

Sounding Rockets : Principle, Functioning and Applications

Florimond Collette
Yann Kempf
BASI-P2, Université du Luxembourg
Małgorzata Karaś
Warsaw School of Economics

Abstract

Sounding rockets appeared in the mid-20th century and proved to be an extremely useful science tool in all fields of physics and even beyond. These rockets are conceived for sub-orbital flights, to take measurement and/or perform experiments in the high atmosphere, in near space and/or in micro-gravity conditions. They also allow to introduce young scientists to space sciences by undertaking a full-scale pedagogical science project with a relatively moderate cost. This paper presents the origins and principles of sounding rockets, how they work, as well as a few recent science applications.

Introduction

Sounding rockets are small rockets (vehicles powered by the high-speed ejection of matter through a nozzle) with one or several stages and solid, liquid or hybrid propellant. They perform sub-orbital flights at maximal altitudes ranging from less than 1 km to more than 1200 km. After a thrust phase, they generally have a ballistic flight phase before touching or splashing down. If they have the right equipment, they can be retrieved after the flight. Apart from the engines, sounding rockets comprise a payload made of science experiments performed during the flight, as well as a data processing system, either with real-time radio downlink, or on-board saving. The first case implies real-time tracking by one or more ground telemetry stations. The second case implies recovery of the rocket after the flight to extract the data.

Sounding rockets are a privileged tool because they reach zones of the atmospheric and near-space environment that are unaccessible by other means. Sounding balloons reach approximately 40 km altitude at most before they stop or even burst, whereas the satellites have got orbits higher than 200 km. Moreover, the conditions offered by sounding rockets cannot be matched by other vehicle or measurement types (balloons, satellites, LIDAR, RADAR,...), or if they do, at much higher costs.

Sounding rockets are much appreciated too for numerous training and educational programmes linked to space sciences. They allow student teams to experience scientific research by developing and performing a science campaign, in the course of which they are strongly responsible of the mission success since they are its actors from end to end. Two of us (M. Karaś & Y. Kempf) took part in such a project, the European Space Camp 2007 at Andøya Rocket Range in Andenes on Andøya Island in Northern Norway, therefore the presentation is largely based upon that experience.

We will present the physical principles underlying the functioning of a rocket, which are accessible with basic Newtonian mechanics, after having given a brief overview of the historic development of rockets. We will then examine a typical sounding rocket as well as the standard structure of a launch campaign. Finally, we will present applications taken from experiments performed in the last years throughout the world.

I. Origins and Principle

1. History

Without precise dates, it is usually considered that the Indians and Chinese have always known the use of rockets. The latter are thought to have invented cannon powder. As an indication, the first rockets appeared between 300 and 100 BC. A Chinese legend tells of a man called Wan Hu, the first flying human in History (after Icarus maybe...), but he disappeared after take-off. Rockets reached the Middle-East and the Byzantine Greek during the 7th century and the Arabs who used rockets for their Greek fire around the 13th century during the 7th Crusade. Originally, the Italians called the item *rochete*, translated into French as *rochette*, later transformed to *roquette*, which the English took over (*rocket*). There were several small

evolutions up to World War I, where mini-rockets were used to destroy enemy observing balloons.

At the beginning of the 20th century, several parallel inventions and discoveries lead to the first true ancestor of the modern rocket by Konstantin Tsiolkovsky, the father of astronautics. He discovers the fundamental mass ratio law, also known as Tsiolkovsky's Law. It links the speed increase and the ratio of the initial and final masses : $\Delta v = v \cdot \ln(m_i/m_f)$ (we will come back to it later on). He also draws plans very similar to our modern rockets, with a segmentation of the rocket and a cooled combustion chamber for two propellants. Pedro Paulet (Peruan) is worth citing as the inventor of the first liquid propellant motor (a mixture of petrol and nitric acid at the time). Robert Goddard (USA) creates the first rocket with a liquids combustion chamber in 1923 and the first gyroscope- and fin-stabilised rocket in 1932.

