HYPERVELOCITY IMPACT ROBUST SPACECRAFT WEBINAR

Concurrent Design Facility Study

CDF Study Team

ESA ESTEC

18/12/2025

Reference: ESA-TECSFD-HO-2025-003733

Webinar presenters

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- HVI Robust S/C CDF

Housekeeping rules

The session will be recorded.

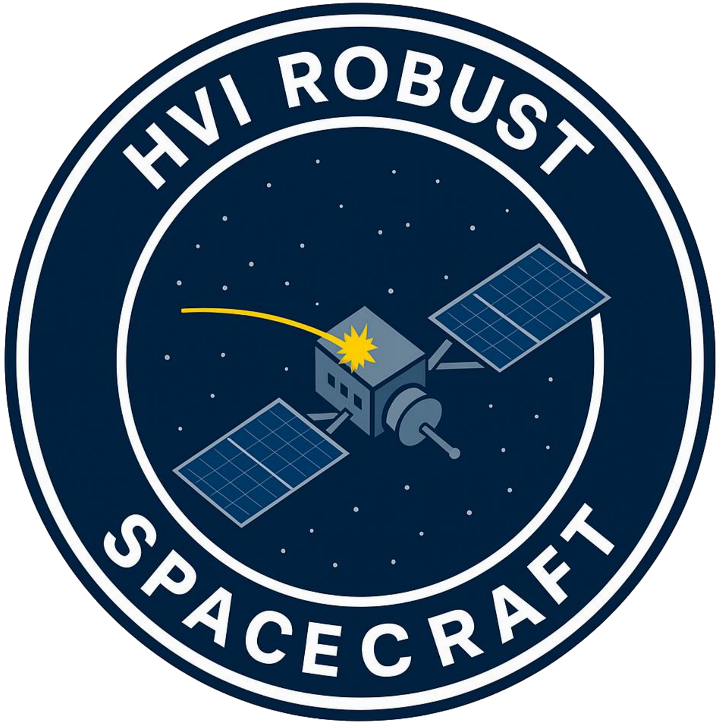
The slides will be distributed.

Put your questions in the Q&A section of Webex. They will be answered at the end of the presentation.

Agenda

Item	Time	Duration
Study Introduction	11:00	10 min
Solutions overview	11:10	45 min
Testing, Verification and Simulation needs	11:55	10 min
Conclusions and Next steps	12:05	5 min
Questions	12:10	20 min

Study Introduction



ESA Concurrent Design Facility

- **ESA Concurrent Design Facility (CDF)**
  - Is used to address ideas for new space missions, systems or structures
  - Allow teams of experts from different engineering disciplines to work in close coordination in the same place at the same time to complete complex designs

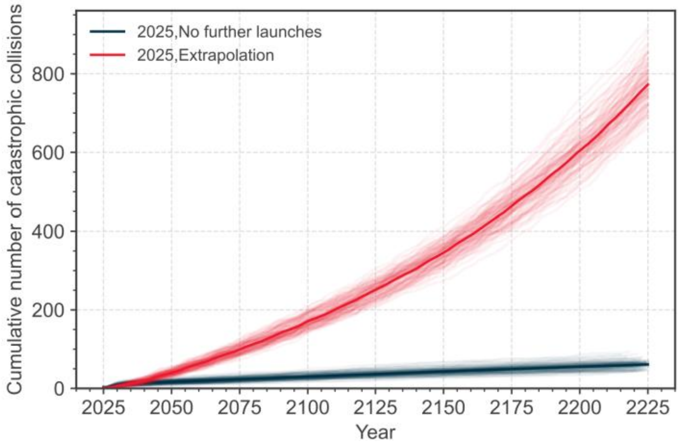
- For this topic, a **MiCRA CDF** study has been performed
  - MiCRA = Mission Concept and Requirements Assessment
  - Reduced number of sessions compared to full CDF & smaller team
  - Not targeting a mission but to prepare industrial activities for technologies development

Further information: ESA - MiCRA: Concurrent engineering for early mission concept assessment in the CDF.

Study Background - Space Environment and HVIs

- The orbital environment is becoming increasingly congested as the number of space objects continues to grow rapidly and is expected to rise further.
- The risk of collision with space debris or micrometeoroids is escalating - particularly in Low Earth Orbit (LEO).

→ The ability of spacecraft to withstand hypervelocity impacts (HVI) is now a key factor for mission success.



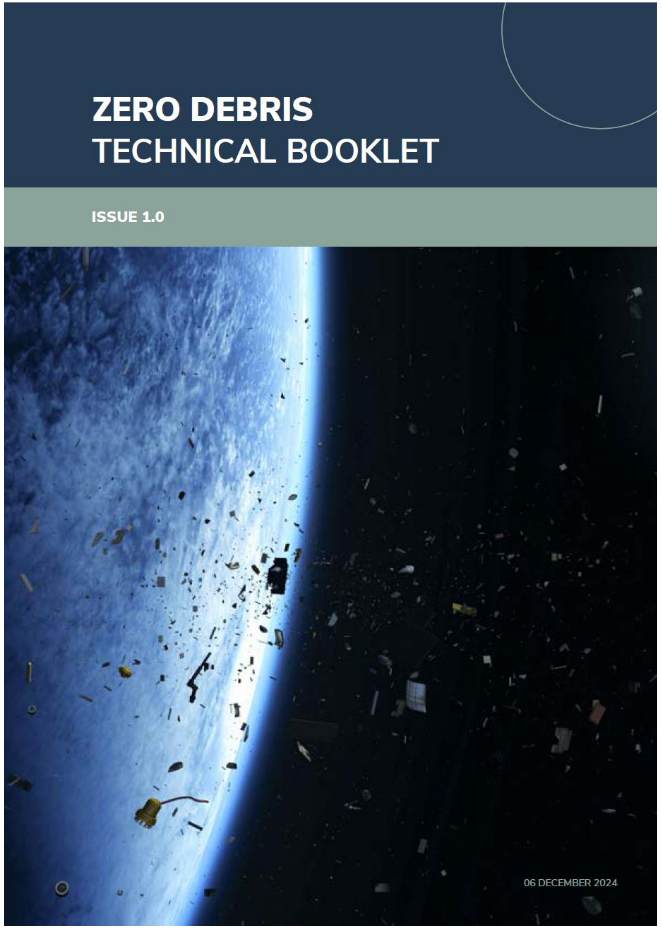
LEO, Space Environment Report 2025

Hypervelocity Impact (HVI)
A collision between objects at extremely high relative speeds, typically above 2–3 km/s, where the impact generates shock waves, fragmentation, and material vaporization.

Study Background - Zero Debris Booklet

These directions are aligned with the solutions and key enablers identified in the Zero Debris Technical Booklet:

- Technological and material solutions to mitigate impact effects **(Solution 1.1.B)**.
- Advanced modelling and testing to better understand the consequences of collisions and internal break-ups **(Solutions 3.1.B and 3.5.A)**.
- Standardized risk assessment methodologies **(Solution 3.2.A)**.
- Design for resilience against untrackable debris and internal failures **(Solutions 3.4.B and 3.5.C)** through smart spacecraft architectures, health monitoring systems, and containment solutions for on-board energy sources.



Study Objectives

This MiCRA-CDF acts as the necessary first integrative step to:

- Investigate platform-level strategies and technologies to enhance spacecraft resilience to HVI and minimize debris generation.
- Define technology priorities and design directions to support the upcoming R&D activities.
- Outline the testing, verification and simulation needs for resilience measures.

Technical Objectives:

1) Reducing the risk of collision*: assess design options to reduce impact probability.

2) Mitigating the effect of HVI on:

a) The **spacecraft:** reduce mission-level consequences.

b) The **environment:** minimize debris generation.

(*) Excluding Collision Avoidance Manoeuvres, Space Surveillance and Tracking, and Space Traffic Coordination improvements, which were not in the scope of the CDF.

Study Team

Customer	Section code
Structures Section	TEC-MSS

System team	Section code
Sustainable Engineering Section	TEC-SFS
CleanSpace and Circular Economy Office	OPS-SY

Experts	Section code
Structures Section - Configuration & Structure	TEC-MSS
Space Debris Office	OPS-SD
Space Environments & Effects Section	TEC-EPS
Material, Manufacturing & Assembly Section	TEC-MSP
Materials, Environment & Contamination control Section	TEC-MSE

Consultant	Section code
Space Segment AIV/AIT Engineering Section	TEC-SYA
Electric Propulsion Section	TEC-MPE
Independent Safety Office	TEC-QI
Power Systems Architecture Section	TEC-EPM

Study Execution

KO
30/10

S2
S3

S4

FP
28/11

Brainstorming for each T-OBJ
1. In sub-groups
2. With the whole team

→ List of solutions to be studied in following sessions

T-OBJ
1. Reduce risk of Collision
2. Mitigate the impact after HVI
   a. On the Spacecraft
   b. On the Environment

