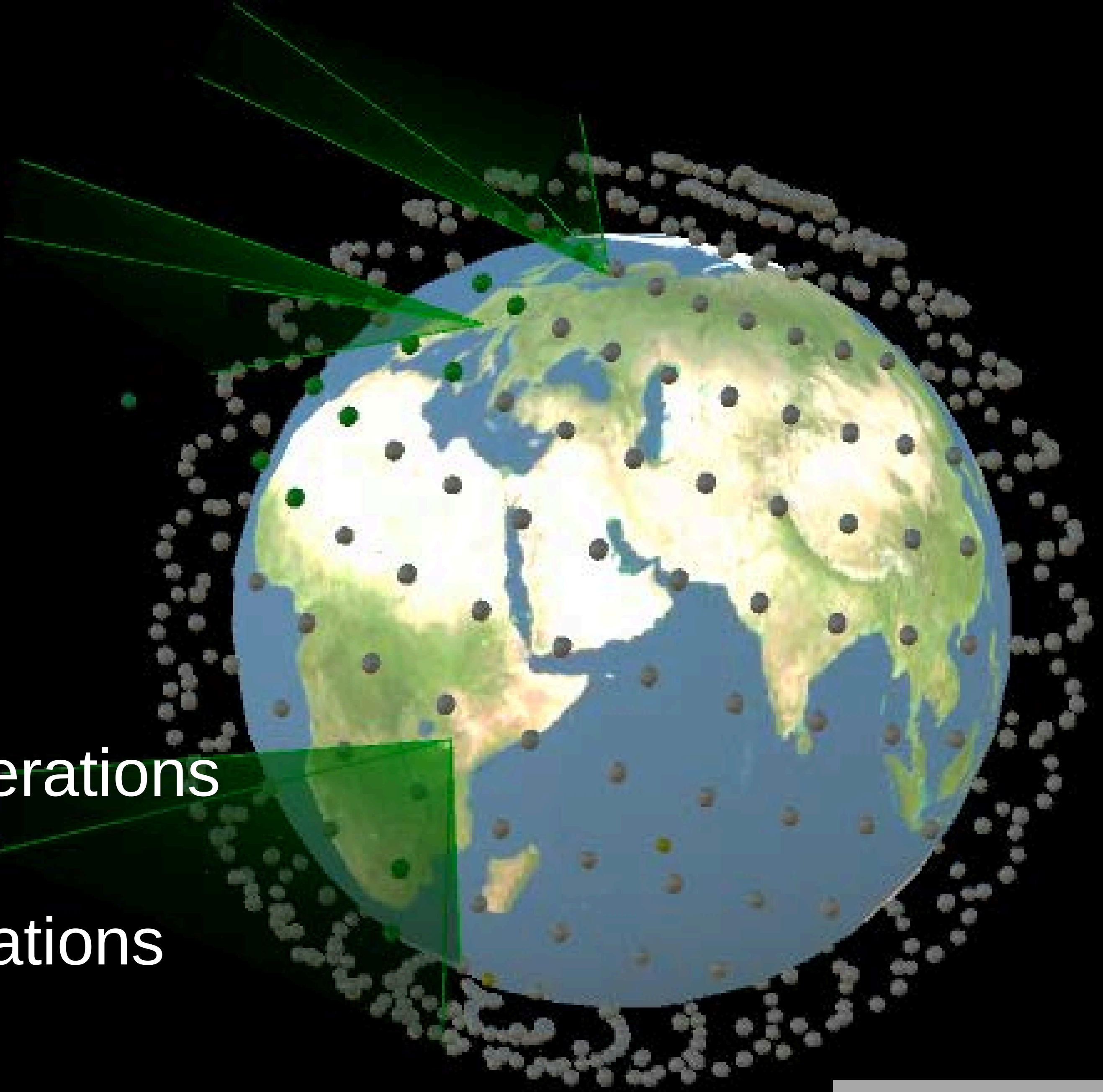


End of Life Operations for Disposal of Mega-Constellations

Final Presentation

ESTEC, 27 February 2018

AIRBUS

Technische Universität Braunschweig
Institute of Space Systems

EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Outline

- Introductory Presentation
  - Background
  - Main Objectives of the Activity
  - Consortium Presentation & Project Organisation
  - WBS
  - Work Logic

- Synopsis of Study Results
  - Work Package Presentations
  - Summary

Introductory Presentation

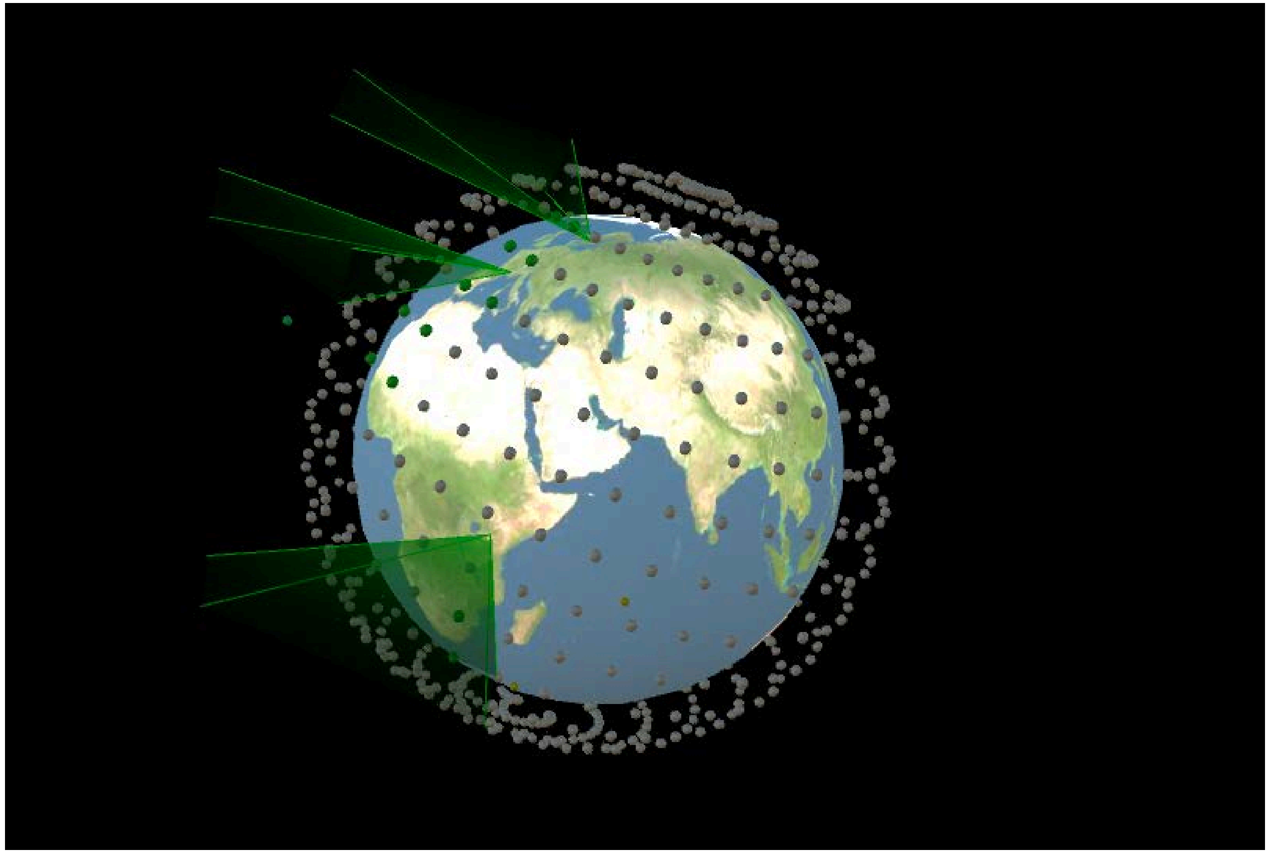
Jens Utzmann – Airbus DS

Background

Recent mega-constellation concepts share critical issues w.r.t. their possible impact on the space debris environment, e.g.:

- **Large number of S/C** (significant combined mass) deployed to **high altitudes** (atmospheric decay very limited), collisions or self-induced fragmentation **will lead to long-lived debris**.
- **Mostly polar inclinations** where even under nominal conditions satellites of adjacent orbit planes might **come as close as few tens or hundreds of kilometres**.
- Large number of spacecraft, combined with **typical reliability figures → unneglectable number of S/C which fail** to reach their planned lifetime.
- **During orbit raising and orbit lowering the spacecraft traverse different orbital regimes** - in some cases a large number of satellites at a time

In order to cope with these issues **new technologies as well as new manufacturing, testing, and operational procedures need to be developed**.



Main Objectives of the Activity

The objective of this activity is to understand the operational complexity of large mega-constellation systems, and the potential needs to operate these, including the complexity of the collision avoidance manoeuvres (CAMS).

This can be achieved by:

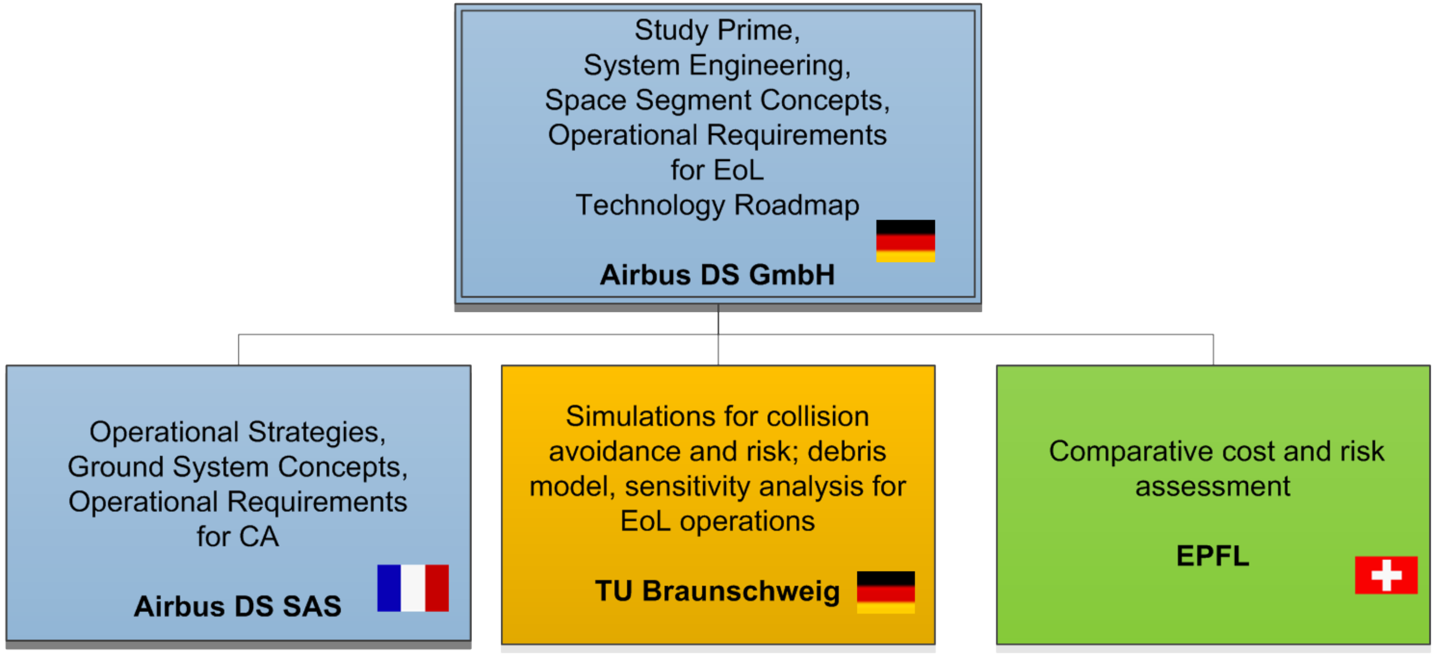
- **Assessing different EoL strategies** for mega-constellations of the size and complexity as foreseen for the future telecommunication mega-constellations.
- **Analysing the implications on space and ground segment design** to support execution of End of Life activities for each of the strategies identified (from the previous bullet) comparing the different ground and spacecraft conceptual architectures.
- **Analyse the execution of both debris and inter-satellite CAMs** during LEOP, orbit raising, routine phases and orbit lowering for mega-constellations.
- **Derive system and operational requirements on mega-constellations for End of Life activities** (EoL) and Space Debris mitigation.
- **Establish a baseline scenario for an operational concept** to handle Space Debris Mitigation for mega-constellations.

Consortium Presentation

Airbus DS (GmbH and SAS): Prime for Security in Space, operational experience in flight dynamics and Collision Avoidance

TU Braunschweig: Leading experts in space debris modelling and simulation frameworks

EPFL: Experts in space debris - related risks management and debris removal concepts



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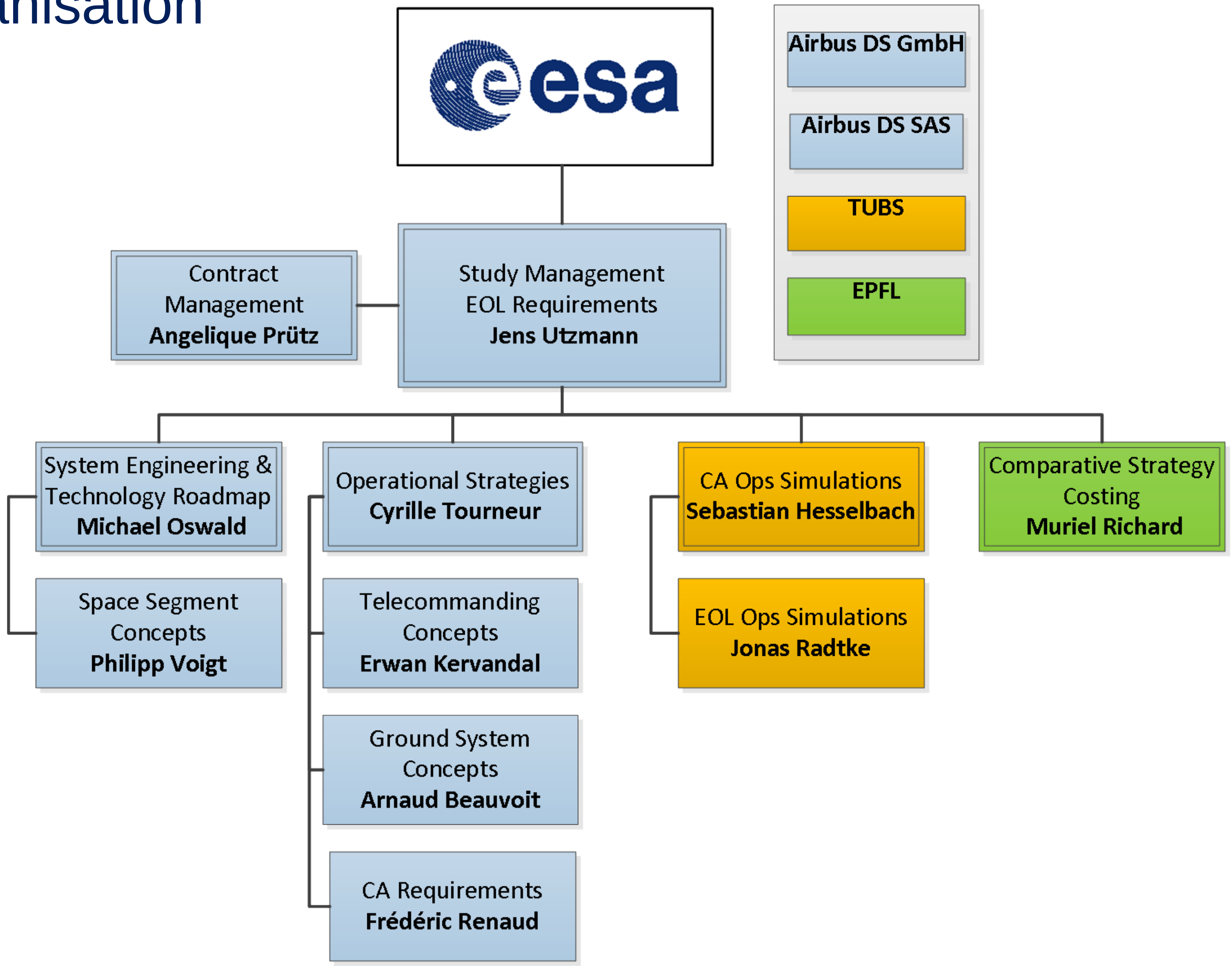
Project Organisation



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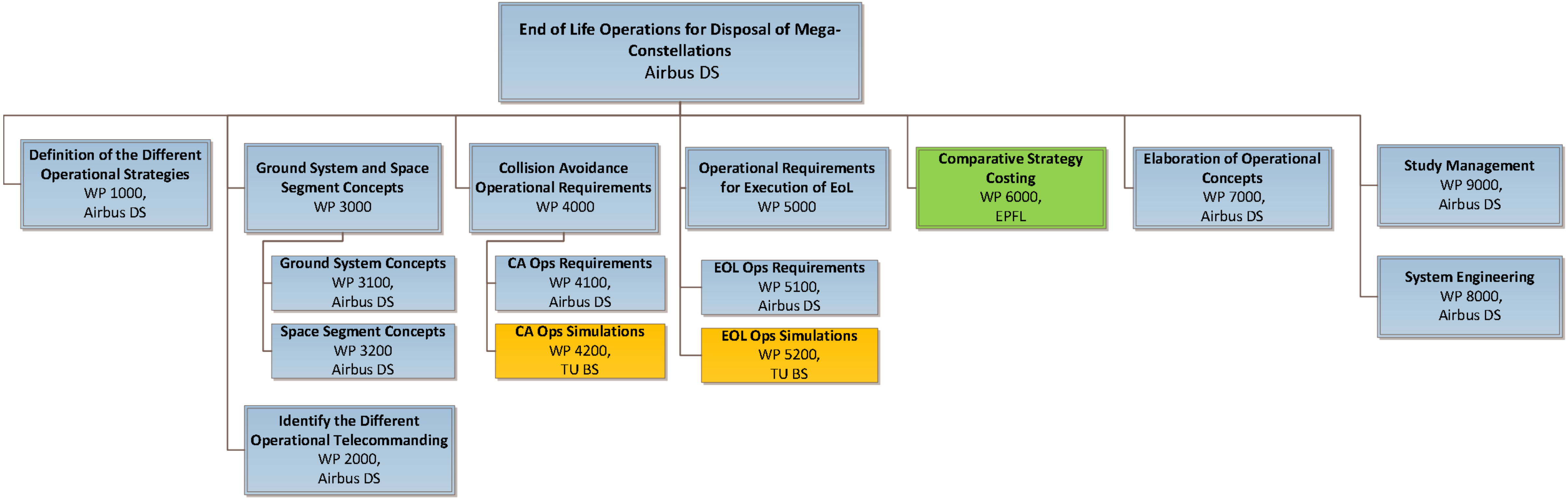
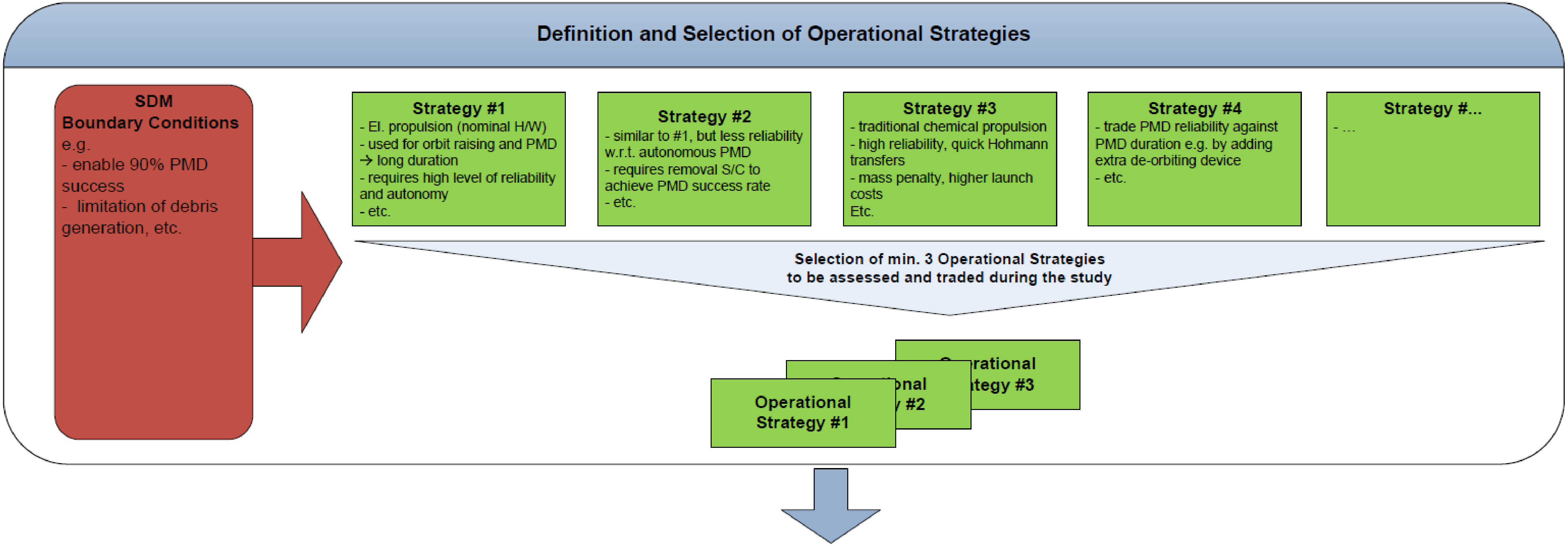
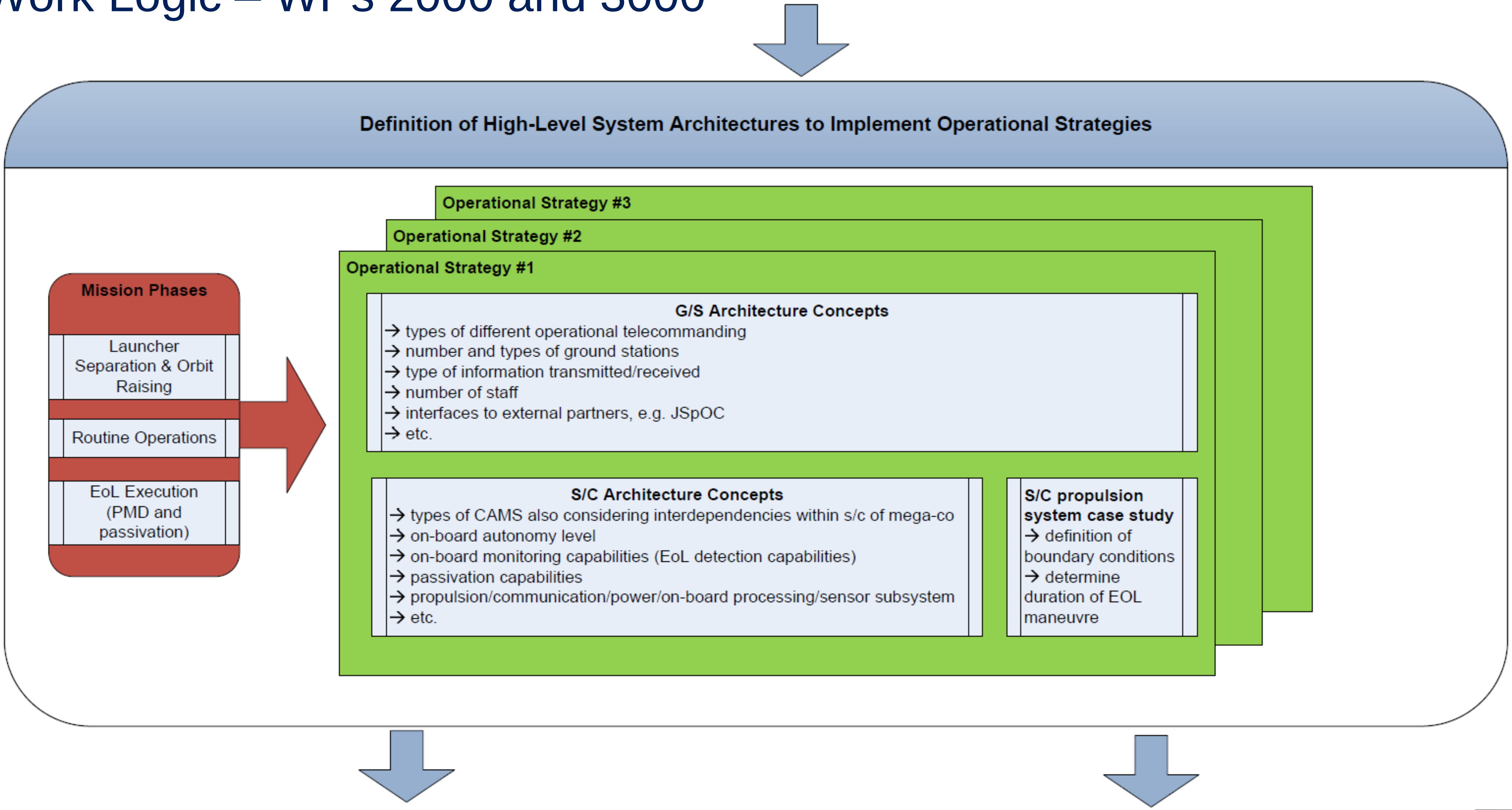
WBS


End of Life Operations for Disposal of Mega-Constellations
Airbus DS
Definition of the Different Operational Strategies
WP 1000,
Airbus DS
Ground System and Space Segment Concepts
WP 3000
Ground System Concepts
WP 3100,
Airbus DS
Space Segment Concepts
WP 3200
Airbus DS
Identify the Different Operational Telecommanding
WP 2000,
Airbus DS
Collision Avoidance Operational Requirements
WP 4000
CA Ops Requirements
WP 4100,
Airbus DS
CA Ops Simulations
WP 4200,
TU BS
Operational Requirements for Execution of EoL
WP 5000
EOL Ops Requirements
WP 5100,
Airbus DS
EOL Ops Simulations
WP 5200,
TU BS
Comparative Strategy Costing
WP 6000,
EPFL
Elaboration of Operational Concepts
WP 7000,
Airbus DS
Study Management
WP 9000,
Airbus DS
System Engineering
WP 8000,
Airbus DS

