DOCUMENT

EXOMARS 2016 - Schiaparelli Anomaly Inquiry

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1 INTRODUCTION

The Schiaparelli module (also called EDM) was part of the ExoMars 2016 mission launched on 14 March 2016 on a Proton rocket from the Baikonur cosmodrome in Kazakhstan. The EDM was conceived with the objective to validate and demonstrate entry, descent and landing on Mars in preparation for the ExoMars 2020 mission.

On 19 October 2016, the Schiaparelli module entered the Mars atmosphere at 14:42:07 (UTC). During its Entry and Descent into the Martian atmosphere, Schiaparelli continuously transmitted telemetry that was received by the TGO. The signal carrier was also recorded by the Giant Metre-wave Radio-Telescope (GMRT) in Pune (India) and by Mars Express. Schiaparelli's signal was lost at 14:47:22 (UTC), about 43 seconds before the expected touchdown on Mars surface

On 20 October 2016, the CTX camera on-board NASA's Mars Reconnaissance Orbiter took a picture of the Schiaparelli landing site and detected the presence of a new large dark spot (~ 15 m x 40 m) in the vicinity of the expected Schiaparelli landing site. About 1 km south of this dark spot, a new white spot was also identified. The white spot corresponds to Schiaparelli's parachute and the dark spot was created by the hard impact of Schiaparelli on Mars surface, evidencing the failure of Schiaparelli's controlled landing.

The ESA Council and the DG of ESA requested an independent inquiry encouraging involvement of NASA/JPL. In consultation with Heads of Delegations of the main contributors to the ExoMars Programme the Schiaparelli Inquiry Board (SIB) was established for the following purpose.

- To establish the circumstances of the anomaly;
- To establish the root cause of the anomaly and the reasons for this root cause;
- To establish recommendations for corrective actions;
- To establish consequences for the 2020 ExoMars mission in terms of lack of demonstration and associated recommendations for remedying of any shortfalls;

The members of the SIB were

Bernard Chemoul	CNES, Advisor in the President's Office	Member
Giovanni Colangelo	ESA, Head of Project Resource Assessment Office in the IG Office	Secretary
Prof. Guido Colasurdo	University of Roma "Sapienza", full Professor of Flight Mechanics.	Member
Michel Courtois	Retired ESA Director of Technology, Engineering and Quality Directorate	Member
John Ellwood	Retired ESA, Head of Science Programme Department	Member
Prof. Dr.-Ing. Walter Fichter	University of Stuttgart, Flight Mechanics and Controls Lab	Member
Dr.-Ing. Ali Gülhan	Head of Department, DLR, Institute of Aerodynamics and Flow Technology	Member
Robert Manning*	NASA/JPL Engineering and Science Directorate Chief Engineer	Member
Prof. Paolo Teofilatto	Dean of the School of Aerospace Engineering of Rome	Member
Alberto Tobias	Retired ESA, Head of Systems and Software Department	Member
Toni Tolker-Nielsen	ESA Inspector General	Chairman

*Rob Manning coordinated support from a team of Mars entry, descent, and landing experts at JPL and an EDL expert team at NASA LaRC (Langley Research Center) lead by David Way.

The SIB report was issued 17 April 2017.

The present report is an abbreviated version of the SIB report for the purpose of a wider distribution than the parties to the Technical Assistance Agreement established in the context of the SIB.

2 ACRONYMS

AOA	Angle Of Attack
ATB	Avionics Test Bench
CM	Cruise Module
COG	Center Of Gravity
Delta-V	Delta Velocity
DM	Descent Module
DOF	Degree Of Freedom
DRB	Delivery Review Board
E2E	End to End
EDL	Entry Descent and Landing
EDM	Entry Demonstrator Module
EGSE	Electrical Ground Support Equipment
EIDP	End Item Data Package
EIM	Electrical Interface Models
EIP	Entry Interface Point
EM	Engineering Model
EQM	Engineering Qualification Model
EQSR	Equipment Qualification Status Review
FDIR	Failure Detection, Isolation and Recovery
GNC	Guidance Navigation and Control
HW	HardWare
I&T	Integration and Test
ICD	Interface Control Document
IMU	Inertial Measurement Unit
ISST	Integrated SubSystem Test
IST	Integrated System Test
ITAR	International Traffic in Arms Regulations
LOS	Loss Of Signal
LP	Landing Platform
LV	Launch Vehicle
MC	Monte Carlo
MMED	Mars Mean Equator of Date
OBSW	On Board SoftWare
PA	Product Assurance
PAS	PArachute Subsystem
PDD	Parachute Deployment Device
PFM	Proto Flight Model
QA	Quality Assurance
RCS	Reaction Control System
RDA	Radar Doppler Altimeter
RIL	Radar In the Loop
RM	Rover Module

RTPU	Remote Terminal and Power Unit
S/W	Software
SAIG	Schiaparelli Anomaly Investigation Group
SCC	SpaceCraft Composite
SIB	Schiaparelli Inquiry Board
SM	Structural Model
SVF	Software Validation Facility
TGO	Trace Gas Orbiter
UHF	Ultra High Frequency
UTC	Universal Time Coordinated

