SHEFEX 2
THE VEHICLE, SUBSYSTEMS AND MISSION CONCEPT FOR A HYPERSONIC RE-ENTRY FLIGHT EXPERIMENT

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ABSTRACT

The first launch of the **SH**arp **E**dge **F**light **EX**periment (SHEFEX) was from Andøya Rocket Range (ARR) Norway, in October 2005. Its purpose was to investigate the aerodynamic behaviour and thermal problems of an unconventional shape for re-entry vehicles comprising multi-facetted surfaces with sharp edges and an asymmetric form and to provide a correlation of numerical predictions with the flight results for velocities up to the order of Mach 7. The success of the first mission has led to the approval of the SHEFEX 2 project which will involve a facetted but symmetrical fore body with a canard control system to obtain further data on the aerodynamic and thermal effects at hypersonic velocities. The canard system should provide control in all axes and predefined angles of attack of up to +/-5 degrees during the re-entry phase. The Mobile Rocket Base (MORABA) of the German Aerospace Centre (DLR) is again responsible for the vehicle, payload, service systems and test flight of the SHEFEX 2 experiment on a two-stage, solid propellant, sounding rocket.

1. MISSION CONCEPT

The initial concept for the SHEFEX 2 mission comprised a 438 mm diameter payload with facetted but symmetrical, approximately ogive front end and canards, on a VSB-30 motor system.

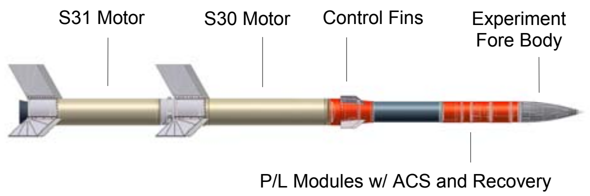

Figure 1. SHEFEX 2 Initial Concept

This configuration would have provided a conventional parabolic trajectory as for SHEFEX I, but with a maximum re-entry velocity of the order of Mach 8. The main disadvantages of this configuration were the reduced experiment duration with a faster but almost vertical descent and the restrictions on experiment payload layout imposed by the vehicle system.

Obviously, a flatter re-entry angle would provide more experiment time, but this imposed greater requirements on vehicle performance and range infrastructure for communication between the payload and ground, and also significant recovery problems.
A solution to the range infrastructure and recovery problem was found in the use of ARR as launch site, the over flight of Svalbard and impact on the pack ice north of the Svalbard archipelago. Both Andøya and Svalbard provide elevated plateaux (270 and 400 metres respectively) with power and communications for extended horizon and also high speed data fibre optic links to the launch site, which permit un-interrupted telemetry and telecommand communications for the whole flight and particularly the re-entry phase. The pack ice, at least in the winter and spring period, still provides a large firm impact area.

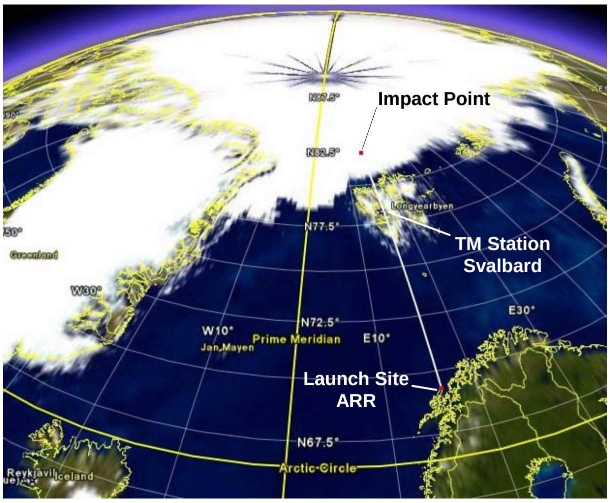

Figure 2. Flight Path

The next problem was a motor system with the range performance and the possibility to provide a flat re-entry trajectory. By choosing a VS-40 unguided sounding rocket and launching it with a conventional elevation of around 82 degrees and then after leaving the atmosphere, tipping the second stage and payload towards the horizontal prior to ignition, a flatter re-entry is possible without the additional dynamic loading problems of a suppressed trajectory for the whole flight.

