Space Debris Mitigation & Re-Entry Requirements

Training Course

European Space Agency

Introduction

1. **Course Overview**
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    b. Areas to be addressed
2. **Space Debris Mitigation: An Overview**
3. **Space Debris Mitigation Requirements**
    a. Historical perspective
    b. International Endeavours
    c. Requirements: Content, Rationale & Examples
4. **Re-entry Safety**
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    b. Re-entry requirements and safety review panels
    c. Break-up and re-entry analysis tools
    d. Design for demise: proactive engineering approach
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6. **Conclusions and Participants feedback**
7. **Questions and Answer**

Course Instructors

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- He belongs to the Business segment “Space Infrastructures & Transportation”, where he leads the space debris activities and coordinates the engineering activities on space environment.
- He is the ECSS discipline focal point for Space Debris and the convenor of ECSS Space Debris WG.

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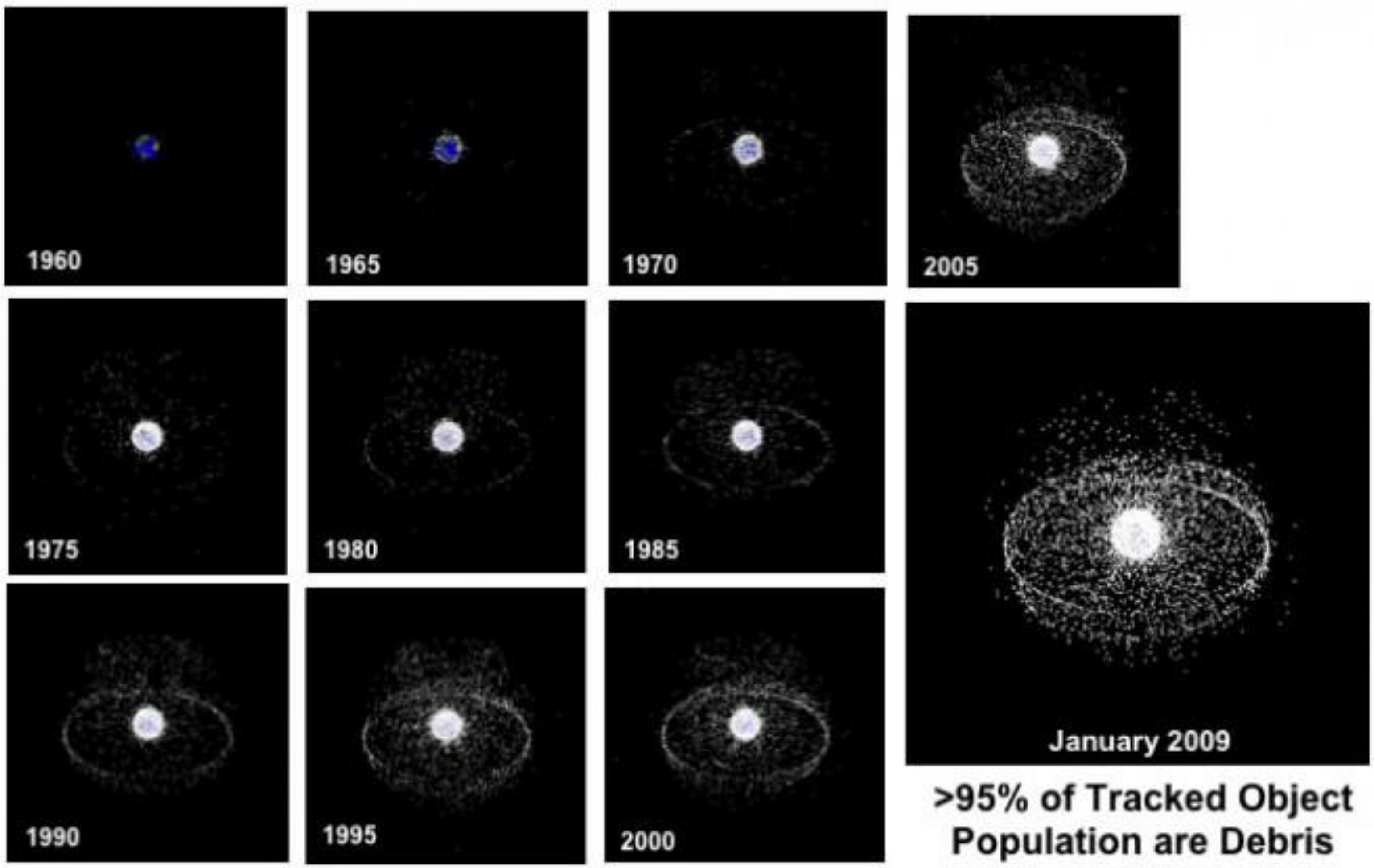
European Space Agency, ESTEC

- She is the Re-entry & Space Debris Safety Manager at the Independent Safety Office (TEC-QI).
- She has the ATV Re-entry Safety Review Board Secretariat function and is a member of ECSS Space Debris WG and related ISO activities.
- Before this appointment, she was involved in UN COPUOS and participated in WG on long term sustainability of outer space activities, incl. space debris mitigation.

Space Debris
An Increasing Problem

Space: Our Past – Our Future



>95% of Tracked Object Population are Debris

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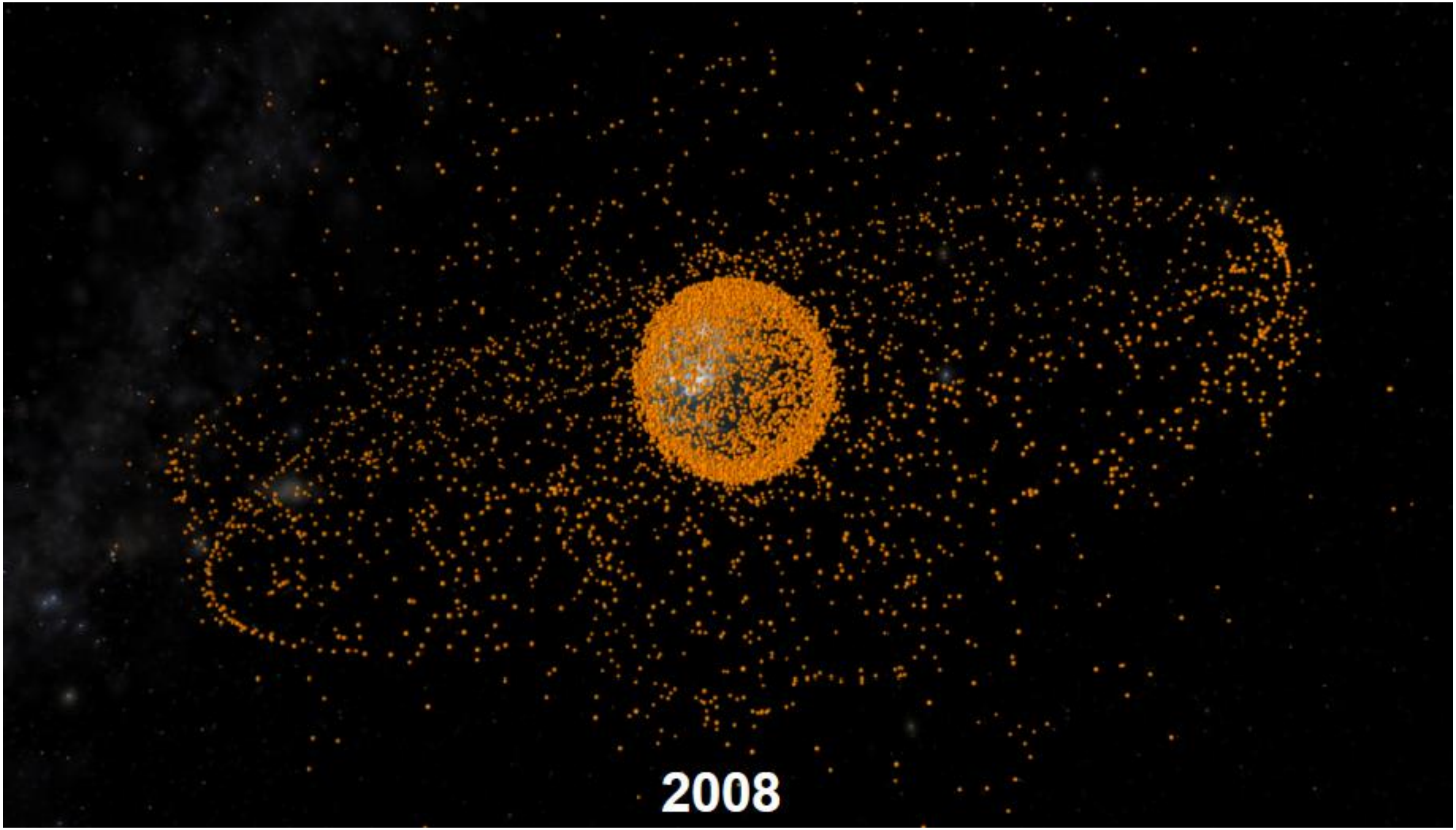
Distribution of Known Objects



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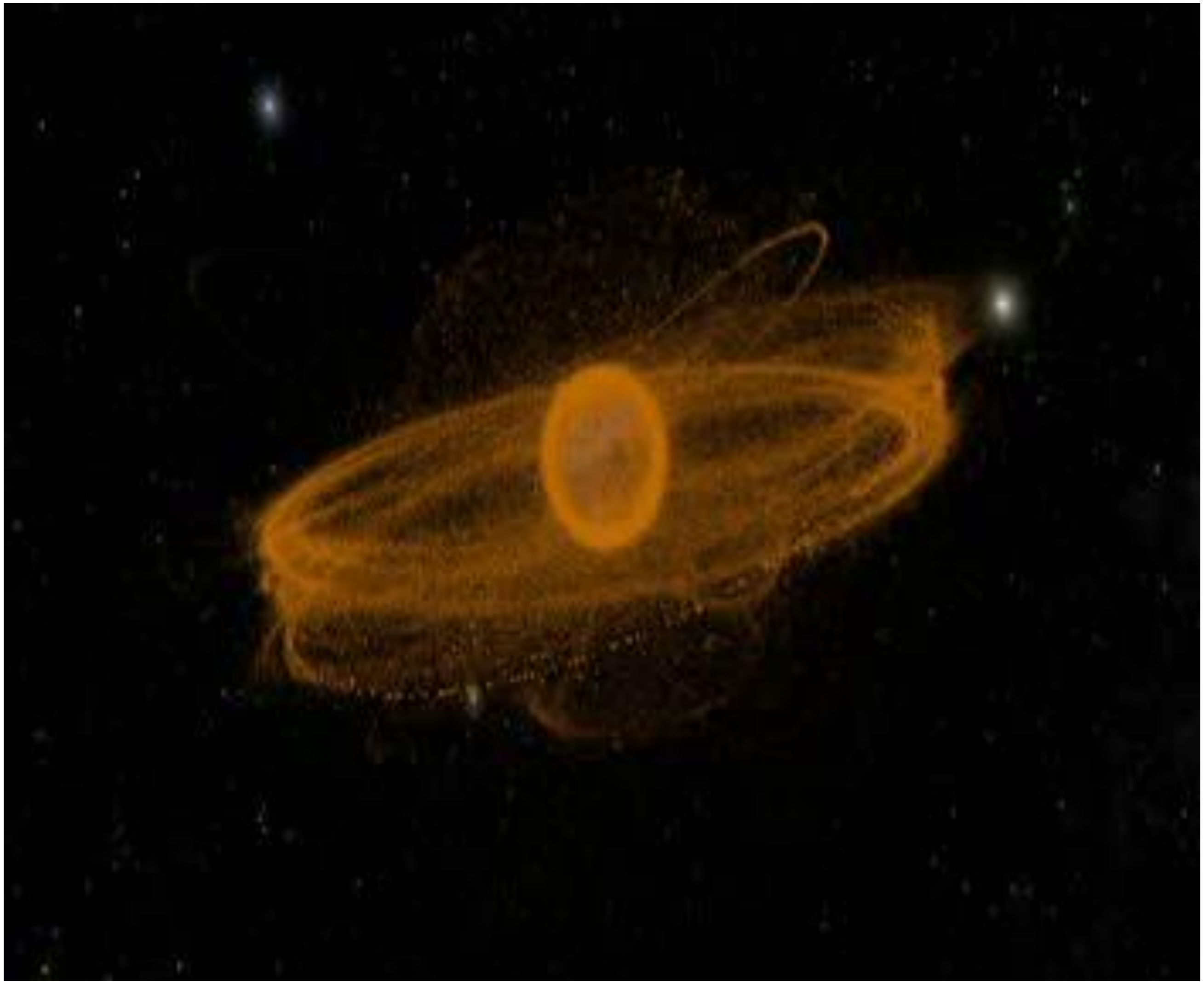
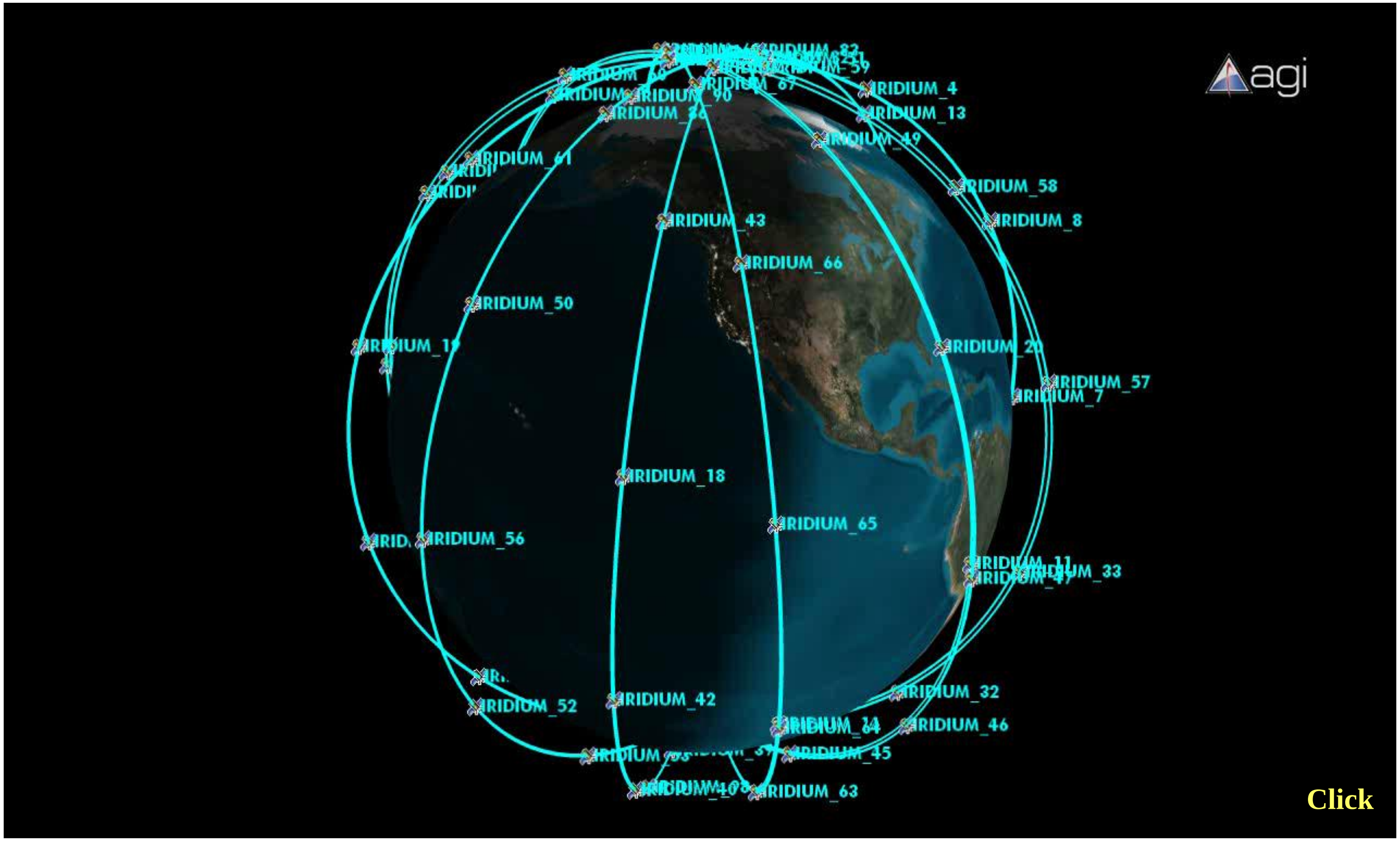
Objects > 1cm



Credits: H. Krag (HSO-GR)

Space Debris Environment and Effects

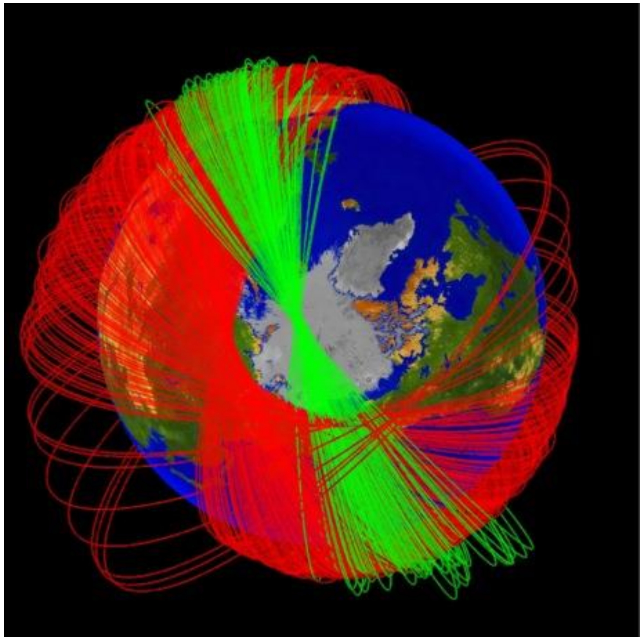
Cosmos 2251- US Iridium 33 collision (2009)



Iridium 33 – Cosmos 2251 Collision (2009)

The first ever accidental collision between two intact satellites occurred on 10/02/2009 at 1656 GMT between Iridium 33 (US Operational communication satellite) and Cosmos 2251 (a Russian decommissioned communications satellite) leaving 2 distinct debris clouds in LEO.

a. Iridium 33 and Cosmos 2251 mass was 560 kg and 900 kg, respectively)
b. Occurred at a relative velocity of 11.6 km/s at an altitude of 790 km
c. As of March 2010, 1228 Iridium 33 and 512 Cosmos 2251 debris were catalogued (plus 400 additional debris identified for future cataloging)
d. Highlighted the orbital debris problem in the LEO region.
e. These clouds pose a significant risk both in the short and long-term. Some of the debris is short lived (would re-enter within the next 5-10 years), but incidents such as this could potentially lead to an “ablation cascade”.

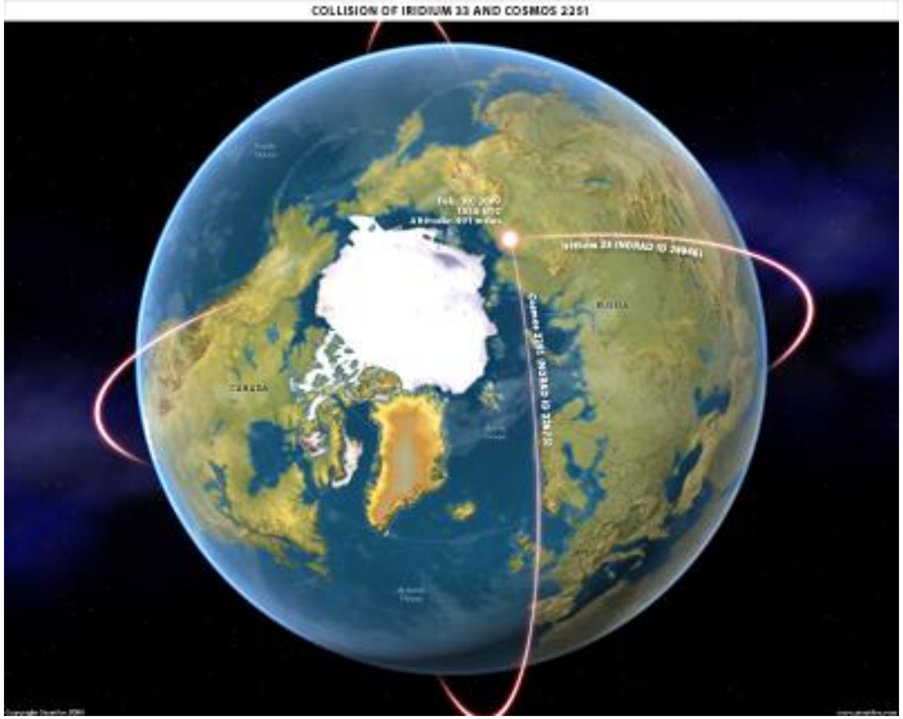


Predicted evolution of the Iridium and Cosmos debris planes by July 10 (six months after the collision)!

Iridium 33 – Cosmos 2251 Collision (2009)

1. From the TLE orbits COSMOS should have passed 400 m far from Iridium.
2. No collision avoidance procedures implemented: “Iridium was receiving an average of 400 reports per week of objects coming within 5 km of one of their satellites” (66 operational satellites + 6 spares, located on 6 orbital planes)
3. “Now, once every couple of weeks we do a maneuver” (S. Smith, Iridium EVP, December 2010)

- Iridium:
  - a = 7174:6984
  - e = 0:0002288
  - i = 86:399
  - 'Ω = 121:703
- Cosmos:
  - a = 7169:649
  - e = 0:0016027
  - i = 74:0355
  - 'Ω = 19:4646
- I '= 100:73
- Hyper-velocity impact:
  - Vimp: 11:48 km/s
  - E: 1010 J



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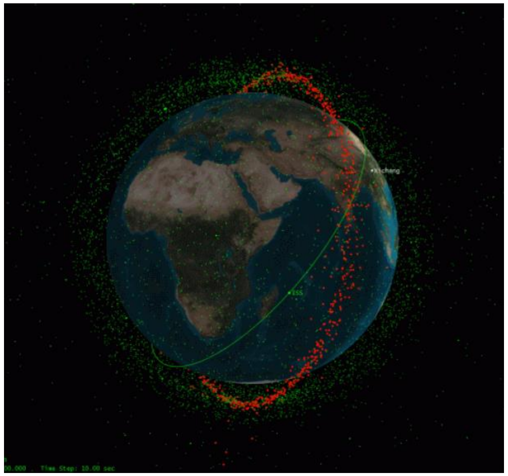
Fengyun-1C (FY-1C) Anti-Satellite Test (2007)

On **11/01/2007**, a 958 kg Chinese satellite Feng Yun 1C (1999) was destroyed by a Dong Feng missile in a Chinese anti-satellite test.

The satellite was on a near-circular orbit of **~850 km** altitude, inclination **98.65° .** The impact was reconstructed from orbital data from the US SSN.

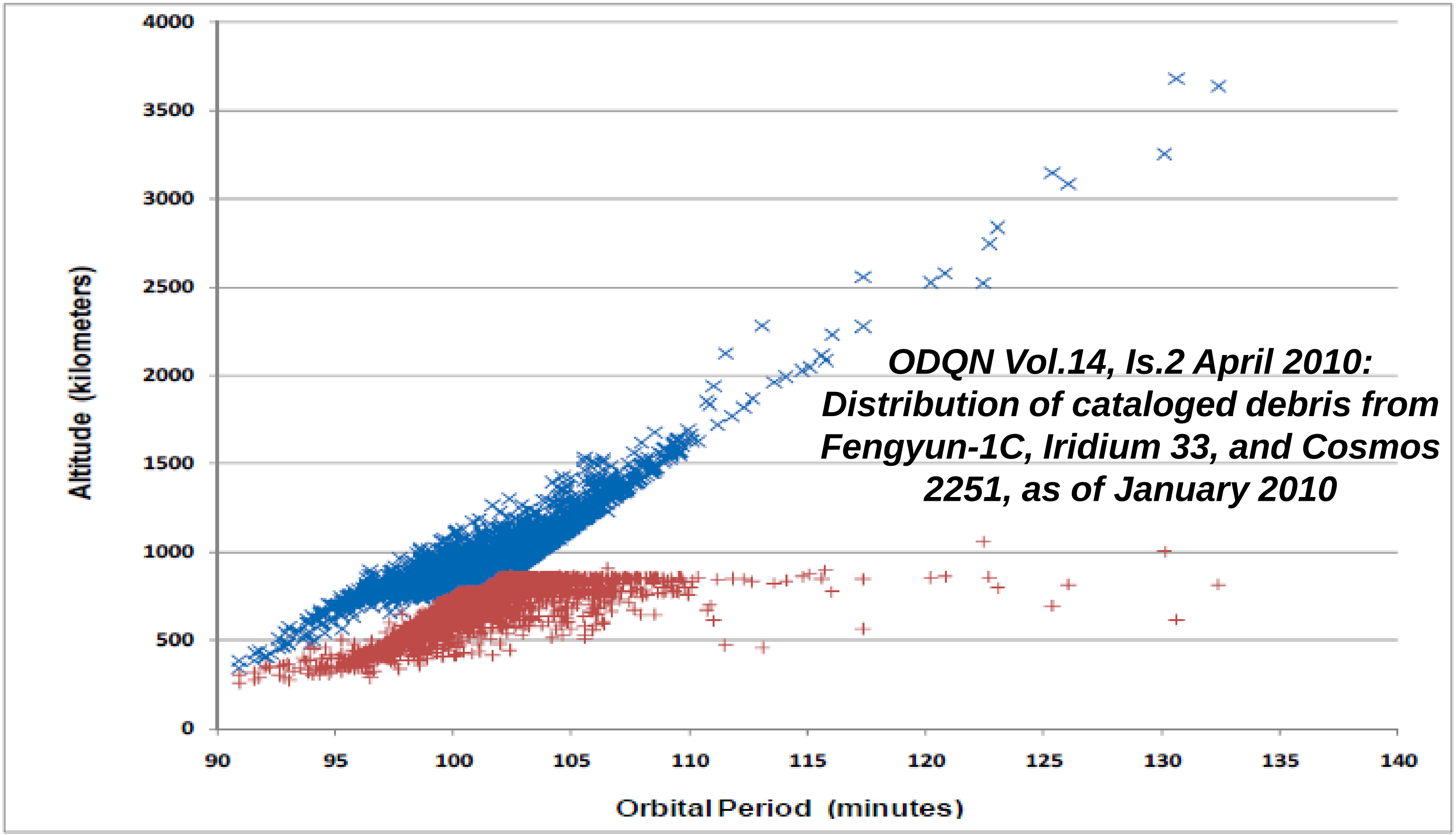
The Fengyun-1C (FY-1C) ASAT is the largest debris-generating event on record, with **2756 objects** still on-orbit, (as of May 2010) i.e., about 18% of the catalog.

The population estimated by the NASA's Orbital Debris Program Office debris larger than 1 cm is greater than 150,000



Iridium 33 – Cosmos 2251 & FY-1C

As of January 2010, the combined cataloged population from these two events, less those debris which have already reentered, was more than 4400.



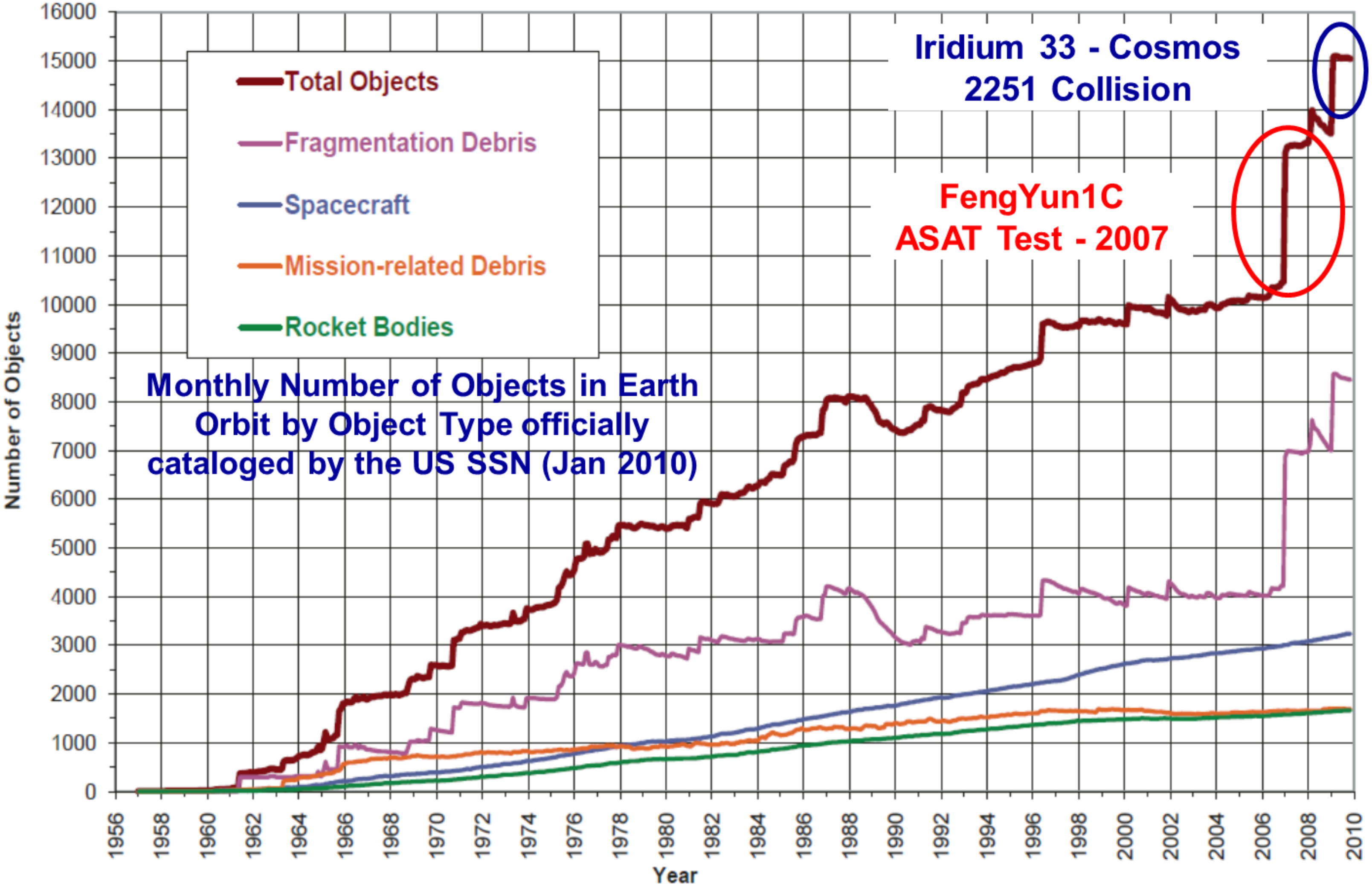
Collisions / Break-up Events

- More than 4700 space missions conducted since 1957
- About 200 break-up events
- Only 10 missions account for 1/3 of all catalogued objects currently in Earth orbit

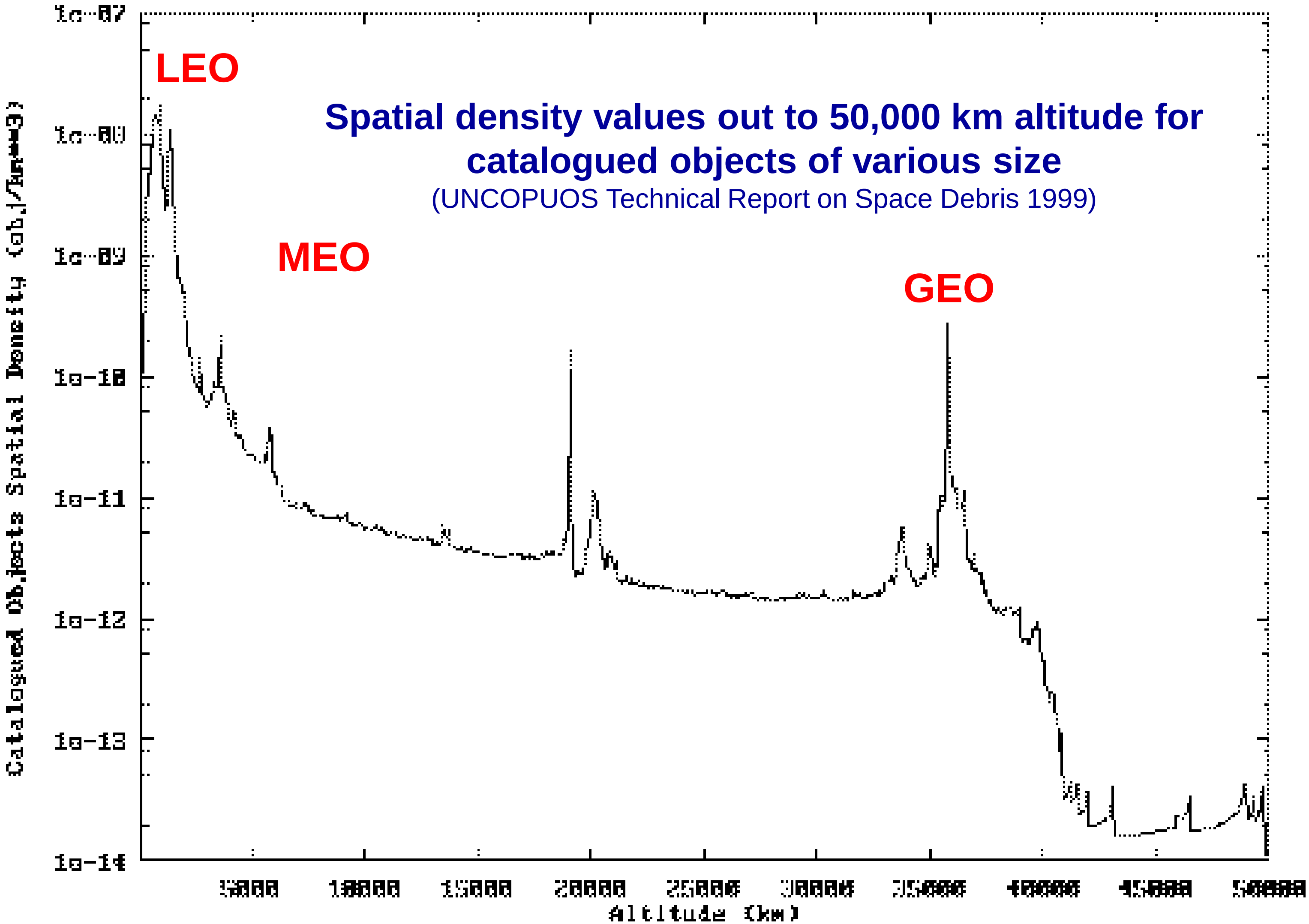
Common Name	Year of Breakup	Altitude of Breakup	Cataloged Debris*	Debris in Orbit*	Cause of Breakup
Fengyun-1C	2007	850 km	2841	2756	Intentional Collision
Cosmos 2251	2009	790 km	1267	1215	Accidental Collision
STEP 2 Rocket Body	1996	625 km	713	63	Accidental Explosion
Iridium 33	2009	790 km	521	498	Accidental Collision
Cosmos 2421	2008	410 km	509	18	Unknown
SPOT 1 Rocket Body	1986	805 km	492	33	Accidental Explosion
OV 2-1 / LCS 2 Rocket Body	1965	740 km	473	36	Accidental Explosion
Nimbus 4 Rocket Body	1970	1075 km	374	248	Accidental Explosion
TES Rocket Body	2001	670 km	370	116	Accidental Explosion
CBERS 1 Rocket Body	2000	740 km	343	189	Accidental Explosion
			Total: 7903	**Total: 5172**	

* As of May 2010

History of On-Orbit Space Objects



History of On-Orbit Space Objects



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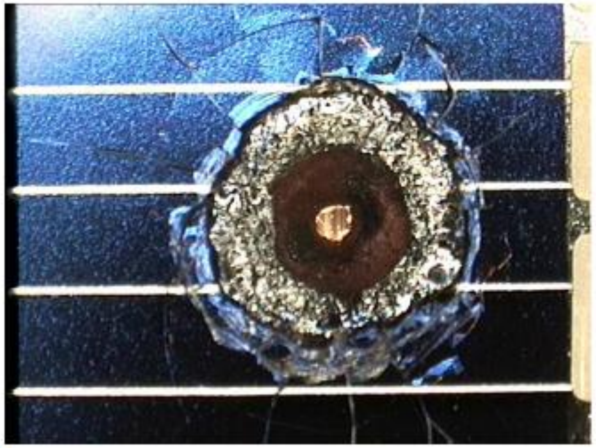
Effects of Space Debris: On-orbit Space Systems

Micrometeorite Orbital Debris: Effects I

Impact on HST Solar Cell
Crater size: 3.5 mm;
Hole size: 0.5 mm

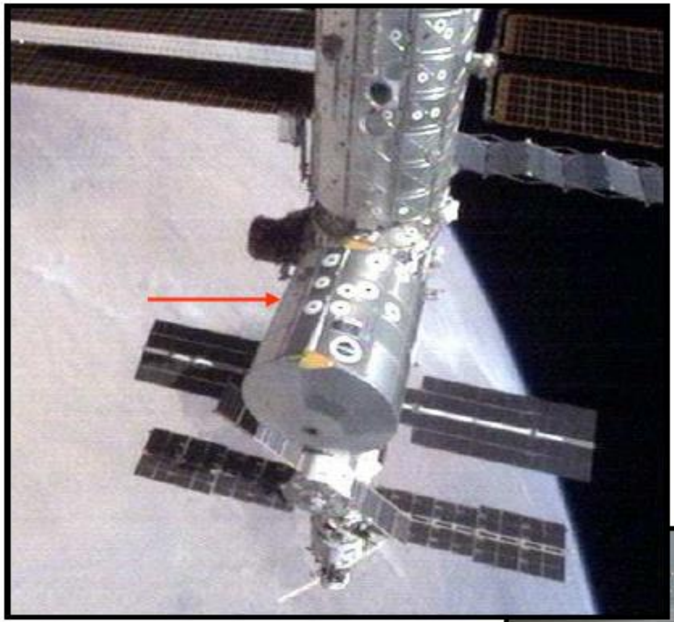


Impact on HST MLI
Outer damage size: 5 mm;
Hole size: 464 um

Al sphere, 12 mm diameter,
Impact velocity: 6.8 km/s

Micrometeorite Orbital Debris: Effects II

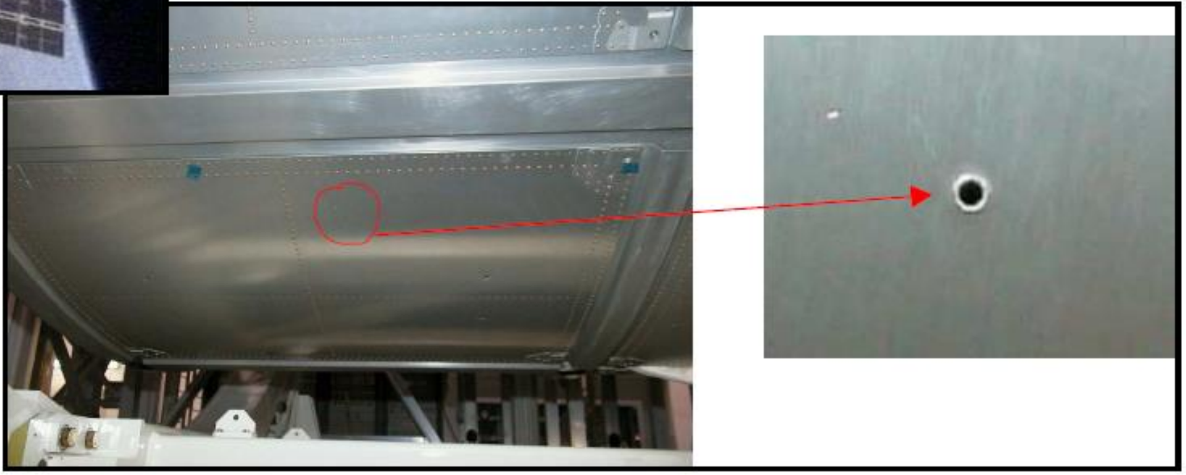
More than 26 impacts reported on MPLM over the first 5 missions



MPLM Leonardo, mission STS-102/5A.1 (March 2001), 3 MMOD impacts.

Largest impact: through hole in bumper shield 1.2 mm diam. According to NASA impactor could be a paint flake about 0.46 mm diam.

No damage to MLI underneath.



