Multi-Disciplinary Assessment of Design for DEMISE Techniques

SCARAB analyses performed for Sentinel-1 and Sentinel-2

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Introduction
HTG - Hyperschall Technologie Göttingen GmbH

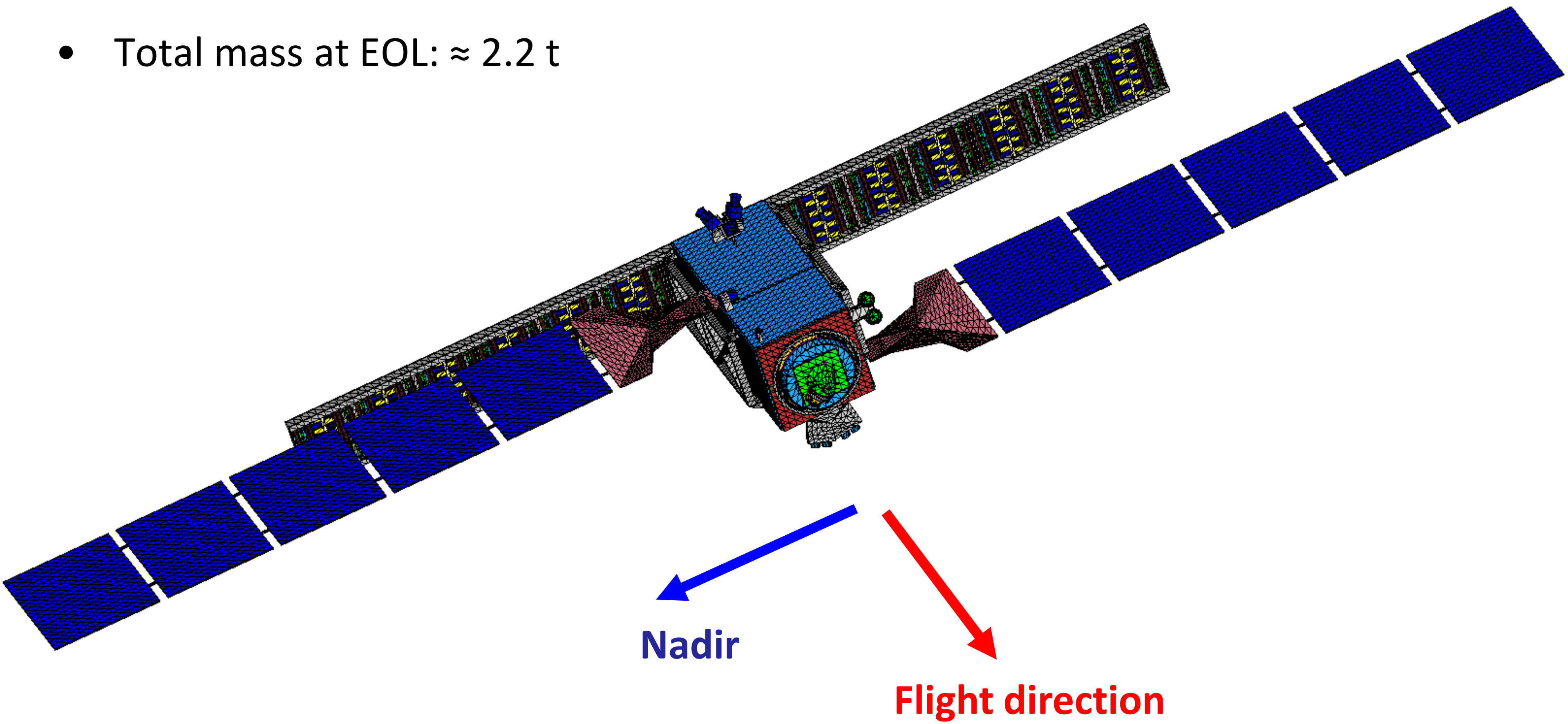
- Founded in 1989 by Prof. Dr.-Ing. Georg Koppenwallner, a worldwide known expert for hypersonic and rarefied aerodynamics and aerothermodynamics
- Today, HTG is a research and development company located in Katlenburg-Lindau, Germany (close to Göttingen)
- One of HTG’s key aspects of activity, with more than 20 years of experience, is the development of software for the simulation of spacecraft re-entries into the Earth’s atmosphere (e.g. SCARAB and DRAMA/SESAM)
- HTG is especially focused on the break-up and demise of such re-entry objects under special consideration of determination/minimization of the ground risk due to surviving fragments
- In this context, HTG is considered as one of the world-leading research entities
- The European space agencies ESA, DLR, CNES, and ASI belong to the group of HTG’s major customers
- In the frame of international research cooperation HTG has established a network also with non-European partners, e.g. NASA, Aerospace Corporation, FAA, etc.

