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Sounding Rockets are unique Experimental Platforms

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Abstract

Sounding rockets are unique experimental platforms! They are unmanned, readily available, cost-effective and can achieve both, in-situ measurements or flight experimentation in all layers of the atmosphere and multi-minute operations in space with altitudes and ranges of well over 1,000 km. During the flight, the data can be sent to ground stations in real-time. The user has the opportunity to interact in the experiment timeline by means of a telecommand and control. The payloads are often recovered by parachute and reused in large parts. Mobile Rocket Base (MORABA), a department of Space Operations and Astronaut Training within the German Aerospace Center (DLR), has the expertise to customize flight systems to suit mission requirements and the mobile infrastructure to launch and operate anywhere in the world. Many applications and have been successfully demonstrated by MORABA with more than five hundred flights since the foundation in 1967. Sounding rockets are versatile and ideal for testing space technologies. Classic parabolic trajectories are standard, but trajectories with low elevations, so-called suppressed trajectories can be performed as well. They allow a longer experiment time in denser atmosphere layers at higher dynamic pressures. For reentry experiments, velocities in excess of Mach 10 and attitude controlled entry conditions are achievable. In hypersonic research, sounding rockets are used as propulsion systems that provide the initial conditions for Scramjet engines, or to validate ground based wind tunnel tests and computer simulations of new aerodynamic configurations. Tests of thermal protection systems can be performed in real atmospheric conditions. In the field of microgravity research, they are an important link between ground-based and airborne research platforms and space stations. Melting furnaces, X-ray sources, even Genetically Modified Organisms (GMO) are easier, faster and safer (and less costly) to implement on sounding rockets compared to manned missions. Although both land and water recovery systems are available, the use of impact-resistant flight recorders to redundantly store large amounts of data has been demonstrated. Sounding Rockets are also the only research platform to offer in-situ measurements of the atmosphere in both the ascent and descent. By tailoring the apogee, the passage speed is adjusted to optimize scientific conditions. In conjunction with the permanent and well-equipped European launch centers Andøya and Esrange Space Center, Mobile Rocket Base offers its expertise and mobility to the national and international research community for missions with Sounding Rockets from anywhere in the world.

Keywords: Sounding Rockets, Technology Testing, Hypersonics, Microgravity, Atmospheric Physics, STEM

Acronyms/Abbreviations

MORABA	Mobile Rocket Base
SHEFEX	Sharp Edged Flight Experiment
MAIUS	Matter Wave Interferometry in Weightlessness
TEXUS	Technology Exeriments under Weightlessness
MAPHEUS	Material-Physical Experiments under Weightlessness
DLR	German Aerospace Center
ReFEx	Reusability Flight Experiment
DCTA	Departamento de Ciencia e Tecnologia Aerospacials
IAE	Instituto da Aeronautica e Espaco
HIFiRE	Hypersonic International Flight Research Experimentation

1. Introduction

Sounding rockets are a proven tool in fundamental and applied research since the early sixties of the last century. In the very early stages, research and development conducted with and on sounding rockets were in large parts pertaining to the development of rocketry and the related technology required to build more advanced guidance and control systems. The use of sounding rockets for fundamental research developed during this phase and superseded the initial technology driven operations. German Aerospace Center's Mobile Rocket Base (DLR MORABA) was created during that time when European rocket technology testing operations began to wind down and fundamental research drove the further operations of sounding rockets.

During the 50 years of existence, DLR MORABA has launched more than 500 rocket vehicles of various sizes into space and has evolved from a user of commercially available systems to a developer of customized launch systems to suit the needs of the research partners. More recent history has seen the expansion from traditional fields of application of sounding rockets into new and renewed research topics such as hypersonic propulsion and reusability technologies. Sounding rockets are proving yet again to be useful and unique testing platforms.

2. Properties of Sounding Rockets

Sounding Rockets come in various sizes and types. In the past, mainly solid propellant rocket motors have been used. Further, many sounding rocket vehicles have made use of one or more military surplus rocket motors in single or multi-stage vehicle configurations. At present, MORABA operates sounding rockets from approximately 600 kg to 7000 kg lift-off mass (see Fig. 2), with no more than two stages in any one vehicle. Internationally, multi-stage vehicles are in use for instance by NASA's NSROC consortium [1].

