Technical report

High altitude test flights –

Sodankyla station

Summary

1. Introduction
2. Payload platform description
3. Test flights objectives
4. Test flights
5. Conclusions

1. Introduction

High altitude balloons have been used in the past couple of decades for multiple types of missions amongst which the most important are:

- Meteorological measurements
- Upper atmosphere physics
- Aeronautics tests (flight tests)
- Space equipment validation (before actually sending it to space)
- Photo and video surveillance of extended territories
- Biological/chemical sampling

The main advantage of high altitude balloons is that they can provide a low-cost access to altitudes otherwise difficult or even impossible to reach with airplanes.

At the same time the high altitude balloons provide longer flight time than a typical sounding rocket which for some experiments (biological probe capturing etc.) is essential.

A typical high altitude balloon flight takes 2.5 hours although there are flights that can be as long as several weeks (polar flights that take advantage of the so called "polar vortex").

For shorter duration flights (~2.5 h flights), latex balloons are used which, once they reach maximum altitude, burst due to the envelope material reaching its maximum strength limit. During the flight the payload is tracked via one or multiple methods while the recovery (after burst) is done via a ballistic parachute. The entire flight trajectory is governed by whatever wind profile exists within the atmosphere at various altitudes during the day of the flight. Trajectory can be made shorter or longer by controlling the ascent rates of the balloon; however there is no total control over the trajectory and the wind profile throughout the altitude domain is still the dominant factor in shaping the trajectory.

Due to uncertainty of winds profile prediction the trajectory and, hence, the landing point cannot be known with high accuracy before the flight. Some predictions can be made but the final landing point can be as far as tens of km away. This can place the payload in difficult to access areas and can increase the recovery time. At the same time for flights that need to be done from small islands, the standard recovery most likely involves the payload to float at least couple of hours on the surface of water before recovery boats can reach it.

Due to the above limitations of a standard flight, an improvement has been envisioned in the form of a steerable parachute that would steer the payload towards a desired landing point despite the wind profile during the flight day. This way the payload can be brought within 1-2 km from the desired landing point making the recovery easier than during the standard case. At the same time this technology opens the possibility to perform high altitude balloon flights on a small island without needing to recover the payload from the water.

2. Payload platform description

A typical flight line for a standard flight without guided recovery is shown in Figure 1 while a typical "modified" flight line for a guided recovery flight is shown in Figure 2.

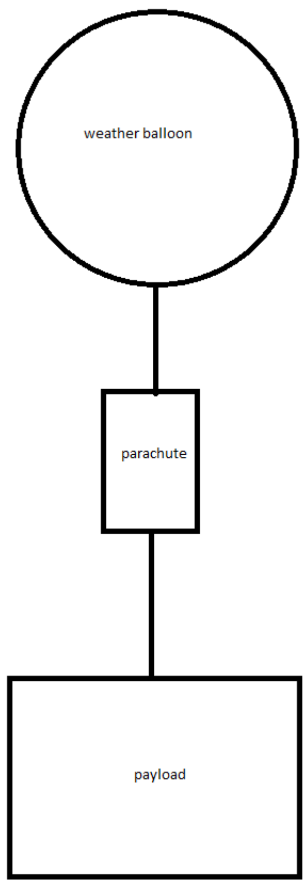


Figure 1: standard flight line for weather balloon flights

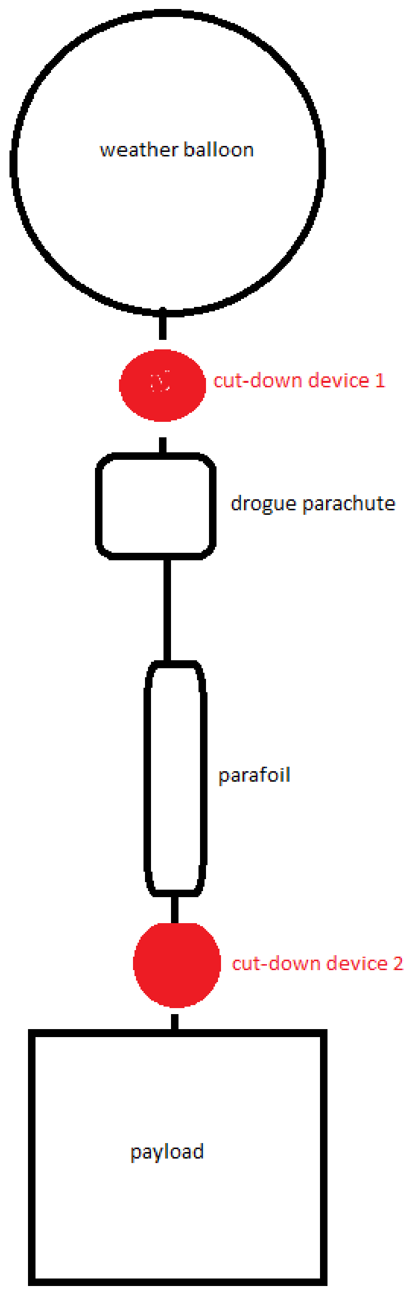


Figure 2- guided recovery flight line

The guided recovery flight line consists of the following elements:

- Weather balloon (WB)
- Drogue parachute (DP)
- Guided parachute/parafoil (GP)

- Steering unit (SU)
- Experimental platform (EP)

Both **SU** and **EP** are within the same package but they are completely separated from the electrical point of view each of them having a separate power supply (battery set).

