Spacecraft Robustness to Orbital Debris
Design Guidelines and Recommendations

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0. SUMMARY

0. INTRODUCTION & Context  
1. Space SAFETY (Debris Regulation & Population)  
2. Space DEPENDABILITY  
3. Mechanical Behaviour Laws  
4. H/W Mechanical Architecture  
5. S/C Mechanical Architecture  
6. S/C System Design  
7. OUTCOMES  
8. NEXT Steps  
9. CONCLUSIONS
0.1. Introduction & Context

1. INTRODUCTION:

- MMOD population (Micro-Meteoroids & Orbital Debris) is now mostly composed of man-made than natural objects.
- Orbital velocities of small debris (untrackable 1mm–10cm) are a lethal threat for S/C and a pollution of space environment.
- Increasing population due to fragmentations (explosions/collisions) is a concern for a sustainable future of space activities (Kessler Syndrome).
- A cascade chain reaction can be initiated above a certain level of debris: (Debris -> Impacts -> Fragments -> New Debris -> ...)

2. CONTEXT:

- Space Community raised 2 requirements on S/C Operations & Design:
  - PNP: Probability of Non-Penetration Demonstration (S/C Robustness)
  - PMD: Post Mission Disposal Capability (Debris Mitigation)
Those requirements are now applicable on S/C (Satellite) Design.

3. CONCLUSION:

- Assess S/C VULNERABILITY is NOW a REQUIREMENT.
- Improve S/C SURVIVABILITY is NOW a CONSTRAINT.
- Increase S/C ROBUSTNESS NOW needs GUIDELINES.
0.2. Intentions & Methodology

1. INTENTIONS

- Recommendations, Guidelines, Requirements, Models Tools currently available
- Examples of FMECA studies dedicated to MMOD impacts damages (DMECA)
- Examples of Design Risks Assessment versus MMOD impacts
- Lessons learnt on Robustness & Survivability of systems (AeroSpace & Others)
- Useful Guidelines and Recommendations for Satellite H/W & systems architecture

2. METHODOLOGY

- ISO_24113: 2011 “Space Debris Mitigations”
- IADC 04–03 v5.0 (2012–10) “IADC Protection Manual”
- ISO_DIS_16126: (E) MMOD risk assessment

3. GOALS:

Give DESIGNERS of S/C easy GUIDELINES for COMPLIANCE
Simplify MMOD Risk Analysis & REDUCE Iterative Process
0.2. Proposed Methodology & Outcomes

Project Methodology

1. SPACE SAFETY
   • Space Debris Regulation
   • Debris Population Characterisation
   • Models & Tools available Assessment per Orbit (Debris Size & Flux / m² year)

2. SPACE DEPENDABILITY
   • Models & Equations
   • Test Correlation
   • H/W Database
   • Shielding Engineering
   • Assessment of limit particle (Size, Kinetic Energy)

3. H/W Damage Laws & Shielding Ways
   • Survivability probability
   • PNP Assessment
   • S/C System Reliability
   • Reliability Assessment
   • S/C System Robustness
   • PMD Probability Assessment
   • Risks Classification Scale
   • Identification of critical systems
   • Criticality Assessment

4. H/W Mechanical Architecture
   • Shielding Integration
   • H/W Design
   • Sandwich panels
   • MLIs & radiative panels
   • Design Guidelines

5. S/C Mechanical Architecture
   • S/C mechanical architecture
   • S/C Shape Design
   • S/C Flight Attitudes
   • 3 Orbits case Studies (LEO, SSO, GEO)
   • 3 S/C case Studies (MicroSat, SmallSat, SATCOM)

   • System Recommendations
   • 3 Orbits case Studies (LEO, SSO, GEO)
   • 3 S/C case Studies (MicroSat, SmallSat, SATCOM)
0.3. Background Presentation

1. **ALTRAN Group**
   - **(in 2011)**
   - 1 420M€
   - 20 Countries
   - 17 000 Employees
   - 30 Years of Consulting

2. **ALTRAN France**
   - 54% of Activities
   - Mother Company

3. **ALTRAN ASD**
   - **AeroSpace Defense**:
     - (Historic Division)
   - **Automotive**
   - **IT Systems**
   - **Energy**

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**A Global Presence WHERE our Clients Need Us as “INNOVATION MAKERS”**
0.3. Background Presentation

1. ALTRAN Space Experience
0.3. Background Presentation

1. ALTRAN Space Experience
   - ESA: ATV Avionics, Hershel/Planck, ATV CC Operation team, SENTINEL 1-3
   - THALES: SPACEBUS, GB2, O3b, NEXT
   - ASTRIUM: ARIANE 5, Alphasat
   - OHB: Galileo FOC, EXOMARS, MTG

2. ALTRAN S3 Experience
   - ALTRAN Portugal: S3 Safety & Quality Team: PA Safety, PA P/F, PA P/L, QA OLCI, QA SRAL
   - ALTRAN Sweden: S3 Mechanical Architecture & Analysis
   - ALTRAN Lux: OLCI Thermal Architecture
   - ALTRAN France: SW Consistency Checks
   - ALTRAN Italia: P/F Project Management

3. ALTRAN Space Safety Experience
   - Involvement in S3 Safety Data package and Launch Safety Submission Process
   - Involvement in S3 Debris Risk Analysis and Retro-Design review
   - IAASS Member & Attendance at Space Safety Conference 4th, 5th, 6th
   - Training at IAASS “ISS Payload Safety Submission” @ Torino 2011

A EUROPEAN Synergy for SPACE Projects
A Reference Frame adapted for Geographic Returns
0.3. Background Presentation

