MAIUS-1 – VEHICLE, SUBSYSTEMS DESIGN AND MISSION OPERATIONS

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ABSTRACT

In November 2015, the DLR Mobile Rocket Base will launch the MAIUS-1 rocket vehicle at Esrange, Northern Sweden. The MAIUS-A experiment is a pathfinder atom optics experiment. The scientific objective of the mission is the first creation of a Bose-Einstein Condensate in space and performing atom interferometry on a sounding rocket [3].

MAIUS-1 comprises a two-stage unguided solid propellant VSB-30 rocket motor system. The vehicle consists of a Brazilian S31 motor as 1st stage, a S30 motor as 2nd stage, a conical motor adapter, a despin module, a payload adapter, the MAIUS-A experiment consisting of five experiment modules, an attitude control system module, a newly developed conical service system, and a two-staged recovery system including a nosecone. In contrast to usual payloads on VSB-30 rockets, the payload has a diameter of 500 mm due to constraints of the scientific experiment. Because of this change in design, a blunted nosecone is necessary to guarantee the required static stability during the ascent phase of the flight.

This paper will give an overview on the subsystems which have been built at DLR MORABA, especially the newly developed service system. Further, it will contain a description of the MAIUS-1 vehicle, the mission and the unique requirements on operations and attitude control, which is additionally required to achieve a required attitude with respect to the nadir vector. Additionally to a usual microgravity environment, the MAIUS-1 payload requires attitude control to achieve a required attitude with respect to the nadir vector.

1. INTRODUCTION

The development of MAIUS-1 started with the Kick-Off Meeting in December 2010 held at the Leibniz Universität in Hanover.

Table 1. The MAIUS-1 Schedule

Milestones	Date
Kick-Off Meeting at Universität Hannover	2010-12-02
Design Workshop at DLR Oberpfaffenhofen	2011-09-20
Presentation of MAIUS-1 at Esrange, Sweden	2012-02-03
MAIUS-1 Service System meets Experiment	2014-03-27
MAIUS-1 Pre-Bench Test 1 at Hannover	2015-06-01
MAIUS-1 Pre-Bench Test 2 at DLR Oberpfaffenhofen, Germany	2015-07-20
MAIUS-1 System Bench Test at DLR Oberpfaffenhofen, Germany	2015-09-21
MAIUS-1 Environmental Test at AIRBUS in Ottobrunn, Germany	2015-10-10
Beginning of Campaign at Esrange	2015-11-16
Launch of MAPHEUS-1	2015-11-26

Currently the system is being tested thoroughly with a set of bench tests to assure a working communication between the MAIUS-A experiment, the service system and the hardware on ground. This will be concluded by a final bench test including a flight simulation and an environmental test including spin balancing in autumn of 2015. Assuming positive tests the campaign of MAIUS-1 will begin in November 2015 at Esrange, Sweden.

2. SCIENTIFIC OBJECTIVE AND EXPERIMENT OVERVIEW

As stated above the scientific goal of MAIUS-1 is to demonstrate all techniques necessary two perform two species atom interferometry in space. Which such an experiment a measurement of the universality of free fall could be unprecedented accuracy [1], [5].

In a first step the creation of Bose-Einstein condensates (BECs) in space will be demonstrated. For this the isotope Rubidum-87 was chosen. Afterwards a technique called Delta Kick Collimation (DKC) will be applied to reduce the expansion velocity of the BEC and finally the delta kicked BECs will be used as the input state for atom interferometry. To measure the properties of both the BEC and the atom interferometer the evolution time of both will then be extended to time scales not reachable on ground and beyond what is possible in the drop tower Bremen.

In the total microgravity time of approximately six minutes a series of sequences consisting of the BEC creation and the atom interferometry will be performed.

In order to conduct these experiments the scientific payload MAIUS-A was constructed. It contains a compete cold atom experiment including an ultra-high vacuum system, a laser system with eight laser sources and distribution optics, the electronics needed to dive these systems, and an battery system. The experiment modules have a total mass of 280 kg, a volume of 0.55 m^3, and an average power consumption of 300 W.

