Space launchers systems

Satellite design & engineering

A. SQUELARD

Objectives of this module

- The launch of a satellite is the first unavoidable phase of its operational life.
- The objective of this short course is to give an overview of the technical challenges that must be met to launch a satellite, the technologies used to solve them, and the different steps for the preparation of a satellite launch.
- This presentation will deal primarily with Ariane 5; some data are still confidential, because Ariane 5 is a commercially operational launcher.

  - Several figures come from the Launcher Course given by CNES

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1. The space launchers : overview

The launchers in the world

Some magnitudes

Staging

Trajectory

Heavy launchers in the U.S. and Europe

European launcher.
Cryogenic core
stages + boosters
109 flights

U.S. government missions.
Cryogenic core stages + 2/4
boosters. 40 flights

U.S. government missions only.
LOX/RP1 core stage (russian engines
RD-180 + 1 to 5 boosters. 85 flights

Low-cost design. Commercial
and government missions. 92
flights. Falcon Heavy version
with 3 first stages in parallel.
First stage recoverable

Heavy launchers in Russia

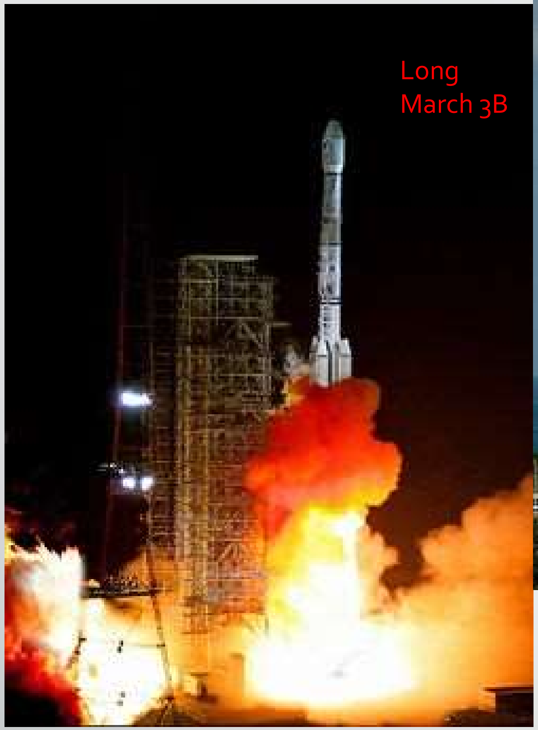
Russian workhorse : more than 1900 launches with several versions.
Soyuz is launched from Plesetsk, Baïkonur and Kourou.

Older design to be replaced by Angara 5, but delayed for unknown reasons.

Launched from an equatorial floating platform. Operational deployment difficult
The future of this launcher is pessimistic due to its Ukrainian/Russian composition. Last flight in 2017 from Baikonur

Only one (successful) flight in 2014

Heavy launchers in the rest of the world



China

Japan
Cryogenic core stages
+ 2 SRB. Expensive.

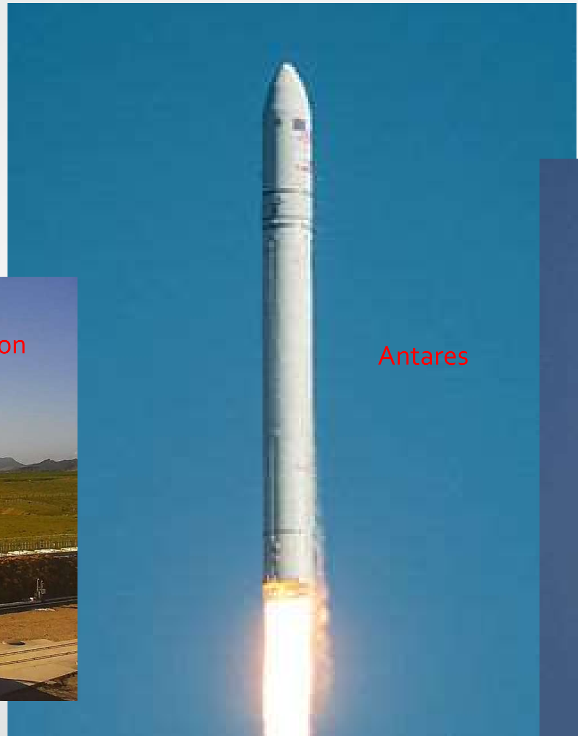
India

China : replaces LM-2F. Five flights (one failure in 2017)

Small launchers with liquid or mixed liquid/solid propulsion

Indian small launcher : solid and liquid stages. 50 flights with 3 failures.

Designed by a private company (RocketLab) (New-Zealand) – 14 launches / 2 failures
Electric-powered turbopumps



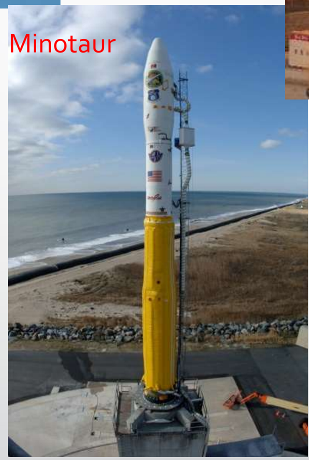
1st stage liquid; 2nd stage solid.
12 flights; catastrophic failure on October 2014 followed by complete redesign

First flight in 2015. First Chinese launcher to use LOX/kerosene. 2nd flight in 2017

Small launchers with solid propulsion

European launcher, mainly Italian with significant contributions from France, Belgium.
15 flights, 1 failure

U.S. air-launched launcher.
44 flights, 5 failures



U.S. small launcher, derived from military missiles. Comparable to Vega.

First Chinese solid propellant launcher; 9 successful flights , 7 in SSO

Small launchers with solid propulsion (cont'd)

Chinese launcher derived from military missile. 12 flights – 1 failure

Air-launched small launcher : maiden flight end of this year

Indian small launcher : maiden flight end of this year

ARIANE 6

Replacement for Ariane 5 – First flight in Q3 2021

- Reasons for replacement :
  - Ariane 5 not flexible (only 1 version)
  - Profitable only with two payloads
  - Upper stage not re-ignitable
  - Expensive (developed for HERMES) and therefore not profitable anymore compared with SpaceX launchers

- 2 versions : 2 or 4 boosters
- Upper stage with Vinci engine : can be re-ignited several times : many more missions are possible, and can push the stage out of orbit to « clean » the orbit

Some magnitudes (Ariane 5)

- 1 minute after lift-off: 500 T faster than a rifle bullet (400 m/s)
- 2 minutes after lift-off : 7 200 km/h
- Equivalent power at lift-off: 17 GW
- LH_2 turbo pump : same power as 2 high-speed trains; empties a bathtub in 50 ms.
- Over 40 cm, the temperatures vary from -250 C to 3 000 C
- The tanks volume is comparable to a swimming pool of 25 meters.

- All this leads to problems of development, safety and infrastructures.

Comparison with other systems

- No full scale tests are possible : engines operation in the vacuum, thermal environment, variable acceleration, acoustics at lift-off, dynamic structural response.
- Fully automatic flight with an injection accuracy of 10 km over 36000 (GTO apogee), and satellite attitude < 0.1° and 0.1°/s.
- Ratio [payload / propellant mass] of 1/100 (1/2 for an airplane)
- Cost aspect :6€ / gram in GTO orbit (pure gold : 40 to 50 € / gram)

Primary mission of a launcher

- To send a satellite weighing a few tons to an accurate point in space, with a velocity of 7 to 8 km/s, and a precise velocity vector.
- These magnitudes come to the edge of what is physically or technically possible

Performance

- Theory reminder : the propulsive ΔV.
    - $\Delta V_p = \int_i^f \Gamma_p \, dt = \int_i^f \frac{F_p}{m} dt$

  With Γ_p = the propulsive acceleration, F_p the propulsive force.
- We have also :
- $F_p = q \; g_0 I_{sp}$; $m = Mi - q(t - t_0)$; $q = -\frac{dm}{dt}$, and after a few calculations :

- $\Delta V_p = -\int_i^f g_0 \, I_{sp} \frac{dm}{m} = \; g_0 I_{sp} ln \frac{M_i}{M_f}$

