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ExoMars Atmospheric Mars Entry and Landing Investigations and Analysis (AMELIA)

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Abstract The entry, descent and landing of Schiaparelli, the *ExoMars* Entry, descent and landing Demonstrator Module (EDM), offered a rare (once-per-mission) opportunity for *in situ* investigations of the martian environment over a wide altitude range. The aim of the *ExoMars* AMELIA experiment was to exploit the Entry, Descent and Landing System (EDLS) engineering measurements for scientific investigations of Mars' atmosphere and

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surface. Here we present the simulations, modelling and the planned investigations prior to the Entry, Descent and Landing (EDL) event that took place on 19th October 2016. Despite the unfortunate conclusion of the Schiaparelli mission, flight data recorded during the entry and the descent until the loss of signal, have been recovered. These flight data, although limited and affected by transmission interruptions and malfunctions, are essential for investigating the anomaly and validating the EDL operation, but can also contribute towards the partial achievement of AMELIA science objectives.

Keywords Mars · Entry Descent and Landing (EDL) · Dynamical models · Trajectory · Attitude · Atmospheric investigations

1 Introduction

The Entry, Descent and Landing System (EDLS) of an atmospheric probe or lander requires engineering measurements to trigger and to control autonomously the events of the descent sequence. These measurements are primarily intended to support a successful and safe landing, but can also provide information for the engineering assessment of the EDLS and essential data for an accurate trajectory and attitude reconstruction of the vehicle. They also have great value as rare *in situ* measurements for atmospheric scientific investigations.

Only eight robotic probes to date have successfully entered the atmosphere and landed on Mars (USSR Mars 3, NASA Viking 1 and 2 Landers, Mars Pathfinder, the two Mars Exploration Rovers: Spirit and Opportunity, Mars Phoenix, and MSL Curiosity), on Venus (8 USSR Venera 7–14's probes, 2 USSR Vega 1 and 2 landers, and four NASA Pioneer Venus probe), or on Titan, the largest moon of Saturn (ESA Huygens probe).

The *ExoMars* program, with the Schiaparelli Entry, descent and landing Demonstrator Module (EDM) in 2016 and the entry module containing the Surface Platform and Rover scheduled for 2020, provides the opportunity for new, direct *in situ* measurements over a wide altitude range and with resolution not achievable over the full altitude range by remote sensing observations.

On the basis of successful experience with the Huygens probe at Titan, a similar opportunity for an experiment concerning the *ExoMars* entry, descent and landing (EDL) science was proposed. At a later time (November 2010), a dedicated Announcement of Opportunity (AO) for "ExoMars Entry, Descent and Landing Demonstrator Module (EDM) science" was issued by ESA in the framework of the NASA-ESA Joint Mars Exploration Programme; besides the provision of a Surface Payload for the ExoMars EDM, the AO also called for Entry and Descent Science with spacecraft EDL engineering sensors. Two proposals were submitted for the EDL Science (March 2011) and selected (June 2011) to be combined into one EDL experiment: AMELIA.

The main objective of the AMELIA experiment was to assess the local atmospheric science and the surface landing site by using the existing EDLS engineering sensors for more than their primary role in monitoring and evaluating the performance of the EDL technology

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demonstrator. The data recorded during different EDL phases would be used for an accurate trajectory and attitude reconstruction and for the retrieval of atmospheric profile to study the atmospheric structure, dynamics and static stability and to assess the landing site context.

AMELIA's objectives included studying some of the major properties of the martian atmosphere, such as density, pressure, temperature and wind, from an altitude of about 120 km all the way down to the surface, and characterizing the nature of the landing site by means of touch-down measurements.

Despite the ultimate failure of Schiaparelli in its landing phase, sufficient EDL data were returned in order to reconstruct the trajectory and attitude of the EDM and to retrieve atmospheric profiles over the altitude range from 121 km to 4 km above the surface (Aboudan et al. 2018), even if at lower resolution, with a significant gap in the middle atmosphere and with higher uncertainty ranges than those that would have been achievable had the full Schiaparelli data-set been recovered after landing, as was originally planned.

2 *ExoMars* 2016 EDL Scenario and Measurements

ExoMars 2016 Schiaparelli was designed in order to demonstrate and validate a European capability for Entry, Descent and Landing on Mars. Launched on 14th March 2016, carried by the Trace Gas Orbiter (TGO), Schiaparelli reached Mars in October 2016. Following separation from TGO (on Oct. 16th), Schiaparelli continued its ballistic trajectory to Mars in a state of hibernation (in order to save battery power) for 72 h and was activated one hour before the nominal atmospheric entry point on Oct. 19th.

The EDL sequence (Fig. 1) was designed to last about 6 minutes starting with a hypersonic atmospheric entry, followed by a passive descent under parachute and an active proximity phase during which retrorockets should have been activated in order to decelerate Schiaparelli and improve the horizontal accuracy of the landing site location. Schiaparelli should have finally landed on a crushable structure, designed to dampen the impact (Ball et al. 2019, this issue).

Schiaparelli was equipped with a set of engineering sensors (Fig. 2, Table 1) in order to monitor the performance of the EDL subsystems and the environment during EDL for verification of the design and technological assessment (Ball et al. 2019, this issue).

The EDL instrumentation included Guidance, Navigation and Control (GNC) equipment: one Miniaturized Inertial Measurement Unit (MIMU) containing three gyroscopes and three accelerometers, a sun sensor (SDS) located on the back shield for attitude determination prior to atmospheric entry, a Radar Doppler Altimeter (RDA), for altitude determination in the lowest 6–3 km of the atmosphere, and three pairs of landing accelerometers (for axial and tangential accelerations) to monitor Mars landing. A set of aerothermal sensors, embedded within the Thermal Protection System (TPS) of the Front Shield (FS) and Back Cover (BC) of the entry probe, complemented the EDL instrumentation: these included pressure transducers (4 on the FS and 1 on the BC as part of COMARS+), thermal plugs and thermistors (7 on the FS and 3 on the BC), and COMARS+ calorimeter and radiometer (Gülhan et al. 2018, this issue).

DECA, the Descent Camera was planned to record downward-looking images, as a burst of fifteen black and white, low resolution frames before touch-down. DREAMS, an environmental station monitoring meteorology for 2–4 sols at Mars' surface (Esposito et al. 2018, this issue), completed Schiaparelli's scientific payload.