System solutions (16)
- Platform impacts
- Mapping & TRL
- Gaps

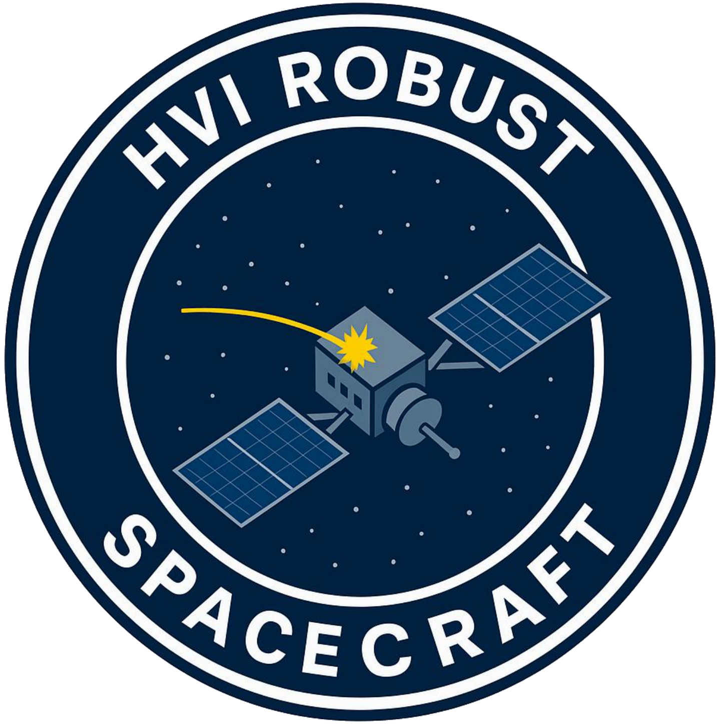
Technologies solutions (21)
- Platform impacts
- Mapping & TRL
- Gaps

Gain (for each T-OBJ) **& Effort**

Testing, Verification and Simulations Needs
- HVI Testing, Simulations and models
- Modelling guidelines
- Space environment model
- HVI Risk analysis, vulnerability assessment

→ Design recommendations

Solutions overview



Solutions Classification

- Solutions divided into "**System-level**" or "**Technology-level**" solutions

- Solutions organized per technical objective:
  - Reducing the risk of collision
    - Reducing the total spacecraft area subjected to the debris flux
    - Mission choices
  - Mitigating the effects of HVI on the Spacecraft, on the Environment or on Both
    - Shielding
    - Halting the propagation of impact forces
    - Increasing our understanding of HVI effects on the spacecraft
    - Configuration changes & increased redundancy
    - Reducing the number of fragments

System-Level Solutions

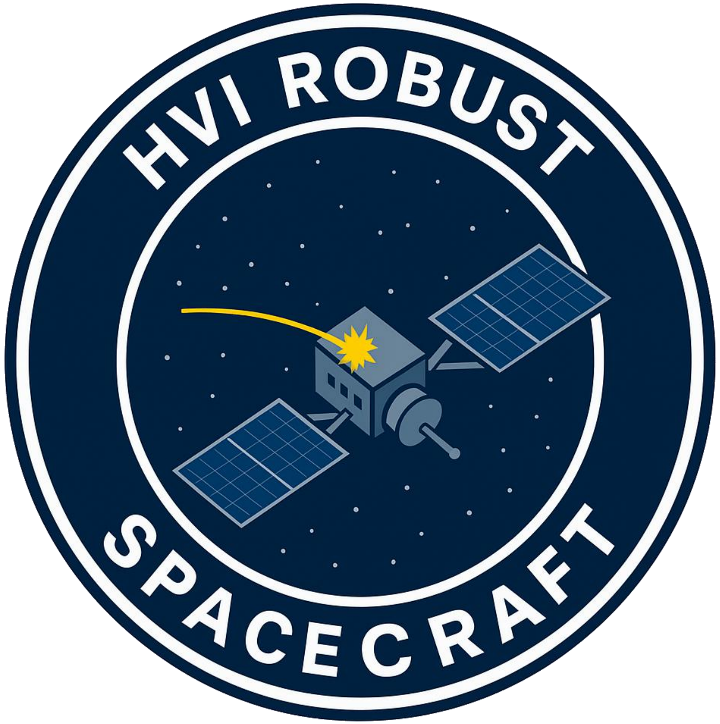
Solutions that will be presented in more details during this Webinar

Solution Name	Goal	Level
Attitude Adjustments	Reducing the risk of collision	System
High aspect ratio spacecraft	Reducing the risk of collision	System
Late commissioning of appendages	Reducing the risk of collision	System
Body-mounted solar panels	Reducing the risk of collision	System
High internal packing ratio	Reducing the risk of collision	System
Less populated orbit selection	Reducing the risk of collision	System
Shorten mission duration	Reducing the risk of collision	System
Launch date optimization	Reducing the risk of collision	System
Use of another spacecraft as a shield	Reducing the risk of collision	System
Post impact retraction/safe state of appendages	Mitigating the effect on both the spacecraft and the environment	System
Health monitoring sensors	Mitigating the effect on the spacecraft	System
HVI sensitive elements identification and characterization	Mitigating the effect on the spacecraft	System
Foams inside the spacecraft body	Mitigating the effect on both the spacecraft and the environment	System
Optimize placement of components	Mitigating the effect on the spacecraft	System
Increase internal compartmentalization	Mitigating the effect on the spacecraft	System
Redundant units and harnessing	Mitigating the effect on the spacecraft	System

Technology-Level Solutions

Solution Name	Goal	Level
Appendages orientation change	Reducing the risk of collision	Technology
Foldable/retractable appendages	Reducing the risk of collision	Technology
Magnetic Field to Divert SD	Reducing the risk of collision	Technology
Standard Whipple Shielding and Variants	Mitigating the effect on the spacecraft	Technology
Curved/angled or corrugated shielding	Mitigating the effect on the spacecraft	Technology
Deployable Shielding	Mitigating the effect on the spacecraft	Technology
Flexible Solar Arrays	Mitigating the effect on both the spacecraft and the environment	Technology
Bullet-proof cover glass for solar panels	Mitigating the effect on the spacecraft	Technology
Covers	Mitigating the effect on the spacecraft	Technology
Perforable and ejecta-less structure	Mitigating the effect on both the spacecraft and the environment	Technology
Shock Absorbers Between Panels on the Spacecraft Structure	Mitigating the effect on both the spacecraft and the environment	Technology
Novel materials and material architecture for shielding	Mitigating the effect on both the spacecraft and the environment	Technology
Materials that fragment into smaller objects	Mitigating the effect on the environment	Technology
Bonded materials with disparate fragmentation properties	Mitigating the effect on both the spacecraft and the environment	Technology
Foam shielding and panels	Mitigating the effect on both the spacecraft and the environment	Technology
Self-healing materials	Mitigating the effect on the spacecraft	Technology
Innovative Honeycomb panels geometry	Mitigating the effect on the spacecraft	Technology
Lattice structures	Mitigating the effect on the spacecraft	Technology
Integrated breakpoints	Mitigating the effect on both the spacecraft and the environment	Technology
Containment of explosions/ejecta	Mitigating the effect on the environment	Technology
Safety tether system for appendages	Mitigating the effect on the environment	Technology

System-Level Solutions



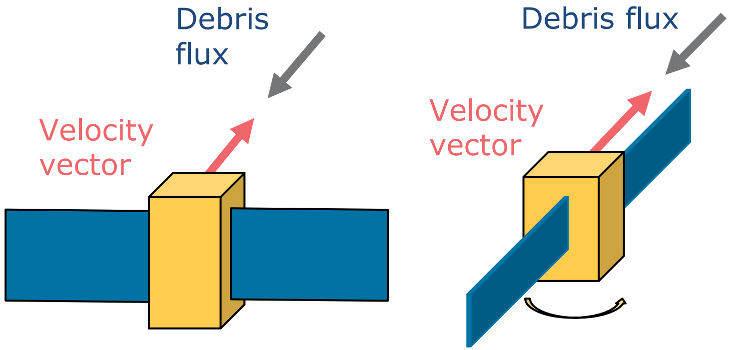
Attitude Adjustments

System-Level Solution	Reducing the risk of collision	Mitigating the effect on the spacecraft
	Reducing the total spacecraft area subjected to debris fluxes	

Adjusting the spacecraft's orientation to minimize the surface area exposed to the debris flux or to prevent exposure of sensitive surfaces.

- **Trackable object**: When a possible conjunction with trackable objects is predicted, the spacecraft can rotate to present its smallest cross-sectional area toward the incoming debris direction, thereby reducing the risk of impact.
- **Untrackable object:** the goal is not continuous attitude changes but adopting an orientation that minimizes exposure to the predominant debris flux.

Main impacts:
- **Mission/System**.
- **Power**
- **Propulsion/AOCS**
- **Thermal**
- **Comm**



Main gaps:
- **Lack of optimized attitude modes during unconstrained phases:** no systematic approach to define attitudes that minimize collision risk during periods without pointing requirements (e.g., eclipse phases).
- **No established procedures:** absence of guidelines for switching to and maintaining an optimized attitude (e.g extended durations).

