HiSST: International Conference on
High-Speed Vehicle Science Technology
26–29 November 2018, Moscow, Russia

# EXOMARS 2020 Entry Descent And Landing Mission Analysis Verification

*D. Bonetti*[1]*, I. Pontijas Fuentes*[1]*, G. Blanco Arnao*[1]*, G. De Zaiacomo* [1]*, L. Lorenzoni*[2]

## Abstract

This paper focuses on the Entry, Descent and Landing (EDL) Mission Analysis verification activities of the ESA/Roscosmos ExoMars 2020 mission, presenting the activities performed by DEIMOS Space in the programme Phase C to support the EDL Critical Design Review (CDR) in strict collaboration with Thales Alenia Space. The ExoMars 2020 mission consists of a Carrier Module (CM), provided by ESA, and a Descent Module, provided by Roscosmos with contributions by ESA and the European industry, which will be in charge of delivering the surface platform and the rover to the surface of Mars. The Descent Module (DM) will separate from the carrier shortly before reaching the Martian atmosphere. During the descent phase, a heat shield will protect the payload from the severe heat flux. Parachutes, thrusters, and landing systems will reduce the speed, allowing a controlled landing on the surface of Mars. After the separation, the carrier module will breakup into Martian atmosphere. The Mission Analysis activities presented in this paper focus on the DM flying qualities analysis, the EDL trajectory analysis and performance (including the CM-DM separation analysis) and at inspecting the applicable Martian atmospheric models. Flight verified design and analysis tools for Mission Engineering and the related design methodology for Atmospheric Flight have been used for this independent verification.

**Keywords**: *Mission Analysis, Entry Descent and Landing, ExoMars, Verification*

## 1. Introduction

The ExoMars programme is pursued as part of a broad cooperation between ESA and Roscosmos with significant contribution from NASA. DEIMOS Space has been involved in Exomars since 2004 providing more than 13 years of technical expertise in Mission Engineering (from launch to landing) and GNC.

Two missions compose the ExoMars programme with launches in 2016 and 2020.

The ExoMars 2016 mission, led by ESA, was launched by the Russian Proton on March 14th, 2016. The mission includes the Trace Gas Orbiter (TGO) and the Entry, Descent, and Landing Demonstrator Module (EDM, named Schiaparelli [1]), both supplied by ESA. Schiaparelli separated from the TGO on October 16th 2016 and reached Mars 3 days later: it successfully entered the atmosphere with a pre-defined FPA and performed a nominal hypersonic entry, decreasing its velocity until reaching subsonic regime under the parachute. During the descent phase an anomaly occurred, and the EDM separated from the backshell earlier than expected, compromising the landing phase. During the EDL, Schiaparelli was able to communicate directly to Earth and to Mars Express the UHF carrier signal and it transmitted its real time on-board telemetry to the TGO. The analysis of the data collected allowed the verification of the EDL performance, the validation of the mission analysis design methodology and tools, and the analysis and identification of the anomaly that occurred during the descent [2]. With Schiaparelli, Europe acquired for the first time flight telemetry of the entry and descent flight phases on Mars

Building on the experience gathered with the Schiaparelli key technologies demonstration, the European Space Agency and Roscosmos are developing the ExoMars 2020 mission, that has recently passed the Critical Design Review (CDR).

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[1] *DEIMOS Space S.L.U., Ronda de Poniente 19, Tres Cantos, 28760, Spain, davide.bonetti@deimos-space.com*
[2] *European Space Agency (ESA), The Netherlands, leila.lorenzoni@esa.int*

The ExoMars 2020 consists of a Carrier Module and a Descent Module which will be in charge of delivering the surface platform and the rover to the surface of Mars. The Descent Module (DM), provided by Roscosmos with contributions by ESA and European industry, will separate from the carrier shortly before reaching the Martian atmosphere.

DEIMOS Space, under Thales Alenia Space (TAS) acting as prime contractor for the ExoMars2020 Mission, is supporting the EDL Mission Analysis activities.

This paper focuses on the phase C Mission Analysis activities of the ExoMars2020 mission, presenting the verification activities performed by DEIMOS Space to support the System CDR in strict collaboration with TAS, aimed at the EM flying qualities analysis, the EDL trajectory analysis and performance (including the CM-DM separation analysis) and at inspecting the applicable Martian atmospheric models. Flight verified design and analysis tools, including the DEIMOS Space Planetary Entry Toolbox (PETBox) [3] for Mission Engineering and the related design methodology for Atmospheric Flight, have been used for this independent verification.

## 2. ExoMars 2020 Mission Overview

The 2020 mission will be launched by a Proton rocket in the 2020 and will arrive to Mars in 2021. The mission is composed of the Carrier Module (CM) which will transport the surface platform and the rover during the launch and cruise phases. During this interplanetary phase, Deep Space Maneouvers (DSMs) are foreseen in order to reach the desired separation conditions that result from the targeting of the desired landing site coordinates and the flight path angle at the Entry Interface Point (EIP). A Descent Module (DM) will separate from the carrier module 30 mins before reaching Martian atmosphere. Parachutes, thrusters and landing legs will speed down the DM allowing a controlled landing on the surface of Mars. While the rover will drive away from the surface platform to perform scientific investigations within several kilometres of the landing site, the platform will remain stationary and will investigate the local surface environment for its normal mission lifetime of one Earth year.

The selection of the landing site is an ongoing activity developed by the ExoMars Landing Site Selection Working Group (LSSWG), a team capable of dealing with the science and engineering constraints to select the landing site which will be certified for the mission. As a result of the fourth Landing Site Selection Workshop held in 2017, Oxia Planum and Mawrth Vallis were selected as the scenarios to be analysed in order to assess the fulfillment of the mission objectives with respect to the engineering requirements and the science objectives.

After landing, the rover will start its science mission and the ExoMars Trace Gas Orbiter (part of 2016 ExoMars mission) will support communications between Rover Operations Control Center (ROCC) located in Turin, Italy, the Surface Platform Operation Center (SPOC), the Martian rover and the Martian Surface Platform.

### 2.1. DM Overview

As a result of the interplanetary transfer, ExoMars will reach planet Mars with an hyperbolic trajectory: following separation from the CM, the DM will perform a direct ballistic entry into the Martian atmosphere followed by a descent phase under a two stage parachute system. Retro-rockets will then slow down the surface platform during the powered descent phase up to the point where the contact with the ground is detected and rockets are cut-off; final impact will be absorbed by the legs of the surface platform. The events sequence is represented in Fig. 1 and the DM design is described in the following sections.

#### 2.1.1. Entry

During entry an aeroshell, composed by the frontshield and the back cover, protects the internal payload and produces the aerodynamic drag necessary to dissipate the arrival energy, down to supersonic conditions.