The technological implications for the vehicle, payload, service systems and launch support are considerable and provide challenges over and above those encountered in our more classical sounding rocket activities. Some of the more significant aspects are described in the following.

2. ROCKET MOTOR SYSTEM (RMS)

The Brazilian VS-40 is an unguided solid propellant sounding rocket, consisting of the S40 and S44 motors as first and second stages respectively. The RMS was originally designed and developed by CTA to collect vacuum in-flight data of the S44 motor, designated as the fourth stage of CTA's satellite launcher VLS.
The S40 is also used as the first stage of the SONDA IV and part of the VLS, operating as the third stage.
The S44 motor case is made of carbon fibre. The interstage adapters are lightweight structures built of Kevlar composites.
The VS-40 was first launched in April 1993 achieving an apogee of 950 km with a payload mass of 197 kg at 81.8 degrees launch elevation. Up to now, two flights have been performed, both successful. [6]

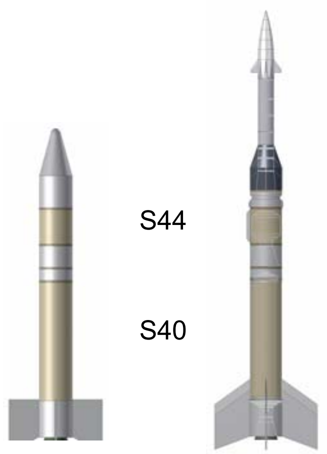

Figure 3. VS-40 (Original) SHEFEX 2 Configuration

The SHEFEX 2 sounding rocket vehicle has an overall length of 13 m with a lift-off mass of 6,675 kg. The motor diameter corresponds is 1 metre.

3. PAYLOAD DESIGN

The layout of the payload is determined mainly by the facetted sharp edge experiment, the position of the canards, the dimensions of the cylindrical section and the stabilizing fins. In addition, the optimum locations for cold gas thrusters are at the forward end for precession, at the aft end for the three axis lateral control and on the maximum radius of the S44 motor for the roll control. A further consideration is that the only practical way to slow down a stable object travelling at the order of Mach 10 to a recoverable velocity at an altitude of less than 20 km is to make it unstable and use the increased aerodynamic drag from tumbling. The simplest way to achieve this is by splitting the payload into 2 separate unstable sections. This separation plane also means that two separate gas systems are required, one forward for the precession thrusters and one aft for the three axis and roll rate control.
The payload configuration is shown in Figure 3. The experiment re-entry body contains the front end processing for all sensors. The canard section comprises a 600 mm module which contains the canard actuators and their battery packs. The precession thrusters, tank and regulator and the main antenna systems, are in the next section. A water tight module contains the inertial platform, the main electronics and all data acquisition, telemetry, telecommand systems, radar transponder and canard sensor package and control processor. The forward recovery system is used to recover these sections after payload splitting at 15 km on the descent.

The aft section comprises the flare and stabilizing fin section, the roll rate and re-entry ACS control thrusters, regulator and tank and the aft recovery system.

4. ATTITUDE AND POINTING CONTROL

The main functions of the attitude control systems are as follows:
- spin rate control of the second stage motor and payload after separation of the burnt out first stage and two axis precession pointing of this spinning configuration for the required trajectory prior to ignition of the second stage,
- three axis pointing to the anticipated re-entry attitude subsequent to second stage burnout, de-spin, fairing ejection and motor separation,
- provision of reference inertial flight vector attitude data to the experiment canard control system,
- Adaptive control of the payload attitude above altitudes where the canards are effective.

