ReFEx launch with a sounding rocket – a challenging mission on a reliable carrier

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Abstract
Sounding rockets are a platform eminently suited for conducting experiments with supersonic and hypersonic experimental vehicles. For many years, but especially during the last decade, DLR's Mobile Rocket Base MORABA took part as a launch provider in a variety of missions dedicated to hypersonic and reentry vehicle research. This included missions for cooperation partners, like the HIFiRE program and the ScramSpace project. These were launched from Andøya Space Center, Norway, as well as Woomera in Australia.
DLR's research and technology program also relies on sounding rockets as carrier vehicles to conduct aerothermodynamic research. The ROTEX-T mission (measurements of loads due to heat and air resistance) as well as SHEFEX I and SHEFEX II (hypersonic reentry experiments) made a significant contribution to hypersonic research in general and demonstrated the applicability of sounding rockets to the research field. Especially SHEFEX II had to master some challenges, like a precession maneuver with a spinning rocket to achieve the required initial conditions for the scientific flight path.
For the ReFEx flight, which is planned to fly in Woomera 2021, MORABA's VSB-30 vehicle was chosen. This vehicle has been launched successfully for more than 30 flights to date and is therefore considered as a reliable vehicle. It also served as a carrier vehicle for some of the above mentioned missions. Consequently, ReFEx as a hypersonic research mission launched on a sounding rocket by MORABA as a propulsion system is a logical choice.
This paper gives an overview on MORABA's activities in the above mentioned programs and an outlook towards the additional challenges the ReFEx mission might face.

Abbreviations

ATEK	Antriebs-Technologien für Kleinträger
CFD	Computational Fluid Dynamics
DCTA	Departamento de Ciência e Tecnologia Aeroespacial (Department of Science and Aerospace Technology)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
ECOMA	Existence and Charge State of Meteoric Dust Grains in the Middle Atmosphere
HIFiRE	Hypersonic International Flight Experiment
IAE	Instituto de Aeronaútica e Espaço (Aeronautics and Space Institute)
MAIUS	Materiewellen-Interferometrie unter Schwerelosigkeit
MAPHEUS	Materialphysikalische Experimente unter Schwerelosigkeit (Material Physics Experiments under Weightlessness)
MASER	Material Science Experiment Rocket
MORABA	Mobile Raketenbasis (Mobile Rocket Base)
PMWE	Polar Mesospheric Winter Echoes
RADAX	Radial Axial
ReFEx	Reusable Flight Experiment
ROTEX-T	Rocket Technology Experiment
SHEFEX	Sharp Edge Flight Experiment
TEXUS	Technologische Experimente unter Schwerelosigkeit (Technological Experiments under Weightlessness)
TT&C	Telemetry and Telecommand
WADIS	Wave Propagation and Dissipation in the Middle Atmosphere

1. Introduction – MORABA at a Glance

DLR's Mobile Rocket Base (MORABA) was founded in 1966 and is now part of the DLR's Institute for Space Operations and Astronaut Training. MORABA's main task is to provide sounding rocket launches for scientific programmes and purposes. This includes, for example, European microgravity research programmes like TEXUS and MASER as well as DLR –internal programmes like MAPHEUS and ATEK. Furthermore, atmospheric research is served in programmes like ECOMA, WADIS and PMWE. A third cornerstone is formed by flights and programmes designed for aerodynamic and especially hypersonic research, which consist of DLR-internal missions like the SHEFEX I and II and ROTEX-T flights and missions for external partners, such as Australia's Defence Science and Technology Group for the HIFiRE program. During the last mentioned programme, MORABA was able to extend its experience and scope to extraordinary trajectories never realized before by MORABA.
MORABA is fully equipped to support these different mission types in the desired way. For example, a mobile S-band telemetry station and a mobile C-band radar station can be installed at the desired launch site and operated in remote areas. Besides the use of launch ranges with permanent installed equipment, MORABA can thus build up a fully equipped "mobile launch range" with its mobile launch rail (MAN launcher) and the TT&C stations at any reasonably reachable location worldwide. This enables MORABA to react quickly and flexible to different mission requirements. In addition, the involvement in the various research fields with more than 500 launches has created extensive experience covering all aspects of rocket science and engineering. This covers also the qualification and testing of new vehicle configurations as well as calculation and qualification of new trajectories and finding new solutions to advanced technical problems like design of ejection mechanisms for free-falling bodies ([1]).
The VSB-30 forms the workhorse in MORABA's rocket vehicle selection since its development in the early 2000s. Its development and operational history has provided for extensive exchange between user's and construction engineers of rocket vehicles, thereby generating a joint understanding of the system that is seldom prevalent. This understanding can be used for specific customisations and adaptions required for the ReFEx mission. More information about MORABA and its abilities as well as recent and upcoming tasks can be found in [2].