Louis Damblanc (French) is most probably the first builder of a sounding rocket. Strongly inspired by Tsiolkovski's work, he builds a two-staged and then a three-staged rocket in 1936. His powder engines have an impressive efficiency for the time. Later on, and this is a fundamental point for our topic, he develops a fully automated test bench able to save a large number of variables (among others pressure, temperature, thrust, etc.). During WWII, the US steal his patents and use them at NACA (National Advisory Committee for Aeronautics), NASA's ancestor, to build the first US rockets.

In 1937, the famous Wernher von Braun, author of a PhD thesis on rocket propulsion, develops among others the V2 rockets for Nazi Germany. He supervises their construction by concentration camps workforce. It is ironically said that the V2 killed more during manufacturing than through their use. In 1945 he gets to the United States of America and becomes head of the ballistic missiles research projects. In parallel, the Soviet V2 equivalent is launched in 1947, triggering the Space Race. Von Braun then becomes NASA's deputy administrator. He develops the Jupiter rocket, which is used in the first official sounding rockets series. In 1958, a squirrel monkey flies up to 600 km altitude and experiences microgravity, which was almost unknown at the time, and a 40 g acceleration too. Von Braun also develops the well-known Saturn rocket. Every five months on average NASA then launched sounding rockets with monkeys on board, until 1962 roughly. All of this happened during the tense Cold War and Space Race period, therefore only very limited information was available.

It is worth noting that in history, rockets were always developed for military purposes and use.

2. Physical Principles

The reaction principle is fairly easy, it is used in rockets by expelling matter at high speed in the direction opposed to the direction aimed at. It derives from the conservation of momentum principle. Momentum is a physical notion representing the product of the mass and speed of a body. In an isolated system, momentum must always be conserved. As mass does not vary, if one part of the body takes up speed in one direction, the other parts must take up speed such as to keep the sum of speeds equal to the original speed. In a rocket, matter is expelled at very high speed backwards through the nozzle, usually provided by the fast combustion of a propellant. Then the rocket must be thrust forward following the reaction principle. Imagine the most common and easiest example of a rocket, a released rubber balloon which empties itself and is therefore propelled. It is exactly this principle, its chaotic trajectory is due to the instability of the nozzle. By orienting the nozzle, i.e. by orienting the gas expansion, one can modify the trajectory. Then comes the aforementioned fundamental law of the masses ratio : $\Delta v = v \cdot \ln(m_i/m_f)$. Δv is the speed variation between the beginning and the end, v is the propellant ejection speed, m_i is the initial total mass, m_f is the final total mass. This equation derives from the integration of the equation gained from the momentum conservation principle. Each expelled particle carries some momentum, and causes the rocket to be accelerated forwards. The equation holds for accelerations and decelerations. The speed increase is only a function of the mass ratio at constant ejection speed. Thus the final mass ought to be as low as possible. Let's see an example to grasp the dramatic effects of the formula. We assume an 'empty' sounding rocket, i.e. basically only the spent motor, weighs 10% of the rocket filled with propellant. We get $\Delta v = v \cdot \ln(100/10) = 2,3 \cdot v$: the rocket reaches 2.3 times the gas ejection speed! Finally, to keep a stable trajectory, the gyroscopic effect is used, in fact the angular momentum conservation principle. The orientation of the fins induces a rotation of the rocket such as to make the rocket less sensitive to orientation changes.

II. A Sounding Rocket in Practice

1. A Typical Rocket

This part is mainly based of the example of the CRV-7 rocket, a common model in student programmes such as the European Space Camp, in which two of us took part (M. Karaś & Y. Kempf). It is nevertheless a typical sounding rocket, which allows to study all common features of sounding rockets.