The flight begins with the ascent from the ground at the pre-set ascent velocity depending on the payload requirements, flight objectives etc. At the top of the trajectory a command is sent to cut the balloon from the flight line. That way the entire flight line starts to fall towards the ground while the balloon is released. Important to note that this should happen BEFORE the burst of the balloon and the purpose of this is to prevent tangling of the parachute lines with the fragments of the balloon. The way we ensure that this happens before the burst of the balloon is by monitoring the ascent velocity and the current altitude. Whenever the ascent velocity starts to decrease we know that the balloon is close to burst and we issue the cut-down command. In other cases a maximum top altitude is desired no matter how much higher the balloon could ascend. In these cases the cut-down command is sent no matter what the values of ascent velocities are; the cut-down command is based solely on altitude.

For a typical flight this cut-down command occurs at ~30-33 km. Next the flight line falls towards the ground until an altitude of 10-12 km is reached. Upon reaching this altitude a second cut-down command is given which separates the **DP** from the rest of the flight line. The **GP** inflates within 20-30 seconds and then the **SU** starts to send commands in order to bring the **EP** as close as possible to the intended landing point. The commands consist of right/left commands that are issued within a PD loop.

The P input of the PD loop is represented by the difference between the current heading and the needed heading in order to get to the landing point.

The D input of the PD loop is represents by the time rate change of the abovementioned angle difference.

In the future we will implement a I term and transform PD into a PID loop. However, for initial testing PD loop is sufficiently robust.

The **SU** unit consists of the following subsystems:

- Autopilot board (6 DOF inertial board)
- GPS module
- Servos (2 servos)
- Battery set (12 V/6000 mAh)

The autopilot would sense both the attitude and the position and would send correction signals to the servos in order to steer the guided parachute/parafoil. Between two readings of the GPS the autopilot would integrate the rotation rates and the linear acceleration in order to get an inertial estimation of both attitude and position. This ensures a smooth correction and a capability to survive through temporary GPS black-outs. The GPS data and the inertial measurements are fused together using Kalman filtering.

The **EP** unit consists of the following subsystems:

- Payload to be carried (in our case the Aircore)
- Tracking unit
- Telecommand system
- Battery set (12V/10000 mAh)

Tracking unit worked on 2 meter band (144.825 Mhz/8 Watts) sending every 5-7 seconds APRS beacons received by a dedicated ground-station. Each beacon contained the following information:

- Latitude
- Longitude
- Altitude
- Groundspeed
- External and internal temperature
- Voltage of tracking unit power supply

Telecommand system worked by receiving commands sent on UHF band (430.325 Mhz/50 Watts) from the ground-station. The commands were encoded (6 character password) and whenever a specific set of characters (numbers) was received a certain command was issued.

In our case the logic was that the system would be blocked unless it received the first set of characters (first password). Whenever it receives it then it would send a command on a specific MOSFET that would generate a high amp current through a thermal knife. This would lead to thermal cutting of the flight line. This leads to separation of balloon from the rest of the flight line.

ONLY after successfully receiving and decoding the first set of characters (first password), the system would accept the second set of characters (second password) that would involve a second cut command of the flight line that leads to separation of drogue parachute from guided parachute/parafoil.

The reason for this is to avoid cutting the guided parachute/parafoil while the flight line is still attached to the balloon.

3. Test flight objectives

The abovementioned equipment have been used in flight on various other missions but this is the first time that a high altitude steerable recovery was to be attempted with them. Otherwise said each component was flight worthy but the entire “product” was never tested in a full high altitude test flight.

Hence, a series of objectives were laid down and test flight had the purpose to validate (or invalidate) them step-by-step. A total number of 4 test flights were performed in Sodankyla in 3 days.

Objective 1:

Validate tracking solution throughout the trajectory without support from third parties.

Resolution: the tracking solution used for the test flights worked flawlessly and ensured tracking and recovery of the equipment for all 4 test flights. More than this, trajectory visibility was ensured on the Internet, hence, users without proper receiving equipment could follow the progress of the flights online on a dedicated website (www.aprs.fi)

Objective 2:

Validate telecommand system for cut-down commands

Validate thermal knives and physical flight line cut events

Resolution: the telecommand system and thermal knives worked on 3 out of 4 flights with a total of 5 cut-down events out of 7 planned cut-down events.

The 1st flight involved one cut-down command- separation of balloon from the flight line while 2nd and 3rd flights involved two cut-down commands each involving both the separation of the balloon from the flight line and the separation of drogue parachute from the flight line.