Table 1. *The MAIUS-1 Mass Budget (Lift-Off Configuration*

1st Stage:	**1004.4 kg**
2nd Stage	**1228.6 kg**
Payload	**397.5 kg**
Motor adapter + Manacle Ring	xx.x kg
Spin-Up Module + Manacle Ring	xx.x kg
Payload Adapter	xx.x kg
MAIUS-1 Experiment Module	280.0 kg
Service System	xx.x kg
ACS Module	xx.x kg
ERS Recovery System incl. NC	53.0 kg
Total	**2630.4 kg**

3. THE VEHICLE DESIGN

MAIUS-1 is a two-stage unguided solid propellant sounding rocket. The vehicle consists of a S31 as 1st stage, a S30 as 2nd stage, a motor adapter, a payload adapter, the MAIUS-A scientific experiment modules, a conical service system, an attitude and rate control system, a recovery module and a blunted nosecone.

The payload is based on modules with 500 mm diameter, which is slightly larger than usual VSB-30 microgravity payloads.

3.1. Lift-Off Configuration

The total lift-off mass of MAIUS-1 is 2630 kg with the rocket motor mass contributing more than 2230 kg. Including both motors the MAIUS-1 rocket has a length of 11.8 m. The payload mass is 398 kg.

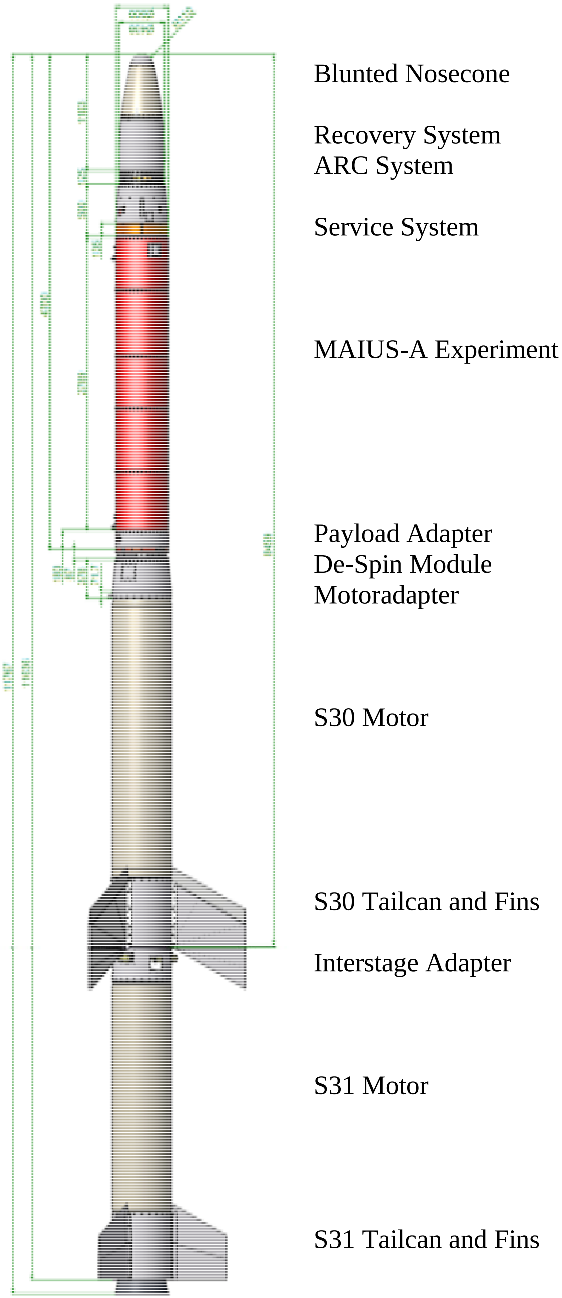

Figure 1. *MAIUS-1 two-stage unguided solid propellant sounding rocket*

Two requirements on the payload configuration are important to ensure a safe flight of a sounding rocket.

