DEIMOS 2 NON-GEOSTATIONARY SATELLITE SYSTEM
EXHIBIT 2
Orbital Debris Mitigation

This exhibit contains the information required by 47 C.F.R. §5.64(b) of the Commission's Rules.

1. **Debris release.**

UrtheCast has assessed and limited the amount of debris released in a planned manner during normal operations of the Deimos-2 satellite. No debris is released during normal operations of the spacecraft.

2. **Collision with small objects.**

UrtheCast has assessed the probability of the space station becoming a source of debris by collision with small debris or meteoroids of less than one centimeter in diameter that could cause loss of control and prevent post-mission disposal. UrtheCast has taken steps to limit the effects of such collisions through shielding, the placement of components, and the use of redundant systems. Specifically, critical components (i.e., computers, battery, and control devices) are built within the structure and shielded from external influences. Items that cannot be built within the spacecraft nor shielded (like antennas) are redundant and/or are able to withstand impact. All the main subsystems of the satellite except the propulsion system have redundant components that can provide the same performance as the primary components. Internally the propulsion system has redundant electronics, but the same performance of the redundant components cannot be guaranteed because an on-orbit anomaly has been detected. The spacecraft will not use any subsystems for end-of-life disposal that are not used for normal operations.

Using the European Space Agency's Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite, UrtheCast has determined that the probability that Deimos-2 will become a source of debris by collision with small debris or meteoroids that would cause loss of control and prevent disposal is less than 0.01.

3. **Accidental explosions and release of liquids.**

UrtheCast has assessed and limited the probability, during and after completion of mission operations, of accidental explosions or of release of liquids that will persist in droplet form.

UrtheCast has reviewed failure modes for all equipment to assess the possibility of an accidental explosion onboard the Deimos-2 spacecraft. The spacecraft manufacturer reviewed each potential hazard relating to accidental explosions in which each subsystem was analyzed for potential hazards. The manufacturer also generated an analysis to identify all potential mission failures, taking into account the risk of accidental explosion.

The design of the Deimos-2 spacecraft is such that the risk of explosion is minimized both during and after mission operations. In designing and building the spacecraft, the manufacturer took steps to ensure that debris generation will not result from the conversion of energy sources on board the satellite into energy that fragments the satellite. Burst tests were performed on all pressure vessels during qualification testing to demonstrate a margin of safety against burst. All pressures, including those of the batteries, are monitored by telemetry. At the end of operational life, all on-board sources of stored energy will be depleted or secured, fuel line valves will be left open, excess propellant and pressurant will be vented, and the batteries will be left in a permanent discharge state.

No liquids that will persist in droplet form will be released during or after the completion of Deimos-2 mission operations.

4. **Collision with large debris or other operational space stations.**

UrtheCast has assessed and limited the probability of the Deimos-2 space station becoming a source of debris by collisions with large debris or other operational spacecraft.

Using the DRAMA tool suite, UrtheCast has determined that the probability of collision between Deimos-2 and other large objects during the total orbital lifetime of the space station, including the de-orbit phase, is less than 0.001. For purposes of this calculation, UrtheCast has assumed a collision risk of zero for Deimos-2 during the operational phase of the spacecraft, during which UrtheCast will maneuver the satellite to avoid colliding with large objects, as described in the Space Debris Mitigation Strategy Memorandum attached as Annex 1.

A number of other systems operate at or near the Deimos-2 nominal altitude of about 620 km.[1] As described in Annex 1, UrtheCast obtains information regarding possible collision events and implements avoidance maneuvers as necessary. UrtheCast does not rely on one-on-one coordination with other systems to manage collision risk.

During the deorbit phase of Deimos-2, at end of life (EOL), the satellite is planned to naturally decay, from its operational orbit, before atmospheric re-entry within 12 years (nominal case). During this uncontrolled orbit decay period, the Deimos-2 satellite is expected to briefly cross the orbit altitude of the international space station (ISS), but at a much higher inclination of 98 degrees. The large difference in inclination between the Deimos-2 satellite and the ISS significantly reduces the probability of a potential conjunction. Additionally, the Deimos-2 satellite, at approximately 310 kg and a size of approximately 1.50 m x 1.94 m, can be routinely and easily tracked using standard methods during the decay orbit, so any unlikely potential conjunction would be clearly known well in advance. The end-of-life orbital parameters will be provided to the 18th Space Control Squadron (18th SPCS) consistent with operational procedures.

[1] Specifically, based on a review of available data, UrtheCast has determined that the following systems have nominal orbital altitudes close to that of Deimos-2: Delfi-C3 (Netherlands); Diwata-2B (Japan); the Flock constellation of Dove satellites operated by Planet Labs (U.S.); Duchifat-1 (Israel); the Iridium Next constellation (U.S.); KhalifaSat (UAE); KX-09 (China); PakTES-1a (Pakistan); Perseus M1 and M2 (U.S./Russia); PolyITAN-1 (Ukraine); Pakistan Remote Sensing Satellite-1 (Pakistan); SEEDS 2 (Japan); Shijian 16-01 (China); and Ten-Koh (Japan).

Aside from collision avoidance maneuvers, the Deimos-2 orbit is not currently actively maintained as it has been shown through analysis that the orbit is sufficiently stable to support commercial imaging operations up to at least 2024, the predicted end of life.

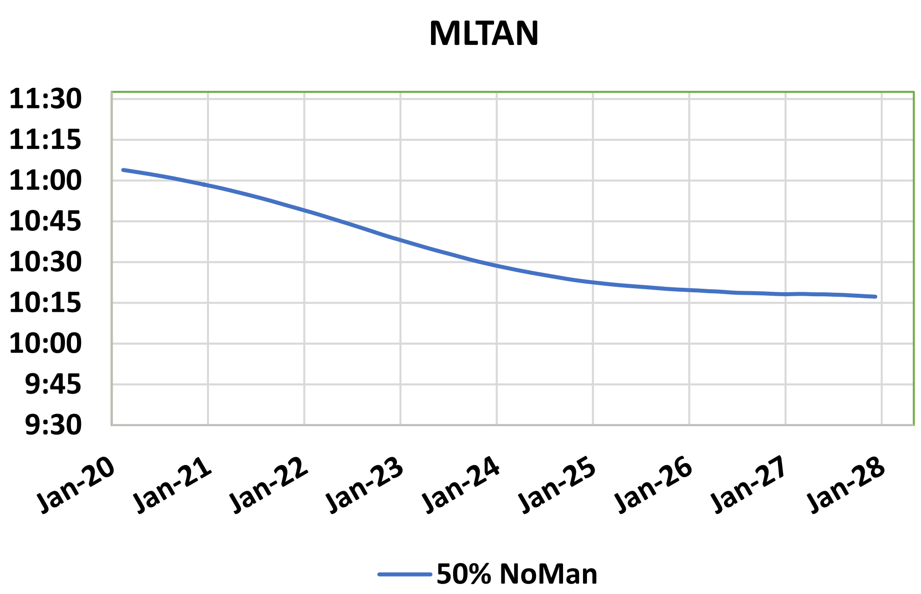
Based on actual orbit data obtained over the last two years via GPS, the variation in orbital parameters is summarized in the following table.

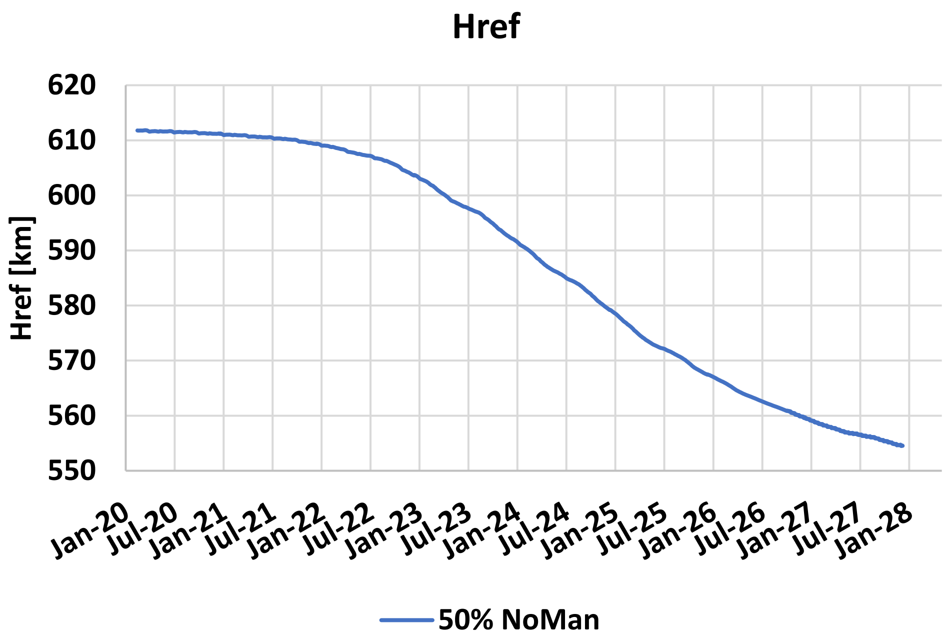
	Min	Max	Range	
Apogee	619.2	621.6	2.3	km
Perigee	602.1	604.4	2.4	km
Inclination	97.81	97.86	0.05	deg
RAAN	0	360	360	deg

The figures below show the expected evolution of the mean reference height (MLTAN), inclination, and longitude. The graphs show the natural evolution of the mean parameters, in which external disturbances like drag, solar radiation pressure and third body, influence the orbit tendency.

The parameter used to define the altitude profile is the mean reference altitude, which is defined as the difference between the mean semi major axis of the orbit and the Equatorial Radius of the Earth.

A 50 percentile solar cycle confidence level has been used in producing the graphs, and it has been assumed that no maneuvers will occur during the period shown.

