THE IMPACT OF WIND PROFILE ON HIGH ALTITUDE FLIGHTS BY FIN STABLISED ROCKETS

Phil Charlesworth MSc CEng

UKRA 1232 L1 RSO

Summary

This paper reflects conclusions which the author has reached as a result of his involvement in such an altitude attempt prior to leaving the team in early 2004. It is based on approximately 18 months research and consultation with academic and industrial colleagues.

The paper considers how the wind changes speed and direction with altitude, and how these changes affect the various stages of flight of a fin stabilised rocket. It concentrates on two main areas: Firstly it considers the initial few seconds of flight, the causes of weathercocking and its impact on launch angle and ballistic range. It then considers parachute drift through the high and low level winds and a method of predicting likely touchdown areas.

The paper considers the relationship between these factors and the design of the rocket, establishing that the process of rocket design and launch conditions are closely interdependent. It links these ideas together by proposing a system for establishing launch conditions and criteria for informed "launch/don't launch" decisions by the RSO.

TABLE OF CONTENTS

Table of Figures

1. Introduction

The majority of rocket flights within the UK are made by single stage rockets with maximum attitudes of under 10,000 ft. Such flights can be expected, in normal flying conditions, to land within a short walk of the launch site. Experience indicates that a large farm, or contiguous set of fields, is adequate for this type of recreational flying.

A minority of flights aspire to reach higher altitudes, whether for the personal challenge or as part of campaigns to set new altitude records. Flights of this type have the potential to travel greater distances, whether by parachute drift from high altitudes or ballistically due to a failure of the deployment system. There are many other means by which a rocket could land outside the range, for example a motor malfunction which could cause it to ignite at some random launch angle. It is probable that rockets designed for high altitude would land outside of a normal club flying site.

The UKRA safety code considers these circumstances in section 3, when it requires minimum site dimensions based on the motor impulse or the apogee altitude, whichever gives the greatest result. The RSO for the flight can grant concessions to the site dimensions. There is also a requirement that the worst case scenarios of a stage misfire or failure of a recovery device should be considered.

The safety code, as currently worded, leaves some ambiguity as to how distances corresponding to worst case scenarios should be calculated and who should calculate them. Section 4 places the RSO in the situation of making the "launch/don't launch" decision, possibly based on incomplete information; it is unlikely that the RSO will have knowledge of the current wind profile or how the rocket will respond to the changes in wind profile. In such circumstances an RSO should refuse permission for the flight, not because it is unsafe but because of lack of information on which to authorise it.

The safety code also requires landowners permission to be obtained for the recovery area. For normal rocket flights, whose recovery direction and distance are dictated by low level winds, this is likely to be some distance downwind. For high altitude flights the high level winds, which can be at right angles to the low level wind, will influence the location of the recovery area. It is likely that this will not be "downwind" from the launch site and may be much further away due to the longer descent time.

Getting landowners permission over a large potential recovery area may well be impractical. Furthermore the larger area may contain villages or farms, increasing both the difficulty of getting multiple permissions and the potential for damage to property.

Making the decision to permit or refuse a high level launch clearly requires a detailed knowledge of prevailing conditions throughout the atmosphere, and the ability to translate these conditions into potential landing sites associated with the successful operation of the rocket, or failures of either the motor or recovery systems. This paper examines some of the factors which contribute to that decision and proposes a standard approach to determining flight conditions. It expresses some of the self-evident principles of rocketry in simple maths, then uses these mathematical models to link the design of the rocket and launch system to a set of “safe to launch” criteria. It is intended to supplement, rather than replace, the existing site dimension criteria.

This paper summarises the conclusions of the author’s research and consultation into these issues over the period mid 2002 to early 2004. It is based on analysis and simulation of the factors which affect flight dynamics, resulting from consultation with academic and industrial colleagues. The basic mathematical models can be found on the author’s website. These were turned into simulations using Excel, Rocksim and MATLAB.

2. The Wind

Wind systems which affect rocket flight can be considered in 3 layers:

- Surface wind
- Low level wind
- High level wind

This section briefly introduces the characteristics of each of these layers, setting the scene for the subsequent discussions.

Wind is caused by differences in the local temperature of air. As air increases in temperature its pressure increases, and as it cools its temperature decreases. At a macro level, this causes high and low pressure regions in the atmosphere. Air flows from the high pressure systems to low pressure systems, however the flow is not constant in either direction or speed.

The Coriolis affect causes the air at lower levels to spiral into low pressure systems, or out of high pressure systems. At high level the winds flow directly into and out of these systems. Furthermore the speed of the wind varies with the rate of change of pressure.

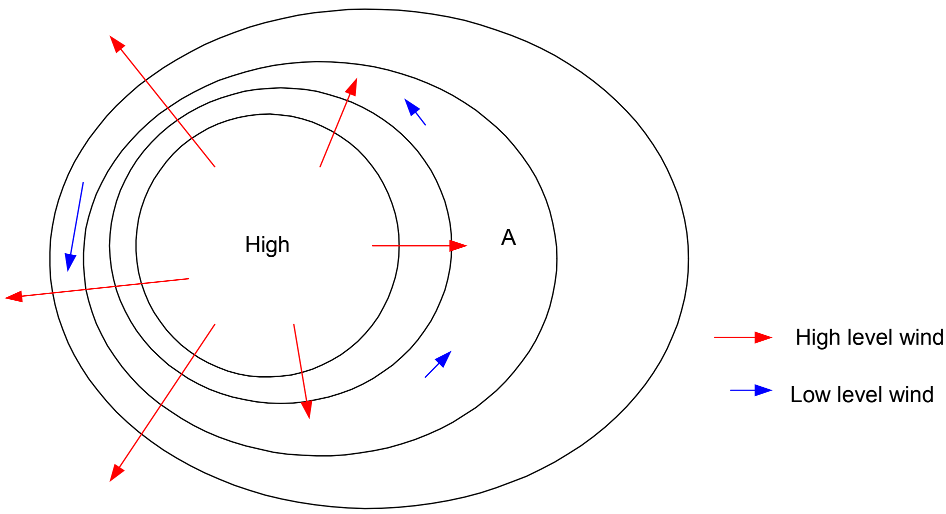

Figure 1 - High and low level winds

The effect of this is that low level winds will circulate around pressure systems, and high level winds move directly into or out of such systems. the wind speed and direction thus changes with altitude. The change from low level to high level occurs in the region of 5,000 ft to 10,000 ft depending on conditions. In this region both wind speed and wind direction will change, and the region will contain some degree of turbulence.