Schiaparelli was designed to communicate via the UHF antenna during the EDL as well as surface operations phases. The Schiaparelli telemetry data downlink concept was based

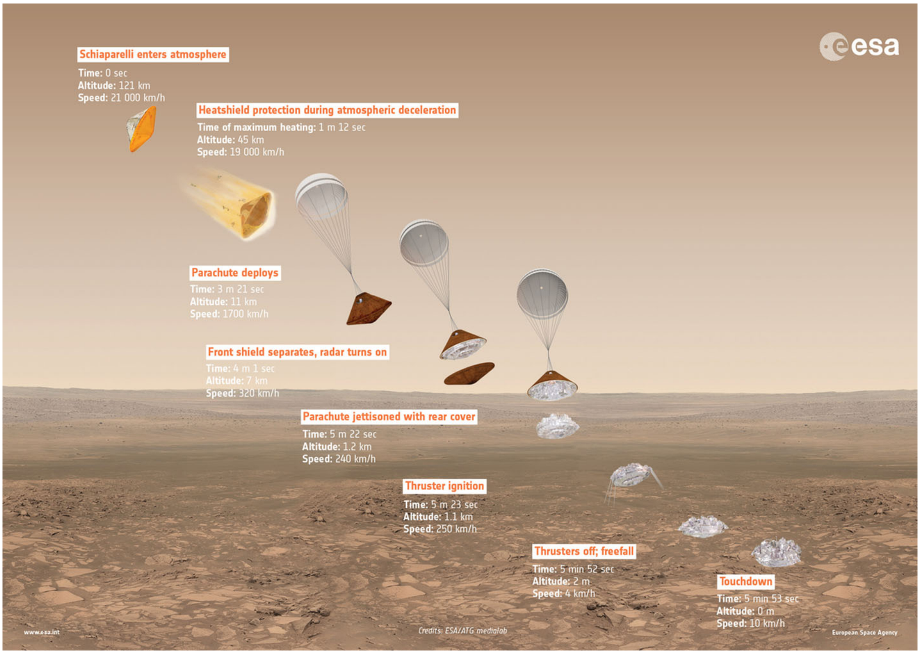

Fig. 1 ExoMars2016 Schiaparelli EDL scenario (credit: ESA) The sequence of entry, descent and landing of the Schiaparelli EDM and relevant events are reported together with the expected timing, altitude and velocity, as simulated for the reference mission using forecast atmospheric scenarios

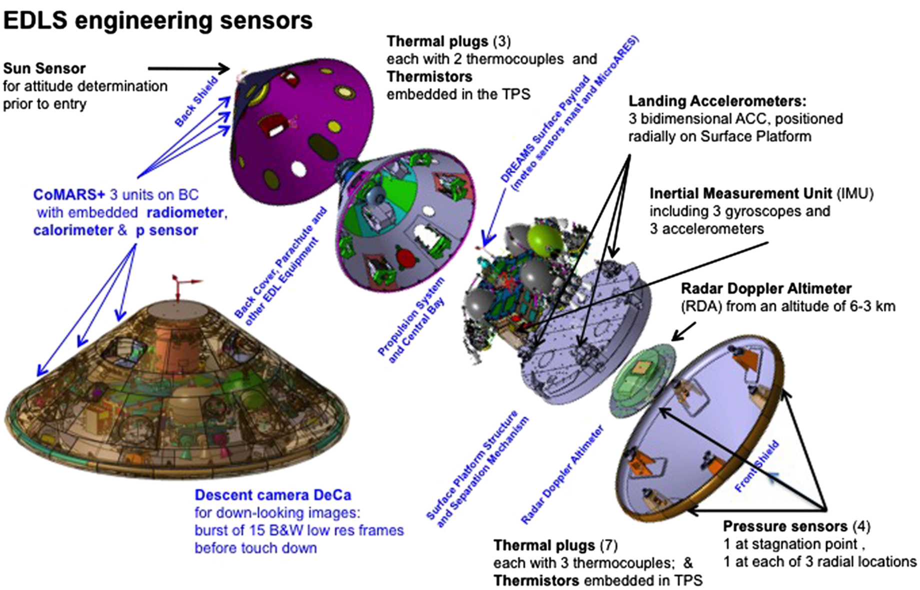

Fig. 2 ExoMars2016 Schiaparelli Entry and Descent Module and EDL engineering sensors (credit: ESA, TAS-I, readapted)

Table 1 Schiaparelli EDL Engineering sensors and data

Subsystem/sensor	Sensor type (#)	Measurement [unit]	Sampling frequency	Telemetry sampling rate/decimation	Mission phase	Notes
GNC Sensors						
MIMU: Honeywell Miniature Inertial Measurement Unit YG9666NK	Ring laser gyroscopes (3)	angular rate [deg/s]	100 Hz	10 Hz	EDL	GNC processed data: valid at 100 Hz and down-sampled to 10 Hz
	Accelerometers (3)	acceleration [m/s^2] (mechanical load)	100 Hz	10 Hz	EDL	
SDS: Sun sensor	a fully passive analog device, based on a quadrant photo detector	solar aspect angles (sun vector)	10 Hz	10 Hz RT/ 1 Hz No RT	Coasting	Used by GNC in order to recover attitude after hibernation
RDA: Radar Doppler Altimeter	Customized radar altimeter with 4 independent beams/antennas	velocity [m/s] and altimetry [m] relative to the terrain	20 Hz	1 Hz RT/ 10 Hz No RT	Terminal D (Proximity)	Antennas at the bottom of the EDM: 3 oriented on a circle separated by 120° for velocity measurement, 1 in the center of circle, perpendicular to EDM for slant measurement
Landing ACC	Endevco 2271 AM20 piezoelectric Accelerometers (6)	3 rotational and translational acc. [m/s^2]			L	3 accelerometer pairs: 1 axial, 1 tangential. Located at the edge of the DM platform at 120°
TPS sensors						
Pressure sensors	FAD: Flush Airdata Sensing Kulite XTL-DC-123C-190M-250-mBAR-A (4)	pressure [bar](pressure field)	10 Hz	1 Hz	E	Sensors located 1 at the stagnation point and 3 at 0.5 m from the centerline, at 120° in triangular configuration,
Thermal plugs	7 on FS, composed of 3 J-type TC; 3 on BC, composed of 2 J-type TC	temperature [K] (thermal loads)			E	embedded into TPS: 7 on FS; 1 at stagnation and other 6 in triangular configuration at 2 different distances from the edge. 3 on the BC: on radial location on a single radius
Thermocouples (TC)	TC direct 12-J-150-118-0.5-21-3P2LA-3.5M-B40JX		10 Hz	0.1–1 Hz	E	3 J-type TC placed at 4, 6 and 8-mm depth
Thermistors	PT200 MEAS PF0002413 (PF0002283 with a 2.5 m cable)		10 Hz	0.1–1 Hz	E	1 for each thermal plug, placed on the structure
DECA Descent Camera	60° field of view camera	black & white images	15 frames at 1.5 s	–	D	down-looking

FS: Front Shield, BC: Back Cover, TC: ThermoCouple, RT: Real Time; E: Entry, D: Descent, L: Landing on relay of data via the currently flying Mars orbiters (ESA TGO and MarsExpress, and NASA Mars Reconnaissance Orbiter, MAVEN, and Odyssey). During the EDL phases, only essential telemetry data were transmitted via the TGO owing to the reduced data rate available. In addition, the EDM UHF carrier signal was recorded by the ESA Mars Express orbiter and by ground stations on Earth (Direct to Earth link): the Giant Meterwave Radio Telescope (GMRT) in India. The Doppler shift and rate of the radio signal could be accurately measured during the EDL and represent a unique "signature" of the entry trajectory.

