VEGA 4TH STAGE DIRECT RE-ENTRY SURVIVABILITY ANALYSIS AND CASUALTY RISK ASSESSMENT

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ABSTRACT

A key task in launch vehicle (LV) system design process consists in the estimation of upper stage fragmentation during atmospheric re-entry once accomplished the launcher mission, and the related probability of making on-ground casualties.
As a European launcher operating from French Guyana, VEGA has to abide by ESA debris mitigation rules, and by the French Law on Space Operations (LOS).

The second flight of VEGA aims at demonstrating the versatility of the launcher by performing a multi-payload launch with different target orbits. From a safety point of view, the compliance of VEGA to the LOS will also be extended through the performance of the direct deorbiting of its upper stage, the AVUM, at the end of its mission. Indeed, during the qualification flight, VEGA had submitted to the safety authorities the derogation envisaged by the LOS: under certain conditions, it allows the indirect re-entry of the launcher's upper stage, provided it shall do so in less than 25 years.

1. INTRODUCTION

The Vega LV is requested to fulfil the requirement to minimize the risk of making on ground casualties linked to the re-entry of its 4th stage AVUM after mission completion.
ELV company is the prime contractor involved in the system design of the European launch vehicle VEGA (Vettore Europeo di Generazione Avanzata), and such kind of analysis is naturally part of the design effort. VEGA launcher (Fig. 1) has being developed within a European Programme promoted by the European Space Agency (ESA), as a cooperative project with Member States within the ESA framework.

VEGA is a single-body launcher [1], composed of three solid-propellant stages (P80, Zefiro 23, Zefiro 9) and a liquid propellant upper module (AVUM, Attitude Vernier Upper Module). VEGA is compatible with payload masses ranging from 300 kg to 2500 kg, depending on the type and altitude of the orbit required by the customer (an orbit altitude range between 300 and 1500 *km*). In this respect, it can provide launch services for a wide variety of missions, from equatorial to Sun-synchronous. Due to the vast range of missions, VEGA LV will fly over practically the whole Earth therefore a casualty assessment is necessary.
Its second flight is scheduled to take place from French Guyana on May 3rd, 2013. It is the first Vega commercial flight that will extend the Vega qualification domain to the multi payload missions, carrying the first satellite *Proba-V* into a sun-synchronous orbit of about 800km altitude and the second passenger into a sun-synchronous orbit of 650km altitude, together with one secondary payload ESTCUbe-1.

Figure 1. VEGA LV during final chronology before lift-off from French Guyana Space center (ESA)

Once released all spacecrafts, AVUM end of life disposal compliance wrt "Requirements on Space Debris Mitigation for ESA Projects"[2] and LOS [8] is already achieved by injecting the spent Vega LV 4th stage on a re-entry orbit with a Impact Point placed in the South Pacific Ocean. On ground Casualty Risk requirement linked to direct re-entry in the occurrence of degraded re-entry phase is also specified in the LOS as well: Risk < $2*10^{-5}$, that should be added to the nominal direct re-entry risk threshold: 10^{-7}.
In the occurrence of the not feasibility of the direct re-entry, the rule of 25yrs maximum orbital lifetime shall be respected and the respective on ground Casualty Risk shall be lower than 10-4. Vega already demonstrated its compliance to this requirement during the mission analysis of VV01, which baseline 4th stage re-entry strategy was the indirect one.

The aim of this paper is to present the studies performed in the frame of the safety analyses to demonstrate the compliance to the requirements of the LOS on the casualty risk linked to the

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direct re-entry of the AVUM. The main different steps leading to this assessment are the following:

- Definition of AVUM fragmentation model, based on AVUM configuration of the second flight ; the main difference is the use of the multi-payload adapter VESPA instead of the single P/L 937 adapter. Fragments are modeled through simplified geometric forms, characterized by their mass and dimensions.
- Survivability analysis of the AVUM fragments ; this study is based on the use of the SESAM module of the ESOC-provided software DRAMA. Starting from a break-up altitude of 78 km, the tool computes the trajectory of the single fragments until their demise or impact on ground.
- Casualty risk analysis: the computation of the probability to make victims during the direct reentry of the AVUM relies on the ELECTRA (Estimation de la Létalité due aux Evènements Catastrophiques sur Trajectoires Rentrant dans l'Atmosphère) software, used by ELV under CNES license. For the risk linked to AVUM direct de-orbiting, the software module for controlled re-entry is used. Only surviving fragments from DRAMA analyses are considered in the computation [4], [5] (Fig. 2).