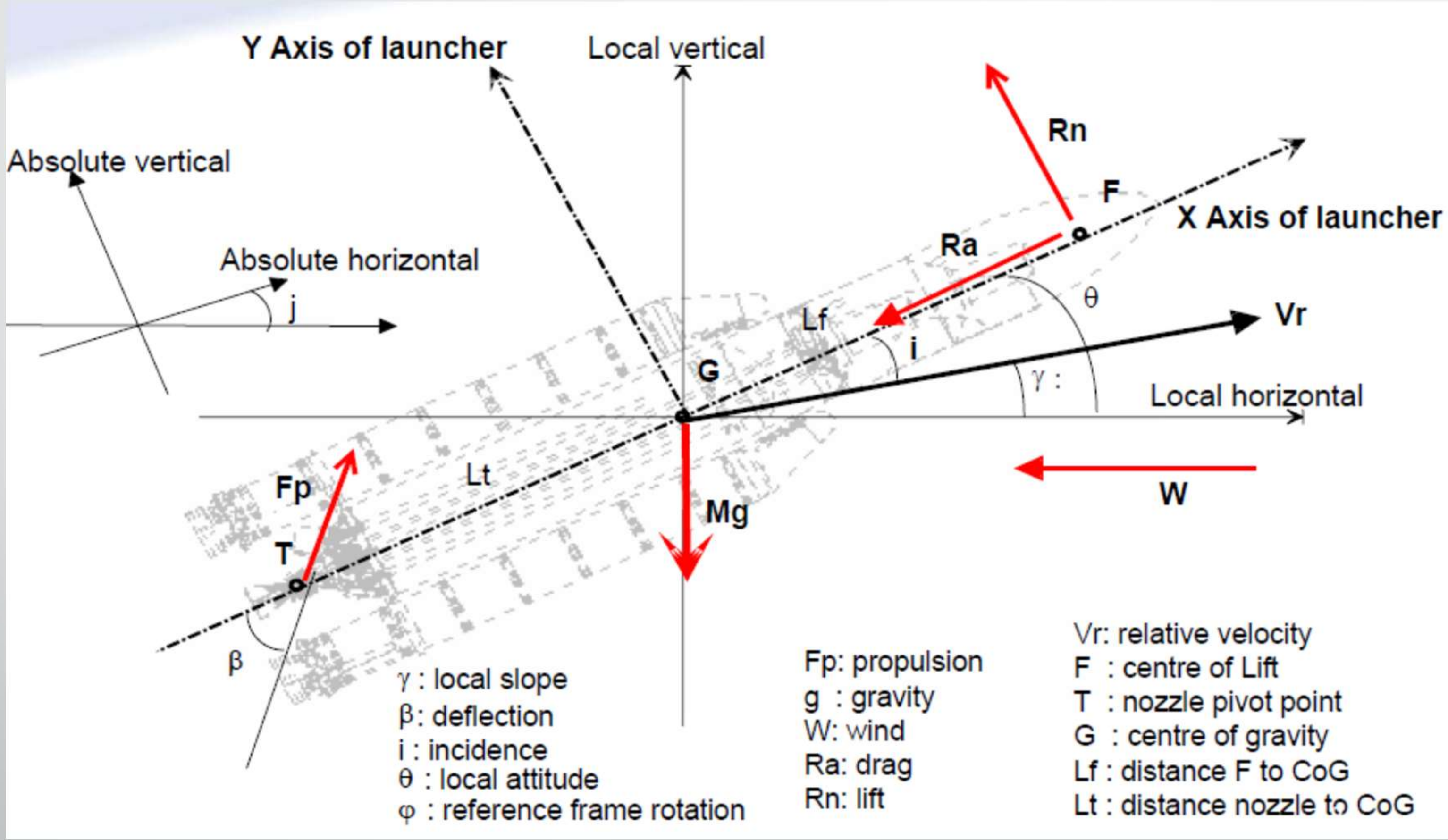
I_{sp} : Specific impulse (s) : ratio between propellant weight flow and thrust

q : propellant mass flow (kg/s)

g_o : gravity acceleration (m s^{-2})

M_i and M_f : initial and final mass of launcher

Overview of the forces acting on the launcher



$$\int_i^f \frac{dV}{dt}dt = \int_i^f \frac{F_p}{m}dt - \int_i^f \frac{F_p}{m}(1-\cos(i+\beta))dt - \int_i^f \frac{R_a}{m}\cos i\,dt - \int_i^f \frac{R_n}{m}\sin i\,dt - \int_i^f g\sin\gamma\,dt$$

Incidence and piloting — Drag — Lift — Gravity

Together, all these losses amount to 20% of the theoretical velocity increase.

$$V_f - V_i = \Delta V_p - losses$$

Losses	Incidence and piloting	Drag	Lift	Gravity
Approximate amount on A5ECA GTO	710 m/s	160 m/s	Practically zero	1 260 m/s

Staging

	LEO	GTO	ESCAPE
V_f	7 500 m/s	10 000 m/s	11 300 m/s
ΔV_p	9 000 m/s	12 000 m/s	13 500 m/s

For a one-stage launcher, introducing $k = M_s/M_e$

[M_s = structural mass, M_e = stage total mass],

$$\Delta V_{max} = g_0 I_{sp} \ln \frac{1+k}{k}$$

(limiting case : payload mass = 0 kg !)

By using present technologies, at a reasonable production cost, one can obtain k = 0.12 ($\mu = M_i/M_f = 8.3$)

Staging

	Required Mass Ratio		
Delta V (km/s)		Isp=310s	Isp=420s
7		9.99	5.47
8		13.88	6.97
9		19.29	8.88
9.5		22.73	10.03
10		26.80	11.33
11		37.23	14.44
12		51.72	18.40
Max possible		16.67	8.33

Today, to launch a satellite of several tons with a single-stage launcher is very difficult.

The solution : the multi-stage launcher

Staging : the multi-stage launcher

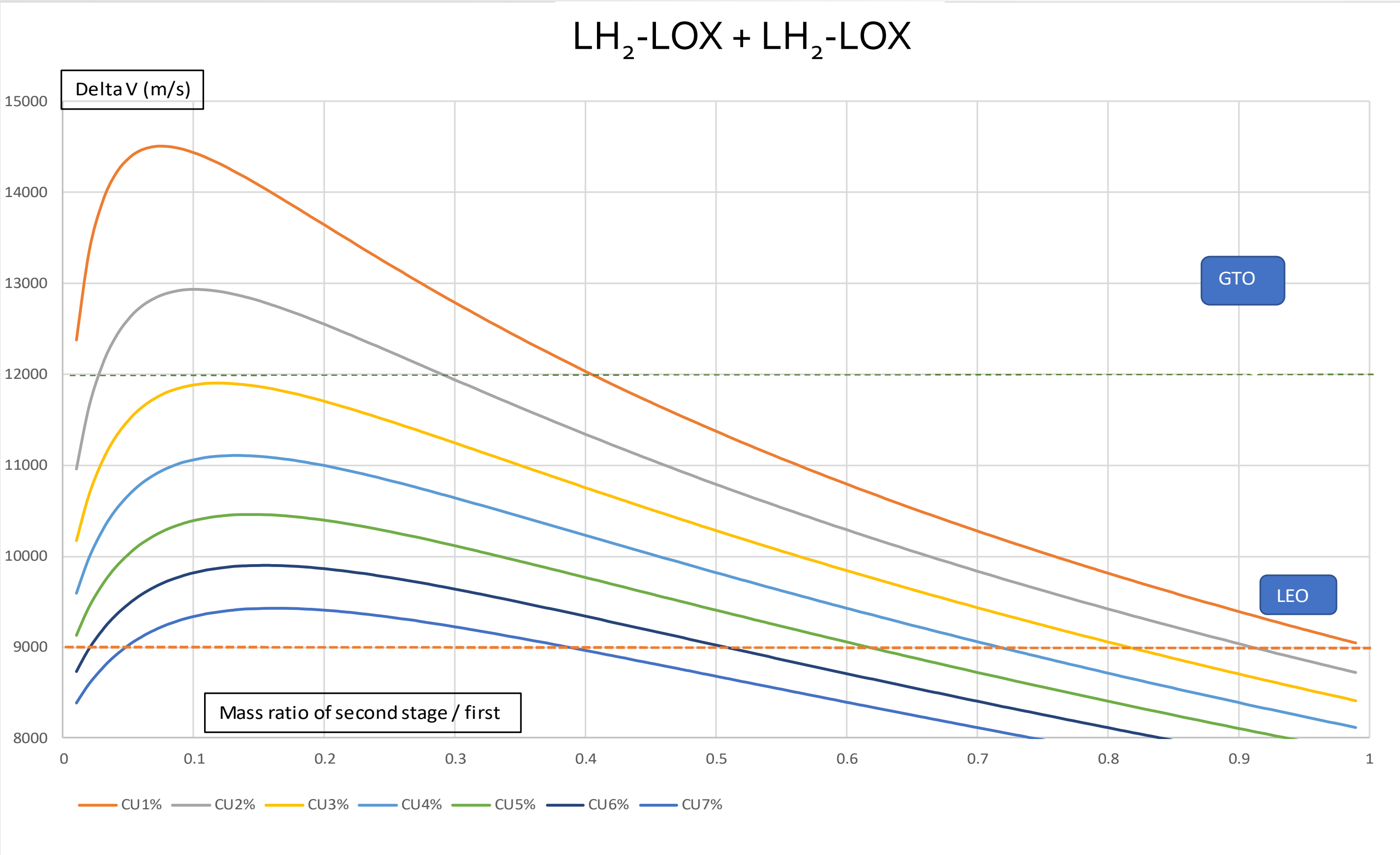
- The staging optimization is a complex parametric study.

