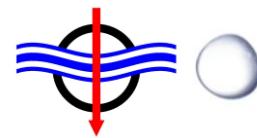


Study on Demisability of Optical Payloads

S. Bainbridge (FGE)
J. Beck (BRL)
P. Doel (UCL)
J. Merrifield (FGE)

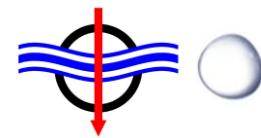
FGE Ref. VF087/17



Introduction

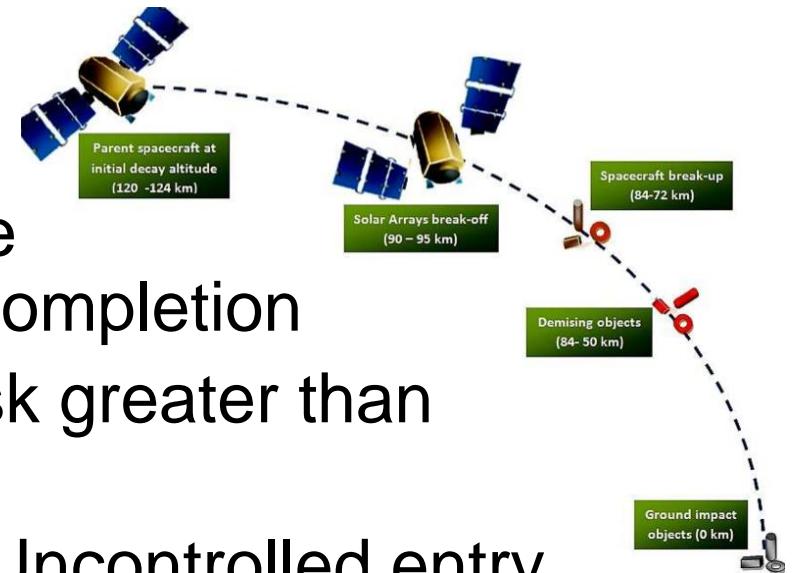
Agenda

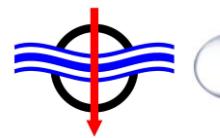
- Introduction to design for demise (D4D)
- Review of SDM requirements
- Optical payload review
- Payload re-entry modelling
- Derivation of D4D techniques
- Assessment of D4D techniques
- Design guidelines and future work



Design for Demise

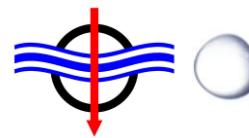
- Spacecraft are required to re-enter Earth's atmosphere within 25 years of mission completion
- Cannot cause a casualty risk greater than 1/10,000
- Two options: Controlled or Uncontrolled entry
 - Controlled
 - Extra fuel & complexity → extra mass → increased cost
 - Potential to fail
 - Uncontrolled
 - Ensure no components survive





Design for Demise

- How to prevent objects impacting the surface?
 - Tailoring specific spacecraft design
 - Materials used
 - Aerodynamic shapes of components
 - Design of joints
- Known as design for demise (D4D)
 - Identify critical items
 - Redesign to improve demise
- Destructive re-entry codes
 - Modelling of fragmentation and demise processes is somewhat basic
 - Material response of non-metals is not very well described
 - Cannot reliably capture effects of object placement and layout
 - Large uncertainties



Project Aims

- “Identify design solutions to improve the demisability of optical payloads carried by satellites flying in LEO, without impacting the payload performance”
- Create a novel way of modelling destructive re-entry, ensuring the uncertainties are captured
- Identify critical payload components
- Derive D4D techniques
- Assess the D4D techniques on reference optical payloads
- Create a set of guidelines and requirements for payload manufacturers and designers



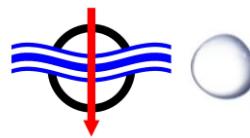
SDM Requirements

- ISO 24113 standards with ESCC amendments
 - 20 requirements
- All those deemed not relevant or outside the scope of the study (accounting for payload manufacturer recommendations) are eliminated
- Those that apply to:
 - Geosynchronous Earth Orbit (GEO)
 - Launch vehicle orbital stages
 - Solid rocket motors
 - Accidental spacecraft break up
 - Removal method from LEO



SDM Requirements

- Majority of the rest can be bypassed following an initial set of D4D guidelines:
 - Avoid the use of pyrotechnic devices
 - Payload will not remain in orbit for longer than 25 years after operational end-of-life
 - No additional power sources will be added to the payload
 - Intentional break-up in orbit shall be avoided
- Only one requirement left
 - 1/10,000 casualty risk requirement for uncontrolled entry
 - Key driving requirement for this study



Optical Payload Review and Classification

Peter Doel (UCL)



Optical Payload Classification (100nm-100μm)

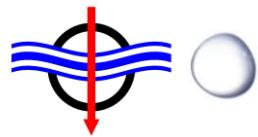
Imagers: These produce a spatial intensity image of the object under study. The image can be panchromatic and/or limited to a selected number of wide or narrow wavelength bands. If there are many filter bands they are often termed *as Multi or Hyper spectral imagers*.

Spectrometers: These give a near continuous spectra on an object field.

Radiometers: Used to measure absolute flux from a source usually at a range of wavelengths. This allows you determine key parameters such as surface temperatures. Absolute flux calibration is an important issue for these systems and they carry on-board black body cavity and solar diffuser calibration sources.

Lidar systems: In a lidar system a laser pulse is directed towards the atmosphere. A return signal is then detected from backscattered light from the air molecules at high altitudes and from aerosols at lower altitudes and velocities can be determined from the Doppler frequency shift.

Payload Breakdown



Fore Optics (telescope)

Reflective or refractive optics
Generally Largest optics (for light gathering)
Light-weighted

Cassegrain,
Three Mirror
Anastigmat
(Korsch)

Processing Optics

Imager: Relay optics, dichroic filters, broad and narrow band filters, beam-splitters, polarisers., $\frac{1}{2}$ and $\frac{1}{4}$ wave plates

Spectrometer: Grating, prisms, interferometers slit

Radiometer: Calibration sources -black body cavities, solar diffusers

Lidar: Laser head components, choppers

Mechanism: Filter wheels, steering/scanning mirrors

Focal Plane Assembly FPA

Detector: CCD, CMOS , and Photo-Voltaic silicon diodes and for NIR and IR applications Mercury Cadmium Telluride (HgCdTe), Indium Gallium Arsenide (InGaAs)

Filters, windows

Mechanisms: Readout electronics, Vacuum vessel, coolers/pumps radiators

Optical Breadboard

Support structure for optical components - A high specific stiffness and thermal stability

Selected Examples

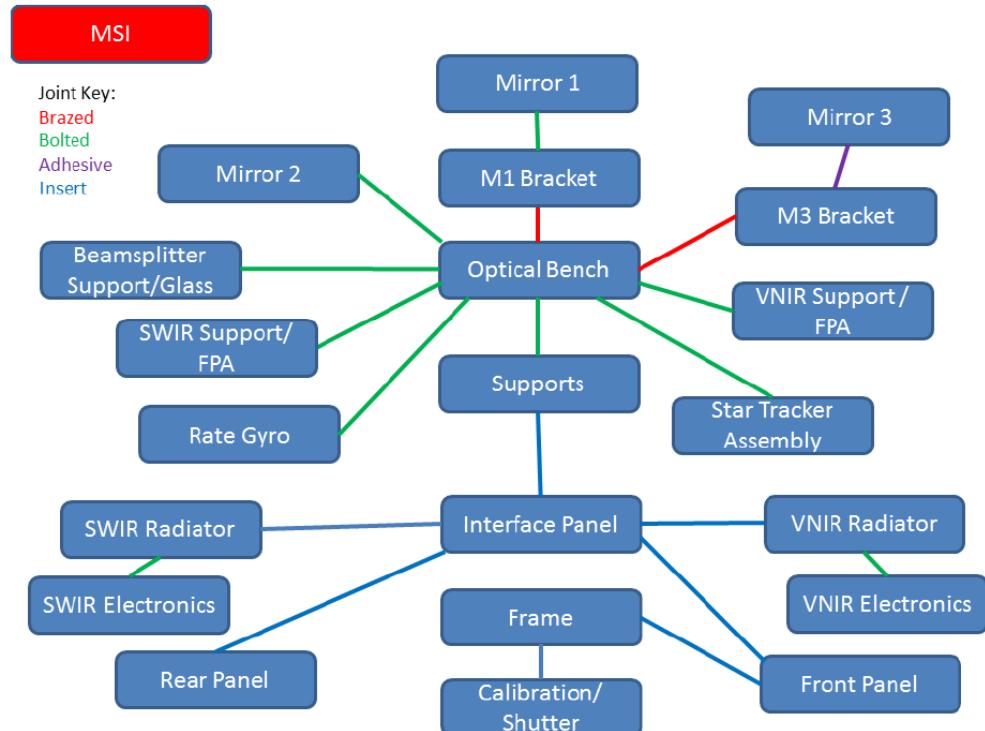
- **Multi-Spectral Imager (MSI) - Sentinel-2a satellite launched in 2015**
 - A 13 band visible/near infra-red (443nm-2190nm) imager launched on the Sentinel 2A
 - Three element Silicon Carbide mirror telescope
 - Instrument mass ~290kg (incl electronics)
- **Pleiades High Resolution Instrument - Pleiades constellation launched 2011 and 2012**
 - Imaging camera giving high spatial resolution images in both a panchromatic mode (470-830nm) and in a series of broad band filters from blue to near-infra red wavelengths (430-940nm)
 - The telescope consists of a three element Zerodur telescope with a fold mirror.
 - Instrument mass ~200kg
- **Sea and Land Surface Temperature Radiometer (SLSTR) - Sentinel-3 satellite in 2016**
 - Measures surface temperature using flux in four wavelength bands from 0.55 to 12 μ m
 - Two off-axis Zerodur mirrors, beryllium scanning mirrors, Stirling cooler.
 - Instrument mass ~140kg
- **3MI imager for the ESA/Eumetsat-MetOp-SG planned for launch in 2021**
 - The Multi-viewing, Multi-channel, Multi-polarisation Imager is primarily designed for the observation of atmospheric aerosols.
 - The instrument consists of two imaging refractive telescopes one for the visible and near infrared (VNIR) 400-920nm; and the other for short wave infrared (SWIR), 1350-2150nm.
 - Instrument mass ~70kg



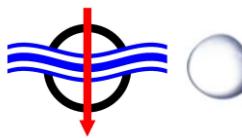
Payload Breakdown

Each payload broken down into key components and a structure chart produced to show their relationship and bonding to the other components in system.

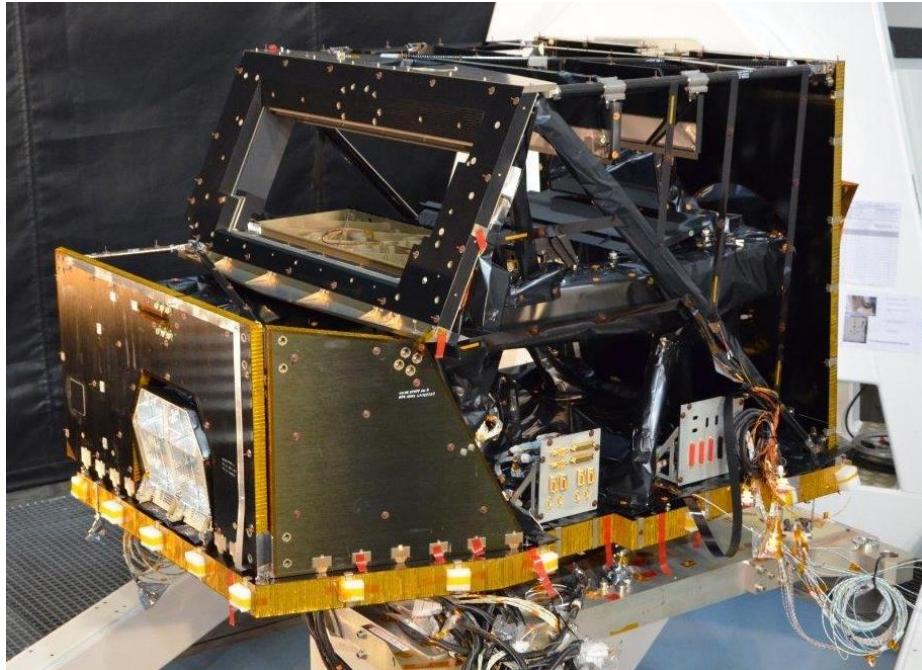
A detailed breakdown was also produced of the components in size, material and mass and this was used to build a representative model of the payload



Example of structure chart for the MSI payload



Sentinel-2 Multi-Spectral Imager (MSI)



(Image: Wiedermann et al. 2014)

Main telescope optics: three SiC mirror system.

Optical bench: SiC structure made of 3 pieces brazed together. Mounted to CFRP/aluminium interface panel.

Mechanism/Optics: Fused Silica beamsplitter mounted in SiC structure.

Focal Plane Assembly: VNIR FPA with CMOS detector and SiC support. SWIR FPA with HgCdTe IR detector and SiC support and radiator.

Other: Calibration and shutter system (PFTF/aluminium). Gyro and star tracker assemblies

Mass: ~290kg



Main structure (44 kg)¹



Main structure and interface panel³



Back of M3 mirror
556x 291mm (5.1kg)¹



SWIR detector support
(5.4kg)¹

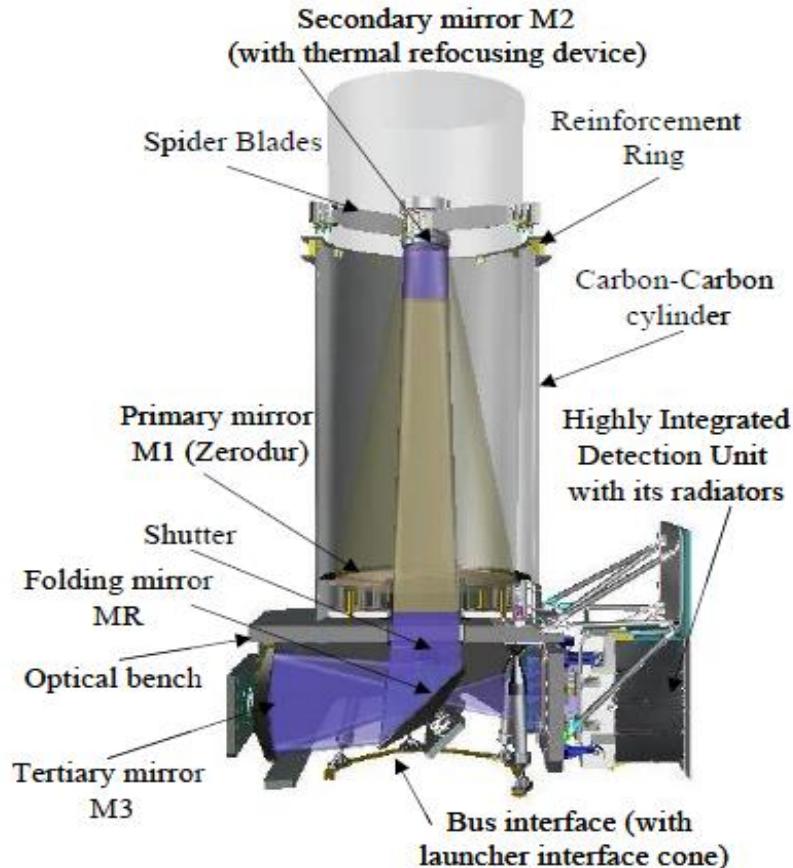


Calibration and shutter
assembly²



VNR detector support
(3.6kg)¹

Pleiades High Resolution Instrument



(Image: TAS CNES)

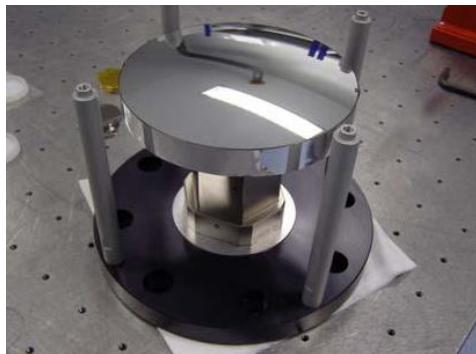
Main telescope optics: three Zerodur mirror system with a zerodur fold mirror.