The frontshield is based on a scaled-up version of the ExoMars 2016 sphere-cone configuration. The capsule diameter is increased up to 3.8 m. The nose radius is 0.95 m and the frontshield cone angle is maintained at 70º. The DM overall mass is about 2 tons. Comparison to past key missions to Mars is given in Table 1.

### 2.1.2. Descent

The descent phase is based on a double stage parachute, each deployed by dedicated pilot chutes:

- The first stage parachute is a 15 m diameter supersonic disk-gap-band (DGB) parachute. It is triggered below Mach 2.2 at an altitude below 8 km.
- The second stage parachute is a 35 m diameter ringslot which decelerates the DM once it is already in subsonic regime.

During descent phase, once capsule oscillations are damped and once the DM, the frontshield is jettisoned in order to allow the subsequent activation of the radar altimeter.

### 2.1.3. Landing

The landing phase is composed by the powered subphase, and the final touchdown. The powered phase starts after the separation of the landing module from the backshell and the second stage parachute and it is based on a set of retrorockets devoted to dissipate the remaining kinetic energy at the end of the descent phase. The final impact of the surface platform on ground is absorbed by landing legs deployed from the surface platform.

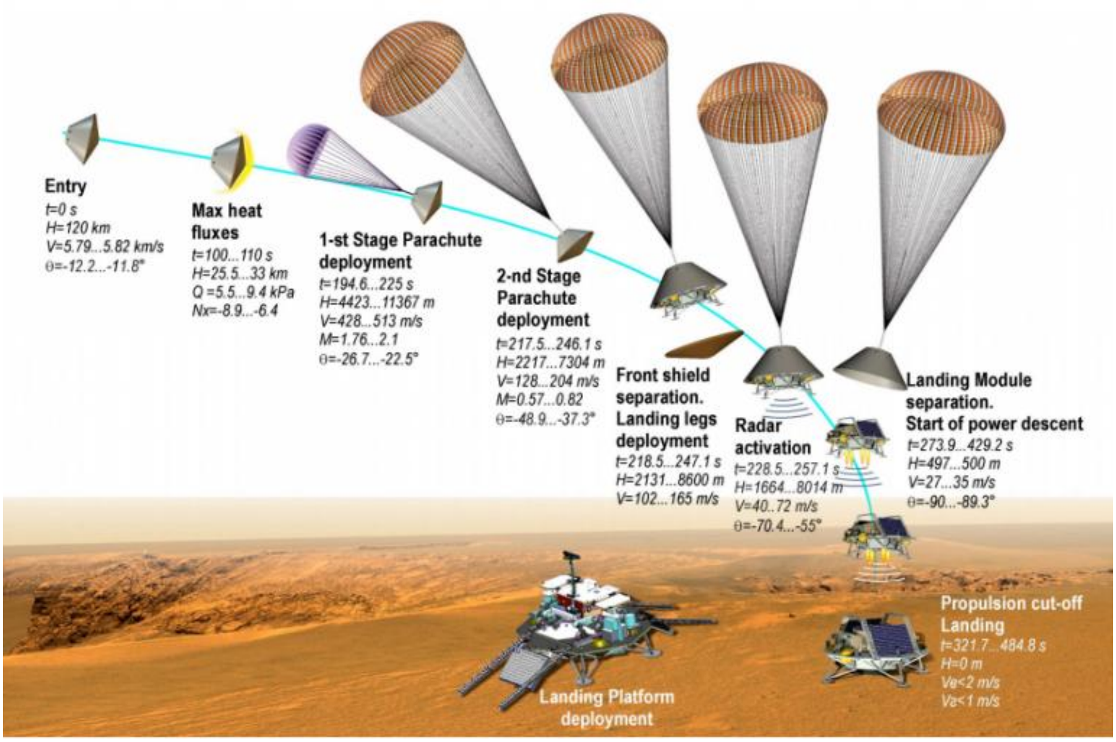

**Fig. 1**. Planned landing sequence of the ExoMars 2020 mission. Credits: ESA

**Tab. 1:** Comparative mass budget of selected missions to Mars (NASA missions from [5])

| Parameter | Viking | MPF | MER | Phoenix | MSL | ExoMars 2016 | ExoMars 2020 |
|---|---|---|---|---|---|---|---|
| Entry Mass (kg) | 980 | 585 | 836 | 603 | 3257 | 576 | **2000** |
| Landed Mass (kg) | 612 | 370 | 539 | 364 | 850 | 274 | **1200** |
| Mobile Mass (kg) | 0 | 11 | 173 | 0 | 850 | 0 | **300** |
| Aeroshell Diameter (m) | 3.5 | 2.65 | 2.65 | 2.65 | 4.5 | 2.4 | **3.8** |

## 3. EDL design verification

The main goal of the EDL design verification activities supported by DEIMOS is to validate the mission analysis performance and verify the fulfillment of the mission objectives while respecting the mission constraints, at aerodynamics (trim, stability), aerothermodynamics (thermal fluxes, thermal loads), mechanical (accelerations, dynamic pressures, parachutes deployment forces), safety (margins and mission success, separation from CM debris) and operational levels (sequencing of events, landing accuracy).

In order to support this verification, several analyses have been performed including Flying Quality analysis, EDL trajectory analysis and performance (including the CM-DM separation analysis), and inspection of the applicable Martian atmospheric models. More details are provided in the next chapters.

### 3.1. Flying Quality Analysis

The Flying Quality Analysis (FQA) consisted of:

- DM AEDB (AErodynamic DataBase, produced by NPO Lavochkin) inspection and analysis.
- Evaluation of static trim and stability entry capsule performance.

The analyses were performed covering all the flight regimes that the DM will experience during entry in the Martian atmosphere, from rarefied flow down to Mach 1.3. Special attention was dedicated to the AoA variability and to the capsule stability performance at the parachute deployment.

The assessment of the FQA performance and the verification of the design with respect to the margin is done with intensive Monte Carlo campaigns (4000 runs) considering applicable uncertainties for MCI (Mass, Center and Inertia), aerodynamics, and flight conditions (trajectory).

According to the output of the Monte Carlo campaign, the peak total trim angle of attack resulted to be 6º at Mach 7-10 considering the 99% percentile with a confident interval of 90% (Fig. 2).

In terms of stability, in a fraction of the MC shots, a statically unstable trim is obtained for the whole Mach range due to the backwards CoG location (see negative SM in Fig.2, right). Below Mach 3.5, a dynamic instability is found (damping ratio below zero for both longitudinal and lateral-directional, see Fig. 3). Overall, the capsule stability during the ballistic entry phase is guaranteed by the capsule spin rate (16.5º/s around the capsule symmetric axis, X). The value is selected to avoid large AoA at the expected parachute deployment, around Mach 2.