2. VSB-30 – A flight proven Sounding Rocket

The VSB-30 has up to now a number of around 30 successful missions. This operational history began with the 2004 maiden flight in Alcântara, Brazil. Reference [3] provides a detailed description of the development of the VSB-30, a summary of which is provided here.

Figure 1 VSB-30 ready for launch at Alcântara launch base , Brazil

2.1 VSB-30 – Reasons for Development

Prior to 1990, MORABA mostly used the British Skylark-Rocket for conducting sounding rocket flights. The first launch of a Skylark rocket was in 1957 from Woomera, Australia – the same launch site that is also intended to be used for the ReFEx mission. The final Skylark flight was in May 2005 from Esrange Space Center near Kiruna in Sweden. As a consequence of the discontinuation of the Skylark, the development of the VSB-30 was initiated in the late 90's. For this development, MORABA and DCTA/IAE of Brazil joined forces and cooperated on the development of what was going to be the backbone of Europe's sounding rocket missions for years to come. The development was planned in steps in order to reduce risks. The first step was the single stage VS-30, proposed from DLR to DCTA, as a development targeting the Mini-TEXUS rocket. After this, a boosted version of the VS-30 was suggested, resulting finally in the development of the VSB-30.

2.2 VSB-30 – Development result and short Description

The VSB-30 is a sounding rocket consisting of a two stage rocket motor system , i.e. an S31 booster, a

boost adapter connecting the two stages, an S30 motor, a motor adaptor and a payload. Both stages are composite solid propellant rocket motors. The nominal burn time of the S31 motor is 14 s with a total thrust of 150 kN in vacuum. The burn time of the S30 is approximately 20 s while the total action time of the S30 is (time where gas is expelled) is 29 s. The average thrust in vacuum is 107 kN.
Additionally, three spin up motors mounted at the boost adapter help to reduce the dispersion. These motors provide a short torque around the longitudinal axis when the rocket leaves the launch rail. During this phase, the vehicle is too slow to build up any appreciable roll rate from aerodynamic surfaces, so that the initial roll torque helps in distributing any asymmetric effects around the flight vector and thereby reduces dispersion.

3. Flight heritage of the VSB-30

The VSB-30 rocket motor system has a 15 year history and a flight heritage of around 30 flights up to June 2019. The VSB-30 is used as a “working horse” for many mission conducted by DLR MORABA for internal as well as external customers. In the following we give a short description of the different missions, with a focus on the types of trajectories flown. These follow an evolutionary development approach, beginning from the “usual” ballistic trajectories for micro-g or atmospheric research to more sophisticated trajectories for aerodynamic and re-entry research. Especially the latter require, due to the desired long and eventually very fast (> Mach 5) flight through the atmosphere, the so called suppressed trajectories. These trajectories are usually launched with elevation angles lower than 80 degrees and reach apogees as low as 30-50 kms.

3.1 VSB-30 based micro-g programmes

The VSB-30 serves as a vehicle for various and versatile micro-gravity research programmes.

