A3

The latest space debris related research and technology activities in the European Space Agency

Holger Krag, ESA

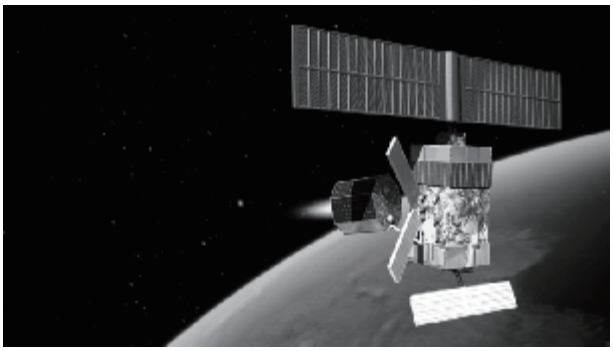
This talk will address ESA's progress in space debris research and technology in 4 domains:

1. ESA operates a conjunction analysis system and currently monitors 10 satellites. The system uses the JSpOC CDM data. A number of novel techniques have been developed including automation in the processing of the data, new algorithms for low delta-v approaches and independent manoeuvre screening. ESA's conjunction assessment system and related statistics and highlights will be presented.

2. Since many years, ESA develops object databases, as well as risk assessment and mitigation analysis software. Methods for the verification of the compliance to on-ground risk and orbital lifetime assessment have been developed. ESA, as an operator of objects in very unusual orbits such as high-eccentric and Lagrange Point orbits has developed novel disposal options which have been validated with these new means. The means and related technology will be presented along with recent examples.

3. Further, ESA runs an ambitious SSA program, for which a system architecture has been designed and a demonstrator phased-array radar has been developed. In addition to this, it operates its own 1m-telescope on Tenerife which has discovered a population of high area/mass objects. Recent radar and optical as well as laser ranging measurements concentrate on the identification of the attitude motion of uncontrolled objects, like Envisat. An overview over the current measurement systems and recent results will be presented.

4. Finally, ESA has been investing in the technology for rendez-vous and capture of uncontrolled objects. Various solutions have been scrutinized in system studies. In parallel, the effect of active removal and the criticality of a given objects in LEO orbit has been studied. This presentation will show ESA's analysis results and the recent plans for the e.Deorbit mission for the controlled removal of an uncontrolled target in LEO.



ESA's e.Deorbit mission

ESA's SSA demonstrator radar

Biography

Dr. Holger Krag

Title: Head of Space Debris Office
Division: Ground Segment Engineering Department
Company: ESA/ESOC
Email: holger.krag@esa.int

Dr. Holger Krag has been a Space Debris Analyst in the Space Debris Office of ESA/ESOC located in Darmstadt, Germany, since 2006. He has worked on the operational conjunction event analysis for various ESA missions, debris risk assessment, mitigation analysis and the Surveillance and Tracking Segment of the European SSA system. Since 2014, he is head of the Space Debris Office. He represents ESA in the IADC (Inter Agency Debris Coordination Committee) and is involved in the development of an ESA mission for the active removal of a non-cooperative space objects from orbit.

From 2002 – 2006 Dr. Holger Krag has served as a System Engineer in the Navigation Business Unit of Thales ATM, responsible for development of a test bed for the ground mission segment of Galileo with permanent collocation in Toulouse, France.

From 1998 – 2002 Dr. Holger Krag was a project scientist at the Technical University of Braunschweig, Germany and conducted more than 4 years of detailed research in the area of space debris environment and observation modeling.

The latest space debris related research and technology activities in the European Space Agency

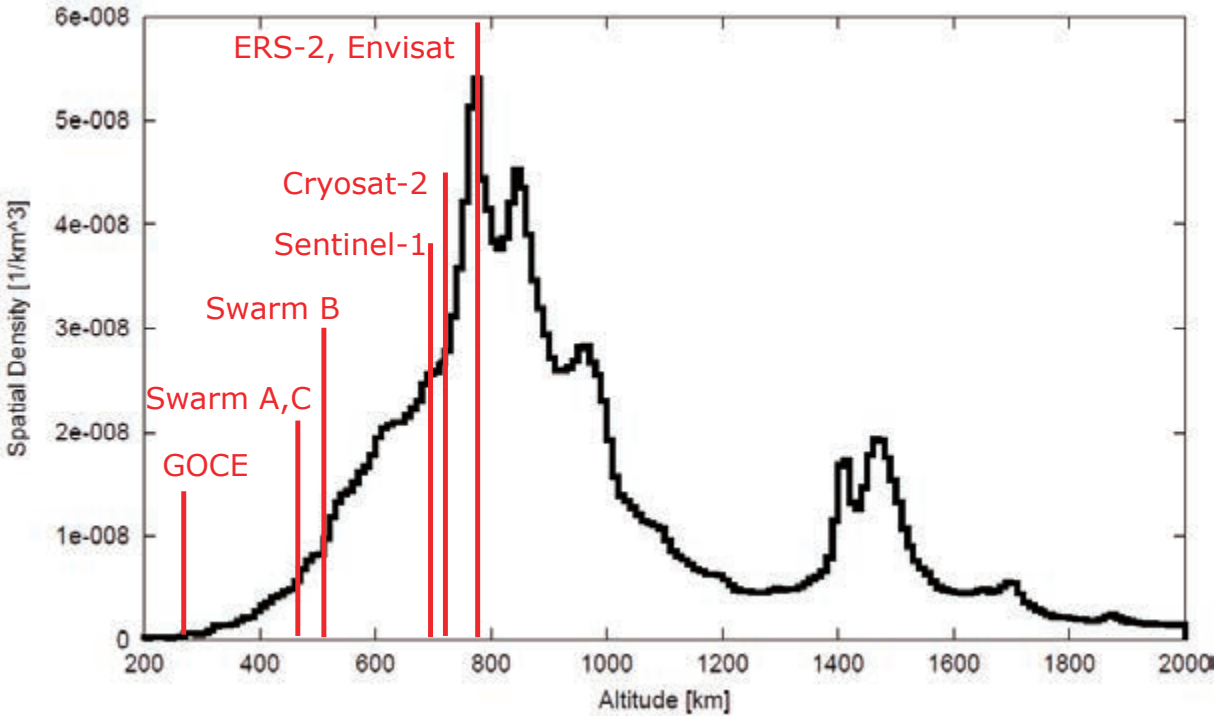
Holger Krag
ESA/ESOC

6th Space Debris Workshop
JAXA Chofu Aerospace Center, December 17-19, 2014

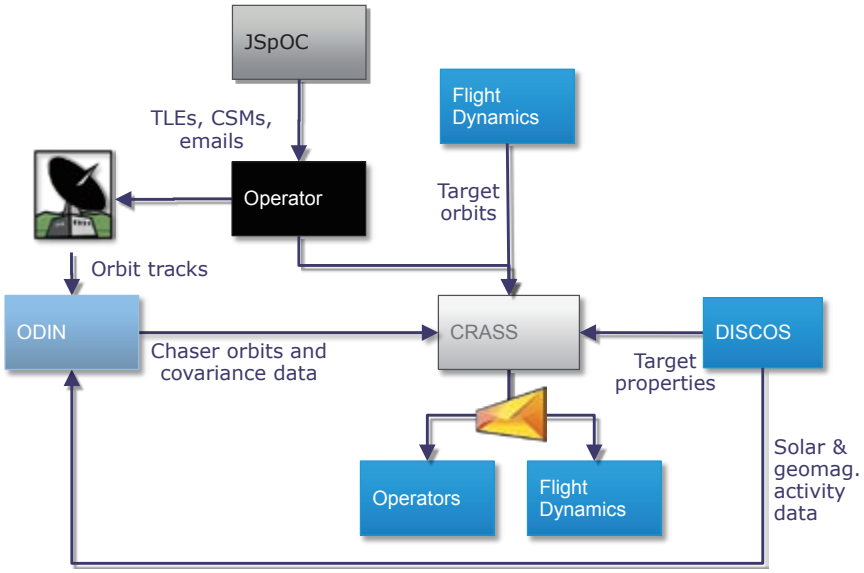
Outline

- *Collision Avoidance*
- *DISCOS Database*
- *Compliance Analysis*
- *Mitigation Technology and Re-entry Assessment*
- *Space Situational Awareness and Measurements*
- *Space Debris Modelling*
- *Attitude Measurements of uncontrolled objects*
- *Active Removal (e.Deorbit)*

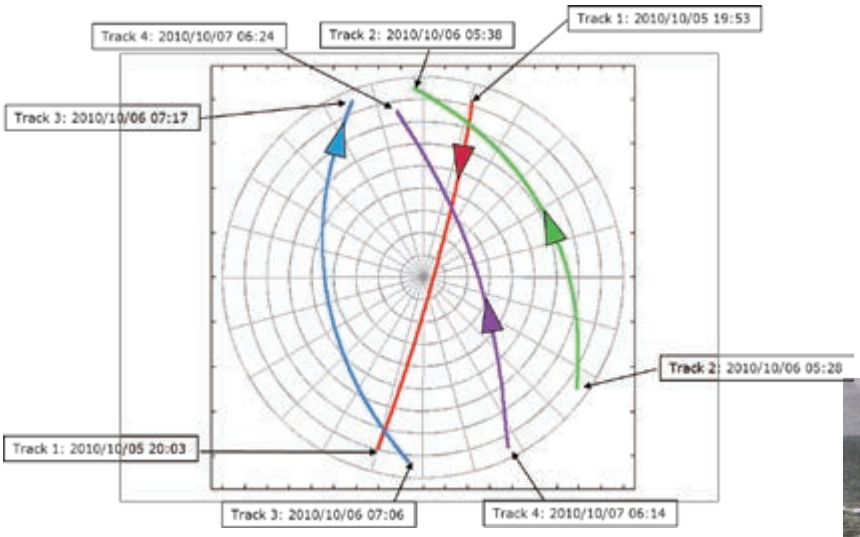
Monitored Missions



Collision Avoidance System (2004-2013)



Orbit Refinement by Tracking

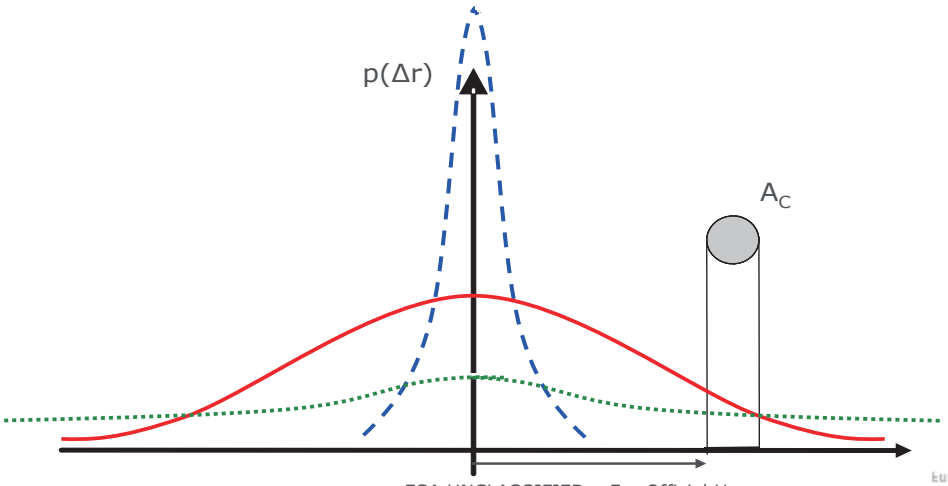


Tracking and Imaging Radar

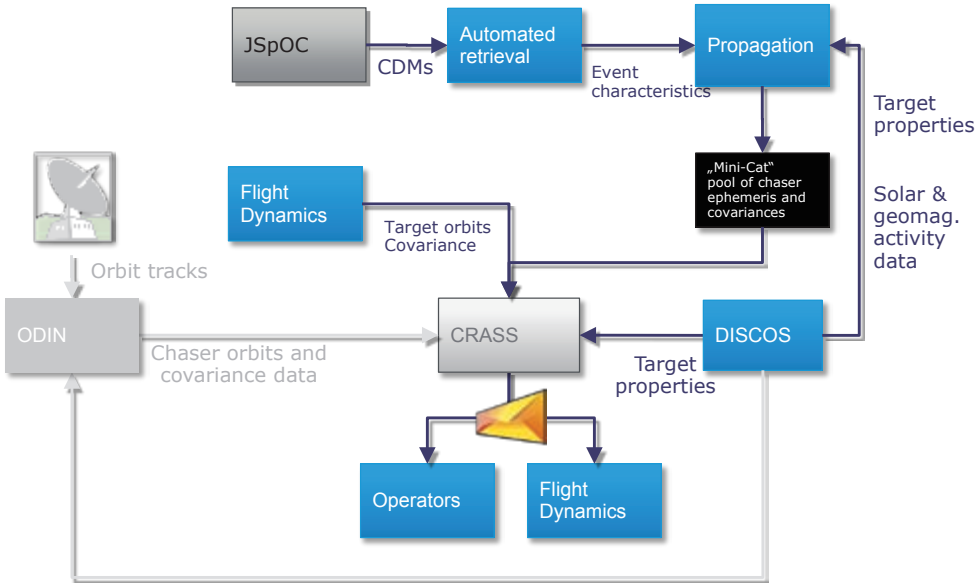
Monge tracking ship

Impact of Orbit Accuracy on Conjunction Analysis

- Establish new Collision Avoidance Procedures based on the CSM:
  - New threshold collision probability
  - Additional minimum (geometry-dependent?) fly-by distance



Collision Avoidance System (since 2014)



CORAM

Features:

•Several Collision Probability Algorithms:

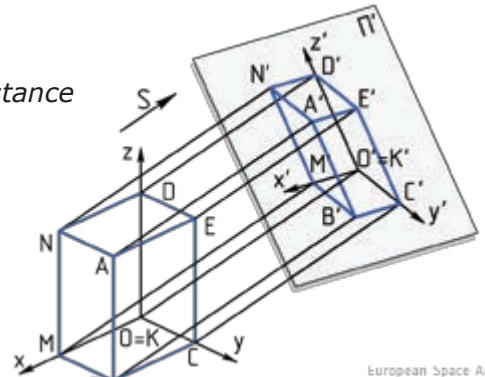
- *Alfriend Akella*
- *Maximum Probability*
- *Algorithms for low delta-v approaches*
- *Monte-Carlo*

•Cross-sectional projections

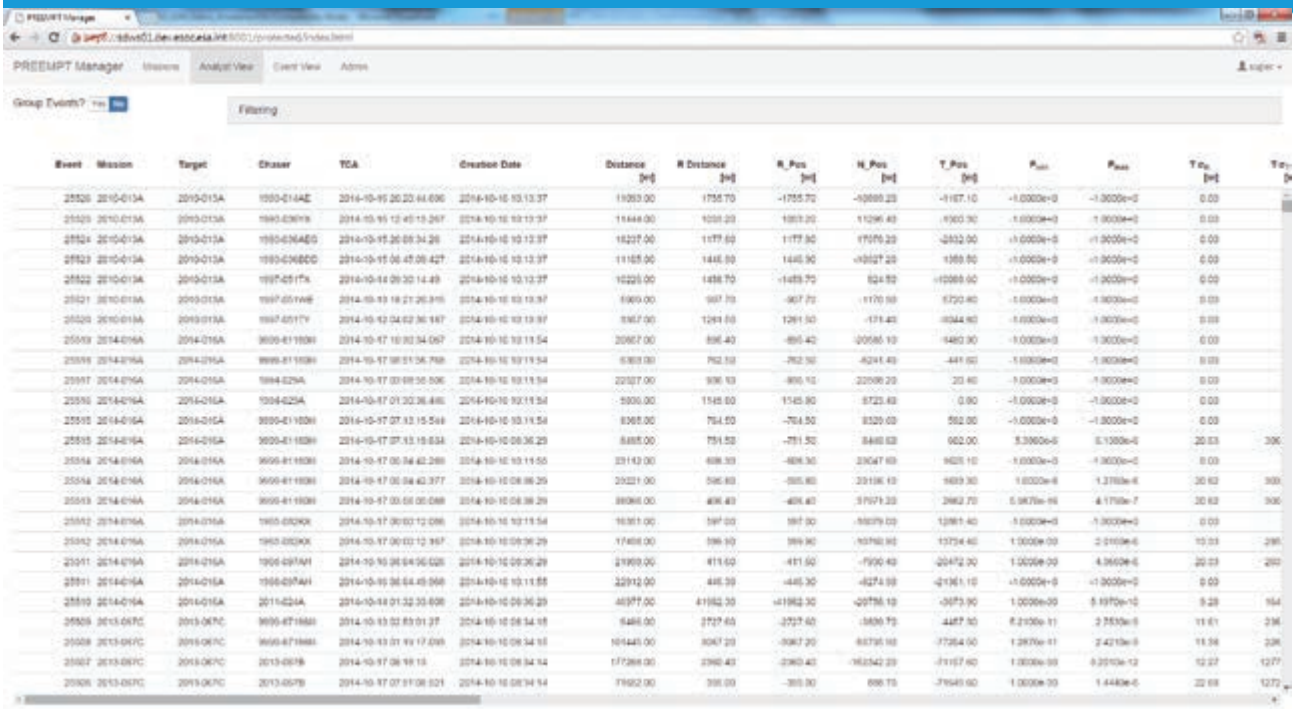
•Manoeuvre planning:

