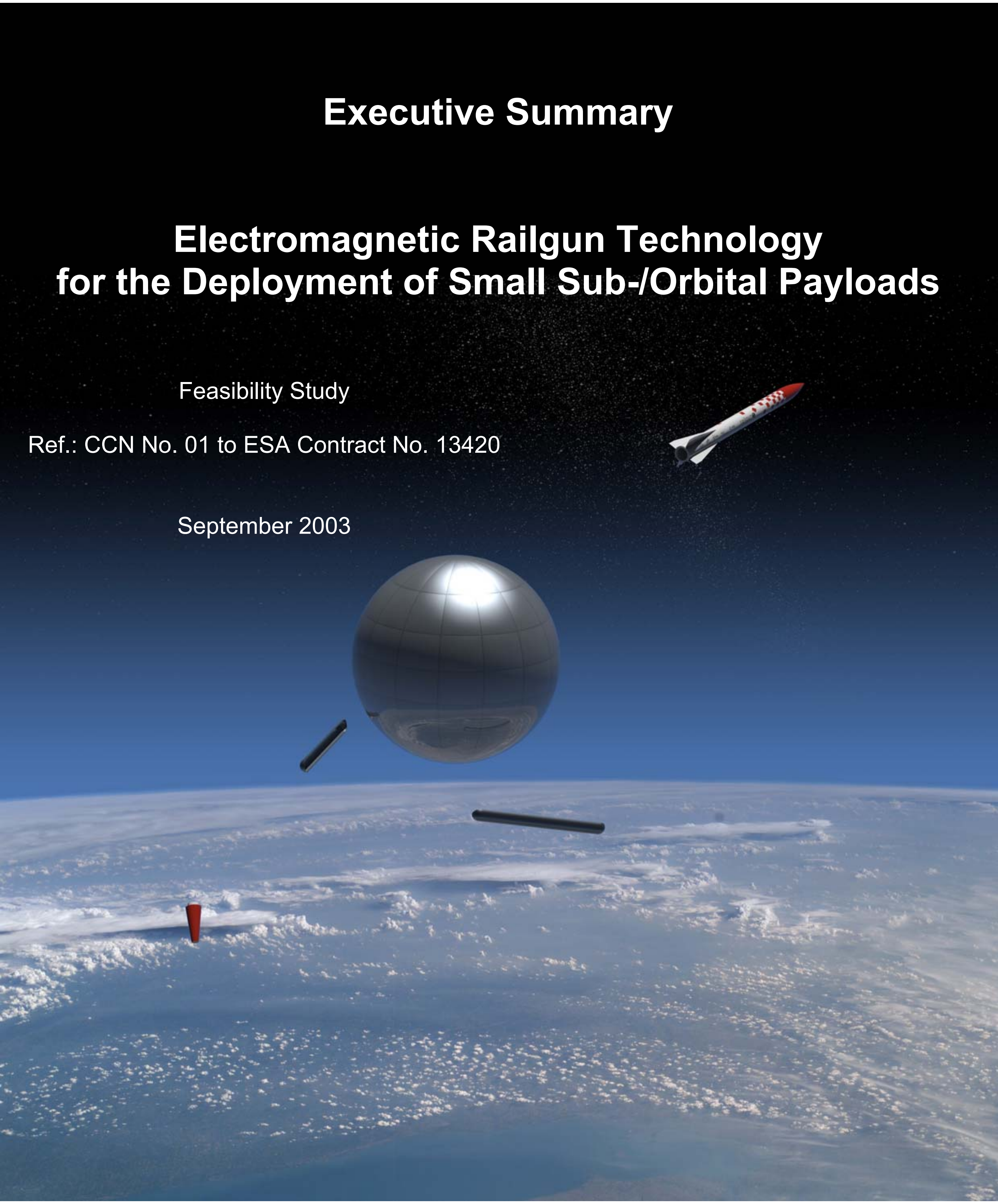
Executive Summary

Electromagnetic Railgun Technology for the Deployment of Small Sub-/Orbital Payloads

Feasibility Study

Ref.: CCN No. 01 to ESA Contract No. 13420

September 2003



1 Introduction

Subject of this study is the assessment and demonstration of the feasibility of the concept to launch very light payloads by means of projectiles, which are accelerated by an electromagnetic railgun to hypersonic speed.
Compared to conventional solid and/or liquid rockets, a railgun offers several advantages like high efficiency with high repetitions rates and low recurring costs, resulting in launch prices which are expected to be very competitive in the corresponding market segments.

This present feasibility study is based on findings of former ESA studies, but concentrates strongly on the usage of the railgun technology for market oriented applications, taking into account the changed market aspects and different needs for very small payloads:

a) supplement for small meteorological sounding rockets, as a stepping-stone for

b) the launch of Nano-Satellites (~1 kg) into LEO as future extension

These applications are considered realistic to be implemented based upon a "reasonable" extension of the existing ISL railgun Pegasus facility. Both are aiming at already existing and established markets and therefore the substitution of small sounding rockets and/or the launch of small satellites into LEO appears to be most promising.

As the focus of this study is the suitability and feasibility for the a.m. different envisaged applications, following main aspects essential for a future railgun launch have been identified and are therefore elaborated:

- Hypersonic projectiles (general layout, load simulations, etc.)
- Railgun (general layout) and
- Market aspects and Payloads

The study team involved in this work consists of the following partners:

- EADS Space Transportation, Bremen (D), System Aspects
- French-German Research Institute, Saint-Louis (F), Railgun
- DLR, Braunschweig (D), Hypersonic Projectile Design
- IAP Kühlungsborn (D), Science Applications

From the programmatic point of view different major milestones have been achieved during the course of this GSP study:

- Start (Contract issued): April 10th, 2003
- Progress-Meeting June 11th, 2003
- Publication/Presentation
  16th ESA Symposium on Rocket and Balloon Programmes, St. Gallen, June 2003
  German Space Days, Braunschweig, September 2003
  IAC Bremen, September 2003
- Final Presentation September 23rd, 2003

2 Reference Mission: Suborbital Launch

Railguns are well-known for their capability to reach very high velocities (v_0 > 2000 m/s) with overall efficiencies over 30 %. The expected high performance concerning velocity, efficiency, cost and repetition rates make this system attractive not only for military but also for space applications.
ISL know-how in railgun technologies allows defining an electric launcher able to replace the traditional rocket technology.

The general operational capability for the railgun system will be demonstrated at first with the launch of small meteorological payloads to sub-orbital altitudes. These payloads, namely falling spheres and/or chaff clouds, which are launched today by very small sounding rockets, have the advantage of restricted requirements with respect to payload mass, volume, target altitude and functionality.

The design of the railgun and the associated hypersonic projectile will be tailored to the launch of these lightweight experiments.

2.1 Scientific Background

Atmospheric altitudes between ~50 and 150 km are of significant scientific interest, however, when it comes to probe this region with sophisticated in situ techniques it turns out that this altitude range is extremely difficult to access at all: sounding rockets provide the only means to probe the mesosphere/lower thermosphere region in situ and so far there are no sufficiently precise remote sensing techniques available that come only close to the accuracy of in situ measurements.

2.2 The Present Sounding Rocket Market

Besides the two ESA Sounding Rockets, Texus and Maxus, which are intensively used for microgravity research, there are currently thirteen operational launch vehicles in the Nasa Sounding Rocket program with different performance parameters, serving different needs.
All sounding rockets use solid propellant propulsion systems (see Figure 1).
Extensive use is made of 20-30 years old military surplus motors in ten of the systems.

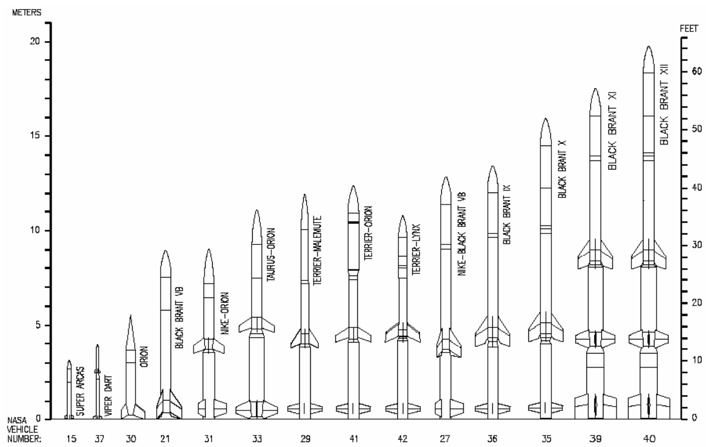


Figure 1 Nasa Sounding Rockets

In particular the very small sounding rockets or Met-rockets, which are used for meteorological sciences, are regularly launched by European user groups either from the Andøya Rocket Range and Svalbard in Norway or from Esrange in Kiruna/Sweden.
Met-rockets are a cost effective method for obtaining in situ measurements in the upper middle atmosphere.
The standard configuration used to launch such systems in the past years has been a combination of a Viper IIIA solid propellant and a Dart 12A payload system (see Figure 2).

