End of Life Operations for Disposal of Mega-Constellations

Final Presentation

ESTEC, 27 February 2018
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
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
Project Organisation

Contract Management
Angelique Prütz

Study Management
EOL Requirements
Jens Utzmann

System Engineering & Technology Roadmap
Michael Oswald

Operational Strategies
Cyrille Tourneur

Telecommanding Concepts
Erwan Kervandal

Ground System Concepts
Arnaud Beauvoit

CA Requirements
Frédéric Renaud

CA Ops Simulations
Sebastian Hesselbach

EOL Ops Simulations
Jonas Radtke

Comparative Strategy Costing
Muriel Richard

Airbus DS GmbH

Airbus DS SAS

TUBS

EPFL

DEFENCE AND SPACE
Work Logic – WP 1000

Definition and Selection of Operational Strategies

SDM Boundary Conditions
- e.g.
- enable 90% PMD success
- limitation of debris generation, etc.

Strategy #1
- BI propulsion (nominal HW)
- used for orbit raising and PMD
- long duration
- requires highest level of reliability and autonomy
- etc.

Strategy #2
- similar to #1, but less reliability w.r.t. autonomous PMD
- requires removal of spacecraft
- achieves PMD success rate
- etc.

Strategy #3
- traditional chemical propulsion
- high reliability, quick Hohmann transfers
- mass penalty, higher launch costs
- etc.

Strategy #4
- trade PMD reliability against PMD duration e.g. by adding extra de-orbiting device
- etc.

Strategy #...

Selection of min. 3 Operational Strategies to be assessed and traded during the study
Work Logic – WPs 2000 and 3000

Definition of High-Level System Architectures to Implement Operational Strategies

Operational Strategy #1
- GIS Architecture Concepts
  - types of different operational telecommanding
  - number and types of ground stations
  - type of information transmitted/received
  - number of staff
  - interfaces to external partners, e.g., JSpOC
  - etc.

- S/C Architecture Concepts
  - types of CAMS also considering interdependencies within s/c of mega-co
  - on-board autonomy level
  - on-board monitoring capabilities (EoL detection capabilities)
  - passivation capabilities
  - propulsion/communication/power/on-board processing/sensor subsystem
  - etc.

Operational Strategy #2

Operational Strategy #3

Mission Phases
- Launcher Separation & Orbit Raising
- Routine Operations
- EoL Execution (PMD and passivation)
Work Logic – WPs 4000 and 5000

Collision Avoidance Operations during the Mission Phases

Operational Strategy #3

Operational Strategy #2

Operational Strategy #1

Requirements & Strategies
- for separation to avoid collisions
- for CAM in different phases
- definition of requirements to implement these strategies

Simulation and Evaluation of Results
- collision risk
- number of required maneuvers
- required SST system
- required TC system (on-ground and in space)
- etc.

EoL Execution

Operational Strategy #3

Operational Strategy #2

Operational Strategy #1

Requirements & Strategies
- how is passivation and PMD performed for single S/C
- requirements on S/C and G/S
- what changes due to mega-co?

Simulation and Evaluation of Results
- perform sensitivity analysis based on the options defined in task 3
Work Logic – WP 6000

Comparative Strategy Costing

Operational Strategy #1
- Parametric and relative assessment of risk and cost
  - Cost effectiveness vs. Risk
  - Success rate
  - Recommendation of an operational strategy

Operational Strategy #2

Operational Strategy #3

Cost Models
- S/C
- G/S Network
- Mission Operations
- Scheduling
- Etc.

Risk Modelling
- Risk Assessment Process
- Uncertainty Modelling

Recommended Operational Strategy

Workshop with Consortium and Stakeholders
Review of technical results, risk, impact on debris population, cost models and non-technical elements

DEFENCE AND SPACE
Elaboration of Operational Concepts

Selected Operational Strategy

- Establish a baseline scenario
- Identify the necessary building blocks of the baseline option e.g.
  - G/S network
  - on-board autonomy
  - ADR technology
  - passivation and PMD technologies,
  - required SSA system
- Definition of technology roadmap for these elements
- Recommendation for simulation approach for mega-constellations
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
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
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

<table>
<thead>
<tr>
<th>Altitude separation configuration with rectangular tiling</th>
<th>Walker &quot;star&quot; configuration tiling</th>
<th>Altitude separation configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min elevation</td>
<td>Payload power augmentation</td>
<td></td>
</tr>
<tr>
<td>Circular -3.5° (57° -&gt; 53.5°)</td>
<td>-14%</td>
<td>1 km</td>
</tr>
<tr>
<td>Rectangular -1.1° (54.6° -&gt; 53.5°)</td>
<td>+20%</td>
<td>No radial separation</td>
</tr>
</tbody>
</table>

Closest inter satellite distance

- Walker "star" configuration
  - Circular 1 km
  - Rectangular < 15 km (TBC)
- Altitude separation configuration
  - 5 km Radial separation

Conventional circular coverage tiling with Walker constellation

Coverage tiling with Altitude separated constellation
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 manoeuvres (SK, EoR, PMD) execution options
     - Layers
     - Autonomy
  5. Collision Avoidance Manoeuvres 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

<table>
<thead>
<tr>
<th>Cat.</th>
<th>Chemical propulsion Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mono propellant</td>
</tr>
<tr>
<td>4</td>
<td>Bi-propellant</td>
</tr>
<tr>
<td>1</td>
<td>Hybrid propulsion</td>
</tr>
</tbody>
</table>

### Electrical propulsion option

<table>
<thead>
<tr>
<th>Cat.</th>
<th>Electrical propulsion option</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>“Basic” configuration</td>
</tr>
<tr>
<td>2</td>
<td>Low power capacity</td>
</tr>
<tr>
<td>2</td>
<td>Permanent capacity</td>
</tr>
<tr>
<td>2</td>
<td>Better-repeatability</td>
</tr>
</tbody>
</table>

