FLIGHT MECHANICS OF THE ENTRY, DESCENT AND LANDING OF THE EXOMARS MISSION

Rodrigo Haya Ramos[†], Davide Bonetti[†]

[†]DEIMOS Space S.L., Ronda de Poniente, 19, Ed. FITENI VI, Portal 2, 2º, 28760, Tres Cantos, Madrid, Spain

rodrigo.haya@deimos-space.com, davide.bonetti@deimos-space.com

ABSTRACT

ExoMars is ESA's current mission to planet Mars. A high mobility rover and a fixed station will be deployed on the surface of Mars. This paper regards the flight mechanics of the Entry, Descent and Landing (EDL) phases used for the mission analysis and design of the Baseline and back-up scenarios of the mission. The EDL concept is based on a ballistic entry, followed by a descent under parachutes and inflatable devices (airbags) for landing.

The mission analysis and design is driven by the flexibility in terms of landing site, arrival dates and the very stringent requirement in terms of landing accuracy. The challenging requirements currently imposed to the mission need innovative analysis and design techniques to support system design trade-offs to cope with the variability in entry conditions. The concept of the Global Entry Corridor has been conceived, designed, implemented and successfully validated as a key tool to provide a global picture of the mission capabilities in terms of landing site reachability.

INTRODUCTION

ExoMars is ESA's current mission to planet Mars aimed for launch between 2013 and 2015. The project is currently undergoing Phase B studies under the European Space Agency (ESA) management and Thales Alenia Space project leadership. In that context, DEIMOS Space is responsible for the Mission Analysis and Design of the Entry, Descent and Landing (EDL).

The mission analysis and design of the EDL comprises the flight from the separation of the Descent Module (DM) from the carrier up to the landing onto the Mars surface. The mission baseline analysed up to the System Requirements Review (SRR) is based on a Soyuz-Fregat launch from Kourou in 2013 of a spacecraft composite bearing a Carrier and DM. A back-up option is proposed in 2015. Additional scenarios with an orbiter have been considered, covering dual launch with Soyuz and single launch with Ariane 5 for launch opportunities at 2011, 2013 and 2015.

At this stage of project, the design of the EDL phases is driven by the flexibility in terms of landing site and the very stringent requirement in terms of landing accuracy. Pre-SRR specification states that the DM must be able to land during daylight within the latitude band (15ºS,45ºN) at a maximum altitude above the MOLA areoid of 0 m with a landing accuracy of ±25 km 3σ. The entry either from the arrival hyperbola or from a High Elliptic Orbit (HEO) will be ballistic, non-propulsive and non-controlled. Two options for the landing systems are analyzed: vented and non-vented airbags.

The envisaged EDL concept will be based on the following general sequence: after the separation from a carrier or an orbiter, the DM enters the atmosphere and deploys a supersonic drogue below Mach 2 and later the main parachute. During the descent, the heatshield is released and, in case of non-vented airbag, the Lander is lowered to allow the operation of the retrorockets. Vertical retrorockets of solid or liquid type are ignited to perform the final braking. The airbags are deployed and the Lander free falls after release from the rest of the DM.

This paper regards the flight mechanics of the EDL phases, with particular attention to the characterization of the mission requirements and constraints that drive the mission feasibility.

After the Implementation Review milestone, the selected mission is based on the release from an orbiting carrier module (CM). The landing accuracy requirement has been relaxed to 50 km 3σ. The mission analysis and design of this mission is currently undergoing and the results are out of the scope of this paper. In any case, some indications of the impact of the new mission in the flight mechanics of the EDL will be provided.

MISSION REQUIREMENTS

The ExoMars mission[1] is meant to search for traces of past and present life, characterize the Mars geochemistry and water distribution, improve the knowledge of the Mars environment and geophysics, and identify possible surface hazards to future human exploration missions.

The pre-SRR mission baseline foresees a single Soyuz 2b launch (from Kourou) of a Carrier spacecraft and a Descent Module (DM). The ExoMars DM will then deploy two science elements on the Martian surface: a high-mobility Rover and a fixed station, the Geophysics/Environment Package (GEP). The ExoMars Rover will carry a comprehensive suite of analytical instruments dedicated to exobiology and geological research: the Pasteur Payload. Over its planned 6-months nominal surface mission, the Rover will ensure a mobility of several kilometres searching for traces of past and present signs of life. It will do this by collecting and analyzing samples from within surface rocks, and from underground down to a depth of 2 meters.