Example (simplified) : two-stages to orbit

$$\Delta V = g_0 \, . \, I_{sp1} \, . \ln\left(\frac{M_T}{M_{S1} + M_2 + M_U}\right) + g_0 \, . \, I_{sp2} \, . \ln\left(\frac{M_2 + M_U}{M_{S2} + M_U}\right)$$

With M_T = Total initial mass, M_{S1}= structural mass of first stage, M_2= total mass of 2[nd] stage, M_U= payload mass, and M_{S2} = structural mass of 2[nd] stage.

Cryogenic dual-stage launcher

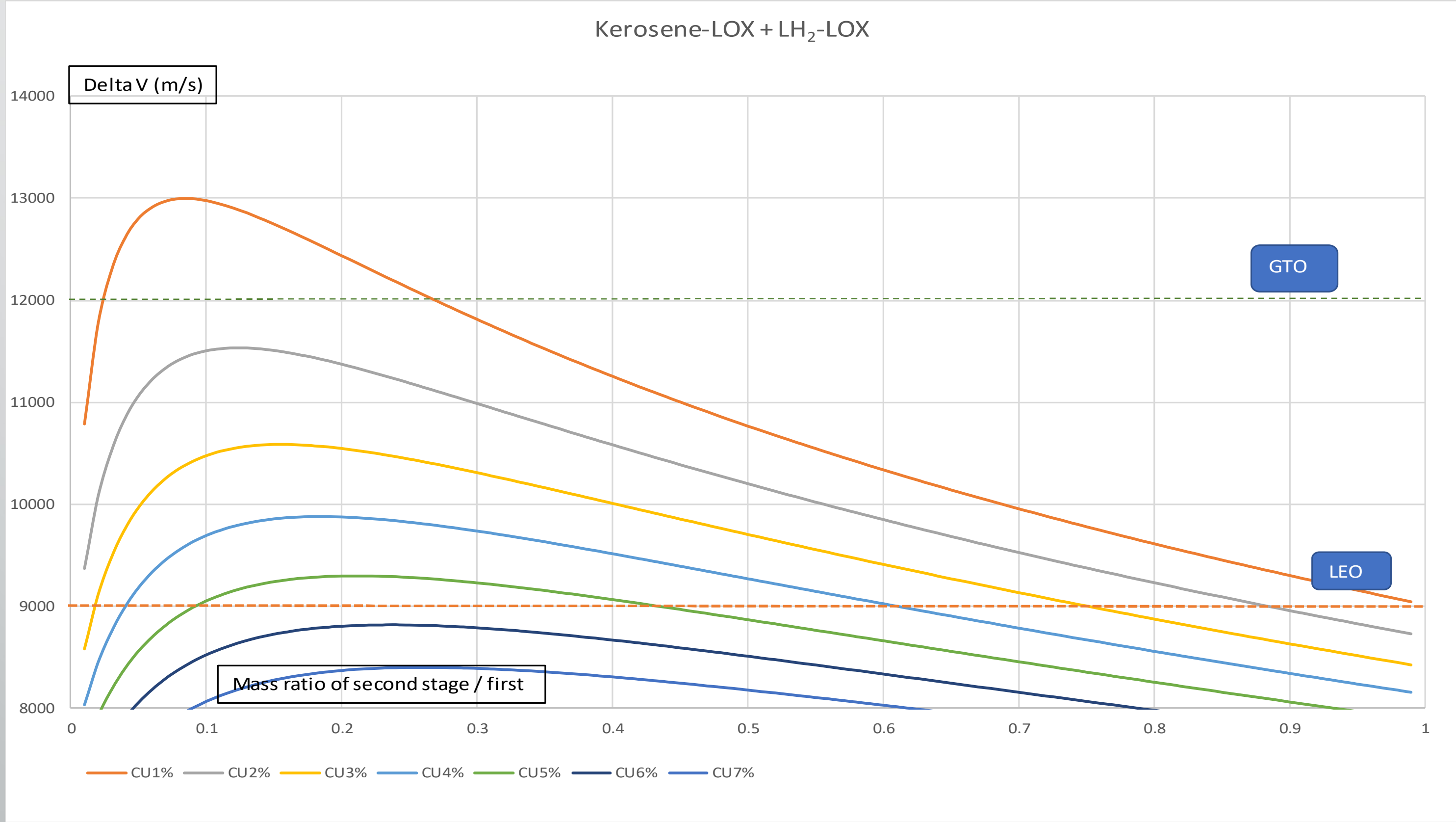


$I_{sp1} = I_{sp2} = 450$ s

$\varepsilon_1 = 0.09$

$\varepsilon_2 = 0.12$

Hybrid dual-stage launcher



I_{sp2} = 450 s

I_{sp} = 330 s

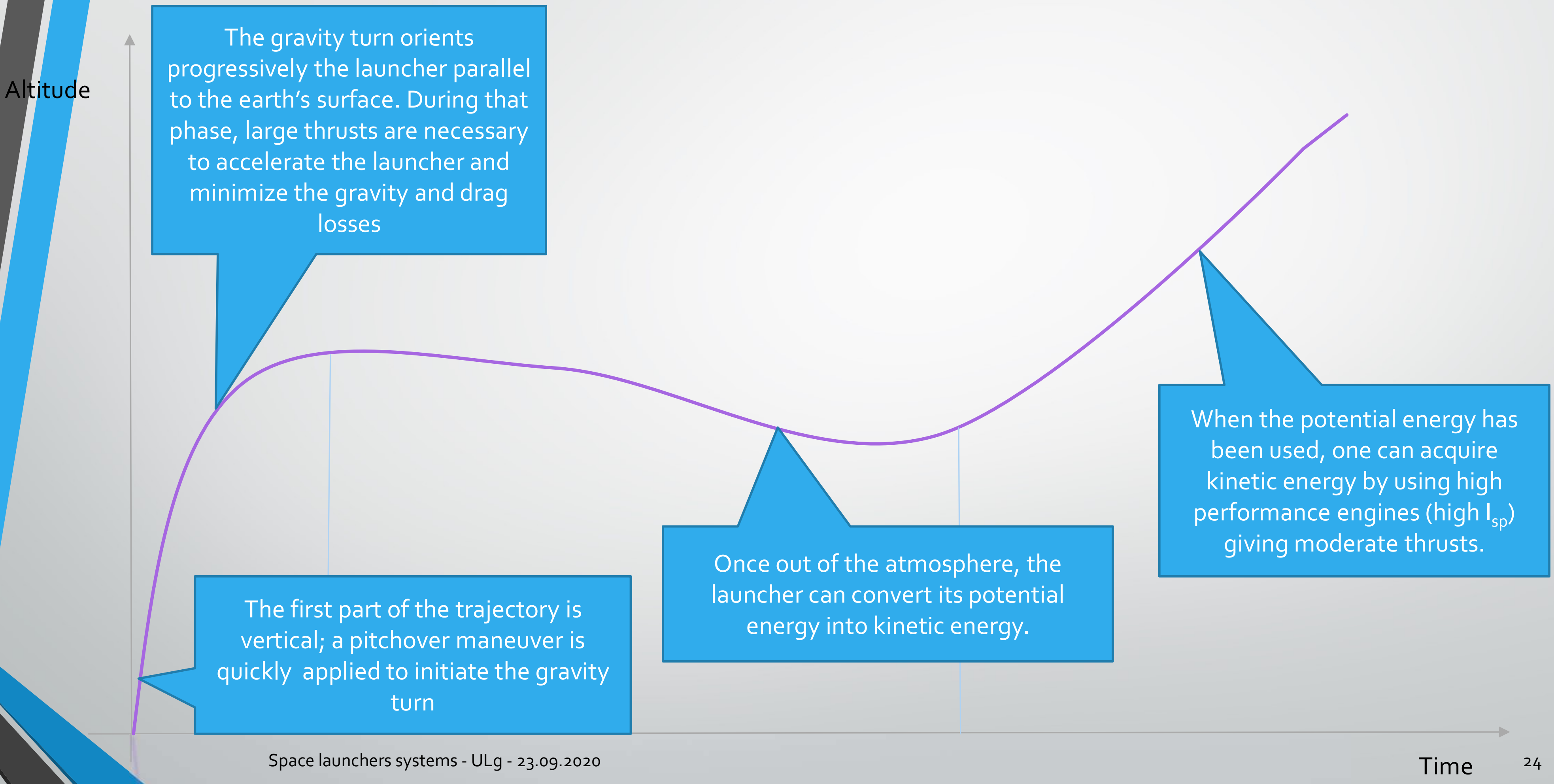
ε_1 = 0.06

ε_2 = 0.12

The trajectory : gravity turn

- The gravity turn is the trajectory of a vehicle that uses only gravity for steering.
  - 1st advantage is that the thrust is used only to accelerate the vehicle
  - 2nd advantage is that the vehicle maintains zero or very low angle of attack. This minimizes the aerodynamic transverse loads onto the launcher.
- If we neglect the air resistance, the flight equations become :
- $m\frac{d\vec{v}}{dt} = \vec{F} - m\vec{g}$, and by projecting on axes // and ⊥ to the velocity vector :
- $\dot{v} = g(n - \cos\beta)$, and $v\dot{\beta} = g\ \sin\beta$, where n = F/mg and β is the angle between the vertical and the velocity vector.
- These equations are non linear and m and F are complex variables as functions of time. These must consequently be solved numerically.