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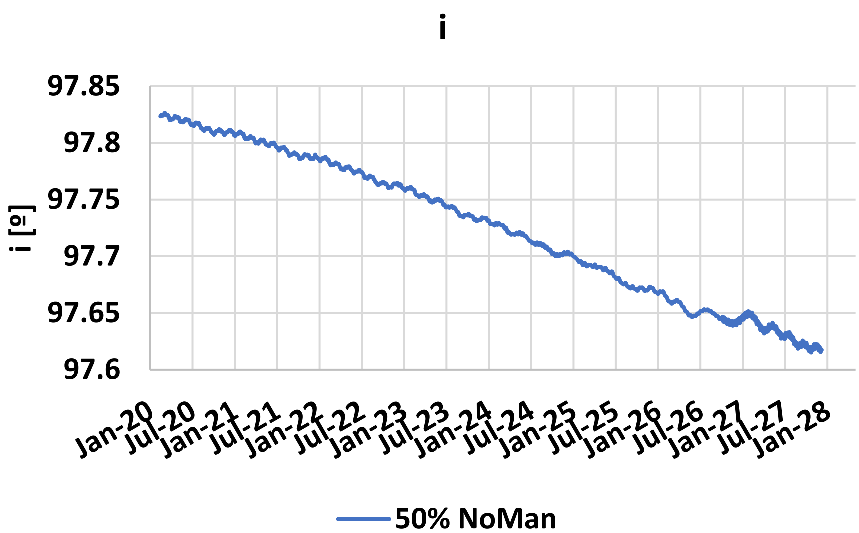
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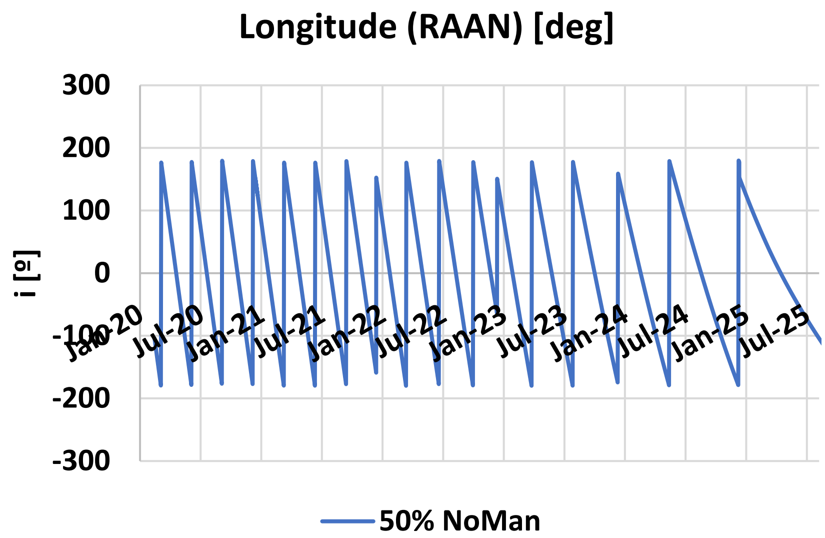


The design of the Deimos-2 propulsion system is described in the Deimos-2 Re-Entry Casualty Risk Analysis, attached as Annex 2. Annex 2 also describes the baseline plan for EOL disposal of the satellite, which included an orbit lowering maneuver. Due to an on-orbit detected anomaly affecting the propulsion system, the ability to perform that maneuver is uncertain, and an updated disposal plan is attached as Annex 3. The Deimos-2 propulsion system remains capable of performing collision avoidance maneuvers.

UrtheCast certifies that upon receipt of a space situational awareness conjunction warning, UrtheCast will review and take all possible steps to assess the collision risk and will mitigate the collision risk if necessary.

5. Trackability of the space station.

The Deimos-2 spacecraft is registered with the 18th SPCS. UrtheCast shares ephemeris data with the 18th SPCS daily and also notifies the 18th SPCS of planned maneuvers. UrtheCast also shares information with the European Union Space Surveillance and Tracking consortium (EUSST). The EUSST is composed of five national operating centers in Italy, Spain, France, Germany, and the United Kingdom that are linked to exchange data. UrtheCast uses the EUSST collision avoidance service that provides analysis of conjunction data messages and includes mitigation risk recommendations and maneuver support.

6. Proximity operations.

No proximity operations are planned for Deimos-2.

7. Space station disposal plans.

A memorandum describing the updated EOL disposal plan through atmospheric re-entry for Deimos-2 is attached as Annex 3. Due to uncertainty created by the propulsion system anomaly, UrtheCast is not able to quantify whether the probability of successful disposal within 25 years is

90% or greater. However, as discussed in Annex 3, the factors that would lead to the 25-year re-entry timeline being exceeded are considered to be unlikely.

As indicated in Annex 2, the calculated re-entry casualty risk for Deimos-2 is less than 1 in 10,000. The calculations are based on the physical characteristics of the spacecraft, and as a result, the possible inability to perform an orbit lowering maneuver at EOL does not affect the validity of the casualty risk assessment.

Collision Avoidance for Deimos-2

At the Deimos-2 altitude of about 620 km, the environment is subject to space debris and an efficient Collision Avoidance (CA) procedure is of importance.

Internal tools to compute the collision probability and geometry at the B-plane based on Conjunction Data Messages (CDMs) are used in actual operations to ease the decision-making process.

Furthermore, a Space Situational Awareness (SSA) sharing agreement has been signed with the Department of Defense of the United States of America (through the United States Strategic Command, USSTRATCOM) to obtain information and services about possible collision events. Currently, Deimos-Imaging is actively participating in updating Deimos satellites ephemeris and maneuvers within the space-track website and is in constant collaboration with the Joint Space Operations Center (JSpOC, now 18th SPCS).

Table 1. Deimos-2 orbit and propulsion details.

Mass [kg]	Launch date	Lifetime [years]	Orbit type	H_{ref} [km]	LTAN [UTC]	Repeat Cycle [orbits/day]	Thruster	Nominal Isp [s]	Nominal Thrust [mN]
300	June 2014	10	Sun-sync & frozen	620	10:30	14 + 13/16	Hall effect	1000	10 (over 4 minutes firing)

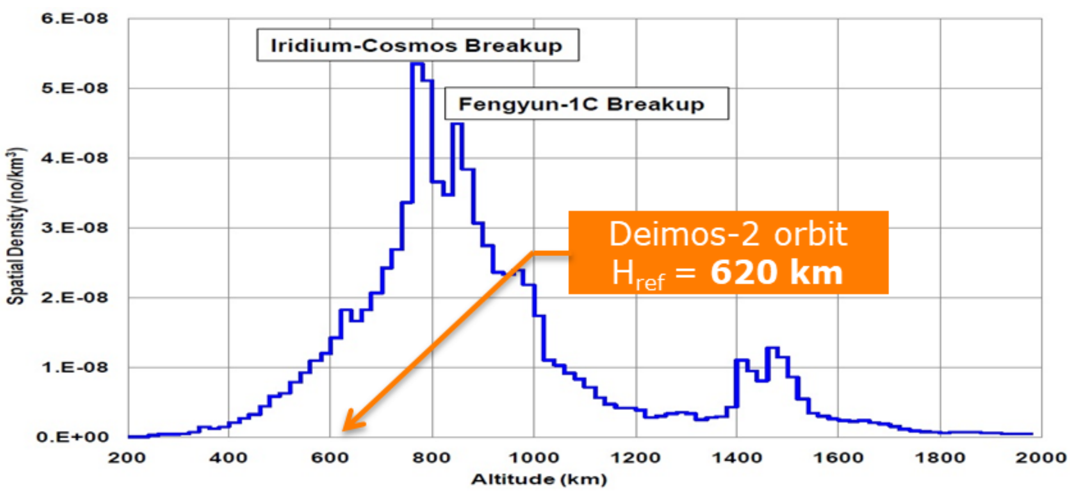


Figure 1. Spatial Density of objects in LEO.

As a collision mitigation strategy, a conservative approach has been used budgeting for one collision avoidance maneuver per year, considering the operational experience of Deimos-1 mission. As a consequence, a total Delta-V budget for collision avoidance of 8e-2 m/s was allocated for that purpose in the mission design phase, over 10 years of lifetime.

As of July 20, 2020 only 2 collision avoidance maneuvers have actually been performed in Dec 2018 and Feb 2019, since launch in 2014. This is approximately 1 maneuver every 3 years.

Nevertheless, tens of other potential risk events have been studied through a series of internal tools and an avoidance protocol has been created in the first years of mission (see Figure 2,

Figure 3, Figure 4); a conjunction Summary Message (CSM) report is generated when a Close Approach Notification (CAN) is received from JSpOC, i.e. there is a colliding object within 3 days, with a total miss distance of less than 1 Km and a collision probability of 10^{-4} . The event data are processed and rewritten in a user-friendly report, containing the summary of the geometry of the event and the collision risk information.

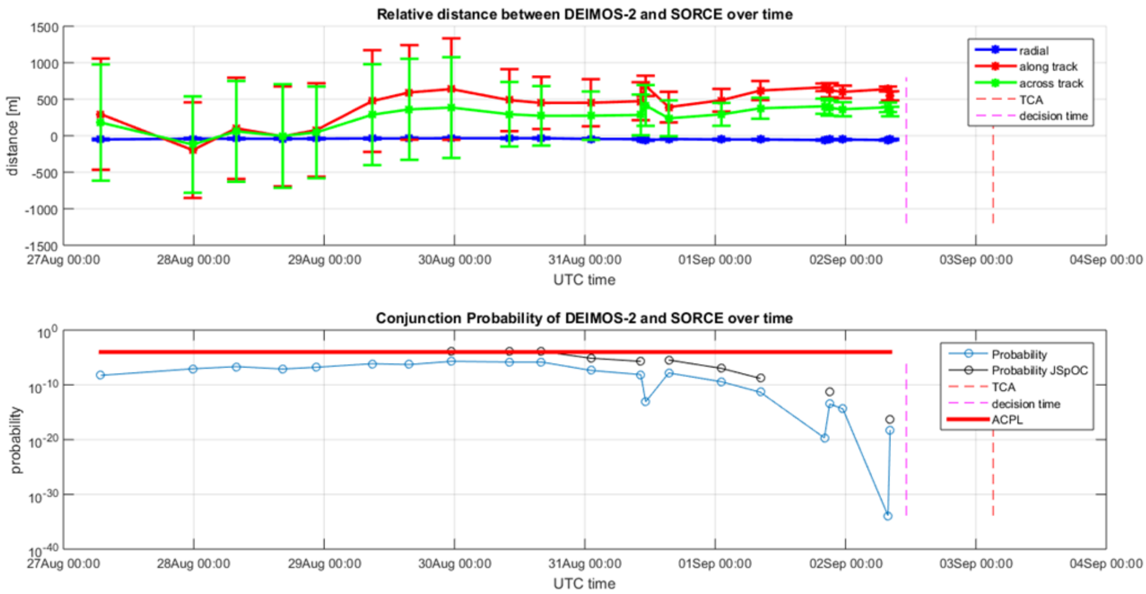


Figure 2. Example of miss distance components between Deimos-2 and SORCE satellite, and collision probability evolution over time.

