



Flight controller and trajectory map

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Introduction

This document deals with the pairing of pyro devices and flight controllers for the DoubleSShot. Each of the flight controllers have their own characteristics, and the pyro devices should be controlled by the most suitable flightcontroller for the task.

Additionally, this document deals with the nature of the recovery process. The recovery strategy has a deep impact on the chute deployment criteria, which in turn affects what flight controller will be most suitable for deployment of each chute.

While there is little doubt that the final stage of the recovery requires a (main) parachute, the initial stage of the recovery *might* utilize a drogue parachute, but other recovery devices like air brake, streamer or even ballute could potentially replace the drogue chute. Therefore, the device responsible for the initial part of the recovery is simply termed "drogue device" to signal that at the current stage, no particular recovery device has been selected.

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Harware

There is basically a requirement for firing 3 pyros during the DoubleSShot flight:

- Phase 2 ignition
- Drogue device deployment
- Main Chute deployment

There may be a need for redundancy, so that each of the pyros have a backup that is triggered by a different device.

The payload carries three devices capable of firing pyros:

- The Telemetrum (2 pyro outputs)
- The Raven (4 pyro outputs)
- UFC4 Main Computer (2 pyro events)

The drogue device deployment is the most complex pyro event to handle, and as such is will be treated in the following chapter.

Drogue device deployment

As the rocket will drift with the wind when the drogue device has been released, and as the recovery from high altitudes will thereby significantly influence the trajectory dispersion, it will be wise to consider when to release the drogue device. Basically, the options are as follows:

- Release the drogue device at apogee. This is the standard approach, but this will also maximize the descent time under canopy, and potentially also the dispersion.
- Post apogee release. Introducing a Post Apogee Delay (PAD) will reduce the descent under canopy, and thereby also the dispersion – but at the same time it will challenge the structural parts belonging to the recovery system.
- Pre apogee release. This approach will limit the altitude, thereby limiting the descent under canopy and reduce the dispersion. The major drawback is that it could potentially jeopardize the altitude goal of the mission – and as with the PAD, it introduces structural loads on the recovery system.
- Flat spin recovery. With this option there is no drogue device. The major drawback is that the aerodynamic properties of a vehicle under flat spin are hard to predict, but potentially this descent mode has little wind sensitivity and could offer a dispersion wise optimal recovery.

The option of releasing the drogue device at apogee is the standard approach. It offers the optimum in terms of minimal mechanical load on the recovery parts, while it subjects the vehicle to the longest descent under canopy. Still, this approach may be acceptable if the drogue device is very small, and the main chute – plus related structure – can be released at a very high level of dynamic pressure. The atmospheric density at 1000m ASL is nearly hundred times as large compared to the value at 33000m ASL. This means that if the main chute can be released at e.g. 200m/s at 1000m ASL, then the drogue device could – in principle - be tailored to a descent speed of 2km/s at 33km ASL, since the equilibrium descent velocity is inversely proportional to the square root of the

atmospheric density.

Introducing a Post Apogee Delay before releasing the drogue device offers a partially free fall trajectory, which has little or no wind sensitivity. The drogue device itself, and its related structural parts will have to be designed to absorb the loads following the release at a high level of dynamic pressure. However, the drogue device does not have to be very large, as the increasing density of the atmosphere during descent may be put to active use. This option is subject to further investigation below.

The physical model describing the conditions of a PAD, also applies in the case of a premature drogue device release. The major difference is that the vehicle will not reach ballistic apogee, thereby possibly jeopardize the altitude goal of the mission. Dispersion wise, this approach does cut the descent under canopy, but in case of heavy cross winds, this may actually increase the overall dispersion zone, as ascent under canopy will be hard to predict.