A ballistic entry with a spinning capsule is a classical approach for Mars entry and has been successfully demonstrated to work on multiple missions with similar aeroshells and inertia ratios (e.g. from MER to Schiaparelli, [1]). The approach is simple and robust with the drawback of large position dispersions due to the lack of the aerodynamic lift and of an active GNC guided control during the entry phase.

Trim and stability predictions of FQA are confirmed by dedicate 6-DoF Monte Carlo simulations campaign of the entry phase (Fig.4). Results obtained at FQA and simulation level contributed to the verification of the successful aerodynamic performance of the configuration design, in particular in terms of entry capsule CoG location and spin rate. Verification of margins in terms of trim (at both hypersonic regime where peak heat flux is reached) and in terms of stability (during the full entry, and in particular at parachute deployment) demonstrate satisfactory flying qualities from CM-DM separation down to 1st stage parachute deployment.

**Tab. 2:** Nominal EDM MCI values

| PARAMETER | Nominal value | Units |
|---|---|---|
| Mass | 1932.5 | Kg |
| CoG at FM frame (from nose) [X; Y; Z] | [-1.056; -0.004; 0.003] | m |
| Roll Inertia ($I_{xx}$), Pitch Inertia ($I_{yy}$), Yaw Inertia ($I_{zz}$) | [2391, 1915, 1532] | Kg/m2 |
| Roll-Pitch Inertia ($I_{xy}$), Roll-Yaw Inertia ($I_{xz}$), Pitch-Yaw Inertia ($I_{yz}$) | [5, 12, 6] | Kg/m2 |

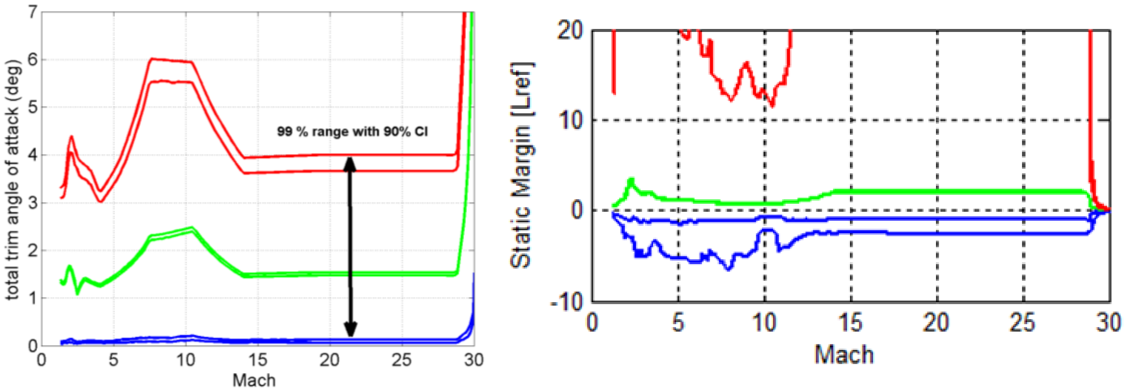

**Fig. 2 Left:** Total trim Angle of attack as function of Mach (99% range and average).

**Right**: Static Margin as function of Mach (99% range and average).

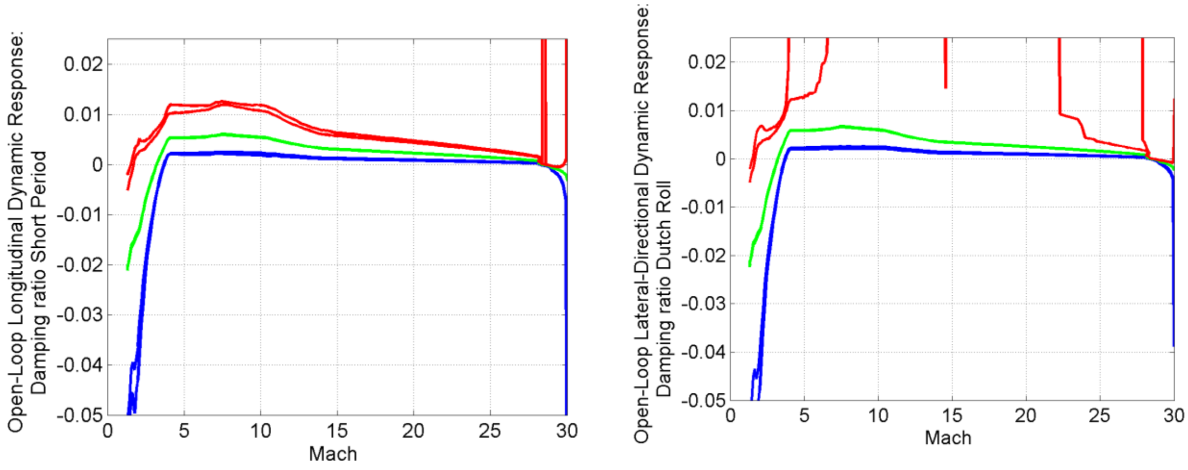

**Fig. 3** Statistics of Short Period and Dutch Roll damping. Credits: DEIMOS.

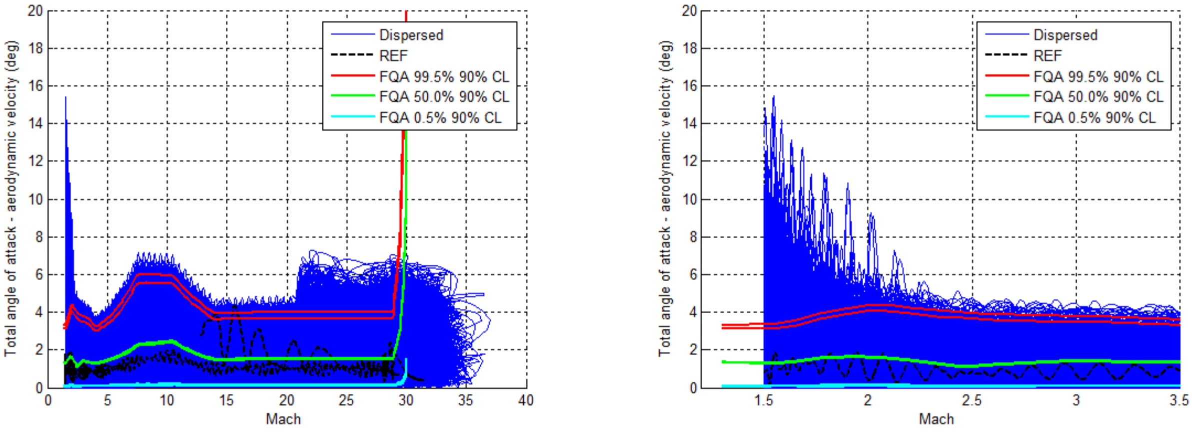

**Fig. 4** Total Angle of attack profiles vs Mach (Left: EIP to Mach 1.5, Right: zoom M<3.5) Credits: DEIMOS.

### 3.2. Environment Inspection

In 2015, a new Mars Climate Database (MCD) version has been released by the LMD team (MCD v5.2 [4]). DEIMOS performed the inspection of this atmospheric model to support the definition of the environmental specification and assess its applicability as the reference environmental model for the ExoMars 2020 programme from phase C [4].