Launcher trajectory logic



Limitations on the trajectory of a launcher

- The first phase of the flight is a vertical trajectory (to avoid collision with the launch infrastructures)
- After the pitchover maneuver in the plan of the targeted azimuth, the flight in the atmosphere is performed with zero incidence to minimize the transversal loads.
- The time and the amplitude of the pitchover are a compromise between max q and performance.
- The velocity increases and we are rapidly limited by the mechanical loads ($q = ½ \rho V^2$) and thermal loads ($\Phi = C_q \rho^{0.5} V^{3.15}$)
- The debris fall back area in the case of launcher neutralization determines limitations in the vertical/horizontal planes.
- The nominal used stages fall back area must occur in uninhabited areas.
- We are also constrained by the visibility of downrange telemetry stations.

Why launch from a point near the equator ?

$$V_i = \boxed{\Omega\, R_t\, \cos(Lat)}\, \sin Az$$

Earth velocity at lift-off point

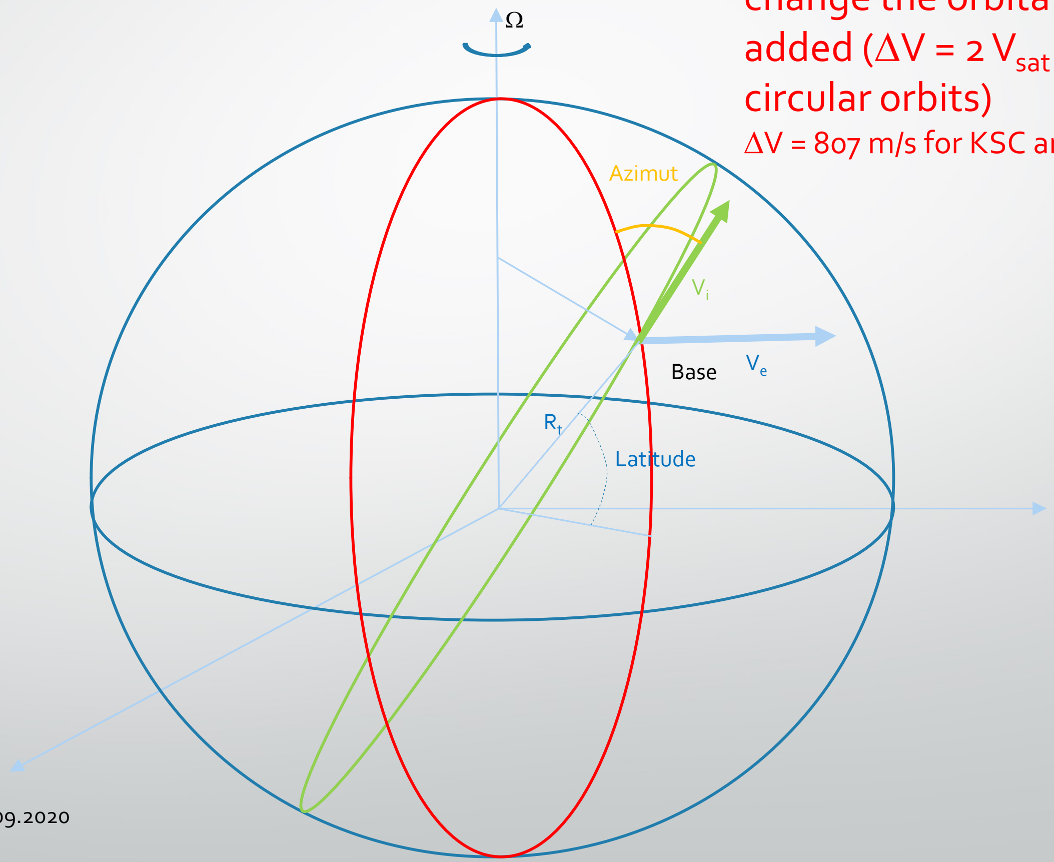
The optimal (and minimal) inclination angle is equal to the latitude of the launch base.

BASE	Latitude	V_e (m/s)	V_i (optimal azimut)
KOUROU	5.23	463	461.07
KSC	28.50	409	359.44
BAÏKONUR	45.00	329	232.64

For polar orbits (Az = 0°), the associated gain is non-existant

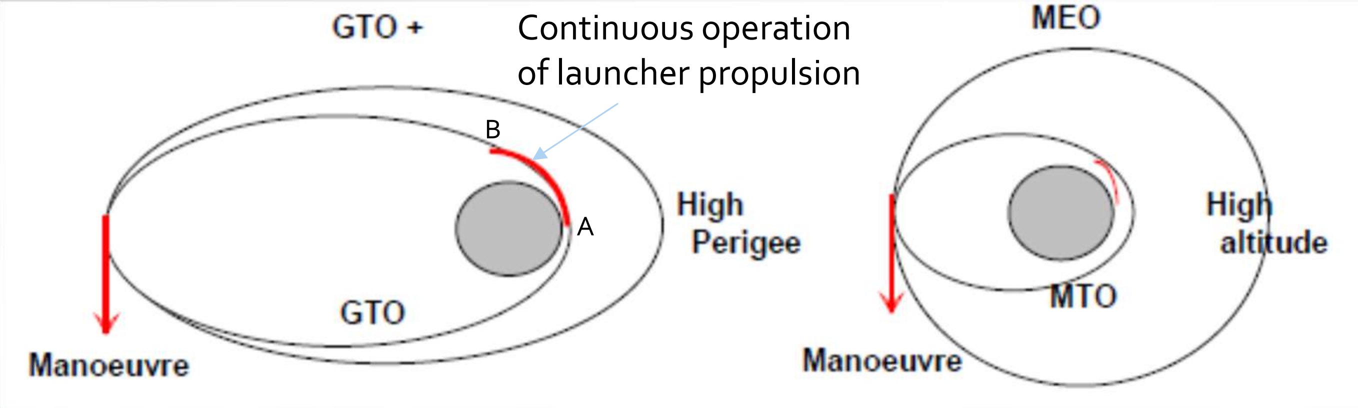
If the satellite has to reach the equatorial orbit, the energy to change the orbital plane must be added ($\Delta V = 2\, V_{sat} \sin(\Delta i/2)$ for circular orbits)

ΔV = 807 m/s for KSC and 1255 m/s for BKN



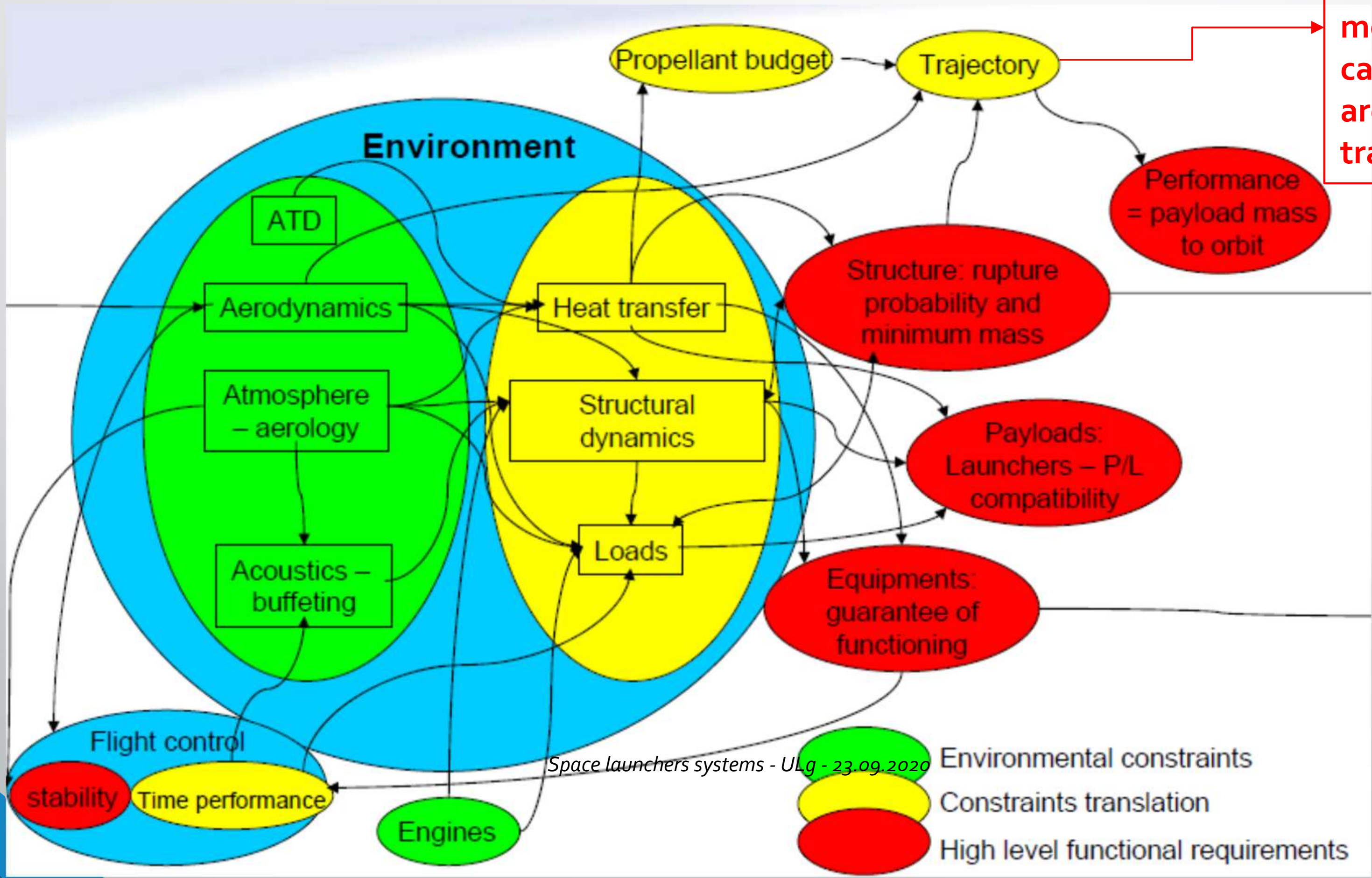
Why are the re-ignitable engines required?