The first requirement is a sufficient static margin during the ascent to enable a stable flight. The static margin is given by the distance between the centre of gravity (CoG) and the centre of pressure (CoP) divided by the diameter of the vehicle. A positive static margin corresponds to a CoG ahead of the CoP. Usually a static margin of 1.5 is desired.
The nosecone design had to be changed to a blunted nosecone to ensure a sufficient static margin. The analysis on the flight stability of the vehicle is described in chapter 6.

3.2. Re-entry Configuration

The second requirement is position of the centre close to 50 % of the payload length during the re-entry. This is necessary to avoid a stable attitude of the vehicle during the descent and prevents the recovery system from too much heat increase. The re-entry payload mass is 384 kg.

3.3. Frequency List

The MAIUS-1 payload has been equipped with several transmitters. Following tables show frequency lists of the service module, the motor telemetry and the recovery system.

Table 2. *The Service System Frequency List*

Denotation	Transfer Rate	Power [W]	Frequency [MHz]
TM TX 1	5 Mbit/sec. NRZL-R	5	2310.50
TM TX 2	5 Mbit/sec. NRZL-R	5	2350.50
TV TX 3	8 MHz, (BAS/Pal)	5	2330.50
TC RX	38,4 kBit/sec. GMSK	Passive	449.95
GPS RX 1	BW= 2 MHz	Passive	1575.40
GPS RX 2	BW= 2 MHz	Passive	1575.40

Table 3. *The Recovery System Frequency List*

Denotation	Transfer Rate	Power [W]	Frequency [MHz]
Beacon 1	1 KHz (AM)	0.2	240.80

Table 4. *Motor System Frequency List*

Denotation	Transfer Rate	Power [W)]	Frequency [MHz]
Motor TM	1 Mbps (burst)	0.1	2400.00

4. DEVELOPMENT OF MAIUS SERVICE SYSTEM & ARCS-SYSEM

The objectives of the Service Module are to establish the bidirectional communication between the ground and the onboard system, to control the experiments and to monitor the housekeeping data and the environmental conditions during the flight. Furthermore it samples significant flight performance parameters, like position, acceleration, speed, rates and attitude. Additionally, the Service Module has the capability to supply energy to the experiments.