Following the outcome of the Ministerial Council of December 2005, two optional mission scenarios including a European Orbiter shall be studied based on an additional launch carrying a European Orbiter for data relay only and a single Ariane 5 ECA launch carrying a European Orbiter and the DM with the Rover and GEP payload. Due to the higher capability of Ariane 5, elliptic entry is considered besides the direct entry.

The scenarios under consideration taking into account the launcher, launch opportunity, number of launches and type of entry applicable for EDL are presented in Table 1.

Table 1: Mission scenarios applicable for EDL (pre SRR)

Launcher	S/C	Entry	Launch Opportunity
Soyuz	Carrier + DM	Hyperbolic	2011 2013 2015
Ariane	Orbiter + DM	Elliptic Hyperbolic	2011 2013 2015

The DM forebody geometry is based on the classical (Viking, MPF, MER) 70 deg cone aeroshell and 47 deg rear cone angle. The maximum mass at entry is limited to 1 Ton for Soyuz and 1.2 Tons for Ariane 5, both with 3.4 m. Some cases up to 1.13 Tons for Soyuz with a diameter of 3.2 m have been also inspected. Several architectures have been evaluated. The options for the DM, parachutes, Reaction and Control System (RCS) and airbags are listed in Table 2.

Table 2: EDL architectures

DM	Parachutes	Retro-rockets	Airbags
70º/47º aeroshell	Single Stage Two Stages	Solid rockets Liquid rockets (Fixed/Modulated Thrust)	Non vented Vented

The Mission Requirements cover the scientific and the technological objectives of the Exomars mission. Many of these requirements have an impact in the design of the EDL. The main ones are summarized in Table 3.

Table 3: Main mission requirements (pre-SRR) applicable for EDL

Subject	Requirement
Landing Latitude	15ºS to 45ºN
Nominal Rover Surface Mission	180 sols, outside Global Dust Storms
Landing accuracy	25 km 3σ (objective), 15 km 3σ (goal)
Landing time	Daylight
Landing altitude	< 0 m MOLA
Oscillations under parachute	< 10º
Descent and Landing Loads	< 40 g
Entry Control concept	ballistic
Terrain Slopes	< 10º (100 m scale), < 18º (10 m scale)
Winds at landing	< 20 m/s (horizontal), < 5 m/s (vertical)

The wide range in terms of landing site latitude besides the compatibility with several launch opportunities lead to a large variability in terms of atmospheric conditions. The compliance of the challenging landing accuracy for a ballistic entry mission relies on an accurate navigation before the separation event. The landing altitude, which is well above past missions, imposes a restrictive constraint for the minimum altitude for deployment of the parachute.

ARRIVAL CONDITIONS

The conditions at the end of the interplanetary cruise from Earth to Mars drive the achievable entry conditions either for direct or for elliptic entry and the capability of targeting the landing site. On the other side, the flight inside the entry corridor during the atmospheric phase imposes a window of conditions at the Entry Interface Point (EIP) that the exo-atmospheric flight must be able to meet.

The arrival conditions depend on the transfer window from Earth to Mars. In the frame of the mission analysis and design of the interplanetary phases of the Exomars mission[2], several windows have been computed for the scenarios under consideration with different transfer strategies (direct and delayed trajectories). Figure 1 shows the solar longitude Ls at Mars arrival for some transfer windows of Soyuz-Hyperbolic and Ariane 5 (AR5) Hyperbolic and Elliptic release entry. The solar longitude of past entry missions is also indicated. The solar longitude is referred to the Mars vernal equinox (Ls=0º). The shaded region indicates the period when Global Dust Storms (MGDS) are likely to occur: it corresponds to 3 months before and 3 months after the Mars perihelion. From this figure, the arrival will occur either at the end of the MGDS or close to the 180 sols margin before the onset, which is the nominal surface mission. In case of arrival during the MGDS, the composite spacecraft must wait on orbit until the end of the MGDS season.