Work Logic – WP 1000



Work Logic – WPs 2000 and 3000



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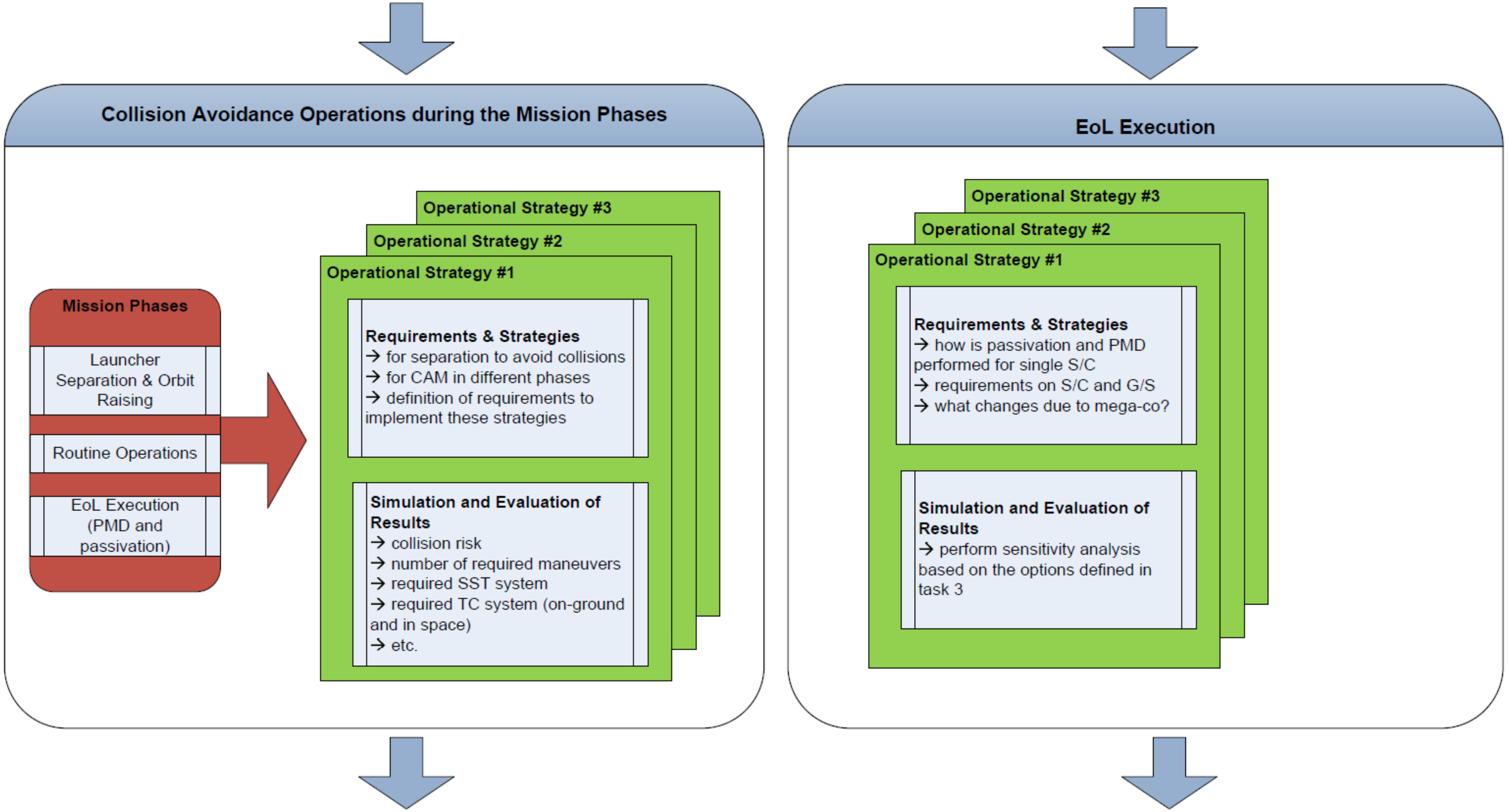
Work Logic – WPs 4000 and 5000



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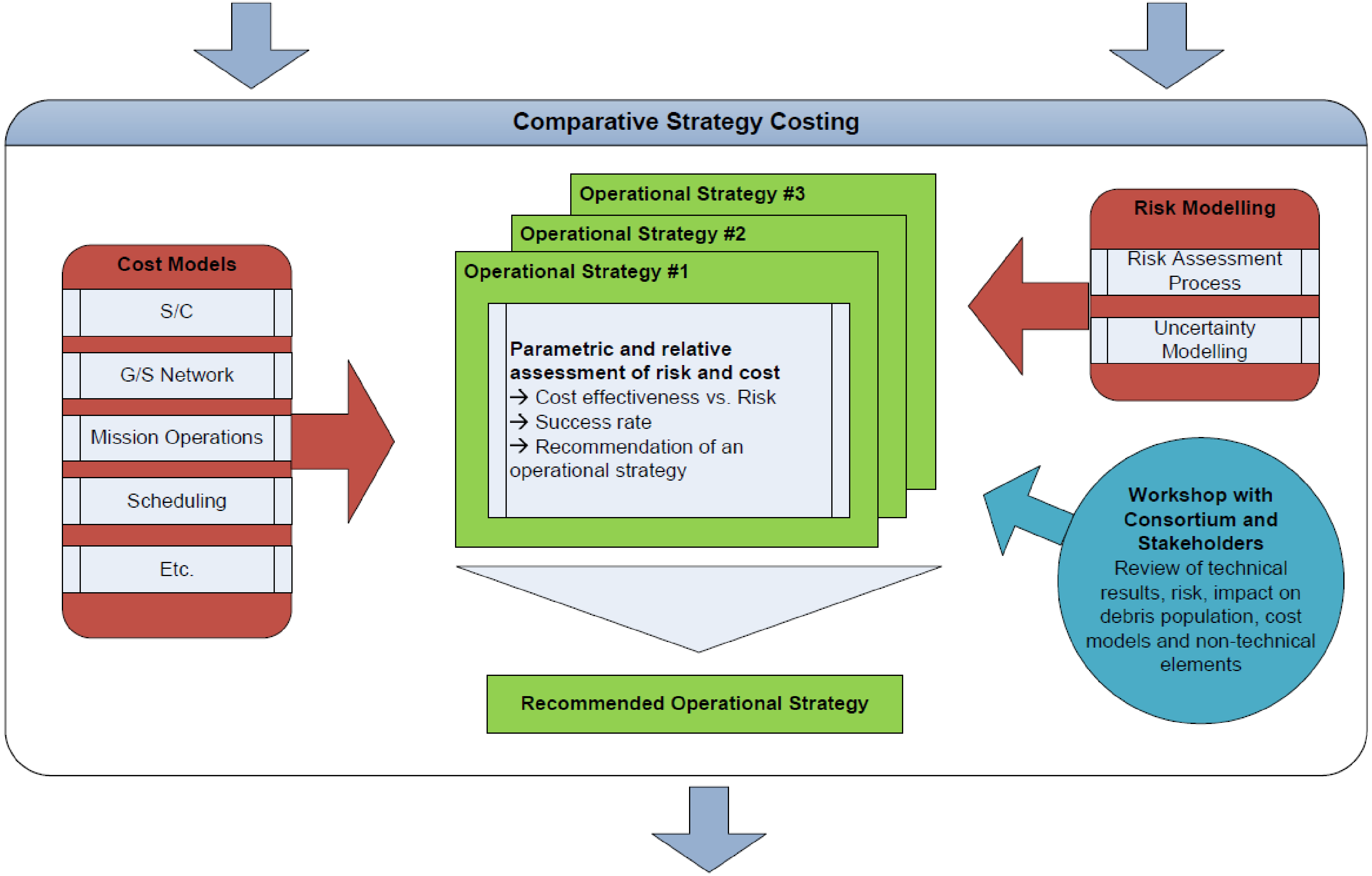
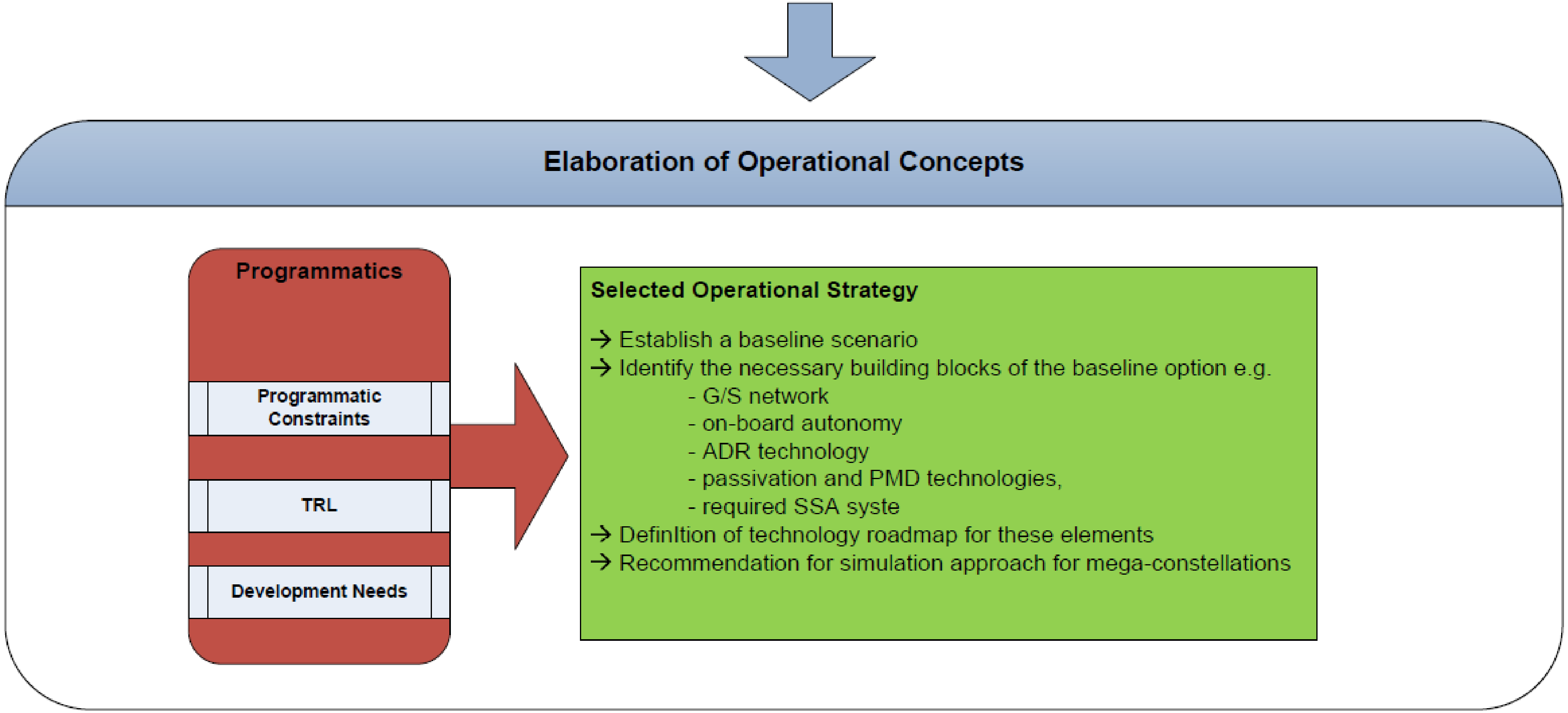
Work Logic – WP 6000



Work Logic – WP 7000



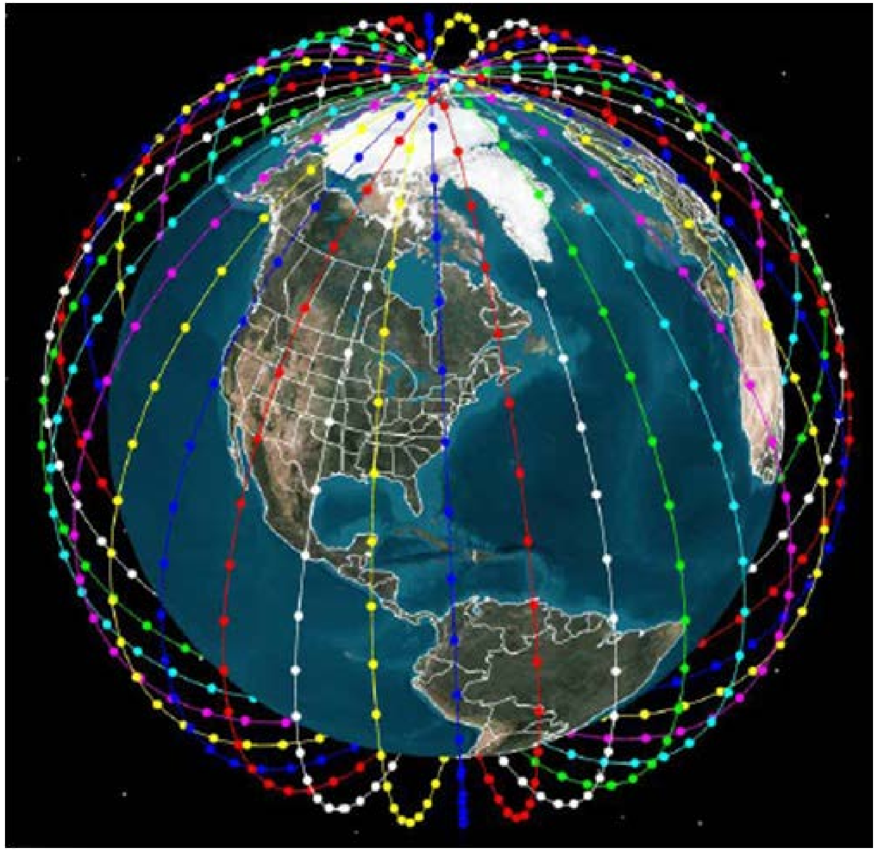
Synopsis of Study Results

WP1000 - Definition of Different Operational Strategies

Cyrille Tourneur – Airbus DS

WP 1000 context

- **WP1000 purpose:** *Definition of **3** reference scenarios to be assessed in the frame of MEGACO study*
  - *Based on exploration of relevant degrees of freedom and down selection of 3 candidate scenarios*
- **MEGACO inputs**
  - *Broadband telecom “mega” constellation*
  - *~1080 satellites nameplate capacity*
  - *Operated on polar inclination @ 1100 km*
  - *200 kg class satellites*



=> Detailed technical characteristics for the 3 reference scenario are available in study report and scenario reference spreadsheet

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WP 1000 overall logic

- Step 1 — Constellation configuration definition and trade
- Step 2 — Exploration of relevant parameters for strategies elaboration
- Step 3 — Assessment, trade and down selection of parameters
- Step 4 — Preliminary strategies and scenarios elaboration
- Step 5 — Metrics definition for short list selection and MEGACO study
- Step 6 — Scenarios short list elaboration for MEGACO study

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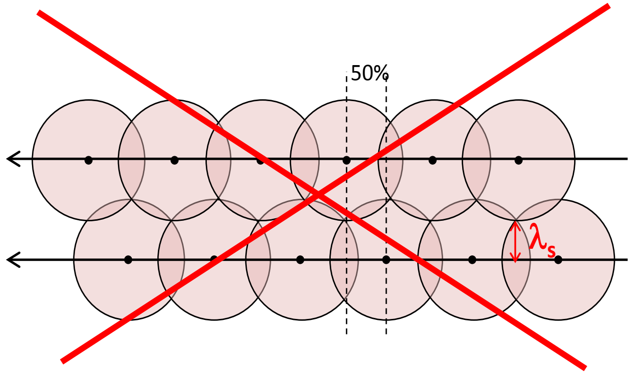
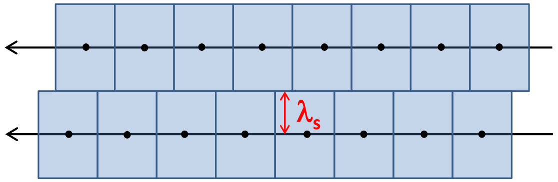
Step 1 summary

- **Constellation configuration trade off: *Altitude separation vs Walker "star" configuration***
  - *Rectangular coverage tiling required for Altitude separation configuration*
  - Altitude separation option provides significant improvement of safety distances between satellites versus moderate mission impacts

  => ***Altitude separation option also selected for MEGACO study***



Conventional circular coverage tiling
with Walker constellation



Coverage tiling with
Altitude separated constellation

Altitude separation vs Walker "star" configuration		***Altitude separation configuration with rectangular tiling***	
		Min elevation	Payload power augmentation
Walker "star" configuration tiling	Circular	-3.5° *(57° -> 53.5°)*	-14%
	Rectangular	-1.1° *(54,6° -> 53.5°)*	+20%

Closest inter satellite distance		Walker "star" configuration		Altitude separation configuration
Tiling	Circular	1 km	No radial separation	5 km Radial separation
	Rectangular	< 15 km *(TBC)*		

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Steps 2 & 3 - summary

- **6 domains explored in terms of options (degrees of freedom) for strategies definition**

1. Satellite propulsion options
   - Chemical propulsion variants
   - Electrical propulsion variants
2. Post Mission Disposal (PMD) approaches and options
   - PMD means
   - PMD orbit
   - PMD reliability
3. Constellation management possible concepts
   - Injection orbit (and transfer)
   - Population/replenishment strategy
   - PMD strategy
   - Spares management
4. Planned manoeuvers (SK, EoR, PMD) execution options
   - Layers
   - Autonomy
5. Collision Avoidance Manoeuvers concepts & options
   - Accepted Collision Probability Level (ACPL)
   - CAM trajectory
   - CAM timeline
   - CA means
   - CAM layer
   - CAM autonomy
6. System commanding architecture concepts & options
   - Inter Satellite Links
   - Ground stations coverages

=> Options assessments / trades and mutual dependence analysis are detailed in study report

Steps 2 & 3 – Summary of selected options (1)

- **Propulsion options**

Cat.	Chemical propulsion Option
1	Mono propellant
~~1~~	~~Bi propellant~~
1	Hybrid propulsion

Cat.	Electrical propulsion option
2	“Basic” configuration
2	Low power capacity
2	Permanent capacity
~~2~~	~~Better repeatability~~

- **PMD options**

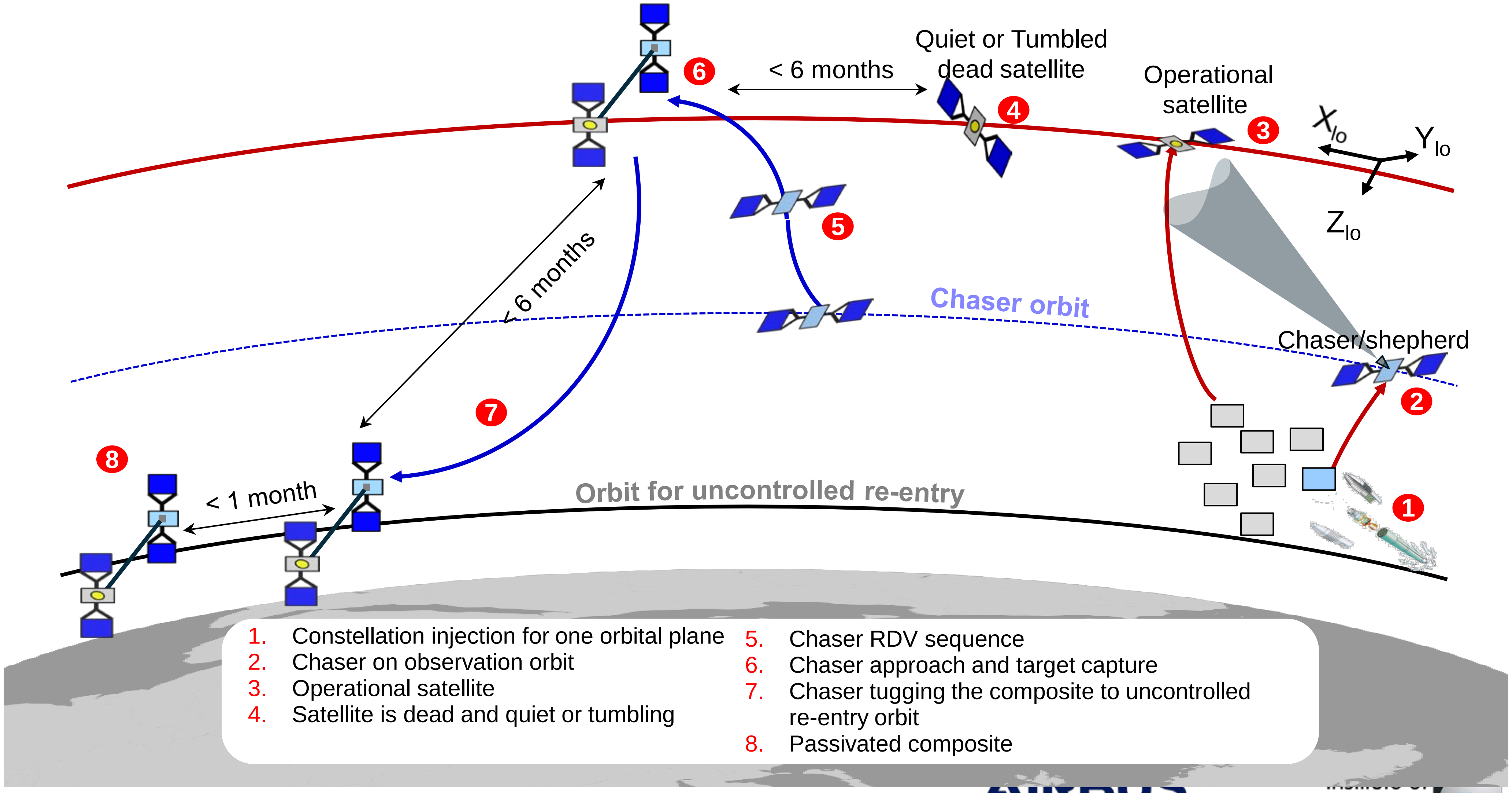
Cat.	PMD means option
1	Mission HW
1	Degraded propulsion mode
1	Low power propulsion mode
2	Embarked active de-orbiting kit
~~2~~	~~Embarked semi passive de-orbiting kit~~
~~2~~	~~Exogenous active de-orbiting kit~~
~~2~~	~~Exogenous semi passive de-orbiting kit~~
3	“One off” external “undertaker”
3	Space tug “undertaking” service

PMD orbit option
“Non autonomously compliant”
“Minimum orbit”
“As fast as possible”

PMD reliability option
“High” reliability
“Medium” reliability
~~“Low” reliability~~

Steps 2 & 3 – Summary of selected options (2)

- **PMD options:** ***Zoom on one off “undertaker” option***



1. Constellation injection for one orbital plane
2. Chaser on observation orbit
3. Operational satellite
4. Satellite is dead and quiet or tumbling
5. Chaser RDV sequence
6. Chaser approach and target capture
7. Chaser tugging the composite to uncontrolled re-entry orbit
8. Passivated composite

Steps 2 & 3 – Summary of selected options (3)

- **Constellation management options**

Injection option
Direct injection
Injection on a transfer orbit

Cat.	Population option
1	Large batch
1	Medium batch
1	Small batch
1	Very small replacement batch
2	Single plane
2	Adjacent planes
~~2~~	~~All planes~~

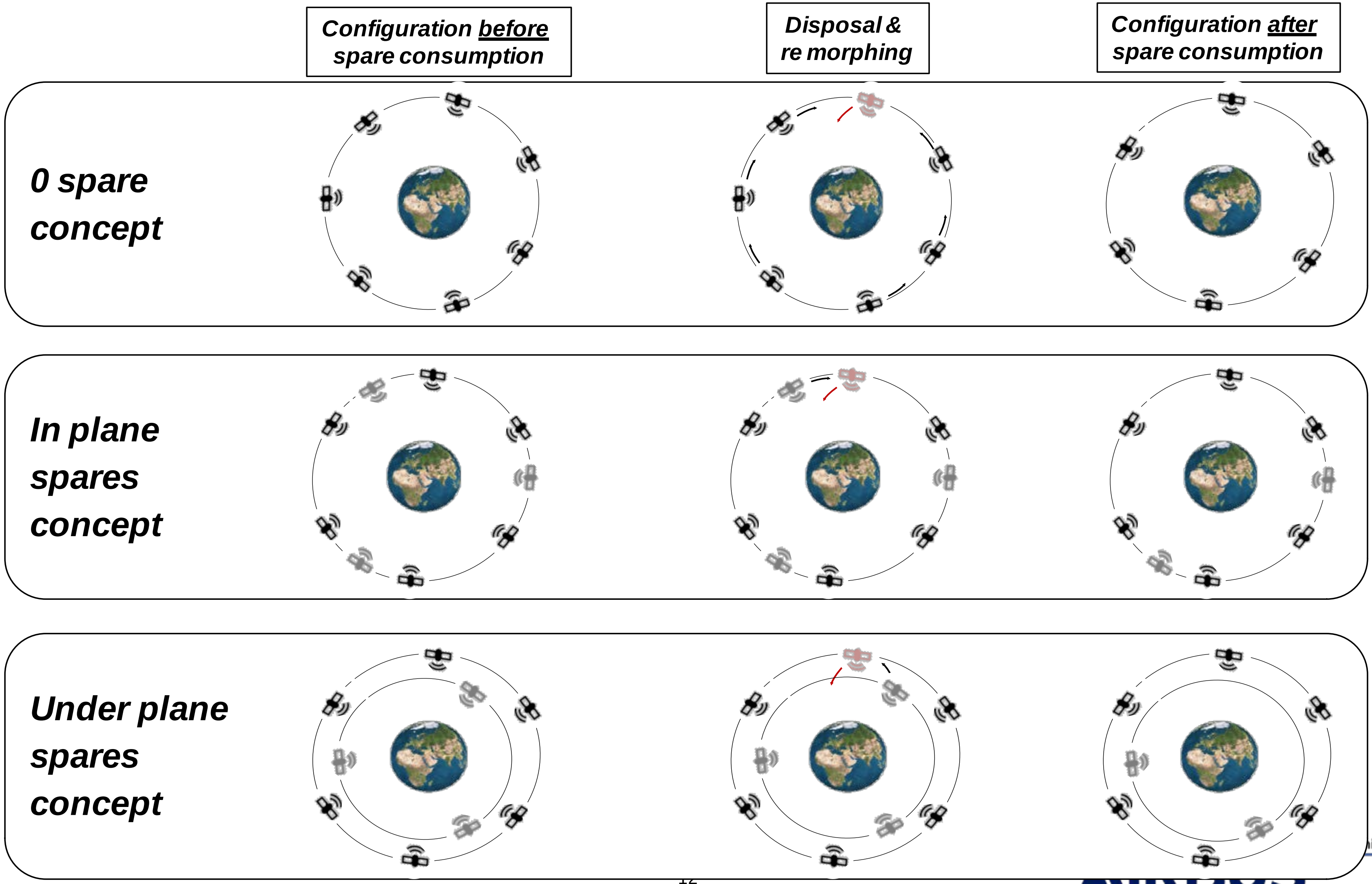
Cat.	PMD trigger criteria option
1	Mission performance
1	PMD HW degradation
1	Spare propellants
1	Spare thrust cycles
1	Design lifetime
1	Mean Mission Duration (MMD)
1	Big data model

Cat.	PMD strategy option
2	Same plane population
2	Close planes population
2	All constellation population
3	Single satellite "bulk"
3	Launch batch "bulk"
3	Intermediate size bulk

Cat.	Spare option
1	No hot spare
1	Per plane spare - *inside the plane*
1 & 2	Per plane spare - *below the plane*
~~2~~	~~Global spare pool - *close to operational altitude*~~
~~3~~	~~Global spare pool - *on transfer orbit*~~
3	On ground spare

Steps 2 & 3 – Summary of selected options (4)

- **Constellation management options:** ***Zoom on short MTTR spare options***



Steps 2 & 3 – Summary of selected options (5)

- **Collision Avoidance Manoeuvers (CAM) options**

ACPL Option
"High" ACPL
"Medium" ACPL
"Low" ACPL

Timeline Option
Immediate
Systematic intermediate
As late as possible

CAM layer Option
Single satellite
Per bulk
Global

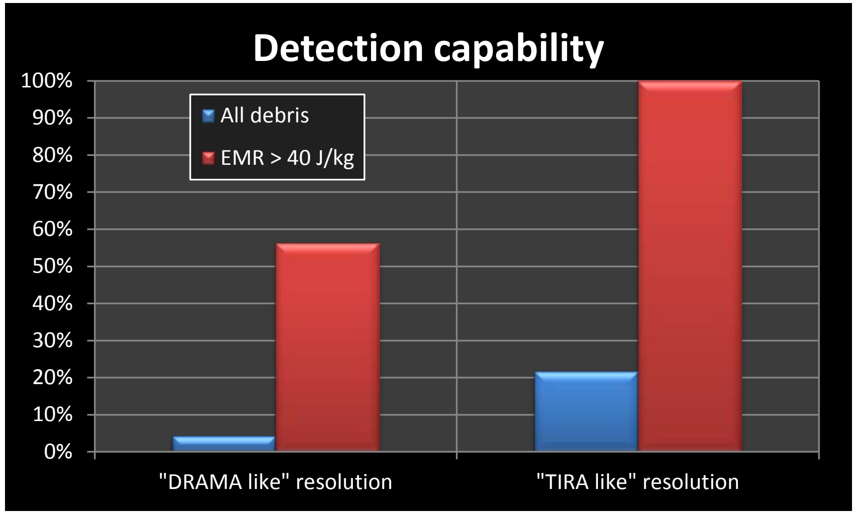
Cat.	Trajectory Option
1	Along track separation
1	Radial separation
1	"Bang bang"
2	Thrust interruption