Introduction
SCARAB

- SCARAB (Spacecraft Atmospheric Re-entry and Aerothermal Break-up) software system developed and operated by HTG since 1995
- Integrated software package (flight dynamics, aerodynamics, aerothermodynamics, thermal and structural analysis) used to perform re-entry risk assessments
- Compared and validated with in-flight measurements and re-entry observations
- Re-entry trajectory and attitude motion are determined by numerical integration of the full 6 degrees-of-freedom equations of motion
- Aerothermal analysis predicts convective heat transfer to the outer surface of the spacecraft
- Destruction/fragmentation by
  - ➢ Melting or
  - ➢ Breaking forces

SCARAB model Sentinel-1

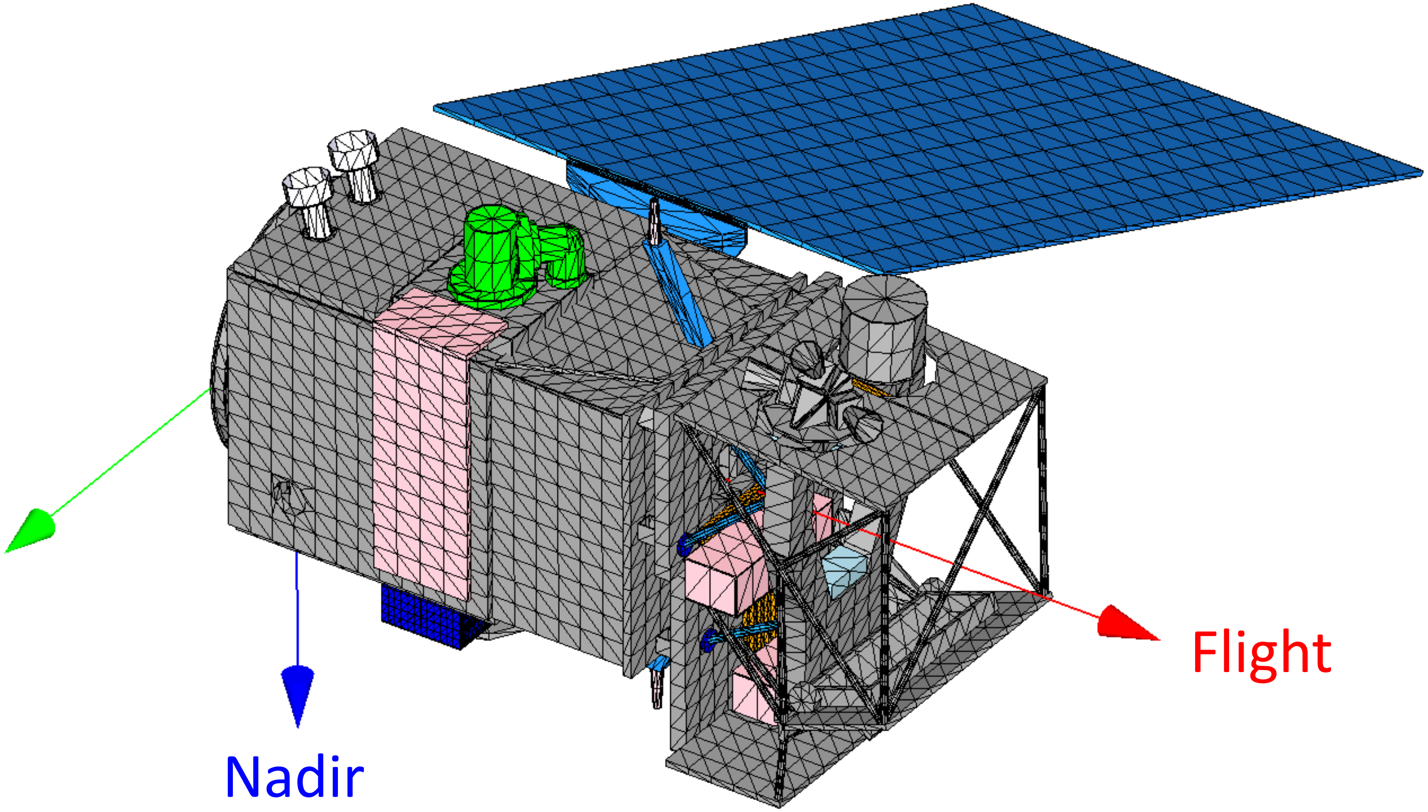
- Gravitation gradient stabilized attitude
- Total mass at EOL: ≈ 2.2 t