4.1 Second stage trajectory alignment

At burnout of the S40 motor, the vehicle will have a nominal zero incidence to the flight vector, which also means that by keeping the system together, the aerodynamic drag will have the minimum effect on the velocity and on the attitude. Above approximately 70 km, after the aerodynamic pressure has reduced sufficiently, the S40 will be actively released and the S44 and payload will have a spin rate of nominally 1.2 Hz. and a small coning motion.
The roll rate system will correct the spin rate to compensate for tolerance in the aerodynamic spin up of the S40 fins and the precession control will de-cone and provide a precession pointing to the required second stage trajectory. As the flight vector of the S44 is actively controlled, this motor will include a flight termination system. Prior to ignition of the S44, the

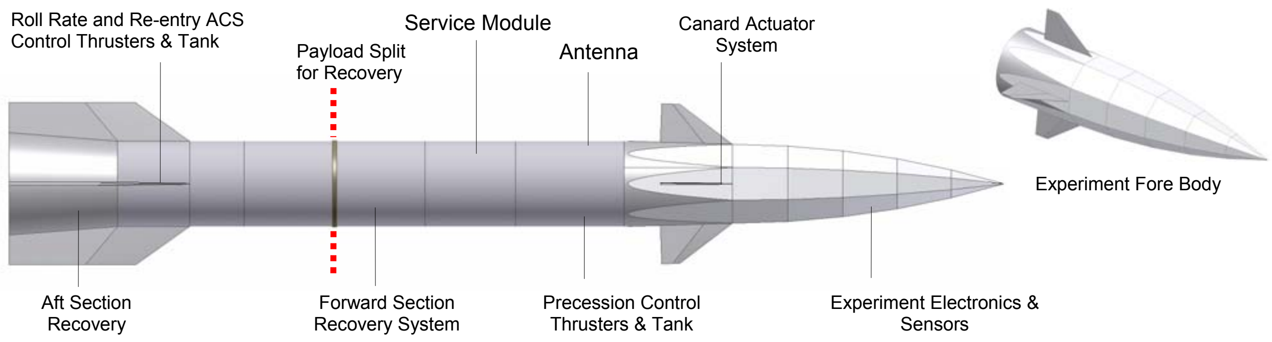

Figure 4. Main Payload Components

trajectory will be that of the S40 and initial vehicle, which means that in the case of a nominal flight, radar or GPS can not detect any problems until after S44 ignition. For this reason, it is essential to provide GO/NO-GO attitude data from the inertial platform for the ignition and flight termination decisions. The alternatives for aligning the trajectory, range from setting a predicted attitude through to impact prediction and correcting for S40 dispersion. A dispersion correction relies on one or both of the navigation data from the platform and or the GPS. The platform navigation data is difficult to test in the laboratory and the GPS must cope with the spin rate, as there is no possibility for our usual tip antenna on the experiment. The actual setting could be either generated on board or loaded from the ground. Also 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.

4.2. Three axis pointing to required re-entry attitude

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 will be ejected and the payload will be stabilized in three axes in the required re-entry attitude. This attitude is that of the trajectory vector and consequently also dependent on the accumulated dispersion. The alternatives here are also similar to those for the previous problem and will be subject to tradeoffs where the available resources will play a significant role.

4.3 Re-entry attitude reference for the canard system

The control of the canards and their manoeuvres are the responsibility of the experimenter. They provide not only an offset pointing about a flight trajectory, but will considerably vary that trajectory. The effectiveness of the canards also varies considerably during the descent into denser layers of the atmosphere. Further aspects are the control algorithm for this system, the raw data rate required from the sensors for a stiff control and not the least, the logistical problems for extended integrated tests with our colleagues in DLR Brunswick. The preferred solution is the provision of reference attitude and measurement data during re-entry from the inertial platform, but actual control of the canards by its own rate sensor package and processor. This area will also provide a major part of the development.

5. AERODYNAMICS

The preliminary design and analysis of SHEFEX 2 aerodynamics and performance was carried out with Digital DATCOM which is a computerized version of the semi-empirical USAF Data Compendium Missile DATCOM.

For comparison with modern methods of computational fluid dynamics (CFD) the TAU-Code, developed at the DLR Institute of Fluid Dynamics and Flow Technology in Brunswick, was used.