- *Sampling of several desired radial fly-by distance*

•Covariance scaling



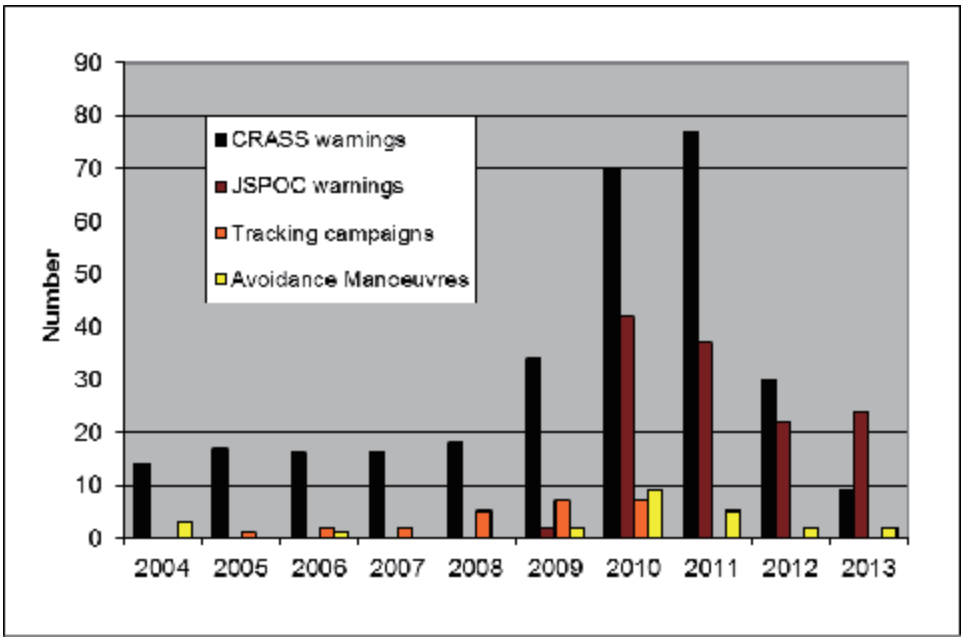
PREEMPT



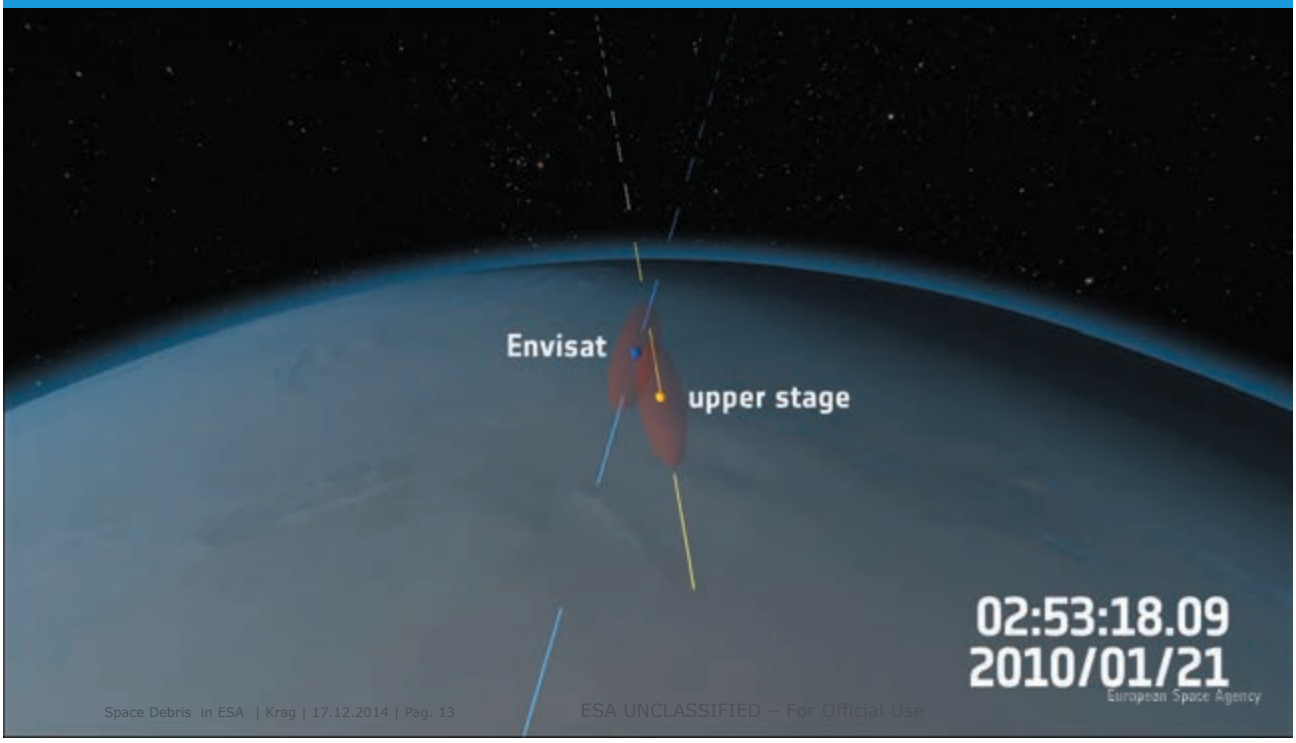
PREEMPT

PREEMPT

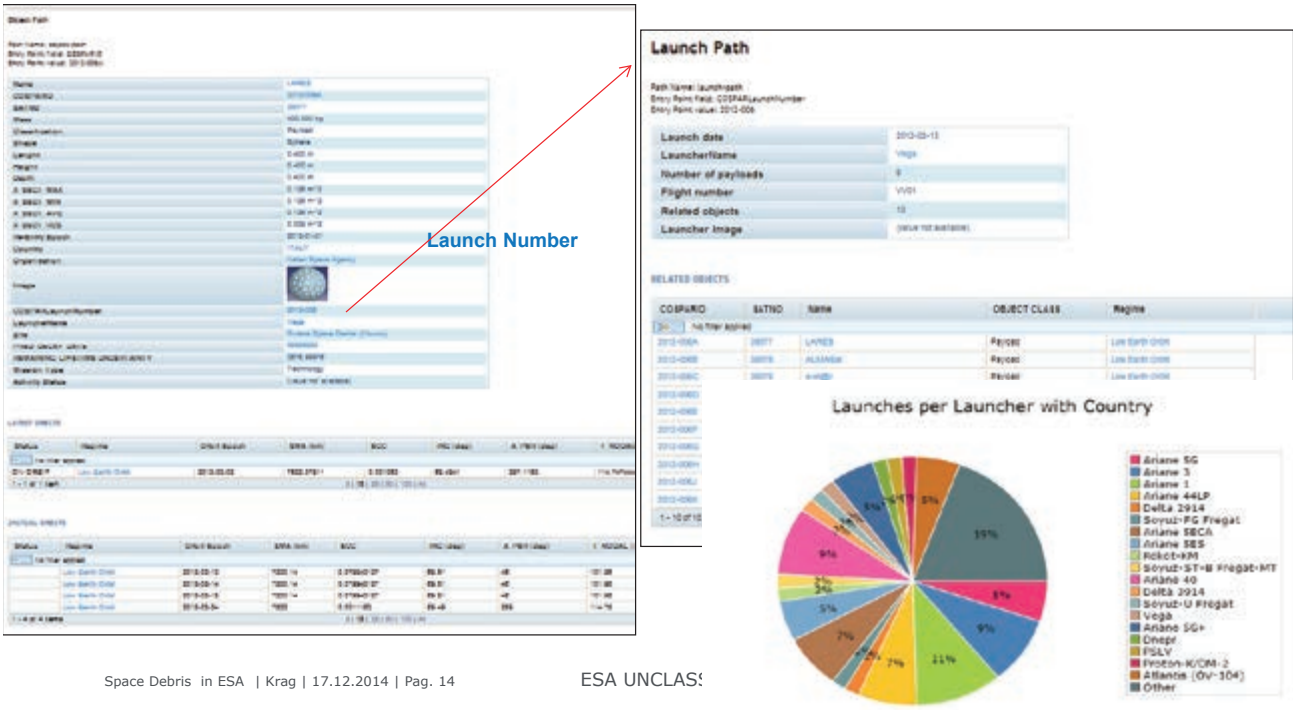
Statistics for ESA Satellites



Envisat Conjunction Jan. 21st, 2010

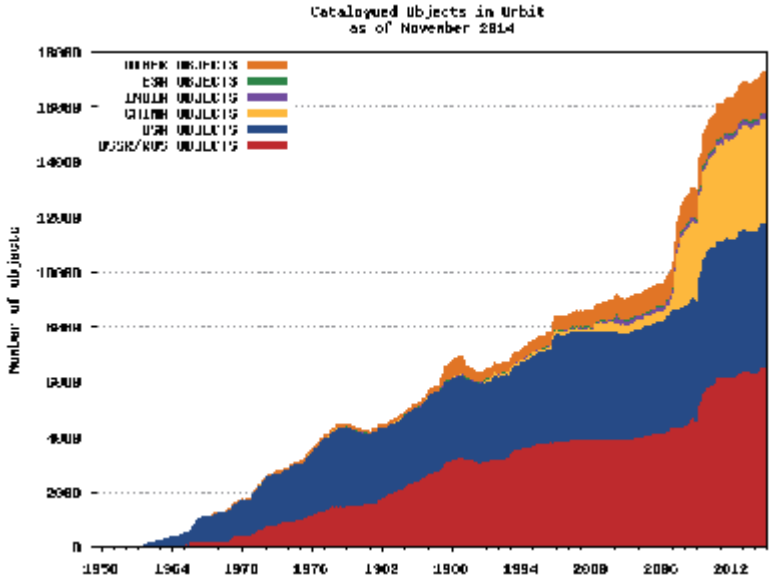


The new DISCOS Web Frontend

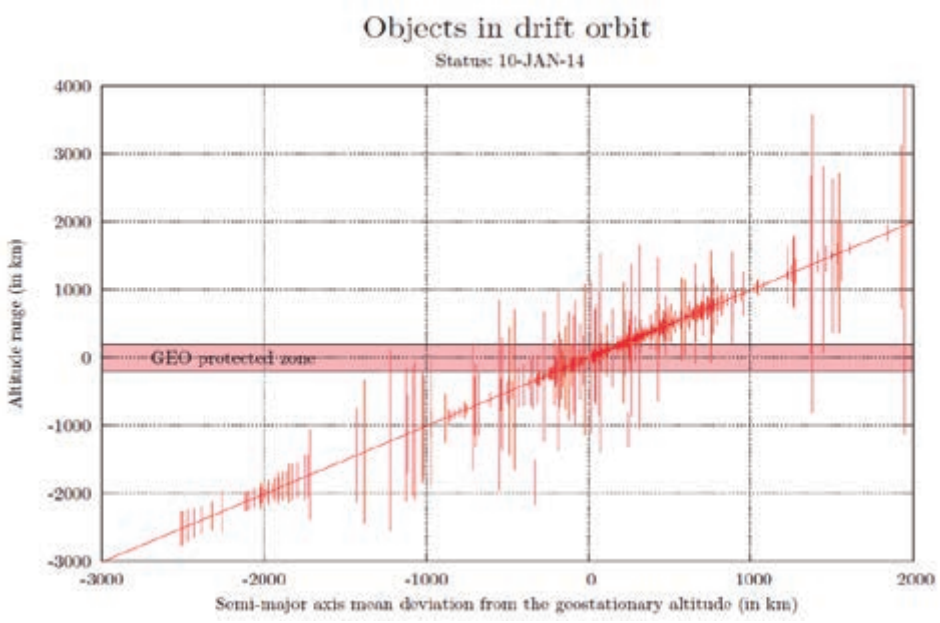


Catalogued objects in orbit

- December 2014: ca. 40000 Objects have been catalogued, of which about 17000 are in orbit

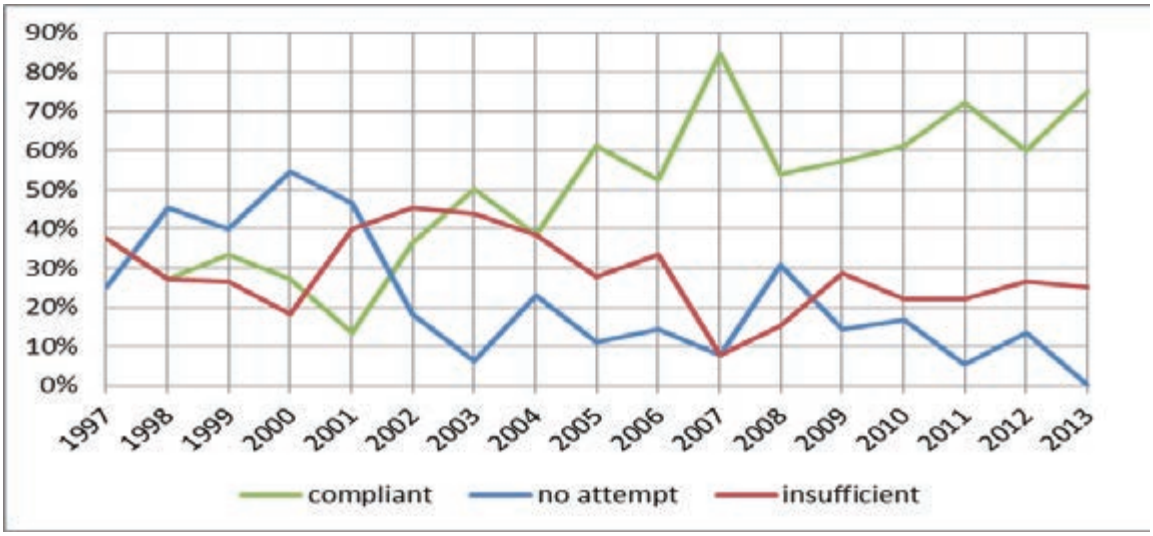


Distribution of drifters
(TLE only)