The MCD v5.2 contains the following updates with respect to previous releases:

- Important fixes concerning vertical velocity winds, total electronic content and interpolations in the near-surface layer.
- Generation of the underlying dust scenarios to better represent the baseline Martian climatology (scenario "clim" based on a geometrical mean of the opacities over several years) and extreme bracketing cases: "cold", "warm" and "dust storm".
- Addition of add-on scenarios for Mars years 24 to 31.

The inspection performed by DEIMOS Space consisted on analyzing the differences between this new release (v5.2) versus the former applicable MCD version (v5.0), focusing on the region around Oxia Planum (the baseline landing site resulting from the ExoMars Landing Site Selection Working Group) and the combination of the MCD scenarios compatible with the arrival epoch: "cold", "dust", "warm" and "MY24" which represents the most fitting estimations of the actual dust and EUV conditions for that Mars year.

Fig. 5 shows the comparison of the density and temperature dispersions with respect to unperturbed profiles for dust and cold scenarios. Differences up to 80 % in density and 15 % in temperature at altitudes above 80 km are observed with respect to previous MCD release. For what concerns the winds estimation retrieved by the MCD v5.2, the decrease of the variability for both zonal and meridional components at low altitudes (below 16 km) is remarkable in the "cold" scenario (Fig. 6). Such differences in atmospheric parameters can be explained due to some changes implemented in new MCD v5.2 in the generation of the scenarios in order to better represent the baseline and extreme Martian climatology.

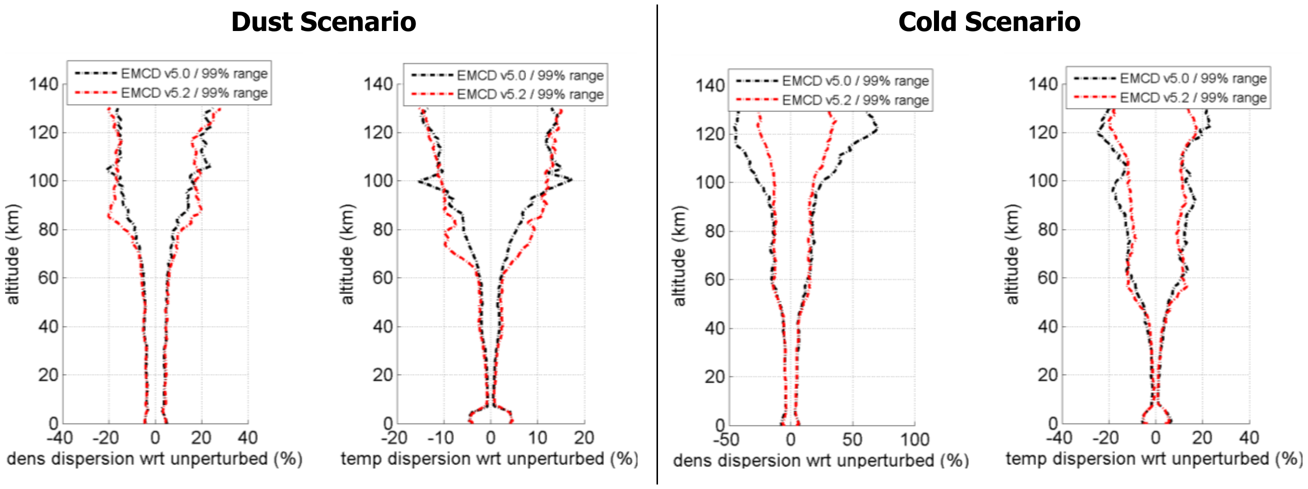

**Fig. 5** Density and temperature dispersion comparison for dust and cold scenario. Credits: DEIMOS.

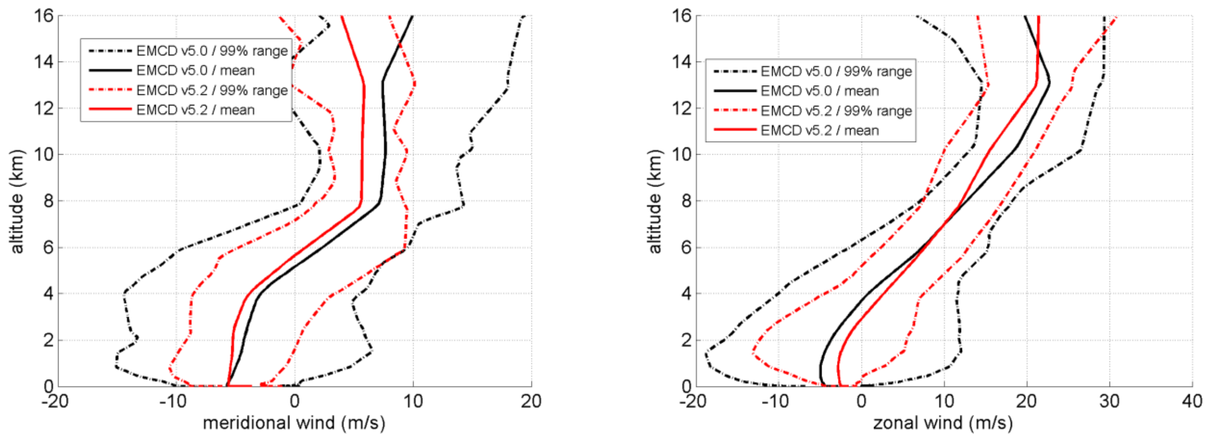

**Fig. 6** Meridional and zonal winds for low altitudes (cold scenario). Credits: DEIMOS.

## 3.3. Trajectory Analysis

Extensive trajectory analysis was performed to verify the trajectory performance and the mission objectives. Trajectory simulations were run from CM-DM separation down to 100 meters above ground, considering the baseline DM design (minimum and maximum mass configurations were analysed, 1900-2000 kg range), and the applicable environmental specification.