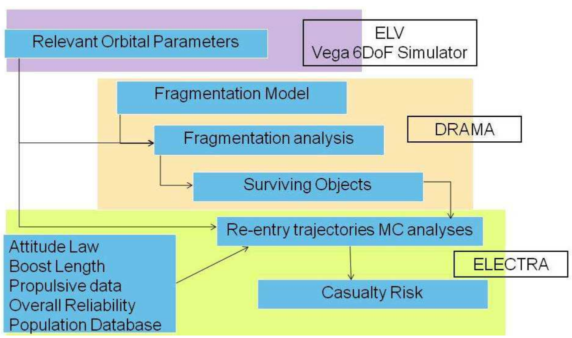


Fig. 2. Logical scheme of tools utilization

Specific re-entry analysis performed for VEGA second flight is presented, as practical evidence of a consolidated methodology part of ELV know-how, to be replicated either for VEGA following flights and for any other similar application.

2. RE-ENTRY, FRAGMENTATION AND CASUALTY RISK

The initial conditions of the re-entry problem are given by the injection points into re-entering orbits.

Due to the large orbital velocity, a spacecraft entering the atmosphere experiences high mechanical loads and heating rates. During the aero-braking process in the atmosphere the initial potential and kinetic energy of the spacecraft is converted into thermal energy that is consumed by the ambient atmosphere and by the spacecraft itself. The resulting thermal and mechanical loads will destroy the spacecraft completely or partially.

As internal components separate, they follow trajectories and heating rates based on the state vector at separation and their respective ballistic coefficients. Internal components can suffer break-up themselves, thus releasing smaller debris pieces with individual ballistic coefficients. This process continues until the heating rates are low enough to prevent further disintegration. Factors that affect satellite break-up and debris survivability are initial speed, flight path angle, melting temperature of components, and the ballistic coefficient of the primary body and the subsequent pieces. The survivability of a particular component also depends on how deep within the structure it is since it could be shielded through much of the peak heating regime. In Fig. 3 is reported a schematic of the re-entry break-up dynamics.

As in any other existing object oriented re-entry tools like DAS [6] or ORSAT, DRAMA is based on the parent / child concept. Initially the S/C is modelled as one parent object, which represents the complete S/C given by the rough shape, the overall dimensions and the total mass. The parent object virtually contains all other components of the S/C. These child objects represent the internal components of the S/C. During re-entry, when the pre-defined break-up altitude is reached, the parent object vanishes and all child objects are released. The child objects finish the re-entry separately until demise or ground impact. An extension to the common parent / child concept was introduced in DRAMA for the solar panel break-off [4]. If the S/C is equipped with solar panels sticking out from the main body, these panels increase the drag of the satellite. Due to the increased drag, the re-entry trajectory is different from the trajectory resulting from an analysis of the main body itself. In addition, solar panels will usually break off at an altitude above the assumed break-up altitude of the S/C. Thus, solar panels are modelled separately from the other child objects. The break-up model of DRAMA is illustrated in Fig. 4.

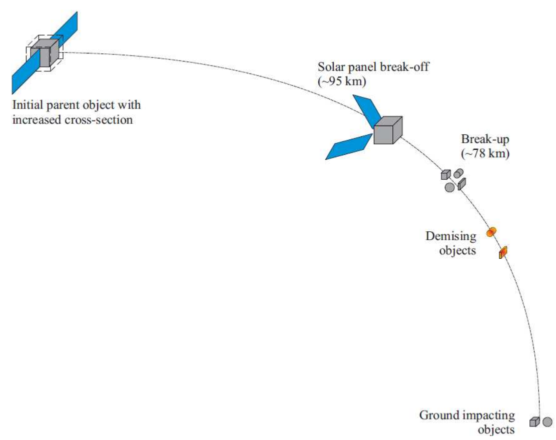


Fig. 3. DRAMA break-up model

The increased drag of the main body / parent object due to attached solar panels is modelled by a linear enlargement of the main body dimensions. This does not change the shape of the main body (drag coefficient) but increases both the mean cross-sectional area and the drag forces. After solar panel break-off the analysis continues with the original parent object

