THE SQUID SOUNDING ROCKET EXPERIMENT


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ABSTRACT

The objective of the SQUID project is to develop and in flight verify a miniature version of a wire boom deployment mechanism to be used for electric field measurements in the ionosphere. In February 2011 a small ejectable payload, built by a team of students from The Royal Institute of Technology (KTH), was launched from Esrange on-board the REXUS-10 sounding rocket. The payload separated from the rocket, deployed and retracted the wire booms, landed with a parachute and was subsequently recovered. Here the design of the experiment and post flight analysis are presented.

Key words: Aurora; KTH; REXUS; SCALE.

1. INTRODUCTION

To advance understanding of the space environment around the Earth, multi-point missions are the natural step to resolve spatial/temporal ambiguity in single probe measurements. Missions such as Cluster and THEMIS have provided rich data for magnetospheric studies. In auroral and atmospheric research sounding rockets are a viable platform, and several multi-payload suborbital missions have been realized. Also, an advantage of suborbital flight is that the payloads can be recovered, thus allowing to eliminate the limitations of the telemetry.

Space and Plasma Physics division (SPP) at the Royal Institute of Technology (KTH) is working on developing a recoverable payload for multipoint sounding rocket measurement, with primary focus on the electric and magnetic fields. Increasing the number of measurement points requires miniaturization of payload. A step on the path was the Light Airbag Protected Lander (LAPLander) project [1] flown on the REXUS 8 mission. The objectives of the project were to develop and test a novel landing system based on an inflatable structure and to test other subsystems for such a probe. The Spinning QUad Ionospheric Deployer (SQUID) project is the second step on the path.

Both LAPLander and SQUID are KTH student projects within the REXUS/BEXUS programme which is a cooperation between the Swedish National Space Board (SNSB), German Aerospace Center (DLR), European Space Agency (ESA) and Eurolaunch. The aim of the programme is to offer student teams the possibility to launch their experiments with a rocket or a balloon.

The SQUID project’s aim is to develop, and in flight verify a single ejectable probe for electromagnetic measurements. The first objective is to develop and fly a wire boom deployment system which is the basis of double probe electric field measurement technique. Due to the limited flight time of sounding rockets, the deployment of the booms must be fast. When fast deployment is abruptly terminated the booms starts to oscillate, disturbing the dynamics of the payload and compromising the measurement quality. To reduce the residual oscillations a special deployment procedure is applied [2]. Validating this method is the second objective of the experiment.

2. EXPERIMENT DESIGN

SQUID consists of two main units positioned underneath the nosecone: the Free Flying Unit (FFU) and the Rocket Mounted Unit (RMU). The FFU is ejected along the rocket’s roll axis and carries all sensors and the wire boom deployment system SCALE. Since the collected sensor data is stored into an onboard memory the FFU includes a recovery system. Before ejection the FFU is secured to the RMU. The RMU is the experiment’s mechanical and electrical interface with the rocket. The unit features an ejection system that separates the FFU from the rocket.

2.1. The Free Flying Unit

The FFU has the dimensions $\varnothing 0.22 \times 0.11 \text{ m}$ and weighs 3.6 kg.
2.1.1. Mechanical Design

The core of the FFU is a box containing all electronics, called the eBox. Positioned diametrically around the eBox are the four SCALE wire boom deployment systems, described in Section 3. The eBox and SCALE systems are attached to the octagonal bottom plate of the FFU. The bottom plate, a frame on top and eight wall pieces form the octagonal outer structure of the FFU. The walls are attached to the bottom plate and the frame by 16 screws, respectively. Resting upon the octagonal frame is an ejectable top plate. The SCALE systems protrude beyond the octagonal envelope.

The top plate is part of an in-house developed landing system. The landing system consists of three main components: a parachute, a streamer and the top plate ejection mechanism. Underneath the top plate a 1.8 m cross type parachute and a 1.8 × 0.2 m streamer is packed. The streamer is connected to the top centre of the parachute by a 1.5 m Kevlar cord. Four loops of cord attached to eight points on the parachute are collected to a shackle that also has one end of a 2 m long High Modulus Aramid fibre cord (HMA) attached. The HMA cord’s other end is attached to another shackle that connects to the loops of two Kevlar cords attached at four points to the frame. The top plate houses two small springs of 130 N and potential energy of 0.69 J, each, that push the plate away during ejection. It is secured by a Kevlar cord guided through the FFU where it is switched to a Spectra cord before going inside the eBox. Inside the eBox the Spectra cord passes through a thermal cutter and is secured by a clamp.