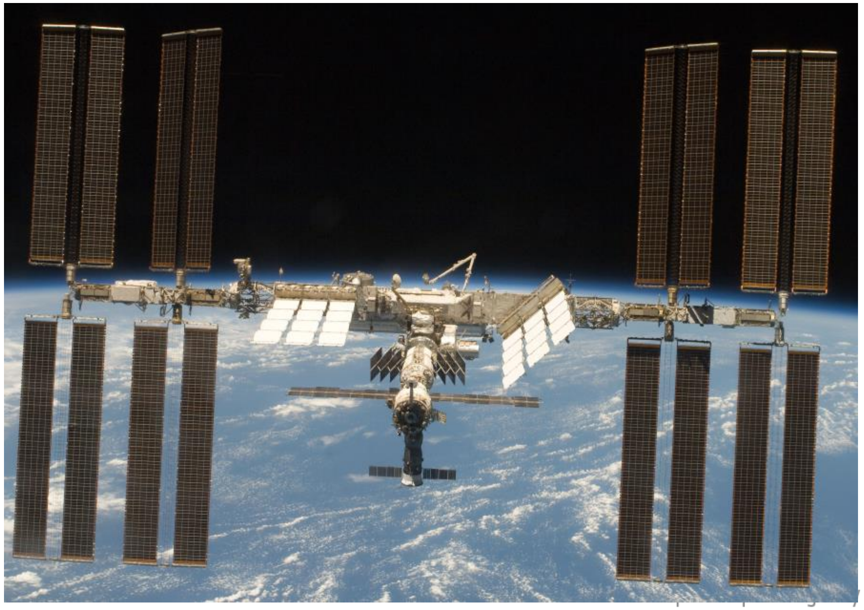
ISS Debris Avoidance Manoeuvre

On April 2, 2011 a collision avoidance manoeuvre was performed by ISS

a. the 12th COLA manoeuvre conducted since October 1999,
b. the fifth in 2 1/2 years
c. the debris was a fragment from Cosmos 2251-Iridium 33 collision.

On March 12, 2009, threat by a small debris: #25090 PAM-D debris (a "yo-tumble" of a Delta II PAM-D stage, launched in 1993) with 0.0092 m2 radar cross section, estimated size/mass about 2 inches/1 kg.

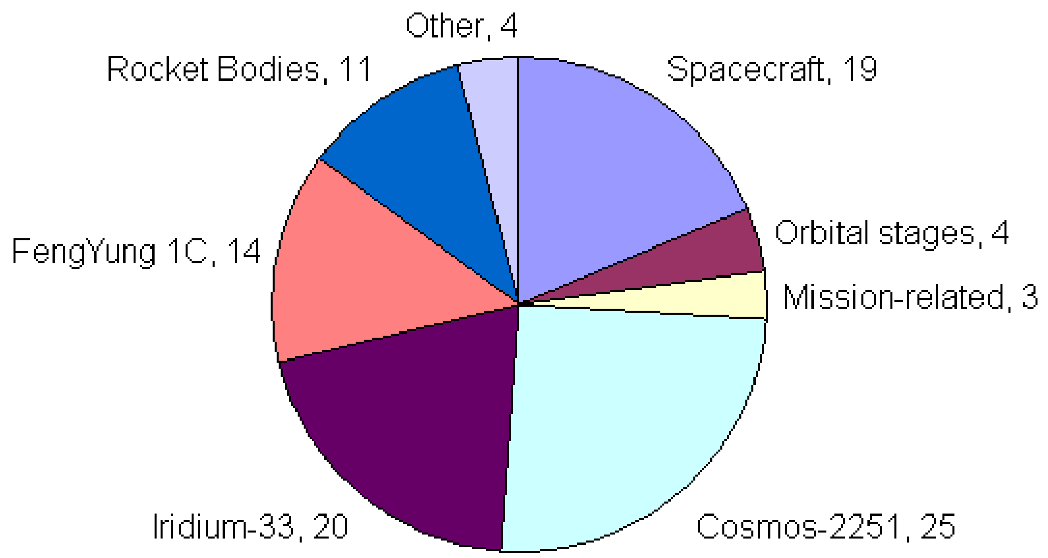
a. Due to late notification, no Debris Avoidance Manoeuvre was performed
b. The 3 crew members of Expedition 18 carried out a contingency "evacuation" into the Soyuz
c. #25090 debris orbit: 4230 km x 143 km, 34.7° inclination, 0.24 eccentricity
d. Closest distance was 2.4 km, relative velocity 9.43 km/s



ESA Collision Event Statistics (2010)

- **Nine avoidance manoeuvres** (4 for Envisat, 4 for ERS-2, 1 for CryoSat-2)
- 5 events exceeded Prob (collision) > 1 in 1,000 (Avoidance Manoeuvre)
  - 4 for Envisat, 1 for ERS-2
- 49 events exceeded Prob (collision) > 1 in 10,000
  - 43 for Envisat, 4 for ERS-2, 2 for Cryosat-2

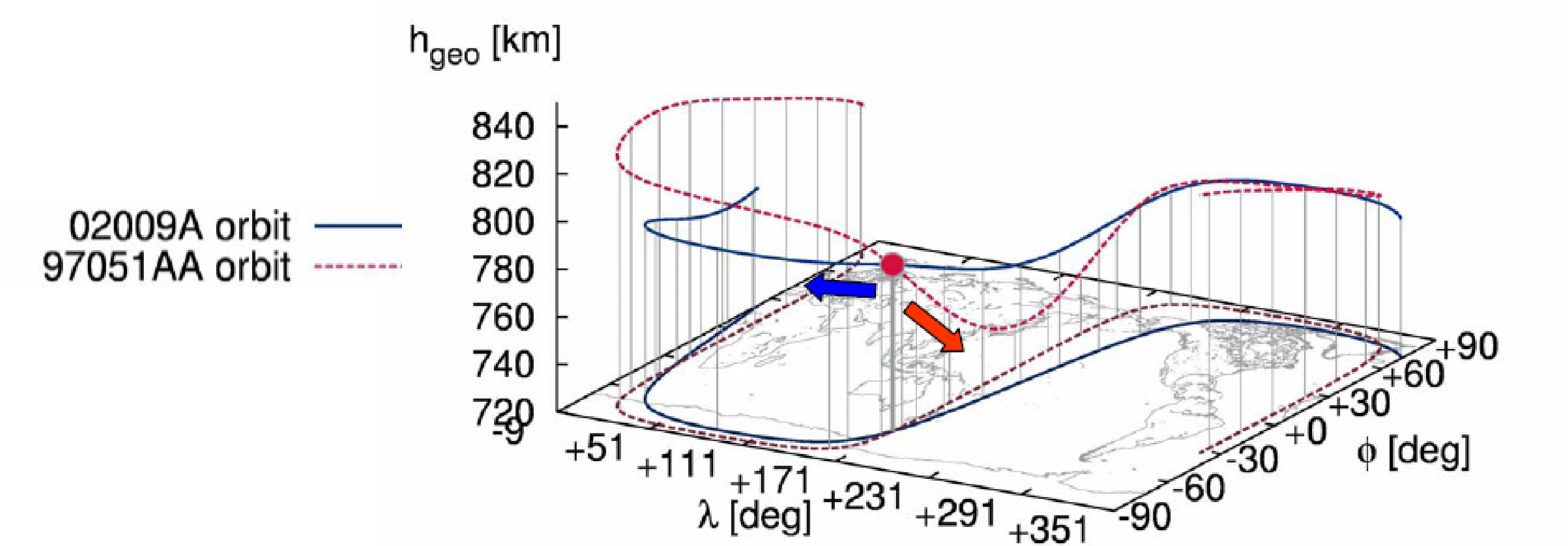
Conjunctor Objects



Source: H. Klinkrad, "Space Debris Mitigation Activities at ESA" Feb 2011 (UN COPUOS)

2010 High-Risk Conjunction: Envisat

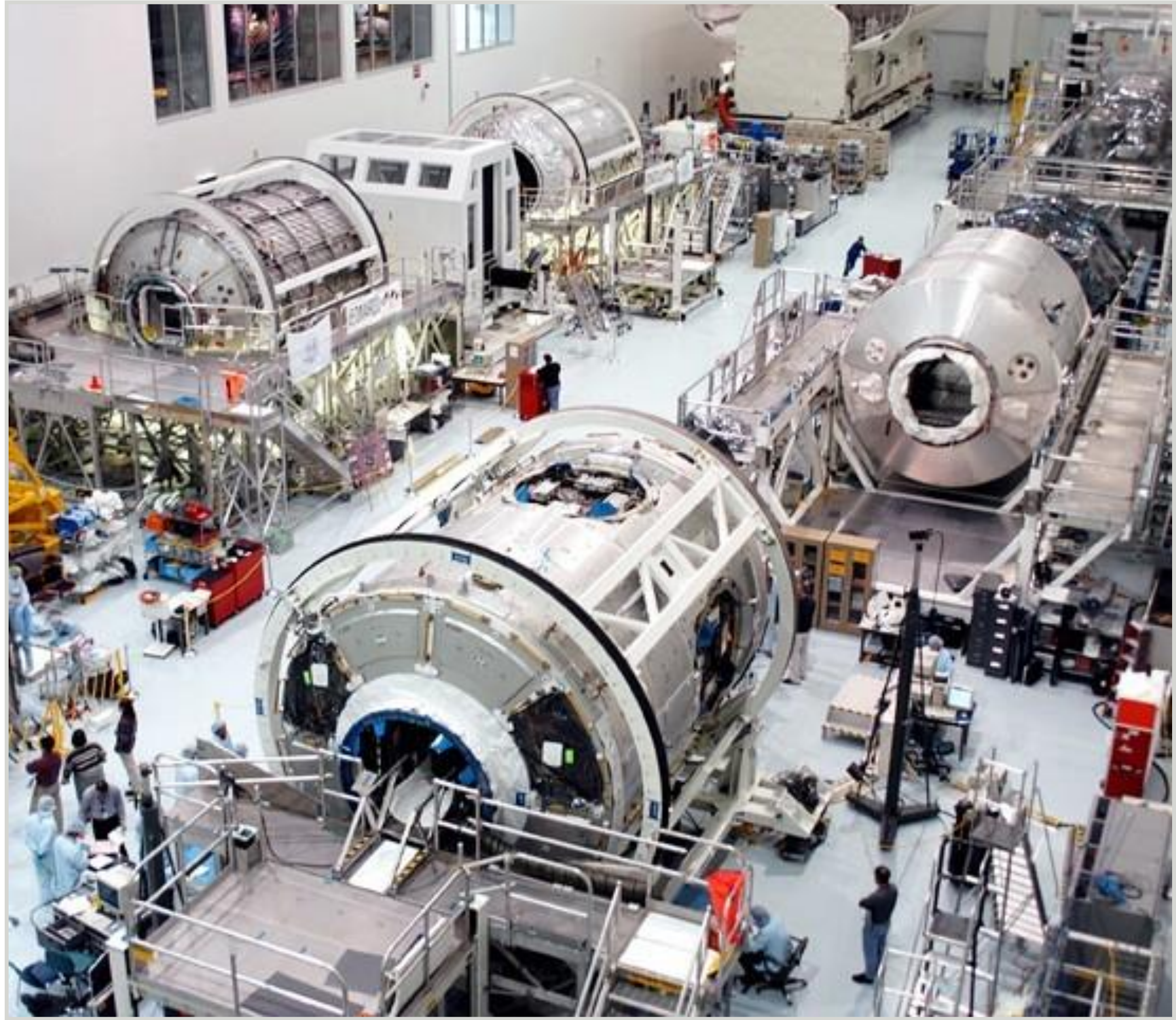
- conjunction of Envisat (02-009A) with an Iridium 33 fragment (97-051AA):
  - predicted conjunctions on Dec. 01, 2010, at 20:01| **21:41**| 23:41 UTC, at a total distance of 757m| **47m**| 794m, with a radial separation of −63m| **+25m** | +66m (based on JSpOC CSM data & ESA Envisat data)
  - Envisat: max. dimension 26m;| Iridium fragment: max. dimension ~0.2m
  - collision probability at t−2d: 1 in 49 (highest so far at maneuver decision time)
  - a two-burn avoidance maneuver (2 × 1.5 cm/s) between the 1st and 2nd, and after the 3rd conjunction increased the min. separation to 160m (100m radial)



Source: H. Klinkrad, "Space Debris Mitigation Activities at ESA" Feb 2011 (UN COPUOS)

MMOD Risk Assessment

TAS-I crewed elements at KSC



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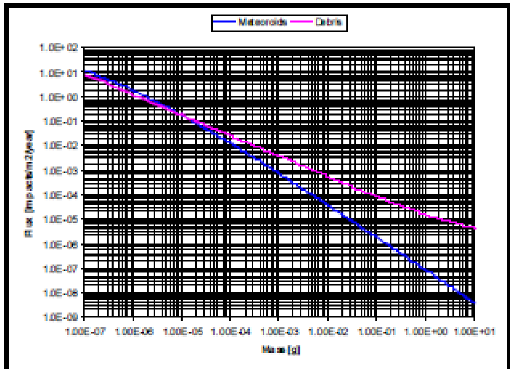
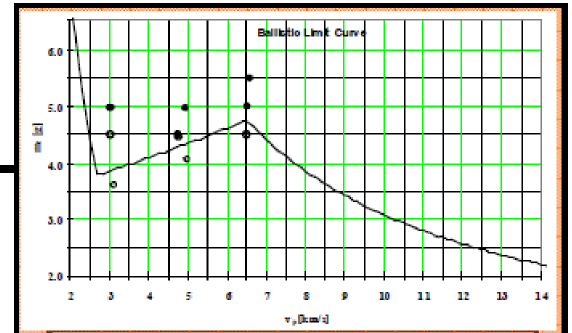
MMOD Risk Assessment

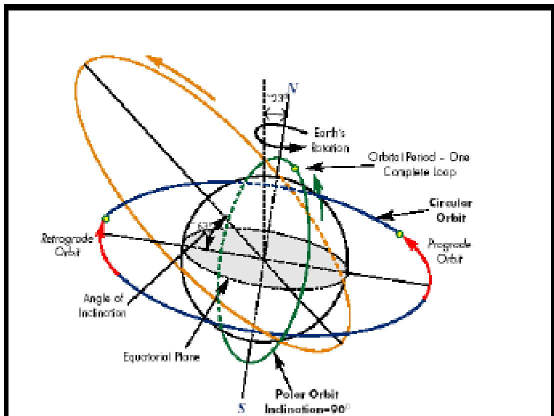


MMOD ENVIRONMENT



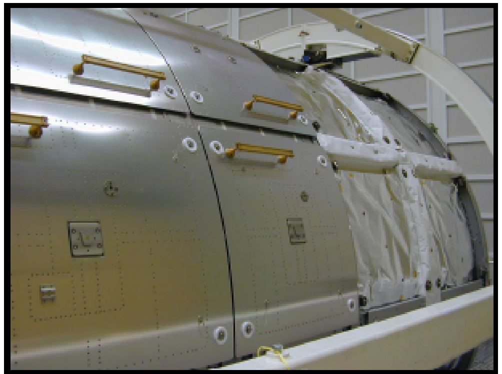
BLE (DAMAGE EQUATIONS)

ESABASE/DEBRIS
3D
TOOLS



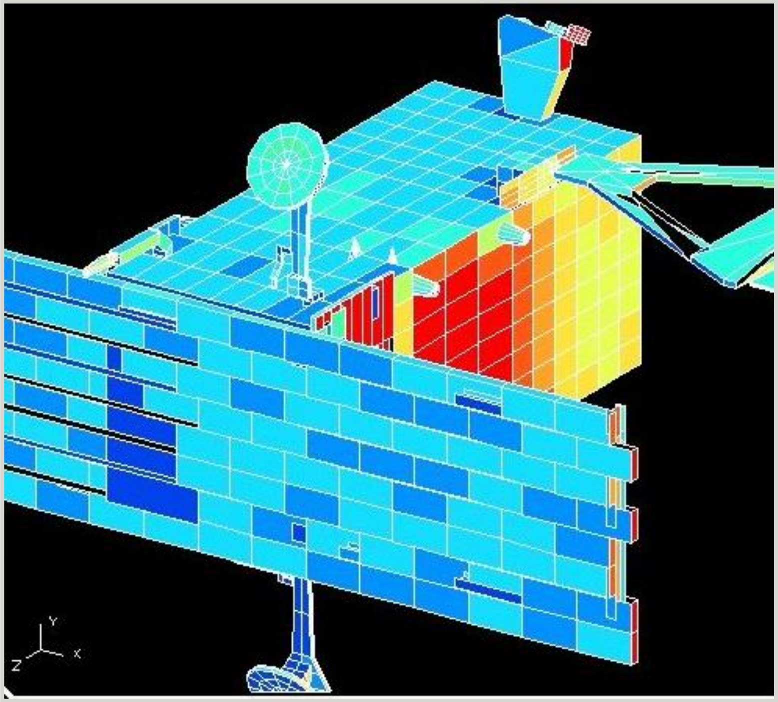
MISSION PROFILE

Number of MMOD impacts / failures
(Risk level)



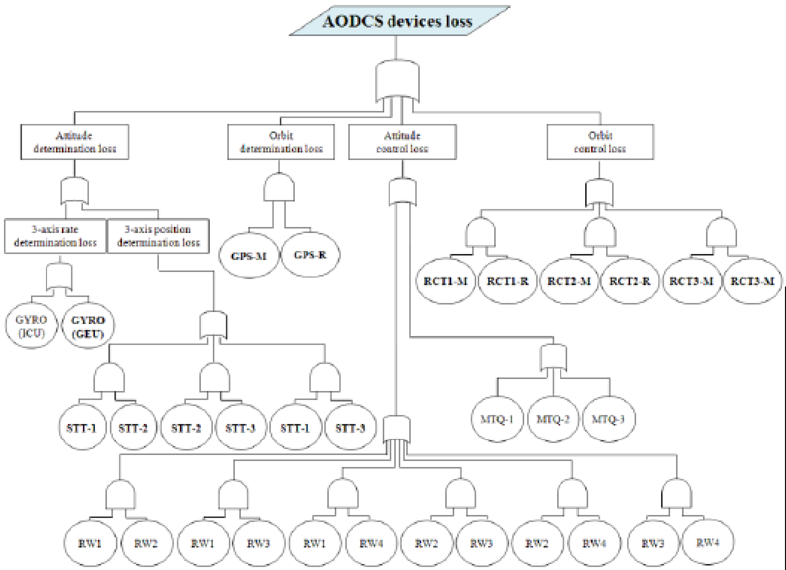
SPACECRAFT GEOMETRY

MMOD Assessments
Example 1: Cosmo SkyMed

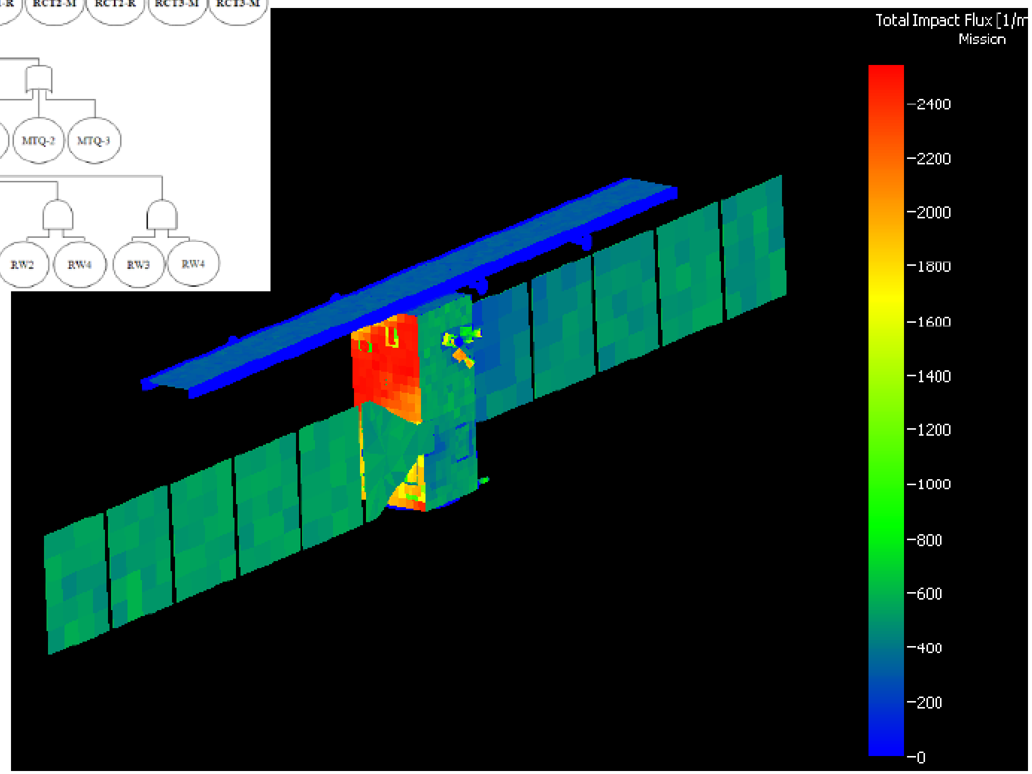


1. Orbit: 619.6 km, 97.86°
2. ESABASE1
3. ORDEM 96 Debris model

MMOD Assessment
Example 2: Sentinel 1



Orbit: 693 km, 98.11°
ESABASE2/Debris
MASTER 2009 Debris model
Fault tree analysis



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Sustainability and survivability research

- Many conferences with sections devoted to the debris issue (e.g., 5th European Conference on Space Debris, IAC, COSPAR, ISU, …)
- Several research projects (ESA, EC, Space Situational Awareness,…)
- FP7 P^2-ROTEC: Prediction, Protection & Reduction of OrbiTal Exposure to Collision Threats, Collaborative Project (FP7 2010.2.3-02, ONERA, OHB, TASI, …)
    a. to assess the risks associated with on-orbit collisions with space debris and to recommend possible solutions to reduce vulnerability of missions (better predictions, S/C protection, Actions on debris environment)
    b. Dissemination workshop on the 20th – 21st March 2012 in Ankara, Turkey (http://www.p2rotect-fp7.eu/index.html - News/Events)

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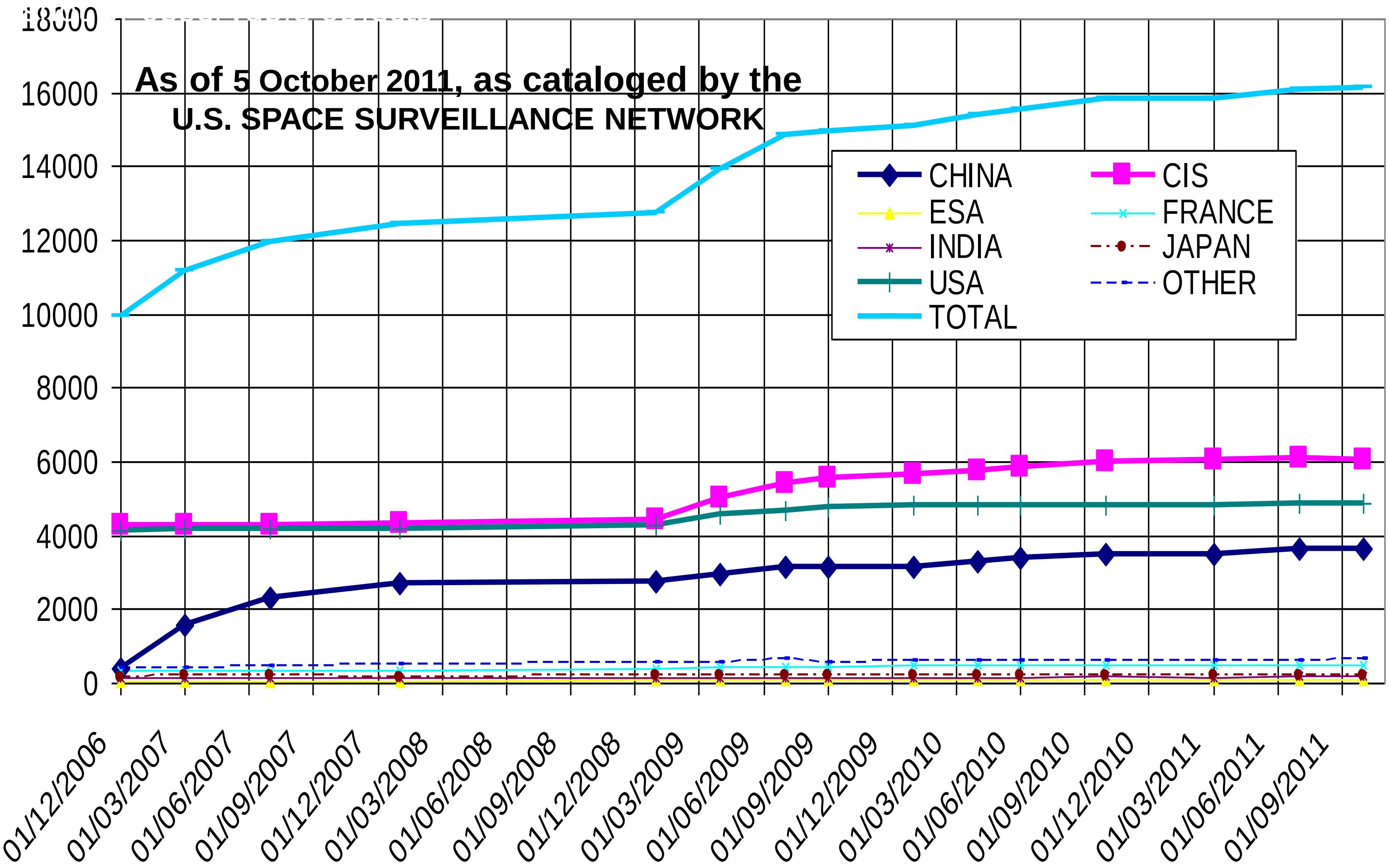
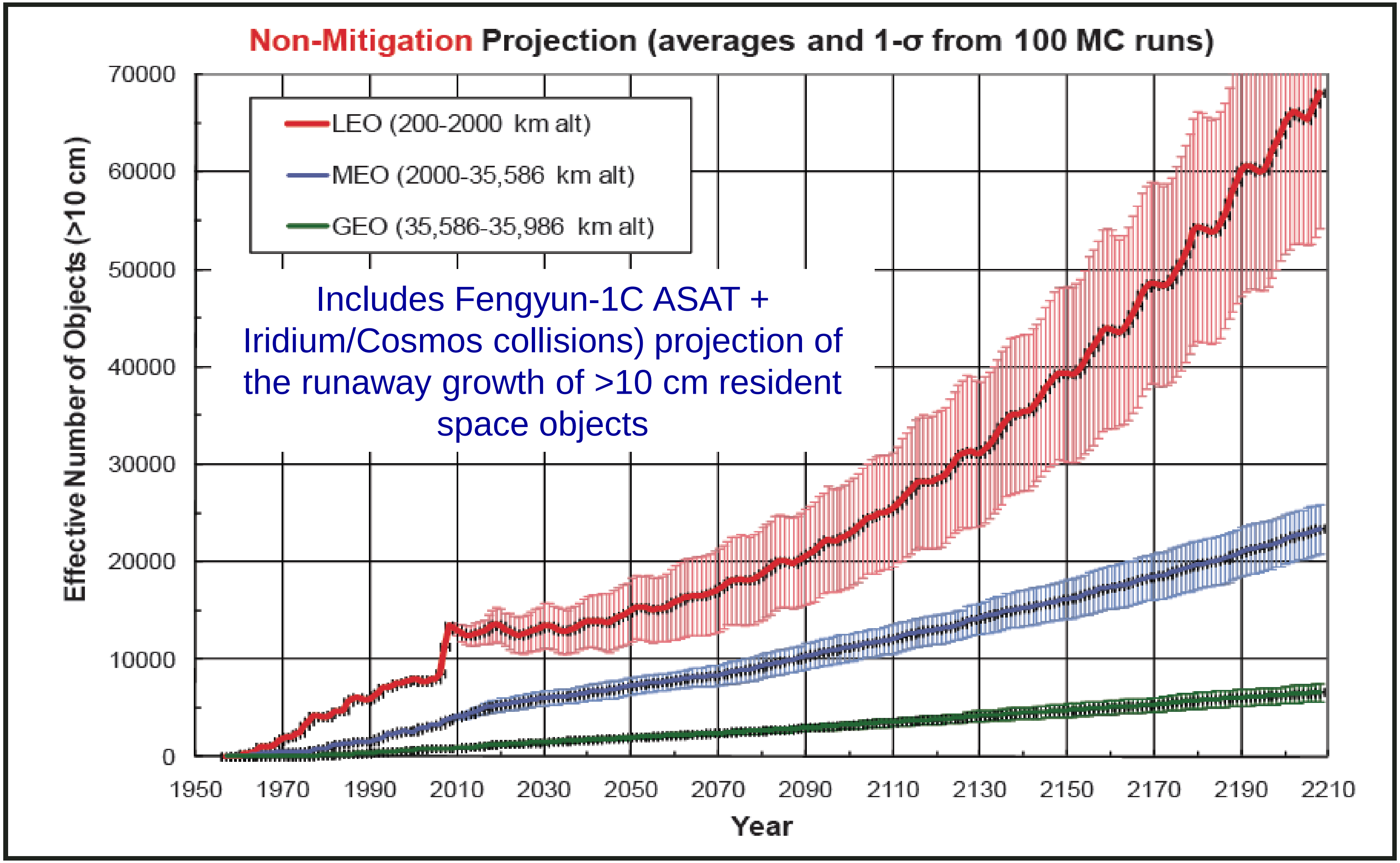
Global Perspective for Space Sustainability

Debris Environment – A Global Issue



Debris Environment – A Global Issue



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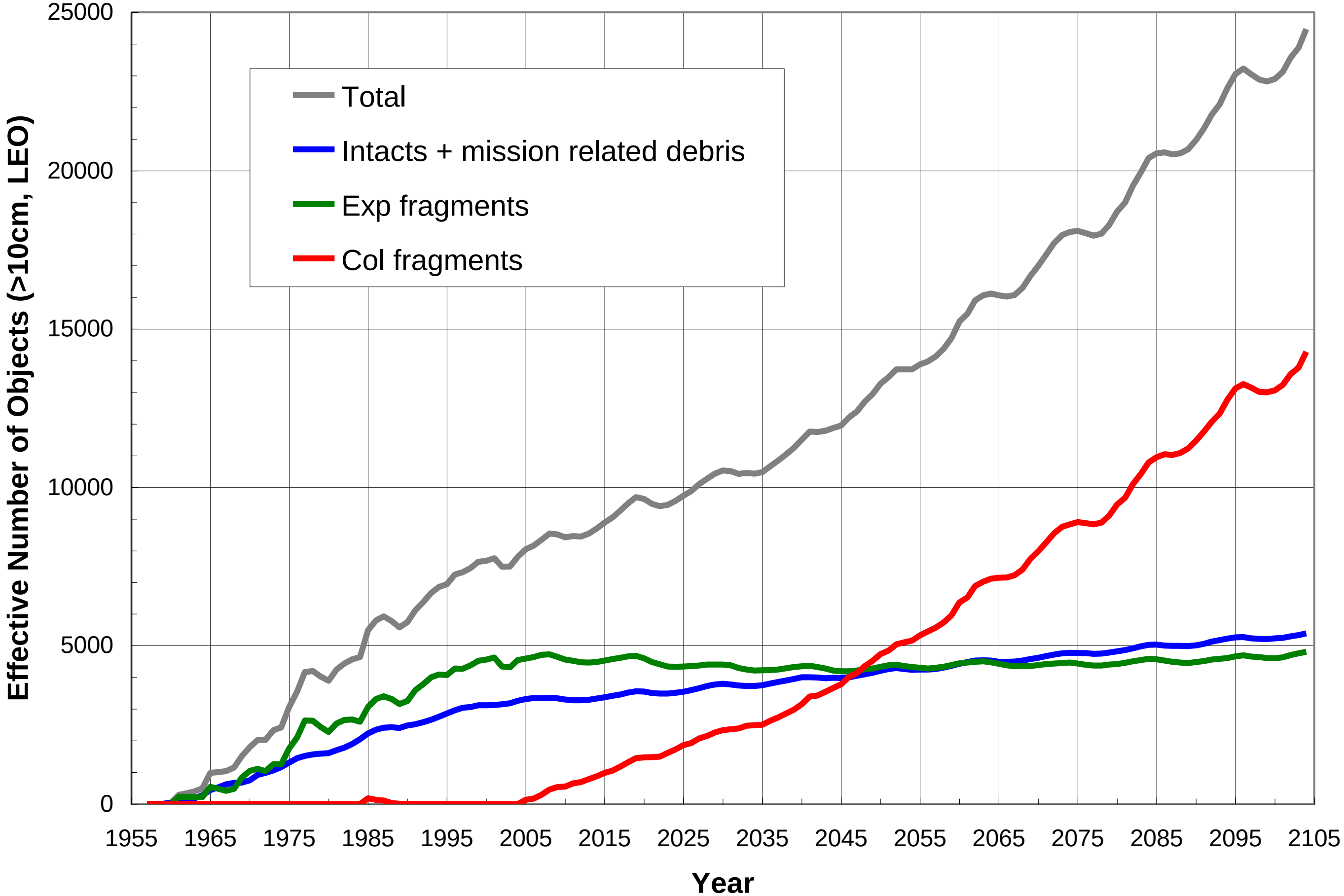
Projections for the Future



J.-C. Liou, "A statistical analysis of the future debris environment," *Acta Astronautica* 62 (2008) 264 – 271.

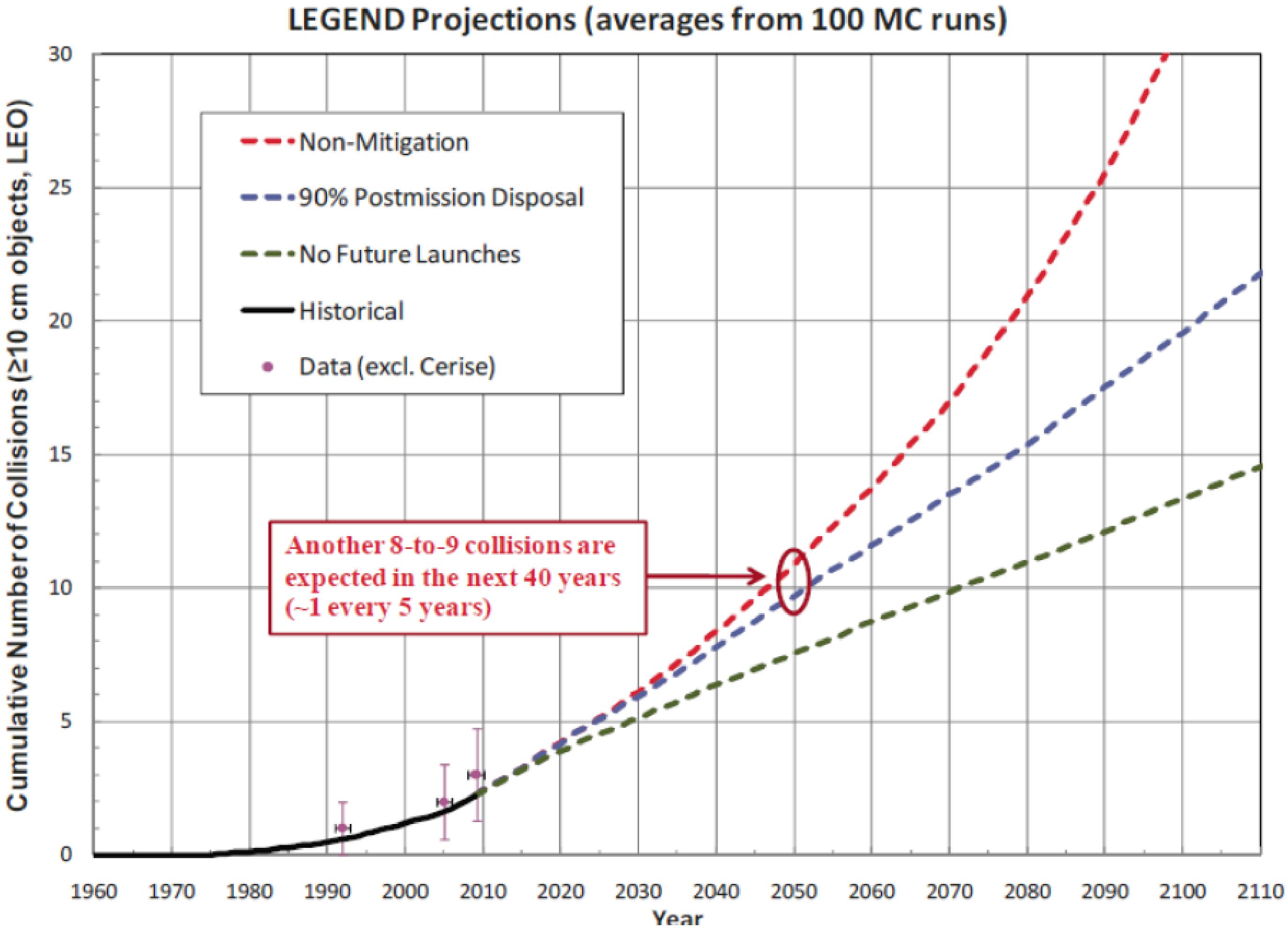
Assumes

- **200 to 2000 km altitude orbits**
- **No mitigation (no post-mission maneuvers to dispose of hardware)**
- **1997-2004 launch cycle**

Predicts ~24 collisions in next 100 years

Kessler Syndrome

NASA LEGEND-predicted accidental collision activities in LEO. An average of about 1 collision / 5 years expected for the next 40 years.



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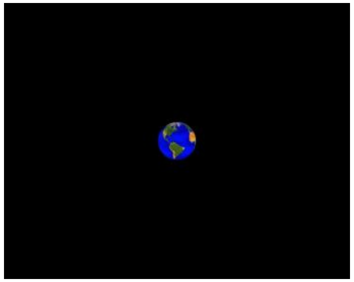
Debris Environment – A Global Issue

- Removing existing, non-cooperative objects is extremely difficult
- Investigated techniques suffer from lack of development and testing and/or economic viability (NASA/DARPA Conf., 2009; IAASS 2011):
  - Ground based laser cleansing
  - Active Debris Removal

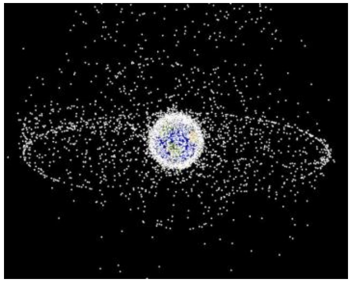
- Necessary, currently available option:

  MITIGATION & Controlled Re-entries

- A global issue requires international solutions: guidelines and standards



Pre 1957



2010

?

2015+

Global Perspective for Space Sustainability Space Debris Mitigation

Guidelines and Standards

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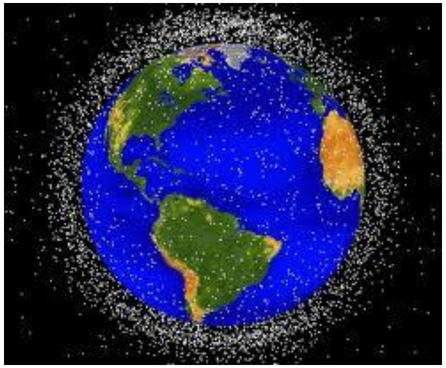
SDM: Standards and Guidelines I

- In the last 15 years, Space Debris Mitigation Standards, Guidelines or Handbooks have been issued by several national, regional and international organizations.
- Since the mid-1990s, space agencies in Europe have developed guidelines.
- In **1993,** the Inter-Agency Debris Coordination Committee (IADC) was formed (now composed of 11 national Space Agencies).
- In **2002**, IADC published the “Space Debris Mitigation Guidelines" and presented to the UN-COPUOS STSC, which served as a baseline for the "UN Space Debris Mitigation Guidelines".

IADC

SDM: Standards and Guidelines II

- In **2006**, the "European Code of Conduct" was signed by ESA, ASI, BNSC, CNES and DLR.
- In **2007**, UN-COPUOS STSC "UN Space Debris Mitigation Guidelines‶ approved by the 63 STSC member nations as voluntary high-level space debris mitigation measures
- In **2007**, NASA policy was established to control the generation of orbital debris: NASA Procedural Requirements 8715.6A, NASA Technical Standard 8719.14 (2007). All NASA projects are required to provide debris assessments and End of Mission (EoM) planning.
- In **2008**, ESA "Space Debris Mitigation for Agency Projects" was published and entry into force for Agency projects. The requirements were mad applicable to all space vehicles, including launchers, satellites and inhabited objects.