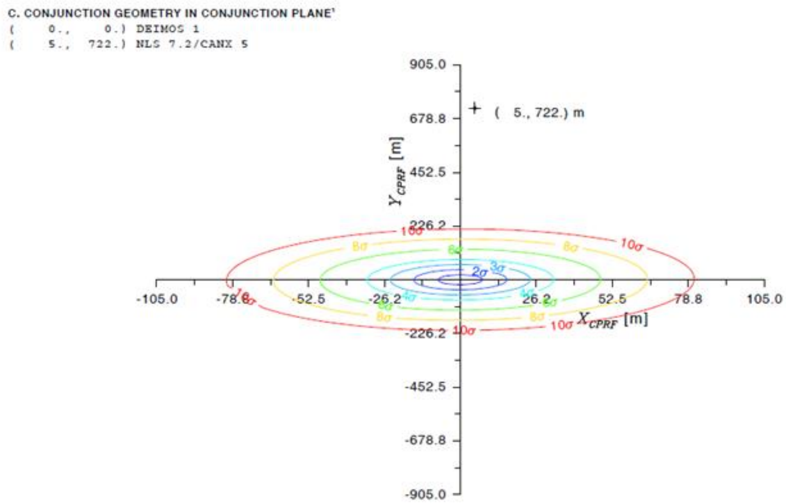


Figure 3. Example of 2D conjunction plane.

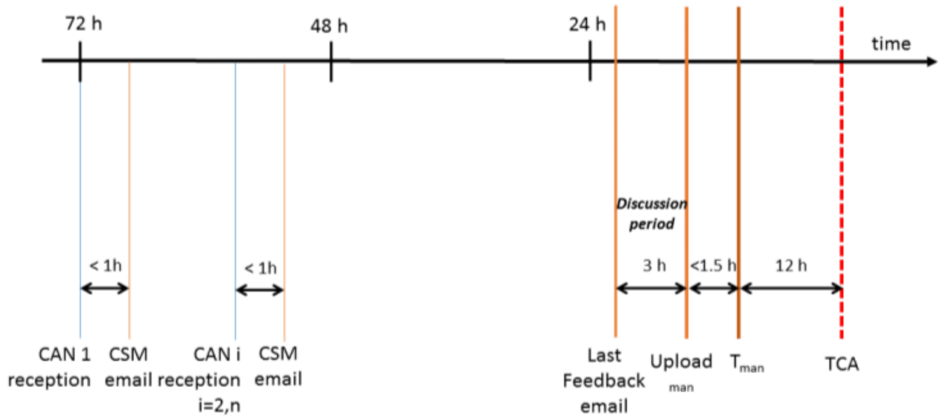


Figure 4. Collision Event timeline internal procedure.

The collision avoidance maneuver is planned according to the along-track separation strategy, which is based on the principle that with a timely radial separation a phase shift between two objects is produced at the conjunction epoch (time of collision approach, TCA).

Since Deimos-2 is equipped with a Hall effect thruster providing thrust in the milli-Newton range (see Table 1), a 72 hour - to TCA scheduling is prepared as follows:

- From 72 h up to 16.5 h to analyze and exchange information with JSpOC
- At 16.5 h, definitely decide whether to perform a maneuver or not
- At 12 h, maneuver

Updated End of Life (EOL) Disposal for Deimos 2

The Deimos-2 mission was designed to comply with the requirement that “satellites and orbital stages shall be commanded to reenter Earth’s atmosphere within 25 years of mission completion, if their deployment orbit altitude is below 2000 km,” and the corresponding disposal Delta-V was included in the propellant computation at the design phase.

The original End of Life (EOL) disposal plan for Deimos-2 was to execute EOL maneuvers, foreseen for the end of 2024, whereby the Deimos-2 satellite would be lowered to an intermediate altitude that guarantees safe uncontrolled decay within 25 years. Maneuvers were expected to lower the perigee altitude to 540 km at EOL. This corresponded to a decrease in semi-major axis of about 37 km.

The propulsion system has experienced an anomaly on-orbit and is now being operated in a ‘degraded’ mode. Although the propulsion anomaly reduces overall confidence in reliability of the propulsion system there is still some effective internal redundancy in the propulsion system and the operational decision to minimize propulsion cycles has been taken to preserve that reliability as much as possible for collision avoidance and EOL maneuvers.

Deimos has subsequently performed 25 small test maneuvers with the support of the manufacturer to confirm a contingency procedure as needed to address the anomaly and has since successfully performed 2 collision avoidance maneuvers (i.e. ~240 second duration, which corresponds to ~+/-200m). Deimos has further decided to suspend routine orbit maintenance maneuvers to be prudent and conserve cycling on the propulsion system, given that the current orbit projected until at least 2024 is sufficient to support normal commercial operations. Given the infrequency of collision avoidance maneuvers, their relatively short duration and steps taken to limit cycling, Deimos is confident in on-going collision avoidance capabilities.

The originally proposed EOL orbit maneuver, however, involves lowering the orbit by ~37 km in semi-major axis, which is a significantly larger set of maneuvers. Deimos will still attempt to perform the originally planned EOL orbit lowering maneuver on a best effort basis. However, given the propulsion anomaly referenced above and the scale of the maneuver Deimos cannot guarantee nor quantify the probability that at EOL the maneuver will be possible or the performance of the maneuver (i.e. how much altitude lowering is achieved).

To be conservative, the end of life analysis summarized here therefore assumes a worst case of no EOL maneuver performed at all. As noted above Deimos expects to do better than this, in terms of EOL maneuvers.

The Deimos-2 disposal phase shall comply with the main guideline that “satellites and orbital stages shall be commanded to reenter Earth’s atmosphere within 25 years of mission completion, if their deployment orbit altitude is below 2000 km”.

For the EOL disposal analysis, the mission analysis now considered the case of no disposal maneuvers and a 50% confidence level of solar activity and geomagnetic indexes.

Table 1: Current Deimos-2 mean orbital parameters.

Mean Orbital parameters at EOL	
Epoch	**30th June 2020**
Semi-major axis [km]	**6989.8**
Eccentricity	**0.00112**
Inclination [deg]	**97.8**
RAAN [deg]	**84.6**
Argp [deg]	**85.7**
Mean Anomaly [deg]	**114.6**

Orbit Propagation with ESA DRAMA-OSCAR until Re-entry

The orbit in Table 1 was used the input for the ESA DRAMA-OSCAR (Orbital Spacecraft Active Removal) tool used to propagate the natural decay orbit for the following 100 years.

The following spacecraft parameters have been considered:

- Cross-section: 3.8 m^2
- Dry Mass: 291.1 kg
- Drag Coefficient: 2.55
- Reflectivity coefficient: 2.3

The Best Case/Worst Case option for solar activity has been selected with a 50% confidence interval. The confidence interval of 50% means that the Best Case is sampled by using the smoothed solar activity value at 75%, while the Worst Case would use the value at 25%.

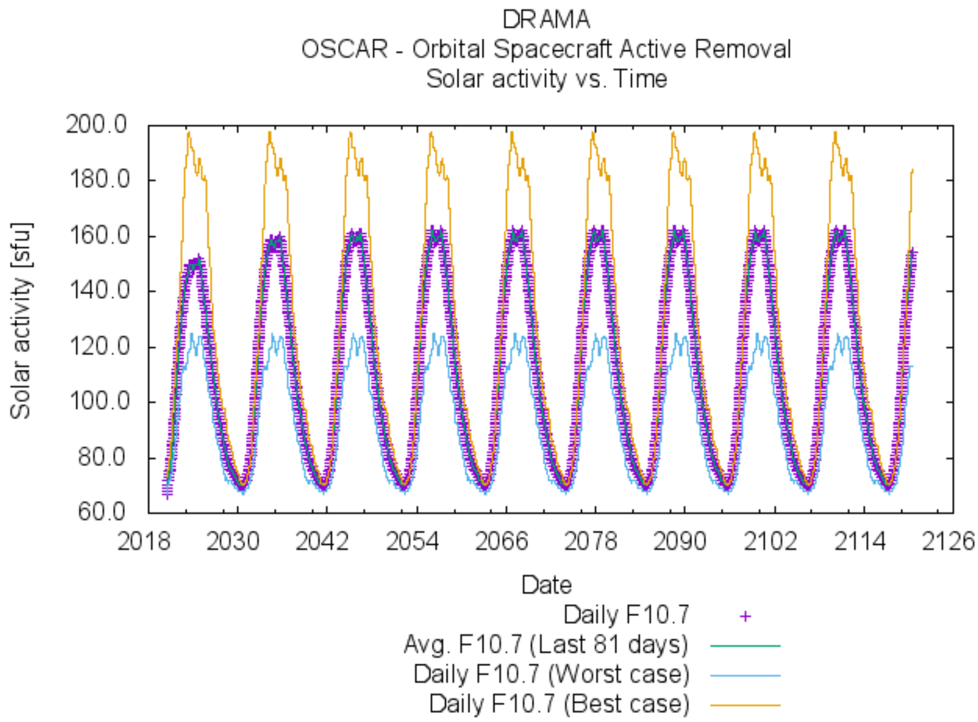


Figure. 1: Solar cycles.