The "workhorse" sounding rocket for MORABA's microgravity missions, the Brazilian-German VSB-30 [2], is shown in Fig. 1. The figure identifies the scientific payload as several red colored modules. The remainder of the vehicle forms the experimental platform.

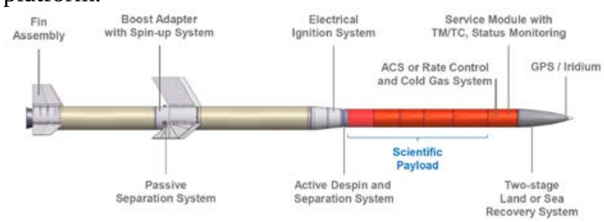

Fig. 1: General Sounding Rocket Layout

The illustrated VSB-30 sounding rocket platform incorporates the typical subsystems necessary for a sounding rocket vehicle:

- *rocket motor systems,*
- *interstage structures,*
- *stabilizing fin assemblies,*
- *ignition systems,*
- *despin systems,*
- *recovery system,*
- *service module, and*
- *attitude or rate control system.*

Mission development and platform capabilities must always account for all engineering disciplines involved in the above systems.

Generally, sounding rocket vehicles are unguided rocket propelled vehicles that are simply a tool to facilitate scientific experimentation. During the atmospheric flight, they spin about their longitudinal axis in order to average out any asymmetries and improve flight trajectory accuracy. Sometimes, part of the sounding rocket itself becomes the experiment, for instance to qualify new materials for fin leading edges or thrust nozzles. Also, differentiation between guided and unguided vehicles from one another and the definition whether this can be called a sounding rocket is not clear. This paper does not attempt to distinguish these properties, but rather focusses in general terms on the experiments that can be supported by the experimental platform of a sounding rocket.

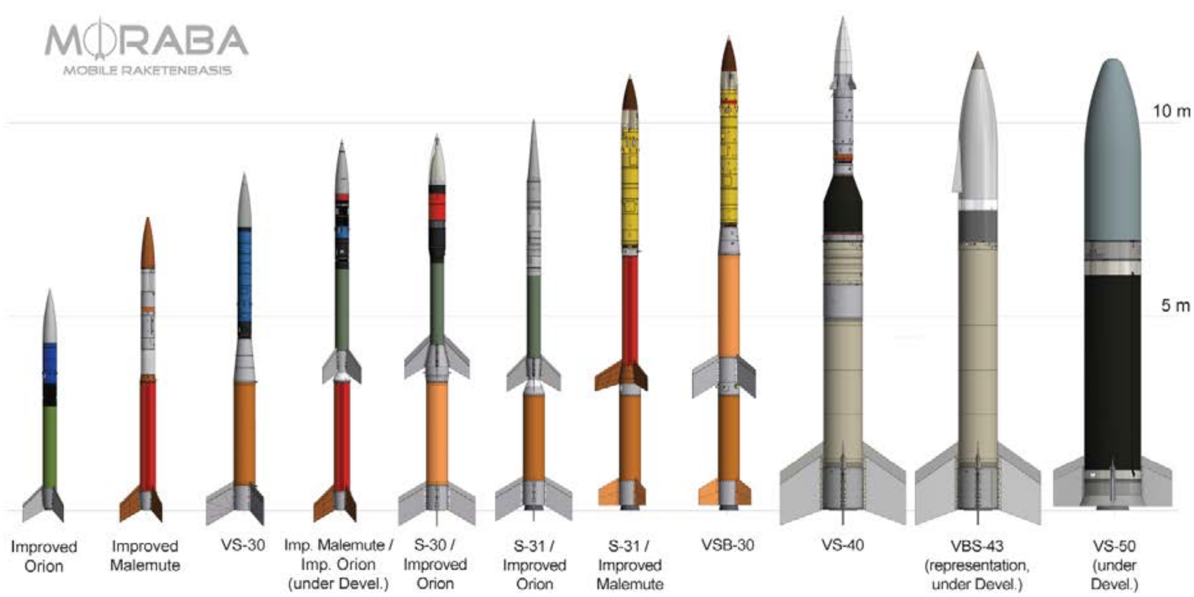

Fig. 2: MORABA Sounding Rocket Vehicle Family (September 2018)

3. Typical Applications of Sounding Rockets in Europe

Traditional applications of sounding rockets are astronomy research, atmospheric physics measurements and research under weightless conditions (so-called micro-gravity research). While the research community in the US is to this day an active user of the exo-atmospheric flight opportunities for astronomy missions, interest in this research field in Europe has been halted since large astronomy satellite missions are in operation.

