ABSTRACT

The goal of the paper is to describe the splash-down conditions and safety-analysis of the most widely possible range of world class launchers.

The article starts with an introduction about the number of launches world wide that have been taken place from the beginning of the space era. The article continues with a description of launch pads locations (per launcher family) around the globe and the corresponding trajectories to reach the specified launcher’s performance maps. After, the article elaborates on orbital targets using all launchers that have occured since 1954 to 2005. Next, the paper details the cases of possible failures in second, third and fourth stages of any given launcher, together with the corresponding re-entry analysis of the remainders of the rocket. Immediately after, the article focuses on the nominal splash-down conditions for each launcher family considered: there are currently about 200 launchers families around the World. Safety constrains are widely addressed. The article further explains that the analysis performed for the study has been done with the ESA trajectory optimization software called ASTOS. This software is a simulation and optimization environment to compute optimal trajectories for a variety of complex multi-phase optimal control problems.

In particular, the article describes the EDA (Entry Destructive Analysis) module of ASTOS used for this second part of the study: the Entry Destructive Analysis module is widely used at ESA for the analysis of guidance trajectories and un-nominal splash down conditions for launchers.

Finally, the paper ends with conclusions and recommendations for the future.

1. INTRODUCTION

Till date, there have been around 57000 launches world wide. From this big number, about 4700 have been orbital launches, 22000 suborbital launches, and 30000 endo-atmospheric flights [R1].

Multistage launchers are the predominant type of launching technology nowadays. Much of the work of the first stages of launchers reusability has been focused on prices cut-down. Stage reusability calls for controlled non-destructive re-entry of these stages. However, the majority of first stages re-enter the Earth in uncontrolled manner.

Several launcher accidents have emphasized the importance of safety and they have lead to the establishment of the “Convention on International Liability for Damage Caused by Space Objects” in 1972 [R2].

The present technology uses the Earth seas as huge trash for the splash down of stage rockets. Splash down at sea reduces risks of damage to persons, animals, and properties. The particular splash down conditions at sea are calculated by means of adequate trajectory and separation analysis prior to the actual flight. This is mainly driven by two prominent factors in rocket industry: cost and availability. Cost is one of the most important factors on the design, construction, and operation of a launcher. Right now, the present technology makes the cost of safe controlled re-entry of non-reusable stages seemingly expensive. Hence, the space industry (involving also space agencies) prefers to splash down pieces of rockets that will not be recovered into the seas. Availability is the second prominent factor in the selection of the seas to splash down rocket stages: on the globe, there is more water surface than ground.

Until today, most launchers trajectory optimization activities for stage re-entry have been carried out with the simplifications of mean drag coefficient or even no drag assumed. However, with the new modern tools (e.g. ASTOS) a detailed analysis of break-up of stages is now possible.

2. LAUNCHING NATIONS

The state of the art knowledge indicates that right now in 2005 there are 12 nations or entities (grouping of nations) that have space launching capability.

As mentioned before, there have been records of about 4700 launches since 1954. However, the repartition of number of launches versus nations is far from even. Fig. 1 shows a pie chart of the 12 nations that had or have launching capabilities. They are USA, Russia (former...
CIS or USSR), Europe, China, Japan, India, Israel, Brazil, North Korea, France, U.K. and Australia.

From all nations, from 1954 till 1999 Russia has the highest record of launches with a total of 2770. It followed by USA with 1313, Europe with 129, China with 67, Japan with 61, India with 13, France with 12, Israel with 4, Brazil with 2 as well as U.K., and North Korea and Australia with 1.

It is expected that more nations will join the space race in the coming decades and that this list will augment. This grow however will not be big since launch capabilities involve not only the rocket and its construction but also the launch pad development, maintenance and its expensive operation.

3. LAUNCH PADS

From all the entire collection of about 57000 launches, the current record shows that a total of about 1350 distinctive launch locations have been used. Every time a launch is declared a launch pad location is revealed and hence entered in the record.

As it can be seen, several launches have taken place on the sea. These are launches corresponding to both civilian and military payloads. The launches happened from balloons, from ships, from submarines, from platforms at sea, and even from airplanes, etc.