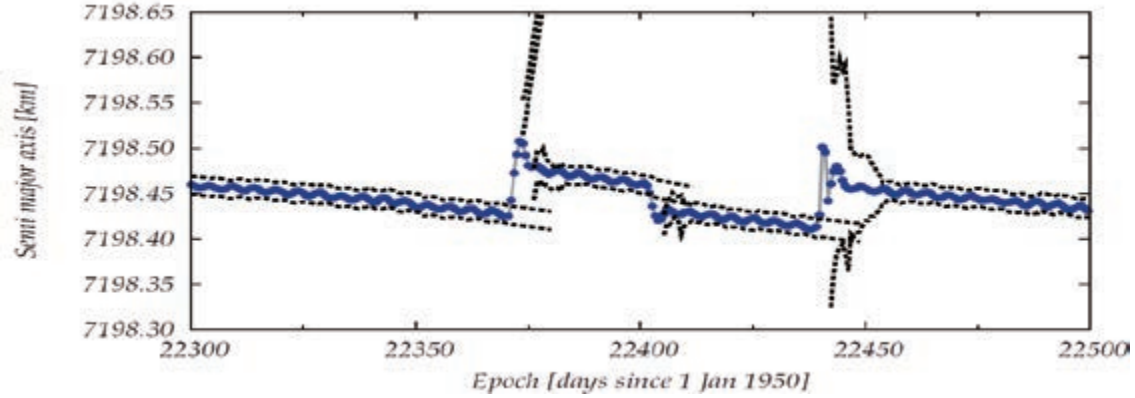
EoL statistics

- Average of 16 annual disposals

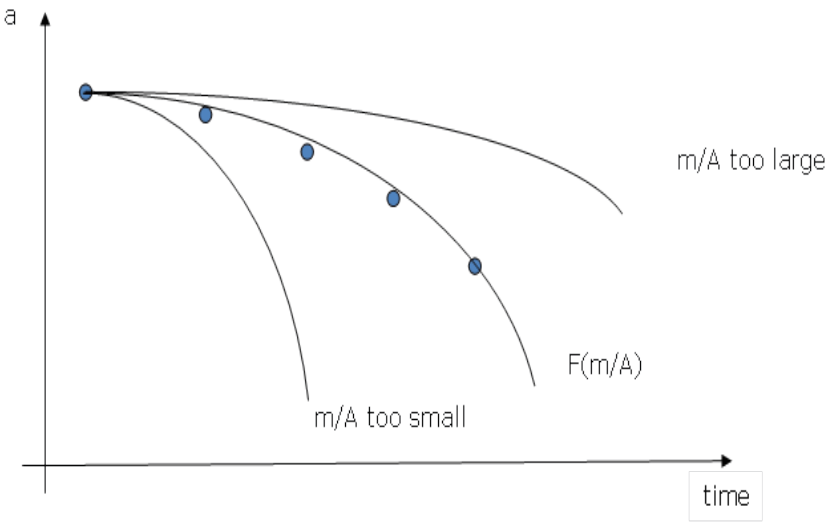


Manoeuvre Detection from TLEs

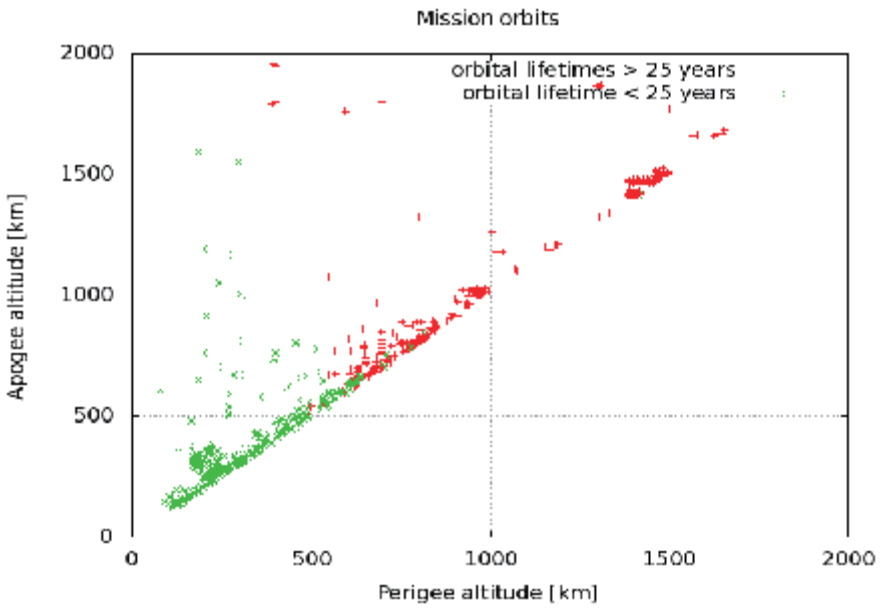
METOP-A between 21/1/2011 and 9/8/2011



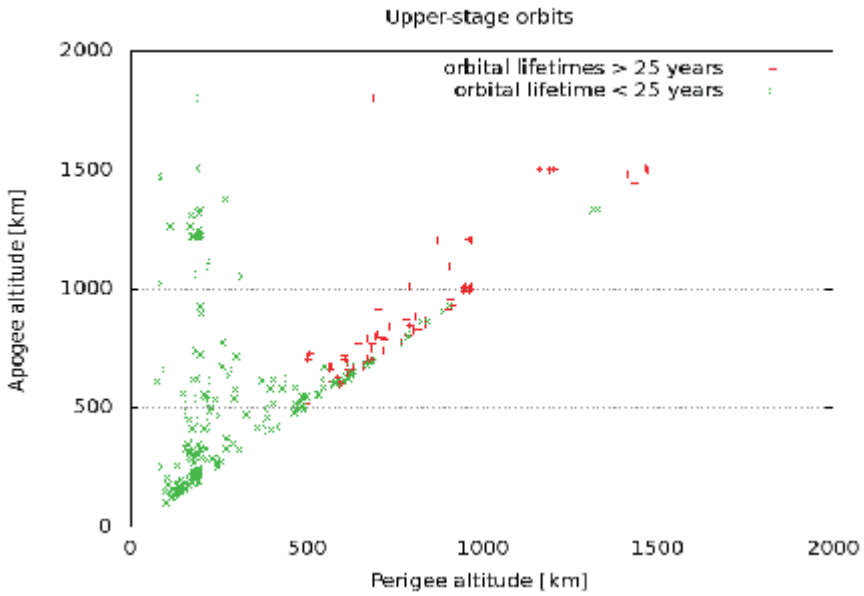
Orbital Lifetime Prediction from TLEs



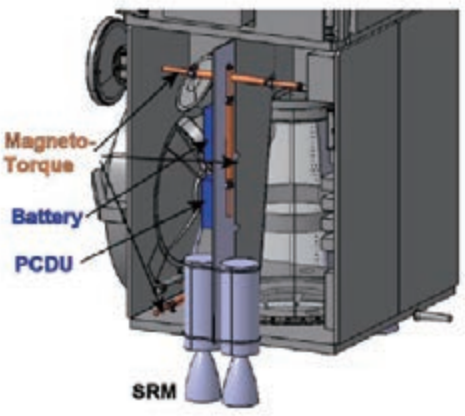
Destination orbits of spacecraft



Destination orbits of upper-stages



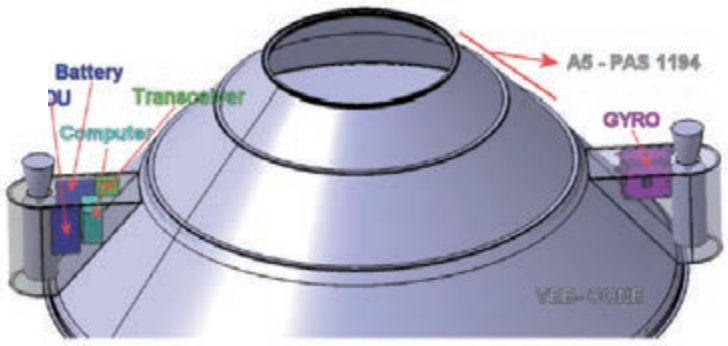
SPADES



Solid **P**ropellant **A**utonomous **De**-orbit **S**ystem

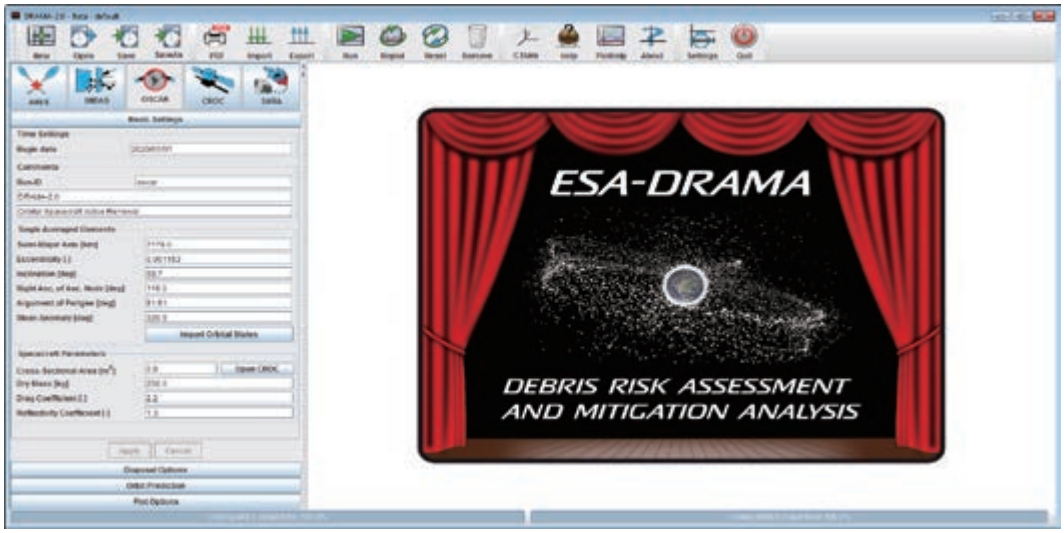
← Accomodation on LEO Satellite

Accomodation on Ariane 5 GTO state →



V2.0 Graphical User Interface

- Windows, Linux, ~~Solaris,~~ **Mac-OS**



The DRAMA 2.0 software suite

ARES: Assessment of Risk Event Statistics:
To consider the possible requirements for collision avoidance manoeuvres during a mission.

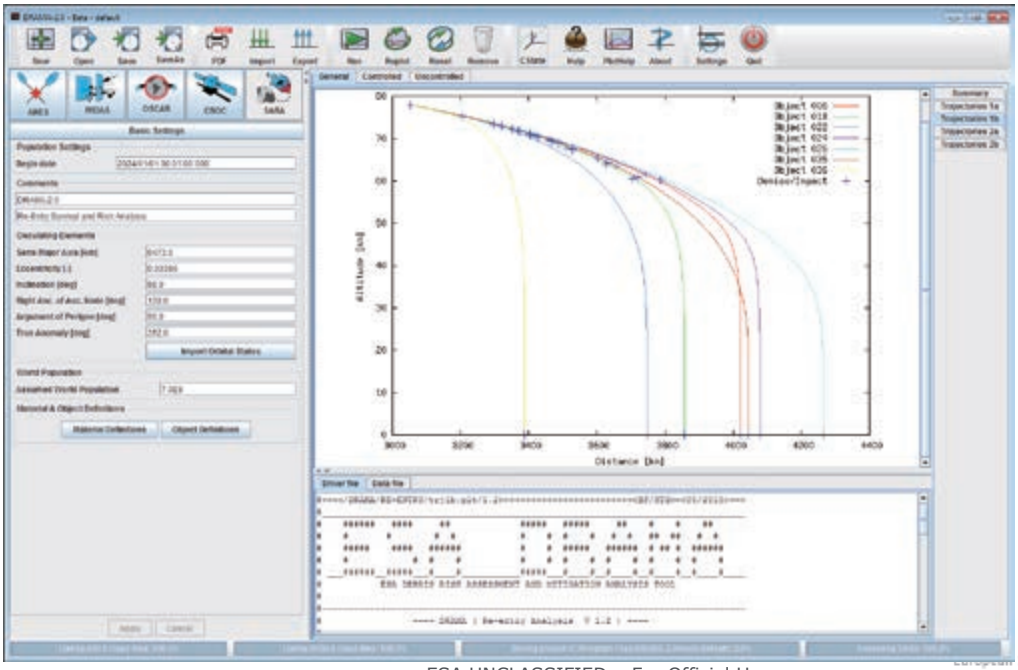
MIDAS: MASTER (-based) Impact Flux and Damage Assessment Software: To model the collision flux and damage statistics for a mission.

OSCAR: Orbital Spacecraft Active Removal: To analyse the disposal manoeuvre performed by a space system at the end of its useful lifetime.

CROC: Compute projected cross-sectional areas of complex bodies

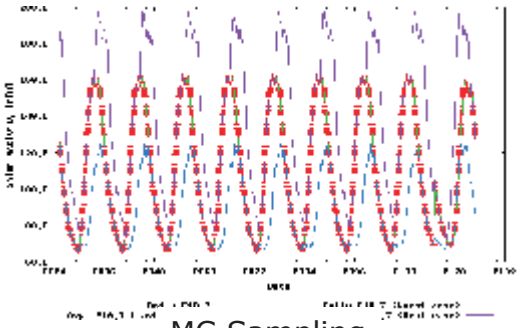
SARA: Spacecraft Entry Survival Analysis Module (SESAM):
To model the re-entry of a space system into the Earth's atmosphere.
Spacecraft Entry Risk Analysis Module (SERAM):
To assess the risk on ground of objects surviving re-entry.

New Presentation of Results

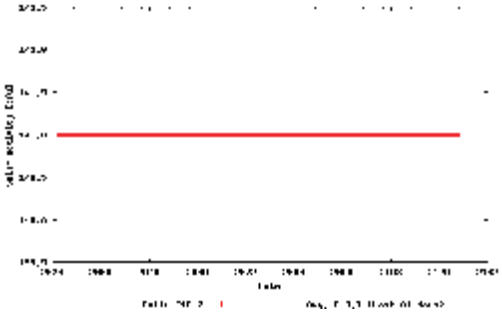


Task #2: Solar Flux Prediction Methods

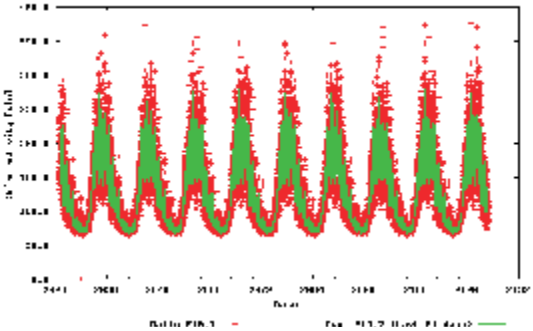
Nominal and Confidence interval



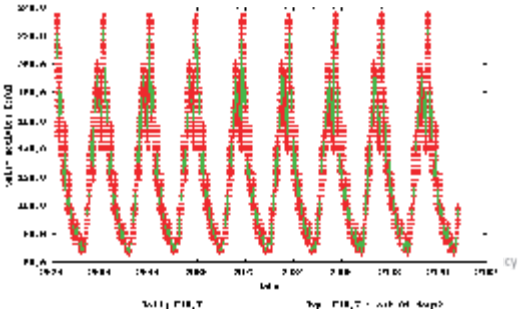
Specific Constant (STELA)