Moderate Gain (1) / Very Low Effort (0)

High Aspect Ratio S/C

System-Level Solution | Reducing the risk of collision

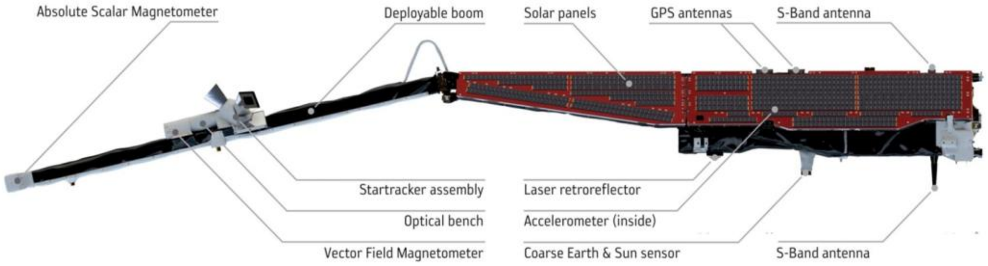
Reducing the total spacecraft srea subjected to debris fluxes

Design spacecraft with elongated shapes, allowing for the cross-sectional area with the highest flux to be minimized through attitude control.

- If feasible the smaller area is already oriented to the high flux side(s) or can actively be oriented towards potential incoming flux.
- This area can also be protected by using local MMOD shielding.

Main impacts:

- **Launcher compatibility**
- **Mission Analysis**
- **Structure**
- **Configuration**
- **Thermal**
- **AOCS/GNC**



SWARM satellite, Credit: ESA

Main gaps:

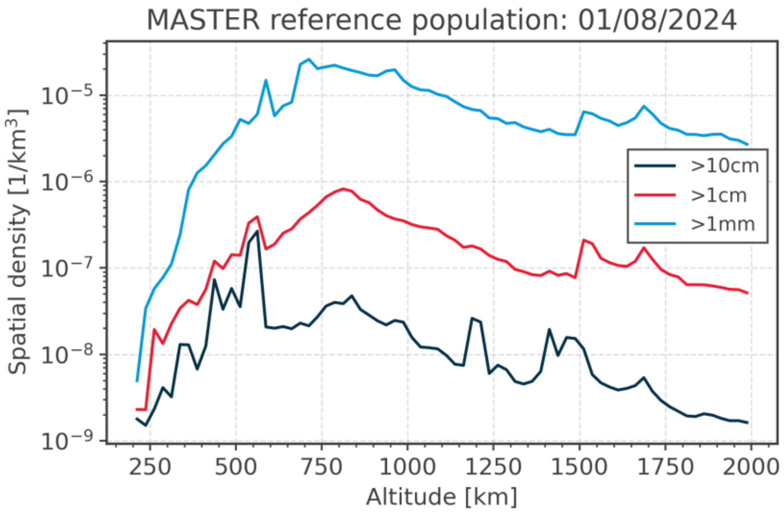
- **Feasibility** of applying a high aspect ratio VS **mission objectives** and criteria, and envisaged Instruments and Equipment.

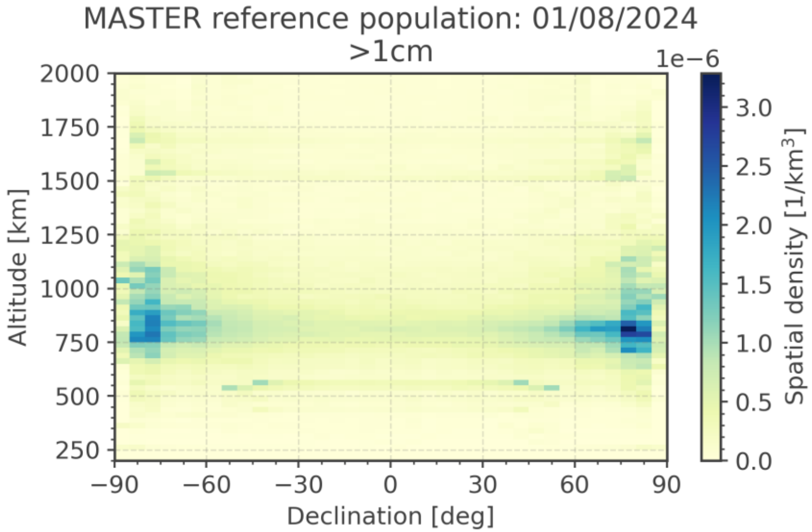
Moderate Gain (1) / Low Effort (1)

Less populated orbit selection

System-Level Solution | Reducing the risk of collision
Mission Choices

The solution consists in the selection of less congested orbits (with lower space debris density)





> ~10 cm trackable (collision avoidance)
> ~1 cm potentially mission-ending
> ~1 mm not shielded by standard spacecraft design

Less populated orbit selection

System-Level Solution | Reducing the risk of collision

Mission Choices

Mapping

Missions/Platform	PF provider	TRL
GOCE (260km)	EADS Astrium GmbH (DE)	TRL9 (Launched 2009)
Clarity-1 (320 km)	Albedo Space (US)	TRL9 (Launched 2025)
SabreSat (VLEO platform)	Redwire Corporation (US)	~TRL 5-6
Phantom (VLEO platform)	Redwire Corporation (US)	ESA Skimsat phase B1
NEO-1 (VLEO platform)	NewOrbit (UK)	~TRL 4-6

+ sub-systems for VLEO (e.g. air-breathing electric propulsion)

Main gaps:

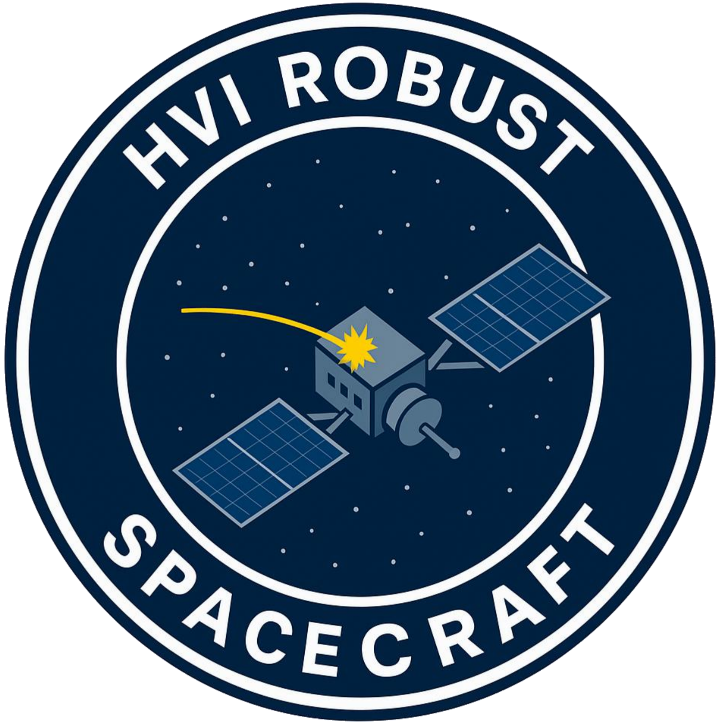
- **Shifting congestion**:
  - Targeting less congested orbits may shift rather than eliminate the problem;
  - Dynamic environment is subject to change – less congested regions during design may not be less congested after launch
- **Validation data**: limited measurement data in 1 mm – 1 cm range for calibrating space debris environment models
- **Launch opportunities**

	Objective	Score
Gain	Reduce the risk of collision	2
	Mitigate the effects of HVIs / Spacecraft Robustness	0
	Mitigate the effects of HVIs / Generation and release of debris	0

→ Benefit may be reduced if the population does not remain as predicted in the future

Effort	Very Low Effort	0

Technology-Level Solutions



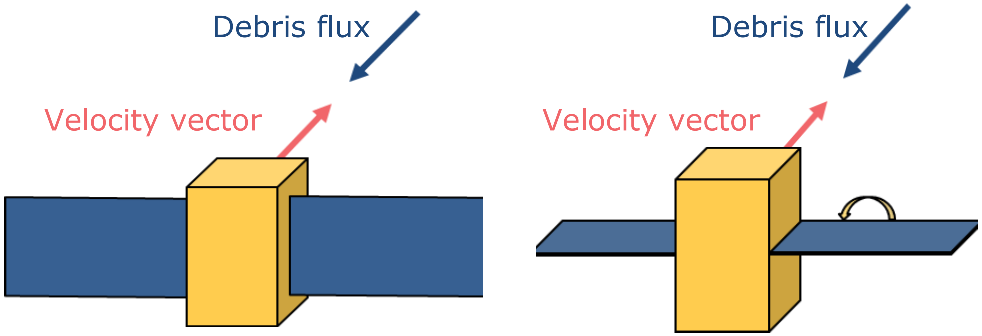
Appendages Orientation Change

Technology-Level Solution | Reducing the risk of collision

Reducing the total Spacecraft Area subjected to debris fluxes

Changing the orientation of appendages such as solar arrays, antennas, or payload booms to reduce the spacecraft's exposed cross-sectional area toward the direction of highest debris flux, typically aligned with the velocity vector.

Main impacts (depend on appendages retracted):
- **Mission**
- **PL**
- **Mechanisms**
- **Power** (if S.A.)
- **COMM** (if antenna)
- **Structure**



Main gaps:
- **Mechanisms Qualification:** increased use and higher rotation cycles if frequent repositioning is required.
- **Rotation Speed Constraints:** Current SADM design rotates at 0.06°/s but can go up to 1°/s; faster rotations may need motorization redesign.
- **Operational Feasibility:** Limited understanding of whether localized debris regions exist and if there's enough time to rotate appendages.