The Viper 3A/12A Dart is a two stage sounding rocket vehicle consisting of a solid propellant Viper 3A rocket motor as the first stage and a non-propulsive, inert Dart containing the payload as the second stage.

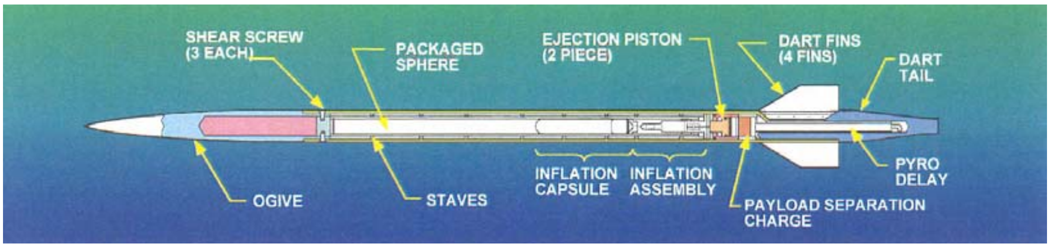


Figure 2

Schematic of a dart payload (source: Orbital Sciences Corporation, 21839 Atlantic Blvd, Dulles, VA20166, USA).

The total hardware price of one complete met-rocket is approximately $12,000 US, however a typical total price for one met-rocket launch (with a typical duration of 5 weeks launching one met-rocket every three days) including hardware, operational costs and radar tracking is ~25,000 Euro.
There is a heavy claim for launch capabilities of small sounding rocket payloads from the user community, but it turns out that right now there is a significant shortage in the availability of such systems:
So far the supplier of the standard met-rocket combination (Viper IIIA + Dart 12A) has been the company Orbital Sciences Corporation. OSC however has recently sold the Viper and Dart-product line to the Canadian company Bristol Aerospace after their production facility in Chandler, Arizona, had burnt down during an accident. Bristol Aerospace, on the other hand, has now begun the development of a substitute for the Viper motor, namely a new motor named Excalibur 2 that should possess similar features like the former Viper IIIA.

The Excalibur 2 motor is significantly more expensive (~$20,000) as the formerly available Viper IIIA motor. Since the number of possible rocket launches per year is directly and only controlled by the availability of corresponding funds this price is certainly a significant drawback for the user-community. In addition, it must be noted that the first two launches of the Excalibur 2 carrying a Dart 12A Mini-payload in a scientific research campaign from the Andoya Rocket Range failed. Hence, at the current stage it is highly questionable if the Excalibur 2 will indeed be a suitable launch vehicle - both considering its prize and its so far performance.

For the time being, alternative suitable rocket motors are not available.

2.2.1 Future Payload Needs

The mission requirements have been evaluated from present and future planned miniaturized sounding rocket experiments: A maximum payload mass of 1,000g with an associated volume of 270cm^3 (a cylinder of 54cm length and 5cm diameter) is considered to cover all future applications incorporating a considerable margin. All payloads are expected to be exposed at a maximum altitude of about 115km.

A demand of ~130 met- or Mini-rocket launches per year is expected provided that suitable launch vehicles are available for dedicated met-rocket research campaigns to study the mesosphere, to support research campaigns utilizing large conventional sounding rockets, to conduct completely active instrumentation missions and to support satellite validation missions.

2.3 The Railgun Launch System

This part of the study is to prove the design feasibility of a non-propelled projectile to be launched with the help of a railgun as a suborbital mission, in order to perform geophysical measurements of the Earth's atmosphere.
The results obtained for the first projectile and mission design will be presented and discussed.
Starting from a data set containing the payload masses, the highest acceleration levels, the elevation angle (as provided by the range operators) and the velocities to be reached, the characteristics of a railgun fitting these requirements have been determined.

It is shown that a projectile with optimized aerodynamic form, i.e. an outer diameter of about 50 mm, 1050 mm length and 3.0 kg total mass at launch is able to fulfill the mission. The required launch velocity to be provided by the railgun is about 2150 m/s.
For a 22m length railgun and a projectile start acceleration of about 12,000 g's, the estimated maximum heat load at the projectile nose cone is 1034 K.
A railgun -coupled to the object to be accelerated- concept is proposed.

2.3.1 The Hypersonic Projectile

These restricted requirements with respect to payload mass, volume and target altitude motivate the idea to use a railgun as launch system due to its great functionality. Indeed, most future meteorological as well as other high altitude applications could be served with a railgun launch system with today's technology. Furthermore, it is envisaged that mastering the railgun technology by this way will allow a wide range of future applications with respect payload mass and target altitude.

2.3.1.1 Aerodynamics

Since bigger outer diameters increase the aerodynamic base-drag deteriorating the ballistic coefficient and hence reducing the mission target altitude, an optimization analysis for the external diameter as a function of target altitude is carried out. The results of such analysis suggest a minimum value for the aerodynamic drag for a slender body combined with a boat tail, as is shown in Figure 3. The projected weight is achieved through application of high technology materials as carbon/ceramic composite for the projectile shield and Aramid fiber (Kevlar, Twaron) for the internal structure.
For the cylindrical part of the body it is possible to apply also high temperature polymers reinforced with carbon fiber and combined with temperature resistant coatings, but it will raise the projectile weight by 25 – 30 %.
For the initial shape of the projectile, Figure 4 shows the total drag and its components as a function of Mach number. The figure shows that the total drag coefficient tends asymptotically to a minimum value close beyond the railgun launch velocity (Ma ~ 7).

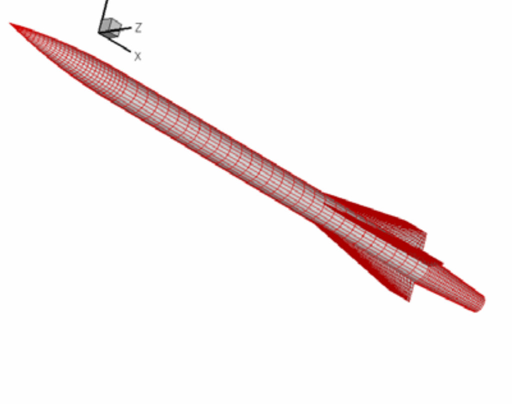


Figure 3 Non-propelled projectile configuration:proposed concept

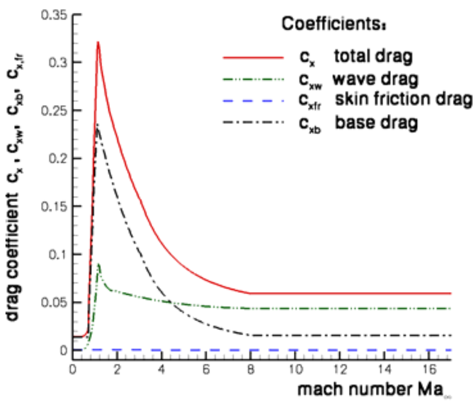


Figure 4 Drag coefficient changes with Mach number

Also, the maximum drag coefficient is achieved for transonic mach numbers, which for the present mission profile implies a fly path segment near to the apogee point, i.e. approx. 115 km. At this altitude the aerodynamic drag can be neglected.
The flight trajectories are computed with a highly complex 3DOF computer code, taking into account a number of different effects.
The sensitivity of the computed flight path to the projectile drag is studied by varying the projectile diameter from 0.04 to 0.06 m. Figure 5 shows that the required altitude is achieved with start velocities less than V_{gun} = 2500m/s for all the projectiles within this diameter range. Therefore a projectile is proposed with d_s = 50mm to account for some reserve in the design. For such a projectile the required launch velocity and launch angle are V_{gun}=2100m/s and Θ = 85°.

Figure 6 shows a zoom of the flight path as a function of time for the first 50 seconds. The projectile passes the troposphere and achieves the stratosphere after about 8 sec (PT2) and it is already at 29000 m after 20 sec (PT3). The calculation also shows that the projectile passes the densest atmosphere range after 32 sec (PT4).