- Objective : to obtain higher perigee altitudes, in order to decrease or even delete the propulsive requirements for the satellite's propulsive system, or to circularize the satellite orbit (for example, the GPS satellites).



To render these maneuvers possible requires the use of re-ignitable engines or an additional stage.

The trajectory is a small part of the launcher development



All the launcher subsystems are interdependant : a modification in one area can influence many other areas, including the trajectory

2. The main systems of a satellite launcher

Propulsion

Navigation

Guidance

Steering

Flight sequencing

Telemetry

Flight Safety

The functions of a launcher

- To give the satellite a sufficient ΔV (propulsive function)
- To put the satellite on the targeted orbit (guidance, steering, navigation functions)
- To ensure the correct sequencing of the different flight phases, and of the stages separations (flight sequencing function).
- To give the launcher and satellite health status (telemetry function)
- To guarantee the integrity and safety of the ground infrastructures and of the overflown areas (flight safety function)

The propulsion

- Solid propulsion
  - High thrusts
  - Easy implementation
  - Low I_{sp}
  - Used primarily for lift-off and atmospheric flight

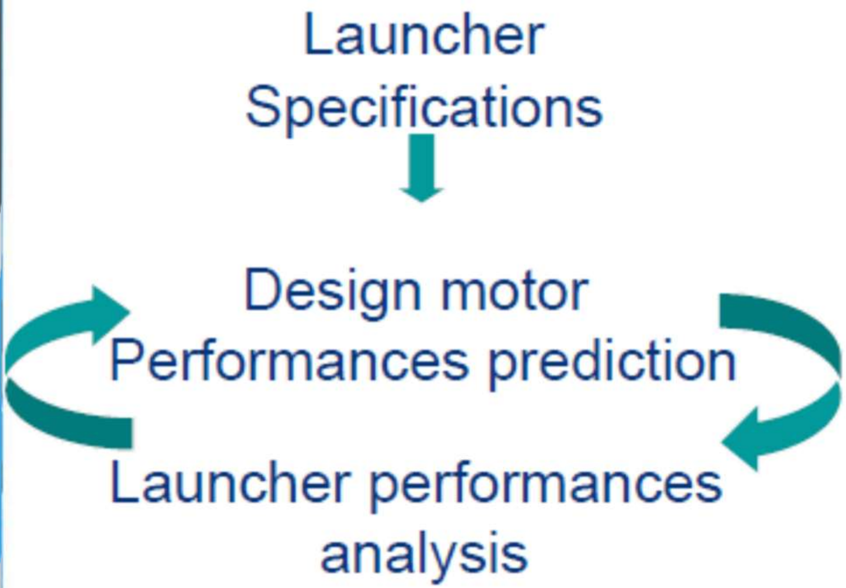
- Cryogenic liquid propulsion
  - Low to moderate thrusts
  - Complex implementation
  - High I_{sp}
  - Used primarily for exo-atmospheric flight (but can be ignited on the ground for reliability reasons)

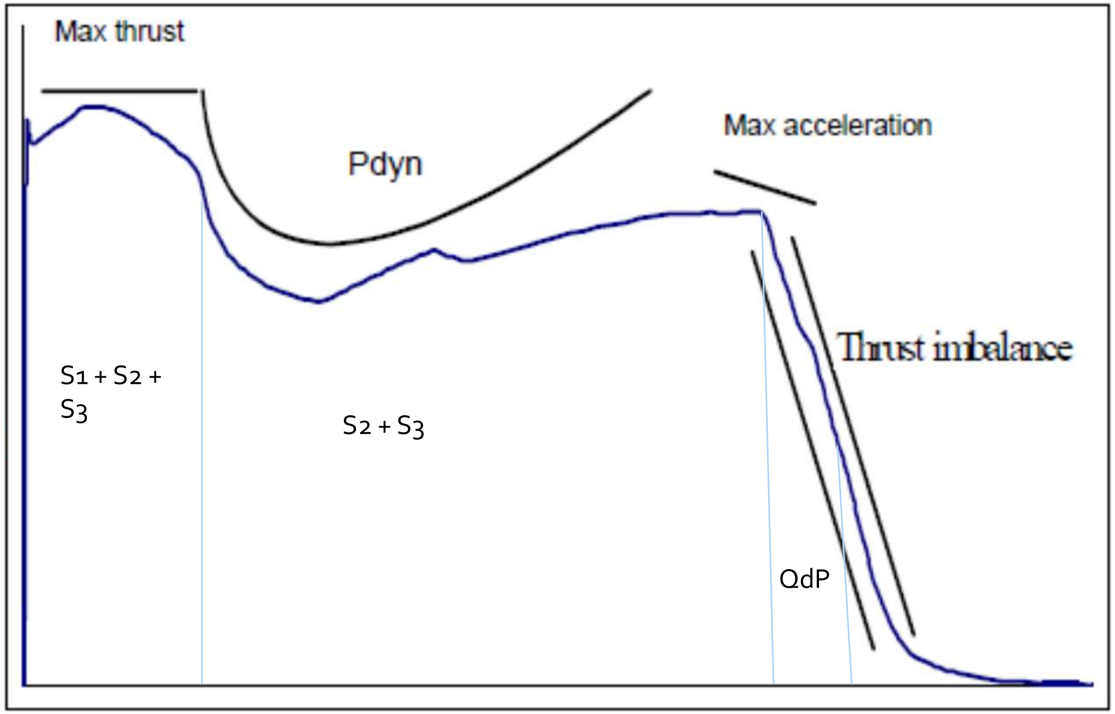
The propulsion

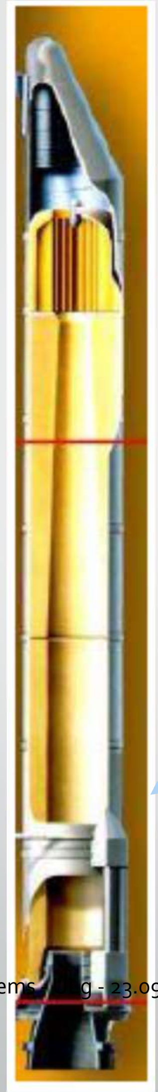
- Storable liquid propulsion
  - Average I_{sp}
  - Complex implementation, but can be anticipated by a few days.
  - Advantage : hypergolic propellants, and the engine can be easily re-ignited, but these propellants are highly toxic !
  - Used in the ballistic phase to reach the final orbit and orient the satellites

Propulsive law

- Determined by the performance requirements of the launcher
- The propulsive system must not exceed the mass requirements
- It must take into account several constraints : q, aerothermal flux, thrust dissymmetry if ∃ 2 boosters, high and low frequency instabilities, etc.
- Production cost


Launcher Specifications
Design motor
Performances prediction
Launcher performances analysis