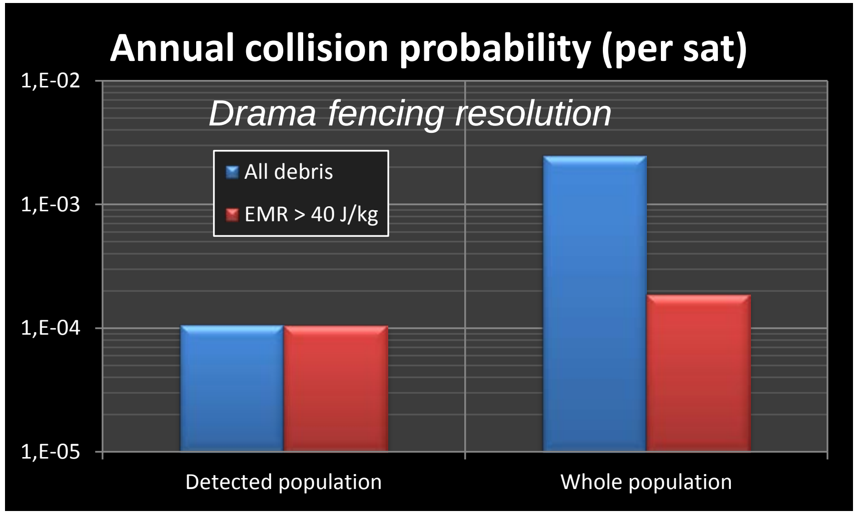
CAM means option
~~TLE only~~
~~CDM only~~
CDM + analysis
CDM + analysis + additional tracking mean
CDM + improved surveillance means + analysis

CAM autonomy option
No autonomy
Ground segment "autonomy"
Improved autonomy
Advanced autonomy
~~Full autonomy~~

Steps 2 & 3 – Summary of selected options (6)

- **CAM options:** ***Preliminary collision probability figures***





"DRAMA" radar resolution	All collisions				
	All population	Detected population	With CAM		
			10^{-3} ACPL	10^{-4} ACPL	10^{-5} ACPL
Annual collision risk (per sat)	2,50E-03	1,07E-04	2,43E-03	2,40E-03	2,39E-03
Avg collision per plane over 30 yrs lifetime	4,05	*0,17*	3,93	3,89	3,88
Avg collision for constellation over 30 yrs lifetime	81,06	3,47	78,62	77,77	77,60

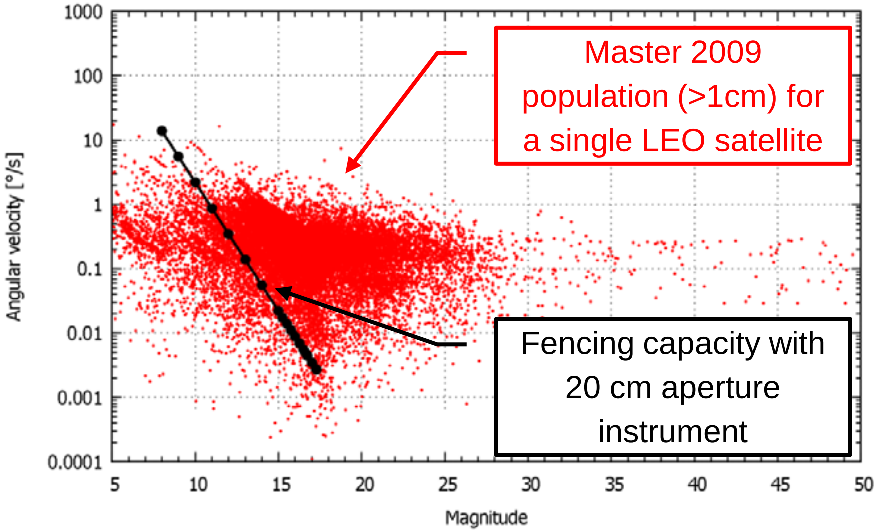
"DRAMA" radar resolution	EMR > 40 J/g (catastrophic collision)				
	All population	Detected population	With CAM		
			10^{-3} ACPL	10^{-4} ACPL	10^{-5} ACPL
Annual collision risk (per sat)	1,89E-04	1,06E-04	1,13E-04	8,76E-05	8,24E-05
Avg collision per plane over 30 yrs lifetime	*0,31*	*0,17*	*0,18*	*0,14*	*0,13*
Avg collision for constellation over 30 yrs lifetime	6,11	3,44	3,67	2,84	2,67

"TIRA like" radar resolution	All collisions				
	All population	Detected population	With CAM		
			10^{-3} ACPL	10^{-4} ACPL	10^{-5} ACPL
Annual collision risk (per sat)	2,50E-03	5,45E-04	2,22E-03	2,03E-03	1,96E-03
Avg collision per plane over 30 yrs lifetime	4,05	*0,88*	3,60	3,29	3,17
Avg collision for constellation over 30 yrs lifetime	81,06	17,65	72,03	65,88	63,49

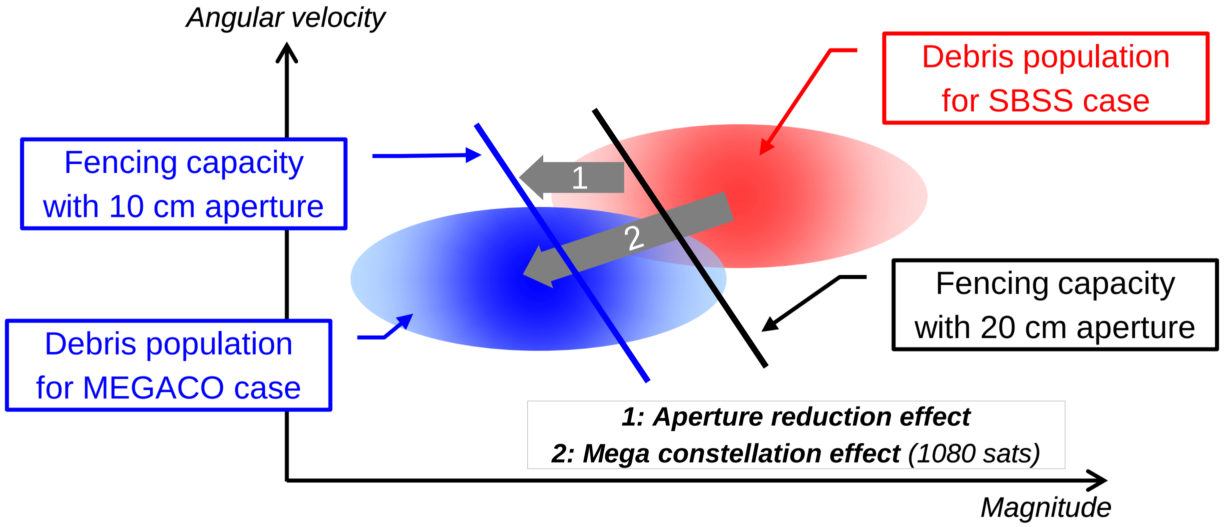
"TIRA like" radar resolution	EMR > 40 J/g (catastrophic collision)				
	All population	Detected population	With CAM		
			10^{-3} ACPL	10^{-4} ACPL	10^{-5} ACPL
Annual collision risk (per sat)	1,89E-04	1,89E-04	6,06E-05	1,07E-05	2,75E-07
Avg collision per plane over 30 yrs lifetime	*0,31*	*0,31*	*0,10*	*0,02*	*0,00*
Avg collision for constellation over 30 yrs lifetime	6,11	6,11	1,96	*0,35*	*0,01*

Steps 2 & 3 – Summary of selected options (7)

- **CAM options: *Fencing option not explored during MEGACO study***
  - An additional option could consist in embarking small optical camera(s) on <u>each</u> satellite of the constellation (typ. a 10cm dioptric camera) as an additional surveillance mean
    - *So as to improve resolution/accuracy of the catalog of debris crossing the constellation's orbit (not a CDM generation mean)*
    - *Detection performance would be modest but, thanks to mega constellation effect (1080 satellites), the proportion of monitored object could be augmented, thus reducing the collision risks and the false alarm rate (if covariance is improved)*



Debris population surveillance capabilities for SBSS study use case



Possible debris population surveillance capabilities with small camera on <u>each</u> MEGACO satellite

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Steps 2 & 3 – Summary of selected options (8)

- **Planned manoeuvers options**

Layer option
Single satellite
Per bulk or per plane
~~Global~~

Autonomy Option
No autonomy
Ground segment “autonomy”
Improved autonomy
Advanced autonomy
~~Full autonomy~~

- **System commanding options**

Cat.	ISL Option
0	No ISL
1	GEO relay
~~1~~	~~MEO relay~~
2	Intra plane ISL
~~2~~	~~Inter plane (global) polar ISL~~
2	Inter plane (global) ISL

Ground station coverage option
~~No ground station~~
Single site
~~Large coverage~~
Nearly global coverage

Step 4 – System and operator profiles (1)

6 profiles used for candidate scenario elaboration

- **Profile 1:**
  - A high end system, operated by a major “established” telecom operator, supported by a major space agency and governmental organizations, taking full benefit of the most advanced available space technologies
- **Profile 2:**
  - A low cost and low quality of service (low end), developed in a low cost of operations and access to space country, with medium to low sensitivity to space debris issues
- **Profile 3:**
  - A medium to high quality of service, based on “more than proven” technologies, developed in an “easy” access to space country
- **Profile 4:**
  - A very high quality of service system, also operated by an established telecom operator, developed according to a comprehensive approach for new technologies implementation on each successive satellite generation
- **Profile 5:**
  - A high quality of service system developed by a powerful “new space /GAFA like ” actor, implementing as much as possible advanced technologies and innovative concepts
- **Profile 6:**
  - A medium quality of service system, with “medium” attributes for all dominant profile characteristics

Step 4 – System and operator profiles (2)

6 candidate profiles summary

Operator & program "profiles"	1	2	3	4	5	6
Quality of Service	Very High	Low	Medium to High	Very High	High	Medium to High
Satellites capacity & oversizing	Very High	Low	Low	Very High	Medium	Medium
Technological maturity	Very High	Very Low	Low	Very High	Very High	Medium
Techno risks aversity	Low	High	High	Progressive approach	Very Low	Medium
Cost of access to space	High	Low	Low	High	High	Medium
Cost of system operators	Very High	Very Low	Moderate	Very High	High	Medium
Sensitivity to debris matters	Very High	Low	Low	Very High	High	Moderate

Step 4 – Strategies salients

- **Salient points of the different profiles**

= major technical decisions made for each scenario in accordance with each system/operator profile

Major features	1	2	3	4	5	6
Propulsion	Electrical with advanced options	Electrical "basic"	Chemical	Electrical with progressive options	Electrical "basic"	Electrical "basic"
Nominal Post Mission Disposal (PMD) Reliability	Very high 95%+	Medium 85%	High 90%+	Very high 95%+	High to very high 90%+	High 90%+
Accepted Collision Probability Level (ACPL)	10-4 to 10-5	10-3	10-3	10-4 to 10-5	10-4	10-3 to 10-4
Re entry orbit after PMD	Fast re-entry (0.5 yrs)	Long re-entry (25 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)	Fast re-entry (0.5 yrs)
Injection orbit	Low altitude transfer orbit	Direct injection	Direct injection	Low altitude transfer orbit	Low altitude transfer orbit	Direct injection
Spare satellites management philosophy	0 spare (oversized) + on ground spares	In plane + under plane (close) spares	Under plane (close) spares	0 spare (oversized) + under plane (close) spares	In plane spares	In plane + under plane (close) spares
Additional PMD means	Degraded propulsion advanced modes	*Nothing*	*Nothing*	Degraded propulsion mode + space tug	Degraded propulsion mode + shepherd	De orbit kit
Conjunction Assessment (CA) means	Extra tracking + fencing facilities	CDM analysis	CDM analysis	Progressive: CDM only -> Tracking means -> Fencing means	Extra tracking facilities	CDM analysis
Autonomy	Advanced	*No autonomy*	Ground Segment automation	Progressive: GS automation -> Improved -> Advanced	Advanced	Ground Segment automation
Inter Satellite Links (ISL) & Ground Stations (GS)	Endogenous ISL + polar station	*No ISL* GateWay stations	*No ISL* polar station	Progressive: GS only -> Endogenous ISL	Endogenous ISL + polar station	GEO ISL + polar station

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Step 5 – Metrics & selection criteria

- **4 metrics defined for scenarios assessment**
  1. Impact of scenario on space **debris** generation
  2. Impact of scenario on telecommunication system **Quality of Service**
  3. Impact of scenario on system development and operation **costs**
  4. **Innovation** and implementation of **new technologies**

- **2 criteria for short list selection**
  1. **Sensitivity** criteria: I.e. select the 2 "extreme" scenarios in terms of ranking according to the above metrics
  2. **Technology & innovation** criteria: Select the most "innovative" approach as the 3rd short listed scenario

	Strategies & generations																	
	1			2			3			4			5			6		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
Debris mitigation	7,5	14,5	14,5	-7	-7	-7	-1	0	0	6	11,5	18,5	6	9	11	2	3	6
	12,2			-7,0			-0,3			12,0			8,7			3,7		

	Strategies & generations																	
	1			2			3			4			5			6		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
Quality of Service	12	10	10	-2	-2	-2	3	3	3	3	11	12	4	8	9	2	5	4
	10,7			-2,0			3,0			8,7			7,0			3,7		

	Strategies & generations																	
	1			2			3			4			5			6		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
Satellites cost	-3	-8	-8	8	8	8	5	3	3	1	-3	-7	7	-1	-3	2	1	-1
	-6,3			8,0			3,7			-3,0			1,0			0,7		
Launch cost	-1	-1	-1	1	1	1	-1	-1	-1	3	0	0	1	0	3	2	2	2
	-1,0			1,0			-1,0			1,0			1,3			2,0		
Ground segment, operations and services cost	-2	0	1	2	2	2	4	8	8	-4	0	-4	-4	3	6	0	5	5
	-0,3			2,0			6,7			-2,7			1,7			3,3		
TOTAL	-7,7			11,0			9,3			-4,7			4,0			6,0		

	Strategies & generations																	
	1			2			3			4			5			6		
	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3	G1	G2	G3
Innovation and new technologies	10	14	14	2	2	2	1	4	4	5	12	15	10	15	15	4	7	7
	12,7			2,0			3,0			10,7			13,3			6,0		

Step 5 – Short list selection

Scenario 2 cannot reasonably be selected for MEGACO study

- Debris management approach is not acceptable and/or legal in ESA countries => not realistic
- Low quality of service scenario => would bias the cost assessment and comparisons for WP 6000

	Scenario					
	1	2	3	4	5	6
Debris generation	1	6	5	2	3	4
Cost	6	1	2	5	4	3
Quality of service	1	6	5	2	3	4
Innovation & technology	2	6	5	3	1	4

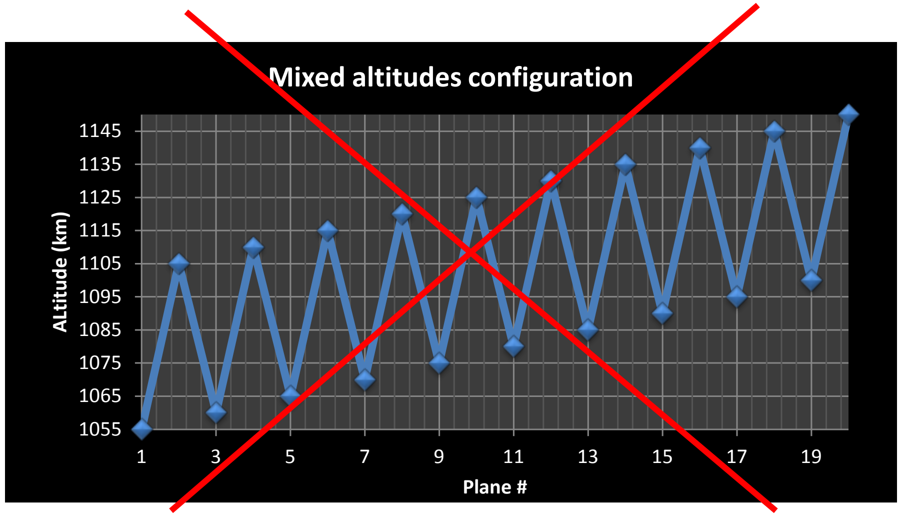
Best ranked scenario for criteria 2

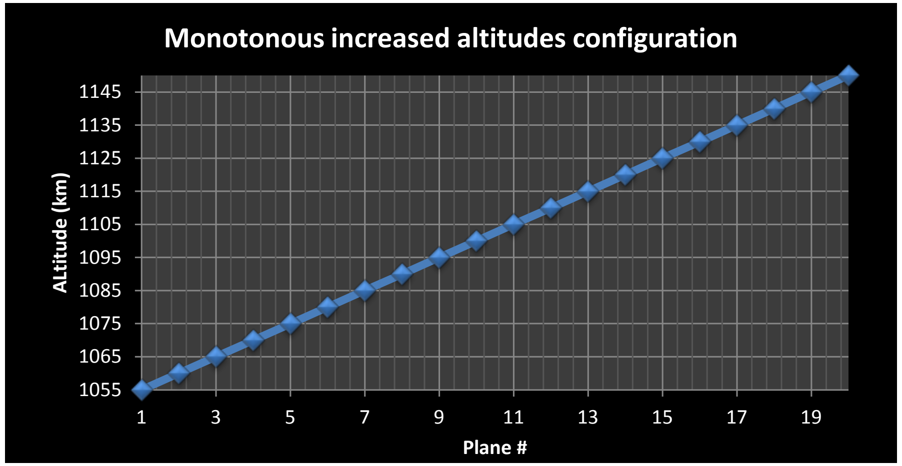
2 most extreme scenario for criteria 1

- **Short list summary**
  - **Scenario 1**: The high end system, operated by a major "established" telecom operator, supported by a major space agency and governmental organization, taking full benefit of the most advanced available space technologies
  - **Scenario 3**: The system based on "more than proven" technologies (e.g. chemical propulsion) and robust concepts, developed in an "eased" access to space environment
  - **Scenario 5**: The system developed by a powerful "new space /GAFA like " actor, implementing as much as possible advanced technologies and innovative concepts

Step 6 – Orbital parameters

- **Selected orbital configuration**
  - Constellation type and main orbital parameters have been selected in the frame of step 1
    - *Altitude separated configuration*
    - *Mean Altitude = 1100 km*
      - Eccentricity ~0°
    - *Inclination ~ 85.27°*
    - *20 orbital planes*
    - *54 satellites per plane*
    - *Planes separation = 9,48° => RAAN separation = 9,51°*
  - **Inter planes altitude separation of 5 km** confirmed
    - *Required for Quality of Service requirements for some scenario (re morphing duration)*
  - Altitude difference between adjacent orbital planes traded: *Monotonous increase selected*
    - *Could be an interlaced separation or a monotonous increase or decrease*
    - *Vs following trade criteria:*
      1. *Inter plane ISL:*
      2. *Mission coverage benefits*
      3. *EOR "synchronization" for dual plane population launches*





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Step 6 –Constellation sizing vs Quality of Service

- **Vs availability**
  - Two levels of availability defined for a broadband internet constellation
    - *Availability for very high quality of service (scenario 1) = **99.9%***
    - *Availability for high quality of service (scenario 3 & 5) = **99%***

  => Drives the amount of satellites to be "in service" for a 20 planes x ~ 54 satellites per plane constellation
  - Also depends on the selected hot spares philosophy
    - *For scenario 1 (0 spare), 99.9% availability can be guaranteed as long as 48 satellites per plane are operational*
    - *For scenario 3 & 5 ("under plane" and "in plane" spares) 99% availability can be guaranteed as long as no more than 10 satellites in the constellation are NOT operational*
- **Vs EoL reliabilities**
  - System EoL reliability depends on satellites EoL reliability, which is also linked to EoL PMD reliability
  - Selected satellites EoL reliabilities:
    - *Consistent with PMD reliability figures for each scenario*
    - *Consider a learning curve effect for each successive generation*
    - *For a 5 yrs design lifetime*

Scenario 1 sizing for availability

Configurations possible for 0 spare strategy only

Sats per plane	Unavailable satellites in constellation										
	1	2	3	4	5	6	7	8	9	10	11
42	99,88%	99,76%	99,64%	99,52%	99,40%	99,29%	99,17%	99,05%	98,93%	98,81%	98,69%
43	99,88%	99,77%	99,65%	99,53%	99,42%	99,30%	99,19%	99,07%	98,95%	98,84%	98,72%
44	99,89%	99,77%	99,66%	99,55%	99,43%	99,32%	99,20%	99,09%	98,98%	98,86%	98,75%
45	99,89%	99,78%	99,67%	99,56%	99,44%	99,33%	99,22%	99,11%	99,00%	98,89%	98,78%
46	99,89%	99,78%	99,67%	99,57%	99,46%	99,35%	99,24%	99,13%	99,02%	98,91%	98,80%
47	99,89%	99,79%	99,68%	99,57%	99,47%	99,36%	99,26%	99,15%	99,04%	98,94%	98,83%
48	99,90%	99,79%	99,69%	99,58%	99,48%	99,38%	99,27%	99,17%	99,06%	98,96%	98,85%
49	99,90%	99,80%	99,69%	99,59%	99,49%	99,39%	99,29%	99,18%	99,08%	98,98%	98,88%
50	99,90%	99,80%	99,70%	99,60%	99,50%	99,40%	99,30%	99,20%	99,10%	99,00%	98,90%
51	99,90%	99,80%	99,71%	99,61%	99,51%	99,41%	99,31%	99,22%	99,12%	99,02%	98,92%
52	99,90%	99,81%	99,71%	99,62%	99,52%	99,42%	99,33%	99,23%	99,13%	99,04%	98,94%
53	99,91%	99,81%	99,72%	99,62%	99,53%	99,43%	99,34%	99,25%	99,15%	99,06%	98,96%
54	99,91%	99,81%	99,72%	99,63%	99,54%	99,44%	99,35%	99,26%	99,17%	99,07%	98,98%

Scenario 3 & 5 sizing for availability

Scenario	Reliabilities	Gen.1	Gen. 2	Gen. 3
1	EoL PMD reliability	95%	96%	97%
	EoL sat. reliability	94%	95%	96%
3	EoL PMD reliability	90%	92%	94%
	EoL sat. reliability	85%	89%	92%
5	EoL PMD reliability	90%	92%	95%
	EoL sat. reliability	85%	89%	92%

Step 6 – Satellite summary

- **Preliminary (optimistic) estimate @ WP1000 completion**
  – See refined figures in WP 2000

Scenario	Sat parameters	Gen.1	Gen. 2	Gen. 3
1	Sat launch mass	~ (200 + 18) kg dry mass + 4 kg propellants = 222 kg		
	Propulsion *high power*	Isp: 3300 s - Thrust: 11 mN Cycles: 10000 - Lifetime: 20000 hrs		
	Propulsion *low power*	Isp: 1650 s - Average thrust over cycle: 0.7 mN MIB/total cycle duration = 450s/3150 s		
3	Sat launch mass	~ 200 kg + 38 kg prop => 238 kg launch mass	~ 200 kg + 26 kg propellants => 226 kg launch mass	
	Propulsion	1N / 210s Isp	1N / 300s Isp	
5	Sat launch mass	~ 200 kg + 11 kg propellants => 212 kg launch mass		
	Propulsion	Isp: 1140 s - Thrust: 14 mN Cycles: 10000 - Total impulse ~ 190 kNs		

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Step 6 – Spares and active satellites sizing

- **Sizing based on required availability, reliabilities, spares philosophy and resulting MTTR requirements**
  - *Cf study report for sizing approach and figures*

Scenario	Sats per plane	Gen.1	Gen. 2	Gen. 3
1	Max active (in plane)		**54**	
	Min active (in plane)		**48**	
	Total launched (in plane)		**54**	
	Cold spares (on ground)	**3**	**2**	**1**
3	Max active (in plane)		**54**	
	Idle (under plane)	**10**	**7**	**5**
	Total launched (in & under plane)	**64**	**61**	**59**
5	Max active (in plane)		**54**	
	Idle (in plane)	**10**	**7**	**5**
	Total launched (in plane)	**64**	**61**	**59**
	Shepherds (under plane)	***7***	***5***	***3***

Step 6 – PMD strategy

- **PMD criteria, monitored population and PMD bulks**
  - Two categories of criteria implemented
    - *Event criteria (often not predictable) which trigger immediate PMD (if possible) of the concerned satellite w:O any bulk consideration*
    - *Systematic criteria which can be anticipated so as to constitute PMD bulks consistent with the replenishment launch philosophy*

PMD strategy		Scenario 1	Scenario 3	Scenario 5
PMD criteria	Event *(triggers immediate PMD)*	telecom mission HW or PMD HW	telecom mission HW	telecom mission HW or PMD HW
	Systematic *(for PMD bulks)*	thrust cycle or big data model	spare propellants	thrust cycle, design lifetime or big data model
Monitored population & PMD bulk	Monitored population *for event criteria*	All planes		
	Monitored population *for systematic PMD bulk*	Adjacent planes	Single plane	Adjacent planes
	PMD bulk size	Full plane or half plane size	1/3 of a plane	Full plane

Step 6 – Launch strategy

- **Strategy summary**
  – *Cf study report for launch batches, candidate launch vehicles and population and replenishment timelines for each scenario*

Scenario	Injection & EOR	Gen.1	Gen. 2	Gen. 3
1	Injection orbit	500 km altitude - *inclination of the highest plane for multiple planes population launches*		
	EOR timeline	Spiral top up 2 months RAAN phasing (2nd plane) + ~ 3.2 months EOR 3/4 orbits thrust ratio	Spiral top up 2 months RAAN phasing (2nd plane) + ~2.7 months EOR 9/10 orbits thrust ratio	
3	Injection orbit	100 km below target plane **Nominal** satellites launches: inclination of target plane **Spare** satellites launches : with inclination matched to provide same J2 secular RAAN drift as target plane (~ +0.2°)		
	EOR timeline	Hohmann transfer with combined inclination + eccentricity correction burns at apogee Possible in less than one day (5 to 4 revolutions with thrust) Thrust performed every 2 revolutions (OD during no thrust orbits)		
5	Injection orbit	500 km altitude - *inclination of the highest plane for multiple planes population launches*		
	EOR timeline	Spiral top up: 2 months RAAN phasing (2nd plane) + ~ 3.6 months EOR 1/2 orbits thrust ratio		

Step 6 – CAM summary

Scenario	On station CAM rate	Gen.1	Gen. 2	Gen. 3
1	ACPL	Medium: 10^{-4}	Low: 10^{-5}	
	Constellation manoeuver rate	~450 man/yr	~3500 man/yr	
	Manoeuvre type	"Bang bang" along track avoidance manoeuvers with propulsion low power mode		
	Average impacts	Lifetime DV < 1 m/s Max dephasing ~ 0.25% Altitude excursion ~ 100 m	Lifetime DV ~ 4 m/s Max dephasing ~ 0.25% Altitude excursion ~ 200 m	
3	ACPL	High: 10^{-3}		
	Constellation manoeuver rate	~50 man/yr		
	Manoeuvre type	Along track avoidance manoeuvers		
	Average impacts	Lifetime DV < < 1 m/s Max dephasing ~ 0.15% Altitude excursion ~ 50 m		
5	ACPL	Medium: 10^{-4}		
	Constellation manoeuver rate	~150 man/yr		
	Manoeuvre type	Along track avoidance manoeuvers		
	Average impacts	Lifetime DV < 1 m/s Max dephasing ~ 0.7% Altitude excursion ~ 160 m		