The thermal cutter consists of a PEEK shell housing a Macor tube carrying a heater wire (170 mm Kanthal ø0.25 mm wire with a resistance of 6.25 Ω) coiled around it. Applying the FFU’s battery voltage (7.2 V nominally) to the wire it heats up the Macor, eventually melting the Spectra cord guided through it. Spectra melts at a temperature of about 160°C and this temperature is reached approximately 20 seconds after activation.

During descent at an altitude of about 6 km (based on a pressure sensor output) the cutter is activated. As the Spectra cord is cut the top plate is released and ejected by the two springs, exposing the streamer and parachute. The streamer is directly caught by the air stream and as the rope connected to the parachute is stretched the drag exerted by the streamer pulls the parachute out from it’s compartment. The descent rate of the FFU with the parachute deployed is 6 m/s by design.

2.1.2. Electronic Systems

Figure 2 displays an overview of the FFU electronic systems. These include the mission systems (Main) and the electromagnetic field measurement instruments. The Main system uses an Actel ProASIC 3 Field programmable gate array (FPGA) to control the SCALE systems, recovery system and the flight dynamics sensors of the FFU as well as housekeeping voltages. Data are saved in a non-volatile Flash NAND memory from HYNIX.

The analog electronics for measuring the potential of the electric field spherical probes shares channels with a search coil magnetometer (Uniprobe), with the sensor mounted in one of the spheres. The data from these channels are handled by a dedicated FPGA. (Due to malfunctioning of the data acquisition no Uniprobe data will be presented).

The system also includes the miniature digital fluxgate magnetometer. The SMILE magnetometer [3] uses a 20 mm³ sensor with volume compensation, and a digital feedback loop implemented in an

![Figure 1. Experiment setup underneath the nosecone.](image1)

![Figure 2. An overview of the FFU electronic system.](image2)
FPGA. In SQUID the sensor was mounted inside the eBox (Figure 3), somewhat compromising the quality of the measurements by proximity to magnetic and current carrying parts of the experiment. Three components of magnetic field are stored with 16 bit resolution at the feedback loop update rate, 8 kHz, and are used for flight analysis (see Section 4.2).

To monitor the dynamics of the FFU four ADXRS610 gyros were used. These were placed in an special arrangement, displayed in Figure 4, allowing to obtain vector angular rate.

Four Faulhaber AM1020-A-0.25-8 stepper motors with 64:1 Precistep planetary gearhead are used to operate the SCALE systems (see Section 3). Motors are coupled in series, with two in house developed motor drivers regulating the winding currents in the motors. Nominal winding current is 250 mA, and is achieved by a frequency modulated H-bridge. A motor step occurs with a change in polarity of one of the windings. The motor controller module in the FPGA controls the speed of the motor by setting the length of each step.

The recovery system of the FFU consists of a commercial off the shelf GPS module (GLOBALSAT ET-318), a GLOBALSTAR satellite modem (AERO ASTRO STX-2) and the frequency modulated beacon transmitter (RADIOMETRIX TX1). As the top plate is released the GPS acquires its position which is then transmitted by the satellite modem and by the beacon transmitter.

After ejection the FFU is powered by internal batteries positioned in the eBox. Two single use SAFT LSH-14 batteries are used with nominal voltage of 3.6 V and capacity of 5.8 Ah each. The batteries are connected in series and can provide continuous current of up to 1.3 A.