Optical bench: Main bench a composite material (carbon-cyanate ester with aluminium honeycomb). Attached to Payload ring by 6 CFRP struts. Carbon-carbon tube for secondary mirror support.

Mechanisms/Optics: Shutter mechanism. Secondary mirror focusing mechanism (invar)

Focal Plane Assembly: SiC structure and beamsplitter. CCD based detectors with multilayer coating filters deposited on thin (1mm) BaK50 glass substrates.

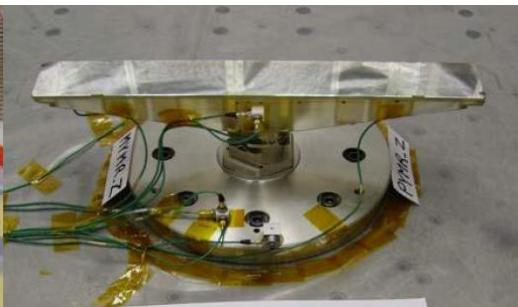
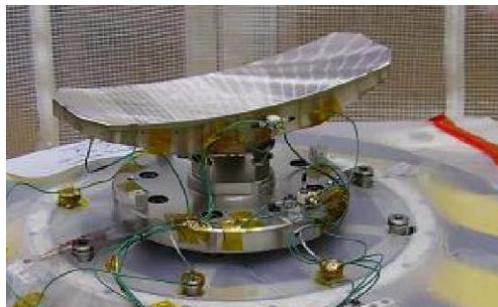
Mass: ~200kg



Primary and secondary mirrors¹



Shutter mechanism²



Tertiary and fold mirrors¹

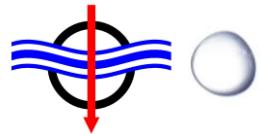


SiC focal plane assembly³

¹ Fappani and Ducollet, 2007

² Andion and Lopez, SENER, 2007

³ Eoportal, image:TAS



Temperature Radiometer (SLSTR)

Main telescope optics: Zerodur off-axis mirrors

Optical bench: CFRP/CFRP honeycomb structure

Mechanisms/Optics: Beryllium scanning mirror, fast flip mirror system

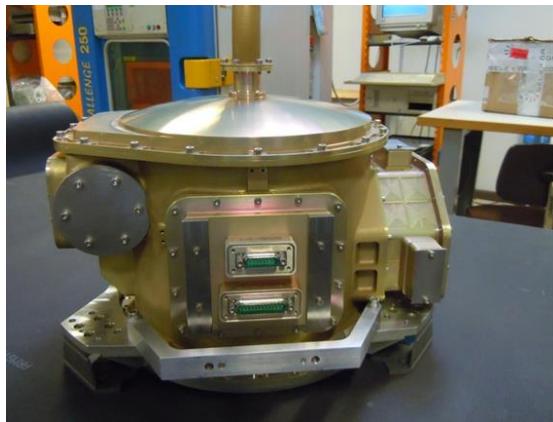
Focal plane assembly: Aluminium structure/vacuum vessel, many refractive optical elements (BK7G18, SFL6, Germanium, fused silica, ZnS), Titanium and invar optics mounts

Other: PTFE zenith reflective diffusers
Black body calibration sources, visible calibration source

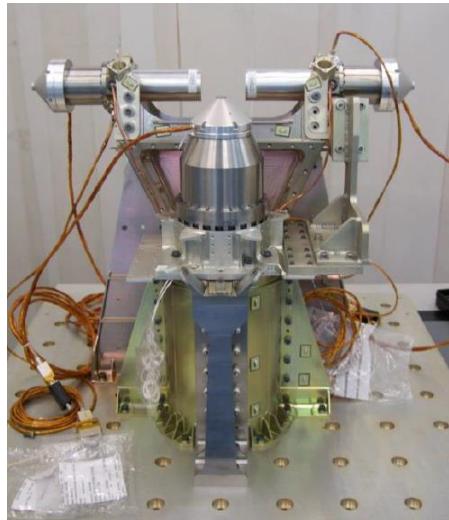
Mass: 140kg



(Image: Coppo et al. 2013)



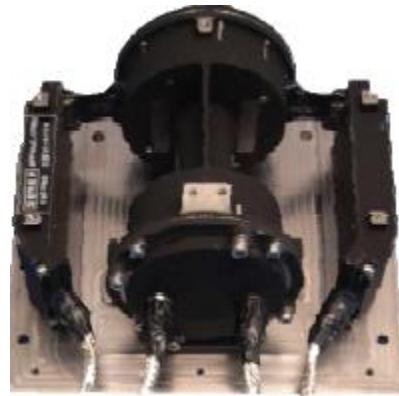
FPA – vacuum vessel¹



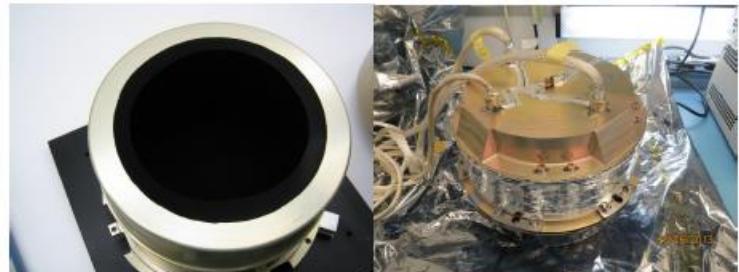
Stirling Cooler¹



Visible calibration unit¹



Flip mirror³



Black body calibration units⁴

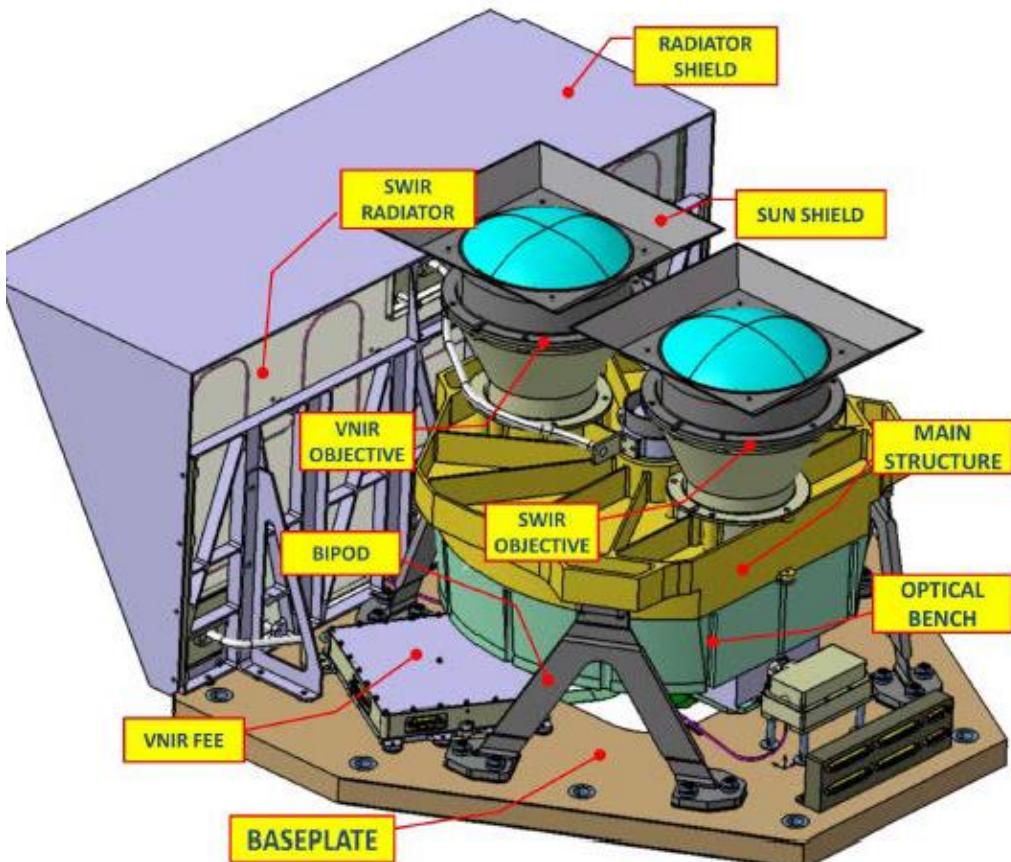
¹ Coppo et al., 2013

² Coppo et al., 2010

³ Arregui et al., 2015

⁴ Smith et al.,

3MI Instrument



(Image: Manolis et al. 2014)

Main telescope optics: Two refractive telescope containing 12 lenses (Fused silica, Calcium Fluoride).

Optical bench: Aluminium structure connected through titanium bipods to baseplate of multi-layer construction, CFRP skins, with CFRP and aluminium honeycomb cores.

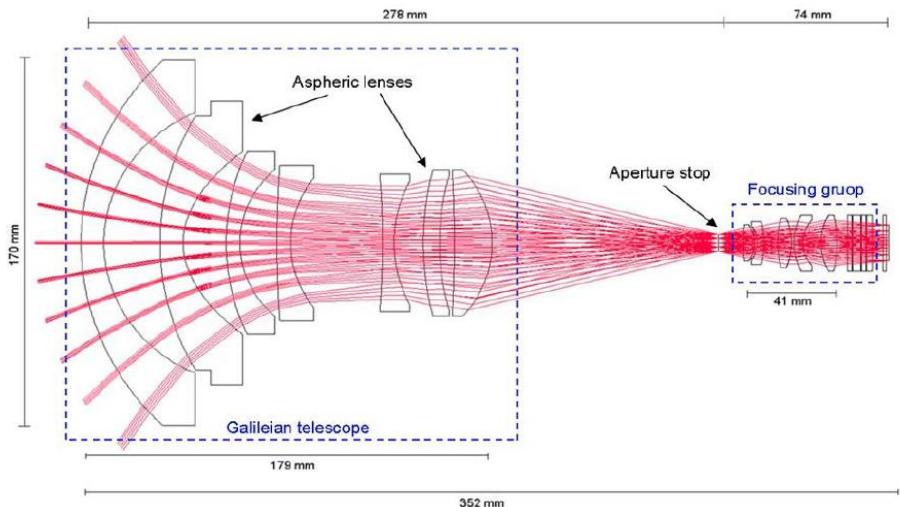
Mechanisms/Optics: 33 slot filter wheel, containing neutral density filters (Schott NG glass), polarisers and bandpass filters (fused silica and quartz).

Focal plane assembly: CCD, and MCT detectors housed in aluminium structures.

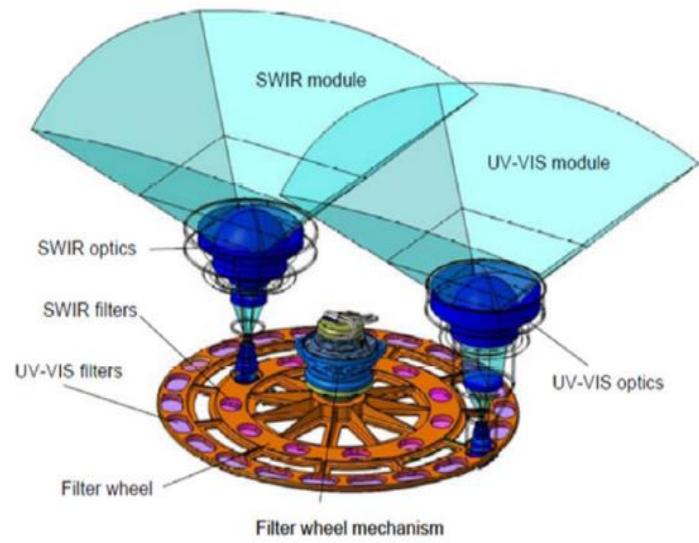
Misc:

Heat pipes and radiator assembly

Mass: 70kg



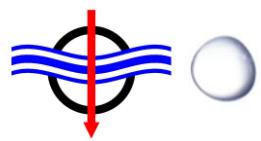
Telescope module design¹



Filter wheel²

¹ Manolis et al. 2014

² Eoportal



Payload Re-Entry Modelling

James Beck (BRL)



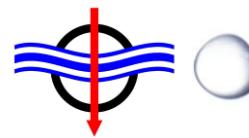
Tool Selection

- Activity Requires Increasing Complexity
 - Building Blocks (simple models)
 - Payload Level (joined components)
 - Spacecraft Level
- SAM has Capability to Model all Levels
 - Consistent modelling throughout
 - Often difficult to understand differences between models
 - Don't have this problem
 - Identify Reasons for Predicted Behaviour
 - In D4D activity, identified different reasons for criticality
 - Granularity (batteries), Heating model (MTQ)