Step 6 – System telecommanding architecture summary

Scenario	Telecommand architecture	Gen.1	Gen. 2	Gen. 3
1	ISL strategy	In plane ISL + direct TTC link with stations	In & out of plane ISL + direct TTC link with stations	
	ISL use	On station ops only *(incl. during CAM & SK)*	On station ops (*incl. during CAM & SK*) and EOR (*incl. CAM interruptions*)	
	Stations strategy	2 polar stations Permanent contact with one operational satellite of each plane required + control of satellites performing PMD during visibilities	2 polar stations for permanent contact with at least one operational satellite of the constellation (*for communications via ISL*) + control of satellites performing PMD during visibilities	
3	ISL strategy	No ISL		
	Stations strategy	3 non overlapping polar stations Amount of antennas to be assessed in the frame of WP 3100		
5	ISL strategy	No ISL	In + out of plane ISL + direct TTC link with stations	
	ISL use		On station ops (*incl. during CAM & SK*) and EOR (*incl. CAM interruptions*)	
	Stations strategy	GW stations network 25 GW over land masses 15° min elevation 1 TT&C antenna per GW station	2 polar stations for permanent contact with at least one operational satellite of the constellation (*for communications via ISL*) + control of satellites performing PMD during visibilities	

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Step 6 – Autonomy

- **Scenario 3**
  - No on board autonomy implemented
  - Limited to ground segment automation upgrades for generations 2 & 3
- **Scenario 1 & 5**
  - Ground segment automation considered for gen 1
  - Advanced on board autonomy implemented for gen 2 & 3 for planned manoeuvers and CAM handling
    - On board elaboration of planned manoeuvers (SK, EOR, PMD)
    - On board elaboration of CAM based on uploaded CDMs and ACPL thresholds
    - Closed loop on board control of trajectory, using on board GNSS based OD, which is useful for:
      - *CA search volume reduction during EOR & PMD (when perigee is high), especially for scenario 1 which implements long continuous thrust durations*
      - *ISL link availability (high gain Ka-band antennas) during EOR*
      - *Relative phasing for scenario 5 (low flexibility since payload is not oversized)*
    - Approval loop with ground control for manoeuver approval

WP3100 – Ground Segment Concepts

Arnaud Beauvoit – Airbus DS

WP3100 – Ground segment concepts
Work logic

Step 1: High level Ground segment requirements

- Features: What the GS should do (focus on cmd & ctrl)
- Performances: What reactivity, connectivity and capacity the GS should provide

Step 2.1: Ground segment architecture

- Processing logic
- Infrastructure solution
- Automation level

Step 2.2: Ground segment sizing

- Number and location of control centers
- Number and type of antennas
- Staffing

WP3100 – Ground segment concepts Requirements

		Scenario 1			Scenario 3			Scenario 5		
		G1	G2	G3	G1	G2	G3	G1	G2	G3
Constellation management & planning										
Orbit raising	Decision of orbit raising									
PMD	Decision of satellite disposal									
EoL	Decision of satellite passivation									
CAM	Validation of CAM triggering									
Remorphing	Definition of constellation evolution after specific events									
Mission	Planning of mission operations									
Priorities	Definition of priorities between operations									
Orbit control										
Orbit transfer, station keeping & CAM	Computation of manoeuvre commands *: still necessary despite autonomy		*	*					*	*
Shepherd	Computation of manoeuvre commands									
Debris list	Retrieval of CDM list for autonomous manoeuvre									
Debris check	Assessment of collision risk associated to a manoeuvre									

Feature requirements distributed in 3 categories

- **Monitoring:** receive and analyze constellation state and alerts
- **Planning/control:** decide and compute maneuvers (OR, SK, CAM, PMD)
- **Command/distribution:** generate commands and share distribution network (antennas, ISL)

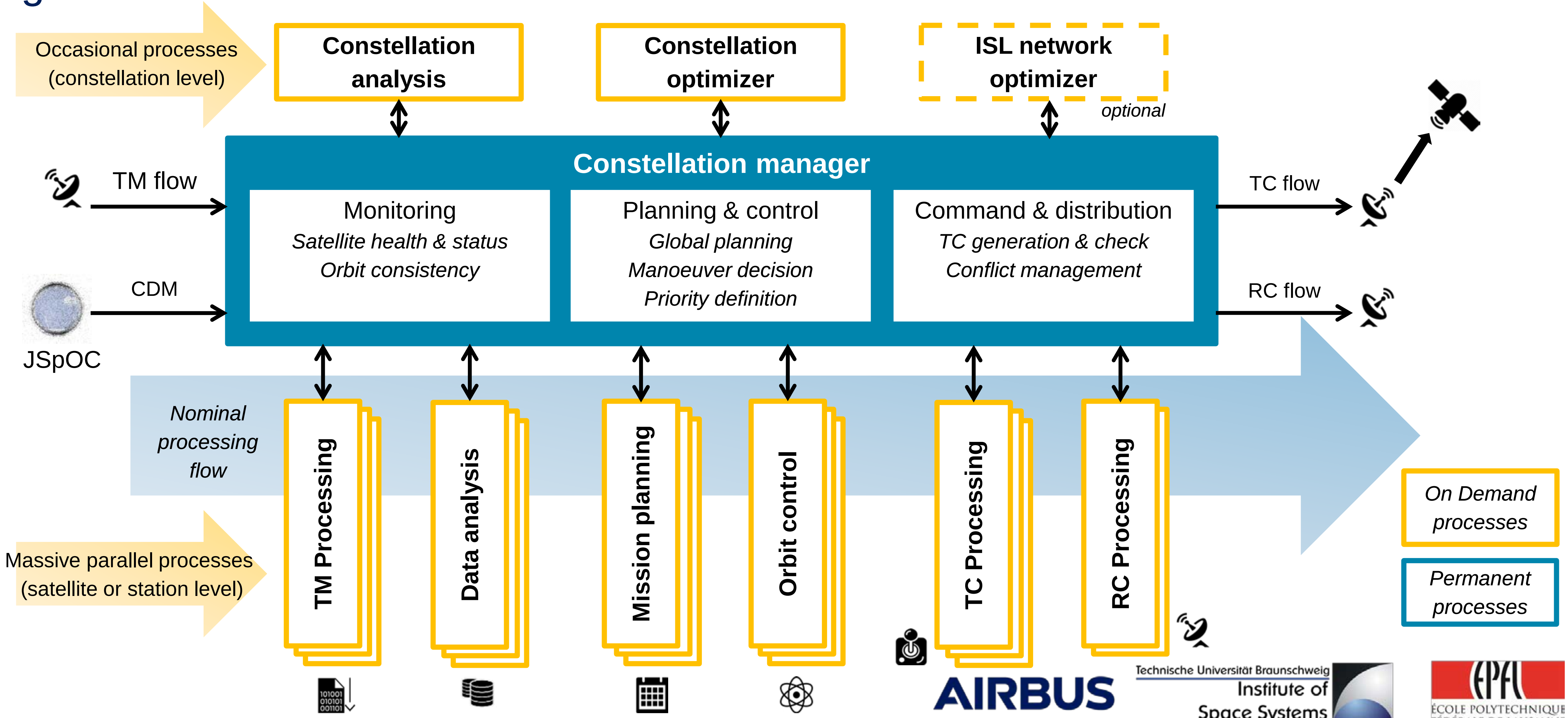
Performance requirements

- **Reactivity:** How fast the system shall react to unscheduled events
  Between 6h and 16h depending on scenario → Not a design driver

- **Connectivity:** How frequently satellites shall be contacted for scheduled operations
  Up to 1 contact per orbit and per satellite during orbit transfers → <u>Stringent requirement for the number of antenna</u>

- **Capacity:** How many satellites shall be operated in parallel
  From 9 (scenario 3) to 800 (scenario 5) satellites to operate in parallel during orbit transfers → Huge variability on antenna needs

WP3100 – Ground segment concepts
High level GS functional chain



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WP3100 – Ground segment concepts
Control center design and sizing

Application of IT infrastructures and redundancy strategies consistent with each scenario

	Scenario 1	Scenario 3	Scenario 5
IT infrastructure	**Private cloud infrastructure** *Data and processing hosted on premises but based on cloud technology*	**Traditional static infrastructure** *Use of VM hosted on a centralized infrastructure*	**Hybrid cloud infrastructure** *Composition of private and public clouds*
Redundancy strategy	1 Nominal + 1 backup center Hot redundancy	1 Nominal + 1 backup center Cold redundancy	Rotating control Hot redundancy
Total number of control centers	**2**	**2**	Gen1 & Gen2: **2** Gen3: **3**
Locations	US & Europe	Russia & Eastern Asia	Gen1 & Gen2: US & Europe Gen3: + Eastern Asia

Example of rotating control (3 sites)

	0h – 8h UTC	8h – 16h UTC	16h – 24h UTC
Team 1	14h – 22h local time	22h – 6h local time	6h – 14h local time
	Active	Off	Backup
Team 2	6h – 14h local time	14h – 22h local time	22h – 6h local time
	Backup	Active	Off
Team 3	22h – 6h local time	6h – 14h local time	14h – 22h local time
	Off	Backup	Active

WP3100 – Ground segment concepts
Conclusions

Impact of ISL

- Simpler TC distribution with less antennas during mission
- Still need for direct links during orbit transfers (most demanding phase with current strategies)

NB: Need for management and monitoring of ISL network at GS level

Impact of automation

- Significant reduction of operators count

Impact of electrical propulsion

- Lead to very long orbit transfers with complex management of collision risk
- Current strategy implies many antennas and operators during such phases

→ Need for mitigation solution

WP3200 – Space Segment Concepts

Philipp Voigt – Airbus DS

Recap of WP3200 Tasks

Major objectives

- Analyse the implications on space segment design to support end-of-life activities.
- For each of the strategies identified, hence comparing the different spacecraft conceptual architectures.

Tasks

- Define and analyse the space segment concepts needed to support the implementation of the SDM measures by mega-constellations. i.e. types of CAMs, monitoring of equipment failures to determine EOL, automated passivation, level of autonomy needed.
  - CAMs: from minimum CAMs strategy to maximum CAMs strategy
  - Monitoring: from no monitoring of equipment failure to full monitoring of equipment failure
  - Passivation: passivation vs. robustness and redundancy of the system and subsystems
  - Autonomy: from full ground control to highly autonomous S/C
- High-level space segment architecture definition for CAM and EOL aspects:
  - Propulsion subsystem (e.g. for CAM)
  - Communication subsystem (e.g. transmit monitoring data, receive CAM orders)
  - Power subsystem (e.g. provide power for SDM measures)
  - On-board processing (e.g. level of autonomy)
  - Sensors (e.g. status of S/C and environment)
- Iteration of concepts with WP 4000

Requirements & Assumptions

Major requirements

- System budgets
  - Total Mass = 200 kg
  - Payload Mass = 60 kg
  - Power of Payload = 200 W
  - Power of electric propulsion system = 420 W
  - 2 x Ka-band antennas incl. pointing mechanisms for operational communication
- Payload must be fully operational 24/7 (also during eclipse)

Assumptions

- Orbital parameters from WP1000:
  - mean altitude = 1100 km
  - Eccentricity = 0
  - Inclination = 85.27 deg
- Inter-satellite link
- Full ground control for CAM and PMD

Summary of mass budgets

	Baseline	Scen. 1	Scen. 3	Scen. 5
Propulsion subsystem	Electric prop., HET	Electric prop., Ion engine	Chem. Prop	Electric prop., HET

Scenario 1 (245 kg)

- highest mass due to the strong mass increase of the power subsystem
- re-morphing of orbit + increase of P/L power to close the gap in case a satellite fails
- P/L and prop. System have to work in parallel and during eclipse

Scenario 3 (213 kg)

- Gen. 1 between scenario 1 and 5, gen. 2 & 3 similar mass like Scen. 5
- Increase of mass due to the increase of fuel mass for chem. prop.
- S/C design might be very different to baseline due to chemical propulsion subsystem
- BUT: no PMD back-up & less satellites per launch due to high altitude injection

Scenario 5 (203 kg)

- Low mass due to the decrease of power demand with a less demanding HET
- re-morphing of orbit + increase of P/L power to close the gap in case a satellite fails
- P/L and prop. system do not work in parallel, prop. System does not work in eclipse
- BUT: additional satellites needed as PMD back-up strategy (shepherd)

WP4100 - Collision Avoidance Operations Requirements

Frédéric Renaud – Airbus DS

Technische Universität Braunschweig
Institute of Space Systems

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WP4100: LEOP / SK - all propulsion cases

LEOP

Launcher in charge of safe injection up to 4 days post separation
(no collision risk between separated objects)

SK phase

- **Rare SK maneuvers expected**
  - Very low drag at mission altitude
  - No inclination maneuver needed thanks to an appropriate initialization
- **Re-morphing maneuver will occur to deal with satellite failure**

Collision risk management

- **Inside a constellation plane** => managed by design
- **With constellation satellites in EOR/PMD** => procedure intra-constellation
- **With other satellites (debris)** => procedure with JSpOC
  - No difficulty expected thanks to thrust level
  - Altitude excursion and dephasing are acceptable
  - Impact on the mission to be studied by operator

Visibility frequency in free drift derives from using up-to-date CDM

=> 1 visibility every day

Procedure intra-constellation

In Free drift and around maneuvers, the operator

- Manages a catalogue of ephemeris/uncertainties of each satellite of the constellation
- Computes conjunctions
  - ✓ On a regular basis
  - ✓ Before each maneuver => GO/NO GO
- Detects alerts according to geometrical criteria
- CAM computation depending on POC computation criteria and/or geometrical avoidance criteria
- In case of CAM, go to collision risk management procedure with JSpOC

Procedure with JSpOC

Free drift

- POC computation on “advanced screening” CDM

Around maneuvers

- Before
  - ✓ Send special ephemeris to JSpOC
  - ✓ Wait for CDM return (2 to 4 h)
  - ✓ Compute POC => GO / NO GO
  - ✓ Send maneuver notification to JSpOC
- After
  - ✓ OD 3h after maneuver to update the collision risk
  - ✓ Send “Special” and “Operational” ephemeris to JSpoC

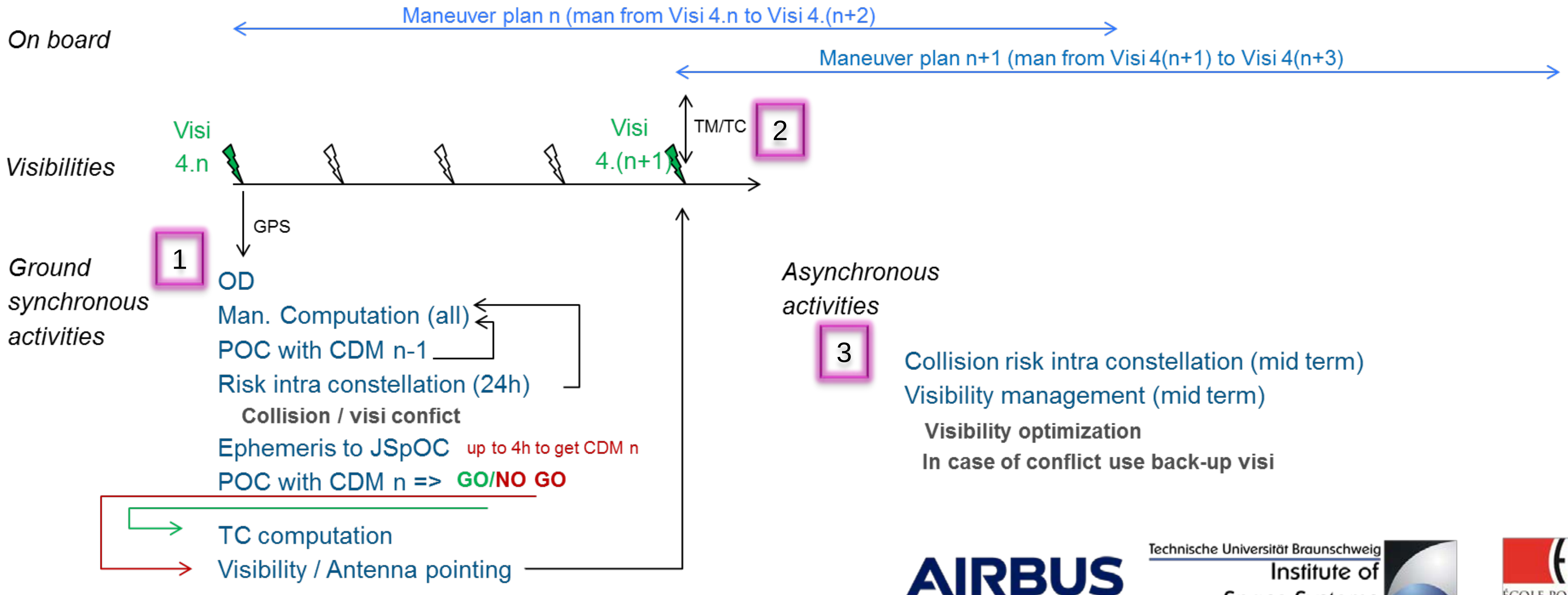
WP4100: OR / PMD with electrical propulsion – automated FDS

OD frequency is driven by 3 constraints

- Keeping satellite inside JSpOC screening volume,
- Computing an acceptable covariance for collision management (to avoid a risk dilution when there is too much uncertainties on the satellite position)
- Along track error for ground station acquisition (critical constraint with Ka band)

In addition, acquisition strategy should be robust to an issue on the nominal visibility.
=> 1 visibility every 4 orbits

Timeline



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WP4100: OR / PMD with electrical propulsion – advanced autonomy (1/2)

Advanced autonomy definition

- On board maneuvers elaboration ← *a process with on ground maneuver elaboration is also studied*
- Ground control confirmation needed
- On board closed loop trajectory control for all maneuvers
- On board collision alert assessment based on CDM uploaded by the ground + on-board decision
- Intra constellation collision risk is managed by the ground

On board closed loop trajectory control

- Nominal trajectory must be computed with the smallest thrust level (considering dispersion)
- The on board closed loop trajectory control guaranties a continuous knowledge of space debris in the satellite close environment.
- CAM can be computed on-board with a small covariance and minor impact on EOR trajectory

Visibility frequency derives from a trade-off between using up-to-date CDM and minimizing the ground station number

⇒ **1 visibility every day**

Suggested timeline:

- Ground maneuvers planning + On-board closed loop trajectory control (see next slide)

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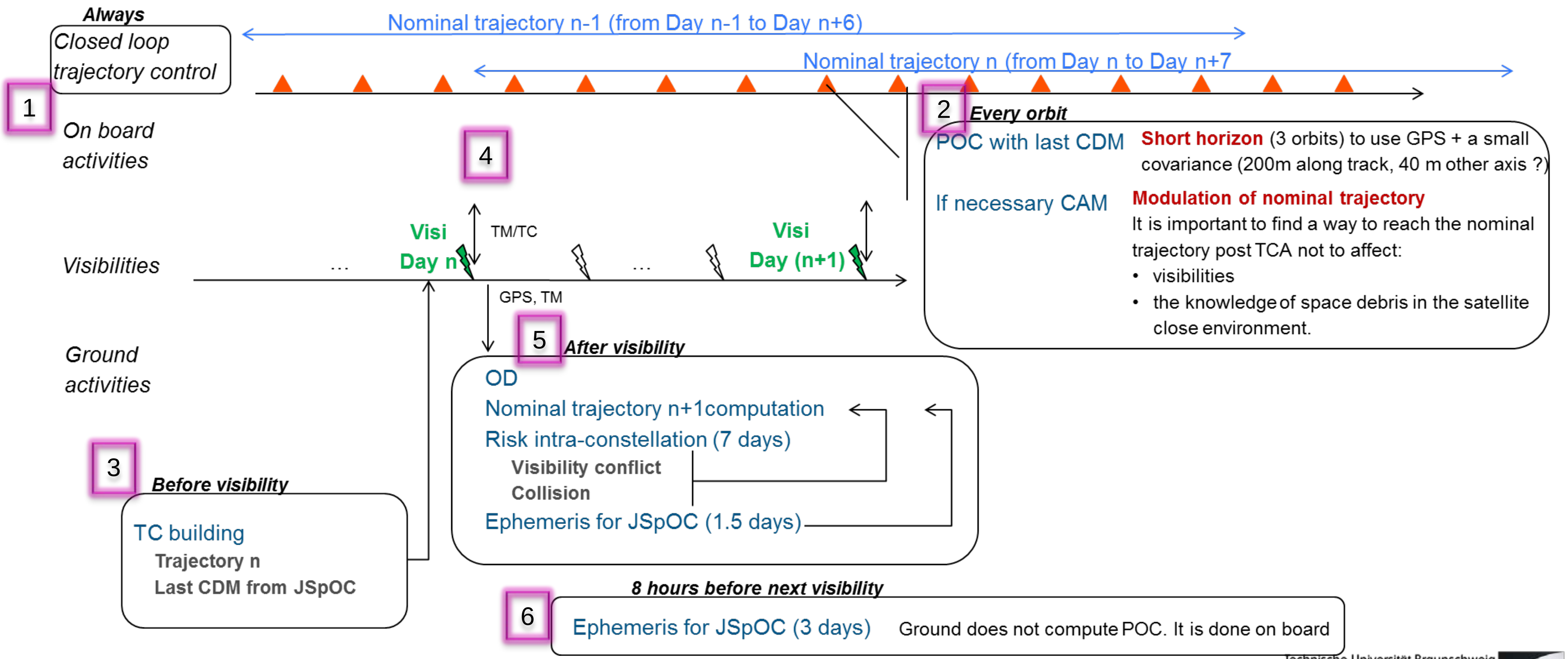
WP4100: OR / PMD with electrical propulsion – advanced autonomy (2/2)

- **Timeline example (case 2 : Ground maneuvers planning + On-board closed loop trajectory control)**



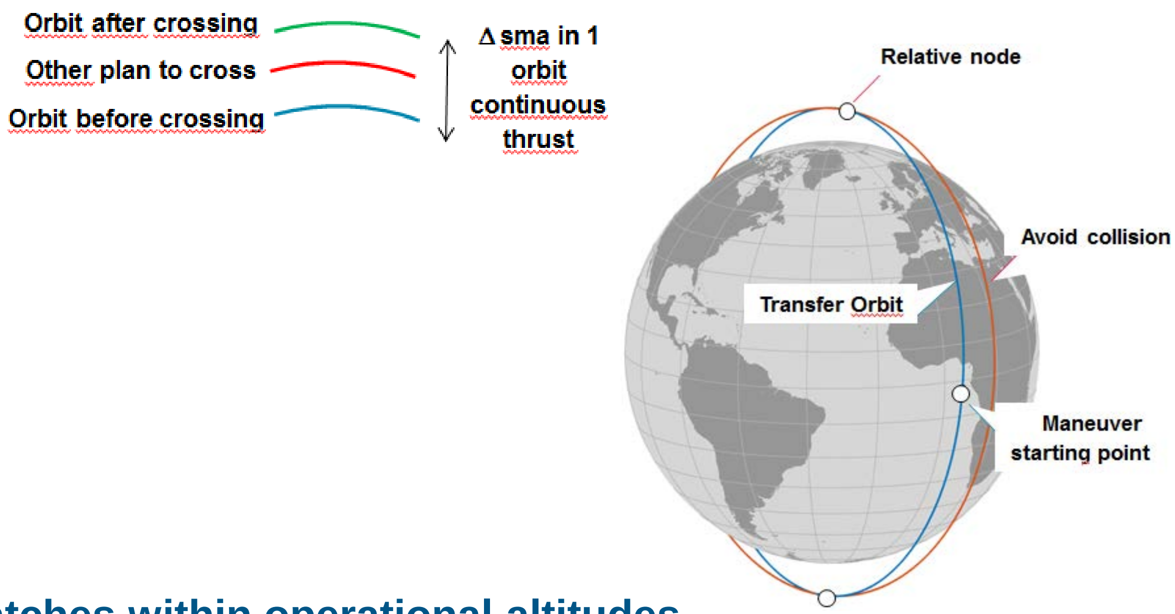
WP4100: Insertion into the operational orbit

Constellation geometry: 20 orbital planes with 5 km altitude separation + ΔRAAN adjacent planes = 9.51 deg

Insertion into the **final orbit** can be done safely thanks to a **classical phasing** for all propulsion kind.

A **radial/normal separation method** can be used to manage the **crossing** of planes below the final orbit

- Electric propulsion
  - o Orbits altitude before/after crossing depends on Δsma in 1 orbit continuous thrust
  - o Maneuver begins 90° before the relative node of the two orbits
  - o If necessary (eccentricity control accuracy) this method could be mixed with a phasing strategy
- Chemical propulsion
  - ✓ a similar separation method can be used with a Hohmann transfer.



=> No collision risk with operational satellites.

Operations should be planned to avoid the crossing of 2 OR batches within operational altitudes.

WP4200 Collision Avoidance Simulations

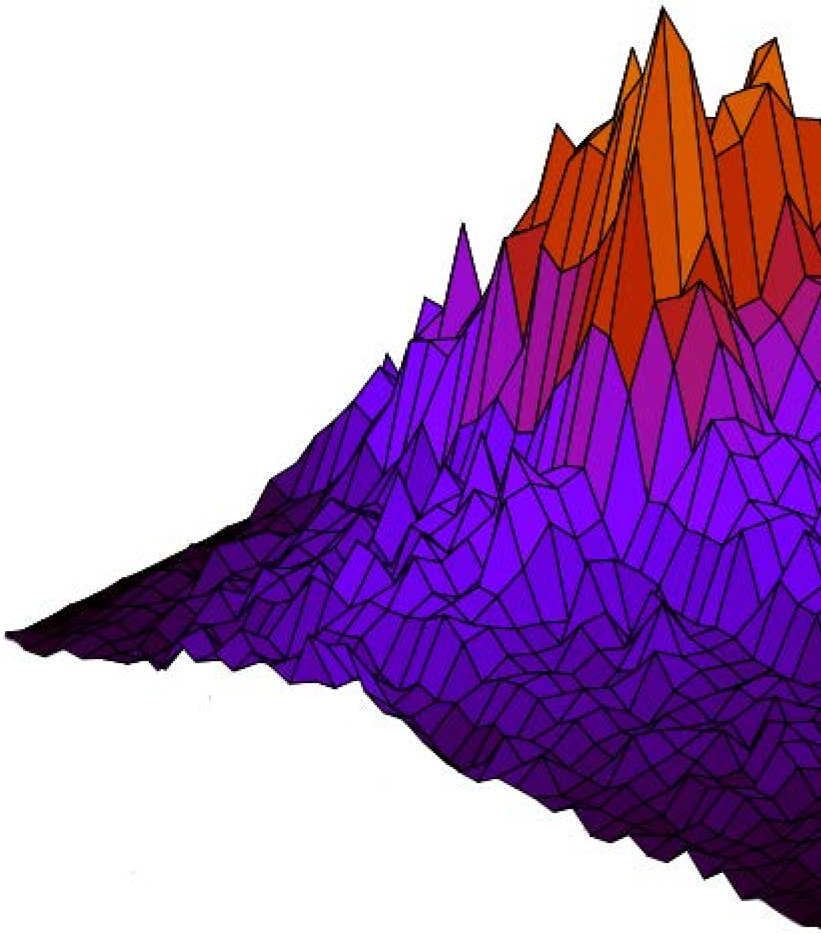
Christopher Kebschull – TU Braunschweig

Outline

1) Overview
   a. Goals
   b. Methodology

2) Simulation results
   a. Phase 1
   b. Phase 2

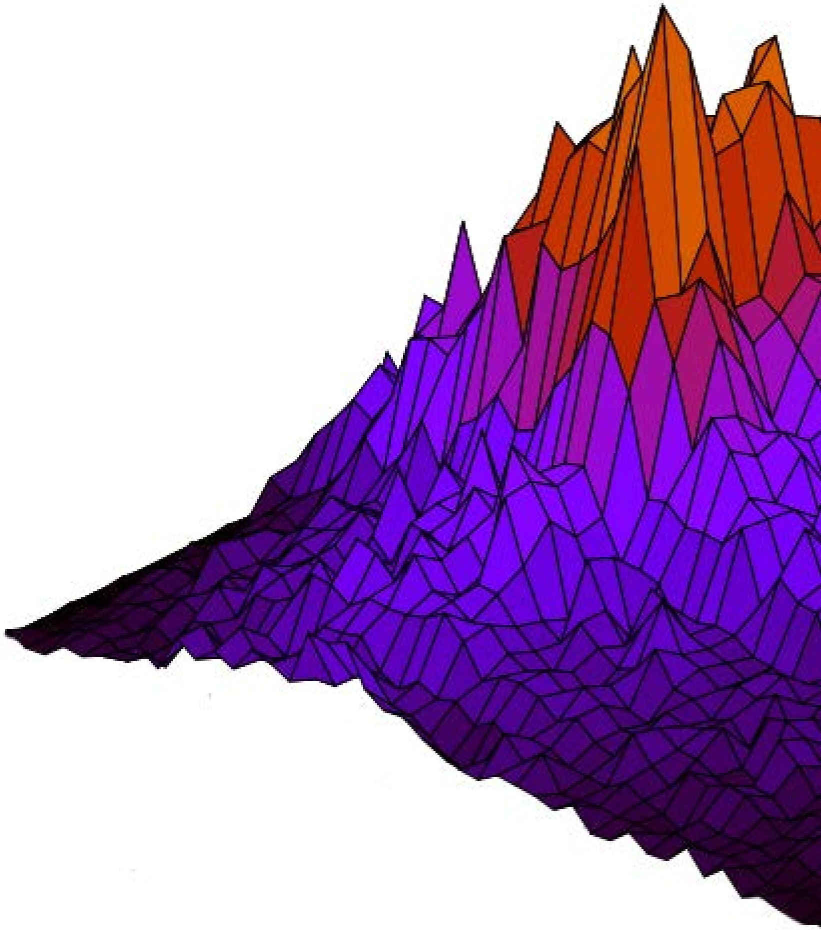
3) Summary and conclusion



Goals

Central questions to answer:

- How does the Space Debris environment impact the operations of the constellation?
- What kind of SST system is necessary to achieve protection of the constellation?