After a successful landing, Schiaparelli telemetry data would have been downloaded by the Mars relay orbiters.

The engineering sensors, their measurements and the expected flight data are reported in Table 1. The telemetry data included also GNC processed data derived from these measurements; EDL measurements and GNC estimates were down-sampled or decimated as required to fit the maximum data volume to be transmitted during EDL (e.g. essential telemetry data) and to be stored on-board for post-landing download.

3 AMELIA Science Objectives

The experiment AMELIA was aiming at the assessment of the atmospheric science and landing site by using sensors of the Entry, Descent and Landing system (EDLS), over and above the expected engineering information.

The primary science objective was to retrieve an *in situ* atmospheric profile along the entry and descent trajectory. This profile permits the investigation of Mars' atmospheric structure and dynamics at high spatial resolution, so as to detect meteorological perturbations and waves, for example, thermal tides and gravity waves.

The scientific analysis of the landing measurements was aimed at the determination of the landing site context (e.g. surface mechanical characteristics, geomorphology, etc.), its characterization and assessment. This analysis would be conducted in combination with remote sensing imaging and mapping.

Of the multiple Mars landings attempted by robotic unmanned spacecraft, only eight were successful: USSR Mars 3 in 1971, NASA Viking 1 and 2 Landers in 1976, Mars Pathfinder in 1997, the two Mars Exploration Rovers (MER, Spirit and Opportunity) in 2004, Phoenix in 2008 and MSL Curiosity in 2012 (Table 2).

The USSR Mars 6 probe in 1973 failed upon impact, but it provided the first *in situ* measurements of the planetary atmospheric structure by transmitting data during its entry (for 224 s, the link was lost before retrorockets ignition). Although the data were unusable as a result of a design flaw, an assessment of the atmospheric parameters from 12–90 km was retrieved from the Doppler measurements of the radio signal received by the Mars 6 descent module (Kerzhanovich 1977).

To date only seven profiles of density, pressure and temperature have been published from *in situ* measurements: both Viking 1 and 2 in daytime (Seiff and Kirk 1977); Mars Pathfinder in nighttime (Schofield et al. 1997; Magalhães et al. 1999); two more profiles from the MER Spirit and Opportunity (Withers and Smith 2006) with much lower accuracy; Mars Phoenix providing the first profile from the martian polar region (Withers and Catling 2010); and, most recently, by MSL-Curiosity (Chen et al. 2014; Holstein-Rathlou et al. 2016) (Fig. 3).

The profiles have been retrieved essentially from the deceleration curves and aeroshell drag properties of the entry modules. With the exception of the Viking landers, no direct

Table 2 Comparison between EDL science of Mars' probes

	Mars 6 (USSR)	Vikings VK1, VK2	Mars Pathfinder MPF	Mars Exploration Rovers: MER1: Opportunity (O) MER2: Spirit (S)	Phoenix PHX	MSL-Curiosity
Time: date, UTC, local time (LT) @EDL (operational sols@ Mars)	M6 12 March 1974 09:05:53 UTC 15:30 LT	VK1 Jul 20 1976 16:15 LT (+2245 Sols) VK2 Sep 3 1976 10:00 LT (+1281 sols)	MPF Jul 4, 1997 02:58 LT nighttime: (+83 Sols)	MER1-O (MER-b mission) 25 Jan 2004 04:55 UTC 13:13 LTST (+5111 sols) MER2-S (MER-A mission) Jan 4, 2004 04:26 UTC 14:16 LTST (+2210 sols)	PHX May 25, 2008 23:53:44 UTC 16.6 LTST (+152 Sols)	MSL Aug 6, 2012 05:18 UTC 15:03 LMST 15:36 LTST (–current >2287 sols)
Landing location	M6 Pyrrhae Regio 23.90 °S, 19.42 °E	VK1 22.7 °N, 312.05 °E −2.69 km VK2 47.62 °N, 134.23 °E 4.23 km	MPF 19.09 °N, 326.74 °E −2.8 km	MER1-O Meridiani Planum 14.57 °S, 354.47 °E MER2-S Gusev crater 1.95 °S, 175.47 °E	PHX Green Valley, Vastitas Borealis 68.21 °N, 234.25 °E −4.45 km	MSL Gale Crater 4.6 °S 137.4 °E, −4.5 km
Season L_S	19.5°	VK1: 97.0° VK2: 117.6°	142.7°	MER1-O: 339.1° MER2-S: 327.7°	76.6°	150.7°
Reference	Kerzhanovich (1977)	Seiff and Kirk (1977)	Schofield et al. (1997), Magalhães et al. (1999)	Withers and Smith (2006)	Withers and Catling (2010)	Chen et al. (2014), Holstein-Rathlou et al. (2016)

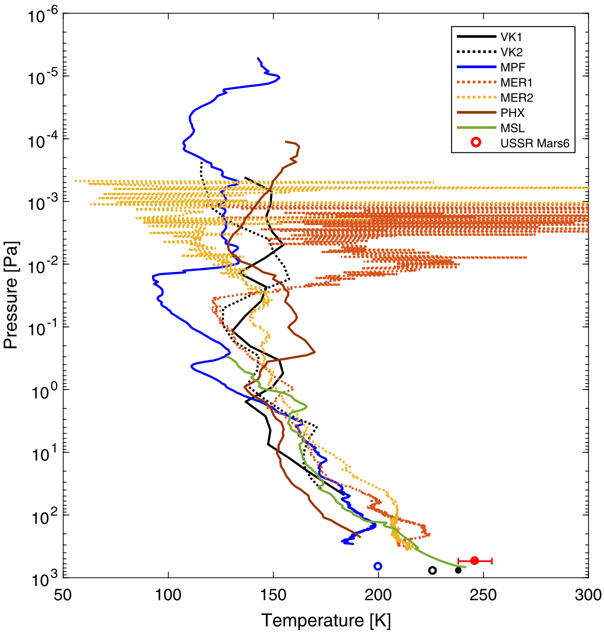

Fig. 3 Mars atmospheric profile as measured by entry probes. The atmospheric profiles as retrieved from the EDL measurements of Mars' entry probes are plotted together with the surface values as measured by the landers ('circles'). The different profiles are relevant to different sites, seasons and local time: refer to Table 2 for details and relevant references. The plotted data have been retrieved from the relevant Planetary Data System (PDS) archives (PDS the Planetary Atmosphere Node: data archive for landers: http://atmos.pds.nasa.gov/data_and_services/atmospheres_data/MARS/mars_lander.html)

atmospheric temperature measurements were performed by any other Mars entry probes. Pressure measurements were attempted by Mars Pathfinder (Seiff et al. 1997) and successfully implemented in MSL Entry Descent and Landing (EDL) Instrumentation (MEDLI) (Cheatwood et al. 2014) as a Flush Air Data System (FADS) (e.g. by pressure transducers connected to flush orifices in the heatshield to measure pressure across the vehicle forebody). A similar system has been implemented on the Schiaparelli entry vehicle (Ball et al. 2019, this issue).