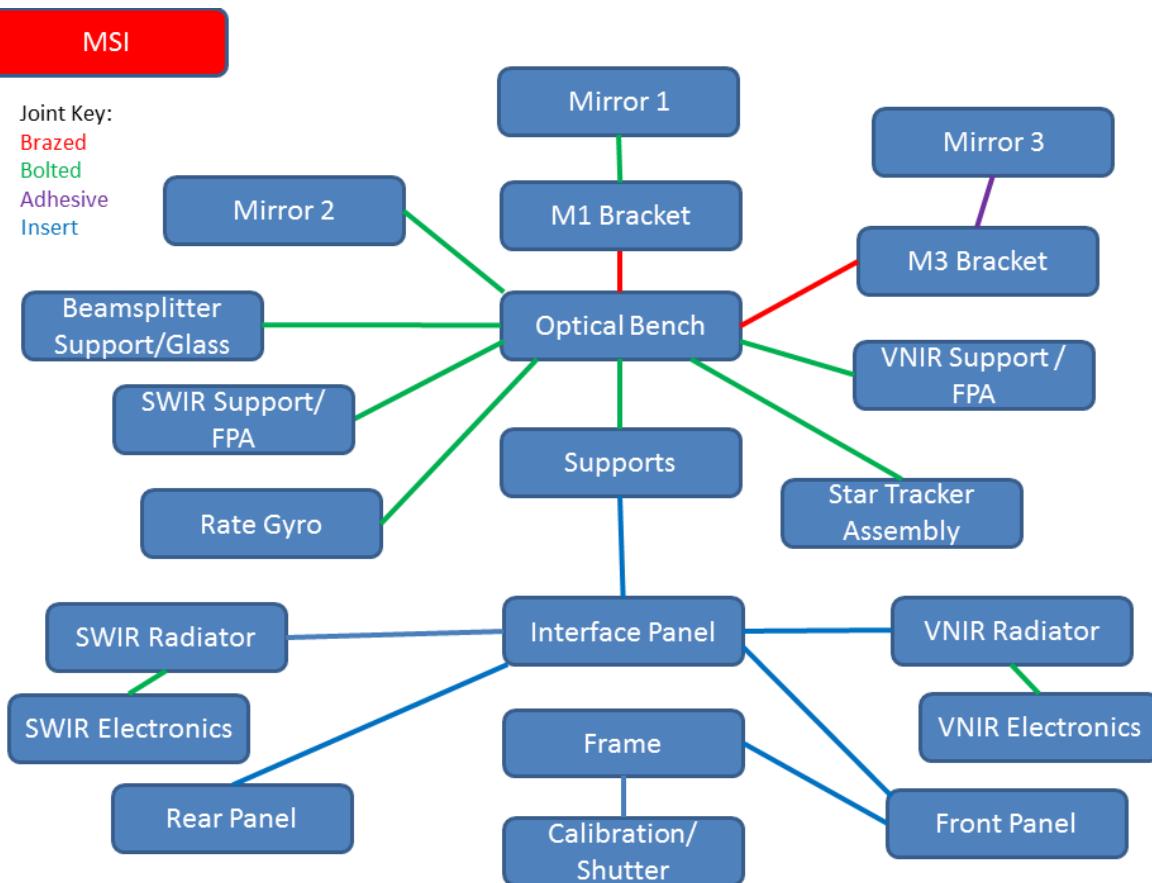
SAM Spacecraft

- Spacecraft is a Set of Components
 - Connected by Joints
 - Predictive Fragmentation
 - Force and Temperature Based
 - At Component Level switch to Object Approach
 - Substantially better heating models
 - Geometric approximation smaller error than heating models
 - Full nesting models and multi-point heating

Building a SAM Spacecraft

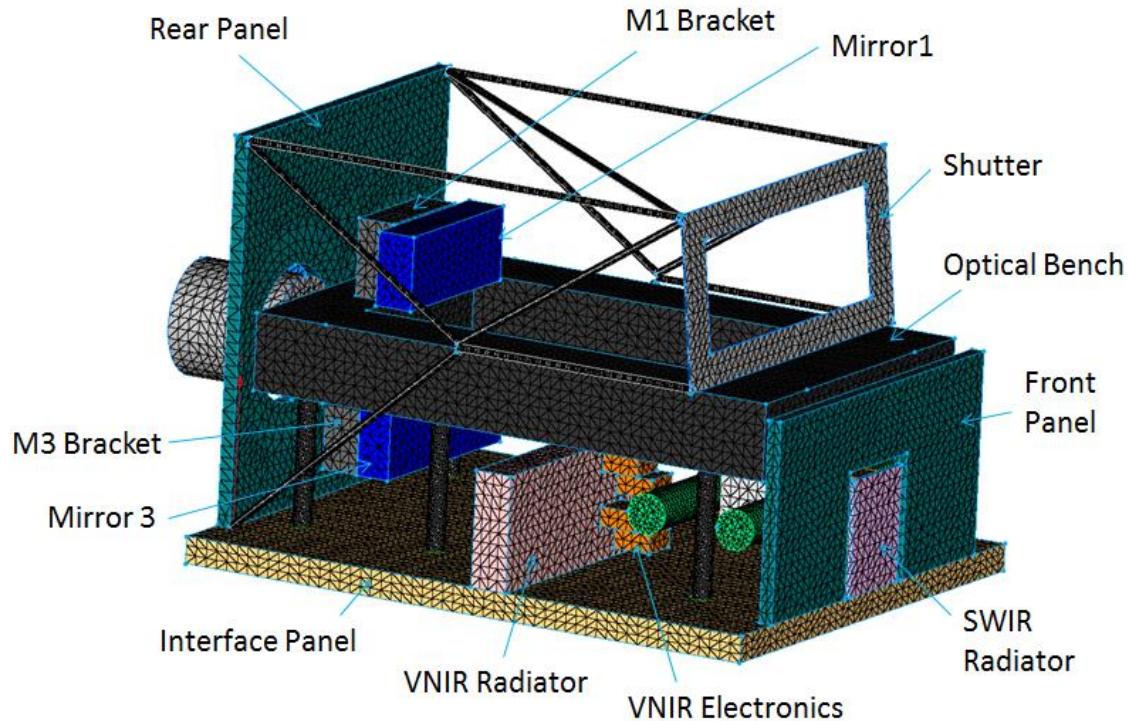


- Set of Primitive Components (Sentinel-2 MSI payload)

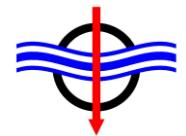


Building a SAM Spacecraft

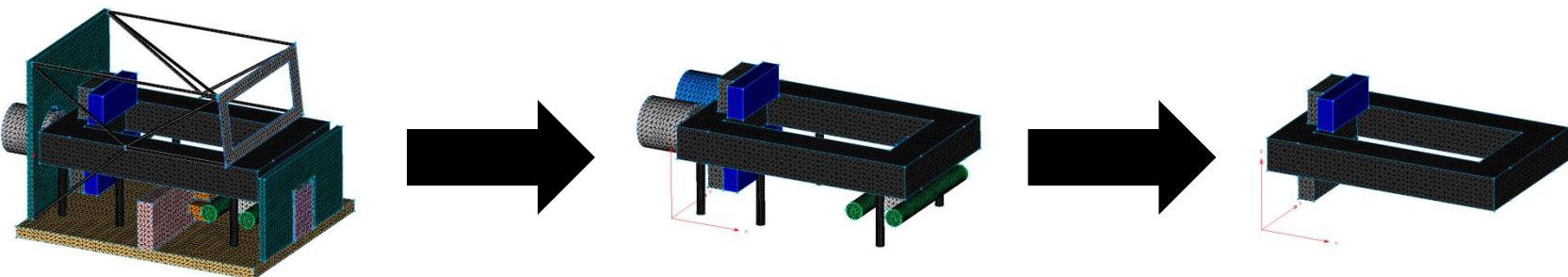
- Full Panel Representation
 - Balance fidelity with approximate geometry
 - Avoid high fidelity geometry / low fidelity physics issues

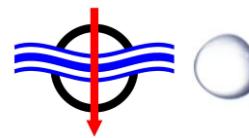


Building a SAM Spacecraft



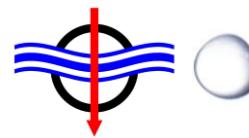
- Fragmentation Modelling
 - Based on Joint Failure
 - Remaining component links assessed and fragments found
 - Multiple component fragment → spacecraft oriented
 - Single component fragment → object oriented
 - Repeat geometries allow database storage
 - Monte Carlo capability





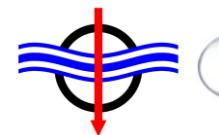
General Modelling

- Identification of Key Parts
 - Model all parts which could be expected to survive
 - Small parts not ignored
 - 15J limit modelled, not assumed
 - Equivalent material method avoided
 - Partial non-demise can be missed using average demise
 - Small fused silica element in aluminium will survive
 - Where elements are monolithic use single material
 - Tend to conservatism for objects which may fragment



Joint Modelling

- Four Key Joint Types
- Adhesive
 - Any adhesive link connection which will fail first
- Insert
 - Potted inserts into sandwich structures
- Bolts
 - Bolted connection with no identified weaker point
- High Temperature Braze (SiC)



Uncertainties

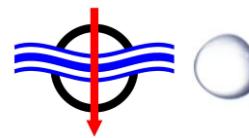
- Fragmentation process is chaotic
- Modelling is highly uncertain
 - Capture key uncertainties
 - First D4D activity to use statistics with sensible sample size – 1000 samples for each assessment

| Parameter | Distribution | Range |
|------------------------------|--------------|--|
| Aerothermodynamic Heating | Uniform | $\pm 20\%$ |
| Fragmentation Altitude | Uniform | $78\text{km} \pm 10\%$ |
| Speed | Uniform | 7700m/s to 7850m/s |
| Flight Path Angle | Uniform | -0.05° to -0.5° |
| Material Emissivity | Uniform | $\varepsilon-0.2(1-\varepsilon)$ to $\varepsilon+0.5(1-\varepsilon)$ |
| Initial Attitude | Uniform | Attack -180° to 180° Sideslip -90° to 90° |
| Joint Fragmentation Criteria | Uniform | Fail temperature $\pm 100\text{K}$ Fail force $\pm 200\text{N}$ |



Materials List

- Standard Materials
 - Aluminium
 - Titanium
 - Silicon Carbide
 - Invar
 - CFRP
 - Carbon-carbon
- Models exist for these materials
 - CFRP models are reasonably weak
 - Honeycomb models are usually based on aluminium (even if really CFRP)



Materials List

- 'Exotic Materials'
 - C-SiC
 - Mirror materials
 - Zerodur
 - ULE
 - Lens materials
 - Fused Silica
 - Borosilicate Glass
 - Calcium Fluoride
 - Germanium
 - Zinc Sulphide
 - Zinc Selenide

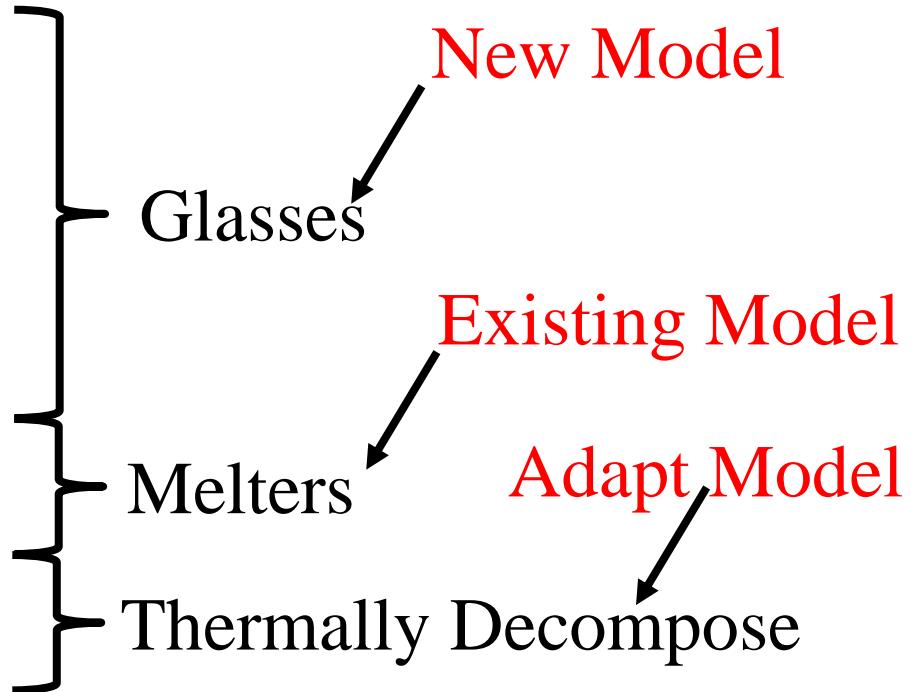
Glasses

Melters

Thermally Decompose

Materials List

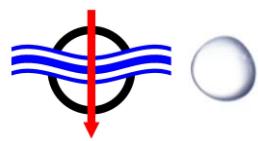
- 'Exotic Materials' **Use SiC Model**
 - C-SiC
 - Mirror materials
 - Zerodur
 - ULE
 - Lens materials
 - Fused Silica
 - Borosilicate Glass
 - Calcium Fluoride
 - Germanium
 - Zinc Sulphide
 - Zinc Selenide



New Model

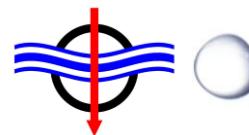
Existing Model

Adapt Model



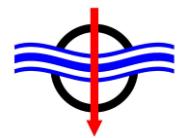
Identification of D4D Techniques

James Beck (BRL)



D4D Techniques

- Three Concepts
 - Enhanced Environment
 - Change conditions
 - Increased Demise Potential
 - Modify components / system
 - Reduced Number of Fragments
 - Prevent separation to land less items
- Three Levels
 - Component; Payload; Spacecraft



Environment

- Configuration / Fragmentation

| Technique | Methodology | Notes | Test Level |
|--------------------------------|--|--|------------|
| Payload Housing | Earlier flow exposure | | Payload |
| Payload Location on Spacecraft | Earlier flow exposure | High uncertainty in models | Spacecraft |
| Payload Layout | Place critical items in flow | High uncertainty in models | Payload |
| Explosive | Breaks large components | Violates SDM requirements | Payload |
| Corrosive Agent Release | Enhances separation | Risk may not be acceptable | Payload |
| Payload Jettison | Enhances heating early in trajectory | Passive heat-based trigger (Shape Memory Alloy) | Spacecraft |
| Failing Element Dynamics | Collapse of charred CFRP under compression | As most forces are compressive, can this have an effect on fragmentation? Behaviour is not well known | Payload |
| Adhesive Joints | Enhance separation | | Payload |

Demise Potential

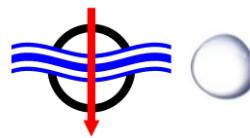
- Material
- Design (mass / size / shape)
- Manufacturing (lightweight, aspheric optics)

| Technique | Methodology | Notes | Test Level |
|---------------------------|---|------------------------------------|------------|
| Modularity | Increases demisability | | Component |
| Component Shape | Tighter curvature of long shapes | | Component |
| Reduced Mass | Lightweighting / design improvement / 3D printing | | Component |
| Materials | Replace with more demisable material | Functionality must not be degraded | Component |
| Critical Item Replacement | Replace with demisable alternative | No performance degradation | Component |
| Critical Item Removal | Remove surviving items | No performance degradation | Component |
| Reduce Component Size | Increases heating | No performance degradation | Component |

Reduce Fragments

- Not really Design-for-Demise
 - But could be effective for undemisable materials
- Containment
 - Many small parts of invar, titanium, glasses
- Non-separation
 - SiC parts