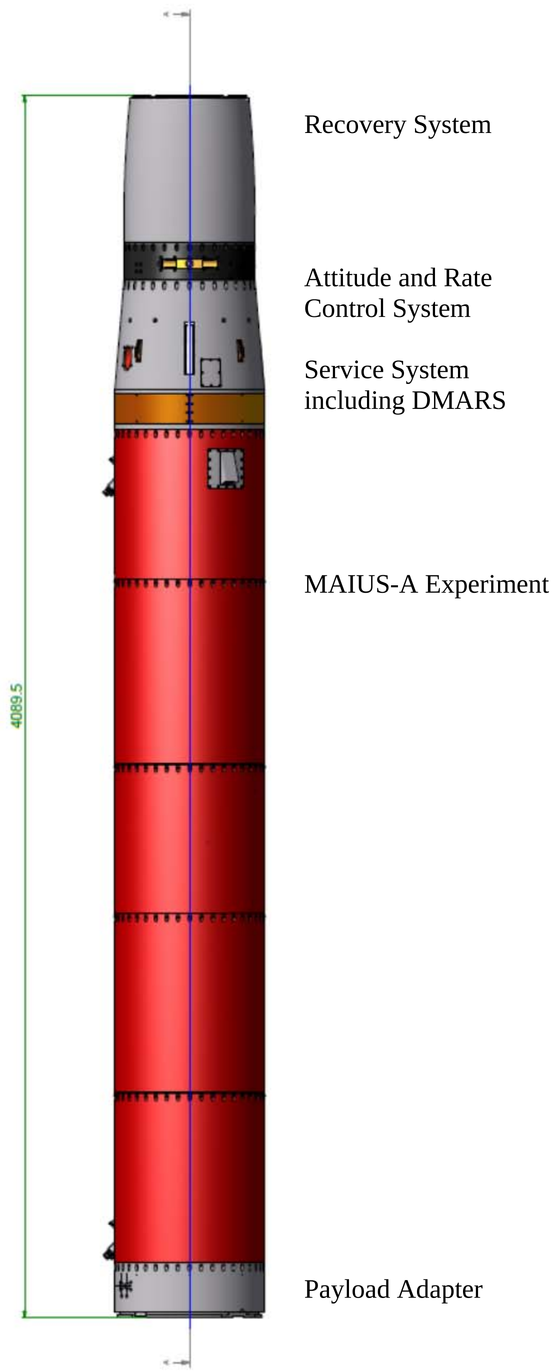

Figure 2. *MAIUS-1 Payload (Re-Entry Configuration)*

4.1. TM/TC

The telemetry system is generating a bitstream with 5MBit/s, coded in randomized NRZ-L (Non Return to Zero – Level). This transfer frame of this datastream is protected with forward error correction (FEC). Due to the FEC each word of the transfer frame is build up of 8 bits of data and 4 bits for protection.

The transfer frame does not have a fixed layout except the frame synchronization words and a free running frame counter to be used for slant-range.
The user data is inserted dynamically using the Dynamic Streams technique which allows the dynamic assignment of bandwidth. The system is designed to handle up to 16 independent streams. Each one has a designated buffer. A round-robin scheduler ensures a deterministic forwarding of data, which makes the system ready for real-time applications.
The uplink direction is also using frequency diversity. Two receivers are read asynchronously. A special algorithm checks the data protection codes (FEC) and avoids double reception. The uplink, similar to the downlink, is also using a dynamic allocation of bandwidth. Therefore both directions can be used fully transparent. The data is forwarded without any knowledge about the contents or syntax.

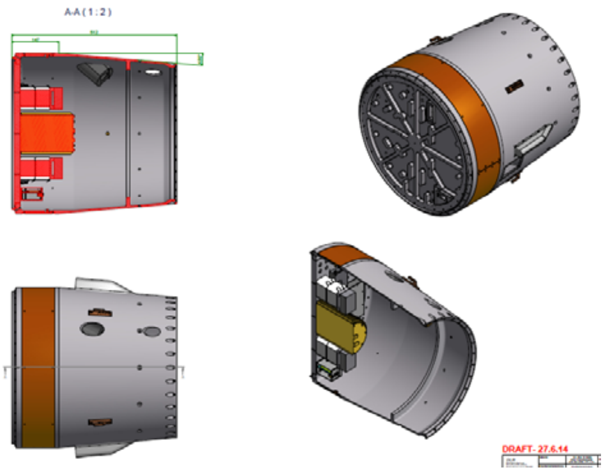

Figure 3. *MAIUS-1 Service System*

4.2. RS422 Experiment Connections

The MAIUS service module is designed to take up to four bi-directional serial interfaces, implemented as the REXUS Standard Interfaces [2].
This standard delivers:

- Power up to 28W,
- 3 Flags (Lift-Off, Start of Experiment and Start of data storage)
- Bi-directional communication capability using UART at RS422 signaling.

Three of these interfaces are connected directly to the service module. The fourth interface is used in a special configuration. The uplink port is used for signaling timing information (see also section 4.5) to the MAIUS-A experiment, the downlink is connected to the TM/TC-system and can be used as designed.

4.3. Switched Ethernet

The MAIUS payload uses a 10/100MBit Ethernet onboard for transport of high bandwidth telemetry data. This network uses a switch to connect all nodes to the service module. A router in the service system connects onboard network segment to the ground networks.
The router forwards IP packets in both directions using the already described up- and downlink channels.
The TCP/IP stack is realized using a partition of the open source LightweightIP Stack. It is running on the board computer as a service (see also section 4.4).