1. **TEXUS:**
   The TEXUS missions are dedicated micro-gravity research flights, supporting all research fields from material to biological sciences. TEXUS is the longest running active space research programme and has conducted 57 flights to date, 14 of which on a VSB-30 (TEXUS 42 –TEXUS 55). The TEXUS missions follow ballistic trajectories with an average apogee of 250 km and an average ground range of 70-90 km.
2. **MASER:**
   MASER is a pendant to TEXUS, mainly conducted by SSC Sweden under contract to ESA. MASER uses a VSB-30 as a launch vehicle since 2008 and had 4 missions based on VSB-30, MASER 11 to MASER 14.
3. **MAPHEUS and ATEK:**
   MAPHEUS and ATEK are DLR-internal missions mainly dedicated to material science. Up to now there have been 8 MAPHEUS flights; out of these, MAPHEUS 5, 6 and ATEK have been flown on a VSB-30.
4. **MAIUS:**
   MAIUS was a mission to produce for the first time a Bose-Einstein-Condensate in space.[4] Two more flights will be conducted in this program.
5. **Brazilian National Program:**
   In Brazil have been launches for national Brazilian research programmes similar to the MASER or TEXUS programmes. These includes the flights of Cajuana, Cuma , Maracati, Rio Verde and the planned mission Igarata in July 2020. Launch site in Brazil has always been Alcântara.

3.2 Hypersonic programmes, partly based on VSB-30 components

1. **SHEFEX I and SHEFEX II:**
   SHEFEX I and SHEFEX II have been successfully conducted test flights, that were mainly geared towards testing of new materials and geometries for possible future planetary entry vehicles. One specialty of the SHEFEX II mission was execution of a so-called precession manoeuvre to change the attitude of a spinning vehicle with the help of cold-gas thrusters towards a tailored re-entry trajectory. The trajectory of SHEFEX I was a standard up and over version, the trajectory of SHEFEX II was designed for a shallow re-entry angle. The SHEFEX I had a S30/improved Orion rocket motor system, SHEFEX II was based on a VS40. More information about the scientific goals of the SHEFEX programme can be found in [5] and [6].

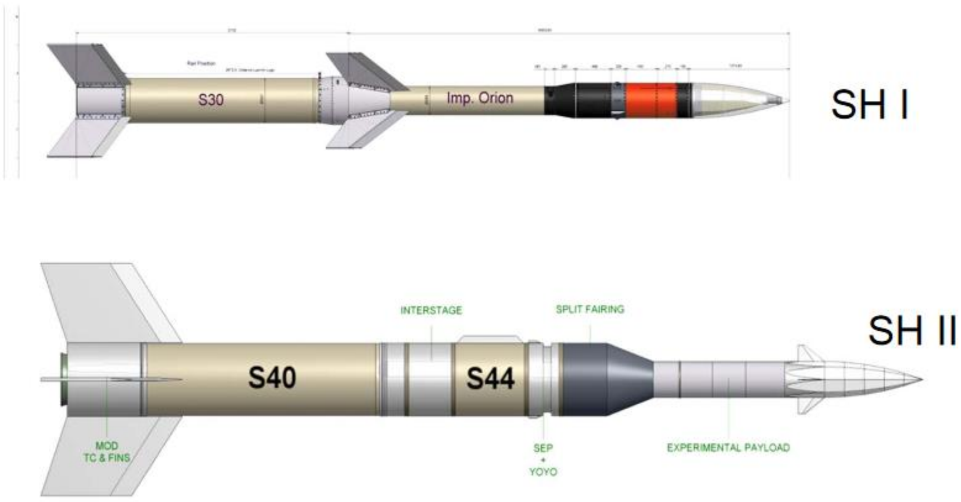

Figure 2 SHEFEX I and SHEFEX II configurations

2. **ROTEX-T:**
   The ROTEX-T mission was launched on a Terrier-Orion launch vehicle from Esrange Space Center in July 2016. Its primary scientific goal was the investigation of instationary aerodynamical phenomena. ROTEX-T followed a ballistic trajectory, but can nevertheless be seen as part of the missions supported by MORABA with the target to better understand aerodynamics at very high speeds [7].