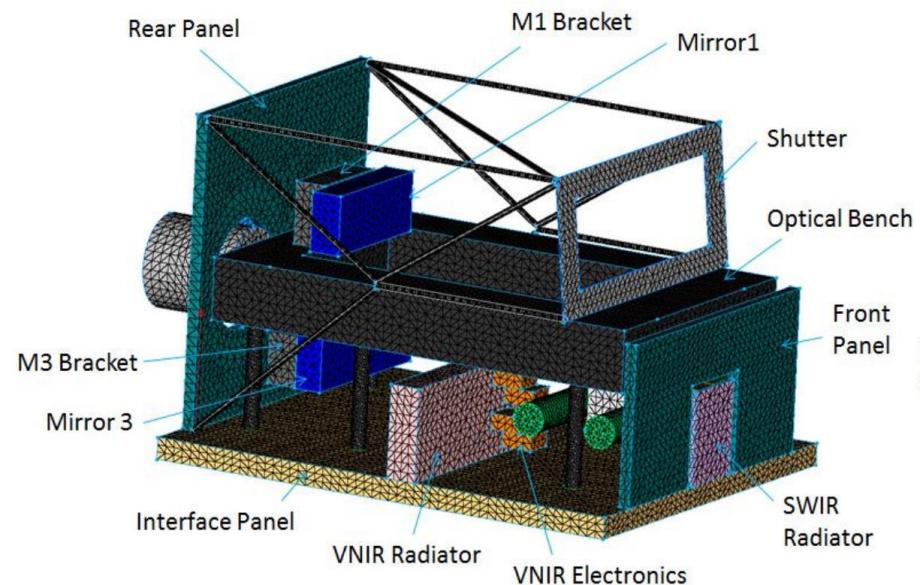
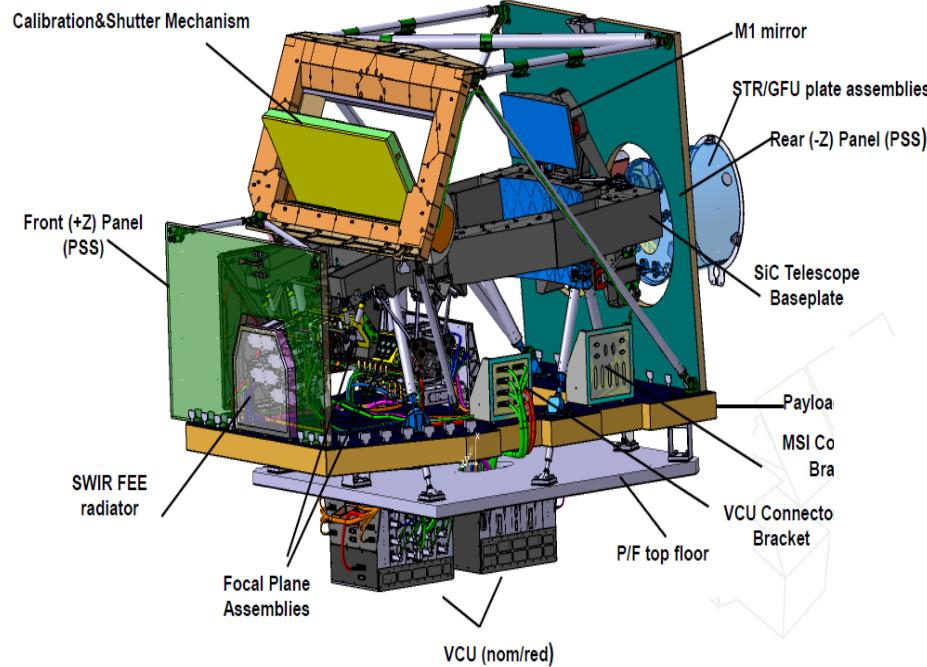
| Technique | Methodology | Notes | Test Level |
|--------------------|---|---|------------|
| Containment | Keep surviving components together | Requires confidence in survival of container | Component |
| Use of Fewer Parts | Less surviving components | Parts must not be more massive to compensate | Component |
| Undemisable Joints | Prevents separation of undemisable components | Ensure critical parts hit ground as single item | Payload |

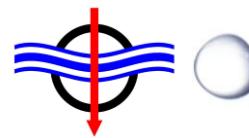


Object and Payload re-entry analysis and D4D identification

J Beck (BRL)

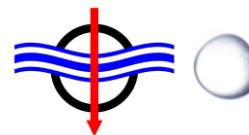
Sentinel-2 MSI





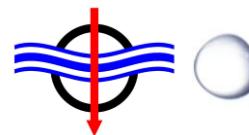
Key Aspects

- Number of Undemisable SiC Objects
 - Prevention of separation
 - Material change
- Beamsplitter Glass
 - Two panels survive
 - Size, material change
- Interface Panel
 - Modularity
 - Issues of CFRP sandwich modelling



Basic Techniques

- Undemisable Joints
 - Clear benefit
- Material Change
 - Benefit from CFRP or Zerodur mirrors
 - Benefit from CFRP Optical Bench
 - Benefit from CFRP Support Structures



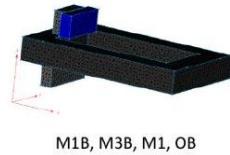
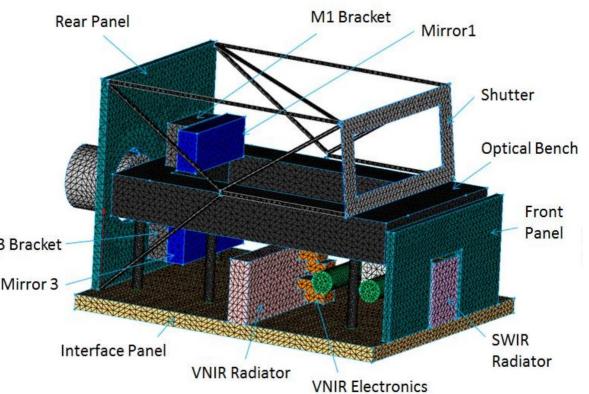
Basic Techniques

- Beamsplitter Glass
 - No improvement for different glasses
 - Smaller lenses => less risk
 - Demise limit is 15J
- Benefit from smaller optical bench
- Modular bench
 - Benefit seen if aluminium, not if CFRP/SiC



Payload Level

- Reduced risk
 - Not all components separate
 - Risk is still high
 - Always a large mass of SiC survives
- Some surviving objects



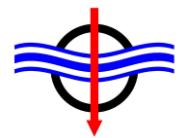
M1B, M3B, M1, OB



M1B, M3B, M1, M2, S, OB



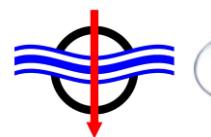
M1B, M3B, M1, M2, S, OB



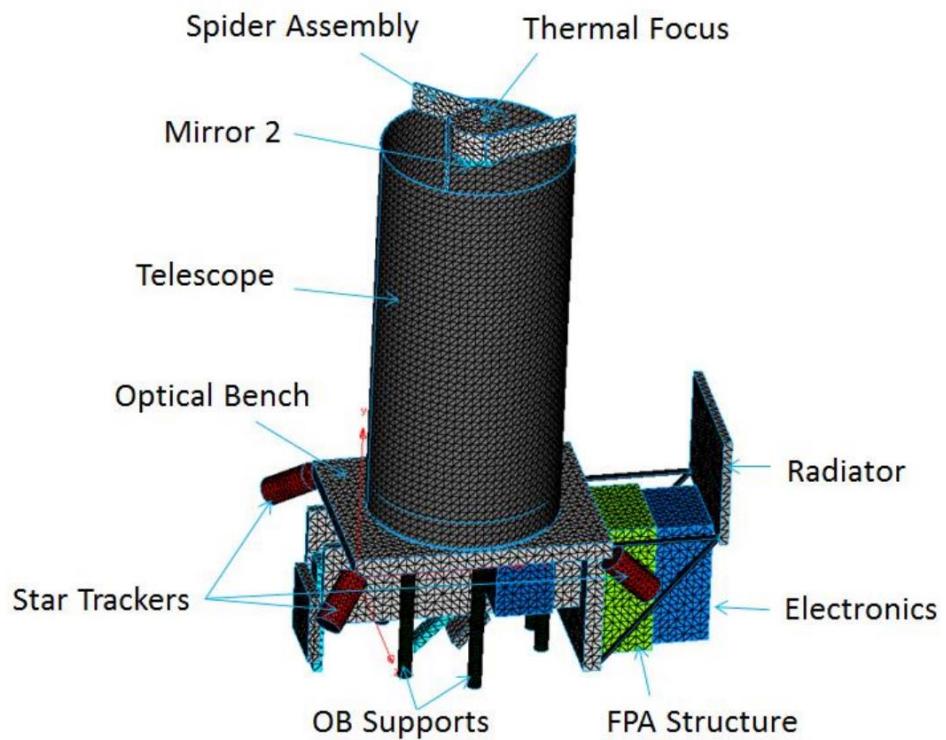
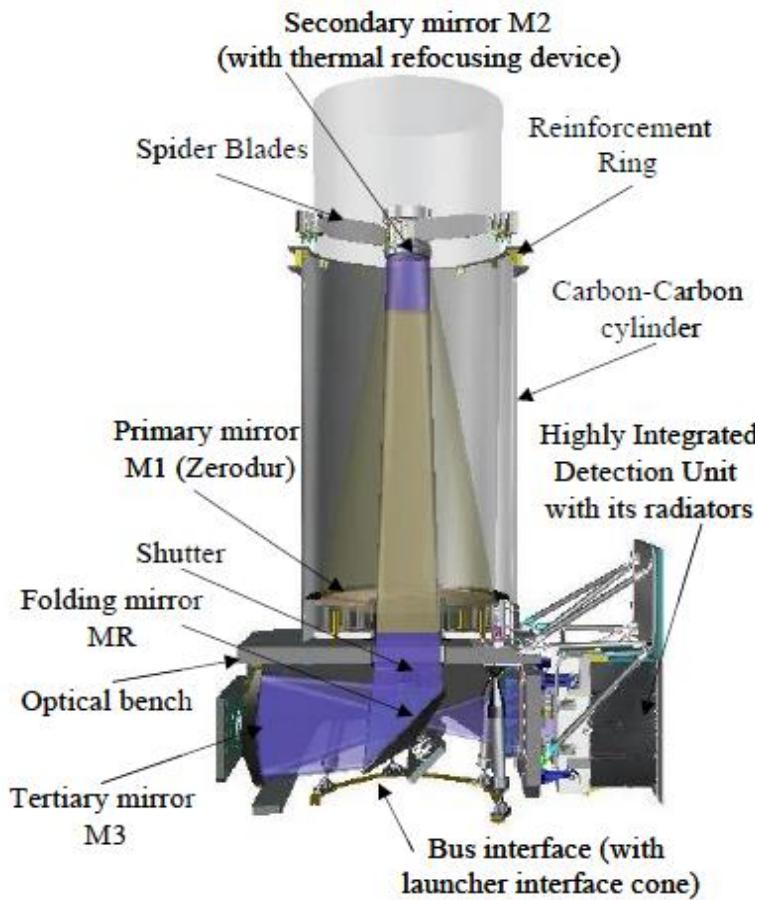
Trade-Off

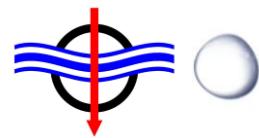
| Technique | Effectiveness | Cost | TRL | Performance |
|------------------------------|---------------|--------|-----|---------------------------|
| Undemisable Joints | VERY HIGH | LOW | 4 | Unaffected |
| Mirror Material Change | MEDIUM | MEDIUM | 9 | Unaffected |
| Optical Bench Material | HIGH | MEDIUM | 9 | Unaffected |
| Support Materials | HIGH | LOW | 9 | Unaffected |
| Smaller Beamsplitter Glass | MEDIUM | LOW | 9 | Needs minor layout change |
| Contained Beamsplitter Glass | MEDIUM-HIGH | LOW | 6 | Unaffected |
| Modular Optical Bench | LOW | HIGH | 9 | May have mass impact |
| Adhesive Joints | MEDIUM-LOW | LOW | 9 | Unaffected |

- Selection for Task 3
 - Undemisable joints
 - Material change for Optical Bench to CFRP
 - Adhesive joints for demisable parts



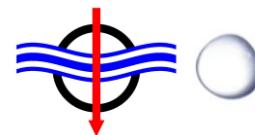
Pleiades-HR





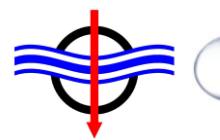
Key Aspects

- Payload separates with modular design
 - Thin structures; different from MSI
- Critical parts are well separated
 - Focus is on individual components
 - Telescope, mirrors, FPA
 - FPA containment



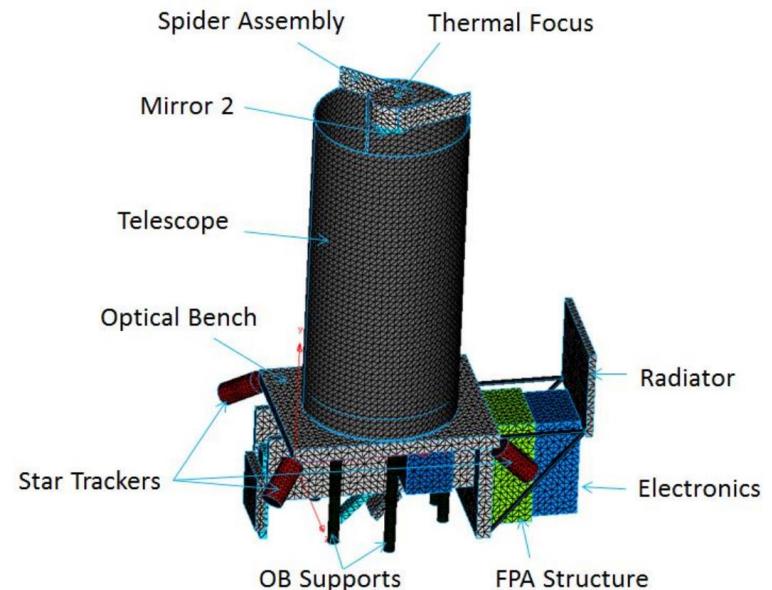
Basic Techniques

- Containment
 - FPA mirror inside structure
- Material Change
 - Mirrors
 - Benefit from Aluminium or CFRP mirrors
 - Telescope
 - No benefit from CFRP
 - Optical Bench
 - Sensitivity is high to model
 - Use of CFRP model for sandwich gives higher risk



Payload Level

- Similar to component level
 - Some benefit from earlier heating
 - Almost all components separate





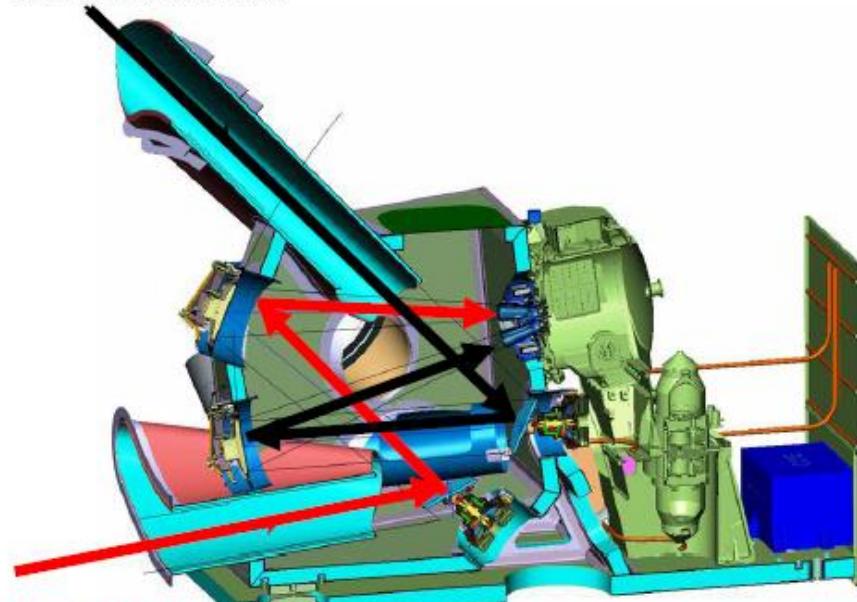
Trade-Off

| Technique | Effectiveness | Cost | TRL | Performance |
|------------------------------|---------------|------------|-----|-------------|
| FPA Mirror Containment | MEDIUM | LOW | 6 | Unaffected |
| CFRP Mirrors | VERY HIGH | MEDIUM | 9 | Unaffected |
| Telescope Material | None | HIGH | 9 | Unaffected |
| Thermal Focus Unit Structure | LOW-MEDIUM | LOW-MEDIUM | 6 | Unaffected |
| Modular Bench | LOW | LOW | 6 | Unaffected |