Max thrust
Pdyn
Max acceleration
Thrust imbalance
S1 + S2 + S3
S2 + S3
QdP



Propulsive law

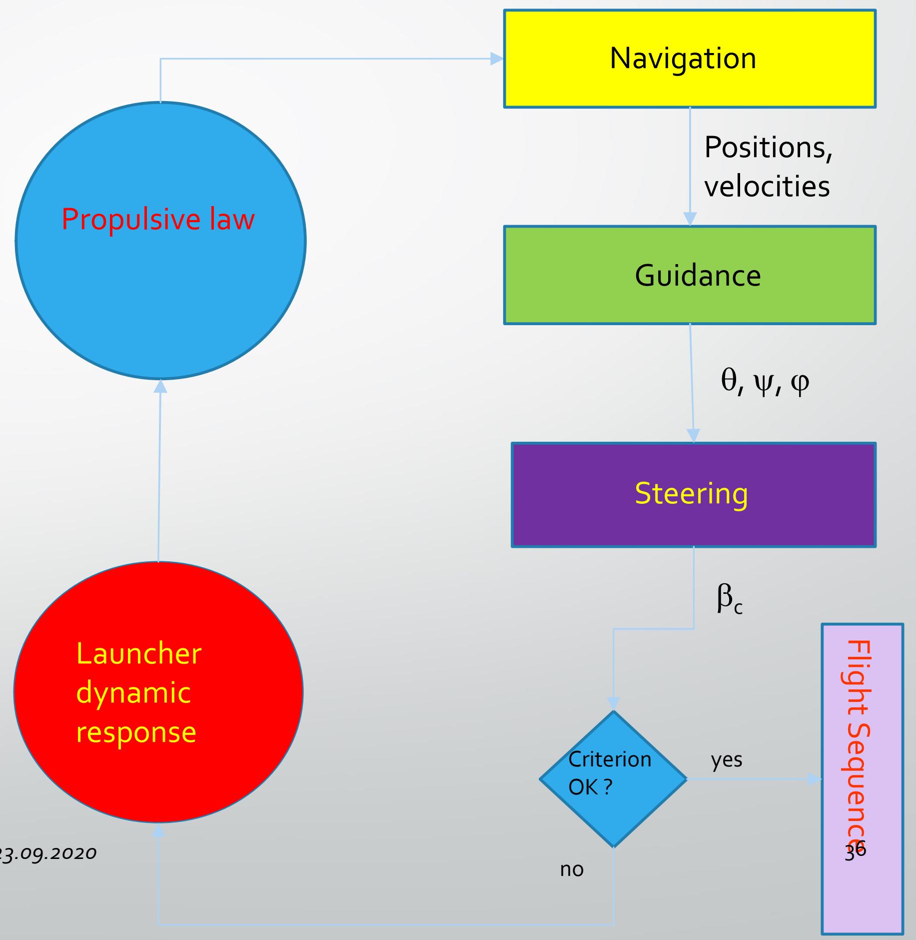
S1 : star-shaped: used for lift-off

S2 and S3 : cruise phase and tail-off ; cylindrical/conical shape

Mission : to put the satellite on the targeted orbit : x, y, z, V_x, V_y, V_z.

This mission is fulfilled by 3 separate systems :

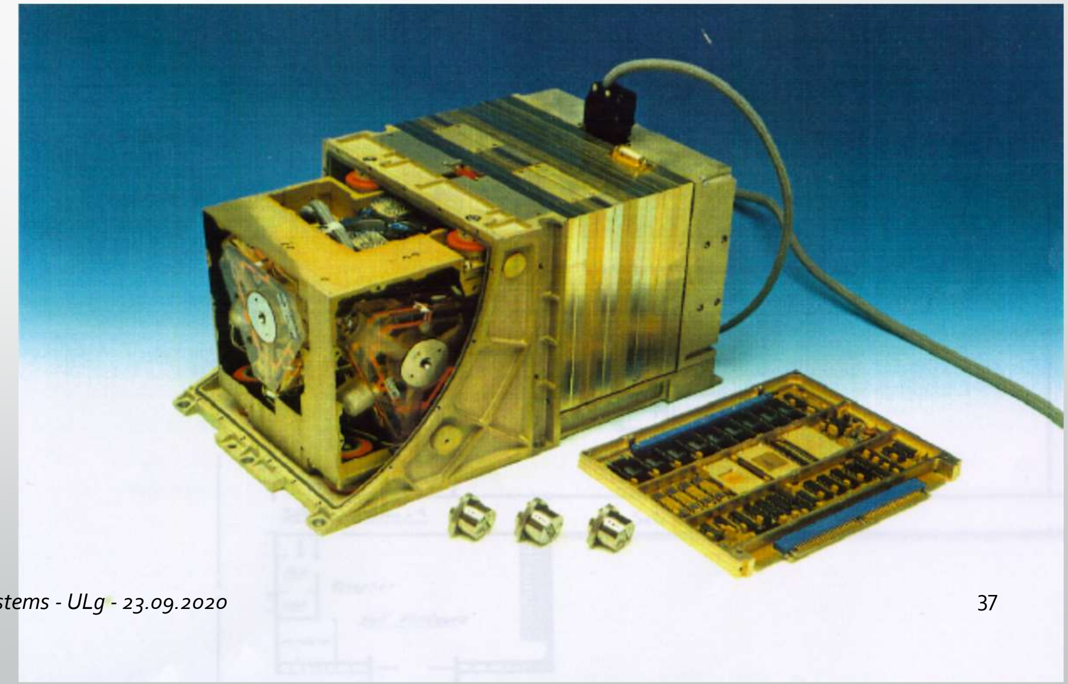
- Navigation : to determine the position and velocity of the launcher, and calculate the deviation from the nominal trajectory
- Guidance : to determine the optimal attitude of the launcher to reach the targeted orbit
- Steering : to orient the thrust according to the guidance commands.



The navigation

- This function is fulfilled by an inertial platform, which is primarily composed of three accelerometers and three gyrometers.

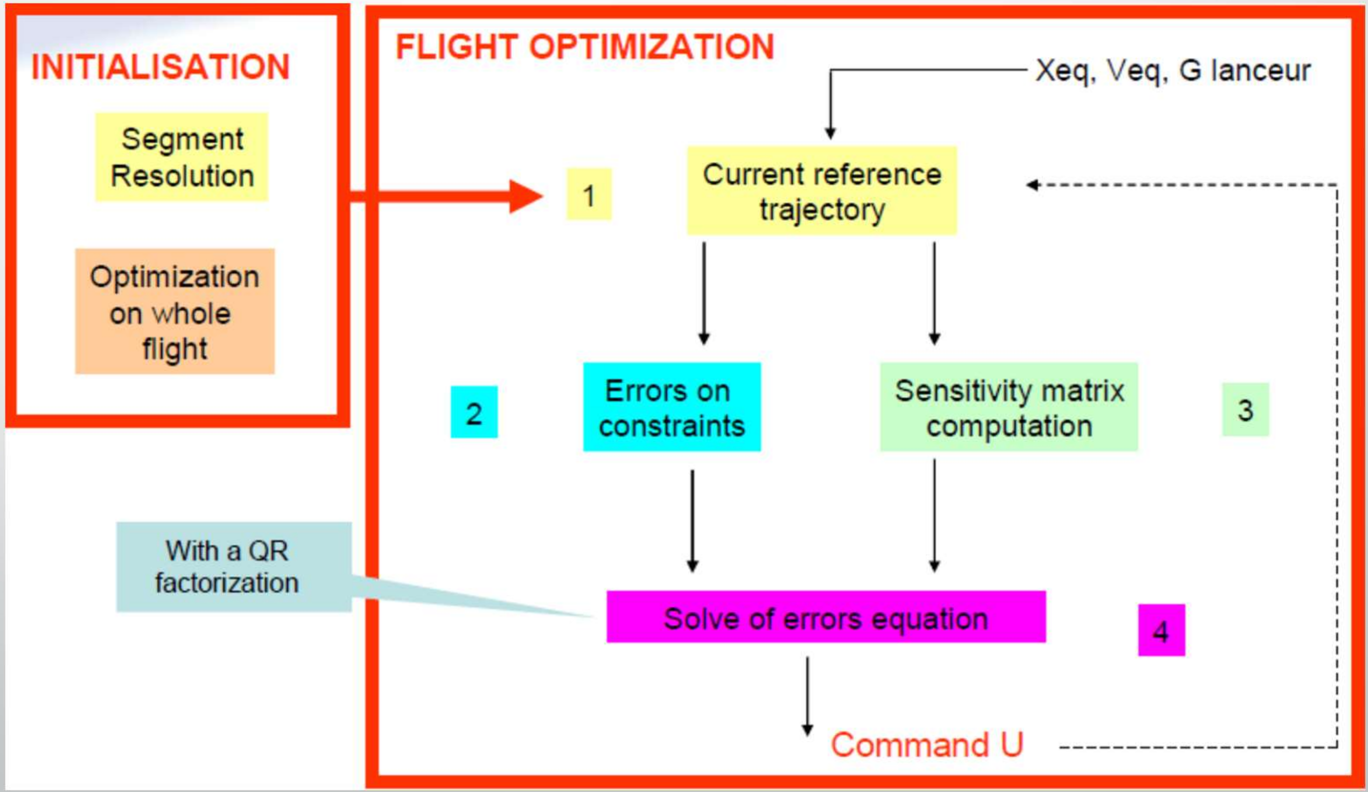
- The platform is aligned just before lift-off.
- The accelerometers detect the accelerations, and the gyrometers the angular velocities, each for 3 orthogonal axises.
- The gravity acceleration is subtracted, and the accelerations are computed in an inertial equatorial reference axis system.
- The velocities and positions are calculated by integrating the accelerations twice.
- On Ariane 5, the redundancy is fulfilled by two parallel platforms which monitor their health, and can automatically commute between each other



The guidance

<u>Objective</u> : to determine the attitude to give to the launcher during the propulsion periods in order to follow the optimal trajectory (propellant consumption), taking into account the functional constraints.