The electronic systems of the FFU all mounted on five boards positioned in the eBox. From top to bottom the boards, see Figure 5, are the: SMILE, Uniprobe, Main, RF and DCDC. Mounted on the sides of the eBox are a total of six connectors, four of which connect to the SCALE systems while one is used for connecting the experiment to ground support equipment. The last connector is for the LED board which, mounted on the side of the FFU, indicates the state of the FFU. Two patch antennas (WS1357 and WS3961 from PCTel, for GPS receiver and satellite transmitter respectively) are mounted on the top of the e-box. An arrangement of sockets mounted on the bottom of the DCDC board acts as the umbilical connector, mating with pins mounted on the RMU.

2.2. Rocket Mounted Unit

When assembled the RMU has the dimensions $0.248 \times 0.042$ m and a total mass of 1.5 kg.

2.2.1. Mechanical Design

The RMU (Rocket Mounted Unit) is composed of 4 elements: the umbilical connectors, NSSB, camera, and ejection system mounted onto the RID (Rocket Interface Disk). The RMU was developed in cooperation with EuroLaunch to allow the SQUID
experiment to be centered along the z-axis of the rocket without interfering with the M-BEAM experiment [4] mounted underneath, inside a cylinder reused from REXUS-8 mission.

Along the wall of the RID-plate are four cut out sections. The largest one is in order to not interfere with a protruding part of the nosecone ejection system. The three smaller ones are used to secure the RID to the rocket cylinder by means of three plates, bolted to the RID and to the cylinder.

The top side of the RMU has five distinguished features as shown by Figure 6. Furthest out toward the edge on the top side is a 40 mm deep gully where a multi coil wave spring is mounted. Continuing inwards is a hole for the lens of the camera mounted underneath that will record the FFU ejection. The three \(20 \times 1.5\) mm support islands, placed at 120° angles, constrain the FFU from in plane motion. The two cut out sections in the middle are for the two sets of umbilical pins that connect through the FFU bottom plate and into the eBox. Between these umbilical connectors is a 3 mm diameter feed through hole for the steel wire that secures the FFU.

Screwed to the bottom side of the RID is the NSSB, camera case, umbilical connectors and the cutter case, see Figure 6. The cutter case is part of the ejection system and has two functions: hold the CYPRES pyro cutter and clamp the steel wire. The camera and NSSB cases shield the circuit boards inside and facilitate their mounting to the RID.

A custom designed ejection system employs a multi coil wave spring that keeps the good strength characteristics of a regular coiled compression spring but reduces the space required. A steel wire, clamped on one end inside the FFU and on the other end inside the RMU, holds the two main parts of the SQUID experiment together until the separation sequence is initiated. Activating a CYPRES pyro cutter results in an instantaneous cutting of the wire and release of the FFU. The system is dimensioned to eject the FFU to a speed between 2.5 and 3.5 m/s relative the rocket to avoid collision with the rocket nosecone and payload section which separate to a speed of approximately 4 and 2 m/s, respectively. The wave spring used has a spring constant of 14.34 N/mm. At maximum compression from 80 to 30 mm the spring can deliver 717 N of force and store about 18 J of potential energy, thus capable of ejecting the 3.6 kg FFU to a speed of up to 3.1 m/s.

2.2.2. Electronic Systems

The RMU electrical system consists of four main parts: the Not So Smart Box (NSSB), the camera and two Umbilical connectors. The core of the system is the NSSB which serves as a interface between the FFU and the REXUS Service Module, providing external power and communication. The NSSB also controls the camera.

The RMU video camera is an off the shelf GoPro HD Hero with its casing replaced by a custom made aluminum casing. It provides 720p HD images at 60 frames per seconds rate with a 170° wide angle lens.

The two Umbilical connectors provide the connection between the FFU and NSSB. Each connector has four pins passing through the RID, the bottom plate and into the eBox. Between these umbilical connectors is a 3 mm diameter feed through hole that secures the FFU.

3. WIRE BOOM SYSTEM

The SCALE wire boom deployment system (Sverker Christenson Advanced Light wEight) is developed at SPP. It allows factor of five mass reduction compared to conventional mechanisms for the same amount of cable [5]. In conventional mechanisms the cable is initially coiled on an axis perpendicular to the deployment direction [6], [7], while in the SCALE system the cable is coiled between two coaxial cylinders parallel to the deployment direction.