Atmospheric profiles retrieved from *in situ* measurements are vital for the cross-calibration of in-orbit remote sensing data, for example from the Mars Climate Sounder instrument (McCleese et al. 2007) on board NASA Mars Reconnaissance Orbiter, the Thermal Emission Spectrometer TES (Smith et al. 2001) on NASA Mars Global Surveyor, the Planetary Fourier Spectrometer PFS (e.g. Grassi et al. 2007) on ESA MarsExpress. They are also useful for the validation of numerical atmospheric models which are applied in many studies related to atmospheric variability on a range of temporal and spatial scales (e.g. Forget et al. 1999; Spiga and Forget 2009); these, in turn, support the mission design by setting constrains and forecasting environmental conditions in order to ensure reaching the martian surface reliably. Finally these profiles complement investigations of the atmosphere and the planetary boundary layer at scales that are difficult to resolve using remote sounding techniques (e.g. Haberle et al. 1999; Montabone et al. 2006).

New data from different sites, seasons and time periods are essential to investigate the thermal balance of the surface and near-surface atmosphere of Mars, diurnal variations in the depth of the planetary boundary layer and the effects of these processes on the martian general circulation. *In situ* measurements of temperature, pressure and wind are fundamental for studying atmospheric structure and dynamics, for investigating the planetary boundary layer structure and other aspects of meteorology on Mars.

ExoMars 2016 Schiaparelli provided an opportunity for new direct *in situ* measurements during the martian seasons when large dust storms are statistically most likely to occur, from autumnal to vernal equinox in the Northern hemisphere. These data permit exploration of an altitude range and a vertical resolution not fully covered by remote sensing observations from an orbiter, providing a surface and atmospheric 'ground truth' for remote sensing observations and providing important constraints for validation of Mars atmosphere models.

In addition to atmospheric science, AMELIA was also intended to characterise and assess the surface at the landing site by means of the *in situ* measurements taken during the terminal descent and at touch-down. The engineering data and the descent images recorded by DECA were intended to be used for supporting characterization of the landing area along the ground track and at the impact site, in the context of the high resolution mapping of the landing ellipse performed with remote sensing observations (Ori et al. 2014; Pacifici et al. 2014).

4 Simulation and Reconstruction Methods

An atmospheric profile of density, pressure and temperature can be retrieved along the entry and descent trajectory using similar methods to those employed in previous entry probe missions, e.g. ESA Huygens at Titan (Fulchignoni et al. 2005; Aboudan et al. 2008; Colombatti et al. 2008), NASA Mars Pathfinder (Magalhães et al. 1999), Mars Exploration Rovers (Withers and Smith 2006), Phoenix (Desai et al. 2011; Blanchard and Desai 2011; Withers and Catling 2010; Withers 2013), and MSL-Curiosity (Chen et al. 2014; Karlgaard et al. 2014; Holstein-Rathlou et al. 2016).

Within the AMELIA team, different approaches, algorithms, methods and data sets were employed for simulation and reconstruction of the Schiaparelli trajectory and attitude during the entry and the descent phases in order to retrieve and validate the most accurate atmospheric profile.

The first step of the investigation is modelling of the dynamics of the EDM and the EDL sensors and measurements during the different phases of the EDL. These phases consistent of:

- *an entry phase,* from the detection of the Entry Interface Point (EIP) down to the parachute deployment;
- *initial descent (Separation),* from parachute deployment until the front shield is jettisoned;
- *mid- & terminal-descent*, from jettison of the front shield down to the separation from the back shell;
- *and landing (proximity)*, from retrorocket activation to touch-down.

The Schiaparelli EDM, protected by its frontal heat shield, was modeled as a single rigid body with 6 degrees of freedom (dof) subject to Mars' gravity and aerodynamic forces. *A priori* expected atmospheric conditions were retrieved from the Mars Climate Database (MCD 5.2) (Millour et al. 2015) derived from numerical simulations performed with the Laboratoire de Meteorologie Dynamique (LMD) Global Climate Model (Forget et al. 1999). Different "dust loading" atmospheric scenarios were used to compute the aerodynamic forces and torques starting from the aerodynamical database.

After parachute deployment, the Schiaparelli module and the parachute system were modeled as two bodies connected by a spherical joint, resulting in a 9 to 12 dof system depending on whether the parachute was modeled as a 3 or 6 dof body. For the separation phase, a model at 18 dof was used for three rigid bodies (i.e. surface platform, front shield and aft cover). The aerodynamical interactions between the different elements of the EDM were taken into account and modeled using inputs from the aerodynamic database.

Simulations were performed and the models were validated against the expected environmental and mission scenarios. Models were validated with data from previous entry probe missions (e.g. Van Hove and Karatekin 2014).

The inputs for the simulations (and reconstruction) are the dynamical models of the EDM, the expected Mars' environment conditions (e.g. gravity and atmosphere models) and the state of the EDM at entry: namely position, velocity and attitude of the probe at the EIP. The EDL data recorded by the engineering sensors and derived from the GNC measurements are used as input, as is the Doppler tracking of the UHF signal.

4.1 Radio Link Doppler Shift Reconstruction

A near-real-time reconstruction of the trajectory can be performed using the radio communication link between the EDM, the radio receivers on board the relay orbiters, and the carrier signal detection by ground telescope (Withers 2010).

From the Doppler shift and rate of the signal, it is possible to detect the different events, retrieve the position and velocity of the probe, and to estimate the wind velocity (Withers 2013; Karatekin and Asmar 2011; Asmar et al. 2013).

4.2 Atmospheric Reconstruction

Atmospheric profiles of density, pressure and temperature, can be derived by several methods including: direct inversion from deceleration measurements, from hypersonic dynamic pressure data recorded during entry, or using more sophisticated estimation methods in which *a priori* knowledge of atmospheric parameters and vehicle dynamics are blended with all the available measurements.

In order to reconstruct the atmospheric parameters (e.g. density, static pressure and temperature) from the measured accelerations and dynamic pressures, the physical properties of Schiaparelli in its different configurations (Fig. 4), its aerodynamical and its aerothermal characteristics must be known.

4.2.1 Reconstruction from Inertial Data

Of the possible methods, historically the primary approach (e.g. Seiff and Reese 1965; Seiff and Kirk 1976), has been the direct numerical integration of the IMU measurements to derive velocity, position and altitude. Measured accelerations can be converted into atmospheric parameters by using the vehicle's aerodynamical database (AeDB): starting from the velocity and position of the probe, its angle of attack (AoA) and the side slip angle (SSA) can be obtained as the ratio of the normal and side to axial accelerations. Atmospheric density is directly related to the deceleration by the atmospheric drag, a pressure profile can be computed using the hydrostatic equilibrium law and then temperature by means of the ideal gas law. Furthermore, having a dynamic model of the EDM (mass, inertia and AeDB), having a sensor model of the on-board accelerometers, and assuming an atmospheric standard model, makes it possible to predict the atmospheric drag and hence update the density profile to match the measured accelerations using an Extended Kalman Filter (Aboudan et al. 2008). This method can be further extended to blend any other available measurements from both on-board sensors (e.g. the radar Doppler altimeter, FADS) and remote sensing data (e.g. imaging and radio science).