Sentinel-1 – Animation
Main break-up (78 – 65 km)

SCARAB Model Sentinel-2

- Total mass at EOL: ≈ 1.1 t



Model created under ESA Purchase Order No. 5401000720

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Baseline Scenario – Animation
Main break-up (80 – 70 km)

D4D technique evaluation
Top ground risk contributors

Sentinel-1

- CSAR panel
- Internal balance mass (50kg)
- Laser Communication Terminal (LCT)
- Reaction wheels (RWs)
- Magnetic torquers
- Tank & attached bus remnants

Sentinel-2

- LCT
- MSI baseplate
- Reaction wheels
- Tank

D4D technique evaluation
D4D techniques tested with SCARAB

D4D technique	Potential influence on	Tested for
Balance mass (internal, 50 kg) layering	Balance mass	Sentinel-1
Bus structure: baseplate early separation	Magnetic torquers, reaction wheels, tank	Sentinel-2
Bus structure: lateral panel dismantlement	Internal components	Sentinel-1
Bus structure: side panel opening	Internal components	Sentinel-2
Magnetic torquer relocation	Magnetic torquers	Sentinel-1
Payload: early separation	Payload*	Sentinel-1/2
Reaction wheels: external mounting	Reaction wheels	Sentinel-2
Reaction wheels: redesign (Al flywheel)	Reaction wheels	Sentinel-1
Tank: redesign to Al-Li	Tank	Sentinel-1/2
Tank: redesign to CFRP overwrapped Al	Tank	Sentinel-1

*no early separation of LCT tested, due to low LCT model granularity

D4D technique evaluation
Balance masses and magnetic torquers – Sentinel-1

Internal (50 kg) balance mass layering

- No surviving fragments in all simulations
- Layering and use of a demisable material to foster early dismantlement is a good general concept for balance mass design

Magnetic torquer relocation to outer panels

- Complete demise through early separation (above 70 km) achieved for 96% of the magnetic torquers
- No surviving fragments, for scenarios with lateral panel dismantlement

D4D technique evaluation
External payload: early separation – Sentinel-1

- CSAR panel (central segment) is the main driver of Sentinel-1‘s on-ground risk
- Brackets are partially shielded (always) until the panel separates from the bus
- Heat accumulation directly from the stream is relatively low compared to fully exposed components like outer CSAR panel segements

Simulation results

- High CA uncertainty through differing fragmentation behaviour and high uncertainty on separation altitude
- Reduction of component casualty area by up to 53% (to baseline scenario without early separation) for separation altitude around 81 km
- Separation of central CSAR panel above 86 km is needed for complete demise

D4D technique evaluation
External payload: early separation – Sentinel-2

- MSI baseplate is one of the top contributors to Sentinel-2‘s on-ground risk
- Baseplate is made of ceramics, which is a critical material in terms of demise
- Early separation has no direct effect on demise of any top-level risk contributor
  - ➢ No (major) effects on Tank, LCT, MSI Baseplate, RWs

D4D technique evaluation
Bus panel modifications – Sentinel-1

Lateral panel dismantlement

- Panel separation at altitudes from 99 to 75 km
- Early exposure has positive effects on demise of
  - Internal components and bus
  - components mounted to lateral panels

CA reduction due to lateral panel dismantlement (LPD):

	Mean Casualty Area [m²] of simulation scenario				
	Al-Li tank			CFRP over-wrapped tank	
	No LPD	LPD		No LPD	LPD
Tank & bus remnants	2.851	0		1.826	1.632
Reaction wheels	2.031	1.643		1.960	1.771
Magnetic torquers	0.160	0		0.075	0