Methodology (1)

1st Phase
Simulating the „thruth“

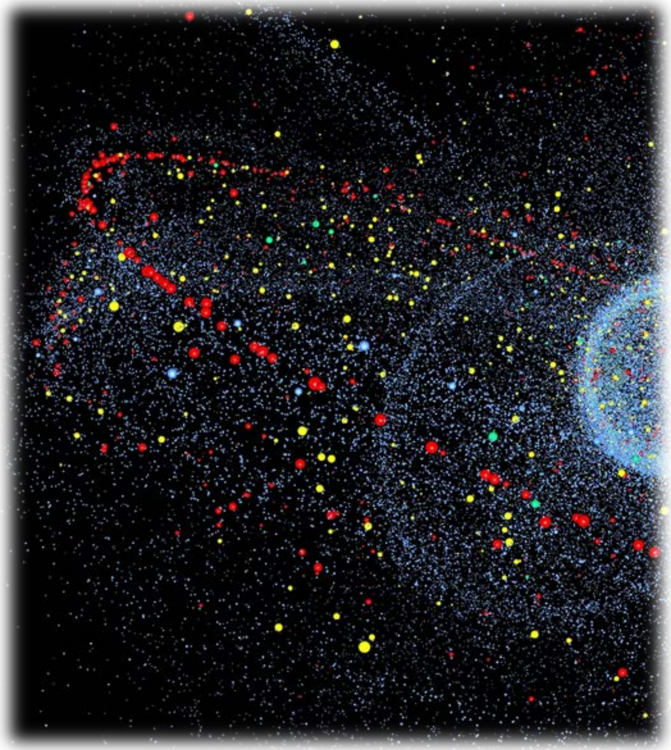
- Background population (d ≥ 4cm)
- Constellation satellites

- Realistic reference
- Determine close approaches (ClAp)

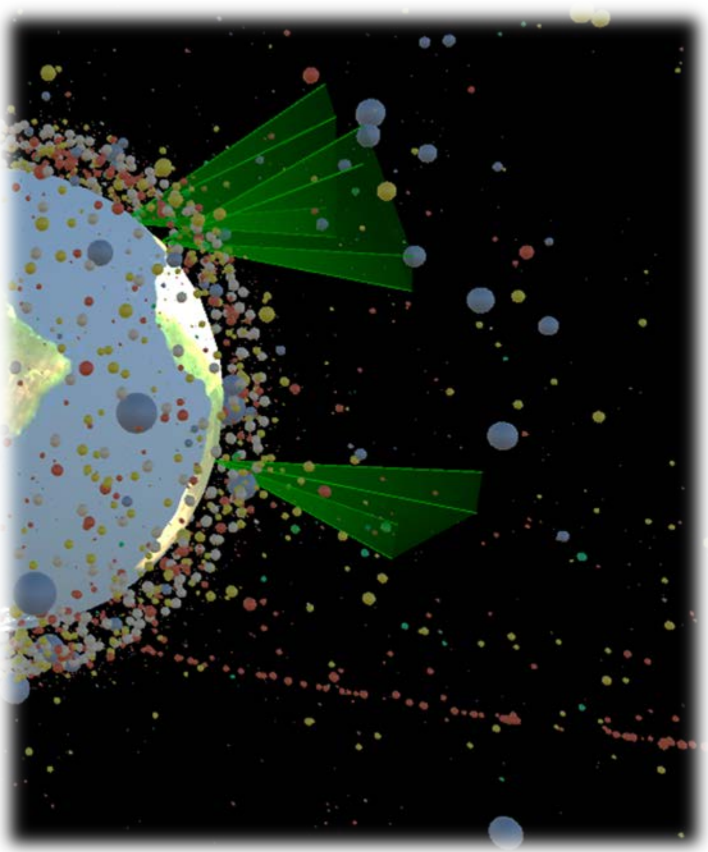
Deterministic snapshot within any random 7 days

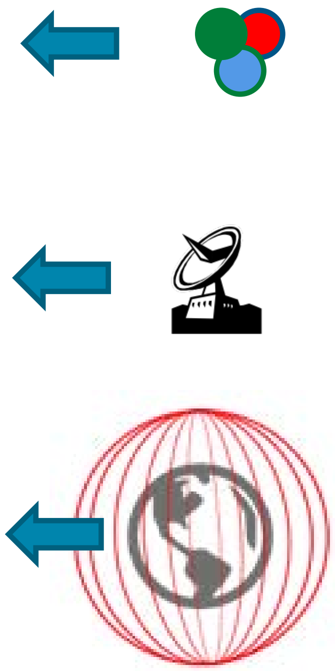
- Close approaches over time (debris vs. satellite)

MASTER 2009



Methodology (2)





Do for selected risk objects

2nd Phase
Simulated world

GPS

1. Generating detections
2. Realistic orbits & covar.
3. Close Approach Analysis
4. Collision Risk

Output

- Close approaches over time
- Collision warnings
- Collision probabilities
- Number of CAMs

Methodology (3)

Assumptions for 3rd party cataloguing services :

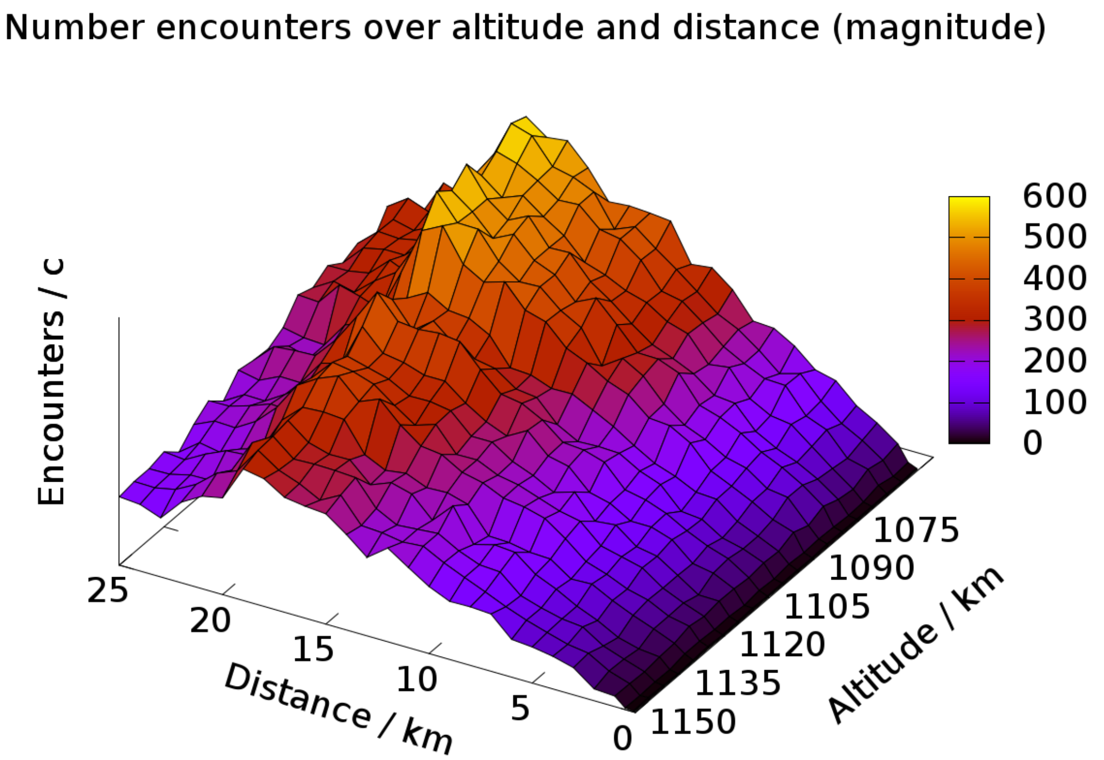
- ❖ Uncertainties:
  - a) UVW STD: **20 m / 282 m / 20 m (JSPOC)**
  - b) UVW STD: **7.5 m / 100 m / 40 m (JSPOC++)**
- ❖ State update interval: **1.5 days**
- ❖ Resolution: **10 cm or 4 cm with “Fencing” option**

Assumptions for additional tracking sensors:

- ❖ Sensors at
  - **a) Wachtberg/Germany („TIRA 0“)**
  - **b) Nairobi/Kenia (“TIRA 1”)**
  - **c) Shanghai/China (“TIRA 2”)**
  - **d) Kiruna/Sweden („TIRA 3“)**

Simulation Results
Phase 1 - On Station

- Overall close approaches for all **1080 satellites** “On Station”
- Spherical threshold: **20x50x20 km**
- More close approaches toward lower operational altitudes
- In the 7-day in the life of the constellation:
  - 176 208 overall encounter
  - 12 275 involved risk objects
  - **57 encounter closer than 500 m**
  - **4 encounter closer than 100 m**



Simulation Results
Phase 1 - EOR and PMD

❖ Overall close approaches for

a) **92 satellites in spiral up (manoeuvring)**

b) **300 satellites in spiral down (passive)**

❖ Crossing high spatial density region results in higher number of encounters

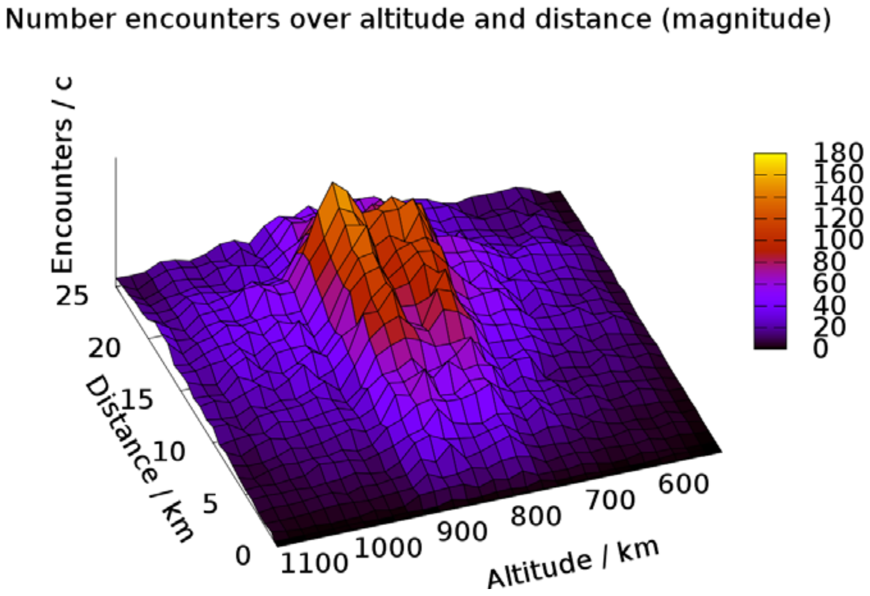
❖ In the 7-day in the life of the constellation:

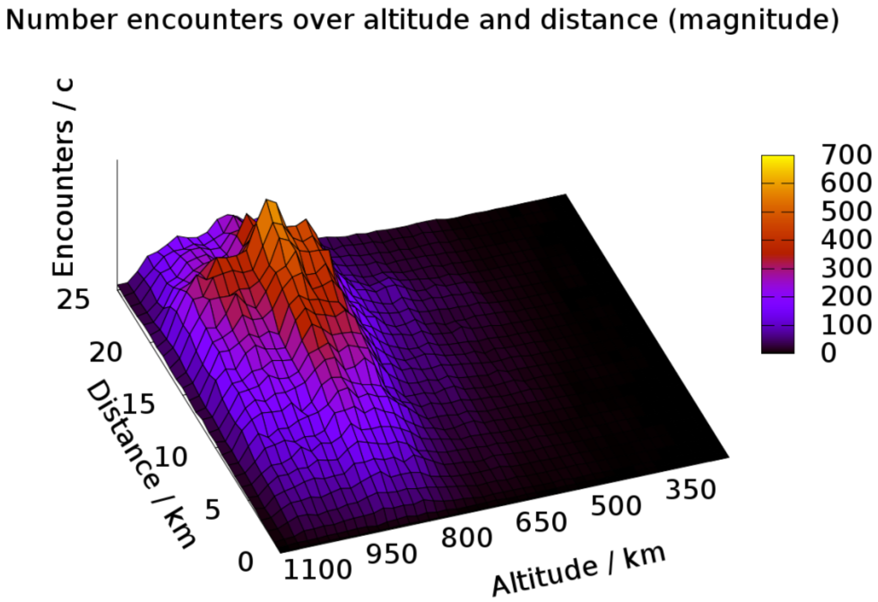
– 30 259 overall encounter (EOR)

– 137 285 overall encounter (PMD)

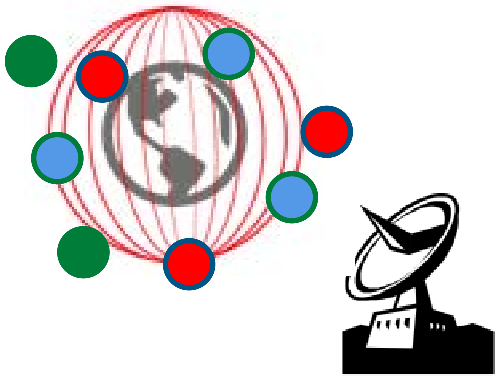
– **41 encounter closer than 500 m (PMD)**

– **8 encounter closer than 500 m (EOR)**





Simulation Results
Preparation of Phase 2

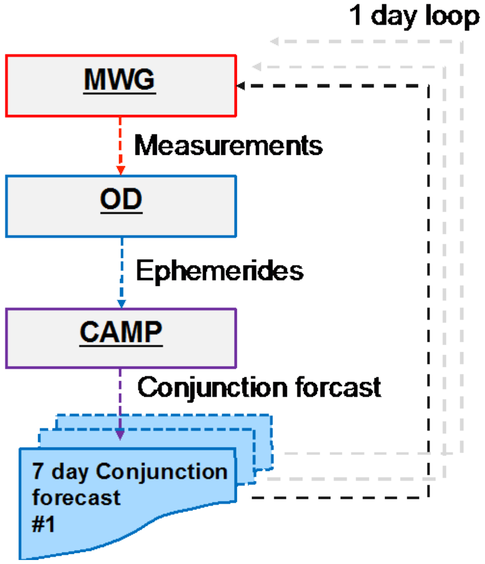


- ❖ How can an SST System deal with these close approaches?

- ❖ Complex Follow-up simulations:

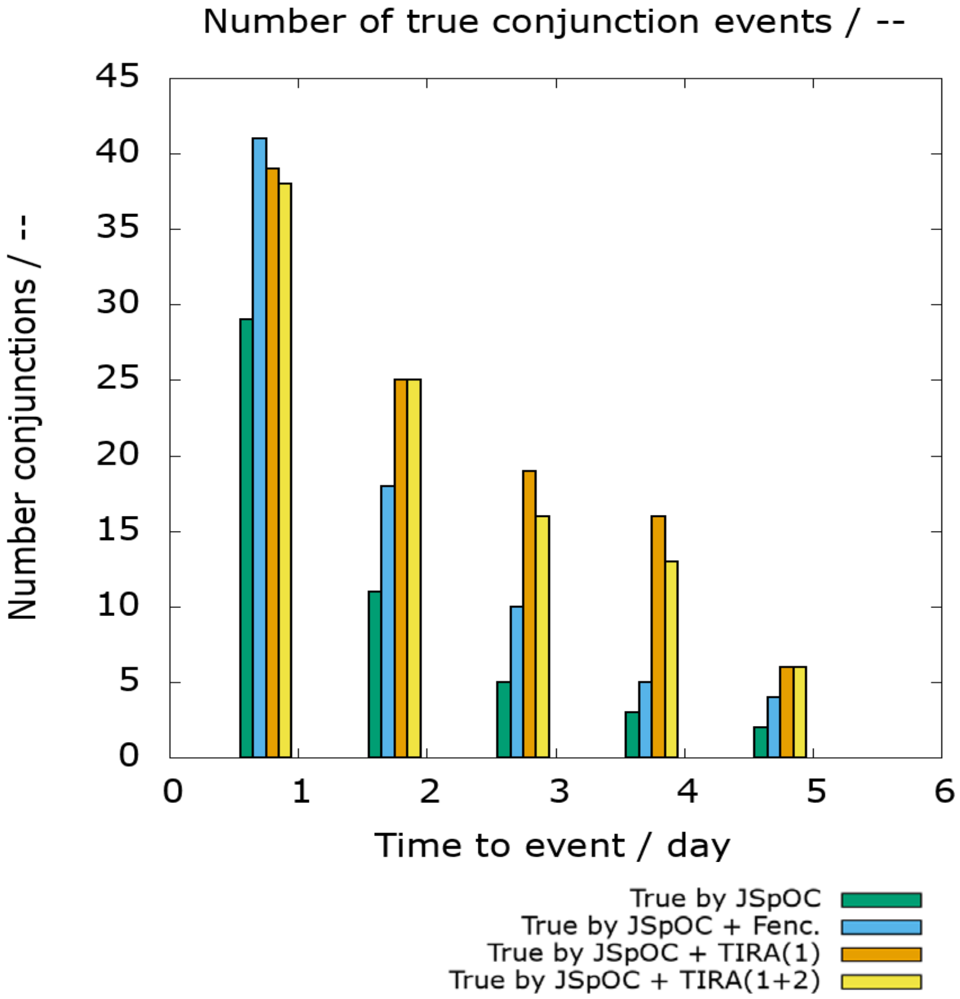
  - ➢ Random selection of **400 identified risk objects** that breach a **2 km threshold**

  - ➢ Setting up the Radar System Generator using
    1. Sensor Simulation (MWG) → Create noisy radar measurements
    2. Orbit determination algorithms (OD) → Create realistic orbit information
    3. Cataloguing service → Populate a catalogue with Target and Risk objects
    4. Perform conjunction analysis (CAMP) → **Daily conjunction reports**
    5. Compare against results of phase 1



Simulation Results
Phase 2 – On Station

- **118 conjunctions to be found**
- The closer to the event the more conjunctions are found
- Success rate is at 18% - 40%, depending on time and sensor
- Additional tracking means are more successful in the forecasts over multiple days ➔ reduced uncertainties through continuous tracking efforts)

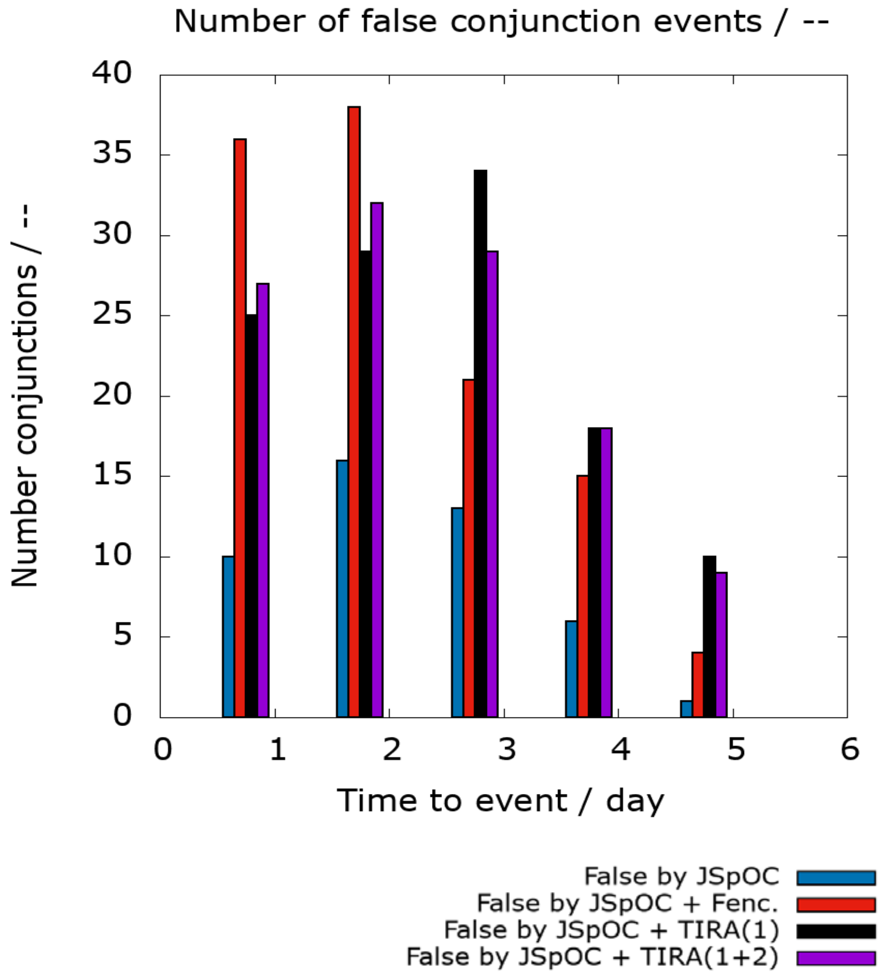


Simulation Results
Phase 2 – On Station

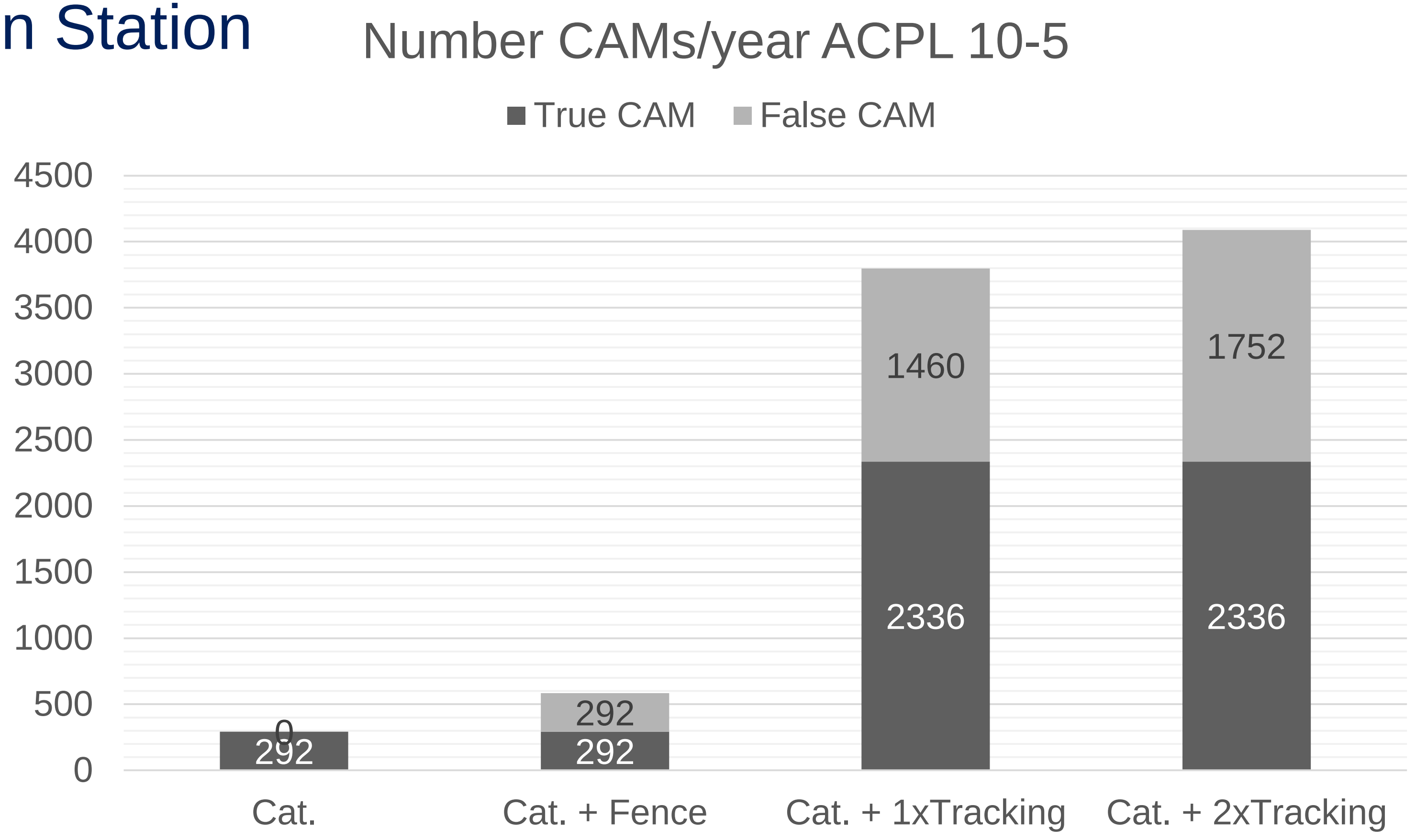
- Close approaches that are registered in phase 2 but not in phase 1 are marked as **'false' close approaches**

- Ratio between 'true' and 'false' close approaches is as low as 50% (especially close to to an event)

- The ratio drops quickly, as the forecast time (time to event) increases to 2 and 3 days