Flat spin recovery is a potentially interesting option, as it does not require any drogue device at all. The flat spin should be introduced at apogee, as the structural loads on the vehicle body might be significant, if the vehicle is taken directly from stable (supersonic) descent into flat spin. The vehicle without motor is likely to be unstable by nature, but it would be wise to include a side thruster to be able to inject a flat spin at will. A side effect of the flat spin recovery is that the aft part of the vehicle needs not to be separated at altitude. Instead it could remain in contact with the payload section through a wire (to avoid any possibility of stable flight) until main chute release, thereby increasing the likelihood of recovering *both* parts. The hard to predict aerodynamic properties of a flat spinning object is a disadvantage, but as a first approximation, it offers similar properties as a small drogue chute. Another potential disadvantage to a flat spin recovery is the increased risk of tangled main chute lines.

Post Apogee Delay

Assuming that the trajectory is entirely vertical, and that the air resistance on the vehicle can be neglected, the velocity is zero at apogee, and the decent velocity at time t_0 after apogee is:

$$V = t_0 * g$$

The corresponding free fall distance from apogee is:

$$S = \frac{1}{2} * g * t_0^2$$

Or

$$S = \frac{1}{2} * V^2 / g \Leftrightarrow V^2 = 2 * g * S$$

The density of the atmosphere decreases approximately exponentially, being halved every 4964 m (average value from sea level up to 50km). This means that the atmospheric density may be approximated as

$\rho = \rho_0 * \exp(-\lambda * S)$ with λ being approximately $1.40 * 10^{-4} [m^{-1}]$ and S_0 being the absolute altitude above the reference altitude (normally sea level), where the density is ρ_0 . However, taking the apogee as reference, the relation between density at apogee and during descent may be written as:

$$\rho_{\text{descent}} / \rho_{\text{apogee}} = \exp(\lambda * S)$$

The dynamic pressure on the drogue device at time of release is $\rho * V^2$, and may thus be written as:

$$P = \rho_{\text{apogee}} * \exp(\lambda * S) * 2 * g * S$$

In reality, the trajectory will not be entirely vertical, and the velocity will be nonzero at apogee. This will blur the direct coupling between S and P somewhat, as P now may be written as:

$$P = \rho_{\text{apogee}} * \exp(\lambda * S) * (2 * g * S + V_0^2) \Leftrightarrow$$

$$P = \rho_{\text{apogee}} * \exp(\lambda * S) * 2 * g * S + \rho_{\text{apogee}} * \exp(\lambda * S) * V_0^2.$$

Since the air density does not change very fast compared to the free fall velocity, P will evolve as a parabola, and the offset caused by the apogee velocity will be negligible after a few seconds. Hence, the assumption regarding vertical trajectory is not unrealistic in this regard.

The working conditions for the drogue device is limited to a certain regime of dynamic pressure with P_{limit} as a suitable value of maximum expected dynamic pressure. This relates to the free fall distance as:

$$P_{\text{limit}} = \rho_{\text{apogee}} * \exp(\lambda * S) * 2 * g * S$$

It is however of interest to include the true altitude with regard to sea level. In this context, ρ_{apogee} may be expressed as:

$$\rho_{\text{apogee}} = \rho_{\text{sealevel}} * \exp(-\lambda * S_{\text{apogee}})$$