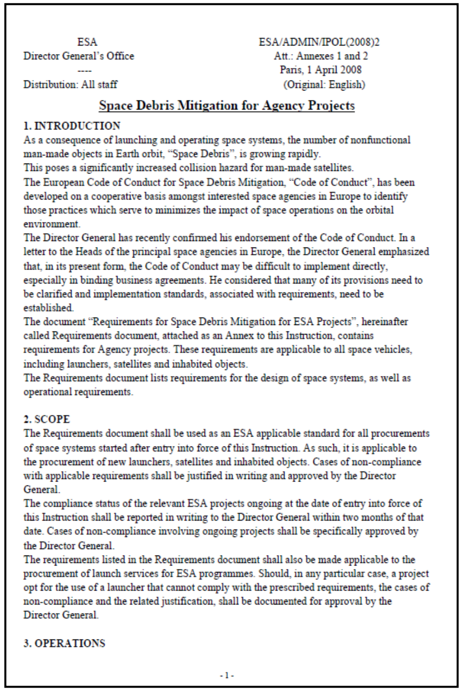
SDM: Standards and Guidelines III

- In June **2008**, Space Debris Mitigation requirements are also part of the French Loi relative aux Opérations Spatiales (LOS, N° 2008-518).
- ISO International debris standards developed by the committee TC20/SC14 “Space systems and operations”, with the participation of 12 nations.
- The ISO key document is “**ISO 24113 - Space Debris Mitigation**”. This standard (published July 2010, 1st ed., May 2011, 2nd ed.) is based on the IADC and UN guidelines, and aims at translating the existing recommendations into quantitative implementation requirements.
- ECSS supports ISO TC20/SC14 development through ECSS SDWG.
- National standards are used by several agencies (ROSCOSMOS, JAXA, …)

ESA Requirements
&
French Space Act (FSOA)

Space Debris Mitigation for ESA Projects

1. In **April 2008**, the Director General confirmed his endorsement to European Code of Conduct for Space Debris Mitigation and released a set of space debris and re-entry requirements applicable to ESA projects.
2. These requirements **are applicable to all space vehicles, including launchers, satellites and inhabited objects**.
3. The Requirements document lists **design and operational requirements for space systems**.
4. The compliance status of the **relevant ESA projects ongoing** at the date of entry into force of this Instruction shall be reported in writing to the Director General.
5. **Cases of non-compliance** involving ongoing projects **shall be specifically approved by the Director General**.
6. The requirements listed in the Requirements document shall also be made **applicable to the procurement of launch services for ESA programmes**.



ESA
Director General's Office

Distribution: All staff

ESA/ADMIN/IPOL(2008)2
Att.: Annexes 1 and 2
Paris, 1 April 2008
(Original: English)

Space Debris Mitigation for Agency Projects

1. INTRODUCTION

As a consequence of launching and operating space systems, the number of nonfunctional man-made objects in Earth orbit, "Space Debris", is growing rapidly.

This poses a significantly increased collision hazard for man-made satellites.

The European Code of Conduct for Space Debris Mitigation, "Code of Conduct", has been developed on a cooperative basis amongst interested space agencies in Europe to identify those practices which serve to minimizes the impact of space operations on the orbital environment.

The Director General has recently confirmed his endorsement of the Code of Conduct. In a letter to the Heads of the principal space agencies in Europe, the Director General emphasized that, in its present form, the Code of Conduct may be difficult to implement directly, especially in binding business agreements. He considered that many of its provisions need to be clarified and implementation standards, associated with requirements, need to be established.

The document "Requirements for Space Debris Mitigation for ESA Projects", hereinafter called Requirements document, attached as an Annex to this Instruction, contains requirements for Agency projects. These requirements are applicable to all space vehicles, including launchers, satellites and inhabited objects.

The Requirements document lists requirements for the design of space systems, as well as operational requirements.

2. SCOPE

The Requirements document shall be used as an ESA applicable standard for all procurements of space systems started after entry into force of this Instruction. As such, it is applicable to the procurement of new launchers, satellites and inhabited objects. Cases of non-compliance with applicable requirements shall be justified in writing and approved by the Director General.

The compliance status of the relevant ESA projects ongoing at the date of entry into force of this Instruction shall be reported in writing to the Director General within two months of that date. Cases of non-compliance involving ongoing projects shall be specifically approved by the Director General.

The requirements listed in the Requirements document shall also be made applicable to the procurement of launch services for ESA programmes. Should, in any particular case, a project opt for the use of a launcher that cannot comply with the prescribed requirements, the cases of non-compliance and the related justification, shall be documented for approval by the Director General.

3. OPERATIONS

- 1 -

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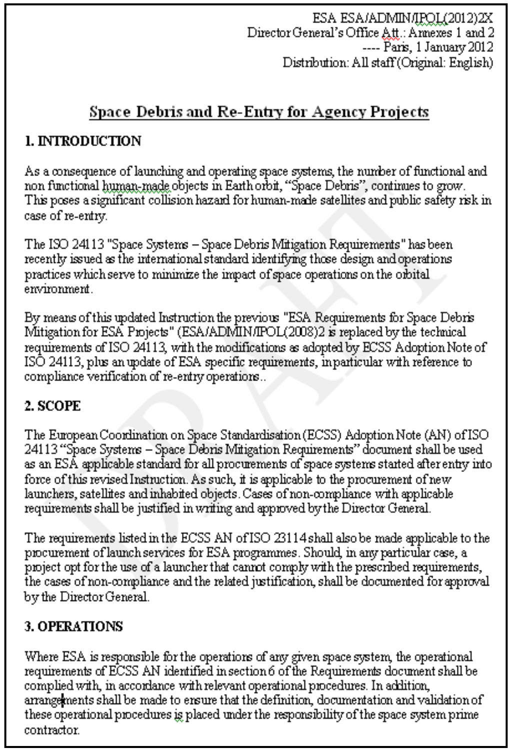
Standardisation Activities: Highlights


ESA ESA/ADMIN/IPOL(2012)2X
Director General's Office Att.: Annexes 1 and 2
---- Paris, 1 January 2012
Distribution: All staff (Original: English)

Space Debris and Re-Entry for Agency Projects

1. INTRODUCTION

As a consequence of launching and operating space systems, the number of functional and non functional human-made objects in Earth orbit, "Space Debris", continues to grow. This poses a significant collision hazard for human-made satellites and public safety risk in case of re-entry.

The ISO 24113 "Space Systems – Space Debris Mitigation Requirements" has been recently issued as the international standard identifying those design and operations practices which serve to minimize the impact of space operations on the orbital environment.

By means of this updated Instruction the previous "ESA Requirements for Space Debris Mitigation for ESA Projects" (ESA/ADMIN/IPOL(2008)2 is replaced by the technical requirements of ISO 24113, with the modifications as adopted by ECSS Adoption Note of ISO 24113, plus an update of ESA specific requirements, in particular with reference to compliance verification of re-entry operations..

2. SCOPE

The European Coordination on Space Standardisation (ECSS) Adoption Note (AN) of ISO 24113 "Space Systems – Space Debris Mitigation Requirements" document shall be used as an ESA applicable standard for all procurements of space systems started after entry into force of this revised Instruction. As such, it is applicable to the procurement of new launchers, satellites and inhabited objects. Cases of non-compliance with applicable requirements shall be justified in writing and approved by the Director General.

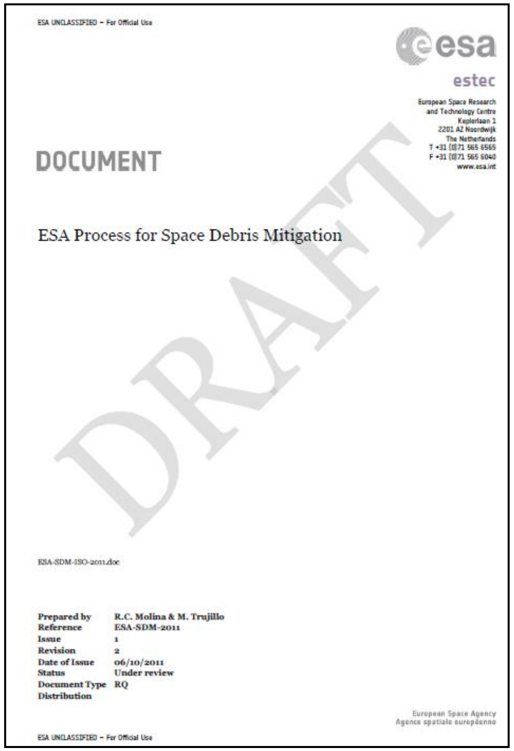
The requirements listed in the ECSS AN of ISO 23114 shall also be made applicable to the procurement of launch services for ESA programmes. Should, in any particular case, a project opt for the use of a launcher that cannot comply with the prescribed requirements, the cases of non-compliance and the related justification, shall be documented for approval by the Director General.

3. OPERATIONS

Where ESA is responsible for the operations of any given space system, the operational requirements of ECSS AN identified in section 6 of the Requirements document shall be complied with, in accordance with relevant operational procedures. In addition, arrangements shall be made to ensure that the definition, documentation and validation of these operational procedures is placed under the responsibility of the space system prime contractor.

DRAFT

Updated IPOL/ADMIN for Space Debris Mitigation (2012)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DOCUMENT

ESA Process for Space Debris Mitigation

DRAFT

ESA-SDM-ISO-2011.doc

Prepared by	R.C. Molina & M. Trujillo
Reference	ESA-SDM-2011
Issue	1
Revision	2
Date of Issue	06/10/2011
Status	Under review
Document Type	RQ
Distribution	

European Space Agency
Agence spatiale européenne

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ESA Process for Space Debris Mitigation


esa
estec

DOCUMENT

Project Name
Space Debris Mitigation Document (SDMD)

DRAFT

(1) Statement of any restrictions on the data in the SDMR such as proprietary, restricted, classification, International Traffic in Arms Restrictions (ITAR), or other export restrictions/controls. If the document does not contain any restrictions, then a statement to that effect shall be included. If the document does contain restricted information, the restricted information shall be summarized and marked clearly on the page(s) where it occurs and on the cover.

Prepared by
Reference
Issue
Revision
Date of Issue
Status
Document Type
Distribution

European Space Agency
Agence spatiale européenne

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Space Debris Mitigation Document (SDMD) – Template

ESA AS ECSS (AN ISO 24113)

European Space Agency

Technical Regulation in the Frame of the French Space Act (FSOA): Overview

4 juin 2008	JOURNAL OFFICIEL DE LA RÉPUBLIQUE FRANÇAISE	Texte 1 sur 129

LOIS

LOI n° 2008-518 du 3 juin 2008 relative aux opérations spatiales (1)

NOR : *ESRX0700048L*

L'Assemblée nationale et le Sénat ont adopté,

Le Président de la République promulgue la loi dont la teneur suit :

TITRE Ier

DÉFINITIONS

Article 1er

Pour l'application de la présente loi, on entend par :

1° « Dommage » : toute atteinte aux personnes, aux biens, et notamment à la santé publique ou à l'environnement directement causée par un objet spatial dans le cadre d'une opération spatiale, à l'exclusion des conséquences de l'utilisation du signal émis par cet objet pour les utilisateurs ;

French Authorisation Procedure

Principle of prior authorisation for:

• any operator, irrespective of nationality, intending to launch or bring back to Earth a space object on French territory.
• any French operator intending to launch or bring back to Earth a space object
• any person of French nationality intending to launch a space object
• any French operator intending to control such an object in space

Conditions for granting authorisations

- The applicant must supply moral, financial and professional guarantees.
- The systems and processes implemented must comply with technical regulations.
- It may be possible to dispense with inspections for technical compliance for operations carried out abroad.

Monitoring to ensure that specific prescriptions are respected

CNES is mandated "to carry out inspections, by delegation from the Ministry with responsibility for Space, to ensure that systems and procedures implemented by space operators comply with technical regulations"

Safety measures

The Minister and the President of CNES are empowered to take all necessary measures to ensure the safety of people, property, public health and the environment

FSOA: Launch Safety Objectives

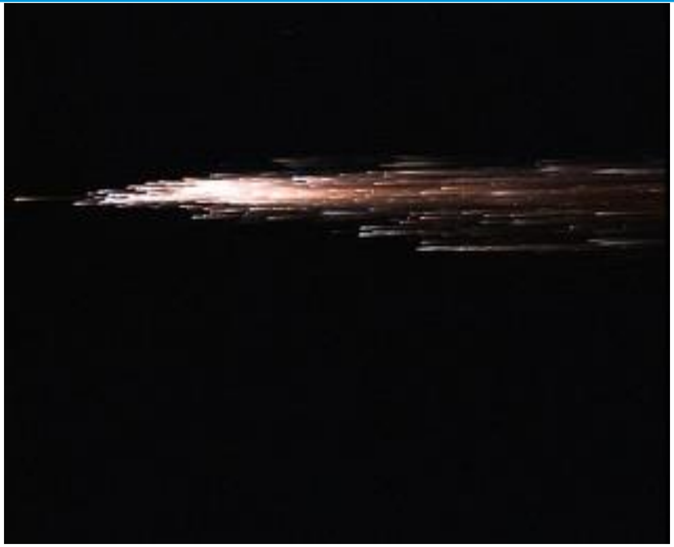
- "**Worst case**" approach in near field
- Collective public risk (Max. acceptable prob.): **$\leq 2\ 10^{-5}$/operation in far field**
- Nominal impact zones outside land masses and territorial waters
- Information to the air and maritime traffic authorities about impact zones for transmission of appropriate notifications
- Criteria for launch collision avoidance with crewed vehicles

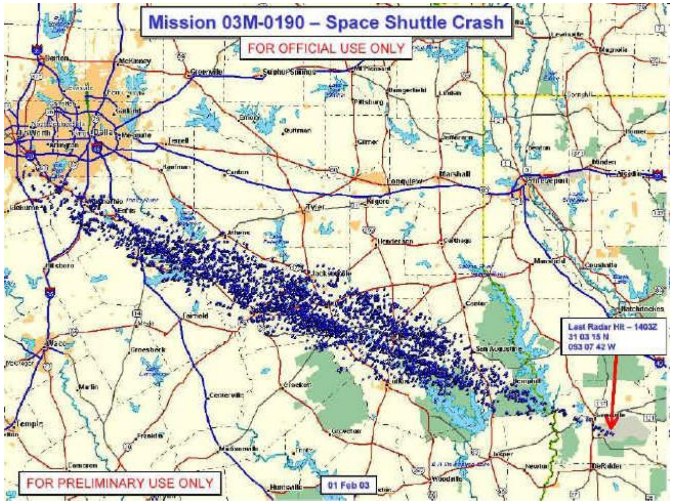
FSOA: Re-entry Safety Objectives

- Collective risk for the population (maximum acceptable probability): **$\leq$ 2 10^{-5}/operation in far field**

- **For destructive re entry nominal impact zones outside landmasses** and territorial waters

- Information to the air and maritime traffic authorities about impact zones for transmission of appropriate notifications



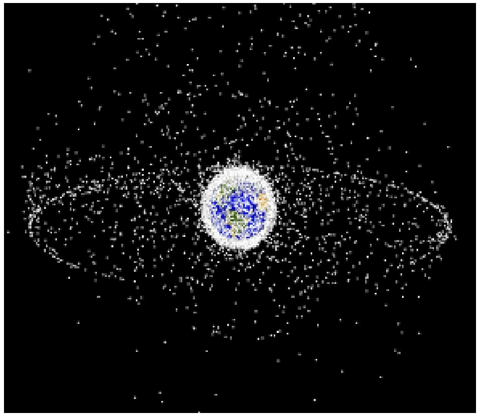


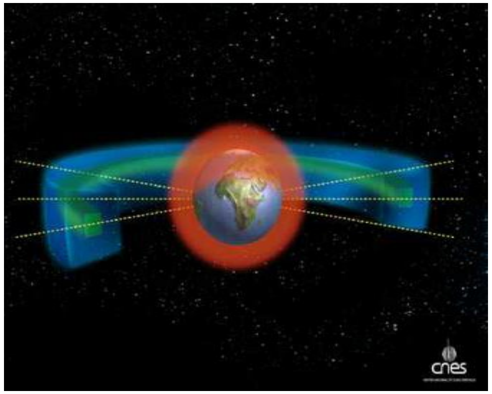
FSOA: Other Safety Objectives

- Protection of public health and the environment

  Mitigating risk of dangerous contamination
  during launch or re-entry

- **Mitigating space debris**
  - Do not generate debris during nominal operations
  - Minimise the probability of accidental break down
  - Remove space vehicles and orbital stages from protected regions after the end of the mission
  - Prevent collisions with GEO satellites whose orbital parameters are known.





European Cooperation for Space Standardisation (ECSS)

ECSS Membership

European Space Agency

European Industry,

represented by

EUROSPACE
The Association of European Space Industry

Some organization have an **observer** role on ECSS, e.g.

- → **CEN,**
- → **EUMETSAT,**
- → **EDA**

National Space Agencies

Agency	Country
agenzia spaziale italiana	**Italy**
cnes – Centre National d'Etudes Spatiales	**France**
DLR	**Germany**
Netherlands Space Office	**The Netherlands**
Norsk Romsenter – Norwegian Space Centre	**Norway**
UK Space Agency	**United Kingdom**
CSA ASC	**Canada**

Voting Members

Observers

European Cooperation for Space Standarization (ECSS)

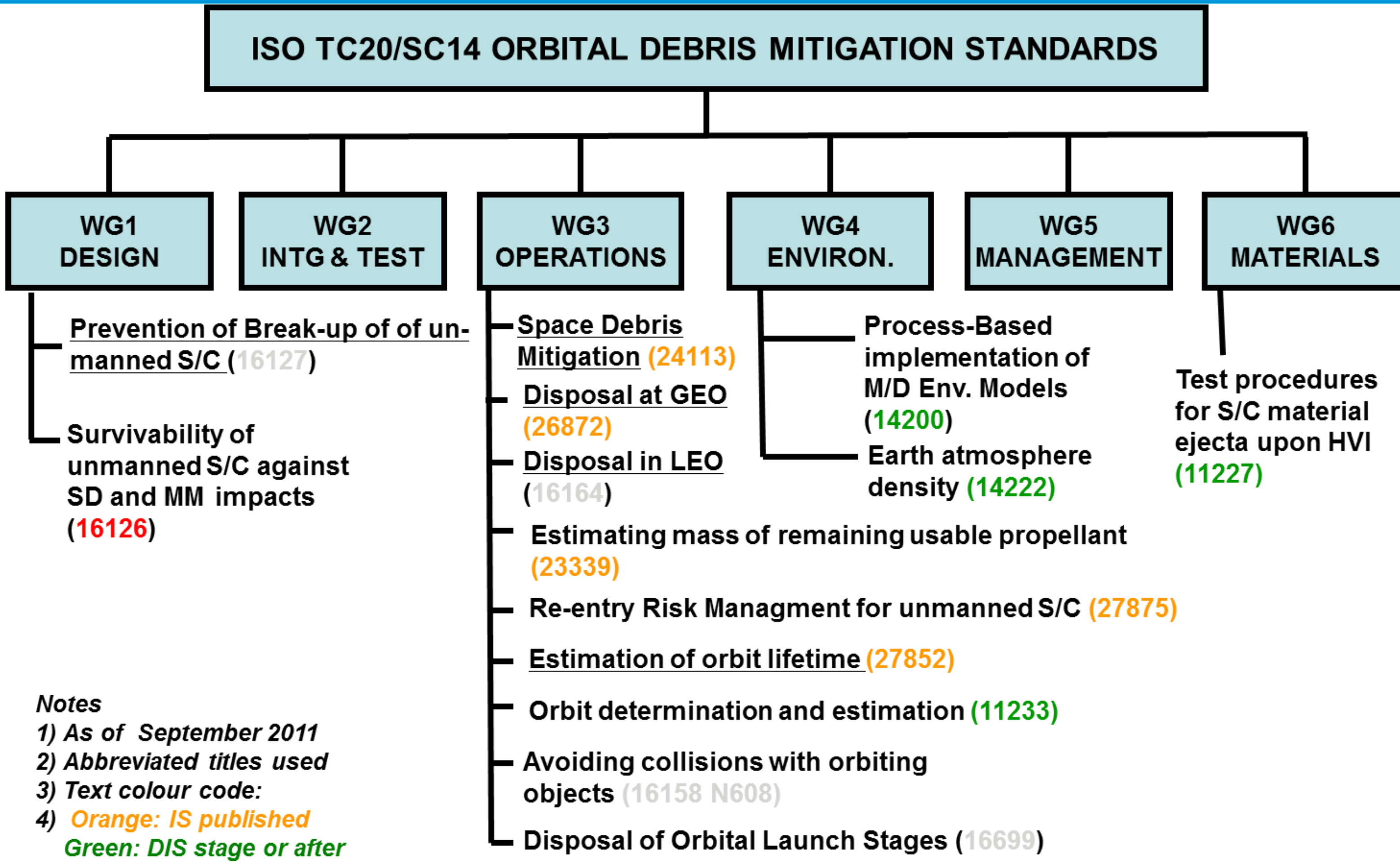
European Space Agency

ECSS Approach to Space Debris Mitigation

esa

- ISO TC20/SC14 - ECSS A-liaison Organization that make an effective contribution to the work of the technical committee or subcommittee for questions dealt with by this TC or SC.
- ECSS Space Debris Working Group (ECSS SDWG):
  a. ECSS relies on ISO to produce norms related to SD. Contribution to the development of SD implementation standards in the framework of ISO TC20/SC14 Orbital Debris Coordination Group (ODCWG):
  b. Participation of SDWG members to ISO ODCWG meetings and activities; inputs and comments provided through SDWG
- ISO Space Debris Mitigation items defined "ECSS High Priority (HP)":
  a. Address main 'debris mitigation issues'
  b. Are candidate for being called as normative reference in existing or future ECSS standards &/or for adoption, etc.

ISO TC20/SC14 Orbital Debris Mitigation Standards



Notes
1) As of September 2011
2) Abbreviated titles used
3) Text colour code:
4) Orange: IS published
Green: DIS stage or after
Red: CD/V passed
Blue: CD stage
4) Items of ECSS high priority underlined

ISO 24113 - Space Debris Mitigation

- ISO 24113 defines **the primary space debris mitigation requirements applicable over the life cycle of a space system**.
- ISO 24113 covers all elements of unmanned space systems launched into or passing through near-Earth space, including launch vehicle orbital stages, operating spacecraft, and any objects released as part of normal operations or disposal actions.
- The requirements aim to reduce the growth of space debris by ensuring that space systems are designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime.
- First Edition Published on 2010-07-01; **Second Edition published May, 2011**
- ECSS adoption process finalized, with few integrations / modifications. **Adoption Notice issued.** To be published.

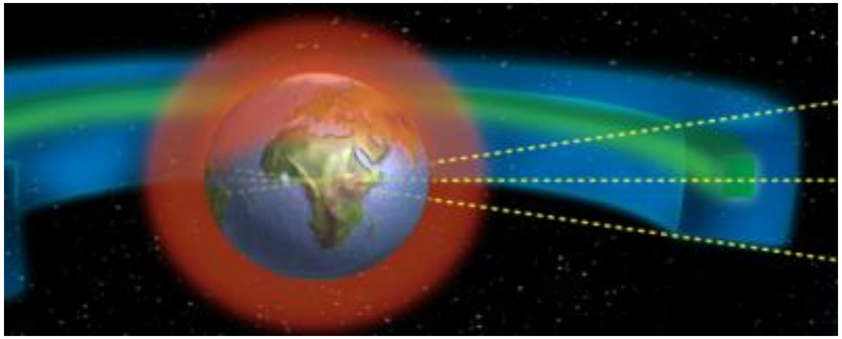
Space Debris Requirements

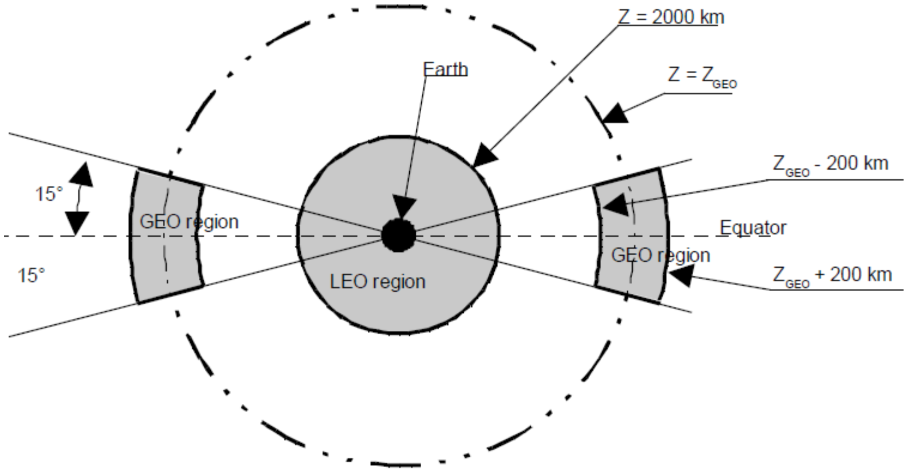
SDM – Main mitigation measures

- Avoiding the intentional release of space debris (Mission Related Objects MRO) into Earth orbit during normal operations
- Avoiding break-ups in Earth orbit (including passivation)
- Remove spacecraft and launch vehicle orbital stages from GEO to a graveyard orbit (GEO + 200 km)
- Remove spacecraft and launch vehicle orbital stages from LEO within 25 years after End of Mission (re-entry controlled or uncontrolled, higher orbit)
- Performing the necessary actions to minimize the risk of collision with other space objects
- Evaluate and control of Re-entry Risk

ISO 24113 Rqmt's: protected regions

- LEO protected region: a shell that extends from the surface of a spherical Earth with an equatorial radius of 6,378 km up to an altitude, Z, of 2,000 km.
- GEO protected region: a segment of a spherical shell with :
    a. lower altitude: geostationary altitude minus 200 km;
    b. upper altitude: geostationary altitude plus 200 km;
    c. latitude sector: 15° South ≤ latitude ≤ 15° North,
    d. ZGEO ~ is approximately 35,786 km





European Space Agency

ISO 24113 Rqmt's: Avoid MRO (1)

Release of space debris during normal operations: to be avoided into Earth orbit

a. Non-combustion debris: no objects are released as part of the nominal mission (review of design)
   - Debris identification: objects released as part of the nominal mission (if any) identified and listed (with dimensions, mass, material, phase of the mission, time and orbit of the expected release).
   - Lifetime data / calculation: For each MRO identified:
     - If in LEO protected region → presence limited to < 25 years after release (demonstration using a rapid semi-analytic propagators).
     - If close to GEO protected region → show that remains outside the GEO region (with a rapid semi-analytic propagators).
   - Debris released during launch operations (ECSS) shall not exceed:
     - One, for the launch of a single spacecraft
     - Two, for the launch of multiple spacecraft

   (this is to limits the possibility (during launch operations) to release adapters or dispensers in case of single or multiple launches.

ISO 24113 Rqmt's: Avoid MRO (2)

- **Pyrotechnic devices**: Review of design to screen pyros and to show that they do not release into orbit any particles > 1 mm.
- **Solid rocket motors**
  - SRM products in GEO (ISO & ECSS):
    - ISO requires that no solid combustion products are released into the GEO protected region.
    - ECSS requires no solid combustion products larger than 1 mm are released into the GEO protected region.

ISO 24113 Rqmt's: Avoiding break-ups in Earth orbit (1)

- **Intentional break-ups**
    a. Declaration that no intentional break-up of a spacecraft is planned.
- **Accidental break-ups**
    a. The probability of S/C accidental on-orbit break-up $< 10^{-3}$ until EoL. Develop a break-up prevention plan, to be reviewed / updated as part of the normal spacecraft design review process and during the operation phase.
    b. After the S/C end of operations (and before its end of life), proper actions are to be taken in order to deplete or make safe all remaining on-board sources of stored energy in a controlled sequence in order to avoid break-ups after the end of life (passivation).
- **S/S / items identification & failure analysis**
    a. System level risk assessment, considering each source of stored energy, potential failure modes resulting in a break-up (and risk mitigation measures, in the design, operational and disposal phases).

ISO 24113 Rqmt's: Avoiding break-ups in Earth orbit (2)

- S/S / items identification & failure analysis (cont'd)
    a. Industry best practice. Consider environmental extremes & potential mechanical degradation or chemical decomposition (during mission and following passivation).
    b. Subsystems to be screened for potential S/C break-up:
        – a) Electrical systems, especially batteries
        – b) Propulsion systems and associated components
        – c) Pressurized systems
        – d) Rotating mechanisms
- After the end of operations, passivation to be performed to avoid break-ups after the end of life:
    a. Energy sources on board to be depleted
    b. Onboard energy generation systems to be permanently deactivated.

  List of components to be passivated at the end of disposal phase (example)

ISO 24113 Rqmt's: Avoiding break-ups in Earth orbit (3)

Components to be passivated at the end of disposal phase (example):

Item	Passivation actions
Batteries	-Discharging batteries -Limit batteries re-charging
-Electro-explosive devices -Pyrotechnic devices -Actuators (e.g., NEAs, TKFs)	Deactivate if not already used during mission / remove electrical power
-Reaction Wheels (RW) -GYRO -C-GYRO	Remove electrical energy inputs
-Propellant tank (propellant and pressurant) -Propulsion PRP S/S lines	-Depressurizing tank (as far as possible) -Empty tank (as far as possible) -Empty propellant lines (as far as possible)
Heat Pipes	Demonstrate low probability of rupture

Generic requirement. Passivation strongly design dependent. It may be impossible to completely deplete some energy sources (residual ergols or pressurizers, battery disconnect, etc.).

ISO 24113 Rqmt's: GEO disposal

End of mission disposal: After EoM, S/C in LEO / GEO protected region to be removed / limit its post-mission presence. Disposal actions to be completed before S/C EoL. GEO disposal manœuvres:

a. At EoM, a GEO S/C shall perform disposal manoeuvres to be removed from the GEO protected region. Operational requirement, to be performed under the responsibility of the operator. During the design phase, provisions and resources (e.g., propellant) for GEO disposal manœuvres to be allocated.

b. GEO disposal - IADC formula: "simple" (and conservative) method. to comply with the requirement is allowed using the so called IADC formula:

$$\Delta H = 235 + (1\,000 \times CR \times A/m)\ [km]; \quad eccentricity < 0.003$$

a. GEO disposal - 100 years rule. More complex method, using a long-term orbit propagator to show the S/C not to re-enter GEO region within 100 years. The use of rapid semi-analytic propagators is acceptable.

b. The operator may require / need to implement specific GEO disposal strategies, with impacts on the design (e.g., use of pressurizer)

c. The passivation activities (e.g., tanks and piping venting) may influence the final orbital parameters in the disposal orbit.

ISO 24113 Rqmt's: LEO disposal

- LEO disposal manœuvres: at EeM, a LEO S/C shall perform disposal manoeuvres to limit its presence in LEO protected region < 25 years (from EoM) by:
  a. retrieving it and performing a controlled re-entry to Earth
  b. manoeuvring it in a controlled manner into a targeted re-entry
  c. manoeuvring it to an orbit with a lifetime < 25 years
  d. augmenting its orbital decay by deploying a device so that the lifetime is < 25 years
  e. allowing its orbit to decay naturally so that the remaining orbital lifetime is < 25 years
  f. manoeuvring it to an orbit with a perigee altitude >> LEO protected region

- For most of LEO missions (orbit < 1300-1400 km), a perigee lowering option is selected:
  a. Compute the orbital lifetime (rapid semi-analytic propagator). If lifetime > 25 years, define an orbit with lifetime < 25 years to be reached at the EoM
  b. Determine the delta-v and/or propellant necessary
  c. Allocate propellant in the resource budget.

- For LEO S/C with perigee > 1300-1400 km consider manoeuvres to an orbit with a perigee >> LEO protected region. Show that long-term perturbation forces do not cause the S/C to re-enter LEO protected region within 100 years.
- Proper assumptions for the evaluation of lifetime &/or propagation to be justified:
  a. Initial orbit parameters and epoch, S/C cross-sectional area after end of life, Drag coefficient, Atmosphere model, Earth gravity models, Solar radiation pressure, Third body perturbations, Solar proxies

ISO 24113 Rqmt's: successful disposal

1. Probability of successful disposal of the S/C in LEO or GEO to be computed and a probability > 0.9 has to be reached.
2. The probability has to be evaluated as a conditional probability weighted on the mission success at the time disposal is executed
    a. Identification of scenario and resources for disposal: start from nominal mission reliability evaluations; include estimation and availability of amount of propellant
    b. Identification of S/S for disposal and disposal reliability calculations
        – S/C bus, excluding P/L
        – Remove unnecessary S/S / equipment
        – Reliability figures composed at functional level
    c. Obtained reliability is composed with the availability of the resources (e.g., propellant) at the time disposal is executed.
3. Start and end of the disposal phase to be chosen ensuring compliance with the probability of successful disposal requirement

ISO 24113 Rqmt’s: reentry risk

1. No detailed requirements are given in ISO 24113 on S/C reentry maximum acceptable casualty risk. Requirements may be imposed contractually, voluntarily, or by Agencies or by national or international authorities.
2. The re-entry of the S/C shall comply with the applicable maximum acceptable casualty risk. Re-entry risk assessments (analyses, reports, etc.) are to be performed to show compliance with proper processes, methods, tools, models and data.

Application of SDM Requirements: Sentinel-1A Case Study

European Space Agency

Sentinel 1A - SDM Assessment

Discusses / verifies compliance with applicable "**Requirements on Space Debris Mitigation for ESA Projects**" (ESA/ADMIN/IPOL(2008)2, April 1, 2008)

a. Compliance matrix established; discussion and justification provided for all of the requirements:

b. Management requirements

c. Design and operational requirements (dealt together)

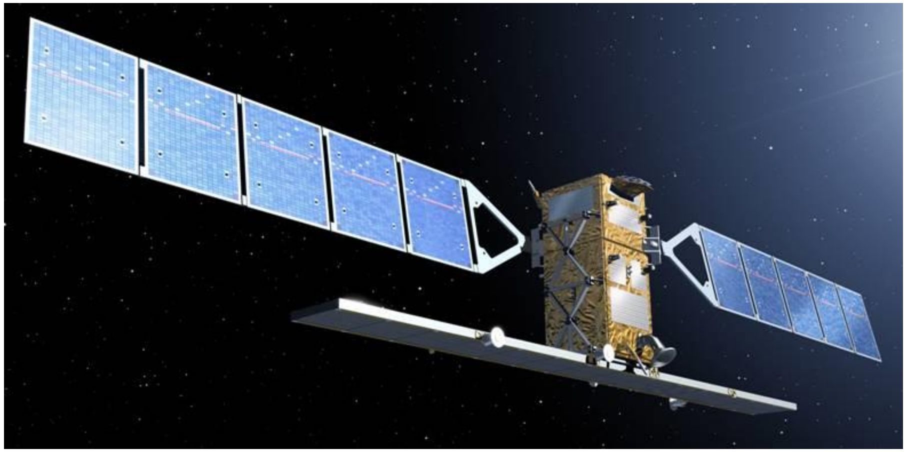
1. Detailed analyses provided in appendices for key requirements:

   a. Orbital lifetime and post-mission disposal

   b. Casualty re-entry risk

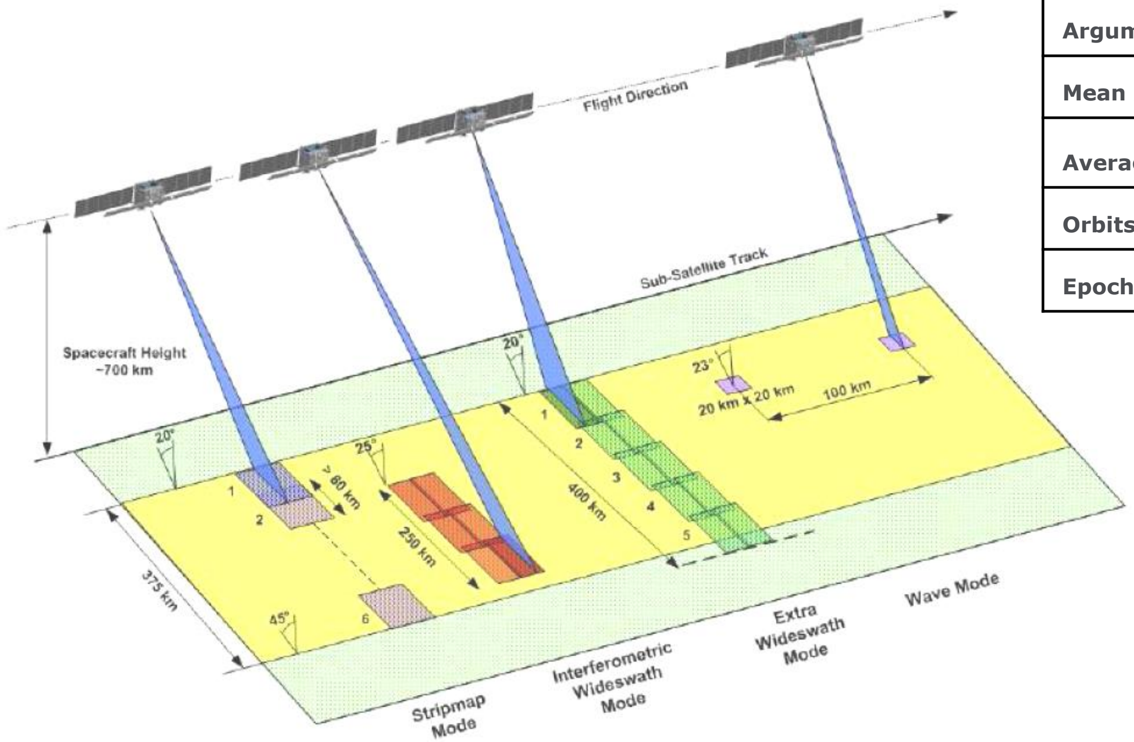
2. Dedicated chapter collecting proposed S/C and lower tiers requirements

1. CDR – June 2010



Sentinel 1A - SDM Assessment

S/C physical characteristics		
Mass	2194.51	kg
Dimensions	1.34 x 1.34 x 3.40	m
X-sec area (rand. tumb)	23.32	m^2



Orbital characteristics		
Semi-major axis	7080.15	km
Eccentricity	0.001266693	
Inclination	98.1124	deg
RAAN	308.545	deg
Argument of Perigee	68.9302	deg
Mean Anomaly	291.228	deg
Average altitude	693 (almost circular)	km
Orbits	Sun-synC, dawn-dusk Polar	
Epoch	2012/30/10-00:00:00.000	

Design requirements

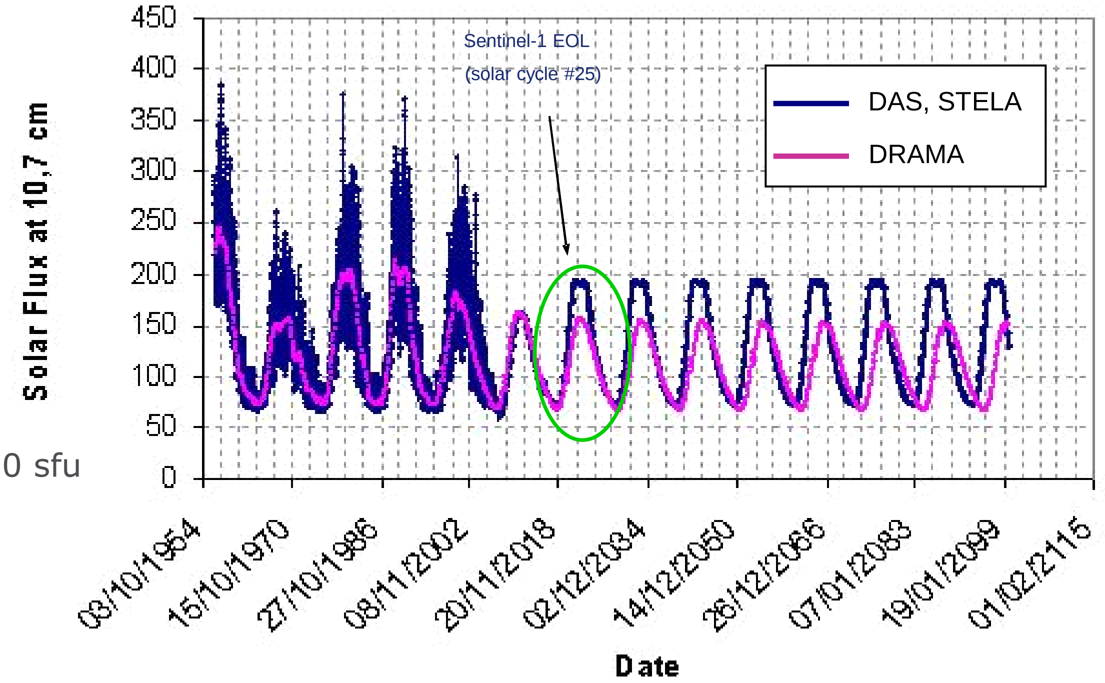
1. **Mission Related Objects**
    a. Launchers (DR-01): N/A
    b. Spacecraft (DR-02): no objects released as part of the nominal mission
2. **Fragmentation**
    a. No intentional destruction envisaged (DR-03)
3. **Solid propellant and pyrotechnics**
    a. Solid rocket motors (DR-04): no solid propellant used
    b. Pyrotechnics (DR-05): no particles > 1 mm released
        – Self contained cable capture Thermal Knife for SAW
        – Non Explosive Actuators (NEA) for SAR antenna
4. **Space System EoL Measures**
    a. Propellant accuracy (DR-08): 2 σ factor / + 5 kg accuracy determined
    b. Passivation (DR-09): recommendations on items / approach provided
    c. Reliability of successful EoL disposal (DR-10): evaluation based on S/S needed for disposal

Operational requirements

1. LEO 25-year Orbit Lifetime (OR-01):
    a. Need for disposal maneuvers
    b. Parameters for perigee lowering maneuvers determined
2. GEO, MEO, Launchers disposal (OR-02,-03,-04): N/A
3. Re-entry casualty risk assessment (OR-06):
    a. Assessment performed with DAS & DRAMA tools
4. Casualty re-entry risk $< 10^{-4}$ (OR-07):
    a. Non-compliance
    b. Additional analysis to be discussed / agreed

End of Life Analysis - Assumptions

1. Tools
   a. DAS 2.0.1 (NASA)
   b. DRAMA 1.0 (ESA)
   c. STELA 1.4.2 (CNES)
2. Mission duration
   a. 7.25 yrs
   b. 12 yrs
3. Solar flux
   a. variable F10.7 (see figure)
   b. constant on time: 140, 145, 150 sfu
4. CD
   a. fixed: 2.2
   b. altitude-dependent
5. Attitude (affecting x-sectional area)
   a. random tumbling
   b. stable attitudes from aerodynamic analysis
6. Atmospheric models
   a. Jacchia 77 – DAS
   b. CIRA-72 – DRAMA
   c. NRMLMSISE-00 - STELA
7. S/C mass
   a. maximum projected dry mass: 2194.51 kg



F10.7 proxies forecasts in DAS, DRAMA and STELA:

- mean solar cycle established from historic data;
- modulations for predicted cycles forecast from offsets of recent data w.r.t. the mean cycle;
- replicate of the mean cycle reproduced.