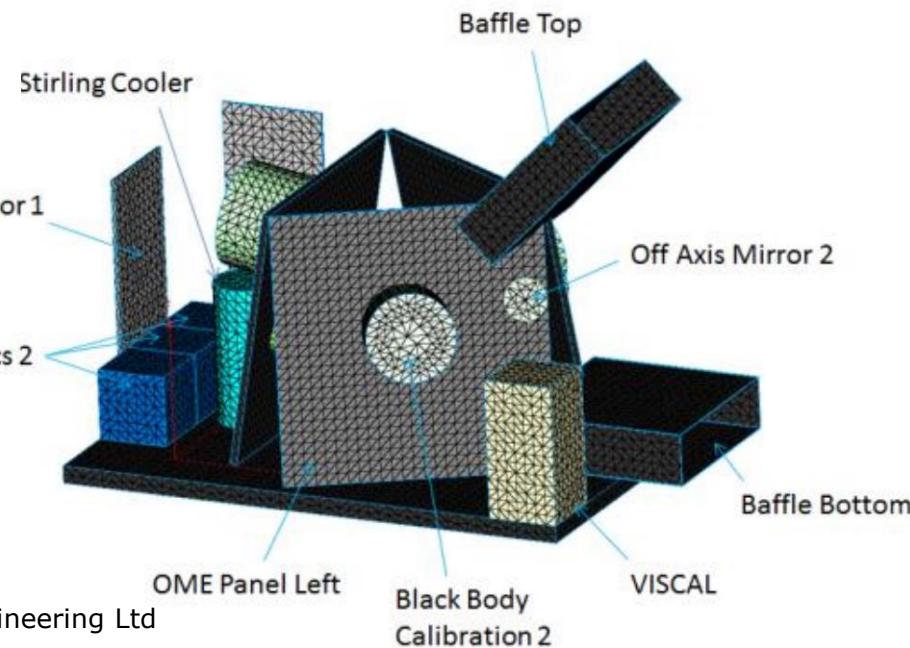
- Selection for Task 3
 - FPA mirror containment
 - CFRP mirrors
 - Redesigned thermal focus unit

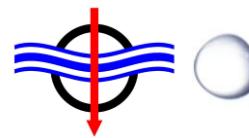
Sentinel-3 SLSTR

EARTH BACKWARD VIEW



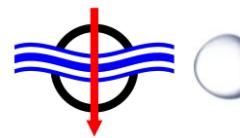
EARTH NEAR NADIR VIEW





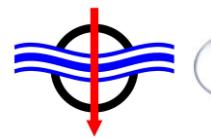
Key Aspects

- Some undemisable parts
 - Beryllium, titanium (scan mirrors), Zerodur
 - Focal plane assembly has many parts
 - Containment?
- Most parts are demisable
 - Aluminium, CFRP
 - Target optical bench and baffles for easy gain
 - Early separation
 - Component mass/size



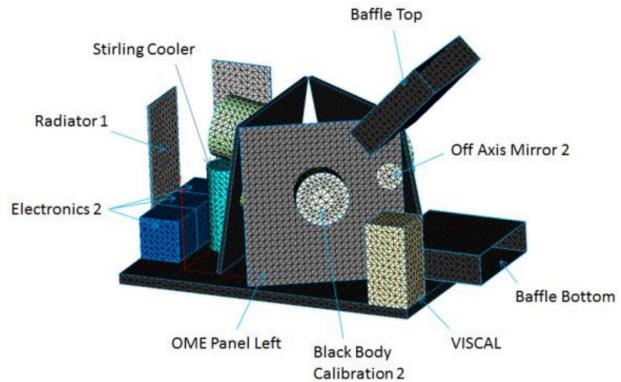
Basic Techniques

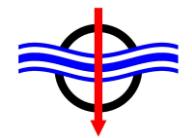
- Materials
 - No improvement found for Scan Mirrors
 - Limited improvement for Baffles
- Containment
 - Focal Plane Assembly has many parts
 - Early release preferred to containment



Payload Level

- All components separate
 - Large influence of early heating
 - Pre-breakup
 - Components are mainly demisable
 - Early heating / release is key
 - Case where object-oriented is insufficient



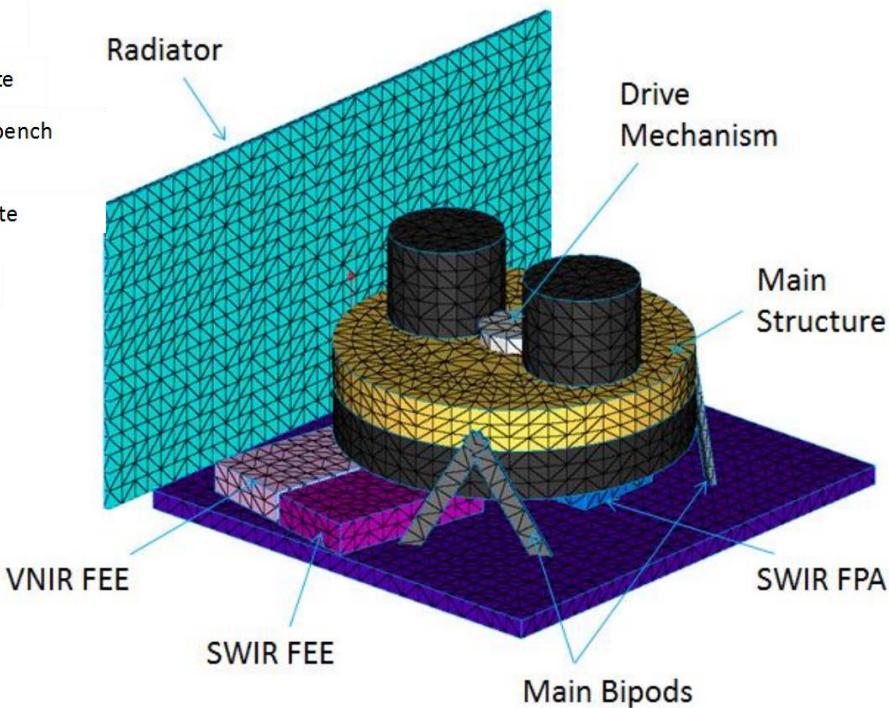
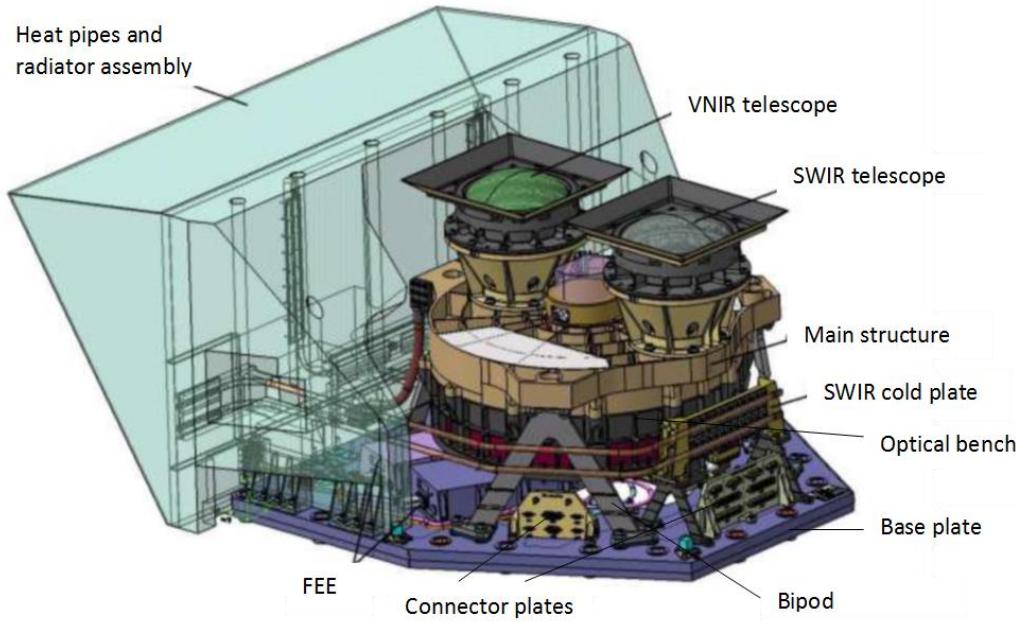


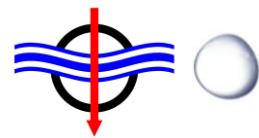
Trade-Off

| Technique | Effectiveness | Cost | TRL | Performance |
|----------------------------------|---------------|--------|-----|--------------------------|
| Single Piece Scan Mirror | LOW | MEDIUM | 6 | Unaffected |
| Fibreglass Baffles | HIGH | LOW | 6 | Unaffected |
| Modular Optical Bench | LOW | MEDIUM | 6 | Unaffected |
| Smaller Black Body Units | MEDIUM | LOW | 9 | Unaffected (expectation) |
| Reduced FPA Housing Mass | MEDIUM | MEDIUM | 6 | Unaffected |
| Use of Smaller Components in FPA | HIGH | MEDIUM | 9 | Unaffected |
| FPA Containment | LOW | LOW | 9 | Unaffected |
| Adhesive Joints | TBD | LOW | 9 | Unaffected |

- Selection for Task 3
 - Fibreglass baffles
 - Smaller black body calibration units
 - Adhesive joints
 - Ensure early failure of FPA housing
 - SiC FPA housing (alternative approach)

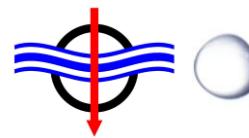
MetOp 3MI





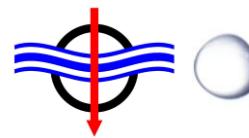
Key Aspects

- Generally more Benign Payload
- Telescopes/Lenses
 - Significant number of surviving lenses released on telescope demise
 - Titanium can melt if a container
- Remaining Contributions are Small
 - Bipods are major contributor



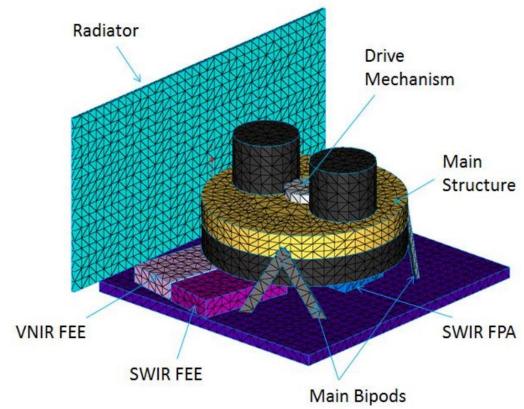
Basic Techniques

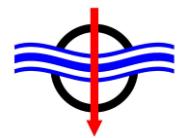
- Material Change
 - Bipods demise if CFRP or Invar
 - Lens risk removed if below 15J
 - Limited benefit from lower quality glass
 - Demisable telescope material results in higher risk
 - Lens release becomes more probable
- Containment
 - Undemisable telescope casings
 - Titanium can demise if a container (needs to be thick)
 - Need carbon-carbon (for example)



Payload Level

- All components separate
 - Small difference
 - Telescopes more demisable
 - Negative (lenses)
 - Remainder more demisable (positive)

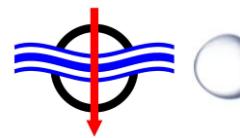




Trade-Off

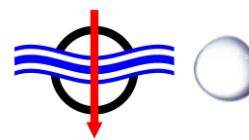
| Technique | Effectiveness | Cost | TRL | Performance |
|------------------------------|---------------|--------|-----|-------------|
| CFRP Main Bipods | MEDIUM | LOW | 9 | Unaffected |
| Smaller Lenses | HIGH | LOW | 9 | Unaffected |
| Carbon-Carbon Telescopes | HIGH | LOW | 9 | Unaffected |
| Undemisable Joints/Structure | MEDIUM | MEDIUM | 4 | Unaffected |

- Selection for Task 3
 - CFRP bipods
 - Carbon-carbon telescope barrels



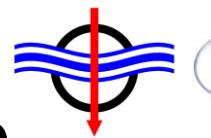
Summary

- Three very similar payloads
 - Mass, Size, Capability (MSI, HR, SLSTR)
- Four different demise signatures
 - MSI is SiC based
 - Land as unit for minimum risk
 - HR has separated critical components
 - Target individual components
 - SLSTR has theoretically demisable components
 - Early separation is key aspect
 - MSI has potential release of undemisable parts
 - Containment



Assessment of D4D Techniques

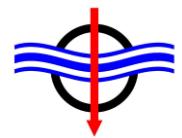
Sam Bainbridge (FGE)



Modelling Approach

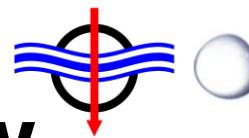
- D4D techniques assessed on the four reference payloads
- Payload-level simulations (spacecraft-oriented)
- Performed using Monte-Carlo based parameter variation
- 1000 runs per simulation
- Ensures representation of significant uncertainties in entry-state, aerodynamics, aerothermal heating and material response

| Parameter | Distribution | Range |
|------------------------------|--------------|--|
| Aerothermodynamic Heating | Uniform | $\pm 20\%$ |
| Speed | Uniform | 7700m/s to 7850m/s |
| Flight Path Angle | Uniform | -0.05° to -0.5° |
| Material Emissivity | Uniform | $\varepsilon-0.2(1-\varepsilon)$ to $\varepsilon+0.5(1-\varepsilon)$ |
| Initial Attitude | Uniform | Attack -180° to 180° Sideslip -90° to 90° |
| Joint Fragmentation Criteria | Uniform | Fail temperature $\pm 100\text{K}$ Fail force $\pm 200\text{N}$ |



D4D Techniques

| Payload | Scenario | Techniques |
|----------------|-----------------------------|--|
| MSI | 1: Reduced Fragment Numbers | Undemisable Joints Adhesive Joints for demisable items |
| | 2: Material Change | CFRP Bench, Mirror, Supports Adhesive Joints for demisable items |
| HR | 1: All Techniques | CFRP Mirrors FPAS Mirror Containment Thermal Focussing Unit Redesign |
| 3MI | 1: All Techniques | CFRP Main Bipods Carbon-Carbon Telescope Barrels |
| SLSTR | 1: FPAS Containment | SiC FPA Housing Fibreglass Baffles Adhesive Joints Smaller Black Body Calibration Units |
| | 2: Demisable FPAS | Thinner FPA Housing Fibreglass Baffles Adhesive Joints Smaller Black Body Calibration Units |
| | 3: Demisable Baffles | Aluminium Baffles Smaller Black Body Calibration Units |