### PMD means option

<table>
<thead>
<tr>
<th>Cat.</th>
<th>PMD means option</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mission HW</td>
</tr>
<tr>
<td>1</td>
<td>Degraded propulsion mode</td>
</tr>
<tr>
<td>1</td>
<td>Low power propulsion mode</td>
</tr>
<tr>
<td>2</td>
<td>Embarked active de-orbiting kit</td>
</tr>
<tr>
<td>2</td>
<td>Embarked semi-passive de-orbiting kit</td>
</tr>
<tr>
<td>2</td>
<td>Exogenous active de-orbiting kit</td>
</tr>
<tr>
<td>2</td>
<td>Exogenous semi-passive de-orbiting kit</td>
</tr>
<tr>
<td>3</td>
<td>“One off” external “undertaker”</td>
</tr>
<tr>
<td>3</td>
<td>Space tug “undertaking” service</td>
</tr>
</tbody>
</table>

### 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
### Constellation management options

<table>
<thead>
<tr>
<th>Injection option</th>
<th>Direct injection</th>
<th>Injection on a transfer orbit</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Population option</th>
<th>Large batch</th>
<th>Medium batch</th>
<th>Small batch</th>
<th>Very small replacement batch</th>
<th>Single plane</th>
<th>Adjacent planes</th>
<th>All-planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PMD trigger criteria option</th>
<th>Mission performance</th>
<th>PMD HW degradation</th>
<th>Spare propellants</th>
<th>Spare thrust cycles</th>
<th>Design lifetime</th>
<th>Mean Mission Duration (MMD)</th>
<th>Big data model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat.</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PMD strategy option</th>
<th>Same plane population</th>
<th>Close planes population</th>
<th>All constellation population</th>
<th>Single satellite “bulk”</th>
<th>Launch batch “bulk”</th>
<th>Intermediate size bulk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat.</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spare option</th>
<th>No hot spare</th>
<th>Per plane spare - inside the plane</th>
<th>Per plane spare - below the plane</th>
<th>Global spare pool – close to operational altitude</th>
<th>Global spare pool – on transfer orbit</th>
<th>On ground spare</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat.</td>
<td>1</td>
<td>1</td>
<td>1 &amp; 2</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

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**Note:** The table above provides a summary of the selected options for constellation management, including different injection options, population options, PMD trigger criteria options, PMD strategy options, and spare options.
Steps 2 & 3 – Summary of selected options (4)

- Constellation management options: Zoom on short MTTR spare options

<table>
<thead>
<tr>
<th>Configuration before spare consumption</th>
<th>Disposal &amp; re morphing</th>
<th>Configuration after spare consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>0 spare concept</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>In plane spares concept</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Under plane spares concept</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Steps 2 & 3 – Summary of selected options (5)

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

<table>
<thead>
<tr>
<th>ACPL Option</th>
<th>Timeline Option</th>
<th>CAM layer Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>“High” ACPL</td>
<td>Immediate</td>
<td>Single satellite</td>
</tr>
<tr>
<td>“Medium” ACPL</td>
<td>Systematic intermediate</td>
<td>Per bulk</td>
</tr>
<tr>
<td>“Low” ACPL</td>
<td>As late as possible</td>
<td>Global</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cat.</th>
<th>Trajectory Option</th>
<th>CAM means option</th>
<th>CAM autonomy option</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Along track separation</td>
<td><strong>TLE-only</strong></td>
<td>No autonomy</td>
</tr>
<tr>
<td>1</td>
<td>Radial separation</td>
<td><strong>CDM-only</strong></td>
<td>Ground segment “autonomy”</td>
</tr>
<tr>
<td>1</td>
<td>“Bang bang”</td>
<td>CDM + analysis</td>
<td>Improved autonomy</td>
</tr>
<tr>
<td>2</td>
<td>Thrust interruption</td>
<td>CDM + analysis + additional tracking mean</td>
<td>Advanced autonomy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CDM + improved surveillance means + analysis</td>
<td><strong>Full-autonomy</strong></td>
</tr>
</tbody>
</table>
Steps 2 & 3 – Summary of selected options (6)

- CAM options: Preliminary collision probability figures

<table>
<thead>
<tr>
<th>CAM Options</th>
<th>Preliminary collision probability figures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preliminary collision probability</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Annual collision risk (per sat)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>25 E-05</strong></td>
<td></td>
</tr>
<tr>
<td><strong>10-4</strong></td>
<td></td>
</tr>
<tr>
<td><strong>50 E-03</strong></td>
<td></td>
</tr>
<tr>
<td><strong>100 E-02</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Detected population</strong></td>
<td>All debris: 25 E-05 10-4 50 E-03 100 E-02</td>
</tr>
<tr>
<td><strong>With CAM</strong></td>
<td>EMR &gt; 40 J/kg: 25 E-05 10-4 50 E-03 100 E-02</td>
</tr>
<tr>
<td><strong>EMR &gt; 40 J/kg (catastrophic collision)</strong></td>
<td>All debris: 25 E-05 10-4 50 E-03 100 E-02</td>
</tr>
<tr>
<td><strong>Annual collision risk (per sat)</strong></td>
<td>EMR &gt; 40 J/kg: 25 E-05 10-4 50 E-03 100 E-02</td>
</tr>
<tr>
<td><strong>Detection capability</strong></td>
<td>All debris: 25 E-05 10-4 50 E-03 100 E-02</td>
</tr>
<tr>
<td><strong>Detection capability</strong></td>
<td>EMR &gt; 40 J/kg: 25 E-05 10-4 50 E-03 100 E-02</td>
</tr>
</tbody>
</table>
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 each 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)
Steps 2 & 3 – Summary of selected options (8)

- Planned manoeuvers options

<table>
<thead>
<tr>
<th>Layer option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single satellite</td>
</tr>
<tr>
<td>Per bulk or per plane</td>
</tr>
<tr>
<td><strong>Global</strong></td>
</tr>
</tbody>
</table>