End Of Life Analysis - Results

1. Lifetime without post-mission disposal (PMD) manoeuvres:
   a. DAS 46 years
   b. DRAMA 73 years
   c. STELA 45 years
2. PMD perigee lowering to meet 25-year rule (see next slide), required propellant mass:
   a. DAS 23 kg (reference for lower tiers req.)
   b. DRAMA 34 kg
   c. STELA 26 kg
3. Direct re-entry, required propellant mass: ~ 170 kg

Reference parameters:

- End Of Mission @ 7.25 years (2020)
- Fixed $C_D = 2.2$
- X-sectional area = 23.32 m^2 (random tumbling S/C)
- Variable solar flux

Sensitivity analyses on lifetime and disposal (see next slides)

Different mission durations. DAS/DRAMA/STELA solar proxies forecast

PMD by perigee lowering to assure **25-year residual lifetime** (delayed de-orbiting)

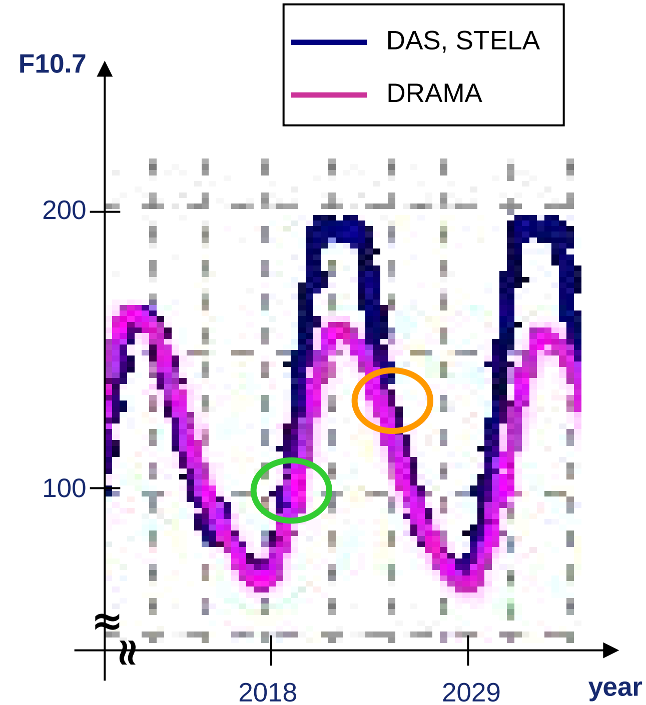
PMD in 2020 = EoM @ 7.25 yrs

	DAS	DRAMA	STELA
Disposal perigee height [km]	614	576	606
ΔV [m/s]	21.10	31.82	23.27
fuel mass* [kg]	23.15	35.00	25.54

PMD in 2024 = EoM @ 12 yrs

	DAS	DRAMA	STELA
Disposal perigee height [km]	590	564	597
ΔV [m/s]	27.57	34.86	25.70
fuel mass* [kg]	30.29	38.37	28.23

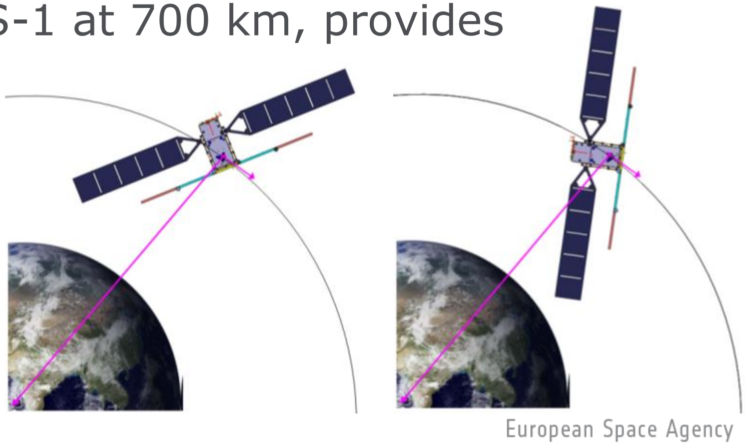
* I_{sp} = 205 s



PMD positions wrt F10.7 proxies

End Of Life Analysis - Sensitivity

1. Time-constant solar proxies
    a. Three different values: 140, 145, 150 sfu
    b. DRAMA average solar flux ~115 sfu (if fixed value 140 sfu, lifetime decreases by about – 40%)
    c. DAS average solar flux ~ 143 sfu (if fixed value 140 sfu, lifetime increases by about +3%)
    d. STELA average solar flux ~ 143 (if fixed value 140 sfu, lifetime increases by about 10%)
2. X-sectional area (and CD) depending on S/C attitude
    a. Aerodynamic analysis, performed on S-1 at 700 km, provides two stable attitudes corresponding to:
        – x-sectional area = 27.62 m2
        – CD = 2.3
    b. Random tumbling attitude chosen (more conservative).

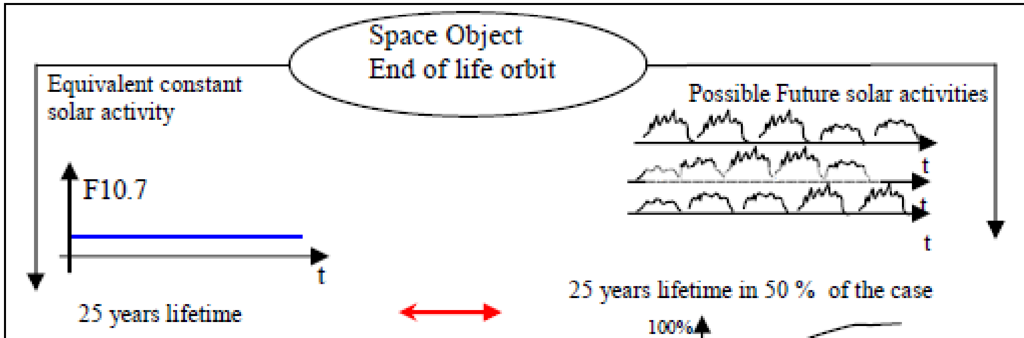


End Of Life Analysis – Sensitivity

1. Variable Solar Flux: results depend strongly on the starting date
2. How to deal with the fact that the S/C end of mission date may shift during the spacecraft development process?
3. CNES / STELA approach:
   a. Normalization approach of the solar activity hypothesis developed, based on an constant equivalent solar activity.
   b. Mean constant solar activity:constant value vs time depending on the S/C ballistic coefficient and on the initial apoapis altitude. Tuned, with a statistical approach, to 25 years re-entry duration (mean value)

Mean Constant Solar Flux:

$$F_{10.7} = 201 + 3.25 \ln\left(\frac{SC_d}{m}\right) - 7 \ln\left(Z_a\right)$$



Equivalency between constant and variable solar activity Flux

C_D depending on altitude (for a standard S/C [CNES]):

a. 2.14 (0-200 km, min); 2.57 (600-700 km, max); average on time = 2.5

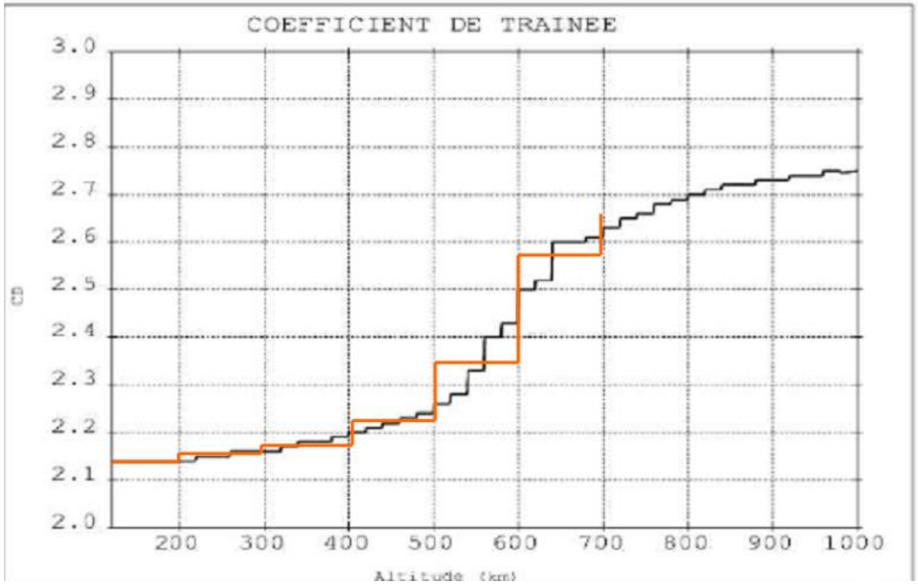
b. Effects on lifetime/propellant (DRAMA and STELA; C_D not editable in DAS):

- No PMD maneuvers → −14% (DRAMA) and −10% (STELA) shorter lifetime
- PMD perigee lowering, required propellant estimated for fixed C_D values (DRAMA):
  - min C_D (2.14): + 5% (too conservative!)
  - average C_D (2.5): – 11%
  - max C_D (2.57): – 13%

Constant value selected 2.2 (fixed in DAS)

because realistic but also conservative

C_D as a function of altitude (CNES)



Disposal Reliability and Propellant Accuracy

- **Reliability of S/S necessary for disposal (requirement ≥ 0.8) evaluated**:
  a. @ 7.25 yrs = 0.864
  b. @ 7.25 yrs + 2 mo's = 0.863
- **Propellant reserve accuracy**:
  a. Accuracy better than 5 kg required (System Requirements Spec.)
  b. With reliability of S/S for disposal = 0.863, to reach an overall reliability for disposal > 0.8:
     - Propellant availability *R* (Propellant Mass for EoL disposal) > 0.9274 (@ 7.25 yrs + 2 mo's)
     - *R* (Propellant Mass for EoL disposal) = Φ (μ + k σ) → k = 1.46 (@ 7.25 yrs + 2 mo's; normal distribution)
     - 2 σ (probability > 99.7%) margins recommended for the propellant reserve measurement
  c. An estimate on the σ to be provided by propulsion / operations, using adequate estimation methods like pVT, bookkeeping, etc.
     - Standard deviation for the selected method such that: 2 σ < 5 kg (σ < 2.5 kg).

Re-entry Safety

Overview

Re-entry Overview

- Since the launch of the first artificial satellite (1957), an average of 1.1 human-made objects per day have returned to Earth.
- Currently more than 40 large, human-made, uncontrolled objects re-enter the Earth's atmosphere every year.
- Sixty spacecraft uncontrolled re-entry events resulting in the recovery of debris on the ground have been documented.
- Apart from high area to mass ratio components (e.g. solar panels), generally lost at an altitude around 100 km, most spacecraft and rocket upper stages mainly disintegrate at an altitude of about 78±10 km.
- The survivability of components depends on shape, materials, accommodation, shielding, etc.
- It has been estimated that, globally, more than 1,400 metric tons of materials have survived re-entry since the beginning of the Space Age.

European Space Agency

Re-entry Overview

- The historical average risk is small, in the order of 10^{-4}.
- The risk of each re-entry depends from and increases with spacecraft mass and number of fragments which may survive.
- Historically 10-40% of a spacecraft mass has been estimated to have survived re-entry and impacted the Earth surface.
- Of the MIR mass of 135,000 kg about 25,000 kg in 1,500 fragments survived re-entry.
- For major systems such as the MIR station or ATV, performing a safe de-orbit (also called controlled re-entry) is the best way of mitigating the re-entry safety risk.

European Space Agency

Debris Incident Report

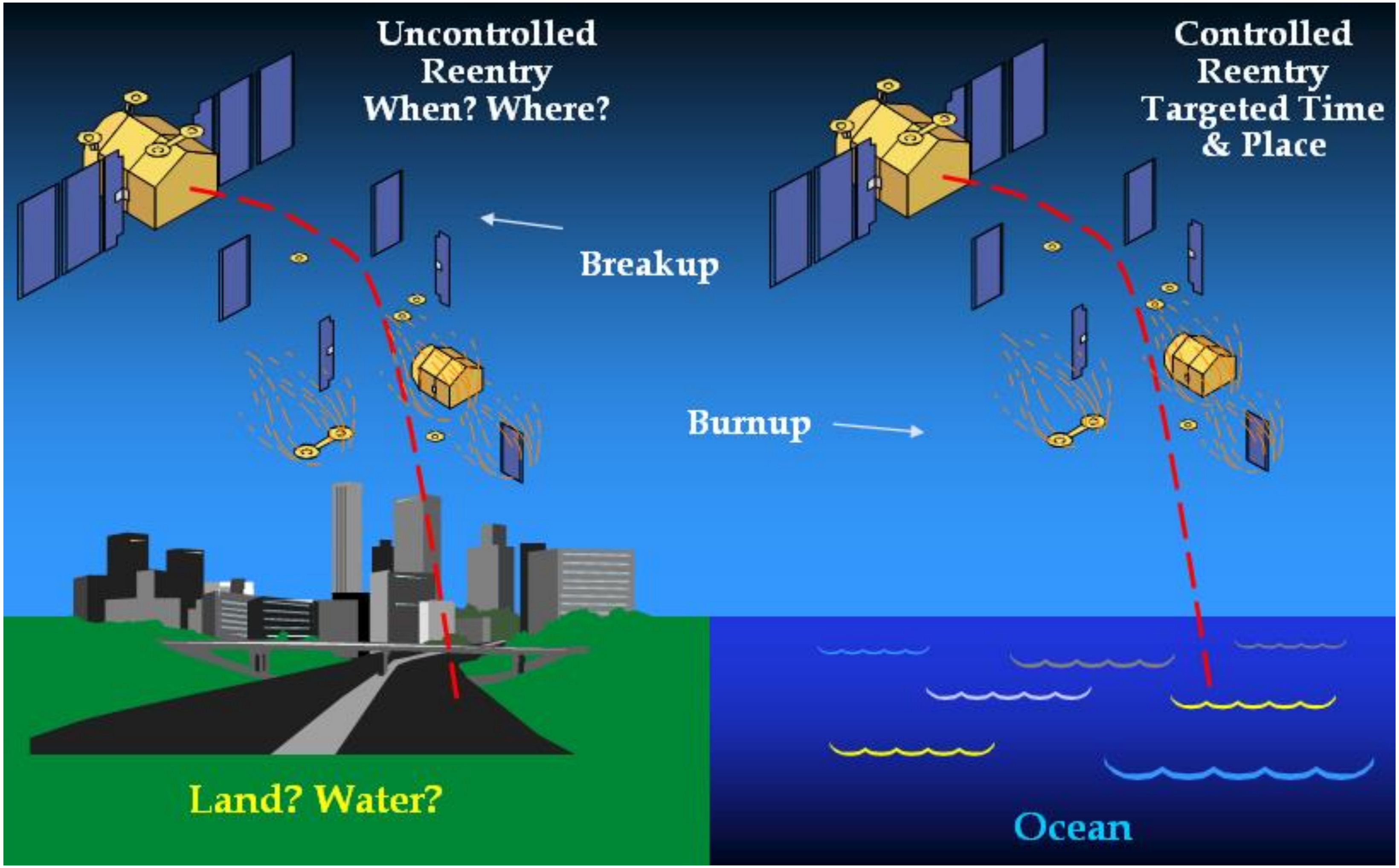
1. There is one reported incident involving a person being hit by a piece of space debris.

2. In January 1997, Lottie Williams was struck on the shoulder by a metal fragment comparable in weight to an empty soda can in Tulsa, Oklahoma, USA.

3. The National Weather Service reported the re-entry of a Delta II rocket body.

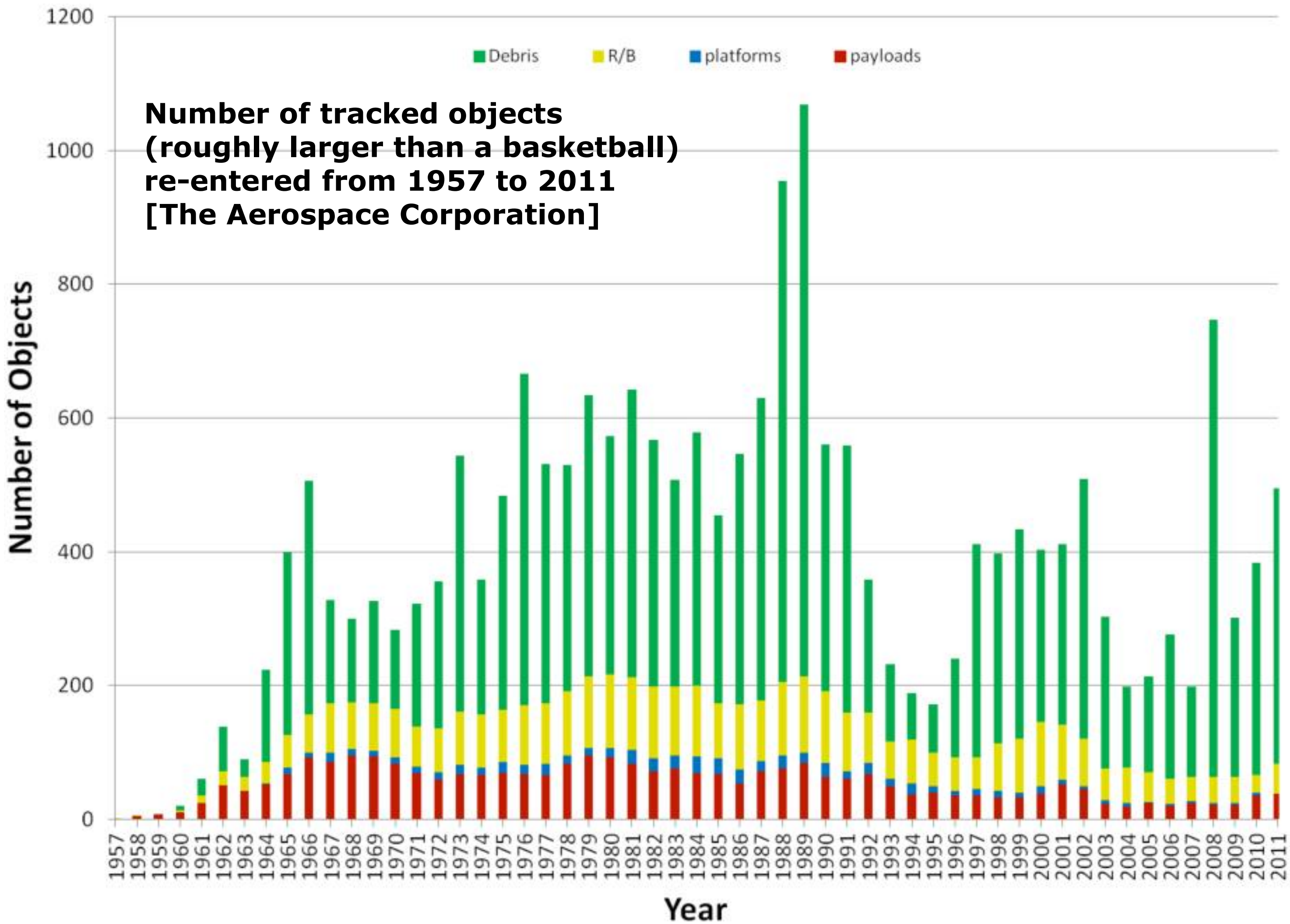
4. The fragment was analyzed and identified as the type of material NASA used to insulate fuel tanks.

Re-entry Terms



Source: S. Hull, J. San, "System Engineering Seminar – Orbital Debris Mitigation", Oct 2003

Tracked Re-entered Objects

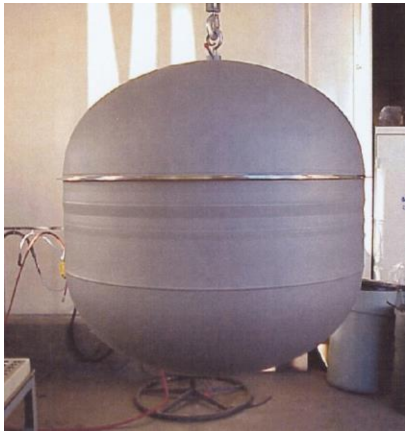


Uncontrolled Re-entries Hazards

Environmental Risks

- Typical fuels used by spacecraft are hazardous should they impact the ground
  - Cosmos 954 Accident (Canada, 1978)
  - The 2003 break-up of space shuttle *Columbia* resulted in numerous tanks reaching the ground (84,000 debris spreading 1000 x 40 km)
  - A Proton launcher failure in September 2007 contaminated a vast swath of agricultural land of Kazakhstan with 200 tons of toxic fuel
  - In 2008 USA-193 was destroyed due to the risk of large quantities of fuel reaching the ground

Haz Mat team response to 2003 *Columbia* break-up



Hydrazine tank used on USA-193

Radioactive Material Dispersal on Earth

1. As of today there have been 11 cases of failures leading to dispersal of radioactive material, including:

    a. plutonium payload on board Apollo 13 lunar module which ended up in the Pacific Ocean close to the coast of New Zealand, or
    b. 68 pounds of uranium-235 from the Russian Cosmos 954 which were spread over Canada's Northwest Territories in 1978;
    c. in 1996, when the Russian MARS96 disintegrated over Chile releasing its plutonium payload which has never been found.

2. Currently there are 32 defunct nuclear reactors, 13 reactor fuel cores and at least eight radio-thermal generators (RTGs) circling Earth. The total mass of RTG nuclear fuel is about 150kg, while there are 1,000kg of radioactive fuel from nuclear reactors.

Operation *Morning Lights* -Canada 1978

Cosmos 954 Accident

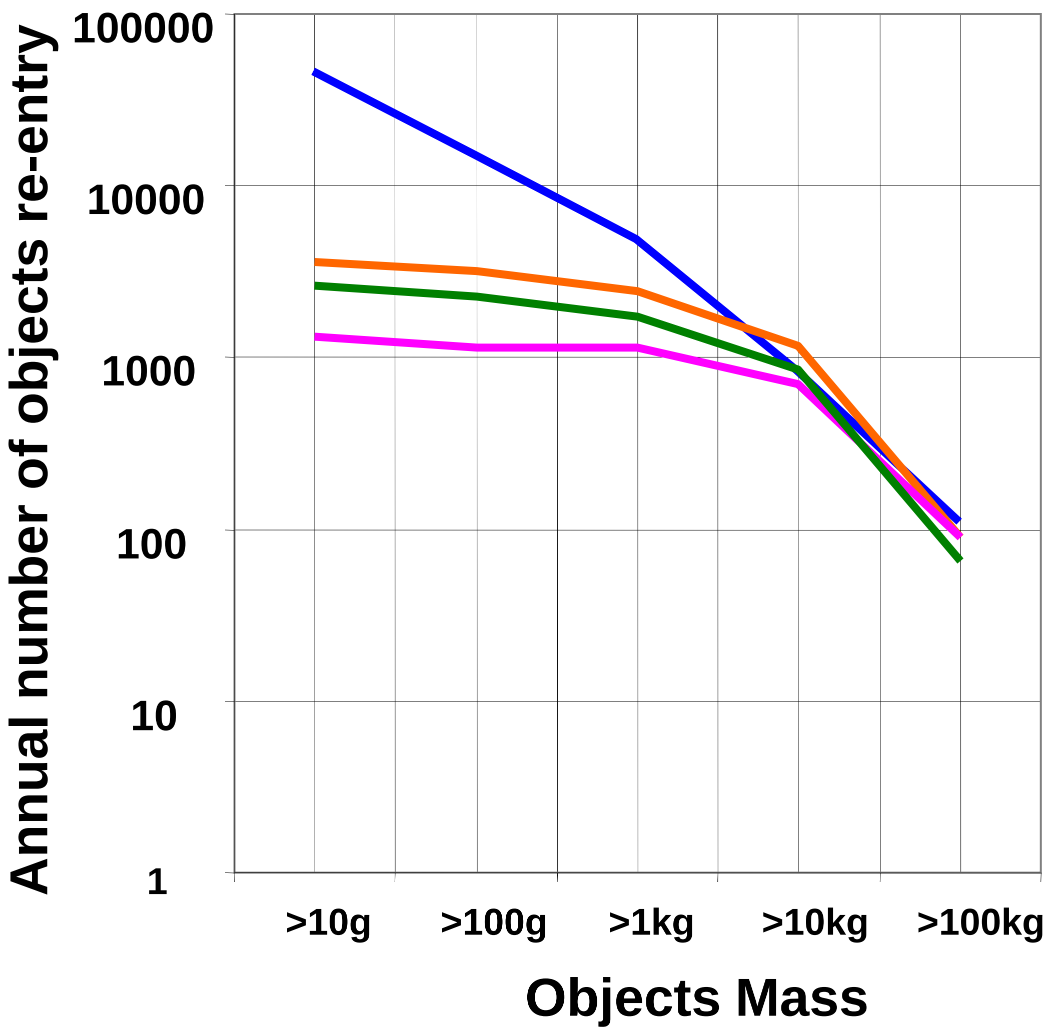
On 24 January 1978, COSMOS 954 nuclear-powered surveillance satellite, crashed in the Northwest Territories, scattering a large amount of radioactivity over a 124,000 square kilometre area in Canada's north, stretching southward from Great Slave Lake into northern Alberta and Saskatchewan.

The clean-up operation (coordinated between US and Canada) continued into October 1978 and resulted in the estimated recovery of about 0.1 percent of COSMOS 954's power source.

Settlement of Claim between Canada and USSR for Damage Caused by "Cosmos 954" (Released on April 2, 1981) for the sum C$ 3,000,000.00

First piece of debris found from the crashed Cosmos-954 Soviet satellite

Annual re-entries: Some Numbers



Summary of Recovered Re-entry Debris, The Aerospace Corporation Center of Orbital Debris studies

C. Portelli , L. Salotti , L. Anselmo , T. Lips , A. Tramutola, BEPPOSAX equatorial uncontrolled re-entry, ELSEVIER, 2003.

Uncontrolled Re-entry: Fuel tanks

- A number of fuel tanks have been recovered after surviving reentry, these pose a risk of casualty or property damage.

South Africa, 2000

Texas, 2001

Saudi Arabia, 2001

Guatemala, 2003

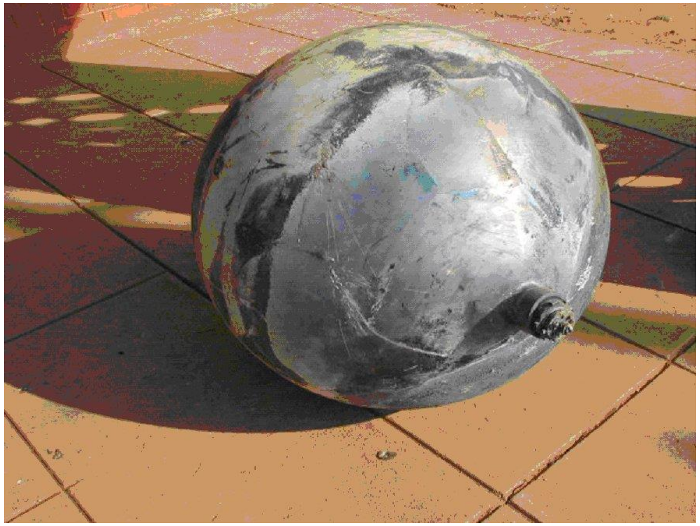
Australia, 2007

- Fuel tanks present impact risk to people, property (should they survive the re-entry) as well as environmental risk due to toxic fuels.

Pressurant Tank: Launcher Upper Stages

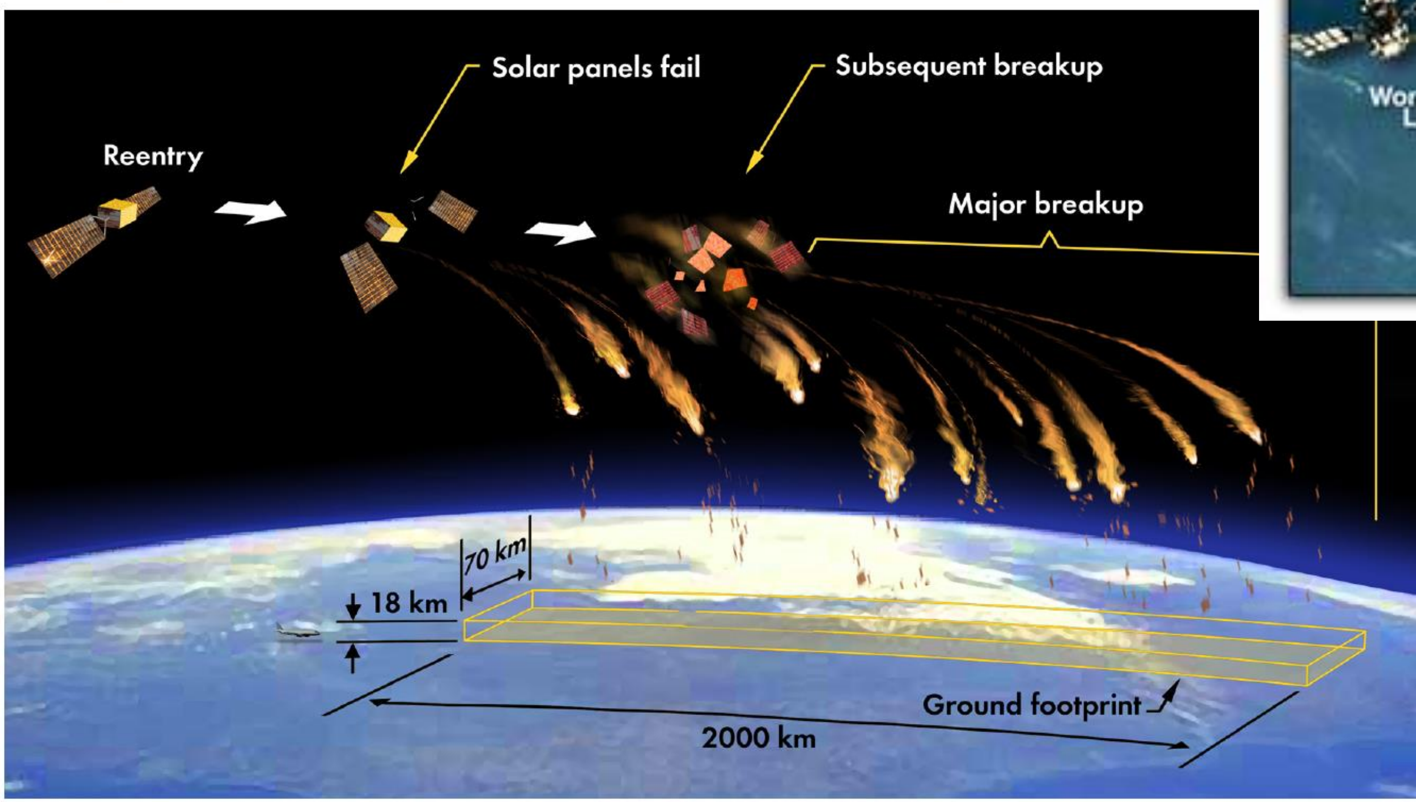
- More than 100 re-entries spacecraft debris are found on the ground.
- In **January 1997**, a 30 kg titanium pressurant tank survived the reentry of the Delta 2 second stage. It was found near Seguin, TX.
- In **March 2002**, a titanium pressure sphere fell near a home in Kasambya, Uganda. It was Identified as debris from 3rd stage of Ariane launch on May 1985.
- The larger part of uncontrolled re-entry debris (60 or 70%) come from Launcher upper stages.

Source: B. Lazare "”



CGRO Debris Footprint

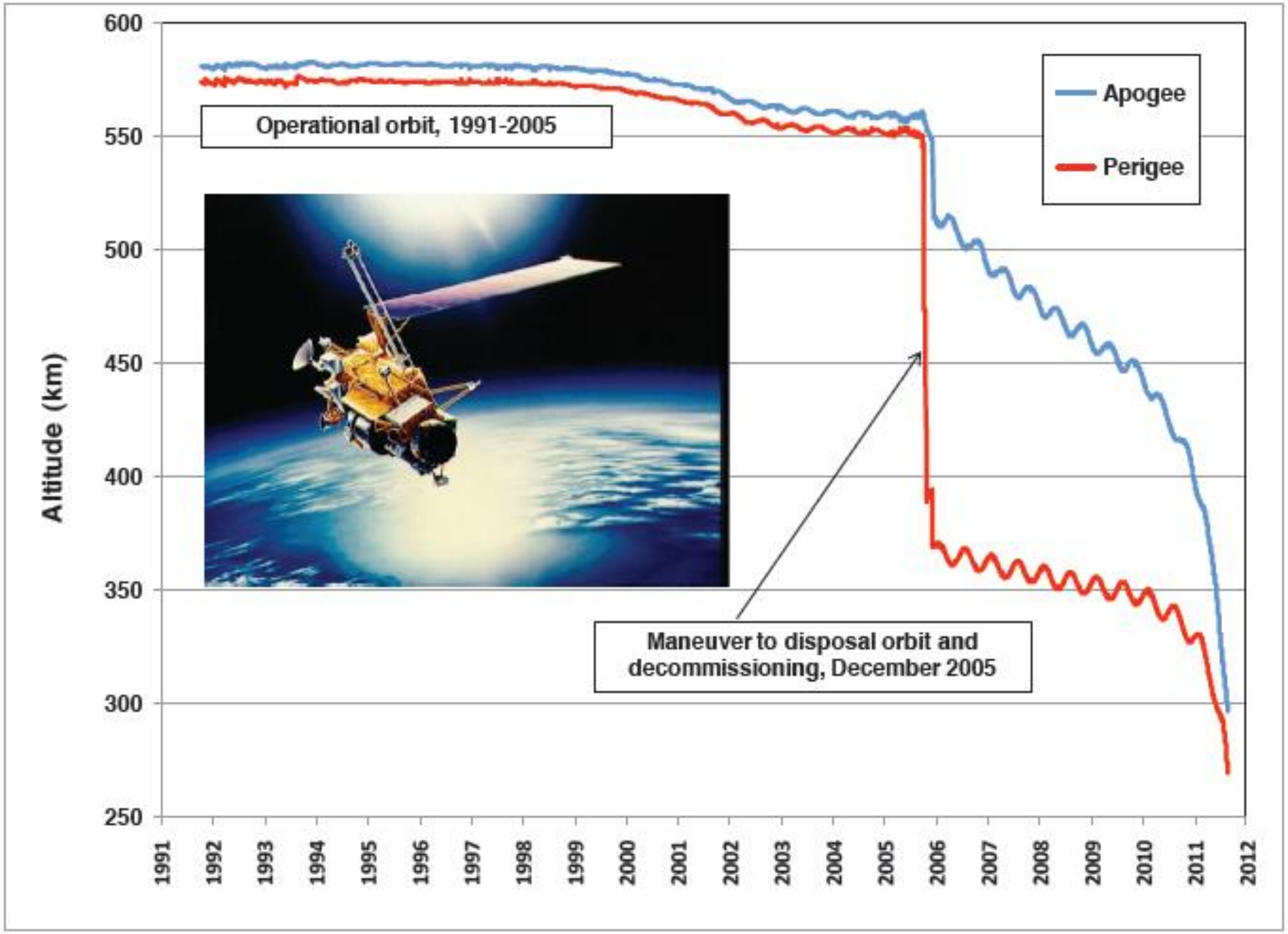
- Compton Gamma Ray Observatory (CGRO), NASA
- Launched in 1991, ~ 11 Ton
- Re-entered into the Pacific Ocean (June, 2000)



Uncontrolled Re-entry Risk: UARS

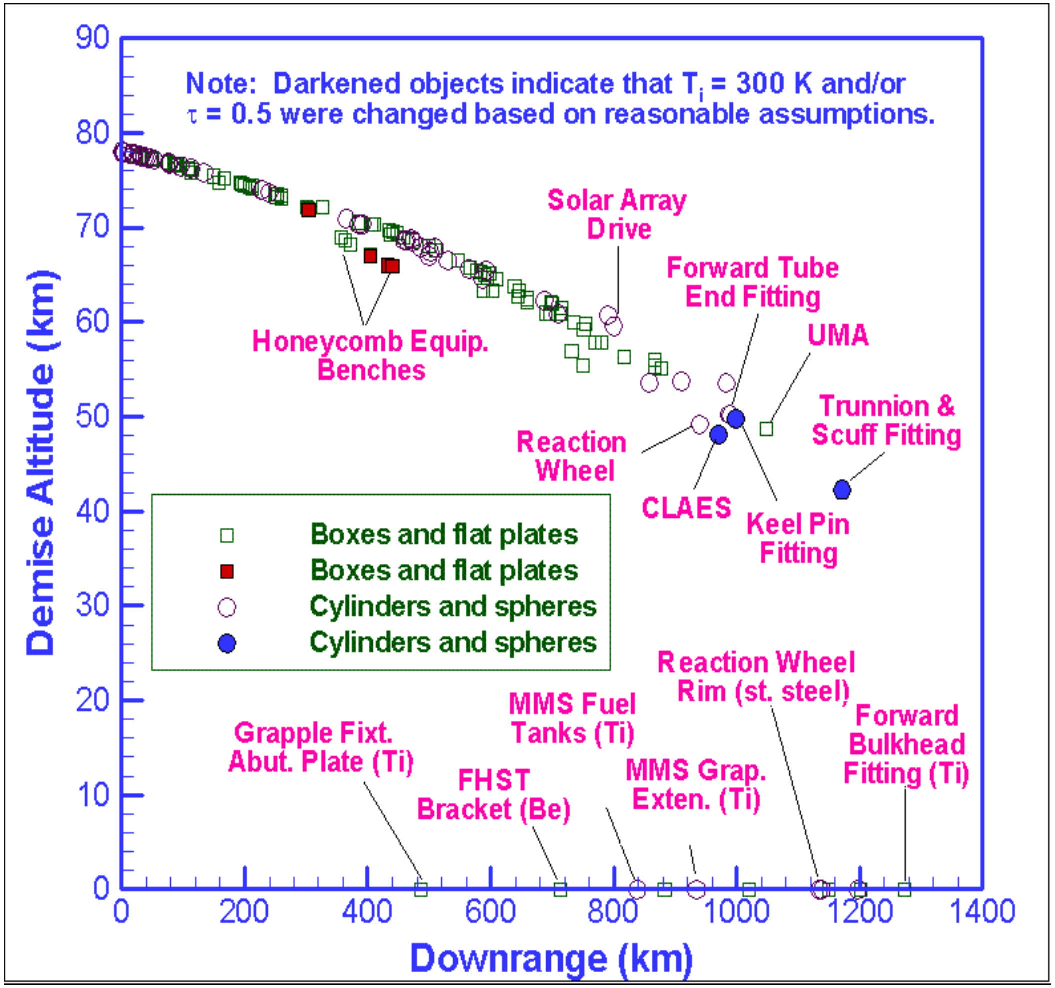
- Early Sept. 2011, NASA warned of the risk of a falling satellite (Upper Atmosphere Research Satellite, UARS) to re-enter the atmosphere on Sept. 23 ±1 day.
- The satellite was launched in Sept, 1991 and decommissioned on 15th Dec. 2005.
- Its dry mass was 5,668 kg.
- As of 18th Sept. 2011, the orbit was 215 km by 240 km.
- The number of "potential" hazardous objects expected to survive was 26 with a total mass of approx. 532 kg.
- Estimated human causality risk = ~1 in 3200
- Any surviving components of UARS were expected to land within a zone between 57º north latitude and 57º south latitude.
- The debris field was located between 300 miles and 800 miles downrange, or generally northeast of re-entry point.
- Final re-entry date was 23rd Sept. 2011.