During the last flight (4th flight) a connector came loose which prevented the cut-down signal to be decoded properly and, hence, the cut-down commands were not passed through. See **Conclusion** section for proposed fixing solution for this problem.

Objective 3:

Validate autopilot algorithm and verify that the inertial solution does not diverge during the ascent and the descent (high rotation rates and linear accelerations) of the payload.

Resolution: autopilot logged the entire flight for all 4 flights. Each flight produced more than 32 Mb of data representing full rotation rates, linear accelerations, attitude estimation, wind velocity calculation, altitude, position and correction commands to be sent. The 1st flight was used with the autopilot in neutral mode. In this mode the autopilot would compute attitude/position and issue correction commands that would be logged on a micro-SD card. Basically the autopilot would work like on a real flight except that the commands would not be sent to servos and instead would be logged on a micro-SD card. Post-flight analysis showed that the autopilot determined correct attitude and position and it sent the correct steering commands attempting to minimize the heading difference (which translates into bringing the payload onto a heading towards the intended landing position).

The 2nd, 3rd and 4th flight were intended to test the autopilot with the parafoil but, unfortunately mechanical problems prevented this from happening- see ***Objective 4.***

Objective 4:

Validate mechanical assembly of parafoil inside deployment bag; validate correct parafoil deployment, inflation and steering.

Resolution:

The deployment bag was too far away from the payload leading to a “too long” distance over which the lines of the drogue parachute should have slided in-between the lines of the parafoil. This lead to tangling observed in the 2nd flight. On this specific flight the second cut-down command worked nominal but the lines of the drogue parachute tangled with the lines of the parafoil while they were pulled away after the cut-down command. Moreover, square connectors were found to “help” tangling the lines when the drogue parachute needed to be pulled away.

A fix was made in reducing the length between the deployment bag and the payload and, hence, reducing the distance over which the drogue parachute lines would need to slide through the parafoil lines. Another fix was done with the connectors which were rounded in order to prevent additional tangling.

Both fixes were effective for the 3rd flight and this time both cut-down commands worked nominally and the drogue parachute detached from the flight line leaving the payload and the parafoil.

However, this time the servos were over-run by the inflation forces of the parafoil and mechanical breakdown occurred within the servos which lead to no steering.

Objective 5:

Validate mechanical construction of the payload box and structural soundness

Resolution:

The box was recovered 4 times with full working equipment on it; 3 times with no structural problems. It ensured full recovery including the recovery of the aircore (main scientific payload). During the last flight the payload suffered a rapid descent from high altitude with no parachute because no cut-down event was done (see **Objective 2** and its **Resolution**). Despite the high speed impact the structure of the payload box hold well and protected all the equipment including the aircore tubing. Damage was done on some structural elements of the box but there was nothing that could not be fixed. Due to non-nominal descent some damage was expected; however the main purpose of the payload box was to protect the instruments inside.

Objective 6:

Demonstrate re-usability of equipment.

Resolution:

Electronic equipment survived 4 flights and 4 landings; out of which one landing (the last one) was at high speed due to no parachute deployment. Everything onboard the payload was re-used except the flight line itself that contained the thermal knives and had to be replaced each flight.

4. Test flighs

Test flight 1:

The flight took-off from Sodankyla. The flight line did not contain the parafoil because this flight was the one that validated the tracking, telecommand and most important the autopilot system.

Throughout the entire flight the autopilot measured and determined the attitude and position. The trajectory as reported by the autopilot is shown in Figure 3.