3 EDM/SCHIAPARELLI SYSTEM & MISSION DESCRIPTION

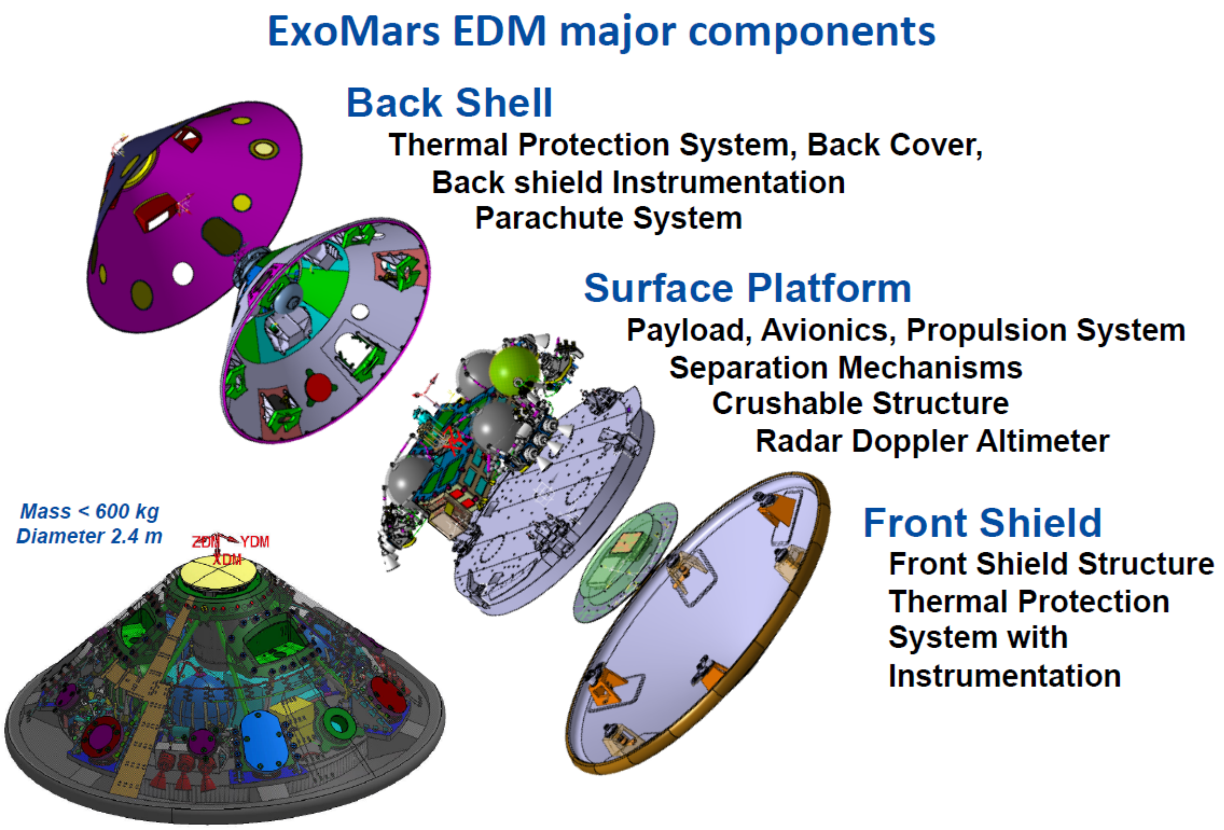

Figure 1: ExoMars EDM major components

The main characteristic of the Schiaparelli vehicle are summarized below.

- Mass: 577 kg after separation, 280 kg at landing
- Configuration:
  - Aeroshape inherited from the NASA Mars vehicles
    - 70 deg sphere-cone front shield
    - 47 deg conical back shield
  - Diameter 2.4 m
  - Height 1.32 m
- Thermal shield:
  - Front shield: Norcoat-Liège ablative material
  - Back shield: Norcoat-Liège ablative material
- Structure: Aluminium sandwich with carbon fiber reinforced polymer skins with crushable structure to absorb landing loads.
- Avionics: No failure-tolerant Avionics design with non-rechargeable batteries and UHF communication system.
- Parachute: Supersonic Disk-gap-band canopy, 12 m diameter deployed via a mortar system
- Propulsion: 3 clusters of 3 hydrazine pulse engines, 400 N (90 lbf) each

The EDM was equipped with:

- 1 Inertial Measurement Unit (IMU) for the measurement of, respectively, inertial angular

velocity components and non-gravitational acceleration components in the body axes;
- 1 Radar Doppler Altimeter (RDA) formed by 1 set of 4 antennas and 2 electronic units (for redundancy reasons) for the measurement of the distance to the terrain along the X body (symmetry) axis and the linear velocity components with respect to the terrain in the body axes.

The attitude is obtained by integration of the gyroscope measurements. After hibernation and before atmospheric entry the attitude is initialised by the use of a Sun Sensor installed on the Back Shield. Figure 1 indicates the various reference frames used. It should be noted that the Inertial Measurement Unit is not situated at the COG.

Regarding Schiaparelli mission, a pictorial view is provided hereafter:

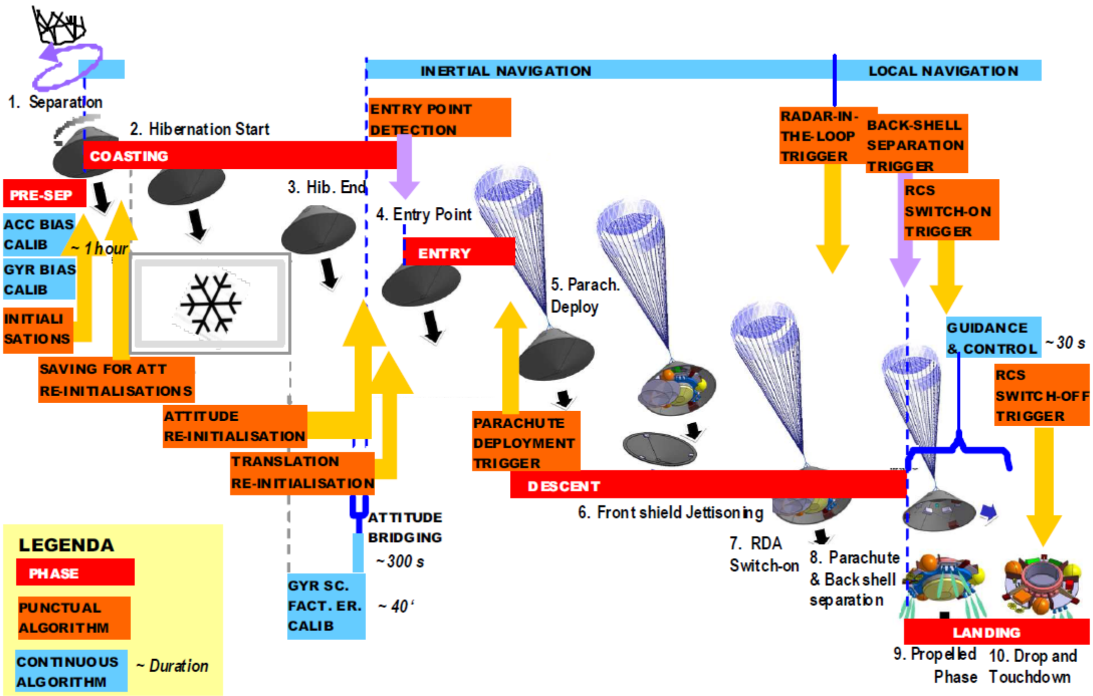

Figure 2: Schiaparelli EDL sequence

Phases of the ExoMars EDM mission and GNC tasks:
- Blue labels represent the GNC functions;
- Orange labels represent the punctual GNC algorithms dedicated to trigger specific events and engage GNC modes;
- Red label are the phases of the EDM mission;
- Violet arrows distinguish the trigger that determines phase changes.

4 EDM SCHIAPARELLI VALIDATION APPROACH

The following models were developed and used for the verification of the EDM performances:

- Breadboards and samples (various purposes)
- EDM Structural Model (SM)
- EDM Software Verification Facility (SVF)
- EDL E2E Simulator including multi body parachute model
- EDM Avionics Test Bench (ATB)
- EDM Proto Flight Model (PFM)

The EDL E2E simulator and the ATB objectives and characteristics are described in the following.