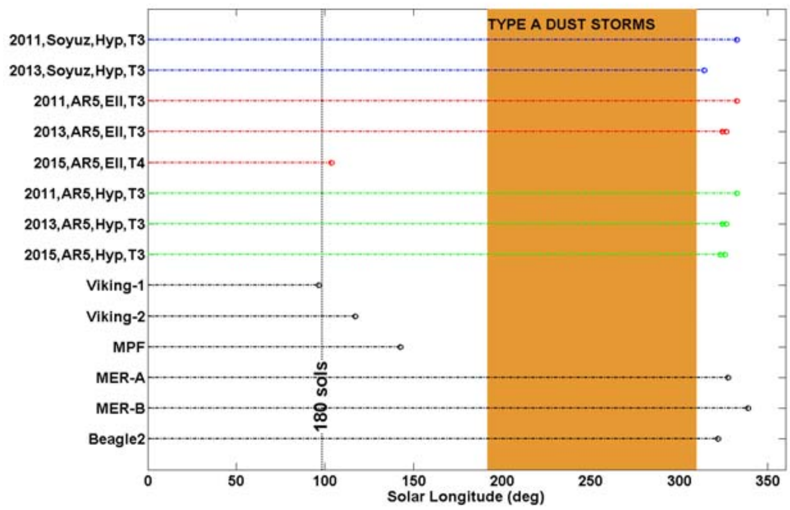

Figure 1 Solar longitude at Mars arrival

Atmospheric conditions at arrival play a key role in the identification of the mission requirements and constraints. The European Mars Climate Database (EMCD) has been extensively used for the atmospheric predictions[4]. The EMCD is a database of atmospheric statistics compiled from state-of-the art General Circulation Model (GCM) simulations of the Martian atmosphere. The models used to compile the statistics have been extensively validated using available observational data and represent the current best knowledge of the state of the Martian atmosphere given the observations and the physical laws which govern the atmospheric circulation and surface conditions on the planet. This model allows the calculation of the atmospheric properties in extreme dust scenarios, ranging from a clear atmosphere up to a Global Dust Storm (optical depth $\tau = 4$).

Extreme atmospheric conditions have been identified as an input to the design of the Entry phase as well as for the Descent and Landing. There is a significant variability induced by the large landing site area and the range of arrival epochs. The design must be able to withstand those extreme conditions.

The targeting capabilities of the arrival orbit are expressed as the position, velocity and timing conditions that can be achieved at the EIP. For arrivals restricted to the landing latitude band with daylight landing, the arrival typically occurs between 10:00 and 15:00 Local Time (LT). In the scenarios with hyperbolic entry, the heading is eastwards, while for the HEO release cases, entry azimuths vary between Northeast and East. The inertial velocities at entry are ≈5.6 km/s for direct entry and ≈4.8 km/s for elliptic. The reduction in the entry velocity significantly alleviates the heat fluxes on the heatshield. An example of the variability of the Local Time at arrival and the heading as a function of the latitude and the targeted entry angle at the EIP is shown in Figure 2. It corresponds to an entry from elliptic orbit (Ariane 5 launcher).

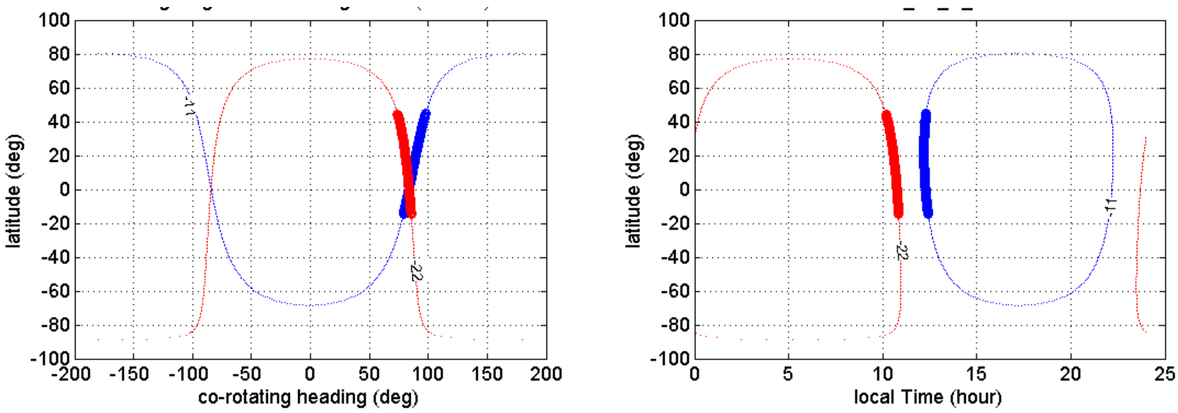

Figure 2 Targeting of landing site for a HEO release (Ariane 5 mission)

The interplanetary mission analysis for the selected mission after the Implementation review is presented in [3] as an update of [2]. This paper is aligned with the last reference, while the former is leading current mission analysis and design of the EDL.

GLOBAL ENTRY CORRIDOR

The entry of a vehicle in a planetary atmosphere is constrained by a set of factors that builds up a lower and upper limit for the trajectory parameters. It is known as the entry corridor. The entry corridor for a ballistic entry is usually expressed in terms of flight path angle at the Entry Interface Point (EIP) and the ballistic coefficient of the entry capsule in a reference flight condition, defined as:

$$BC = m / SC_D \tag{1}$$

where m is the mass, S the aerodynamic reference surface and C_D the drag coefficient of the DM.