A further factor is that hot air is less dense and will rise, whereas cool air is more dense and will sink. Rockets will descend more slowly in rising air, and faster in sinking air. Such effects can be very local.

As most rocket flight take place under the influence of low level winds, that is less than 10,000 ft, simple 2-D models of the atmosphere are generally sufficient. Once a rocket enters the high level winds the increased speed and change of direction need to e taken into account.

The wind observed at, or near, ground level at the launch site is not a true representation of the low level wind. This wind, sometimes referred to as the "surface wind", is not a wind per se but reflects the results of the interaction between the low level wind and surface features. Its effects are generally not felt more than a few hundred feet above the ground, but are very significant at ground level.

Surface wind is affected by the shape of the terrain. When it encounters rising ground the wind accelerates, an effect predicted by Bernoulli's equation. Close to the ground the wind forms eddies and turbulence due to its interaction with obstructions such as trees, hedges and buildings. These effects can cause local and often large variation in windspeed and direction which strongly influence the first few seconds of flight. Weathercocking, and the subsequent launch angle of the rocket, will be dictated by the surface wind.

3. Practical Considerations

3.1 Issues of High Altitude Flight

When a rocket flies to high altitude two main sets of criteria will dictate where its lands. The first is its ballistic range, which is the distance it will coast in the event of some failure. The second set of criteria is the distance which the rocket will drift during parachute decent. Each of these distances can be linked to a set of factors which include:

- High altitude windspeed and direction
- Low altitude windspeed and direction
- Rocket design (moment of inertia, susceptibility to wind torque)
- Launch tower design (length, stiffness)
- Failure modes of motors or deployment systems
- Rate of descent
- Apogee altitude

By analysing these factors it is possible to understand and "tune" the launch criteria. It becomes possible to trade off aspects of the design, for example minimum rail length against desired launch angle, surface wind speed against fin area, location and moment of inertia. This reduces the dependence on intuition, and allows informed decisions to be made during the design phase, launch campaign and on the day.

3.2 Ballistic Range

If a rocket is launched at an angle other than vertical and the deployment mechanisms fail, then it will follow a parabolic trajectory. It will land some distance from the launch site, and this distance is called the ballistic range.

The classical approach to calculating ballistic range is to use the vertical velocity component to calculate time of flight the use this flight time to calculate the horizontal range. The assumptions in this method are that the only retarding acceleration is due to gravity, so that the horizontal velocity component is constant. The ballistic range thus depends on the angle at which it is launched and its velocity.

Consider a simple textbook example of a particle launched at a velocity V and a launch angle θ, as shown below.

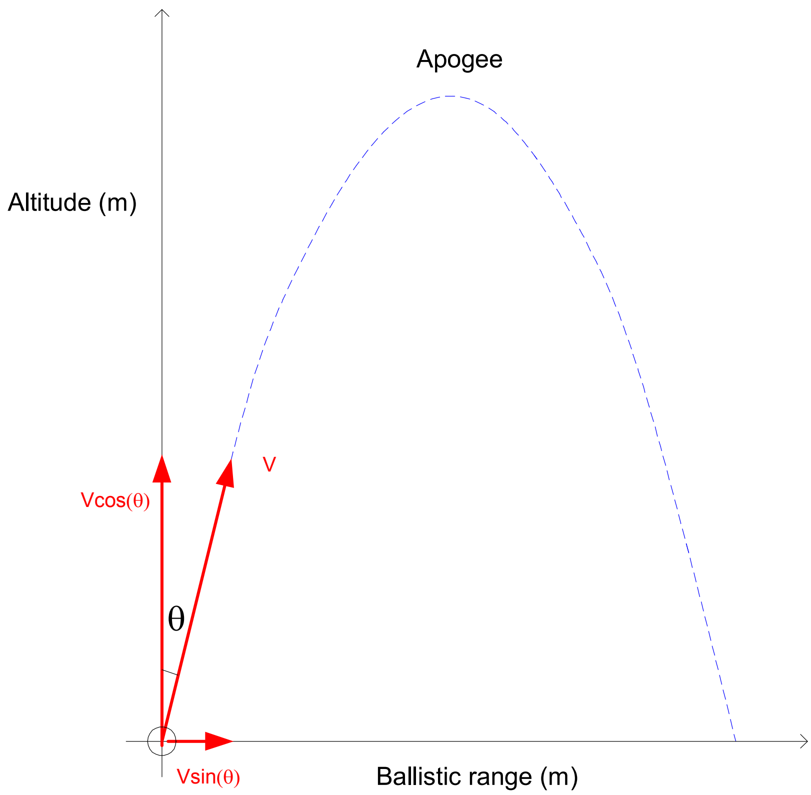

Figure 2 - Ballistic Range Model

Resolving the initial velocity into vertical and horizontal components we get:

$$V_{vertical} = V\cos(\theta)$$

$$V_{horizontal} = V\sin(\theta)$$

Solution of the equations of motion for the vertical component gives us the time t taken to reach apogee. After apogee the projectile will fall for a further time t until it lands. The total flight time is thus $2t$.