From a technical point of view, the motor is obviously the main part of the rocket. It can be with solid

propellant, in which case the motor cylinder is filled with propellant, hollow or full. If the propellant is liquid or hybrid, that is in two different phases, the liquid and/or gaseous phases are injected in the engine where the combustion takes place. The thrust direction and efficiency are determined by the shape of the nozzle through which the hot gases are expelled. Its shape, which can vary during the burn, is fundamental for the acceleration of the gases and therefore the obtained thrust. The thrust profile is determined by the propellant cross-section in the case of solid or hybrid motors. The time evolution of the thrust will be different with a full or hollow cylindrical section, various layers or a hollow, polygonal section for instance. Large rockets can comprise several stages, mainly necessary to reach high altitudes. Each stage is equipped with a separate engine which performs a part of the climb.

The sounding rocket's core is the scientific payload, which comprises one or several science experiments performed during the flight, measurement and monitoring devices, as well as one or several data processing systems. It is located under the nose cone or fairing, on top of the engine, in a cylindrical tube, within the rocket's wall, or even under a jettisonable fairing, depending on the experiments. Experiments on-board sounding rockets are primarily space sciences experiments, such as astrophysics, geophysics and atmospheric physics, because these rockets allow for in-situ measurements, in all layers of the atmosphere, and with a wealth of instruments (optical, radar, lidar, sampling, spectrography, magnetography etc.). However the long microgravity phases (a few minutes) during the ballistic flight phases in near space and the upper atmosphere attract a lot of research in fields ranging from biology (spatial orientation of fish, for example) to material sciences (formation and evolution of metal foams for instance). Monitoring systems can include accelerometers, thermometers, manometers... in short anything that yields useful data for the monitoring and interpretation of the flight conditions. Finally, a part which is as fundamental as the previous ones is the data processing. The mission goal being data collection, the saving of the data must be guaranteed in order not to spend 1 M€ on a campaign vainly. A small rocket such as the CRV-7 does not include a retrieval system, it is lost in sea at splash down. The data must be transmitted to the ground station without delay. It is the object of telemetry. The analogue readouts from the sensors are encoded digitally and transmitted via a radio downlink, which is received by directional antennas at the ground station. During a flight, operators track the rocket in real-time not to lose the signal, and heavy redundancy guarantees the data will be stored safely. Our main station at Andøya comprised two separate antennas, then the processed signal was saved by a recorder on large magnetic tapes, a standard tape recorder, two double hard drives and an analogue printer, as well as on the computers of the science team to which the data was transmitted in real-time. There were other redundant devices still, and a similar equipment including a further antenna in the secondary telemetry station. The heavy redundancy in the signal acquisition and processing and in the data storage ensure the success of the operation even in the case of partial failure within the system. For certain experiments, it is necessary to retrieve the equipment to analyse it or to reuse it for further flights. In that case, the rocket must be fit with retrieval tools; parachutes, buoys, beacons. It happens in those cases that the rocket comprises an on-board data storing system, which must be retrieved to gain the data.

Other less conspicuous elements contribute strongly to the rocket's shape and aerodynamics, since they are located on the outside of the rocket. These are the antennas, the fins and the launch lugs (if present) The antennas are obviously fundamental to telemetry. The CRV-7 has got two, on either side of the head. The fins allow the stabilisation of the rocket, for instance by giving it a spin around its main axis. On large rockets, they can be part of an active in-flight guiding system. Finally, some rockets are launched from launching ramps. They are attached to a guiding rail with the means of T-shaped metal pieces, which create a non-negligible drag at the speeds reached by the rockets.

These are the technical characteristics of the CRV-7 rocket, as well as the flight characteristics of our June 2007 rocket at Andøya. Its low mass and small size make it one of the fastest sounding rockets and with an extremely high acceleration.

• motor length	1033 mm
• total length	1700 mm
• diameter	69.85mm (2.75 in)
• nominal burn time	2.21 s
• initial motor mass	6.50 kg
• initial (solid) propellant mass	4.80 kg
• total mass	11.6 kg
• peak thrust	6.90 kN
• fins	3 folding fins
• launch	in an alt-azimuth adjustable tube, on a launch pad
• peak spin rate	>10 rps
• peak acceleration (z axis)	>80 g
• peak velocity	>1000 m/s

- flight duration 87 s
- maximum altitude 9.5 km
- launch angle 78°
- launch azimuth 320°
- splash down distance 5.4 km

2. A Launch Campaign

A launch campaign is a long process, as much for the scientific development as for practical and technical aspects.