- System commanding options

<table>
<thead>
<tr>
<th>Cat.</th>
<th>ISL Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No ISL</td>
</tr>
<tr>
<td>1</td>
<td>GEO relay</td>
</tr>
<tr>
<td>1</td>
<td><strong>MEO relay</strong></td>
</tr>
<tr>
<td>2</td>
<td>Intra plane ISL</td>
</tr>
<tr>
<td>2</td>
<td><strong>Inter-plane-(global)-polar ISL</strong></td>
</tr>
<tr>
<td>2</td>
<td>Inter plane (global) ISL</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Autonomy Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>No autonomy</td>
</tr>
<tr>
<td>Ground segment “autonomy”</td>
</tr>
<tr>
<td>Improved autonomy</td>
</tr>
<tr>
<td>Advanced autonomy</td>
</tr>
<tr>
<td><strong>Full-autonomy</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ground station coverage option</th>
</tr>
</thead>
<tbody>
<tr>
<td>No-ground-station</td>
</tr>
<tr>
<td>Single site</td>
</tr>
<tr>
<td><strong>Large coverage</strong></td>
</tr>
<tr>
<td>Nearly global coverage</td>
</tr>
</tbody>
</table>
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
### 6 candidate profiles summary

<table>
<thead>
<tr>
<th>Operator &amp; program &quot;profiles&quot;</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of Service</td>
<td>Very High</td>
<td>Low</td>
<td>Medium to High</td>
<td>Very High</td>
<td>High</td>
<td>Medium to High</td>
</tr>
<tr>
<td>Satellites capacity &amp; oversizing</td>
<td>Very High</td>
<td>Low</td>
<td>Low</td>
<td>Very High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Technological maturity</td>
<td>Very High</td>
<td>Very Low</td>
<td>Low</td>
<td>Very High</td>
<td>Very High</td>
<td>Medium</td>
</tr>
<tr>
<td>Techno risks aversity</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Progressive approach</td>
<td>Very Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Cost of access to space</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Cost of system operators</td>
<td>Very High</td>
<td>Very Low</td>
<td>Moderate</td>
<td>Very High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Sensitivity to debris matters</td>
<td>Very High</td>
<td>Low</td>
<td>Low</td>
<td>Very High</td>
<td>High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
**DEFENCE AND SPACE**

**Step 4 – Strategies salients**

- Salient points of the different profiles
  
  = major technical decisions made for each scenario in accordance with each system/operator profile

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

<table>
<thead>
<tr>
<th>Strategies &amp; generations</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<td>Quality of Service</td>
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<td>10.7</td>
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<th>3</th>
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<tr>
<td>Satellites cost</td>
<td>-3</td>
<td>-8</td>
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<td>8</td>
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<td>8</td>
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<td></td>
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<td>G3</td>
<td>G1</td>
<td>G2</td>
<td>G3</td>
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<td>8.0</td>
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<td>Launch cost</td>
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<td>-1</td>
<td>1</td>
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<td></td>
<td>-1</td>
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<td>-1</td>
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<td>G3</td>
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<td>G2</td>
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<td>Ground segment, operations and services cost</td>
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<td>8</td>
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<td>8</td>
<td>-4</td>
<td>0</td>
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<td>G2</td>
<td>G3</td>
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<tr>
<td>TOTAL</td>
<td>-7.7</td>
<td>11.0</td>
<td>9.3</td>
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</table>

<table>
<thead>
<tr>
<th>Strategies &amp; generations</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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</thead>
<tbody>
<tr>
<td>Innovation and new technologies</td>
<td>10</td>
<td>14</td>
<td>14</td>
<td>2</td>
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<td>2</td>
</tr>
<tr>
<td>G1</td>
<td>G2</td>
<td>G3</td>
<td>G1</td>
<td>G2</td>
<td>G3</td>
<td></td>
</tr>
<tr>
<td>12.7</td>
<td>2.0</td>
<td>3.0</td>
<td>10.7</td>
<td>13.3</td>
<td>6.0</td>
<td></td>
</tr>
</tbody>
</table>
Step 5 – Short list selection

- **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.

**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

**2 most extreme scenario for criteria 1**

**Best ranked scenario for criteria 2**

**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
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

### Table: Scenario Reliabilities

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Reliabilities</th>
<th>Gen.1</th>
<th>Gen. 2</th>
<th>Gen. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EoL PMD reliability</td>
<td>95%</td>
<td>96%</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td>EoL sat. reliability</td>
<td>94%</td>
<td>95%</td>
<td>96%</td>
</tr>
<tr>
<td>1</td>
<td>EoL PMD reliability</td>
<td>90%</td>
<td>92%</td>
<td>94%</td>
</tr>
<tr>
<td>3</td>
<td>EoL sat. reliability</td>
<td>85%</td>
<td>89%</td>
<td>92%</td>
</tr>
<tr>
<td>5</td>
<td>EoL PMD reliability</td>
<td>90%</td>
<td>92%</td>
<td>95%</td>
</tr>
<tr>
<td>5</td>
<td>EoL sat. reliability</td>
<td>85%</td>
<td>89%</td>
<td>92%</td>
</tr>
</tbody>
</table>
Step 6 – Satellite summary

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

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Sats per plane</th>
<th>Gen.1</th>
<th>Gen. 2</th>
<th>Gen. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Max active (in plane)</td>
<td>54</td>
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</tr>
<tr>
<td></td>
<td>Min active (in plane)</td>
<td>48</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total launched (in plane)</td>
<td>54</td>
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</tr>
<tr>
<td></td>
<td>Cold spares (on ground)</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Max active (in plane)</td>
<td>54</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Idle (under plane)</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Total launched (in &amp; under plane)</td>
<td>64</td>
<td>61</td>
<td>59</td>
</tr>
<tr>
<td>5</td>
<td>Max active (in plane)</td>
<td>54</td>
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<td></td>
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<tr>
<td></td>
<td>Idle (in plane)</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Total launched (in plane)</td>
<td>64</td>
<td>61</td>
<td>59</td>
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<td></td>
<td>Shepherds (under plane)</td>
<td>7</td>
<td>5</td>
<td>3</td>
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</table>
**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