4. TARGET ORBITS

Where are the orbits into which the satellites are launched? For this study, several sets of data have been gathered and classified into two distinctive groups:

- Satellites classified by orbit type (GEO, LEO, Eccentric...)
- Satellites classified by mission type (amateur, engineering, science, military...)

The satellites orbit analyzed comprise the period between 1954 and 2004. The idea is to perform a quick easy search of target satellite orbits using the publicly available orbital knowledge. If we know the altitudes and inclinations of the satellites, we will be able to extrapolate some requested mission features of their launchers. The work strategy has been to obtain the NORAD Two-Line-Elements (TLEs) of all satellites. Then to convert the TLE data into orbital parameters, place all data inside a spreadsheet, and finally, to analyze the data and extract conclusions about the most likely parameters needed.

![Fig. 2. Launch pads in the world](image)

Fig. 2 shows a Miller projection of Earth. The red spots show an even time launch pad.

![Fig. 3. All satellite orbits in 2004 for three satellite families](image)

Fig. 3 shows one of the graphs generated from the analysis of all data gathered. It shows three types of satellites orbits in 2004: the GEO, the LEO and the ones with eccentric orbits.

Fig. 4 shows data from all satellites (from 1954 till 2004). In abscises it shows the year of the launch while in coordinates it shows the respective inclinations.

A detailed analysis of all data gathered allows establishing some astonishing conclusions on the final orbit at which the satellites will go. The major conclusions derived in this work can be written down as follows:
• The majority launches are directed in an inclination band of [20,110]°.

Fig. 4. All satellites orbits and their inclinations

• There are practically no launches to equatorial orbits at low altitudes.
• The Sun synchronous orbit (SSO) launches are located in two altitude apoapsis segments: [600,1200]km and at [1450, 1700]km.
• Polar orbit launches are mainly ranging from altitudes [600, 1200]km.
• Highly Inclined launches are ranging from altitudes [600, 4000]km.

Fig. 5. Apogees of all satellites vs inclinations

• Low inclined orbit launches are ranging from altitudes [600, 2500]km.
• There are practically no orbital launches for orbits under 300 Km.

One of the most impacting conclusions is that there are regions in which no launches have ever been recorded. There has never been any launch in the following zones (see Fig 5):
• Orbits with inclinations in [120,180]° at any LEO altitude.
• Orbits with inclinations in [40,50]° at altitudes [920, 1500]km.
• Orbits with with inclinations in [55,62]° at altitudes [320, 880]km.

5. LAUNCH FAILURES

In history of rocket development there have been a considerable number of failures. Records show a total of about 400 failures.

Fig. 6 shows a chronological history of launch failures. The record presented starts in 1957 and ends in 1999. There is a clear trend towards less failure since the 90’s in comparison with the initial days of rocketry in the 60’s and 70’s.

A comparison with launch successes in Fig. 7 shows that the proportion between success and failure depends on the history of launch development.

The highest number of failures corresponds to the nations with the highest number of launches. However, the proportion is not uniformed as depicted in Fig. 8 for the period 1957 to 1999.

The highest number of failures in history corresponds to Russia with 181. It is followed by USA with 164. Then Europe appears with 12, China with 11, Japan with 9, India with 7, Brazil and France with 2 each, and Israel, North Korea and UK with 1 respectively.
As a general rule, any national or international liability for damage caused by launchers activities shall be covered by the country hosting the launch pad facilities. Therefore, launch pads have become the facto safety authorities in case of any flight certification for the nation hosting the pad.

In ESA, Ariane and future VEGA and Soyuz launch activities are covered by the “Liability Convention” that entered into force 1 September 1972. ESA declared its acceptance of rights and obligations in 1976. Since then, liability is followed by the launch pad authority at the GSC (Guyane Space Center).

In general, a launching state is absolutely liable to pay compensation for damage caused by its space object on the surface of the Earth or to aircraft flight. For damages caused elsewhere, the launching state is only liable if the damage is due to its fault.

The affected area by launch failures can be divided into several regions: the area around the launch pad, where most of the failures in early space times took place.

An area in the range of several hundred kilometres, where impacts take place in case of a failure during the first minutes of flight. Also this area is somehow related to the launch pad as normally a launch direction is only oriented into directions of uninhabited areas or the sea. More unpredictably is the area afterwards. It goes far several thousand of kilometres and often it cannot be avoided, that populated area would be affected in case of a failure.