The horizontal component of velocity is unimpeded, as the acceleration on the rocket in that direction is negligible. The distance travelled in time $2t$ is thus the ballistic range, which can be found from:

$$\textit{Ballistic range} = r_{ballistic} = 2Vt\sin(\theta) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

This simplistic analysis ignores the third force, drag, as it makes the equations of motion practically insoluble by analytic means. We can, however, take drag into consideration by using numeric solutions based on Euler's method or the Runge-Kutta method, both of which are used in Rocksim for their computational simplicity. These can give us values of V and t for any particular rocket flight. These values can be fed into equation 1 to produce an estimate of ballistic range.

3.2.1 Maximum Ballistic Range

It can be shown that the maximum ballistic range occurs when θ=45 degrees. The maximum range can be shown to be twice that apogee from vertical flight. This rule is often called “Tartaglia’s rule” after the mathematician who discovered it while investigating the behaviour of artillery.

Such a situation would not occur in normal flight, but as a result of some type of failure. It is not possible to consider all failure modes, but two immediately spring to mind. The first is a structural failure of the launch stand, which is uncommon and can be overcome by good design. The second is a failure of the motor, for example it fails to fully ignite causing the rocket to tumble as it leaves the launch rail. Ignoring the laxative effects of such an event, a rocket expected to reach 15000 ft/5 km apogee has a maximum ballistic range of 10km. As few launch sites are 20km across, such a flight would undoubtedly land outside the range, and would have considerable potential for adverse publicity. A rocket intended to reach 40000 ft/17 km has a maximum ballistic range of 34 km, requiring a launch site 68km across!

While such a motor failure is uncommon it is not unprecedented. Most HPR fliers will have seen launch failures of this type. In mitigation, the maximum range would only be achieved by failure of both the motor and deployment system on the same flight. It is more probable that a low angle flight would be terminated by parachute deployment.

If CPR is used, this deployment would occur at about half the maximum ballistic range and about half the apogee altitude. A rocket with a planned apogee of 15,000 ft/5km would this deploy at a range of 5km would drift from 7,500 ft. Rockets with timers or standard delay grains set for 15,000 ft would deploy beyond 5km while travelling at high velocity. The site dimensions table in the safety code assumes the greater of half this distance, in this case 2.5 km radius, or half the site dimension corresponding to the impulse of the rocket. This is reasonable for the current generation of high altitude rockets, but may need to be reconsidered as designs improve and records increase.

3.2.2 Expected Ballistic Range

The expected ballistic range for a rocket which launches successfully, but suffers a failure of its deployment system, can be calculated from equation 1.

The graph below plots ballistic range against launch angle for a 10kg, 4 inch diameter, rocket. The two altitudes, 15,000 ft and 40,000 ft, reflect the current records for flights inside and outside the UK. Knowledge of a particular rocket design would permit equivalent graphs to be produced quite simply.

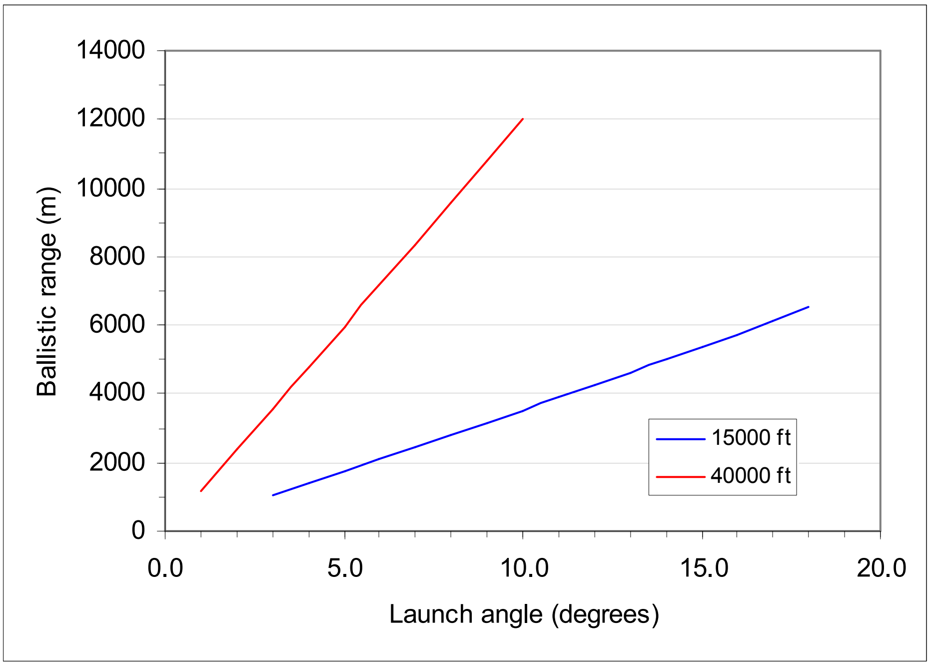

Figure 3 - Ballistic Range vs Launch Angle Example

As an example of how to use Figure 3; if the nearest inhabited area is 4km from the launch site, then a launch to 15,000 ft would be acceptable if the launch angle could be assured to be within 11 degrees, whereas a launch to 40,000 ft requires a launch angle of no greater than 3 degrees. Unless the launch system and conditions could provide a high degree of confidence that the launch angle would not exceed 3 degrees, a launch to 40,000 ft would not be advisable from that site.

As seen earlier, the ballistic range is a function of initial velocity and launch angle. If launch angle can be kept low, the ballistic range can be reduced. This leads to the conclusion that any launch attempt needs to be supported by analysis of the launch angle and the consequent ballistic range. As launch angle is determined by weathercocking, and weathercocking is due primarily to the torque applied from the wind pressure on the rocket and the moment of inertia of the rocket about its CG, there is a clear relationship between launch conditions and rocket design. This relationship allows anyone comfortable with basic aerodynamics and differential equations to make a good estimate of the maximum permissible low level windspeed for a launch.