<table>
<thead>
<tr>
<th>PMD strategy</th>
<th>Scenario 1</th>
<th>Scenario 3</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PMD criteria</strong></td>
<td>Event <em>(triggers immediate PMD)</em></td>
<td>telecom mission HW or PMD HW</td>
<td>telecom mission HW or PMD HW</td>
</tr>
<tr>
<td></td>
<td>Systematic <em>(for PMD bulks)</em></td>
<td>thrust cycle or big data model</td>
<td>spare propellants</td>
</tr>
<tr>
<td><strong>Monitored population &amp; PMD bulk</strong></td>
<td>Monitored population <em>for event criteria</em></td>
<td>All planes</td>
<td>thrust cycle, design lifetime or big data model</td>
</tr>
<tr>
<td></td>
<td>Monitored population <em>for systematic PMD bulk</em></td>
<td>Adjacent planes</td>
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</tr>
<tr>
<td></td>
<td>PMD bulk size</td>
<td>Full plane or half plane size</td>
<td>1/3 of a plane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Full plane</td>
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</table>
DEFENCE AND SPACE

Step 6 – Launch strategy

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Injection &amp; EOR</th>
<th>Gen.1</th>
<th>Gen. 2</th>
<th>Gen. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Injection orbit</td>
<td>500 km altitude - <em>inclination of the highest plane for multiple planes population launches</em></td>
<td>Spiral top up 2 months RAAN phasing (2nd plane) + ~ 3.2 months EOR 3/4 orbits thrust ratio</td>
<td>Spiral top up 2 months RAAN phasing (2nd plane) + ~2.7 months EOR 9/10 orbits thrust ratio</td>
</tr>
<tr>
<td></td>
<td>EOR timeline</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td>Injection orbit</td>
<td>100 km below target plane <strong>Nominal</strong> satellites launches: inclination of target plane <strong>Spare</strong> satellites launches: with inclination matched to provide same J2 secular RAAN drift as target plane (~ +0.2°)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EOR timeline</td>
<td>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)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Injection orbit</td>
<td>500 km altitude - <em>inclination of the highest plane for multiple planes population launches</em></td>
<td>Spiral top up: 2 months RAAN phasing (2nd plane) + ~ 3.6 months EOR 1/2 orbits thrust ratio</td>
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## Step 6 – CAM summary

<table>
<thead>
<tr>
<th>Scenario</th>
<th>On station CAM rate</th>
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<th>Gen. 2</th>
<th>Gen. 3</th>
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<tr>
<td></td>
<td>ACPL</td>
<td>Medium: $10^{-4}$</td>
<td>Low: $10^{-5}$</td>
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<tr>
<td>1</td>
<td>Constellation manoeuvre rate</td>
<td>$\sim450$ man/yr</td>
<td>$\sim3500$ man/yr</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manoeuvre type</td>
<td>&quot;Bang bang&quot; along track avoidance manoeuvres with propulsion low power mode</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
|          | Average impacts     | Lifetime DV $< 1$ m/s  
Max dephasing $\sim 0.25\%$  
Altitude excursion $\sim 100$ m | Lifetime DV $\sim 4$ m/s  
Max dephasing $\sim 0.25\%$  
Altitude excursion $\sim 200$ m |        |
| 3        | ACPL                | High: $10^{-3}$ |        |        |
|          | Constellation manoeuvre rate | $\sim50$ man/yr |        |        |
|          | Manoeuvre type      | Along track avoidance manoeuvres |        |        |
|          | Average impacts     | Lifetime DV $< < 1$ m/s  
Max dephasing $\sim 0.15\%$  
Altitude excursion $\sim 50$ m |        |        |
| 5        | ACPL                | Medium: $10^{-4}$ |        |        |
|          | Constellation manoeuvre rate | $\sim150$ man/yr |        |        |
|          | Manoeuvre type      | Along track avoidance manoeuvres |        |        |
|          | Average impacts     | Lifetime DV $< 1$ m/s  
Max dephasing $\sim 0.7\%$  
Altitude excursion $\sim 160$ m |        |        |
## Step 6 – System telecommanding architecture summary

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

- **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
WP3100 – Ground segment concepts
Control center design and sizing

Application of IT infrastructures and redundancy strategies consistent with each scenario

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 3</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IT infrastructure</strong></td>
<td><strong>Private cloud infrastructure</strong>&lt;br&gt;Data and processing hosted on premises but based on cloud technology</td>
<td><strong>Traditional static infrastructure</strong>&lt;br&gt;Use of VM hosted on a centralized infrastructure</td>
<td><strong>Hybrid cloud infrastructure</strong>&lt;br&gt;Composition of private and public clouds</td>
</tr>
<tr>
<td><strong>Redundancy strategy</strong></td>
<td><strong>1 Nominal + 1 backup center</strong>&lt;br&gt;Hot redundancy</td>
<td><strong>1 Nominal + 1 backup center</strong>&lt;br&gt;Cold redundancy</td>
<td>Rotating control&lt;br&gt;Hot redundancy</td>
</tr>
<tr>
<td><strong>Total number of control centers</strong></td>
<td><strong>2</strong></td>
<td><strong>2</strong></td>
<td>Gen1 &amp; Gen2: <strong>2</strong>&lt;br&gt;Gen3: <strong>3</strong></td>
</tr>
<tr>
<td><strong>Locations</strong></td>
<td><strong>US &amp; Europe</strong></td>
<td><strong>Russia &amp; Eastern Asia</strong></td>
<td>Gen1 &amp; Gen2: <strong>US &amp; Europe</strong>&lt;br&gt;Gen3: + Eastern Asia</td>
</tr>
</tbody>
</table>

Example of rotating control (3 sites)