First of all a science project must be put up, and an experiment that goes onto a rocket must be conceived, which is not the point of this paper.

Apart from the concept and feasibility, the project must then be adapted to the technical constraints of the selected launcher; volume, mass, resistance to the pressure and temperature conditions, electric and magnetic fields, axial and radial accelerations etc. The integration into the launcher and the integration of the telemetry are equally crucial.

Then comes the launch campaign itself. Its period in the year can be conditioned by the expected conditions, in particular for geophysical or atmospheric experiments. The trajectory and impact point must be determined accurately, and these data (date and flight configuration) are transmitted at least one month in advance to the civil air, marine and terrestrial authorities, to the national military authorities, as well as to all the country's embassies such as to avoid any material, personal or diplomatic risk. The day of the flight, air and sea traffic is diverted from the zone, and the fire brigade is put on alert. Before launch, the nearby roads are shut, a sirene resounds and a safety perimeter is established around the launch pad.

The count-down is a perfectly planned procedure, to the second, which can extend over several hours or even days. It takes place after the pre-flight meeting, and is started when the mission scientist considers the flight conditions are optimal, but it can be put on hold as soon as an incident occurs, or as long as the required conditions do not occur. A grave incident compromising the safety or the success of the flight can even cause the stopping of the count-down. The procedure comprises the installation of the rocket, the alerting of the air authorities and the fire brigade, the control of all ground and on-board systems, the calibration of all posts, mainly of the telemetry station, the continuous monitoring of the local conditions, for instance through the release of sounding balloons and radar/lidar/weather measurements, radio silence, the putting under tension of the rocket, the launch, the flight, the splash down, the signal loss confirmation, and then the post-flight meeting.

After the flight, the science work begins with the data analysis and interpretation, which are the mission's only object. We present now a few results yielded by sounding rocket campaigns.

III. Science Applications

In-Situ Geophysical Observations

Numerous missions are aimed at atmospheric observations, to understand phenomena as diverse as polar lights, noctilucent clouds (polar mesospheric clouds), aerosols and their origins, etc.

The MAGIC (Mesospheric Aerosol-Genesis, Interaction and Composition) mission, launched from ESRANGE in Kiruna, Sweden, studied the solid particles present in the winter in the mesosphere between 80 and 85 km height in January 2005. Using detectors mounted on the outside of the rocket, the researchers have been able to determine the density, higher than 1000 particules per cm³, and the size, higher than a nanometer, of the electrically loaded aerosols present in the atmosphere. These particles are very likely to be produced by the disintegration of the meteorites hitting the atmosphere.

Observational Astronomy

Despite what one might expect, rockets are also used in the domain of observational astronomy. Before the launch of the first dedicated X-ray satellites in the 1970s, all observations at those energies were performed from sounding rockets, which were the only means to get over the dense atmosphere which blocks out these radiations.

Sounding rockets are nevertheless still in the game nowadays, successive launch campaigns being cheaper than the launching of a dedicated satellite. A US team currently develops an instrument called Micro-X, the High-Resolution Microcalorimeter X-ray Imaging Rocket, which will allow the observation of extended sources in the X-ray band with an unprecedented spectral resolution. The development is based on 20 years of research and development, and the amelioration of existing devices which have already flown. The Micro-X launch is currently scheduled for February 2011.

Behavioural Biology

Researchers from Vermont University noticed in a space research project that *Drosophila melanogaster* (fruit flies) were more active in orbit than on Earth and on Earth after a spaceflight. They assume microgravity influences their locomotion system and forces them to be “agitated”. To test their hypotheses and observe this in detail, they launched a sounding rocket with 120 male and 120 females aboard and sensors measuring 9 out of 12 of the drosophiles' movements.