The entry corridor typically takes into account thermo-mechanical limits, conditions at the parachute deployment and mass limitations. In addition, landing accuracy has been considered for the entry corridor calculation, as it is no more a figure of merit (performance) of the mission but a leading constraint that strongly drives the mission capabilities. The selected model has been validated with dedicated Monte Carlo simulations. For an objective landing accuracy, the maximum dispersion in position and velocity can be derived as specification for the navigation at release.

The dispersions at the EIP are the main contributor to the landing accuracy: the entry is uncontrolled and the dispersion at the deployment of the parachute is derived from the navigation performances at the last Trajectory Correction Manoeuvre (TCM). Due to the different approach for the navigation, the dispersions at EIP are significantly lower for the release from HEO than the direct entry and the accuracy requirement is feasible. However, navigation support from an orbiter, like the Mars Reconnaissance Orbiter (MRO), for single beam interferometry or direct link between the composite spacecraft and that orbiter is needed in case of release from the arrival hyperbola in order to obtain dispersions at entry compatible with the required landing accuracy.

Figure 3 shows an example entry corridor for a landing site with thick atmosphere. It corresponds to a direct entry with Soyuz with parachute deployment at Mach 2. The grey area is the available entry corridor. The altitude at deployment usually limits the steep values for elliptic release entries, while heat flux is active constraint in case of release from the arrival hyperbola in most of cases. The shallow entries are limited in both cases by the landing accuracy. This limit is very restrictive and in case of a landing site with low density, it may prevent the vehicle from flying at shallow angles in order to respect the minimum altitude for parachute deployment, i.e., the corridor can close.

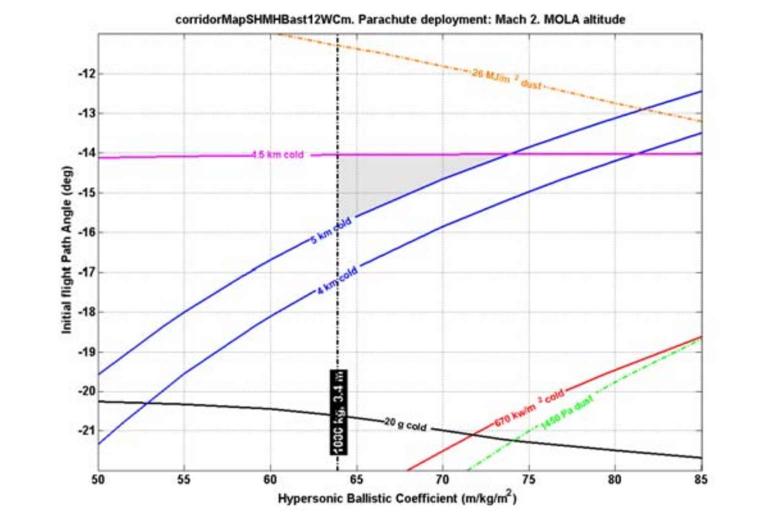

Figure 3 Entry corridor for Direct Entry and high density landing site

The entry corridor depends on the arrival conditions, atmosphere variability, local time and local topography, i.e., it is associated to a specific region and date. The generation of a single corridor valid for the required landing latitude band would require the cumulative adding of worst-case conditions. It leads to unrealistic scenarios due to the large variability between sites in terms of atmosphere (thin or dense regions for high and low atmosphere layers at several arrival dates) and surface altitude with respect to MOLA areoid.

For these reasons, a single design cannot cover the full range of landing regions. Moreover, the worst-case condition varies with the constraint, i.e. there is not a single scenario that is a worst case for all of them. Due to those limitations, the concept of the entry corridors has been extended. The approach is to extend entry corridors to a planetary level for identification of realistic worst cases in the latitude band of interest with direct mapping of landing site location with mission performance. On a planetary scale, Global Entry Corridor (GEC) maps can be generated for a given Ballistic Coefficient and mission scenario: they provide the global capability of the Descent Module to safely land inside the required landing latitude band.