<table>
<thead>
<tr>
<th>Team</th>
<th>0h – 8h UTC</th>
<th>8h – 16h UTC</th>
<th>16h – 24h UTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team 1</td>
<td>14h – 22h local time</td>
<td>22h – 6h local time</td>
<td>6h – 14h local time</td>
</tr>
<tr>
<td></td>
<td>Active</td>
<td>Off</td>
<td>Backup</td>
</tr>
<tr>
<td>Team 2</td>
<td>6h – 14h local time</td>
<td>14h – 22h local time</td>
<td>22h – 6h local time</td>
</tr>
<tr>
<td></td>
<td>Backup</td>
<td>Active</td>
<td>Off</td>
</tr>
<tr>
<td>Team 3</td>
<td>22h – 6h local time</td>
<td>8h – 14h local time</td>
<td>14h – 22h local time</td>
</tr>
<tr>
<td></td>
<td>Off</td>
<td>Backup</td>
<td>Active</td>
</tr>
</tbody>
</table>

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AIRBUS

Technische Universität Braunschweig
Institute of Space Systems
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

<table>
<thead>
<tr>
<th>Propulsion subsystem</th>
<th>Baseline</th>
<th>Scen. 1</th>
<th>Scen. 3</th>
<th>Scen. 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electric prop., HET</td>
<td>Electric prop., Ion engine</td>
<td>Chem. Prop</td>
<td>Electric prop., HET</td>
</tr>
</tbody>
</table>

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
**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)

Timeline

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

- On board maneuvers elaboration
- 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)
WP4100: OR / PMD with electrical propulsion – advanced autonomy (2/2)

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

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WP4100: Insertion into the operational orbit

**Constellation geometry:** 20 orbital planes with 5 km altitude separation + $\Delta$RAAN 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
  - Orbits altitude before/after crossing depends on $\Delta$sma in 1 orbit continuous thrust
  - Maneuver begins 90° before the relative node of the two orbits
  - 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 „truth“

- Background population
  \((d \geq 4\text{cm})\)
- Constellation satellites
- Realistic reference
- Determine close approaches
  \((\text{ClAp})\)

Deterministic snapshot within any random 7 days

- Close approaches over time
  (debris vs. satellite)
Methodology (2)

**2nd Phase**

Simulated world

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 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

<table>
<thead>
<tr>
<th>Category</th>
<th>Number CAMs/year ACPL 10^-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat.</td>
<td>292</td>
</tr>
<tr>
<td>Cat. + Fence</td>
<td>292</td>
</tr>
<tr>
<td>Cat. + 1xTracking</td>
<td>1460</td>
</tr>
<tr>
<td>Cat. + 2xTracking</td>
<td>1752</td>
</tr>
</tbody>
</table>

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

Number CAMs/year - 20 km x 2 km

- True CAM
- False CAM

- 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
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 resolve the operations of constellation satellites
- Post-process simulation outputs
WP5200: Simulation environment

- Initial population
- Constellation definition
- LUCA2
- Collision statistics
- Population Files
- Prb-Files
- probdens
- Long-term evolution statistics
- Criticality values
- Ares
- Collision avoidance manoeuvres
- Apollon
- Close approach analysis
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

Number of effective objects in LEO ≥ 10 cm

Cumulative number of catastrophic collisions

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Simulation results: Constellation scenarios

- **Scenario 1**
- **Scenario 3**
- **Scenario 5**
- **Baseline scenario**

**Number of effective objects in LEO ≥ 10 cm**

**Cumulative number of catastrophic collisions**
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 likelihood 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

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Ranksum, #objects</th>
<th>Ranksum, collisions</th>
<th>ΣNorm, #objects</th>
<th>Norm. Rank</th>
<th>ΣNorm, collisions</th>
<th>Norm. Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 3</td>
<td>No impact*</td>
<td></td>
<td>1.07</td>
<td>0.8</td>
<td>0.03</td>
<td>0.2</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>Significant impact</td>
<td></td>
<td>4.03</td>
<td>3.0</td>
<td>0.70</td>
<td>3.00</td>
</tr>
<tr>
<td>Scenario 5.1 (low rel.)</td>
<td>Significant impact</td>
<td></td>
<td>1.95</td>
<td>1.5</td>
<td>0.12</td>
<td>0.51</td>
</tr>
<tr>
<td>Scenario 5.2 (medium rel.)</td>
<td>Significant impact</td>
<td></td>
<td>3.5</td>
<td>2.6</td>
<td>0.51</td>
<td>2.2</td>
</tr>
<tr>
<td>Scenario 5.3 (later ADR)</td>
<td>Significant impact</td>
<td></td>
<td>2.8</td>
<td>2.1</td>
<td>0.41</td>
<td>1.8</td>
</tr>
</tbody>
</table>

→ 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.
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 occurring collisions (in parts 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

<table>
<thead>
<tr>
<th>Constellation 1</th>
<th>ACPL</th>
<th>Generation 1</th>
<th>Generation 2</th>
<th>Generation 3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constellation 1</td>
<td>1.e-4*</td>
<td>1.07</td>
<td>1.08</td>
<td>1.16</td>
<td>3.31</td>
</tr>
<tr>
<td>Constellation 1</td>
<td>Fence**</td>
<td>1.07</td>
<td>18.19</td>
<td>17.99</td>
<td>37.25</td>
</tr>
<tr>
<td>Constellation 3</td>
<td>1.e-3*</td>
<td>0.074</td>
<td>0.09</td>
<td>0.115</td>
<td>0.279</td>
</tr>
<tr>
<td>Constellation 5</td>
<td>1.e-4*</td>
<td>0.96</td>
<td>0.98</td>
<td>1.05</td>
<td>2.99</td>
</tr>
</tbody>
</table>