Atmospheric physics is however a research field of the first hour and is still a strong driver of sounding rocket operations and development. Research vehicles relying on lift (aircraft) or floatation (balloons) cannot reach the altitudes of interest between 60 and 350 km above mean sea level, while satellites cannot orbit in the middle atmosphere. Rocket propelled vehicles therefore are the only means to study the phenomena in the middle atmosphere at a meaningful scale by in-situ measurements. At this point in time, these measurements cannot be substituted by remote sensing technology from space or ground. The technological developments and opportunities together with the scientific requirements make this research field a driver for the development of supporting infrastructure, demanding data rates and sensing capabilities far surpassing those of the past. The medium timeframe future will see strategies implemented to allow 3D distributed in-situ measurements and lateral as opposed to vertical measurement trajectories. These strategies serve to collect more data per flight and enhance the understanding of spatial distribution of atmospheric phenomena.

Micro-g research is continuing to be a major user of sounding rockets in Europe. Research programs with a long history are TEXUS in particular as well as MASER. Flights number 56 and 14 respectively are presently being projected and prepared. Derivative and complementary programs such as MAXUS, Mini-TEXUS, MAPHEUS, Cryofenix and MAIUS have been devised and prove the versatility as well as the demand for individual and customized solutions in a research field that seemingly requires only free-fall conditions. Micro-g experiments on sounding rockets can often be precursor experiments for long duration missions on satellites, probes or the ISS. Residual accelerations on sounding rocket payloads can be as low as 10^{-4} to 10^{-6} g for multiple minutes.

For the conduct of such missions, MORABA employs a series of rocket based vehicles as shown in Fig. 2. These vehicles are generally unguided and configured to fly semi-ballistic trajectories, such as shown in Fig. 3. Payload Support Systems can be adapted and made available to suit the specific mission and generally encompass data and power handling, including data storage and real-time transfer to as well as distribution on ground (telemetry and telecommand), combined with a rate or attitude control system and a water or land parachute recovery system to allow re-use of the payload systems. The combination of these payload support systems, together with the rocket motor system, form the experimental platform.

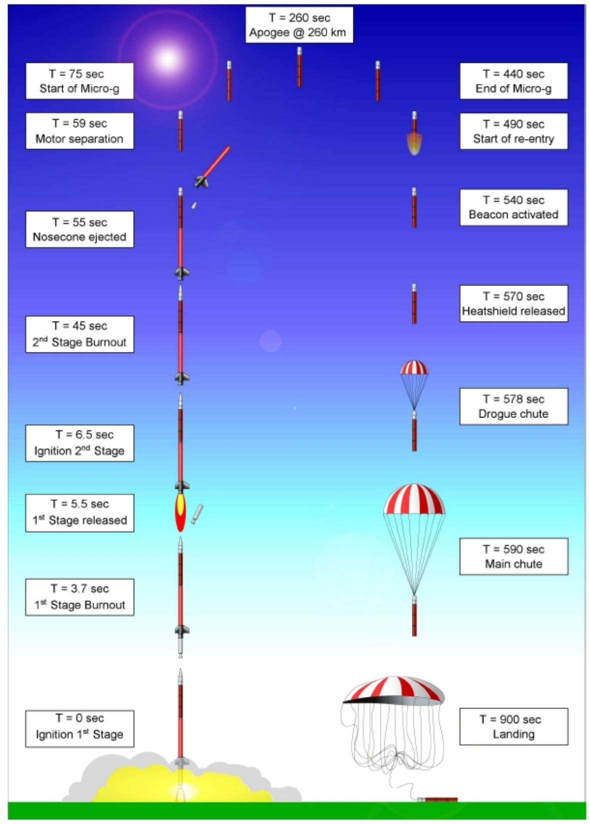

Fig. 3: Typical Trajectory of Sounding Rockets for Microgravity Experimentation [3]

4. Adaptability of Sounding Rocket Platforms

New requirements for sounding rocket missions mostly evolve based on existing or past missions and the combining of the demonstrated capabilities with the desires of the researchers. Possibilities are explored iteratively together with the scientists and solutions are often a novel combination of existing subsystems or capabilities with more or less elaborate modifications and additions or extensions. Such a novel combination of existing capabilities often results in a new field of application. It is important to note that changes in one subsystem often require adaptions of another – the entire platform is a highly integrated research facility.