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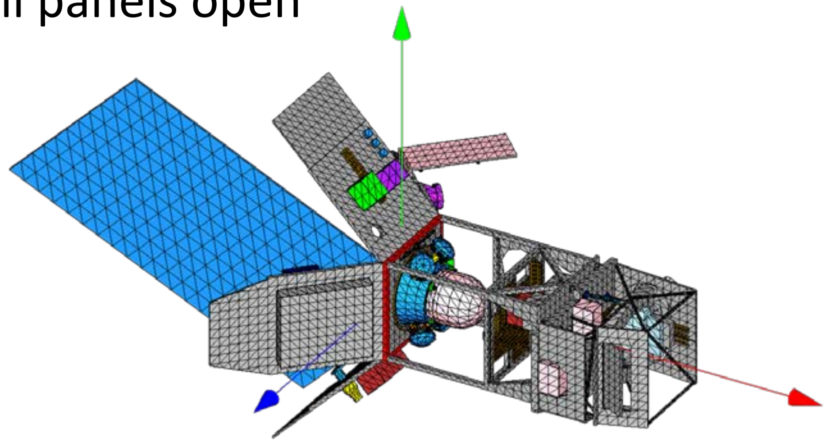
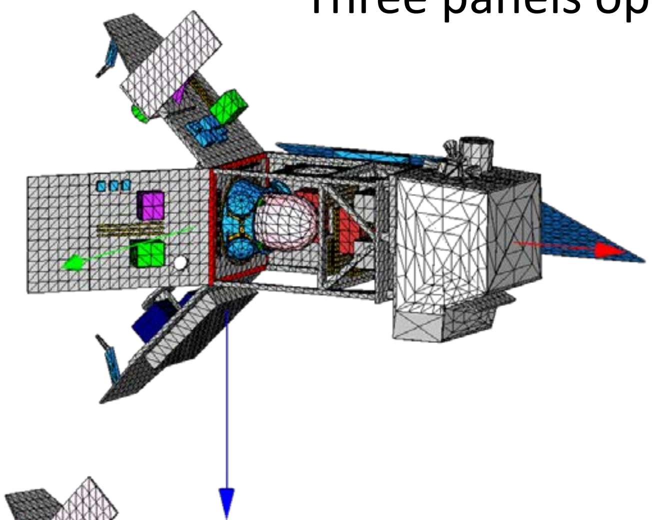
D4D technique evaluation
Bus panel modifications – Sentinel-2

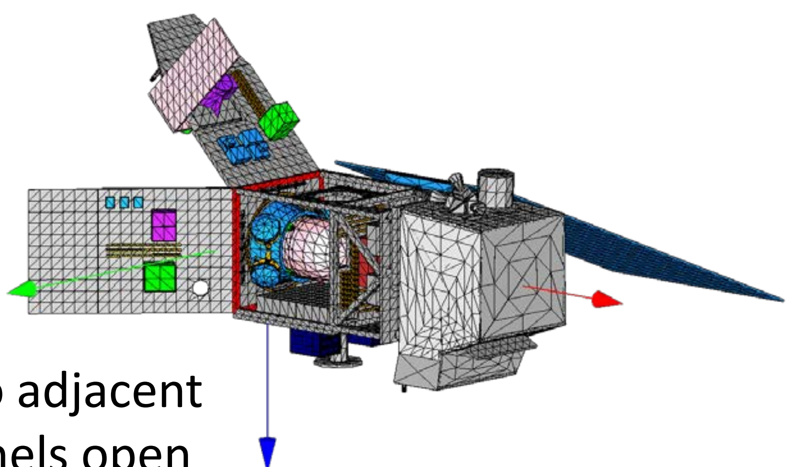
Side panel opening

All panels open

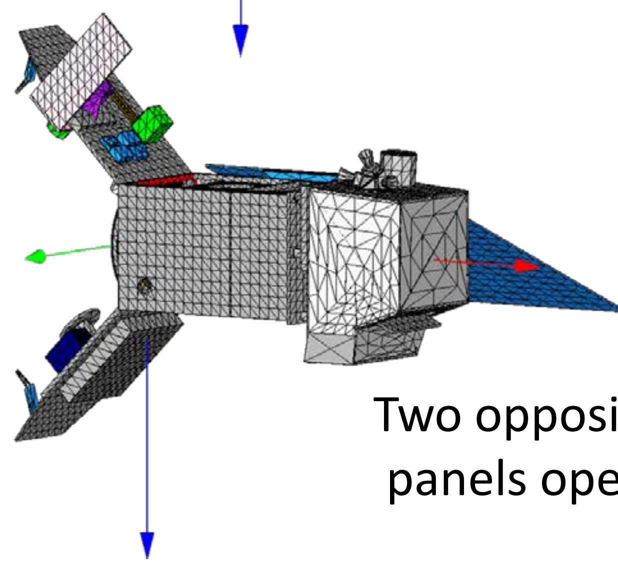


Three panels open





Two adjacent panels open



Two opposite panels open

D4D technique evaluation
Bus panel modifications – Sentinel-2

Baseplate separation

- Early separation better than later
- No (major) effect on LCT, MSI baseplate, Tank
- RW demisability increases with higher separation altitude