*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

<table>
<thead>
<tr>
<th>Scenario</th>
<th># total manoeuvres / sat / 15 a</th>
<th># max. avoidable cat. coll</th>
<th># max avoidable non-cat coll</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.31</td>
<td>Ca. 0.93</td>
<td>Ca 0.4</td>
</tr>
<tr>
<td>1, fence</td>
<td>37.25</td>
<td>0.93</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>0.279</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>5</td>
<td>2.99</td>
<td>0.95</td>
<td>0.6</td>
</tr>
</tbody>
</table>

➔ 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 almost 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
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, recommend a scenario

In this presentation, MgC = MegaConstellation, ADR = Shepherd
0. Cost Models

ALL COST in FY2017 €

SSCM and USCM8

Avail. mass = f(altitude)
Dispenser model
# Launched sats
# launches for all Gen
Cost per launch

COCOMO

SSCM and USCM8

Custom bottom-Up
SME-SMAD CER

SSCM and USCM8

COCOMO
### 2.0 Launch Segment - results

#### 2.0 LAUNCH COST (M€)

<table>
<thead>
<tr>
<th>Domain</th>
<th>Sub domain</th>
<th>Cost Inputs</th>
<th>Units</th>
<th>GEN 1</th>
<th>GEN 2</th>
<th>GEN 3</th>
<th>GEN 1</th>
<th>GEN 2</th>
<th>GEN 3</th>
<th>GEN 1</th>
<th>GEN 2</th>
<th>GEN 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total of nominal + spares MgcSats</td>
<td>WP1009</td>
<td></td>
<td>1080</td>
<td>1080</td>
<td>1080</td>
<td>1280</td>
<td>1220</td>
<td>1180</td>
<td>1280</td>
<td>1220</td>
<td>1180</td>
</tr>
<tr>
<td></td>
<td>Number of spares added during the mission</td>
<td>WP5209</td>
<td></td>
<td>15</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Number of Shepherd satellites used, M</td>
<td>WP5209</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Total of nom. + spares + ADR sats</td>
<td>WP1009</td>
<td></td>
<td>1080</td>
<td>1080</td>
<td>1080</td>
<td>1280</td>
<td>1220</td>
<td>1180</td>
<td>1373</td>
<td>1284</td>
<td>1212</td>
</tr>
</tbody>
</table>

#### Launch of Constellation

<table>
<thead>
<tr>
<th>Primary launch vehicle type</th>
<th>Target orbit altitude (km)</th>
<th>Number of sat per launch (effective)</th>
<th>Required total number of primary launches</th>
<th>Extra-satellites to be used with smaller launchers</th>
<th>Secondary launch vehicle type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Falcon 9 FT</td>
<td>500</td>
<td>49</td>
<td>22</td>
<td>2</td>
<td>Virgin LauncherOne</td>
</tr>
<tr>
<td>Soyuz-2</td>
<td>500</td>
<td>56</td>
<td>22</td>
<td>2</td>
<td>Soyuz-2</td>
</tr>
<tr>
<td>PSLV</td>
<td>500</td>
<td>56</td>
<td>22</td>
<td>2</td>
<td>PSLV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total prim.+sec. launch cost</th>
<th>M€</th>
<th>3,386</th>
<th>1,736</th>
</tr>
</thead>
</table>

#### Launch of Additional Spares and Shepherd Sats

<table>
<thead>
<tr>
<th>Primary launch vehicle type</th>
<th>Target orbit altitude (km)</th>
<th>Mass injected in target orbit (kg)</th>
<th>Number of sat per launch (effective)</th>
<th>Required total number of extra launches</th>
<th>Cost of extra launch vehicle/launch M€</th>
<th>Total cost of extra launch vehicles M€</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSLV</td>
<td>500</td>
<td>1,176</td>
<td>1</td>
<td>3</td>
<td>31</td>
<td>93</td>
</tr>
</tbody>
</table>

| Total extra spares+shepherd | M€ | 93    | 50    | 30    | 0      | 0        | 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

**3.0 FLIGHT SEGMENT COST (M€)**

<table>
<thead>
<tr>
<th>Flight Segment Cost Breakdown</th>
<th>Cost for GEN1</th>
<th>Cost for GEN2</th>
<th>Cost for GEN3</th>
<th>Cost for GEN1</th>
<th>Cost for GEN2</th>
<th>Cost for GEN3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of MgC Satellites (kg)</td>
<td>254</td>
<td></td>
<td></td>
<td>213</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass of ADR Satellites (kg)</td>
<td></td>
<td></td>
<td></td>
<td>263</td>
<td></td>
<td>250</td>
</tr>
</tbody>
</table>

**Dev 1st Unit** | **2nd Unit** | **Total** | **Dev 1st Unit** | **2nd Unit** | **Total** | **Dev 1st Unit** | **2nd Unit** | **Total** |
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.1 Structure (k€)</td>
<td>3944</td>
<td>5349</td>
<td>11293</td>
<td>4233</td>
<td>3810</td>
<td>8044</td>
<td>4368</td>
<td>3877</td>
</tr>
<tr>
<td>3.1.2 Thermal (k€)</td>
<td>622</td>
<td>560</td>
<td>1182</td>
<td>381</td>
<td>343</td>
<td>723</td>
<td>437</td>
<td>393</td>
</tr>
<tr>
<td>3.1.3 ADRs (k€)</td>
<td>8168</td>
<td>7351</td>
<td>15519</td>
<td>7616</td>
<td>6855</td>
<td>14471</td>
<td>7068</td>
<td>6914</td>
</tr>
<tr>
<td>3.1.4 Electrical Power System (k€)</td>
<td>8638</td>
<td>7774</td>
<td>16412</td>
<td>4357</td>
<td>3921</td>
<td>8278</td>
<td>5409</td>
<td>4688</td>
</tr>
<tr>
<td>3.1.5 Propulsion (k€)</td>
<td>2442</td>
<td>2189</td>
<td>4640</td>
<td>1048</td>
<td>1483</td>
<td>3131</td>
<td>1761</td>
<td>1585</td>
</tr>
<tr>
<td>3.1.6 TT&amp;C (k€)</td>
<td>8127</td>
<td>2984</td>
<td>6320</td>
<td>3156</td>
<td>2841</td>
<td>5997</td>
<td>3177</td>
<td>2659</td>
</tr>
<tr>
<td>3.1.7 Integration, Assembly, &amp; Test (k€)</td>
<td>1544</td>
<td>1389</td>
<td>2933</td>
<td>1491</td>
<td>1842</td>
<td>2384</td>
<td>1498</td>
<td>1548</td>
</tr>
<tr>
<td>3.1.8 Flight Software (k€)</td>
<td>2580</td>
<td>2833</td>
<td>5413</td>
<td>3181</td>
<td>2853</td>
<td>6034</td>
<td>3574</td>
<td>3036</td>
</tr>
<tr>
<td>3.1.9 Flight Software Total (k€)</td>
<td>88757</td>
<td>88757</td>
<td>88757</td>
<td>70479</td>
<td>70479</td>
<td>70479</td>
<td>(8706)</td>
<td>(8706)</td>
</tr>
<tr>
<td>1.2 Payload (k€)</td>
<td>12273</td>
<td>20525</td>
<td>32798</td>
<td>9125</td>
<td>20850</td>
<td>50976</td>
<td>(9709)</td>
<td>(9709)</td>
</tr>
</tbody>
</table>