GEC maps are generated by using specific models calibrated on a reduced number of entry corridor width evaluations, which avoids fine grids in three dimensions (latitude, longitude and time). Maps are metamodels of the problem, giving a fast and quite accurate prediction of the corridor width on any point that is not included in the set of the evaluated sites. Since they predict the most probable value as a function of the known samples evaluated, their accuracy clearly increases with the number of function evaluations. It is possible to refine a metamodel guess by adding new samples in strategic regions of the domain: if an iterative process is set, it is possible to progressively generate new metamodels by evaluating new entry corridors and adding new samples to the list. Accurate models of the entry corridor can be obtained within little iteration. The final model can be queried in a short time and gives the possibility of generating reliable predictions of any modelled variable.

Global Entry Corridors have been produced for all the scenarios and arrival conditions. As an example, Figure 4 shows the corridor width inside the landing latitude band for the Soyuz 2013 mission (delayed transfer T3) with direct prograde entry at a solar longitude of Ls=312º compatible with parachute deployment between Mach 1.8 and Mach 2.1 and any local Time inside the operationally valid range. Atmospheric and aerodynamic uncertainties are considered. The 0 m MOLA contour has been added as a reference (pink line). Wide and almost flat areas, like Arcadia, Amazonis, Isidis and Elysium Planitia are suitable landing sites; the Olympus Mons and Tharsis Mons are clearly identified as non-feasible regions. The Mars environment in this map is the one expected just a short period after the Dust Storm Season, and is characterized by a cold scenario.

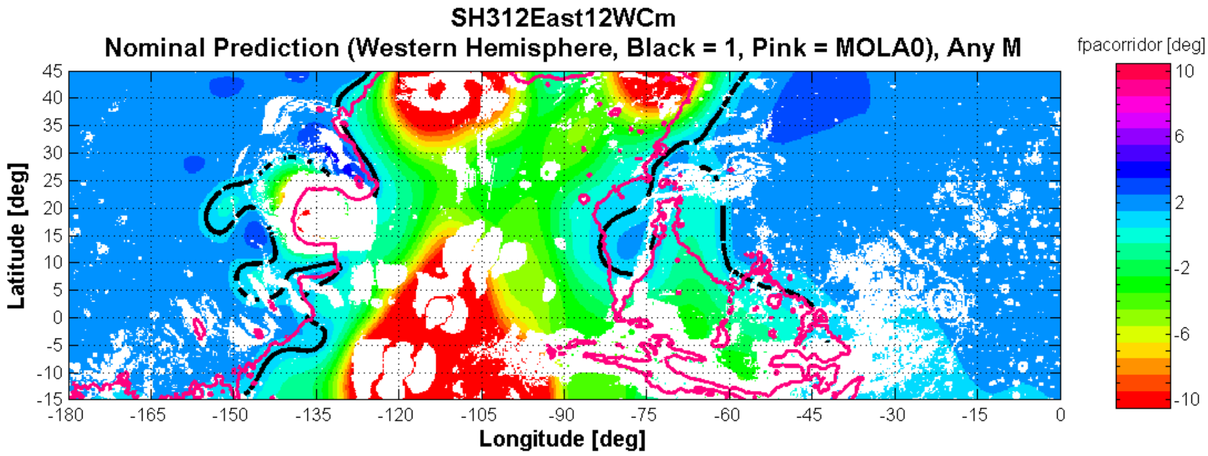

Figure 4 Global Entry Corridor for hyperbolic release (Soyuz, 2013, delayed transfer T3)

If a minimum flight path angle corridor of one degree is set to ensure margins, the available regions for landing are smaller than the part of planet at altitudes below 0 m MOLA. There are a few small regions above 0 m MOLA where a safe entry trajectory exists. The regions where there is no corridor indicate that the required flight path angles to comply with the altitude at deployment are so shallow that the landing accuracy requirement is not met. The worst region is the Tharsis one, where no corridor is available. Wide regions, like Arabiae Terra and Kasei Valles are close to 0º corridor values, indicating that they could be opened up if the constraints were slightly relaxed.

The GEC process gives the possibility to consider all the constraints of the entry phase in one step, to generate Maps assessing the quality of the feasible and non feasible solutions in terms of entry corridor width, to highlight the regions with the widest entry corridors, to highlight the true non-feasible planet regions, to update the MOLA 0 m constraint with the more realistic minimum corridor width criteria, to have global view of the mission performance capabilities depending on location (Latitude and Longitude) and to identify regions with underperformances. Global Maps can be used to characterize the value of parameters like the maximum and minimum heat flux, heat load, landing accuracy or dynamic pressure at parachute deployment within the entry corridor, given that any entry variable can be modelled and plotted in Maps as the presented entry corridor.