dimension specified in the model input file. In summary, DRAMA considers the following two break-up events:
1. Solar panel break-off at 95 km altitude
2. S/C break-up at 78 km altitude.
This is the classical approach of "Object oriented methods": they analyse only individual parts of the spacecraft. These methods usually assume that at a certain altitude the spacecraft is decomposed into its individual elements. For each critical element of the decomposed spacecraft a destructive re-entry analysis is then performed. Object oriented methods thus reduce the re-entry analysis of a complete spacecraft to the individual destruction analyses of its critical parts. The concept of a fixed, common break-up altitude usually in the range between 75 km and 85 km, allows the determination of a ground impact footprint for the surviving debris objects. This footprint depends on the break-up conditions (position, altitude, velocity vector) and on the ballistic coefficients of the debris objects.

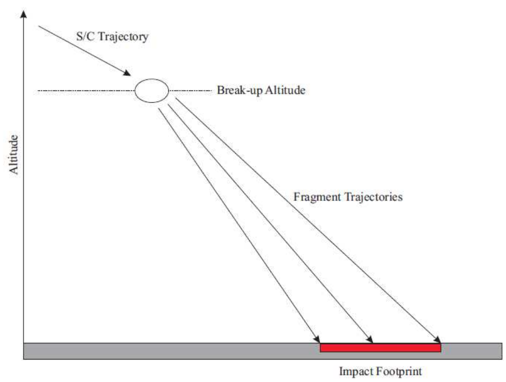


Fig. 4. Typical fragmentation and on-ground footprint

Due to this simplification, only the critical individual parts of the spacecraft could be modelled and not the complete spacecraft assembly. The preparatory work for the spacecraft model construction is thus greatly reduced. Anyway, full S/C description can be implemented, mainly useful for sensitivity approach versus number of modelled fragments or to consider a model as much as possible complete. In all object oriented methods the spacecraft to be analysed is represented only by a parts list containing information on basic geometry, size, mass and material. Object oriented codes are therefore not able to analyse the re-entry of a complete spacecraft with its full dynamics, the fast heating of external parts, and the protection of internal spacecraft parts by the outer shells. Because of this simplified approach object oriented codes are very fast, without loss of consistency of results.

Once determined the surviving objects by means of DRAMA, the assessment of casualty risk shall be performed. ELECTRA tool (CNES property) allows the calculation of risk of making casualties linked to the controlled re-entry of spacecraft fragments, according to a population distribution model and the re-entering orbit trajectory [4]. In fact, if a failure occurs during the de-orbiting boost the predicted re-entry path could not be achieved and the safe impact are not met. Computation is done by propagating each fragment: they will have been defined by user in relation to output of DRAMA: only surviving objects found, in fact, represent input data to ELECTRA which, on its turn, performs the final propagation and returns related casualty risk.
On ground, the surface portion affected by the re-entry is the *"casualty area"*: in literature ([3], [4], [5], [6]) it conventionally corresponds to an area around a debris impact point in which a person who is present will become a casualty in the event of that debris impact. The casualty area of a single piece surviving the atmospheric re-entry is, hence, defined as the average debris cross-sectional area increased of a factor for the cross-section of a standing individual. The total debris casualty area for a re-entry event is the sum of the debris casualty areas for all debris pieces surviving atmospheric re-entry. Eq. 1 is used to calculate the total debris casualty area A_c:

$$A_c = \sum_{i=1}^{N} \left(0.6 + \sqrt{A_i}\right)^2 \qquad (1)$$

where N is the number of objects that survive re-entry and A_i is the area of surviving pieces.
The average cross-sectional area of a standing individual, viewed from above, was taken to be 0.36 m^2, under the hypothesis that the pieces are re-entering vertically. The 0.6 term is then the square root of this area.

Deterministic simulation can be performed, but also Monte-Carlo approach can be selected, in order to cover uncertainties that mainly affect fragments ballistic properties, aerodynamic characteristics and lateral velocity in case of fragments generated by explosion.

Both propulsive and attitude failures can be accounted for each instant of the predicted nominal de-orbiting boost.

The tool foresees the possibility to consider coefficients that lower the casualty risk for a user-defined percentage of people living inside buildings, which offer protection with respect to falling debris. Coefficients are, in fact, defined on the basis of demographical studies taking into account seasonal behaviour of people living in the different zones of the globe.