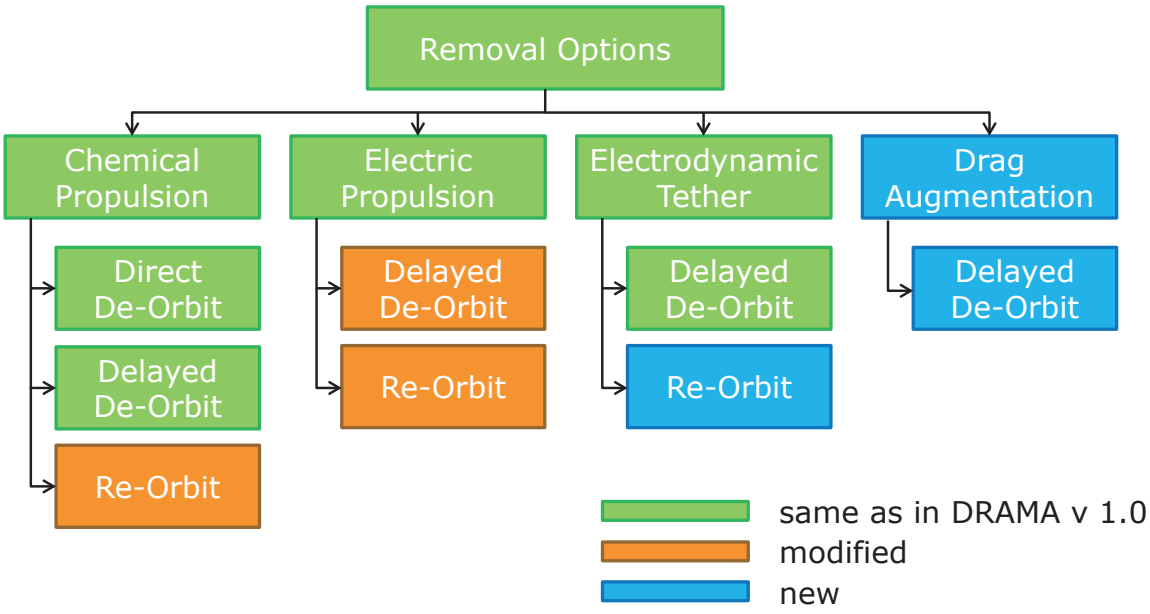
MC Sampling



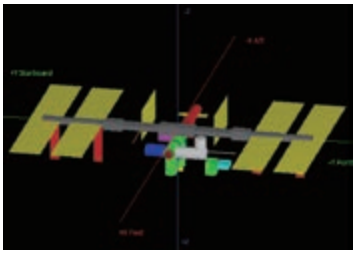
ECSS Reference Cycle

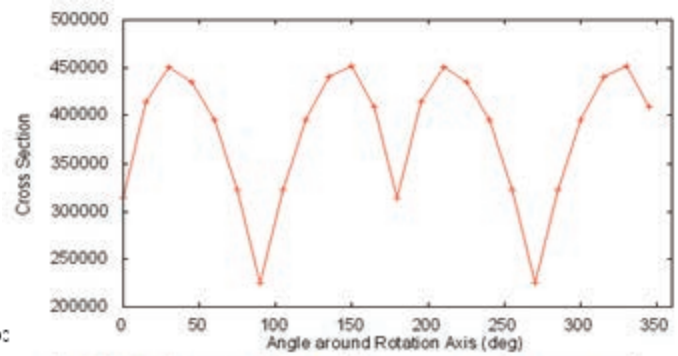


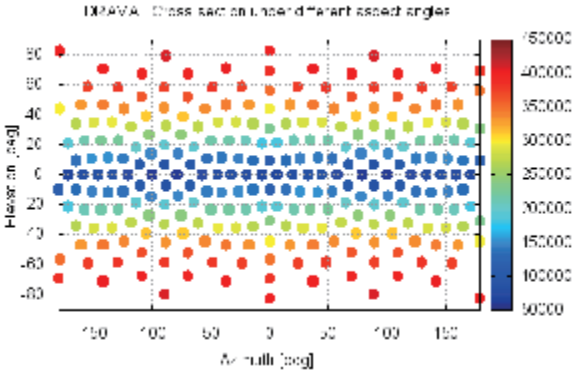
Removal Options Analysed by OSCAR

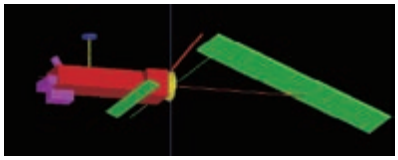


Cross-Section Computation



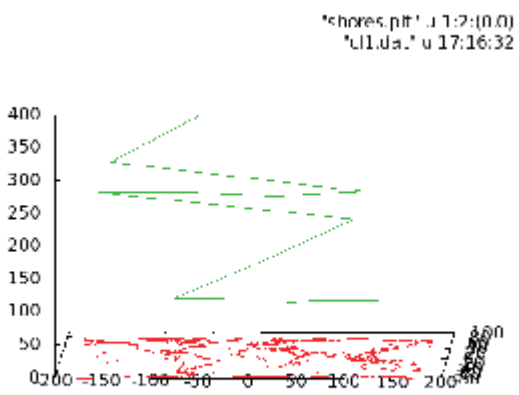


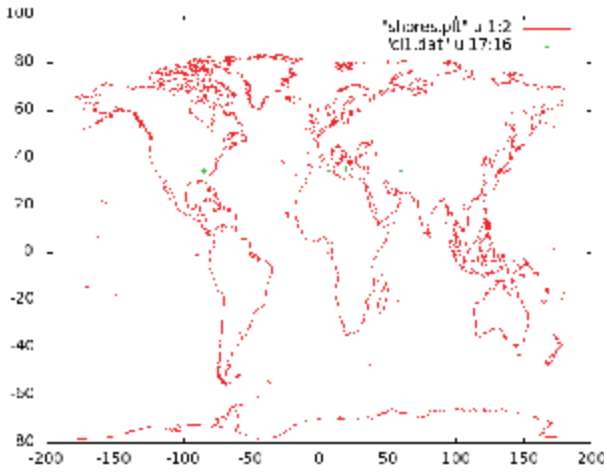




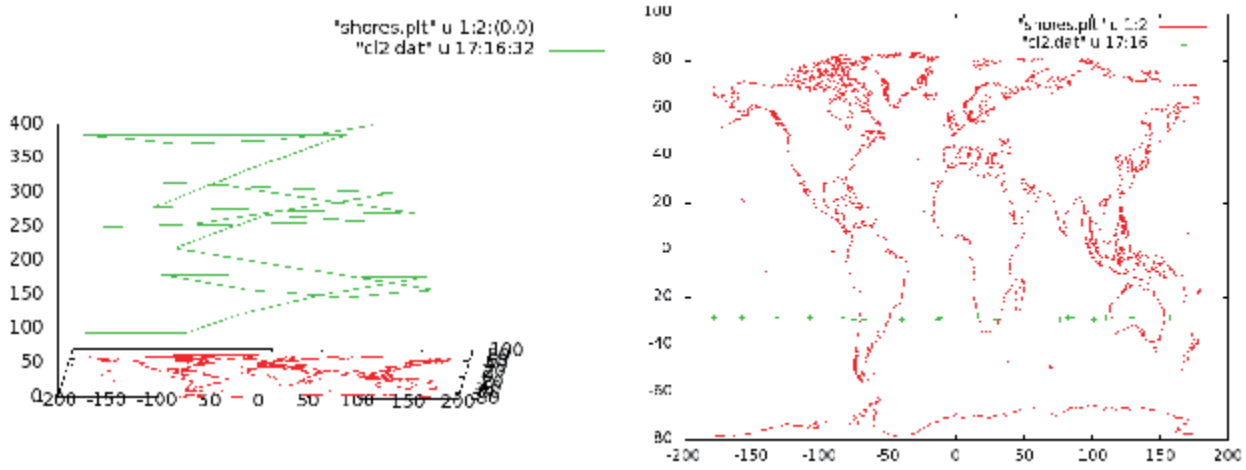
Cluster-II Re-entry

Cluster-II S/C 1

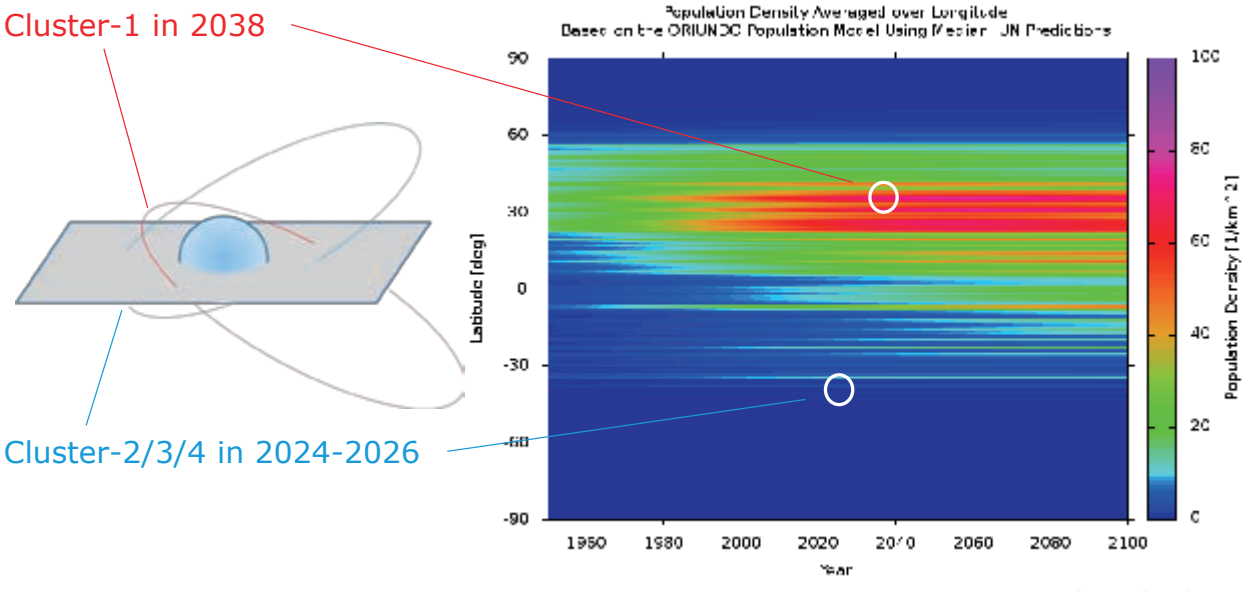




Cluster-II S/C 2



Cluster-II Line of Apsides and On-ground Risk



Determining Break-Up process and Survivability

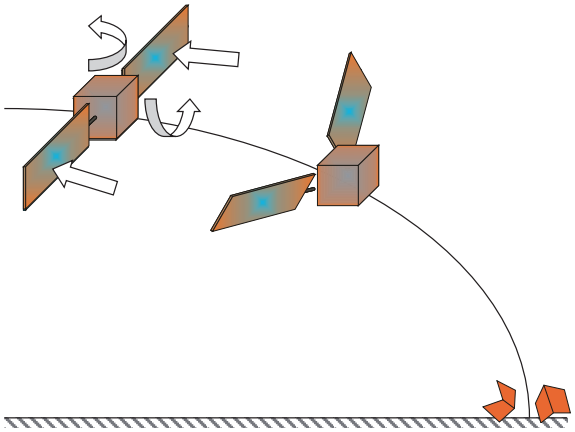
S/C modeling
→ simplified model

Aerodynamic analysis
→ forces and torques

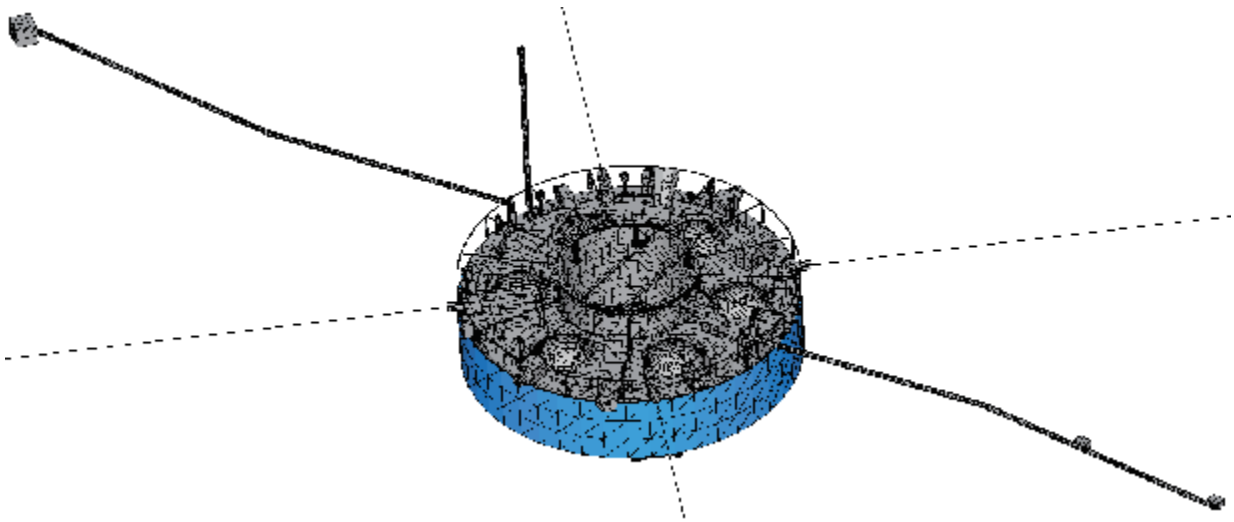
Dynamic analysis
→ trajectory and attitude motion

Aerothermal analysis
→ heating and melting

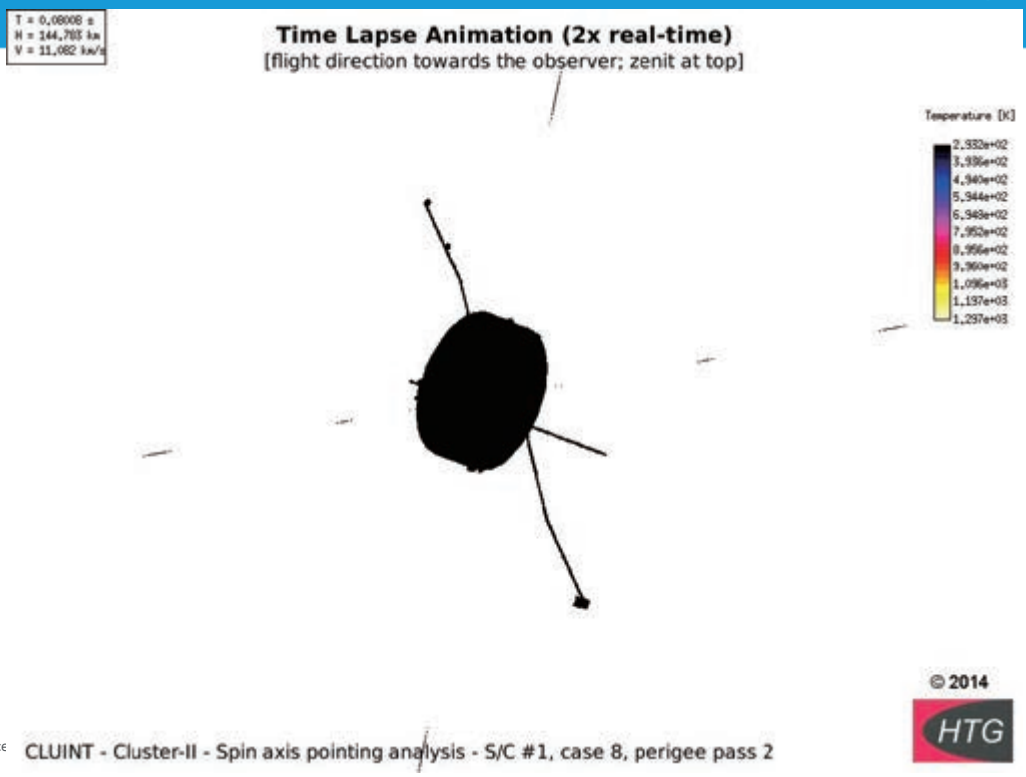
Fragmentation analysis
→ structural fracture and separation due to melting



Modelling
Cluster-II – SCARAB Model



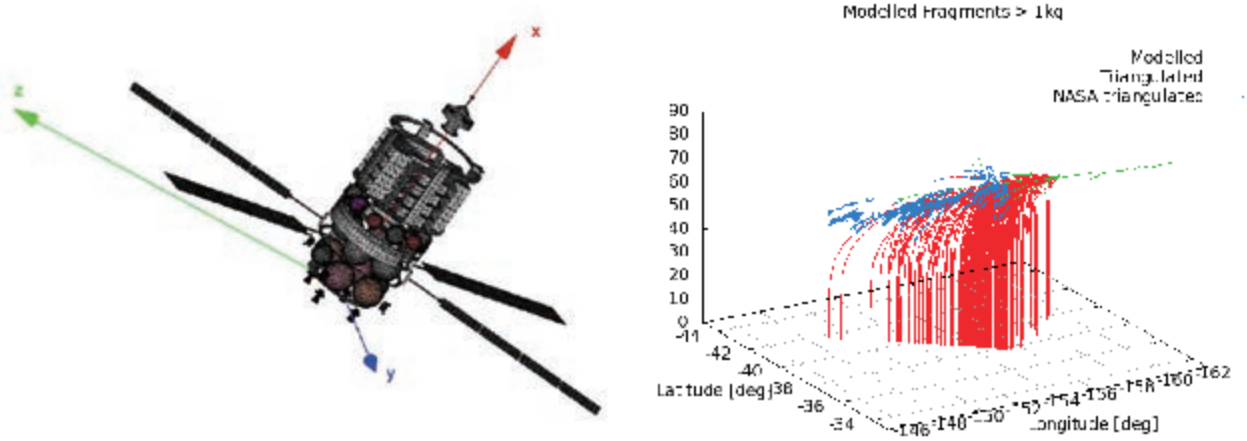
Simulation for Cluster-II Spacecraft 1



Observations of the ATV-5 Shallow Re-entry

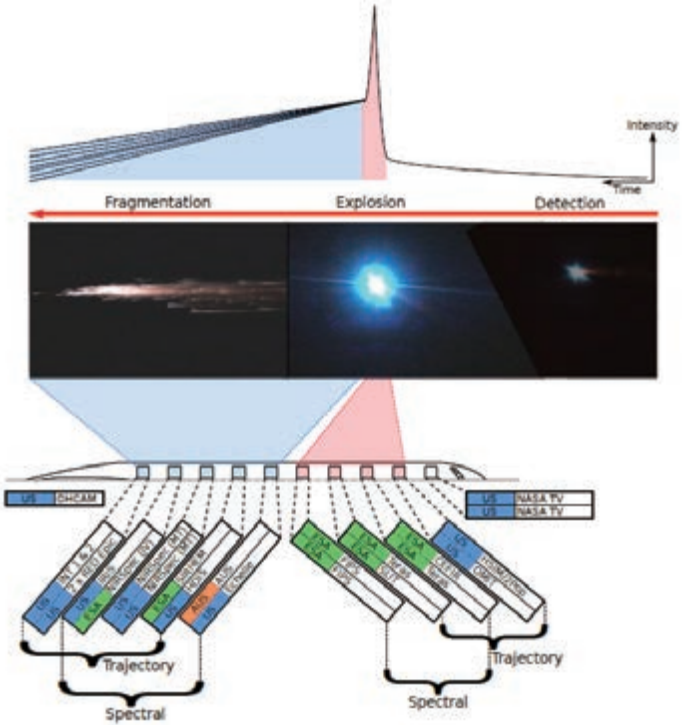
- Re-entry Trajectory: 190km x 75km (normal trajectory: 400km x 0km)

Observation results of ATV-1

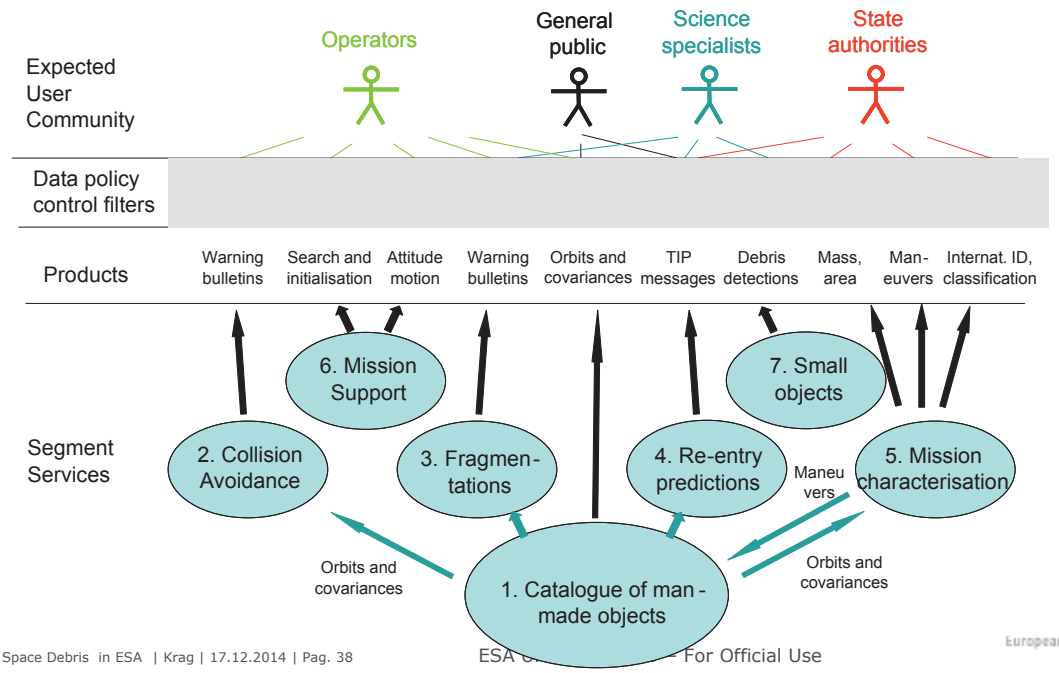


ATV: Re-entry observations (1/3)