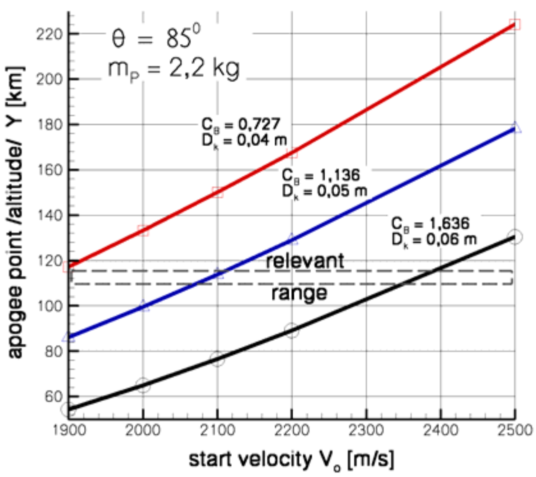


Figure 5 Apogee vs. start velocity and projectile diameter

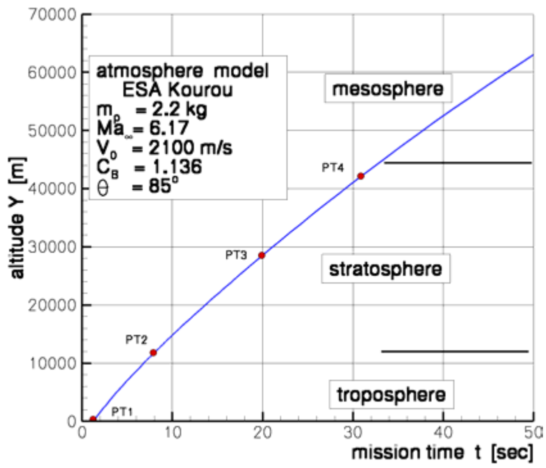


Figure 6 First 50 seconds of flight for the proposed projectile configuration

Pressure distribution and thermal loads are primarily computed for the initial projectile shape for the most critical trajectory point, i.e. just after the start (mission time 0.1 sec, see Figure 7). A strong bow shock in the nose area, a thin boundary layer along the body and a recirculation zone at the boat tail can be seen. Also, in all mentioned zones is to recognize strong velocity gradients due to the strong energy dissipation which induce high local heat loads.

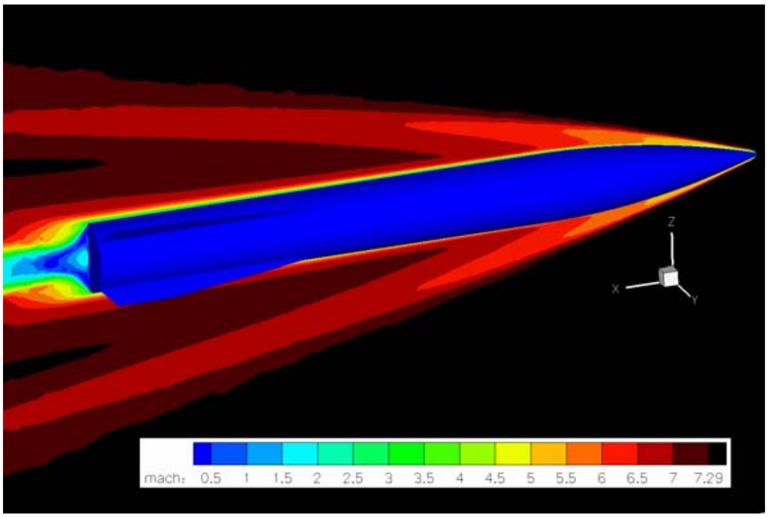


Figure 7 Flow field Mach number distribution. TAU computation

The resulting surface pressure distributions under such flow conditions, predicted by the two different methods employed in this study (i.e. DLR HOTSOSE and TAU) are presented in Figure 8. The Figure shows a good qualitative and quantitative correlation between both techniques with the exception of the stagnation point value, where due to the sharp edge configuration HOTSOSE is unable to provide with a value. Furthermore, the analysis of the figure indicates a strong pressure gradient on the nosecup of the projectile. Indeed, the static pressure drastically reduces from p_d = 37.7bar at the stagnation point to p_d = 3.4bar shortly downstream.
Thermal loads for the above mentioned flow conditions are also computed with the same two methods. However, the prediction of heat loads depends strongly on the state of the flow. It was considered sufficient in this first assessment no to compute the heat loads as unsteady but to correct obtained steady state temperature values with to the experimental results.
The resulting values are conservative since they do not account for any altitude variations. Figure 9 presents the obtained surface temperature distribution by the two computed methods here employed, after the above mentioned corrections. The results compare qualitative and quantitative rather good.

The materials for the construction of the projectile nose cone and the case have not been yet selected. However, based on the aerodynamic, heat loads and trajectories here computed it is evident that non-exotic materials, which are inexpensive and easy to work, may be chosen to handle the expected temperatures and mechanical loads for the here limited mission time. Indeed, the fly through the dense part of the earth atmosphere takes approx. 40 sec (valid for the initial projectile configuration with a diameter of 75mm) and hence metals with high temperature resistance and/or carbon composites for the nose cone and thermoplastic fiber composite for the slender cylindrical body and fins combined with stiffened insulation to support the entire structure and to protect the payload may be used. Indeed, it is expected that any environmental condition the projectile will experience along its flight path can be handled with today's available materials and knowledge.

In general, it is feasible to develop a projectile for geophysical measurement with the given boundary conditions with today‘s state of the art technology. Based on the present study a projectile to fulfill such suborbital mission, consisting on a nose cone, fuselage with fins and boat tail, interior structure and payload may be proposed.

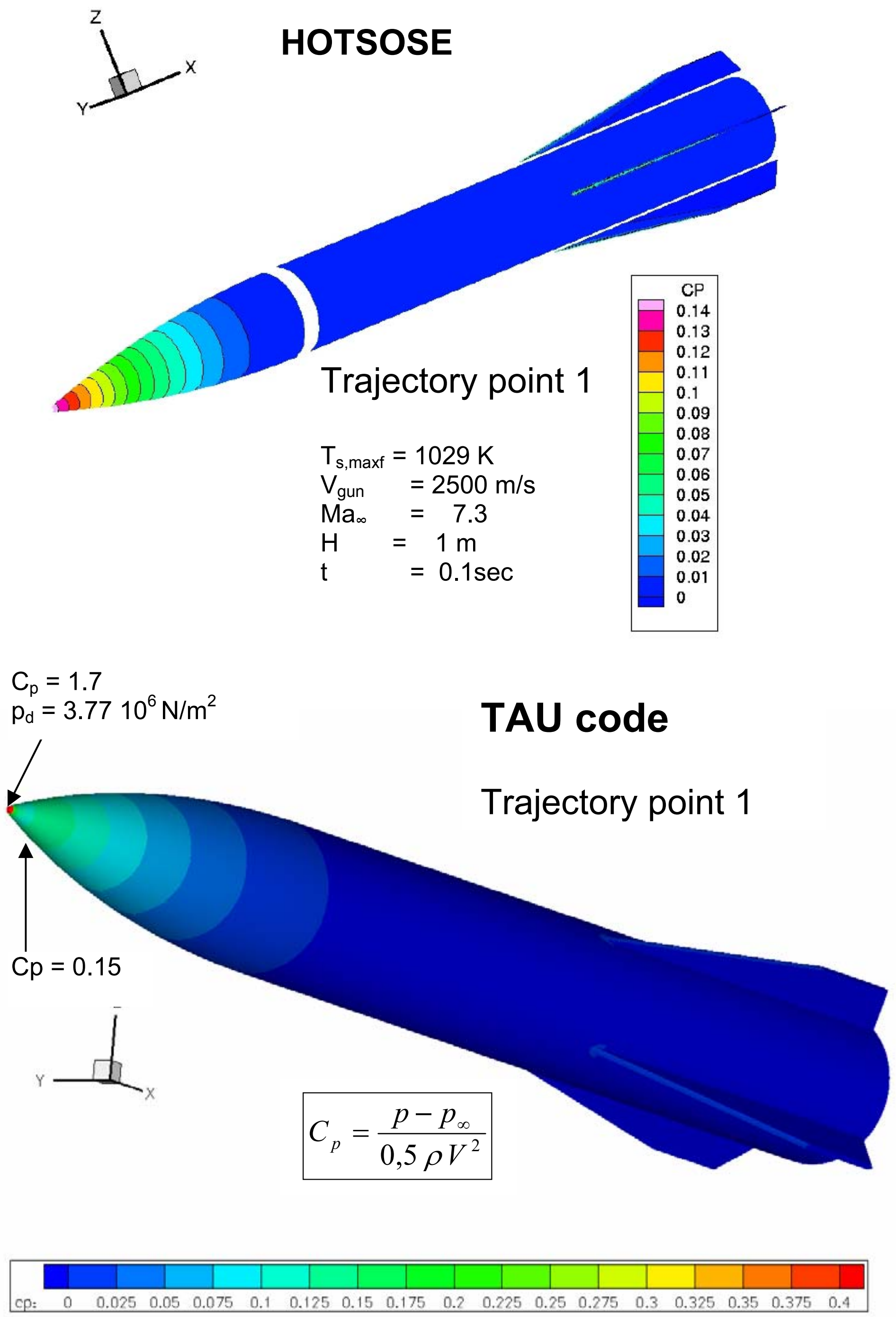


Figure 8 Computed static surface pressure distribution. Top: HOTSOSE. Bottom: TAU