Entry Descent and Landing simulator, EDL, E2E simulator

The EDL simulator, also called the EDL E2E simulator was conceived to support:

- EDL mission design definition and validation
- GNC design development and verification
- Mission operational phases during phase E

The main components of the EDL E2E simulator are:

- Mission Manager and Schedulers
- Libraries
- Models repository:
  - EDM dynamics (6 DOF)
  - Atmosphere and gravity models
  - Aero-database and solar pressure data
  - DHS model with all GNC algorithms
  - Terrain, plume impingement and impact models
  - TPS erosion/ablation model
  - Parachute multi-body model
  - SDS, IMU models
  - RDA model
  - RCS pressure and thrusters model
  - EDL characteristics (CoG evolution, inertias, parachute attachment etc)

The EDL E2E simulator, is the unique tool used to verify the capability of the EDM to fulfil the key Mission and System requirements in terms of Entry, Descent and Landing performance, before it actually happens on Mars. It consists of a high number of models, which each must be validated with test and analysis, in order to make the E2E simulation valid. The EDL E2E simulator is used to perform Monte Carlo simulations taking into account a certain spread of uncertainties and variations in the driving parameters of each sub-model. The results of these simulations are used to define the design margins. This approach is State of the Art, also used by JPL/NASA. One mistake in any of the sub-models can ruin everything so each sub-model must be thoroughly validated

EDL Avionics Test Bench (ATB)

The objectives of the Avionics Test Bench are:

- debugging of the flight units electrical I&T procedures and ISSTs procedures
- debugging of the IST sequences before run on PFM
- validation of the OBSW by using flight-like HW environment
- validation of Flight Operations Procedures before delivery to ESOC
- troubleshooting of EDM PFM anomalies
- OBSW qualification
- non-nominal scenario tests

The avionics test bench is Composed of:

- Engineering Models (EM) for CTPU, IMU, SDS, RDA, RCS thruster valve
- Engineering Qualification Models (EQM) for RTPU, UHF Transceiver, Batteries and Relay Boxes
- Electrical Interface Models (EIM) for COMARS+, DeCA and DREAMS
- EGSE: Data Handling, Power, UHF, GNC
- Harness
- Mission phase simulation including environment

The GNC representativeness has some limitations:

- Simplified models are used for real-world simulation (aerodynamics, parachute dynamics, RCS forces/torques), due to real-time constraints,
- Simplified modellisation is used for the dependence on Mach number of the normal and moment aerodynamic coefficients (this is valid for the E2E simulator and the ATB),
- Parachute model does not include disturbances at parachute inflation such as lateral movement and area oscillations (this is valid for the E2E simulator and the ATB),
- Models are not configuration controlled versus as built EDM; CoG evolution, inertias, asymmetry of the EDM, etc (this is valid for the E2E simulator and the ATB),
- IMU EM are used only for electrical interface and polarity tests – the IMU cannot be stimulated to be included in the navigation function or in the GNC closed-loop tests.

5 THE CIRCUMSTANCES OF THE ANOMALY

The sequence (timeline) of the events is reported below with respect to UTC time.

a) *Separation from TGO on 16/10/2016 at 14:42:00.*
b) *Awakening from hibernation on 19/10/2016 at 13:29:48.*
c) *Entry in the Mars atmosphere (EIP) detected at 14:42:22 through accelerometers.*
d) *Between EIP and Parachute Deployment triggering, an unexpected evolution in the spin rate of the EDM was noticed.*
e) *At 14:45:23 the parachute deployment was triggered (trigger is the g-level).*
   - *The dynamic conditions at the moment of parachute deployment derived from telemetry showed a total angle of attack (AOA) estimated of about 6.5 deg and a lateral angular rate < 3 deg/s*
f) *Parachute deployment time (time from mortar firing to peak load factor) was circa 1 sec (in line with the predictions).*
   - *The parachute was deployed, and the parachute inflation triggered some oscillations of Schiaparelli at a frequency of approximately 2.5 Hz.*
   - *About 0.2 sec after the peak load of the parachute inflation, the IMU measured a pitch angular rate (angular rate around Z-EDM axis) larger than expected.*
   - *The IMU raised a saturation flag,.*
   - *During the period the IMU saturation flag was set, the GNC Software integrated an angular rate assumed to be equal to the saturation threshold rate. The integration of this constant angular rate, during which the EDM was in reality oscillating, led to an error in the GNC estimated attitude of the EDM of about 165 degrees. This would correspond to an EDM nearly turned downside up with the front shield side pointing to quasi-zenith.*
   - *After the parachute inflation, the oscillatory motion of Schiaparelli under its parachute was mostly damped and Schiaparelli was descending at a nominal descent rate, with very small oscillations (< 3 deg) around pitch and yaw axis.*
   - *After parachute inflation the angular acceleration around the spin axis changed again*
g) *The Front Shield was jettisoned as planned 40s after parachute deployment (timer based command) at 14:46:03*
h) *The RDA was switched on at 14:46:19 (15s after Front Shield separation acknowledgment) and provided coherent slant ranges, without any indication of anomalies;*
   - *Once the RDA is on, RIL mode, "consistency checks" between IMU and RDA measurements are performed. The parameters checked are: delta velocity and delta altitude. The altitude is obtained using the GNC estimated attitude to project the RDA slant ranges on the vertical.*
   - *Because of the error in the estimated attitude that occurred at parachute inflation, the GNC Software projected the RDA range measurements with an erroneous off-vertical angle and deduced a negative altitude (cosinus of angles > 90 degrees are negative). There was no check on board of the plausibility of this altitude calculation*
i) *Consequently the "consistency check" failed for more than 5 sec. after which the RDA was forced anyway into the loop based on the logic that landing was impossible without the RDA. The correctness of the other contributor to the altitude estimation, i.e. the attitude estimate, was not put in question. The RDA was put in the loop (event signalled by RIL time-out flag at 14:46:46).*
   - *The GNC mode entered was TERMINAL DESCENT where the altitude is scrutinized to release the Back-Shell and parachute if the altitude is below an on board calculated limit.*

- *Because of the incorrect attitude estimation leading to an estimated negative altitude, the GNC Software validated the conditions for separating the back-shell and parachute*

j) *Back-shell separation at 14:46:49.*

k) *Switch-on of the Reaction Control System (RCS).*
   - *First RCS thruster operation was at 14:46:51 (no backshell avoidance manoeuvre)*

l) *Switch-off of the RCS 3 seconds later at 14:46:54.*
   - *The criterion for the RCS switch-off was based on the estimation of the EDM energy (as combination of the altitude and vertical velocity) being lower than a pre-set threshold. Since the estimation of the altitude was negative and very big, the negative potential energy was much higher than the positive kinetic energy (square of the velocity) and this criterion was immediately satisfied the RCS was commanded off as soon as allowed by the thruster modulation logic. This occurred just 3 seconds after the RCS switch on command when the capsule was at an altitude of about 3.7 km, leading to a free fall of Schiaparelli and to the impact on Mars surface about 34 seconds later.*

m) *The Touch Down occurred at <u>14:47:28</u> corresponding to the crash of the surface platform on the surface of Mars at an estimated velocity of ≈150 m/s. The expected landing time was 14:48:05 (some 37s later).*

6 INVESTIGATION AND FINDINGS FROM INTERVIEWS & DOCUMENTATION REVIEW

This section provides the description on how the investigation has been performed and the main findings.

From the review of the elements available to the SIB, it was evident that the Schiaparelli "hard landing" was ultimately due to the large attitude error created by the GNC software by integrating the saturation threshold rate during the saturation flag persistence. Shortly after parachute inflation high angular rates occurred and the subsequent "saturation" of the IMU.