The percentage of regions within the latitude band (15ºS, 45ºN) where the corridor is wider than a minimum value is set as a figure of merit to compare the mission scenarios. Considering all of the scenarios, 40% of the landing sites inside that latitude band, regardless of the surface altitude, can be reached during entry. The Ariane Hyperbolic release scenario is the worst case due to the higher entry mass compared to the Soyuz scenario. In both cases, precise navigation is needed, as a regular interplanetary navigation approach does not provide the level of dispersions at EIP required to comply with the accuracy at landing. If this precise navigation is achieved, the Ariane HEO release scenario provides similar performances to Soyuz Hyperbolic. The reason is that, despite the better landing accuracy and lower entry velocities, the ballistic coefficient is higher and it reduces the entry corridor (Figure 3).

The Global Entry Corridors are being applied to the enhance mission selected after the Implementation Review. The specific characteristics of this scenario have lead to the extension of the GEC by increasing the number of variables. Five dimensional GEC have been implemented providing a fast modelisation of the entry capability of the DM depending on the landing site location, season, local time and mass. As in the case presented in this paper, the calibration of the GEC is performed with high-fidelity models of the trajectory dynamics, environment and aerodynamics.

SUPPORT TO LANDING SITE SELECTION

It is not possible to land in any point of the planet. There are regions that are not compliant with engineering requirements and regions that are less interesting from a scientific point of view. Engineering requirements can be strictly defined and filtered areas derived; however, scientific objectives expressed as specific landing sites have not been specified yet for Exomars.

Independently from the entry capabilities of the DM presented in the previous section, the landing regions can be filtered taking into account the available mission requirements (Table 3): landing site latitude and ground altitude. The application of a restriction in the terrain slope depends on the scale. Current requirements are applicable only for local analyses, like hazard avoidance. The evaluation of intermediate and small length scale slopes are expected to be determined for only the highest priority sites, as they cannot be determined just using MOLA data and high-resolution stereo images are needed. Thus, for the preliminary filtering of landing sites, a large-scale criteria will be considered.

In MER, the slopes on the scale of 1 km were restricted to about 2º to limit the bouncing after the first impact[5]. Thus, for an Exomars DM with a non-vented airbag system this limitation would be applicable. Due to radar altimeter errors at the beginning of the powered descent, an initial specification of 3º in the 2-5 km scale has been set. The applicability of this constraint depends on the navigation concept (sensors and filter) finally selected for the descent phase, which will provide the required altimeter accuracy and tolerance to slopes.

The application of these criteria allows the identification of candidate regions for landing just using terrain characteristics. A clearance area of the size of the landing ellipse around a particular site is imposed to ensure the compliance of the terrain constrains within the footprint. Figure 5 shows the feasible regions for landing after filtering of the terrain for the quadrant (90ºW, 0º) in the landing latitude band with a clearance box of 25 x 25 km. The grey area indicates that the landing site violates any of the constraints (altitude above MOLA, terrain slope, clearance). The landing site of Viking-1, MER-B and MPF is indicated in the figure. Different sizes and shapes for the landing ellipse have been considered.

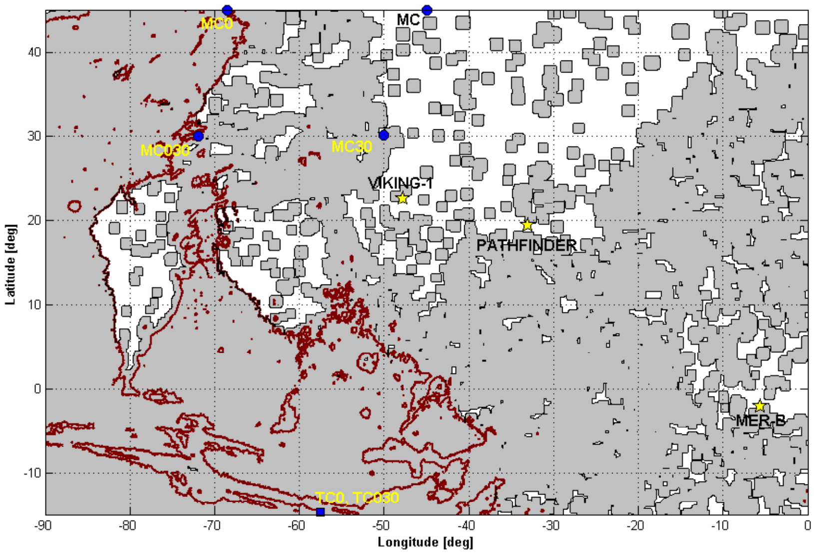

Figure 5 Feasible landing sites based on terrain filtering

The terrain filtering due to engineering constraints can be combined with the scientific goals in terms of preferred landing sites for evaluating its feasibility. The landing site selection process for Exomars has not been carried out yet. Thus, this combination has been validated using potential regions of interest[6]. The overlap of this map of filtered terrain with the Global Entry Corridors provides the landing site regions that can be really reached by the DM. An example is shown in Figure 6, where the orange contours are the feasible landing sites compatible with the scientific requirements, engineering requirements and the Global Entry Corridors for the same case presented in Figure 4. This region corresponds to Terra Meridiani and some of the feasible areas are close to the Opportunity landing site, which validates the approach.