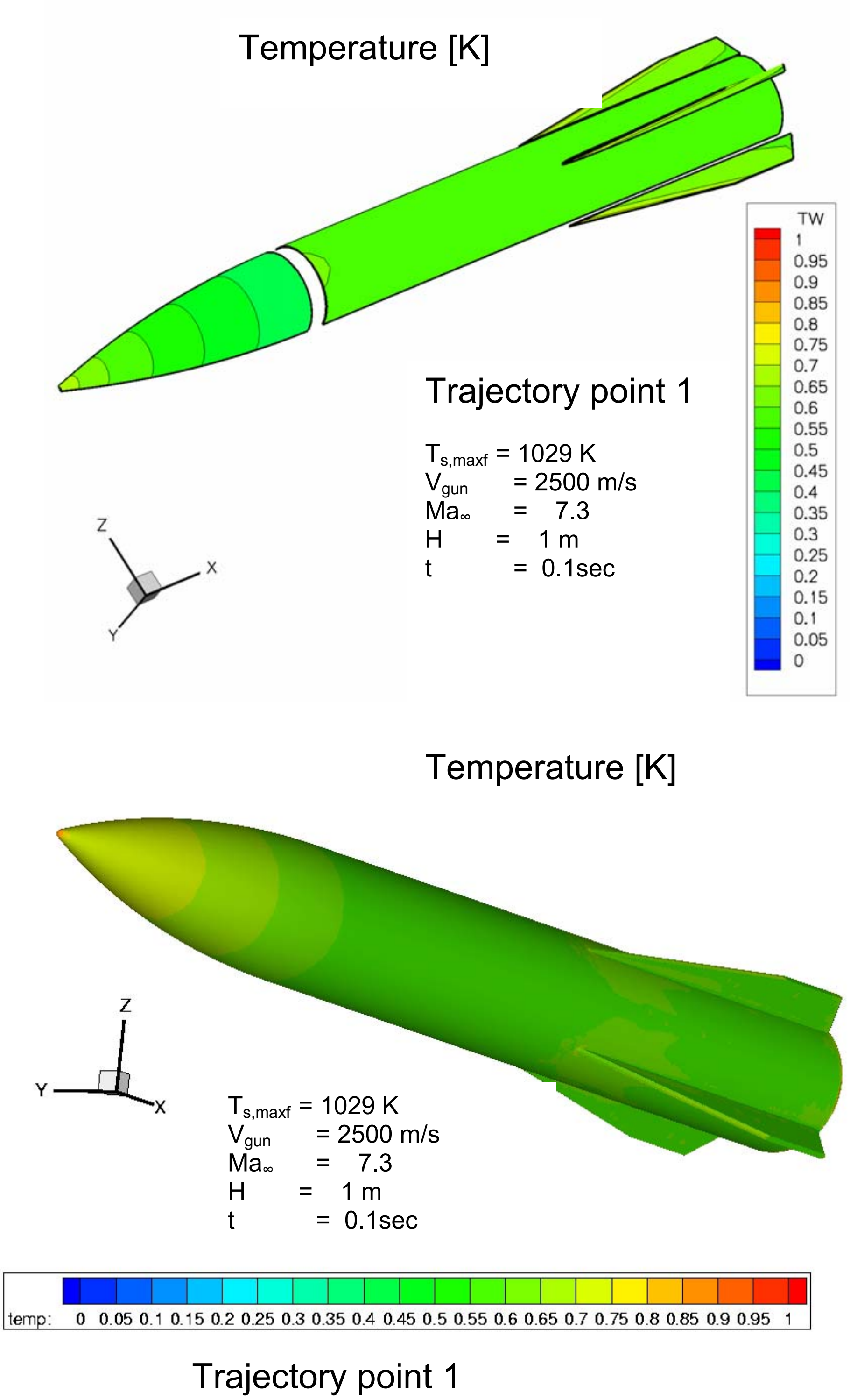


Figure 9 Computed surface temperature distribution $T/T_{s,Max}$ after 0.1 sec mission time (initial projectile configuration).
Top: HOTSOSE code, Bottom: TAU code

2.3.2 The Railgun

The technology of electromagnetic railguns is well known since the first experiments in France in the 1910's and are to date primarily used in military research for the launch of high speed shells. The Institute Saint Louis (ISL) in France is presently with DSTL in UK the only European organization still working on electromagnetic railguns.

The physics of a railgun are not conceptually difficult. A current, flowing through rails and a conductive armature, which is free to slide, forms a closed loop, which in turn creates a magnetic field. This magnetic field generates a Lorentz force on the movable armature in an outward direction.
The railgun takes advantage of this phenomenon and uses the Lorentz force to accelerate the armature and fire a projectile out of the gun barrel (see Figure 10).

This energy is provided in the ISL railgun Pegasus facility by a modular 10 MJ capacitor bank, which consists of 200 individual modules of 50 kJ each; every module is made up of a fast discharge capacitor associated with a semiconductor switching system (10kV, 70kA), a coil and coaxial cable.
To improve the efficiency of the railgun, a so-called "Distributed Energy Storage" (DES) is used, which delivers the energy along the rails.
With DES railguns an overall efficiency of 30% to 40% is possible with muzzle velocities up to 3000 m/s.

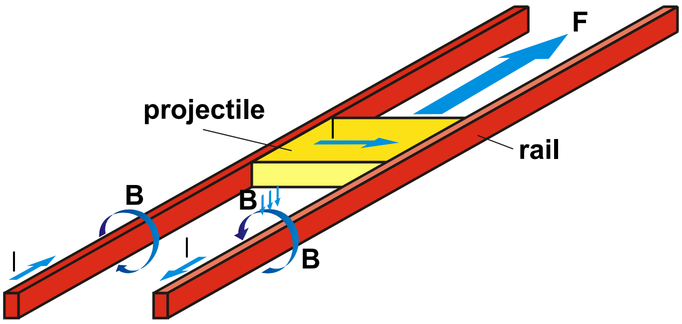


Figure 10
Scheme of the
railgun principle

To determine the characteristics of the railguns the total mass of the projectile (payload, armature and sabot) had to be evaluated. For that purpose a push sabot including the armature was selected.
The sabot armatures used at present in ISL railguns are made of Glass-fibre-Reinforced Plastic (GRP) and equipped with metallic fibre brushes made of thin Cu-Cd wires. Figure 11 shows a typical projectile equipped with fibre brushes used in one of the ISL facilities.

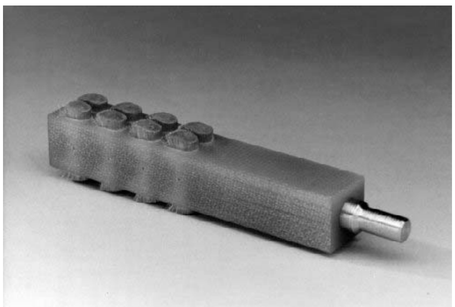


Figure 11 Photograph of a projectile with GRP sabot equipped with copper brushes and a penetrator (ϕ = 7.5 mm)

This kind of projectile has been accelerated with currents reaching 500 kA up to 1970 m/s without any arcing at the rail-projectile interface. Above these current and velocity values, plasma arcs occur.

A flash radiograph of the projectile at the muzzle of the ISL railgun (Figure 12) shows the behaviour of the copper brushes. After the fusion and vaporization of the part of the rear brush in contact with the rails, the current goes forward to the next brush. During the acceleration of the projectile, the brushes are straightened and pushed against the rails by the Lorentz (EM) force. This phenomenon improves the electric contact.

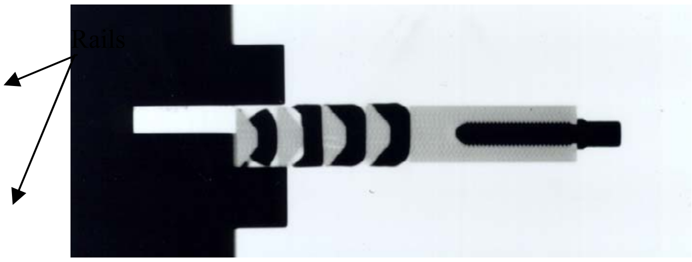


Figure 12 Flash radiograph of a projectile at the muzzle of the ISL railgun; the brushes on the rear side are no longer in contact with the rails; the current has moved to the next row of brushes (this is shown by the straightening of the brushes by the Lorentz force)

Within the framework of this study we consider a sabot armature similar to those used in the experimental facilities. A rough scaling of the existing sabot armature system allows determining a mass of 1.7 kg. The projectile has then a total mass of about 3.9 kg.

ISL has chosen to use a capacitor bank to feed the railgun. This technology is well-known and reliable. The scheme of the electrical circuit is shown Figure 13.