3. PROCESS AND LOGIC

Process leading to estimation of casualty risk linked to controlled re-entry is the key point to achieve consistent results able to satisfy Safety Requirements applicable to European Space Programs. The necessary steps are hereunder explained.

4. INITIAL CONDITIONS

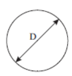
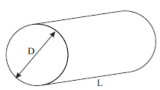
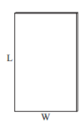
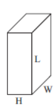
DRAMA tool is able to manage Spacecraft (S/C) re-entry computations from given atmospheric initial conditions. For this aim the re-entry path injection condition are considered.

4.1 Definition of Fragmentation Model

Re-entering objects are modelled as spheres, cylinders, boxes or plates only (Tab. 1). This means that the fragments, which are rarely uniform in shape, require some "adaptation" to be modelled as the closest equivalent to one of these shape options: this process is guided by specific rules.

Starting from the spacecraft breakdown structure, each components is modelled into an equivalent geometry to be set into DRAMA fragmentation model. Level of detail can reach the modelling of items like bolts.

Preliminary activity is, hence, needed to define the geometry of proper equivalent model of each component to be considered in fragmentation analysis.

Geometric Shape	Geometric Parameters
Spheres 	D Diameter
Cylinders 	D Diameter L Length
Flat Plates 	L Length ($L \geq W$) W Width
Boxes 	L Length ($L \geq W \geq H$) W Width H Height

Tab. 1. Simplified geometric shapes for fragmentation model

5. DRAMA SETUP

Characteristics of each fragment shall be defined in a dedicated input sheet, reporting name of the object, shape, geometry, mass and material. The latter is needed in order to perform aerothermal calculations leading to the material melting and the consequent object demise. Material database is available inside the tool, considering the most of materials used in space applications. User-defined material can be also entered. Number of the same object is also requested if the same equipment is present on-board more than once.

Parent / Child relation shall be also defined, in order to allow the tool to expose the children objects to external fluxes once the parent is demised.

Initial parent object representative of the entire spacecraft kinematic initial condition definition is needed: it is required to calculate the body energy at its atmospheric entry, from which will depend the entire trajectory and loads. This information can be provided in terms of Cartesian coordinates or keplerian elements as well, through a graphical user interface.

Finally, simulation starting date is needed for propagation issues.

6. IMPORT DRAMA OUTPUT IN ELECTRA TOOL

Fragmentation numerical simulations provide the user with the mass evolution of every objects versus time. This represents the effect of aerothermal loads which firstly lead the object to its melting temperature, then heat flux causes the object melting process, represented as a "mass consumption". If the instantaneous aerothermal flux decreases in relation to object trajectory evolution and the object wall temperature decreases under the melting value defined for that material, the melting process ends and the object mass remains constant.

At the end of the process, each object presents a certain "residual mass": some of them could be demised if the residual mass is zero, the other have withstood the atmospheric re-entry. Only these latter have to be considered for following step: casualty risk assessment by means of ELECTRA tool.

In particular, initial geometry of surviving objects shall be set into ELECTRA fragmentation model input sheet, reporting all the geometric, aerodynamic and material characteristics of the object, as they were defined in DRAMA input file.

7. FINAL CASUALTY RISK ASSESSMENT

Once the fragmentation model composed only of surviving fragments found by DRAMA has been defined into ELECTRA, the following other input data are requested. In particular, the orbital parameters before the de-orbiting boost, the programmed attitude law, the propulsive data (Isp, thrust, mass flow rate), the reliability of the de-orbiting boost and the boost length.

The number of failure to be analyzed can be chosen.

In addition population density can be selected between models available containing estimations at different years. Protection coefficients are defined for the percentage of people living inside and/or outside buildings.

Finally, statistical approach is adopted, by means of Monte-Carlo simulation.

8. VEGA SECOND FLIGHT NUMERICAL EXAMPLE

Evidence of practical application is given in this section. Results shown are relevant to analyses performed [7] for VEGA LV VV02.

Some data or results are strictly confidential and cannot be disclosed, according to ELV industrial policy.

AVUM is programmed to be injected at the end of its nominal mission to a re-entry path that will make it splashing down safely into the Pacific Ocean off to the Chilean coasts.

Orbital parameters of AVUM were set in DRAMA.

Considering that the initial altitude cannot be greater than 160km, the orbital parameter to be set in the tool shall propagated (i.e. by STELA).