The wrong attitude estimate resulted in large altitude estimation errors and as a consequence on fast transitions to new modes when triggered by altitude. This resulted in early activation of the terminal descent phase with untimely parachute jettisoning, and in RCS activation for 3 sec only, leading to a free fall of Schiaparelli and the impact on Mars surface about 33 seconds later at a speed of approximately 150 m/s.

6.1 Anomaly Tree and investigation directions

The investigation performed focussed on the understanding of the causes of the IMU saturation and of the high dynamic phenomenon, in line with the anomaly tree depicted below:

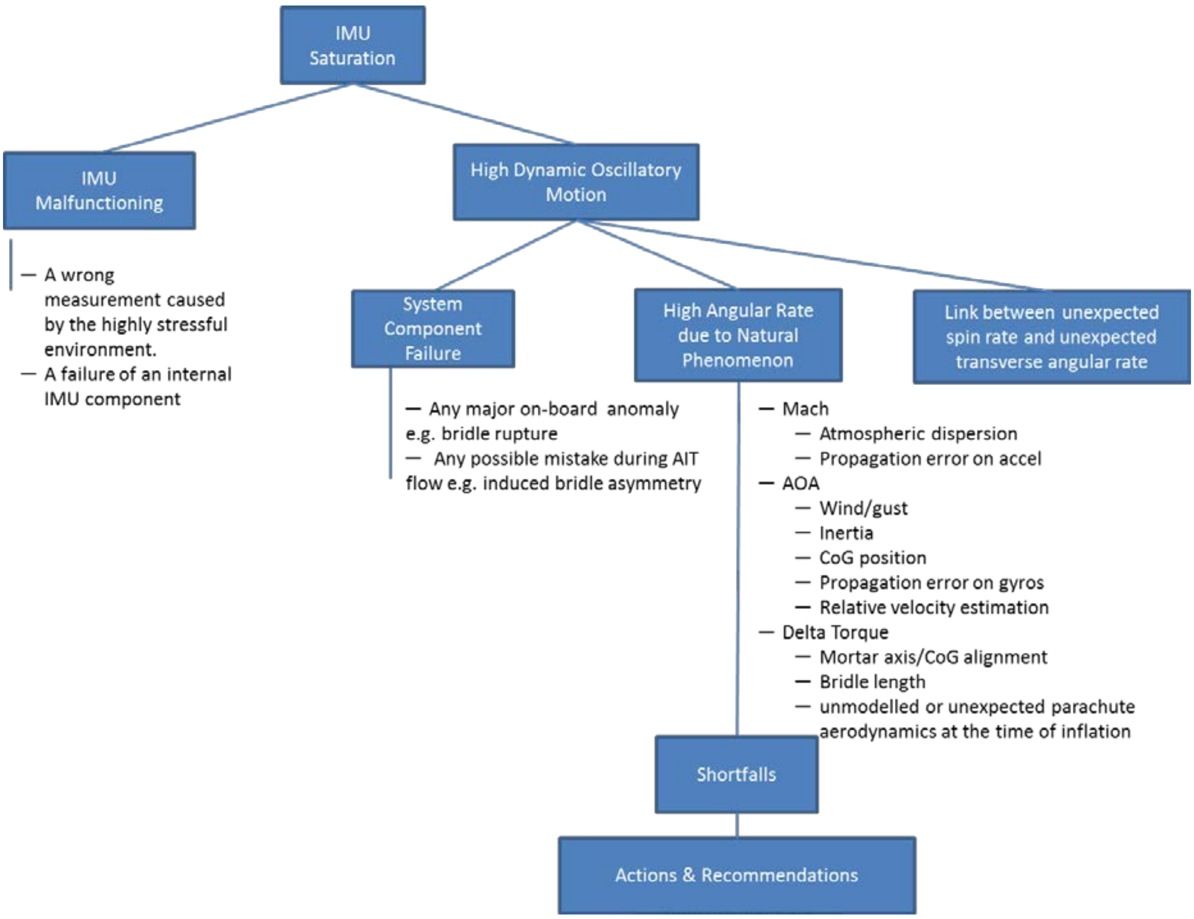

Figure 3: Failure tree

Two possible reasons for IMU saturation (on one axis, Z_EDM) were investigated

- IMU malfunctioning (real actual angular rate < saturation limit)
- Measurement of angular rate performed by the IMU represents the actual dynamics of the EDM during the parachute deployment, i.e. in a short time there was an important oscillatory motion, that caused one or, maybe, several saturations (real actual angular rate > saturation limit)

6.2 Anomaly Tree Investigation Outcome

6.2.1 *IMU Malfunctioning*

Regarding a potential IMU malfunctioning, this could have been caused by the following reasons:

- A wrong measurement caused by the highly stressful environment encountered during the parachute deployment phase, or sensitivity to high angular acceleration.
- A failure of an internal IMU component,

To investigate a possible malfunctioning of the IMU under highly stressful environment some additional analysis and tests were performed aimed at checking IMU functioning:

- when angular rates exceed IMU measurement capability;
- when the IMU simultaneously experiences high angular acceleration and linear jerk environments in which the IMU was not previously tested.

The conclusion of the above activities showed that the IMU performs nominally when subjected to high angular accelerations and jerk.

The good functioning of the gyro of the IMU is also confirmed by the restitution of rotation from the accelerometer measurements (the IMU is not situated at the CoG of the EDM), which compares well to the rotation measured by the gyros.

Considering the plausible output of the IMU after the saturation event there is no indication of permanent component failures.

It can, therefore, be concluded that there is no indication of any anomalies **occurred in the IMU and that the measured environment was a real one**.

6.2.2 *High dynamic oscillatory motion*

Regarding the high dynamic phenomenon two root causes were investigated:

- The high angular rates were caused by some failures occurred before or during the parachute deployment.
- The high angular rates are an actual, unpredicted, phenomenon caused by a combination of influential parameters but not associated to a specific failure/anomaly.

6.2.2.1 System/Component failure leading to high dynamics at parachute deployment

Regarding this branch of the failure tree, it is to be noted that no anomalous functioning during the phases preceding and following the parachute deployment, which could indicate any system/component failures, has been identified

The Prime contractor was requested to perform an investigation into Request for Deviations and Waivers (RFDs, RFWs) and Non Conformance Reports (NCR) of the hardware, which could explain the observed behaviour. In addition an independent Product Assurance Tiger Team consisting of experts from ESA's Directorate of Technology, Engineering and Quality (D/TEC) was mandated to do the same.

None of the two investigations identified any recorded RFDs, RFWs or NCRs that could explain the observed behaviour.

For those reasons it is to be concluded that **the high dynamics motion experienced during parachute deployment was most likely not caused by a specific system or component failure**.

6.2.2.2 High angular rate due to natural phenomenon

With respect to this branch of the failure tree, it has to be noted that hypersonic parachute deployment is a very complex and dynamic phenomenon affected by several uncertainties (winds, wake, etc.) and therefore very difficult to predict (and model).