1. **S3 Debris Mitigation COMPLIANCE**
   - 25 years natural Reentry due to 38% propellant budget for disposal
   - Reliability P/F >0.9 , 7yrs lifetime , Prop° Systems 12yrs lifetime
   - Reliability Disposal=0.9 @ 10years
   - PNP>0.99 for critical units (Tank, SMU, PCDU, with MASTER 2005)
   - Critical particle : 0.3–0.5 mm (worst case without shielding)
   - PNP Compliance IMPOSSIBLE for an entire panel

2. **S3 Development Experience**
   **DEBRIS RISKS** Assessment was quite innovative at that time
   - DEIMOS (E) MASTER 2001 + ETAMAX (D) ESABASE 2.0
   - TAS (F) – TAS(I) – RUAG (CH): Retro-Design needed
   ⇒ Long and Iterative Process but needed for next generation

3. **ALTRAN Space Safety Experience**
   - S3 Experience Debris mitigation & Retro design
   - Internal Workshop on Debris risk assessment
   - ESA BID “Simplified S/C Robustness Models for CDF” in 2012
   - ALTRAN RESEARCH Project (6WP in 2013) (MASTER 2009, ESABASE)
   - IAASS presentation “S/C Debris Robustness Guidelines

**Sharing LESSONS Learnt for Safety Community**

**A INNOVATIVE Project for SPACE Sustainability**
1.1. Regulations & Requirements

1. ORGANISMS:
   - *IADC Guidelines*, *UN–COPUOS*, *ISO*,
   - *NASA*, *JAXA*, *CSA*, *ESA*, *CNES*, *SPACE Codes of Conduct*

2. DOCUMENTATION:
   - *ISO 24113 : 2011*
     Space Systems _ Space Debris Mitigation
   - *IADC–02–01*
     Mitigation Guidelines _2007–07–05
   - *NASA–STD–8719–14A CHG–1*
     Limiting Orbital Debris _2012–05–25
   - *ESA AD4–Requirements*
     Space Debris Mitigation for ESA–Projects

3. GOALS:
   - Clarify Up-to-date STATUS of Space Debris REGULATIONS
   - Give DESIGNERS of S/C clear OBJECTIVES of COMPLIANCE
1. Regulations & Requirements

1. REGULATIONS:
*DEBRIS RISKS MITIGATIONS* _NASA-STD-8719-14 Chg1_2012_

- Uptodate, most detailed & general requirements for Spacecrafts & Satellite

2. REQUIREMENTS:

- **PMD > 0.9**: Post-Mission Disposal *(Rq56567)*
  - Considered for the *Manoeuvre* alone:
  - NOT including S/C Mission Lifetime reliability = 0.9 (P/F Lifetime)
  - NOT including Debris Robustness reliability = 0.99 (Debris Impacts)
  => 20% S/C still may be lost during lifetime (worst case)

- **PNP > 0.99**: Probability of NON-Penetration *(Rq56507)*
  - Considered *Panel penetration only* and *lifetime to prevent disposal*
  - S/C may be *lost even without Panel penetration* due to Debris impact (external SPF?)
  - S/C can survive even after Panel penetration due to Debris impact (internal unit shielding)
  - Damage Mode Analysis (DMECA) is due to assess accurately Probability of Non-Failure
  => 10% S/C still may be lost due to Debris Impacts (worst case)

- **PNF > 0.999**: Probability of NON-Explosion *(Rq56449)*
  - Considered for S/C explosion and NOT debris impact related
  => 1% S/C still may explode due to debris impacts (worst case)

3. CONCLUSIONS: WORST CASE is still MARGINAL for Acceptability

   Next Gen° S/C should anticipate STRONGER requirements
1.1. Regulations & Requirements

1. STATUS:

*Internal WORKSHOP intention*:

- STRINGENT & EASIER Design Objectives
- ENVELOPPE of potential regulations evolutions & Debris population scenarios

2. RECOMMENDATIONS:

- **PNF > 0.9 : S/C NON COMPLIANT (all Causes) (Mission Catastrophic)**
  - Including Mission Reliability till end of Disposal > 0.9 (P/F Lifetime)
  - Including Lifetime = Disposal time (Mission & Disposal included)
  - Including margin = Space Debris Impacts (external causes)
- **PNF > 0.99 : S/C LOST (by Debris) (S/C Catastrophic)**
  To be considered lifetime to prevent disposal usually assessed with Panel penetration only
  - IncluS/C may be lost even without Debris impact Panel penetration (external SPF?)
  - S/C can survive even after Debris impact Panel Penetration (internal unit shielding)
- **PNF > 0.999: S/C EXPLOSION (all Causes) (Space Envt CATASTROPHIC)**
  - Internal causes (Critical SYSTEMS: Propulsions, Pressurised systems)
  - External causes (Space DEBRIS impacts on critical systems)

3. CONCLUSIONS: STRINGENT & EASIER Design Objectives

- ENVELOPPE of potential regulations evolutions
1.1. Regulations & Requirements

1. REGULATIONS:

*DEBRIS RISKS ASSESSMENT* (PNP assessment)

2. REQUIREMENTS:

- PNP: Probability of NON–Penetration
  - Debris Population Assessment per Orbit (Debris models)
  - Critical Particle Assessment (Damage Laws of H/W)

- PNF: Probability of NON–Failure
  - DMECA : Damage Mode and Critically Analysis (Impact related)
  - FMECA : Failure Mode and Critically Analysis (Systems related)

3. CONCLUSIONS:

*Clarify DESIGNERS the Analysis METHODOLOGY*
1.1. Regulations & Requirements

1. REGULATIONS:

POST MISSION DISPOSAL (PMD assessment)

2. REQUIREMENTS:

• PMD: Post Mission Disposal
  • Probability 0.9 to perform Delta-V for S/C commissioning at end of life, and Systems Passivation
  • Commissioning for LEO: 25 Years Atmospheric Reentry, MEO-GEO: 200 km Graveyard Orbit
  • Passivation of Energetic systems (propulsion, batteries, ...)