VV02 Before De-orbiting boost			Disposal Orbit	
Hp	Ha	ι	Hp	Ha
[km]	[km]	[°]	[km]	[km]
663.0	671.0	98.1	-26.0	689.0

Tab. 2. VV02 Vega LV Upper Stage Disposal orbit

The following picture shows the trajectories vs. distance of fragments until their demise (if any).

Fig. 4. Vega VV02 Upper Composite ready to flight (AE)

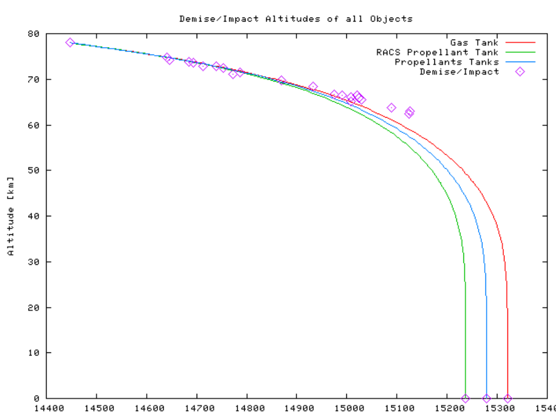


Fig 5. Results of survival analysis: re-entering objects and demised ones

Fig. 5 provide evidence that only tanks are able to withstand atmospheric re-entry. This results can be considered coherent with expectation, as usually experienced from generic spacecraft re-entry. This kind of components is, in fact, the one most likely able to survive, for two main reasons. First cause is the very limited area-to-mass ratio. They are generally compact bodies (spheres or cylinders), with very high mass, needed to ensure structural integrity under high pressure internal conditions. Second cause is the typical material used for tanks design, as titanium alloys: high performance are required from mechanical and thermal points of view, leading to high stresses and high melting temperature material survival capability. From parent body break-up, aerothermal fluxes are not sufficient to demise them.

The total casualty area of re-entering fragments is therefore evaluated.

In order to assess the casualty risk on ground due to the controlled re-entry of these surviving fragments, ELECTRA simulation has been performed, by means of RC application (Rentrée Contrôlée). As input fragmentation model, the initial geometries, masses and shaping (before re-entry) of survived objects, as per DRAMA analysis, have been set, not considering the reduction of mass due to melting process.

ELECTRA also asks for the following other input data: the orbital parameters before the de-orbiting boost, the programmed attitude law, the propulsive data (Isp, thrust, mass flow rate), the reliability of the de-orbiting boost and the boost length.

X ECI	Y ECI	Z ECI	VX ECI	VY ECI	VZ ECI
[m]	[m]	[m]	[m/s]	[m/s]	[m/s]
-4313761	4634023	3085658	-1355	3192	-6678

Tab. 3. ELECTRA state vector input

Isp	T	MFR	THETA	PSI	PHI
[s]	[N]	[kg/s]	[deg]	[deg]	[deg]
314.7	2450	0.80	law	law	Law

Tab. 4. ELECTRA propulsive inputs

A Monte Carlo analysis is performed taking into account all the recommendations suggested in the ELECTRA User Manual [4]

The assessed value of risk is compliant with the requirements [9] of risk <2* 10-5 for controlled re-entry.

Besides, during VV02 will be also released the jettisonable Upper Part of VESPA. It will be left in the transfer orbit between the first and the second target orbit, because of the mission constraints was not possible to further lowering the VUP (VESPA Upper Part) perigee, this resulted in a predicted orbital life of 26yrs, slightly above the 25yrs requirement.

9. CONCLUSIONS

Since the LOS fully applicability to VEGA operations, the re-entry strategy baseline for Vega launches is the direct re-entry.

For the VV02 the first Vega commercial flight, the direct re-entry at the end of the mission has been programmed.

Present paper reported the detailed analysis done to assess the VV02 compliance to the French Law for Space Operations.

Methodology for this kind of activity, applicable to either launch vehicles' upper stages and satellites, has been presented. Tools used to implement the methodology in practical analyses leading to quantitative estimation of casualty risk has been also described and applied.

This represents a key rule owned by ELV know-how, to be applied to VEGA itself following flight, as well as to any other re-entering spacecraft as a complementary service offered for space debris international requirements verification [2,8], on the basis of its application aimed to obtain the flight license of Vega launcher, reached with its successful maiden flight on February 13^{th} 2012.

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