Mechanisms based on the SCALE system are currently being built for ESA/JAXA’s BepiColombo
and NASA’s MMS missions [5]. The SQUID experiment’s version of the system is simplified and miniaturized for use in ionospheric missions, allowing a storage of up to 3 m of cable on a $61 \times 61 \times 75$ mm device, with a mass of 300 g including the sphere and the cable.

The SCALE system consists of a rectangular frame, formed by the front and back caps and side walls. The inner cylinder, mounted to the front cap, and the outer cylinder, fixed in the back cap contain the coiled cable between them. At the back the cable crosses the feeder wheel (which is a 96 teeth 0.5 mod spur gear in Delrin), and after making a loop around the cylindrical protrusion on the back cover is guided through the main axis towards the open end of the inner cylinder. A pusher ring is placed between the cylinders, mounted on two M4×0.35 threaded shafts opposite to each other. The threaded shafts are constrained by the glide bearings in the front and back caps, and connect by 23 teeth spur gears to the feeder wheel. The feeder wheel is attached to the main shaft, which is constrained between the glide bearings in the back cover and the wall inside the inner cylinder (see Figure 7). The stepper motor drives the feeder wheel by the 10 teeth brass pinion on the motor shaft.

The cable is 1.5 mm thick seven lead cable with outer shield. The sphere is a two part aluminium sphere, of 30 mm diameter, housing inertial sensors (in three of the systems) and the Uniprobe induction sensor (in the fourth sphere).

During deployment, the stepper motor drives the feeding wheel, which picks up the cable from between the cylinders. An open ring of elastic plastic pushes the cable against the cylindrical part of the back cover, providing high friction without sliding. On the other end of the open ring the cable is guided inside a Teflon tube towards the main shaft and through it in the axial direction of the system. At the same time, the threaded shafts rotate synchronously and the pusher ring moves along them towards the feeder wheel, ensuring that the remaining coiled cable is pushed against it. With the selected motor and gearhead, the deployment rate is 14.5 mm/s with the motor rotating at 4000 rpm.

To protect the spheres during launch the SCALE systems are closed with a round hatch that is kept in place by two bolts placed on the front end of the threaded shafts. When the deployment starts, the bolts release the door, which is loaded by three blade springs placed the inner part of the hatch.

4. RESULTS

The SQUID experiment, displayed in Figure 8 was launched onboard the REXUS-10 rocket at 10:00 UTC on February 23, 2011, the FFU ejected at T+72.8 seconds and was later recovered on the ground. Figure 9 shows a summary of the angular rate sensors, REXUS-10 altitude, and dynamic pressure (calculated based on GPS data from the REXUS 10 service module). Figure 10 presents snapshots from the RMU camera, and Figure 11 presents an overview of the SMILE data.
4.1. Ejection system

Data from the video show that the ejection was performed successfully, releasing the FFU with a very clean spinning along the rocket z-axis as seen in the gyro and SMILE data.

The FFU separation speed relative to the rocket is estimated from the RMU imaging. The apparent size of the FFU in the image is proportional to the inverse of the distance, reducing with time as the FFU flies away, see Figure 10. A control measurement is used to calibrate this dependence, and the pixel area covered by the FFU in the flight images is converted to distance. Ejection speed of 1.5 m/s was obtained in this way from the first 3 seconds after the ejection. Due to rocket coning and subsequent de-spin the FFU is lost from the camera field of view five seconds after the ejection.

4.2. SCALE wire boom deployment system

Deployment of the SCALE boom systems should have nominally started 1 second after ejection, and continued for 60 seconds, followed by a half-speed deployment [2] optimized to the initial spin rate of the FFU. After 16 seconds the booms were to retract.

Imaging data only covers the initial stage of the deployment, showing the opening of the hatches and the spheres appearing from the FFU, see Figure 10. Inertial sensors in the spheres were not mounted at launch due to persistent problems in testing. The deployment is reconstructed from the angular rate and magnetic field data.

Proximity of the stepper motors to the SMILE sensor...
resulted in noticeable interference during motor operation, which allows some monitoring. The bottom panel of Figure 11 shows a sliding window Fourier transform of the spin-axis component of the magnetic field, showing a pronounced spectral peak with a frequency proportional to the motor rotation rate.