Recent Orbital History of UARS



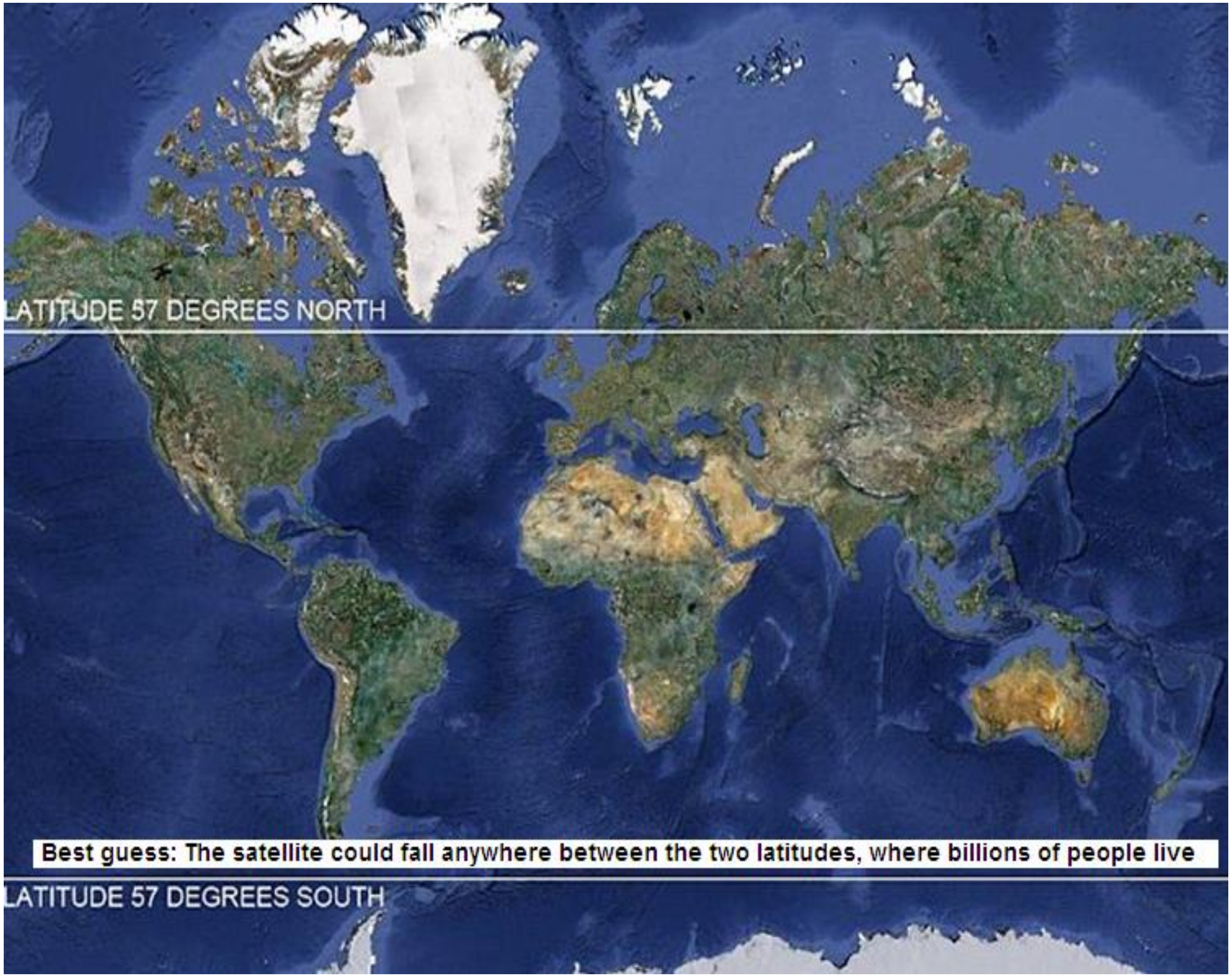
NASA/JSC/ODPO

Prediction of UARS Reentry Breakup



Demise altitude vs. downrange evaluated for nearly all of the UARS components.

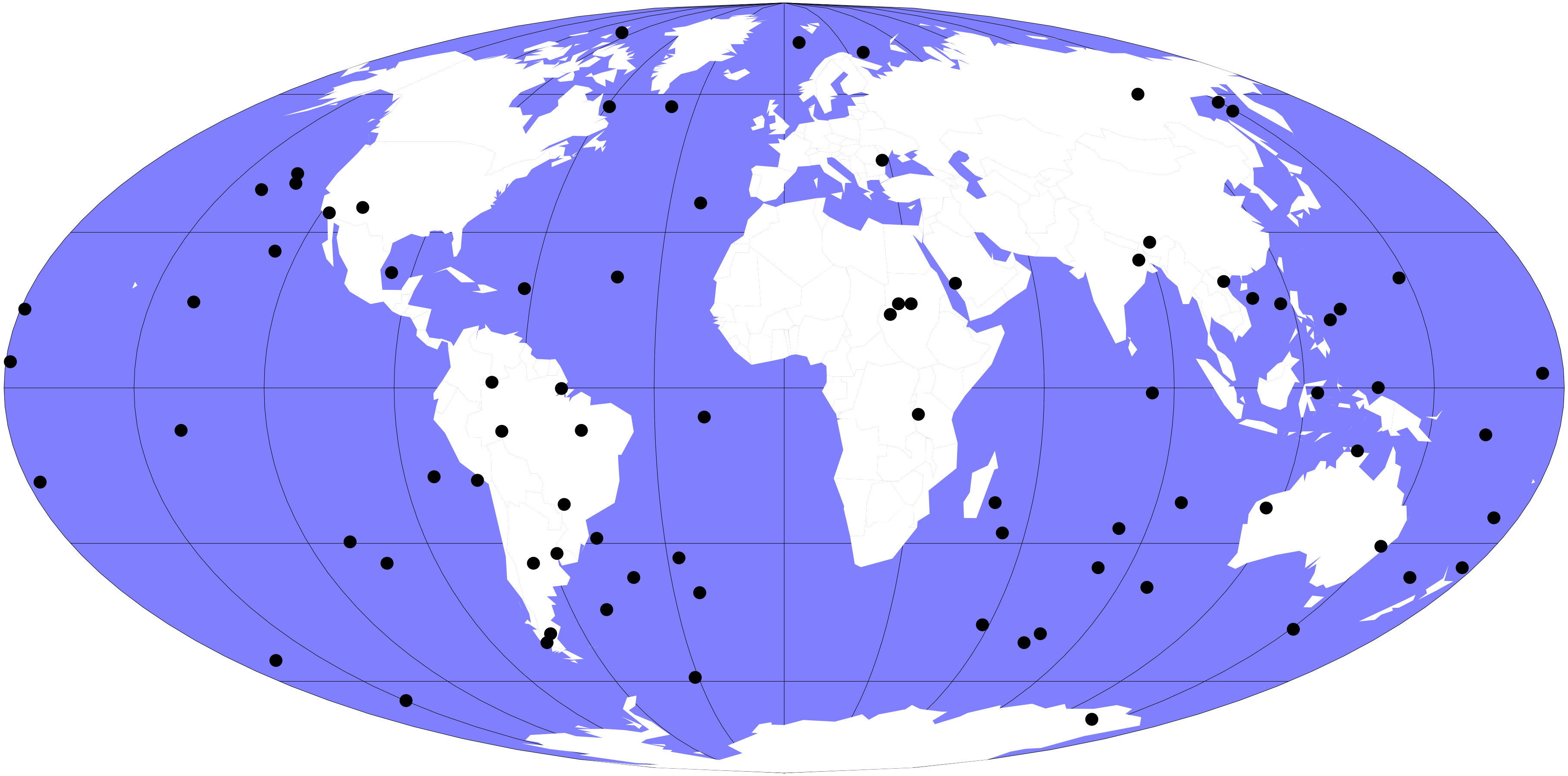
Where does UARS could have fallen?



RORSAT (2011)

European Space Agency

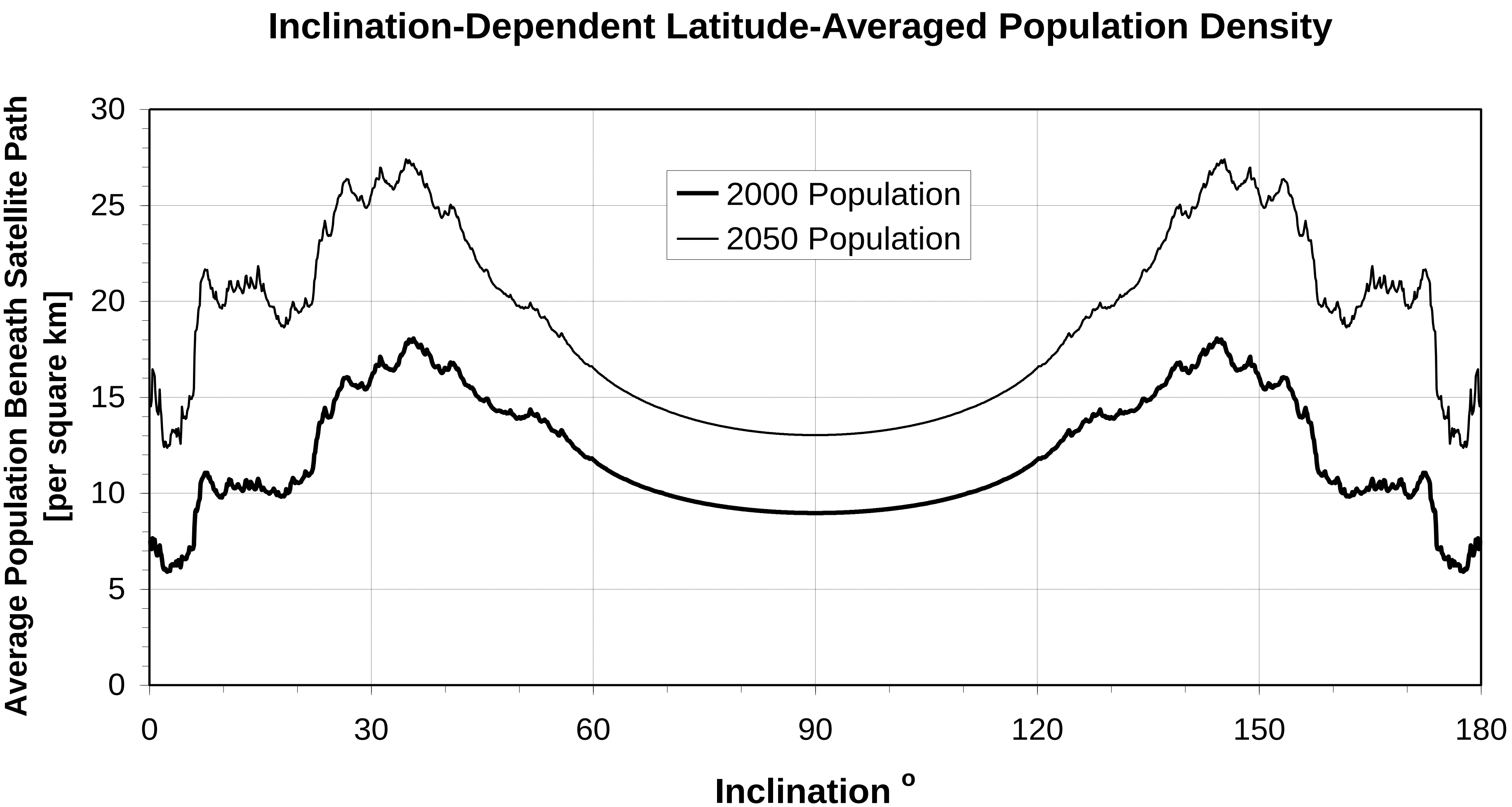
Global Distribution of Circular Orbit Reentries



81 intact satellites (both rocket bodies and spacecraft) that reentered between 2003 and 2011 (including UARS)

Source: Matney, M., "Empirical test of the predicted footprint for uncontrolled satellite reentry hazards", Proceedings 5th IAASS Conference, Oct. 2011.

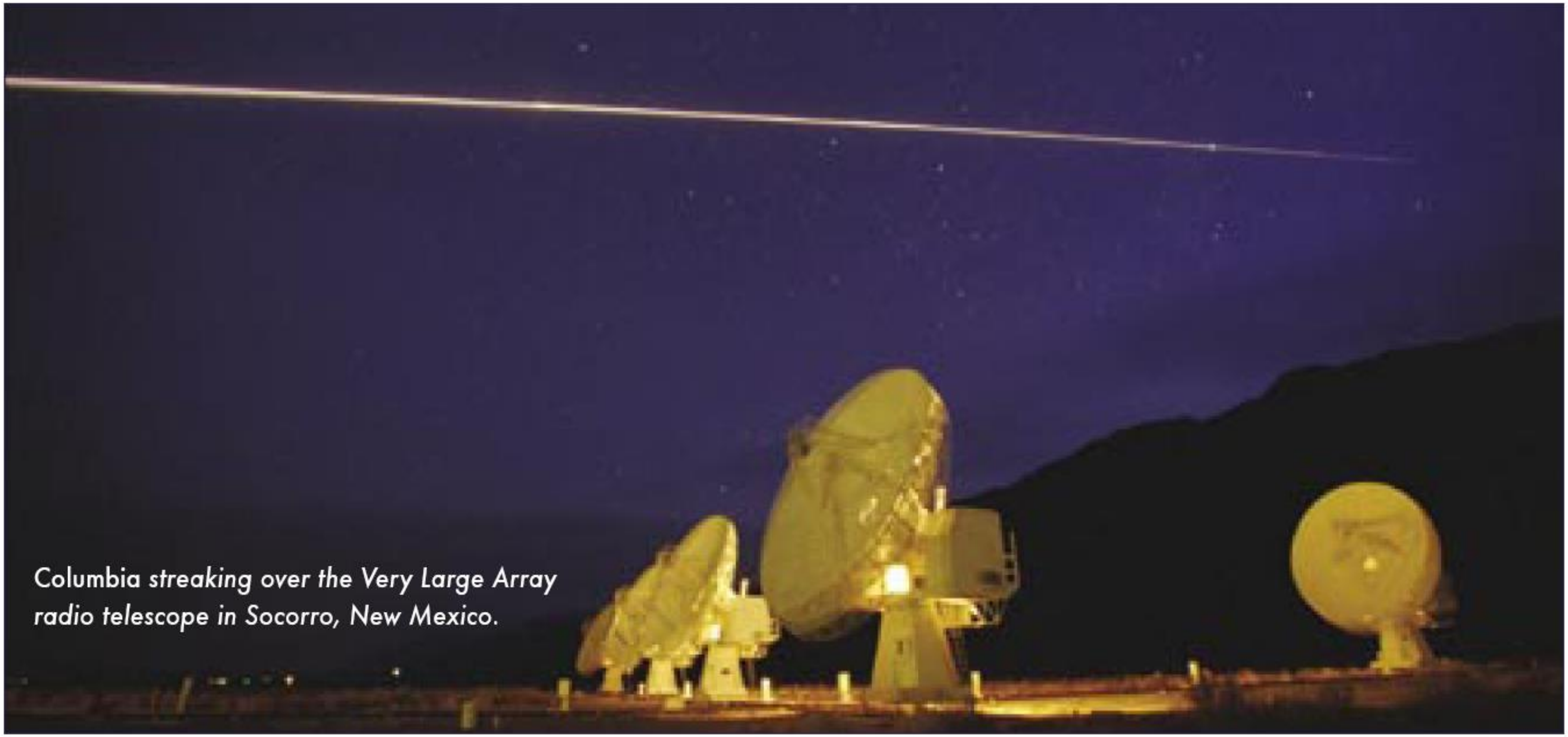
Average Density of People Below Satellite Path



Source: Matney, M., "Empirical test of the predicted footprint for uncontrolled satellite reentry hazards", Proceedings 5th IAASS Conference, Oct. 2011.

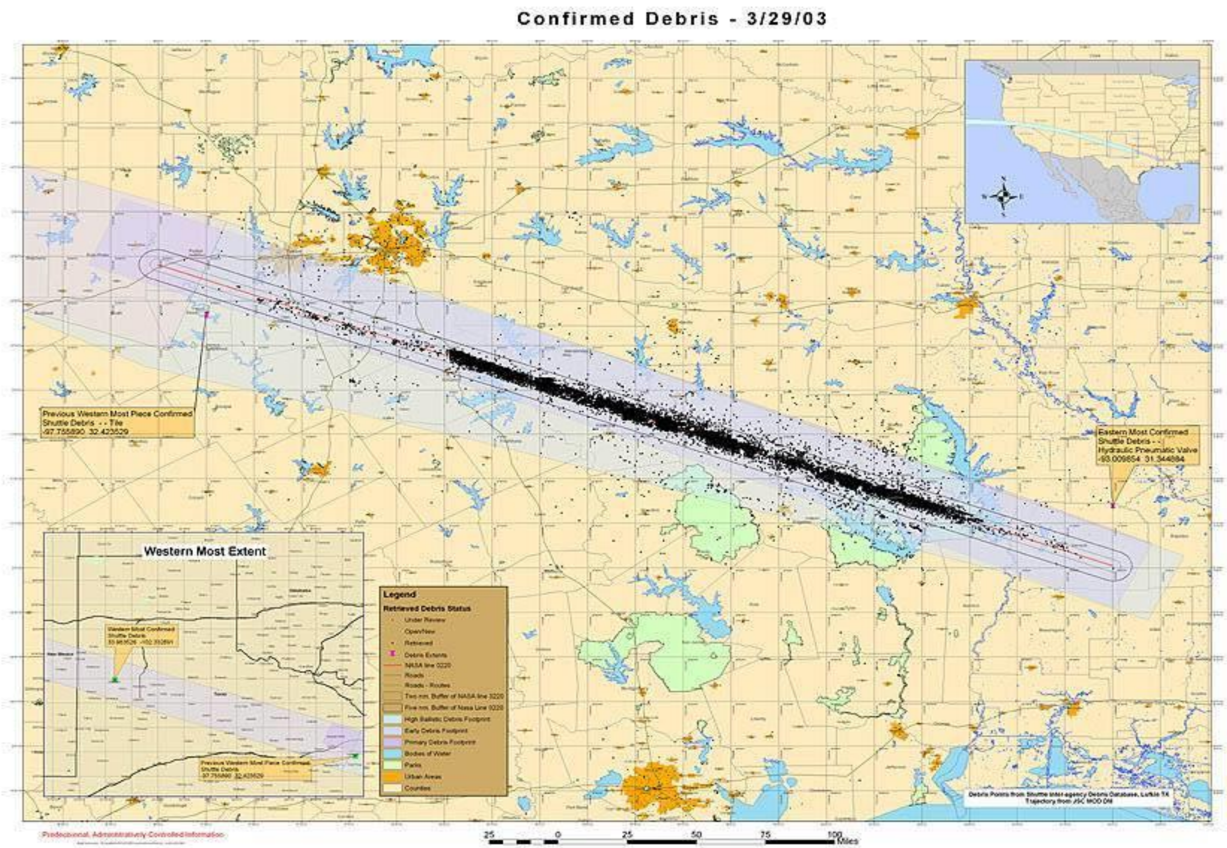
Re-entry Events
Aviation Safety Risk

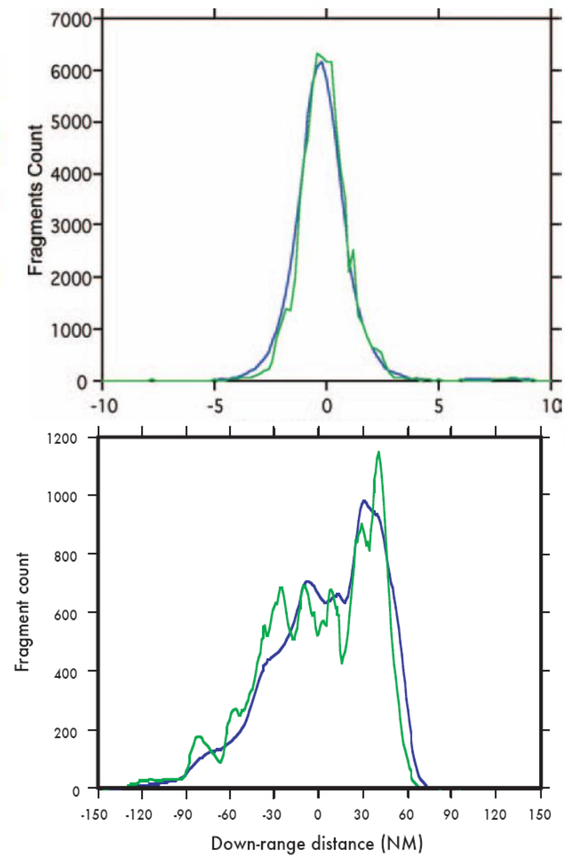
Space Shuttle Columbia Accident



From: *Columbia* Accident Investigation Board (CAIB), *CAIB Report*, GPO, Washington, DC, August 2003.
Photograph reprinted courtesy of the United States Government.

Columbia Debris

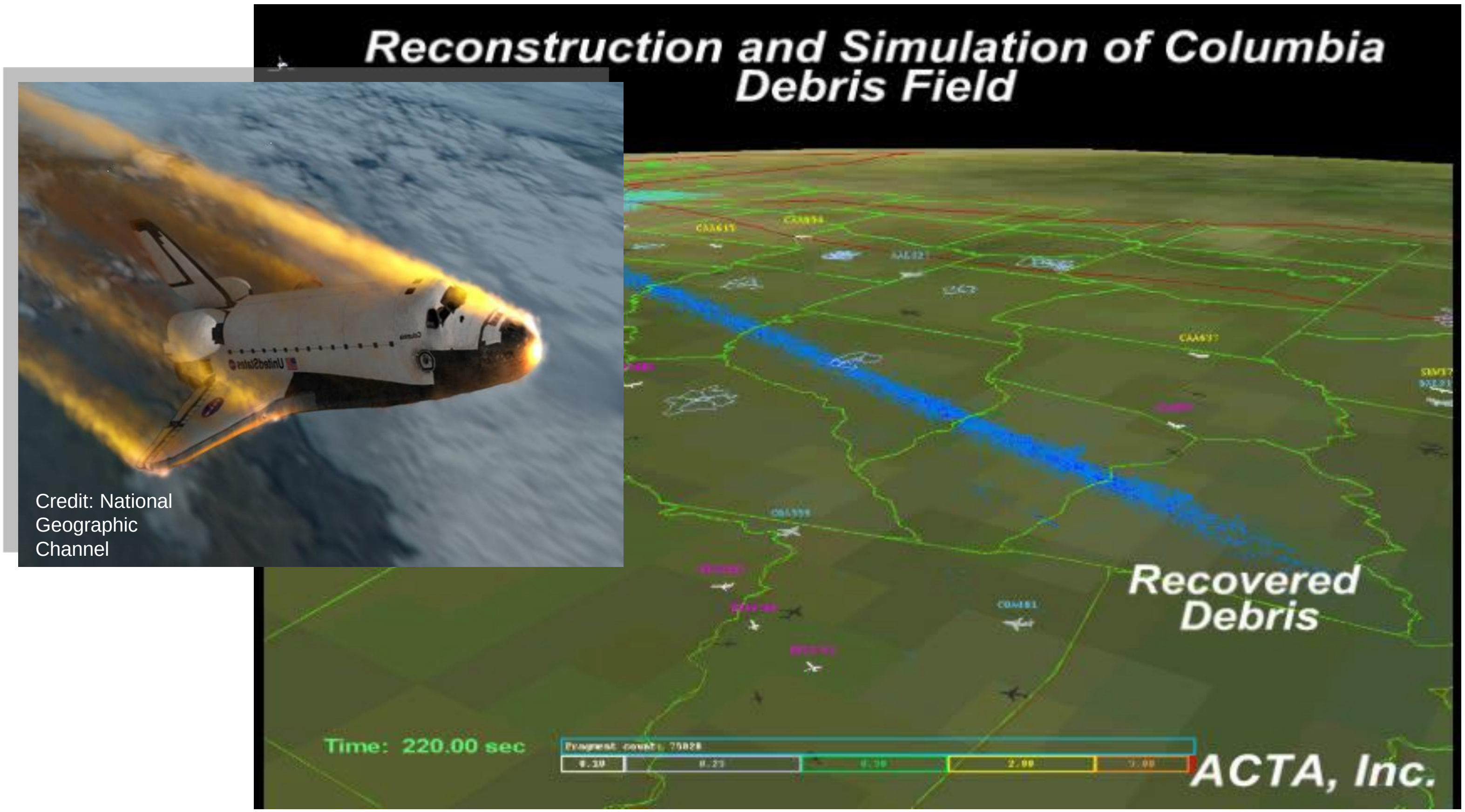




>84000 fragments recovered

From: *Columbia* Accident Investigation Board (CAIB), *CAIB Report*, GPO, Washington, DC, August 2003.
Image reprinted courtesy of the United States Government.

Spacecraft Failure: Re-entry Events



Credit: National Geographic Channel

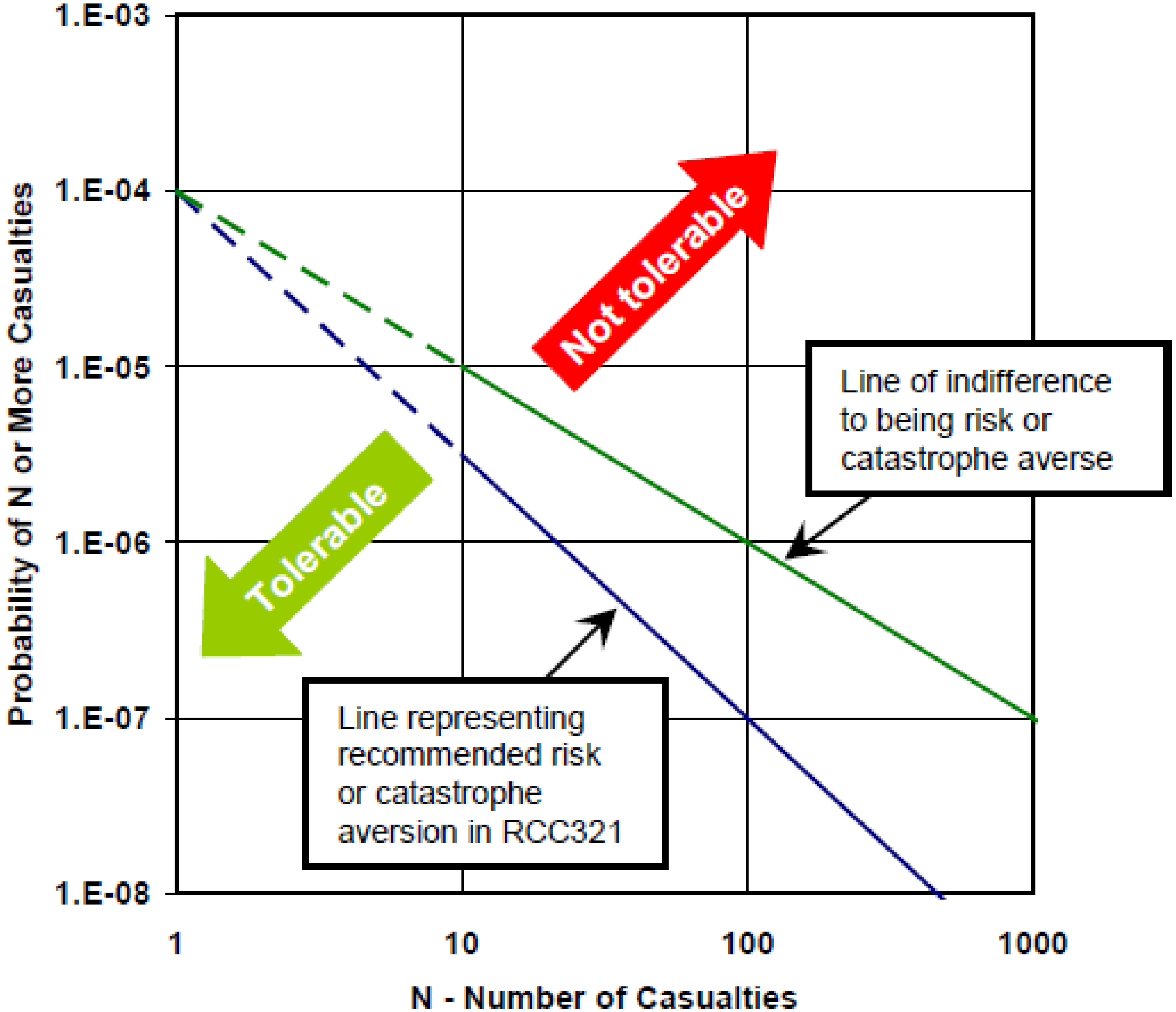
Debris Risk to Aircraft

1. Debris as small as several grams are a potential risk to aircraft due to collision velocity.
2. Many existing debris lists have ignored small fragments and are believed to underestimate risk to aircraft.
3. ACTA recently began adding fragment categories for small debris (connectors, wire harness fragments, tubing, small brackets etc.)
   a. Raised complaints from new vehicle manufacturers as "unfair" because existing launch vehicles are not held to the same condition.
4. Recommended RCC 321 debris mass thresholds for aircraft hazards are listed below (based on solid metal objects):

Aircraft Class	Threshold mass (g)
Commercial passenger transport jets	2.1
Business jets	0.6
All other aircraft	1.0

Source: Nyman, R., Collins, J., Wilde, P., "Development of Debris Lists for Launch and Re-entry Risk Analysis", ESA-IAASS Proceedings, October 2011.

Risk Profile for Catastrophe Aversion



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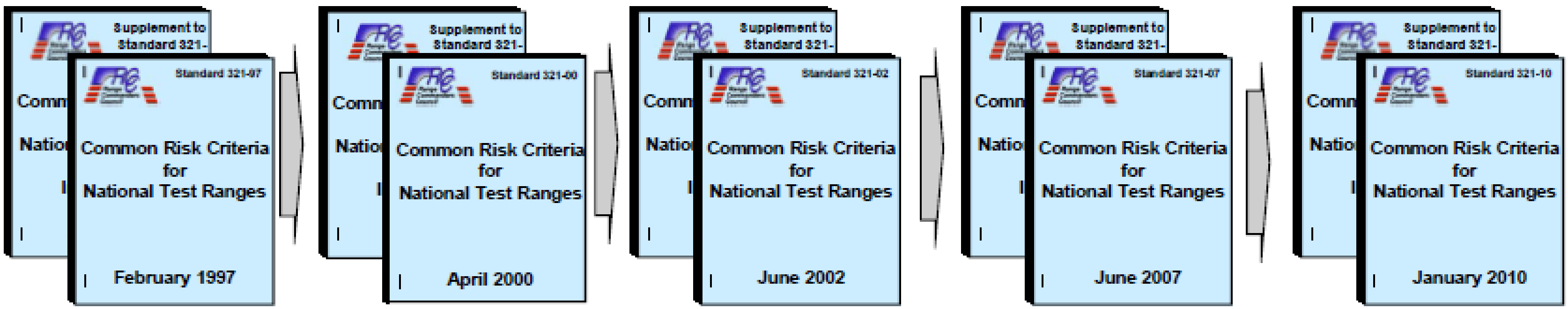
RCC 321: US Launch Risk Acceptability Document History



Tolerable aircraft
P_I = 1E-9

Protect against
m≥1 g

Tolerable aircraft
P_I = 1E-7

Protect against
m≥1 g

Tolerable aircraft
P_I = 1E-7

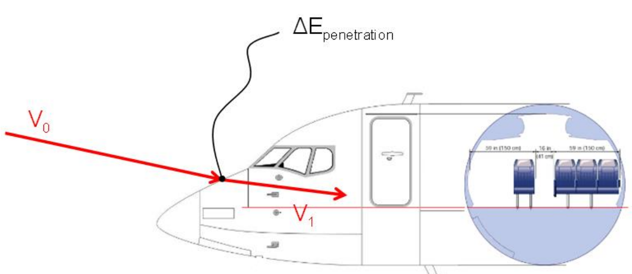
Protect against
m≥1 g

Protect aircraft passengers against individual risk and catastrophic risk

Two P_I criteria
Two definitions of hazardous fragments

New concerns:

1. Adequate debris list
2. Excessively conservative vulnerability model
3. Ability to support missions



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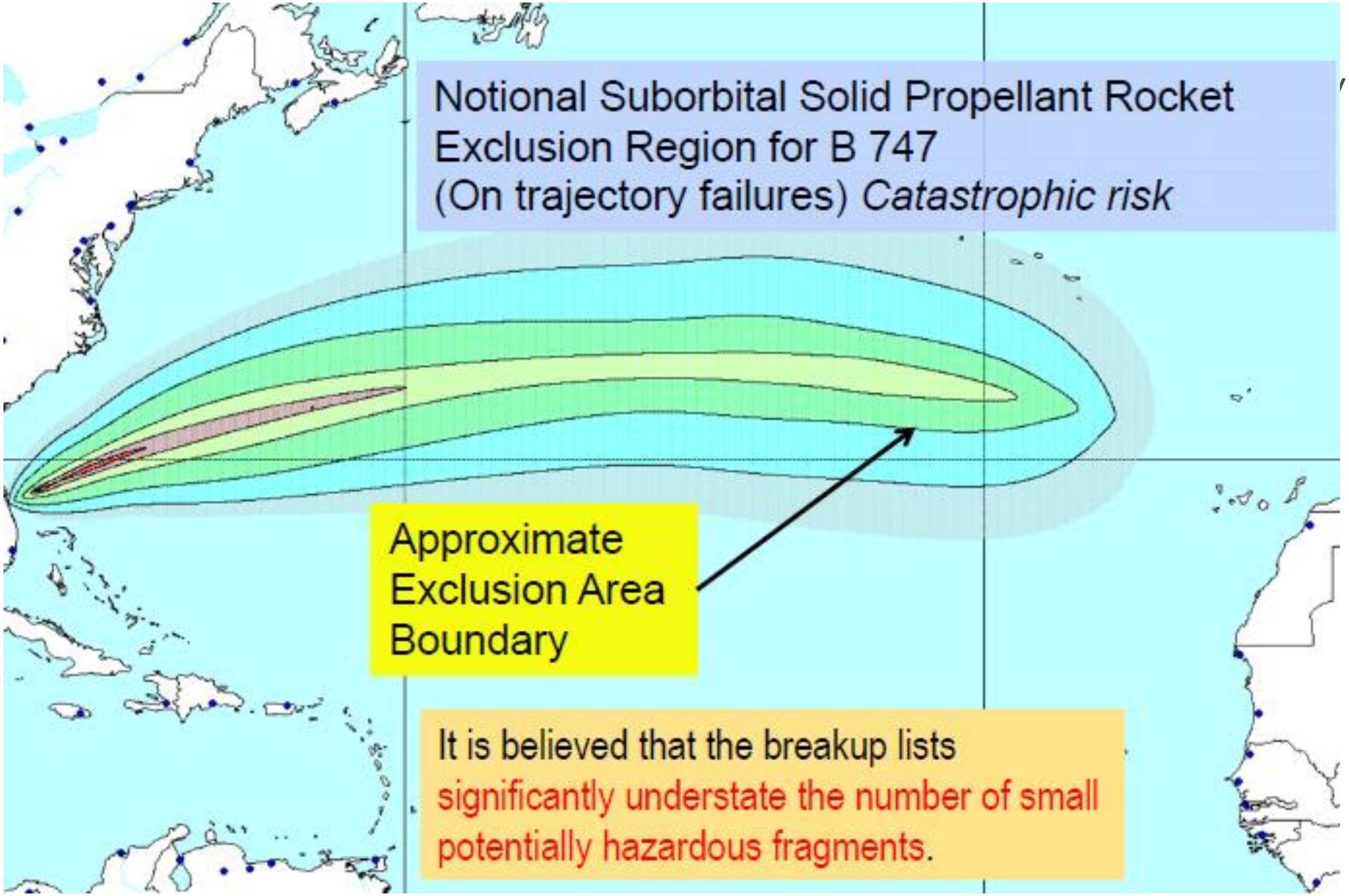
RCC 321

	TABLE 3-2. SUMMARY OF COMMONALITY CRITERIA			
	General Public		Mission Essential and Critical Operations Personnel	
Per Mission	Max. Acceptable	Undesired Event	Max. Acceptable	Undesired Event
	1E-6[b]	**Individual Probability of Casualty**	**10E-6**	**Individual Probability of Casualty**
	100E-6[b]	**Expected Casualties**	**300E-6**	**Expected Casualties**
	0.1E-6[a]	**Individual Probability of Fatality**	**1E-6[a]**	**Individual Probability of Fatality**
	30E-6[a]	**Expected Fatalities**	**300E-6[a]**	**Expected Fatalities**
	0.1E-6	**Probability of Aircraft Impact**	**1E-6**	**Probability of Aircraft Impact**
	10E-6	**Probability of Ship Impact**	**100E-6**	**Probability of Ship Impact**
	- - -	- - -	**1E-6**	**Manned Spacecraft**
Annual	**3000E-6**	**Expected Casualties**	**30000E-6**	**Expected Casualties**
	1000E-6[a]	**Expected Fatalities**	**10000E-6[a]**	**Expected Fatalities**

[a] **Advisory Requirements.**

[b] **If a flight operation creates a toxic risk, then the range must separately ensure the allowable level of risk enforced by them does not exceed other standards for toxic exposure limits for the general public when appropriate mitigations are in place. Chapter 8 of the Supplement provides an approach for implementing this requirement.**

Aircraft Exclusion Areas



Ground Safety
Casualty Risk Evaluation for Re-entry Compliance Requirement

ESA Re-entry Requirement

- **OR-06**: For space systems that are disposed of by re-entry, the **prime contractor shall perform an analysis to determine the characteristics of fragments surviving to ground impact, and assess the total casualty risk to the population on ground** assuming an uncontrolled re-entry.

- **OR-07**: In case the **total casualty risk is larger than 10^{-4}**, **uncontrolled re-entry is not allowed**. Instead, a controlled re-entry must be performed such that the impact foot-print can be ensured over an ocean area, with sufficient clearance of landmasses and traffic routes.

Acceptable Risk (10-4)

A fundamental human casualty risk threshold of 1 in 10,000 per reentry event was adopted by NASA in 1995, which was equivalent to a debris casualty area of no more than 8 m^2 averaged over all inclinations for that year.

ESA Re-entry Safety Reviews: Scope

- ESA **RSRP** is established as a self-standing entity with the **mandate to review and assess all public safety aspects.**
- Whenever a controlled re-entry, destructive or non-destructive is planned, the re-entry safety reviews for ESA space systems will be independently performed by ESA Re-entry Safety Review Panel (RSRP) under the supervision of the ESA Re-entry Safety Review Board (RSRB).
- Independent Safety reviews are also required in all those cases in which an uncontrolled re-entry is foreseen but the ESA re-entry safety requirements cannot be met by the project.

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RSRP Duties & Responsibilities

- Perform the safety review of the spacecraft/vehicle configurations and of planned and contingency operations products relevant to re-entry, including flight dynamics, model assumptions, risk assessments, tracking and monitoring support;
- Perform the safety review of the re-entry observation campaign and of spacecraft/vehicle recovery operations, when foreseen.
- Review and approve the safety dossier provide by the Project and related hazard reports, flight rules, supporting data and plan of notification to national and international bodies;
- Assess and provide recommendations to the ESA Re-entry Safety Review Board on the approval or disapproval of non-compliances submitted by the project against Agency level requirements.

ATV Re-entry Safety Review Panel (RSRP)

1. Before each ATV re-entry, a dedicated re-entry safety review is conducted by RSRP.
2. The RSRP has among others the following responsibilities.

    a. Perform, in preparation of the planned undocking of the ATV from the ISS, a dedicated safety review of the actual vehicle configuration and any relevant on-orbit anomaly resolution status, of the re-entry operations and ground segment readiness, and of any update to Hazard Reports, flight rules, supporting data and plan of notifications to national and international bodies;

    b. Provide to the ATV Re-entry Safety Review Board supporting the ESA Director General, assessments and recommendations on the safety of the ATV re-entry;

    c. Assess and provide recommendations to the ATV Re-entry Safety Review Board on the approval or disapproval of waivers submitted by the responsible project and operations organizations.