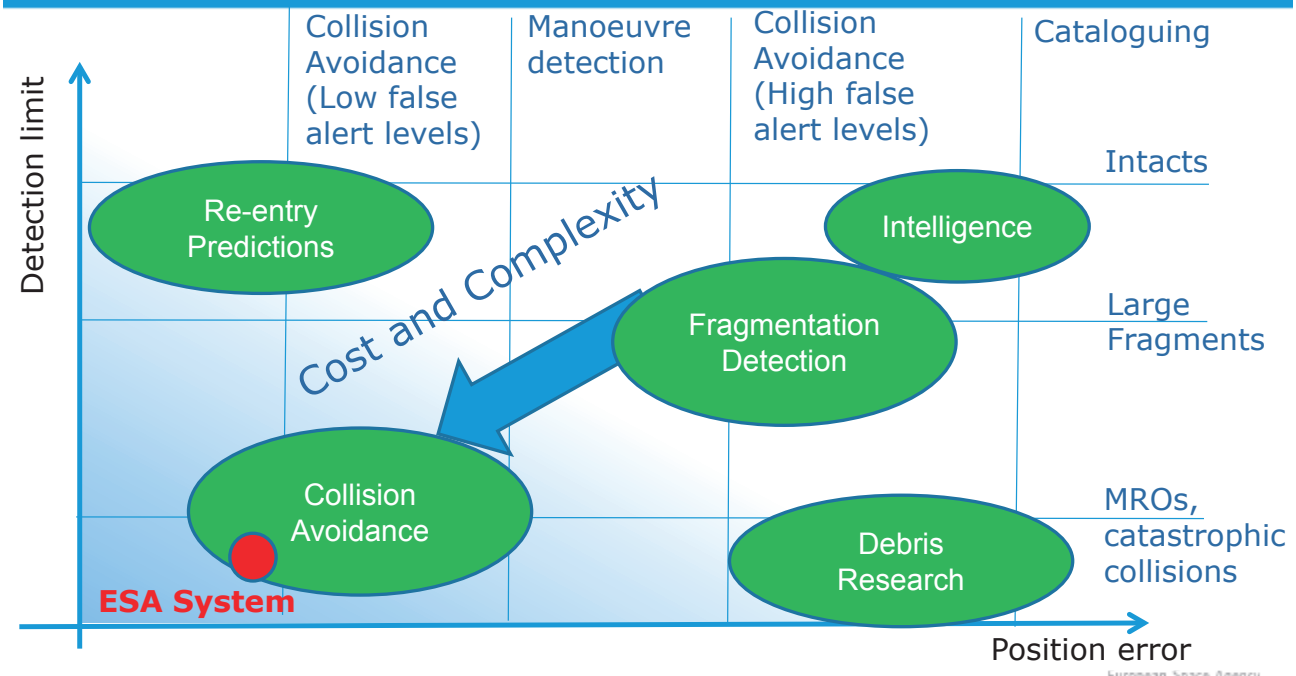
NASA DC-8 Research Aircraft



Surveillance and Tracking Services (as per ESA program)

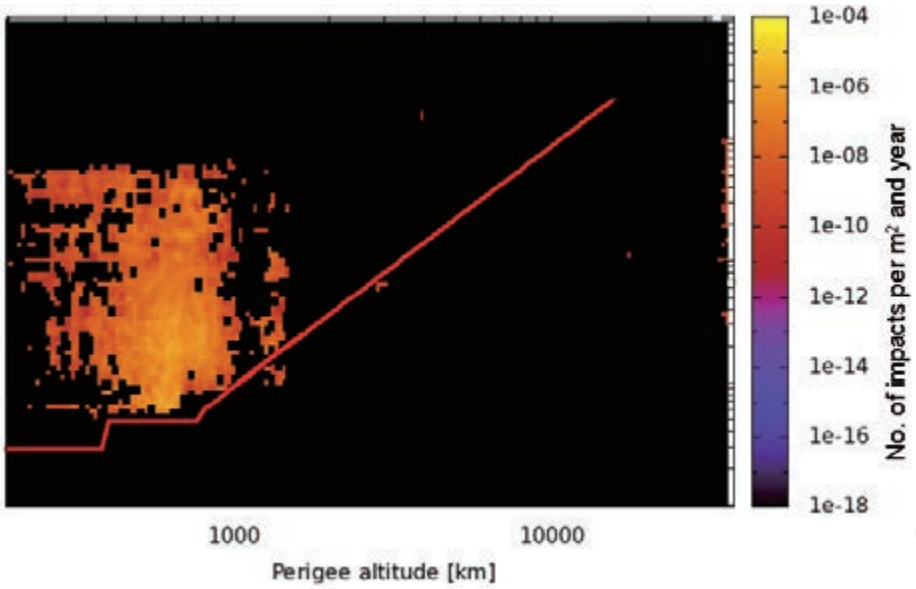


Surveillance Performance (LEO)



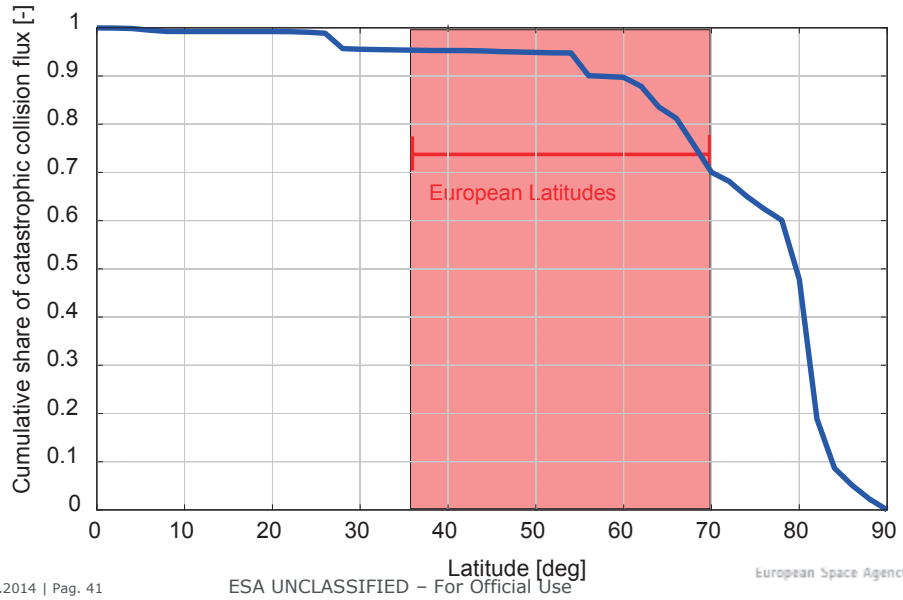
Required System Sensitivity (2/2)

- 98% coverage correspond to the follow radar performance envelope:
  - 32cm @2000km altitude, 8cm @1000km altitude



Loss due to Selected Sensor Latitude

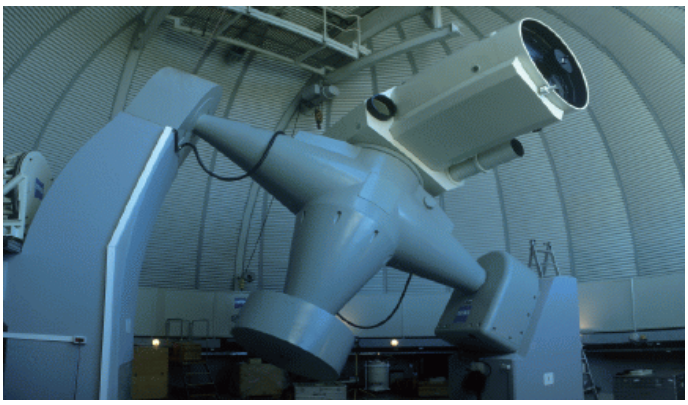
– Loss of another at least 5% due to selection of a site on European mainland



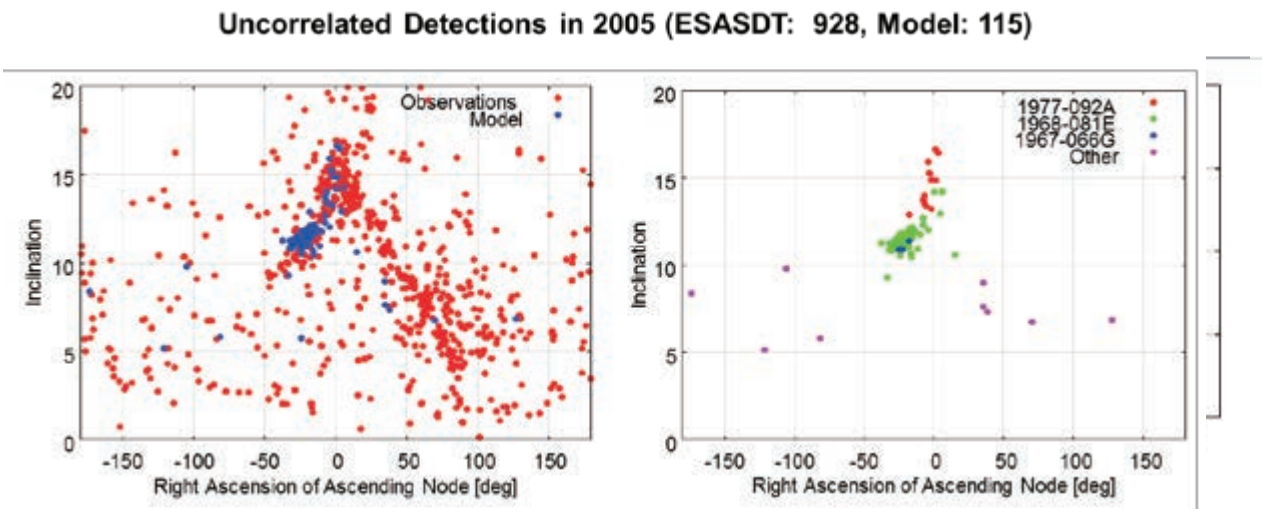
Demonstrator radar in Santorcaz (Spain)

ESA Space Debris Telescope Tenerife/Spain (EU)

- Zeiss telescope of 1m aperture and 0.7º field-of-view, Tenerife (lat = 28.17º N, long = 16.30º W)
- Detection threshold: mag 19 - 21 (~ 15 cm objects in GEO), 120º of GEO ring visible



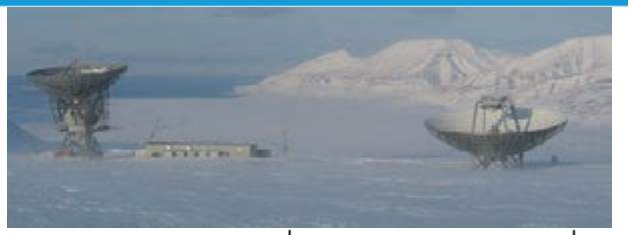
ESA Space Debris Telescope Tenerife/Spain (EU)



Beampark experiments

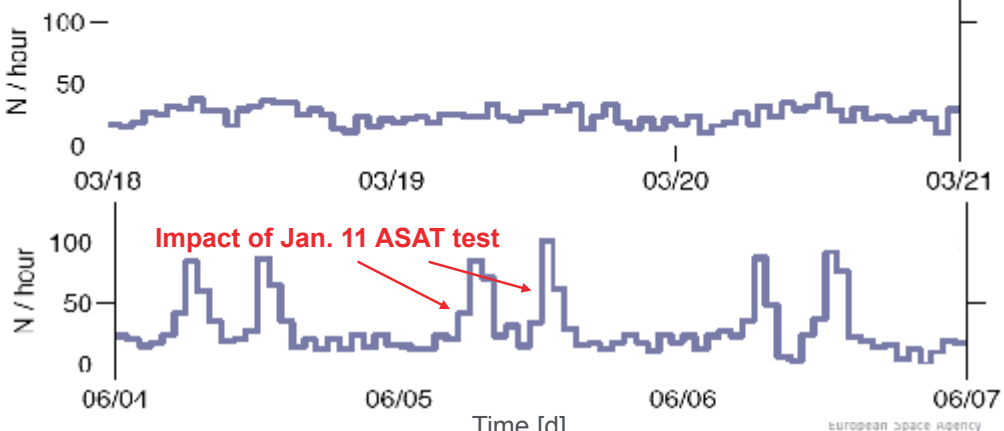
FY-1C ASAT (2/2)

EISCAT Svalbard radar (lon: 16.029° , lat: 78.153°)
(42m and 32m UHF antennas)

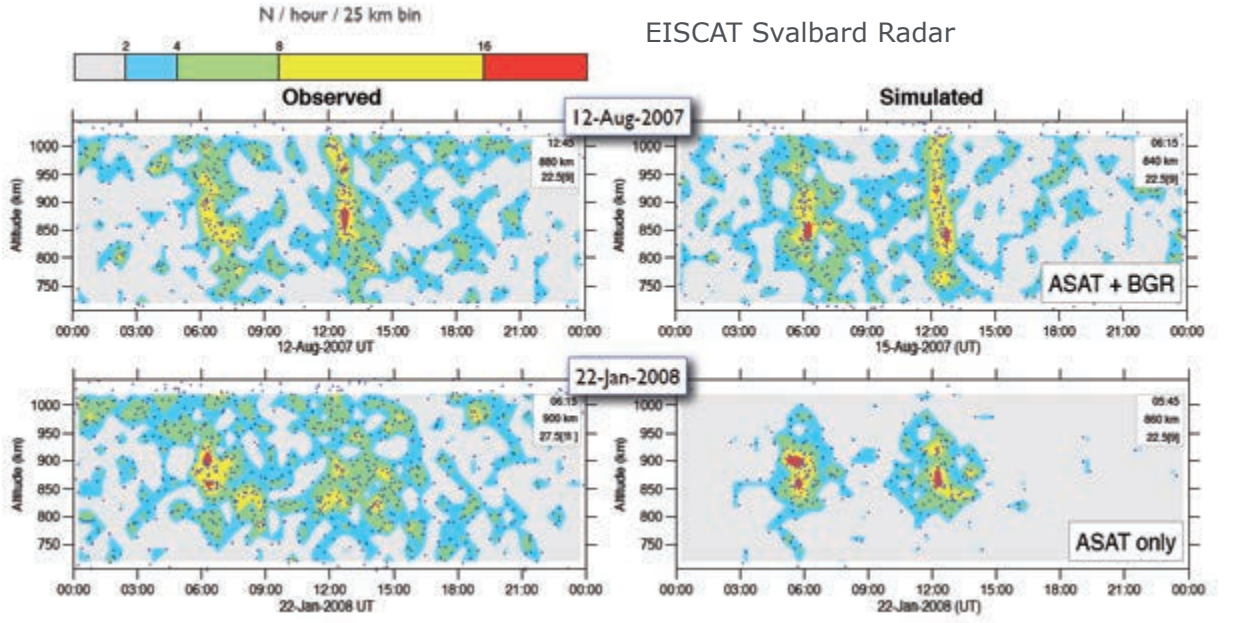


March 2006,
18th-21st

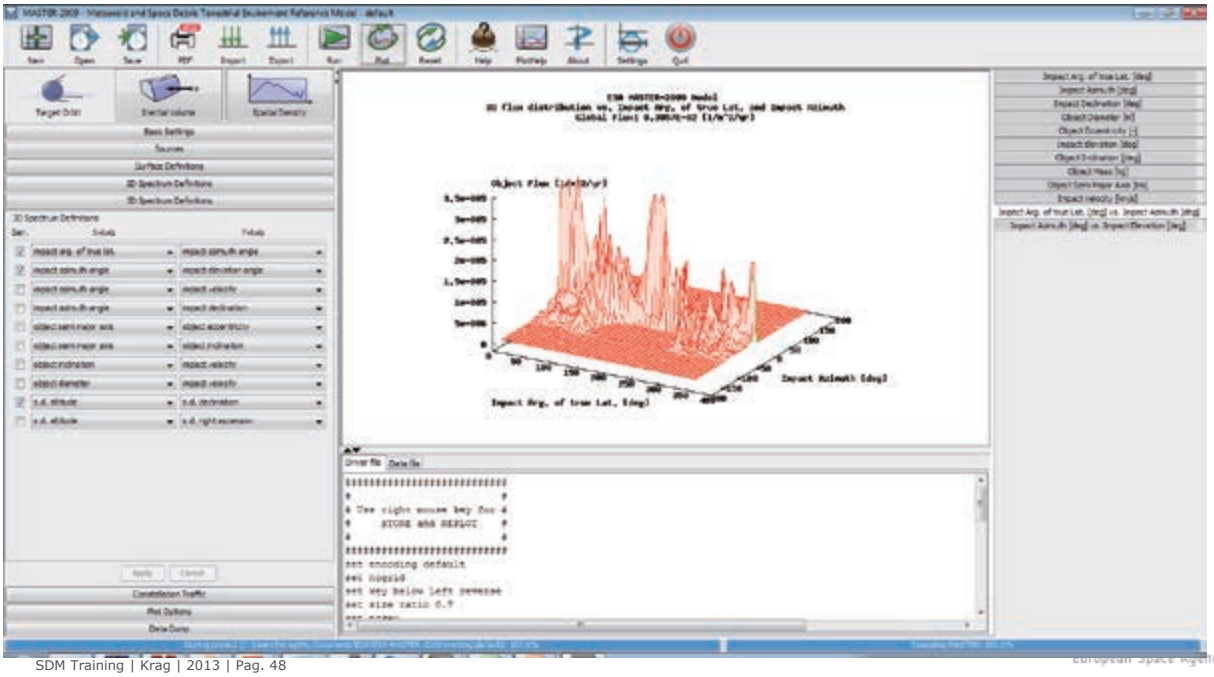
June 2007,
4th-7th



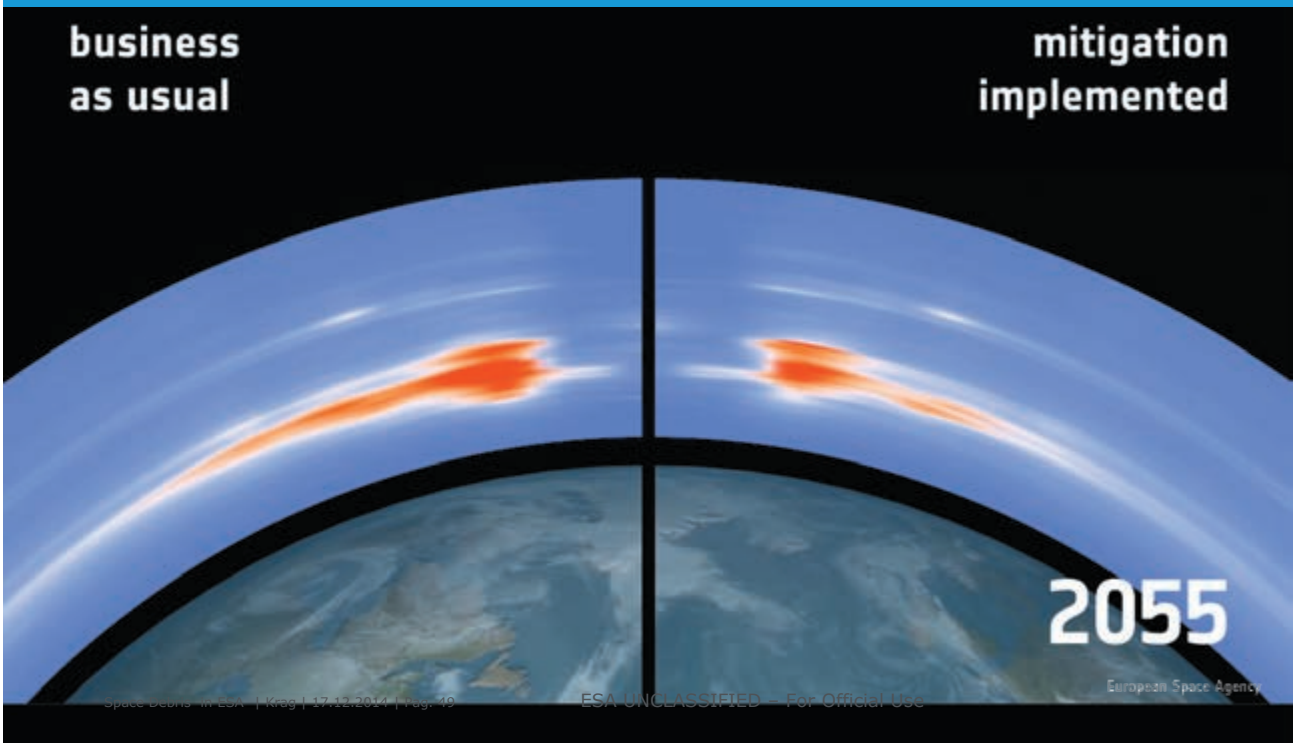
Comparison to measurements (2/2)



