

INNOVATIVE STRATEGY FOR Z9 REENTRY

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Abstract

Large footprint of Zefiro 9 (Z9), the Solid Rocket Motor (SRM) 3rd stage of VEGA launcher, spanning even more than 2000 km in equatorial missions, is one of the major system drawbacks constraining both performances and missionization process.

Z9 is one of the specific characteristics of VEGA: it works at high velocities and high altitude. Being a solid rocket motor it cannot be simply cut off and the delivered velocity impulse depends on the propulsion scattering, not known a priori. This uncertainty produces a big variation in the Z9 impact point, function of the propulsive performance of the SRM.

Current solution for the Z9 footprint reduction foresees the employment of so called Neutral Axis Maneuver (NAM) that dis-optimizes trajectory therefore a certain percentage of its propulsion capability is lost in the maneuver.

This paper proposes a new strategy for Z9 reentry that permits to avoid the neutral axis maneuver and exploit the whole Z9 energetic capacity. Footprint is reduced by employment of retro rockets: small solid rocket booster with a fixed impulse of velocity positioned at separated stage. After Z9 exhaustion a slew manoeuvre points the launch vehicle to the target attitude computed on-board and retro rockets are activated immediately after separation. Activation of the retro rockets compensates the scattering of the velocity impulse delivered by all previous propulsion.

The reentry logic is deeply analyzed and the adopted optimal reentry strategy is formulated. The improvements are evaluated in terms of Z9 footprint extension. Obtained results are compared with respect to the current reentry strategy.

1. INTRODUCTION

Zephiro 9 a third stage of VEGA launcher reaches high altitudes and high velocities inherited by the previous P80 and Z23 stages. Being the solid rocket motors they cannot be simply switched off and their delivered energy depend on the scattering of the propulsion. The actual Z9 reentry approach permits to mitigate the risk of large reentry areas by employing the neutral axis maneuver. But it has some drawback discussed below.

Objective of this paper is to introduce a new reentry strategy for VEGA third stage by means of retro rockets. Proposed solution produces two main advantages in terms of performances:

- The reduction of Z9 footprint guiding the separated stage by retro rockets to the desired

impact point, previously defined during the missionization phase.

- The possibility to exploit the whole energetic capacity of the third stage erasing the problem of uncertainty for propulsion scattering.

Price to pay is the introduction of additional hardware, the retro rockets, so layout modifications and obviously an increase of mass.

In the following paragraph the current logic based on neutral axis maneuver is deeply explained, evaluating its pros and cons in terms of performance and flexibility in missionization phase. Then in §3 the new reentry approach will be presented, highlighting the possible improvements and drawbacks with respect to the current strategy.

2. NEUTRAL AXIS MANEUVER

Current solution for the Z9 footprint reduction foresees the employment of so called Neutral Axis Maneuver (NAM). Neutral Axis (NA) is a specific direction linked to every point of trajectory. Velocity impulse applied along the NA does not shift impact point on the Earth surface. NAM is performed in open loop guidance several seconds before Z9 burnout and dis-optimizes trajectory therefore a certain percentage of its propulsion capability is lost in the maneuver.

Neutral Axis (NA) approach is based on the technic used for ballistic missiles as "Null Miss Condition" (NMC) [1], [2].

This technique makes uses of the range partials derivatives with respect to velocity module and flight path angle to determine the launcher attitude that allows nulling the range dispersion at the impact point (in a pure keplerian motion).

The orientation of the thrust along this direction so called Neutral Axis several seconds before the Z9 burnout minimizes the impact point variation. The NA designed for VEGA GNC reduces significantly Z9 Footprint making it acceptable for VEGA mission trajectories but it has also some drawbacks.

First of all the footprint remains still big: about 1300 km for polar missions and more than 2000 km for equatorial ones, because of attitude control accuracy during the rotation maneuver dedicated to reach NA attitude is limited and delta velocity vector delivered during the maneuver remains scattered.

Then it represents a major constraint for trajectory optimization during the missionization phase.

But most important drawback is that some energy delivered by Z9 motor is wasted during the rotation maneuver reducing the VEGA performances.

3. RETRO ROCKET EMPLOYMENT FOR Z9 REENTRY

In this paragraph the new Z9 reentry strategy is presented. The main innovation of the proposed solution is the possibility to use the third stage up its end and to define the impact point for third stage within the missionization phase. Retro rockets are employed at the end of Z9 coupled with closed loop guidance in order to achieve the desired impact point.

The section is organized as follows. Reentry logic strategy is presented and a first evaluation of system impact in terms of performances is presented. Resulting footprint extensions are shown for a VEGA equatorial mission (the most dimensioning for footprint) considering both nominal and scattered (for specific impulse and combustion time) thrust profiles.