(*) Mapping: Preliminary list available in the CDF report but focused on solar array mechanisms.

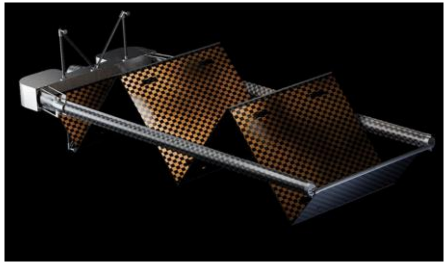
Moderate Gain (1) / High Effort (3)

Foldable/Retractable Appendages

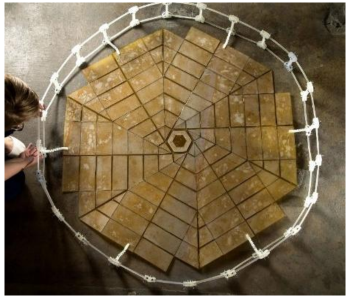
Technology-Level Solution | Reducing the risk of collision

Reducing the total Spacecraft Area subjected to debris fluxes

Retracting or folding appendages (e.g. solar arrays, antennas, payload booms) when not in use as a way to reduce the spacecraft's exposed cross-sectional area and, consequently, its collision risk.



Credit: Atomic-6



Credit: NASA

Mapping

Product	Supplier	TRL
Deployable and retractable solar array	DLR	4
Adaptation of existing Solar Arrays for missions to Saturn	Airbus NL	3
Solar Flex	Thales Alenia Space	5
Light Wing retractable solar arrays	Atomic-6	First flight 2026
Lightweight Antenna with Rollable Array	DCUBE	3, target 4
Sunflake Solar Array	Folditure	4-5

Main gaps:

- **Qualification:** Uncertainty about TRL maturation and qualification for frequent retraction.
- **Operational Feasibility:** Limited understanding of whether localized debris regions exist and if there's enough time to retract appendages.
- **Single-Point Failure Risk:** Folding mechanisms introduce a critical failure point.

Moderate Gain (1) / High Effort (3)

Standard Whipple shielding and Variants

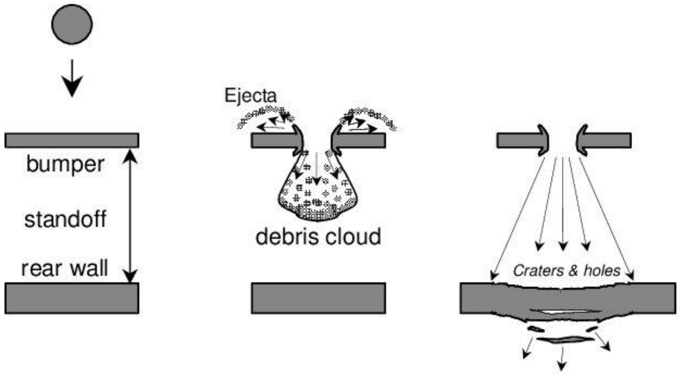
Technology-Level Solution | Mitigating the effect on both the spacecraft and the environment

Shielding

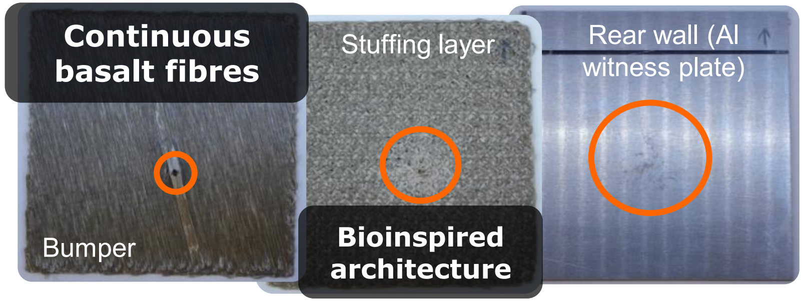
Whipple shields consist of a thin outer layer called a bumper (used to spread the initial impact energy) and a thicker layer called rear wall (used to absorb the impact energy).
Advanced variants of the Whipple shields include Fiber metal laminates, multi-layer setups with additional bumpers and/or intermediate layers for enhanced protection.
This solution is widely used for crew-rated missions (e.g., ISS modules) and large spacecrafts and has the biggest heritage.

Main impacts:

- **Mission:** Increased mass and volume, verification of launcher fairing compatibility.
- **Structure:** Additional structural interfaces; potential influence on stiffness and vibration modes.
- **Thermal:**
  - additional assessment of heat dissipation and insulation.
  - Reduced available space for radiators.
  - Complexity to optimize MLI location.
- **AIV:** Vibration and thermal tests.



3D-printed ISRU-based composites for MMOD impact protection (ESA co-funded Ph.D. thesis)



https://doi.org/10.1016/j.addma.2025.104875

Credit: ESA

Standard Whipple shielding and Variants

Technology-Level Solution	Mitigating the effect on both the spacecraft and the environment

Shielding

Whipple shields are standard technologies for man-rated spacecraft (e.g. ISS, Gateway), with a **very high TRL (9).** The current mapping primarily relates to non-human applications.

Mapping

Product	Supplier	TRL
GIOTTO Whipple Shield	ESA	9
COMET interceptor Dust shield	ESA, OHB Czechspace	5
TARGE	Aphelion	4-5
Nyx Whipple Shield	The Exploration Company	6-7
MMOD Shielding	Magellan Aerospace, University of Manitoba	5 TBC

Main gaps:

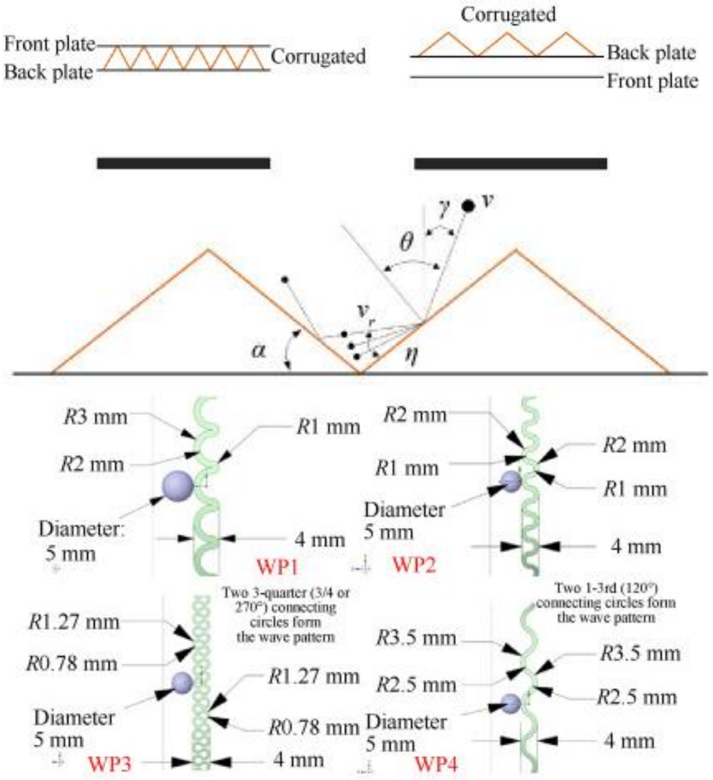
- **Design Optimization:** Current sizing methodologies may not be directly applicable to small platforms.
- **Materials Trade-Offs:** Few studies on lightweight alternatives that reduce mass while maintaining protection.
- **Limited Test Data:** Material properties and fragmentation behaviour are difficult to model, thus creating a dependency on test data. Because of this. A small number of tests need to be extrapolated to varied parameters; this includes failure modes (e.g., tank/battery perforation) assumed to be catastrophic.

	Objective	Score
Gain	Reduce the risk of collision	-1
	Mitigate the effects of HVIs / Spacecraft Robustness	2
	Mitigate the effects of HVIs / Generation and release of debris	1-2
Effort	**Low Effort**	1

Corrugated shielding

Technology-Level Solution | Mitigating the effect on both the spacecraft and the environment

Shielding



https://doi.org/10.1016/j.dt.2024.09.002

This solution represents a modification of the standard Whipple shield design, from flat material 'slabs' to irregular surfaces, typically of the bumper layer. The underlying concept is that inclined impacts are typically causing less damage, and the ejecta and perforation clouds are deflected.

For strong corrugation, the same surface may be crossed multiple times and cavities might also contain fragments and ejecta.

Main impacts:

- **Mission:** more mass of shielding since angles are introduced.
- **Structure:** Deforming layers of structural panels might affect performances.
- **Thermal:** view to open space limited.
- **AIV:** TBC mounting of units on irregular surfaces.

Corrugated shielding

Technology-Level Solution	Mitigating the effect on both the spacecraft and the environment

Shielding

Mapping

Product	Supplier	TRL
Various studies for corrugate bumpers but no flight heritage	e.g. https://doi.org/10.1016/j.dt.2024.09.002	3-4

	Objective	Score
Gain	Reduce the risk of collision	-1
	Mitigate the effects of HVIs / Spacecraft Robustness	2
	Mitigate the effects of HVIs / Generation and release of debris	1

→ Might slightly increase the S/C exposed area; Higher dissipation impact energy, lowering penetration risk, trapping debris within cavities to limit internal damage and ejecta.