6. ASTOS BACKGROUND

Since 1989, ESA has developed, and improved a trajectory optimization software tool called ASTOS [R3]. This tool is a simulation and optimization environment to compute optimal trajectories for a variety of complex multi-phase optimal control problems.

ASTOS consists of:
- several fast and powerful optimization solvers (PROMIS, TROPIC, CAMTOS, etc), that handle large and highly discretized problems,
- a user interface which enables the user to operate the software efficiently, in particular allows him to edit the discretized problem graphically (Graphic I/O),
- an integrated graphical iteration monitor to review the optimization process and plot the state and control histories at intermediate steps during the optimization,
- a multi-purpose simulation and plot tools, and
- filters for exporting simulation data for plotting purposes to products like MATLAB and STK, etc.

ASTOS presently runs in Windows and Unix platforms and it is maintained and commercialized by TTi GmbH for ESA.

7. EDA MODULE FOR ASTOS

EDA stands for ENTRY DESTRUCTION ANALYSIS. It is an ASTOS module. The EDA module has been introduced in the new ASTOS version 5.1.3.

In the context of launch trajectory optimization safety, EDA can be used to compute destruction of upper stages of launchers, or entry vehicles flying in a planetary atmosphere. As an add-on to ASTOS is able to:
- Simulate Break-up pieces of vehicles during flight.
- Propagate the trajectory of pieces and their final splash down.
- It allows for new constraint types to be able to calculate safe trajectories for given lines, areas, or points.

EDA has been programmed by HTG (Hypershall Technologie Goettingen). HTG has a long standing experience for destructive entry analysis in projects like ATV. HTG is the vendor of the software tool SCARAB (SpaceCraft Atmospheric Re-entry and Aerothermal Break-up) well know at ESA and Industry.
EDA can be used together with any ASTOS application but requires some more partly very detailed input information:

- **Object_File**: the name of the objects file
- **Material_File**: the name of the material file
- **Num_Objects**: the number of defined object (incl. parent object)
- **Max_Perigee_Radius**: above this initial perigee radius the action of EDA will be disabled to avoid endless (no) entry simulations.

The list of objects specifies into which objects a parent objects breaks up at an altitude of 78km. Specified size, mass and material are decisive, if an object may demise or impact. Most important are the corresponding definitions in the material file. The advantage of EDA in contrast to a computation without drag or with an average drag is, that additional information about the demised objects is available and that the computation of impact points is more accurate. However, in order to achieve reliable results the definitions of the object and material file requires calibrations from more accurate computations or tracking data.

### 8. SAFETY CONSTRAINTS

With a software like ASTOS and the new EDA module, it is possible to study launcher safety features during the trajectory optimization work.

Fig. 9 shows a Miller projection of the Earth containing a plot of launch pads (red spots) over imposed on a map that shows population density in the World.

![Fig. 9. Polar orbit launches](image)

Launch pads are not frequently placed close to high populated areas. Some exceptions however are to be mentioned: the west coast of US, Florida in US, some of the installations in China and in Japan. In all these places, safety is ensured by strict flight rules and adequate trajectory optimization.

While launch pads play a significant role on the determination of safety constraints of a launch vehicle and its operation, a big part is determined by the launcher’s trajectory. Section 4 (Target Orbits) explained the final orbits of the satellites, including data about their inclinations, apoapsis, etc. From this section and using a trajectory optimization software it is possible to compute optimal ascent trajectories for the major launch pads.

Fig. 9 and 10 shows a Miller projection of the Earth in which the red ellipses represents the ground probability areas in which a splash down of a rocket stage of a piece may happen.

Only the major launch pads have been represented. The ellipses have been pondered using the number of flights recorded.

![Fig. 10. Equatorial launches](image)

The highest concentration of danger happens with the red ellipses overlap the high density population areas.

### 9. CONCLUSIONS

This paper has shown that ASTOS EDA is able to compute risks during the trajectory optimization process of any launcher system. This leads to a reduction of risk due to stage impact, etc.

A broad study about orbits, launchers, launch failures, launch pads, etc has been presented. Safety
consideration impacting launcher’s operations have been identified and studied.

10. REFERENCES