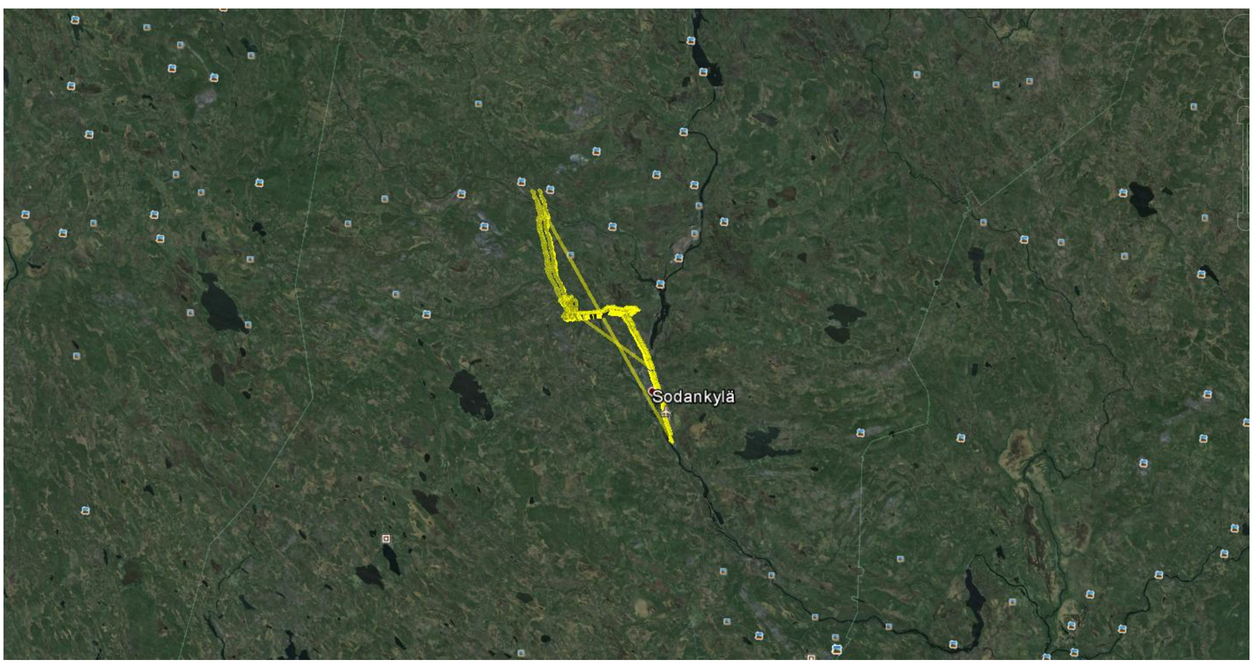


Figure 3- Trajectory test flight 1

Test flight 2

During the test flight 2 it was first attempted to detach the parachute from the rest of the flight line and deploy the parafoil. Unfortunately the lines became tangled due to two main reasons:

- Square connectors used for the electrical lines for the thermal knives that helped the parachute and parafoil lines to get tangled
- Long distance between the parafoil deployment bag and the payload which meant that the DP (drogue parachute) should have been pulled away on a long distance before it would separate with the parafoil bag from the parafoil and payload. This lead to additional tangling of the drogue parachute lines and parafoil lines.

The tracking, telecommand and autopilot worked nominal. Figure 4 shows the trajectory as recorded by the autopilot.

Figure 4 – Trajectory test flight 2

Test flight 3

Test flight 3 attempted to fix the separation problems encountered on the previous flight. Main measures taken:

-round up the connectors (to prevent line tangling)

-decrease distance between the parafoil bag and the payload

This time the drogue parachute separated from the flight line and the parafoil was deployed from the deployment bag. However, the deployment forces overcome the servos and mechanical failure inside the servos occurred.

Again tracking, telecommand and autopilot worked nominal. Figure 5 shows the trajectory was reported by autopilot.

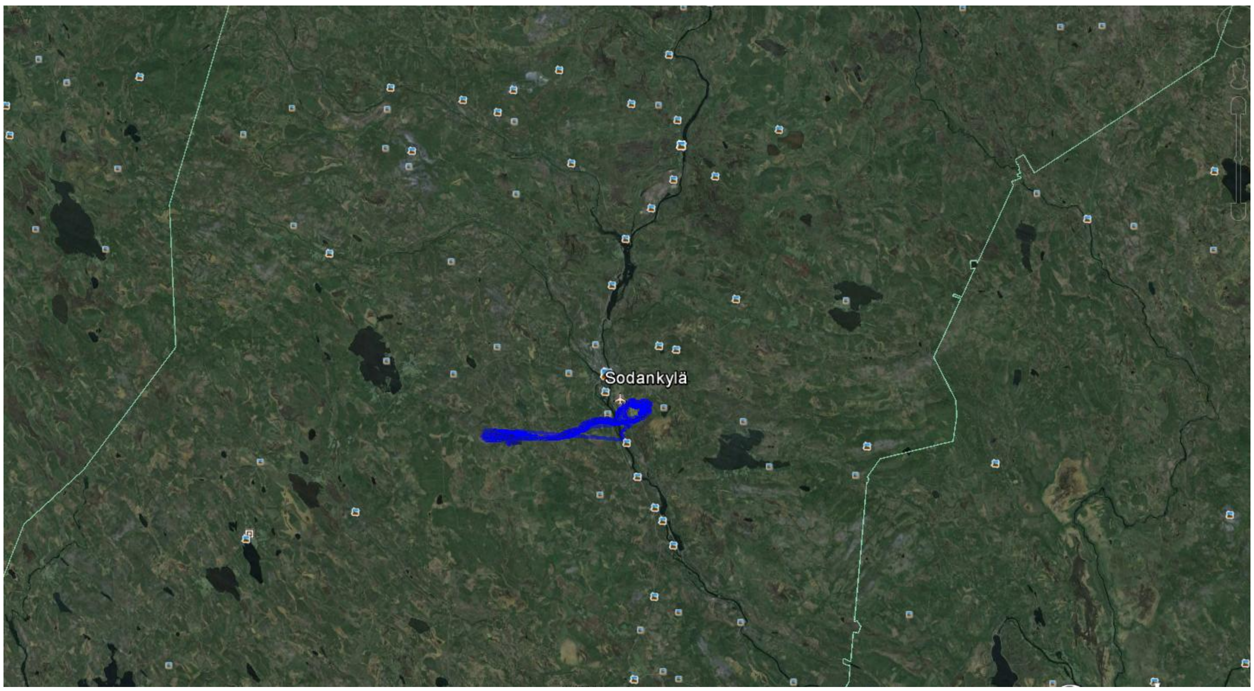


Figure 5- Trajectory test flight 3

Test flight 4

On this test flight a lower altitude deployment was tried. The drogue parachute was eliminated from the flight line. A single cut-down event was to be performed during the flight once the balloon would reach 10 km altitude.