According to the launch window, two different opportunities have been analyzed: launch period open (LPO) and launch period close (LPC) for the two landing sites selected in Landing Site Selection Working Group: Oxia Planum and Mawrth Vallis. The TCMs executed during the interplanetary cruise will aim at targeting the correct position and velocity conditions at CM-DM separation in order to enter the atmosphere with the desired Flight Path Angle (inertial FPA = -12.4 deg for all scenarios) and to land at the desired landing site.

The next sections present the verification results and the associated performance for each phase of the ExoMars 2020 EDL mission for the minimum mass configuration. A detailed assessment of the mission performance and of the design margins was performed by DEIMOS Space with multiple 3DoF Monte Carlo simulation campaign (1000 runs for every applicable atmospheric scenario), considering applicable uncertainties in the DM design (MCI, aerodynamic), the mission design (variability in the predicted arrival conditions at Separation from the interplanetary cruise, and uncertainties in the mission events), and in the environment (atmosphere, winds).

DEIMOS Space simulations results (PETbox) have been numerically validated against NPO Lavochkin simulation results for the entry phase, in both nominal and dispersed flight conditions.

### 3.3.1. Coasting

The coasting phase starts 30 minutes before Entry Interface Point (EIP) when separation event between Carrier Module and Descent Module occurs (for comparison, in ExoMars 2016 Schiaparelli separated from TGO 3 days before EIP). The separation mechanism imparts to the DM a relative delta-V of 0.32 m/s.

The 99% dispersion range at EIP, taking into account the uncertainties in the state at separation (from ESA-ESOC interplanetary navigation results), MCI properties, separation mechanism and environment, is summarized in Tab. 3 for the different scenarios analysed. Wider dispersion is expected in LPO scenarios due to the shallower co-rotating flight path angle at EIP (Fig. 7).

**Tab. 3** Position dispersions at EIP (minimum mass configuration). Credits: DEIMOS.

| Parameter | Scenario | | | |
|---|---|---|---|---|
| | LPO | LPC | LPO | LPC |
| | Oxia Planum | | Mawrth Vallis | |
| ellipse dispersion (3-sigma): semi-minor axis (km) | 1.625 | 1.935 | 1.553 | 1.882 |
| ellipse dispersion (3-sigma): semi-major axis (km) | 25.162 | 20.034 | 27.254 | 20.861 |
| Cross track dispersion 99%ile, 90% CL (km) | 1.621 | 1.726 | 1.897 | 1.688 |
| Along track dispersion 99%ile, 90% CL (km) | 20.678 | 16.754 | 22.005 | 17.082 |

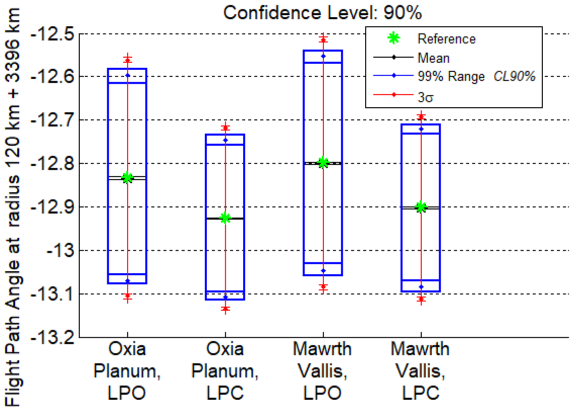

**Fig. 7** Co-rotating flight path angle comparison. Credits: DEIMOS.

### 3.3.2. Entry

The main objective of the DM during this phase is to dissipate the kinetic energy by means of the aerodynamic drag force acting on the vehicle and to maintain the thermal fluxes within the constraints considered. During the ballistic entry, no active guidance or control is present. The EDM is stabilized through a spin motion and its attitude is slightly oscillating around the equilibrium trim line.

The 3DoF performance assessment verified the design margins taking into account the uncertainties in the atmospheric model and aerodynamics considering the two landing sites and two launch opportunities for the minimum mass configurations. Tab. 4 summarizes the values of the aero thermo mechanical constraints for the different scenarios assessed.

The four scenarios are well within the limits in terms of the mechanical and thermal loads (e.g. 750kW/m2 heat flux at stagnation point and 10g accelerations), noticing that LPO scenarios are the sizing cases during entry phase due to the higher arrival velocity linked to LPO scenarios (Fig. 8).

**Tab. 4** Aero thermo mechanical performance (minimum mass configurations). Credits: DEIMOS.

| Parameter | Scenario (99%ile – 90% CI) | | | |
|---|---|---|---|---|
| | LPO | LPC | LPO | LPC |
| | Oxia Planum | | Mawrth Vallis | |
| Maximum Total Load factor (entry) (g) | 9.435 | 8.788 | 9.486 | 8.773 |
| Maximum Total Heat Flux (kW/m^2) | 580.628 | 505.970 | 581.341 | 507.044 |
| Maximum Total Heat Load (MJ/m^2) | 30.637 | 27.148 | 30.910 | 27.314 |
| Maximum dynamic pressure (Pa) | 9258.788 | 8722.477 | 9259.853 | 8700.981 |

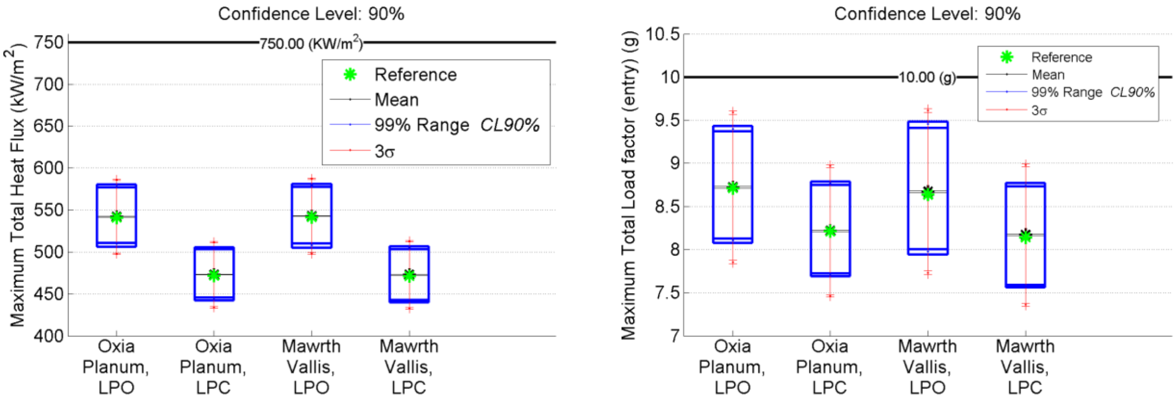

**Fig. 8** Maximum total heat flux (kW/m$^2$) and total load factor (g) during entry. Credits: DEIMOS.

### 3.3.3. Descent

The descent phase two stage parachute system is triggered with the following logic:

- The 15 m-diam DGB parachute is triggered by an acceleration-based trigger tuned to activate the mortar firing below Mach 2.2. The mortar deploys a pilot chute that extracts the DGB.
- The 35-m diam ringslot deployment starts approximately 20.3 seconds after first stage deployment. A second mortar deploys a pilot chute that extracts the ringslot.