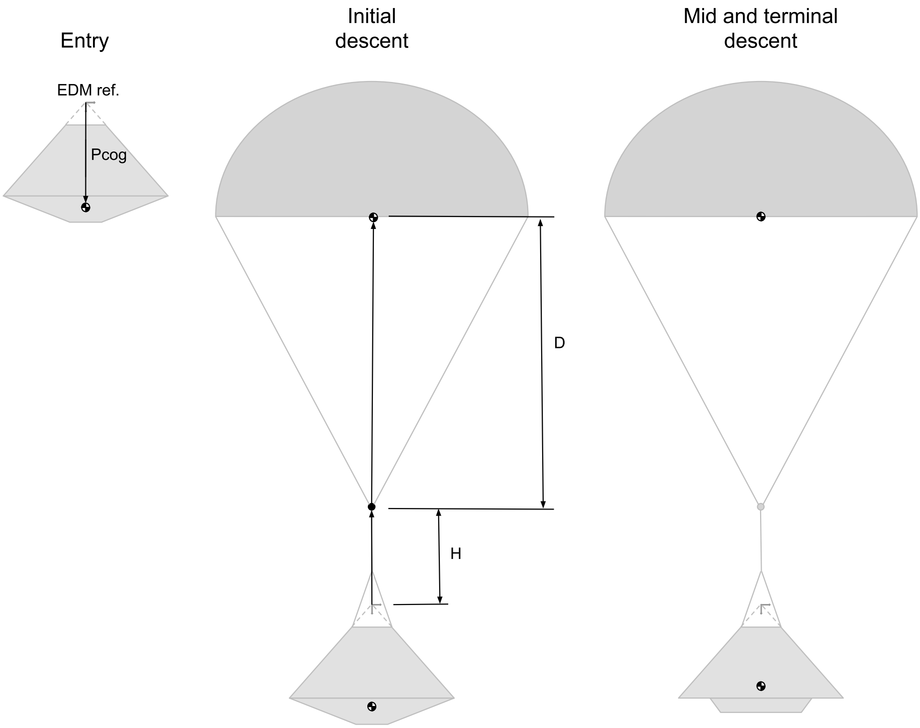

Fig. 4 Schiaparelli EDM configurations at the different EDL phases

During the last part of the descent (terminal descent) a direct measurement of the elevation and velocity of the EDM above Mars' surface was provided by the radar Doppler altimeter. These data, together with the descent images of DECA, were intended to contribute to the assessment of the EDM trajectory and attitude in its terminal part of the parachuted descent

4.2.2 Reconstruction from Pressure Data

Schiaparelli was equipped with aerothermal sensors embedded into the thermal protection system (TPS) of the frontshield and aft cover (Ball et al. 2019, this issue). These sensors together with CoMARS+ (Gülhan et al. 2018, this issue) were aimed at monitoring the entry vehicle's surface pressures and heat shield temperature in order to investigate Mars' entry environment and the vehicle's response to it. The readings of the four heatshield pressure sensors, one placed at the stagnation point and the others at three radial locations, provide the pressure distribution across the shield and could be used for an independent reconstruction of the atmospheric parameters. Atmospheric free stream conditions and density may be determined with the help of aerothermal dynamical database (ATDB) using all pressure sensors at once, or at a single location (Karlgaard et al. 2013; Van Hove and Karatekin 2017). These profiles do not depend on assumed EDM aerodynamics, and provide independent observations of the atmospheric conditions.

The pressure-based reconstruction using all pressures consists of making a least-squares fit of the surface pressure measurements to the modeled pressure distributions to obtain a

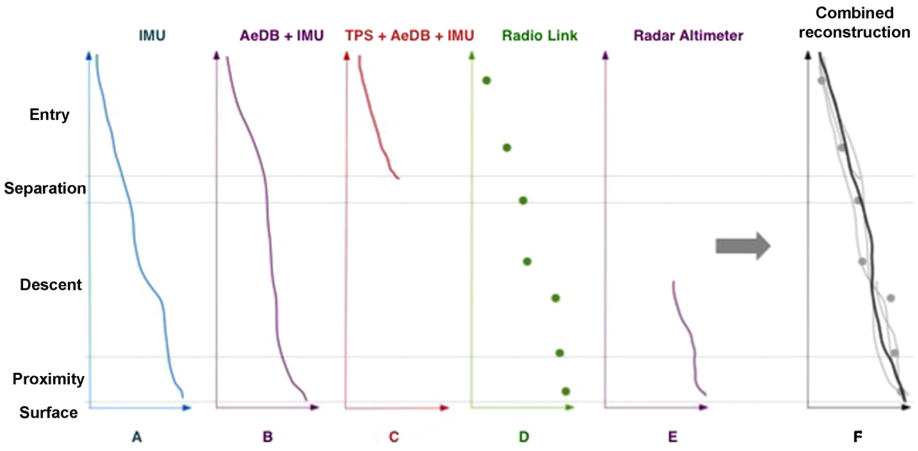

Fig. 5 A schematic view of the AMELIA reconstruction approach. (**A**) Starting from the direct numerical integration of IMU data velocity, position and attitude are derived. (**B**) The aerodynamical data base (AeDB) is used in order to convert the sensed accelerations into atmospheric parameters; outputs are velocity, position, angle of attack (AoA), side slip angle (SSA) which give the density, pressure and temperature profiles. (**C**) IMU aided TPS pressure data processing provides the static and dynamic pressures which give density and temperature profile. (**D**) From the Doppler shift of the radio link received on ground and via the Mars Relay orbiters, it is possible to measure the EDM velocity in Line-of Sight and to derive position, and possibly winds. (**E**) The EDM radar altimeter provides a direct measurement of the EDM elevation with reference to the Mars ground. (**F**) The combined reconstruction is assessed by checking the agreement of the different techniques, using data assimilation and by Extended Kalman filtering.

minimum-variance estimate of the atmospheric pressure. Multiple pressure measurements give the stagnation location and pressure and the true flow angles. All pressure measurement locations can be processed simultaneously to determine the atmospheric state variable estimates.

Combining the information from environmental sensors with velocity and attitude derived from the inertial measurements by IMU can enable the estimation of atmospheric winds (Karlgaard et al. 2013).

4.2.3 Synthesis of Different Techniques

The final step in the overall analysis is the consolidation of the reconstructions by different techniques and using different data and measurements (Fig. 5); the resulting combined reconstruction can be assessed by checking the agreement of the different techniques and data assimilation, and by performing the optimal blending of all the measurements by Bayesian estimation (e.g. using Extended Kalman filters or smoothers as baseline).

5 Mars Atmosphere and Environment Modelling

In order to safely design the entry, descent and landing operation of a probe the status of the atmosphere and the variability of the environmental and dynamical conditions that it will face need to be predicted sufficiently accurately.