- The reference trajectory is specific to each flight, and is included in the flight software.
- Atmospheric flight : simplified optimization to get i = 0°
- Exo-atmospheric flight : the trajectory is computed by segments.
- Computed by the On Board Computer



The steering system

- The steering system determines the nozzle deflection angles β to obtain the optimal launcher attitude, calculated by the guidance system.
- If we assume the launcher is a rigid body, the following simplified equation is used (example for one axis) :
- $$\ddot{\theta} = \boxed{\frac{q\, S_{ref}\; C_{zi}\,(x_F - x_G)}{I_z}}\, i + \boxed{\frac{F\,(x_T - x_G)}{I_z}}\, \beta$$

A6 K1

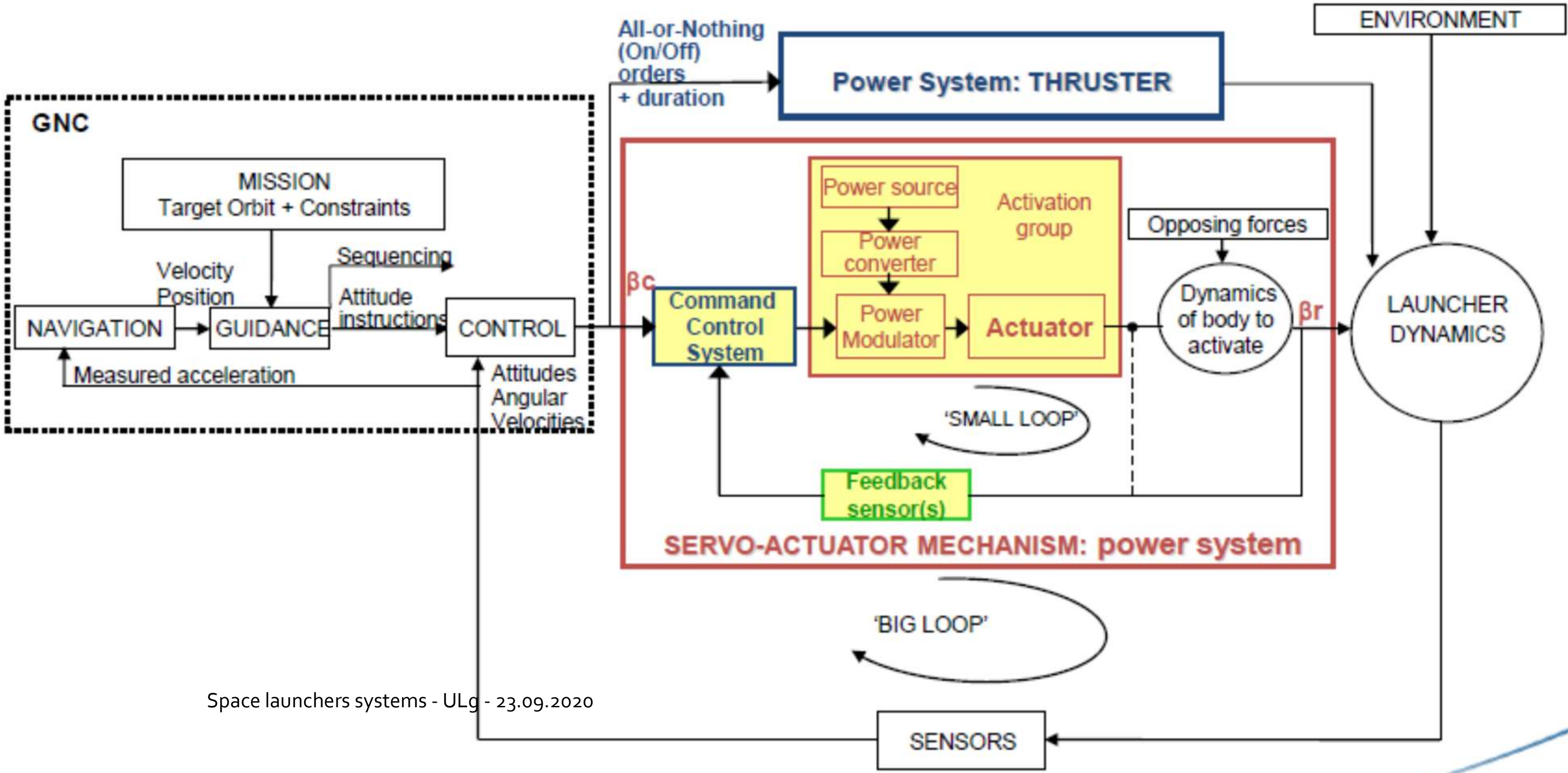
The A6 coefficient gives the launcher aerodynamic stability

The K1 coefficient determines the steering efficiency.

Practically, the launcher is far from rigid : optimal control methods are applied to minimize the needed energy to operate the actuators, and to remain in the stability domain

Large loop (launcher dynamic response)

Small loop (servo-actuator)



The steering, from the technology point of view.

- In the early stages of astronautics, vernier (auxiliary) engines were used.
- For pitch and yaw, actuators are now used to orient the nozzle.
- The actuators can be closed loop hydraulic (Ariane 4 and H10), open loop hydraulic (Ariane 5), or electric (EPS, Vega), according to the required power, the available volume and weight, and reliability.
- For the roll axis with one engine, small nozzles are used.

The flight sequence system (1)

- The flight sequence system sends the essential commands for flight operation :
  - The pyrotechnic commands to perform the engine ignitions, the stage separations, the neutralization in case of a critical anomaly ;
  - The electric commands to the payloads to perform the satellite separations ;
  - The electrovalves commands to perform the normal operation of the liquid engines and the tanks pressurization.
- The instructions are stored in the flight software, and sent to the different subsystems.

The flight sequence system (2) – Safety and reliability

- The flight sequence system manages critical functions.
- Two types of failures must be avoided :
  - Operation of a subsystem without command
  - No operation when the command has been sent
- This is managed by multiple redundancies (serial and parallel)

The flight sequence system (3) – Pyrotechnic commands

- The pyrotechnic commands are critical for safety : additional protections have been included : mechanical barrier opened just before lift_off (BSA)

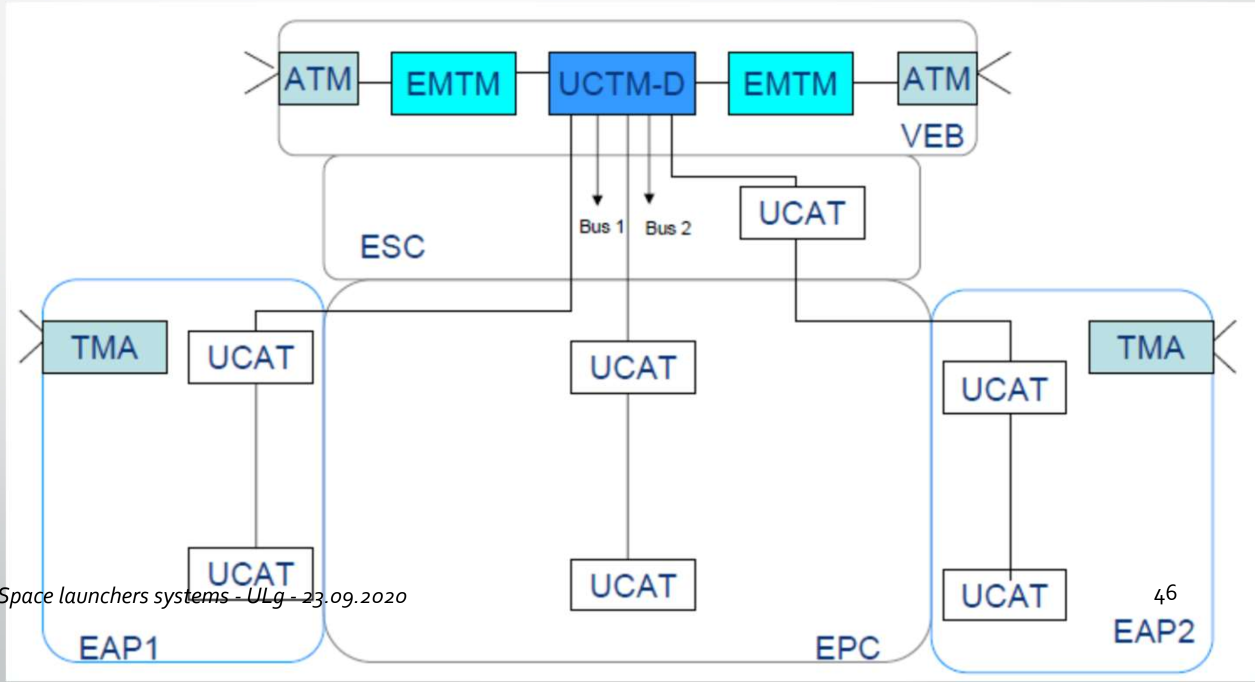
The flight sequence system (4) – Stages separation

- The stages separation is performed by pyrotechnical cutting of a weak area.
- It is commanded by the on-board computer, when a specific criterion is met (on A5 EAP : residual acceleration)
- Physical contact between the separated stages and the rest of the launcher must be avoided, and the distance between the two must be rapidly increased : on A5 : separation and acceleration rockets)
- The separation sequence is complex and must remain fully operational in case of non-operation of a separation rocket.
- The steering system must be able to compensate the perturbation generated by the stage separation.