ESA Re-entry Safety Boards

ESA

Director General

↑ RSRB

Re-entry Safety Review Board

↑ RSRP

Re-entry Safety Review Panel

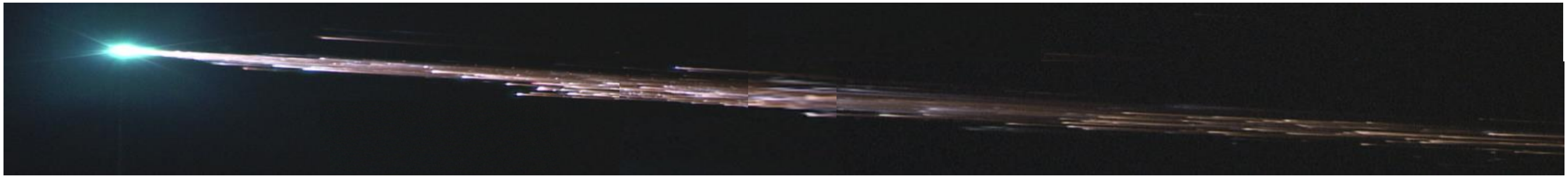
Membership

Franco Ongaro (D/TEC)

Thomas Reiter (D/HSO),

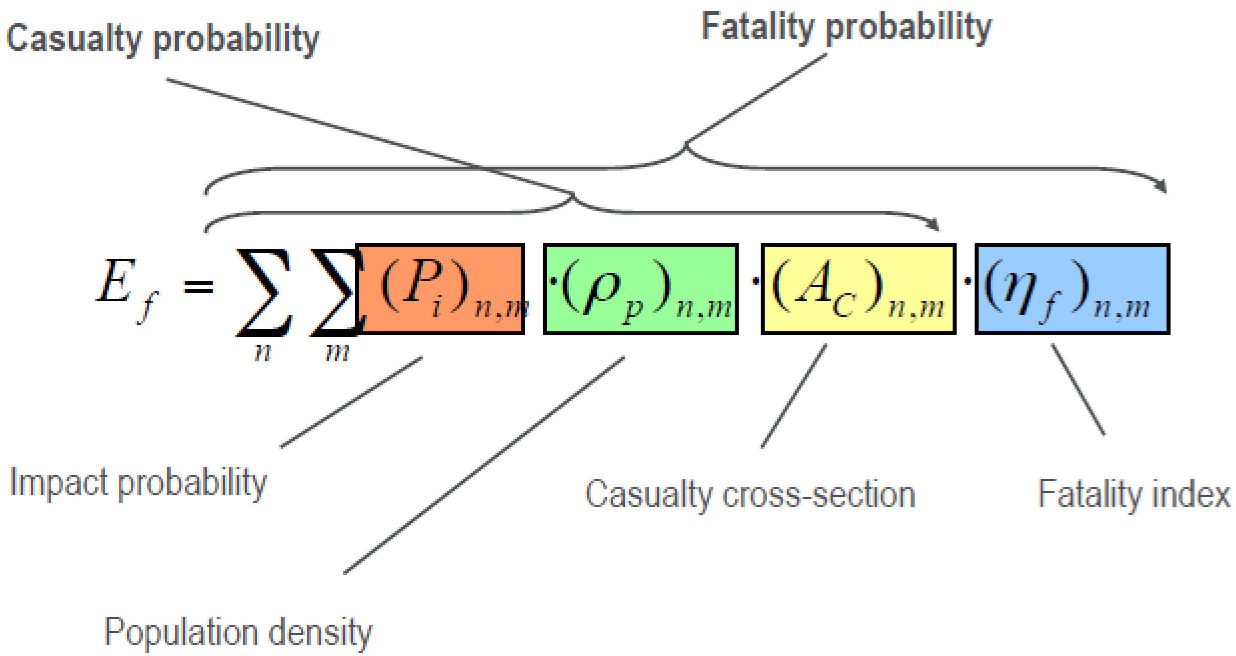
Marc Pircher, CNES Director

Name	Function	Organization
T.Sgobba	Chairperson	TEC-QI
F.Alby	Member	CNES-CST
L.Bianchi	Member	TEC-QQD
R. Schmidt	Member	DG-I
H.Klinkrad	Member	OPS-GR
M. Trujillo	Secretary	TEC-QI



On-Ground Casualty Analysis

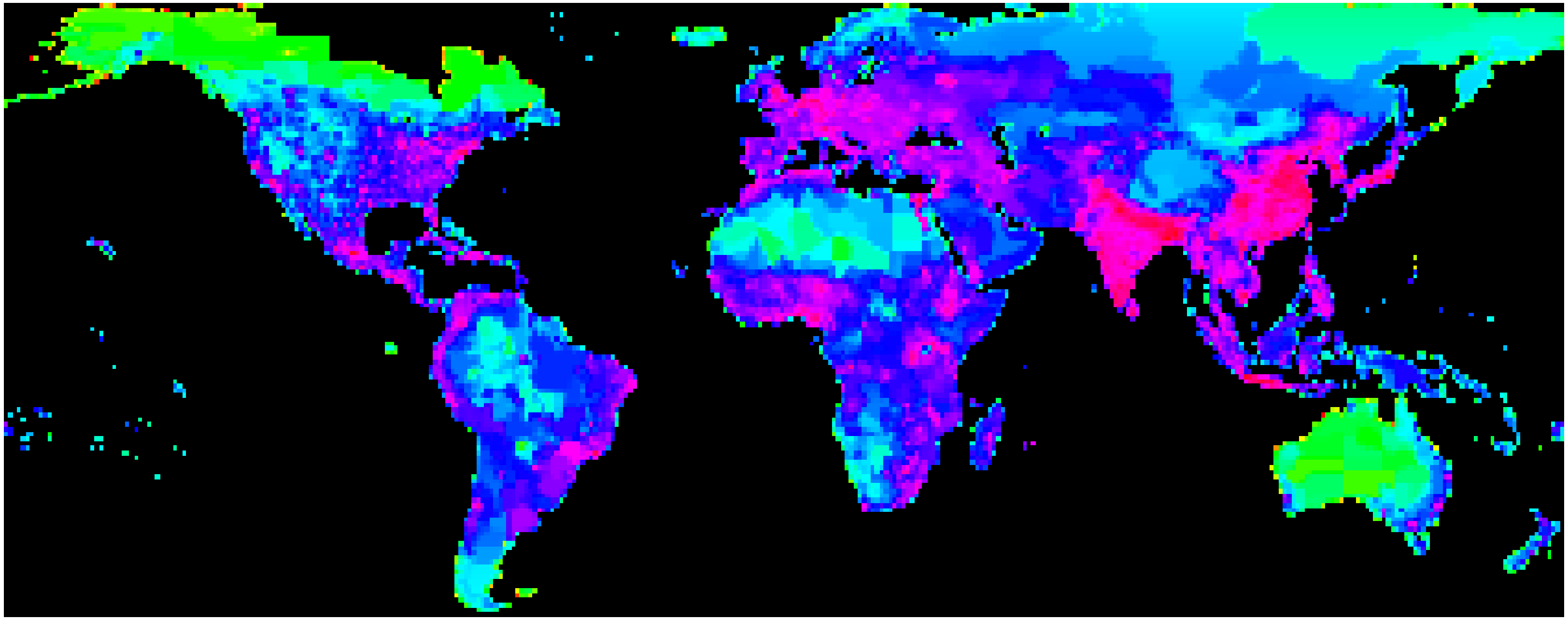
- On-ground Casualty depends (among others) on:
  a. Mass (actually: mass of certain materials, attitude motion, spacecraft geometry, explosive fragmentation events)
  b. Inclination (i.e. the latitude band concerned on Earth which encapsulates different fractions of the population)
  c. Epoch (population grows with time)



$$E_f = \sum_n \sum_m (P_i)_{n,m} \cdot (\rho_p)_{n,m} \cdot (A_C)_{n,m} \cdot (\eta_f)_{n,m}$$

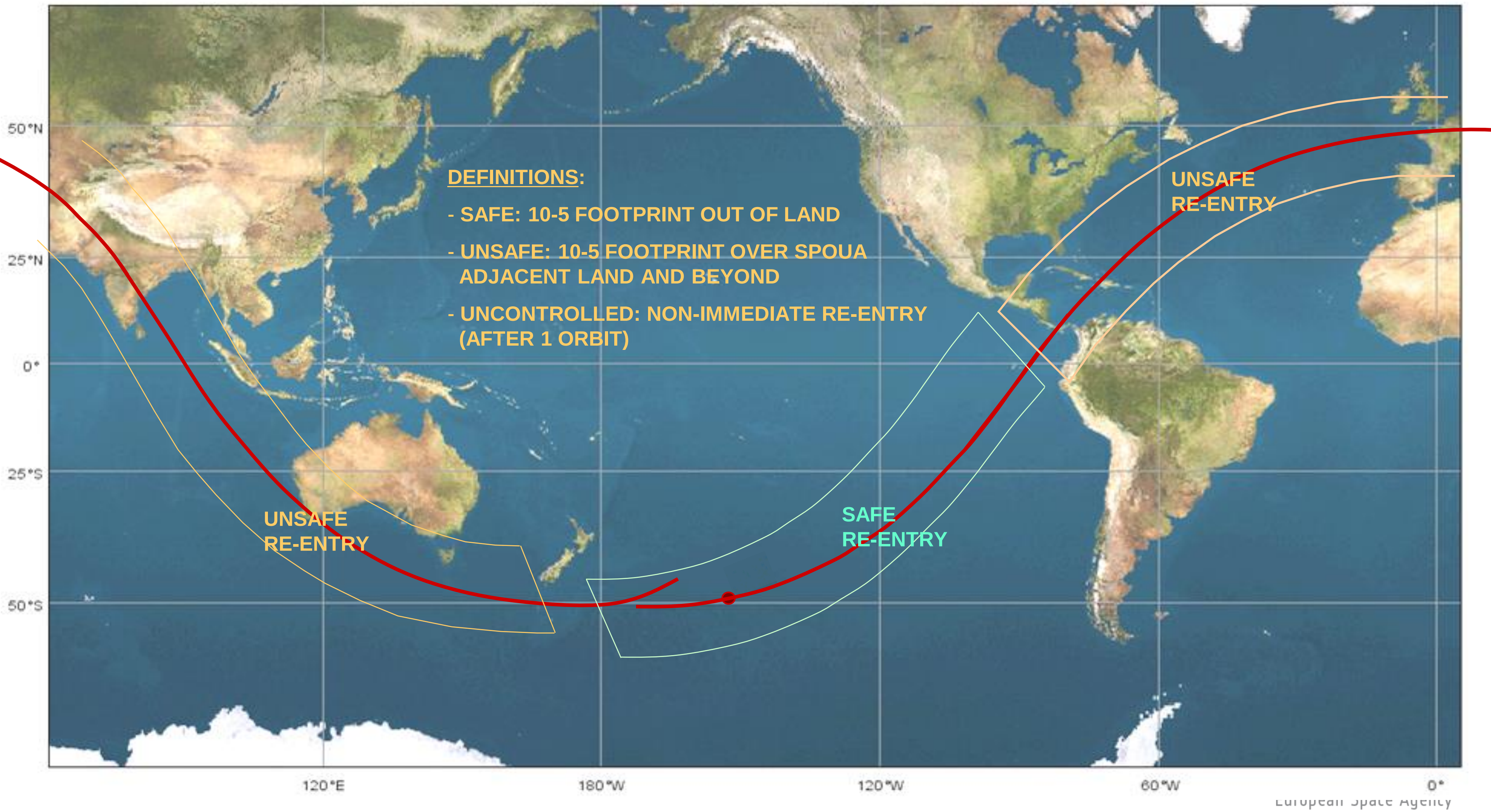
European Space Agency

Earth Population Distribution

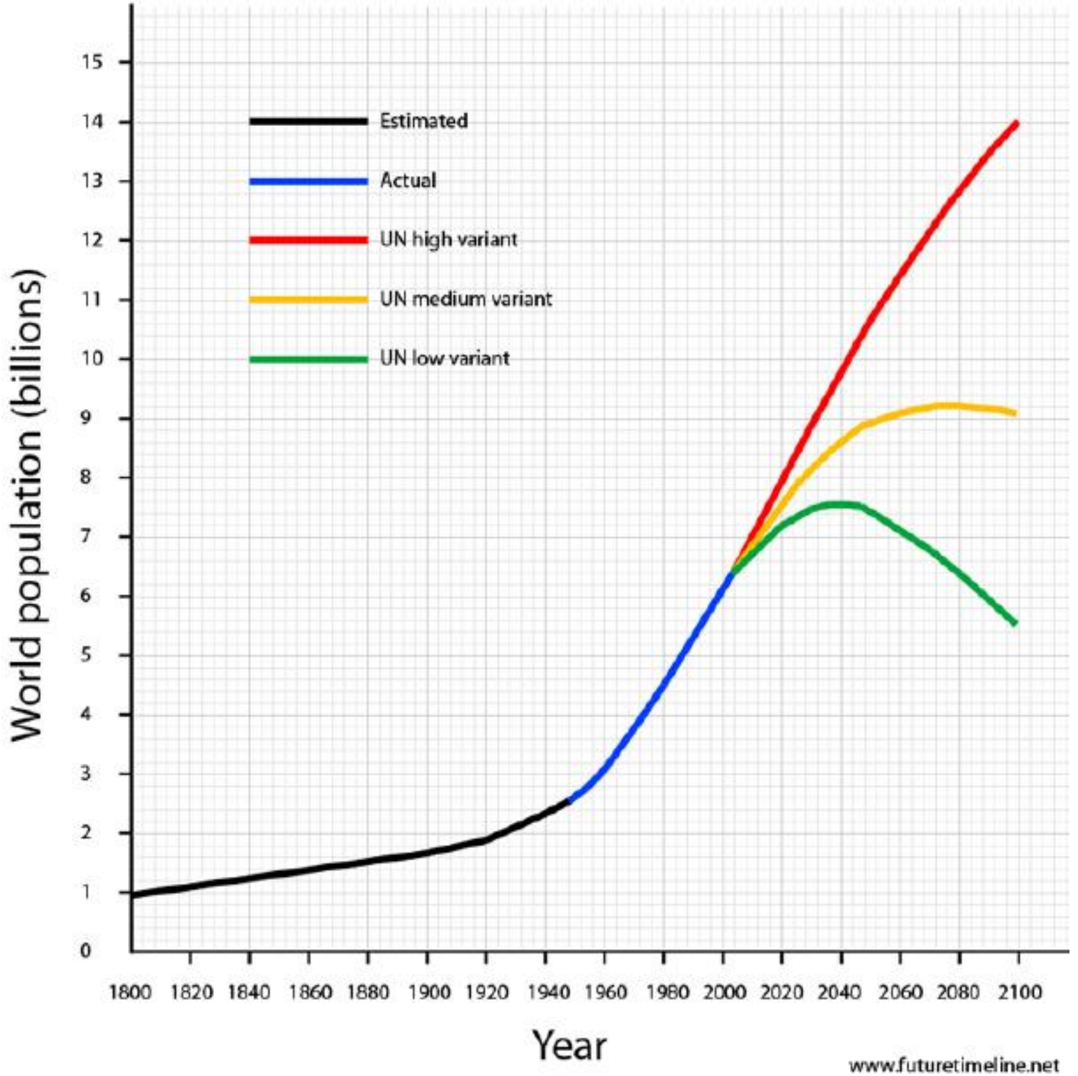


- Gridded Population of the World, version 3 (GPWv3)
- Socioeconomic Data and Applications Center (SEDAC) at Columbia University
- 2.5 × 2.5 arc minute cells = 4.6 km × 4.6 km cells at the Equator
- Reference years 1990-2015 in 5-year intervals

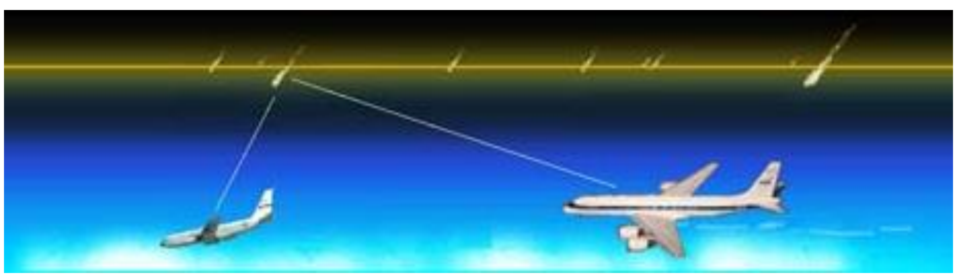
Controlled Re-entry over SPOUA



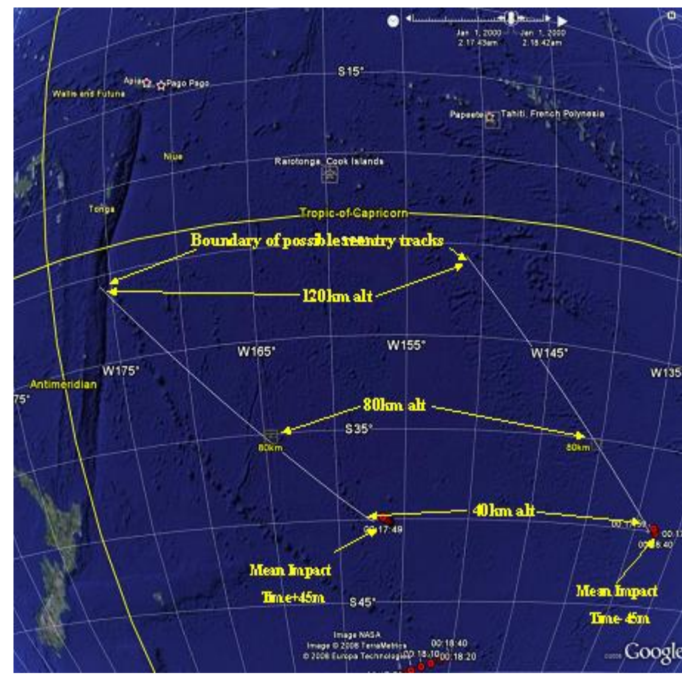
Population Growth Models



ATV-1 Observation Campaign (2008)



Artist illustration of fragments' trajectories
observation from 2 aircrafts



European Space Agency

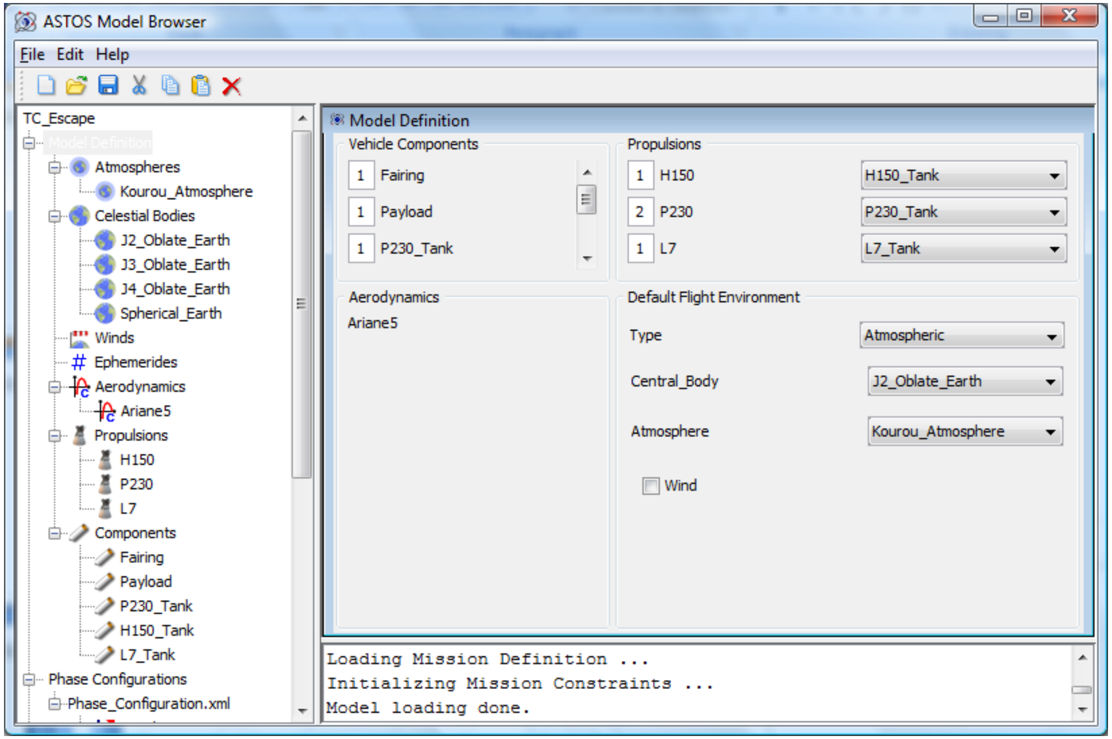
Break-up and Re-entry Analysis Tools

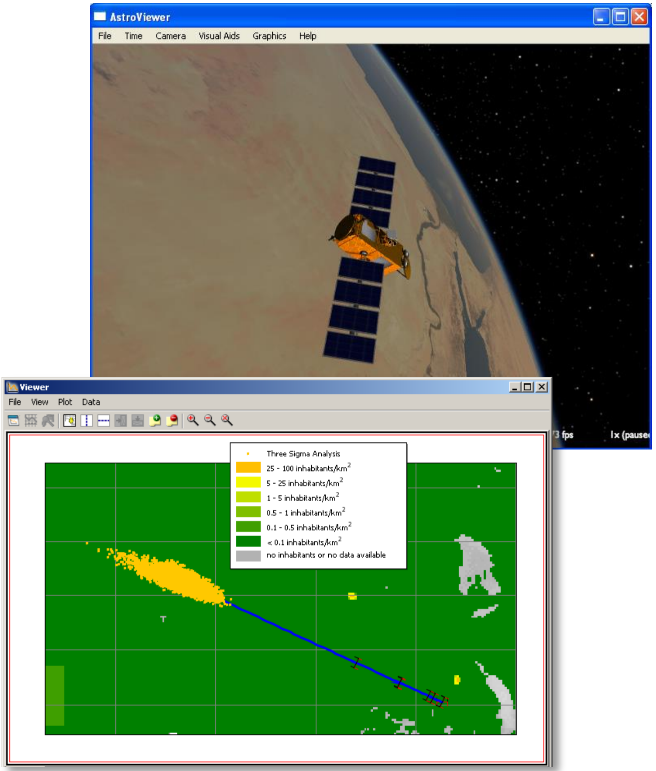
Object-oriented and Spacecraft-oriented Tools

	Object-oriented Tools	Spacecraft-oriented Tools
Geometry	• List of parent and child simple objects defined by shape (e.g., spheres, boxes, cylinders, plates), mass, and material	• Geometrical assembly of finite elements defined by shape, mass, and material
Simulation Method	• 3 DOF dynamics equations (pre-defined tumbling attitude) • 1D thermal equations	• 6 DOF dynamics equations • 3D thermal equations
Break-up Event(s)	• At fixed altitude (typically at 78 km)	• Result of thermal ablation, mechanical fracture, and/or explosions based on force, torque and heat loads
Fragmentation Process	• Decomposition of the parent object into pre-defined child objects at break-up altitude	• Thermal ablation and/or mechanical fracture based on force, torque and heat loads during trajectory
Computational Cost	• < 1 min / simulation	• 1-2 days / simulation
Work Cost	• 1-2 days / man / assessment	• ~ 3 months / man / assessment
Main Reference Tools	• **DRAMA/SARA (ESA)** • **ASTOS/DARS (ESA, ASTOS Solutions)** • **DAS, ORSAT (NASA)** • **DEBRISK, ELECTRA (CNES)**	• **SCARAB (ESA/HTG)**

ESA ASTOS/DARS/RAM

- **D**estructive **A**nalysis of **R**e-entry **S**pacecraft (**DARS**) / **R**isk **A**ssessment **M**odule (**RAM**) by ASTOS and ESA-ESTEC
  a. Develop by ESA/ESTEC
  b. Lead by "Guidance & Navigation Control" (TEC-ECN)



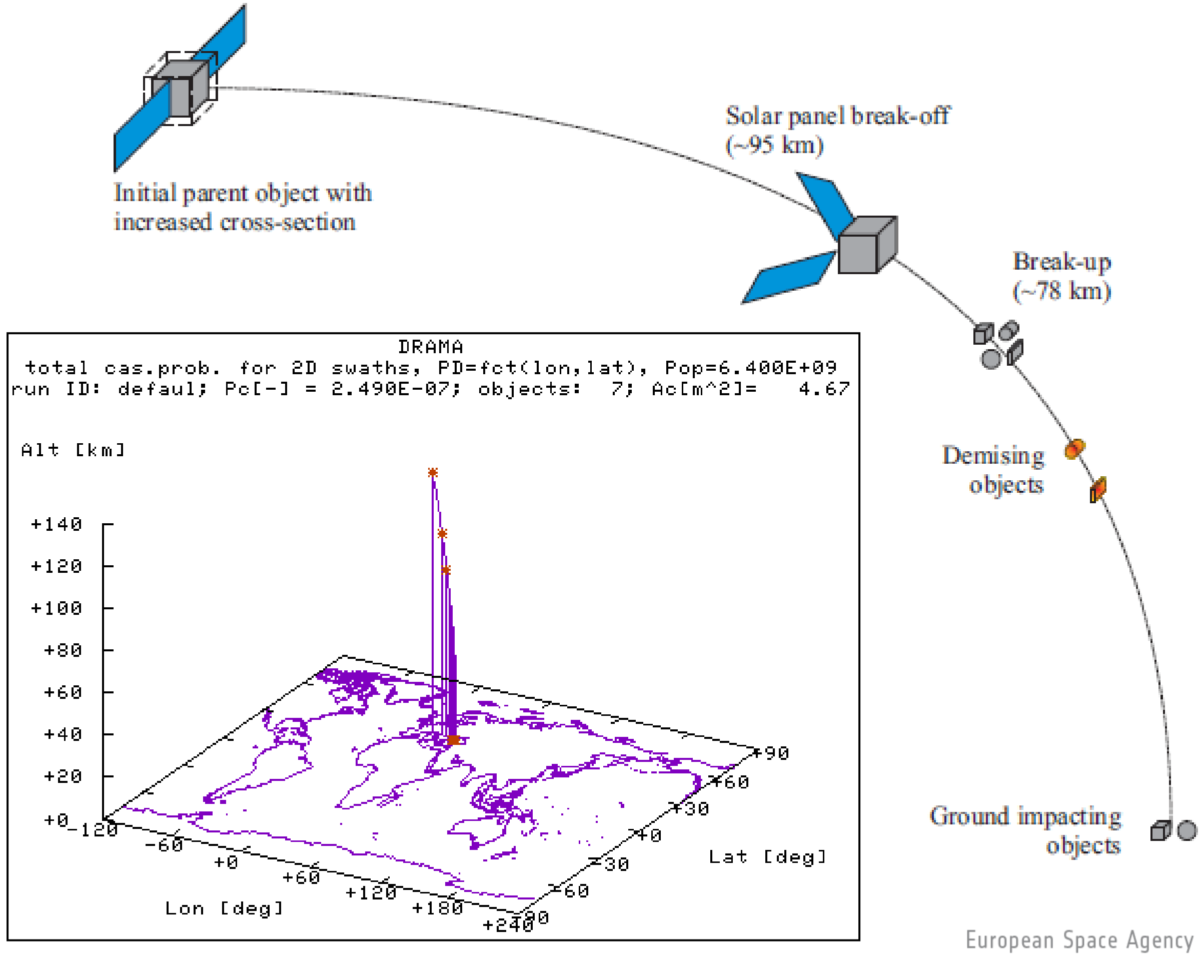


ESA DRAMA/SESAM/SERAM (SARA)

- **D**ebris **R**isk **A**ssessment and **M**itigation **A**nalysis (**DRAMA**) by QinetiQ, DEIMOS Space S.L., Etamax GmbH, HTG, and ESA-ESOC

   a. **S**pacecraft **E**ntry **S**urvival **A**nalysis **M**odule (**SESAM**) to model the re-entry into the Earth's atmosphere

   b. **S**pacecraft **E**ntry **R**isk **A**nalysis **M**odule (**SERAM**) to assess the risk on-ground of objects surviving re-entry



NASA DAS and ORSAT

Debris **A**ssessment **S**oftware (**DAS**)

and

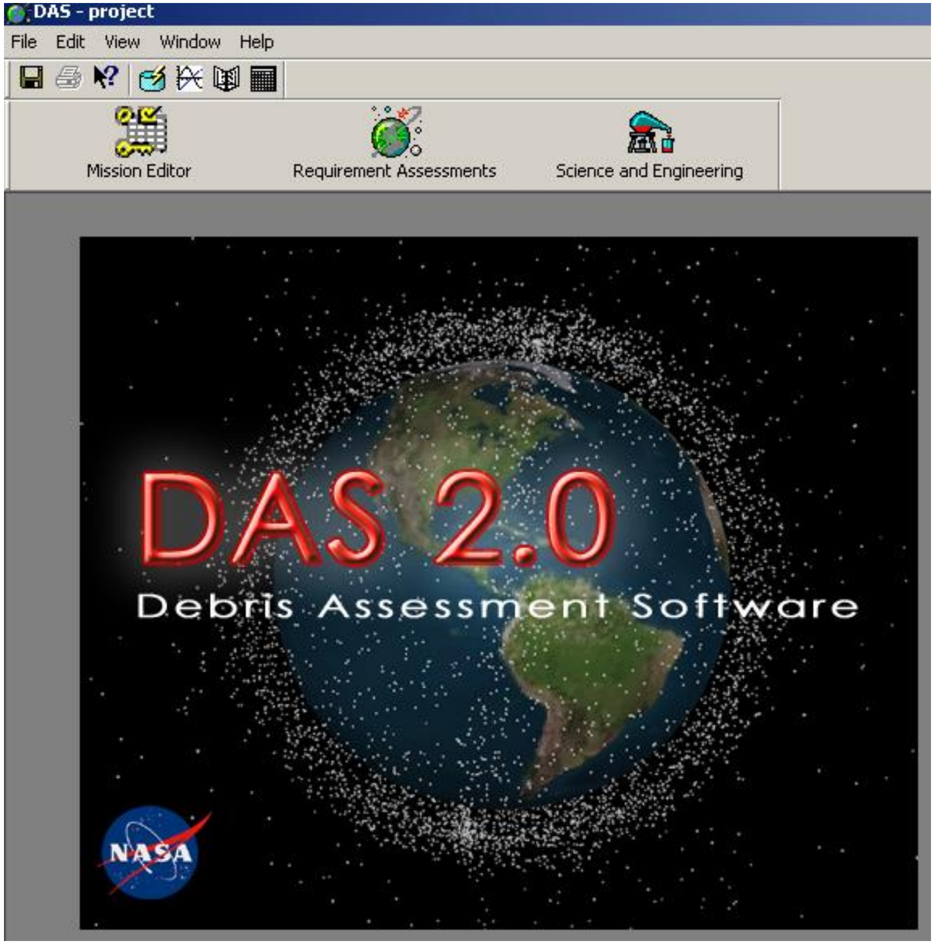
Object **R**eentry **S**urvival **A**nalysis **T**ool (**ORSAT**)

a. Developed by the NASA/JSC Orbital Debris Program Office since 2003.

b. Designed to assist programs in performing orbital debris assessments (ODA)

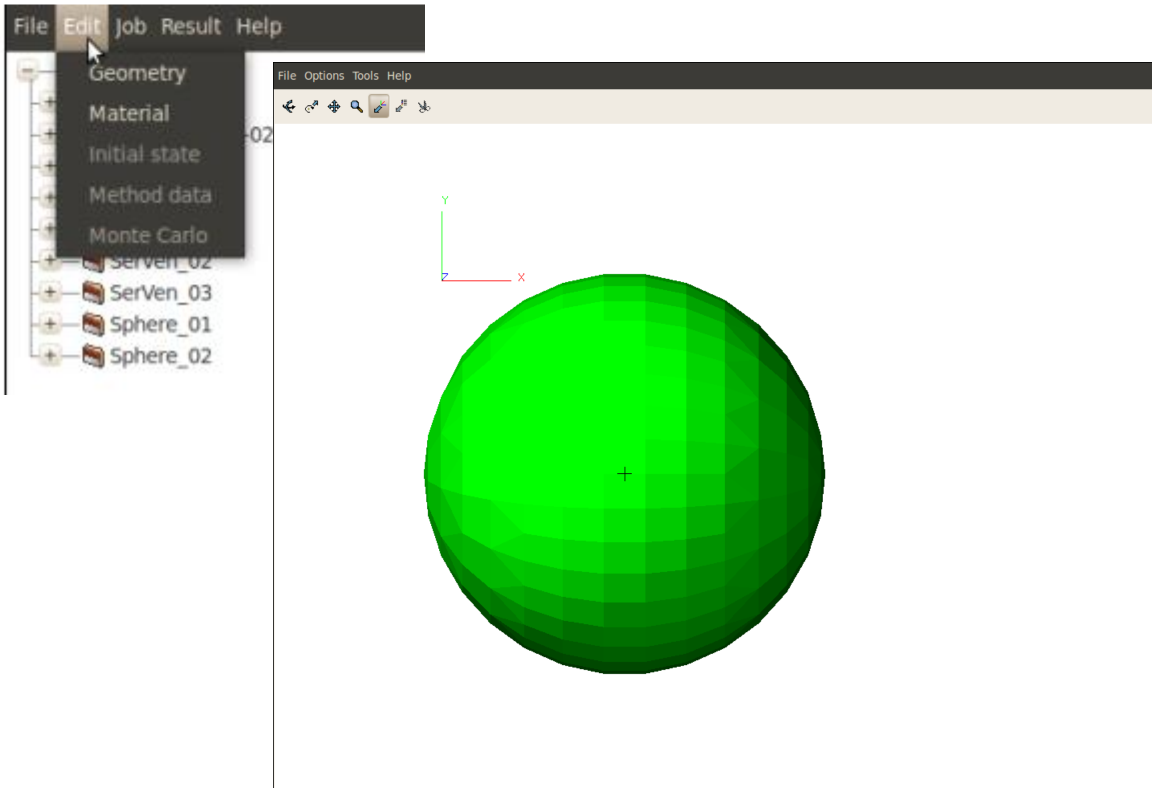
c. Updated propagators, environment models, and a re-entry survivability model.

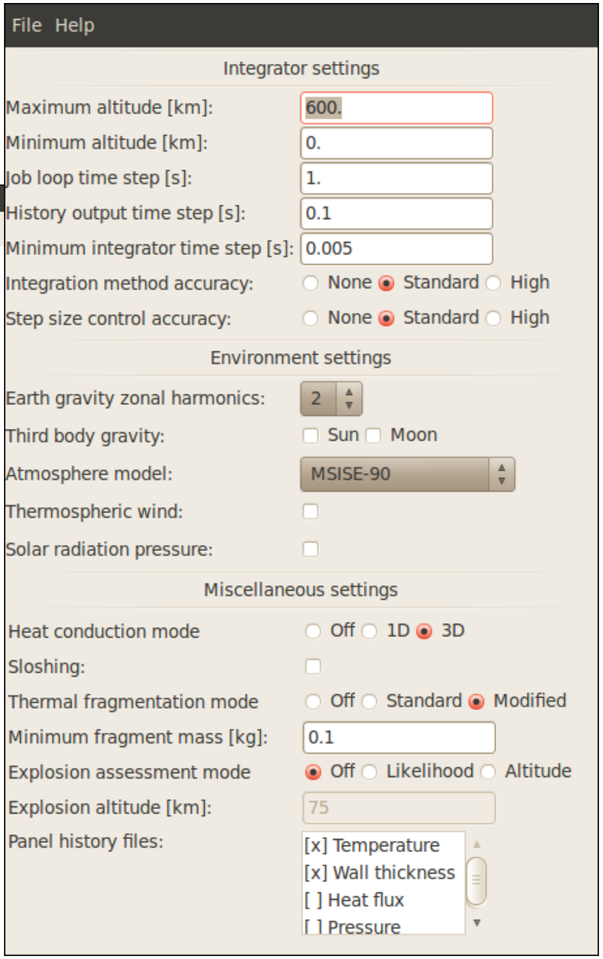
d. Numerous upgrades applied to the assessment of human casualty due to re-entering debris.



ESA/HTG SCARAB

- **S**pacecraft **A**tmospheric **R**e-entry and **A**erothermal **B**reak-up (**SCARAB**) by HTG
  a. Develop by ESA/ESOC
  b. Lead by "Space Debris Office" (HSO-GR)





SCARAB: Determining Break-Up Process

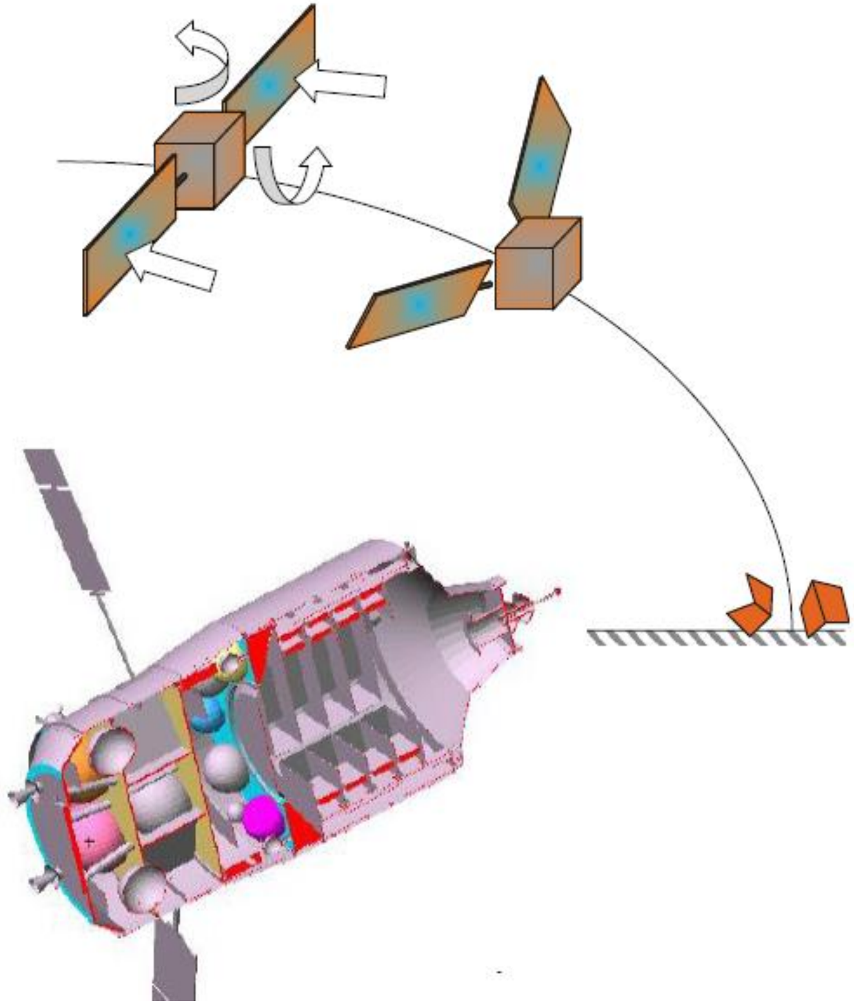
S/C modeling
→ simplified model

Aerodynamic analysis
→ forces and torques

Dynamic analysis
→ trajectory and attitude motion

Aerothermal analysis
→ heating and melting

Fragmentation analysis
→ structural fracture and separation due to melting



On-ground Casualty Risk Assessment: Initial Conditions

Epoch: 2010-01-01 12 : 0 : 0 . 0

State Vector (6 components)

Co-ordinate system	Cartesian Inertial	
State Vector		
r_x :	6500.0	[km]
r_y :	2.0E-4	[km]
r_z :	35.0	[km]
v_x :	130.0	[km/s]
v_y :	90.0	[km/s]
v_z :	10.0	[km/s]

Co-ordinate system	Cartesian Earth Fixed	
State Vector		
r_xe :	6500.0	[km]
r_ye :	2.0E-4	[km]
r_ze :	35.0	[km]
v_xe :	130.0	[km/s]
v_ye :	90.0	[km/s]
v_ze :	10.0	[km/s]

Co-ordinate system	Keplerian	
State Vector		
semimajor axis :	6500.0	[km]
eccentricity :	2.0E-4	[km]
inclination :	35.0	[deg.]
RAAN :	130.0	[deg.]
perigee arg. :	90.0	[deg.]
true anomaly :	10.0	[deg.]

Co-ordinate system	Trajectory Earth Fixed	
State Vector		
h :	122.0	[km]
lat :	45.2	[deg.]
lon :	10.0	[deg.]
v :	7.3	[km/s]
gam :	-2.0	[deg.]
azi :	0.0	[deg.]