MASTER-2009 Application

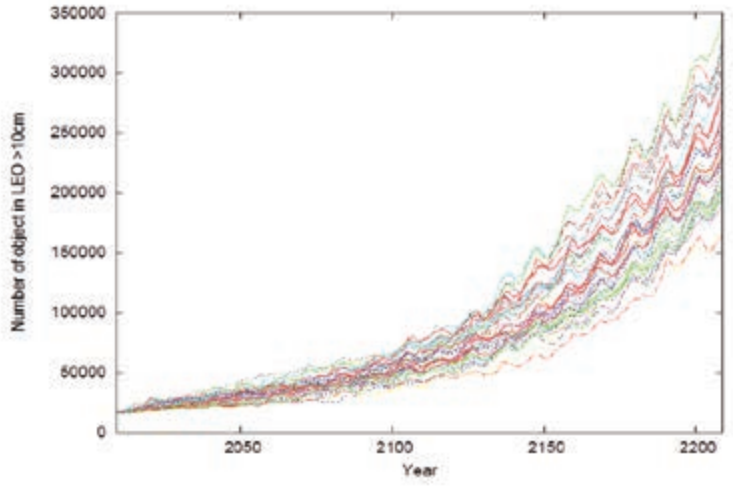


Target orbits

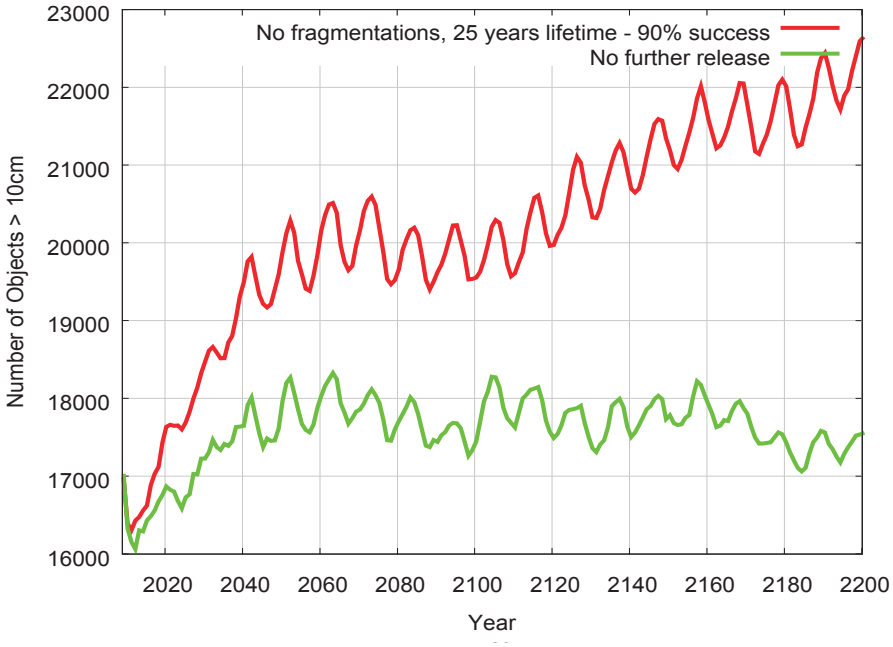


Environment Projections

- DELTA
  - Debris Environment Long-Term Analysis
  - 3-D time dependant semi-deterministic model
  - Traffic models (launch cycle of th past 8 years)
  - Debris mitigation measures
  - Simulation of environment response to active debris remova



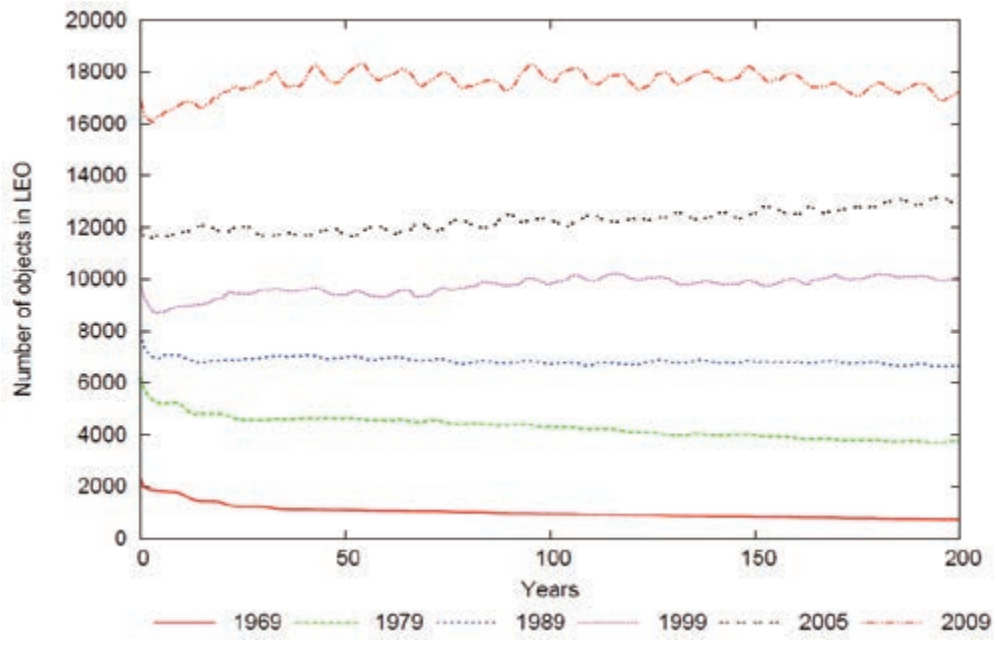
DELTA results: Future evolution of the environment



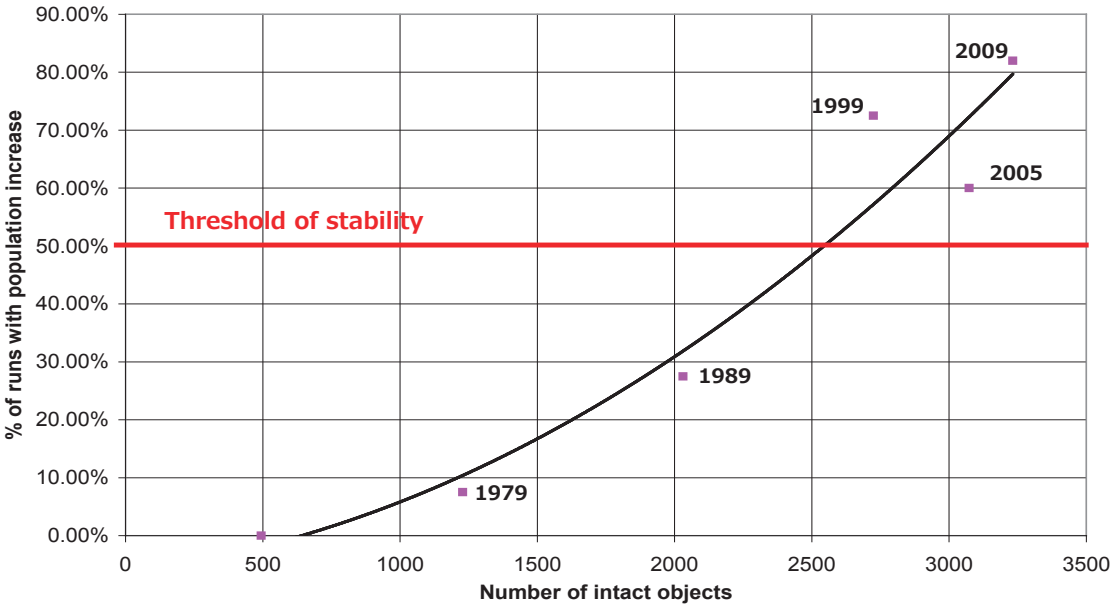
Analysis of different historical populations

No further release:

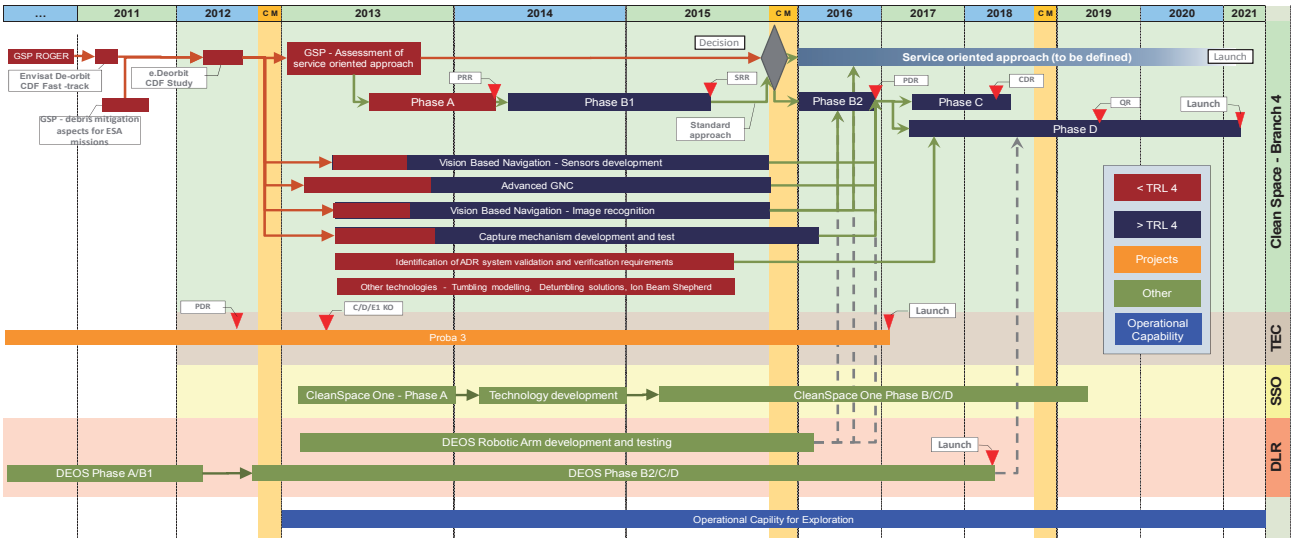
- No launches
- No explosions



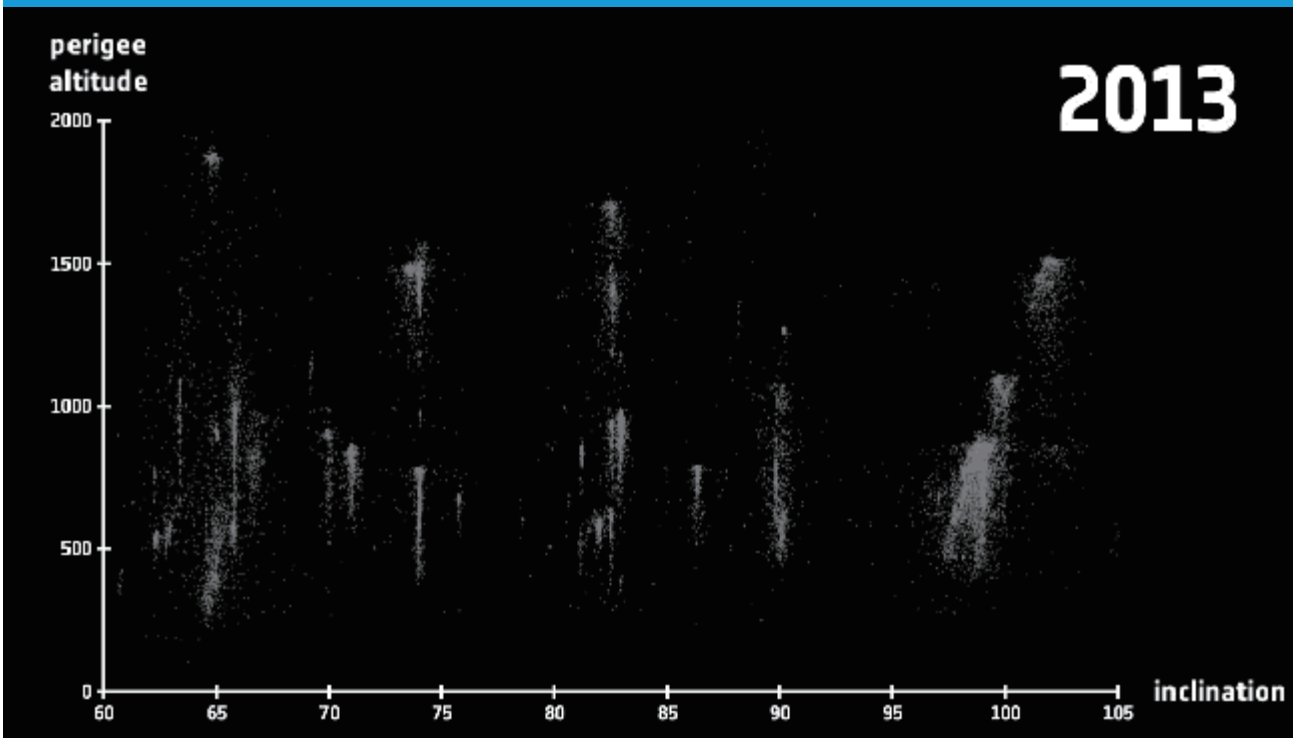
Stability of historical populations



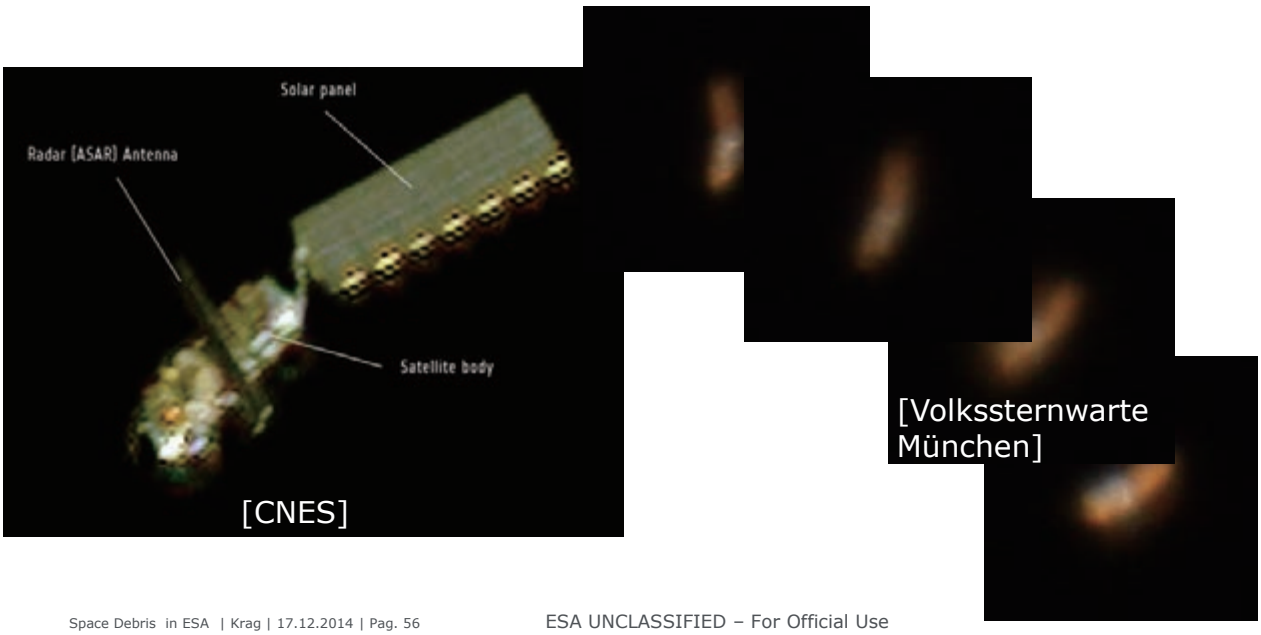
Branch 4 Space Debris Remediation
Roadmap