The motivation of further developments in sounding rocket technology often also originates from discontinuation of previously used and proven systems. When the production of Skylark rocket motors in England ceased in the late 1990's, MORABA together with its long-standing cooperation partner DCTA/IAE of Brazil conceived a customized two-stage sounding rocket vehicle. The resulting VSB-30 vehicle was designed specifically to meet the requirements of the TEXUS and MASER type micro-g research programs as well as the boundary conditions of the Esrange Space Center launch range. In the course of the development, the entire vehicle configuration was designed, tested and built and, in Brazil, a new rocket motor was developed, the S31 booster stage. The development program was building on the existing S30 rocket motor and performed custom modifications to its design in order to arrive at a booster solution that would specifically address the micro-g research missions launched from Esrange Space Center in northern Sweden [4].

MORABA has taken this approach to further its own understanding of the rocket related subsystems and has since built up expertise to quickly establish new launch vehicles according to the user's needs. The last 5 years saw the decommissioning of the military surplus NIKE booster from and the addition of the more performant Improved Malemute to the launch vehicle family in use by MORABA. The resulting family of rocket vehicles brings a large versatility and flexibility for the mission definition to the table when iterating the scientific and technological goals of the missions to be conducted.

Reliable and robust electronic systems are mandatory equipment for the efficient conduct of high quality experiments with remote controlled or automated timelines. The environmental conditions during the thrusting phase, in exo-atmosphere altitudes, at arctic and tropic ground facilities or during water recovery all must be handled without loss of function by the electronic systems. These systems are responsible for the implementation of the timeline, the provision of experimental conditions (rate and attitude control systems), the collection of data, the telemetering and storage of that data and the initiation of safety and flight critical events. The strong competence in electronic systems, including rate and attitude control systems, was continuously expanded and brought to fruition in projects like SHEFEX and MAIUS [5] where high accuracy pointing was successfully demonstrated for an aerothermodynamic and a micro-g mission respectively.

Attitude control systems were already available long ago for the observation of the sun or other stars during astronomy missions. Rate control systems form a subset, optimized to reduce any body rates in order to diminish residual centrifugal accelerations during a micro-g free-fall phase. Both systems make use of cold-gas thrusters and, depending on the purpose, a specific set of sensors. The addition of another set of controller and cold gas thruster allows the exploration of liquid propellants under linear acceleration in weightlessness – Cryofenix. Combining a rate control optimization with a high accurate attitude control yields the ability to conduct cold atom interferometry under free-fall conditions – MAIUS. Controlling attitude prior to ignition of a second stage yields trajectory design options and dispersion reduction without guided flight – SHEFEX II. The boundaries between fundamental research and technology testing and between new and old applications are fluid and not easily identified. These are prime examples where technology (attitude control) from one research area, astrophysics, was adapted for others, hypersonics and micro-g, to enable new research fields to be unlocked for exploration with the help of cost-efficient sounding rockets.

Throughout all of the different competences and their development, the approach taken by MORABA remains that evolutionary design and development is much preferred to large steps in technology to be introduced within a single mission. The result is a better understanding of the new system prior to use than for larger developments steps. The system's behavior is easier to grasp and the mission can be conducted with suitable reliability. For unguided vehicles, range safety conditions of the launch range can be met with sufficient fidelity when changes are introduced incrementally, often eliminating the need for flight termination systems. For new rocket vehicles, only one new rocket motor is introduced at any one time. Ideally, a single stage flight is conducted to enhance performance understanding before the rocket motor is introduced into multi-stage vehicles. Safety critical items such as stabilizing fins are generally carefully and incrementally modified for improvements and the same is true for recovery and ignition systems.