The following aspects, on which the investigation has focussed, have been identified as potentially contributing to the high angular rates at parachute deployment:

1. Mach number different than estimated, potentially due to
    a. Atmospheric dispersion (density/temperature)
    b. Propagation error from accelerometers into position and velocity
2. AOA higher than estimated, potentially due to
    a. Presence of Wind/gusts
    b. Inertia values and evolution/CoG position and evolution during descent in line with change of EDL configuration
    c. Propagation error from gyros from last known attitude
    d. Relative velocity estimation (see Mach estimation point 1b above)
3. Additional torques at Parachute mortar firing and inflation, potentially due to
    a. Mortar axis not aligned with CoG
    b. Bridles asymmetry
    c. Incorrect modelling of parachute riser angle at inflation
    d. Oscillation of parachute force along the riser due to parachute area oscillation
    e. Large canopy motion due to unsteady wake dynamics causing large riser angle variations including bridle slacking
    f. Asymmetric canopy inflation

Monte Carlo simulations of the Schiaparelli parachute deployment performed by NASA/JPL using their high fidelity model revealed an important number of cases where angular rates were above the EDM IMU saturation level. Simple planar oscillation wrist mode modelling concurs with these Monte Carlo simulations.

Post flight analysis reconstructed parachute riser angles based on angular rates and linear accelerations of the EDM indicated large parachute riser angle and riser force variations after parachute inflation, well above the expected and which were not identified in the E2E simulations.

Comparing such parachute behaviour to wind tunnel test at similar Mach numbers performed in the context of NASA missions and with NASA flight experience indicates that such high parachute dynamics were to be expected.

Each of the potential contributors to high angular rates have been analysed. The main contributors appears to be:

- 2.a Presence of Wind/Gust
- 3.d Oscillation of parachute force along the riser due to parachute area oscillation
- 3.e Large canopy motion due to unsteady wake dynamics causing large riser angle variations including bridle slacking
- 3.f Asymmetric canopy inflation

From SIB analysis it can be concluded that oscillation of parachute forces due to parachute area oscillations can explain alone the unexpected high rates just after parachute inflation. The phenomena of parachute area oscillations was not considered in the multi body model used in the E2E simulator.

Based on the analyses performed, **the SIB consider that rates saturating the IMU were to be expected for the EDM system and parachute deployment conditions and configuration.**

6.2.3 *Links between unexpected spin rate and unexpected transverse angular rates*

During entry and descent the EDM spin rate showed an unexpected behaviour

Between EIP and PDD triggering the spin rate:

- increases from 16 to 18 deg/s before the black-out;
- decreases to 12 deg/s before PDD.

After PDD triggering the spin rate

- decreases up to almost zero before Front Shield Jettisoning.

A similar anomaly was observed during NASA's Mars Exploration Rover mission[1]. In that case inspection using the Opportunity Rover on the surface of Mars revealed that remaining thermal blanket hardware could induce torques explaining the unexpected spin rate after black-out. This flight experience supports the hypothesis that the unexpected spin rate during entry could be due to uneven disintegration of thermal blankets and associated hardware, nevertheless the SIB did not perform an in depth investigation of the possible root cause of the spin rate evolution beyond its possible impact on the unexpected transversal angular rates.

The angular acceleration around the spin axis changed value again after parachute deployment. The root cause of this is believed to be a possible slight twist in the parachute riser after deployment.

Based on the analyses performed, **the SIB consider that there is no link between the unexpected spin rate behaviour and the unexpected transverse angular rates that saturated the IMU.**

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[1] **Mars Exploration Rover Heat Shield Observation Campaign**, Christine E. Szalai1, Benjamin L. Thoma, Wayne J. Lee, Dr. Justin N. Maki, Jet Propulsion Laboratory, American Institute of Aeronautics and Astronautics, February 2006

6.3 EDM Failure Root Causes Analysis Summary

The high dynamic phenomenon experienced during the parachute deployment phase was not due to the failure of a specific subsystem or component but rather due to a natural phenomenon caused by a combination of various parameters, which were not properly predicted/expected before flight.

On the basis of the outcome of the investigations performed, the SIB members identified four main root causes that led to the Schiaparelli failure:

- Insufficient conservative modelling of the parachute dynamics which led to expect much lower dynamics than observed in flight;
- Inadequate persistence time of the IMU saturation flag and inadequate handling of IMU saturation by the GNC;
- Insufficient approach to FDIR and design robustness;
- Mishap in management of subcontractors and acceptance of hardware, (the persistence of IMU saturation time was not recorded at acceptance and instead believed to be 15 ms).

It should be borne in mind that if the persistence time of the IMU saturation flag would have been 15 ms the landing would probably have been successful, in which case the other root causes would probably never have been identified.

6.3.1 *Modelling of Parachute Deployment Dynamics*

The parachute deployment is a very complex dynamic unsteady phenomenon affected by several uncertainties and therefore very difficult to model and to predict (RD 23). It is evident from the restitution of the riser angle (angle between EDM longitudinal axis and the parachute riser direction) based on in-flight data, that the prediction from the multi-body simulations did not provide a realistic behaviour of the parachute deployment.

This is supported by JPL/NASA previous experience[2] which indicates that:
- the position of the parachute as it begins inflating does not correlate with the attitude of the vehicle at mortar fire, as it is assumed in the EDM modelling
- the EDM parachute models also do not account for the large, non-linear and non-stationary parachute forces (i.e. over-inflation and area oscillations) that occur when parachutes are deployed at supersonic conditions, which is known to excite wrist mode dynamics considerably.

Considering that, according to NASA's experience[2] the non-linear and non-stationary parachute forces increases exponentially above Mach 1.4 and becomes severe at Mach 2[3], the SIB members confirmed that the cancelled subsonic High Altitude Drop Test would not have revealed the underestimated supersonic dynamic behaviour of the parachute at Mach 2.

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[2] **Parachute Models Used in the Mars Science Laboratory Entry, Descent, and Landing Simulation,**
Juan R. Cruz,1 David W. Way,2 Jeremy D. Shidner, Jody L. Davis, Richard W. Powell5, *NASA Langley Research Center,*
Devin M. Kipp, Douglas S. Adams, Anita Sengupta, *Jet Propulsion Laboratory,*
Al Witkowski, Mike Kandis, *Pioneer Aerospace, South Windsor, Connecticut, 06074*
American Institute of Aeronautics and Astronautics, March 2013

[3] **The Schiaparelli parachute deployment is estimated to have occurred at Mach 2.05, for a pre-flight predicted range of [1.88; 2.07]**

Riser angle at inflation

One important parameter that drives lateral angular rates is the riser angle, that is, the angle of the parachute riser, aligned to parachute drag force, with respect to longitudinal vehicle axis at the end of inflation.

Angular transverse rates (rotation around Z and Y axis) different from zero at PDD may have a positive or negative impact (i.e. increasing or decreasing the limit maximum angle of attack) depending on the sign (i.e., direction) of the initial angular transverse rate; in any case it is considered rather likely that the actual riser angle at the moment of parachute inflation and just after was indeed higher than 8-9 degrees resulting in angular rates higher than the IMU saturation rate.

Uncertainty Management and Margin Policy

A sufficiently conservative uncertainty management along all simulation / analysis activities was missing. This may include methods beyond standard modelling and simulation procedures.