The velocity at which the rocket leaves the launch rail is also significant. It is self evident that a longer launch rail will support the rocket to a higher forward velocity. The higher velocity airflow over the fins generates lift which opposes any torque induced by the wind. The length of launch rail required for any given rocket in any windspeed is thus estimable on a case-by-case basis.

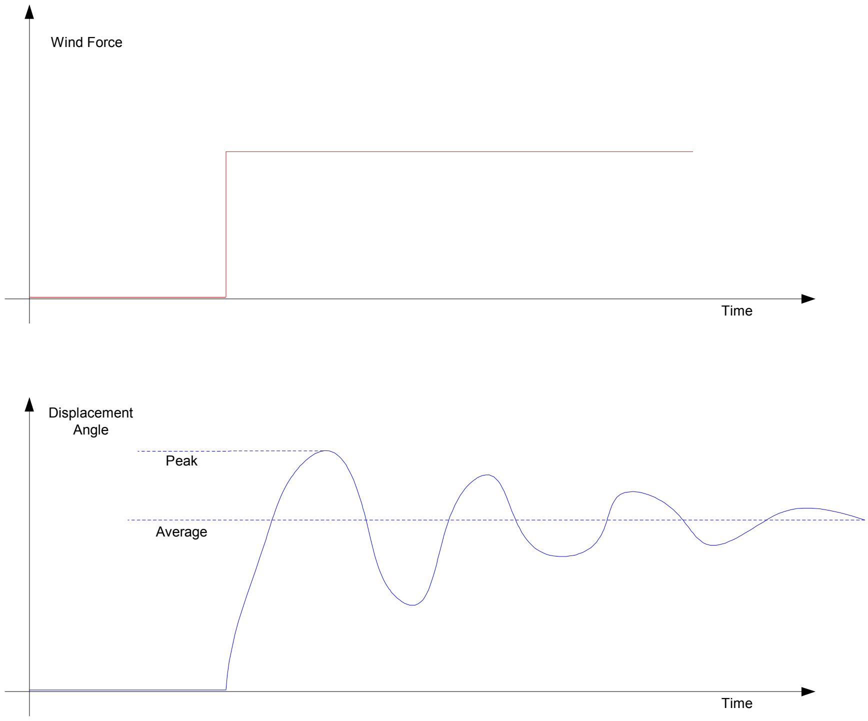

Figure 4 - Angular Displacement by Wind

If we consider a suddenly applied wind force, analogous to the force applied when the rocket leaves the rail, the rocket will rotate about its CG. This angular displacement is opposed by the lift from the fins, which increases as the angle of attack increases. The opposition of the wind and lift forces causes the rocket to oscillate about its CG, eventually converging on an average displacement. Figure 4 shows the typical response to a sudden change in crosswind.

The frequency of the oscillation about the average displacement angle, and the time it takes to settle to the new angle, are strongly influenced by the mass distribution of the rocket (moment of inertia) and the rocket's dimensions. In a poorly designed rocket this oscillation will never terminate, or even increase. This corresponds to the definition of an unstable rocket. Alternatively the rocket may settle very slowly, corresponding to an over stable rocket. Ideally the rocket should be designed to settle to the average angle as quickly as possible. Empirically, this leads to the rule of the CP being 1 or 2 diameters behind the CG. This rule of thumb is not universally applicable and starts to break down with tall slender rockets such as are used to reach high altitudes. The behaviour of rockets with transitions, parallel staging, and multiple fin sets can also diverge significantly from this rule of thumb.

A well designed rocket will settle quickly at the average displacement angle, and for practical purposes this angle can be considered as the launch angle θ.

The low level wind speeds, rail length, and the dynamics of a particular rocket should be analysed by the rocket designer so as to ensure understanding of launch conditions. It is strongly suggested that such calculations are checked independently as a prerequisite to launch approval by the RSO.

3.3 Drift

The troposphere is not a predictable environment, as shown earlier. The high level winds flow from high pressure areas to low pressure areas, whereas the Coriolis effect causes low level winds to circulate around these areas. The lower and high level winds can be up to 90 degrees apart, so the region where they interact is subject to some turbulence. Wind direction and speed in this region can be very unpredictable, and its height and depth vary considerably. Local wind effects also influence the air flow. These include rising and falling currents of air due to ground heating, and air masses rising over hills.

The Met Office has difficulty predicting the behaviour of the wind and airflows in the troposphere, so it is unreasonable to expect UKRA members to do any better.

Drift of a relatively light object such as a spent rocket is thus a highly complex subject, as the behaviour of the atmosphere is not regular and predictable but statistical. Predicting exactly where a rocket will touch down is impractical, however models may be derived which identify where a rocket should touch down, and defining the area surrounding that point where you have high confidence that it will touch down.

It is clear that establishing the touchdown point of a rocket requires prediction of drift through the high and low level winds. Consequently a 3D model of the atmosphere is required. Programmes such as Rocksim make the simplifying assumption that wind changes in neither speed nor direction with altitude, so drift can be plotted as a straight line from apogee. This assumption is adequate for flights in the low level winds where direction is usually within 10 degrees and the influence of changes in windspeed profile is not significant for short descents.

Descent from high altitude requires that the direction and speed of both the low and high level winds be considered. The longer descent time, higher windspeeds at high level, and difference in direction between low and high level winds result in a touchdown point which can be for from that predicted by simple 2D models such as Rocksim.

A simple 3D model is described in the following paragraphs. The model is based on that used for the recovery of stratospheric balloons and by freefall parachutists.

3.3.1 Drift Model

If we cannot describe the path which a descending rocket will follow from apogee, maybe we can consider its behaviour over short distances and apply some statistics to its behaviour.