Various tools have been developed and implemented in order to model Mars' environment at different scales, taking into account the different processes and phenomena

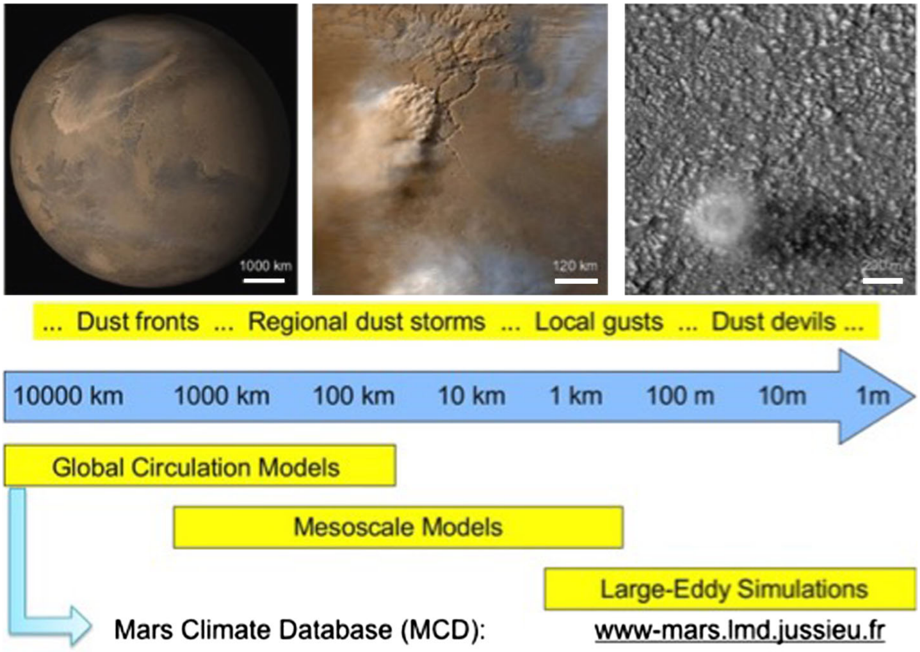

Fig. 6 Tools to model Mars' environment. Typical Mars' weather events related to dust lifting (top images + yellow strip), relevant spatial scales (middle blue arrow) and meteorological models for their analysis (bottom yellow strip) are reported. The outputs of the integrated models have been implemented into the Mars Climate Database (MCD www-mars.lmd.jussieu.fr) in order to forecast the mean environmental parameters at a specific place, season, time of the day and altitude (image credits, left: NASA-MGS-MOC, middle: NASA-MRO-MARCI, right: NASA-MRO-HIRISE; images retrieved from the NASA Planetary Data System PDS. Figure published in Spiga and Lewis 2010, modified with permission)

that govern atmosphere dynamics: Global Circulation Models (GCMs) with resolution on the order of 100 km; Mesoscale models simulating regional environments (resolution ∼10 km); and Large-Eddy Simulations able to resolve the convective boundary layer in the altitude range below 20 km (resolution ∼10–50 m) (Fig. 6). The outputs of the LMD GCM (Forget et al. 1999) have been implemented into a Mars Climate Database (MCD www-mars.lmd.jussieu.fr) that can provide the expected mean environmental parameters at a specific place, season, time of the day, and altitude (from the surface to the thermosphere). The amount of dust in Mars' atmosphere is one of the main sources of variability for the weather conditions, with different processes acting at different scales, e.g. from global dust fronts, to regional dust storms, to local gusts and dust devils, dust laden convective vortices that cross the surface of Mars.

Within the AMELIA team, considerable effort has been put into atmospheric modelling (e.g. Forget et al. 1999; Spiga and Forget 2009) and data assimilation (e.g. Lewis et al. 1999, 2007; Montabone et al. 2005) in order to improve predictions and weather forecasts, to monitor weather conditions and to assess the atmospheric context at entry. Predictions have been used in order to forecast the environmental conditions that Schiaparelli was likely to face for mission design, in order to manage and optimize the EDL sequence versus different expected atmospheric scenarios. An extended MonteCarlo simulation campaign has been performed by the EDM Prime contractor (Thales Alenia Space, Torino, Italy—TAS-I) using a combination of Global, Mesoscale and Large-Eddy simulations (Forget et al. 2011).

These simulations resulted in the reference Schiaparelli EDL trajectory that has been used for comparison with the AMELIA simulations/reconstruction. Finally, expertise in modelling and data assimilation is fundamental for the scientific analysis and interpretation of the AMELIA results.

Remote sensing observations (e.g. NASA Mars Reconnaissance Orbiter—MCS and MARCI records and ESA MarsExpress—PFS) and *in situ* measurements (e.g. from MER-Opportunity PanCam) taken around the time of the ExoMars2016 mission at Mars (19th Oct 2016 local solar time 13:16), provide additional data (e.g. inverted temperature profiles and dust opacities) to assess the atmospheric context through assimilation within models and for direct comparison with the AMELIA reconstructed profile.

6 Atmospheric Science

The main objective of the AMELIA experiment was to retrieve the atmospheric profile, in terms of density, pressure and temperature, along the entry and descent trajectory by means of an accurate trajectory and attitude reconstruction.

In situ measurements made by an entry probe permit retrieval of atmospheric profiles with higher vertical resolution than remote sensed data and provide 'ground truth' for remotely-sensed observations and important constraints for updates and validation of the Mars atmospheric models.

The density profile can be retrieved directly from measurements of the deceleration of the probe due to the atmospheric drag; pressure and temperature can be derived assuming the hydrostatic equilibrium law and by means of the ideal gas law.

AMELIA characterizes the atmospheric structure along the entry probe trajectory, thereby contributing to study of the general atmospheric structure. Attempts to measure winds in the free atmosphere were also planned by retrieving the wind profile along the entry probe path from the EDM radio tracking both by TGO and from Earth, e.g. as was done by the Huygens Doppler Wind Experiment (DWE) (Bird et al. 2005), and from trajectory and attitude variations and the horizontal motion of the pendulum system of parachute chain and EDM during the descent phase (e.g. Seiff 1993).

Based on the sampling rate of the Schiaparelli engineering sensors, the expected spatial resolution of the retrieved atmospheric profiles should range from 13 to 2 m. This resolution, achievable only by means of *in situ* measurements, would allow the detection and resolution of small, localized and wave-like structures propagating within the atmosphere.

By resolving and detecting horizontal structures, AMELIA could observe inertio-gravity waves and therefore help to constrain their properties and parameterization. AMELIA was also intended to characterize the thermal tides and their sensitivity to dust loading in the atmosphere, and to determine the vertical propagation of both gravity waves and tides to characterize the range of the vertical variations of temperature and density in the Martian troposphere and mesosphere.

Aerosol abundance could be assessed by a combination of measurements: atmospheric opacity (e.g. from solar flux measured by the sun sensors and COMARS+ radiometer on the back shield, from DECA images), and from the front shield ablation. Dust load and condensates (e.g. fog and clouds) could be detected as detached layers from the temperature inversions and as sources of extra opacity.

