SHEFEX 2
DEVELOPMENT STATUS OF THE VEHICLE AND SUB-SYSTEMS FOR A HYPERSONIC RE-ENTRY FLIGHT EXPERIMENT

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ABSTRACT

The SHarp Edge Flight EXperiment (SHEFEX) is a DLR program to investigate aerodynamic behaviour and thermal protection problems of re-entry vehicles at hypersonic velocities, using unconventional shapes comprising multi-facetted surfaces with sharp edges. SHEFEX 1 was launched on a parabolic trajectory from Andøya Rocket Range in 2005 to provide a re-entry velocity in the order of Mach 7. To obtain greater velocities in the order of Mach 10, without reducing the experiment time, a larger vehicle and a flatter re-entry trajectory are required. A Brazilian VS40 motor system will be used, whereby the S40 first stage will provide a conventional spin stabilized unguided flight, but a pitch down precession manoeuvre of the S44 second stage will be performed prior to its ignition above the atmosphere. This will result in a suppressed trajectory and a re-entry angle of the order of 40 degrees. In addition to the thermal protection experiments, a canard system will provide data on the aerodynamic control parameters at hypersonic velocities. A further experiment comprises a separate inertial navigation system with a star reference update and GPS, which should determine the instantaneous flight vector and provide fine corrections to the main payload attitude control system to reduce any angle of attack inaccuracy.

1. SHEFEX 2 EXPERIMENT

The SHEFEX 2 experiment comprises five sections, each with eight flat surfaces. The forward tip is constructed as a single facetted ceramic cone, whereas the remaining four sections each comprise eight separate flat plates of various materials and with a variety of sensors, including thermocouples, pressure sensors and a pyrometer system. The Thermal Protection System (TPS) tip and plates are mounted on an aluminium structure with additional thermal insulation. A data acquisition system collects and preprocesses the signals from approximately 160 sensors and sends this data as a serial packet to the service module, for inclusion in the payload telemetry. Apart from the temperature, pressure and heat flux measurements, two further experiments are included. A Flush Air Data System (FADS) uses differential pressure measurements around the tip to indicate the pitch and yaw angular offsets to the velocity vector and compare these with the payload attitude sensor data. An actively cooled TPS plate will provide data on the cooling effect of passing gas through a porous ceramic material also.

The canard experiment module is mounted immediately behind the facetted “cone”. It provides the mechanical transition from the eight segment surface to the 500 mm diameter payload cylindrical section. Four electrically driven canards will be locked at zero incidence to avoid destabilization of the vehicle during ascent, but after burnout of the second stage motor, they will be released and activated by the Canard Control Computer (CCC) to perform preset manoeuvres during the atmospheric re-entry sequence. The SHEFEX 2 TPS and canard experiment modules are illustrated in Fig. 1 below.

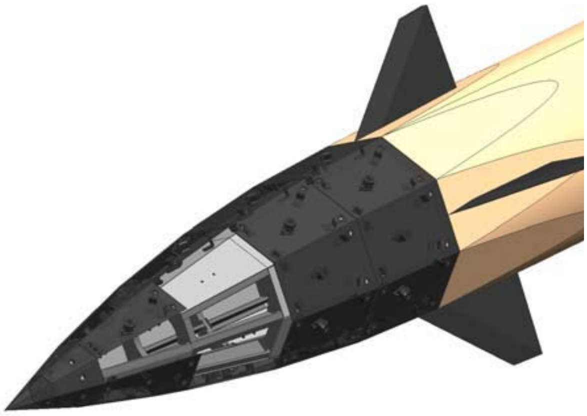

Figure 1. Facetted Fore Body with Canards

2. PAYLOAD AND VEHICLE DESIGN

The shape, dimensions and functions of the payload were determined by the experimental requirements, available motor systems and trajectory limitations. The requirement for Mach >8, together with an acceptable passive stability during re-entry, longer experiment duration and a high priority on recovery, led to the selection of a Brazilian VS40 two stage motor combination adapted for a suppressed trajectory. The main launch site requirements included the possibility for down range telemetry reception as well as impact and recovery on either land or ice. The aerodynamic requirements during re-entry meant that the payload required a flare and fins at the aft end and a centre of gravity close to the centre of the payload, rather than the usual case of as far forward as possible. The active suppression of the trajectory with this vehicle is only possible with an exo-atmospheric precession manoeuvre, which means that a reasonably predictable roll rate and a precession control system are required. A star update of the inertial reference system after second stage burnout and despin, required a three axis attitude pointing manoeuvre with fast acquisition to a stellar target and fine pointing angular rates of less than 0.5 degrees per second. Subsequently, a fast acquisition to the re-entry attitude and then a rate damping mode to reduce oscillation in the upper atmosphere due to the fin stabilization, were also required. The vehicle and payload configurations are shown in Figs. 2 and 3.