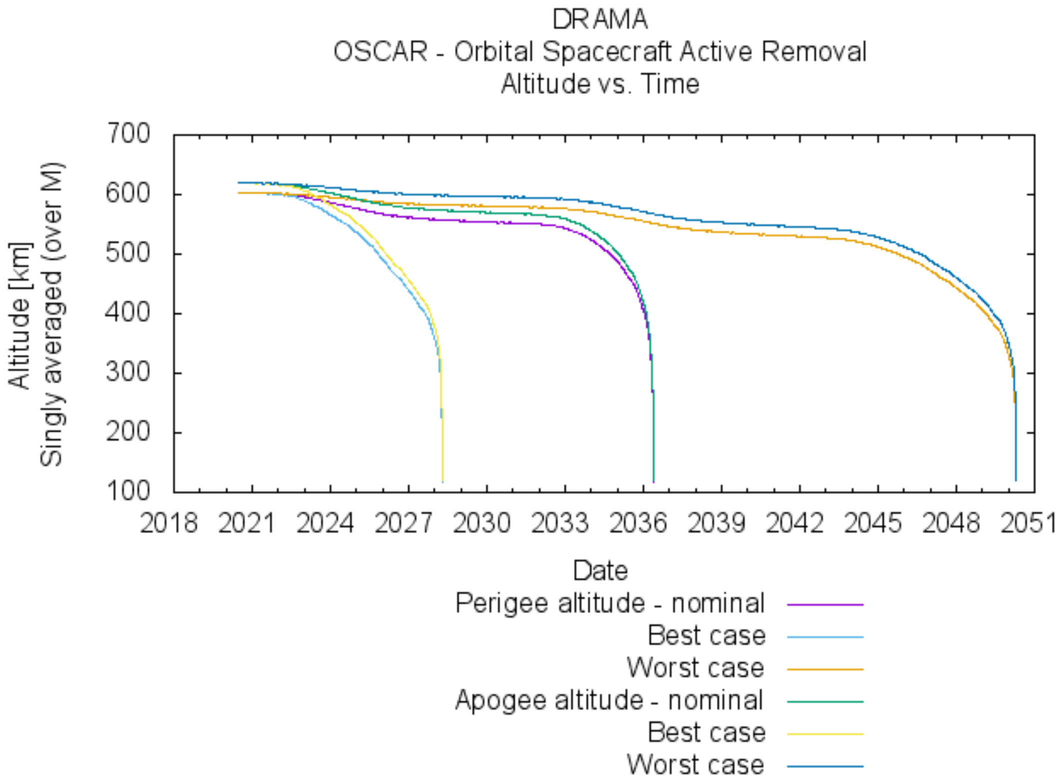


Figure. 2: Deimos-2 altitude evolution.

The final orbit at re-entry (approximately 120 km of altitude) is shown in Table 2.

Table 2: Deimos-2 mean orbital parameters at nominal re-entry.

Mean Orbital parameters at EOL	
Epoch	**18th May 2036**
Semi-major axis [km]	**6496.31**
Eccentricity	**0.00028**
Inclination [deg]	**97.39**
RAAN [deg]	**330.13**
Argp [deg]	**222.64**
Mean Anomaly [deg]	**290.05**

The OSCAR (DRAMA) analysis gives the following re-entry epoch results:

- Best case: 2028 (4 years after EOL)
- Nominal case: 2036 (12 years after EOL)
- Worst case: 2050 (27 years after EOL)

Thus, the analysis demonstrates that Deimos-2 re-entry based on only natural orbit decay will likely be within a 25-year time span (starting from the estimated end of life of 2024) – under both the best and the nominal case. The worst case (solar activity) results in re-entry of 27 years, however this worst-case is in addition to the worst-case scenario of no EOL maneuver

ESA UNCLASSIFIED – For Official Use

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

Deimos-2 re-entry casualty risk analysis

Prepared by	**Independent Safety Office (TEC-QI)**
Reference	**ESA-TECQI-TN-006277**
Issue	**1.0**
Revision	**0.0**
Date of Issue	**18/10/2017**
Status	**Approved/Applicable**
Document Type	**TN**
Distribution	**ESA TEC-QI, Deimos Imaging (Deimos-2 Project)**

European Space Agency
Agence spatiale européenne

APPROVAL

Title Deimos-2 re-entry casualty risk analysis	
Issue 1.0	**Revision** 0.0
Prepared by Sergio Ventura (Independent Safety Office – TEC-QI)	**Date** 18/10/2017
Approved by	**Date**
Rosario Nasca (Head of the Independent Safety Office – TEC-QI)	18/10/2017

CHANGE LOG

Reason for change	Issue	Revision	Date

CHANGE RECORD

Issue 1.0	**Revision** 0.0		
Reason for change	**Date**	**Pages**	**Paragraph(s)**

Disclaimer

Table of contents

1 INTRODUCTION

This Technical Note has been prepared by the ESA Independent Safety Office (TEC-QI), hereinafter referred also as "ESA", in the frame of the Contract ESTEC/CPQ 17.505 covering consultancy services to the company Deimos Imaging, Spain.

This Technical Note contains the results of the re-entry casualty risk analysis for the spacecraft Deimos-2.

The Spanish Ministry of Foreign Affairs requested Deimos Imaging to supply them with an independent assessment of the re-entry casualty risk for the Deimos-2 spacecraft to be performed by the European Space Agency. The independent assessment of the re-entry casualty risk has been requested for the purpose of registration of the Deimos-2 spacecraft in the "Registro Español de Objector Lanzados al Espacio Ultraterrestre" and further communication from the Spanish Government to the General Secretary of the United Nations.

This Technical Note is valid for any administration or company that needs an analysis of the Deimos-2 re-entry casualty risk.

2 APPLICABLE DOCUMENTS AND REFERENCE DOCUMENTS

2.1 Applicable documents

[AD1] Contract ESTEC/CPQ 17.505

2.2 Reference documents

2.2.1 Documents provided by Deimos Imaging to ESA

[RD1] DMISLA-D2EOL-DMS-TEC-TN001, Issue 1.0 – DMISLA-D2EOL – Informe de Daños del DEIMOS-2 – Elecnor Deimos, 15/12/2015

[RD2] Some more info on DEIMOS-2 - e-mail from M. Carballo (Deimos Imaging) to ESA TEC-QI, 04/07/2017

[RD3] DM2PM16200 – Deimos-2 Preliminary Design Review (PDR) – Satellite Mechanical Design Interface – 19-21/07/2011

[RD4] DM2PM16300 – Deimos-2 Critical Design Review (CDR) – Mechanical Design Interface – 18-22/06/2012

[RD5] DMI-TNO-D2FD-03-01 – End of Life Disposal for Deimos-2 – Memorandum – Deimos Imaging, 04/07/2017

[RD6] DM2_FM.stp (Deimos-2 CAD model)

[RD7] DMI-TNO-D2FD-04-02 – Deimos-2 orbit at end of life – Memorandum – Deimos Imaging, 18/07/2017

[RD8] SimulationD2_OSCAR_SARA – Deimos Imaging, 18/07/2017

2.2.2 ESA documents

[RD9] ESA/ADMIN/IPOL(2014)2 – Space Debris Mitigation Policy for Agency Projects – ESA, 28/03/2014

[RD10] ESSB-HB-U-002 – ESA Space Debris Mitigation Compliance Verification Guidelines – ESA, 19/02/2015

3 TERMS, DEFINITIONS AND ABBREVIATED TERMS

3.1 Terms

For the purpose of this Technical Note, the terms and definitions from ESSB-HB-U-002 and ESA/ADMIN/IPOL(2014)2 apply.

3.2 Abbreviated terms

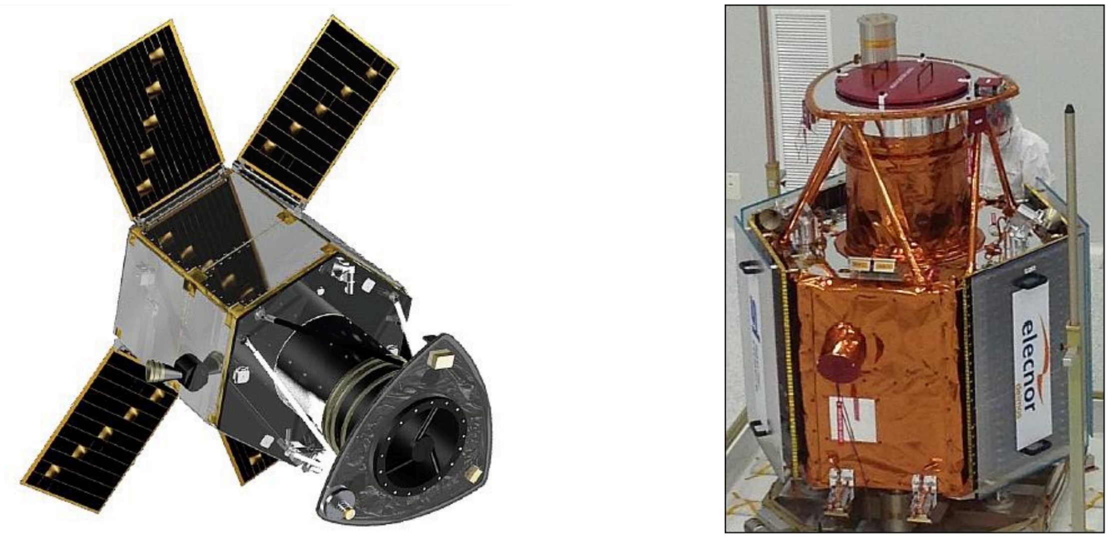
Abbreviation	Meaning
ACMU	auxiliary camera module unit
AIB	actuator interface board
AOCS	attitude and orbit control subsystem
AOP	argument of perigee
CSS	coarse Sun sensor
CDHU	command and data handling unit
EOS	electro-optical subsystem
ESA	European Space Agency
FPA	focal plane assembly
FSS	fine Sun sensor
GR	gyro
GRIB	gyro interface board
HEPS	Hall effect propulsion system
MAG	magnetometer
MTR	magnetotorquer
PB	processing board
PPMU	primary power management unit
PSSM	power safety and separation module
PPU	power processing unit
RAAN	right ascension of ascending node
RF	radio frequency
RW	reaction wheel
SB	sensor board
SI	Sartrec Initiative
SP	solar panel
SPMU	secondary power management unit
SSRU	solid-state recorder unit
STCU	star tracker camera unit
STEU	star tracker electronic unit
THU	thruster head unit
TTC	telemetry, tracking and command
UMBIB	umbilical interface board
XAPM	X-band antenna point mechanism
XFU	Xenon fuel unit
XTU	X-band transmitter unit

4 DEIMOS-2 PROJECT OVERVIEW

4.1.1 Project description

Deimos-2 is an agile spacecraft designed for cost-effective, dependable and high-resolution Earth observation applications. With a total mass of 310 kg, the spacecraft is capable of providing 75-cm pan-sharpened imagery and 3-m multi-spectral images in 4 bands (red, green, blue and NIR), with a 12-km swath at nadir from its 620 km of altitude. The Deimos-2 spacecraft was launched in June 2014.