The overall percentage of landing areas within the landing latitude band that can be reached according to the Global Entry Corridors and the engineering constrains for the Soyuz 2013 mission with two different transfers and DM sizes is summarized in Table 4. The percentage refers to the area below 0 MOLA in the latitude band 15ºS,45ºN. For the 3.4 m case, the feasible landing sites (rightmost column) are mostly filtered with the engineering constraints, while for the 3.2 m case, the minimum corridor size additionally reduces 11% the feasible sites.

Table 4: Soyuz 2013. Percentage of feasible areas depending on the constraints

Case	Global Entry Corridor	Engineering Constraints	Both
Soyuz 2013, T3, 3.4 m DM	78%	32%	30%
Soyuz 2013, T4, 3.2 m DM	40%	32%	21%

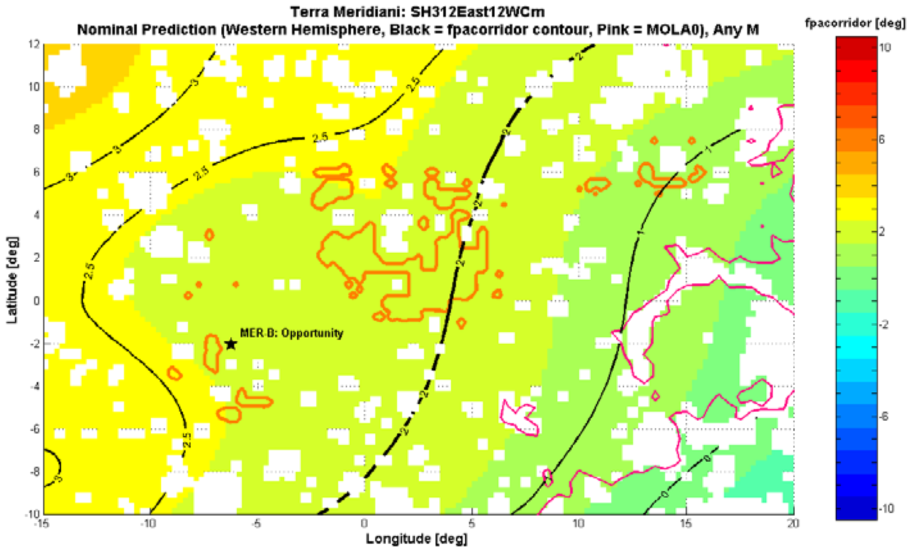

Figure 6 Feasible Sites: Global Entry Corridors +Engineering & Scientific Constraints

SIZING TRAJECTORIES

The Global Entry Corridor method supports the preliminary evaluation of any variable related to the entry phase. The predictions given by the model are fast and no simulation is required once the model has been created. With the support given by this tool, it is easy to extract extreme values of any entry variable besides the prediction of the landing sites where such as extreme values are reached. Moreover, the range of variability of any variable of interest (heat flux, heat load, landing accuracy…) inside the latitude band for the sites where an entry corridor exist, can be easily obtained.

This method has stressed the fact that a single trajectory for sizing does not exist, as the worst condition for the parameters that drive the design does not correspond to a single trajectory. The example of the heat transfer is clear: maximum heat fluxes, that drive the selection of the material, are associated to steep entries while the integrated heat flux (heat load), that drives the heatshield mass, is obtained in shallow flights.

Thus, two main sizing trajectories, one associated to a steep case and another to a shallow case are recommended as specification for the design of the subsystems. Additional trajectories can be computed as modification of those main profiles for specific purposes. Figure 7 shows the profile of a end-to-end trajectory used for assessment of the Guidance, Navigation and Control (GNC) and events triggering during the descent and landing phases. The events since drogue deployment to touchdown are indicated. The descent system corresponds to a two stage parachute system based on a Disk Gap Band (DGB) drogue and a ringslot main parachute, the RCS system is throttleable (liquid retrorockets) and the airbag is vented.