Effort	**Medium**	**2**

→ Structural redesign and qualification of non-standard shield geometries + HVI tests.

Main gaps:

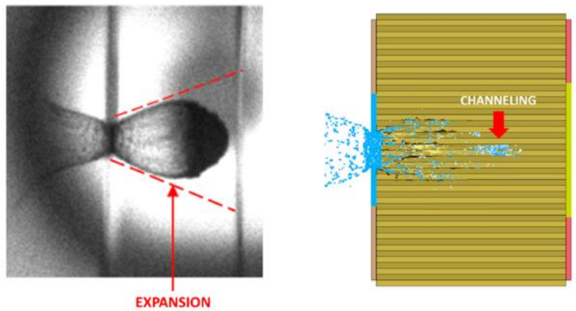
- **Lack of process**: No design and industrial process to produce corrugated design elements (e.g. on structural panel)
- **Limited Test Data**

Foam Shielding and Panels

Technology-Level Solution | Mitigating the effect on both the spacecraft and the environment

Shielding

This solution consists in either adding foam-like materials in the form of tiles or panels, or to use foams as a sandwich panel filler. On top of reducing the risk of rear-wall penetration, this could help slow down ejecta and reduce secondary fragmentation to potentially improve the debris cloud dispersion, as well as absorb the impact energy and attenuate shock.
Experiments also show that incorporation of STF (such as Silica nanoparticles in Polyethylene glycol) into honeycomb aluminium core has the potential to dramatically improve the hypervelocity penetration resistance in a large velocity range.



Whipple shield (experiment) Honeycomb-core panel (simulation)

https://doi.org/10.3390/applmech2010003

https://doi.org/10.1016/j.dt.2024.09.002

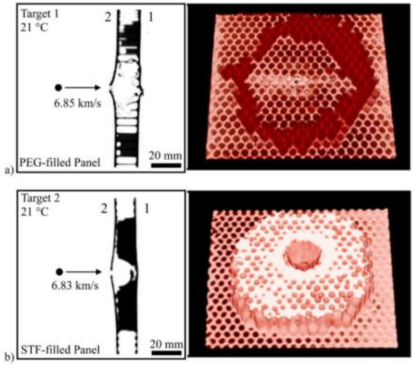


Fig. 2. 2D CT scans and 3D renderings of impacted PEG and STF-filled panels where Facesheet 2 was impacted a) PEG-filled core and impacted at $T_1 = 21°C$ and at $V_1 = 6.85$ km/s b) STF-filled core and impacted at $T_1 = 21°C$ and at $V_1 = 6.83$ km/s

https://doi.org/10.1016/j.ijimpeng.2020.103803.

Main impacts:

- **Space Environment:** Additional qualifications needed.
- **Mission:** Increased mass and volume.
- **Structure:** Grounding of foams may be needed to avoid arcing.
- **Thermal:** Potential influence on thermal balance (assessment on heat dissipation/insulation is needed).

Foam Shielding and Panels

Technology-Level Solution	Mitigating the effect on both the spacecraft and the environment

Shielding

Mapping

Product	Supplier	TRL
IMPACT2SPACE (patented STF)	SpacEngineer (PT)	4-5
Rohacell PMI foam	Evonik Industries	Space qualified HVI testing unknown
Metallic foams (FOAMINAL®)	Fraunhofer IFAM	HVI tested Lack of space qualification
Space Armor	Atomic-6	4-5
Silfoam/Aeroflex/Silflex	ESA COMET-I (Dust shield) (High Tech Material Solutions)	5

Main gaps:

- Sparse literature on the solution
- Compatibility of STF with space environment is unknown
- Potential lack of manufacturing and industrial process to produce these panels at a large scale
- Filling honeycomb cells and ensuring consistent bond between foam and cell walls / face sheets is a manufacturing challenge. Voids, delamination and uneven filling produce local weak spots that drastically change HVI response and reduce repeatability between panels

	Objective	Score
Gain	Reduce the risk of collision	0
Gain	Mitigate the effects of HVIs / Spacecraft Robustness	2
Gain	Mitigate the effects of HVIs / Generation and release of debris	1
Effort	**Medium Effort**	3

Innovative honeycomb panels geometry

Technology-Level Solution | Mitigating the effect on the spacecraft

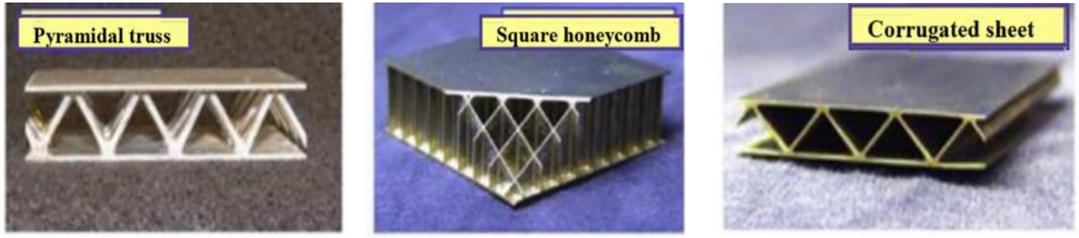
Shielding

This solution comprises novel configurations for honeycomb panels geometry, including **multi-layer panels, corrugated panels, angled honeycomb cells, increased honeycomb density, auxetic cores**.

Typical Honeycomb panels can induce channelling of the secondary debris cloud if it is oriented parallel to the cell direction; this concentrated jet of debris is very high energy and can cause penetration of the rear face plate. This new geometries help mitigate this effects.

Main impacts:

- **Mission:** Increased mass.
- **Structure:** Potential influence on stiffness under bending loads/vibrational loading (e.g. at launch).



Yixiong, Feng & Qiu, Hao & Gao, Yicong & Zheng, Hao & Tan, Jianrong. (2020). Creative design for sandwich structures: A review. International Journal of Advanced Robotic Systems. 17. 172988142092132. 10.1177/1729881420921327.

ReDSHIF: Experimental characterization of multi-layer 3D-printed shields for microsatellite

Innovative Honeycomb panels Geometry

Technology-Level Solution | Mitigating the effect on the spacecraft

Shielding

Mapping

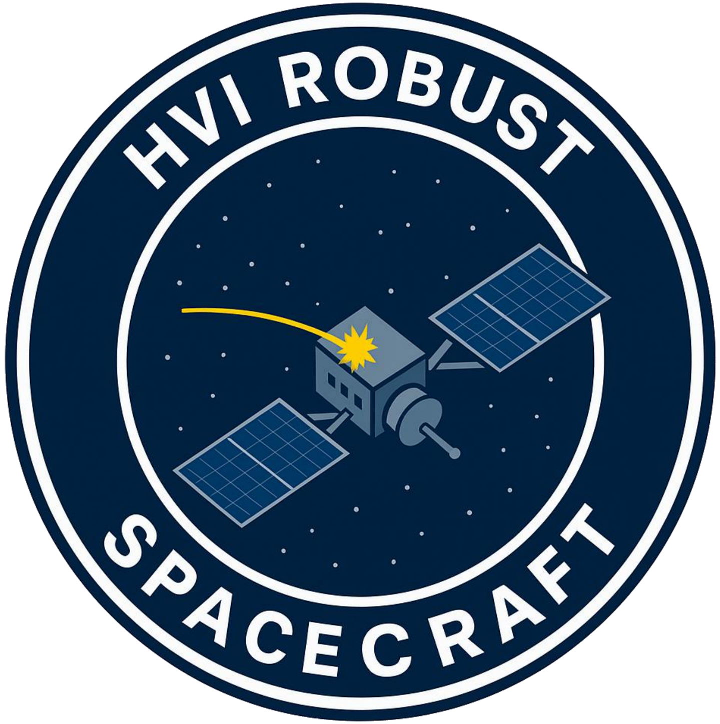
Papers	Research Group
Negative Stiffness honeycomb structures for Impact protection	University of Texas Integrating Materials and Manufacturing Innovation, 2015/2018
Ballistic Impact Response of an Aluminium Sandwich panel with Auxetic Honeycomb Core Structure	Military technical College, Kobry El-Kobbah, Cairo, Egypt. 17th International Conference on Applied Mechanics and Mechanical Engineering, 2016
3D-auxetic elastomeric cellular structures for impact protection	University of Bath; International Journal of Protective Structures, 2024
ReDSHIFT/Experimental characterization of multi-layer 3D-printed shields for microsatellites	International Astronautical Congress, 2019

Main gaps:

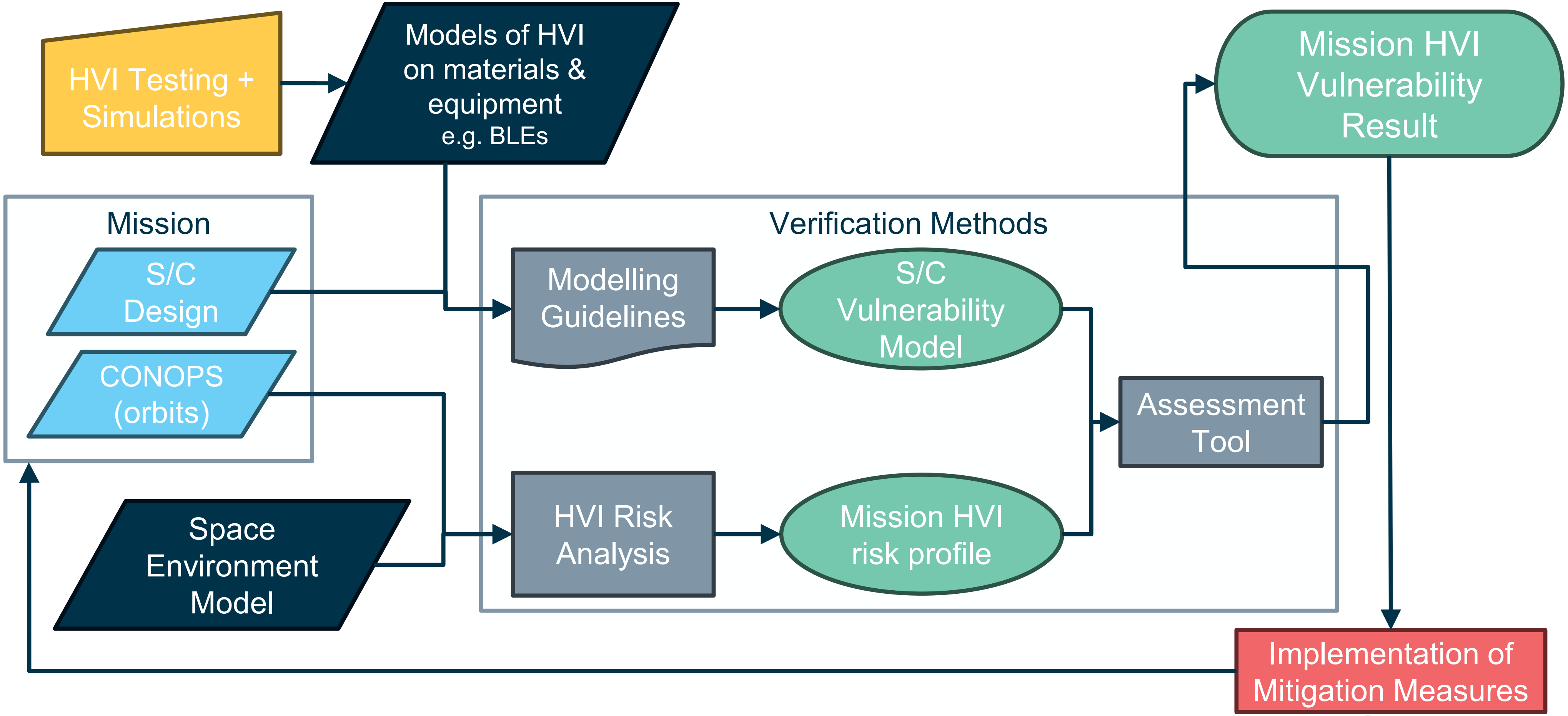
- **Low TRL:** Much of this technology is still experimental so is at a very low TRL.
- **HVI testing:** For innovative geometries, a lot of the focus has been on low velocity impacts/Quasi-static tests. The behaviour of these materials in the high velocity regime is not well understood.

	Objective	Score
Gain	Reduce the risk of collision	0
	Mitigate the effects of HVIs / Spacecraft Robustness	1 - 2(TBC)
	Mitigate the effects of HVIs / Generation and release of debris	1 (TBC)
Effort	**Medium Effort**	**2**

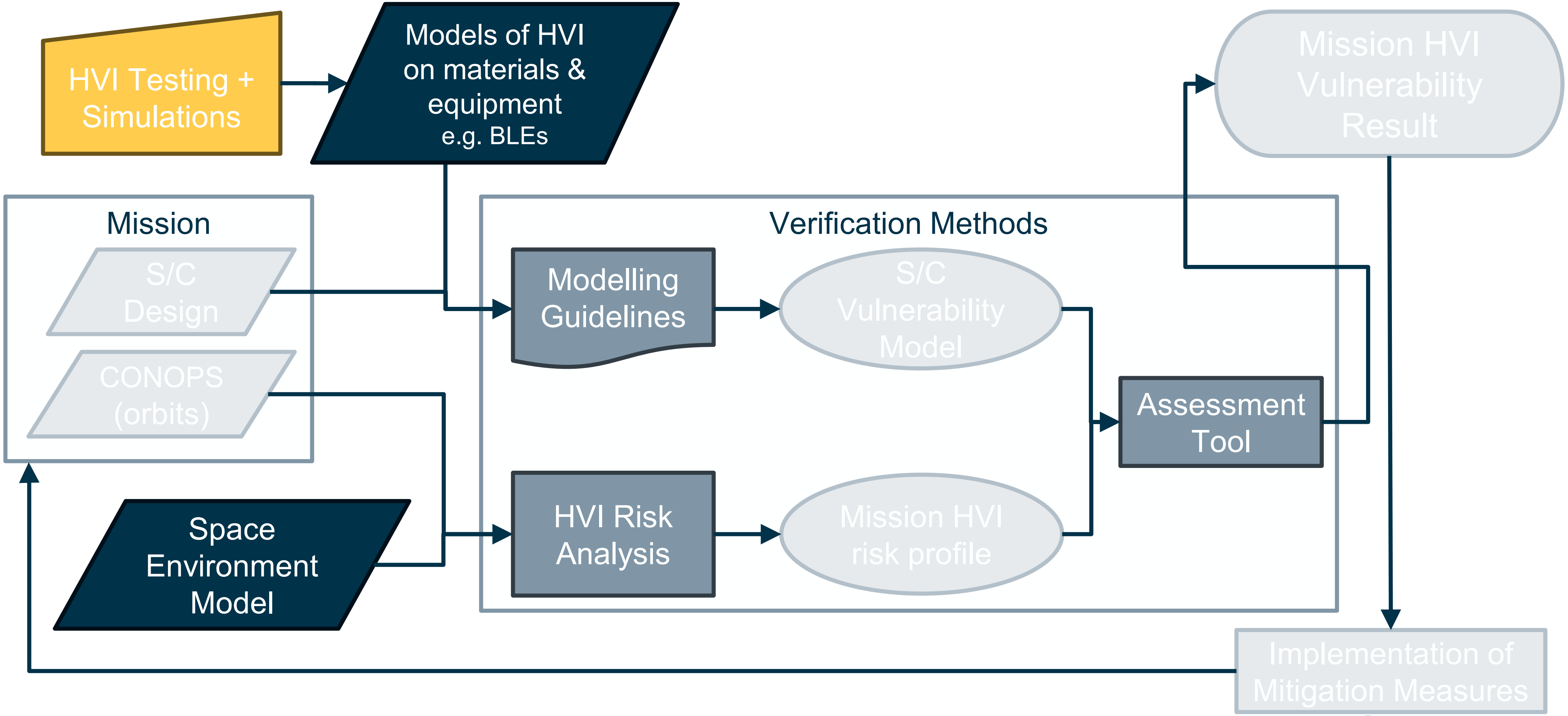
Testing, Verification and Simulation Requirements



The HVI Vulnerability Assessment Flow Chart



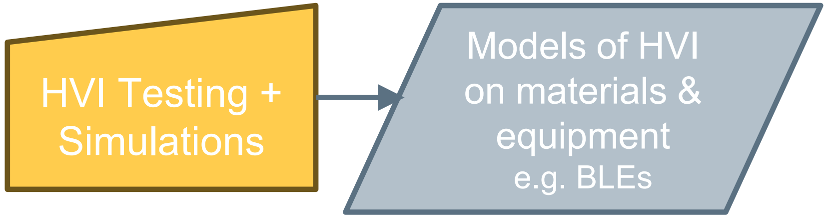
The HVI Vulnerability Assessment Flow Chart



HVI Testing + Simulations

Testing

- HVI testing currently performed using light gas guns/laser driven flyers
    - A list of European facilities is present in the report; 8 are available with various capabilities
    - 1.3-10km/s maximum firing speed (depending on particle size)
        - Can go higher, but risk damaging the facilities, limiting repeatability



Simulations

- Simulations can be performed using numerical methods, FEM, and smoothed particle hydrodynamics codes
- Each has its own limitations, but are all very computationally intensive
- Some materials and boundaries are more challenging to model (e.g. foams, anisotropic materials)
- **Generally, difficult to model effects on the entire spacecraft**

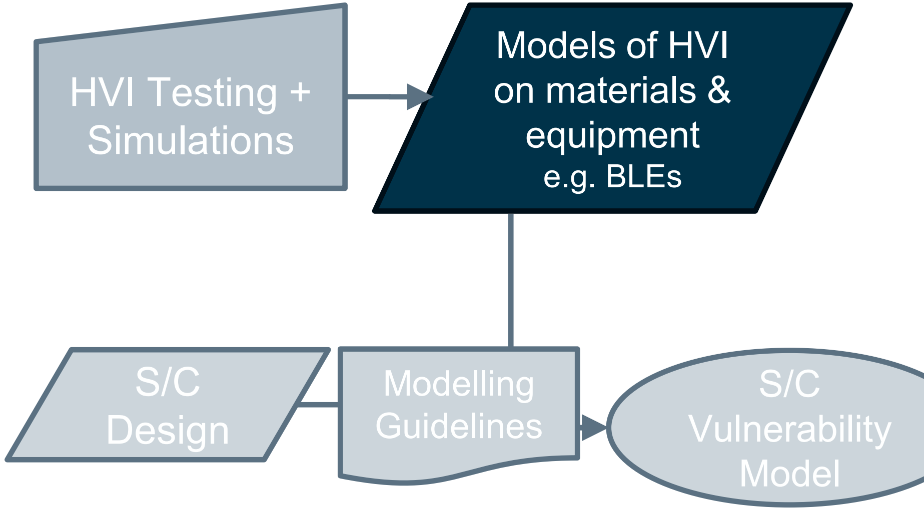
Not always trivial to match simulations and testing