The first stage motor of the vehicle comprises the S40 with canted fins for a nominal parabolic trajectory. The interstage adapter with active separation system releases the spent S40 from the S44 and payload, after the aerodynamic forces have reduced sufficiently to provide negligible destabilizing effects. After separation, the S44 and payload have a nominal spin rate of 2 ± 0.5 Hz and an attitude of around 70 degrees elevation. At this point, the roll rate is corrected to 2 Hz by cold gas thrusters on the motor adapter and at the same time, the precession control system with radial thrusters in the module next to the canards, cause the spinning payload and S44 motor to point to the desired angle of the suppressed trajectory, before ignition of the second stage. After burnout of the second stage, a yo-yo system on the payload despins the payload and S44. The split fairing, which is necessary during the atmospheric flight to prevent the payload fins from moving the centre of pressure forward and destabilizing the complete vehicle, are then ejected. After that, the spent S44 motor is also released and the payload can then be manoeuvred for the star update and subsequently to the re-entry attitude.

To successfully recover the payload after the completion of the experiment phase at 20 km altitude, it is essential to reduce the velocity from approximately 2.5 km per second to about one tenth of this. The only way to achieve this is by destabilizing the payload. This is performed by splitting the payload into two unstable sections, which will then tumble and produce the necessary drag to achieve a recoverable velocity at an altitude of 4.5 km. The necessity to split the payload, resulted in the need to incorporate two gas systems. The forward gas system supplies the precession thrusters which need a large moment arm to turn the 1.5 ton mass of the payload and S44 motor, to the suppressed ignition vector. The aft gas system supplies the motor adapter roll rate thrusters and the three axis attitude and rate control thrusters for star pointing, re-entry control and rate damping during initial aerodynamic stabilization.