Imagine a rocket falling through a slice of the atmosphere which is not very thick, maybe a few hundred feet. Over that distance it will be subjected to a crosswind, so the true path will not be vertical but will follow the vector sum of the descent velocity and wind velocity. If we consider the whole descent from apogee as a sequence of *n* layers, where the descent velocity vector is approximately constant (neglecting the atmosphere's density profile) and the wind velocity changes with each layer, we can establish the ideal touchdown point.

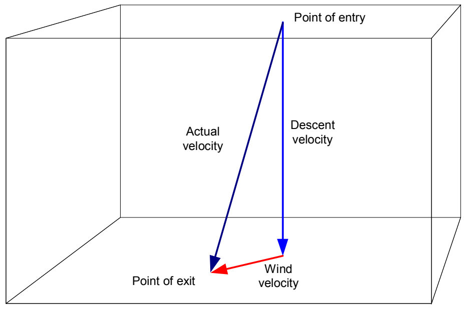

Figure 5 - An Ideal Wind Layer

In practice, the wind vector will vary in each layer. We can refine the model by assuming that the magnitude of the vector has a mean value, obtained from a reliable source and a standard deviation. The exit from the layer is thus not a point but a probability distribution based around that point.

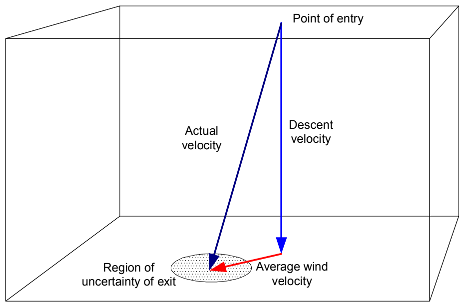

Figure 6 - A Practical Wind Layer

If we assume that the amplitude of the wind velocity vector is normally distributed about the means speed, and assume a standard deviation, we can link the radius of the circle to the probability of the exit point lying within that circle. The linkage is:

Diameter	Probability
1 SD	68.2%
2 SD	95.4%
3 SD	99.7%

Why select a normal distribution? Two reasons: firstly many natural occurrences exhibit this distribution, and secondly because of its mathematical convenience.

By considering the effect of descent through *n* layers we can establish an ideal touchdown point, and the probability of the actual touchdown point lying within a circle around this point.

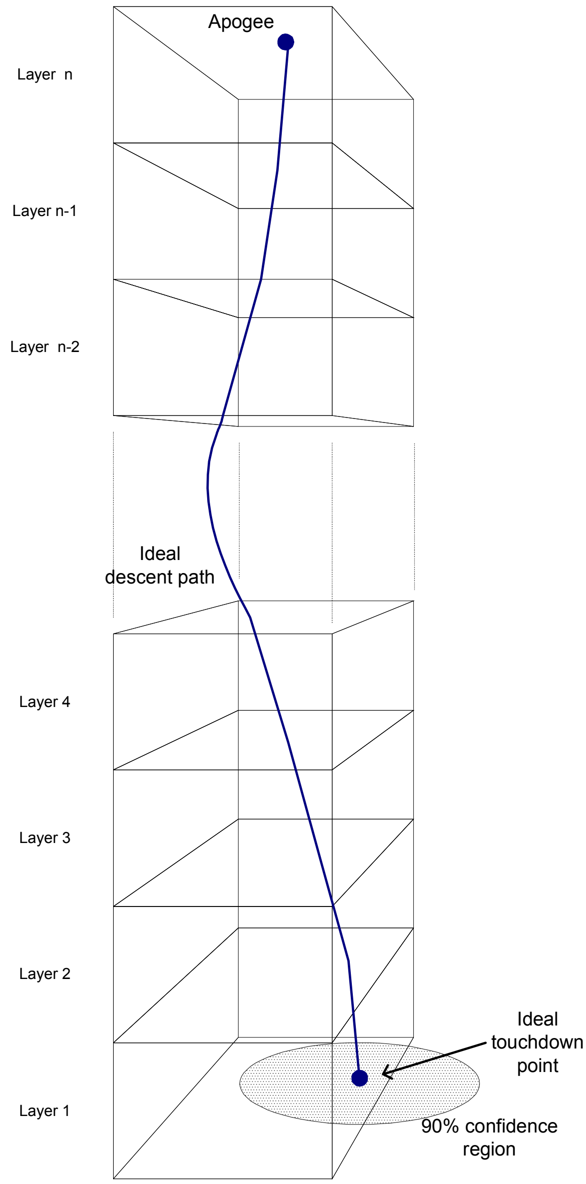

Figure 7 - Drift Through Multiple Wind Layers

3.3.2 Implementing the Drift Model

The model was written as an Excel workbook. The input data was interpolated from the Met Office F214 for the Bristol area for 0600 to1200 on a day which looked like a good flying day. The layers were each considered to be 1000 ft thick. A drogue descent rate of 60 mph from an apogee of 40,000 ft was modelled. The F214 data input is shown below:

INPUTS

F214 Input

Alt (k ft)	Heading	Variable	Speed	
24	130	0	53	
18	130	0	48	
10	130	0	40	
5	60	1	25	
2	60	1	15	
1	40	0	10	
0	40	0	8	From local observation

Descent Input

Altitude	40	,000 ft
Descent rate	60	mph

Figure 8 - Data for Example

The data was plotted onto heading and speed graphs. In order to extend the F214 data to above 24,000 ft three assumptions were made:

1. The peak windspeed occurs at 40,000 ft, corresponding to the average altitude of the peak over the UK.
2. The windspeed dies off linearly above this altitude until it reaches a negligible speed in the tropopause, around 60,000 ft.
3. The high altitude wind has a constant heading above 24,000 ft

These three assumptions are meteorologically reasonable, and should not introduce large errors into the model except in unusual met conditions. As no sensible rocketeer would launch in those conditions, the assumptions are viewed as practical. The wind profile on the day is plotted below.