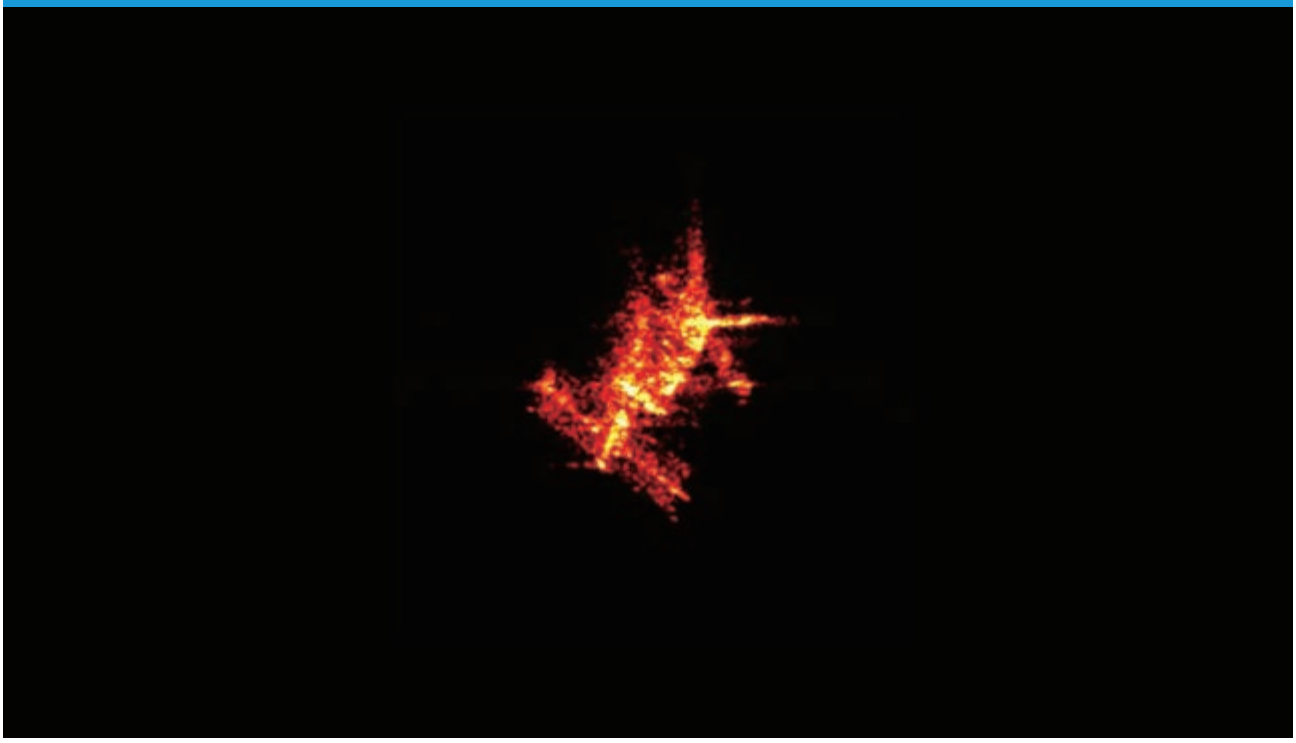
Orbital regions of interest (1/2)



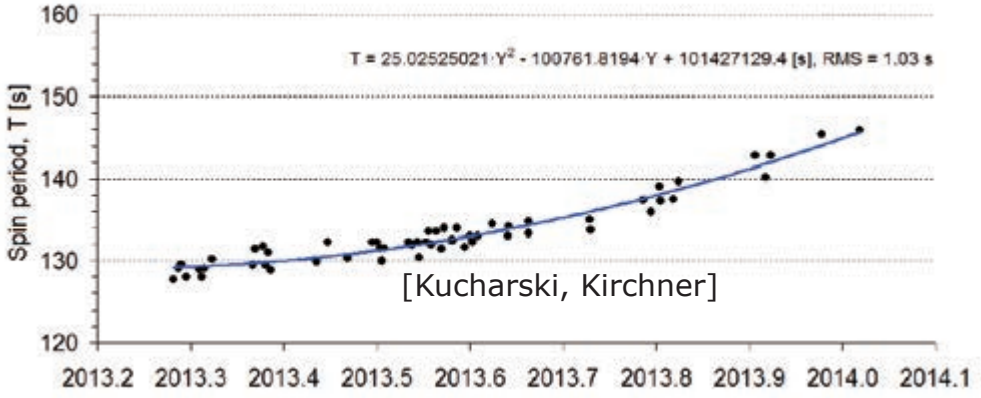
Attitude Measurements

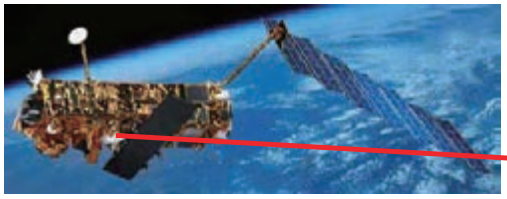


Identification of attitude motion from ground (TIRA imaging radar)



Laser Ranging for Attitude Measurements





Laser Retroreflector

Space Debris in ESA | Krag | 17.12.2014 | Pag. 58

ESA U

Capture (controlled re-entry): Robotic Arm

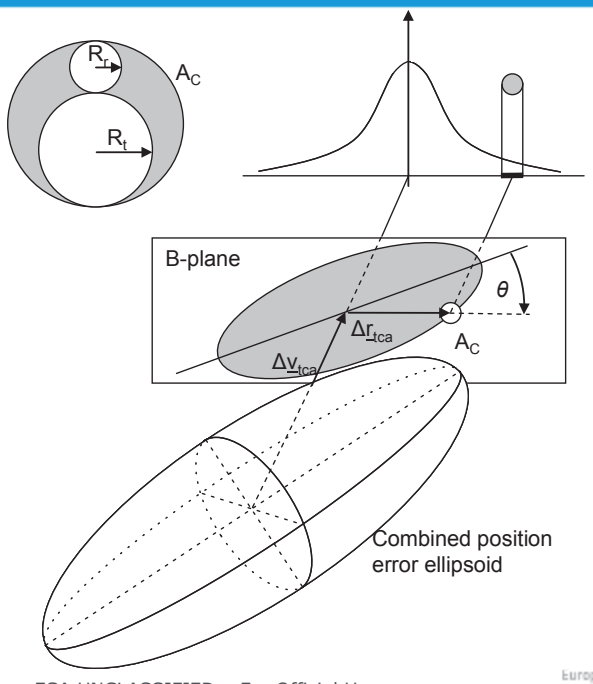
Capture (controlled re-entry): Tentacles

Capture (controlled re-entry): Net

Back-Up Slides

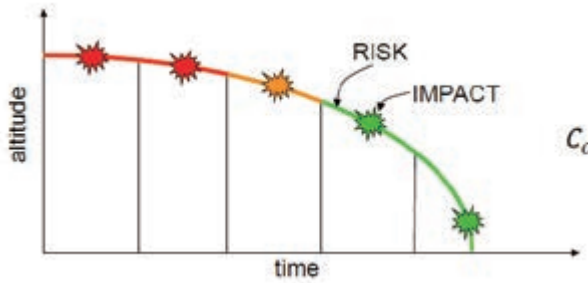
Collision Probability Algorithm

1. Determination of combined target+chaser cross section
2. Combination of the two error covariance matrices into a single one (3D ellipsoid)
3. Projection of ellipsoid onto the B-plane
   a. ∣ distance vector
   b. ⊥ relative velocity vector
4. Integration of projected probability over cross-section = collision probability



Approaches to describe criticality

ESA approach considers:
•the risk of this object to collide with other objects,
•the impact a fragmentation of this object would have on the overall population



$$C_{crit} = c_{risk} \cdot c_{impact}$$

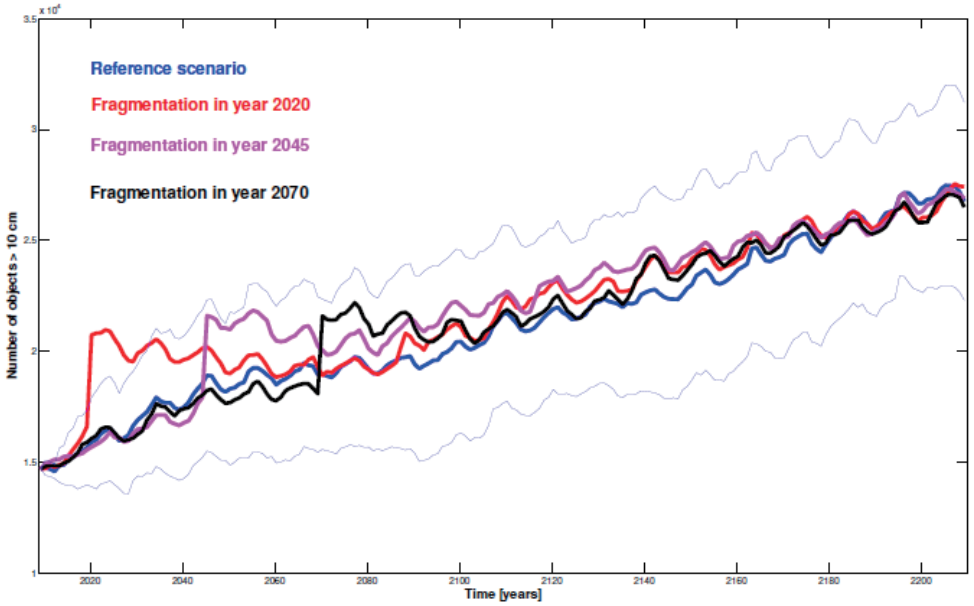
$$C_{crit} = \sum_{t=t_{start}}^{t_{end}} [c_{risk,t} \cdot \int_{\tau_{frag=t}}^{\tau_{end}=t_{end}} (\Delta p)\, d\tau]$$

Other approaches:

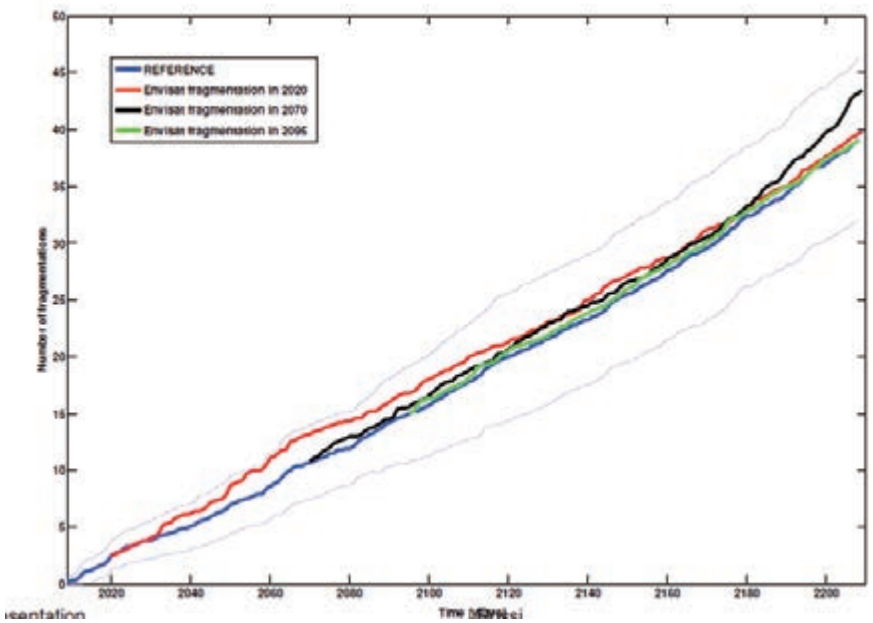
Figure-Of-Merit: FOM = flux * A * $m^{0.75}$ * ROL

- flux [1/m^2/yr]: Debris flux in the target's orbit
- A [m^2]: Geometrical cross-section area
- $m^{0.75}$ [kg]: Mass of target raised to the power of 0.75
- ROL [yrs]: Remaining orbital lifetime of the target object

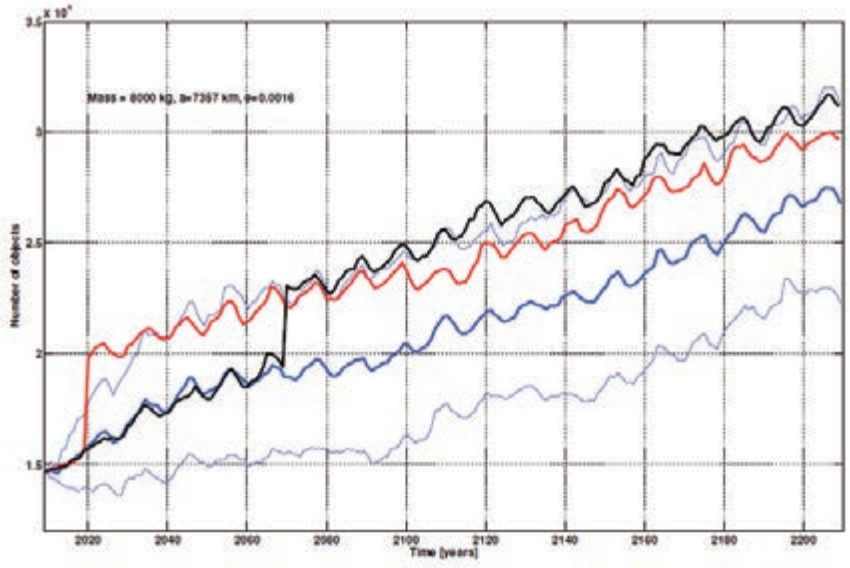
Envisat Break-Up Consequences



Envisat Break-Up Consequences



Zenith Break-Up Consequences



Technology Required for Remediation

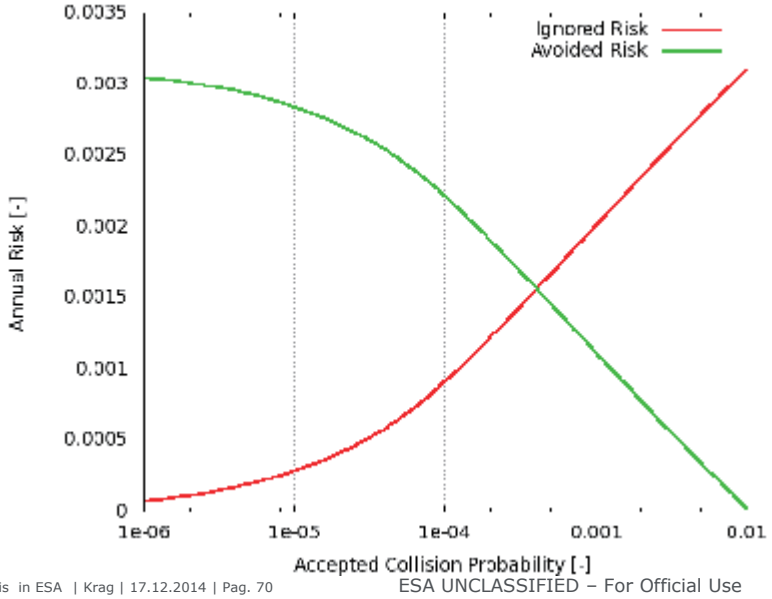
Object	Norad Designator	a [km]	e [-]	Incl [°]	-log(crit)	Changed*	
SL-16 R/B	25400	7190.04	0.001194708	98.32	0.37	↗	2
SL-16 R/B	25407	7223.23	0.000427786	71.01	0.37	↗	3
SL-16 R/B	17590	7219.87	0.001134369	71.00	0.37	↑	9
SL-16 R/B	19120	7211.76	0.001566885	71.02	0.37	↑	15
ENVISAT	27386	7148.48	0.00113031	98.40	0.43	↘	-4
METOP-A	29499	7202.59	0.001121819	98.68	0.92	↑	60
COSMOS 2360	25406	7234.58	0.000468583	70.81	0.98	↑	22
RESURS O1-N4	25394	7192.94	0.001076055	98.39	1.11	↑	17
COBE	20322	7260.29	0.001874581	99.00	1.15	↑	58
ARGOS	25634	7210.65	0.001504719	98.78	1.16	↑	34
SPOT 3	22823	7211.21	0.001397824	98.78	1.30	↑	45
ARIANE 40+ R/B	23561	7150.34	0.001092256	98.66	1.41	↑	21
ARIANE 40 R/B	25261	7164.84	0.001233803	98.39	1.41	↑	22
ARIANE 40 R/B	21610	7140.48	0.001878068	98.75	1.41	↑	46