3. **ScramSpace:**
   The ScramSpace mission was launched on a S30/ Improved Orion configuration. Unfortunately the mission was not able to reach the desired altitude and only sent 3 seconds of data before splashing into the ocean. The Scramspace trajectory was planned as an up and over trajectory.

4. **HIFiRE:**
   HIFiRE was a program conducted by Australia's DSTO (Defence Science and Technology Organization, now DST Group) and the US Air Force Research Laboratory, to conduct basic research on hypersonic flow phenomena, propulsion and aerodynamic control. MORABA cooperated with DST Group and was responsible for the launch vehicle and operation of 6 flights within the programme, of which 3 were conducted with VSB-30 vehicles. The demanding mission profiles added a new component to the VSB-30's flight heritage.

During all of the aerodynamic research programmes, different kinds of trajectories have been flown, some of them greatly varying from the basic requirements of conventional micro-g missions. So this can be seen as a kind of evolution from basic ballistic trajectories to the suppressed and thus more demanding ones, where thermal and mechanical loads increase, thermal protection systems (TPS) are required and the mission design is more prone to uncertainties which, in turn, also result in greater deviations. ReFEx is a next step in this line, aiming also for a suppressed trajectory and a relatively low altitude payload separation.

4. ReFEx and VSB-30

The primary mission goal of ReFEx is to perform an autonomous and controlled flight starting at a predefined altitude and hypersonic speed and gliding down to ground to subsonic velocities along a predefined trajectory similar to that of a winged first stage of a reusable space transportation system. Hence, ReFEx has to be designed to be able to handle the aerodynamic challenges of a winged re-entry vehicle, resulting in sometimes contradictory requirements.

4.1 VSB-30 as a chosen launch vehicle for ReFEx

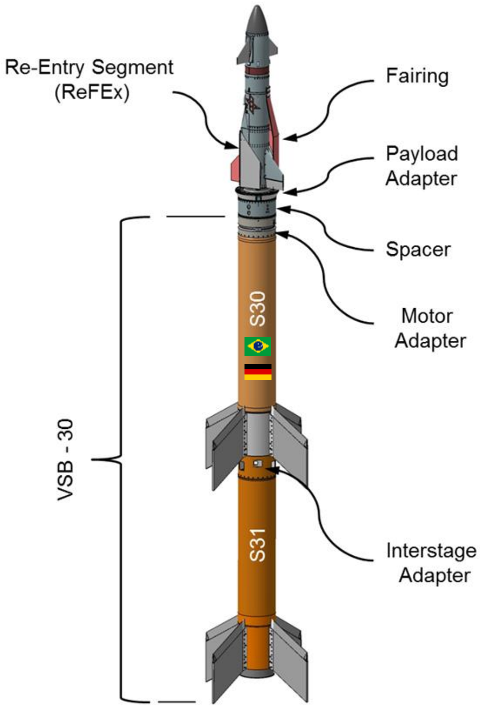

Figure 3 ReFEx Launch Configuration

The ReFEx experiment constitutes a complex mission that requires the experimental vehicle to master a broad range of flight conditions. The resulting complexity of the vehicle itself introduces an appreciable amount of mission risk, so that it was decided to utilise a well proven launch vehicle for the propelled part of the trajectory rather than adding further developmental risk to the project by employing a launch vehicle yet to be developed. This means, that the main focus will be on the core experiment rather than on the rocket motor system used. However, for a complex experiment like ReFEx, extensive customisation is necessary in all interfaces between launch vehicle and payload. The aerodynamic layout of the overall vehicle for the ascent phase is one of the most important and prominent interfaces to be controlled for ReFEx.