An inflation model of the parachute and a Drag Equivalent Model (DEM) are implemented to simulate the dynamic of the parachute stages during descent. The total load factor exerted over the DM capsule due to the two-stage parachute deployment is shown in Fig. 9 for the Oxia Planum LPC scenario, which is the sizing scenario in terms of this performance parameter due to the steeper co-rotating flight path angle which induces a higher dynamic pressure at parachute triggering. However, the predicted performance verifies that the parachute deployments occurs within the design limits (Mach-dynamic pressure parachutes qualification boxes, deployment forces, altitudes above ground) with margins even considering the applicable uncertainties over the nominal scenarios (Fig. 10).

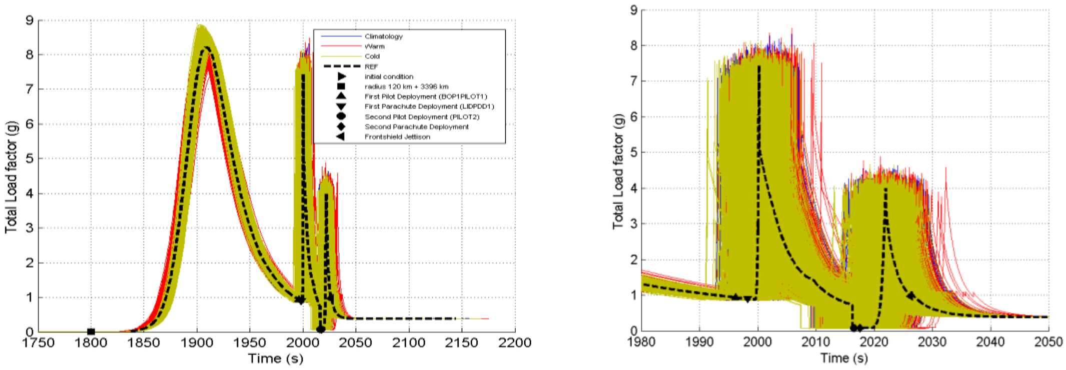

**Fig. 9** Total load factor: EDL(left) and descent (right). Oxia Planum, LPC scenario. Credits: DEIMOS.

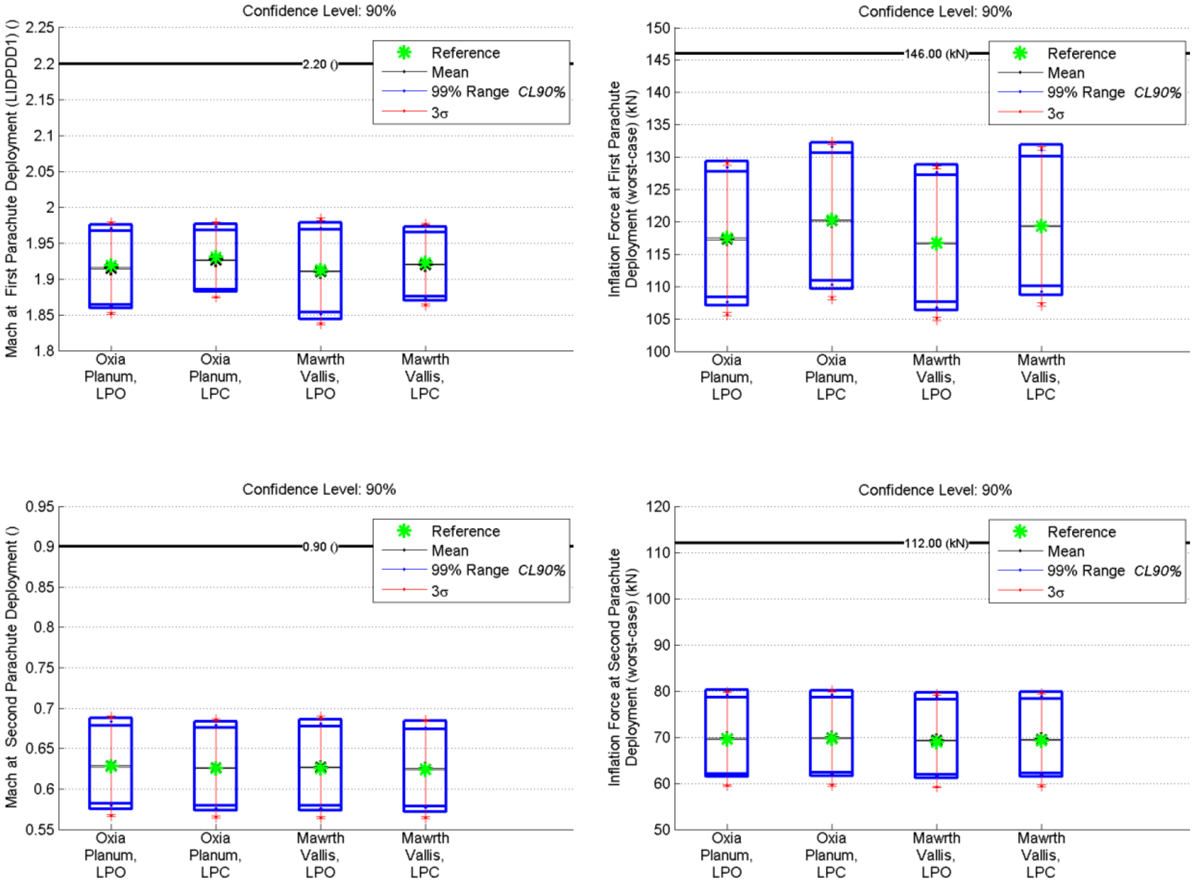

**Fig. 10** 1st and 2nd Stage Parachute Performance (4 scenarios). Credits: DEIMOS.

### 3.3.4. Landing

The verification performed by DEIMOS Space of the landing trajectory performance does not include the powered final approach to the desired landing sites and, therefore, the final verification ends up when the DM capsule reach 100 meters above ground. The performance of the landing accuracy (constraint at landing is 50 km) is then represented at this altitude for the four scenarios analyzed (Fig. 11 and Fig. 12), noticing that Mawrth Vallis LPO scenario is the worst in terms of landing accuracy and both Mawrth Vallis LPO/LPC scenarios represents a challenge in terms of topographical aspect due to the extreme orographic variety and landing site altitude above MOLA 0 level.