Re-entry Removal List

OBJ. TYPE	IDYR	IDN	IDP	OWNER	OBJECT NAME	MASS [tonnes]	A-SECT. [sqm]	H_APO [km]	H_PER [km]	INC [deg]	LIFETIME [years]	10cm FLUX [1/sqm *year]	COLL. RATE [1/year]	#	Σ # %	COLL. SEVERITY [kg/year]	#	Σ # %	COLL. CONSE-QUENCES [kg]	#	Σ # %
DC	2002	9	A	ESA	Envisat	8111	63.0467	786.039878	783.403991	98.5491	223.3147	2.22E-05	1.40E-03	1	100%	1.14E+01	1	100%	2.54E+03	20	46%
RB	1998	51	B	RU	Zenit-2 second stage	8226.97	33.4262	842.420994	839.496076	70.9916	747.3423	1.96E-05	6.61E-04	6	46%	5.36E+00	2	47%	4.02E+03	2	73%
RB	1999	43	G	RU	Zenit-2 second stage	8226.97	33.4262	818.783209	800.410411	99.33	474.4788	1.91E-05	6.37E-04	5	46%	5.24E+00	3	46%	2.49E+03	21	48%
RB	2002	6	B	RU	Zenit-2 second stage	8226.97	36.1642	854.645796	838.434309	70.9966	896.0166	1.79E-05	6.31E-04	7	46%	5.13E+00	4	46%	3.61E+03	5	66%
RB	1998	48	B	RU	Zenit-2 second stage	8226.97	33.4262	844.917217	836.303482	71.2115	714.9631	1.84E-05	6.18E-04	8	44%	5.06E+00	5	44%	3.62E+03	4	66%
RB	1988	102	B	SU	Zenit-2 second stage	8226.97	33.4262	849.612987	831.452151	70.9988	687.7599	1.83E-05	6.11E-04	9	44%	5.02E+00	6	44%	3.45E+03	11	63%
RB	1994	77	B	RU	Zenit-2 second stage	8226.97	33.4262	844.92155	840.094128	70.9764	775.0091	1.83E-05	6.10E-04	10	43%	5.02E+00	7	44%	3.56E+03	3	70%
RB	1995	55	B	RU	Zenit-2 second stage	8226.97	33.4262	852.096752	833.413696	71.021	764.5923	1.80E-05	6.00E-04	11	43%	4.94E+00	8	43%	3.45E+03	9	63%
RB	1990	46	B	SU	Zenit-2 second stage	8226.97	33.4262	866.30672	833.433179	70.998	896.8942	1.77E-05	5.92E-04	12	42%	4.87E+00	9	43%	3.39E+03	12	61%
RB	1988	39	B	SU	Zenit-2 second stage	8226.97	33.4262	843.661263	814.700526	71.0124	571.8422	1.72E-05	5.74E-04	14	41%	4.72E+00	10	42%	2.70E+03	19	49%
RB	1987	41	B	SU	Zenit-2 second stage	8226.97	33.4262	847.175881	824.376581	71.0072	662.6458	1.71E-05	5.70E-04	15	41%	4.69E+00	11	41%	3.10E+03	15	56%
RB	1987	37	B	SU	Zenit-2 second stage	8226.97	33.4262	841.455573	833.068617	71.0005	703.5773	1.70E-05	5.69E-04	16	41%	4.68E+00	12	41%	3.29E+03	13	60%
RB	1985	97	B	SU	Zenit-2 second stage	8226.97	33.4262	845.625457	832.419493	71.002	694.0896	1.70E-05	5.67E-04	17	40%	4.66E+00	13	41%	3.24E+03	16	59%
RB	1984	23	B	RU	Zenit-2 second stage	8226.97	33.4262	847.186476	841.033119	70.9968	766.6691	1.68E-05	5.62E-04	18	40%	4.62E+00	14	41%	3.54E+03	7	64%
RB	1992	93	B	RU	Zenit-2 second stage	8226.97	33.4262	848.489199	838.883473	71.0301	784.1832	1.67E-05	5.59E-04	19	40%	4.60E+00	15	40%	3.47E+03	10	63%
RB	1983	16	B	RU	Zenit-2 second stage	8226.97	33.4262	850.911879	838.984396	71.0102	709.1643	1.67E-05	5.58E-04	20	40%	4.60E+00	16	40%	3.26E+03	14	59%
RB	1993	59	B	RU	Zenit-2 second stage	8226.97	33.4262	850.780307	823.336878	70.9912	692.0008	1.68E-05	5.61E-04	21	39%	4.63E+00	17	40%	2.95E+03	18	54%
RB	1982	76	B	RU	Zenit-2 second stage	8226.97	33.4262	847.383131	829.386908	70.9987	666.8037	1.63E-05	5.44E-04	22	39%	4.48E+00	18	39%	3.07E+03	17	56%
RB	2007	29	B	SU	Zenit-2 second stage	8226.97	36.1642	847.014601	843.987898	70.979	926.0499	1.49E-05	5.24E-04	23	37%	4.31E+00	19	39%	3.56E+03	6	66%
RB	2004	21	B	RU	Zenit-2 second stage	8226.97	36.1642	848.49523	843.344478	71.0029	816.1111	1.48E-05	5.20E-04	24	37%	4.28E+00	20	39%	3.49E+03	8	63%
DC	2002	56	A	JP	MIDORI-2 (ADEOS 2)	3650	60	805.17955	803.615067	98.6223	205.1914	1.90E-05	1.14E-03	2	51%	4.20E+00	21	37%	5.61E+02	22	16%
RB	2001	56	F	RU	Zenit-2 second stage	8226.97	36.1642	1007.91194	995.423199	99.1949	1535.8615	1.94E-05	3.89E-04	25	28%	3.00E+00	22	28%	5.51E+03	1	100%
DC	2006	44	A	EUM	METOP-A	4085	34.2012	820.953254	819.591237	98.67	274.6389	1.93E-05	6.60E-04	3	47%	2.70E+00	23	34%	7.41E+02	23	13%
RB	1999	39	B	RU	Zenit-2 second stage	8226.97	33.4262	850.40694	829.364118	97.7447	78.213	9.71E-06	3.26E-04	26	23%	2.67E+00	24	23%	2.09E+02	26	4%
RB	2002	56	E	JP	H-2A second stage	4000	31.4276	841.45484	736.903416	98.558	121.9933	2.29E-05	6.58E-04	4	47%	2.63E+00	25	23%	3.21E+02	24	6%
RB	1994	74	B	RU	Zenit-2 second stage	8226.97	33.4262	849.680283	840.304433	98.0807	88.798	9.67E-06	3.20E-04	27	23%	2.63E+00	26	23%	2.34E+02	25	4%
DC	2006	2	A	JP	DAICHI	4000	31.7611	698.469766	693.623784	98.1519	43.6674	1.13E-05	3.87E-04	13	42%	2.36E+00	27	21%	1.49E+02	27	3%

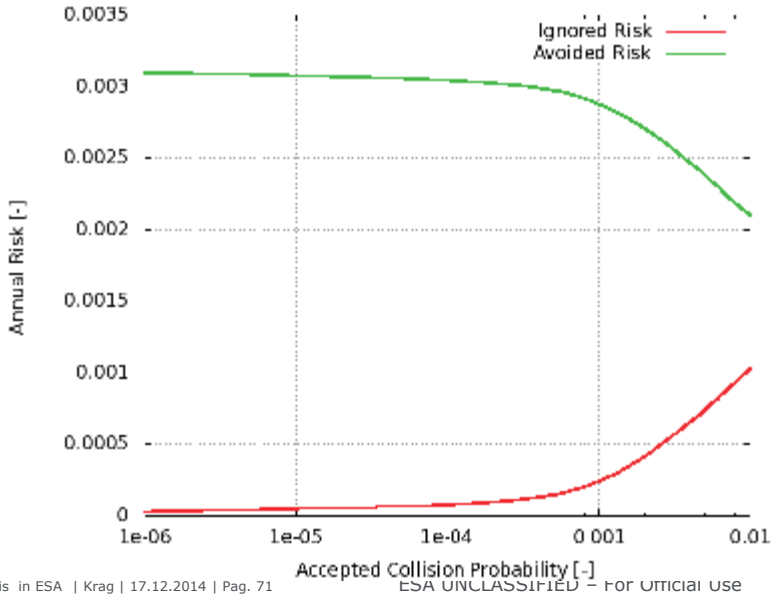
Situation before CSM

- Example: Envisat: 26m span, 8t mass, initial covariance ca. 10m x 56m x 14m
- TLE screening (initial chaser covariance ca. 225m x 750m x 195m)



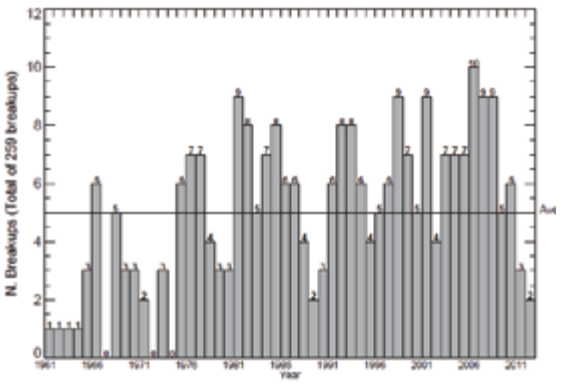
Situation with the new CSM

- Example: Envisat: 26m span, 8t mass, initial covariance ca. 10m x 56m x 14m
- JSPOC screening (CSM chaser initial covariance ca. 23m x 75m x 20m)

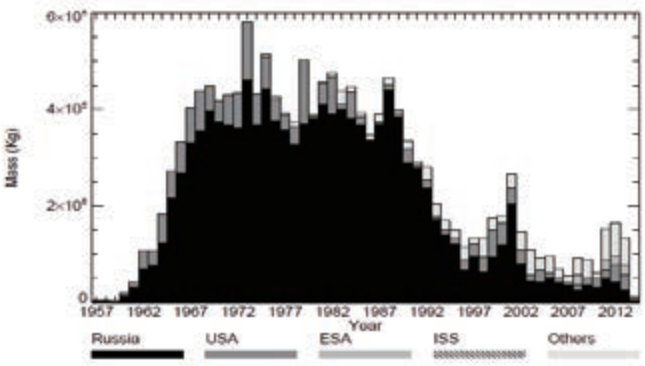


Analyses with DISCOS

Number of events per year

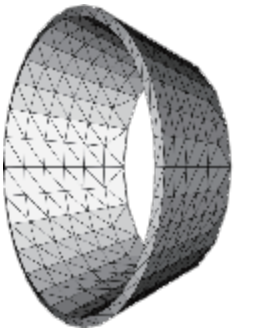


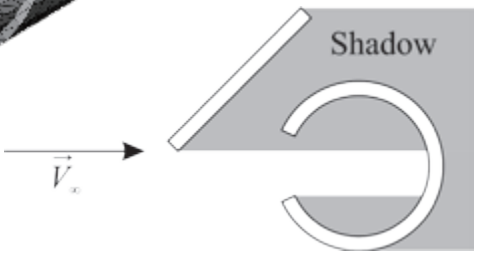
Re-entering mass per year (uncontrolled)

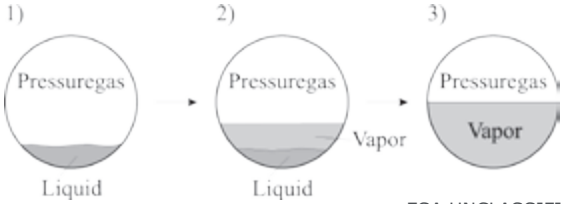


SCARAB modelling principles

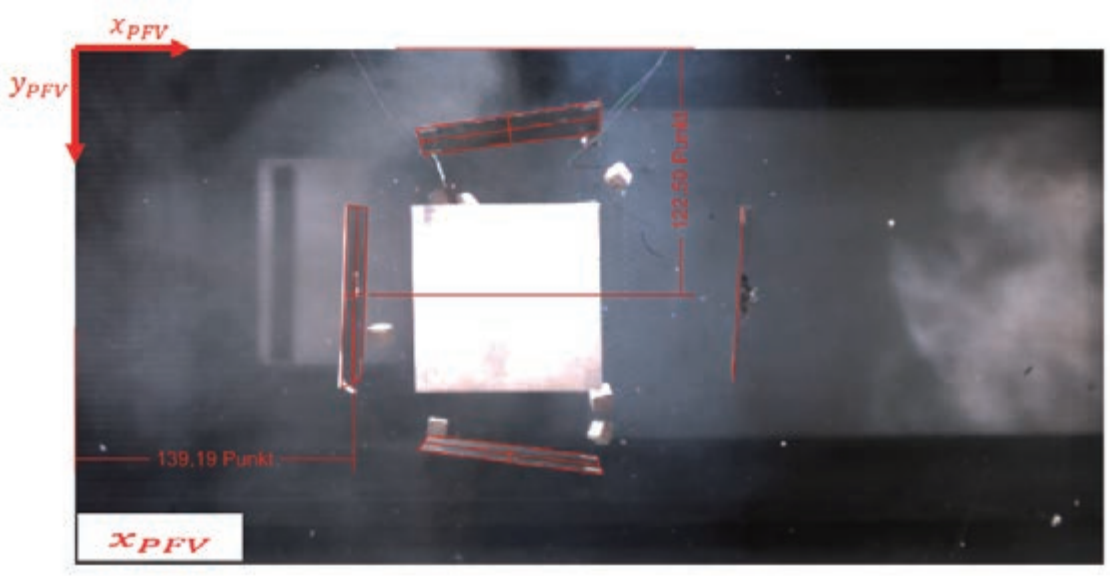
- Model built from “primitive shapes”
- Modelling approachare subject to a shadow analysis based on geometric area projections in flow direction.
- No flow expansion behind shadowing panels (Ma∞, S∞ → ∞)
- Tank bursting analysis



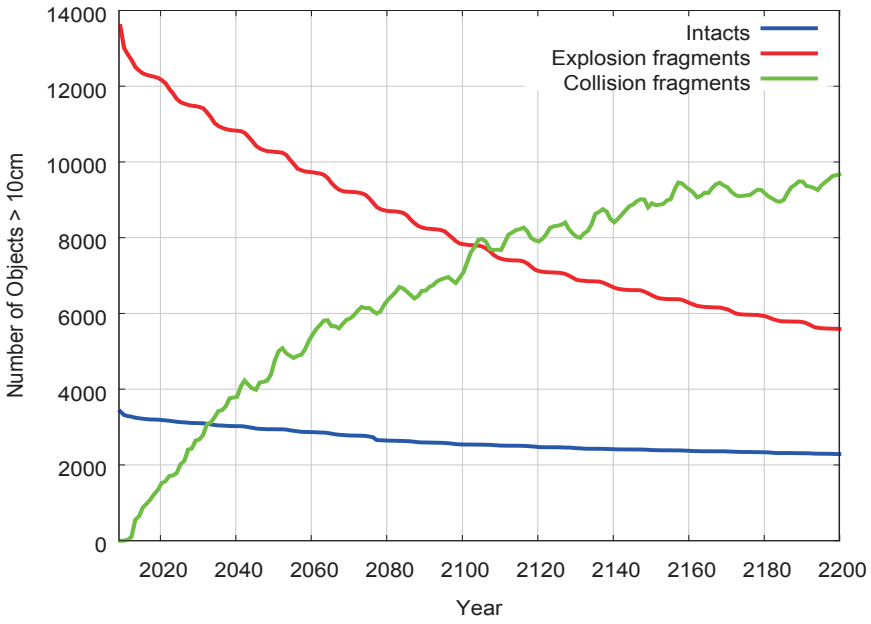




Understanding catastrophic break-up



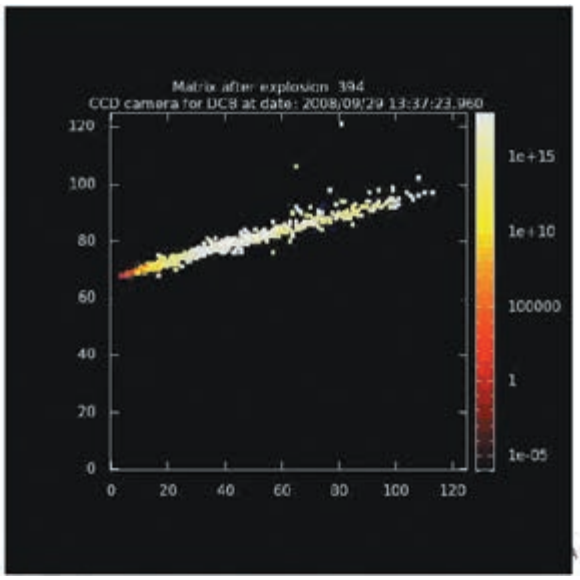
No further release scenario



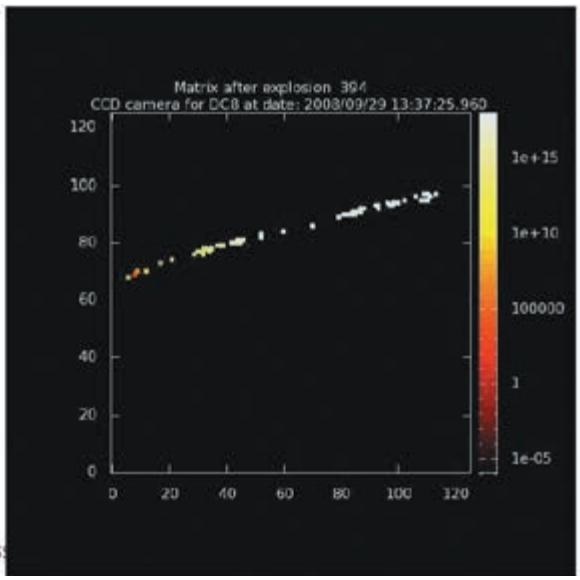
ATV-1 DC-8: different fragmentation model

DC8 airplane, Camera mounting: AZ=100deg, El=0deg.
Camera properties: FOV=40deg, Lpix=0.02mm, D=0.3m, Npix=125
Solar panel break-off altitude = 95km. Explosion altitude = 78km.

Evolve Model



ACTA Model



Latest Envisat ISAR observation