Trajectory development for specific research areas is accomplished in the same manner – evolutionary changes from mission to mission ultimately lead to a new class of trajectory, allowing a new class of research. The changes in trajectories from "true parabolic" up-and-over trajectories to shaped "suppressed" trajectories with gravity turning of upper stages (ReFEx) or re-orientation prior to ignition of upper stages (SHEFEX II) in combination with the necessary aerothermodynamic adaptions for stability and thermal protection, allow the conduct of research with lifting bodies at very high velocities. The supporting platform can thereby remain to be a cost effective, unguided sounding rocket.

5. Recent Developments in Technology Projects

Sounding rockets as an experimental platform in technology development provide an excellent opportunity for the testing of technologies and applications for space related developments. Recent examples are:

- *Propellant handling examined at low linear accelerations during the Cryofenix project [6],*
- *optical frequency comb testing for the next generation precision clocks,*
- *fundamental research on matter wave interferometry in weightlessness for long-term atomic clock developments, MAIUS, [7, 5]*
- *Thermal protection system tests in the SHEFEX flight series for planetary entry vehicles, [8]*
- *Hypersonic laminar to turbulent flow transition experiments necessary for better accuracy in thermal loads prediction in access-to-space as well as planetary entry vehicles, ROTEX-T [9], HIFiRE [10], SHEFEX [8],*
- *Testing of sub-scale thrusting devices, such as rocket motor nozzles in the ATEK mission,*
- *Propelling an upper stage rocket motor with gelled propellant to its testing conditions for horizontal flight in the middle atmosphere – a new experimental platform for atmospheric physics? [11]*
- *Return trajectory demonstrators for reusability strategies of space access vehicles, ReFEx, [12]*
- *As well as the continuous re-use of the platform's subsystems such as service and recovery systems.*

The common denominator of all of these projects is that the sounding rocket platform provides the basis of the experiment in the sense that it delivers the scientific payload to the desired experimental conditions. Be it that the desired condition was a certain aerodynamic condition for hypersonic and re-usability research, that the residual movements of the payload were minimized for micro-g research or that the payload pointed to earth's nadir in order to let gravity act in the direction of the measurement device for matter wave interferometry. The sounding rocket platform can thus act as a flying wind tunnel, as a long duration drop tower as well as a preparatory "first stage" for the testing of upper stage technology, such as propellant handling. The employed subsystems in each application are adapted for the specific mission, but not fundamentally different.

5.1. *Space Access Launcher Technology*

Space access launcher technology development is actively being supported by direct technology testing such as during the Cryofenix project. Liquid propellant handling experimentation under weightless conditions was supported with controlled moderate linear acceleration (thrust <28 N for approx. 400 kg payload). Residual accelerations of less than 10^{-4} g can generally be achieved during the baseline free-fall part of the mission.

The linear acceleration module was a derivative of the rate control systems that are used on all microgravity missions and could be further extended for instance to induce lateral movements for the investigation of sloshing behavior during free-fall. Readily available cold-gas thrusters with impulse control can deliver up to 100 N each and can be bundled if necessary. Accurate rate and attitude data can be provided and attitude can be controlled.

5.2. *Reusability Technology Testing*

The recently developed project ReFEx plans to make use of a sounding rocket platform to bring its lifting body vehicle to flight conditions resembling those that can be experienced by a potential reusable first stage of an access to space system. The sounding rocket is intended to be unguided and the entire vehicle is planned to be scaled to small size for this type of research, with the payload mass being less than 600 kg. This payload shall be brought on a "flattened" trajectory with an apogee of less than 85 km [12]. This is achieved by a prolonged coast phase after first stage burn-out and before second stage ignition, resulting in a significant gravity turn of the free-flying second stage and payload. The planned delivery point provides the experiment with a Mach number of 5.5, at an altitude of 75 km.

The ReFEx project thus employs cost effective sounding rockets to conduct a highly complex experiment. The sounding rocket platform's abilities will be yet expanded to shallow trajectories with the associated thermal protection systems. The approach should ultimately allow the regular conduct of low cost experiments to expand knowledge of high to low speed aerodynamic control of lifting body vehicles.