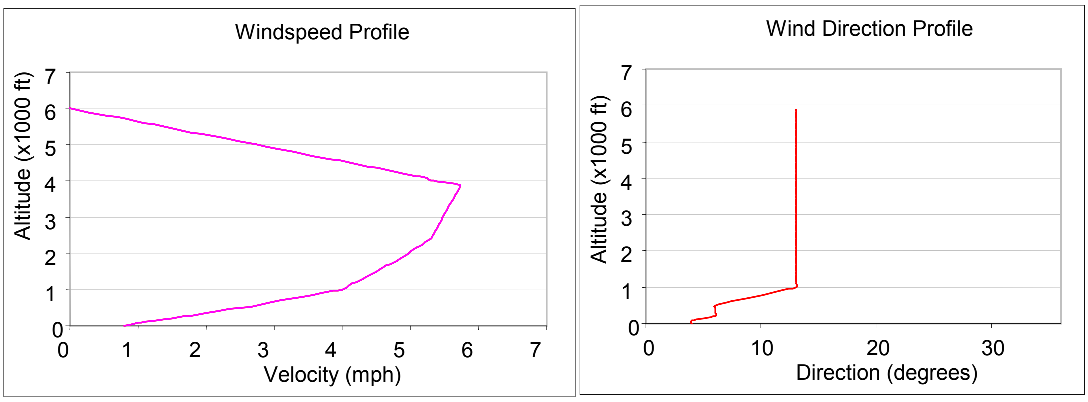

Figure 9 - Wind Profile for Example

It was assumed that the standard deviation of the windspeed was the mean windspeed divided by 6. This allows the very unlikely probability of the windspeed being 0 mph and the equally unlikely probability of gusts being twice the mean speed. Confidence levels of 99.7%, or 3 SD, were expected. The results of this simulation are shown below.

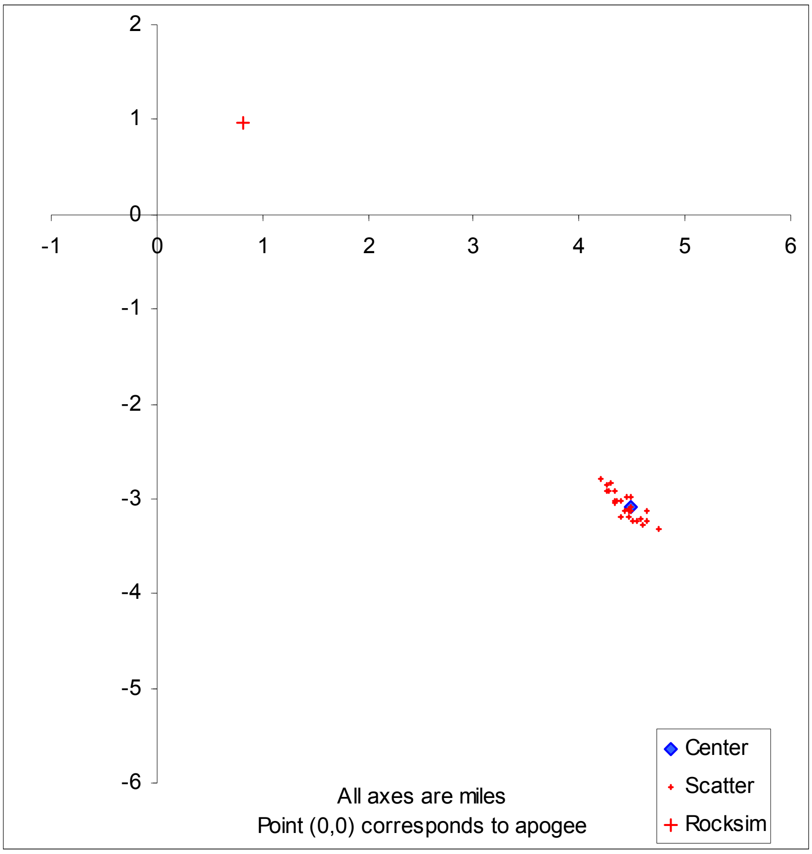

Figure 10 - Drift Simulation

The plot on Figure 10 shows the scattering of potential touchdown points. These are centred on a point 5.5 miles SE of the apogee point (NOT the launch site) and scattered in a one mile long ellipse. The location of the touchdown area, and orientation of the major axis of the ellipse, suggest that the touchdown area location is strongly influenced by the direction and speed of the high altitude wind. Only 25 points were plotted for clarity.

This scattering is intuitively correct, since 75% of the descent would be through the high altitude wind which was, on the day of the example, moderately strong and blew on a consistent heading of 130 degrees. This wind would have influenced descent from 40,000 ft to 10,000 ft, over 75% of the path.

Rocksim's 2D model puts the touchdown point about 1.2 miles NE of the apogee point, some 5 miles away from the predicted point and in the wrong compass quadrant. It is possible that a recovery team would be incorrectly deployed and watching the wrong part of the sky if a 2D model was used, with consequent risk of loss of the rocket.

3.4 Sources of Weather Information

It is clear from the above that the low and high level wind profiles have a very significant influence on the launch and recovery criteria for a high altitude rocket. Practical sources of wind profile information tend to have their limitations, the most significant of which are the timeliness and granularity of the information. A few sources of data have been uncovered while researching this subject. While not exhaustive, this list may help to uncover the practical issues surrounding making a launch decision based on weather conditions.

3.4.1 Broadcast Weather Forecasts (Low level wind)

Weather forecasts from the TV and radio only provide mean windspeed data at 10m above ground level for a 12 hour period over a wide area. Such data is of little value in planning a high altitude launch.

3.4.2 Local Weather Station (Surface and low level wind)

A weather station at the launch site would be an unreliable source of information. The surface wind can vary a lot due to terrain profile and local obstructions. A local weather station would need to measure wind at the launch site at several altitudes. Typically this would be from ground level to an altitude corresponding to that where any weathercocking tendency is negligible. Building a weather station on a mast of this height may be impractical.