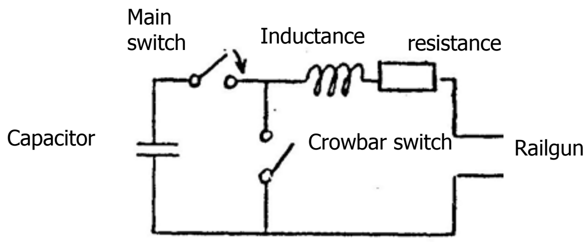


Figure 13 Scheme of the electric circuit used to feed the railgun

The capacitor bank is composed of 50 kJ modules. The main advantages of a modular energy supply are:

- a high security standard: each Pulse Forming Unit (PFU) is disconnected from the next one,
- a good reliability,
- a high flexibility: an arbitrary total current pulse can be formed by choosing the triggering instant for each PFU,
- an enhanced overall efficiency of the railgun,
- the possibility of using semiconductor switches as the current for each module is limited to 50 kA (this avoids the parallel connecting of thyristors).

Each module is composed of a capacitor of 865 µF, connected to a semiconductor switching unit, a pulse forming inductance and a coaxial cable. Each module has a charging voltage in the order of 10 kV and can deliver a peak current of about 50 kA.

The railgun used at ISL are usually fed using the Distributed Energy Storage (DES) principle (where the energy is distributed along the rails) to enhance the efficiency of the railgun system.
The rails of the railguns used in the ISL facilities are usually made of Cu-Cr with an electrical resistivity of 2.5 μΩ·cm. They are mounted into a housing made of glass/carbon wound material or insulated steel plates. We assume a calibre of 80 mm for this application and the inductance gradient is then assumed to be L' = 0.45 μH/m. The schematic view of the rail launcher facility is given Figure 14.

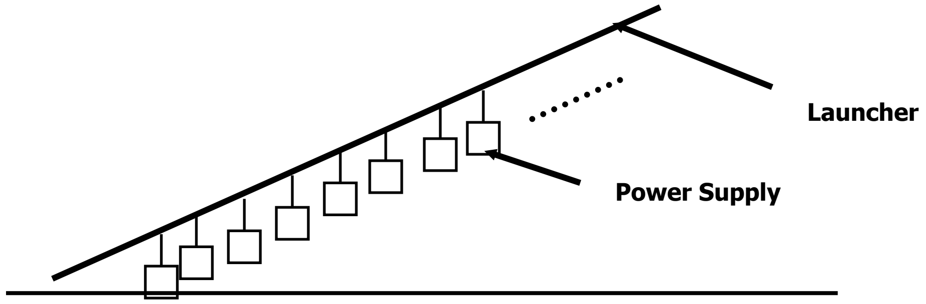


Figure 14 Schematic view of the railgun

The power supply is arranged along the launcher. The distribution of the current injections along the barrel (DES principle) allows a smooth variation of the mean acceleration. The number of the stages (feeding each current injection), the number of modules per stage and the position of the current injections were varied in order to obtain high overall efficiencies. The results presented in this Report are obtained with an energy storage system composed of 80 stages consisting of eight 50-kJ modules each (that means up to 32 MJ stored energy with U_0 = 10.75 kV and 27.7 MJ with U_0 = 10 kV).
Figure 15 to Figure 16 show the time variation of the velocity and acceleration for an 80-stage DES railgun accelerating the projectile. A muzzle velocity up to 2158 m/s corresponding to a kinetic energy of 9.08 MJ with an overall efficiency of about 33% is reached within a length of 22 m (maximum acceleration in the order of 13200 g's) and an acceleration time of 21 ms. The parameters of the railgun are summarized in Table 1.

The analysis of the results presented here shows that the railgun system is feasible based upon today's knowledge and the use of already existing technology. No major issues have been identified which could not be implemented.

∅(mm)	80
l (m)	22
L' (μH/m)	0.45
number of stages	80
number of modules	640
I_{max} (MA)	1.5
I_{mean} (MA)	1.3
duration of the shot (ms)	21
E_c (MJ)	9.1
$E_{electric\ (MJ)}$	27.3
γ (g's)	13200
η(%)	33

Table 1 Parameters of the railgun used in the sub-orbital application

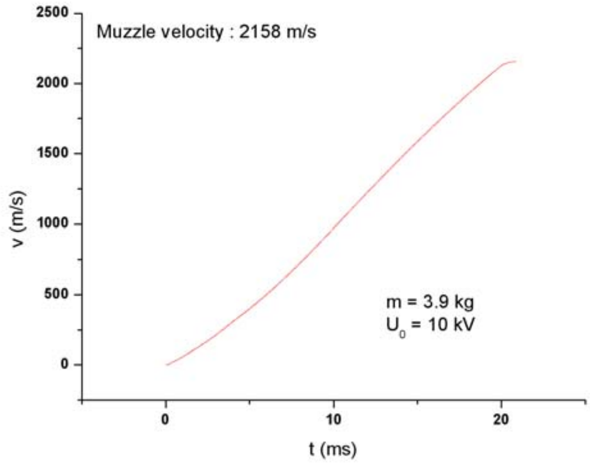


Figure 15 Velocity as a function of time

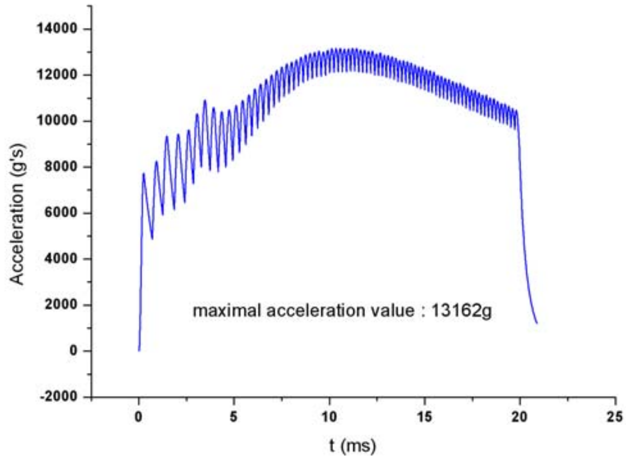


Figure 16 Acceleration as a function of time

2.4 Résumé Suborbital Launch

The main focus of this study was the launch of hypersonic projectiles, accelerated by an electromagnetic railgun, to substitute and compete with small conventional sounding rocket systems.
As a very promising result it could be shown, that with today's state of the art technology it is feasible to develop a projectile accelerated by an electromagnetic railgun to hypersonic speeds (v_o=2100 m/s), carrying along a payload of 0.4 kg to an target altitude of 115 km (see sketch of the proposed projectile in Figure 17).

The current design of the hypersonic projectile guarantees the accommodation of any existing and future meteo-payloads, thus exceeding the capability of any existing conventional small rocket system.
The thermal and mechanical loads acting on the projectile during the initial acceleration and the ballistic flight have been estimated and are considered decent imposing that non-exotic and non-expensive materials may be used for later implementation and production.

The electromagnetic railgun parameters derived are based upon the long-lasting experience in developing and operating electromagnetic railguns at ISL.

The railgun-version required for the launch of a 4kg hypersonic projectile (incl. payload and support structures) is about four-times the current size of the actually Pegasus facility operated at ISL (see Table 2). This result is considered very reasonable.

Figure 17 Proposed hypersonic Projectile

	Barrel Length [m]	Projectile Mass [kg]	V_o [m/s]	Stored Energy [MJ]
ISL Pegasus Facility	6	1	2500	9
Facility for Suborbital Launch	22	4	2158	28

Table 2 Comparison between ISL Pegasus facility and railgun facility for suborbital launch

The projectile will experience a maximum acceleration of about 12,000 g's within a time-period of less than 21 ms.
A market assessment for the presently used small sounding rockets was performed. It shows, that there is a demand (at the given budgets) of about 130 met- or Mini-rocket launches per year. Due to a changed market situation, no serious competition for a newly developed railgun system is expected in the next years.
The envisaged reduction of the launch costs per probe should be significant and will further enhance the competitiveness of the railgun system: the recurring costs of one probe including the supporting equipment like armature and sabot should be in the order of $^{1}/_{4}$ - $^{1}/_{5}$ of the conventional small sounding rockets (see Figure 18).

Keeping in mind the extreme flexibility of the design of the railgun system to cope with future user needs (which cannot be incorporated in any existing small sounding rockets), this system will be easily in the position to compete today's available sounding rocket system in both, price and performance.