• Combined Requirements:
  Compliance ? = Reliability (Mission Lifetime x Debris impacts x Disposal)

3. CONCLUSIONS:

Clarify DESIGNERS the Analysis METHODOLOGY
1.2. Debris Population Status

1. STATUS:
Debris Population Models
- ISO_DIS_14200:2012
Implementation of MMOD Environmental models

2. METHODOLOGY
Debris Population per Orbit / Face / Debris Size
- Flux rate : Nb (n/m²/Yrs) per Azimut / Elevation
- Flux rate : Size (mm/m²/Yrs) per Azimut / Elevation

3. GOALS:
- Lethality / Orbit
- Lethality / Surface

Give DESIGNERS of S/C clear Population Data & Evolutions Trends
1.2. Debris Population Status

1. STATUS:
Most concerned Orbits:
- 700–900 km: LEO–SSO
- 1500 km: Globalstar constellation
- 20–22000 km: GPS–GNSS constellation
- 36000 km: GEO

2. RECOMMENDATIONS:
LEO–SSO needs specific cares
- Debris Models are late versus S/C needs
- Introduction of scenarios (BAU, PMD, ADR)
- Uptodate Population models to be used

Debris population needs calibration
- Earth returned space H/W now less available
- On-board debris sensor (DEBIEE etc.)

3. CONCLUSIONS:
Population Models are more accurate, but
Still random and not accurate enough
1.2. Debris Population Status

1. STATUS:
   Population Constitution
   • Ratio MM/OD = 1/2 (at ISS orbit)
   • 3 Log (Nb Debris) = – Log (Debris Size)

   Population Evolution Trends
   • Debris Flux MASTER 2001
   • Debris Flux MASTER 2005
   • Debris Flux MASTER 2009

2. RECOMMENDATIONS:
   • Debris Critical Size = 0.5–1 mm
   • Debris Lethal Size = 0.5–1 cm

NEVER FORGET: 1 g @ Mach 28 => 800 g @ Mach 1
Small Washer in Orbit => Petanque Bowl in Supersonic

3. GOALS:
   Satellite DESIGNERS shall consider those Sizes as LETHAL
1.2. Debris Population Status

1. STATUS:
Population Caracterisation versus S/C faces:
- V (MMOD) = \( f^\circ \) (Cos angle)
  - V (OD) = 14km/s (0°) – 10km/s (45°) – 7Km/s (90°)
  - V(MM) = 20–30km/s (0°) more random direction
- Nb (MMOD) = \( f^\circ \) (Cos angle)

2. RECOMMENDATIONS:
Most Exposed Surfaces by order of Lethality:
- Velocity : Front Face
- In plane : Lateral/ Side Faces
- Anti–Earth : Zenith/ Top face
- Earth : Nadir/ Bottom Face
- Anti–Velocity : Rear/ Back face

3. CONCLUSION:

DESIGNERS shall consider LETHAL and SAFE Faces
Locate CRITICAL Units on SAFE Faces
1.2. Debris Population Status

1. STATUS:
Population Characterisation:
• Azimuth (MMOD) = −90°/90°
• Elevation (MMOD) = −30°/30°

2. RECOMMENDATIONS:

Faces considered with different Lethalities:

<table>
<thead>
<tr>
<th></th>
<th>Front</th>
<th>Side</th>
<th>Top</th>
<th>Bottom</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris (Low)</td>
<td>3</td>
<td>3</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Meteoroid (Low)</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

* Front = facing direction of motion, Side = perpendicular to the direction of motion and the surface of the Earth, Top = facing the zenith, Bottom = facing the centre of the Earth, Rear = facing opposite to the direction of motion.

3. CONCLUSION:
DESIGNERS shall consider Debris FLUX directions as LETHAL
Protect CRITICAL Units from LETHAL Flux
2.1 FMECA dedicated to MMOD impacts

1. STATUS
   - FMECA never included Disposal & Penetration probability
   - METHODOLOGY:
     - CONSEQUENCE Classification on Satellite (of Debris Impact)
       1. S/C Minor = P/L or P/F Major = Sub System Major = Equipment Critical
       2. S/C Major = P/L or P/F Critical = Sub System Critical
       3. S/C Critical = P/L or P/F major = Mission lost with correct disposal of S/C
       4. S/C Catastrophic = S/C lost w/o disposal or major fragmentation
       5. Space Envt Catastrophic = S/C Explosion = Complete Fragmentation & Environmental Pollution
     - Dedicated Classification on Space Environment (of Debris Impact)
       1. Space Envt Negligible = No Ejectas Produced
       2. Space Envt Minor = Few Ejectas Produced
       3. Space Envt Major = Large Ejectas population produced, minor fragmentation
       4. Space Envt Critical = Debris S/C stuck in useful protected orbit, major fragmentation
       5. Space Envt Catastrophic = Complete S/C Fragmentation & Environmental Pollution
    - Added Classification related to SPACE ENVIRONMENT

3. GOALS:
   OVERVIEW all Systems & Assessment of related VULNERABILITY
   Identify CRITICAL Systems & focus on ROBUSTNESS Improvements
2.1 FMECA dedicated to MMOD impacts