Side panel opening

- Four panels open is better than only three or two
- No difference between two adjacent or opposite panels open
- No (major) effect on MSI Baseplate and Tank
- LCT and RW demisability slightly increased

D4D technique evaluation
Demisable reaction wheels / external mounting

RW redesign (Sentinel-1)

- Separation altitude varies within cases due to uncertainty (63 km – 78 km)
- RW core survives in all but one simulations
- In one single simulation: 2 of 4 RWs demised (separation at 78 km)
  - Lower separation altitude in all other simulations
  - „demisable RWs“ can demise, if separation altitude high enough

External mounting (Sentinel-2)

- No complete demise of RWs
- Partial demise can be achieved through early exposure by
  - (Early) separation of bus baseplate (above ≈ 90 km, in orbit at best)
  - External mounting (but separation above ≈ 70 km needed, e.g. through „weak“ brackets)
  - Side panel opening (but all 4 panels need to be open)

D4D technique evaluation
Demisable tank: Al-Li / CFRP over-wrapped Al

Al-Li tank

- **Sentinel-1**
  - Al-Li tank breaks into pieces with or without bus parts attached
  - Likeliness of demise of smaller fragments depends on ballistic coefficient, separation altitude of initial fragment and altitude of further fragmentations
  - Complete demise with additional lateral panel dismantlement
- **Sentinel-2**
  - Complete demise of the tank

CFRP over-wrapped Al tank (Sentinel-1)

- No break-up or significant demise
- Low mass loss for simulations without lateral panel dismantlement due to shielding and late exposure
- But CFRP modeling is difficult in general due to differing compositions

Summary and conclusions

Positive effect on CA	No effect on CA	Negative effect on CA

D4D technique	Effect on	Tested for
Balance mass (internal, 50 kg) layering	Balance mass (CD)	Sentinel-1
Bus structure: baseplate early separation	Magnetic torquers (CD), reaction wheels (PD), tank	Sentinel-2
Bus structure: lateral panel dismantlement	Internal components (CD/PD)	Sentinel-1
Bus structure: side panel opening	Internal components (CD/PD)	Sentinel-2
Magnetic torquer relocation	Magnetic torquers (CD)	Sentinel-1
Payload: early separation	Payload (PD)	Sentinel-1 Sentinel-2
Reaction wheels: external mounting	Reaction wheels (PD)	Sentinel-2
Reaction wheels: redesign (Al flywheel)	Reaction wheels (PD)	Sentinel-1
Tank: redesign to Al-Li	Tank (CD*/PD)	Sentinel-1 Sentinel-2
Tank: redesign to CFRP overwrapped Al	Tank	Sentinel-1

CD: Complete demise

PD: Partial demise

*for Sentinel-1 only in combination with lateral panel dismantlement, else: increased casualty risk

Summary and conclusions

- Top-level risk contributors: Payload (CSAR panel, MSI Baseplate), heavy balance masses, LCT, magnetic torquers, RWs, Tank
- Nearly all D4D techniques provide risk reductions; only one (Al-Li tank on Sentinel-1) is increasing the risk, if applied without additional early exposure
- D4D for 2 ton class satellites is not a „pick one from the list“ approach
  - ➢ Combiation of multiple D4D techniques is needed to enable compliance with ESA‘s space debris mitigation guidelines
  - ➢ Best case scenario of SCARAB analysis for Sentinel-1, including all D4D tested with Sentinel-1: compliance

Summary and conclusions

- Final recommendation for successful D4D technique development:
  - ➢ Select a D4D target from top-level risk contributors (e.g. those causing ~75% of the total risk)
  - ➢ Check if target component is demisable at all (e.g. due to material)
  - ➢ Reduce survivability of the selected target by achieving earlier melting, either by material changes (lower melting temperature), by early exposure (increase heating) or both, at best