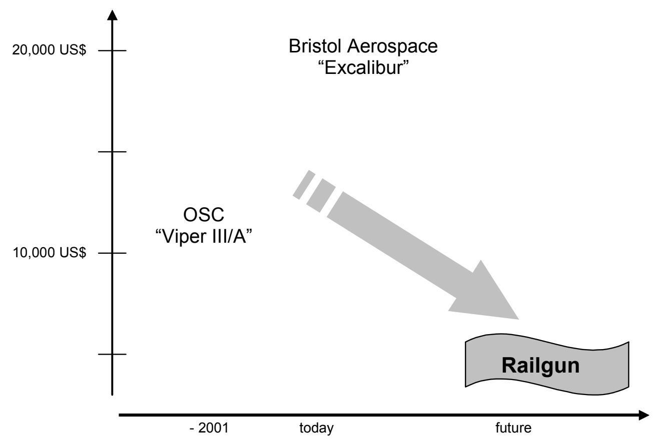


Figure 18 Launch price comparison between conventional small sounding rockets and the Railgun system

3 Reference Mission: Orbital Launch

The main goal of the subsequent work is to continue and expand the field of applications and to identify possible key-technologies and their mutual interactions to verify the use of railgun technology for an even more complex system, namely the launch of small satellites into Low-Earth-Orbit by means of an electromagnetic railgun.

It is shown that launching today small payloads into LEO by means of a railgun system is a realistic goal.

3.1 Nano-Satellite Market

The development for very small satellites has changed drastically; miniaturization of satellites proceeded in the last decades significantly due to new technologies and components.
A new emerging market segment is today concentrating on extremely lightweight satellites, so-called Nano-Satellites with a launch mass in the order of 1 kg.
Stanford University has promoted for the last years a quasi open standard for this new generation of satellites, applicable for science and industry. The design concept foresees a so-called Cubesat, which is a 10-centimetre cube with a launch mass of 1kg.
Such small satellites are low cost technology demonstrators with a wide variety of different applications and a potential source of manifold and original experiments for educational purposes.

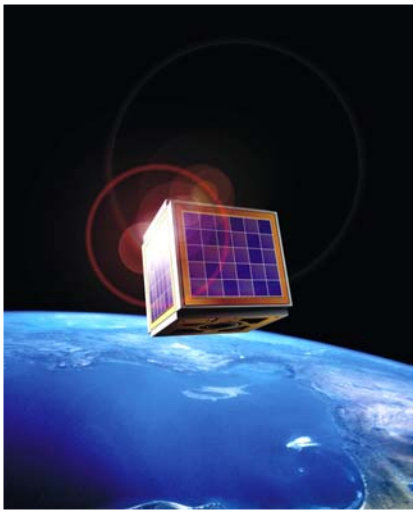


Figure 19 Artists impression of a CubeSat-Satellite

According to a personal communication with Prof. Twiggs, Stanford University, the demand will be at about 100 satellites a year.

Up to now six cubesats have been launched on the most recent Eurockot flight in June 2003 as piggy-backs. Furthermore two Dnepr flights, each with 18 Cubesats as piggy-backs and one OSP Minotaur with 15 Cubesat are scheduled for 2003/04. The satellites are very flexible with respect to orbit altitude and inclination.
The corresponding launch service market for small satellites however is somewhat indifferent:
Up to now no Western launch vehicle exists for a dedicated launch of a single small satellite into Low-Earth-Orbit.
Only two Russian boosters from KB Makeyev, the submarine based Shtil 1N and Volna, were especially used for launches at a price of \$3M and \$1M, respectively.

To assess the size of this launch market segment, price data have been evaluated (Figure 20). It is evident, that for a 1kg satellite a launch-prices between \$190k and \$300k is paid for a piggy-back ride. This gives also a good classification for launch prices onboard any dedicated launch vehicle: It is assumed that a launch price of ~\$250k appears to be acceptable for a dedicated launch in the future.

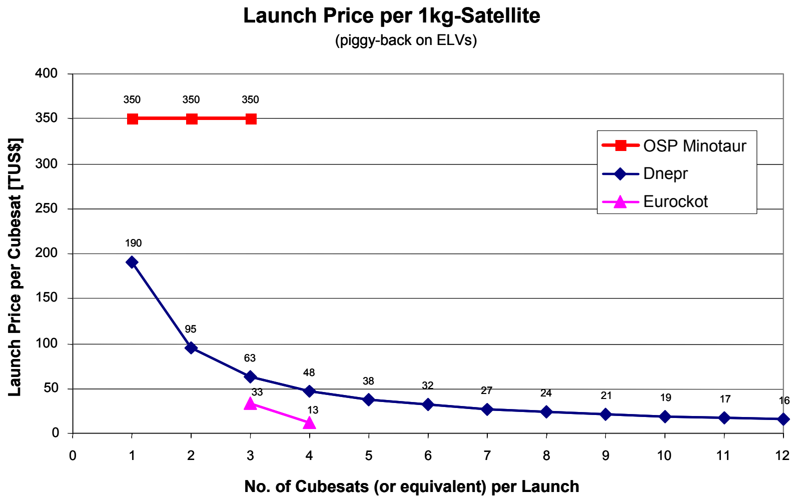


Figure 20 Launch prices for small satellites as piggy-backs

3.2 The Railgun Launch

The present scenario foresees an initial launch of a projectile (120 mm diameter; 42kg mass) with a speed of 6 km/s by an electromagnetic railgun. In order to achieve orbital motion and to compensate the velocity losses due to gravity, a simple rocket engine is integrated into the projectile. Three concurrent propulsions systems are here considered for the rocket engine: solid, liquid and hybrid type. It is shown that hybrid rocket engines are today most promising, because they have a lower total mass, are simpler, cheaper and more reliable.
The aerodynamic form of the projectile is optimized to achieve minimum drag force, which leads to lower heat loads. Launch angles and trajectory analysis are carried out by means of 3 degree of freedom simulations (3DOF). The calculations have been done accounting for two different technology levels on propellants (present, near term), launch altitudes (geographical elevation) and elevation angles of the railgun muzzle.

3.2.1 The Hypersonic Projectile

The objective of the present study is to determine the feasibility of combining a railgun with a single stage rocket projectile as a competitive system for routine access to LEO with 5 kg payloads.
The mission profile is shown in Figure 21. The propelled projectile starts from an electromagnetic accelerator at 6 km/s, i.e. M_a = 17.7. The hypersonic launch velocity is of great advantage because the drag coefficient (c_x) drastically decreases for Mach number Ma ≥ 4. The projectile ignites its rocket motor short before it reaches apogee, which burns for approximately 10 sec, providing the projectile with the additional velocity to insert the payload into orbit.
The above required values of specific impulses can be reduced if the launch site is not located at sea level. The present study indicates a specific impulse reduction rate of about 15 sec for each 2000 m altitude increase.

The flow around the projectile is very complex: viscous, turbulent and fully unsteady. Furthermore, practical experiences or measurements on projectiles at high hypersonic velocities (Ma>15) within dense atmosphere conditions close to sea level are not known. Shortly after the start, real gas effects dominate the flow field.

Areas of high risk damages due to the high temperatures are the tip of the nose cone (where a low or medium ablation is expected), the junction between fuselage and fins and the leading edges of the fins. However, the projectile experiences the maximum heat loads and surface temperature only during the first 10 sec of the flight mission. Indeed, for an elevation angle of the railgun muzzle between 27 - 35 deg. and depending on the aerodynamic properties of the projectile and the launch-geographical altitude, the projectile needs approx. 20 sec to pass through the dense earth atmosphere, the troposphere and stratosphere (Figure 22). After that, the heat loads at the projectile surface sharply decrease.

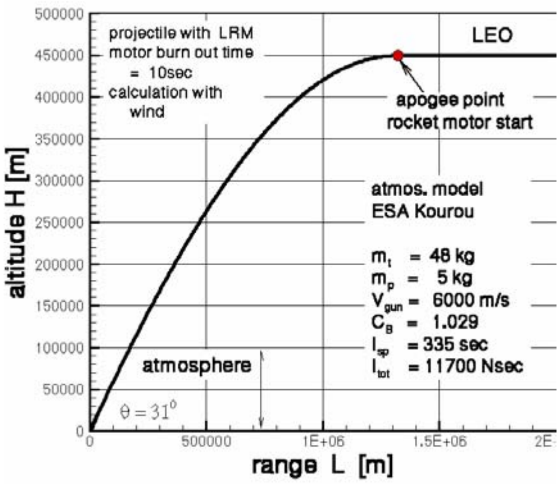


Figure 21 Propelled projectile mission profile

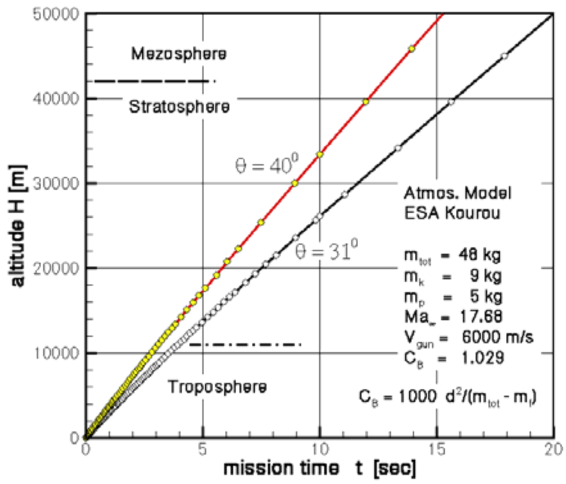


Figure 22 Propelled projectile flight time mission

According to the above considerations the critical case for the dimensioning loads (thermal and mechanical) are shortly after the mission start, at about 0.01sec flight time. Simulations of the 3D flow around the projectile configuration for such conditions are here done with the DLR Navier-Stokes code TAU.