3.1 Hypothesis

Reentry strategy can be described in the following points:

- Neutral axis maneuver is not performed: Z9 is used up its exhaustion, permitting to fully exploit its propulsive capacity;
- Optimal reentry angle to achieve the desired impact point is computed after Z9 exhaustion, accounting actual LV state without uncertainties due to SRM scattering. The computation is done at a certain time before separation basing on the ballistic reentry trajectory.
- Slew maneuver is achieved during coasting phase throughout RACS, the Roll & Attitude Control System of the launcher, able to orient the LV in the desired optimal direction with a precision of few tenths of degree;
- Retro rockets are ignited once the third stage is separated. Ignition should be done as soon as

possible after stage separation in order to reduce the propagation of disturbances induced during the separation event, being the separated stage not controlled.

Desired impact point is defined during missionization phase. It is the nominal Z9 impact point, i.e. the point at which the separated stage falls down in nominal conditions if no NAM is performed. Maximal DV required from RR is comparable with the SRM energy loss due to scattering.

3.3 Optimal angle computation

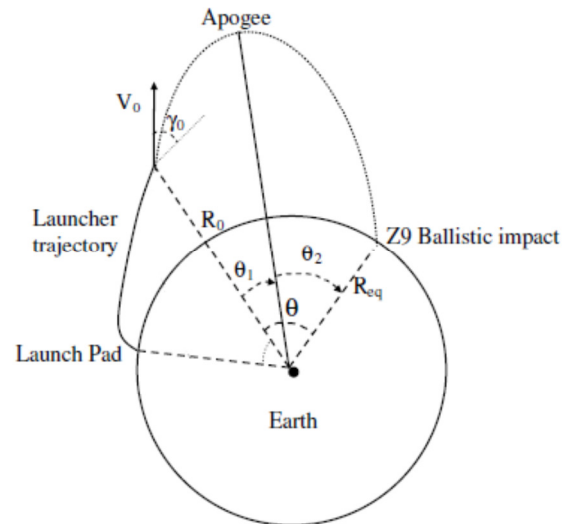
The optimal angle to orient the Z9 in order to have a ballistic reentry in the desired impact point is computed through the classical orbital equations based on ellipse parameters.

$$p = \frac{R_0^2 V_0^2 \cos \gamma_0}{\mu};$$

$$e = \sqrt{\sin^2 \gamma_0 + \left(\frac{V_0^2 R_0}{\mu} - 1 \right)^2 \cos^2 \gamma_0}$$

$$\theta_1 = \frac{(1 - p/R_0)}{e}; \theta_2 = \frac{(1 - p/R_{eq})}{e};$$

$$\theta = \text{sign}(\sin \gamma_0) \text{acos} \theta_1 + \text{acos} \theta_2;$$



3.2 Performances impact

Retro rockets are assumed to be of the same family of those used for the separation 1-2 of VEGA, providing an impulse of velocity in about one second.

Considering a Z9 mass and the DV provided by each RR a set of 4 RRs would assure a certain margin wrt the desired DV to be applied. Increase of the mass due to retro rockets however should be mitigated by the fact that, being the footprint much smaller, the constraints to be applied on the trajectory in order to have sufficient margins are less severe.

3.3 Results

The results in terms of error wrt desired impact point for a VEGA equatorial mission are reported in Table 1. Both nominal case and scattered thrust profiles are considered. The scattering is applied on combustion time and on specific impulse.

Calculation of the optimal angle is done 50s before the separation, in order to have time to perform the orientation slew. The acceleration provided by RRs is assumed almost impulsive (75 m/s² during 1 s of burning time).

Case	Optimal Angle [°]	Error [km]
Nominal	98.0	22.9
dIsp +	153.5	23.6
dIsp -	42.5	26.8
dTc +	94.0	24.8
dTc -	87.5	19.7
dTc + dIsp +	147.0	28.9
dTc + dIsp -	34.5	22.4
dTc - dIsp +	73.0	17.9
dTc - dIsp -	48.5	24.0

Table 1 Footprint for different propulsion curves

Table 1 reports the computation of the optimal reentry angle and of the absolute error with respect to the target impact point for each Z9 extreme curve (max and min Isp, max and min Combustion Time, combination of Isp and Combustion Time).

The error appears to be very small, with a reduction of two orders of magnitude wrt the NAM footprint.