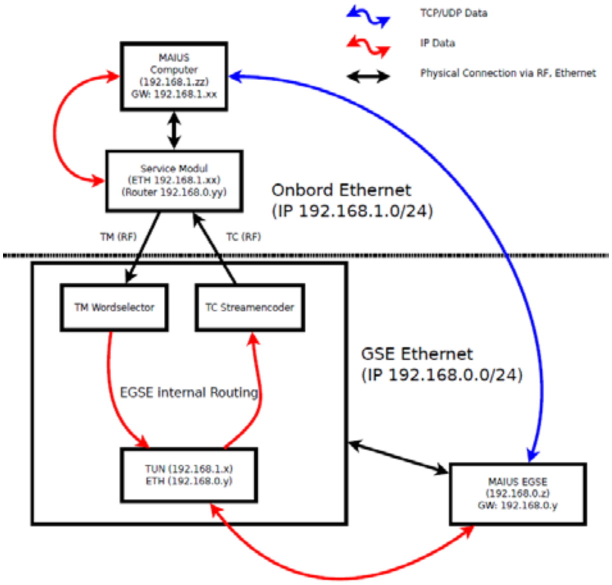

Figure 4. *MAIUS-1 Communication Network*

4.4. Software

The onboard telemetry and telecommand system is based on the RODOS (Realtime Onboard Dependable Operating System). It is a priority based pre-emptive multi-threading system, which provides the possibility for real time control algorithms. Its powerful middleware, which is based on a publisher subscriber protocol, provides a simple and flexible interface for software applications. More information about RODOS is available in [4].

4.4.1. Services

RODOS Applications encapsulate the different software modules. The services are based on RODOS applications with the additional feature of a dependency check.
In the MAIUS service system the following features are implemented:

- BoardConfig as a module for housekeeping data acquisition.
- ConfigManager, which provides an interface to a data base stored on a frame device for board configuration.
- FlightParameter, responsible for data acquisition, check and distribution of GPS and DMARS sensor data

- Massstorage as control service for the onboard massstorage device.
- Network, provides a TCP/IP stack for the ethernet and ip over dynamic streams.
- Timing, provides an interface to a clock synchronized with the GPS.
- TMTC, provides a gateway from or to the middleware to the ground support equipment

The list above describes the main features for the MAIUS-1 service system. Additional services are implemented for timeline, control and monitoring.

4.4.2. Middleware

The middleware is based on a publisher subscriber protocol. It allows building up communication channels, called topics, between different services. This method allows the connection between different sources and sinks. As an example the command which start a record of the telemetry stream on the mass storage device can be published through the TM/TC service through a control computer on ground and can also be published automatically with the timeline service on board with no additional code in the masstorage service.

4.5. Timing Interfaces

The service module is providing a timing service based on the global positioning system (GPS). The system is generating an internal timestamp with precision of milliseconds. This timestamp is sent to the MAIUS-A experiment as a 4 Octetts long UART message (115200 Bits/s, 8E1) 10 times a second. This message consists of 5 flags and 27 Bits for milliseconds of the current day. The least significant byte is send first.
For the experiment the flags are assigned to Lift-Off and the ARCS-On information. ARCS-On is also assigned to the SODS flags of the REXUS type interfaces. It is set to logically high if the ARCS system is active.
The message is also send to the ARCS system but with 100 Hz update-rate and a different assignment of the flags.

4.6. Attitude and Rate Control System

The Attitude Control System is a subunit of the service system with the task to control the orientation of the payload above an altitude of 100 km. To achieve the desired attitude accuracy it is necessary to use a two-staged cold gas (nitrogen) system in the order to perform the control sequences in coarse and fine mode.
The MAIUS Attitude will be regulated 3 times during a nominal flight to fulfil the attitude requirements of the experiment regarding Nadir vector.

5. RECOVERY SYSTEM

The European Recovery System (ERS) is mounted onto the forward end of the 438 mm diameter ACRS module with data interface to the service system. The blunted nosecone containing the tip separation mechanism is followed by the ERS aft ogive, equipped with electronics, batteries and the parachute recovery system. The complete system mass is 55 kg.
The outer structure of the forward ogive is made of forged AlMg1 aluminium alloy with an average wall thickness of 2.2 mm and an ogive ratio of 1:2.95.
The manacle flange is made of aluminium alloy with anodized surface. The manacle interface is milled as a high precision part guaranteeing perfect fit of the manacle clamp band. The separation plunger and manacle ring opener are attached to the manacle flange. Two floating diametrically installed Canon D-Sub 9P type connectors are used as electrical interfaces to the EAGER-PAK valve.
The blunted nosecone comprises the aluminum nosecone structure, a pyrotechnically actuated high pressure gas manacle ring release and plunger separation system, the forward manacle flange and a releasable manacle ring.
The nose tip is attached to the payload by the segmented manacle ring, which parts are flexibly connected and fixed by a locking mechanism that is released by a pneumatically actuated piston. The manacle ring release and the forward ogive ejection are initiated by a pyrotechnic valve.