Figure 23 displays a typical grid used for the present study. The simulation conditions are Ma = 17.69, zero angle of attack, 300 m altitude. The figure displays through contours of constant Mach number, a strong bow shock in the nose area, a thin boundary layer along the body and a recirculation zone at the boat tail. Also, in all mentioned zones is to recognize strong velocity gradients due to the strong energy dissipation which induce high local heat loads on the projectile surface.

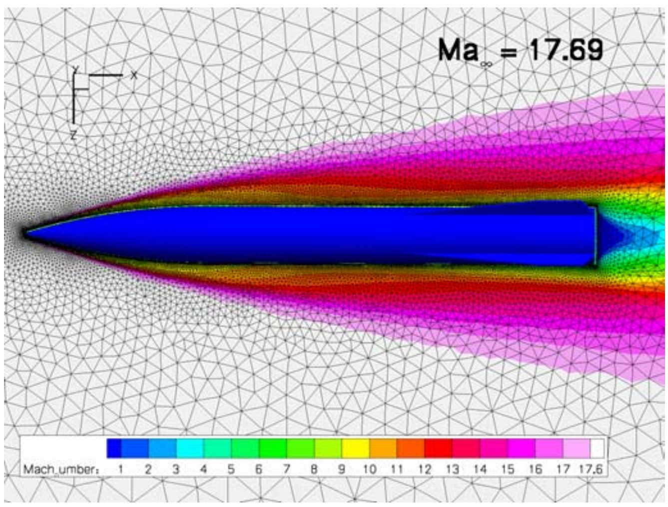


Figure 23 Mach number contours around the propelled projectile. Unstructured Navier-Stokes grid with 3.7 million points (second adaptation)

The computed surface temperature distribution shows (Figure 25) that the hottest locations are the tip of the nose cone, approx. 2900 K, and the fins leading edges, approx. 1700 K, calculated for steady conditions

The pressure distribution presented in Figure 24 shows a strong pressure load at the tip of the nose cone of the projectile. Assuming a 2 mm nose radius, the resulting absolute pressure value is 21.42 10^6 N/m^2. However, short downstream the pressure drops to 3.2 10^6 N/m^2 and further downstream to 0.3 10^6 N/m^2.

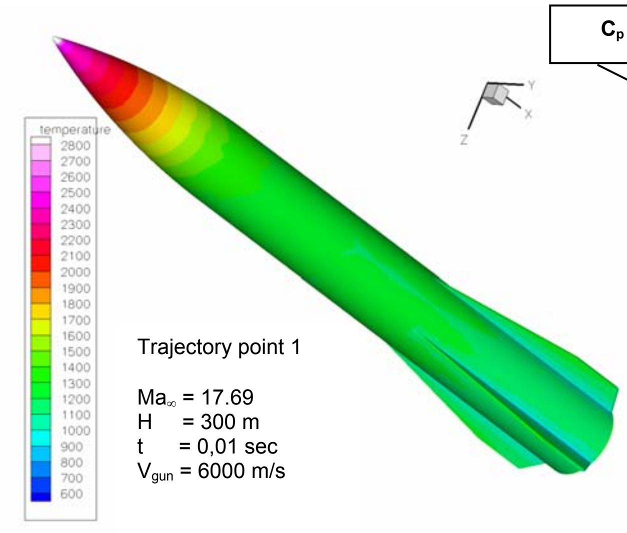


Figure 25 Propelled projectile surface temperature distribution

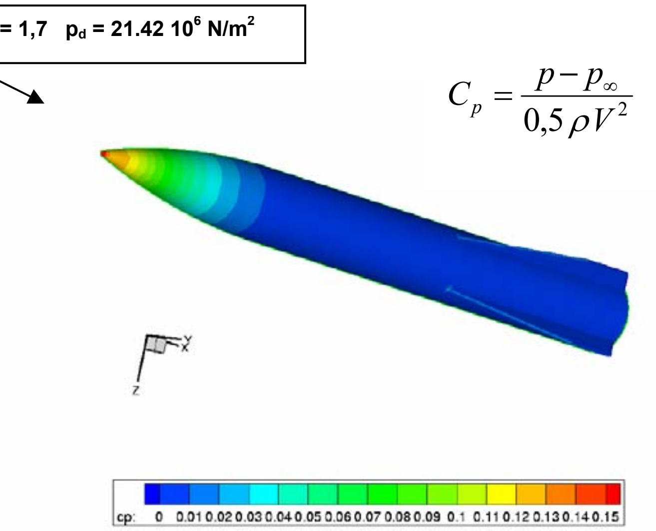


Figure 24 Propelled projectile surface pressure distribution

Three different types of propulsion systems, solid, liquid and hybrid (combined solid fuel – liquid oxidizer) can be considered as potential candidates for the propelled projectile. However, solid propellants are rapidly excluded since they do not provide high specific impulses as required by the mission and also they present high security concerns with respect to propellant shear strength and crack risks due to the high acceleration at launch.

In a second step two different propelled projectiles are compared, one based on liquid bipropellant H_2O_2/kerosene (see Figure 26) and the other one based on a hybrid propellant H_2O_2/wax (Figure 27).

For both systems a selection has been made for a simple pressure feeding system on the basis of helium as a working gas, a simple control and condition monitoring system, a combustion chamber with short burning time (approx. 10 sec) and a carbon based ablation cooling system and finally an ablation cooled plug (aerospike) nozzle.

Also, a high integration level of all components is proposed which is accomplished mainly by carbon fiber based composite technology. Beside the plug nozzle, the liquid rocket motor (LRM) features a catalytic bed for H_2O_2 vaporization into high temperature oxygen rich steam. Additives containing salts of transition metals (catalyst) and combustible organic compounds (promoter) added to kerosene make liquid bipropellant hypergolic.

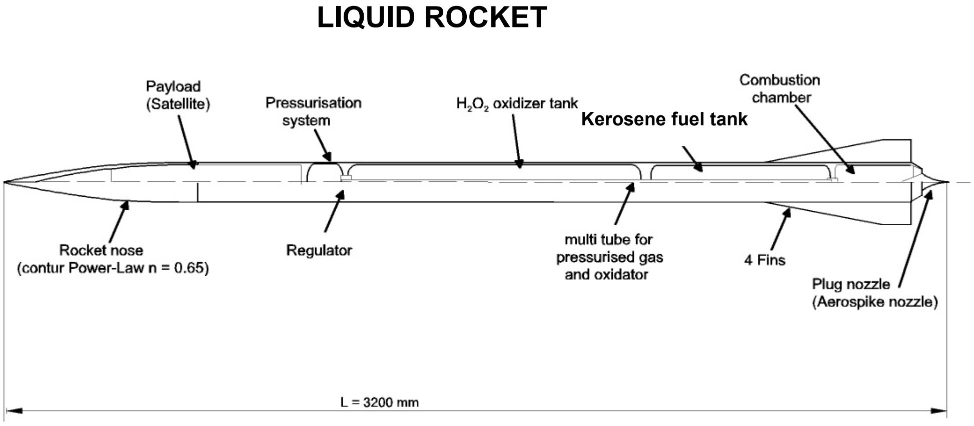


Figure 26 Concept of Propelled Orbital Payloads Projectile with liquid rocket motor

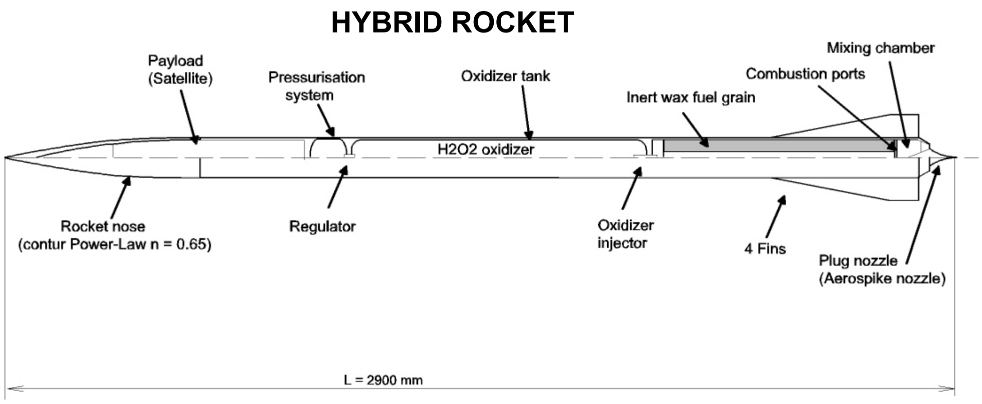


Figure 27 Concept of Propelled Orbital Payloads Projectile with hybrid rocket motor

The comparison is carried out with a dedicated computer code which calculates at first the mass and the energy balances for each projectile, defines the combustion properties and finally delivers the main dimensions and weights of the system elements.
For the selected concepts it turns out that the weight of a propelled projectile with a hybrid rocket motor and a 5kg payload is about 41 kg while for a liquid rocket motor and a same payload weight it is about 46 kg. However, a hybrid rocket motor (HRM) based on hydrogen peroxide H_2O_2/wax propellant has more advantages:

Hybrid rocket motors are in comparison with a LRM, based on liquid bipropellant H_2O_2/kerosene lighter. Indeed a HRM has no fuel tank since it is integrated in the combustion chamber. Also the injector, propellant valving, piping and tanks venting are simpler and lighter. Furthermore a HRM has a lower number of components and lower production cost.