Telecommand system didn't work this time (although it worked nominal on the previous 3 flights). Upon recovery the telecommand individual components worked. Upon additional inspection of the microcontroller board it was observed that a data line connector became loose and, hence, prevented the transmission of telecommand signal.

The payload suffered high speed descent which leads to partial damage of the payload mechanical structure. However, all equipment was protected and recovered in perfect working condition (including the batteries).

Tracking and autopilot worked flawlessly and the entire trajectory was recorded by autopilot - Figure 6.

Figure 6- Trajectory test flight 4

5. Conclusions

The following conclusions were drawn upon the abovementioned 4 flights experience. The conclusions also contain proposed solutions for the technical problems encountered.

- **Tracking system:** worked flawlessly and no modification is envision for the future flights; this equipment will be used as it is
- **Telecommand system**: worked nominal except the signal line connector that became loose on the last flight. Proposed solution is to use soldered wires between the radio receivers and the microcontroller board in order to avoid future problems. Besides this a more ruggedized

casing will be built (made of fiberglass) that would enclose both the radio receiver and the microcontroller board.

- **Flight line cutting devices**: the cutting devices can be used as they are; they worked nominal and no problems (either mechanical or electrical) were observed. However, as an improvement a lower resistance nichrome wire together with a thinner flight line could be used in order to decrease the cutting time. These improvements would not involve any modification of the MOSFET stage of the telecommand system that gives the cut-down command.

- **Autopilot+GPS:** this unit will be used as it is because it worked perfectly on all the 4 flights; whenever the GPS was in black-out (due to high rotation/velocity) the autopilot filled in with correct inertial estimations; no confusion (even at high rotation rates) was observed on the autopilot side. All the correction (steering) signals were correct for all the 4 flights.

- **Batteries:** the same type of batteries will be used (Lipoly). It was demonstrated once again that these batteries can provide the required power for the electronic systems and that they do not have a problem at low temperatures encountered at high altitudes.

- **Temperature and pressure sensor for the aircore:** adhesive tape fixing will be used instead of the thermal conducting paste. Adhesive tape was originally designed to be used with this system but while in Sodankyla we thought that we could improve the performance by using thermal conducting paste. The unit worked for many hours (with adhesive tape fixing for the sensors) on the ground and failed to worked only after applying the thermal conducting paste. We applied the thermal conducting paste (although this measure was not included in our nominal instructions on how to use this unit) because we wanted to ensure that best thermal joint will be made between each temperature sensor and the aircore tubing. **Lesson learnt: never change procedures on the fly no matter the good intention!**

- **Payload box:** similar ruggedized structure will be used but emphasize will be made on making it lighter (0.5-1 kg lighter). This is needed in order to minimize the weight of the payload that needs to be flown under the balloon and decrease the chance of third party accidents.

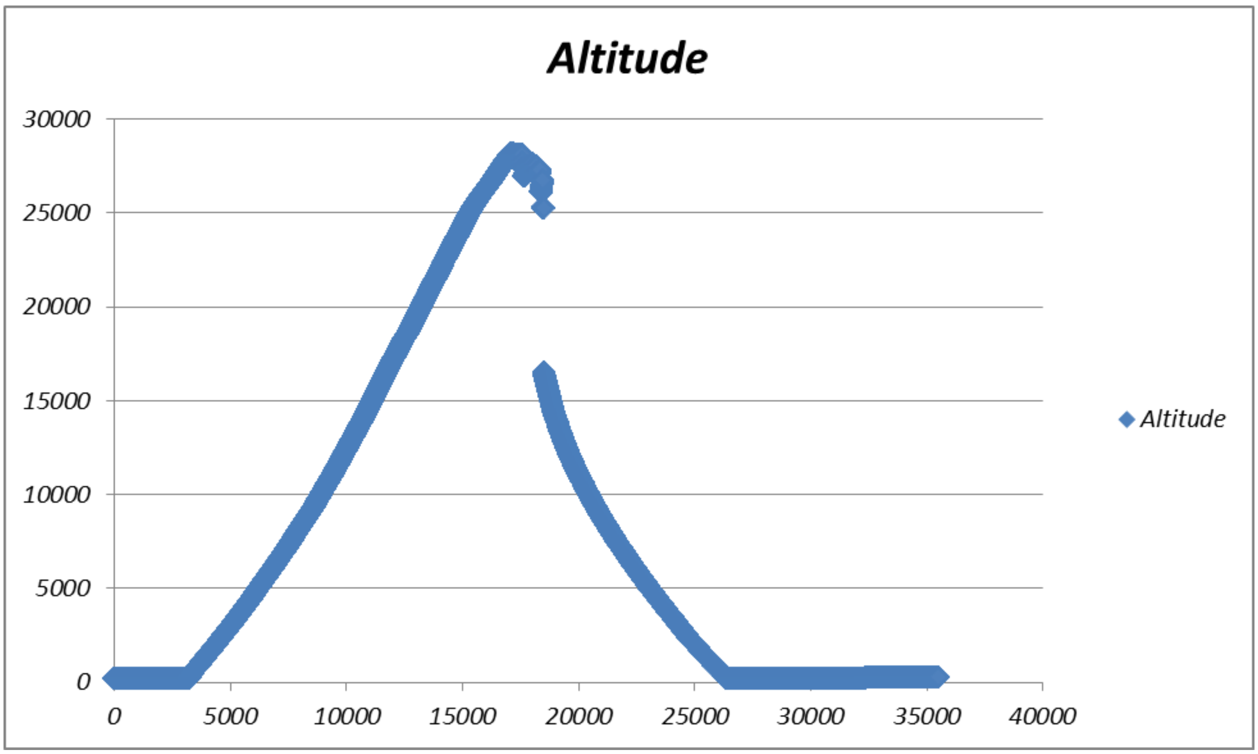
- **Steering system+parafoil:** the bag will be maintained at closer distance from the payload box minimizing the lines that can be tangled. The entire parafoil lines will be hidden inside the deployment bag instead of hanging them outside. The deployment will be tested through low altitude deployments from a high bridge to which we have access in Galati county. At the same time some lower altitude flights under a balloon are envision depending on the results obtained from the bridge.