1. STATUS
   • DMECA has to be performed for Debris impact risk scenarios (Survivability)

   • METHODOLOGY
     • Dedicated LIKELIHOOD Classification = \( F^\circ \) (1/Energy or Debris Size/Velocity)
       1. NRJ= 5: EMR >> 40J/g or Debris >10cm (Complete Fragmentation)
       2. NRJ= 4: EMR >40J/g or Debris >1cm (Several Penetrations)
       3. NRJ= 3: EMR >4J/g or Debris >1mm (Panel Penetration)
       4. NRJ= 2: EMR >0.4 J/g or Debris >0.1 mm (Surface Penetration)
       5. NRJ= 1: EMR >0.04 J/g or Debris >0.01mm (Surface Erosion)

     • Dedicated LIKELIHOOD Classification = \( F^\circ \) (Exposed Critical Area)
       1. Critical Area <10cm² or Punctual critical zone (critical connectors)
       2. Critical Area <100 cm² or Small Equipment size (TTC Switch)
       3. Critical Area <1m² or Equipment size / Harness length
       4. Critical Area <10m² or Sub Panel Size / Instrument
       5. Critical Area >10m² or Satellite Panel Size / Solar Array surface

     • Criticality : \( Cn=Sn \times Pn \) : Severity x Probability

2. GOALS:
   OVERVIEW all Systems & Assessment of related VULNERABILITY
   Identify CRITICAL Systems & focus on ROBUSTNESS Improvements

   • Criticality : \( Cn=Sn \times Pn \) : Severity x Probability

   1  2  3  4  5

   5  10  15  20  25

   4  8  12  16  20

   3  6  9  12  15

   2  4  8  10

   1  2  3  4  5
2.1 FMECA dedicated to MMOD impacts

1. STATUS

External Equipments:
- Propulsion SPF = FDVs, (External Tubing leak), THR FCV? => High Potential LOS
- Electrical SPF = Single SAW Harness/Connectors => Potential LOM or LOS
- Electro-mecha SPF = Single SADM => Potential LOM or LOS
- TTC SPF = P/F Antenna & Coax (S-Band) => Potential LOM or LOS
- TTC SPF = P/L Antenna, Wage guide (X-Band) => High Potential LOM
- Instruments SPF = Optics, Baffles, Horns, Reflectors => Potential LOM
- C/C SPF = SKC & UMB? connectors (if segregated) => Switch to RED
- Thermal SPF = MLI radiative panels, OSR => Acceptable due to margins

2. RECOMMENDATIONS:
- REDUNDANCY: Avoid Mono SAW deployable & orientable
  Harness routing multi segregated, Connectors protected
- SHIELDING of FDVs, THRls, RF Systems
  Addition of a FDV panel shielding after fuelling, THR FCV in P/F
  Robustness of TTC via real segregation multi (P/L Rx)
- FDIR, DNEL and Ground Operations Strategy
  Operations Check monitoring period & Emergency Time response < BATT autonomy

3. CONCLUSIONS:

Identify CRITICAL Systems & focus on ROBUSTNESS Improvements

Protection on ALL SPFs, REDUNDANCY and SEGREGATION
2.1 FMECA dedicated to MMOD impacts

1. STATUS

**Internal Equipments:**
- Propulsion SPF = Propellant tank => Potential EXPLOSION
- Propulsion SPF = Tubings (several meters) => High Potential LOS
- TTC SPF = P/F RF switch - Coax routing (2meters) => Potential LOS
- Electrical SPF = PCDU & PWR wiring => Potential LOM or LOS
- Electro-meca SPF = SADM => Potential LOM or LOS
- TTC SPF = P/L Antenna, Wage guide (X-Band) => High Potential LOM
- C/C SPF = SMU & C/C Wiring => Switch to RED, Potential LOM or LOS
- Thermal SPF = Heat Pipes => Acceptable due to margins

2. RECOMMENDATIONS:

- Critical Harness Routing SEGREGATION
  RF & C/C Harness segregated (5–10cm)
  Connectors protected by Unit (vs Debris Flux)
  PWR Harness multi segregations (pending acceptable loss of power)
- **SHIELDING and REDUNDANCY**
  Tank & related Tubings Double–Protected (Tube–Cone)
  Redundant THR sets (Double branches) where only one single Panel protection

3. CONCLUSIONS:

Identify CRITICAL Systems & focus on ROBUSTNESS Improvements
DOUBLE Protection on small SPF, REDUNDANCY and SEGREGATION
2.2. Impacts Risk Assessment

1. STATUS:

Tools Available:
• NASA: DAS 2.0.2 & BUMPER2 Code
• ESA: DRAMA & ESABASE2 v3.0

2. METHODOLOGY:

• IADC 04–03 v5.0 (2012–10)
  “IADC Protection Manual”
• ISO_DIS_16126_(E)_Draft
  MMOD risk assessment

3. INTENTIONS:

Give DESIGNERS friendly TOOLS for Impact Risk Assessment
2.2. Impacts Risk Assessment

1. STATUS

2. RECOMMENDATIONS:

   • **Promote Software tools**: ESABASE2, Bumper Code
   • **Improve Software tools**:
     - Geometrical CAD I/F
     - Mission Orbit Analysis
     - Debris Population Models
     - H/W Mechanical Behaviour (BLE)
     - H/W Database characterisation
     - PNP assessment geometrical models
     - Shielding Solutions