AMELIA also had the ability to probe the Planetary Boundary Layer (PBL) of Mars, estimating the altitude of its top (e.g. by comparison with Large Eddy simulation model, Spiga et al. 2010) and, by measuring wind speeds and turbulence inside the PBL, observing

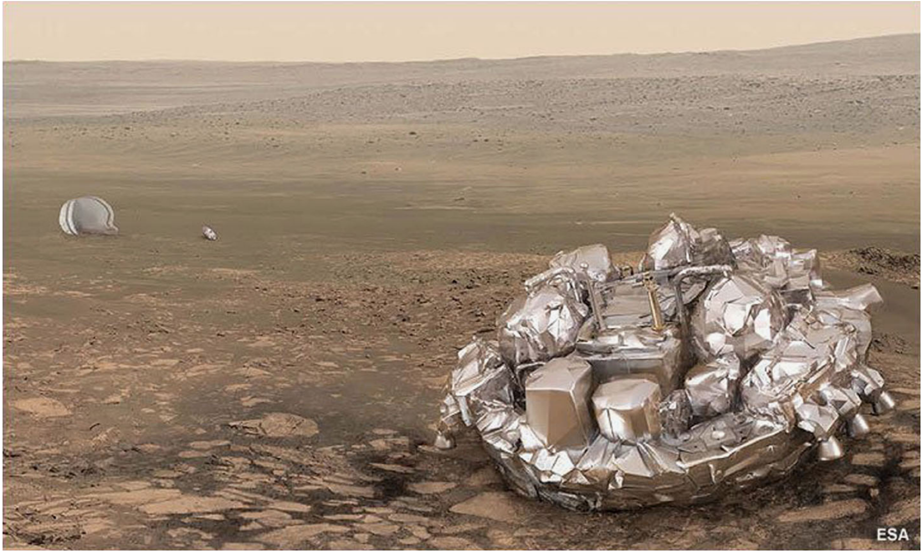

Fig. 7 Artist's view of Schiaparelli at the touch-down with the surface of Mars. In the background at the left side the back shell is visible, with the parachute still partially inflated (credit: ESA)

the turbulence scale and intensity. Finally, AMELIA results could have been investigated in synergy with DREAMS (Esposito et al. 2018, this issue) that should have provided meteorological and environmental measurements at the surface of Mars, in order to study the meteorology and climate of Mars.

7 Surface Science

Scientific analysis of the landing measurements were aimed at the determination of the landing site context (e.g. surface mechanical characteristics, geomorphology, etc.), its characterization and assessment also in combination with remote sensing imaging and geological mapping (Fig. 7).

From the impact trace (that should have been recorded by the IMU and the landing accelerometers had the landing been successful) it would have been possible to derive the dynamic response of the EDM structure to the impact, to retrieve the post-impact movements and attitude, and possibly to determine the mechanical properties/characteristics of the soil at the touch-down.

From radio tracking and the radar Doppler altimeter data the orographic profile (i.e. elevation) over the ground track of the descent module should have been retrieved and returned after landing.

The *a priori* characterization of the landing site of the ExoMars2016 (Fig. 8) was performed by a careful analysis of the engineering constraints used in order to assess the safety of the landing in Meridiani planum (Ori et al. 2014, 2015). Low to very high-resolution data acquired by previous and current Mars missions have been used in order to distinguish and characterize geomorphological units and in order to realize a geological-geomorphological map within the landing ellipse (Pacifici et al. 2014).

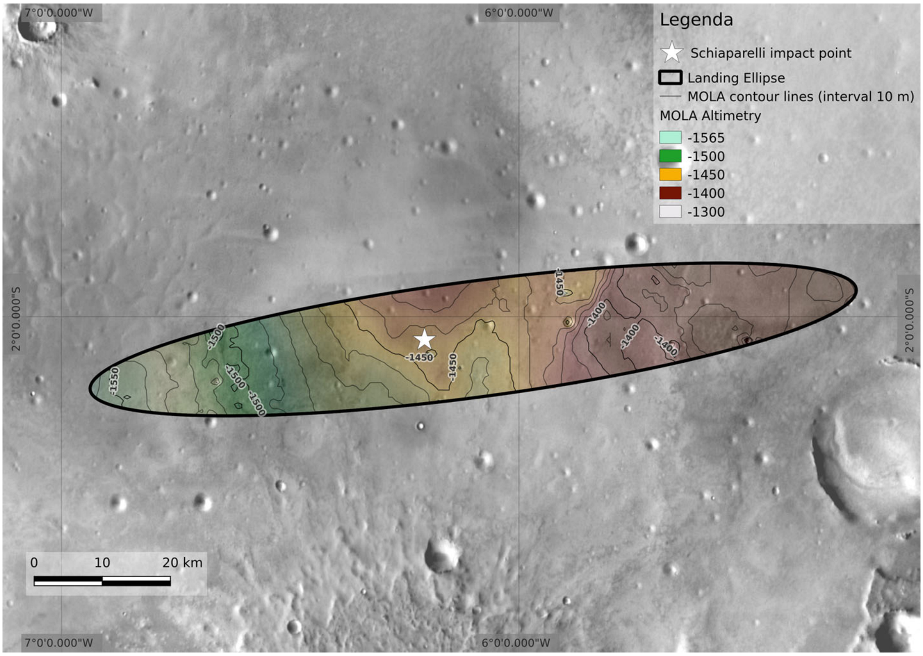

Fig. 8 ExoMars2016 Schiaparelli landing site in Meridiani Planum. The landing ellipse, centered at 6° West and 2° South, measured about 100 km East-West and 15 km North-South; it was located on a relatively smooth, flat region as evidenced by the overlaid topographic map (Mars Odyssey—THEMIS Day-IR, MGS—MOLA data). The actual Schiaparelli impact site, as detected in the MRO HIRISE images, is marked with a star (credit: IRSPS/TAS-I/ESA)

The characterization and assessment of the landing site would have been improved by combining remote sensing and descent images by DECA, co-registering the descent images with MRO-HiRiSe by matching geological and geomorphological mapping also in order to study aeolian and sedimentary processes at the landing site.

8 Schiaparelli's Entry and Descent

Schiaparelli, the Entry Demonstrator Module (EDM) of the ESA ExoMars Program, entered into the martian atmosphere on 19th October 2016. Although it did not complete a safe landing, it transmitted data throughout its descent to the surface, but the signal was lost about 1 minute before the expected touch-down on Mars' surface. Due to an anomaly in the guidance, navigation and control (GNC) loop, Schiaparelli crash-landed on the surface of Mars from an altitude of about 4 km. The crash was later confirmed by Mars Reconnaissance Orbiter images of the impact site (Fig. 9).

Schiaparelli continuously transmitted telemetry that was received by the TGO (Trace Gas Orbiter), while the signal carrier was recorded by the Giant Metre-wave Radio Telescope (GMRT) in Pune (India) and by MarsExpress until the loss of signal. The radio signal and essential telemetry data received from Schiaparelli during EDL were interrupted for about 1 minute as a result of the expected plasma blackout during the hypersonic entry, covering an altitude range from about 70–30 km above the surface.