The Deimos-2 spacecraft was co-developed by Elecnor Deimos, Spain, together with the South Korean company Sartrec Initiative (SI). Nowadays, the spacecraft is owned, operated and commercially exploited for use in Earth Observation applications by Deimos Imaging, a Spanish private company, subsidiary of UrtheCast Corp., Canada.



(a) (b)

Figure 4-1: (a) A Deimos-2 illustration; (b) Deimos-2 during integration (https://directory.eoportal.org/web/eoportal/satellite-missions/d/deimos-2).

4.1.2 Spacecraft description

Information about the Deimos-2 spacecraft design are contained in [RD3], [RD4], and [RD6]. A schematic and the gross dimension of the Deimos-2 spacecraft are reported in Figure 4-2 and Figure 4-3. The Deimos-2 launch mass is about 310 kg.

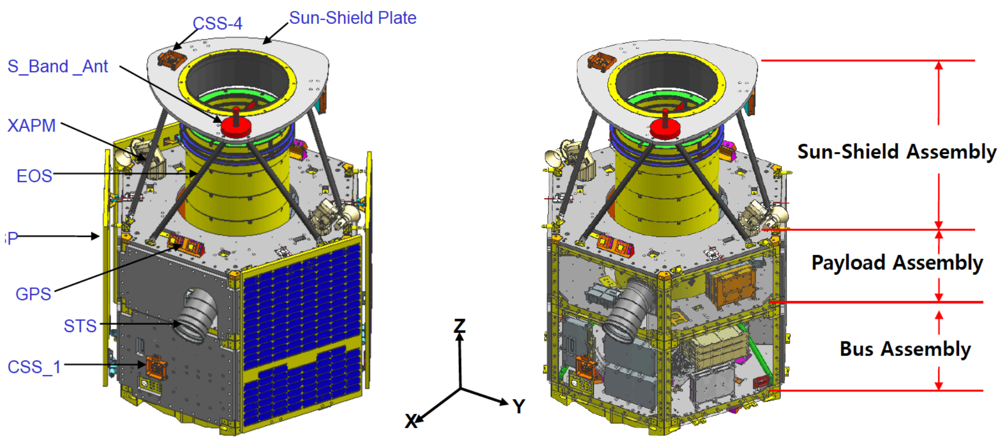


Figure 4-2: Deimos-2 spacecraft overview ([RD4]).

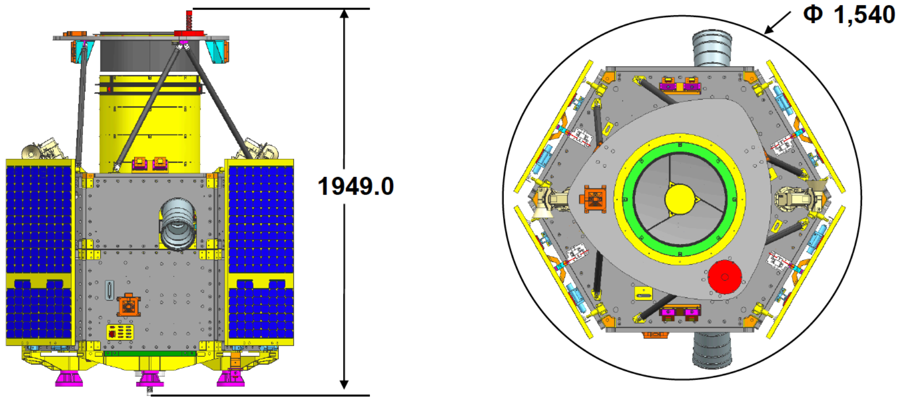


Figure 4-3: Deimos-2 gross dimensions ([RD4]).

Deimos-2 is a 3-axis stabilized spacecraft. The Deimos-2 platform is the SpaceEye platform provided by Sartrec Initiative (SI-300), which was previously adopted for the design of DubaiSat-1, launched in 2013, except for a higher battery capacity.

The main subsystems of the Deimos-2 platform are the following:

- AOCS:

  The AOCS provides satellite pointing capability for single-strip, multi-strip and single-pass stereo imaging. Five reaction wheels are used for attitude control along with four Fiber Optic Gyros. Attitude data is provided by Star Trackers for fine-pointing and magnetometers and sun sensors for coarse pointing in safe and acquisition mode. Deimos-2 has a pointing accuracy of 0.03° on all axes. A key-feature of the satellite is a high-agility to allow fast body-pointing of up to 45° off nadir, however, during nominal operations off-nadir angles of up to 30° will be used.

- Propulsion subsystem:

  A HEPS (Hall Effect Propulsion System) is used for orbit maintenance and orbit adjustments. It uses electric propulsion utilizing Xenon gas and a microwave cathode. HEPS consists of a XFU (Xenon Fuel Unit), THU (Thruster Head Unit), PPU (Power Processing Unit) and the MCU (Microwave Cathode Unit). The XFU holds about 2 kg of Xenon fuel that is held at a pressure of 150 bar. Via pressure valves and orifices, Xenon is allowed to flow into two smaller tanks, each at 3 bar for the anode and cathode. The thruster head includes magnets for ion motion detection while the PPU provides the different voltages for the HEPS system to accelerate generated Xenon ions to high velocity for ejection. The HEPS provides 7 mN of thrust consuming about 300 W of power.

- CDHS:

  The CDHS handles all telecommands sent to the satellite and collects all telemetry from the satellite's subsystems. Two CAN networks with data rates of 500 kbit/s are using a series of Interface Boards to connect all satellite modules to the networks. The Interface Boards are in charge of formatting telemetry data and handling messages received from the main computer. The Actuator Interface Board (AIB) controls the speed of the reaction wheels and provides a speed feedback to the computers.

- RF communications:

  The TTC data are transmitted in S-band. The payload imagery is transmitted in X-band at a data rate of 160 Mbit/s (QPSK modulation). The imagery is stored on a high-capacity solid-state recorder (256 Gbit). The recorder compresses, encrypts and encodes the data in real-time during transmission (lossless compression of image data). CCSDS encoding during transmission. The X-band antenna is steerable in one axis in the range of ±90°. Two telemetry and telecommand boards are operated in hot-redundancy to perform all telecommand decoding and telemetry encoding directly interfacing with the S-Band system that is used for command uplink and telemetry downlink.

The main characteristics of the Deimos-2 spacecraft are summarized in Table 4-1.

Table 4-1: Deimos-2 spacecraft design summary (https://directory.eoportal.org/web/eoportal/satellite-missions/d/deimos-2)

Parameter	Feature	Comment
Spacecraft launch mass	~310 kg	Payload inclusive
Spacecraft size	Ø 1,500 x 1,940 mm height	Hexagonal shape
Attitude subsystem	Pointing error: 0.15° (3σ) Attitude knowledge: 0.1° (3σ) Stability: 0.009°/s (3σ)	3-axis stabilization
Agile platform	±45° pointing in cross-track (max) ±30° pointing in cross-track (nominal)	High-performance AOCS for pointing accuracy & stability
OBC (On-Board Computer)	LEON3 FT, with VxWorks OS	Fully redundant, cross-strapped C&DH, 2 CAN busses (500 kbit/s each, redundant)
Power generation	450 W @ EOL Li-Ion battery, capacity of > 30Ah @ EOL	4 GaAs solar panels
GSD (Ground Sample Distance)	1 m (PAN), ~ 4 m (MS)	@ 600 km altitude, nadir view
Swath width	> 12 km	
Spectral bands	PAN + 4 MS	PAN + RGB, NIR
TT&C	S-band (32 kbit/s in up- and downlink)	Telemetry, telecommand & tracking, CCSDS protocol, PTD chip, authenticated commands and encrypted TLM
Image transmission	X-band with 160 Mbit/s downlink rate	QPSK modulation
On-board recording capability	256 Gbit	Equivalent to 1400 km observation strip
Propulsion subsystem	> 10 mN of thrust, > 1000 s of I_{sp}, 3 kg of Xenon	Orbit control and maintenance
TCS (Thermal Control Subsystem)	Passive and and thermal control	5 operational heaters+2 survival heaters; dedicated temperature sensors, uniform distribution

4.1.3 Mission description

The Deimos-2 spacecraft was launched on 19/06/2014, 19:11:11 UTC, with a Dnepr-1 launch vehicle, from the Yasny Cosmodrome, Dombarovsky region, Russia. The Deimos-2 spacecraft is currently operational on a Sun synchronous orbit at about 600 km altitude.
As of June 2017, the following set of parameters is known about the orbit ([RD2]):

- Epoch: 31/05/2017, 08:02:12
- Semi-mayor axis: 6989.200885 km
- Eccentricity: 0.001257795
- Inclination: 97.884860°
- RAAN: 55.553766°
- AOP: 84.911800°
- Mean anomaly: 300.309409°

These orbital parameters correspond to a perigee altitude of 611.58 km and an apogee altitude of 598.56 km.

Regarding the disposal of Deimos-2 at end of mission it is understood that ([RD5]):

- The spacecraft disposal phase shall comply with the requirement to leave the LEO Protected Region in less than 25 years from the time of end of mission.

- A delta-V of about 20 m/s has been allocated for de-orbiting the spacecraft to a lower orbit (it has been estimated that as of May 2017, a delta-V of 70 m/s is currently available).
- The de-orbit manoeuvres will consist in lowering the perigee altitude to 540 km corresponding to a decrease in the semi-major axis of about 37 km.
- The end of mission is foreseen for end of 2024.

5 RE-ENTRY CASUALTY RISK ANALYSIS

5.1 Introduction

The section provides the re-entry casualty risk analysis for the Deimos-2 spacecraft performed by ESA. The analysis is based on the information and documentation provided by Deimos Imaging.

5.2 Tools

The following tools are used in the analysis:

- ESA DRAMA/SARA (version 2.1.0) for the detailed re-entry survivability analysis;
- HTG SCARAB for limited checks in support of the re-entry survivability analysis;
- ESA ORIUNDO (version 2017) for Earth population density data.

The ESA tools DRAMA/SARA and ORIUNDO are available, free of charge, from the following ESA web site: https://sdup.esoc.esa.int/web/csdtf/home.