HVI Models

Models are driven by **testing and simulations**, **and need to be considered together**

Main Gaps

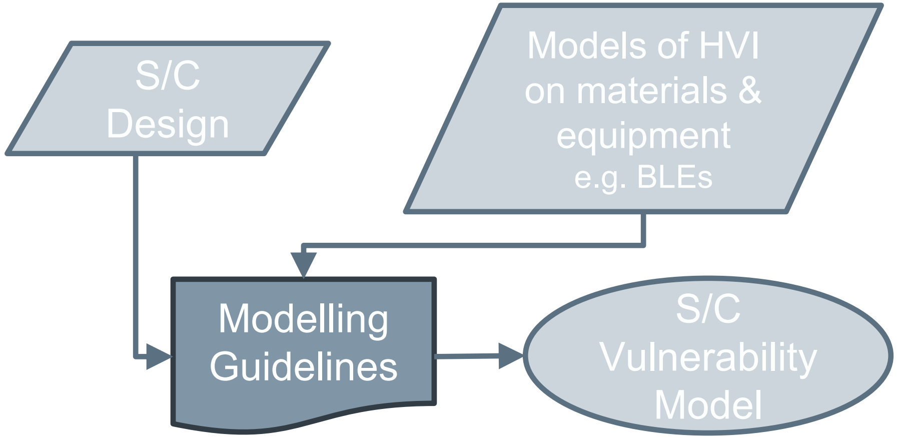
- **Limited covering of shielding designs and materials**
  - Hinders analysis in case of deviation from typical designs
- **Limited testing on shape and material effects of impactors, and therefore lack of models**
- **Ejecta clouds and fragmentation modelling is limited**
  - Distinction between partial and complete break-up is challenging to find in practice
  - Often extrapolating from few cases
- **Failure criteria of different types of equipment are not always well-defined**
  - Difficult to find what exactly leads to a failure depending on the equipment
- **Uncertainties are often not quantified as part of the models**



Modelling guidelines

Some guidance documents and information exist from various sources on how to model a spacecraft and perform a HVI vulnerability analysis

- ISO 16126, MIDAS verification guidelines, IADC protection manual, ESSB-HB-U-002 etc.



Main Gaps

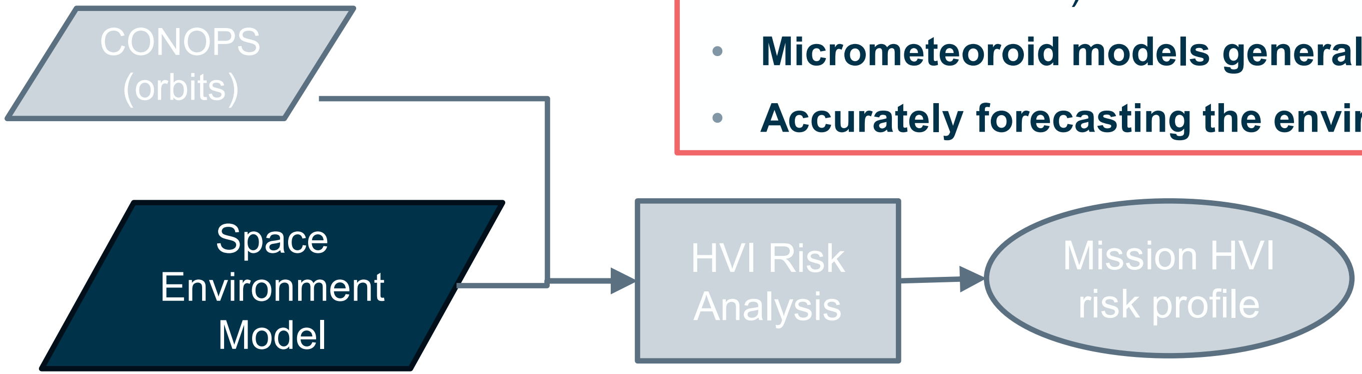
- **However, none of these guidelines are used universally, and as a result a risk assessment's result can vary significantly based on the entities and experts performing the analysis**
- Disagreement on several key definitions and thresholds (such as "catastrophic break-up") further lead to inconsistencies in analysis
- **Tackling this is outside the scope of this CDF, but could be seen as a key point to address in future**

Space Environment Models

MASTER is the space debris model that ESA develops and maintains, and uses for SDM requirement verification

Main Gaps

- **Source data availability for certain size ranges leads to high uncertainty**
    - 1mm-1cm debris objects: very limited observations
    - 1cm to trackable objects: some European detection capability >~3cm, but no cataloguing capability
- **Debris has other important properties** (shape, materials), **which aren't always modelled** (currently being addressed, planned for MASTER in 2026)
- **Micrometeoroid models generally have high uncertainty**
- **Accurately forecasting the environment remains very challenging**



HVI Risk Analysis, Vulnerability Assessment

In general, many tools exist to perform a HVI Vulnerability analysis

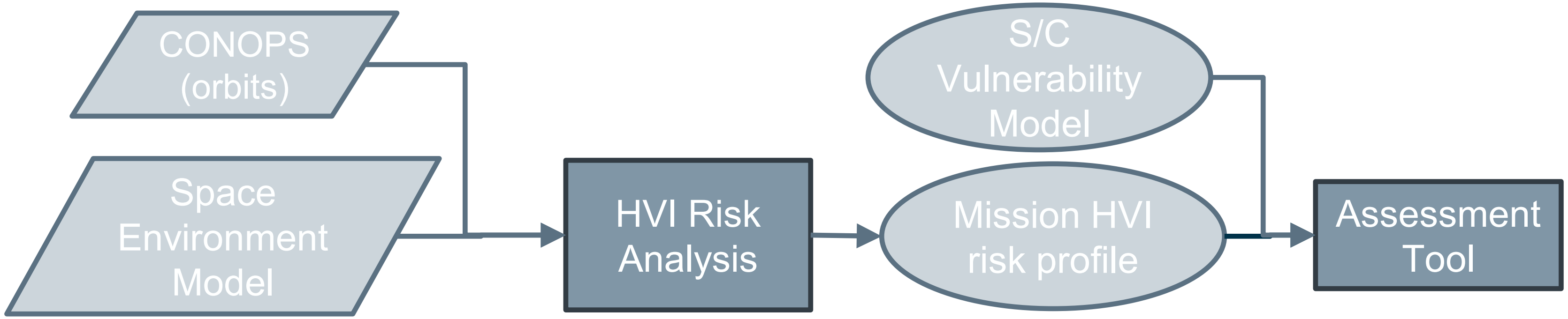
ESA has tools available

- DRAMA MIDAS: simpler, suited to early phases
- ESABASE: 3D model of the spacecraft

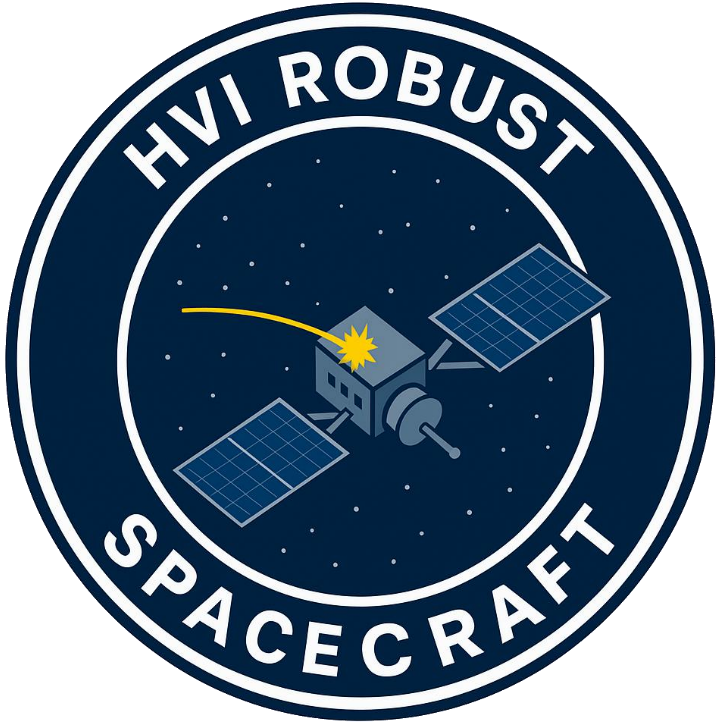
- Other non-ESA European tools exist
  - E.g. Systema/Debris (ADS), PIRAT (EMR Fraunhofer)

Main Gaps

- Interoperability is often limited
- Even 3D tools do not always consider propagation of impacts inside the spacecraft
- Which tool to use in which mission phase is not always well defined
- Modelling gaps carry over (uncertainty quantification)



Conclusions and Next steps



Main takeaway & Recommendations

- Main Takeaways
  - Several proposed solutions require **additional HVI testing and simulation** to validate their effectiveness and feasibility.
    - *E.g. material characterization to HVI is essential for accurate assessment.*
  - Applicability of solutions **varies by mission type**. Their impact on the platform can differ significantly depending on the specific case and the design phase in which they are introduced.
  - The lack of **standardised practices and modelling guidelines** for **HVI vulnerability assessment** makes the results difficult to compare. This is a key point to address in future.
- Design Recommendations
  - **Consider HVI mitigation early in the design process**. Late integration often leads to major impacts on platform design and performance.
  - Some measures should become **standard practice**, such as:
    - Identification and characterization of HVI-sensitive elements
    - Optimized placement of critical components
    - Selection of less-populated orbital regimes, when possible
- Implementation
  - Prioritize **low-effort, high-impact** solutions for **short-term missions**.
  - Medium-effort solutions with **high potential gains** are strong candidates for **future development**, and **medium-term implementation**.