The GNC design and verification approach was based on statistical Monte Carlo analysis, and pre-flight simulation already showed that values larger than 150deg/sec were possible. No specific worst case/stress analysis versus influential parameters (e.g. riser angle) was performed to investigate the system behaviour around this Monte Carlo case in a worst case input combination scenario.

The margin taken with respect to the 150 deg/sec on a single axis Monte Carlo case was clearly not adequate.

As no such dynamics was expected, there was no consideration of saturation as a feared event.

6.3.2 *Persistence time of IMU Saturation Flag*

For angular rates in excess of the saturation limit the IMU shows indication of the exceedance by setting a bit (Rate Flag Bit). The so-called persistence flag for the IMU saturation was found to be set too high for the mission.

As the GNC integrated such a rate, during the whole IMU saturation persistence time, it developed a bias error on the attitude. There was no analysis of plausibility of such an attitude, which was clearly impossible, e.g. the RDA echoes were received from the surface of Mars.

The mission would not have been jeopardised by the attitude knowledge error induced by IMU saturation, if the persistence time would have been set at a lower value.

6.3.3 *System Engineering Approach and Design Robustness*

From the System point of view the main weaknesses of the adopted approach were the fact that insufficient FDIR analysis, "what if"/robustness analysis, and worst case analysis were performed for the most critical mission phases of the EDL. In the adopted system approach only failures or anomalies of the RDA were considered, i.e. if consistency checks of the altitude derived from slant ranges and GNC estimated attitude would fail, it was considered that it would be due to an RDA anomaly, no fear of inconsistency due to wrong attitude estimate was identified. Nevertheless, as the RDA was absolutely necessary to land, it was included in the loop without putting in question the other component of the altitude determination, the GNC attitude estimate.

The presence of different measurements (accelerations, angular rates, radar altimeter measurements, time, etc.) could have been exploited for cross check purposes and to elaborate a parallel logic for degraded modes leading to a safe landing.

The design and verification of the entry descent and landing relied on Monte Carlo analysis with sophisticated models. The outcome of such analysis is highly depending on the models used. If one model, e.g. the parachute model, is not sufficiently representative, results of the MC analysis become meaningless. For a robust design, MC analysis must be supplemented by worst-case analysis taking into account uncertainties of the most influencing parameters identified by pertinent sensitivity analyses.

A group of Software and System specialist from ESA's Technology, Engineering and Quality Directorate was mandated to support the SIB with an assessment of the flight software behaviour and the relation SW – system and GNC. One of the conclusions of this investigation is that the software performed as expected, including even propagating a sign error due to an incomplete requirement in the specification (management of the sign of the angular rate under saturation). The GNC algorithm model contained the error. It was provided to the GNC-SW subcontractor that propagated the bug. It has been demonstrated by post-flight tests that the error of the sign had no influence on the failure as it does not matter in which direction the large angular error is built up by integrating the wrongly estimated rate (it is the duration of the saturation flag that what was the key factor).

6.3.4 *Mishap in management of subcontractors and acceptance of hardware*

The too long persistence of the saturation flag in the application software of the IMU, was the fundamental cause of the Schiaparelli landing mishap. This ambiguity was not identified, nor measured during acceptance of the unit and the saturation behaviour of the IMU was never tested after delivery. The mathematical model of the IMU used for simulations was established by the prime contractor. It is the SIB opinion that such intricate model is better established by the equipment supplier and must in all cases be formally validated by the supplier.

7 GENERAL OBSERVATIONS AND RECOMMENDATIONS

7.1 General Observations

During the conduct of the Schiaparelli Inquiry Board, the board has noted important facts concerning ExoMars teams that deserve explicit mention:

- Strong delivery-oriented team: After a difficult and long period of Programme reconfigurations and delays the Programme launched the Exomars 2016 mission at beginning of 2016
- Openness towards the aims of the SIB: ESA and the industrial ExoMars projects provided support and feedback with an open mind and fruitful cooperation spirit. Exchanges were thoughtful and productive, thereby facilitating the independent review process

7.2 Identified Weaknesses and Areas for Improvements

This chapter addresses identified weaknesses and areas for improvement in general. Specific recommendations for the 2020 mission is addressed in chapter 8

System Engineering approach and Design Robustness

As mentioned before, the parachute deployment is a very complex and highly dynamic phenomenon affected by several uncertainties and therefore very difficult to model and to predict. Indeed, it is evident from the analysis performed by the SIB members, that the prediction from the multi-body simulations did not provide a realistic behaviour of the parachute deployment phase. A robust approach with large margins should have been implemented on the basis of a Worst Case and Robustness analyses.

Recommendation 01 – The multi-body modelling used for the simulation of the parachute inflation needs improvements at least in the following areas:

- *Riser angle at inflation*
- *Area oscillations as a function of Mach number*
- *Lateral instability as a function of Mach number*
- *Asymmetric inflation*
- *Physical parameters must be configured according to the as built,(, bridles lengths, Inertias and CoG variations,…)*

It is also recognised that very complex physics make it difficult to establish accurate models. The SIB recommends implementing a heuristic approach when modelling of the physics becomes too complex.

Recommendation 02- An overview and verification plan of all sub models and their parameters shall be established.

The main weakness of the adopted decision logic was the fact that the FDIR focussed on RDA failures. Insufficient general "what if" analysis and Worst Case analysis were performed for the characterization of this critical phase. The fact that the system was Zero Failure Tolerant does not justify an over simplistic approach with no possibility of recovery from anomalies (even with degraded performance). In particular, partially redundant data were available on board.

Recommendation 03 – Robustness of the system design shall be confirmed through:
- An analysis per phase, for all events with change of vehicle configuration, taking into account system and S/S level status including degraded cases, shall be introduced as integral part of the design and verification process, such analysis should be done as concurrent engineering (plateau) covering all disciplines.
-"what if"/robustness, WCA, FDIR and "degraded case" analyses at GNC and System level (to be done at design, implementation and verification levels)

Monte Carlo analyses have limitations if influential parameters are not modelled correctly. The most influential parameters should be identified and their effects on the capsule dynamics must be assessed through a Worst Case analysis. An adequate margin policy, resulting from sensitivity analysis of main drivers and the fact that the perturbation at parachute deployment will be with large unknowns, shall be implemented.

Recommendation 04 – Analysis of design robustness shall be performed through:
- Dedicated Parametric and sensitivity analyses where for each parameter/contribution a +/-delta% and the change in output (angular rate) is deterministically quantified
- Understanding for each parameter/contribution the expected worst case condition during flight.
- Perform a deterministic worst case analysis starting from the expected worst case conditions (see bullet above).
In addition a critical analysis should be performed with the objective to find any additional parameter/contribution having a significant impact on the dynamics and angular rates and not covered by the list above

<u>Not robust decision logic in the GNC S/W</u>
The presence of several measurements (accelerations, angular rates, radar altimeter measurements, time, etc.) could have been exploited to elaborate alternative modes attempting a safe landing under degraded conditions.