A gradual ramp-up at the start is seen between T+73.8 s and T+78 s, with the deployment until T+139 s followed by a ramp down a short period of half-speed deployment. Ramp-up and ramp-down were introduced to prevent motor stalling at rapid changes of rotation rate. However, it became clear post-flight that the ramp-down was too slow to properly test the optimized deployment mode.

The angular rate sensors record a decrease of spin rate of the FFU as the booms are deployed, and increase as the boom are retracted, see Figure 9. Analyzing the rotation phase from the magnetic field data the spin rate can be obtained. Figure 12 shows the spin rate time history, and the results of the modelling of the deployment. For modelling, a massless cable was assumed with spheres of 20 g at the end, deployed from a payload with 0.0242 kg m$^2$ moment of inertia about the spin axis. The deployment was started with 3.47 rps spin rate, and proceeded at 14.5 mm/s to a total length of 0.93 m of deployed cable. The observed spin rate (red curve) starts to deviate from the model after T+101 s with angular speed decreasing slower than expected. This is interpreted as a malfunction of one of the SCALE systems, stalling with 0.35 m cable deployed. If this stall is introduced in the modelling, a reasonable match is obtained to observations (blue curve), confirming that three wire booms deployed nominally.

During the retraction of the booms another system failed, but two booms retracted completely, and spheres were inside the SCALE cylinders at the payload recovery. The flight sequence timing was predefined, and as the apogee was reached somewhat earlier than predicted, the retraction was not complete when the FFU started the re-entry. Around T+220 s, as the dynamic pressure started to grow, the FFU lost its flat spin and went into a more wobbling motion.

### 4.3. Landing system

The landing system worked nominally, the cutter was activated at 5.80 km and the top plate was released after 20 seconds, as expected, whereafter the parachute deployed at a altitude of 4.80 km. Altimeter data show that the landing speed of the FFU was 6 m/s.

Prior to the flight it is not known what the motion of the FFU would be after re-entry, whether it would retain the spin, wobble, fall flat side down or sideways, or autorotate. Autorotation is a coupled rectilinear motion with a rotation about a body axis which is not the major principle inertia axis. As the FFU is not a rigid body at re-entry (due to late retraction and failure of two systems), it is hard to judge whether the loss of stable spin at T+220 s is due to the booms or intrinsic at re-entry. However, it is clear from the SMILE data that autorotation indeed starts at T+370 s (9 km altitude based on the altimeter data), and continues until the parachute deployment at T+490 s. Autorotation is visible as a 8-10 rps peak in the measured Z component of magnetic field, which corresponds to rotation about and axis in XY plane.

### 4.4. Recovery system

The FFU started transmitting the signals shortly after the parachute deployment. The first satellite message was received at 10:08:39 UTC, about 35 seconds after parachute deployment. After another three minutes the GPS lock was acquired with position sent via the satellite and the wireless link. The FFU coordinates were received until it reached ground at T+1170 s, 10:20:55 UTC. The last position was N 68°15.8795 E 21°05.1386 which is 41.6 km north of Esrange. This is the position where the FFU was later recovered by the helicopter crew.

The beacon transmitter also worked nominally. However, due to limitations of the localization system at Esrange the FFU was not followed during the complete descent. With the last position received by the Esrange base receiver from an altitude of 800 m. The helicopter later received the signal from the beacon during the recovery.
5. CONCLUSIONS

SQUID project succeeded in producing a small stand-alone recoverable probe for suborbital missions. The landing and localization systems of the payload performed nominally.

Magnetic field data, angular rate sensors data, and imaging allow to reconstruct the flight events. Failure to integrate the inertial sensors inside the spheres limits the analysis of the dynamics of the boom deployment. Malfunctioning of the data system for Uniprobe and electric field probes made it impossible to validate those systems.

The objective of developing and validating the miniaturized version of the SCALE system was achieved, although only partially. Two systems performed nominally, deploying 0.92 m wire in about a minute, while the other two stalled during the deployment and retraction. The failure is likely to be due to a combination of the friction in the system and low torque margin of the stepper motors coupled in series.

REFERENCES