3. CONCLUSIONS:

   Give DESIGNERS friendly TOOLS for Impact Risk Assessment
3.1. H/W Damage Laws

1. INPUT DATA

**HIT Correlation** (Hypervelocity Impact Tests)
Inventory of available **BLE**
(Ballistic Limit Equations)

2. CURRENT STATE of ART

- Standard NASA TM2009–214785
  “MMOD Protection Design”
- Standard NASA TM2009–214789
  “Shield Ballistic Limit Analysis”
- IADC 04–03 v5.0

3. GOALS:

Overview of ALL Damage Laws applicable to S/C Hardware
Give DESIGNERS of S/C data for H/W ROBUSTNESS characterisation
3.1. H/W Damage Laws

1. STATUS

- **Single Wall Panel** (Metallic Unit Skin)
  - Mc Donnel Sullivan, Pailer-Gruen, etc...
- **Double Wall Panel** (Sandwich panels)
  - Cours Palais, Maiden Mc Millan
- **Multiple Wall Panel** (Unit behind panel)
  - Maiden Mc Millan, Ryan Schaeffer Lambert
- **Honeycomb Panel**
  - New Cours Palais Equations
- **MLI Contribution** (Thermal insulation)
  - New Cours Palais Equations

2. RECOMMENDATIONS:

1. Characterisation of Satellite H/W
2. Related Equation Damage Database
3. GOALS:

**Overview of ALL Damage Laws applicable to S/C Hardware**

**Give DESIGNERS of S/C data for H/W ROBUSTNESS characterisation**
3.2. H/W Shielding

1. INPUT DATA
Heritage shielding (ISS)

2. INTENTIONS
- Improve H/W Shielding for S/C
  - Whipple Shields, Stuffed Whipple (Nextel, Kevlar)
  - Increase Stand-Offs distance
  - Reinforced MLI (Textile toughened with Kevlar, Carbon)
- State of Art on Shielding Processes:
  - Lesson learnt from in other domains (Automotive, Military, …)
  - Ballistic impacts, lightweight shielding
- Innovative Shielding H/W Processes:
  - Nanomaterials – Nanotubes Carbone – Ceramics

3. GOALS:
Overview of ALL Shielding Processes applicable
Give DESIGNERS new SHIELDING Solutions
3.2. H/W Shielding

1. STATUS
Benefit of Impact Angle in BLE
(honeycomb multi-shock effect)

2. RECOMMENDATIONS:
\[ \cos \left( -\frac{1}{2}, -\frac{2}{3}, -1, -\frac{3}{2} \right) \]
- Critical particle size increased: + (25-50)%
- Critical Flux increased: \( f_0 \cos^{(2)} \)
- Nb Critical Particles decreased
- PNP increased: \( f_0 \cos^{(3\text{or}4)} \)
- PNP Equivalent Surface: \( f_0 \cos^{(2\text{or}3)} \)

3. GOALS:
Panels Optimisation
3.2. H/W Shielding

1. STATUS
Benefit of Bumper Wall material

2. RECOMMENDATIONS:
   • Integrate shielding material in H/W design
   • Toughened MLI
   • Stuffed multi-Sandwich panels

3. GOALS:
   Materials Optimisation
3.2. H/W Shielding

1. STATUS
Innovative Materials & Processes

2. RECOMMENDATIONS:
- Innovative Materials: Carbon Nano-Tubes
- Innovative Textile Sandwich: Kevlar, Synthetic Spider wire
- Innovative Foams: Aerogel, Metallic
- Innovative Resins: Carbone or Nano particle charged

3. GOALS:
Overview of ALL Innovative Shielding
Synthesis from NON-Space Domains
4. H/W Mechanical

1. STATUS
Sandwich Panels (Skin & Honeycomb)
- **BENEFIT of Stand-Off, BUMPER Wall**
- **BENEFIT of Multi-.Shocks**

2. RECOMMENDATIONS:
- Implement Bumper wall Effect via MLI
- Double–Triple Sandwich (multi shocks)
- Sandwich Panel Stuffed (Kevlar layer)
- Thicken Rear Wall (Unsymmetrical Panel)
- Optimize Definition (Shielding/Weight)
- Optimize Process (Complexity/Costs)

3. GOALS:
**New Designs of Mechanical H/W**
4. H/W Mechanical

1. **STATUS**
   Multi Layer Insulation (MLI)
   - *BENEFIT of Stuffed shielding*
   - *BENEFIT of Toughened Layers*

2. **RECOMMENDATIONS:**
   - Install Toughened MLI
   - Install MLI on Stand-off Frame
   - Provide Max Stand-Off
   ⇒ **PB on S/C Radiative faces (OSR)**
   - MLI & Stand-off is prohibited
   - Max radiative view is needed
   - Shielding layer need thermal properties
   ⇒ **New Design to be investigated**
   - Ondulating Frame Rails
   - Thermal drains

3. **GOALS:**
   - New Designs of Thermal H/W
4. H/W Mechanical Architecture

1. STATUS
   Electrical Units
   Electrical Harness

2. RECOMMENDATIONS:
   • **Connector face** are only SINGLE-protected
     ➞ to be protected by unit shadowing
     (unit orientation vs Debris Flux)
     ➞ Mother board face is double protected
   • **Unsymmetrical** Boards implementation
     ➞ Risk on central boards (N+R) in regard
     NOM boards vs Flux gives triple protection for RED boards
   • **Electrical harness SEGREGATION**
     ➞ SEGREGATION NOM / RED Routings
     ALWAYS to be implemented

3. CONCLUSION:
   Robustness can be easily achieved (No cost – No mass)
   Geometrical LOCATION & SEGREGATION versus main Debris FLUX
4. H/W Mechanical Architecture