Space Engineering

A Japanese collaboration has performed and is working further on technology demonstration projects using sounding rockets. They develop small-scale demonstrations of multiple satellite configurations to unfurl square-km scale arrays to be used as radio antennas or solar satellites. The concept consists of several small satellites unfurling, controlling and keeping the large sheet-like structure deployed and orientated as needed in orbit. The unfurling and control systems are to be tested on board sounding rockets through deployment in a microgravity environment at 150 km altitude.

Conclusions

Sounding rockets are an extremely versatile science instrument, which makes them an essential research and education tool, and this in numerous science domains, from Earth and space sciences to engineering, condensed matter physics and biology.

References

K. Amyx, Z. Sternovsky, S. Knappmiller, S. Robertson, M. Horanyi, J. Gumbel

In-situ measurement of smoke particles in the wintertime polar mesosphere between 80 and 85 km altitude

Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 61–70

doi:10.1016/j.jastp.2007.09.013

ESC 2007 : EUROPEAN SPACE CAMP 2007

Official Andøya Rocket Range documentation

Among others : Countdown Procedure

Lectures

Among others : Amund Nylund : Introduction to Rockets

Group presentations & Group work

Group A – Rocket Systems Design

Group B – Experimental Instrumentation

Group C – Rocket Payload Assembly

Group D – Rocket Telemetry

Group E – Rocket Physics

Amund Nylund, Jøran Antonsen, Aleksander L. Marthinussen, Åge-Raymond Riise and Torstein Wang, Ottar Cleveland

Eivind K. Buer Johansen, Eirik Wie Furunes, Ida Benedikte A. Hole, Patrick Raanes, Hege Øiseth, Amelia Travers, Salomé Matos

Dev Sharma, Peter Schwab, Hannes Schmeiduch, Ole Krister Randa, Astrid Brodtkorb, Alexander Vahl, Hans-Georg Engler, Fei He, Ellen Marie Høye, Malgorzata Karaś, Karin Ipsen, Camilla Lytomt, Børge Andreassen, Jakub Sikorowski, Barbora Sramkova, Špela Zupančič, Erlend Ingebrigtsen, Daniel Eika, Stian Kristoffersen, Jakob Wärnhjelm, Maria Teresa Bezem, Merethe Grande, Christian Einvik, Nora Lyngra, Børge Irgens, Henrik Thingbø, Naomi Røkkum, Yann Kempf

E. Figueroa-Feliciano, S.R. Bandler, M. Bautz, G. Brown, S. Deiker, W.B. Doriese, K. Flanagan, M. Galeazzi, G.C. Hilton, U. Hwang, K.D. Irwin, T. Kallman, R.L. Kelley, C.A. Kilbourne, S. Kissel, A. Levine, M. Loewenstein, D. Martinez-Galarce, D. McCammon, R. Mushotzky, R. Petre, F.S. Porter, C.D. Reistema, T. Saab, P. Serlemitsos, N. Schulz, R. Smith, J.N. Ullom

Micro-X: Mission Overview and Science Goals

J Low Temp Phys (2008) 151: 740–745

doi:10.1007/s10909-008-9732-7

Mark S. Miller, Tony S. Keller
Drosophila melanogaster (fruit fly) locomotion during a sounding rocket flight
Acta Astronautica (2008) (In Press)
doi:10.1016/j.actaastro.2008.01.033

Shinichi Nakasuka, Tsukasa Funane, Yuya Nakamura, Yuta Nojiri, Hironori Sahara, Fumiki Sasaki,
Nobuyuki Kaya
Sounding rocket flight experiment for demonstrating “Furoshiki Satellite” for large phased array antenna
Acta Astronautica 59 (2006) 200–205
doi:10.1016/j.actaastro.2006.02.014

Amund Nylund, Jan-Erik Rønningen
Technical and educational improvements of the Student Rocket Program at NAROM and Andøya Rocket
Range
Acta Astronautica 61 (2007) 506–513
doi:10.1016/j.actaastro.2007.01.058

Roland Sanctuary
Physique Expérimentale 1a : Mécanique Newtonienne
Experimental Physics lecture, Bachelor Académique en Sciences et Ingénierie filière Physique
Université du Luxembourg