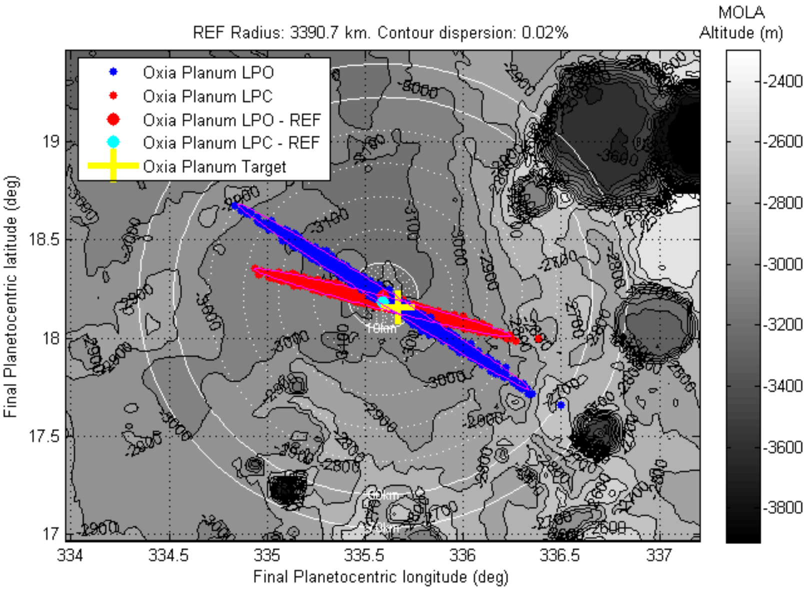

**Fig. 11** Position dispersion at 100 m above ground for Oxia Planum landing, LPO/LPC scenarios. Credits: DEIMOS.

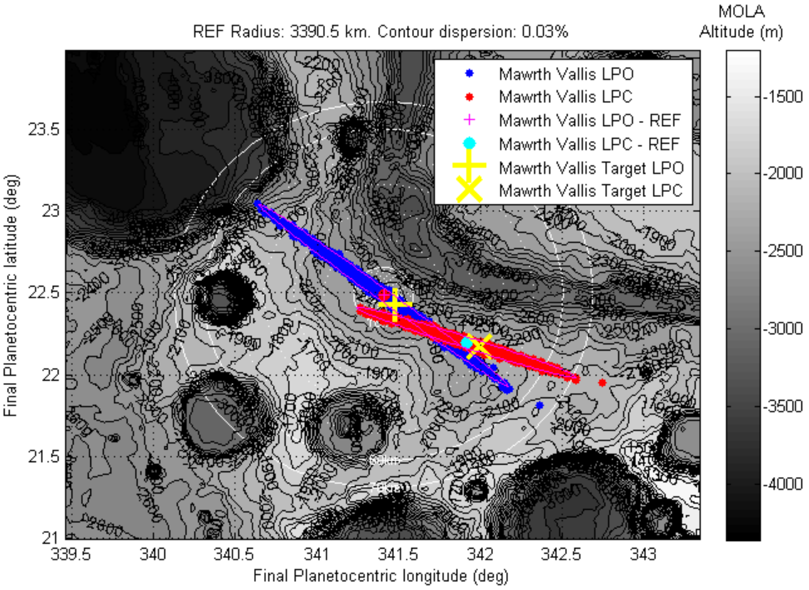

**Fig. 12** Position dispersion at 100 m above ground for Mawrth Vallis landing, LPO/LPC scenarios. Credits: DEIMOS.

## 4. CM-DM separation analysis

This analysis has been performed using the DEIMOS in-house tool DEBRIS (DEIMOS proprietary software) within the Planetary Entry Toolbox (PETBox) [3] that estimates the survivability and risk of debris of uncontrolled or controlled re-entry objects. This tool is based on an object-oriented debris analysis approach. The core analyses consist on estimating the distance between the CM and the DM after separation, including CM debris due to break-up event of Carrier Module.

### 4.1. Worst-Case Scenario Definition

The criteria to define the worst-case scenario is based on two aspects:

- Minimum distance between CM and DM
- Maximum altitude of the break-up event

Considering the four mission scenarios: Oxia Planum and Mawrth Vallis for LPO/LPC opportunities (Fig. 13) the worst-case scenario is the Mawrth Vallis, Launch Period Open scenario.

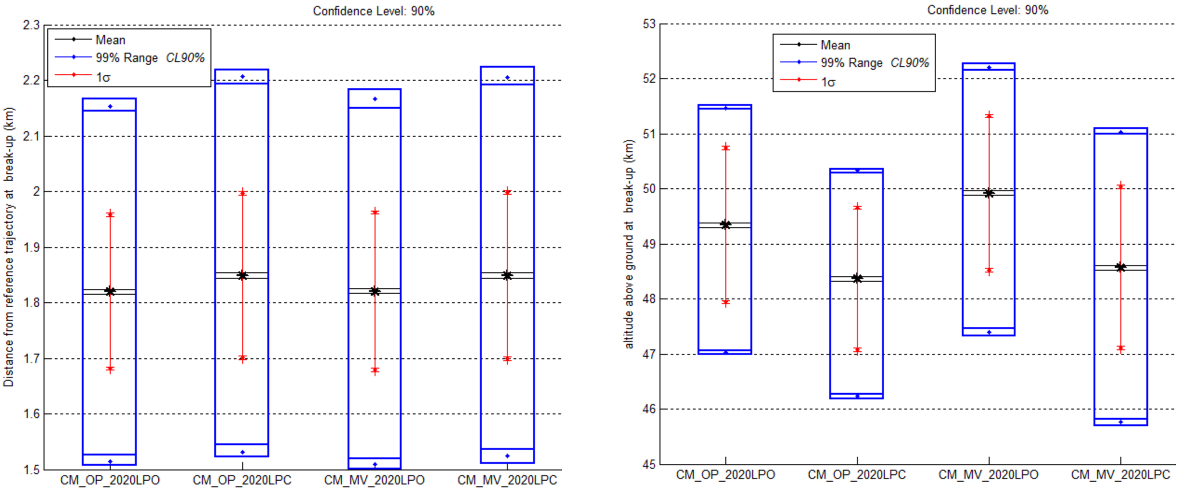

**Fig. 13** CM – DM distance at break-up (left) and CM break-up altitude (right). Credits: DEIMOS.

## 4.2. Detailed analysis of worst-case scenario

The analysis consists of the assessment of the distance between CM and DM after separation at 30 minutes before EIP in order to assess the safety of the DM trajectory with respect to CM and CM fragments. The analysis is based on intensive Monte Carlo simulations considering the influence of uncertainties applied in initial conditions, atmosphere, mass, aerodynamics and CM break-up altitude.