Simulation Results
Phase 2 – On Station



- CAM is triggered when
  - 1 day to the event
  - The ACPL (10^5) is reached

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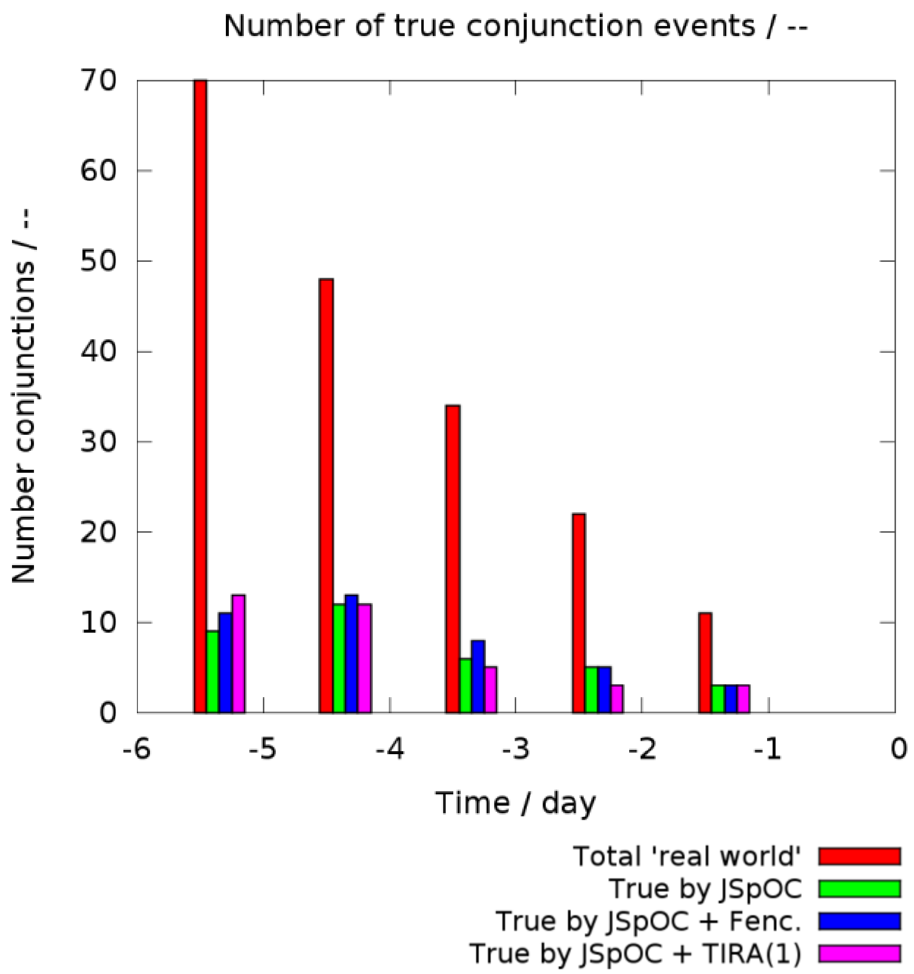
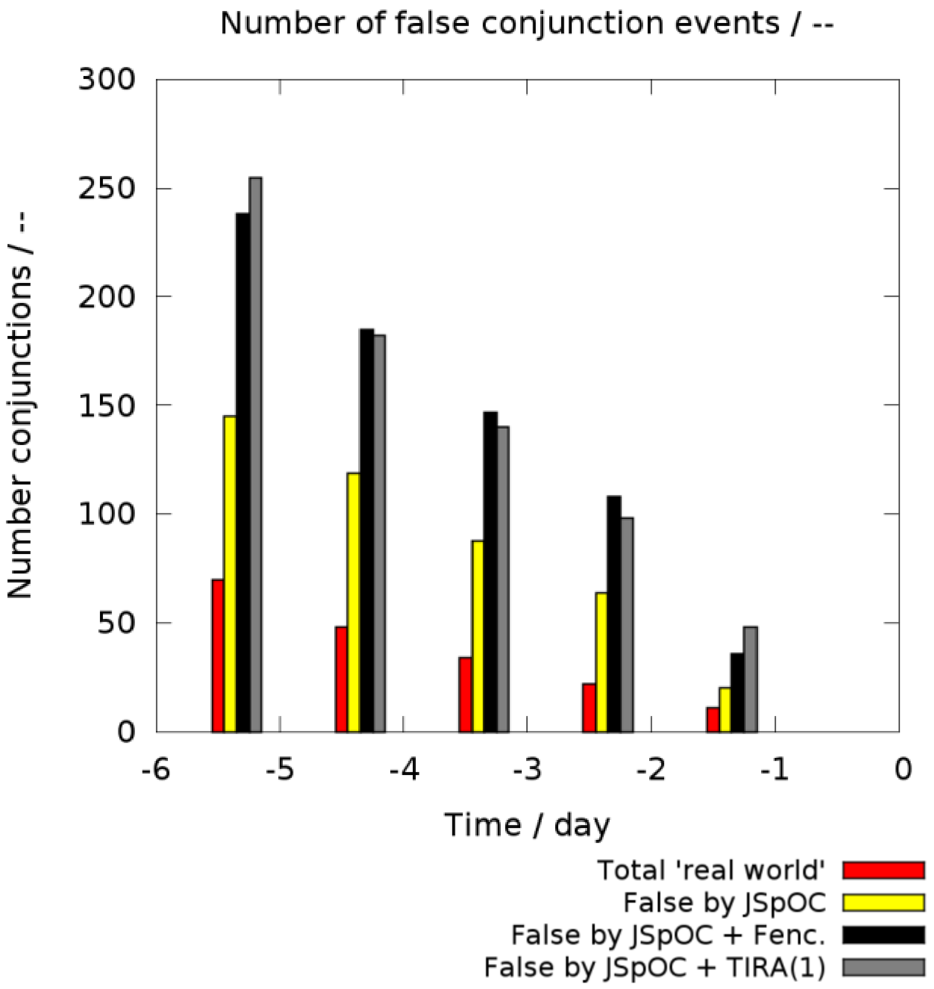
Simulation Results
Phase 2 – EOR

- **70 conjunctions to be found**
- Different representation of the data: per report vs per day to event
- Lower number of found conjunctions

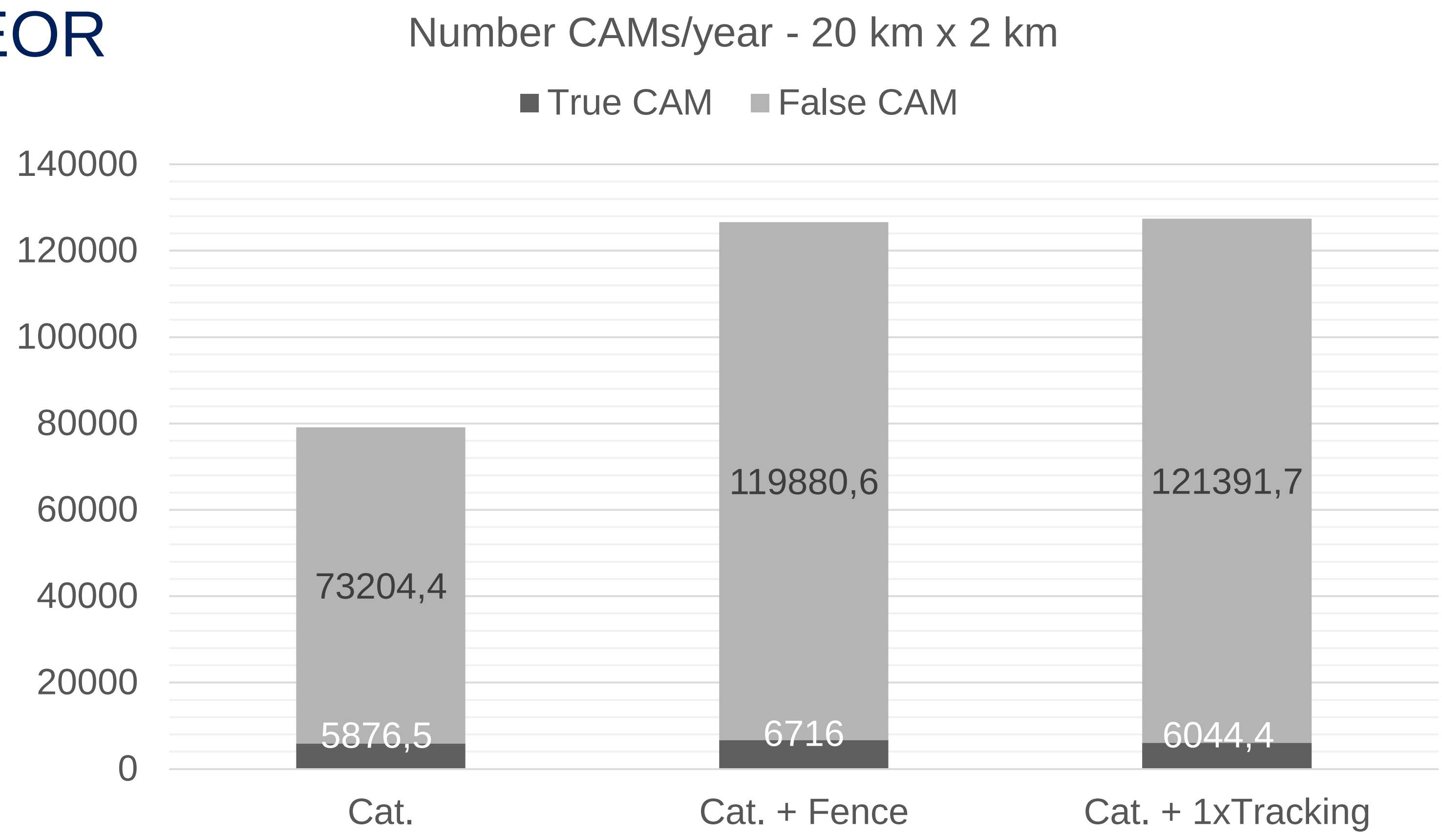


Simulation Results
Phase 2 – EOR

- **70 conjunctions to be found**
- Different representation of the data: per report vs per day to event
- Lower number of found conjunctions
- A lot **worse 'true' vs 'false' conjunction ratio ➔** caused not by uncertainty in the state vector of the risk objects by the **thrust uncertainty of the target** (constellation satellite)



Simulation Results
Phase 2 – EOR



- CAM is triggered when
  - 1 day to the event
  - Risk object penetrated 20 x 2 km threshold

Summary and conclusion

- ❖ Deterministic simulations show the ‘7 days in the life of a constellation’
- ❖ Under the chosen assumptions the SSA capabilities show weaknesses
  - ➢ Conjunctions are found only partially; ‘false’ conjunctions are ‘created’ by uncertainties in risk objects orbital states
  - ➢ Additional tracking means can complement available cataloguing services and reduce uncertainties in risk objects’ state vectors
  - ➢ Thrust phases of constellation satellites are problematic, as the uncertainties in the thrust phases propagate into the future ➔ larger threshold volumes are used, which can be penetrated by many more risk objects causing potential CAMS
- ❖ Caution: The numbers are too small to draw universal conclusions, even though trends are reflected, as one would expect and some numbers can also be found in statistical analysis tools, like ARES.

WP5200: End of Life Simulations

Jonas Radtke – TU Braunschweig

WP5200: Aims

Overall aim:

- Determine the impact of different constellation scenarios **defined in this project** on the
  - Constellation itself,
  - Overall space debris environment.

- Estimate the impact on the environment, use established environmental criticality criterions.

- Estimate the impact on the constellation itself, analyse:
  - Collision rates of constellation objects,
  - Assess collision avoidance efforts to be performed in the scenario.
  - Re-Run „Phase 1“ simulations of WP4200, using populations including possible feedback from the constellation scenario.

- Provide results as inputs for WP6000

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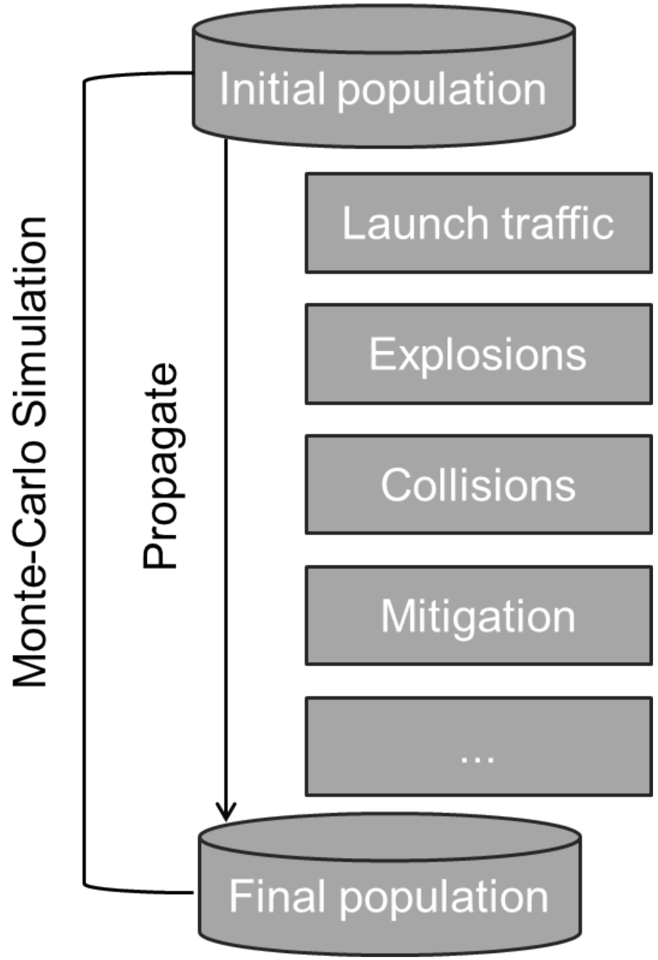
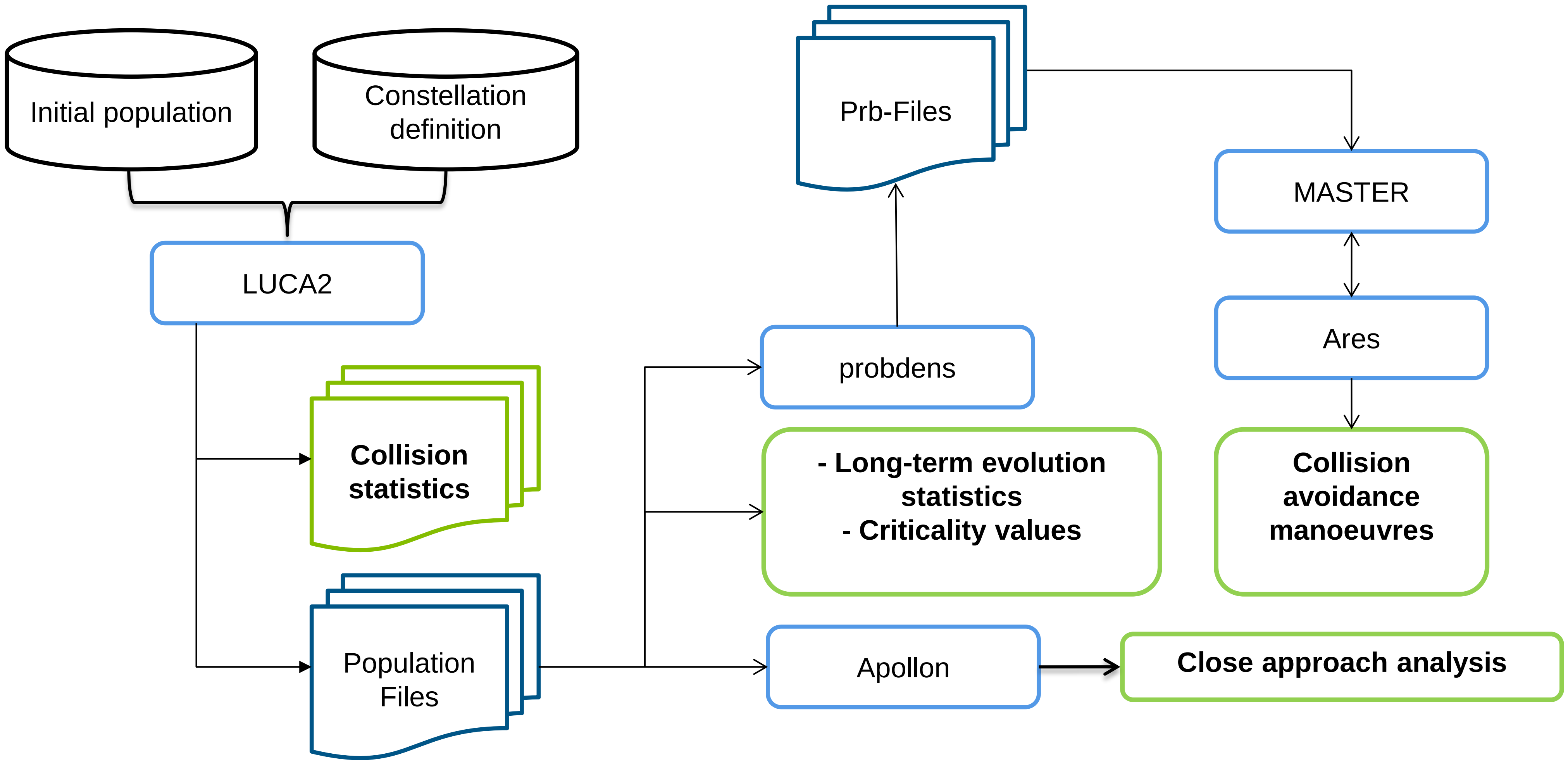
WP5200: Approach



- Run long-term simulations of the complete space debris environment
- Model the different constellations very detailed within the generally high-level simulations
- Consider all other objects in the environment ≥ 2 cm
- Run simulations in a reasonable small time step, to resolute the operations of constellation satellites
- Post-process simulation outputs

WP5200: Simulation environment

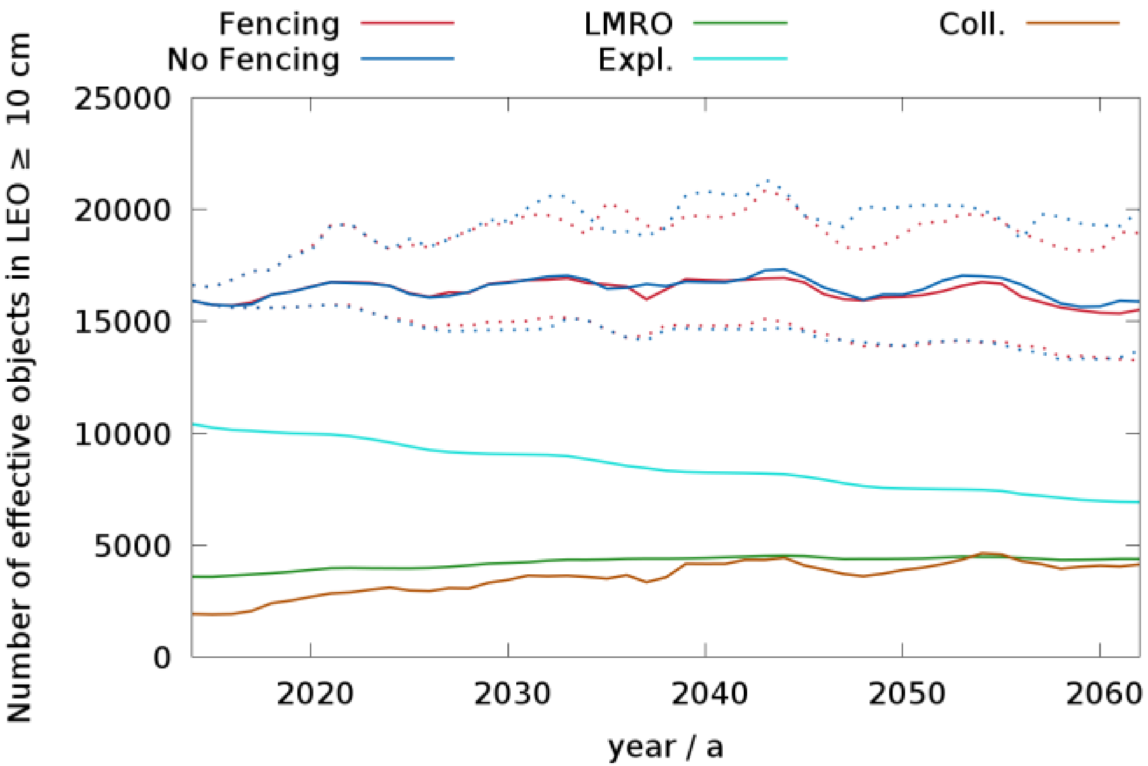


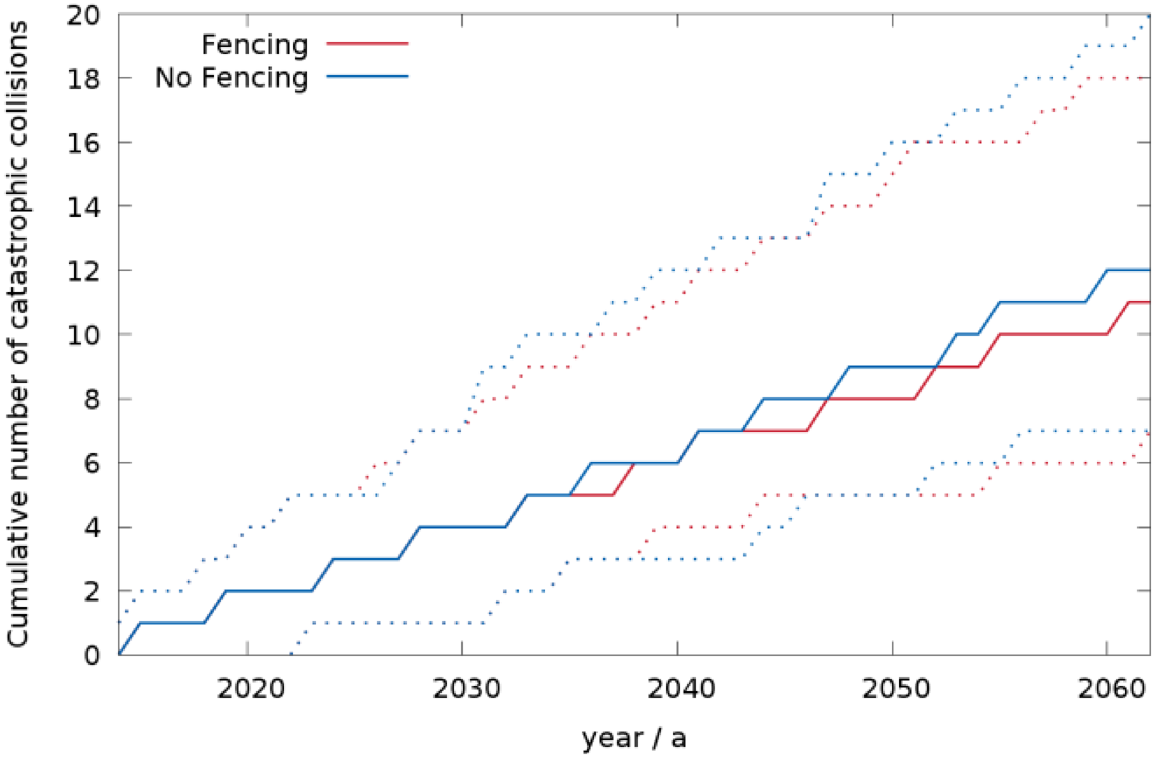
WP5200: Scenarios

In total, **eight scenarios** where simulated:

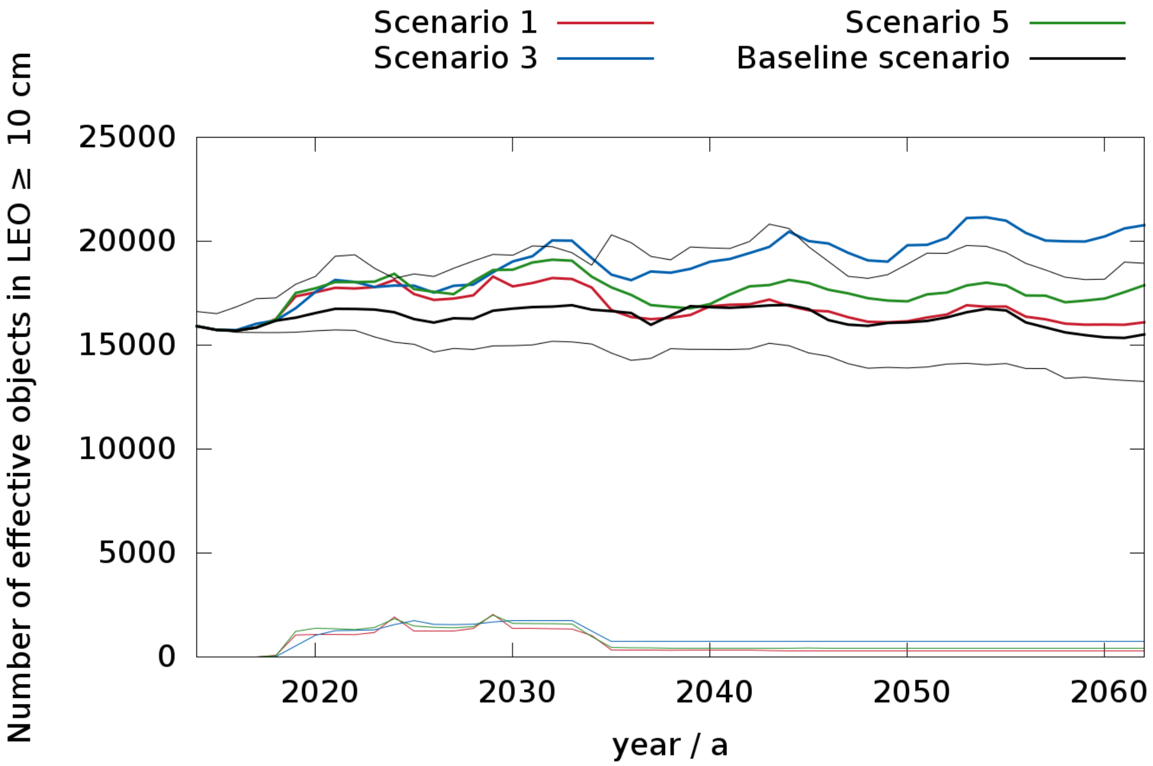
- Two **reference scenario**, which are used to assess the impact on the overall environment.
  - Assuming cataloguing capabilities as during Scenario 1 (10 cm catalogue until 2022, 2 cm visibility in 1100 km from 2023) as reference for Scenario 1 and standard 10 cm cataloguing performance (10 cm objects are visible) as reference for other scenarios.
  - Simulation time frame of 50 years, starting from January 1st 2013.
  - Repeating launch-cycle of non-constellation (= background) objects based on launched from 2005 to 2012
  - Assume a 90% post-mission disposal success rate to eccentric 25 year orbits for all non-constellation objects
- Three **constellation scenarios**, superimposing the defined constellations on top of the reference scenarios.
- **Three** additional **variations of constellation scenario 5**, varying the reliability and ADR availability.