Digital DATCOM determined the static longitudinal stability at lift-off to 1.5 calibres. The minimum static stability occurs at 39 seconds with 1.15 calibres (D_{ref} = 1.007 m).

Mach numbers for all flight regimes were chosen, with an angle of attack of 2 degrees for all cases:

a) M = 0.6 (subsonic speed)
b) M = 0.9 (transonic speed)
c) M = 2.7 (supersonic speed, q_{max})
d) M = 4.3 (hypersonic speed, pitch/roll coupling)

Table 1 shows the centre of pressure (CoP) variation quantitatively, as well as in relation to the overall length L_{ref}, and to the motor diameter D_{ref}.

Table 1. CoP Variation Digital Datcom / TAU-Code

Mach No.	0.6	0.9	2.7	4.3
Datcom	10.457 m	10.424 m	9.598 m	9.077 m
TAU	10.837 m	10.936 m	10.518 m	9.783 m
ΔL_{ref}	+ 2.9 %	+ 3.9 %	+ 7.1 %	+ 5.4 %
ΔD_{ref}	+ 0.4 cal	+ 0.5 cal	+ 0.9 cal	+ 0.7 cal

The uncertainties of Digital DATCOM in comparison to the TAU-code are in the order of magnitude of 3-7 % or less than 1 calibre. In each case, Digital DATCOM predicts a smaller stability margin, meaning always forward of the prediction from the TAU-Code. The loss

of stability margin due to aeroelasticity is not considered yet.
The next comparison, accomplished for subsonic speed only, shall prove that the exposed fore body can be launched without a protective ogive. Apart from a mass saving this solution already permits measurements during the ascent phase.

Table 2 CoP Variation for Ogive / Facetted Fore Body

Mach No.	0.6	0.9
Ogive	10.606 m	10.881 m
Facetted	10.682 m	10.884 m

Table 2 shows, that for the SHEFEX 2 configuration, the centre of pressure variations differ insignificantly for the nose cone shape geometry, either facetted with sharp edges, or a smooth ogive, so that from an aerodynamic point of view the experiment can be flown without a protective cover.

6. FLIGHT DYNAMICS

The following figures and tables display the preliminary flight performance. The maximum altitude for this scenario is approximately 215 km, the ground range is predicted as 1,170 km. The re-entry flight path angle at 100 km is approximately 30 degrees.
The experimental phase on the downleg from 100 km down to 20 km comprises 50 seconds of experimental time providing velocities in the region of 3.1 km/sec and 2.7 km/sec respectively which conforms to a Mach regime between 11.0 and 9.5.

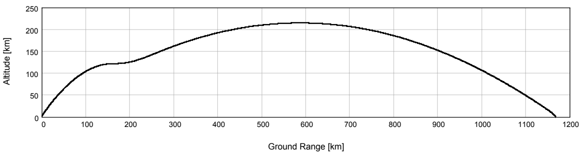

Figure 5. Altitude vs. Ground Range

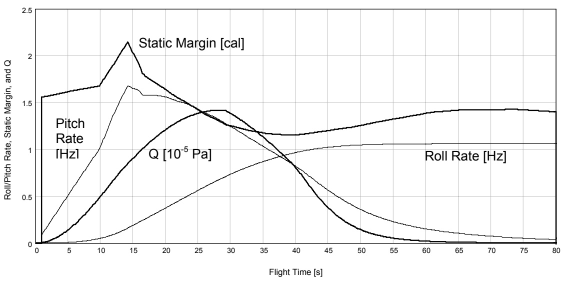

Figure 6. Ascent Flight Parameters

Table 3. Critical First Stage Flight Events

Event	Value	Time	Altitude
Lift-off SM	1.5 cal.	0 s	0 km
Mach No.	1.0	11 s	1.7 km
Max. Pitch	1.7 Hz	14 s	2.7 km
Max. Q	140 kPa	29 s	11 km
P/R coupling	0.9 Hz	37 s	20 km
Min. SM	1.15 cal.	39 s	21 km
Max. Roll	1.1 Hz	62 s	48 km