The complete vehicle design was defined with minimum interfaces in mind, so that the only interface between the rocket motor system and the payload is the mechanical one between the motor adapter and the payload adapter. This interface is rigid and not designed to be released during flight. It consists of a RADAX screw joint as well as electrical interfaces that are used mainly for the initiation of pyrotechnic events. The ignition unit situated in the motor adapter will be programmed to control the flight safety relevant events such as fairing separation and the separation of the experiment vehicle from the payload adapter. Furthermore, the yoyo-despin system is located on the motor adapter and will be activated to despin the rocket in order to minimize the remaining work for the reaction control system. The de-spun rocket vehicle at the predefined altitude and velocity provides, from a launch vehicle point of view, the requested initial conditions to the experiment.
The mentioned subsystems are typically employed in VSB-30 missions and therefore fully flight proven. This includes the use of MORABA developed ignition units to trigger pyrotechnical events.

4.2 Modifications of the VSB-30 and trajectory subtleties

As a payload, ReFEx induces some delicate features which make the determination and calculation of the ascent trajectory a specialised task, significantly differing from standard missions. Especially the necessary aerodynamic shape of the experimental vehicle induces challenges for the overall ascent configuration. One main difficulty is caused by the wings, which generate significant lift at angle of attack and thus induce high aerodynamic moments during the ascent due to the offset position and the lifting body shape. Furthermore, the large wing surface shifts the overall center of pressure forward, such that flight stability during ascent could not be achieved with the standard VSB-30 fins. To alleviate this, a solution of SHEFEX II flight heritage can be employed – the wings can be covered by a fairing which is aerodynamically significantly less effective. As a result, the configuration produces significantly less lift and, most importantly, the lift is evenly distributed about the roll axis. Due to the fact however, that the diameter of the rocket motors is quite small, the allowable payload diameter is also limited. The maximum payload diameter ever flown on a VSB-30 to date is 620 mm, so that this was selected as the maximum diameter of the fairing to cover the wings. As a result, the payload body diameter is limited to 14 inch diameter and the wings had to be designed to be foldable to fit under the fairing. The wings will be unfolded only after releasing the split fairing. This ensures that the ReFEx wings cannot have a disturbing effect to the trajectory during ascent.