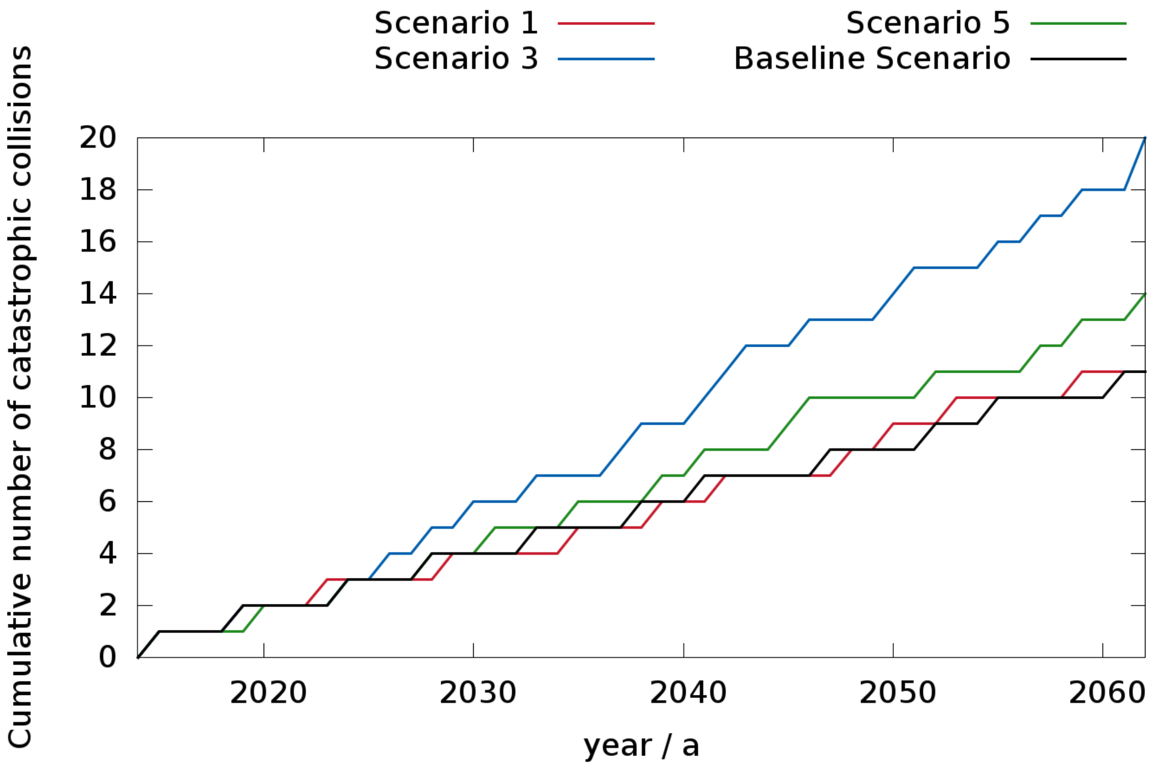
Simulation results: Reference scenarios





Simulation results: Constellation scenarios





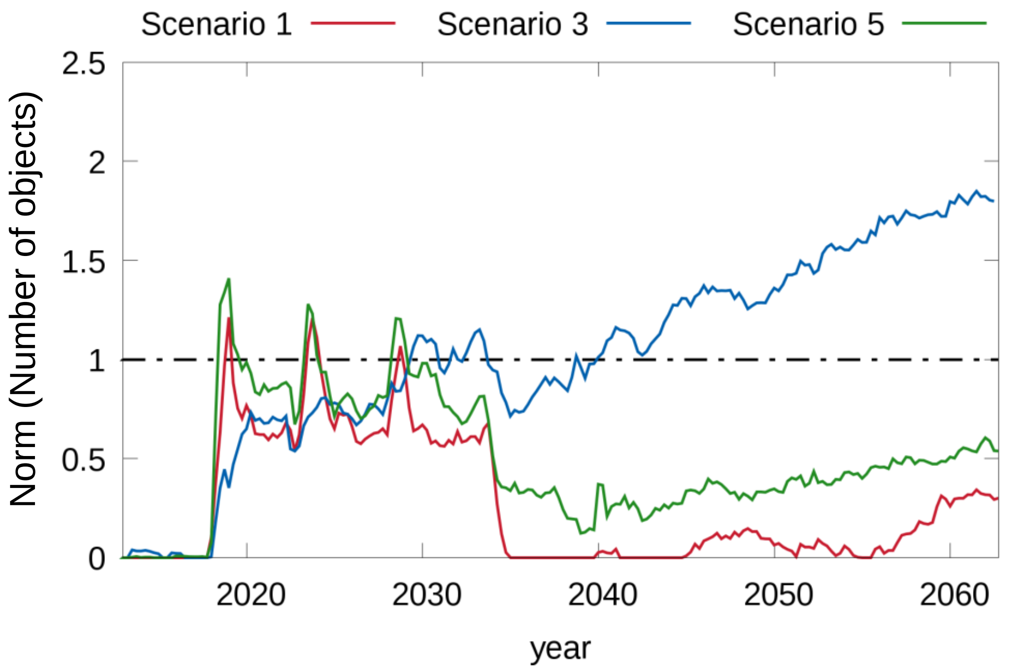
Simulation results: Impact on the environment

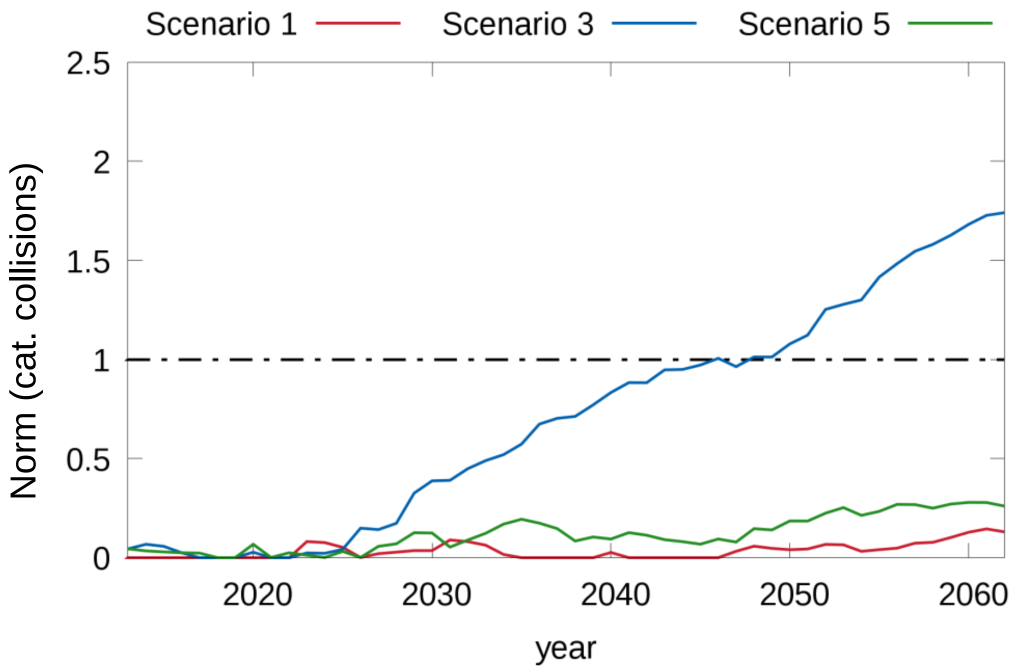
Measured in two different ways:

1. **Ranksum test** to identify the statistical significance of the difference in results.
    - Determines the likelyhood of two random sets of values to be based on populations with identical medians.

2. **Environmental criticality** to state „how far the results of a test scenario are outside those of a reference scenario“.

Simulation results: Impact on the environment: Criticality norm





→ The constellations show an impact on the number of objects during their operational lifetime. The long-term impact directly depends on the number of constellation objects left in the environment.
→ The impact on the catastrophic collisions increases over time, until left constellation objects start colliding.
→ Results from the ranksum allow similar conclusions.

Simulation results: Environment impact summary

	Ranksum, #objects	Ranksum, collisions	ΣNorm, #objects	Norm. Rank	ΣNorm, collisions	Norm. Rank
Scenario 1	No impact*		1.07	0.8	0.03	0.2
Scenario 3	Significant impact		4.03	3.0	0.70	3.00
Scenario 5	Significant impact		1.95	1 .5	0.12	0.51
Scenario 5.1 (low rel.)	Significant impact		3.5	2.6	0.51	2.2
Scenario 5.2 (medium rel.)	Significant impact		2.8	2.1	0.41	1.8
Scenario 5.3 (later ADR)	Significant impact		2.54	1.9	0.33	1.4

*impact on number of objects significant while constellation is operational.

- → A carefully designed constellation can be operated in the environment without causing a long-term impact.
- → The results are very sensitive to small changes in the constellation design.
- → Changes in the number of satellites, reliability, operational lifetime etc. have the potential to turn-around a “no-impact” constellation into a “significant impact” constellation.
- → It was assumed that all constellation rocket bodies performed a direct re-entry.

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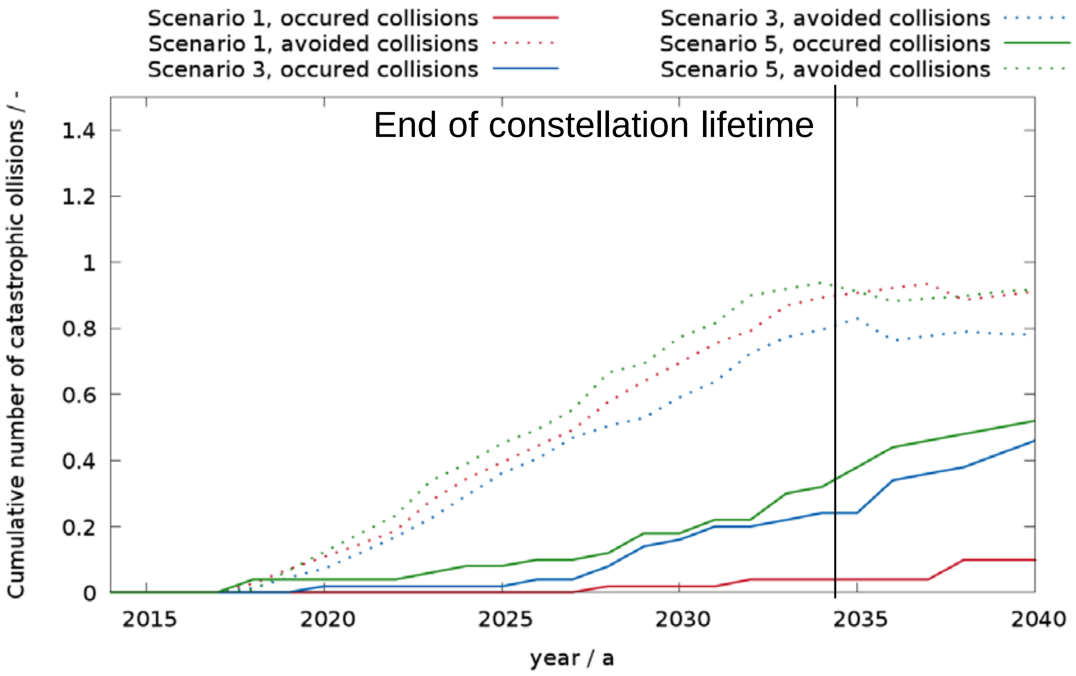
Simulation results: Impact on the constellation

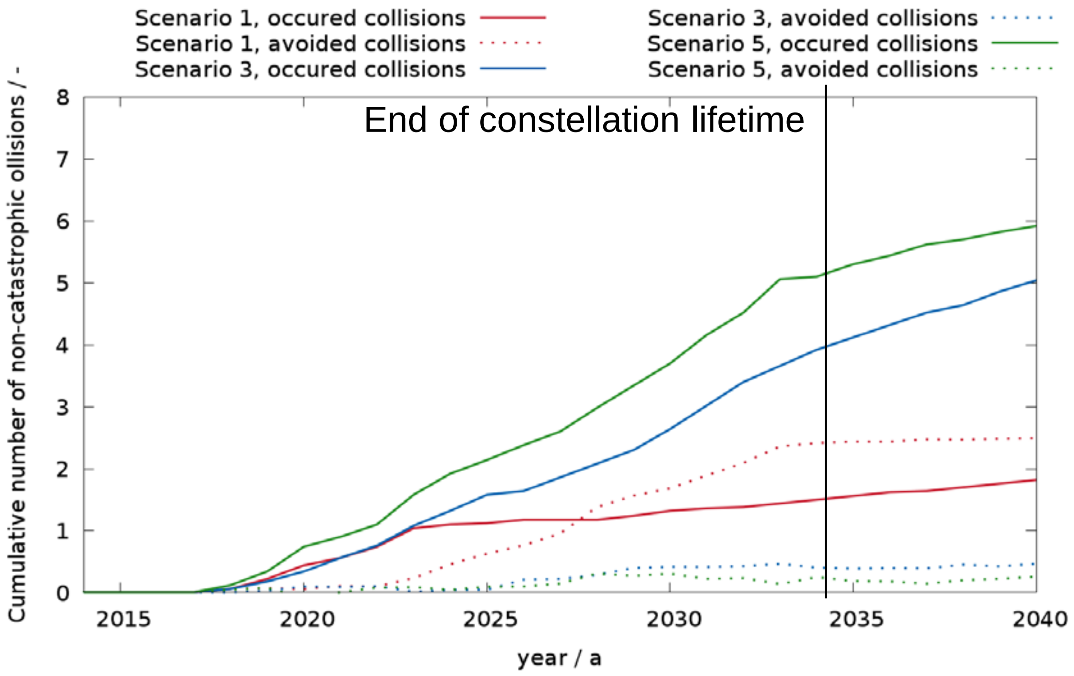
- The impact on the constellation itself was measured using three different methods:
  - Based on the actual collisions and collision rates taken from the long-term simulation results.
  - Analyse the long-term simulation results with DRAMA-ARES to get the expected number of collision avoidance manoeuvres.
  - Re-perform simulations from WP4200 with population snapshots from the long term simulations.

- Analysis has been performed for Scenarios 1, 3 and 5, iterations of Scenario 5 have not been considered.

- **Note:** In the direct results from long-term simulations, no ACPL as threshold for collision avoidance could be considered. In there, all collisions with objects larger than the visible object threshold were avoided.

Collision rates from the long-term simulations





- **Catastrophic collisions:** Scenario 1 shows the overall lowest collision rates (in parts due to less constellation objects and higher satellite reliability) and lowest number of occuring collisions (inparts due to lower collision rates and a better SSA system).
- **Non-catastrophic collisions:** Again, Scenario 1 shows lowest collision rates (due to similar reasons), furthermore, due to the enhanced SSA system, it is the only scenario in which non-catastrophic collisions can be avoided effectively.

Collision avoidance efforts

	ACPL	Generation 1	Generation 2	Generation 3	Total
Constellation 1	1.e-4*	1.07	1.08	1.16	3.31
Constellation 1	Fence**	1.07	18.19	17.99	37.25
Constellation 3	1.e-3*	0.074	0.09	0.115	0.279
Constellation 5	1.e-4*	0.96	0.98	1.05	2.99

*Stated ACPL was used against 10 cm objects.

**Generation 1 used an ACPL of 1e-4 against 10 cm objects, for generation 2 and 3, an ACPL of 1e-5 against 2 cm objects was used.

→ Values stated are valid for the complete active lifetime of one satellite of each generation (thus, they are valid for timespans of 5 – 5.75 years).

→ Number of avoidance manoeuvres mostly depends on the sensitivity of the SSA system and the ACPL.

→ No clear trends of changes in the collision avoidance effort over time visible.

Summary: Impact on the constellation

Scenario	# total manoeuvres / sat / 15 a	# max. avoidable cat. coll	# max avoidable non-cat coll
1	3.31	Ca. 0.93	Ca 0.4
1, fence	37.25	0.93	2.4
3	0.279	0.8	0.4
5	2.99	0.95	0.6

→ In terms of catastrophic collisions, all scenarios are very similar. All available SSA systems are capable of avoiding almost all catastrophic collisions during the active lifetime of the constellations. Furthermore, over this time frame, no clear changes in collisions rates and/or expected number of avoidance manoeuvres could be observed.

→ For non-catastrophic collisions (which might lead to total losses of satellites), the results is different. In here, a more sophisticated SSA system is a clear benefit for the constellation, as it helps avoiding alomst all non-catastrophic collisions of active satellites. Nevertheless, compare with satellites lost due to system reliability, these numbers are very low.

WP6000 – Comparative Strategy Costing

Luc Piguet, Muriel Richard-Noca
Thierry Meyer, Marie-Valentine Florin

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WP6000 Objectives

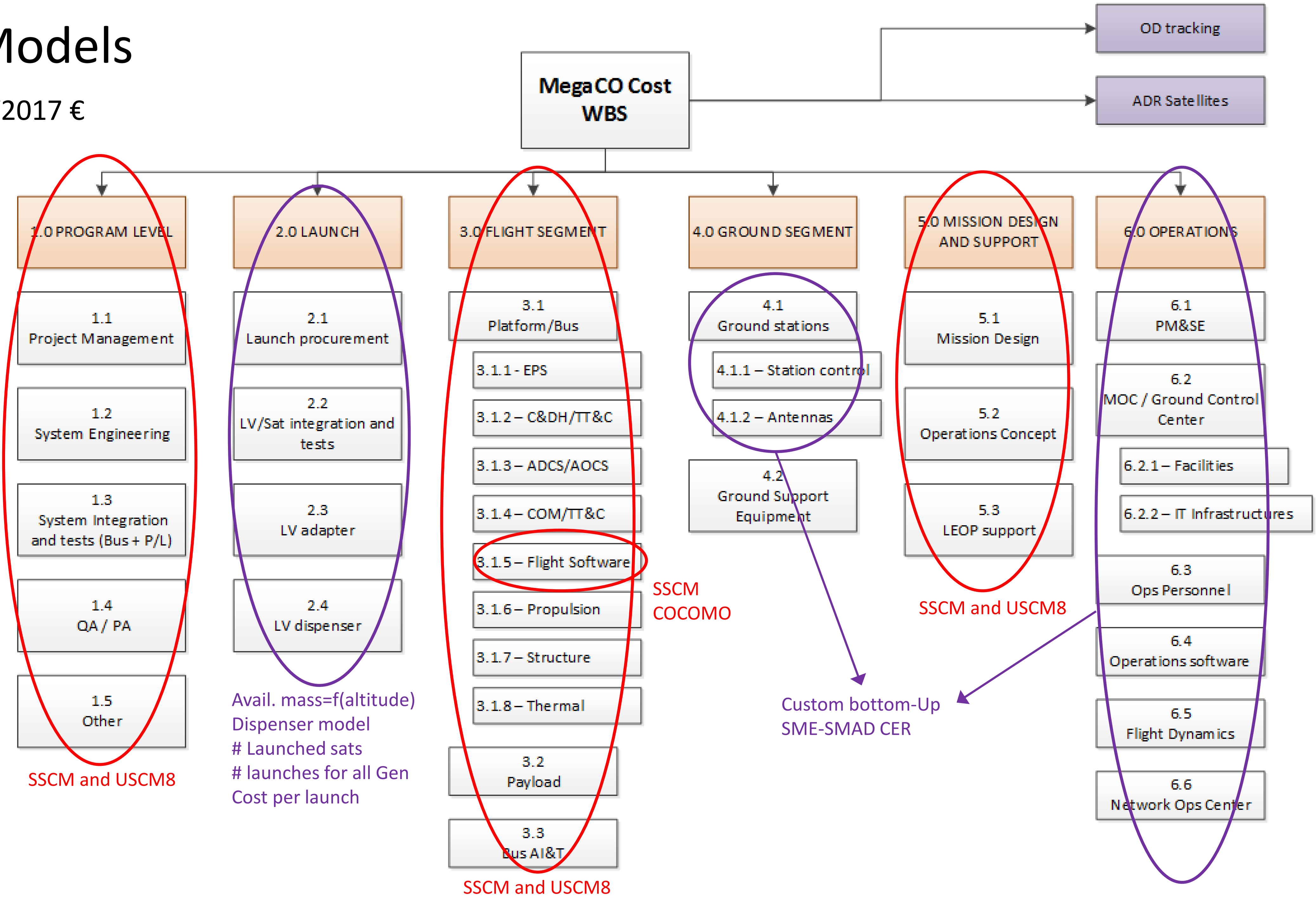
- **Relative** cost and risk assessment of operational scenarios 1-3-5 and selection of scenario to push forward

- Process:
  1. Established cost WBS and cost models based on outputs of preceding WP
  2. Ran the models for all 3 major cost items:
     a. Launch cost
     b. Flight system cost
     c. Ground system and Operations
  3. Outline cost and impact for salient choices
  4. Summarize cost and impact, recommand a scenario

In this presentation, MgC = MegaConstellation, ADR = Shepherd

0. Cost Models

ALL COST in FY2017 €



2.0 Launch Segment - results

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2.0 LAUNCH COST (M€)			SCENARIO 1			SCENARIO 3			SCENARIO 5		
				High end system			Proven Tech			"New Space"	
Domain	**Sub domain**	**Parameter**	GEN 1	GEN 2	GEN 3	GEN 1	GEN 2	GEN 3	GEN 1	GEN 2	GEN 3
Cost Inputs	**Units**										
Total of nominal + spares MgC sats		WP1000	1080	1080	1080	1280	1220	1180	1280	1220	1180
Number of spares added during the mission		WP5200	15	5	3	0	0	0	0	0	0
Number of Shepherd satellites used, M		WP5200	0	0	0	0	0	0	93	64	32
Total of nom. + spares + ADR sats		WP1000	1080	1080	1080	1280	1220	1180	1373	1284	1212
LAUNCH OF CONSTELLATION											
Primary launch vehicle type			Atlas 551	Falcon 9 FT	Falcon 9 FT	Atlas 551	Falcon 9 FT	Falcon 9 FT	Atlas 551	Falcon 9 FT	Falcon 9 FT
Target orbit altitude	km		500	500	500	1000	1000	1000	500	500	500
Number of sat per launch (effective)			49	39	39	56	42	42	62	49	49
Required total number of primary launches			22	27	27	22	29	28	20	24	24
Extra-satellites to be used with smaller launchers			2	27	27	48	2	4	40	44	4
Secondary launch vehicle type			Virgin LauncherOne	Falcon 9 FT	Soyuz-2	Soyuz-2	PSLV	PSLV	Soyuz-2	Falcon 9 FT	PSLV
Mass injected in target orbit	kg		300	11760	4627	4290	1229	1229	4627	11760	2000
Number of sat per launch (effective)			1	39	15	17	5	5	19	49	8
Required total number of secondary launches			2	1	2	3	1	1	3	1	1
Total prim.+sec. launch cost	**M€**		**3 386**	**1 736**	**1 834**	**3 606**	**1 829**	**1 767**	**3 300**	**1 550**	**1 519**
LAUNCH OF ADDITIONAL SPARES AND SHEPHERD SATS											
Primary launch vehicle type			PSLV	Virgin LauncherOne	Virgin LauncherOne	PSLV	PSLV	PSLV	Atlas 401	PSLV	PSLV
Target orbit altitude	km		500	500	500	1000	1000	1000	500	500	500
Mass injected in target orbit	kg		2000	300	300	1229	1229	1229	6955	2000	2000
Number of sat per launch (effective)			6	1	1	4	5	5	29	8	8
Required total number of extra launches			3	5	3	0	0	0	4	8	4
Cost of extra launch vehicle/launc	M€		31	10	10	31	31	31	109	31	31
Total cost of extra launch vehicles	M€		93	50	30	0	0	0	436	248	124
Total extra spares+shepherd	**M€**		**93**	**50**	**30**	**0**	**0**	**0**	**436**	**248**	**124**
TOTAL Constellation Launch cost		**M€**	**3 479**	**1 786**	**1 864**	**3 606**	**1 829**	**1 767**	**3 736**	**1 798**	**1 643**

3.0 Flight Segment

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3.0 FLIGHT SEGMENT COST (M€)			SCENARIO 1			SCENARIO 3			SCENARIO 5		
				High end system			Proven Tech			"New Space"	
Cost Inputs	Units										
Mass of MgC Satellites	kg		254			213			203		
Mass of ADR Satellites	kg								250		
Flight system cost breakdown			Cost for GEN1			Cost for GEN1			Cost for GEN1		
1.1 Spacecraft Bus			Dev 1st Unit	2nd Unit	Total	Dev 1st Unit	2nd Unit	Total	Dev 1st Unit	2nd Unit	Total
1.1.1 Structure	k€		5944	5349	11293	4233	3810	8044	4308	3877	8186
1.1.2 Thermal	k€		622	560	1182	381	343	723	437	393	830
1.1.3 ADCS	k€		8168	7351	15518	7616	6855	14471	7683	6914	14597
1.1.4 Electrical Power System	k€		8638	7774	16412	4357	3921	8278	5409	4868	10277
1.1.5 Propulsion	k€		2442	2198	4640	1648	1483	3131	1761	1585	3345
1.1.6a TT&C	k€		3327	2994	6320	3156	2841	5997	3177	2859	6036
1.1.6b Command & Data Handling	k€		1544	1389	2933	1491	1342	2834	1498	1348	2846
1.1.7 Integration, Assembly, & Te	k€		4265	3838	8103	3181	2863	6043	3374	3036	6410
1.1.9 Flight Software†	k€	SLOC in first cell	38100		20955	38100		20955	38100		20955
1.1 Spacecraft Bus Total Cost	k€				87357			70475			73481
1.2 Payload	k€				12273			9153			9709
DEVELOPMENT COST			GEN 1	GEN 2	GEN 3	GEN 1	GEN 2	GEN 3	GEN 1	GEN 2	GEN 3
Total satellite development co	**M€**	***dev TRL 6 to 9***	**100**	**50**	**33**	**80**	**40**	**27**	**83**	**42**	**28**
Satellite development + series production cost			**299**	**50**	**33**	**239**	**40**	**27**	**250**	**42**	**28**
RECURRING COST											
Total of nom. + total spares + ADR sats			1095	1085	1083	1280	1220	1180	1373	1284	1212
Cost of MgC sats	ESA estimate/sat M€:	0.5	548	543	542	640	610	590	640	610	590
Cost of ADR sats	Discussed estimate/sat:	1							93	64	32
Total recurring cost of sats	**M€**		**548**	**543**	**542**	**640**	**610**	**590**	**733**	**674**	**622**
TOTAL Flight Segment cost		**M€**	**647**	**592**	**575**	**720**	**650**	**617**	**816**	**716**	**650**
TOTAL ALL GEN				**1 814**			**1 986**			**2 182**	
TOTAL Flight Segment + Prod cost		**M€**	**846**	**592**	**575**	**879**	**650**	**617**	**983**	**716**	**650**
TOTAL ALL GEN with PROD				**2 013**			**2 145**			**2 348**	

4.0-6.0 Ground Segment and Operations

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4.0-6.0 GROUND SEGMENT + OPS COST (M€)				SCENARIO 1				SCENARIO 3				SCENARIO 5			
				High end system				Proven Tech				"New Space"			
Domain	Sub domain		Parameter / selected opt	TRL	GEN 1	GEN 2	GEN 3	TRL	GEN 1	GEN 2	GEN 3	TRL	GEN 1	GEN 2	GEN 3
Cost Inputs		Units													
Mission duration			yrs		5	5	5		5	5	5		5	5	5
EOR duration			yrs		16	12	12		-	-	-		20	10	10
Ground segment and operations cost															
Ground Control Centers (GCC)															
	Control centers (CC)				2	2	2		2	2	2		2	2	3
						1 nominal + 1 cold redundant (2x staff)				1 nominal + 1 hot redundant (2 x staff)				Rotating control + 1 Hot redund (2x12/24 or 3x12/24)	
		Number of m2/center	# of staff * 10 m2/staff, m2		3 000	3 360	3 360		6 220	1 060	1 020		4 060	4 340	4 100
		Space cost/location/m2	6000	Europe	5 400	5 400	5 400	ern asia	3 240	3 240	3 240	Europe	5 400	5 400	5 400
		CC building cost	k€		16 200	18 144	18 144		20 153	3 434	3 305		21 924	23 436	22 140
		Total CC building cost	**k€ (for x centers)**		**32 400**	**36 288**	**36 288**		**40 306**	**6 869**	**6 610**		**43 848**	**46 872**	**66 420**
	IT infrastructure					Private cloud				Traditional				Hybrid cloud	
		Total IT infrastructure cost	**k€ (for x centers)**		**2 000**	**2 000**	**2 000**		**2 000**	**2 000**	**2 000**		**4 000**	**4 000**	**6 000**
	Ground control software														
		CAM automation	TRL		4	2	2		8	4	4		4	2	2
			Dev. + maintenance cost, k€		4 714	9 429	9 429		2 000	4 714	4 714		4 714	9 429	9 429
		Other ground automation	TRL		5	4	4		6	5	5		5	4	4
		Delta-dev. cost, k€	100000		40 122	46 295	46 295		30 863	40 122	40 122		40 122	46 295	46 295
		Maintenance cost	k€		20 061	23 147	23 147		15 432	20 061	20 061		20 061	23 147	23 147
		Total GCS cost	**k€**		**60 183**	**69 442**	**69 442**		**46 295**	**60 183**	**60 183**		**60 183**	**69 442**	**69 442**
Staffing cost/yr															
	Managers		k€/yr		2 184	2 184	2 184		2 184	2 184	2 184		2 184	2 184	2 184
	System administrators		k€/yr		1 578	1 578	1 578		2 366	2 366	2 366		789	789	789
	Experts		k€/yr		1 092	1 092	1 092		546	546	546		1 638	1 638	1 638
	Engineers		k€/yr		1 984	1 984	1 984		1 984	1 984	1 984		1 984	1 984	1 984
	Operators during orbit transfers		k€/yr		49 600	54 560	54 560		14 880	1 984	1 984		72 416	80 352	75 392
	Operators during mission		k€/yr		17 856	21 824	21 824		131 936	16 864	15 872		21 824	20 832	19 840
	Total staffing cost/Gen		**k€ (x centers+redundancy)**		**331 587**	**352 088**	**352 088**		**1 538 964**	**259 284**	**249 364**		**226 414**	**186 734**	**178 467**
External interfaces															
	JSpOC		Free												
	Alternative tracking means		See Advanced OD capabilty		GNSS + JSpOC	GNSS + JSpOC + Fencing 2 cm			GNSS + JSpOC	GNSS + JSpOC			GNSS + JSpOC	GNSS + JSpOC + "TIRA"	
	Alternative fencing means		COMSPOC		-	1 000	1 000		-	-	-		0	0	0
	Network Operations Center		-												
	Total fencing means cost		**k€**		**-**	**1 000**	**1 000**		**0**	**0**	**0**		**0**	**0**	**0**
Ground stations															
	Antenna/station control		k€ upfront cost		1 000	1 000	1 000		1 000	1 000	1 000		1 000	1 000	1 000
	Type of antennas				Traditional	Reactive	Reactive		Traditional	Traditional	Traditional		Gateways	Reactive	Reactive
	Antennas for orbit transfers		#/site*nb of sites		44	12	12		6	6	6		58	14	14
	Antennas for mission phase		#/site*nb of sites		12	6	6		15	15	15		0	6	6
	Antenna upfront cost		k€		800	300	300		800	800	800		-	300	300
	Maintenance cost/antenna		7%		56	21	21		56	56	56		-	21	21
	Total cost related to antennas		**k€**		**48 936**	**6 778**	**6 778**		**18 976**	**18 976**	**18 976**		**1 000**	**7 420**	**7 420**
Network			-												
Total Ground Control Center cost			**M€**		**475**	**468**	**468**		**1 647**	**347**	**337**		**335**	**314**	**328**

Cost deltas of specific topics

A. Impact of overall reliability (satellite + PMD)
- Captured in the extra flight system development cost (Sc1 is 25% > Sc3, Sc5 4%>Sc3), the overall flight segment cost (Sc1/Sc3 are ~10% > Sc 3), and the associated launch cost (few% differences)
- The overall cost impact of a high reliability compared to a low reliability system is relatively small at constellation level, but has a large impact on the debris environment.