There is some potential for near real time measurement using, perhaps, lightweight model rockets and observers. By simultaneously plotting the drift of a descending model rocket a 3-D picture of the wind speed and direction could be established. By radioing the results of several observers back to a suitable PC, the surface and low level profile could be quickly computed. After several flights (to eliminate any rogue results) a good picture could be established in near real time.

3.4.3 Met Office UK Low Level Spot Wind Chart (low and high level wind)

The Met Office provides a free lower wind service up to 24,000 ft at spot heights of 1, 2, 5, 10, 18 and 24 kft. This service, known as the F214, is part of its aviation services, and is intended for flight planning purposes. Interpolation between the spot heights can give a good idea of the wind profile below 24,000 ft, but extrapolation beyond these altitudes requires caution. This service only covers a few points over the UK, and gives a 6 hourly mean value for horizontal wind components. It doesn't cover windspeeds and directions at ground level and through the critical first few seconds of flight.

Typically the F214 can be used to give 6 to 12 hours notice of conditions, which is adequate for its target audience of flight planners but may not be adequate notice to make a decision as to whether to travel to a launch site and prep a rocket.

3.4.4 Local Meteorology Sources (low and high level wind)

Local sources such as the met officer on civilian and military airfields may be able to provide more comprehensive meteorological data. Like the F214, they may not be able to offer much advance notice of particular wind conditions, but their local experience may be able to assist with identifying periods when conditions are likely to be come favourable. A launch team could then be brought to a state of readiness for a possible launch window, and preparations be made while watching the short term weather information.

Building a positive relationship with the met officer near the site is clearly beneficial.

3.4.5 Atmospheric Research Centres (low and high level wind)

The Met Office, and a number of universities, conduct measurement of the wind profile using radio techniques. Such information tends to be local to the site of the instrument, but has the advantage that it is real time and accurate. A launch site located near such an instrument could get high quality and local wind information.

The Met Office sites are used as the source of F214 information so their processed data is released every 6 hours. Also, these sites are constrained to reporting at an altitude of 24,000 ft and below. Some of the university sites look beyond the troposphere into the tropopause, and report on winds up to 100,000 ft. One university, Aberystwyth, has a mobile sounder but it only looks at low level winds. It is worth monitoring this area of research as universities may develop mobile sounders capable of looking at the high level winds, and such a capability may be available for a "one off" altitude attempt.

3.4.6 Radiosondes (low and high level wind)

There are a number of Met Office and university radiosonde launch sites around the UK. These are used to generate a range of metrological data including wind profile. Radiosonde flights are limited to a few per day, so the timeliness of the data may be less than ideal.

Radio interference issues prevent the launching of radiosondes by private individuals, otherwise this would be an ideal way of establishing local conditions. The author has not investigated the idea of inviting an authorised radiosonde launch to be made from the rocket launch site, but this may be worth exploring.

4. A Zonal Approach

The previous section established some criteria for establishing where a rocket might touch down in the event of failure or due to drift. The next significant issue is to assess the impact of either situation.

Conceptually, the models produce 4 touchdown zones:

1. A green zone, within which the rocket will touchdown if the flight goes to plan, and the rocket launches within its intended launch angle.
2. A blue zone, which is where the rocket will touchdown if the deployment mechanisms fail and the rocket flies ballistically.
3. An amber zone, which is where the rocket will touchdown if the motor misfires on launch but the deployment mechanisms work, causing ballistic flight.
4. A red zone, which is where the rocket will touchdown if the motor misfires on launch and the deployment mechanisms fail.

The zones are shown below.