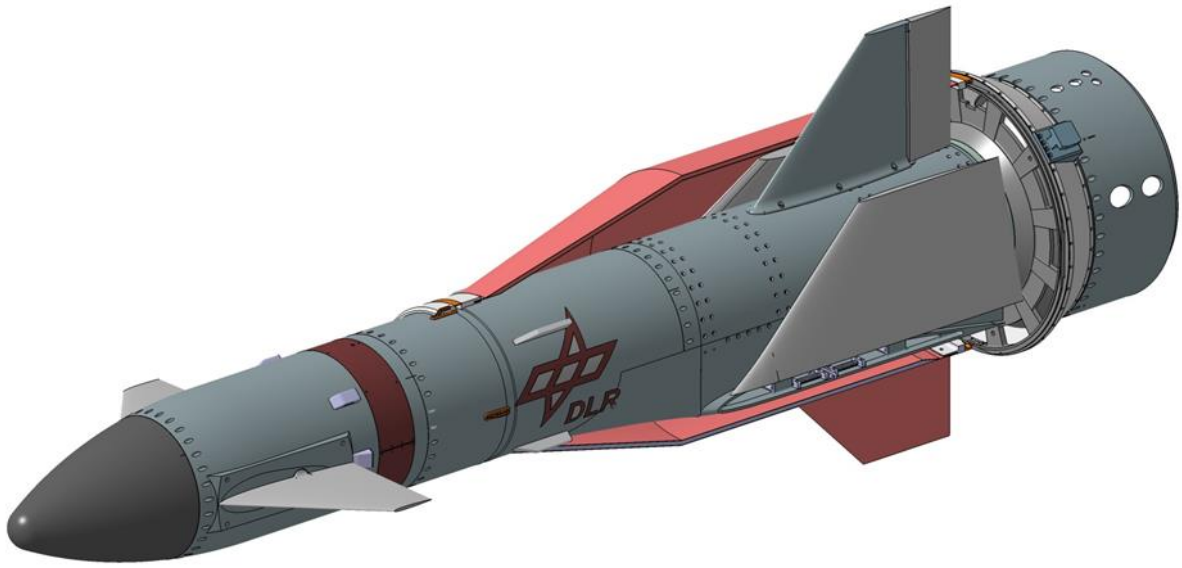

Figure 4 ReFEx payload with folded wings

Figure 4 shows another aerodynamic stabiliser: the tail rudder which cannot be folded and therefore it protrudes out of the fairing partly. To avoid asymmetric effects, a dummy rudder is mounted on the opposite of the tail rudder and fixed to the fairing. This rudder will be released together with the fairing, prior to the aerodynamic re-entry flight of the ReFEx vehicle.

To ensure an aerodynamically stable configuration for the ascent, both rocket motors will be equipped with standard S30 fins. These fins are bigger than the normally used S31-fins on the first stage and therefore have a higher stabilizing effect.

As another parameter that is pushing the limits of the launch vehicle, the total payload mass is at the upper limit of what has been qualified for the VSB-30. The largest mass flown up to date is around 470 kg (MAIUS). ReFEx will have an estimated total payload mass of around 450 kg. Taking into account the Motor Adapter mass of about 20 kg, the total mass above the motor joint is in the order of 470 kg. This means, that in principle, the Center of Mass is moved forward, enhancing static stability. However, the large mass reduces launch acceleration, thus making the vehicle more perceptible to wind gusts.

MORABA has conducted parameter studies of possible ascent trajectories depending on different payload masses, i.e. for the masses 450, 500 and 550 kg. Fig. 5 shows the respective plots referring to the stability of the vehicle. As one can see, the heavier the payload the more stable is the vehicle. By default, MORABA uses 1.5 cal as a conservative stability requirement for determination with engineering tools. The graph shows that especially for the lower mass values, this limit is violated and thus an additional, higher fidelity CFD computation is necessary. If the stability can be assessed with high reliability of the results, the limit of 1.5 cal can be reduced on a case by case basis.

Fig. 6 presents the static margin indicating the stability for a baseline payload mass of 450 kg, for the two different orientation planes. It is clear that the most instable plane is the canard plane. Pending higher fidelity computational checks, the displayed lower limit of static stability is deemed acceptable.