The telemetry function

- Objective : transmit to the ground all the necessary parameters to monitor the health of the launcher and the payloads.
- General architecture (A5) :

The parameters (pressures, temperatures, etc.) are converted to voltages, then to digital format, multiplexed, and eventually sent to the ground by a radio emitter.



Flight safety

A launcher exploding on the launch pad or just after liftoff has devastating effects on the base, and can be hazardous for personnel : Metal parts and chunks of propellant weighing several tons fall back on the ground


Video : Delta 2 explosion

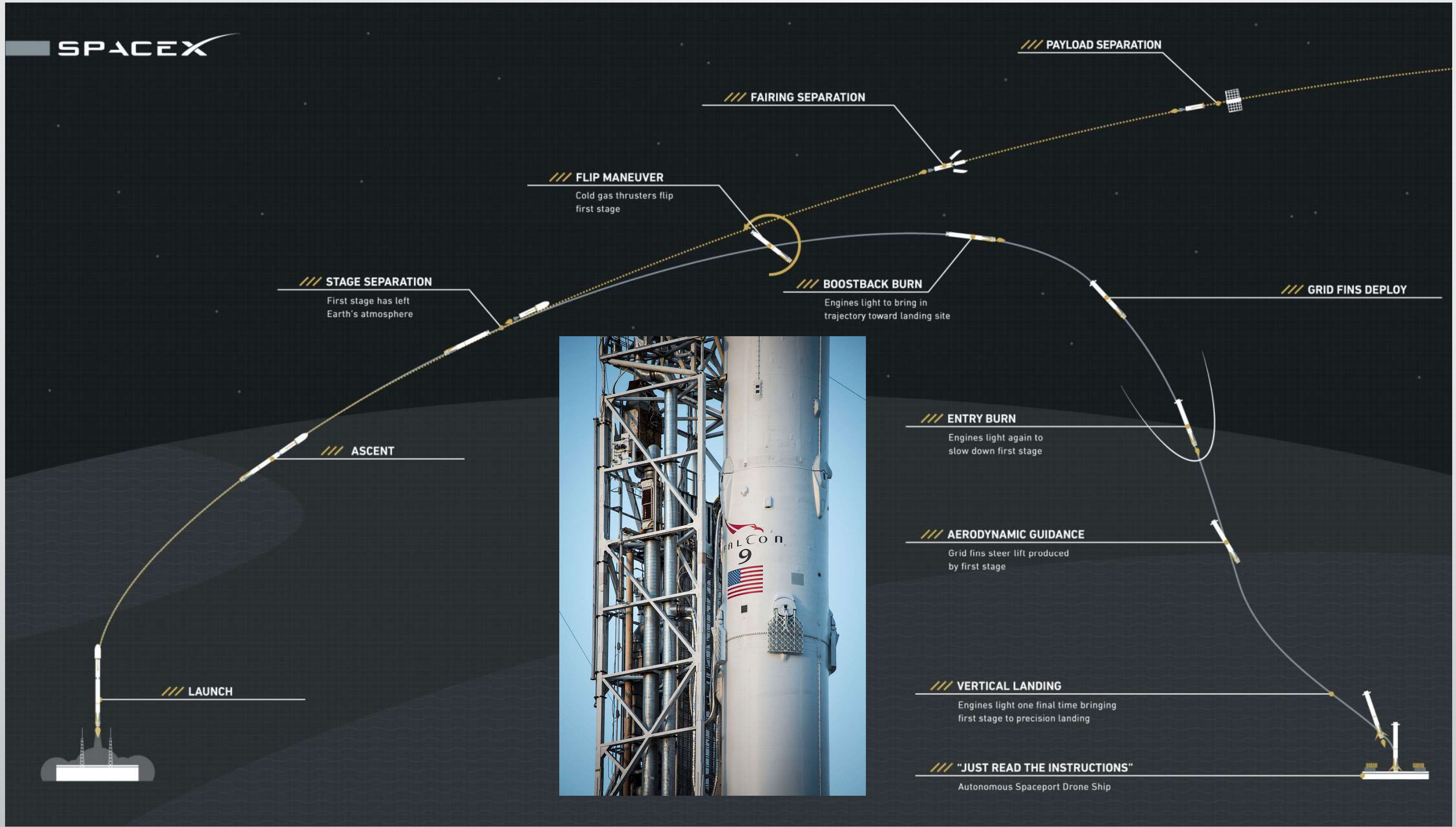
Flight safety

- Objective : to minimize the risks for personnel and ground infrastructures in the case of a mission failure.
- In the case of a critical failure, the flight safety subsystem has to determine if the mission can be fulfilled; if not , the launcher is destroyed avoiding the debris fallback on inhabited areas and ground installations. It is completely independant of the other systems of the launcher.
- First question : the decision of launcher destruction : two types of destruction :
  - Automatic destruction in the case of a non-commanded stage separation;
  - Commanded destruction : human decision, function of operational parameters.

Recovery of first stage (Falcon 9) – (1/2)

- For cost reasons, Space X developed a recoverable first stage
- After separation, the used stage guides itself to a barge in the ocean, and lands there
- To perform this operation, new technologies are needed
  - A restartable engine to perform three starts in hypersonic, supersonic and transonic regime. Its thrust must also be variable to control the stage velocity during the landing phase.
  - An attitude control system to avoid stage break-up in flight
  - Grid fins to aerodynamically control the trajectory
  - A terminal guidance system coupled to a navigation system and thrust control to land the stage on the barge.
  - A landing gear to stabilize the stage on the barge.

Recovery of first stage (Falcon 9) – (2/2)



3. The launch : the base, the operations

The launch base

The launch campaign

The flight analysis

The launch base.

- Determination of the launch base location.
  - Next to the equator
  - Weather risks (absence of tornados, hurricanes)
  - Geologic stability (earthquakes, volcanoes)
  - No inhabited areas to the East (GTO orbit), to the North (SSO orbit) and to the North-East (ISS rendez-vous).
  - Logistic and transportation infrastructures : deep-water haven, airport.
  - Existence of downrange tracking and telemetry stations
  - Political stability : long-term investment, consequences on local economy.
  - Growth potential : Kourou : ELA1 → ELA2 → ELA3 → ELA4

The launch base : design and development

- Problem : the building works start when the launcher definition is not stabilized yet.
- The launch base dimensioning depends of the following parameters :
  - Launch rate
  - Safety : distances between the hazardous sites, wind directions, installations protection.
  - Reliability: redundancies, independant infrastructures (energy, telecom)
  - Vulnerability to the explosion of a launcher at lift-off.
  - Development and utilization cost.

Synthesis of a launch campaign (1)

- Two campaigns (assembly and testing) in parallel : launcher and satellite : these campaigns join when the satallite is hoisted on top of the launcher (combined operations)
- The satellite campaign starts when the launch contract is signed.
- A preliminary analysis is started 20 months before launch to verify the launcher/satellite compatibility on the following areas :
    - Trajectory
    - Physical interferences during separation
    - Coupled analysis (structural dynamics)
    - Electromagnetic analysis
    - Thermal analysis

Synthesis of a launch campaign (2)

- One year before the launch, the final analysis is started, and the results are presented at the RAMF, 4 months before the launch.
- The launcher campaign starts six weeks before the launch, and proceeds in three successive sites :
  - BIL : launcher integration and control.
  - BAF : payload integration, transfer preparation and launcher/satellite armament
  - ZL : cryogenic propellants fillings

Flight analysis (1)

- A couple of hours after the flight : preliminary analysis of a few parameters : orbit characteristics, satellite orientation after propelled phase, and normal operation of the propulsive systems.
- Two weeks after the flight : detailed analysis of the flight telemetry curves : search for anomalies, statistical analysis of some parameters, inspection of liftoff videos.
- Two months after the flight : detailed analysis by industrial subcontractors.

Flight analysis : procedure in case of an anomaly (2)

- Is the observed anomaly real ? (physical likelihood, correlation between parameters)
- Collaborative analysis
  - List of possible scenarios
  - From possible scenarios to probable scenarios : correlation between sensors, numerical simulation, new analysis of previous flights, etc.
  - From probable scenario to proven scenario : logical chain of events compatible with measurements
- Corrective actions, or risk lowering actions if not possible.

4. Conclusion

- To launch a satellite is a complex operation, asking for highly qualified personnel, with huge infrastructures and strict safety rules.
- Technically, to launch a satellite is a difficult undertaking, at the limit of the engineering capability, and minor discrepancies can sometimes lead to catastrophic consequences.
- To launch a satellite is a very costly operation, from several tens of millions $ to more than a hundred million $.
- But it is an interesting professional environment, motivating, varied, where the final objective is useful for human societies (GPS, Internet in remote areas), or for scientific knowledge (Rosetta).

- Belgium is actively participating to the Ariane and Vega programs through several companies :
  - SABCA : hydraulics, booster structures, VEGA thrust orientation system.
  - Safran Aero Boosters : valves on the Vulcain and Vinci engines.
  - Thales-Alenia : launcher and ground electronics (launcher control desks).