  Yet another measure is to use triple strength servos (we have enough battery reserve) and mechanical stoppers. These stoppers will be enforced throughout the deployment of the parafoil. They will be retracted only after the parafoil was deployed. This should decrease the shock that the servos get from the deployment of the parafoil.

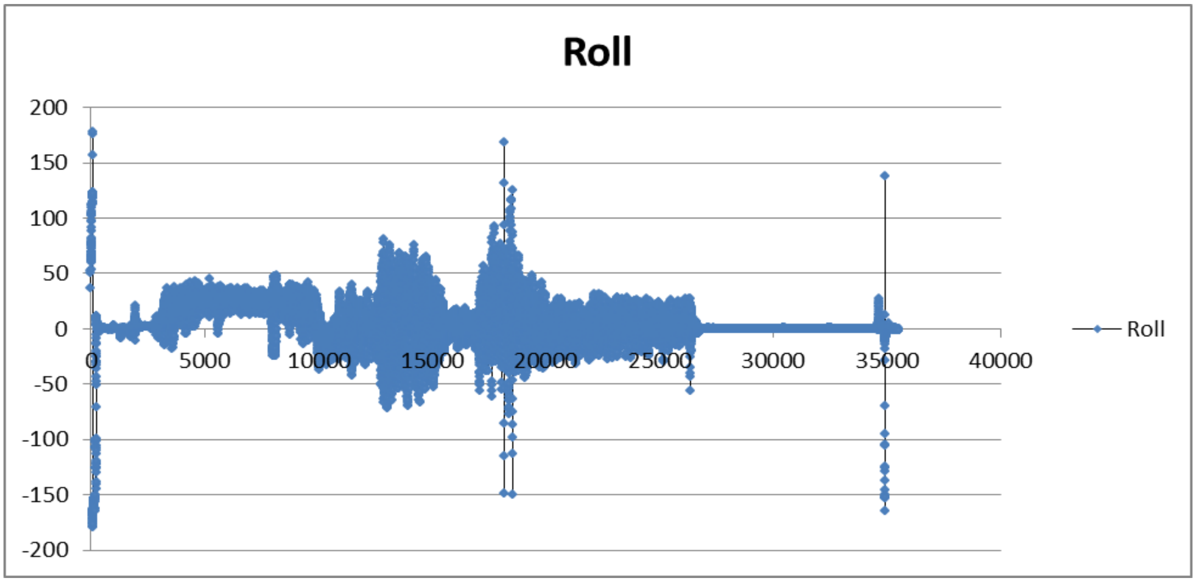
Appendix:

We show below some typical data recorded by the autopilot throughout any of the 4 flights. As an example we use the data recorded on the 1st flight.