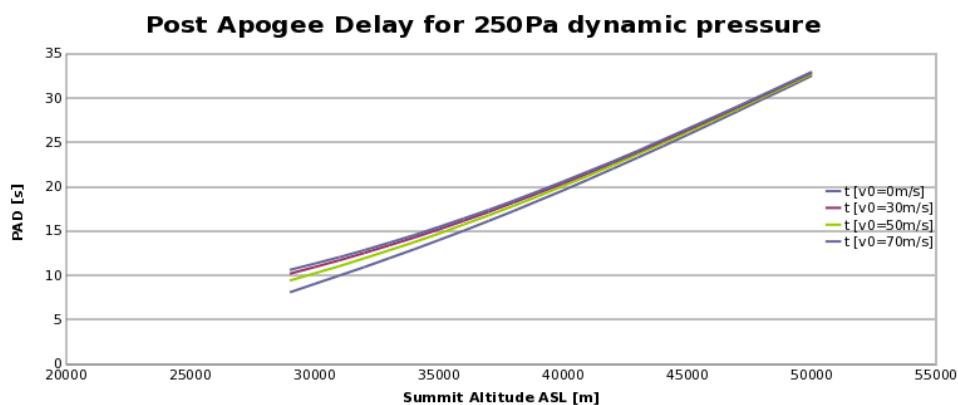
And as

$$S = S_{\text{apogee}} - S_{\text{release}}$$

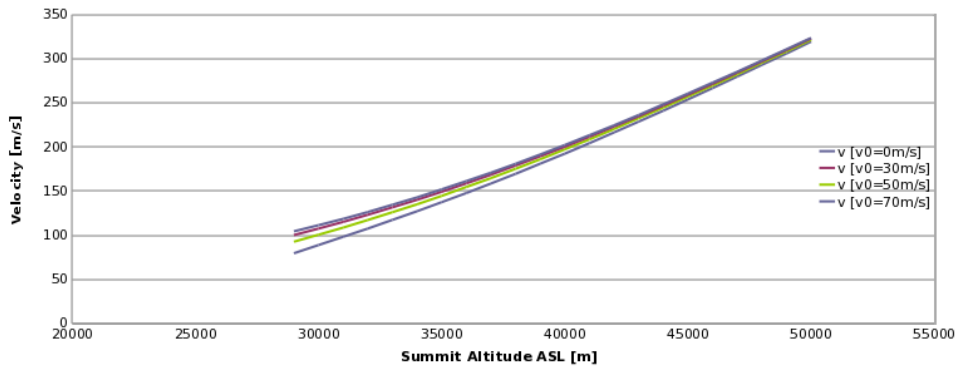
$$P_{\text{limit}} = \rho_{\text{sealevel}} * \exp(-\lambda * S_{\text{release}}) * 2 * g * (S_{\text{apogee}} - S_{\text{release}})$$

This gets rather nasty and there is no simple relation between the absolute apogee and the drogue release event. Assuming some fixed value of P_{limit} , the corresponding release altitude is almost proportional to the summit altitude. This is a consequence of the atmospheric density being rather low at the stipulated altitudes and of the rather slow rate of change.

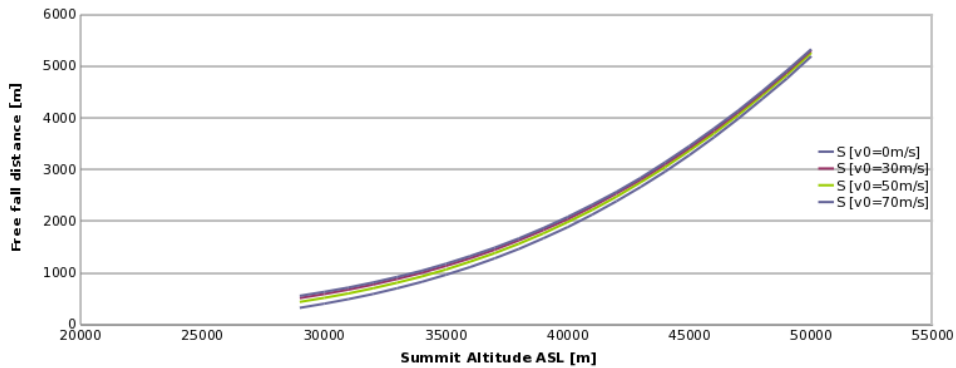
The following charts show the conditions at which P_{limit} equals 250Pa:



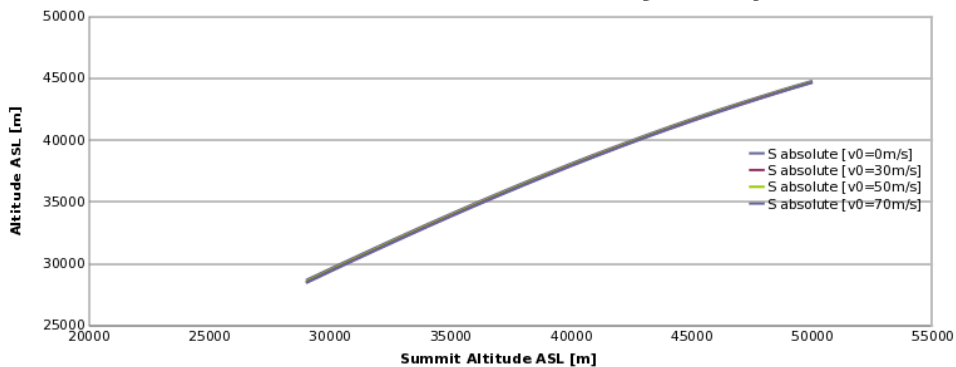
Vertical velocity for 250Pa dynamic pressure



Free fall distance for 250Pa dynamic pressure

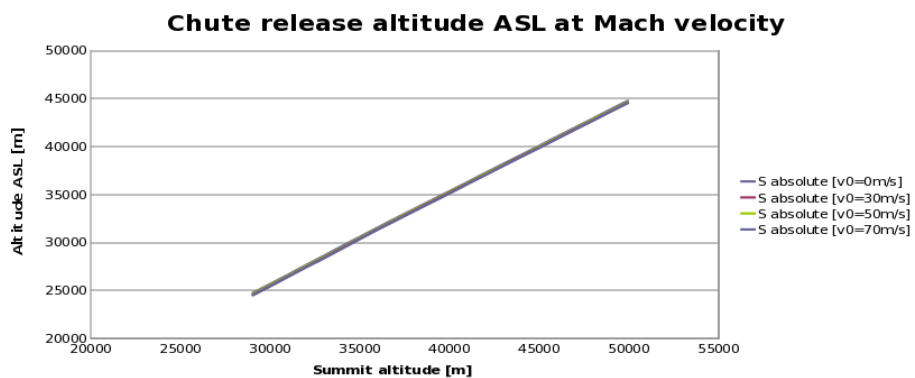
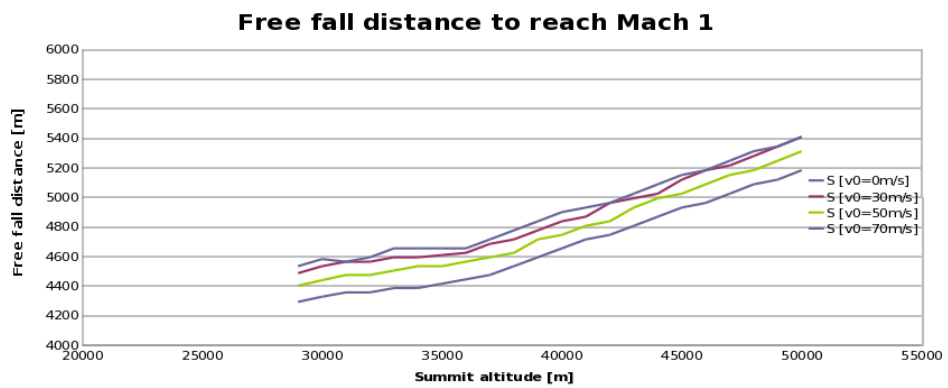
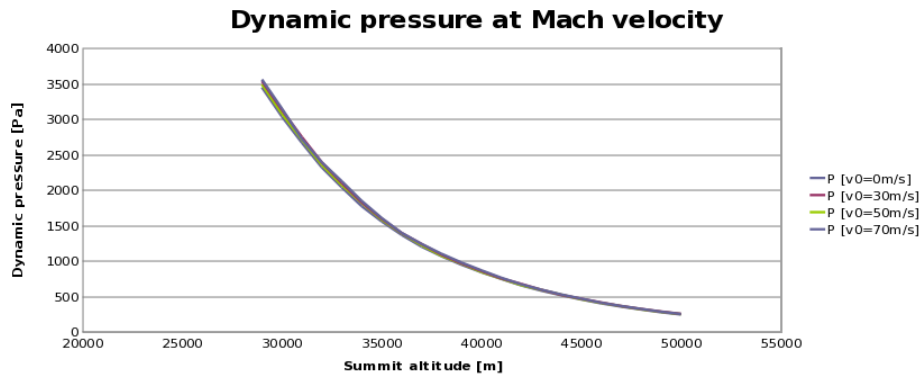
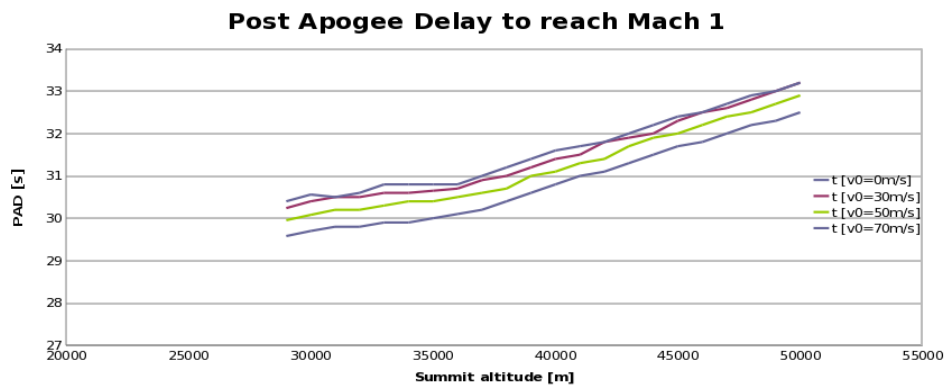