1. STATUS
   Structural Panels
   • Shielding Materials
   • Tilted Panels
   • Cylindrical Structures

2. RECOMMENDATIONS:
   • “Aerodynamic” Shaped structure
     ⇒ Tilt panels in Elevation direction 45°
     ⇒ Tilt panel in Azimuth direction : 60°
   • Cylindrical Structure
     ⇒ less surface in normal incidence
   • Lessons learnt from Military World
     (F-117, B-2, F-22, M-1, Shielded Jackets..)
     ⇒ Less Cross Section & Surface wrt Debris Flux
     ⇒ Stuff panels with Shielding devices
     ⇒ Redundancy (NOM,RED,SAFE) & Segregation

3. CONCLUSION:
   Robustness can be easily achieved (Less cost – Less mass)
   RESHAPE Envelope Frames versus main Debris FLUX
5. S/C Mechanical Architecture

1. STATUS

P/L is always considered as the KING of the S/C
- P/L accommodation is always considered as a major S/C Design Driver, BUT
Loosing Mission is BAD, Loosing Satellite is WORST
- P/F Systems are CRITICAL for S/C survivability (Prop, EPS, TTC, C/C, AOCS)
No more Missions if No more S/C or No more SPACE activities
- Criterion shall be based on Space Environment Sustainability

2. RECOMMENDATIONS:

- PROTECT P/F Equipments
  - Critical units Installed in S/C Core Structure (not on panels)
  - Propulsion Tanks in Double Structural protection (Central Tube or Cone)
- P/L Equipments USED as Protective units for P/F units:
  - Case by Case for Critical systems
- General Guidelines of Shielding ways
  - Optimised mechanical architecture more "debris-proof" oriented

3. CONCLUSION:

PAYLOAD is EXPENDABLE and can be SACRIFICED
PLATFORM is CRITICAL and shall be PROTECTED
5. S/C Mechanical Architecture

1. STATUS
   *Critical units or SPF SHALL be protected*

2. RECOMMENDATIONS:
   - Mitigate Exposed surfaces to Debris Flux:
     - Less critical surface in debris flux side (velocity vector)
     - Shadowing by unit itself (critical connector face)
   - **Critical Unit in the Core of the S/C**
     - Less critical surface in debris flux side (velocity vector)
   - **Critical Unit out of Lethal faces**
     - Less critical surface in debris flux side (velocity vector)
   - **Critical Units (P/F) protected by less critical units (P/F)**
     - Less critical surface in debris flux side (velocity vector)

3. CONCLUSION:
   - ACHIEVABLE at LOW Cost, Low EFFORT
   - BASICS RULES are RELOCATION and ORIENTATION
5. S/C Mechanical Architecture

1. STATUS
   SATCOM comparative Architecture
   • Spacebus Family (THALES)
   • Eurostar Family (ASTRIUM)

2. RECOMMENDATIONS:
   • Propellant Tank Double Shielding
     • Inside a Central Tube, Central Cone
     • Protection by Compartments
     • Multi panel protection
     • Critical unit in S/C core
     • Location on Shear Webs

3. CONCLUSION:
   ARTEFACTS are possible to give ADDITIVE protection
   To be introduced in very EARLY Design Phase (0 or A)
5. S/C Mechanical Architecture

1. STATUS

*S/C Attitude vs Velocity Vector*
- SATCOM Old generation: Eurostar, Spacebus
- SATCOM New generation: ALPHASAT

2. RECOMMENDATIONS:

- Mitigate Exposed surfaces to Main Debris Flux:
  - Less surface in front velocity vector
  - Less surface on lateral panels (parallel to orbital plane)
  - More surface in protected area (anti-velocity vectors)
- Protection by Equipment Shadowing:
  - Reflectors, Solar Arrays
  - Provide *bumper effect* and *energy dissipation* to critical P/F panels

3. CONCLUSIONS:

ARTEFACTS are possible to give ADDITIVE protection
To be introduced in very EARLY Design Phase (0 or A)
5. S/C Mechanical Architecture

1. STATUS
   S/C Attitude vs Velocity Vector
   • Comparative GMES Sentinel-1,2,3

2. RECOMMENDATIONS:
   • Present Less surface to Main Debris Flux:
     • Increase impact angle and critical particle diameter
   • Preserve P/F critical equipments
     • Optimised mechanical architecture more “debris-proof” oriented
   • Present Less critical unit to Main Debris Flux
     • Give shadowing to critical units

3. CONCLUSIONS:
   S/C Mechanical Robustness is Possible at ISO-Cost & Technology
   DEBRISPROOF Designs & improve SHIELDING by Architecture
5. S/C Mechanical Architecture

1. STATUS
   S/C Structural Frames Shape
   • Comparison: Proteus, Astrobus, Leostar, GB2

2. RECOMMENDATIONS:
   • Present Tilted surfaces to Main Debris Flux:
     • Increase impact angle and critical particle diameter
   • Fly on tilted vector at ISO-structural geometry
     • Optimised S/C Attitude more "debris-proof" oriented

3. CONCLUSIONS:
   S/C Mechanical Robustness is Possible at ISO-Cost & Technology
   DEBRISPROOF Designs & improve SHIELDING by Architecture
5. S/C Mechanical Architecture

1. STATUS
   S/C Structural Frames Shape

2. RECOMMENDATIONS:
   • **Present Tilted surfaces to Main Debris Flux:**
     • Increase impact angle and critical particle diameter
   • **Present less Front Cross Section**
     • Optimised S/C mechanical architecture more "debris-proof" oriented

3. CONCLUSIONS :
   S/C Mechanical Robustness is Possible at almost ISO-Cost & Technology DEBRISPROOF Designs & improve SHIELDING by Architecture