Simulation Overview

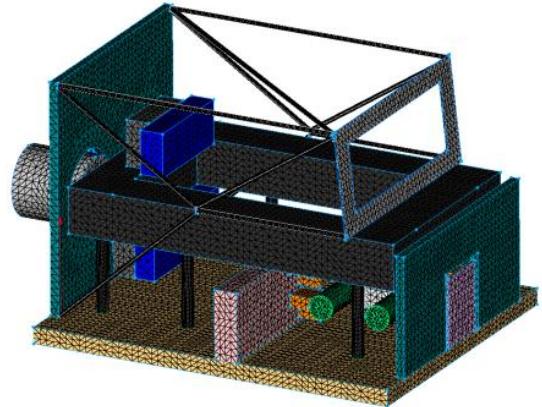
| Payload | Scenario | Sensitivity Analysis | Sensitivities |
|---------|-----------------------------|----------------------|--|
| MSI | 0: Updated Baseline | Full | Four Initial Altitudes - 80km - 90km - 100km - 120km |
| | 1: Reduced Fragment Numbers | | |
| | 2: Material Change | | |
| HR | 0: Updated Baseline | Full | Two Shielding Attitude Ranges - Half-sphere - Three-quarter sphere |
| | 1: All Techniques | | |
| 3MI | 0: Updated Baseline | Full | |
| | 1: All Techniques | | |
| SLSTR | 0: Updated Baseline | Full | |
| | 1: FPAS Containment | | |
| | 2: Demisable FPAS | | |
| | 3: Demisable Baffles | | |

- Total number of payload level simulations = 65,100
- Only 100 runs completed for MSI Scenario 2 at 80km release

Baseline Impact of Payload D4D Techniques

Sentinel-2 Multi-Spectral Imager

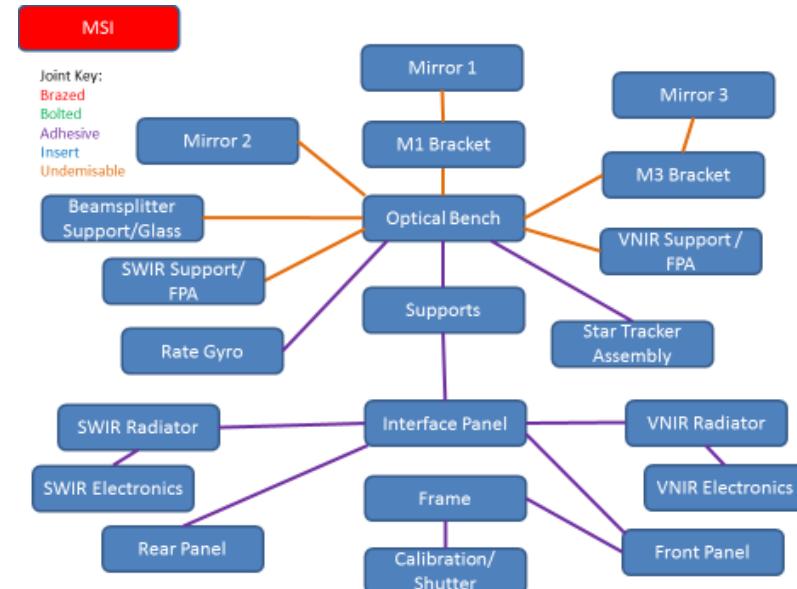
- Casualty risk driven by undemisable components
- Two mutually exclusive approaches
 - Reduced fragment number (undemisable joints)
 - Material substitution (CFRP mirrors and support structures)
- Adhesive joints for demisable items



Baseline Impact of Payload D4D Techniques

Sentinel-2 Multi-Spectral Imager

- Scenario 1: Reduced Fragment Numbers



| Technique | Baseline Casualty Area (m ²) | Scenario 1 Casualty Area (m ²) | Casualty Area Reduction (%) | Effectiveness |
|-------------------------------------|--|--|-----------------------------|---------------|
| Undemisable Joints | 7.465 | 2.818 | 63 | HIGH |
| Adhesive Joints for Demisable Items | 0.869 | 0.342 | 61 | HIGH |
| Total | 8.334 | 3.160 | 62 | HIGH |

Baseline Impact of Payload D4D Techniques

Sentinel-2 Multi-Spectral Imager

- Scenario 2: Material Substitution

| Technique | Baseline Casualty Area (m ²) | Scenario 2 Casualty Area (m ²) | Casualty Area Reduction (%) | Effectiveness |
|-------------------------------------|--|--|-----------------------------|---------------|
| CFRP Substitution | 6.461 | 0.004 | 99 | VERY HIGH |
| Adhesive Joints for Demisable Items | 0.873 | 0.347 | 60 | HIGH |
| Total | 8.334 | 1.355 | 84 | VERY HIGH |



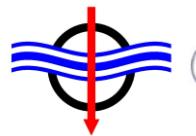
Payload D4D Techniques

Sentinel-2 Multi-Spectral Imager

- Both scenarios very effective
- Scenario 2 is the most effective
 - Impact of spacecraft will be more adverse for this case

| Configuration | Total Casualty Area (m ²) | Casualty Area Reduction (%) | Effectiveness |
|---------------|---------------------------------------|-----------------------------|---------------|
| Baseline | 8.334 | - | - |
| Scenario 1 | 3.160 | 62 | HIGH |
| Scenario 2 | 1.355 | 84 | VERY HIGH |

Note on Ballistic Coefficient



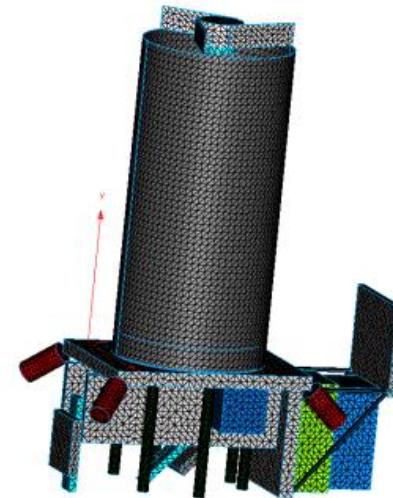
- Earlier release (adhesive joints) had an adverse effect on low ballistic coefficient components' casualty risk
- Earlier release of low β items → lower velocity when components hit the denser air
- Leads to reduced heating and as such demise
- Important to consider β when selecting D4D techniques
- Phenomena only identified through spacecraft-oriented simulations

| Component | Material | Baseline | | Scenario 1 | |
|-----------------|----------|--------------------|--------------------------------------|--------------------|--------------------------------------|
| | | Impact Probability | Mean Casualty Area (m ²) | Impact Probability | Mean Casualty Area (m ²) |
| Interface Panel | Al | 0.258 | 0.172 | 0.376 | 0.272 |

Baseline Impact of Payload D4D Techniques

Pleiades High Resolution Optical Instrument

- Critical components: telescope, mirrors, focal plane assembly and thermal focussing unit
- Infeasible to ensure critical components land as a compound object
- Unable to reduce the contribution from the telescope
 - Limiting the possible reduction in casualty risk
 - Demonstrates the concept of considering a casualty area budget in the design phase
- D4D techniques:
 - CFRP mirrors
 - Focal plane assembly containment
 - Thermal focussing unit redesign



Baseline Impact of Payload D4D Techniques



Pleiades High Resolution Optical Instrument

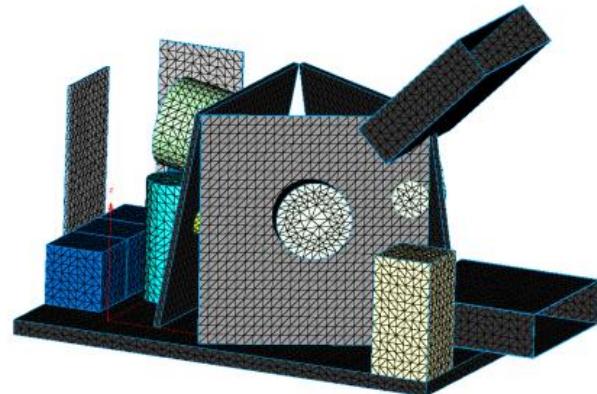
- Largest reduction from mirror's material substitution
- FPAS containment limited by undemisable housing

| Technique | Baseline Casualty Area (m ²) | Enhance Demise Casualty Area (m ²) | Casualty Area Reduction (%) | Effectiveness |
|---------------------------------------|--|---|--------------------------------|---------------|
| FPAS Mirror Containment | 1.643 | 0.983 | 40 | MEDIUM |
| CFRP Mirrors | 1.231 | 0 | 100 | VERY HIGH |
| Thermal Focussing Unit Redesign | 0.971 | 0.064 | 85 | VERY HIGH |
| Total | 6.409 | 4.128 | 36 | MEDIUM |

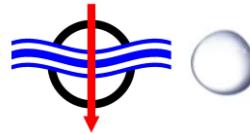
Payload D4D Techniques

Sentiel-3 Sea and Land Surface Temperature Radiometer

- Casualty risk driven by materials which are essentially demisable
- Earlier release or reduced mass should improve demisability
- Two scenarios envisaged:
 - FPAS containment: prevents release of internals however, guarantees the housing will survive
 - Reduced FPAS housing mass: ensures earlier release of internals
 - Mutual techniques:
 - Fiberglass baffles
 - Smaller black body calibration units
 - Adhesive joints



Baseline Impact of Payload D4D Techniques



Sentiel-3 Sea and Land Surface Temperature Radiometer

- Containment had a negative impact on casualty area
- Fibreglass baffle performed worse than baseline (CFRP)
 - Selected from component-level analysis
- Baseline: 3.40m²
- Scenario 1 (FPAS containment): 4.65m²
- Scenario 2 (Demisable FPAS): 4.07m²
- Third scenario envisaged
 - Aluminium baffles
 - Smaller black body calibration units

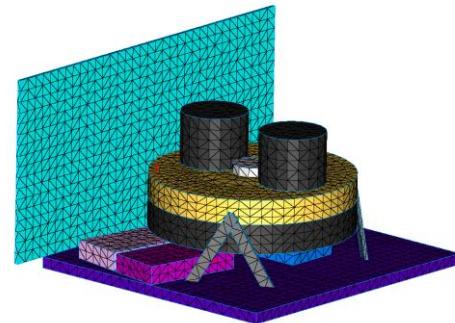
| Technique | Baseline Casualty Area (m ²) | Enhance Demise Casualty Area (m ²) | Casualty Area Reduction (%) | Effectiveness |
|--------------------------|--|--|-----------------------------|---------------|
| Aluminium Baffles | 1.30 | 0 | 100 | VERY HIGH |
| Smaller Black Body Units | 0.14 | 0 | 100 | VERY HIGH |
| Total | 3.40 | 1.97 | 42 | MEDIUM |



Payload D4D Techniques

ESA/EumetSAT – MetOp 3MI Imager

- Critical components
 - SWIR and VNIR lenses
 - Titanium main bipods
- D4D techniques:
 - Carbon-carbon telescopes (containing the lenses)
 - CFRP main bipods



Baseline Impact of Payload D4D Techniques



ESA/EumetSAT – MetOp 3MI Imager

- Successful containment
- Telescopes will always land

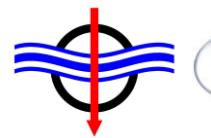
| Technique | Baseline Casualty Area (m ²) | Enhance Demise Casualty Area (m ²) | Casualty Area Reduction (%) | Effectiveness |
|---------------------------------|--|--|-----------------------------|---------------|
| CFRP Main Bipods | 0.340 | 0 | 100 | VERY HIGH |
| Carbon-Carbon Telescope Barrels | 3.002 | 1.218 | 59 | HIGH |
| Total | 3.342 | 1.218 | 64 | HIGH |

Payload D4D Techniques

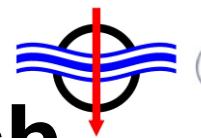
Summary

- The majority of the D4D techniques have proven to be beneficial
- Enhance demise scenarios reduced payload casualty risk to below critical threshold
- D4D techniques are bespoke
- Techniques must be applied with care (e.g. adhesive joints & containment)
- SLSTR case is a good example of the benefits of running a spacecraft-oriented simulation

Impact of Spacecraft Bus



| Approach | Pros | Cons |
|----------------------------------|--|--|
| Fully spacecraft oriented | <ul style="list-style-type: none">Representative exposure of the payload to hypersonic flowCan address D4D techniques involving spacecraft | <ul style="list-style-type: none">Resources spent developing spacecraft model instead of understanding better the payload demiseSpacecraft demise is not the focus of the study (although related)Risk of introducing dependence on a particular spacecraft into final conclusions |
| Payload oriented | <ul style="list-style-type: none">Parametric treatment of flow exposureMore analysis possible with available resourcesRemoves dependence on specifics of the spacecraft and focuses on the payloadPayload manufacturers will be required to consider demisability aspects for future missions but often have little knowledge of the spacecraft details | <ul style="list-style-type: none">Spacecraft related D4D inferred from the parametric study but not demonstrated |



Parametric Approach

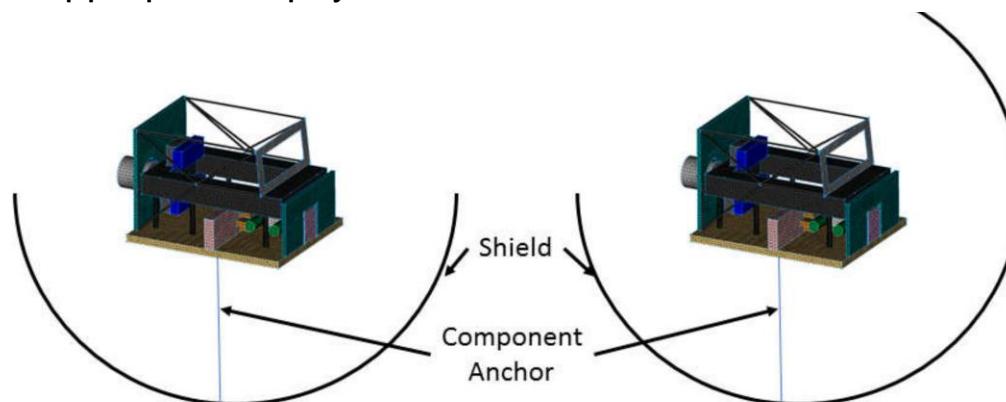
Two methods:

1. Release altitude

- Payload is not exposed to the flow, thus the heating, until a given altitude
- Release altitude range: 120km – 80km
- Lower limit is approximately equivalent with the component level analysis