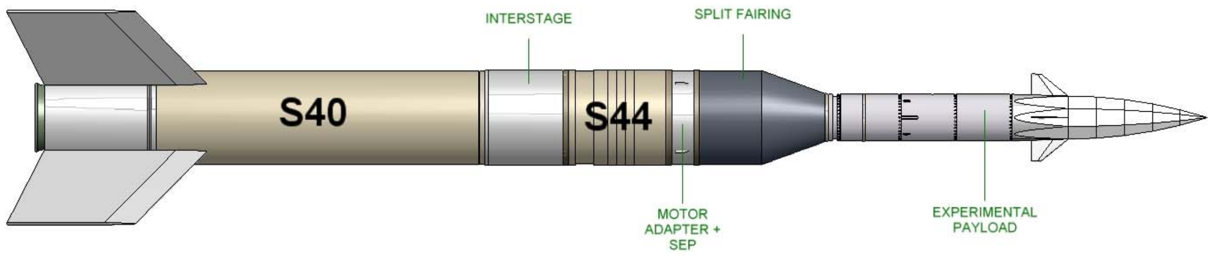

Figure 2. Complete Vehicle

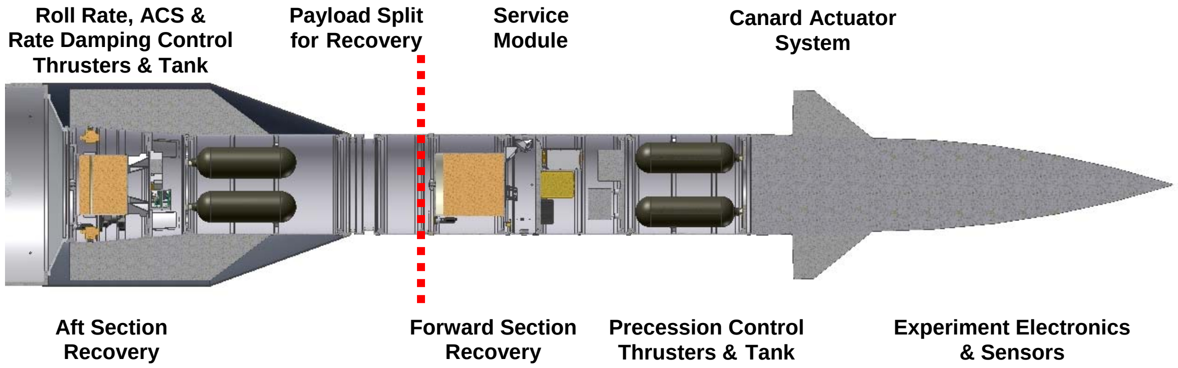

Figure 3. Experimental Payload

3. ATTITUDE AND RATE CONTROL

The control sensor for the attitude and rate control system is a Digital Miniature Attitude Reference System (DMARS), as used for SHEFEX 1. All real time critical control algorithms are implemented in the DMARS computer, whereas flight sequencing, interfaces to the experiments, telemetry and telecommand are performed in three multifunction processors in the service module electronics. The payload attitude and rate control system performs four main functions:

- spin rate correction of the second stage motor and payload after separation of the burnt out first stage
- two axis precession pointing of this spinning configuration for the required trajectory prior to ignition of the second stage
- subsequent to second stage burnout, de-spin, fairing ejection and motor separation, three axis pointing to the required attitude for star update and the anticipated re-entry attitude are performed
- Three axis rate damping during the initial aerodynamic stabilization of the payload

3.1 Roll Rate Control

At burnout of the S40 motor, the vehicle should have a small coning about the flight vector and a nominal spin rate generated by the canted fins of the S40. The S40 with its fins provides the only aerodynamic stability at this stage and for this reason, it will not be separated from the S44 and payload until the aerodynamic drag disturbances become small in comparison to the available control torque of the precession thrusters. At an altitude of the order of 70 km, the S40 will be actively released and the spin rate of the S44 and payload corrected to 2 Hz by the roll rate control system. The roll rate solenoid valves are situated in the aft end of the payload and supplied from the aft gas system, but connect through the payload separation plane to roll rate thrusters on the motor adapter ring, for maximum moment arm. The accuracy of the roll rate is not critical, but the test, qualification and operation of the precession system is simplified by reducing the tolerance of the spin rate produced by the canted fins and the aerodynamic effects on the vehicle.

3.2 Precession Control

The precession control torquer system comprises three radial thrusters in the forward gas system, which will remove any coning and also precess the longitudinal axis of the spinning payload to the inertial attitude required such that ignition of the S44, will provide the required second stage trajectory. To simplify the system, no precession correction control will be used after ignition of the S44. As the flight vector of the S44 is actively controlled, this motor will include a flight termination system. Before ignition of the S44 motor, the payload trajectory will be that generated by the first stage S40, which means that in the case of a nominal flight and prior to S44 ignition, radar or GPS can not indicate any problems which might have occurred with the precession pointing system. For this reason, it is essential to provide a comprehensible interpretation of the attitude data from the inertial platform for the ignition and flight termination decisions. The alternatives for aligning the S44 motor and payload, range from setting a fixed attitude based on the nominal predicted trajectory through to impact prediction and correction for S40 dispersion. A dispersion correction on board would require navigation data from the platform or the GPS and the test and qualification of such a system is beyond the available resources. A major component of the final impact dispersion, is dependent on the performance and stability of the S44 with payload and the operation of the canards during re-entry. This will therefore provide a major area for investigation in the safety analysis.

3.3. Three Axis Attitude Control

Subsequent to burnout of the S44, the yo-yo despin system will reduce the spin rate to nominally zero, then the fairings covering the experiment stabilizing fins and the S44 motor will be ejected and the payload will be attitude controlled in all three axes. The first task is to point the star camera towards the zenith and with sufficient offset to the sun and moon, such that a star image can be obtained and processed by the Hybrid Navigation System (HNS) experiment to determine the inertial attitude of the payload independently from the DMARS. This data is used to correct the instantaneous attitude of the HNS which is fed to the Canard Control Computer (CCC). The CCC uses this, together with the instantaneous GPS position to calculate the trajectory, the actual flight vector and the pointing error of the payload attitude control system. As the control and pointing quaternions of the DMARS are also provided to the CCC, it can calculate the required offset and produce the modified pointing data which can be fed to the control system to correct the angle of attack.