5.3 Methodology

- The re-entry model for Deimos-2 is uncontrolled re-entry.
- For a more detailed description of the methodology used for the re-entry casualty risk analysis for uncontrolled re-entry, see Annex C of ESSB-HB-U-002 – ESA Space Debris Mitigation Compliance Verification Guidelines – 19/02/2015.

5.4 Initial conditions

5.4.1 Re-entry state vector

The initial re-entry conditions were not completely provided by Deimos Imaging and they were not specifically computed in this Technical Note due to lack of detailed information. The simulation is based on the input parameters reported in Table 5-1.

Table 5-1: Initial conditions (orbit parameters) and derived trajectory parameters (altitude, velocity, flight path angle) for the re-entry analysis with the ESA tool DRAMA/SARA.

Epoch	[dd/mm/yyyy]	01/01/2050
Time	[hh:mm:ss]	00:00:00
Semi-major axis ($a_{re\text{-}entry}$)	[km]	6500
Eccentricity ($e_{re\text{-}entry}$)	[deg]	0.00001
Inclination (i)	[deg]	98.88
RAAN	[deg]	0
AOP	[deg]	0
Mean Anomaly	[deg]	0
Altitude (H)	[km]	121.8
Velocity (v)	[km/s]	7.91
Flight Path Angle	[deg]	$-5.2*10^{-7}$

5.5 Re-entry object model

5.5.1 Spacecraft model

The Deimos-2 spacecraft has been modelled in the DRAMA/SARA tool as a parent-object and a list of child-objects. The list of objects is mainly based on the list of objects already prepared by Elecnor Deimos in Table 3-1 of [RD1] since no detailed spacecraft system design report has been made available to ESA.
From the available spacecraft design description and drawings it was found that the following items of the HEPS may have been missed in the objects list for the re-entry model provided by Elecnor Deimos in Table 3-1 of [RD1]:

- 2 small HEPS tanks
- 1 Microwave Cathode Unit (MCU)

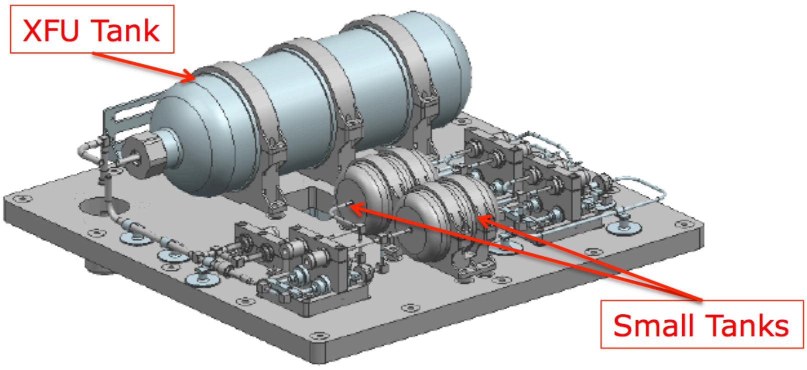


Figure 5-1: 2 small HEPS tanks and 1 MCU maybe neglected in Table 3-1 of [RD1].

No sufficient detailed information about the mass, geometry details and material of the 2 small HEPS tank and the MCU was found in [RD1], [RD2], [RD3], [RD4], [RD5], and [RD6]. Therefore, conservative assumptions on the demisability have been taken into account in this assessment.

Table 5-2: Deimos-2 object list for DRAMA/SARA analysis.

Object Name	Object ID Number	Shape	Qty	Width / Diameter	Length	Height	Mass	Material
				[m]	[m]	[m]	[kg]	
Parent Object	Parent-Object		1	1.5400	1.9500		255.5100	
Solar Panel	Object-00	Plate	4	0.9450	0.6660	0.0000	3.4000	'CFRP-SA'
Base Adapter	Object-01	Box	3	0.7410	0.1500	0.1000	3.7000	'AA7075'
Spar Bus	Object-02	Plate	6	0.5125	0.0800	0.0000	0.3690	'AA7075'
Lower Rail	Object-03	Plate	2	0.5680	0.1030	0.0000	0.4605	'AA7075'
Lower Rail SP	Object-04	Plate	4	0.5680	0.1030	0.0000	0.5795	'AA7075'
Lower Rail Fitting A	Object-05	Plate	3	0.1576	0.1355	0.0000	0.1760	'AA7075'
Lower Rail Fitting B	Object-06	Plate	3	0.1576	0.0885	0.0000	0.1420	'AA7075'
Lower Strut End Fitting	Object-07	Cylinder	3	0.0300	0.5335	0.0000	0.6300	'AA7075'
Middle Rail	Object-08	Plate	6	0.5680	0.1500	0.0000	0.6275	'AA7075'
EOS IF Ring	Object-09	Cylinder	1	0.7200	0.0500	0.0000	5.0720	'AA7075'
Spar EOS	Object-10	Plate	6	0.3585	0.0800	0.0000	0.2580	'AA7075'
Top Rail	Object-11	Plate	6	0.5680	0.1030	0.0000	0.4245	'AA7075'
Top Rail Fitting A	Object-12	Plate	4	0.1576	0.0915	0.0000	0.2300	'AA7075'
Top Rail Fitting B	Object-13	Plate	2	0.1576	0.0915	0.0000	0.2480	'AA7075'
Bottom Deck	Object-14	Plate	1	1.1880	1.1020	0.0000	6.5050	'AA2014'
Bottom Deck Stiffener	Object-15	Box	1	0.9960	0.5100	0.0511	2.2748	'CFRP-Bus'
Payload Deck	Object-16	Plate	1	1.1990	1.1020	0.0000	4.1960	'AA2014'
Top Deck	Object-17	Plate	1	1.2530	1.1230	0.0000	4.9580	'AA2014'
Closure Panel Bus	Object-18	Plate	6	0.6480	0.5110	0.0000	1.9462	'HC-AA2014'
Closure Panel Payload	Object-19	Plate	6	0.6480	0.3630	0.0000	1.2673	'HC-AA2014'
Sun Shield Plate	Object-20	Plate	1	0.9860	0.0200	0.0000	2.2950	'AA2014'

Object Name	Object ID Number	Shape	Qty	Width / Diameter	Length	Height	Mass	Material
				[m]	[m]	[m]	[kg]	
Sun Shield	Object-21	Cylinder	1	0.5030	0.2000	0.0000	0.8800	'CFRP-Bus'
Sun Shield Flange	Object-22	Cylinder	1	0.5800	0.0300	0.0000	0.6800	'AA6061'
Sun Shield Strut Rod	Object-23	Cylinder	6	0.0300	0.7600	0.0000	0.1943	'CFRP-Bus'
Sun Shield Strut End Fitting	Object-24	Cylinder	12	0.0300	0.0550	0.0000	0.0740	'TiAl6V4'
Camera Main Structure Assy	Object-25	Cylinder	1	0.6730	1.1120	0.0000	11.7910	'CFRP-PL'
Camera Flexure	Object-26	Box	3	0.2200	0.0360	0.1150	0.2760	'TiAl6V4'
M1 Mirror	Object-27	Cylinder	1	0.4150	0.0550	0.0000	8.4310	'Zerodur'
M1 Flexure	Object-28	Box	3	0.1860	0.0390	0.0931	0.3490	'Super Invar'
M1 Bezel	Object-29	Cylinder	1	0.6728	0.0596	0.0000	4.6920	'AA6061'
M2 Mirror	Object-30	Cylinder	1	0.1000	0.0240	0.0000	0.2667	'Zerodur'
M3 Mirror	Object-31	Box	1	0.1500	0.1000	0.0374	0.6435	'Zerodur'
FPA PB Assy	Object-32	Box	1	0.2150	0.1325	0.0840	0.9000	'AA6061'
FPA SB Assy	Object-33	Box	1	0.2693	0.0906	0.0923	1.1150	'TiAl6V4'
FPA Detector Assy	Object-34	Box	2	0.1450	0.0450	0.0220	0.6489	'Tungsten'
PPMU	Object-35	Box	1	0.3946	0.3000	0.1940	16.4014	'AA6061'
SPMU	Object-36	Box	1	0.3000	0.1316	0.1940	5.5690	'AA6061'
PSSM	Object-37	Box	1	0.2940	0.1740	0.0440	1.0962	'AA6061'
Battery	Object-38	Box	2	0.2870	0.1735	0.0791	5.5690	'AA6061'
CDHU	Object-39	Box	1	0.2610	0.1620	0.2036	4.2549	'AA6061'
UMBIB	Object-40	Box	1	0.1761	0.1466	0.0310	0.5374	'AA6061'
STU	Object-41	Box	1	0.2750	0.2300	0.1945	6.4160	'AA6061'
S-Band Antenna	Object-42	Cylinder	2	0.1498	0.1364	0.0000	0.5678	'AA6061'
GPS Antenna	Object-43	Box	6	0.0740	0.0540	0.0386	0.1368	'AA6061'
FSS	Object-44	Box	2	0.1030	0.0890	0.0465	0.3250	'AA6061'
CSS	Object-45	Box	4	0.1200	0.1180	0.0260	0.2320	'AA6061'
MAG	Object-46	Box	2	0.0900	0.0860	0.0363	0.2160	'AA6061'

Object Name	Object ID Number	Shape	Qty	Width / Diameter	Length	Height	Mass	Material
				[m]	[m]	[m]	[kg]	
GR Assy	Object-47	Box	1	0.1800	0.1330	0.1400	2.0262	'AA6061'
GRIB	Object-48	Box	1	0.2126	0.2010	0.0540	1.4951	'AA6061'
STEU	Object-49	Box	2	0.1720	0.1250	0.0405	0.6340	'AA6061'
STCU	Object-50	Box	2	0.1270	0.0940	0.3110	2.7880	'AA6061'
RW	Object-51	Box	5	0.1355	0.1300	0.1035	2.6820	'AA6061'
MTR	Object-52	Cylinder	3	0.0260	0.3500	0.0000	0.8935	'A304'
AIB	Object-53	Box	1	0.2242	0.2010	0.0550	1.4700	'AA6061'
PPU	Object-54	Box	1	0.3490	0.2393	0.2574	11.5000	'AA6061'
XFU	Object-55	Plate	1	0.4500	0.4500	0.0109	5.9623	'AA6061'
XFU Tank	Object-56	Cylinder	1	0.1066	0.3660	0.0000	1.4500	'CFRP-Bus-AA6061'
THU	Object-57	Box	1	0.1870	0.1115	0.6300	1.2894	'AA6061'
THU Head	Object-58	Cylinder	1	0.0800	0.0800	0.0000	0.4930	'Iron'
XTU	Object-59	Box	2	0.2140	0.1940	0.1140	3.5420	'AA6061'
SSRU	Object-60	Box	1	0.2600	0.1310	0.1980	8.2040	'AA6061'
ACMU	Object-61	Box	1	0.2600	0.1280	0.2400	3.4480	'AA6061'
X-Band Antenna	Object-62	Cylinder	2	0.0980	0.1361	0.0000	0.2420	'AA6061'
XAPM	Object-63	Box	2	0.1410	0.1100	0.2256	1.1260	'AA6061'
Harness	Object-64	Cylinder	1	0.0200	6.1500	0.0000	15.0000	'Copper'
TOTAL							255.9524	