This is the ideal case: the only source of error is the approximation in the computation of the optimal angle (it can be addressed as “guidance error”). Current optimization algorithm uses a discretization of 0.5° for the angular deviation of DV. This value can be reduced, but however it is useless to improve it too much (increasing the computational time) because of control errors and disturbance errors, that are much higher.

The description of the different error sources is treated in the next section.

3.4 Other error sources

Errors that can impact the accuracy of the Z9 reentry with RRs are the following:

- Control Errors (ACS accuracy around θ_{cmd} and ψ_{cmd});
- Separation disturbances ($\Delta\theta$ and $\Delta\psi$ separation);
- Navigation errors on position and velocity;
- Mass error (Z9 inert mass scattering);
- RR impulse error;
- Orbital propagation error.

For each source the entity of these disturbances will be quantified and then the impact in terms of footprint (range) will be evaluated.

• Attitude Control Error

The VEGA baseline approach uses only TVC to control pitch/yaw attitude before Z9 separation (RACS is only devoted to roll control during Z9). The proposed strategy introduces a RACS 3axes controlled phase after Z9 burn out, in order to execute the slew manoeuvre and to reduce as much as possible the error between the optimal angle and the realized one at separation event. RACS pointing accuracy gives an error of the order of some tenth of degree. This error could be limited under 0.5°, but it cannot be null, so it has to be taken into account to compute the footprint extension.

• Separation Disturbances

The RRs have to be ignited just after separation command. Separation disturbances for the current VEGA configuration are very important. They can be expressed as a disturbance on transversal angular rate, given by:

$$\omega_{SEP} = Torque * dt / J_{Z9}$$

Considering a RR firing time of about 1 second, the attitude error can reach 2°, that is the most dimensioning error between the others already mentioned.

If the direction of the RR impulse is not the optimal one, we will have a deviation of the impact point wrt the target.

In order to quantify the impact of attitude error on footprint extension a sensitivity analysis has been

performed considering increasing values of attitude errors.

The behavior is quite linear with the attitude error.

We can quantify the sensitivity of footprint extension to attitude error with $40\text{km}/^\circ$.

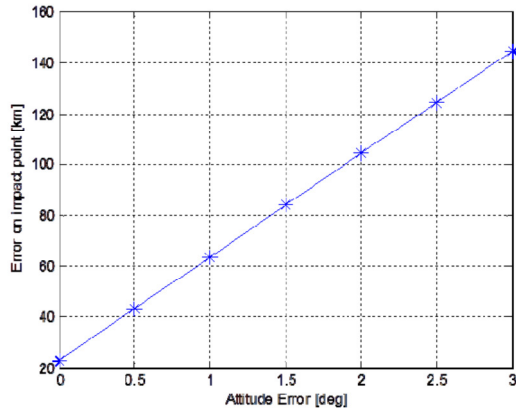


Figure 1 Footprint extension wrt Attitude Error

- **Navigation Error**

IRS Navigation error has been estimated evaluating the difference between IRS output and real positions/velocity at Z9 exhaustion on 1000 runs of a Monte Carlo campaign for a VEGA equatorial mission.

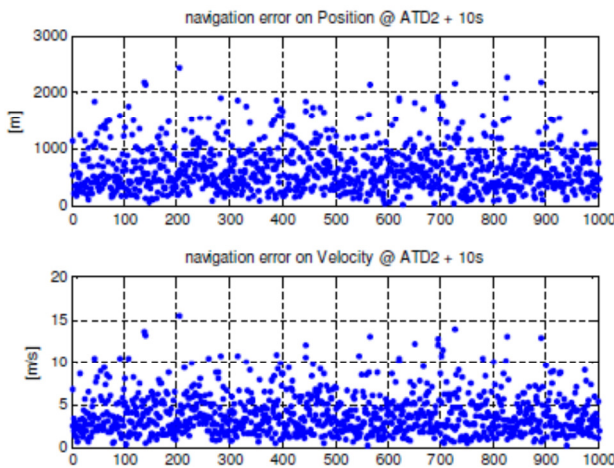


Figure 2 IRS navigation error at Z9 exhaustion

We can consider a maximum value of error of 2km on position and 12m/s for velocity. In the following table the footprint extension for a VEGA equatorial mission is presented, where error on position and velocity is introduced. Error on final impact point still remains within acceptable values.

Case	Error [km]
Nominal	104.3
dIsp +	145.2
dIsp -	142.5
dTc +	105.4
dTc -	65.8
dTc + dIsp +	107.8
dTc + dIsp -	115.8
dTc - dIsp +	146.9
dTc - dIsp -	126.3

Table 2 Impact of navigation error

- **Mass Error**

The error on inert mass for Z9 stage can be estimated in a conservative way equal to 5% at 3σ . This error impacts directly on the footprint extension, as shown in the following table for an equatorial mission.