1. STATUS

ENVISAT Lessons learnt
- Enhance Robustness to failure for Disposal
  ⇒ Double Failure Tolerant ?
- Improve Alert, Recovery, Investigation capabilities

2. INTENTIONS

- Complete Redundancy of all Systems ?
  - Probably not cost efficient for satellite if designed as manned S/C
    (4 Gyros , 4 On-Board Computers , 4 Prop' systems .. !!)
- Inventory of on–board redundancies provided by subsystems
  - Investigate all redundancies capabilities inside a same system , using a different system
  - Duplicate capabilities in several electronic units (ACMU, CDMU, PDHU)
- Autonomous safety or Emergency devices ?
  - OBCP for degraded scenarios and contigency scenario (FDIR, DNEL, SAFE mode philosophies)
  - Autonomous capability for deorbit ? Autonomous on-board decision ?

3. GOALS:

Give DESIGNERS Recommendations for RELIABILITY Improvements
INVESTIGATE new Solutions of improved ROBUSTNESS on Systems

1. INPUT DATA

PROPULSION SYSTEM

2. RECOMMENDATIONS:

- **CRITICAL parts of SYSTEMS** (double protected)
  - Tanks and upstream tubing & units upstream LVs
  - Close LV when Prop° not used, Consider leak failure at each LV opening

- **REDUNDANCY of THR set** (as not double protected):
  - Always provide 3 axis for S/C torque capability
  - Capability to be achieved on each set independently

- **SHIELD “tubing” external parts**
  - FDVs (could be protected after fuelling)
  - THR Flow control valves (if external of panels)

- **ANTICIPATE contingency procedures**
  - Gauging via PVT, Pulse counting etc…
  - Deorbit with only redundant THR set in boost & attitude control mode

3. GOALS:

   - Give DESIGNERS Recommendations for RELIABILITY Improvements
   - INVESTIGATE new Solutions of improved ROBUSTNESS on Systems

1. INPUT DATA

ELECTRICAL POWER SYSTEM

2. RECOMMENDATIONS:

- Avoid SPF (if possible)
  Solar Arrays on P/F (no external harness, no SADM)

- Improve Redundancy & Segregation
  2 SAW, 2 SADMs,
  Harness routing segregation, connectors protection

- Assess PWR performance & autonomy (in case of impact failure)
  Loss of harness & PWR connector has to be assessed (as few impact protection)
  Emergency PWR scenario to be investigated in order to comply deorbit time / Ground operation reactivity
  => Need of Requirements, Need of analysis scenarios

3. GOALS:

Give DESIGNERS Recommendations for RELIABILITY Improvements
INVESTIGATE new Solutions of improved ROBUSTNESS on Systems

1. INPUT DATA

RF SYSTEMS

2. RECOMMENDATIONS:

- Remove SPF
  - RF Harness SEGREGATION !!
  - RF Switch Redundancy & Segregation

- Alternative way of getting TC On-Board
  - Safety RF link ?
  - Alert on-Board & Ground monitoring ?

3. GOALS:

Give DESIGNERS Recommendations for RELIABILITY Improvements
INVESTIGATE new Solutions of improved ROBUSTNESS on Systems

1. INPUT DATA

AOCS SYSTEM

2. RECOMMENDATIONS:

- Having Redundant capabilities
  - Most AOCS already implement 2 redundant systems
  - Fine Mode for Mission Mode: RWA (wheels), STR (Star tracker)
  - Coarse Mode for SAFE Mode: CSS (Sun Sensor), MTB (magnetotorquers)
  - THR set ways should always remain multi-axis capable (even in degraded mode)
  - MTB may be an alternative torque capability for deorbit

- Implement both independent capabilities
  - SW patch allows mission in 2 RWA instead of 4 (GB2 experience)
  - Contingency OBCP shall allow degraded modes for disposal

3. GOALS:
   Give DESIGNERS Recommendations for RELIABILITY Improvements
   INVESTIGATE new Solutions of improved ROBUSTNESS on Systems

1. INPUT DATA

C/C SYSTEM

2. RECOMMENDATIONS:

- **Redundancy for Disposal ? (ACMU -PDHU)**
  Current trends is to rely on OBC/ SMU for all critical systems (AOCS, TTC,PWR)
  ACMU or PDHU alternative capability with TTC in addition of SMU/OBC
  Rustic architecture allowing to roughly deorbit
  Alternative rustic S/W able to roughly deorbit

- **Autonomous Deorbit capability ?**
  OBCP ready for disposal?

- **Autonomous Deorbit decision ?**
  On-board health check , Decision after long loss of TC ?

3. GOALS:

Give DESIGNERS Recommendations for RELIABILITY Improvements
INVESTIGATE new Solutions of improved ROBUSTNESS on Systems

1. INPUT DATA

SAFETY KIT SYSTEM

Giving partial or total redundant and autonomous capability

2. RECOMMENDATIONS:

- SAFETY BEACON (TM&TC Alert & Emergency RF Link)
  Alert service to Ground operations and Emergency Remote Control (TDRS, EDRS like ?)
- BLACK BOX (Data Recorder& Transmitter)
  Airliners ACARS-Like for investigation and alert
- Autonomous Deorbit capability
  OBCP ready for disposal? Onboard decision ?
- PASSIVE DEORBIT DEVICE Actuation
  Safety devices: Solar sails, deployable devices, inflatable devices to reduce deorbit time
- Autonomous PWR (Battery & Charge)
  1 month autonomy ?
- Debris & Shock impact SENSOR
  Debris population characterisation, Impact shock detection