5.5.2 Material properties

The list of materials and their properties is based on the information provided by Elecnor Deimos in Table 3-2 of [RD1]. The material properties used in the analysis are reported in Table 5-3. With respect to Table 3-2 of [RD1] an Aluminum honeycomb material with lighter density than a bulky aluminium block (i.e. HC-AA2014) was added in Table 5-3 in order to model the Closure Panel Bus and the Closure Panel Payload. In fact, it has been noted that in Table 3-1 of [RD1] the Closure Panel Bus and the Closure Panel Payload were modelled as bulky aluminium panels, while according to their mass, they may be probably composite (honeycomb) panels (as usually found in typical spacecraft designs).

Table 5-3: Material properties.

Material name	Density (ρ)	Specific heat capacity (Cp)	Melting temperature (T_m)	Melting heat (Q_m)	Emissivity (ε)
	[kg/m^3]	[J/kg/K]	[K]	[J/kg]	[-]
A304	8000.0	500.0	1728.2	247112.5	0.110
AA2014	2800.0	880.0	911.2	396567.5	0.050
AA6061	2700.0	896.0	924.9	396567.5	0.050
AA7075	2801.0	1040.0	870.0	385000.0	0.155
CFRP-Bus	1700.0	1047.0	500.0	135149.9	0.040
CFRP-Bus-AA6061	1700.0	1047.0	924.9	396567.5	0.040
CFRP-PL	1600.0	1020.0	530.0	105000.0	0.870
CFRP-SA	1700.0	1047.0	500.0	135149.9	0.840
HC-AA2014	280.0	880.0	911.2	396567.5	0.050
Iron	7874.0	449.0	1811.2	247112.5	0.030
Super Invar	8137.0	502.4	1700.2	247112.5	0.870
TiAl6V4	4420.0	746.4	1900.0	400000.0	0.392
Tungsten	16500.0	132.0	3695.2	190382.9	0.030
Zerodur	2530.0	821.0	873.2	237252.0	0.900

5.6 Earth population density

In view of uncertainties of the re-entry epoch, a set of possible re-entry epochs (years) has been used to estimate the Earth population density using the ESA ORIUNDO tool for the orbit inclination of 97.9°.

5.7 Results

5.7.1 Re-entry trajectory

The graphs showing the re-entry ballistic trajectory and fragmentation of the Deimos-2 spacecraft predicted with the ESA tool DRAMA/SARA are reported in the Figure 5-2 and Figure 5-3.

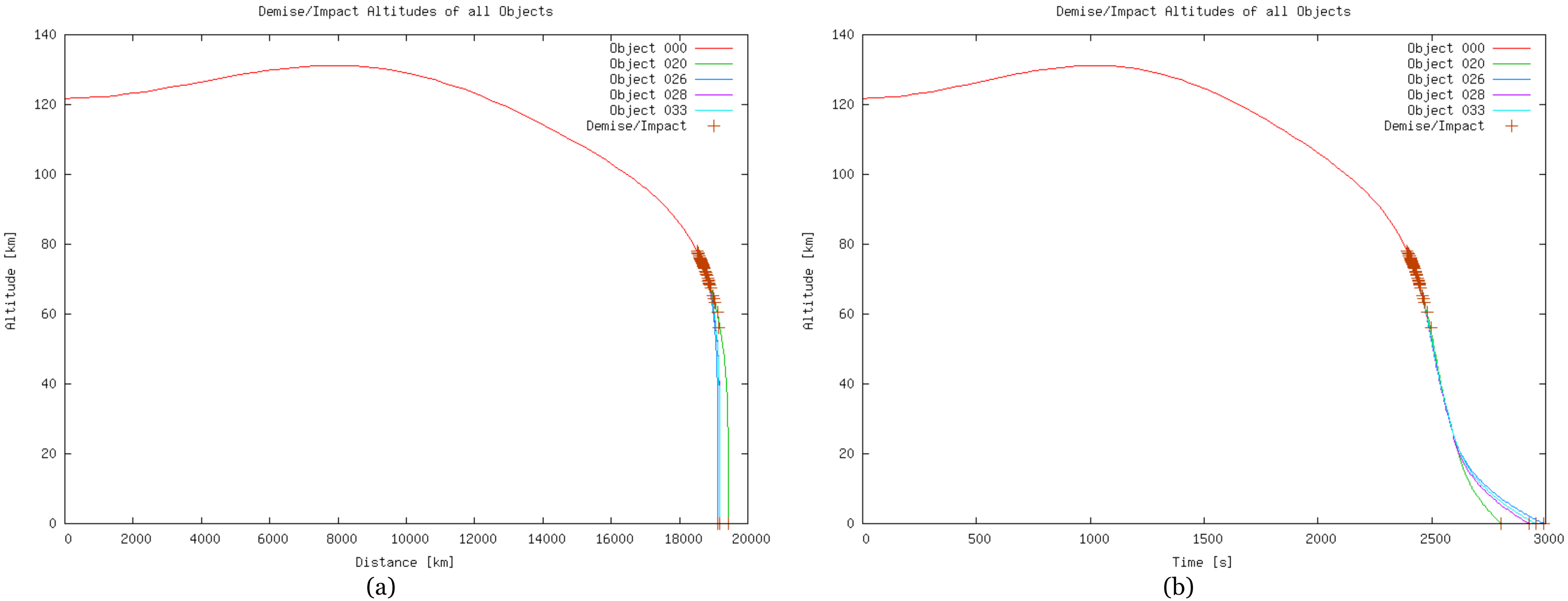


Figure 5-2: (a) Altitude vs distance and (b) altitude vs time of the ballistic re-entry of the Deimos-2 spacecraft predicted with the ESA tool DRAMA/SARA.

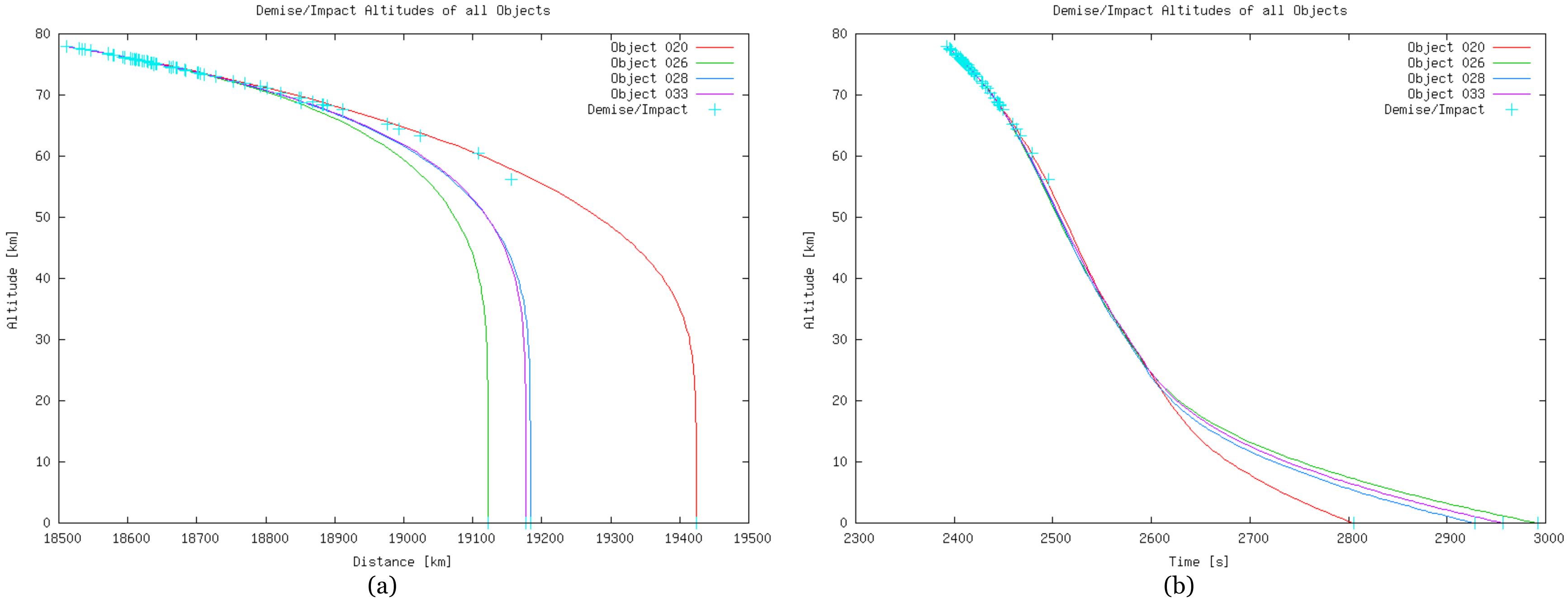


Figure 5-3: (a) Altitude vs distance and (b) altitude vs time of the fragmentation of the Deimos-2 spacecraft predicted with the ESA tool DRAMA/SARA.

5.7.2 Surviving fragments

The list of fragments which are predicted to survive the re-entry according to the ESA tool DRAMA/SARA are reported in Table 5-4 with their respective impact kinetic energy and casualty area.