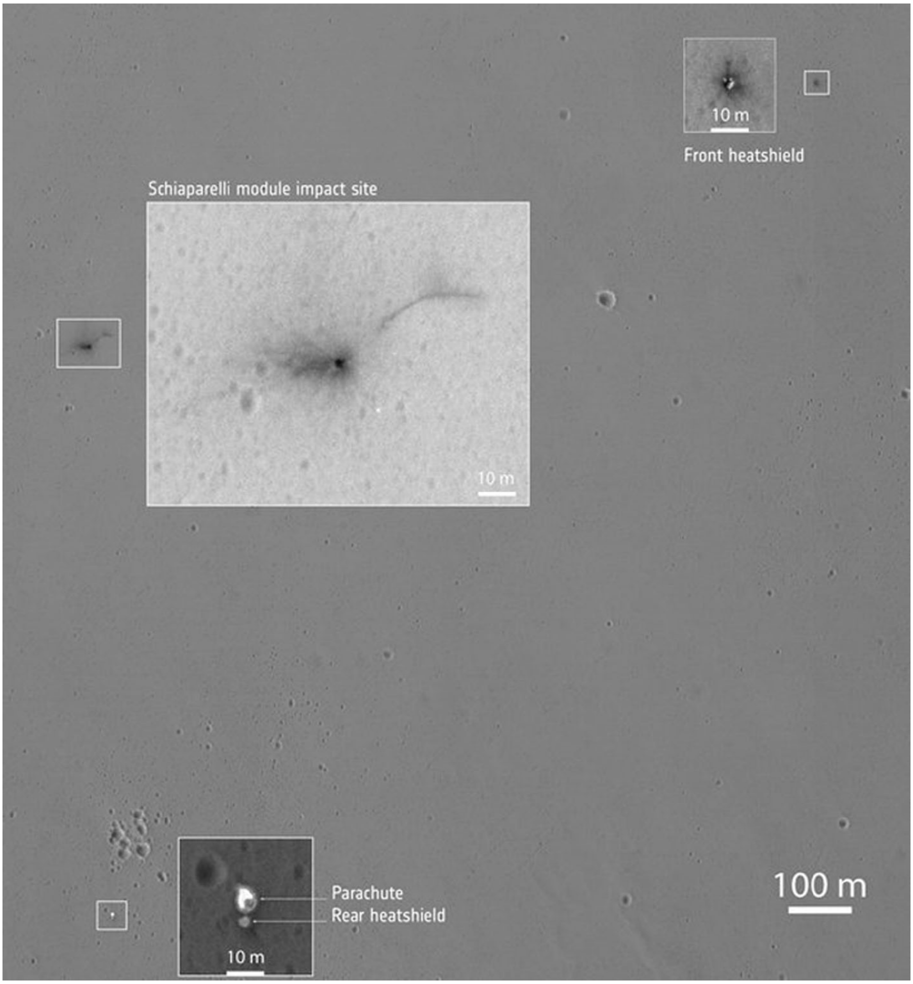

Fig. 9 ExoMars2016 Schiaparelli impact site on Mars as recorded by the NASA Mars Reconnaissance Orbiter HiRISE camera (image taken on 25 October 2017). The locations of the surface platform crash site, parachute with back cover (at the lower left corner) and front heat shield (at the upper right corner) impact site on Mars' surface are marked. Close-up views of the related hardware components are provided in the zoomed insets (credit: NASA/JPL/UA/ESA)

Radio contact with Schiaparelli was lost shortly after front shield release, which is where flight data end (at about 4 km from the ground). Because of the limitation on bit rate and data volume, the EDL flight data received by TGO contain only GNC measurements at reduced sampling rates, and decimated pressure data. The complete EDL data set, including data from the plasma black-out phase, the GNC data and sensor measurements at higher rates, and also DECA images, were recorded on board and should have been transmitted after landing. As a consequence of the crash, no data have been returned from the Mars relay orbiters during the planned subsequent passages.

The radio signal and the flight data, although more limited than would be ideal, are essential to investigate the anomaly that caused the crash landing and in order to achieve the AMELIA scientific objectives. At the time of writing, the data were under analysis to establish the reasons for the Schiaparelli's landing failure and under embargo. Then at a later time, the outcome of the Schiaparelli flight anomaly investigation was officially presented (Tolker-Nielsen 2017) and the results of the analysis published (e.g. Portigliotti et al. 2017; Bonetti et al. 2018) as were the results of the AMELIA reconstructions (Aboudan et al. 2018).

9 Conclusions

The ESA—Roscomos ExoMars Project provided a rare opportunity (once per mission) for *in situ* measurements within the atmosphere of Mars and at the landing site. These measurements allow for sounding the atmospheric structure along the trajectory of the descent module and the assessment of the landing site.

The ExoMars Atmospheric Mars Entry and Landing Investigation and Analysis (AMELIA) experiment in 2016 aimed to exploit the engineering data recorded during the Entry, Descent and Landing (EDL) of the Schiaparelli descent module in order to perform scientific investigations of the atmosphere and surface of Mars along the descent track and at the landing site. The AMELIA scientific objectives and the intended investigations have been presented in the context of the ExoMars2016 Schiaparelli mission. The Schiaparelli EDL scenario and measurements have been described as they were planed, and some science may be recovered with the more limited data set returned following the events on 19th October 2017. Beside the unfortunate conclusion of the Schiaparelli mission, the signal and data transmitted during the EDL provide unprecedented real-time data set for validating and assessing of the EDL sequence. We anticipate further scientific exploitation of the Schiaparelli EDL flight data for investigation of the martian atmosphere, and to contribute to the lessons learned for the upcoming ExoMars2020 mission and for a new EDLS opportunity.

We have been able to make reconstructions of the profile down to 4 km, but at reduced resolution compared to what would have been achievable had the spacecraft landed successfully and returned all its data. The vertical resolution achieved was still significantly higher than is possible by remotely-sensed measurements, even those made with a limb-sounding instrument such as MCS, and cover a much larger altitude range than is possible with radio occultation retrievals. Unfortunately, data taken during the plasma blackout (e.g. in the altitude range from 70–30 km) and the terminal descent phase (the last 4 kilometers above the surface) are impossible to recover. Data that would enable a refined reconstruction by assimilation and measurement blending have been lost, as have images from DECA and landing investigations. The techniques described above have been adapted and further developed to make use of the limited returned data and to cope with the transmission loss in order to retrieve the atmospheric profiles along the entry and descent trajectory of Schiaparelli into the atmosphere of Mars.

Acknowledgements AMELIA is an experiment for scientific investigations of Mars' atmosphere and surface by means of the Schiaparelli measurements during its entry, descent and landing on Mars. The International AMELIA team built under the joint coordination of Principal Investigator: Francesca Ferri (Italy) and 3 Co-Principal Investigators (CoPIs): François Forget (France), Stephen R. Lewis (United Kingdom), Özgür Karatekin (Belgium). The team includes scientists from Italy, France, UK, Belgium, Finland, Germany, Australia and USA.

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