Figure 5. *European Recovery System*

The aft ogive part consists of an up to 6 mm thick Nicoated aluminum alloy, machined from a rolled onepiece raw material. The forward manacle flange is used for the fixation of the forward ogive by the manacle ring. Behind that, a heat shield protects the parachute inside the parachute compartment from hot

gases outside during the re-entry. The heat shield release mechanism, interface connectors and a camera system are implemented to the flange ring.
The lift-off switch, mounted to the cylindrical part of the aft outer structure, initializes the system in parallel to acceleration sensitive g-switches. The rear part of the aft ogive contains the ignition unit, barometric system, main parachute brackets, battery packs, and a beacon system assembled on the mounting plate. The main parachute, released by the stage line cutter system, is attached to the main parachute brackets. The two redundant system battery packs can be installed through access doors.

6. FLIGHT STABILITY & BLUNTED NOSECONE

The specific payload geometry of MAIUS-1 with a slightly larger diameter than usual VSB-30 microgravity payloads requires measures of vehicle stabilization during the ascent phase. Naturally, there are two options to increase the static stability margin: 1) moving the centre of gravity forward by balance mass and 2) relocate the centre of pressure backwards by altering the vehicle's outer shape. Both options are adversely affecting flight performance and thus a careful trade-off has to be done to meet the minimum mission requirement of 6 min microgravity time, which requires an apogee of 253 km. As the necessary balance mass of the first option would imply a performance reduction below the minimum experimental requirements and moreover would be difficult to integrate, measures of influencing the centre of pressure need to be considered. An easily realizable option complying with both, the stability criterion and experimental requirements would be the integration of a fourth fin on the upper stage. However, this solution has not been selected because of the structural constraints of a launch from the Skylark-Tower, which is the standard launcher for VSB-30 rockets from ESRANGE and is preferable in terms of payload support. Analyses on different nosecone shapes, kindly supported by CFD Euler simulations conducted at DLR AS-RFZ, identified the benefit of spherically blunted nose shape on the centre of pressure position of the total vehicle. At the same time, performance losses due to the additional drag are acceptable and the entailing design modifications of the ERS only affect the most forward part of the nosecone. Therefore, the conical part of the nosecone is replaced by a spherically blunted shape of 180 mm diameter with tangential transition to the unaltered ogive part. As the nose tip integrated GPS antenna falls away with this solution, a wraparound GPS antenna had to be integrated into the MAIUS Service module. The critical mission point in terms of static stability margin during the atmospheric ascent is predicted at T+30s, Mach 4.6 and 18 km altitude, see *Figure* 6. The minimum static margin is calculated to 1.21 cal using Missile Datcom output and 1.36 cal using Euler CFD method. A trade-off between stability margin and flight performance yielded to the recommendation of 180 mm bluntness diameter. The effect of this measure on both is summarized by *Table 2*.

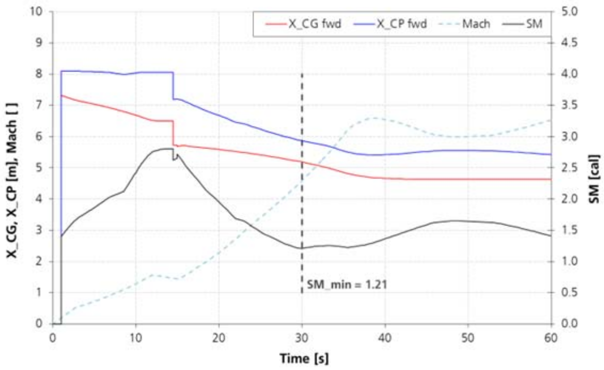

Figure 6. *Evolution of Static Margin (SM) during atmospheric ascent*

Table 2: Trade-off between Static Margin (SM) and Flight Performance

Configuration	SM_min [cal] (by Missile Datcom)	SM_min [cal] (by CFD Euler)	Apogee [km]
Standard nose	0.96	0.73	267
Blunted nose Ø 180 mm	1.21	1.36	259