5.3. *Fundamental Flow Physics*

The investigation of fundamental physics within high speed flows is a critical technology for any planetary entry, earth reentry or space access system. The present uncertainties in flow properties at high speed result in increased thermal protection mass and hence reduced payload capacity. While simple parabolic trajectories on sounding rockets have been demonstrated during the HyShot, HYCAUSE, HIFiRE and SHEFEX I flights, the Mach 10 flight of SHEFEX II has taken this further. The second stage was reoriented prior to ignition, allowing the trajectory to be shallower than previously flown by MORABA. This resulted in a prolonged travelling time through the dense atmosphere at high speeds, for the evaluation of facetted thermal protection systems as well as aerodynamic control strategies.

The more recent flight of ROTEX-T has simplified flight testing by storing very high data rates onboard without the need to transmit telemetry data to ground. Further, complex and costly reorientation systems to align the body axis with the flight vector were omitted for simplicity of the mission and higher flight velocities, yet resulting in valuable high speed data at more than Mach 5 [9]. The experimental body impacted in the Esrange Space Center impact area after separation from the stabilizing aft end and was successfully recovered. Such approaches to high speed flight testing open the opportunity to gather large amounts of high speed flow data at low cost.

5.4. *When the Platform is the Experiment*

In some cases, the sounding rocket platform itself becomes part of or the main experiment. Recent developments on launcher technology for instance by PLD Space in Spain have seen the effort to create a sounding rocket (Arion 1) as a technology demonstrator for orbital launch systems [13]. While MORABA has not gone thus far, the present ATEK project makes the second stage rocket motor an experiment. The second stage is a unmodified S30 rocket motor from Brazilian production, with a ceramic composite nozzle throat made by DLR. This nozzle insert has been tested in a full scale static firing at the new Esrange static testing facility and will now be flight qualified. Thus the concept of evolutionary changes in the vehicle was taken further to technology testing and allowed the testing of materials in a highly demanding high temperature and high density abrasive particle loaded flow of a composite solid propellant rocket motor.

Further experiments on sounding rocket vehicles have been conducted where composite fins and thermal protection systems were tested in flight.

6. Future Abilities

One of the key capabilities and tasks of Mobile Rocket Base is the continuous development of new, customized sounding rocket platforms, serving the needs of the scientific community. New rocket stages, commercial or military surplus, will be combined with existing, flight proven motors. This concept reduces significantly the development effort, time, cost and the risk for the first flight. The maiden flight is often used for scientific as well as technology demonstration experiments as a secondary objective. New flight vehicles enlarge the performance spectrum, but also ensure the availability of sounding rockets in general, even in the case of a failure of certain stages due to an incident or production delays.

Three-stage combinations are more complex, but offer a wider range of performance, in particular for the support of both hypersonic and microgravity research. Higher velocities create higher temperature and pressure regimes and thus allow the testing of new materials, improving sophisticated software tools such as high fidelity CFD and validating wind tunnel tests. The development of thrust vector and magnitude controlled hybrid and gel upper stages offers new opportunities as the trajectory can be shaped to extend operational times in atmospheric layers such as the mesosphere. Multi-stage systems often use or even require guidance systems for flight control in order to reduce dispersion and satisfy flight and range safety requirements.

Sounding Rockets are an ideal platform to mature technologies to a higher TRL and conduct tests in the real space environment for novel materials such as ceramics or carbon fiber, new propellant concepts or subsystem development demonstration.

The reusability of systems and payloads for cost savings and faster return-to-flight capability has been part of the standard repertoire of sounding rockets for decades. Payloads are recovered by parachute systems on land and from the water and delivered back to the scientist within a few hours after lift-off.

One of the biggest future challenges will be to continue to support outstanding science while research funding for the traditional fields appears to be reducing. A possibility is to shorten the operational days by delivering ready-to-fly payloads, and/or to conduct the payload refurbishment on-range and re-fly within a few days. Both methods were recently successfully demonstrated by MORABA as part of the O-STATES and PMWE missions. The continuous standardization of flight hardware, the dedicated use of 3D printing components, as well as the open access of scientific programs for external users will secure sounding rockets as a research platform also in the future, having in mind that the ISS will be de-commissioned in the next five to ten years.

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