Although LRMs which use hydrogen peroxide/kerosene propellants show lower performances compared to hybrid rocket motor, they ought not to be excluded from further considerations. Liquid rocket motors have in general a significant development potential in future, as well as in applications combined with railgun concepts. Some other fuels on hydrocarbon basis, for instance propylene, methylacethylene, UDMH combined with hydrogen peroxide can be concurrent to the here proposed hybrid rocket motor. However, the security aspects are a clear advantage of the hybrid rocket motors.

3.2.2 Railgun Characteristics

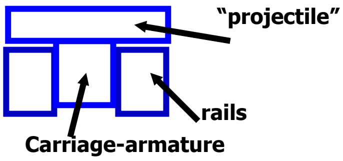
As for the suborbital mission the mass of the total accelerated package was determined to assess the railgun parameters. In a first and rough approximation it was assumed that the sabot-armature will represent a third of the total mass of the accelerated object that means a mass of about 20 kg. This allows to determine the current needed to accelerate the projectile, the length of the railgun tube, the shot duration and the kinetic energy of the projectile. The numerical values for the nano-satellite application are given in Table 3.

I (MA)	5 - 6
l (m)	180
t (ms)	60
E_c (GJ)	1.12

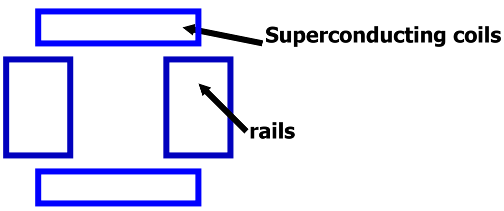
Table 3 Parameters of the railgun used in the orbital application

In the case of the nano-satellite application the first calculations where based on the use of a classical railgun like those studied for military applications at ISL where the magnetic field is only created by the current flowing through the rails. The design of the projectile is not optimised for "satellite launching" and consequently the current intensities are too large.
To launch satellites several other possibilities could be studied for further improvements:

- appropriate rail-projectile design like the principle of carriage armature:



- external field applied to the railgun to reduce the current flowing through the armature:



3.3 Résumé Orbital Launch

Based upon the first assessments performed in the frame of this study, a launch system for small payloads into LEO is considered as a realistic option today, using an electromagnetic railgun and an additional propelled stage as part of a hypersonic projectile.
The present study could demonstrate that there are no marked critical problems or processes, which cannot be solved with today's technology and expertise. Future developments should furthermore contribute to a reduction of total rocket mass and to the increase of the payload mass.

The possible scenario may be such that a 120mm diameter projectile will be accelerated by a railgun to high hypersonic velocities (Ma>15).
The projectile launch mass is estimated to be >40kg, incorporating an additional small liquid or hybrid rocket motor for a later 10sec circularization burn of the payload. Solid motors have been discarded for any further in-depth analysis because of safety considerations and their small specific impulse, which is too small. The payload itself (maximum 5kg) is being encapsulated by the projectile and will serve the new emerging market of nano-satellites. Figure 28 presents a first layout of a propelled projectile on the basis of a hybrid rocket motor.
The elevation angle of the railgun muzzle is calculated to be relatively flat at about 30 deg. Although it enhances the flight time in the Earth's atmosphere, it optimizes the entire mission trajectory.
The projectile experiences the maximum heat loads and surface temperature mainly during the first 10 sec of the flight mission. However, sophisticated materials already available today for the thermal protection system should enable the projectile to withstand the envisaged high temperatures and high shocks. An advantage will be to use a launch range at high altitudes (>4000m) to reduce significantly the losses induces by the very dense atmosphere.

A first evaluation of the railgun parameters has shown that a 180 m long railgun should be in the position to launch a nano-satellite into LEO.
Further improvements, for instance using superconductors, advance projectile-armature design etc. should lead to a more optimized overall system design.

Figure 28 Propelled orbital payloads projectile layout – optimised configuration

4 Tentative Development Plan / Next Steps

Although the results of this study for both, suborbital and orbital launch of payloads by means of an electromagnetic railgun, look very promising, it is considered appropriate to include an intermediate step for in-depth work on possible critical technical items before finally implementing this project.
The first operational implementation of the railgun is envisaged to cover applications in the fields of small sounding rockets with a possible extension to higher payload masses and higher altitude ranges. Based upon the experience gained by operating such a railgun, the second implementation step, namely the large railgun to launch small satellites into LEO, is planned. A corresponding, tentative project plan is shown in Figure 29.

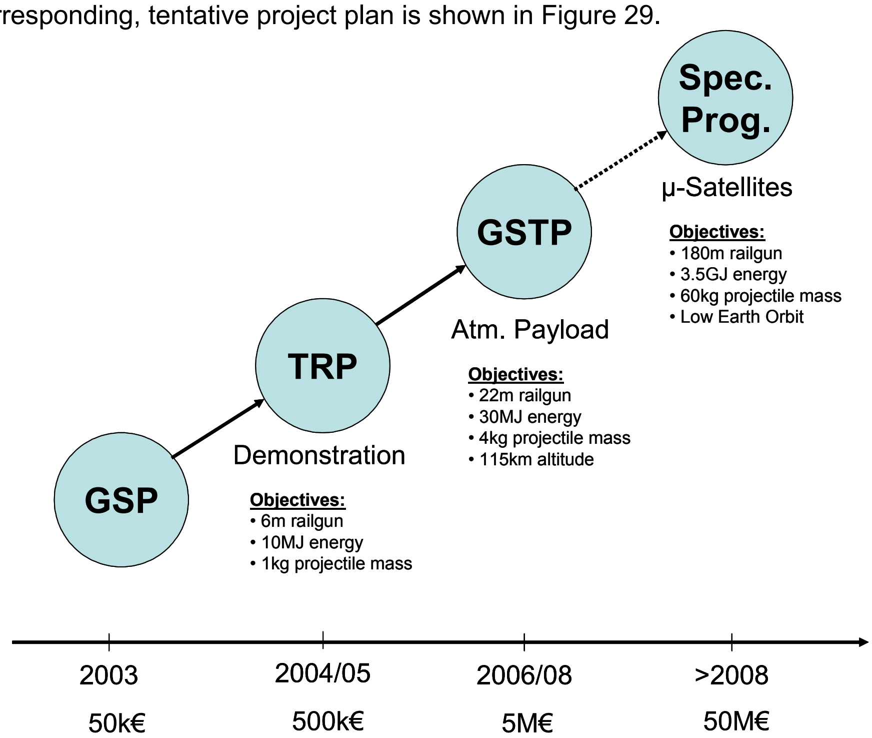


Figure 29 Tentative development plan

The timeframe for an intermediate step, named demonstration mission, should last for 1-2 years followed by an implementation phase in the same order for the suborbital launch. It is important to note, that there is a strong growing demand by the scientists to get future access to the middle atmosphere (~120km altitude), because of identified severe supply problems of the conventional boosters. Therefore the entire project implementation should be kept as short as possible to enter this market segment of sounding rockets with a competitive substituting product.

The cost figures given in Figure 29 reflect a first very rough estimate for developing the complete system, based on the assumption of a 22m long rail-gun barrel and the known capacitor-bank costs. The length of the barrel however is subject to change corresponding to a later approved system layout and given acceleration limits. These data have to be confirmed.
Envisaged non-recurring costs for developing the entire system are assumed to be in the order of 5-6M€, taking into account the:

- Engineering costs for the entire system
- Railgun incl. capacitor bank and switching system
- Engineering costs for the enhancement of the railgun to the envisaged length
- Engineering costs for the hypersonic projectile incl. payload accommodation/release