7. MISSION OPERATIONS

The MAIUS-1 vehicle will be launch at the Skylark Tower at Esrange. The orientation of the DMARS navigation platform is defined in *Figure* 7. The 0° Position in the Payload is aligned with the direction to the South. For the ARCS system the Pitch Axis is at position 270°, the Yaw Axis is at position 0° and the Roll Axis is aligned with the longitudinal axis in flight direction.

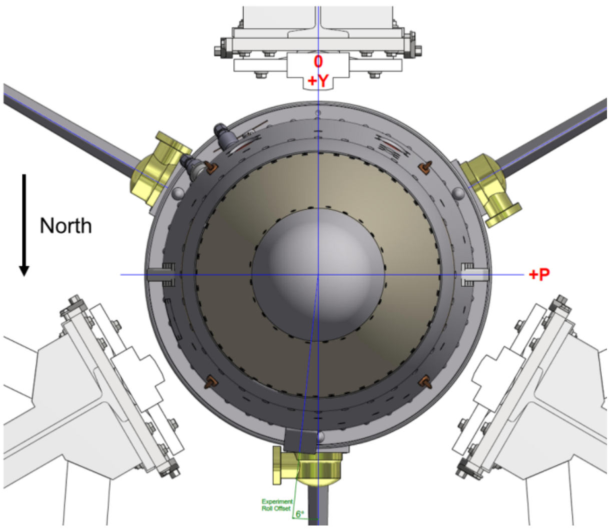

Figure 7. *Orientation of MAIUS-1 in the Skylark Tower*

As explained in chapter 6 the apogee of the MAIUS-1 mission will be around 259 km. The predicted altitude in respect to the flight time is shown in *Figure* 8.

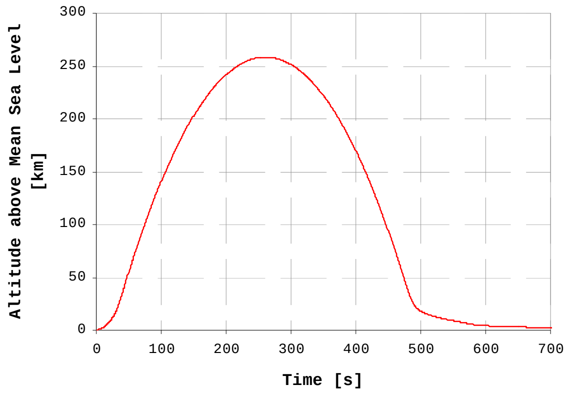

Figure 8. *Predicted Altitude vs. Flight Time*

In difference to usual microgravity mission additional attitude maneuvers will be performed. It is planned to do three maneuvers to align a certain experiment axis, 45° angle in respect to the longitudinal body axis of the payload and 6° in respect to 180° position of the payload, with the local Nadir vector. See also *Figure* 9. During this maneuver also rates will be controlled to the possible minimum value. Experiment cycles will be perfomed in the microgravity phase between the control phases of the ARCS system.