For the purpose of comparison with the simulation performed by Elecnor Deimos ([RD1]), the last column of Table 5-4 contains the impact probability of fragments predicted with the Deimos tool DEBRIS. In particular, it was noted that:

- The Camera Flexures (3), the M1 Flexures (3) and the Focal Plane Assembly (FPA) Sensor Board (SB) Assembly are predicted to survive the re-entry according to both the analysis performed by ESA with the tool DRAMA/SARA and the analysis performed by Deimos with the tool DEBRIS. These items represent the major contributions to the total re-entry casualty risk of the Deimos-2 spacecraft.
- The Sun Shield Plate is predicted to survive the re-entry according to the ESA analysis performed with the tool DRAMA/SARA. However, the shape of this item in the re-entry model has been approximated with respect to the original design (Figure 4-2) to cope with the DRAMA/SARA input format for the object definition. A more accurate modelling of this item with a higher fidelity tool (e.g. SCARAB) would easily demonstrate that this item demise during the re-entry. The Deimos analysis performed with the tool DEBRIS did not predict the Sun Shield Plate surviving the re-entry.
- The Sun Shield Strut End Fittings (12) are predicted to survive the re-entry according to the Deimos analysis performed with the tool DEBRIS with a probability of about 10%, while these items are found not contributing to the re-entry casualty risk according to the ESA analysis performed with the tool DRAMA/SARA. The Sun Shield Strut End Fittings are placed outside the spacecraft structure, therefore exposed early to the re-entry thermal flux. In case of ground impact, the intact items would have a kinetic energy of about 61 J (i.e. higher than 15 J considered threshold for casualties) and a casualty area of about 0.42 m^2/item (mostly due to the conventional human cross-section of 0.36 m^2). Since there are 12 Sun Shield Strut End Fittings, their total casualty area would be 5.04 m^2. A simplified analysis with the tool SCARAB considering the Sun Shield Plate plus the Sun Shield End Fittings (without the rest of the spacecraft, released from 122 km altitude) confirmed that the Sun Shield Strut End Fittings can reach the Titanium alloy melting temperature (1900 K) and completely demise at about 79 km altitude due to the relatively small thermal mass (0.0740 kg/item).
- The Focal Plane Assembly (FBA) Detector Assemblies (2) are predicted to survive the re-entry according to the Deimos analysis performed with the tool DEBRIS with a limited probability of about 32.2%, while these items are found not contributing to the re-entry casualty risk according to the ESA analysis performed with the tool DRAMA/SARA. In case of ground impact, the possible intact items would have a kinetic energy of about 887.3 J (i.e. higher than 15 J considered threshold for casualties) and a casualty area of about 0.450 m^2/item (mostly due to the conventional human cross-section of 0.36 m^2). Since there are 2 Focal Plane Assembly (FBA) Detector Assemblies, their total casualty area would be 0.90 m^2. A simplified analysis with the tool SCARAB for the FBA Detector Assemblies with release from 78 km altitude, an initial velocity of 7.28 km/s and a flight path angle of -1.02°, confirmed that they can reach the Tungsten melting temperature (3695.2 K) and completely demise at about 59 km altitude due to the relatively small thermal mass (0.6489 kg/item).
- As underlined in sect. 5.5.1, 2 small HEPS tanks and 1 MCU are probably missing in the object list provided by Elecnor Deimos in Table 3-1 of [RD1].

  Regarding the 2 small HEPS tanks, it has assumed that they have a shape close to a sphere with diameter approximately of 0.1 m (captured from Figure 5-1 through rough proportions with respect to the known XFU tank), but mass, material and details of the geometry (e.g. thickness) are unknown.

  Hollow spheres having the size of the small HEPS tanks are usually found to demise during the re-entry when they made of aluminum alloy. For example, a simplified analysis with the tool SCARAB of a 0.1 m-diameter 3 mm-thickness hollow sphere with release from 78 km altitude, an initial velocity of 7.28 km/s and a flight path angle of -1.02°, showed that if the hollow sphere is made of TiAl6V4 (mass 1.60 kg) or A304 (mass 2.92 kg) it does not demise impacting on the ground, while if it is made of AA6061 (mass 0.98 kg) it completely demises around 75 km. In case of ground impact, the possible intact HEPS tanks would lead to a casualty area of about 0.84 m^2/item (mostly due to the conventional human cross-section of 0.36 m^2). Since there are 2 small HEPS tanks, their total casualty area would be 1.68 m^2.

As a conservative approach, an increment of 1.68 m^2 in the spacecraft casualty area has been considered due to the small HEPS tanks.

The material, mass and geometry of the MCU are unknown and, therefore, it was not possible to assess their impact.

Table 5-4: List of Deimos-2 fragments surviving re-entry according to DRAMA/SARA.

Object Name	Object number	Qty	Material	Surviving mass (per 1 item)	Impact velocity	Impact kinetic energy	Average casualty area (per 1 item)	Max casualty area (per 1 item)	Impact probability (DEIMOS/ DEBRIS)
				[kg]	[m/s]	[J]	[m^2]	[m^2]	[%]
Sun Shield Plate	Object-20	1	'AA2014'	1.47	61.30	2759.02	0.4662	0.5226	0
Sun Shield Strut End Fitting	Object-24	12	'TiAl6V4'	0	-	-	0	0	10
Camera Flexure	Object-26	3	'TiAl6V4'	0.28	32.40	146.98	0.5174	0.5562	100
M1 Flexure	Object-28	3	'Super Invar'	0.35	38.18	255.04	0.4924	0.5195	99
FPA SB Assy	Object-33	1	'TiAl6V4'	0.81	35.50	508.45	0.5623	0.5911	99.5
FPA Detector Assy	Object-34	2	'Tungsten'	0	-	-	0	0	32.25
Small HEPS Tank		2	'TiAl6V4'	1.60	84.2	5674.5	0.84	0.84	-
TOTAL		8					5.74	6.02	

5.7.3 Re-entry casualty risk

Table 5-5 reports the re-entry casualty risk of the Deimos-2 spacecraft corresponding to the maximum casualty area predicted with the ESA tool DRAMA/SARA and considering a set of re-entry epochs for the Earth population density.

Table 5-5: Re-entry casualty risk results with the ESA tool DRAMA/SARA and ORIUNDO.

Re-entry casualty area (A_c)	Inclination (i)	Year	Population density (ρ_p)	Re-entry casualty risk (P_c)
[m^2]	[deg]	[yyyy]	[persons/km^2]	[-]
6.02	97.9	2042	13.0	7.85E-05
6.02	97.9	2050	13.4	8.07E-05
6.02	97.9	2060	13.9	8.37E-05

The maximum re-entry casualty risk predicted for Deimos-2 for a re-entry in 2060 is $8.37*10^{-5}$. This risk figure is less than 10^{-4}, therefore, the re-entry of Deimos-2 is considered compliant with the maximum acceptable casualty risk adopted by ESA in the policy on Space Debris Mitigation ESA/ADMIN/IPOL(2014)2.

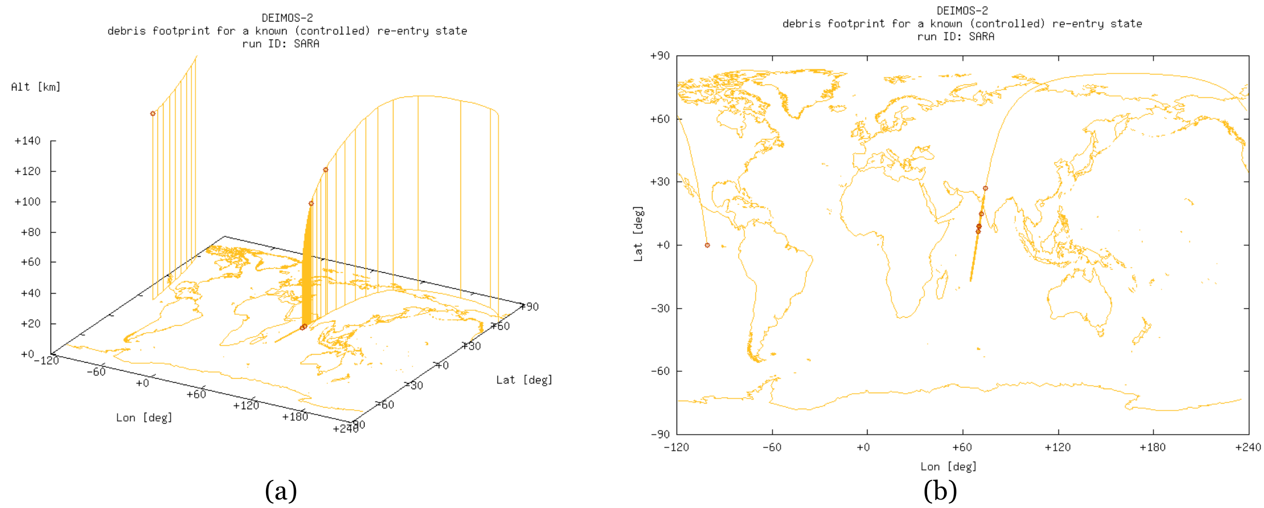


Figure 5-4: Indicative re-entry footprint size
(real footprint location is not predictable with accuracy at this phase due to uncertainty in the re-entry epoch for an uncontrolled re-entry)

6 CONCLUSIONS

The ESA Independent Safety Office (TEC-QI) performed a re-entry casualty risk analysis of the Deimos-2 spacecraft. The analysis was performed with the tools DRAMA/SARA and ORIUNDO. Additional simple checks with the higher fidelity tool SCARAB were also performed in support to the analysis with DRAMA/SARA. The input data for the analysis were based on the design and orbit information provided by the spacecraft operator Deimos Imaging.

The maximum re-entry casualty area estimated with the ESA tools DRAMA/SARA is 6.02 m^2 corresponding to a re-entry casualty risk of $8.37*10^{-5}$ based on the Earth population density estimated with the ESA tool ORIUNDO for a re-entry in the year 2060.

The results of the re-entry casualty risk analysis confirmed that the Deimos-2 spacecraft re-entry is compliant with the ESA 10^{-4} re-entry casualty risk requirement.

DECLARATION

I, Bernard Poller, hereby certify under penalty of perjury that I am the technically qualified person responsible for preparation of the technical information contained in the foregoing exhibit and that I either prepared or reviewed the technical information contained in the exhibit and that it is complete and accurate to the best of my knowledge, information and belief.

Director, Optical System Engineering
UrtheCast Corp.

Dated: July 16, 2020