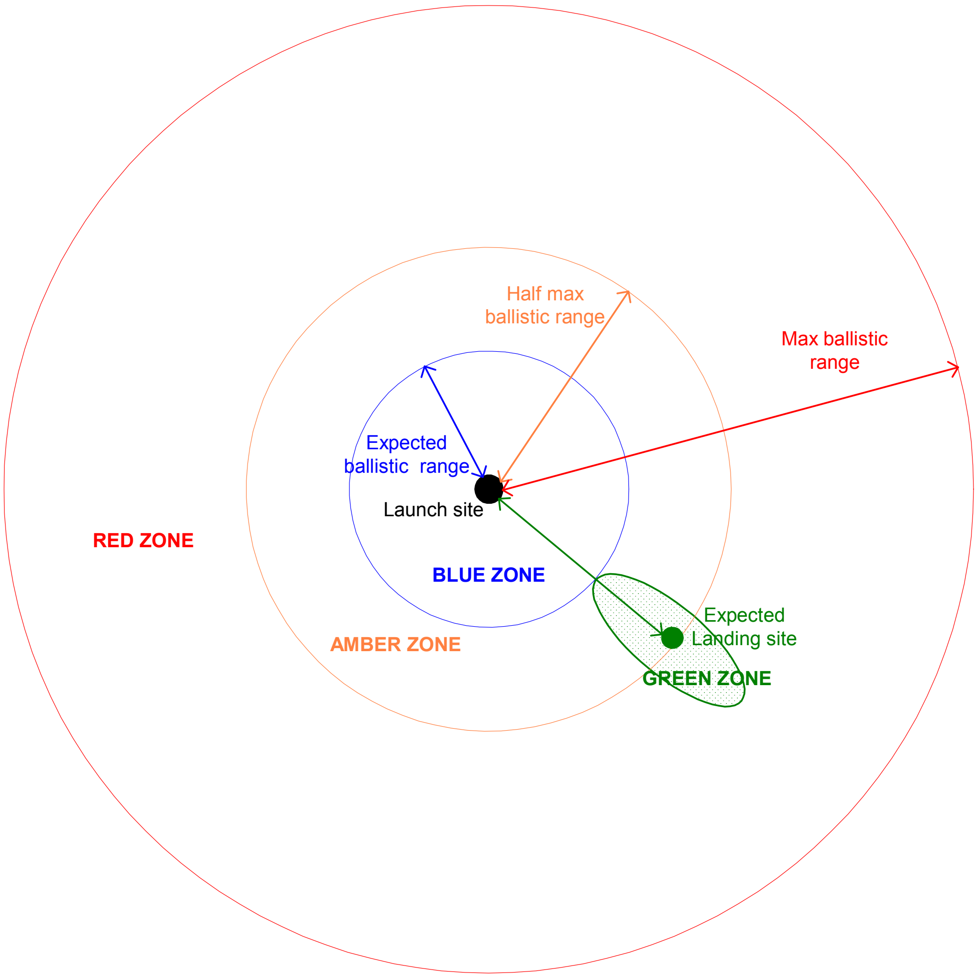

Figure 11 - Zones

It is assumed that the blue zone lies entirely within the amber zone.

The green zone will move around with its radius and location being dependent on the wind profile at the time of launch, apogee altitude and descent rate. It is necessary to plot the location of the green zone as close to the launch time as possible.

The remainder of this section considers launch constraints and how they relate to the zones. In planning a high altitude flight, and subsequent recovery, the impact of landing in each of the zones needs to be assessed. Issues to be considered include:

- Are the zones inhabited?
- Do roads pass through the zone?
- Who are the landowners?
- Are there any inaccessible areas?

4.1 Habitation

Curiously, the safety code does not comment on the presence or absence of houses in the areas in which a rocket could land. It is theoretically possible to launch in the middle of a town, provided that all the landowners give consent! In practice it would be unwise to launch if there is the possibility of the rocket landing in a populated area, so some criteria need to be set. The following criteria are proposed.

If there are any populated areas inside the amber zone then a flight should not take place from that site. If there are a small number of houses on the edge of the amber zone then the RSO may judge the risk to be acceptably small.

The blue zone should be entirely unpopulated. In writing this paper consideration was given to a "mail shot" to anyone who lives within the blue zone, however this may generate more issues than it solves.

A launch should only be permitted if simulation shows that the green zone lies entirely inside a depopulated area. There may be a case for increasing the size of the green zone to allow for random factors, such as a reduction of descent rate due to thermals.

4.2 Roads

Consideration should be given to closing any roads within the amber, blue or green zones for the duration of the flight, requiring Police involvement. A site several miles from a motorway or major route may be OK for normal flying, but could be unsuitable for high altitude flights due to the drift distances. Practically, this requires that the zones may contain infrequently used rural roads but no major routes.

The mobility of the green zone raises practical issues here: how likely is it that the police will respond to close a road in response to the short timescales associated with identifying good launch conditions and plotting the green zone? In practice the green zone may have to contain no roads.

4.3 Landowners

In normal club and event flying, all rockets will land in a contiguous set of fields for which permission has been obtained. As the size of the zones increases, the difficulty of obtaining all the landowners' permissions increases significantly. Some landowners may be relaxed about a rocket landing on their plot, others may be hostile.

One approach may be to approach landowners in which the green zone may fall, and use their responses to plot areas where the green zone may occur and where it may not. If a landowner refuses permission then a launch which shows their land in the green zone should not take place. The position becomes ambiguous where no response is received as the landowner's intentions cannot be assumed. The situation becomes more complex for a 2-stage rocket as there would be two green zones.

The ballooning community have had mixed experiences of landing without permission; in some areas there is considerable hostility, though this may be due to overuse. The British Balloon and Airship Club (BBAC) issue a monthly update on sensitive areas, and have guidelines for landing. We could learn from their experiences, and an approach to the BBAC may help to establish guidelines for rocketry.

4.4 Inaccessible Areas

If the rocket comes down in any inaccessible areas such as dense forestry, lakes or mud flats, then it's tough luck! The rocket should be considered lost. The landowner should be contacted to advise him of the event as the rocket may still be armed.

5. Responsibilities

Effectively, this proposal requires that the individual or group planning to launch a high altitude rocket flight presents the RSO with a data pack. This can be done in 2 stages.

Stage 1 considers the calculation of the launch conditions and plotting of the red amber and blue zones based on calculation of the initial flight parameters and failure modes. As this depends on the rocket and launch tower design it cannot commence until that process is complete. It should include the calculations used to determine the maximum surface and low level windspeed for a launch within the launch angle imposed by the site. It should also include a recce to establish occupied areas, and subsequent contacting landowners. This information should be presented to the RSO some weeks before the planned flight to allow it to be checked.

Stage 2 is considers the prevailing conditions on the day of an intended launch. It is primarily concerned with measurement of the low level wind, to establish safe launch conditions, and using data on high level winds to plot the location of the green zone(s).

Once the RSO is satisfied that the launch and recovery conditions are within the design limits, an informed launch/don't launch decision can be made relatively easily.

6. Conclusions

The wind profile has a very significant effect on the flight of a fin stabilised rocket to high altitude. An understanding of the interactions between wind profile, rocket design, launch criteria and parachute drift can only be achieved by analysis and modelling. Programmes such as Rocksim have a role in this, but the inbuilt assumptions and simplifications of that package will give unreliable results. Rocksim's 2D model is unsuitable for estimating parachute drift from high altitude.

Good analysis of the interactions of any high altitude rocket and the wind are needed, particularly for the initial stages of flight and during recovery. Suitable models will permit a trade off between rocket design factors, wind conditions at all altitudes, and site limitations. It is proposed that consideration of the outputs of such models should form an essential part of the RSO's decision to allow or refuse a launch.

A method of presenting the outputs of the models is proposed. This involves plotting a number of zones on a map of the proposed launch and recovery areas, and considering the land use in each of those zones. Such a method would allow the RSO to make an informed decision as to the safety of the launch and recovery.