7. MECHANICAL FLIGHT SYSTEMS

The implementation of a new vehicle with an unusual payload form, guidance system and trajectory performance criteria as well as a recovery operation requiring extreme aerodynamic braking at a low altitude, has imposed a wealth of technical problems in the mechanical design. The main problem areas are the aerodynamic stability of the complete vehicle during ascent in spite of payload fins and inactive canards, active separation of the two motors after an extended coast phase, incorporation of two cold gas systems with thrusters at optimum locations and splitting the payload at hypersonic velocities for pre-recovery aerodynamic braking. In addition, a payload length of 5.5 metres and a maximum mass of 350 kg was the target.

7.1 Fairings and Motor Fins

A solution for the payload fin and canard problem would have been to place a fairing over the complete payload; however, the increased mass would have reduced the performance of the first stage and particularly the second stage, unless it could be ejected under spin before ignition. The qualification of such a system was considered to exceed our available resources. A compromise was chosen which comprises a small fairing over the payload fins which will be ejected after S44 burnout and de-spin. The fairing will be of composite material and consist of two or four segments approximately 1.4 metres in length, which are released by pyrotechnic actuators on the payload and the attachment module. The canards will be locked by retractable pins until apogee, but as they are exposed, still contribute to the need for larger but lightweight fins on the S40. The S40 fins with a span of greater than 1 metre and an extended root chord on the motor case, provide the required lift-off stability. The design and construction of these hybrid fins will be performed in a co-operation with the DLR Stuttgart institute for materials research.

7.2 Payload attachment Module

The interface between the S44 motor and the payload fulfils several functions. A YO-YO de-spin system removes the 1.2 Hz spin rate which is required to stabilize the burn phase of the S44. The forward end of the attachment module is used to clamp the aft end of the payload fin fairings. Once the fairings are released, a manacle ring clamping the aft end of the smaller diameter (600 mm) payload flare adapter to the attachment module is released and simultaneously 3 separation plungers accelerate the payload away from the motor.

7.3 Payload Fins

The payload fins are small span fixed stabilizers of about 1200 mm root chord length and 230 mm span and are constructed from high temperature resistant composite material because of the aerodynamic and thermal loading during re-entry. Because of the necessity for roll rate control with a large inertia filled S44 motor, the roll thrusters must be integrated into the fins for maximum torque moment arm. In addition, as these fins will be on the prime payload axes, the lateral control thrusters must also be integrated into the aft end of the fins. This in turn means that the fairings must include a cutout at least for the roll thrusters which will be operated before fairing ejection.

7.4 Recovery

At approximately 15 km altitude on the descent, the payload will be separated by a manacle ring release and high velocity separation system into two sections which are inherently unstable. This will produce a tumbling motion with extremely high deceleration which results in velocities of less that 250 metres per second by the time the payload sections have descended to 4.5 km, where the heatshields are deployed and normal recovery parachute system operation is possible. Experience with the SHEFEX I payload has shown that provided the problem of ram air spikes is accounted for and the centres of gravity of the payload sections are correctly placed, that the aerodynamic braking is adequate. High velocity recovery systems are installed at the aft ends of both payload sections.

8. ON BOARD DATA COMMUNICATION

8.1 Telemetry

The Service System comprises a redundant S-Band transmitting system consisting of two 10 Watt 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 which have been flight qualified during the SHEFEX I mission. 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.

8.2 Payload Telecommand

The payload telecommand system is identical to the system used for the SHEFEX I project. The onboard system comprises two L-Band telecommand receivers coupled to two high temperature antenna spaced at 180 degrees. The demodulated video is directly routed to the GMSK demodulator units. The bit rate is 19.2 KBaud. Error detection and correction combined with CRC checking and interleaving provides a high degree of safety and ensures correct commands even under severe receiving conditions. The command system provides up to 64 single bit commands and several serial byte command channels which are transparent for the users.