**Total satellite development co M€** | **DEV TRL 6 to 9** | **DEV TRL 7 to 9** | **DEV TRL 8 to 9** |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>GEN1</td>
<td>100</td>
<td>50</td>
<td>33</td>
</tr>
<tr>
<td>GEN2</td>
<td>80</td>
<td>40</td>
<td>27</td>
</tr>
<tr>
<td>GEN3</td>
<td>230</td>
<td>42</td>
<td>28</td>
</tr>
</tbody>
</table>

**Satellite development + series production cost** | 299 | 50 | 33 | 239 | 40 | 27 |

**RECURRING COST**

- Total of nom. + total spares + ADR sats: \(1095 + 1085 + 1083\) = 3263
- Cost of MgC sats: \(0.5\) M€
- Cost of ADR sats: \(1\) M€

**Total recurring cost of sats** | \(548\) | \(543\) | \(542\) | \(640\) | \(610\) | \(590\) | \(733\) | \(674\) | \(622\) |

**TOTAL Flight Segment cost** | 647 | 592 | 575 | 720 | 650 | 617 | 816 | 716 | 650 |

**TOTAL ALL GEN** | 1814 | 1986 | 2182 |

**TOTAL Flight Segment + Prod cost** | 846 | 592 | 575 | 879 | 650 | 617 | 983 | 716 | 650 |

**TOTAL ALL GEN with PROD** | 2013 | 2145 | 2348 |
## 4.0-6.0 Ground Segment and Operations

### 4.0-6.0 GROUND SEGMENT + OPS COST (ME)

<table>
<thead>
<tr>
<th>Domain / Sub-domain</th>
<th>Parameter / selected opt</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>High end</td>
<td>Proven Tech</td>
<td>&quot;New Space&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>system</td>
<td>system</td>
<td>system</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cost Inputs</strong></td>
<td></td>
<td>TRL GEN 1</td>
<td>GEN 2</td>
<td>GEN 1</td>
<td>GEN 2</td>
<td>GEN 3</td>
</tr>
<tr>
<td>Mission duration</td>
<td>yrs</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>EOR duration</td>
<td>yrs</td>
<td>16</td>
<td>12</td>
<td>12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ground segment and operations cost</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Control centers (CC)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of m2/center</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td># of staff * 10 m2/staff, m2</td>
<td></td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Space cost/loc/m2</td>
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<td>6000</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
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<tr>
<td>CC building cost</td>
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<td>16,200</td>
<td>18,344</td>
<td>18,444</td>
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<td>Total CC building cost</td>
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<td>76,788</td>
<td>76,288</td>
<td>84,390</td>
<td>6,390</td>
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<td><strong>IT infrastructure</strong></td>
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<tr>
<td>Total IT infrastructure cost</td>
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<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
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<tr>
<td>Ground control software</td>
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<td>80,244</td>
<td>80,244</td>
<td>40,122</td>
<td>40,122</td>
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<td>CAM automation</td>
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<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
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<tr>
<td>Dev. maintenance cost, k€</td>
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<td>4,714</td>
<td>9,429</td>
<td>9,429</td>
<td>4,714</td>
<td>4,714</td>
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<tr>
<td>Other ground automation</td>
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<td>30,000</td>
<td>30,000</td>
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<td>Delta-dev. cost, k€</td>
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<td>40,122</td>
<td>80,244</td>
<td>80,244</td>
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<tr>
<td>Maintenance cost</td>
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<td>20,061</td>
<td>23,147</td>
<td>23,147</td>
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<td>20,061</td>
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<tr>
<td>Total GCS cost</td>
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<td>70,183</td>
<td>79,482</td>
<td>79,482</td>
<td>70,183</td>
<td>70,183</td>
</tr>
<tr>
<td>Staffing cost/yr</td>
<td></td>
<td>2,184</td>
<td>2,184</td>
<td>2,184</td>
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<tr>
<td>Managers</td>
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<tr>
<td>System administrators</td>
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<td>1,578</td>
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<tr>
<td>Experts</td>
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<tr>
<td>Engineers</td>
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<td>1,578</td>
<td>1,578</td>
<td>1,578</td>
<td>1,578</td>
</tr>
<tr>
<td>Operators during orbit transfers</td>
<td></td>
<td>49,600</td>
<td>54,560</td>
<td>54,560</td>
<td>41,880</td>
<td>1,984</td>
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<td>Operators during mission</td>
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<td>21,824</td>
<td>21,824</td>
<td>13,513</td>
<td>18,984</td>
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<tr>
<td>Total staffing/Gain</td>
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<td>311,587</td>
<td>352,088</td>
<td>352,088</td>
<td>311,587</td>
<td>352,088</td>
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<tr>
<td><strong>External interfaces</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>JSEP: free</td>
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<td></td>
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</tr>
<tr>
<td>Alternative tracking means</td>
<td></td>
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</tr>
<tr>
<td>New Advanced OD capability</td>