3. GOALS:

Give DESIGNERS Recommendations for RELIABILITY Improvements
INVESTIGATE new Solutions of improved ROBUSTNESS on Systems
7. Outcomes

1. GUIDELINES
   • **Most Easy Ways for Robustness** (Shorter Cost / Time Development)
     - Trade-off on existing best design platform for **DEBRISPROOF** capability (tilted panels, multi-panels)
     - Most of time P/F & P/F are based upon specific design / W Shielding Design (Applicable to S/C & Innovative Processes)
     - Redundancy & **SEGREGATION Rules** in H/W & S/C architecture
     - Redundancy & Segregation Rules in S/C Systems & Multi-Capability/Purpose inter-systems
     - Worst Easy ways for Robustness (Longer Cost / Time Development)
       - Mechanical shielding for Satellite / Material Improvement (Time, cost weight, tests, qualification)
       - Miniaturisation of Systems (Efficient SMALLSAT)

2. RECOMMENDATIONS:
   • DEBRIS POPULATION characterisation / identification (DEBIEE)
   • Improve RESEARCH on **INNOVATIVE Materials** & Shielding techniques
   • Design Innovative / Experimental Satellite (DEBRISPROOF)
   • Design ROBUST SYSTEMS / MULTI capabilities (NOM/RED/SAFE)
   • Investigate Innovative BACK-UP Systems (SAFETY DEVICES)

3. GOALS: **Ensure SPACE activities SUSTAINABILITY**
   SAFER Systems for a SAFER Space and a SAFER World
8. Next Steps

1. SPECIFIC FOCUS
   • H/W Shielding Design (Improved H/W Applicable to S/C & Innovative Processes )
   • S/C Mechanical Architecture (State of Art of DEBRISPROOF Designs : internal & external : P/F & P/L)
   • S/C Systems Reliability (Multi-redundant architecture, Safety systems for alert, investigation, disposal.)

2. SPECIFIC CASE STUDIES
   • Observation SAT in SSO (Sun Synchronous Orbit)
     • Heavy Shielding = Weight impact ? Thermal Performance? => Impact of Mechanical architecture
     • Disposal = Natural of Controlled Reentry? => Propellant Budget ? Prop° systems ? Disposal reliability ?
   • Constellation SAT in LEO (GB2 like orbit 1500km)
     • Less Shielding = P/L Expendable wrt P/F Critical systems !! => Impact on System architecture (low-cost?)
     • Disposal = graveyard or reentry orbit ? => Propellant Budget ? Autonomous deorbit capability ?
   • Telecom SAT in GEO (Geo Stationary Orbit)
     • Shielding ways = Alphasat like architecture & Shielding ways => Impact on Heavy S/C structures
     • Disposal = 200Km ReOrbit => Propellant budget? Accuracy in EOL ? Disposal decision point ? Safety Systems ?
   • Micro-Sat in LEO (Low Earth Orbit)
     • Shielding ways = Few !! => Small size reduce Debris impact risk but increase natural reentry after failure
     • Trade-Off : BIG & ROBUST satellites with short natural reentry / SMALL & WEAK with longer natural reentry

3. GOALS: Give DESIGNERS of S/C easy GUIDELINES for COMPLIANCE
   Simplify MMOD Risk Analysis & REDUCE Iterative Process
9. Conclusions

1. CONTEXT

• A project oriented for a Sustainable Future of Space Activities
• An engineering study clearly in the Space Trends and a need for Space Industry
• An answer to problematic concerns raised by Space Debris Population

2. INTENTIONS

• Robustness to Space Debris Survivability
  • Current Status of S/C Vulnerability
  • State of Art of Shielding process applicable to S/C
  • Trade-off of Innovative process & implementability on S/C
• Robustness to Mission Disposal Capability
  • Current Status of S/C Reliability (3 cases)
  • State of Art of Reliability Improvement applicable to S/C
  • Trade-off of Innovative process & implementability on S/C

3. GOALS:

Design Guidelines & Recommendations HELPFUL for the Space Community
“SAFER SYSTEMS for a SAFER SPACE and a SAFER WORLD”
Any Questions?
Any Comments?
10. Schedule

1. Planning

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2. Assumptions

- TO = 15/01/2013, Total Duration 9 months
- All Work package are assessed as 50% part time activities

3. GOALS:

**Paper & Presentation for IAASS Conference in April/May 2013**

**Final Report and full documentation for activity closure in 2013Q4**
11. Key Personnel

1. Work Packages
   • WP 0: Documentation & Management
   • WP 1: Safety Regulation & Debris Population
   • WP 2: FMECA & Reliability Analysis
   • WP 3: Damages Equations / H/W Shielding Database
   • WP 4: H/W Mechanical Architecture
   • WP 5: S/C Mechanical Architecture
   • WP 6: S/C Systems Architecture

2. Working Skills:
   • WP 0: Overall Management & Coordination : S.HEINRICH
   • WP 1: Space Safety : D.LEGLOIRE – S.HEINRICH
   • WP 2: Space Dependability : R.AMIEL – S.HEINRICH
   • WP 3: Mechanical Behaviour & Computation Analysis: D.LEGLOIRE – A.TROMBA
   • WP 4: H/W Mechanical Architecture : D.LEGLOIRE – A.TROMBA
   • WP 5: S/C Mechanical Architecture : A.TROMBA – S.HEINRICH

3. GOALS:
   An Equivalent Full Time: 1p/9m _ 3p/3m
   An integrated Team with wide skills range peoples
### 12. Acronyms

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<td>BLE</td>
<td>Ballistic Limit Equation</td>
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<td>Damage Modes &amp; Effect Analysis</td>
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