8.3 Television

During the ascent of the vehicle, real time video data from a camera looking aft will be transmitted to the ground station using a S-Band 10 Watt video transmitter. The RF output of this transmitter is connected to the same combining network and antennae 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. After deployment of the S44 and payload fairings, a second camera looking forward from the payload flare will use this link. At separation of the two payload sections and shortly before activation of the recovery system, the video input to the transmitter is switched to a third camera in order to monitor the recovery sequence.
The transmission standard for the colour video signal is PAL-G using the CCIR 405 convention. As with the payload PCM data, all video information is recorded with a solid state recorder on board the payload.

8.4 Radar Transponder and GPS System

The payload is equipped with a 400 Watt radar transponder and an appropriate antennae system which receives and transmits with a circular polarization. In addition, the qualified DLR ORION GPS receiver will be used to obtain velocity and position data. The onboard generated IIP information is used as a backup source to the ground safety system using radar data.

9. LAUNCH MISSION AND CAMPAIGN

At ARR the 3 m and the 6 m monopulse tracking stations will we used to receive the payload PCM data and the video images. Both receiving chains are configured to provide polarization and frequency diversity reception. This concept will ensure good data quality during that part of the trajectory visible from the range. The ARR mobile telemetry station will be located and operated in the same way as during the SHEFEX I mission. During this flight, the station demonstrated its value at this local elevated position. With this station it will be possible to receive direct payload data down to a flight altitude of less than 100 km on the down-leg part of the trajectory.

The MORABA mobile telemetry station will be set up on the elevated plateau at Longyearbyen. This location enables the reception of the payload signals as soon as the vehicle is visible over the local horizon which corresponds to a flight altitude of approximately 70 km on the ascent. From this point onwards the payload data is received and the demodulated PCM signal is sent back to Andenes using the submarine high data rate optical fibre link. As the ground range to the nominal landing point of the payload is in the order of 300 km, the RF link can be maintained down to an altitude of approximately 4 km. As the initiation of the recovery sequence will start at about 15 km altitude with splitting the payload, most of the recovery events can be monitored. A second payload telecommand station will be used at this location to transmit commands which are received through the optical fibre connection from the payload engineer at Andøya as soon as a reliable downlink to the payload is achieved.

A preliminary link budget calculation for the main tracking stations at Andøya during the whole time of visibility, shows a comfortable 6 dB margin (not including the pre-detection diversity improvement) when using 10 Watt payload transmitters for the PCM data.
For the TV link a minimum video signal quality of around 30 dB can be expected. At all times an adequate link margin is guaranteed with the high power destruct and payload command transmitters.

10. SAFETY

As the second stage of the VS-40 vehicle will be re-oriented with an active control system before ignition, a fully redundant flight termination system is necessary. This system permits the destruction of the S44 motor in the case of an abnormal flight.

During the burn phase of the first stage, the system is treated as a normal unguided sounding rocket. The ignition of the second stage is effectively controlled by a number of conditions:

- Precession manoeuvre achieved
- Ignition time window open
- TC ignition inhibit not active

The onboard inertial guidance platform signals to the ignition system that the pointing of the second stage is achieved and correct. Via telemetry, the payload engineer and safety officer can verify this information on ground and correlate with additional information such as payload GPS and radar. Should there be a failure of the attitude control system, an ignition inhibit signal can be sent to the second stage ignition system by the payload telecommand system. Should all conditions be fulfilled, the second stage will ignite at a preset time.

CONCLUSION

At the start of our involvement with the SHEFEX programme five years ago, we assumed that apart from the obvious differences in experiment requirements, trajectory, attitude control and measurement and difficult recovery operation, the performance of a hypersonic experiment in the upper atmosphere at the end of a ballistic flight would pose no great problems. We have now obtained first hand experience of the construction of vehicles which from the standpoint of aerodynamics, structures, thermal protection, payload and ground support subsystems and attitude control, bear little resemblance to our usual sounding rockets for exoatmospheric research. We now look forward to applying this experience in the next stages of the SHEFEX hypersonic re-entry research program.

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