Case	Error [km]
Nominal	22.9
dIsp +	121.6
dIsp -	76.8
dTc +	16.8
dTc -	5.0
dTc + dIsp +	117.3
dTc + dIsp -	91.0
dTc - dIsp +	51.7
dTc - dIsp -	72.3

Table 3 Impact of mass dispersion

- **RRs Impulse Error**

RR impulse scattering can be considered 2% at 3σ . Impulse scattering should be distributed on 4 RRs. Scattering on combustion time doesn't impact reentry performances.

Impact of impulse error is evaluated for an equatorial mission, as presented in the following table. It is evident that the impulse error influences marginally the final error on impact point.

Case	Error [km]
Nominal	22.9
dIsp +	33.4
dIsp -	16.7
dTc +	24.0
dTc -	17.2
dTc + dIsp +	37.8
dTc + dIsp -	11.7
dTc - dIsp +	11.0
dTc - dIsp -	14.5

Table 4 Impact of RR impulse dispersion

- **Propagation Error**

The propagation errors accounts the assumption accepted to evaluate the position and velocity the launcher will have at the retro rocketed ignition:

- J2 gravity term is neglected (but it can be included using the navigation function, even if we consider this effect very small).
- perturbations of the orbit coming from RACS thruster activation are neglected.

Propagation error remains quite small: less than 500 m for the position and 0.5 m/s for the velocity.

- **Error Synthesis**

Error Sources	Footprint Impact
Navigation Error	147 km
Attitude Error (control, separation, guidance optimization errors)	40 km/°
Mass Scattering (worst SRM scattering combination)	122 km
Retro Rocket Impulse Error	40 km
Propagation Error	Negligible
Quadratic Sum (considering 3° of attitude error)	230 km

Table 5 Error synthesis

The table highlights the big improvement that the Z9 reentry produces in the footprint extension: considering the whole set of errors the reentry zone remains an order of magnitude lower than the footprint obtained by NAM.

3.5 Monte Carlo Verification

A set of 1000 simulations has been performed in order to verify, with a Monte Carlo statistical approach, the reduction of the footprint obtained considering all the error sources acting together.

The hypotheses of the simulations are the following:

- Gaussian distribution of the Z9 propulsive curve between minimum and maximum Isp;
- Gaussian distribution of navigation error;
- Gaussian distribution of attitude error wrt optimal reentry angle;
- Gaussian distribution of mass for Z9 separated stage;
- Gaussian distribution of Retro Rocket Impulse.

Results are reported on the plot below. The extension of the footprint is about 400km, in line with the estimation provided in Table 5 (near the Equator 1 degree of longitude corresponds to about 110km of footprint).

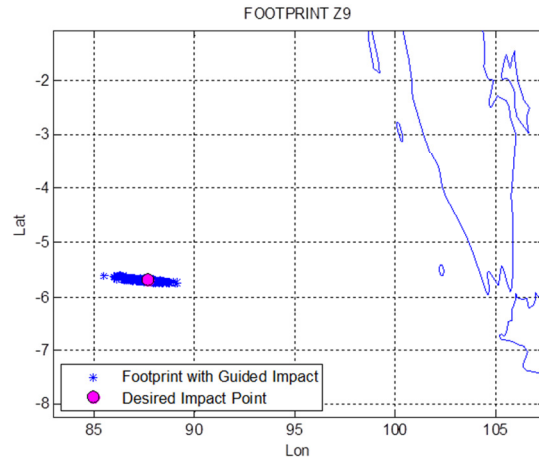


Figure 3 Z9 Footprint with Retro Rocket strategy

4. CONCLUSIONS

Reentry achieved by RRs has been investigated and possible error sources have been studied.

Introduction of a set of 4 retro rockets for the guided reentry of Z9 separated stage has demonstrated to be a feasible way to drastically reduce footprint extension.

It has been shown that footprint extension is halved for polar missions and reduced of an order of magnitude for equatorial ones. A quadratic sum of the different sources of possible errors produces an extension of the footprint lower than 460km (+/- 230km), against the current 2000km for the equatorial missions.

The main drawback of this solution is the impact in term of layout, with the introduction of 4 retro rocket in the Z9 configuration.

5. REFERENCES

- [1] F.J. Regan, S.M. Anandkrishnan, Dynamics of Atmospheric Re-entry, AIAA Education Series, 1993 AIAA, pg 175-177
- [2] P. Zarchan, Tactical and Strategic Missile Guidance, AIAA Technical Missile Series, 1994-AIAA, pg 297-305