Chute release altitude ASL for 250Pa dynamic pressure



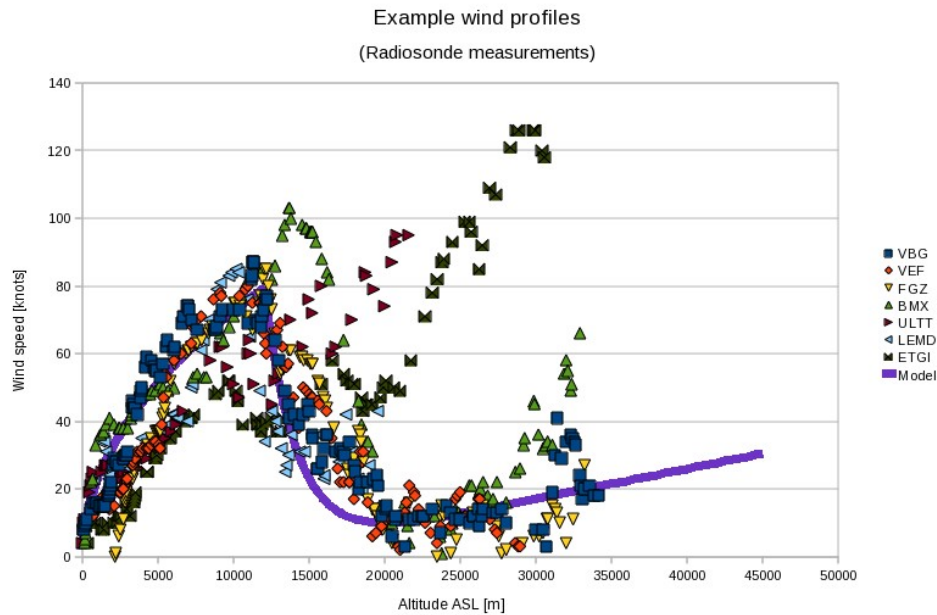
No fixed conclusions can be drawn from this however. The vehicle and parachute specifications must be known to a more specific level before the release conditions can be chosen. What this overview shows is that PAD, absolute altitude and vertical velocity all have nearly linear relationship with the summit altitude. The free fall distance shows a nearly parabolic relationship with summit altitude indicating that the "free fall until given dynamic pressure" approach is more beneficial at higher summit altitudes.