Apart from the onboard stored target data and those generated by the HNS / CCC, pointing offsets may also be sent by telecommand from the ground. This gives the possibility to perform instantaneous impact prediction or radar trajectory updates to the flight vector data on the ground and uplink the corrections via telecommand, although experience with such systems has shown that automatic systems are to be preferred. The logic of the DMARS and HNS / CCC control is shown in Fig. 4.

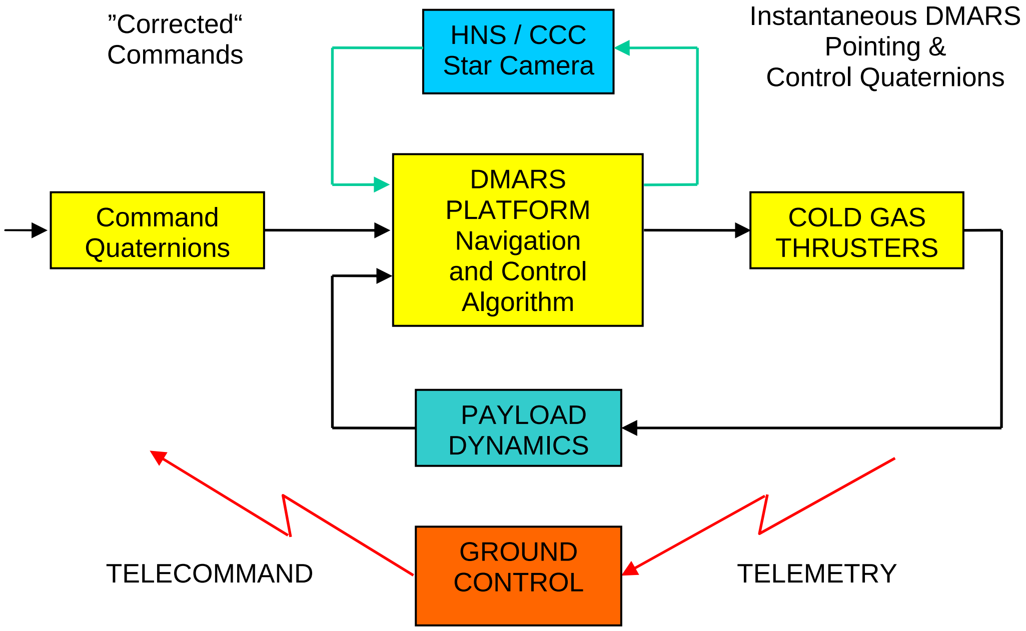

Figure 4. Three Axis Attitude Control Logic

3.4. Three Axis Rate Control

Shortly after the payload commences the experiment phase at 100 km on the descent, the three axis attitude control will be disabled. The payload will then begin to stabilize in the direction of the flight vector because of the fins and the aerodynamic flow. Experience with SHEFEX 1 showed that this results in a relatively undamped oscillation. The three axis attitude control includes a mode where the angular position terms can be disabled such that the control is limited to rate damping. This will permit the payload to align to the real flight vector but the oscillation will be damped out.

4. DATA COMMUNICATION

The service system comprises a redundant S-Band transmitting system consisting of two 5W RF transmitters and two antennae systems. This enables the ground stations to receive the downlink using both polarization and frequency diversity at the same time. One antennae system uses four MORABA high temperature antennae. With a very low loss passive combining network, the antennae are combined to produce a right hand circular polarized field (RHCP) to transmit the PCM data with TX1. The second antennae system consists of two patch antennae residing under RF transparent Whipox thermal protection tiles. This antennae system produces a linear polarized field and transmits the PCM data with TX2. In addition, all PCM data is recorded with an onboard solid state recorder and can be retrieved after recovery of the payload. The command uplink has a comprehensive structure to allow the transfer of packets as well as up to 128 discrete bit commands. In principle there are three different types of commands as service module commands, serial data packets and discrete bit commands. For the transfer via the telecommand link, GMSK (Gaussian minimum shift keying) code is used. The main attribute of this coding is the very small bandwidth required. Additionally a forward error correction code is added to decrease the bit failure rate. The probability of an erroneously decoded bit command is less than $1*10^{-11}$ at the worst bit failure rate (S/N ratio = 0) for the serial commands (18 Bytes), this rate is about $1*10^{-7}$ at the worst bit failure rate. The transfer of both telemetry and telecommand data on ground is via LAN and RS 232 and RS 422 serial interfaces.