The sanity checks implemented were focussed on the RDA and the RDA – GNC altitude estimates (IMU based) in which the GNC attitude estimate was considered perfect. The whole issue of sanity checks in the measurement preparation and navigation functions needs to be readdressed carefully. Essential variables as attitude and altitude were not monitored, though there were means for detection of major problems, e.g. the attitude estimated by GNC after IMU saturation, with the reception of RDA echoes, etc. No recovery strategy was defined for degraded cases. In fact, the on-board software correctly detected an inconsistency between radar altimeter and IMU measurements but was instructed to mix inconsistent information (slant range and attitude).

Recommendation 05 – Robust and reliable sanity checks shall be implemented in the on-board S/W to increase the robustness of the design, which could be, but not limited to :
- Check on attitude
- Check on altitude sign (altitude cannot be negative).
- Check on vertical acceleration during terminal descent and landing (cannot be higher than gravity).
- Check altitude magnitude change (it cannot change from 3.7 Km to a negative value in one second).
- Check wrt pre-flight timeline (altitude or acceleration profile vs time) to check consistency of measurements

The SIB believes that with the resources available on board, landing could potentially have been achieved even after the wrong handling of saturation. For instance, the RDA could have been used to determine attitude in two axis with respect to vertical and a proper set of GNC modes could have posed the EDM softly on the surface. As consequence of implementation of robust “sanity checks”, GNC “back-up modes” would need to be implemented to attempt landing in degraded cases.

Recommendation 06 – The critical highly disturbed dynamics of the descent phase must be acknowledged and the GNC should be designed to be robust whatever the EDM motion during parachute deployment. Suitable GNC modes should be foreseen to implement landing with degraded conditions (e.g. using the RDA or additional sensors).

The SIB noted the strategy to have real time telemetry (8 kbps) and stored telemetry that would have been recovered and analysed after landing. It is recommended to revisit the approach and plan real time TM according to the phase and mode.

Recommendation 07 – The measurement plan and the allocation of parameters to real time telemetry must be revisited and adapted to the observability needs of phases and modes. Use of data memory and down load of parameters during Entry Descent and Landing should be considered

<u>Management Sub-co’s</u>

The following main weaknesses in the overall process led to the failure of the landing of Schiaparelli:

- Lack of specification and focus on a mission critical parameter from Prime to Supplier. The persistence of the saturation flag in the application software, became the ultimate cause of the Schiaparelli landing mishap.
- Lack of rigorous verification approach (including testing of failure/anomaly cases and recording of closure of requirements).
- Lack of PA/QA rigorousness for acceptance of the unit.

It must be said that as the expected angular rates were considered to be sufficiently below the saturation threshold value, saturation was not an event treated at GNC and system level.

Recommendation 08 – Ensure proper procurement process through:

- *Detailed procurement specifications to be updated after negotiation/EQSRs made applicable to supplier contracts;*
- *Verification that all requirements are properly verified (key requirements preferably by test) and followed up, in particular identify all embedded SW in Equipment with full knowledge of their content, verification status at supplier level and representativity in various system benches;*
- *Proper implementation of PA/QA process for acceptance of units (formal EIDP verification and acceptance at DRB).*
- *Reinforce the project organisation with a dedicated function for controlling the process of equipment acceptance*
- *Ensure full representativeness of mathematical models through validation of models by equipment suppliers*

8 CONSIDERATION FOR EXOMARS 2020 PROJECT

8.1 General Observations

ExoMars-2020 Spacecraft Composite (SCC) includes the Cruise Module (CM), Descent Module (DM) and adapter with DM/CM separation system. The SCC insertion into the Mars flight trajectory shall be performed by the Russian Proton-M LV and Breeze-M upper stage from the Baikonur launch site.

The ESA-built Cruise Module is to deliver the DM to Mars. The Cruise Module shall provide the following: SCC control during the interplanetary flight, trajectory corrections, command and telemetry data transmission and the specified SCC state vector at DM separation instant ensuring the required parameters for the DM entry and landing on the selected landing site. The manoeuvres are to be performed by means of the CM's own propulsion system. SCC control at cruise phase and guidance for the subsequent DM entry shall be implemented by ESA's ground stations and supported by Russian ground stations and ballistic support centers.
The ROSCOSMOS/NPO Lavochkin built Descent Module is to deliver the stationary Landing Platform (LP) with the Science Equipment Complex (SEC) and ESA's autonomous Rover to the Mars surface. The LP active lifetime shall be not less than one Martian year, which is about two Earth years. The LP landing on Mars surface shall be performed once the local dust storms season is ended.

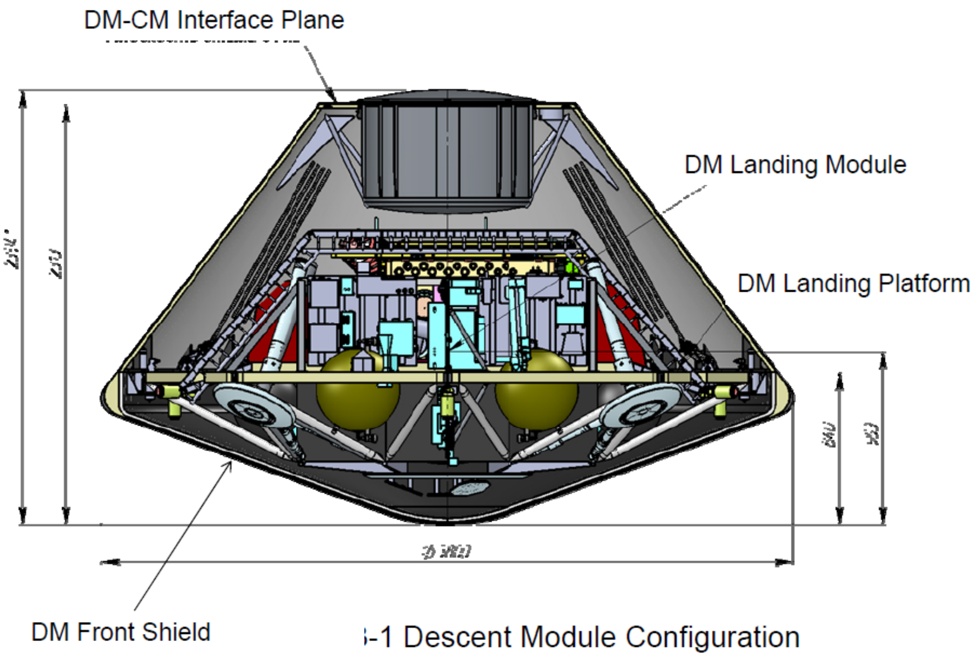

Figure 4: Descent Module of the ExoMars 2020 mission

From the development point of view the following is noted:

- The DM just underwent a delta-PDR;
- The RM is performing its own CDR and

- The System CDR is planned to take place around fall 2017

8.2 Main differences between ExoMars 2016 and ExoMars 2020

Main differences mission 2016 vs mission 2020 are:

- No long coasting phase implies that no hibernation and attitude reconstruction is necessary;
- 2 parachutes (each one extracted by a pilot): first one supersonic, the second one subsonic;
- Landing on legs will require more stringent requirements on lateral velocity (<2m/s).