Attitude (6 components)

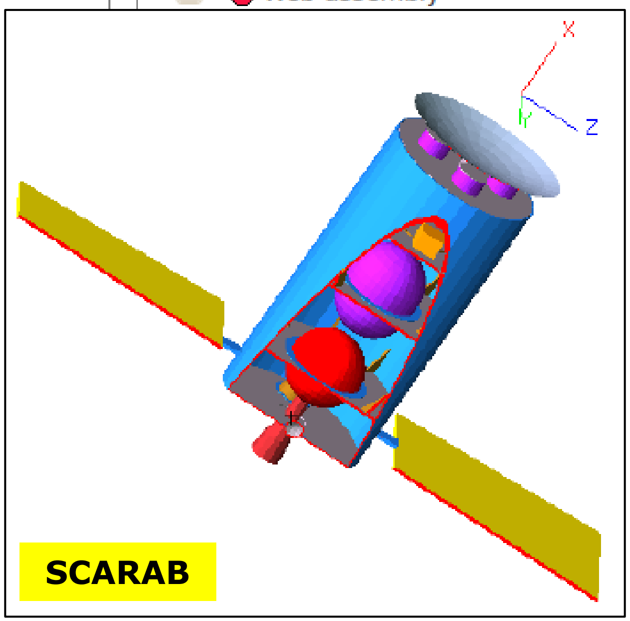
Roll angle [deg]	0
Pitch angle [deg]	0
Yaw angle [deg]	0.
Roll rate [deg/s]	0.
Pitch rate [deg/s]	0.
Yaw rate [deg/s]	0.

On-ground Casualty Risk Assessment: Spacecraft Geometry

File Edit View Help

SCARAB

- Tank-he2
- Structure
  - structure
  - Cyl-shell
  - Base-plate
  - Platforms
  - Web-triangle
  - Web-assembly



Add/Del Leak | Add/Del Separation

Name	Test-Sat/Payloads/Instrument/Disk	
Identifier		
Subsystem		
Operation	Add	
Color	{0.600,0.600,0.600}	
Position x	0.2	m
Position y	0.	m
Position z	0.	m
Rotation x	0.	deg
Rotation y	0.	deg
Rotation z	0.	deg
Material	aa7075	see list
Temperature	300.	K
External radius	0.2	m
Internal radius	0.0	m
Thickness	0.01	m
Sector size	360.	deg
anel size in radial directic	0.05	m
Panel size on arc	0.05	m

On-ground Casualty Risk Assessment: Spacecraft Geometry

Name	Shape	No.of Obj.	Width/Diam. ...	Length [m]	Height [m]	Mass [kg]	Material
'Parent'	'Cylinder'	1	1.7	4.8	0.0	1200.0	'n/a'
'SolarP'	'Plate'	2	2.0	2.0	0.0	20.0	'n/a'
TCU	Box	1	0.52	0.38	0.27	33.0	'AA7075'
PCU	Box	1	0.23	0.18	0.16	5.0	'AA7075'
BCDR	Box	1	0.57	0.31	0.18	19.0	'AA7075'
BCU	Box	1	0.3	0.2	0.14	4.0	'AA7075'
PPDU	Box	1	0.41	0.32	0.17	13.0	'AA7075'
Batt	Box	1	0.54	0.4	0.21	50.0	'AA7075'
Decoder	Box	1	0.26	0.2	0.19	6.0	'AA7075'
CTU	Box	1	0.4	0.25	0.25	17.0	'AA7075'
RTU	Box	1	0.32	0.27	0.25	13.5	'AA7075'
MBU	Box	1	0.24	0.22	0.09	4.0	'AA7075'
TRU	Box	2	0.2	0.2	0.15	6.7	'AA7075'
X-PND	Box	2	0.23	0.17	0.13	5.0	'AA7075'
MTR	Cylinder	3	0.025	0.74	0.0	2.2	'A316'
ACC	Box	1	0.26	0.22	0.13	6.5	'AA7075'
MRU	Box	1	0.29	0.16	0.12	3.5	'AA7075'
PDU	Box	1	0.39	0.3	0.16	11.3	'AA7075'
GYRE	Box	2	0.26	0.2	0.08	3.3	'AA7075'
RWL	Cylinder	4	0.31	0.05	0.0	6.1	'A316'
RWE	Box	2	0.22	0.22	0.12	4.5	'AA7075'
STRE	Box	3	0.2	0.16	0.12	3.3	'AA7075'
STR	Box	3	0.2	0.12	0.12	3.0	'AA7075'
Tank	Sphere	1	0.45	0.048	0.0	5.5	'TIAl6V4'
Thrsts	Cylinder	12	0.032	0.13	0.0	0.3	'Inconel'
PL1	Cylinder	1	0.5	0.66	0.0	94.0	'AA7075'
PLE1	Box	1	0.4	0.25	0.24	15.5	'AA7075'
PL2	Box	1	0.5	0.5	0.5	160.0	'AA7075'
PLE2	Box	1	0.4	0.25	0.24	18.0	'AA7075'
PL3	Box	2	0.9	0.4	0.4	45.0	'AA7075'
PLE3	Box	1	0.25	0.23	0.12	5.3	'AA7075'
PL4a	Cylinder	4	0.17	0.35	0.0	13.4	'AA7075'
PL4b	Cylinder	4	0.12	0.22	0.0	6.9	'AA7075'
PLE3a	Box	1	0.4	0.25	0.24	18.0	'AA7075'
PLE3b	Box	1	0.35	0.21	0.19	8.0	'AA7075'
PLE3c	Box	1	0.32	0.22	0.09	1.9	'AA7075'

DRAMA/SESAM

On-ground Casualty Risk Assessment: Material Properties

File Edit Help

Material	Type	Comment	Last change
a286	Solid	Not editable	2011-01-24 09:24:11
a286test	Solid		2009-08-05 13:41:05
a316	Solid		2009-08-11 14:42:05
aa2024	Solid		2009-08-11 14:45:34
aa2219	Solid		2009-08-11 14:46:59
aa5052	Solid		2011-01-20 10:06:34
aa6060-63	Solid		2009-06-17 10:02:03
aa6060-jwst-...	Solid		2009-08-11 14:53:06
aa7075	Solid		2009-08-11 14:56:09
aa7075-s2-ba...	Solid		2011-03-31 09:15:05

aa7075

	Value	Dimension
ortho		-
density	2.801	g/cm^3
weight	31.06	g/mole
elongation	5.5	%
expansion	2.2e-05	1/K
melting	870	K
heatmelt	385	J/g
poisson		-
shear		kN/mm^2
heatevap	110000	J/g
avap	35763.5	K
bvap	24620000000	N/m^2
proof	Interpolation	N/mm^2
strength	Interpolation	N/mm^2
module	Interpolation	kN/mm^2
capacity	Interpolation	J/g/K
conductivity	Interpolation	W/m/K
nocan	0	-
nocar	0	-
nocbn	0	-
nocbr	0	-
catality		-
sigman	1	-
sigmat	1	

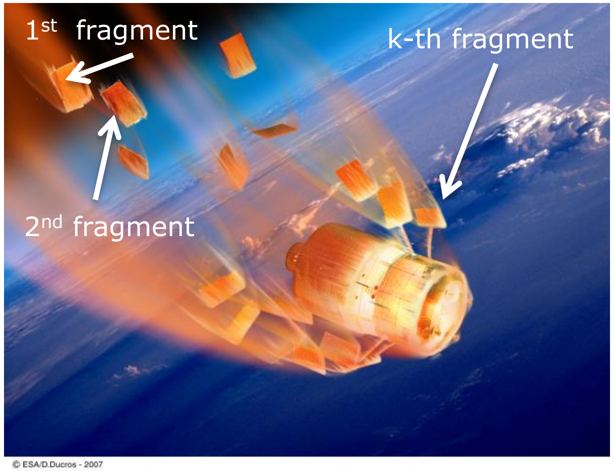
SCARAB

Name	Density [kg/m³]	Specific Heat Capacity [J/kgK]	Melting Temperature [K]	Specific Heat of Melting [J/kg]	Emission Coefficient
'AA7075'	2801.0	746.4	870.0	385000.0	0.154
'A316'	8030.0	611.5	1650.0	274000.0	0.591
'TiAl6V4'	4420.0	746.4	1900.0	400000.0	0.392
'Copper'	8960.0	434.1	1356.0	243000.0	0.256
'Inconel'	8190.0	673.0	1570.0	309000.0	0.171
'AA6060'	2700.0	1071.4	900.0	389000.0	0.155
'HC-AA7075'	280.1	746.4	870.0	385000.0	0.154
'TIAl6V4'	4420.0	746.4	1900.0	400000.0	0.392
'CFRP'	1550.0	879.0	700.0	232.6	1.0

DRAMA/SESAM

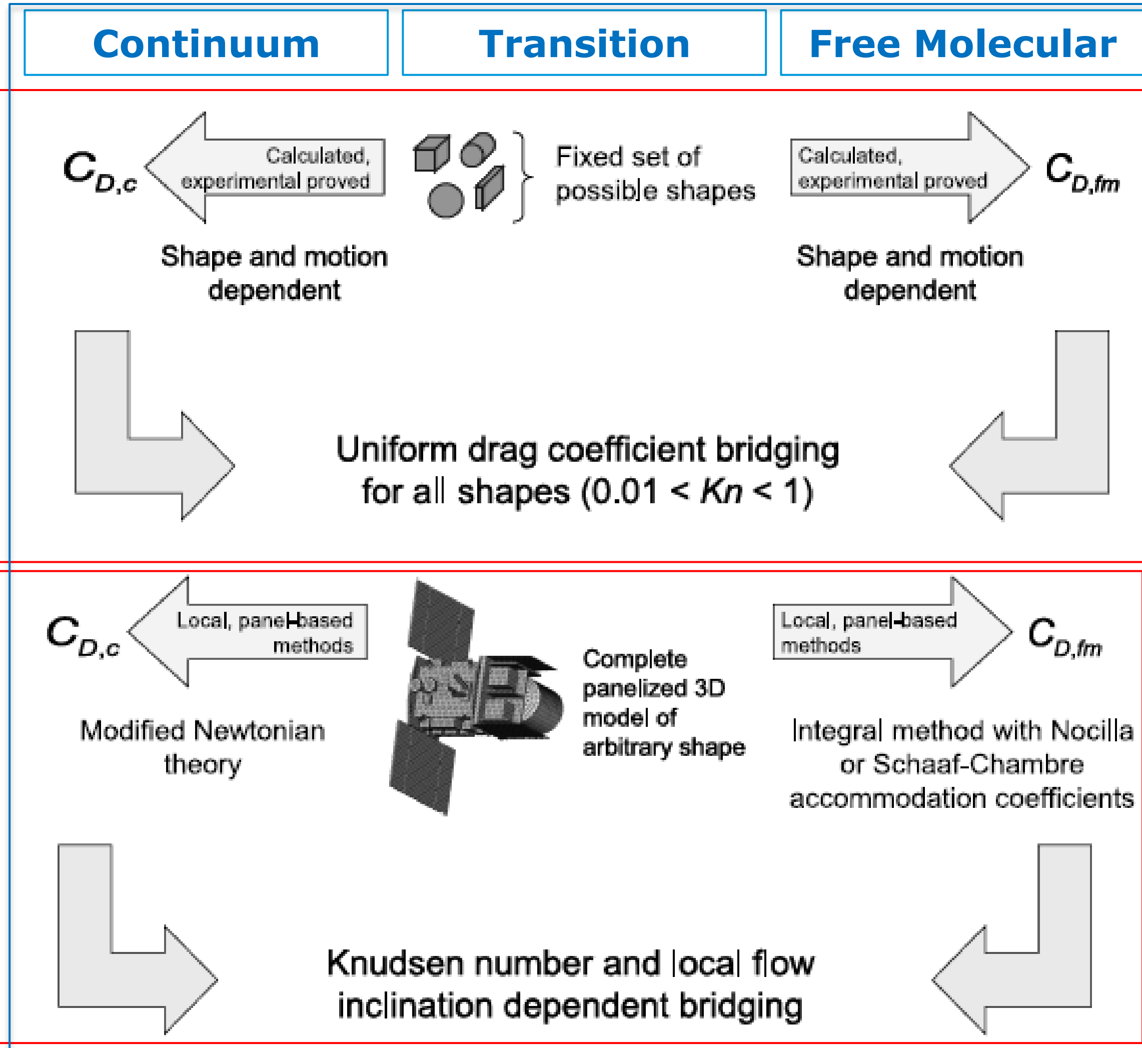
Trajectory and Fragmentation

Spacecraft-oriented Tools	Object-oriented Tools
Spacecraft	Parent Object
Fragments generation if the melting condition occurs for finite-elements	Parent object split into child objects at fixed Break-up Altitude
Independent fragments trajectory and thermal status	Object ablation If the melting condition occurs
Possible non-demised fragments	Independent child objects trajectory and thermal status
	Possible partially or completely non-demised objects
6DOF/3DOF Trajectory and 3D/1D Thermal Equations	3DOF Trajectory and 1D Thermal Equations



Drag Coefficient

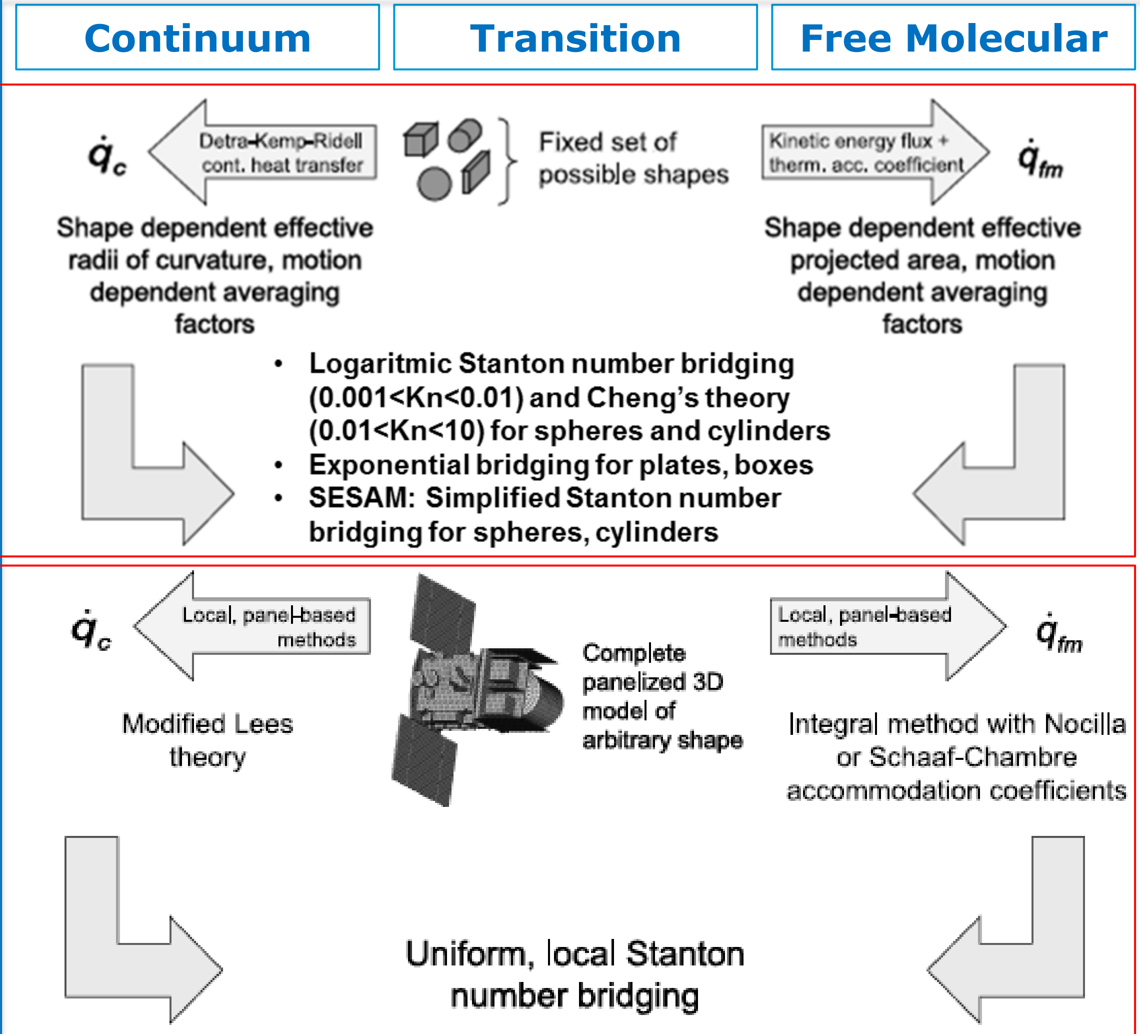
- DRAMA/SESAM
- SCARAB



Risk if Fragment Survivability and Definition of Risk Scenarios – Technical Note No.1 – ESA Contract No. 20413/06/NL/SFe, 05/12/2007

Aerothermal Heat Transfer

- DRAMA/SESAM
- SCARAB



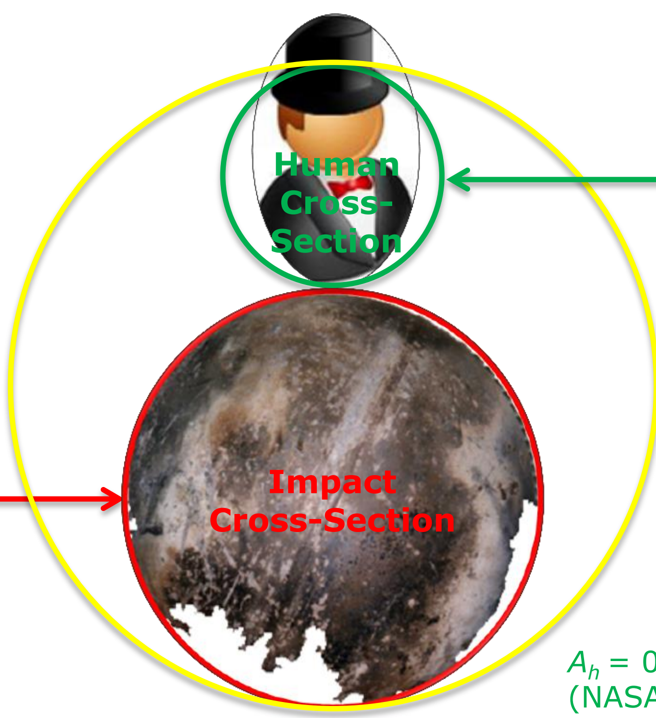
Risk if Fragment Survivability and Definition of Risk Scenarios – Technical Note No.1 – ESA Contract No. 20413/06/NL/SFe, 05/12/2007

Surviving Fragments

- A number of fragments (*N*) can survive the re-entry and impact on the ground.
- A k-th surviving fragment (debris) is characterized by:
  - Mass: M_k
  - Velocity: V_k
  - Average or Maximum Cross-section: A_k
  - Ballistic Coefficient: $B = \frac{M_k}{C_{D,k} A_k}$
  - Kinetic Energy: $E_k = \frac{1}{2} M_k V^2{}_k$
  - Flight Path Angle: γ_k
  - Azimuth Angle: θ_k
  - Impact Cross-section: $A_{i,k} = \frac{A_k}{sin(\gamma_k)}$
  - Casualty Area: $A_{c,k} = \left(\sqrt{A_{i,k}} + \sqrt{A_h}\right)^2$

Casualty Area

$$A_{c,k} = \left(\sqrt{A_{i,k}} + \sqrt{A_h}\right)^2$$



A_h = 0.36 m^2
(NASA Safety Standard NSS 1740.14)

Debris Casualty Area

- Equivalent impact area that will lead injury or death if a person is struck by a debris
- Dependence on fragment trajectory and size and projected area of the human body from above

Casualty Area

- *Total Casualty Area*:

$$A_c = \sum_{k=1}^{N} A_{c,k}$$

Casualty Area
(k-th fragment)

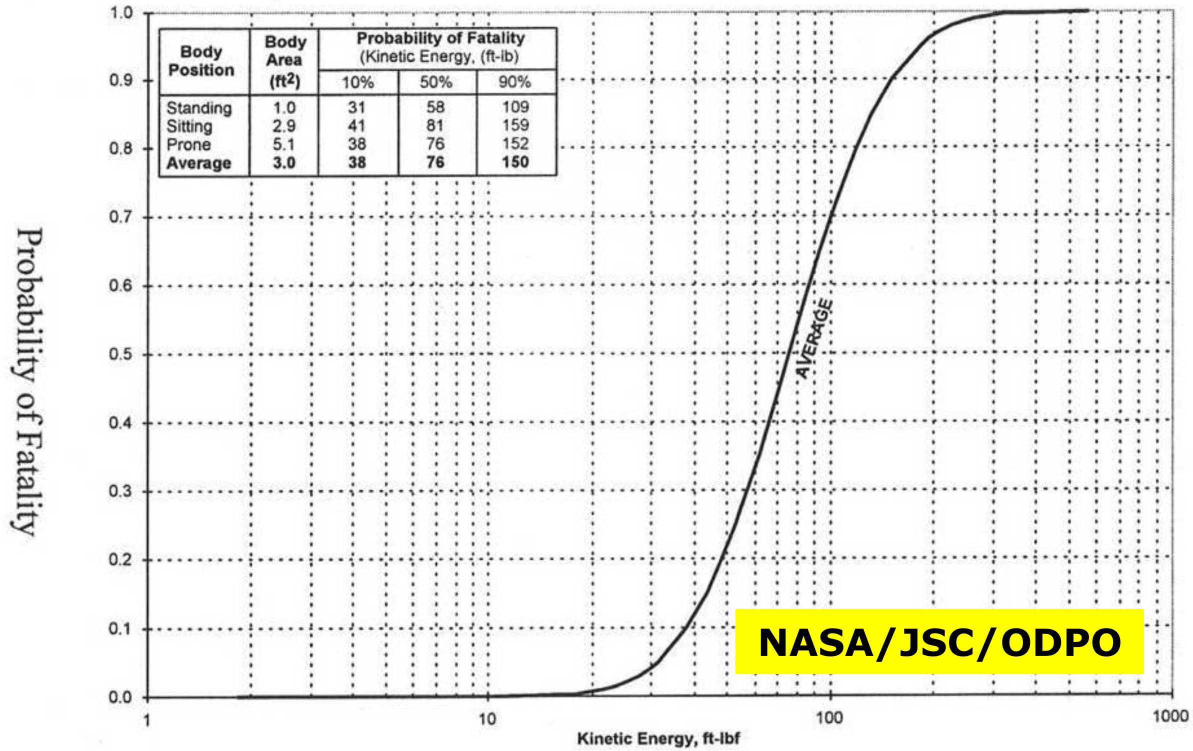
- *Total Fatality Area:*

$$A_f = \sum_{k=1}^{N} A_{c,k} \eta_{f,k}$$

Fatality Index
(k-th fragment)

Fatality Index

- *Fatality Index* ($\eta_{f,k}$) is the severity of injury caused to humans by fragment impact.
- From various position and medical considerations, the limit of 15 J was found to cause injuries.



European Space Agency

Abbreviated Injury Scale (AIS)

- Anatomical-based coding to assess incoming patients
- Introduced by *Association for the Advancement of Automotive Medicine* and used by ERs.
- **Casualty ➔ AIS ≥ 3**
- **Fatality ➔ AIS ≥ 6**

AIS SCORE	SEVERITY OF INJURY	INJURY TYPE
0	NONE	NONE
1	MINOR	SUPERFICIAL
2	MODERATE	REVERSIBLE, MEDICAL ATTENTION REQUIRED
3	SERIOUS	REVERSIBLE; HOSPITALIZATION REQUIRED
4	SEVERE	LIFE THREATENING; NOT FULLY RECOVERABLE W/O CARE
5	CRITICAL	NON-REVERSIBLE; NOT FULLY RECOVERABLE EVEN WITH CARE
6	VIRTUALLY UNSURVIVABLE	PROMPT FATALITY

Casualty Risk Analysis

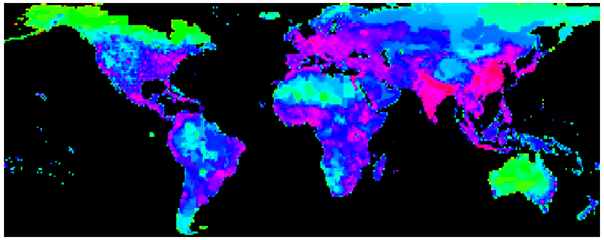
- The impact location is generally determined stochastically due to uncertainties in some re-entry variables as ballistic coefficient, atmospheric density, solar radiation flux, and geomagnetic index, which depend on the epoch and type of re-entry (uncontrolled or controlled).
- Depending on the type of re-entry different resolution criteria are used to assess casualty risk.
- A *low resolution mode* is more convenient especially for uncontrolled re-entries, when the impact point is further quite uncertain since any object can splash down at any latitude in the range *[-i, i]*, where *i* is the orbit inclination.
- A *high resolution mode* is more useful for controlled re-entries, when the impact location is less uncertain and the impact distribution of the fragments needs to be predicted more accurately through multiple simulations (e.g., with Monte Carlo methods to compensate residual uncertain variables).

Casualty Low Resolution Mode

- *Casualty Probability*: $P_c = \rho_p(i) A_c$

Population density

- *Fatality Probability*: $P_f = \rho_p(i) A_f$



$\rho_p(i)$ average in the latitude range *[−i, +i]*

- Population density is provided through periodical spatial-resolution censuses and populational trend predictions as:

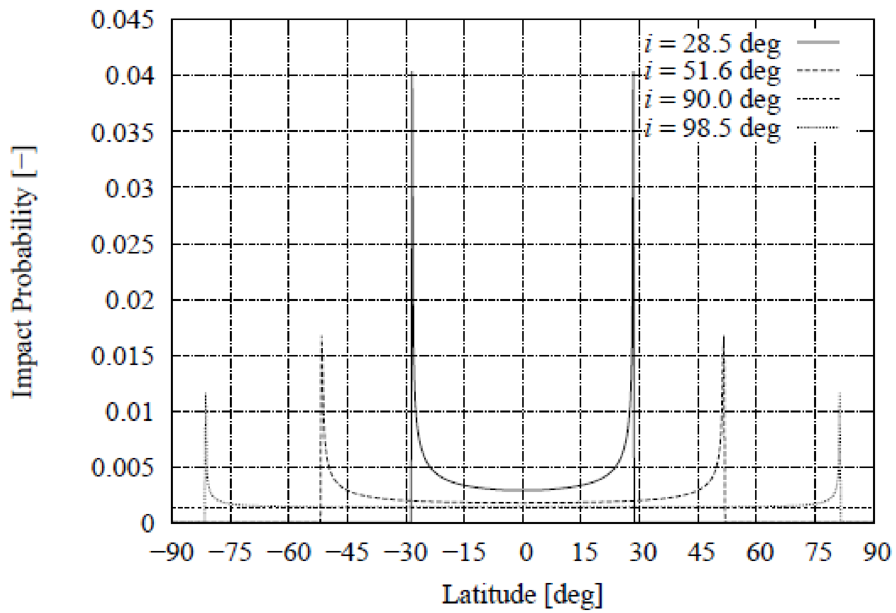
  ✓ Gridded Population of the World Version (GPW) (http://www.sedac.ciesin.columbia.edu/gpw/)

  ✓ Global Demography Project (http://www.ncgia.ucsb.edu/pubs/gdp/)

- *Impact Location Probability Density function (λ(L,i))* in the latitude range *[−i, +i]* depends on orbit inclination (*i*):

$$\lambda(L,i) = \frac{\cos(L)}{\pi(sin^2(i) - sin^2(L))^{1/2}}$$

- Impact probability higher nearby the extremes of the latitude range *[−i, +i]*.



Risk Mitigation Measures – Technical Note No.3 – ESA Contract No. 20413/06/NL/SFe, 07/01/2009

Casualty High Resolution Mode

- Impact region as *n x m* area bins
- *Casualty Probability (k-th fragment)*:

$$P_{c,k} = \sum_n \sum_m (P_{i,k})_{n,m} (\rho_p)_{n,m} (A_{c,k})_{n,m}$$

- *Fatality Probability (k-th fragment)*:

$$P_{f,k} = \sum_n \sum_m (P_{i,k})_{n,m} (\rho_p)_{n,m} (A_{c,k})_{n,m} (\eta_{f,k})_{n,m}$$

$(P_{i,k})_{n,m}$ → Local Impact Probability

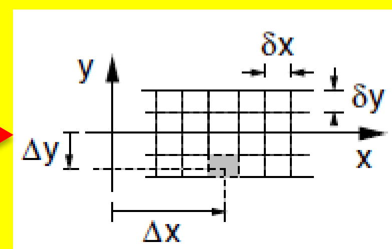
$(\rho_p)_{n,m}$ → Local Population Density

$(A_{c,k})_{n,m}$ → Local Casualty Area

$(\eta_{f,k})_{n,m}$ → Local Fatality Index

Local Impact Probability

$$(P_{i,k})_{n,m} = (PDF_{i,k})_{nm} \delta x \delta y$$



Local Probability Density Function

$$(PDF_{i,k})_{nm} = \frac{j_{n,m}}{j_{MC}}$$

$j_{n,m}$ → Number of impacts in nm-bin

j_{MC} → Monte Carlo runs

Casualty High Resolution Mode

- *Casualty Probability:*

$$P_c = 1 - \prod_{k=1}^{N} (1 - (P_c)_k)$$

→ *To be multiplied to Failure Probability* and *Explosion Probability* to obtain the Total Casualty Probability for the whole scenario

- *Fatality Probability:*

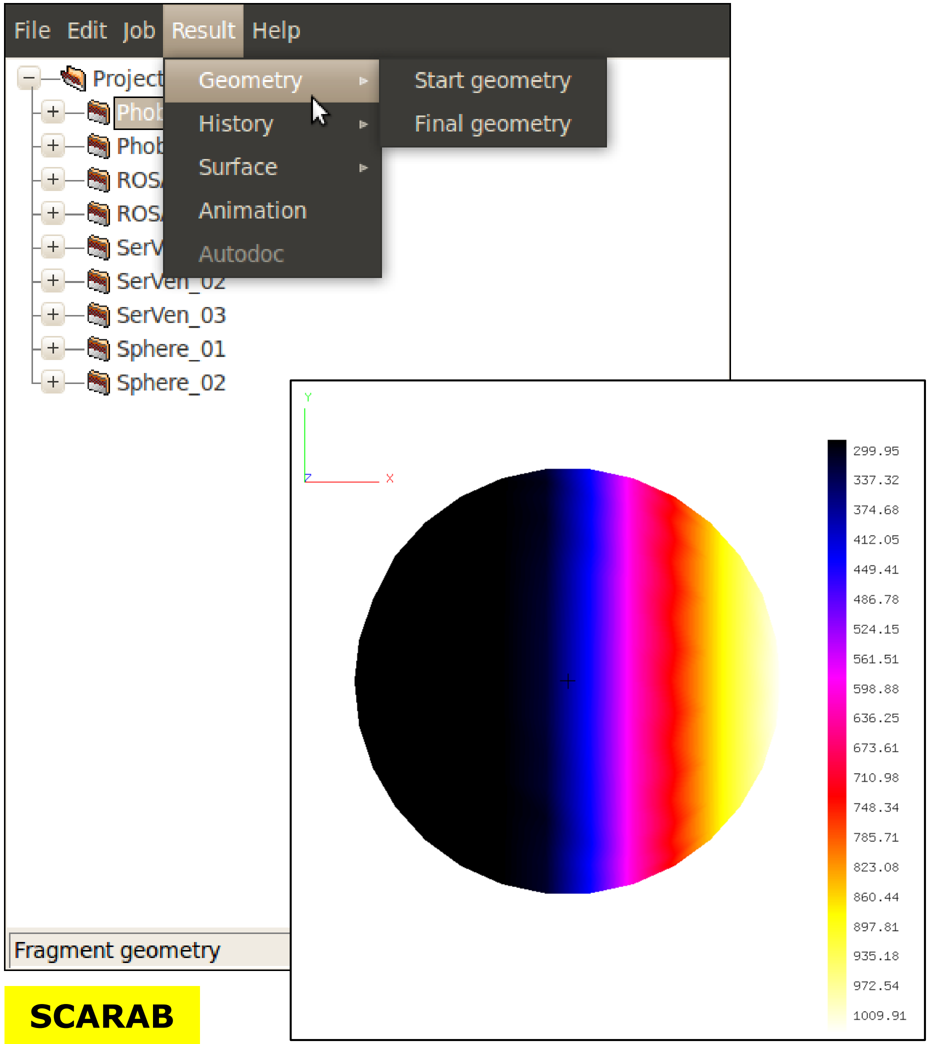
$$P_f = 1 - \prod_{k=1}^{N} \left(1 - \left(P_f\right)_k\right)$$

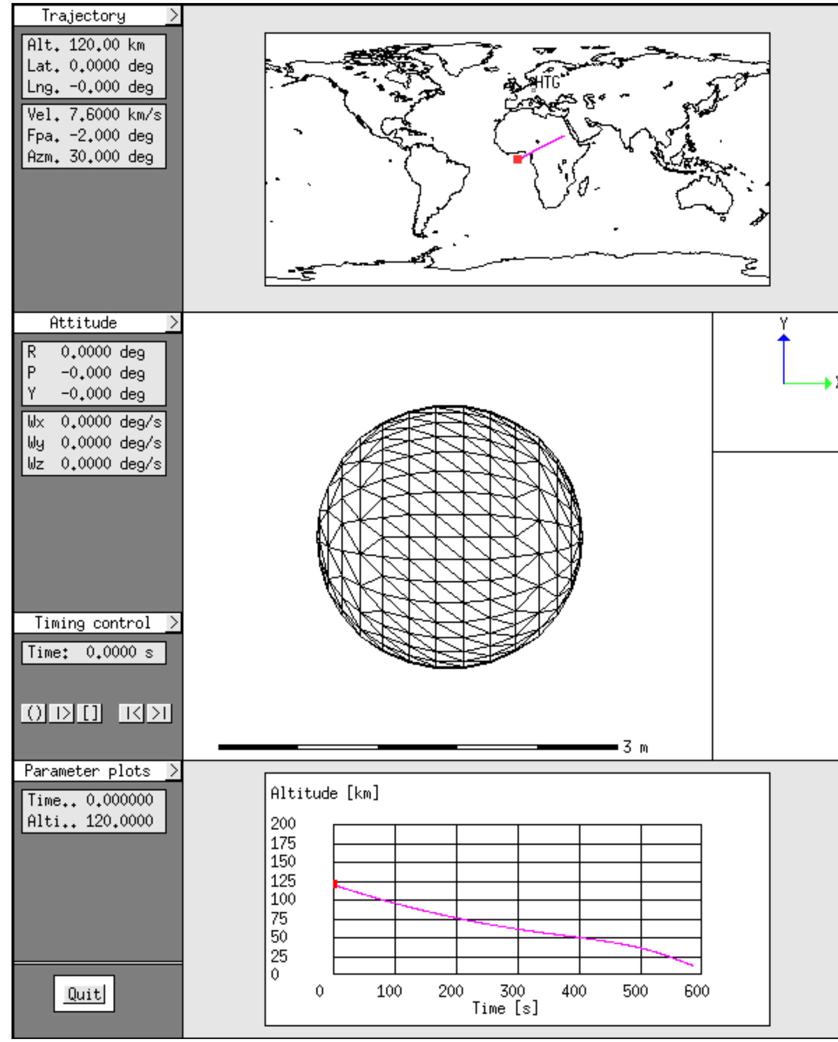
→ *To be multiplied to Failure Probability* and *Explosion Probability* to obtain the Total Fatality Probability for the whole scenario

Tools Performance

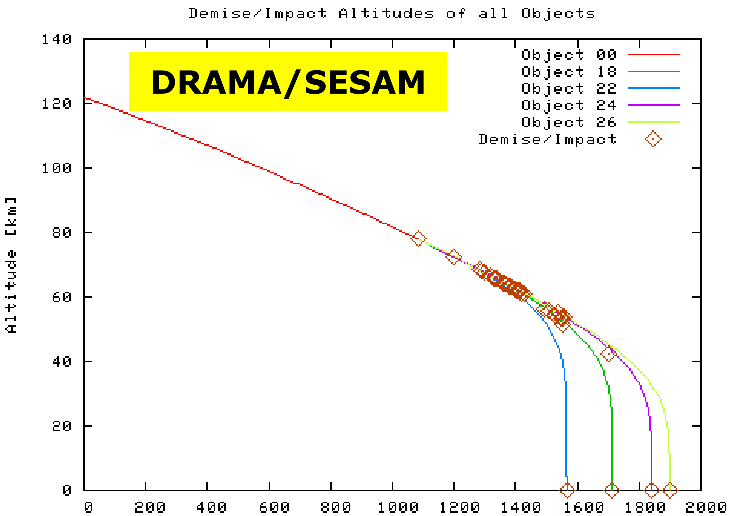
	Low/Mid Fidelity Re-entry Model	High Fidelity Re-entry Model
	- Basic S/C aerodynamics and mechanical features - Static Earth atmosphere models - Simple break-up model	- More accurate S/C aerodynamics and mechanical features - More Earth atmosphere models - More accurate break-up model
Casualty Risk Low Resolution Mode	• **NASA DAS**	• **ESA/HTG SCARAB** • **NASA ORSAT**
Casualty Risk High Resolution Mode	• **ESA DRAMA/SESAM/SERAM** • **ESA ASTOS/DARS/RAM**	

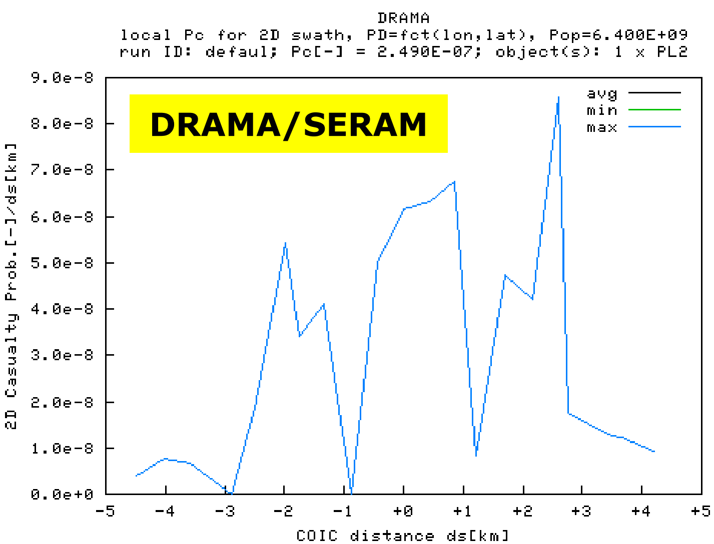
Re-entry Results

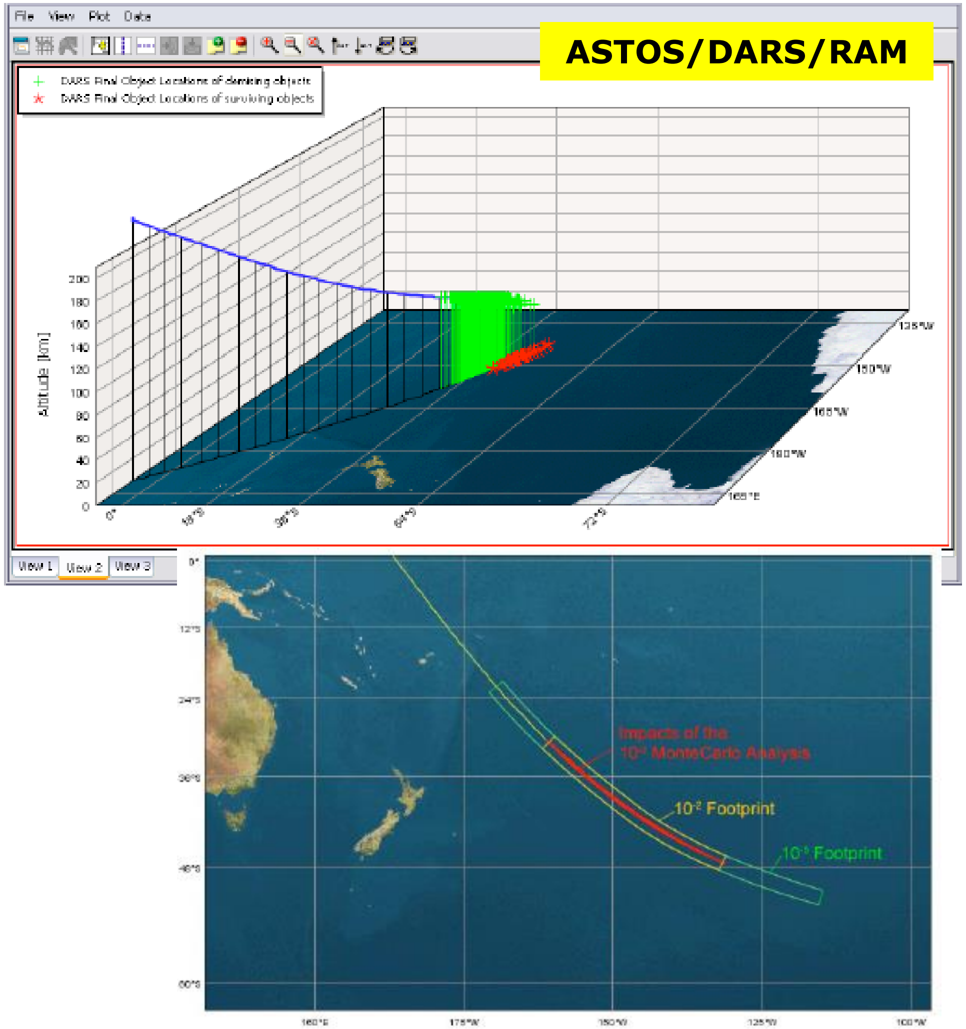




Re-entry Results







European Space Agency

Re-entry Results

Output

Object Name	Compliance Status	Risk of Human Casualty	SubComponent Object	Demise Altitude (km)	Total Debris Casualty Area ...	Kinetic Energy (J)
EO_23	Non-Compliant	1:8400			5.85	
			Side Panels	76.3	0.00	0
			Bottom Panel	77.1	0.00	0
			Top Panel	76.2	0.00	0
			Prop Tanks	0.0	1.72	9744
			Pressurant Tank	0.0	0.54	42022
			Service Valves	56.6	0.00	0