To improve the cross-correlation of experiment data from different sources, UTC time from the GPS receiver and its one second pulse output will be used to synchronize all onboard data to a resolution of one millisecond.

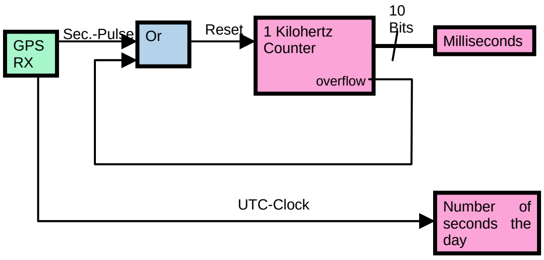

Figure 5. Time Synchronization Logic

A one kilohertz counter in each experiment data communication system will be synchronized by the GPS one second clock pulse and provide a time tagging of seconds and milliseconds of day as in Fig. 5.

5. TELEVISION CAMERAS

SHEFEX 2 will include two cameras which will look backwards from the forward gas system to monitor the first stage boost phase and separation, the precession manoeuvre, second stage burn, despin, fairing release, second stage motor separation, star camera door release and any re-entry effects on the payload fins. During re-entry, two forward looking cameras in pods on the payload flare, will provide views of the re-entry attitude, the operation of the canards and the angular motion of the payload. After payload split at the end of the experiment phase, a fifth camera in the forward recovery system will show the separation of the aft part of the payload and the parachute deployment. The camera data will be stored on solid state video recorders and one of these channels will be transmitted to ground by a 10W video transmitter. The RF output of this transmitter is connected to the same combining network and antenna array which is used for transmitting the payload TX1 PCM data, but in this case a left hand circular polarized field (LHCP) is radiated to further decouple the transmitters. The transmission standard for the color video signal is PAL-G using the CCIR 405 convention.

6. MECHANICAL FLIGHT SYSTEMS

A major area of development is the mechanical sub-systems for the vehicle as it was required to redesign the vehicle around the existing motors due to payload and mission complexity.

6.1. S40 Fins and Tail Can

The somewhat unusual experiment payload and vehicle necessitated a complete redesign of the main vehicle stabilizing fins which are necessary to guarantee sufficient aerodynamic stability for the unguided atmospheric ascent phase.

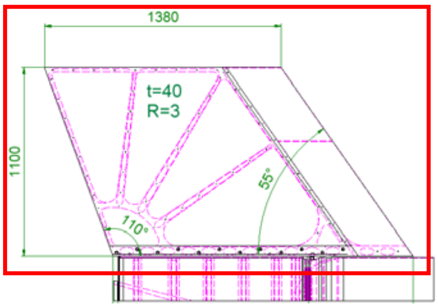

Figure 6. S40 Fin Design

To compensate for the heavy payload, the exposed canards and conical flare from payload to motor diameter, the fin area was drastically increased while being constrained by mass, jet plume effects on the trailing edge, nozzle length and motor case geometry for attachment on the leading edge. The fin design in Fig. 6 consists of an aluminium basic frame with load optimized layout, honeycomb filling, metal sheet cover and steel leading edge. This also required a modification of the standard S40 tail can to carry the new fins and withstand all the loads.

6.2. S44 Motor Payload Adapter

The S44 motor-payload adapter is the main interface between the motor system and the payload and provides a manacle flange to the conical aft section of the experiment payload. Additionally, the motor adapter houses the ignition system for interstage separation of the S40 motor, ignition of the S44, flight termination, the aft fairing release, pneumatic manacle release and payload separation system and the coarse roll rate control thrusters with their detachable connection to the aft cold gas system