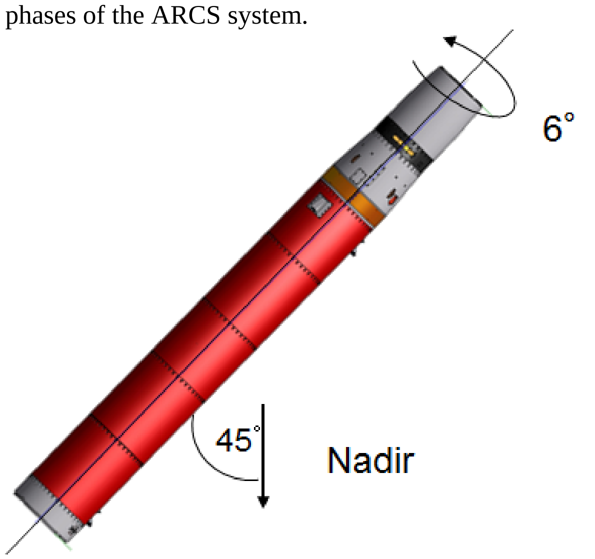

Figure 9. *Attitude Control Maneuver*

The recovery system heat shield will be ejected a 4.7 Km and the payload will be recovered with a two stage parachute system

8. SUMMARY & OUTLOOK

The QUANTUS-IV programme includes two more rocket launches, MAIUS-2 and MAIUS-3. Both will carry an upgraded scientific payload called MAIUS-B. This experiment will be able to create BECs from Potassium-41 additionally to the Rubidium-87 BEC in MAIUS-A. The goal of these missions is to study the simultaneous creation of BECs from both species and to then perform atom interferometry with them. Therefore the missions will test all tools necessary needed for a measurement of the universality of free fall. The launch of MAIUS-2 is planned for autumn 2017 and of MAIUS-3 for autumn 2018.

Table 3: Time Event List for the MAIUS-1 Flight

Time [s]	Alt [Km]	Event
T+ 0.0	0.33	Lift-Off
T+ 0.0	0.33	MAIUS-A LO (Signal and Bit)
T+ 13.5	4.30	Burnout 1st Stage (S31)
T+ 15.0	5.00	Ignition 2nd Stage (S30)
T+ 44.0	43.40	Burnout 2nd Stage (S30)
T+ 55.0	64.90	YoYo De-spin
T+ 56.0	66.79	GPS Antenna Switch
T+ 58.0	70.56	Nosecone Separation
T+ 60.0	74.29	Motor/PL Separation
T+ 61.0		MAIUS-A ARCS On (Bit)
T+ 75.0	101.02	Begin of microgravity phase
T+ 91.0		MAIUS-A ARCS Off (Bit)
T+ 180.0		MAIUS-A ARCS On (Bit)
T+ 190.0		MAIUS-A ARCS Off (Bit)
T+ 260.0	258.30	Apogee
T+ 300.0		MAIUS-A ARCS On (Bit)
T+ 310.0		MAIUS-A ARCS Off (Bit)
T+ 446.0	100.00	Begin of Atmospheric Re-entry
T+ 448.0	97.40	RCS Re-Entry Detection Mode
T+ 468.0	60.93	Re-Entry Mode, Spin-Up by ARCS
T+ 487.0	27.00	Maximum Deceleration
	4.70	Heat shield, Stab Chute Activation + Beacon Activation
	~3.9	Stab Chute De-Reefing
	~2.9	Main Chute Activation
	~1.7	Main Chute De-Reefing
T+ 900.0		Power Off for Experiments
T+1000.0		Power Off TM/TV

9. ABBREVATIONS AND ACRONYMS

ARCS	Attitude & Rate Control System
BEC	Bose-Einstein-Condensate
BW	Bandwidth
CFD	Computational Fluid Dynamics

CoG	Center of Gravity
CoP	Center of Pressure
DKC	Delta Kick Collimation
DLR	Deutsches Zentrum für Luft- und Raumfahrt
ERS	European Recovery System
FEC	Forward Error Correction
GMSK	Gaussian Minimum Shift Keying
GPS	Global Positioning System
LO	Lift-Off
MORABA	Mobile Raketenbasis
NC	Nosecone
NRZL-R	Non Return to Zero Level
PL	Payloads
REXUS	Rocket-borne Experiments for University Students
RODOS	Realtime Onboard Dependable Operating System
RX	Receiver
SM	Static Margin
TC	Telecommand
TCP/IP	Transmission Control Protocol / Internet Protocol
TM	Telemetry
TX	Transmitter
UART	Universal Asynchronous Receiver Transmitter

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