2. Shielding attitude

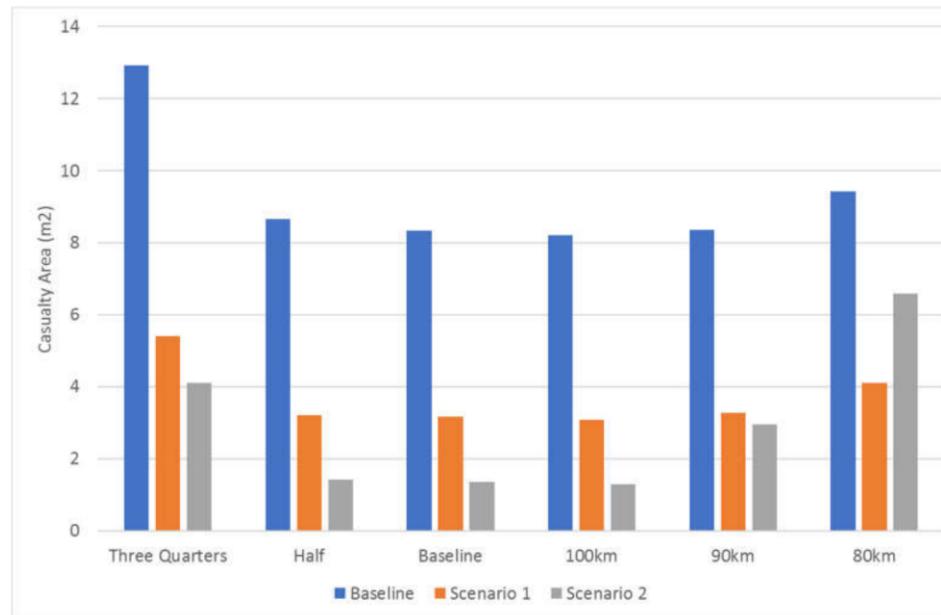
- Accounts for heat flux shielding of spacecraft bus
- Shield 'linked' to anchor component for payload release
- Release at 70km if not before
- Half shield: appropriate if payload is at end
- $\frac{3}{4}$ shield: appropriate if payload more embedded



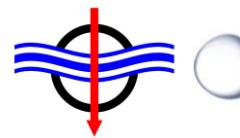
Impact of Spacecraft Bus

Sentinel-2 MSI

- Shielding effect is relatively small
 - Techniques are effective
 - Higher benefit from material change
 - Undemisable joints more robust
- Spacecraft leads to a relatively minor increase in casualty risk
 - Unless payload is particularly well shielded

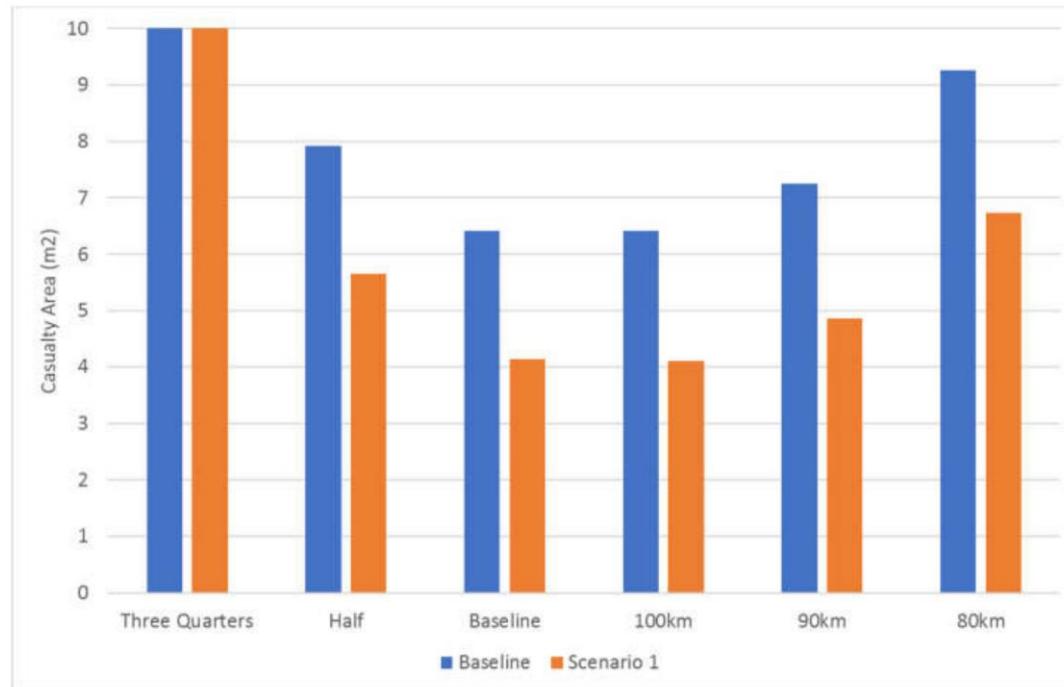


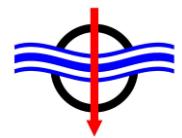
Impact of Spacecraft Bus



Pleiades HR

- Shielding effect is larger
 - More demisable parts
 - Impact of $\frac{3}{4}$ shielding extreme
- Demonstrates the potentially large effect of shielding

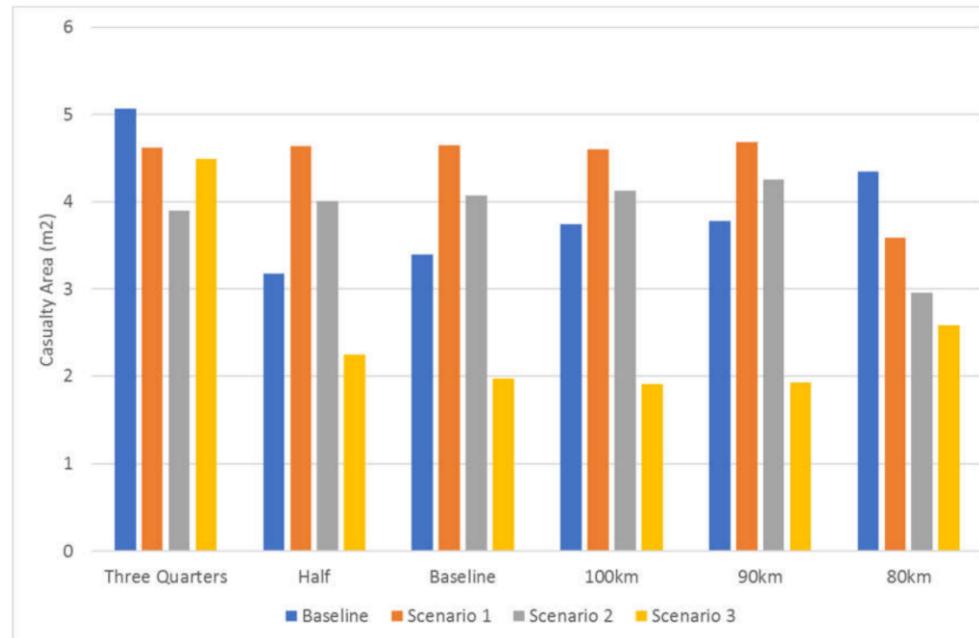




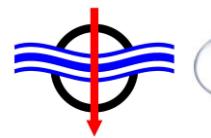
Impact of Spacecraft Bus

Sentinel-3 SLSTR

- Small shielding effect
 - Ineffectiveness of selected techniques
 - Extra technique better
 - Insensitive to shielding
- Worst case still significantly better than component-level analysis



Impact of Spacecraft Bus

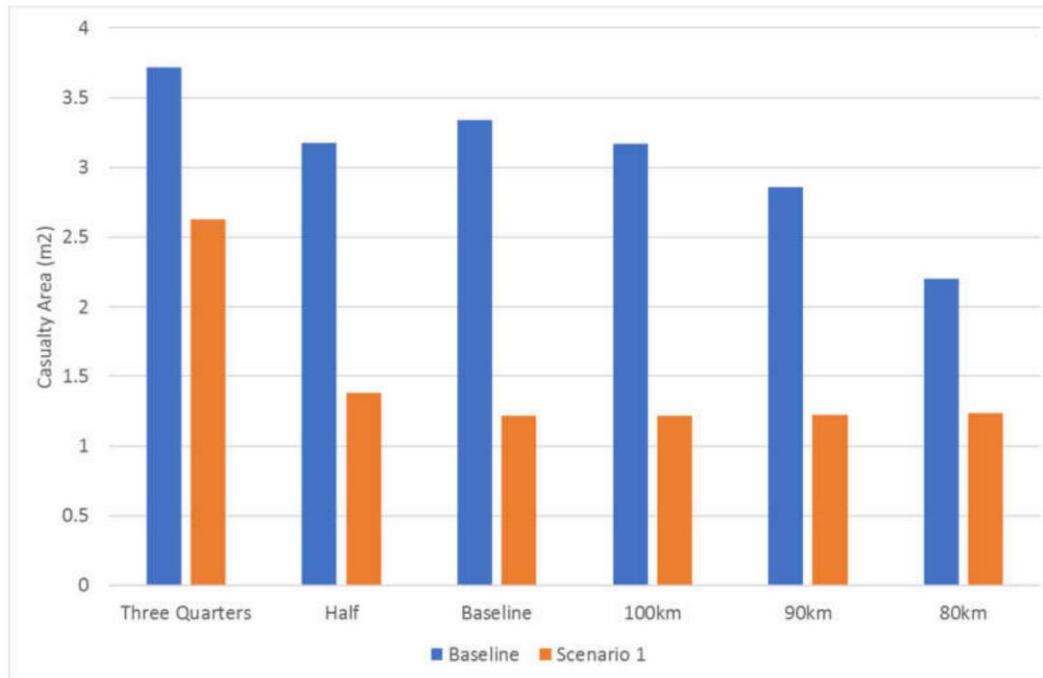


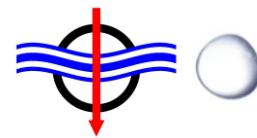
Belstead

UCL

MetOp 3MI

- Shielding effect small
 - Counter-intuitive reduction in casualty area as release altitude reduces
 - Large shielding needed for impact on technique





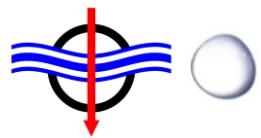
Summary

Release altitude

- Lower release altitude leads to an increased casualty risk
- Variations of this behaviour (due to the bespoke nature of the payloads) has been observed

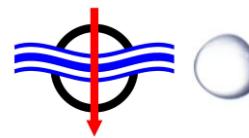
Shielding attitude

- Shield concept successful
 - Provides good indication of bus effect
 - Half shield seems appropriate
 - $\frac{3}{4}$ shield provides quite conservative limit
- Story in line with release altitude investigation



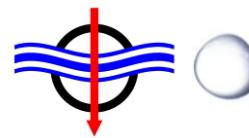
Critical Design Requirements and Guidelines

James Beck (BRL)



Guidelines

- Conversation starter
 - Top level simple insights
 - Which components are important
 - How to assess the payload configuration relative to these components
 - Provide an idea of the payload “demise characteristic”
 - Good practice
 - What can be done for each “demise characteristic”
 - Keep it simple
 - What choices can be made to benefit demise and minimise impact on cost and performance?



Guidelines

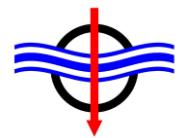
- Thought Process
 - Identification of critical elements
 - Identification of payload demise characteristic
 - Direction to relevant demisability guidelines
- Notes
 - More complex issues (ballistic coefficient / material modelling) are omitted from this first pass
 - Only passive techniques considered, so no issues with debris mitigation guidelines



Components

- Critical component sizes
 - Materials behaviour at current understanding
 - Subject to changes from improved testing
- What is a potential risk from the payload?

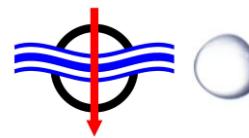
| Material | Mass for Potential Risk | Notes |
|--------------------|-------------------------|---|
| Silicon Carbide | 30g | |
| Titanium | 30g | |
| Invar | 1.5kg | |
| Fused Silica | 40g | |
| Zerodur | 1kg | |
| Carbon-carbon | 40g | |
| Borosilicate glass | 1kg | |
| CFRP | 5kg | Large, light items have lower mass threshold Large uncertainties in CFRP behaviour |
| Aluminium | 10kg | |



Components

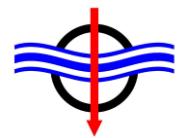
- Component risk guide
 - 8m² is casualty area guide for 1:10000 risk
 - Approximate values for components from study
 - Get an idea of the casualty risk budget

| Component | Material | Casualty Area |
|--------------------|------------------------|-----------------------|
| Optical Bench | Silicon Carbide | ~2m ² |
| | CFRP | Small |
| | Aluminium | Small |
| Support Structures | Silicon Carbide | 0.5-1m ² |
| Mirrors | Silicon Carbide | 0.3-1m ² |
| | Zerodur | 0-1m ² |
| | CFRP | Small |
| Beamsplitter Glass | Fused Silica | 0.5m ² |
| Sandwich Panels | CFRP/Aluminium | 0-0.3m ² |
| Electronics | | 0-0.5m ² |
| Telescopes | Titanium/Carbon-carbon | 0.5-2.5m ² |
| Lenses | Fused Silica | ~0.2m ² |



Payload Guide

- Use Simple Q&A Format
 - Try to identify payload demise characteristic
 - Try to identify D4D techniques to improve demise
 - Work from least impact on payload design to greater impact changes
 - Can we use undemisable joints?
 - Do we want to improve breakup (adhesive joints)?
 - Can we use containment?
 - Can we reduce sizes of critical items?
 - Can we change material?



Payload Guide

Is there a substantial structural part, such as the optical bench, constructed from an undemisable material such as silicon carbide or carbon-carbon?

YES

In this case, there is the possibility to connect the undemisable parts such that they can reach the ground as a single piece. Techniques for undemisable joints, such as the high-temperature brazing of silicon carbide parts could be considered.

NO

In this case, there is a high likelihood that the connecting parts will demise, and the undemisable components will fall separately. This results in the need to consider the components at an individual level.

Are the components of concern primarily constructed of materials which are potentially demisable such as aluminium, CFRP or Invar?

YES

In this case, there is substantial benefit in releasing these components from the payload as early as possible in the re-entry. This can potentially be achieved by the use of adhesives in the joint failure path, as this will cause failure at relatively high altitudes.

NO

In this case, increasing the fragmentation altitude will have a limited effect on these components. This results in the need to consider the component demisability at an individual level.



Payload Guide

Are a number of components of concern co-located such that there is the potential to contain a number of items inside one larger item, such as a number of fused silica lenses inside a telescope?

YES

In this case, there is a potential benefit from constructing the larger item from an undemisable material such as carbon-carbon in order to ensure that the contained items do not escape, increasing the casualty risk.

Are any of the components of concern relatively small, such that there is a possibility they could be made to fit under the critical mass threshold?

YES

Reducing the size of such components can remove them from the risk assessment completely.

Can the component material be changed for a more demisable material?

YES

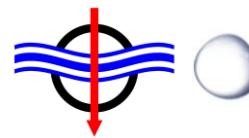
This can provide a large benefit, but is considered likely to be a last resort for designers



Primary Techniques

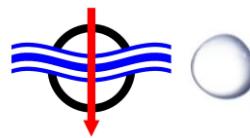
- Techniques to Consider at Design Stage
 - Basic techniques, and recommendations for use

| Technique | Applicable | Recommendations |
|---------------------------------|--|--|
| Undemisable Joints | Undemisable structure | Appropriate for silicon carbide structures |
| Adhesive Joining Technologies | Components constructed from potentially demisable materials | |
| Containment | Group of undemisable components are housed together within another component | Do not use titanium for the undemisable housing. It can demise when a shell on a larger object. Carbon-carbon is preferred |
| Smaller Components | All components of potentially demisable materials | In general, smaller components are more demisable |
| Reduce Size Below 15J Threshold | Components under ~100g | Likely to be possible for many lenses |
| Material Change | Components of undemisable material | Only applicable where performance, mass and cost are minimally affected |



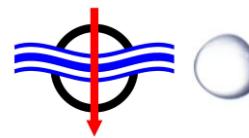
Overall Approach

- Establish a Risk Budget for the Payload
 - Of the order of six small surviving objects
- Identify Critical Components
- Identify Payload Demisability Characteristic
 - Identify potential techniques using Q&A
- Consult with Demise Experts
 - Consolidate understanding and likely effectiveness of possible techniques



Technology Roadmap for Optical Payloads

Peter Doel (UCL)



Development Aims

1. Smaller
2. Lighter
3. Use of materials with increased demisability

First two are general aims of most satellite technology developments.