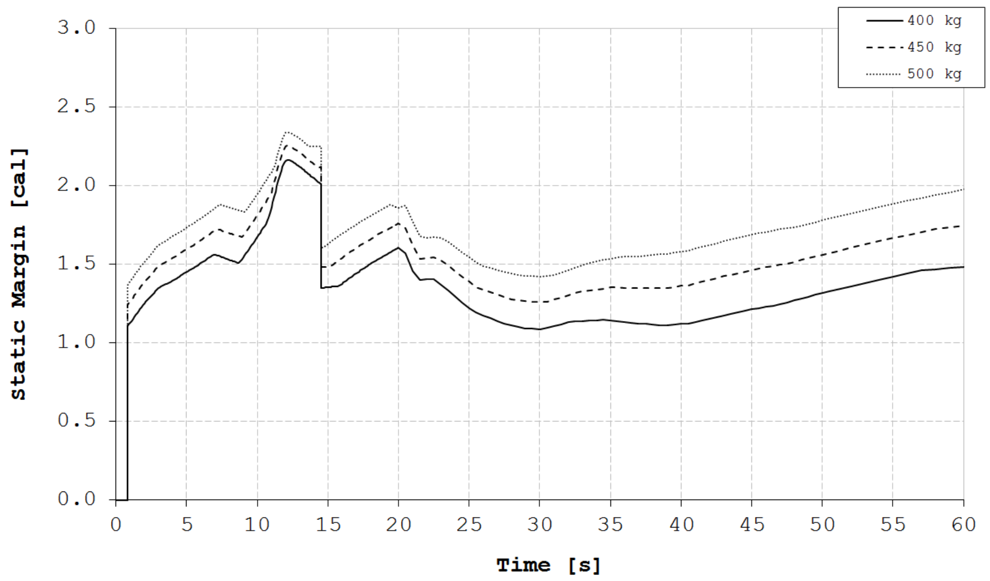

Figure 5 Static margin depending on the payload mass

To achieve the desired flight corridor, the launch elevation must be adjusted to as low as 76° and the 2nd stage ignition is delayed to T +20 s (compared to normally T+15 s) – a modification which has been flight proven. The baseline vehicle with 450 kg payload mass will reach an apogee of about 132 km with an horizontal speed of Mach 5.0. The hand over point is defined at T+ 94 s – at this point the ReFEx experiment vehicle will be released from the rocket motor system. Fig. 7 shows the 3 sigma dispersion parameters at the altitude 88 kms.
These graphs have been generated using the programmes MissileDatCom and ROSE as computational tools.

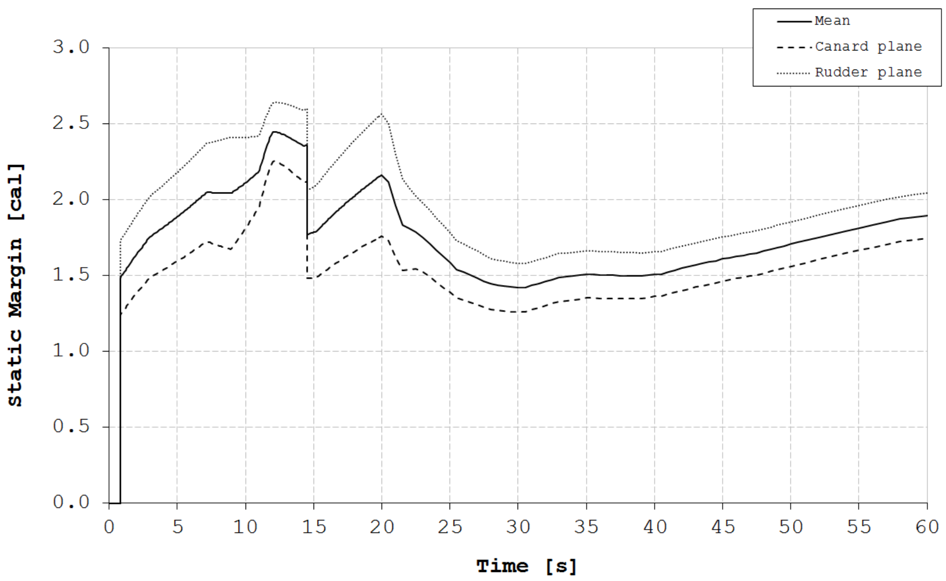

Figure 6 Static margin as function of different vehicle planes

Parameter	Unit	-3 sigma	Nominal	+3 sigma
Altitude	[km]	80.0	88.0	96.0
Down Range	[km]	56.7	64.5	72.3
Cross Range	[km]	-9.4	0.0	+9.4
Total Velocity	[m/s]	1293	1395	1492
Flight Path Angle	[deg]	40.9	44.2	47.0

Figure 7 Release point parameters 3 sigma

3. Conclusion and Outlook

The launch of ReFEx on a VSB-30 rocket is a perfect way for a first test of this new kind of RLV's. Due to its huge flight heritage and the familiarity MORABA has gained with this Rocket Motor System in the past 15 years, the use of this carrier for ReFEx is a logical choice for a successful flight.

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