B. Impact of CAM strategies
- EP's assumed dispersions in the thrust during orbit transfers increases the complexity of the operations, of the CAM and thus the staff required on the ground, and number of ground station antennas (by a factor of 2-3 compared to Chemical). The effects of CAM autonomy are second order from a cost point of view.

C. Fencing and tracking means
- Calculated based on the number of CAM to be performed per year by the MgC satellites
- Also tracking and fencing means both also require about 50% more operational manpower for SK and CAM
- The cost of advanced tracking capability is evaluated and is a major driver. However, the benefits will be tangible if the cost/CAM can be reduced by a factor of 10 compared to current ground capabilities. The Fencing cost are also second order.

D. Impact of PMD strategies
- Driven by the choices of the propulsion system (development cost), PMD orbit, reliability at the EoL, to some extend ground automation, and the required number of antennas
- Delta cost between PMD options are relatively low, second order

Overall scenario cost analysis results

- The results at generation level and constellation scenario level show a wide spread of cost. One must remember all the scenario design choices made for each Generation before drawing conclusions.

- The “traditional” versus “new tech/enhancements” are shown in the differences between G1 and G2 in most scenarios. Taking G2 as a reference, it is possible to highlight the major cost drivers that affected the scenario in order of importance

Cost in M€ FY2017	SCENARIO 1			SCENARIO 3			SCENARIO 5		
	High end system			Proven Tech			"New Space"		
	GEN 1	GEN 2	GEN 3	GEN 1	GEN 2	GEN 3	GEN 1	GEN 2	GEN 3
2.0 LAUNCH	**3 479**	**1 786**	**1 864**	**3 606**	**1 829**	**1 767**	**3 809**	**1 798**	**1 643**
Total prim.+sec. launch cost	3 386	1 736	1 834	3 606	1 829	1 767	3 373	1 550	1 519
Total extra spares+shepherd	93	50	30	0	0	0	436	248	124
3.0 FLIGHT SEGMENT	**846**	**592**	**575**	**879**	**650**	**617**	**983**	**716**	**650**
Satellite dev. + series prod. set-up cost	299	50	33	239	40	27	250	42	28
Total recurring cost of sats	548	543	542	640	610	590	733	674	622
4.0 GROUND SEGMENT + 6.0 OPS	**475**	**468**	**468**	**1 647**	**347**	**337**	**335**	**743**	**756**
Total Ground Control Center cost	475	468	468	1647	347	337	335	314	328
Advanced OD capability cost	0	0	0	0	0	0	0	428	428
TOTAL/GEN	**4 809**	**2 855**	**2 915**	**6 138**	**2 833**	**2 727**	**5 134**	**3 263**	**3 056**
TOTAL 3 GENERATIONS			**10 579**			**11 698**			**11 453**

Table 8-2: Major cost impacts by value.

Cost impact, in scenario	Delta-value (M€)	Increase wrt reference
Selection of launch vehicle	1’700	Sc1/G1: **+95%** Ref: Sc1/G2
Ground automation	1’300	Sc2/G1: **+374%** Ref: Sc2/G2
Additional tracking means (potential if cost lower x 10 times)	428 (42)	Sc5/G2: **+136%** (+14%)
Selection of the EP system (launch+ operations)	128	Sc1-5/G2: **+37%** Ref: Sc3/G2
Reliability (overall launch + flight system)	~ 40-50 M€	Sc3-5/G2: **+5%** Ref: Sc1/G2

Recommendations and future work

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- Recommendation:
  - The obvious choice is Scenario 1, as it:
    - Has the highest reliability (Sat 95%, PMD 97%), but reliability not carried in recurring cost
    - Operational and environmental implications of EP are offset by the reliability
  - A more realistic choice is Scenario 5, as it is the most probable to happen
  - Sceanrio 3 has too low a reliability (Sat 89%, PMD 92%), which also stresses the sensitivity to this parameter

  => Recommandation: continue forward with Scenario 5

- Future work, it is recommended to further:
  - Refine the modelling of the recurring cost and associated reliability in the context of series manufacturing taking into account various technology choices
  - Perform a complementary cost analysis of the recurring "shepherd" option
  - Insert a more comprehensive risk analysis inerting non-technical parameters that would enhance the understanding and feasibility of really implementing risk mitigation measures.

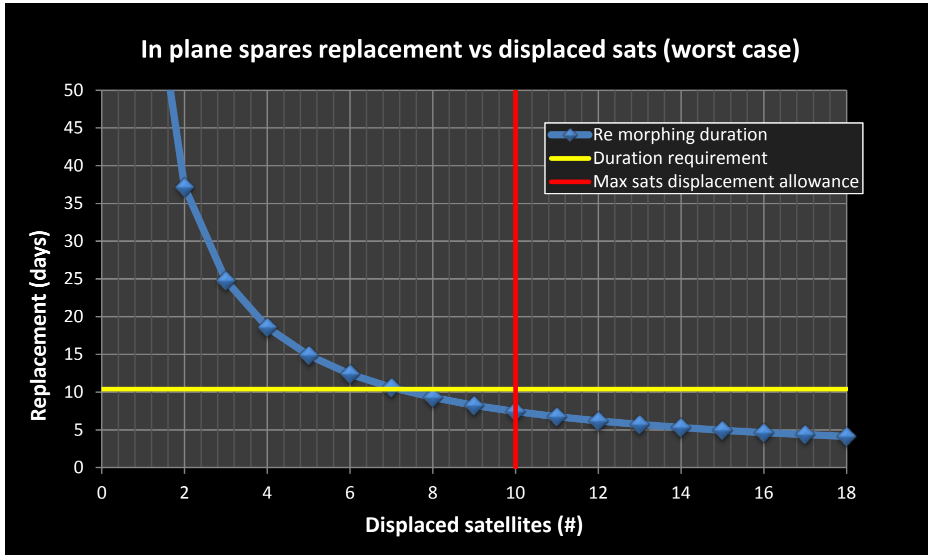
WP7000 – Elaboration of Operational Concepts

Michael Oswald – Airbus DS

Operational Concept – Spares Management

Spares Philosophy:
- “in plane” hot spares
- idle hot spares inserted between the 54 operational satellites of a plane

“Short term” satellites replacement
- Satellite replacement must be performed each time an operational satellite fails and/or is disposed with
- Consists in displacing one or several satellites so as to minimize the replacement time
- But due to “basic” electrical propulsion solution adopted for scenario 5, the displaced satellites are not operational during the replacement time (either operate payload or electrical propulsion)
- Wrt. availability sizing (no more than 10 satellites unavailable in the constellation), this limits the amount of displaceable satellites to 10

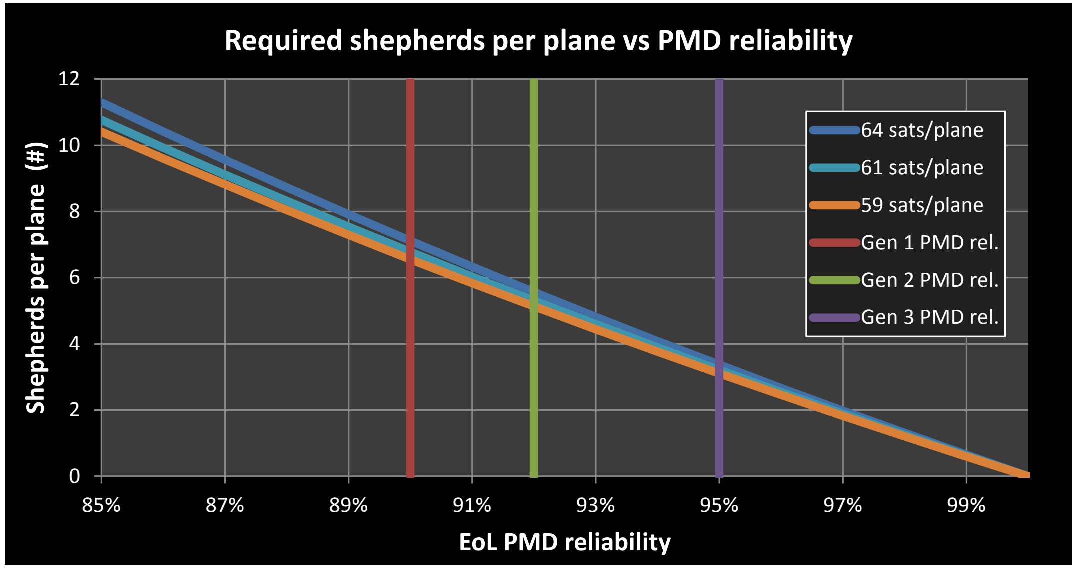


Sats per plane	Gen.1	Gen. 2	Gen. 3
Max active (in plane)		54	
Idle (in plane)	**10**	**7**	**5**
Total launched (in plane)	**64**	**61**	**59**
Shepherds (under plane)	***7***	***5***	***3***

Operational Concept – Post Mission Disposal / Backup

Backup PMD solution relies on “shepherds”

- Launched with constellation satellites
- Located 100 km below each related orbital plane with matched inclination for similar J2 secular RAAN drift (~+0.2 °)
- So as to avoid managing collision risks with operational satellites of the constellation
- Use same platform HW but with a dedicated “undertaking” payload
- Undertaking payload = rendezvous GNC, additional cold gas propulsion for final rendezvous, capture HW (harpoon, robotic arm,..)
- Same platform HW = same propulsion which must be sized in terms of tank capacity for the shepherd case which is the most demanding one (or extra tank to be added for shepherd)
- Shepherds amount depends on PMD HW reliability, which must also be accounted for for the shepherd itself
  - 7 shepherds per plane needed for gen 1
  - 5 shepherds per plane needed for gen 2
  - 3 shepherds per plane needed for gen 3



Operational Concept – Launch

Injection Orbit and Orbit Raising

- low altitude (500km) transfer orbit
- inclination of the highest plane for launches to populate multiple planes
- Spiral top up: 2 months RAAN phasing (2nd plane) + ~ 3.6 months EOR
- 1/2 orbits thrust ratio

Batches

- Launch batches evolve continuously for each generation since the amount of spares and shepherds is reduced thanks to the progressive reliability augmentation
- Medium batches for gen1 are dedicated to spares and shepherds launches so as to optimize overall reliability

Launch batches	Gen.1	Gen. 2	Gen. 3
Batch sizes	Large batches: 59 sats + *1 shepherd* per launch Medium batches: 10 sats + *12 shepherds* per launch	122 sats + *10 shepherds* per launch	59 sats + *3 shepherds* per launch
LV types	Atlas V 551 for large batches Atlas V 501 for medium batches	Falcon Heavy	Atlas V 551
Batches assignment	Large batches: Single plane (nominal + spares) Medium batches: Two planes (spares + shepherds)	2 adjacent planes	Single plane

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Operational Concept – Collision Avoidance (On Station)

Concept is driven by

- minimization of satellites dephasing impacts (payload is not oversized)
- and necessity to minimize manoeuvre rates since use of payload is exclusive with propulsion (hence impact on availability)
- lack of additional fencing means for debris detection resolution augmentation
- Additional tracking means available for “conjuncting” objects covariance reduction => Enables false alarms rate reduction
- => Medium ACPL of 10-4 selected for all generations (no consideration of 10-5 w/o improved fencing resolution)
- Long term along track avoidance manoeuvres strategy selected so as to minimize dephasing and unavailability impacts

<table>
<tr><th>On station CAM timeline</th><th>Gen.1</th><th>Gen. 2</th><th>Gen. 3</th></tr>
<tr><td>Manoeuvre type</td><td colspan="3">Along track avoidance manoeuvers</td></tr>
<tr><td>Average impacts</td><td colspan="3">Lifetime DV < 1 m/s
Max dephasing ~ 0.7%
Altitude excursion ~ 160 m</td></tr>
<tr><td>Timeline</td><td>Manœuvre to be started @ TCA - 13h</td><td colspan="2">Manœuvre to be started @ TCA - 13h
Last CDM/GO NO GO to be sent to satellite @ TCA - 15h</td></tr>
</table>

Operational Concept - Autonomy

Ground segment automation considered for gen 1

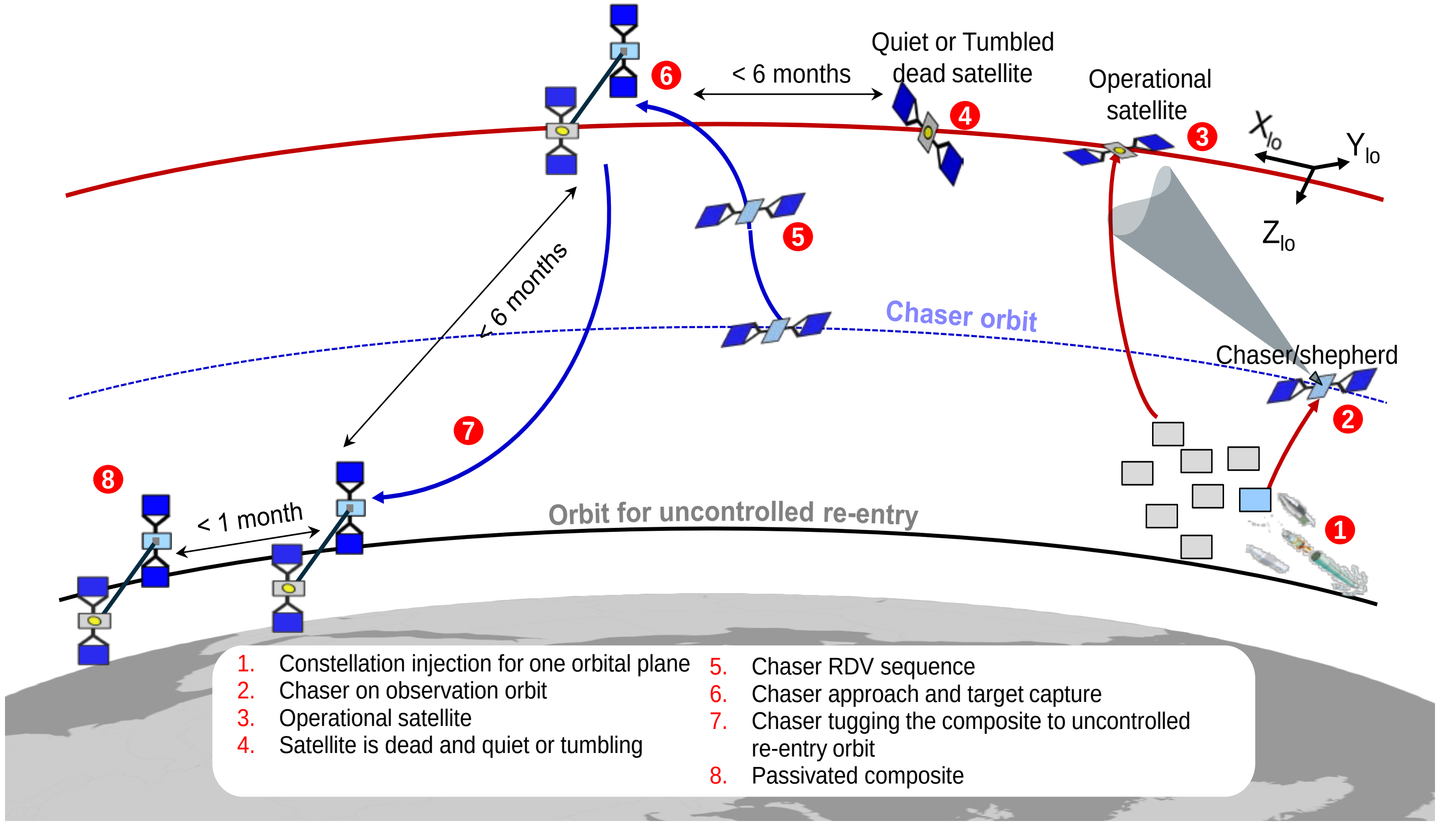
Advanced on board autonomy implemented for gen 2 & 3 for planned manoeuvers and CAM handling
→ See WP 4100 slides

Building Blocks / Roadmaps – Space Segment

Shepherd Satellite

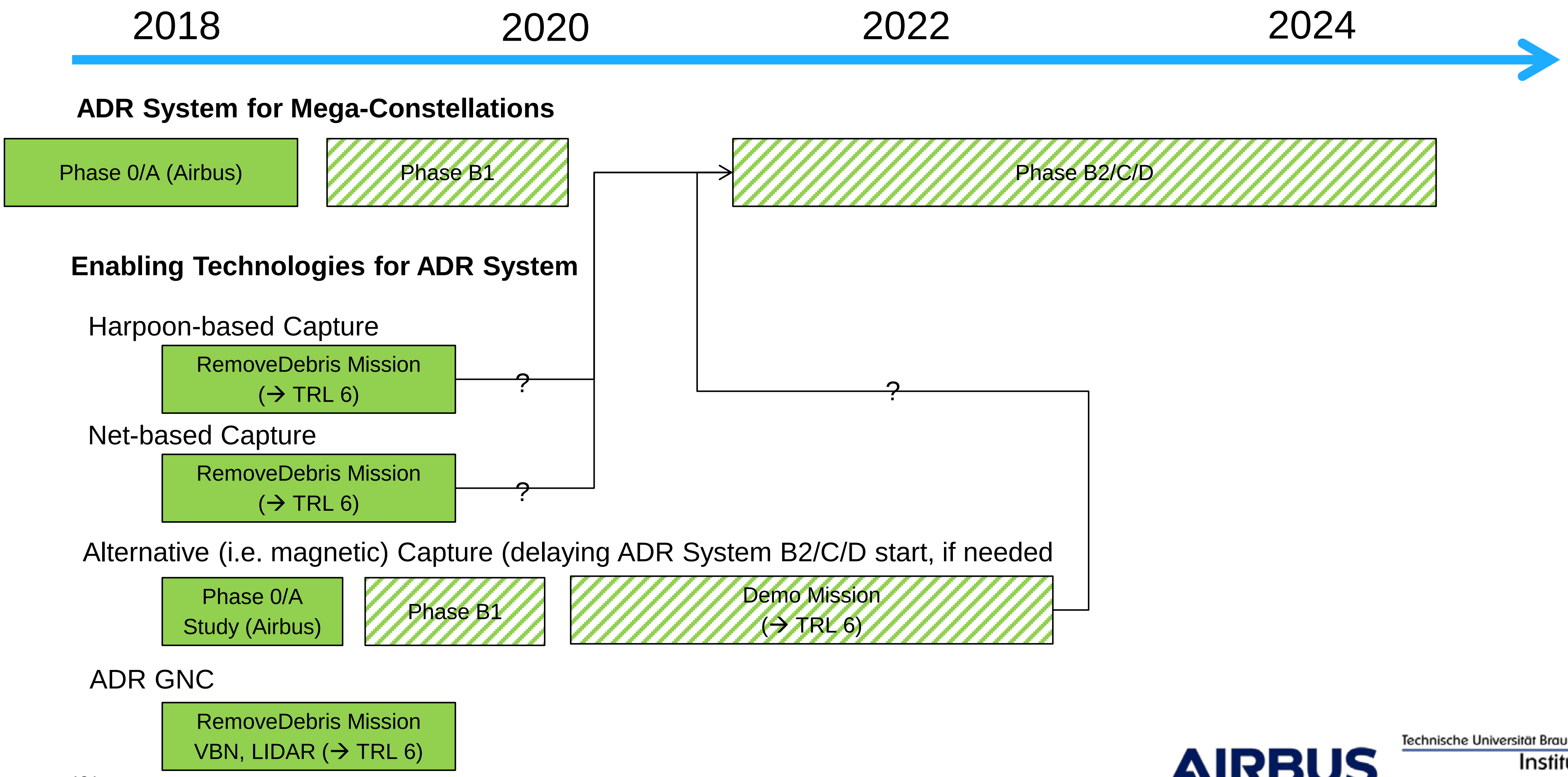
- Shepherd Satellite offering capability to
  - Capture non-cooperative spacecraft
  - Perform de-orbit of itself and the dead satellite

- Needed Technologies
  - Close proximity navigation using active or passive sensors
  - De-tumbling of non-cooperative spacecraft
  - Capture of non-cooperative spacecraft with i.e.
    - robotic arm
    - net
    - harpoon
  - Rigidization of chaser/target stack or, alternatively:
  - De-orbit of tethered chaser/target stack



Building Blocks / Roadmaps – Space Segment

Shepherd Satellite / ADR Satellite / Constellation Cycler



Building Blocks / Roadmaps / Future Work – Space Segment

Electrical Orbit Raising / Electrical PMD

Considering typical thrust uncertainties for electrical propulsion (3%...5%), and considering long thrust arcs, covariances grow quite rapidly, resulting in

- frequent maneuvers
- a significant number of non-detected close encounters

Possible elements for a solution:

- For a Close Encounter Service: Increased temporal resolution for critical close encounter analyses based on more frequent observation of the prospective collision targets
- Continuous evaluation of the electrical propulsion thrust level – to calibrate for systematic biases in thrust level, and to improve the assumptions regarding the control volume used for close encounter predictions
- Improved thrust accuracy

Building Blocks / Roadmaps / Future Work

SSA System

The study has shown that the need for a high performance SSA system capable of:

- Maintaining a highly accurate catalog
- Frequently updating that catalog

is an important building block to be able to maintain a good awareness of the existing collision risks throughout all mission phases of the satellites of a Mega-Constellation.

Here, the specifics of electrical propulsion pose a significant challenge – as they make more frequent updates regarding the collision risk necessary. Electrical propulsion appears – however – the obvious choice for mega-constellation, as its power demands are compatible with a telecom application. On the other hand electrical propulsion offers a significant decrease in launch cost and a robust way of dealing with dead-on-arrivals.

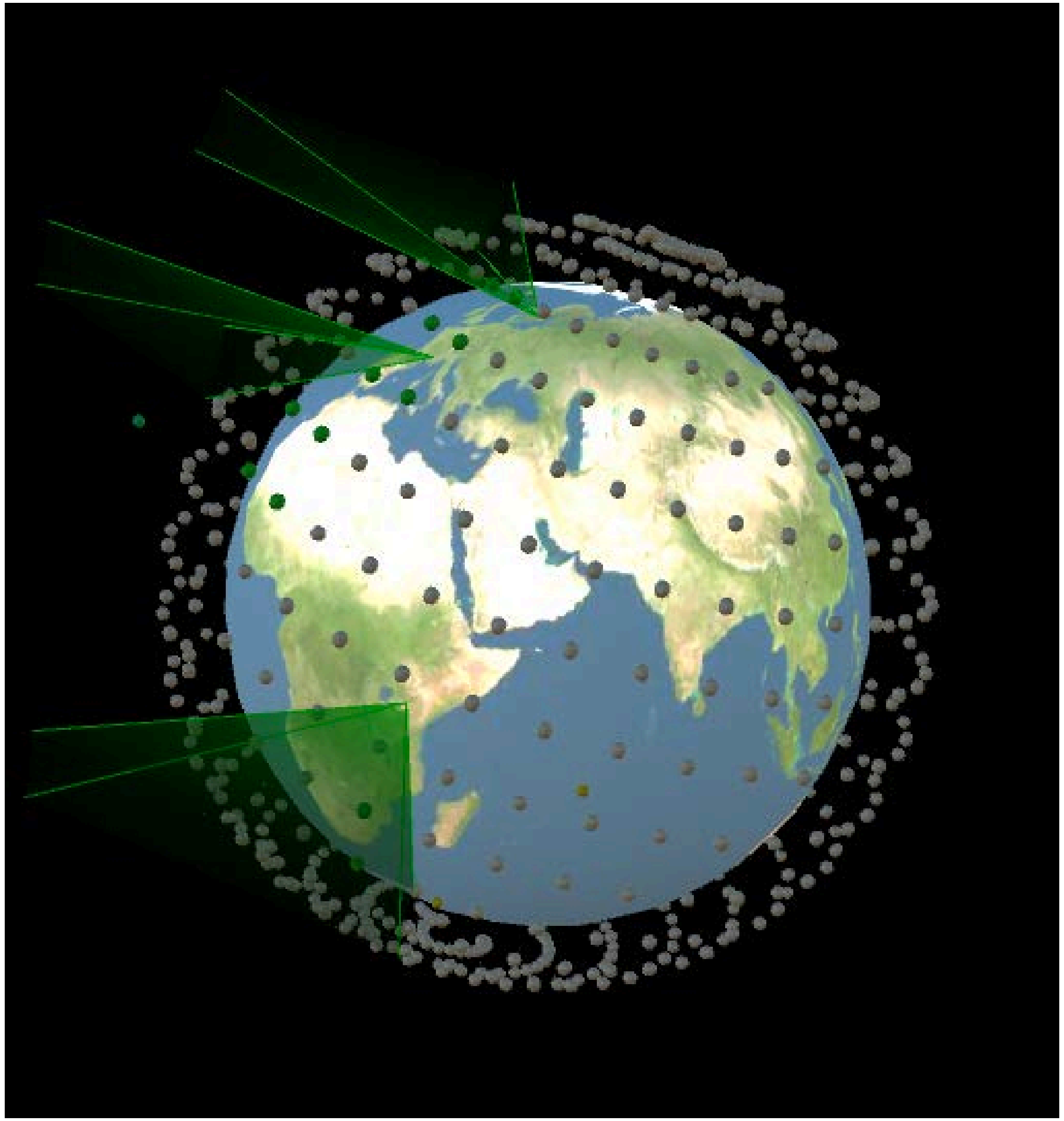
Summary

Jens Utzmann – Airbus DS

Summary

Goal: Understand complexity of mega-constellation systems, in particular w.r.t. CA and EoL operations

- **Detailed definition of three reference scenarios** (1 = high end system by established operator, 3 = medium-high QoS based on "more than proven" tech, 5 = high quality of service by new space actor)
- **Derivation of respective Space & Ground Segment Concepts**
- **Collision Avoidance** Requirements & Simulations
- **EoL** Requirements & Simulations
- **Relative cost & risk assessment** of operational scenarios 1/3/5
- **Elaboration of Operational Concept for Scenario 5**
  incl. definition of building blocks / roadmaps for crucial elements (ADR satellites, EOR and Electrical PMD, SSA system)



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Thank you