Additive manufacturing

– Metal structures

- A lot of development being done on additive manufacturing especially in metals e.g. FP7 program AMAZE, one of which aims is the development and space qualification of additive manufactured components for aerospace applications.
- Obvious advantages for demisability not only to large optical bench structures but also to extreme light-weighting of titanium and invar fixtures.
- Additive manufactured components have already flown on satellites (e.g. SKY Perfect JSAT's JCSAT-110A satellite).



40cm Prototype Antenna Bracket – 40% mass saving (source: RUAG, EOS, GmbH)

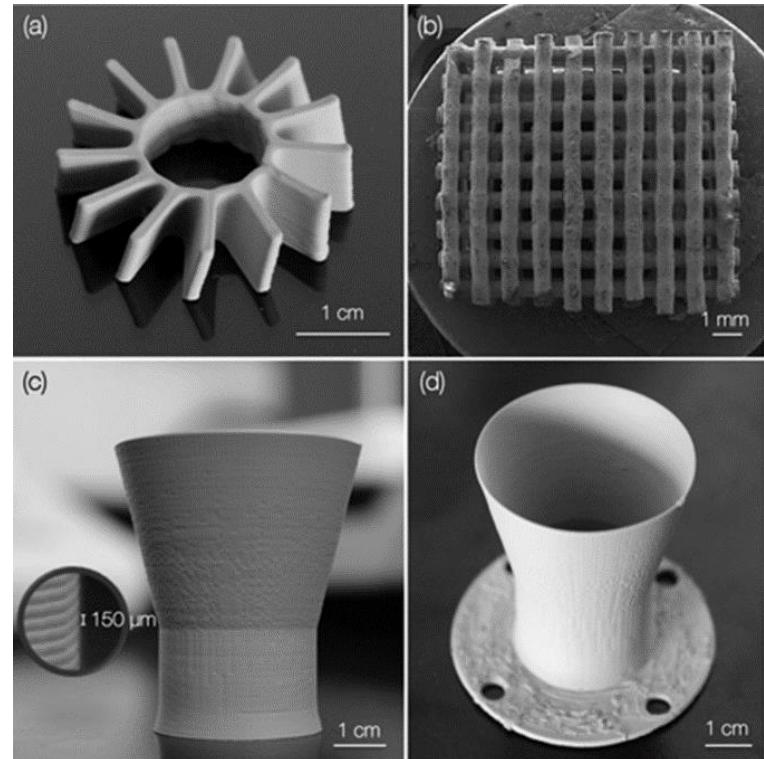
- Need to prove stability and size requirements for satellite optical bench (Currently there is an ESA TRP on this)

Additive Manufacturing



– Ceramic structures

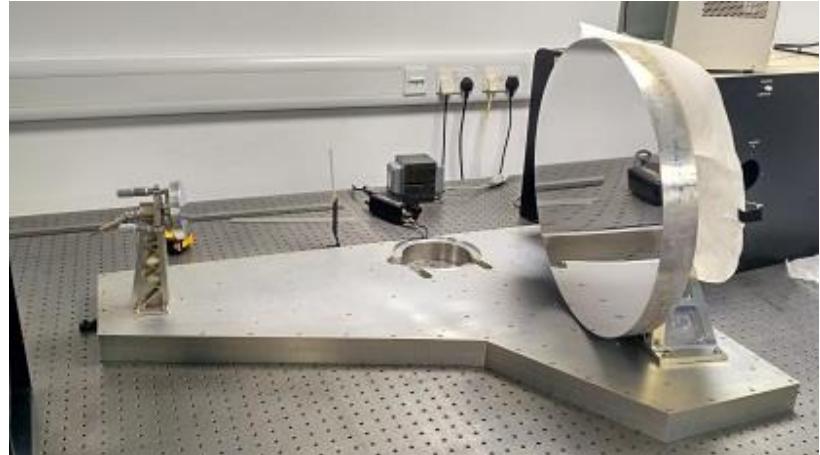
- Potential increase in demisability by extreme light-weighting of mirror/optical bench of Silicon Carbide structures
- Currently an issue with the production of large monolithic ceramics with the same material properties as traditional methods.
- Good review of current status – Zocca et al. “Additive manufacturing of ceramics: Issues potentialities and opportunities (2015)



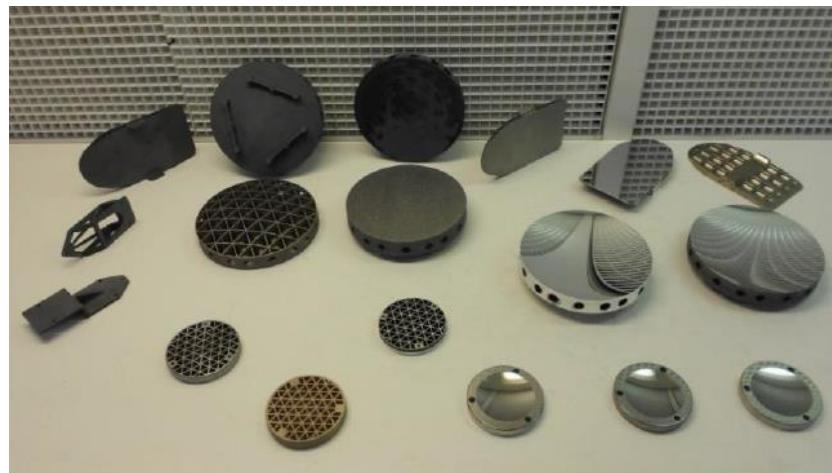
C. Larson, J. Choi, P. Gallardo, S. Henderson, M. Niemark, G. Rajagopalan and R. Shepard, “Direct Ink Writing of Silicon Carbide for Microwave Optics,” *Adv. Eng. Mat.*, vol. 18, 2016.

Metal Mirrors

- Aluminium mirrors have advantages in demisability over glass, SiC and Be mirrors
- Have a space heritage though mainly limited to the mid to far infrared wavelength regimes.
- Limited use at present due to high CTE issue and problems with attaining high optical surface quality.
- Nickel coated aluminium mirror have been developed (can get high surface quality) but suffer bimetallic effect. However, there is recent research into use of CTE matching aluminium silicon alloys to overcome this effect.
- A lot of recent research into additive manufactured metal mirrors – extreme light-weighting possible.



Far-infrared LOCUS prototype, Savini, UCL (2017)



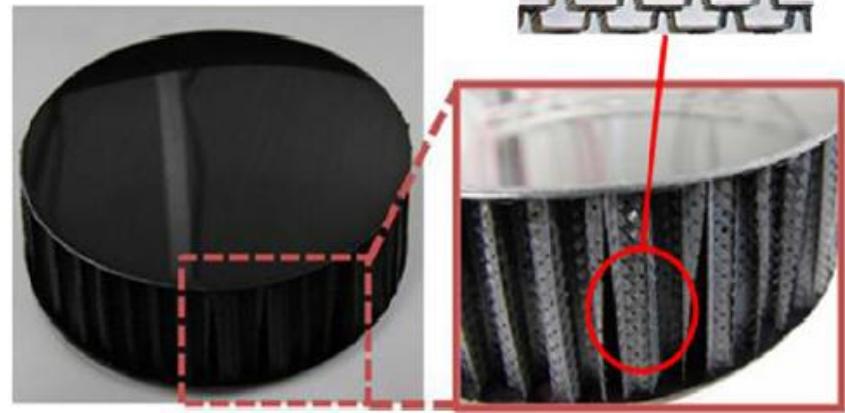
Sweeney et al. (2015)



CFRP mirrors

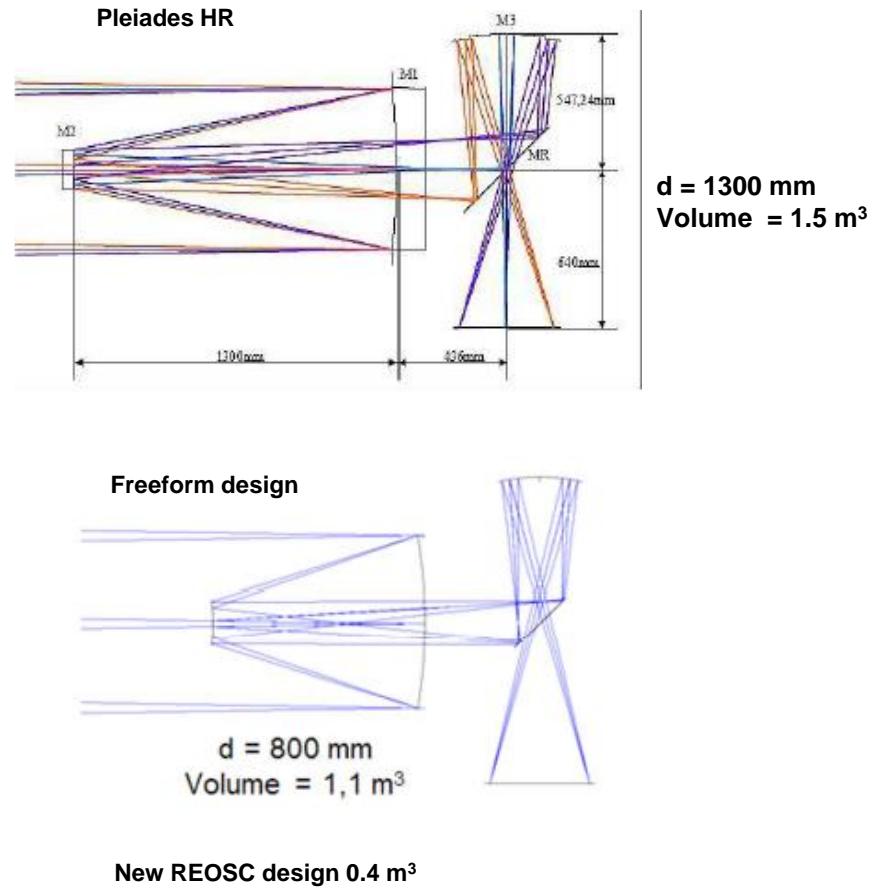
- Ultra low areal density, very low CTE.
- CFRP skins, CFRP (or C-C) honey-comb style cores.
- Nanometre RMS surface can be obtained.
- Issues: accuracy of optical surface form, moisture absorption.

Utsunomiya et al (2013)



Freeform Optics

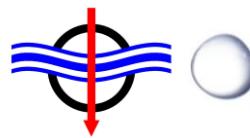
- The use of free form optics (non axisymmetric, higher order polynomial, Zernike polynomial..)
- Potential to enable more compact designs with the same performance.
- Made possible by development of 5 and 6 axis CNC polishing machines.
- Current limitation due to measurement of optical surface.
- Development of new testing techniques, such as phase deflectometry.



Figures from Geyl et al. (2016)

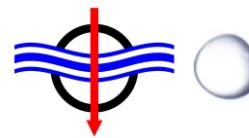
TRL levels

| Technology | TRL Level |
|--|-----------|
| Additive manufactured metal optical bench and support structures | TRL 3-4 |
| Additive manufactured metal mirrors | TRL 3-4 |
| Additive manufactured silicon carbide structures | TRL 3-4 |
| Carbon fibre composite mirrors | TRL 5-6 |
| Compact free form optics | TRL 2 |



Test Plans

Sam Bainbridge (FGE)

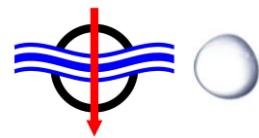


Test Plans

Aims:

- Increase confidence and development of the recommendations and guidance
- Improve the accuracy of the modelling approach employed
- Demonstrate the feasibility of identified D4D solutions and their future development

Four main uncertainties identified



Uncertainties

Demise behaviour of sandwich structures

- Most critical
 - In regular use
 - Usually large components
- Demise behaviour is largely unknown
 - Likely to consist of several modes of failure including ablative and mechanical processes
 - Lack of experimental data
 - Current testing, EU Redshift project, will provide first set of data
- Current models:
 - Aluminium proxy (aluminium melt model)
 - CFRP skin model (provides a lower demise rate)



HR Optical Bench



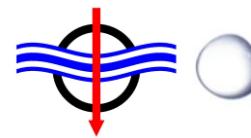
Uncertainties

Optical glasses demise behaviour

- New glass demise model developed during study
 - Failure mechanism based on the shear of the reduced viscosity, with temperature, material
 - Believed to be more representative than a latent-heat melting (metal-like) model
- Requires validation
 - Experimental testing



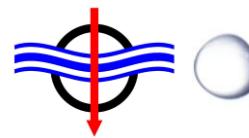
Zerodur post test



Uncertainties

Undemisable Joints

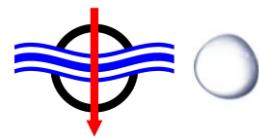
- Very effective D4D technique (MSI)
- Identification of methodologies
 - Brazed joints for SiC components very promising
- Testing of identified solutions
- Critical issue: thermal shock induced fragmentation
 - Severe thermal gradients → increased internal stress → development of cracks and eventually object failure
 - Potentially problematic for brittle components which are suddenly exposed to extreme heating as the payload breaks up
 - Testing required to determine if this phenomena is a concern
 - Potential to compromise undemisable joints technique
 - Should be tested first



Uncertainties

Gas-surface catalysis

- Stagnation point heating algorithm employed in SAM is after Detra and Hidalgo
- Correlates closely to CFD simulations of spheres using a fully-catalytic wall condition
- A fully catalytic wall condition is not conservative for the re-entry of a spacecraft
- A non-catalytic wall condition provides lower heat fluxes and is expected to be more realistic (material dependent)
- For example, ceramics are considered to have low catalycity
- 20-30% uncertainty depending on catalycity
 - Much smaller than the others mentioned
 - Much broader scope than just optical payload demise
 - As such, it should not be the focus of the proposed study



Test Plans

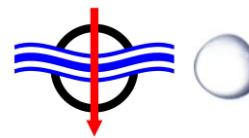
Objectives:

- Characterise the demise behaviour of sandwich structures
- Characterise the demise behaviour of glass materials
- Investigation of material response to thermal shock
- Characterise the demise behaviour of undemisable joints (if technique remains valid)
- Validate and calibrate the numerical models



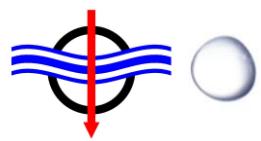
Conclusions

Sam Bainbridge (FGE)



Conclusions

- Statistical approach provides a good indication of the casualty risk
- Optical payloads are bespoke
 - Require different D4D techniques
- Guidelines should help optical payload manufactures early on during design phase
 - Identify critical components
 - Apply effective and non-invasive techniques
- New branch of the systems engineering process is required
 - Optical payload manufactures and aerothermal-demise engineers working collaboratively
 - Large emphasis must be made on helping designers understand what a payload looks like from a demise point of view



Any questions?