Another interesting observation is that the vertical velocity approaches the speed of sound. It may be that the parachute needs to be designed to operate at supersonic speeds. This does not have to be a problem, but it could affect the choice of parachute, and it may also affect the choice of release mechanism. As an example, the above calculations have been repeated, with the release conditions set at the local speed of sound:



As expected from a free fall, the time to reach Mach 1 is around 30 seconds, and the free fall itself

is around 4.4km, only slightly depending on the summit altitude. Even if Mach 1 is only an example and not a limiting case, the conclusion must be that the free fall until drogue device release will only be a small fraction of the total descent, regardless of the specifics of the vehicle.



Even if the free fall may only be in the order of 5km, it may still be enough for reducing dispersion. As can be seen from the example wind profiles, the wind speed increases at altitudes above approximately 22km. Depending on the local wind conditions at the time of launch, removing the drift during the first 5km of the descent *will* reduce the dispersion. However, in most cases, the descent from 12km ASL to ground will be the main contributor to the overall wind drift.

Chute design and release summary

The main chute should be released shortly before touchdown, as the descent under the main chute will be a major contributor to the wind drift. The release conditions should be set to a speed well below the local speed of sound to avoid the risk of fooling a barometric altimeter. At the same time, the speed should be as high as may be acceptable considering the mechanical stress on the chute and related parts. The release altitude should be as low as possible, although 1-2km AGL is probably the lowest feasible release altitude. The main chute should be sized to provide the desired descent rate at ground level.

The drogue device should be sized to meet the main chute release conditions. It should be designed to operate at high supersonic speeds, and it should be released “shortly” after apogee. There is no need to risk either the loss of altitude due to a premature release or the complications of deployment under high dynamic pressure. On the other hand, releasing the chute at apogee includes the risk of slow deployment and tangled lines. The deployment should be timed to occur at a suitable dynamic pressure that creates safe deployment conditions for the particular drogue device in question.

As an example, assume that the main chute is released at 200m/s descent rate at 2km AGL. This provides a 10 second crash margin. If the GPS coordinates during descent are known until the final moments before main chute deployment, and the local wind conditions are known (or measured), then this would narrow down the landing zone even if radio transmission is lost during the final

descent.

When the drogue device is sized to provide a descent rate of 200m/s at 2km AGL, it will be insignificant at 30km AGL. The main concern will be that the dynamic pressure is sufficiently high to assure proper deployment, without tangling the lines, in the thin atmosphere.

Even if the main chute is suitable for release only at a lower speed, like 100m/s or less, the considerations regarding the drogue device are essentially the same.

With the exception of a flat spin recovery, the payload and booster sections of the vehicle will be recovered separately. The payload section requires a much softer landing than the booster, allowing the booster to employ a single chute recovery for simplicity. If the booster recovery is tailored for a ~50 m/s landing speed, the drift at altitude could still be moderate, although higher than with a two stage recovery. The PAD will have to provide acceptable release conditions for both booster and payload recovery systems, and both systems must be able to operate at supersonic speeds (Mach 2-3).

Device mapping

The firing of phase 2 is purely a timing based operation. This is most conveniently handled by the main computer, with the Raven as backup device.

The drogue device deployment is to occur shortly after apogee. Had it not been for the altitude, this would be handled by any barometric altimeter. Since however, the summit altitude is expected to exceed (or be at the limit of) the working range of any known altimeter, the most suitable way to find the time of apogee is by use of a Kalman filter algorithm. The Kalman algorithm of the MiniSShot may be implemented on the Telemetrum since its design is open. This makes it the main candidate for handling drogue device deployment. An acceleration based algorithm, such as the one implemented on the Raven is probably the best backup scheme for this event.

The Main chute is to be deployed at a specific altitude, within the working range of both the Raven and the Telemetrum. The Raven's altimeter has better spec's than that of the Telemetrum, making the Raven the most suitable primary controller of main chute deployment with the Telemetrum as backup.

Summary:

Event	Phase 2 ignition	Drogue device deployment	Main chute deployment
Primary device	Main Computer	Telemetrum	Raven
Backup device	Raven	Raven	Telemetrum

This scheme uses both pyro outputs on the Telemetrum and three of four outputs on the Raven and one of two outputs on the UFC4..