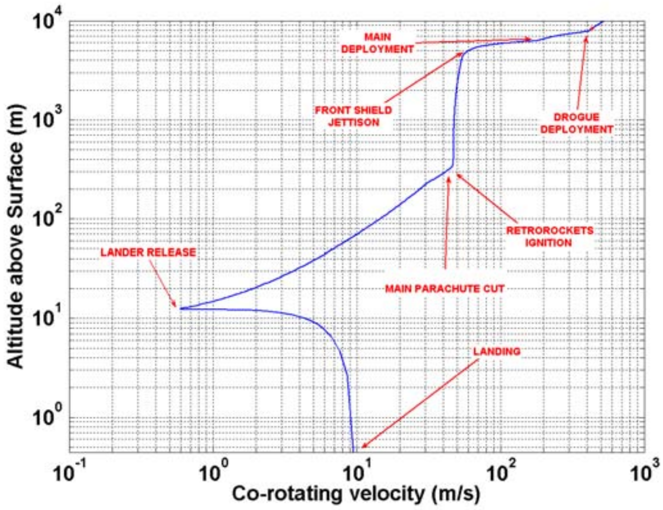

Figure 7 Descent and landing trajectory for a vented airbag system with two stages parachute system.

CONCLUSIONS

The design of the EDL phases for the Exomars mission is characterized by the large variability of the conditions in terms of landing site, arrival date and entry conditions associated with the pre-SRR scenarios Soyuz Hyperbolic release, Ariane Elliptic release and Ariane Hyperbolic release.

A new approach to the worst-case analyses conceived by DEIMOS Space has been implemented based on the calculation of Global Entry Corridors maps. The combination of this technique with worst-case selection methods is recommended as a further exploration in the worst-case analysis and margins philosophy. The Global Entry Corridors assess the capability of the DM to land on a specific landing site inside the landing latitude band regardless of the altitude of the site. On the other hand, the landing sites can be filtered using engineering criteria leading to Maps with feasible landing sites.

The superposition of both maps will provide a complete view of the mission capabilities to be compared with the set of landing sites of scientific interest. This is a global scale analysis that does not replace the local analyses needed once a subset of landing sites is proposed by the Exomars scientific community, but it provides a valuable input for such as landing site selection.

The sizing trajectories can be derived from the global view of the mission performances provided by the Global Entry Corridors maps. In this way, it is ensured that the sizing trajectories really bracket the extreme entry conditions the vehicle might find during the entry in any site within the required landing latitude band. It has been clearly demonstrated that a single trajectory is not able to represent the sizing case for all of the parameters that drive the design of the subsystems, like the heat flux and heat load for the Thermal Protection System (TPS) or the load factor for the structural design. Even if the worst case condition of several parameters were obtained for the same type of trajectories (shallow or steep), the rest of conditions (atmospheric uncertainty, dust scenario, aerodynamic dispersion, heading…) would be different and hence, there would be no a single steep and shallow trajectory that provides the worst case value for all of them.

From the pool of extreme trajectories identified for each parameter of interest, at least two, one associated to shallow and other to steep flight, have been extracted for the design of the EDLS components.

The results of these analyses have significantly contributed to the definition of requirements and constraints for the Phase B1 of the Exomars mission. The approach presented in this paper is currently applied to the selected mission after the Implementation Review, based on the release from orbiting Carrier Module (CM) with launch either with Ariane 5 or Proton M. The GEC method has been extended in terms of number of modeled variables to provide a more complete view of the DM capabilities that has notably increased the inputs for the Exomars system engineers.

REFERENCES

[1] J. Vago at al. *ExoMars. Searching for Life on the Red Planet*. ESA Bulletin 126, May 2006.

[2] J.L. Cano at al. *Exomars Mission Analysis and Design - Launch, Cruise And Arrival Phases*, 17th AAS/AIAA Space Flight Mechanics Meeting, Sedona, Arizona, January 28 - February 1, 2007

[3] J.L. Cano at al. *ExoMars Mission Analysis and Design - Launch, Cruise and Arrival Analyses*. 20th International Symposium on Space Flight Dynamics (ISSFD). Annapolis, USA, September 2007

[4] F. Forget at al. *Mars Climate Database. User Manual*. June 2005

[5] M.P.Golombek at Al. *Selection of the Mars Exploration Rovers Landing Sites* Journal Of Geophysical Research, Vol. 108, No. E12, 8072

[6] Bibring et al. *Global Mineralogical and Aqueous Mars History Derived from OMEGA/Mars Express Data*. Science. VOL 312, April 2006.