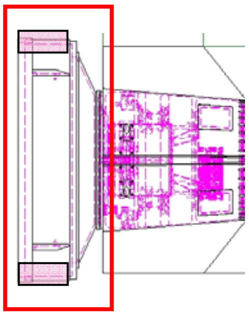

Figure 7. S44 Motor-Payload Adapter

6.3. Forward and Aft Recovery System and Despin

After completion of the experiment phase and initiation of payload splitting, the two payload parts will be recovered by two dedicated recovery systems, one main recovery system for the forward part and one auxiliary recovery system for the rear payload part. Both systems comprise two stage, subsonic parachute systems with modified high strength drogue parachute and cross canopy main parachute and are based on standard DLR designs. The forward system is situated aft of the service module, interfacing the payload split plane and the aft system is installed in the aft end flare of the experiment payload with the interface to the motor adapter. The parachute systems are activated by barometric altitude switches at 15 kft. A yo-yo despin system is used to reduce the 2 Hz vehicle spin to nearly zero after second stage burnout. The despin system is placed in the middle of the experiment vehicle and is based on standard DLR systems.

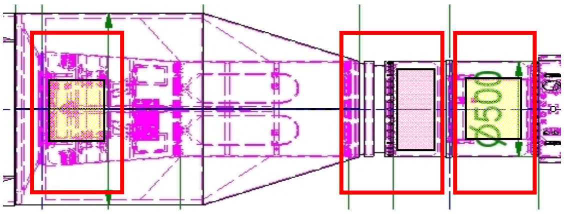

Figure 8. Recovery Systems and Yo-Yo Despin

6.4 Payload Fin Fairing

Due to aerodynamic stability requirements of the complete vehicle during the flight trajectory ascent, the payload aft fins are covered by a conical fairing. The fairing consists of two carbon fibre half shells, stiffened by aluminium rings on the front and aft ends, which also contain the interface geometry for attachment to the structural modules. The basic design for the release mechanism incorporates a spring loaded system fixed by steel cables.

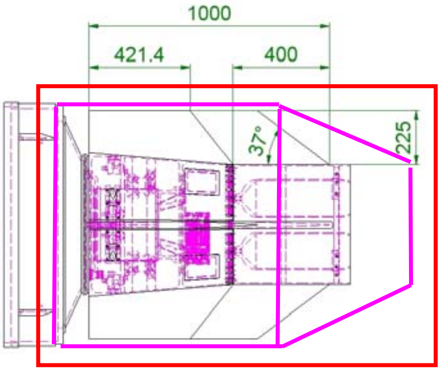

Figure 9. Payload Fin Fairing

6.5 Manacle Ring 500 mm and 600 mm

For the payload motor connection as well as the connection of both separate payload parts, a 600 mm respectively 500 mm releasable manacle ring has been designed based on standard designs with segments, lock and turnbuckle. The manacle rings have to withstand extreme structural loads during atmospheric ascent of the complete vehicle and during the experimental phase on re-entry, hence both the rings and also the flanges are subject to structural analyses and load tests. The release is realized by a pyrotechnically actuated high pressure nitrogen, high velocity separation system including manacle lock opener and separation plungers.

7. TRAJECTORY AND LAUNCH SITE

Figs. 10 and 11 show the implications of range on the time available for the events between burnout of the S44 and start of re-entry at 100 km altitude. These events include despin, fairing release, payload separation, acquisition of the star update attitude, star update operation and three axis alignment for the re-entry. The green, red and blue colours represent the trajectories and flight times while the coloured bars indicate the payload manoeuvre times for ranges of 1000, 900 and 550 km respectively.