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<tr>
<td>GNS + JSEP</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>GNS + JSEP + Fencing 2 cm</td>
<td></td>
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</tr>
<tr>
<td>Alternative means</td>
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<td>CORS/JSEP</td>
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<tr>
<td>Total fencing means cost</td>
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<tr>
<td>Ground stations</td>
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<td>Antenna/Station control</td>
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</tr>
<tr>
<td>Type of antennas</td>
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</tr>
<tr>
<td>Traditional</td>
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<td>Reactivated</td>
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<tr>
<td>Reactive</td>
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</tr>
<tr>
<td>Traditional</td>
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<td>Traditional</td>
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<td>Traditional</td>
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<tr>
<td>Traditional</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total cost related to antennas</td>
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<td>48,156</td>
<td>67,788</td>
<td>67,788</td>
<td>18,576</td>
<td>18,576</td>
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<tr>
<td>Network</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Ground Control Center cost</strong></td>
<td></td>
<td>475</td>
<td>468</td>
<td>468</td>
<td>1,647</td>
<td>347</td>
</tr>
</tbody>
</table>
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.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>High end system</th>
<th>Proven Tech</th>
<th>“New Space”</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEN 1</td>
<td>3 479</td>
<td>3 606</td>
<td>3 809</td>
</tr>
<tr>
<td>GEN 2</td>
<td>1 786</td>
<td>1 829</td>
<td>1 798</td>
</tr>
<tr>
<td>GEN 3</td>
<td>1 864</td>
<td>1 707</td>
<td>1 643</td>
</tr>
<tr>
<td>Total prim.+sec. launch cost</td>
<td>3 386</td>
<td>1 736</td>
<td>1 834</td>
</tr>
<tr>
<td>Total extra spares+shepherd</td>
<td>93</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>3.0 FLIGHT SEGMENT</td>
<td>846</td>
<td>592</td>
<td>575</td>
</tr>
<tr>
<td>Satellite dev. + series prod. set-up cost</td>
<td>299</td>
<td>30</td>
<td>239</td>
</tr>
<tr>
<td>Total recurring cost of sats</td>
<td>548</td>
<td>542</td>
<td>604</td>
</tr>
<tr>
<td>Total Ground Control Center cost</td>
<td>475</td>
<td>468</td>
<td>468</td>
</tr>
<tr>
<td>Advanced OD capability cost</td>
<td>0</td>
<td>0</td>
<td>428</td>
</tr>
<tr>
<td>4.0 GROUND SEGMENT + 6.0 OPS</td>
<td>475</td>
<td>468</td>
<td>468</td>
</tr>
<tr>
<td>Total Ground Control Center cost</td>
<td>475</td>
<td>468</td>
<td>468</td>
</tr>
<tr>
<td>Advanced OD capability cost</td>
<td>0</td>
<td>0</td>
<td>428</td>
</tr>
<tr>
<td>TOTAL/GEN</td>
<td>4 809</td>
<td>2 855</td>
<td>2 915</td>
</tr>
<tr>
<td>TOTAL 3 GENERATIONS</td>
<td>6 138</td>
<td>2 833</td>
<td>2 727</td>
</tr>
</tbody>
</table>

Table 8-2: Major cost impacts by value.
Recommendations and future work

• 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
  • Scenario 3 has too low a reliability (Sat 89%, PMD 92%), which also stresses the sensitivity to this parameter

  => Recommendation: 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

<table>
<thead>
<tr>
<th>Sats per plane</th>
<th>Gen.1</th>
<th>Gen. 2</th>
<th>Gen. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max active (in plane)</td>
<td></td>
<td></td>
<td>54</td>
</tr>
<tr>
<td>Idle (in plane)</td>
<td>10</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Total launched (in plane)</td>
<td>64</td>
<td>61</td>
<td>59</td>
</tr>
<tr>
<td>Shepherds (under plane)</td>
<td>7</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>
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

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

On station CAM timeline

<table>
<thead>
<tr>
<th>Manoeuvre type</th>
<th>Gen.1</th>
<th>Gen. 2</th>
<th>Gen. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Along track avoidance manoeuvres</td>
<td></td>
<td>Lifetime DV &lt; 1 m/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max dephasing ~ 0.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Altitude excursion ~ 160 m</td>
<td></td>
</tr>
<tr>
<td>Timeline</td>
<td>Manoeuvre to be started @ TCA - 13h</td>
<td>Manoeuvre to be started @ TCA - 13h</td>
<td>Last CDM/GO NO GO to be sent to satellite @ TCA - 15h</td>
</tr>
</tbody>
</table>
Operational Concept - Autonomy

Ground segment automation considered for gen 1

Advanced on board autonomy implemented for gen 2 & 3 for planned manoeuvres and CAM handling

→ See WP 4100 slides
**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

---

**Scenario Diagram**

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
Building Blocks / Roadmaps – Space Segment

Shepherd Satellite / ADR Satellite / Constellation Cycler

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase 0/A (Airbus)</th>
<th>Phase B1</th>
<th>Phase B2/C/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>RemoveDebris Mission (→ TRL 6)</td>
<td>Net-based Capture</td>
<td>Alternative (i.e. magnetic) Capture</td>
</tr>
<tr>
<td>2020</td>
<td>Shepherd Satellite / ADR Satellite / Constellation Cycler</td>
<td>Demo Mission (→ TRL 6)</td>
<td>ADR GNC</td>
</tr>
</tbody>
</table>

ADR GNC

RemoveDebris Mission, VBN, LIDAR (→ TRL 6)
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
The study has shown that the need for a high performance SSA system capable of:

- Maintaining a highly accurate catalog
- Frequent updates to 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)
Thank you