Messages

EO_23 Requirement 4.7-1 Non-Compliant
Detail R/B 2nd Stage Requirement 4.7-1 Non-Compliant

DAS

Object Number	Object Name	Qty	Material	Body Type	Demise Factor (%)	Debris Casualty Area (m^2)	Total DCA (m^2)	Downrange (km)	Impact Mass (kg)	Total Impact Mass (kg)	Kinetic Energy (J)	Ballistic Coefficient
1.18	Balance Mass A	1	Tungsten	Box	39.63	0.49	0.49	9509.37	3.00	3.00	6583.40	267.95
1.19	Balance Mass B	1	Tungsten	Box	39.63	0.49	0.49	9509.37	3.00	3.00	6583.40	267.95
1.20	Balance Mass C	1	Tungsten	Box	39.63	0.49	0.49	9509.37	3.00	3.00	6583.40	267.95
1.21	Balance Mass D	1	Tungsten	Box	39.75	0.45	0.45	9423.27	1.00	1.00	1516.80	186.42
1.42.1.1	Primary Tank and foam	1	Al 6061-T6	Flat Plate	72.78	1.498	1.50	9061.97	7.2	7.20	2190.5	37.83
1.42.1.2	Secondary Tank and foam	1	Al 6061-T6	Flat Plate	41.88	3.979	3.98	9049.87	32.1	32.10	8706.5	33.74
1.42.1.4	Thermal Link End Fitting (Ring)	1	Beryllium	Flat Plate	31.9	0.492	0.49	8995.07	0.1	0.10	15.9	19.81
1.42.1.5	Thermal Link End Fitting (Plug) *	2	Beryllium	Box	57.14	0.395	0.79	9046.07	0.03	0.06	7.5	37.15
	Totals						**7.90**			**49.46**		
	RISK (Assumes 2013 Reentry)	**1:**	**12158**									

* Not Included in DCA total due to low Kinetic Energy (<15J)

ORSAT

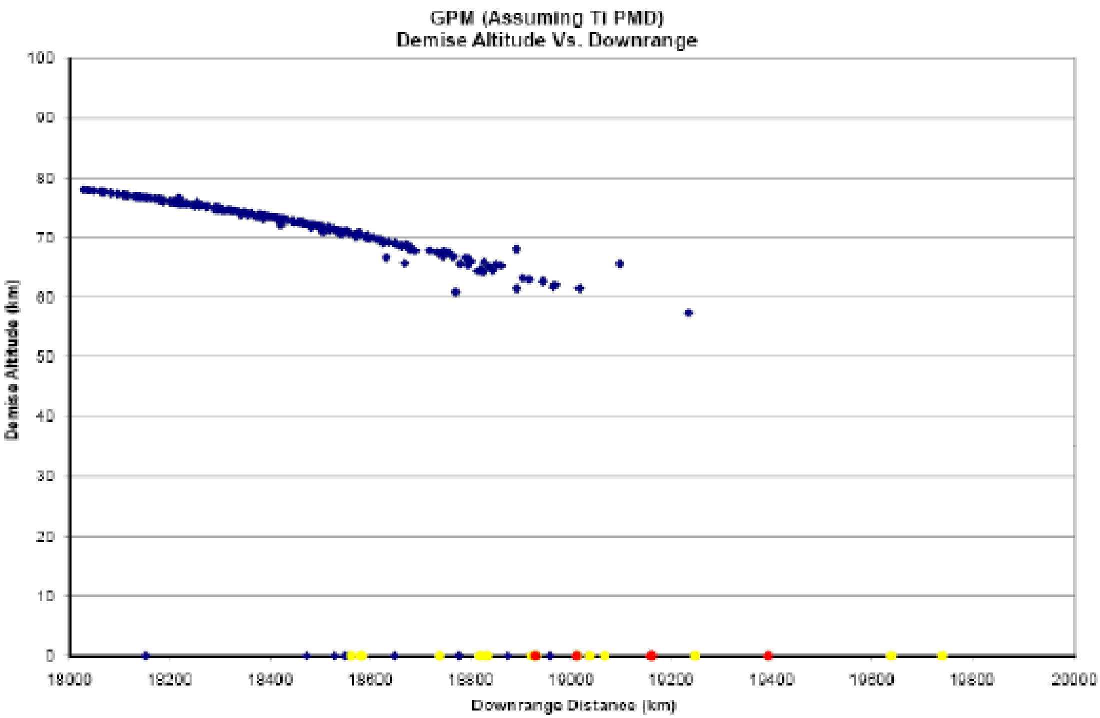
Proactive Design Strategies

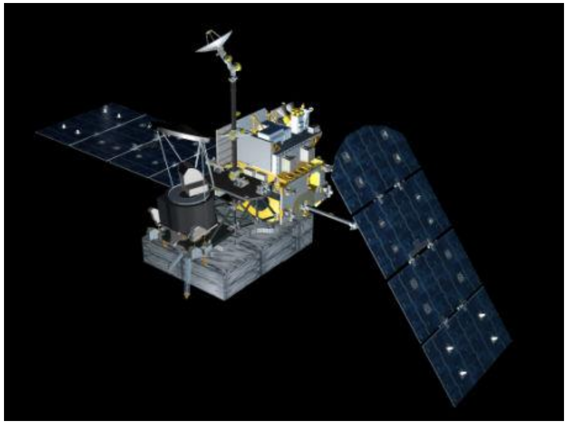
Design for Demise

Design for Demise: GPM Case Study

- The Global Precipitation Measurement (GPM) spacecraft is a joint NASA/JAXA project, planned to be launched in 2013/2014.
- From the beginning, the project team's goal was to design the vehicle to reduce the risk of human casualty (**not to exceed 1:10,000**) following re-entry by reducing spacecraft component survivability and/or by executing a controlled re-entry. Thus, the GPM team from the beginning adopted a "**Design for Demise**" mind-set.
- Debris casualty area (DCA) goals were allotted for each subsystem in much the same way that typical satellite design teams assign mass and power allotments.
- These assessments for items such as fuel tanks and reaction wheel assemblies (which typically survive, to identify alternate component designs which would be more likely to demise during re-entry.

GPM Surviving Components (ORSAT)





GPM (assumed mass = 2676 kg)
Dimensions:
L = 4.28 m,
W = 2.54 m
H = 2.39 m

- DCA > 15 J (impact energy) are in yellow
- Propellant management device (PMD) are in red.
- Items with impact energies < 15 J are ignored

GPM: Analysis Outcome

- The **total surviving mass** is:
  - 75.9 kg or 2.8% of the total for the aluminium PMD scenario
  - 82.6 kg or 3.1% for the titanium PMD.

- The result is a Debris casualty area (for Propellant Management Device):
  - DCA = 23.38 m^2 for the aluminium
  - DCA = 26.71 m^2 for the titanium.

- Depending on the year of re-entry, this re-entry risk casualty risk is approximately 1:3500 to 1:2800 depending on the case.

- As a result, the GPM project selected a **controlled re-entry** as the primary means of disposal.

ESA Space Debris Mitigation Management Requirements

MR-01: Implementing Space Debris Mitigation

- The **prime contactor of the space project shall be responsible for the implementation of space debris mitigation measures**.
- The prime contractor **shall deal with these requirements using the same engineering methodology** and the same reporting as for all other contractually applicable Agency requirements.

European Space Agency

MR: Specific Responsibilities

1. **MR-02**: In order to implement the space debris mitigation measures defined in this document the space project prime contractor shall:
   a) define derived design requirement specifications at system and sub-system level;
   b) verify compliance with the design requirements;
   c) define and verify necessary operational procedures prior to launch;
   d) document activities and procedures resulting from a, b, and c.
2. **MR-03**: **Verification of and compliance with the applicable space debris mitigation requirements shall be reported** by the space project prime contractor as part of the overall space project verification control **up to Flight Acceptance Review**.

European Space Agency

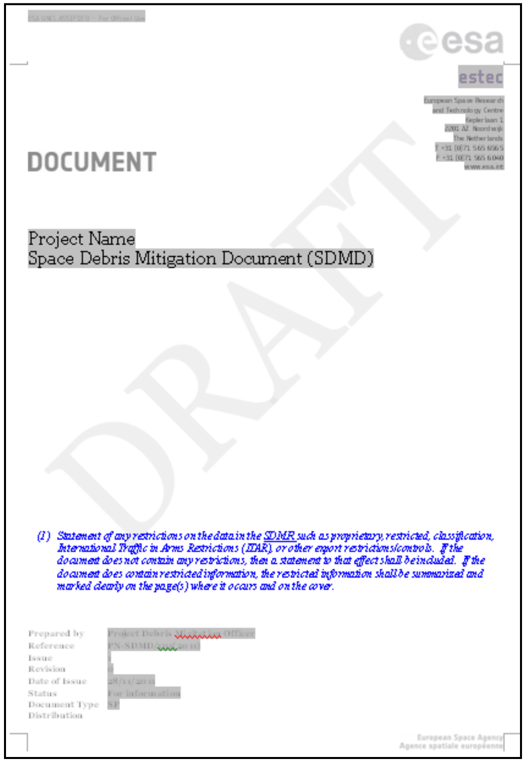
MR: Space Debris Mitigation Document

1. **MR-04**:
    a. The space project prime contractor **shall document** in a "**Space Debris Mitigation Document**" the **measures put in place to implement and fulfil the applicable requirements**.
    b. The document **shall be part of the Design Justification File**.
2. **MR-05**: **Space Debris Mitigation Document (SDMD)**
    a. A) be provided for and reviewed at the space project System Requirements Review (SRR);
    b. b) be updated for and reviewed at the space project Preliminary Design Review (PDR);
    c. c) be updated and revised by the space project prime contractor to follow the design evolution of the space project;
    d. d) be updated for and reviewed at the space project Critical Design Review (CDR).

Space Debris Mitigation Document (SDMD) Draft Template

SDMD: Structure & Content (MR-06)

- **MR-06**: The Space Debris Mitigation Document (SDMD) **shall contain as a minimum**:
  - a. a table of compliance with the requirements;
  - b. a description of design and operational measures put in place to achieve compliance;
  - c. a list of objects (mission-related objects or space debris) released as part of the nominal mission. For these objects, the physical characteristics, the orbital characteristics and the predicted on-orbit lifetime shall be provided;
  - d. a feared-events list of malfunctions of the space system which have the potential to cause space debris, and a description of the characteristics of the debris so caused.


estec

DOCUMENT

Project Name
Space Debris Mitigation Document (SDMD)

DRAFT

(1) *Statement of any restrictions on the data in the SDMR such as proprietary, restricted, classification, International Traffic in Arms Restrictions (ITAR), or other export restrictions/controls. If the document does not contain any restrictions, then a statement to that effect shall be included. If the document does contain restricted information, the restricted information shall be summarized and marked clearly on the page(s) where it occurs and on the cover.*

Prepared by: Project Debris Mitigation Officer
Reference
Issue: 1
Revision: 0
Date of Issue
Status: For information
Document Type: SP
Distribution

European Space Agency
Agence spatiale européenne

Space Debris Mitigation Document (SDMD) – Template

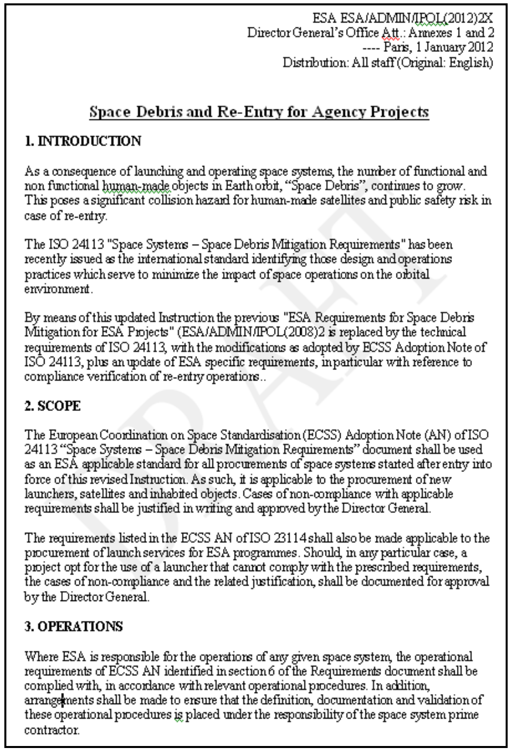
Independent Verification of SD&R Requirement Compliance

Independent Compliance Verification

- In addition to the responsibility, in your projects, to define, monitor and control re-entry and space debris mitigation requirements and provide evidence if these requirements are or not met.

- There is a responsibility assigned to the Independent Safety Office (TEC-QI), an independent entity verifying the compliance of these requirements.

Standardisation Activities: Highlights


ESA ESA/ADMIN/IPOL(2012)2X
Director General's Office Att.: Annexes 1 and 2
---- Paris, 1 January 2012
Distribution: All staff (Original: English)

Space Debris and Re-Entry for Agency Projects

1. INTRODUCTION

As a consequence of launching and operating space systems, the number of functional and non functional human-made objects in Earth orbit, "Space Debris", continues to grow. This poses a significant collision hazard for human-made satellites and public safety risk in case of re-entry.

The ISO 24113 "Space Systems – Space Debris Mitigation Requirements" has been recently issued as the international standard identifying those design and operations practices which serve to minimize the impact of space operations on the orbital environment.

By means of this updated Instruction the previous "ESA Requirements for Space Debris Mitigation for ESA Projects" (ESA/ADMIN/IPOL(2008)2 is replaced by the technical requirements of ISO 24113, with the modifications as adopted by ECSS Adoption Note of ISO 24113, plus an update of ESA specific requirements, in particular with reference to compliance verification of re-entry operations..

2. SCOPE

The European Coordination on Space Standardisation (ECSS) Adoption Note (AN) of ISO 24113 "Space Systems – Space Debris Mitigation Requirements" document shall be used as an ESA applicable standard for all procurements of space systems started after entry into force of this revised Instruction. As such, it is applicable to the procurement of new launchers, satellites and inhabited objects. Cases of non-compliance with applicable requirements shall be justified in writing and approved by the Director General.

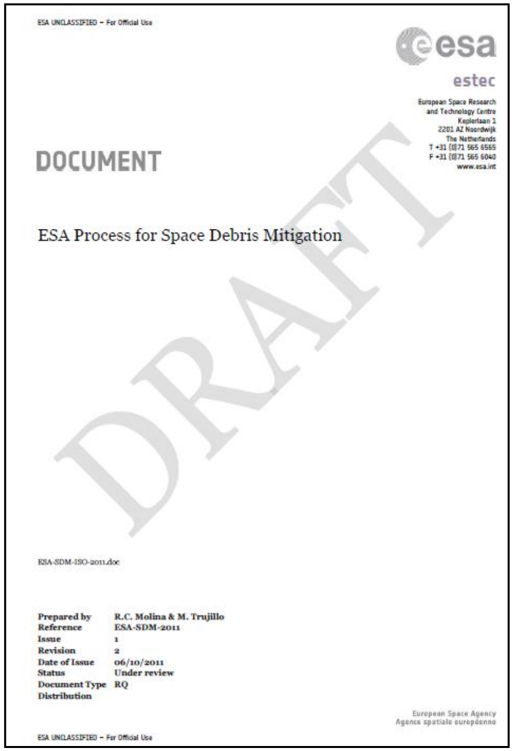
The requirements listed in the ECSS AN of ISO 23114 shall also be made applicable to the procurement of launch services for ESA programmes. Should, in any particular case, a project opt for the use of a launcher that cannot comply with the prescribed requirements, the cases of non-compliance and the related justification, shall be documented for approval by the Director General.

3. OPERATIONS

Where ESA is responsible for the operations of any given space system, the operational requirements of ECSS AN identified in section 6 of the Requirements document shall be complied with, in accordance with relevant operational procedures. In addition, arrangements shall be made to ensure that the definition, documentation and validation of these operational procedures is placed under the responsibility of the space system prime contractor.

DRAFT

Updated IPOL/ADMIN for Space Debris Mitigation (2012)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DOCUMENT

ESA Process for Space Debris Mitigation

ESA-SDM-ISO-2011.doc

Prepared by	R.C. Molina & M. Trujillo
Reference	ESA-SDM-2011
Issue	1
Revision	2
Date of Issue	06/10/2011
Status	Under review
Document Type	RQ
Distribution	

European Space Agency
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ESA Process for Space Debris Mitigation


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DOCUMENT

Project Name
Space Debris Mitigation Document (SDMD)

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Prepared by	Project Debris Mitigation Officer
Reference	
Issue	1
Revision	0
Date of Issue	28/11/2011
Status	For information
Document Type	SP
Distribution	

European Space Agency
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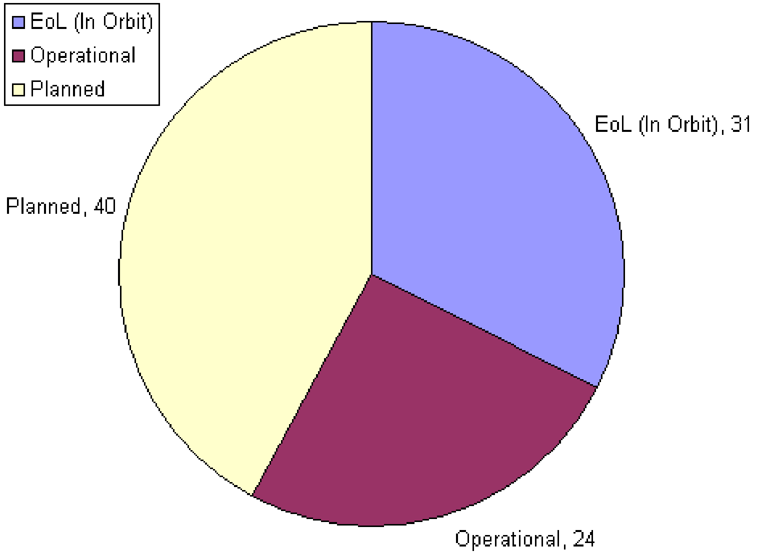
Space Debris Mitigation Document (SDMD) – Template

ESA AS ECSS (AN ISO 24113)

ESA Missions:
A look ahead

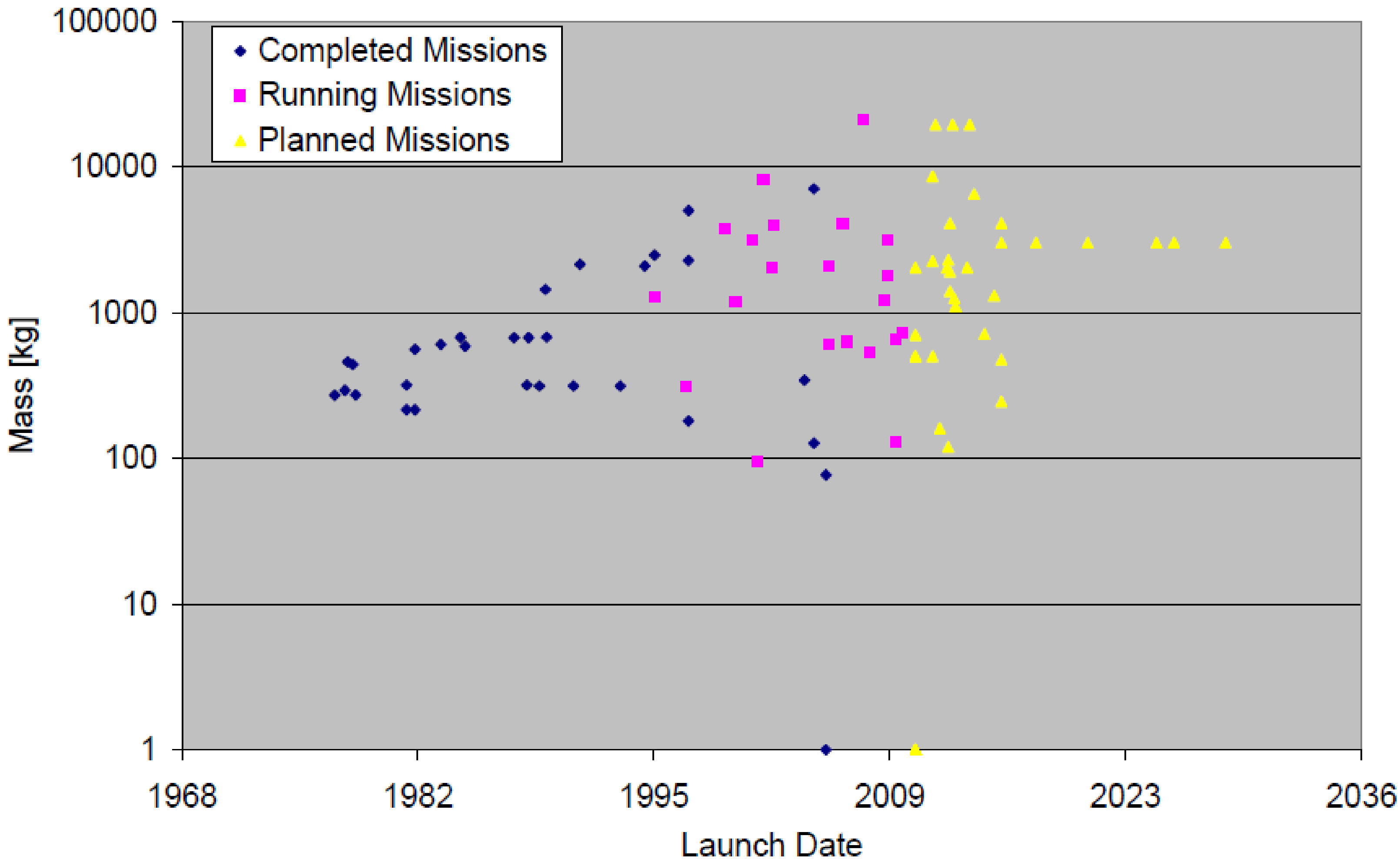
Overview of ESA Payloads

1. 95 Payloads have been launched since 1977
2. Total Mass
    a. Past Missions: 31 Tns
    b. Operational Missions: 64 Tns
    c. Planned Missions: 121 Tns



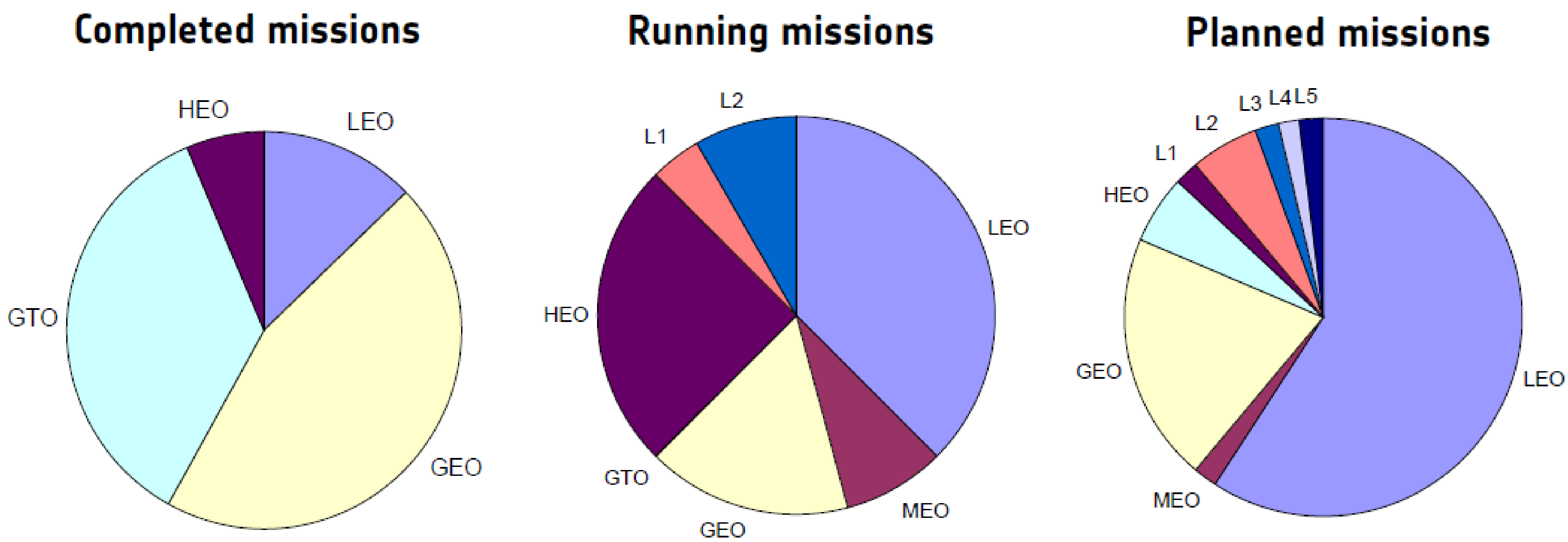
Source: "Preliminary compliance of ESA Missions "H. Krag (2011)

ESA Spacecraft Mass



Source: "Preliminary compliance of ESA Missions "H. Krag (2011)

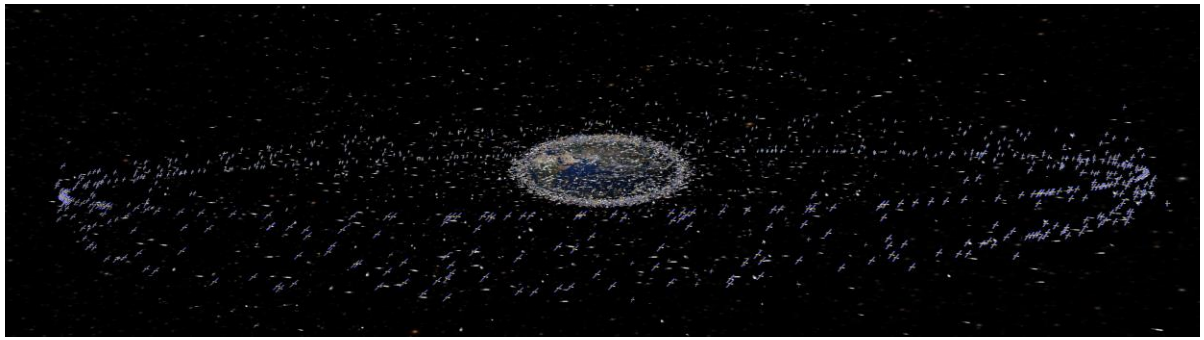
ESA Missions: Orbital Distribution

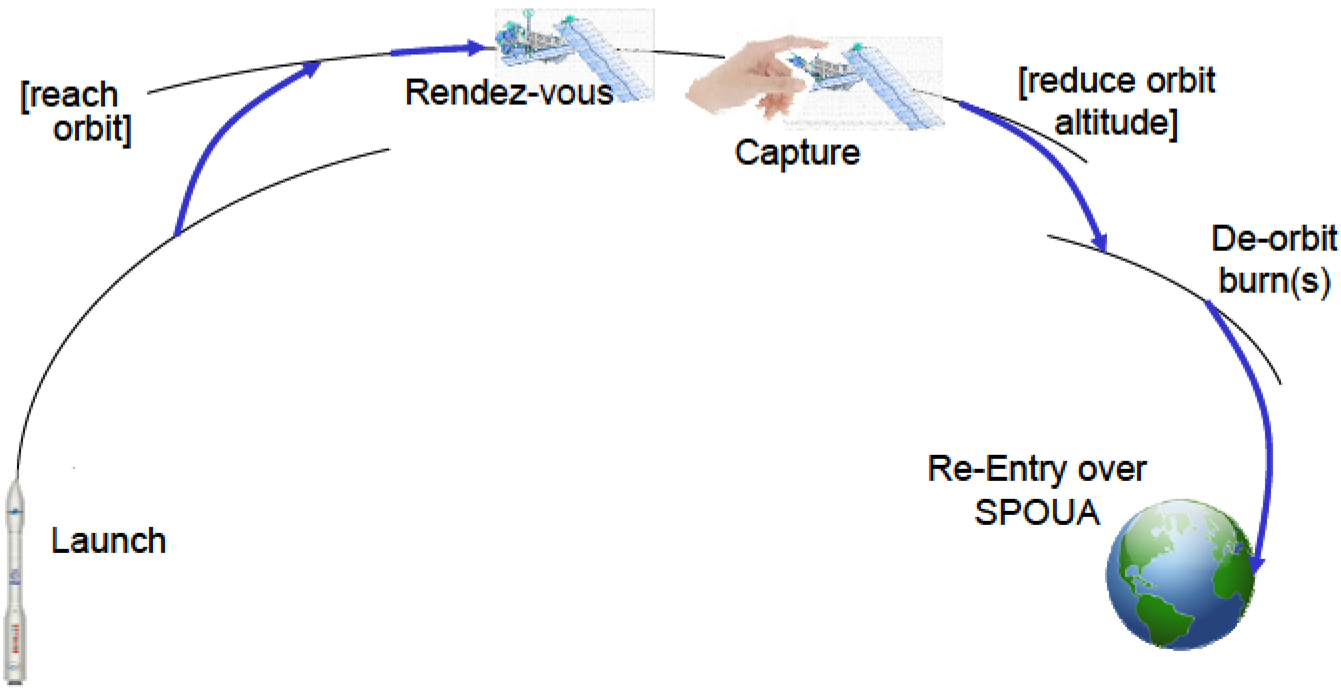


Source: "Preliminary compliance of ESA Missions" H. Krag (2011)

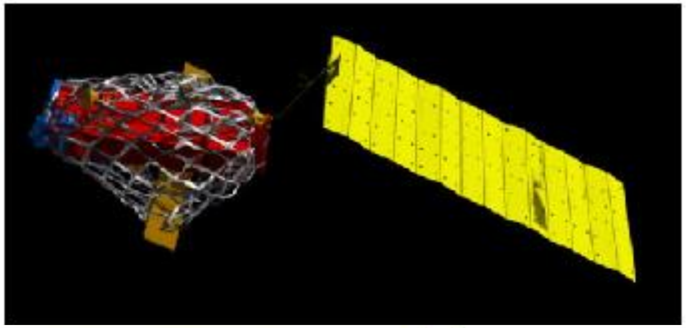
Some Spacecraft Removal Strategies

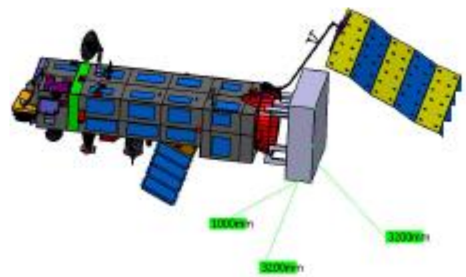
Spacecraft Removal Strategies

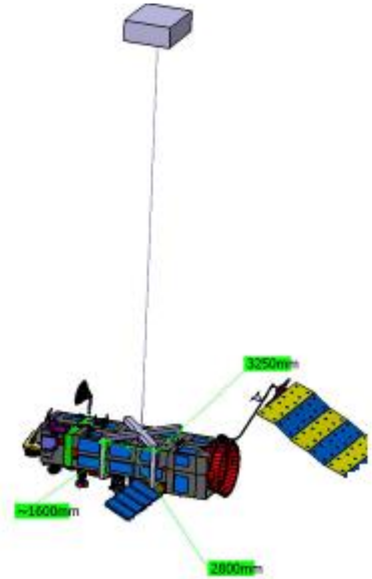




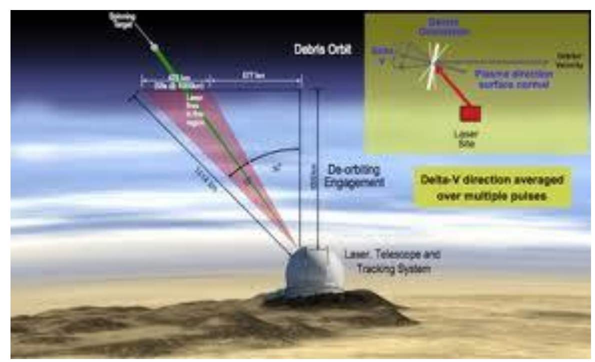
Some Removal Strategies







ROGER study (Astrium)



European Space Agency

Material Covered

- **Space Debris Mitigation: An Overview**
- **Space Debris Mitigation Requirements**
    a. Historical perspective
    b. International Endeavours
    c. Requirements: Content, Rationale & Examples
- **Re-entry Safety**
    a. Problematic and examples
    b. Re-entry requirements and safety review panels
    c. Break-up and re-entry analysis tools
    d. Design for demise: a proactive engineering approach
    e. Aviation Safety risk: an overview
- **ESA SDM Management Requirements**
- **Some Spacecraft Removal Options**
- **Conclusions and Participants feedback**

Thank you

Your feedback is valued

Back-up Slides

Other ISO Space Debris Mitigation Standards

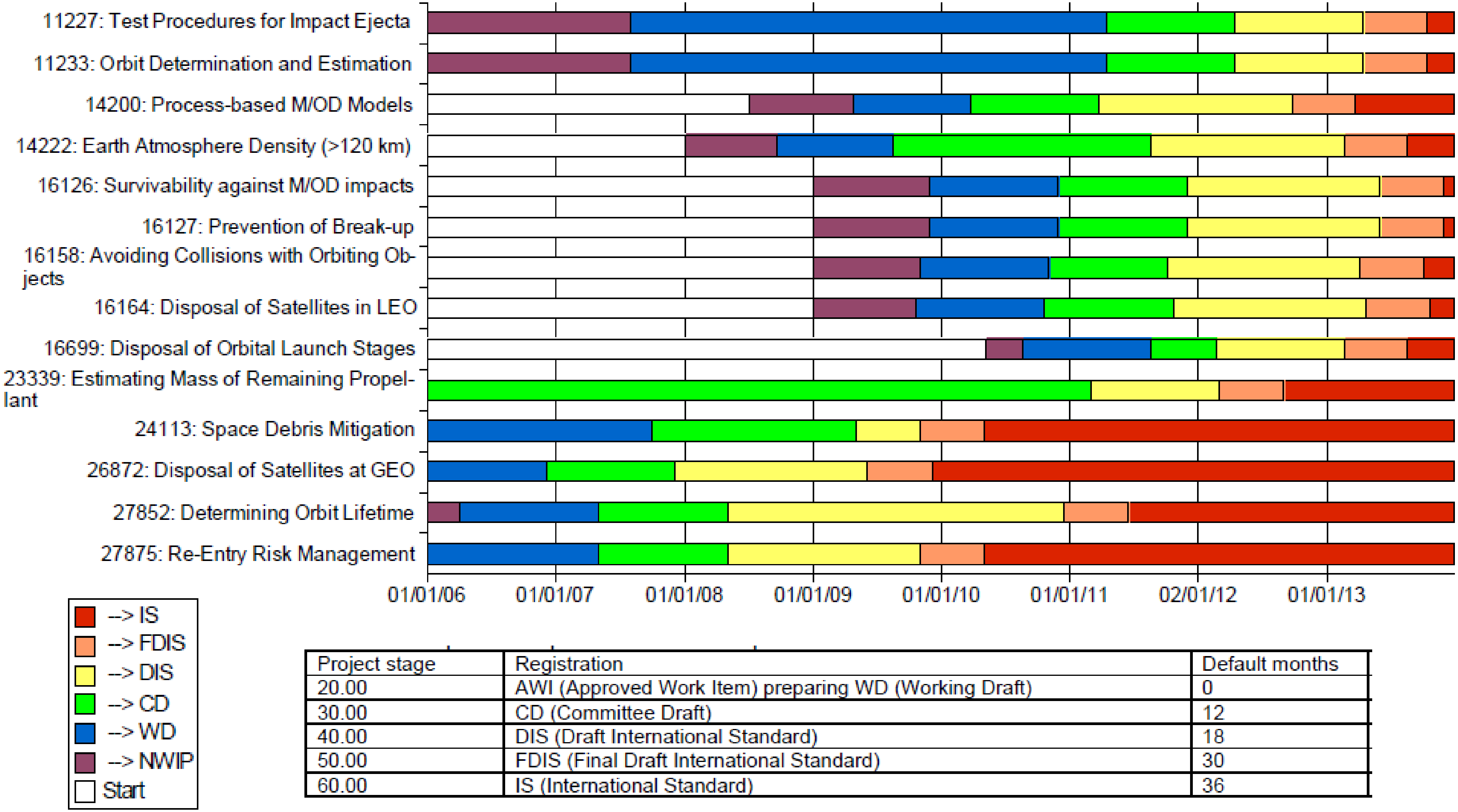
ISO TC20/SC14 Orbital Debris Mitigation Standards

ISO TC20/SC14 ORBITAL DEBRIS MITIGATION STANDARDS

- **WG1 DESIGN**
  - <u>Prevention of Break-up of of un-manned S/C</u> (16127)
  - Survivability of unmanned S/C against SD and MM impacts (16126)
- **WG2 INTG & TEST**
- **WG3 OPERATIONS**
  - <u>Space Debris Mitigation</u> (24113)
  - <u>Disposal at GEO</u> (26872)
  - <u>Disposal in LEO</u> (16164)
  - Estimating mass of remaining usable propellant (23339)
  - Re-entry Risk Managment for unmanned S/C (27875)
  - <u>Estimation of orbit lifetime</u> (27852)
  - Orbit determination and estimation (11233)
  - Avoiding collisions with orbiting objects (16158 N608)
  - Disposal of Orbital Launch Stages (16699)
- **WG4 ENVIRON.**
  - Process-Based implementation of M/D Env. Models (14200)
  - Earth atmosphere density (14222)
- **WG5 MANAGEMENT**
- **WG6 MATERIALS**
  - Test procedures for S/C material ejecta upon HVI (11227)

Notes
1) As of September 2011
2) Abbreviated titles used
3) Text colour code:
4) Orange: IS published
Green: DIS stage or after
Red: CD/V passed
Blue: CD stage
4) <u>Items of ECSS high priority underlined</u>

ISO-Schedules for development of SDM Standards



Project stage	Registration	Default months
20.00	AWI (Approved Work Item) preparing WD (Working Draft)	0
30.00	CD (Committee Draft)	12
40.00	DIS (Draft International Standard)	18
50.00	FDIS (Final Draft International Standard)	30
60.00	IS (International Standard)	36

ISO documents – ECSS Classification HP/LP

ECSS High Priority (HP) SDM items (6):

a. ISO 24113 - Space Debris Mitigation (ECSS adoption)

b. ISO 16164 - Disposal of satellites operating in or crossing LEO
c. ISO 16127 - Break up prevention of un-manned S/C
d. ISO 16699 - Disposal of Orbital Launch Stages

e. ISO 26872 - Disposal of satellites operating at geosynchronous altitude (for the time being used as reference information when needed, w/o ECSS adoption process)
f. ISO 27852 - Estimation of orbit lifetime (for the time being used as reference information when needed, w/o ECSS adoption process)

ISO documents – ECSS LP Classification

1. ECSS Low Priority (LP)" SDM items (8):
    a. ISO 27875 - Re-entry risk management for unmanned S/C and launch vehicle orbital stages
    b. ISO 23339 - Unmanned S/C - Estimating the mass of remaining usable propellant
    c. ISO 11227 - Test procedures to evaluate S/C material ejecta upon hypervelocity impact
    d. ISO 14200 - Guide to process-based implementation of meteoroid and debris environmental models
    e. ISO 16126 - Assessment of survivability of unmanned S/C against space debris and meteoroid impacts to ensure successful postmission disposal
    f. ISO 16158 - Avoiding collisions with orbiting objects (TR)
    g. ISO 11233 - Orbit determination and estimation - Process for describing techniques (TS)
    h. ISO 14222 - Earth Atmosphere density above 120 km

Annexes

- ESA/ADMIN/IPOL(2008)2