_D\mu\pi r^2 m}{2\mathrm{g}}} \quad \text{...c10}$$

then

$$T = M\ X \quad \text{...c11}$$

and so if measurements of the tine taken to fall to the ground from known drop hights then the coefficient M can be found from the linear graph of T against X and thus the drag coefficient can be found.

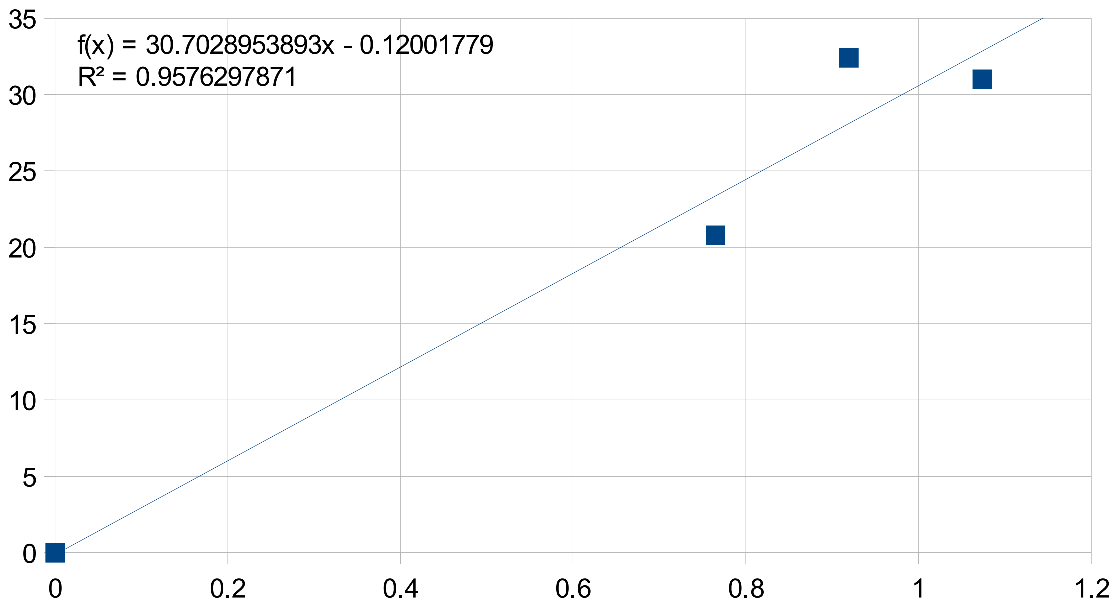
Rearranging (c8), squaring and substituting for "a":

$$C_D = \frac{T^2 \rho^2 g}{2 m \pi \mu r^2} \frac{1}{\left(1 - \sqrt{\left(\frac{\rho s_0}{m} + 1\right)}\right)^2} \quad \text{...c12}$$

C1. Measurements

Using r = 0.8 m, ρ = 0.061 kg/m, μ = 1.225 kg/m3, m = 9kg; we measure:

Drop height s_0, m	Time, s
396	32.4
312	20.8
487	31



From the measurements in the above table the value of $C_D = 0.77 \pm 0.07$

Therefore, in the worst case, for the chute assembly without cable, the descent velocity is 9.6 +/- 0.9 m/s. More drop tests will be required to reduce the uncertainty in the result.

References

1. "Flight on the winch", P.J. Goulthorpe, Sailplane and Gliding, June/July 1996 https://s3-eu-west-1.amazonaws.com/bga-sg-archive/Sailplane+&+Gliding+1955+to+2000+-+274+mags+9.32GB/volume_xlvii_no.3_june_july_1996.pdf
2. "The Mechanics of the Winch Launch", John Gibson, BGA Manual. https://www.bfgc.co.uk/Technical/BGAmanual.pdf