The analyses results have been reviewed during the S-CDR. In the following the preliminary observations are reported.

CM fragments are specified by Thales Alenia Space and the analyses are run under the conservative assumption of zero mass consumption during the fragments flight.

CM fragments characterized by a ballistic coefficient higher than 16 kg/m2 get closer to the DM during flight and landing and special concern should be taken in those elements composed by Titanium, Tungsten alloys or Stainless Steel due to the high likelihood to survive the re-entry.

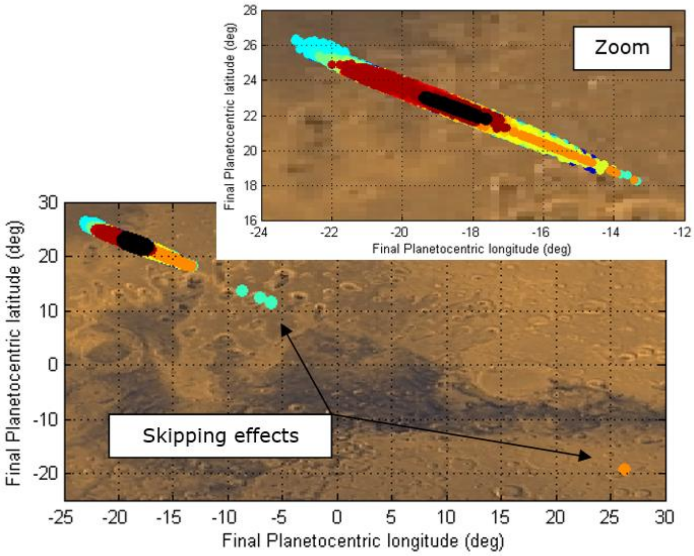

**Fig. 14** CM fragments footprint (colours) and DM footprint (black) for separation at EIP – 30 min Mawrth Vallis, Launch Period Open. Credits: DEIMOS.

From the analyses of CM and DM footprints (Fig. 14), it can also be noticed that:

- Fragments with BC higher than 26 kg/m2 reach ground before DM
- Fragments with BC lower than 18 kg/m2 reach ground after the DM
- Fragments with BC between 18 and 26 kg/m2 land at almost the same time that the DM
- Fragments with very high BC experience some skipping effects and are predicted to land far away from the landing area

Regarding the full catalogue of fragments which form the Carrier Module, five of them get to a minimum distance (0.5% percentile with 90% of confidence interval) during flight below 100 m Fig. 15. These are the fragments that get closer to the DM during flight. In particular, this is observed during entry (between 35 and 40 km of altitude), before triggering the first pilot deployment event.

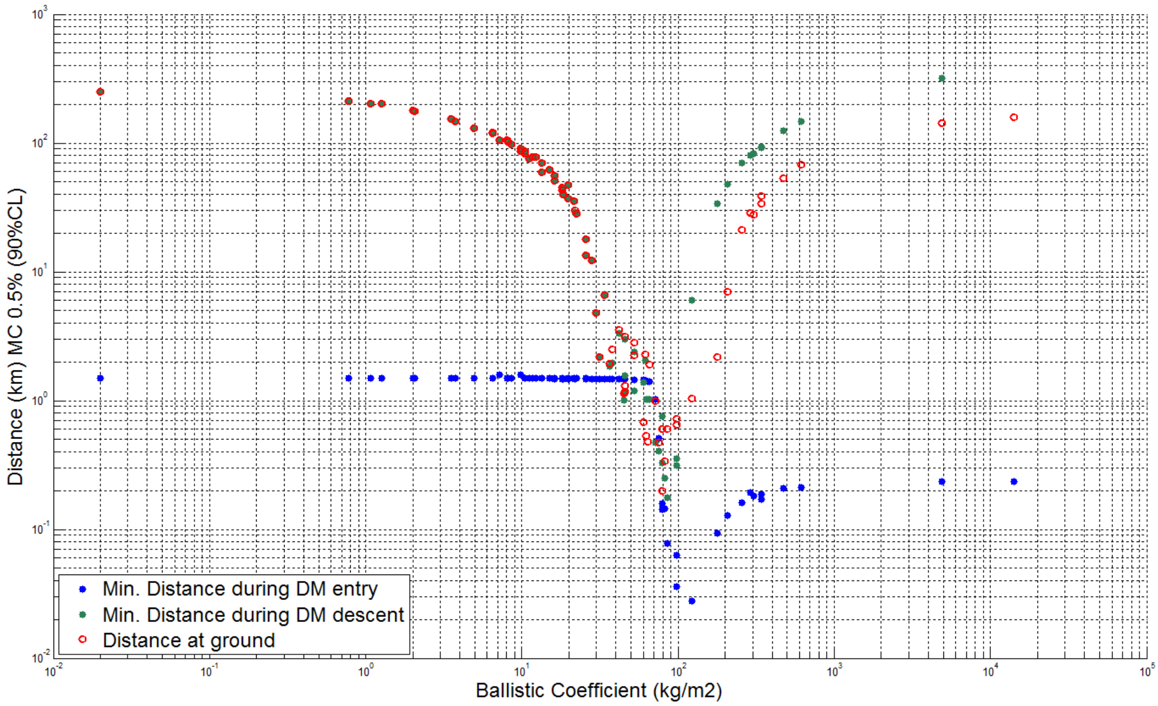

**Fig. 15** Distance between DM and CM fragments (entry, descent, ground). Credits: DEIMOS.

## 5. Conclusions

This paper presents key results of the Coasting, Entry, Descent and Landing analysis performed by DEIMOS Space over a range of mission scenarios and also selected analyses of the environmental models for Martian atmosphere and the assessment of the re-contact risk between Carrier Module and Descent Module after separation.

These results have been obtained by DEIMOS Space S.L.U. during ExoMars 2020 programme phase C, building upon company expertise and tools heritage from the ExoMars 2016 Schiaparelli mission.

Each phase of the Descent Module mission has been presented, showing the main results in terms of key performance, and significantly contributing to TAS and ESA verifications of the compliance of the mission and system design with respect to applicable constraints.

## Acknowledgements

The authors wish to thank Fabio Calantropio (TAS) and the TAS and ESA teams which contributed to the study in support to the mission analysis independent verification activities and whose cooperation was fundamental for the outcome of the project.

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