From H/W & S/W point of view, the following main characteristics are highlighted for the 2020 mission:

- GNC design strongly inherited from 2016 mission;
- Parachutes are designed by the Schiaparelli parachute designer and the parachute model is based on the 2016 one;
- IMU is different ;
- RDA is recurrent from 2016;
- Actuators (thrusters) completely new from NPO Lavochkin ;
- Models of Atmosphere, Winds, Gravity, Sun-Ephemeris – simplified, Sun-Ephemeris - CSPICE as per 2016;
- Model of Sun, Planets Gravity Perturbation, Sun radiation, Aerodynamic Model, Sun Gravity as per 2016;
- Model of dynamics, parachute, multi-body from 2016 heritage.

8.3 ExoMars 2020 Specific Recommendations

In addition to the recommendations in chapter 7 the following recommendations apply specifically for the ExoMars 2020 mission.:

Recommendation 9 – It is recommended that also a simple model consisting of an applied oscillating force, representing the force in the parachute raiser, that can change in magnitude and direction to be used to define the "stress cases" and improve the robustness of the GNC S/W.

Recommendation 10 – As the success of the ExoMars 2020 mission is of paramount importance to the European exploration programme, it is recommended to reinforce the project with partnership with agencies (NASA / JPL, DLR, CNES,…) or universities (Roma, …) using their own competencies in order to secure the model validation and to assess the GNC design options. It is also suggested to cross-validate the TAS multi-body model by asking JPL/NASA to review the DM parachute model and wrist mode dynamic using their tools and experience.

Recommendation 11 - Due to the complexity of the actual bridle loads it is recommended that peak bridle load calculations (including linear and rotational acceleration) are double checked and adequate strength margins are properly verified

Recommendation 12 – Although the IMU is different from the previous mission, the SIB members highlight the importance of having the correct threshold for the saturation limits, if any, and that the design be robust to manage saturation as necessary (e.g. IMU inputs inhibition during parachute deployments to *avoid to control instabilities due to high dynamic motion, etc.) Maximum benefit of the presence of two IMU's to be robust to loss of attitude knowledge should be implemented.*

Recommendation 13 – Using all lessons learned from the 2016 mission, a revisit of the EDL of the 2020 mission is to be performed by the project and be submitted to a formal standard peer review process is recommended. A dedicated GNC review is recommended to be held prior to the System CDR to assess design robustness, GNC logic verification, FDIR.

The retro-propelled phase from parachute release down to the drop-point two meters above the Martian surface was not demonstrated during the 2016 mission.

Recommendation 14– Taking into account the specificities of the 2020 mission the project should consider which additional activities, test and/or analysis must be undertaken to make up for the missing demonstration of the retro-propelled phase of the 2016 mission.

The organisation of the 2020 mission in terms of responsibilities is particularly complex with Lavochkin responsible for the DM and TAS-I responsible for the on board computer, GNC, software, RDA, IMU and parachute.

Recommendation 15 – It is strongly recommended to create an integrated system engineering team integrating staff from NPO Lavochkin and TAS-I and give the responsibility of system engineering and verification to this integrated team. Such integrated system engineering team shall organise concurrent design sessions with relevant entities in order to shorten schedule.

The 2016 mission was implemented with a constant shortness of finances, which lead to the decision, en route, to change from redundant avionics to a single string architecture, which under schedule pressure to meet the 2016 launch window opened the door for undue shortcuts in FDIR implementation. Missions to Mars have a launch window every 26 months, which means that launch dates become very constraining, with tendency to keep launch dates at all costs.

Recommendation 16 –Maintain a robust schedule. Avoid giving overweight to schedule when trading technical risks against schedule.

9 CONCLUSION

The Schiaparelli Entry, Descent and Landing sequence was nominal until "consistency checks" between the IMU and the RDA measurements were performed. The following mission phases was successfully performed prior to that:

- Correct separation from the TGO (delta-V slightly higher than expected, without any impact on the mission)
- Correct wake-up from hibernation after 3 days of coasting
- Correct detection of the Martian atmosphere
- Correct entry and aero braking in the Martian atmosphere
- Correct detection of parachute deployment time
- Deployment and inflation of the parachute. The deployment and inflation of the parachute did cause lateral angular oscillations of the capsule above the saturation threshold of the IMU in one axis corrupting the estimated attitude because of its undo long persistence time. This should have been identified as a risk and carefully handled at both system and IMU level, taking due account of off-axis deployment, possible asymmetric inflation, and area oscillations of the parachute and by adequate verification of the IMU saturation flag persistence time. The parachute worked, but its behaviour at Mach 2 was not sufficiently understood.
- Correct jettison of the Front Shield
- Correct functioning of the Radar Doppler Altimeter

The logic, in case of inconsistency between IMU and RDA measurements, was to force the RDA in the loop and enter TERMINAL_DESCENT mode in spite of the fact that the altitude derived, when combining slant ranges from the RDA with the corrupted attitude, was negative. Subsequent mode changes, conditioned on altitude, immediately triggered the Back-shield Separation, activated the Reaction Control System for the minimum time of 3 seconds, which lead to the free fall of Schiaparelli from an altitude of around 3.7 km.

After entering in TERMINAL_DESCENT mode:

- The Back Shell and parachute separation worked correctly (the timing was obviously wrong)
- The reaction control system was successfully primed and seemed to work correctly during 3 seconds (until it was switched off triggered by the estimated negative altitude)
- *The Back Shell and Parachute avoidance manoeuvre was not demonstrated because it was not necessary with the lateral velocity measured.*
- *The retro-propelled descent phase down to the drop point around 2 meters above the Martian surface was not demonstrated*
- *The free fall survival of the EDM from the drop point to the Martian surface was not demonstrated*
- The switch to surface mode and initialisation of instruments was demonstrated during the free fall.
- The location of the impact on the Martian surface was close to the centre of the ellipse of the predicted landing site.

In conclusion, the Schiaparelli demonstrator was very close to land successfully on Mars at the planned location. A very important part of the demonstration objectives have been achieved, which allows to validate tools and to identify the required upgrades.

The following root causes for the mishap have been identified:

- Insufficient uncertainty and configuration management in the modelling of the parachute dynamics which led to expect much lower dynamics than observed in flight;
- Inadequate persistence time of the IMU saturation flag and inadequate handling of IMU saturation by the GNC;
- Insufficient approach to Failure Detection, Isolation and Recovery and design robustness;
- Mishap in management of subcontractors and acceptance of hardware.

Within this report general recommendations to avoid such defects and weaknesses have been established and specific recommendations for the ExoMars 2020 mission have also been established. The SIB reviewed Lessons Learned Implementation plans established by both ESA and the industrial project teams. The recommendations raised in this report corresponds well to the project's plans, some SIB recommendations are complementary.

Not reported above is an unexpected evolution of the spin rate of the EDM with no apparent links to the landing failure. The root cause of this anomaly is believed to be linked with uneven degradation of thermal blankets during entry and a possible slight twist in the parachute riser after deployment.