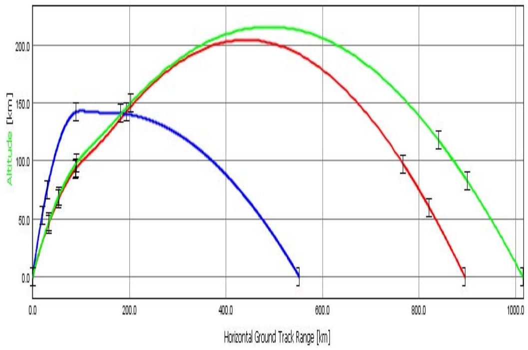

Figure 10. Altitude vs. Ground Range

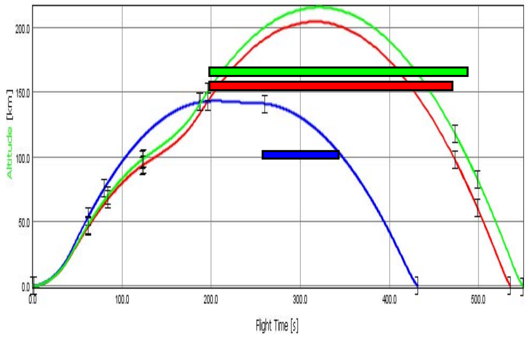

Figure 11. Altitude vs. Flight Time

The main considerations for the launch site are good communication with the payload, both for telemetry and telecommand from launch until at least end of the experiment phase at 20 km altitude, good recovery conditions on land or pack ice and minimum risk of flight termination. The baseline is Andøya Rocket Range, with impact at 1000 to 1200 km range. This scenario involves the use of the KSAT facility at Longyearbyen and the optical fibre communications from Spitsbergen to Andøya and is limited to early spring when enough daylight and frozen impact area is available. Because of the severe requirements on the position of the payload centre of gravity, it appears likely that considerable ballast will be required, which will possibly reduce the range such that Spitsbergen can not be reached and this would result in an impact in the sea, which with the probable large dispersion, would make recovery extremely difficult, if not impossible.

An alternative is a land range with an impact of less than 600 km, however, this requires a greater precession manoeuvre and results in a drastically reduced time for all events between burnout of the S44 and re-entry, which would endanger the star update and the achievement of the desired re-entry attitude. The only realistic alternative to Andøya is a land range with an impact range possibility of at least 800 km. Initial investigations have been commenced with the Woomera Range in Australia.

8. CURRENT STATUS

The main milestones for development, test, qualification and launch have been defined as follows:

- Construction, assembly and test of all payload components required to verify the operation of the service module and the four control system modes. This implies all modules except the recovery and separation systems and motor components. This also includes full flight telemetry and telecommand systems and ground support equipment.
- Preliminary integration tests with data and mechanical interfaces of all experiment modules.
- Construction and prototype testing of S40 fins, fairing release system and manacle joints and release.
- Completion of all additional payload and motor sub-systems, integration, calibration and environmental qualification and construction of all ground support equipment.
- Negotiations for technical support and installation of facilities at the selected range.
- Transport and launch campaign.

The motor procurement is proceeding and the qualification of the modified S40 is planned for October 2009. The largest schedule risk factors are the experiment module and the vehicle system development and the heavy workload of MORABA, but the launch campaign is planned for either late 2010 in Woomera or early 2011 in Andøya.

9. CONCLUSION

As the development, construction, test and qualification of the SHEFEX 2 payload and vehicle systems proceeds, it is already apparent that the experiment requirements, aerodynamics, trajectory, attitude control and measurement, thermal protection, recovery and safety considerations for a suppressed trajectory, hypersonic experiment payload, bear little resemblance to our usual sounding rockets for exo-atmospheric research. Experience gained with the SHEFEX 1 mission has proved invaluable to this mission in the appreciation of the problems confronting us. We now look forward to applying this experience in tackling the expected and unexpected problems which will confront us in the next stages of the SHEFEX hypersonic re-entry research program.

10. ACKNOWLEGEMENT

SHEFEX is a DLR project and thanks are due to the project manager Hendrik Weihs from DLR Stuttgart and a number of colleagues at MORABA and the other participating DLR institutes, who have and will contribute further to the design, construction, qualification and launch of the SHEFEX 2 vehicle and experiment.

11. REFERENCES

1. Turner J., Hörschgen M., Jung W., Stamminger A., Turner P., *SHEFEX Hypersonic Re-entry Flight Experiment – Vehicle and Subsystem Design, Flight Performance and Prospects,* 14th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Canberra, 2006
2. Turner J., Hörschgen M., Jung W., Turner P., *SHEFEX 2 – The Vehicle, Subsystems and Mission Concept for a Hypersonic Re-entry Flight Experiment*, 18th ESA Symposium on European Rockets and Balloon Programmes and Related Research, Visby, 2007.
3. Weihs H., Turner J., Hörschgen M., *SHEFEX II – The Next Step within Flight Testing of Re-entry Technology,* 57th International Astronautical Congress, Valencia, 2006
4. Weihs H., Longo J., Turner J., *The Sharp Edge Flight Experiment SHEFEX II – A Mission Overview and Status,* 16th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, 2008