Sustainable Space - Context: ESA sustainable strategy

ESA/ADMIN/IPOL(2023)1 (link)

ESA Zero Debris Policy

ESA Green Agenda

ESA is dedicated to:

- *"spearheading a Zero Debris future by 2030 and to enable the establishment of a circular economy in space from 2040"*
- *lead in sustainable space operations, providing a competitive edge to the European space industry and ensuring the long-term sustainability of space activities"*

Zero Debris

"implement a Zero Debris approach for its missions; and to encourage partners and other actors to pursue similar paths", by developing and integrating innovative solutions to **significantly limit the generation of debris in Earth and Lunar orbits** for all future missions, programmes and activities **by 2030**.

[source: Ministerial Conference of 2022]

Zero Debris CM25 goals

Technologies to support Spacecraft platform evolution

- Design for Demise (D4D) of critical equipment
- Resilience to hyper velocity impact
- Technologies for inherently safe passivation
- Reliable disposal systems for small satellites
- Support to removal in case of failure

Development and validation of verification models

- Operational evaluation of probability of successful disposal
- Enhance debris generation models
- Enhance demise characterization of materials and equipment

SST & STC technologies

- Technologies to enhance tracking of cm scale debris
- Implementing effective collision avoidance strategies with enhanced autonomy
- Improve characterisation of object state in orbit

ESA Zero Debris Roadmap

Extract relevant to HVI mitigation

On-going
ZD roadmap

esa

Webinar

2025 | CM25 | 2026 | 2027 | 2028 | CM28

HVI Robust S/C CDF

T711-902SM
2 **Innovative resilient satellite space system design solutions for Zero Debris. TDE, 1000k** 4

GT1C-815MS
4 **Innovative materials and structural concepts for a resilient satellite to debris collisions. GSTP (Compendium), 2500k** 5

GT1C-806MS
3 **Advanced simulation for resilient collision modelling to enhance health monitoring and prognostics GSTP (Compendium), 2000k** 6

Zero Debris Large PF – Phase 1

Zero Debris Large PF – Phase 2

Other GSTP opportunities as Direct Negotiation (DN) with Letter of support from your Delegation

- **GSTP Element 1: DEVELOP** → *100% ESA funded, co-funding possible*
  - **Frameworks: proposed spontaneously by industry: De-risking activities** (<250 k€, OSIP link), **Building Blocks** (<1 M€, OSIP link)
  - **Workplan: continuation of previous activities** *(e.g. 35% of the de-risk are continued, no budget limit)*
- **GSTP Element 2: MAKE** → *products for market competitiveness, industry driven, always co-funded (OSIP link)*

concurrent design facility

Innovative materials and structural concepts for a resilient satellite to debris collisions (TDE T711-902SM)

Objective: Develop and test satellite technologies to ensure the satellite robustness to debris impact and minimize debris generations.

Start year: 2026
Duration: 18 months

Budget: 1000 k€
Current / Target TRL: 2-4

Tasks:

- Define requirements for HVI (velocity, size, mass, impact frequency) and system constraints for spacecraft based on literature, available data, and simulations.
- Perform vulnerability assessment using statistical ray-tracing analysis, considering location and satellite attitude.
- Develop a computationally efficient methodology to decouple vulnerability from environmental factors and establish a standardized format for sharing non-proprietary vulnerability data between participants.
- Identify and trade-off technologies, including evaluation of mass, volume and power consumption of candidates to ensure feasibility for implementation.
- Develop and test material coupons and element level samples to de-risk the feasibility of each HVI technology (e.g. use of HVI testing facilities).
- Update trade off based on the studies and tests done and provide recommendations for designing HVI robust spacecraft.

Innovative resilient satellite space system design technologies for Zero Debris (GSTP GT1C-807MS)

Objective: Develop and qualify material(s) and structural concept(s) ensuring the satellite robustness to debris impact and minimize debris generations.

Duration: 24 months

Budget: 2500 k€
Current / Target TRL: 4-5

Tasks Phase 1:

- Review the HVI technologies identified in the previous activity at conceptual stage and then trade off the most promising candidates considering the state-of-the-art material technologies available in the market.
- Perform screening using simulation and hypervelocity testing of samples at appropriate facilities to validate performance of identified material technologies, particularly the requirements to survive the HVI requirements while being as lightweight as possible.
- Perform another trade study of the candidate materials technologies accounting for the actual demonstrated performance against the different requirements in particular HVI resistance and potential applications that enable the HVI shield concepts identified from previous tasks.

Tasks Phase 2:

- Develop different detail designs of HVI shields using the most promising material technologies down selected from the previous phase, accounting for combinations of passive structures and/or deployable mechanisms as needed to provide an optimised design that meets system requirements (e.g. Whipple shield bumper for front/rear wall, deployable structures for Whipple shield, integrated sensors).
- Design review to identify the most promising HVI shield design(s) that satisfy system requirements, particularly mass, volume and power constraints. At least one design shall be selected to build the demonstrator breadboard.
- Manufacture at least two versions of the demonstrator breadboard for each selected shield design and test them under hypervelocity impact conditions to assess their performance.

Advanced simulation for resilient collision modelling to enhance health monitoring and prognostics (GSTP GT1C-806MS)

Objective: Develop advanced collision and structural models integrated into operational simulators to enhance impact detection, damage assessment, and satellite health monitoring.

Duration: 24 months

Budget: 2000 k€
Current / Target TRL: 3-6

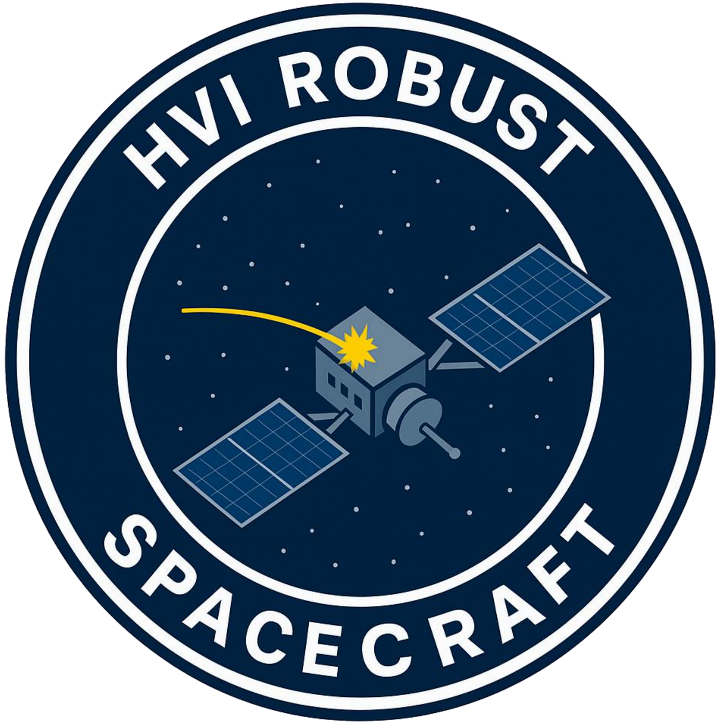
Tasks Phase 1:

- Definition of a representative structure, high-velocity impacts (HVI) and micro-meteoroids and orbital debris (MMOD) simulations, definition of structural health monitoring (SHM) system and assessment of requirements for the usage in testing and operations.
- Development of a simulation model of a digital twin representative structure able to analyze HVI and MMOD damages.
- Ground HVI testing of physical hardware (coupon/assembly level) to validate the HVI detection capability of the SHM, to assess real impacts/damage and potential failure, correlation with simulation. This task shall leverage the developed simulation model to optimize the needed physical testing.

Tasks Phase 2:

- Integration of the developed model into a simulation platform (e.g., operational simulators) and ensure the compatibility with existing tools, PHM algorithms and monitoring dashboards.
- Validation of the structural module in the operational simulator, together with other operational environment (telemetry/housekeeping data) to demonstrate the capability of decision making after HVI.
- Deploy the framework and prototypes to end-users.
- Assess the performance and impact of the solutions.

Q&A



ESA Space Debris Mitigation framework

All resources: https://technology.esa.int/page/space-debris-mitigation

Policy

Requirements

SDM training

Handbook

Tools

Tools Forum

Zero Debris community

Zero Debris Charter

Zero Debris Booklet

For general questions:

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