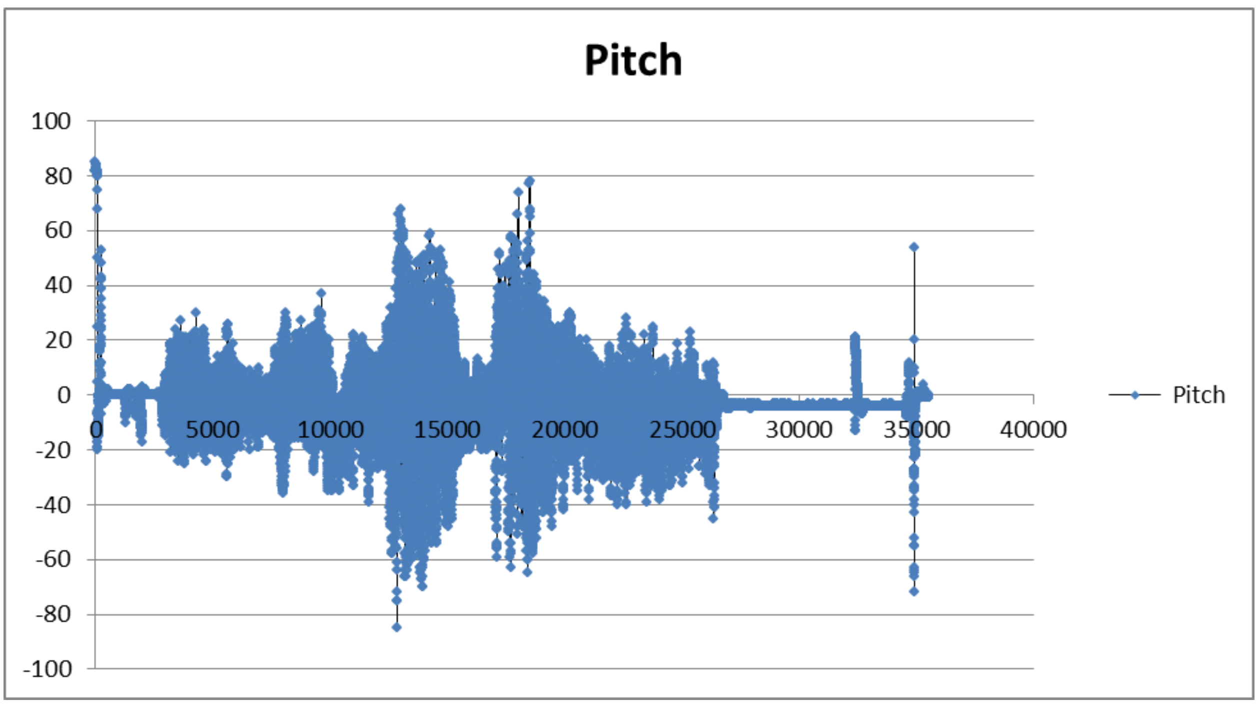
Altitude versus time:



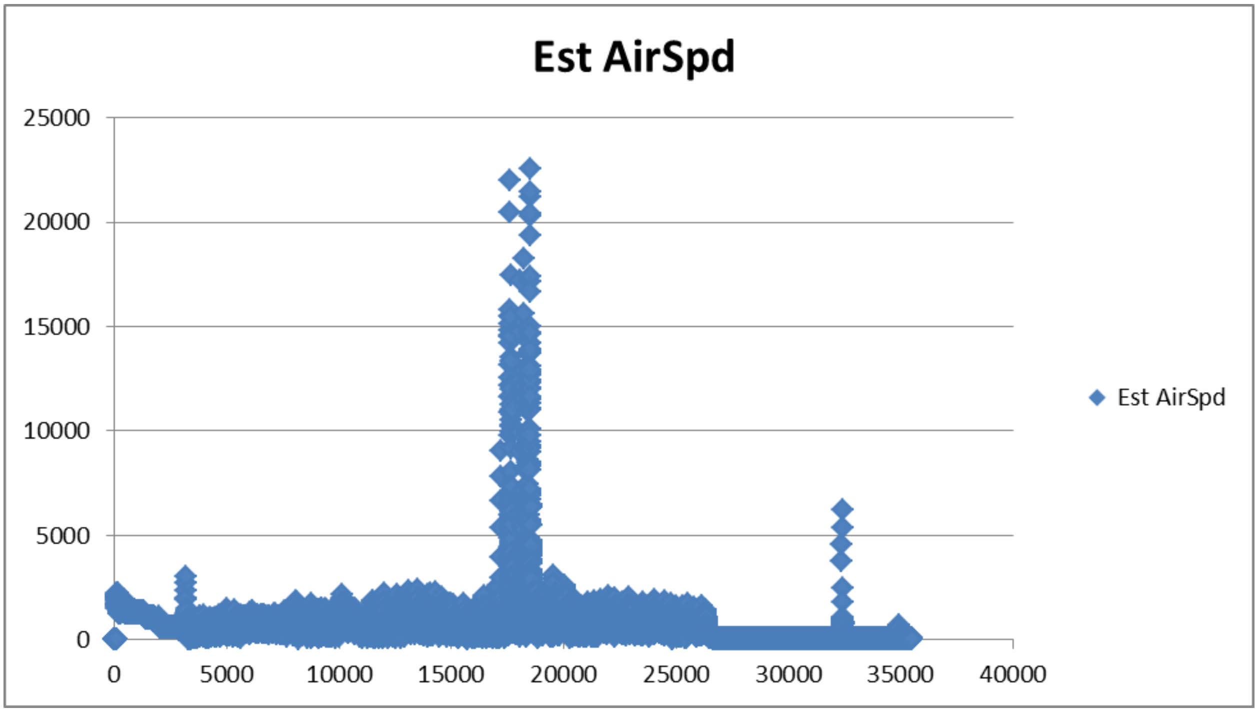
Roll versus time:



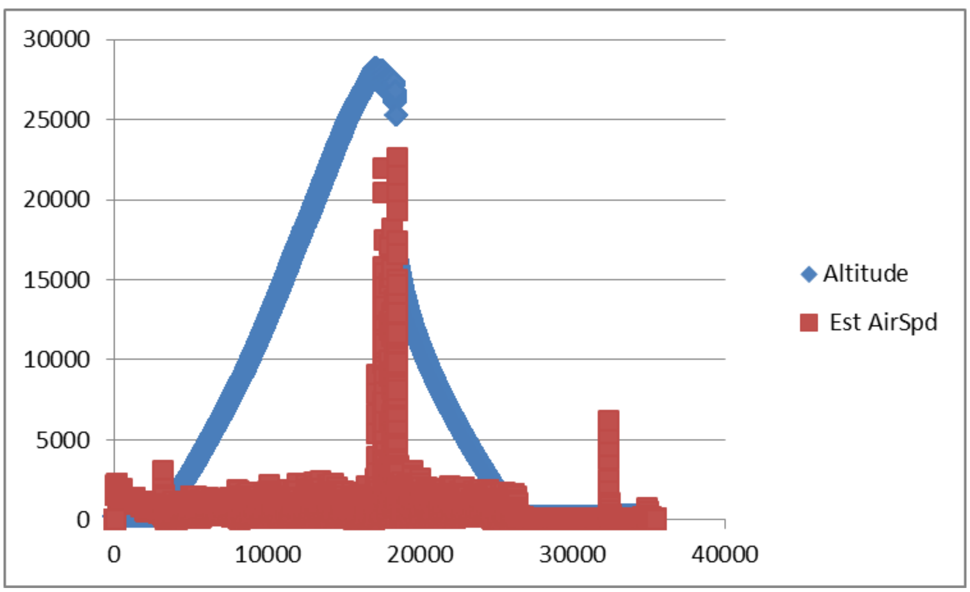
Pitch versus time:



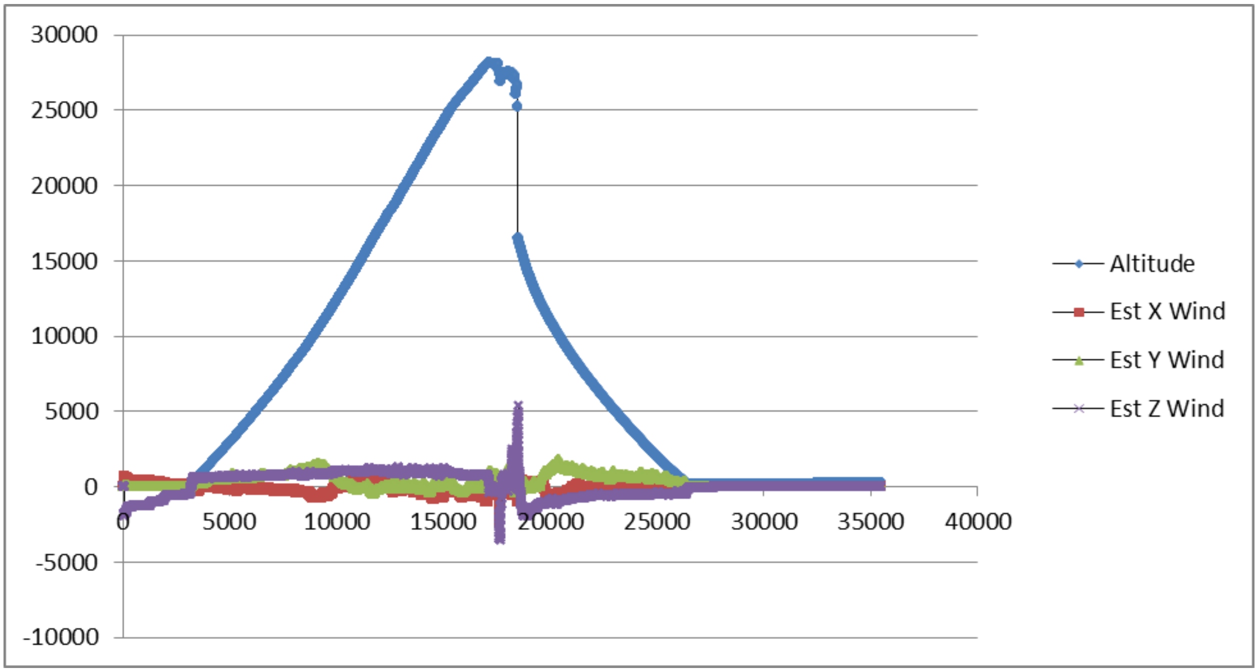
Airspeed over time:



Airspeed versus altitude (we can observe the altitude region where the winds were the strongest):



Estimated real wind velocities (X, Y and Z components) versus time (altitude also plotted on the same graph):



Position and velocity components as determined by the inertial unit: