0 TABLE OF CONTENT

1. INTRODUCTION
2. SMALL SATELLITE SECTOR
3. BEGLIAN SATELLITES
4. CASE STUDY
5. CONCLUSION
INTRODUCTION
1 INTRODUCTION

A satellite is a product sold for a given price to a customer

Products can be classified using their application (Earth Observation, Communication, Navigation), using their mass (1kg, 50kg, 100kg), using their standard (1U, 6U, 12U)
1 INTRODUCTION

- **What is the price of these satellites?**

  - Earth Observation 6U Cubesat (12kg)
  - Worldview-4: Earth Observation (2,800 kg)
1 INTRODUCTION

- How much profit do you make?
INTRODUCTION

Mandatory ECSS

Usefull ECSS

LEGEND

Published

Document affected by update of other doc.

Ongoing update of an existing document

New document in production

CAN bus extension protocol

SPACECRAFT transference protocol for MIL STD 1553B

Interface and communication protocol for MIL STD 1553B

Radio frequency and modulation

Space data links - Telecommand and channel coding

Space data links - Telemetry synchronization and channel coding

NOTE 1: At next issue, this document might be renumbered to: ECSS-E-ST-50-50

(as of 16 April 2010)
1 INTRODUCTION

- **Satellite Engineering**
  1. Customer Need (Scientist)
  2. Creation of System Requirements
  3. Phase 0 (CDF Study)
  4. Phase A (Feasibility Study)
  5. Phase B (Preliminary Design)
  6. Phase C (Final Design)
  7. Phase D (Manufacturing / Testing)
  8. Phase E (Launch / Commissionning & Operations)
  9. Phase F (De-orbiting)
1 INTRODUCTION

- **Satellite Engineering**
  1. Customer Need (Scientist)
  2. Creation of System Requirements
  3. Phase 0 (CDF Study)
  4. Phase A (Feasibility Study)
1 INTRODUCTION

- Satellite Engineering

5. Phase B (Preliminary Design)
   - Detailed System Analysis
   - Preliminary Subsystem Analysis
   - Trade-offs

6. Phase C (Final Design)
   - Detailed Subsystem Analysis
   - Procurement
   - Qualification Testing
1 INTRODUCTION

- **Satellite Engineering**

7. Phase D
   - Manufacturing
   - Acceptance Testing
   - Requirement Verification
   - Shipment to Launch site
1 INTRODUCTION

- Satellite Engineering

8. Phase E
   - Launch
   - Commissionning
   - Operations

9. Phase F (De-orbiting/End of Life)
   - None in this case
2 SMALL SATELLITE SECTOR

**NANOSATELLITE**
1 – 10 kg
- Prospector-X.
  - Compare size to Toaster

**MICROSATELLITE**
10 – 100 kg
- Prospector-1
  - Compare size to Beachball

**SMALL SATELLITE**
100 – 500 kg
- NigeriaSat-2
  - Compare size to Beer Fridge

**STANDARD SATELLITE**
>500 kg
- ESA Sentinel-3
  - Compare size to Sport Utility Vehicle
2 MAIN PRODUCTS

- SSTL-150
- SSTL-300S
- Satellogic-1
- SpaceEye-D
- Myriade Evolution
- PROBA
- Skysat-1
- Skysat-3
- Skysat-1
- Myriade Evolution
- PROBA
- SpaceEye-X
- SSTL-50 Platform
- 3U Cubesat
- 12U Cubesat
MARKET MAP

2007-2016
- ~180 Satellites
- $17.4B Manufacturing revenue
- ~$95M Average satellite cost
- 34% of the satellites in <$50M price range

2017-2026
- ~600 Satellites
- $33.6B Manufacturing revenue
- ~$55M Average satellite cost
- 57% of the satellites in <$50M price range

FOCUS ON SATELLITES >50KG (NON-METEO)

9th SUMMIT ON EARTH OBSERVATION BUSINESS
2 MARKET MAP

POTENTIAL DEPLOYMENT OVER 2017-2021

Earth observation (incl. meteo)

350-400

>100

~75

~40

~165

Of which 88% for 5 commercial constellations

Data collection (IoT/M2M/AIS/ADS-B etc.)

~150

<10kg

10-50kg

51-250kg

251-500kg

>501kg

81 of Iridium NEXT satellites equipped with Aireon ADS-B payload - 20 already launched

9th SUMMIT ON EARTH OBSERVATION BUSINESS
© EUROCONSULT 2017
3 BELGIAN SATELLITES
3 ACHIEVEMENTS

- **PROBA-1 (2001)**
  - Earth Imaging
  - Technology Demo

- **PROBA-2 (2009)**
  - Sun Observation
  - Technology Demo

- **PROBA-V (2013)**
  - Global Vegetation Monitoring
  - Operational Mission
3 ACHIEVEMENTS

- **PROBA-1 (2001)**
  - Earth Imaging
  - Technology Demo

- **PROBA-2 (2009)**
  - Sun Observation
  - Technology Demo

- **PROBA-V (2013)**
  - Global Vegetation Monitoring
  - Operational Mission
3 PROBA - 2
Mission

1. In orbit Demonstration, PROBA-2 aimed at technological innovation.

Altogether, 17 new technological developments and four scientific experiments are being flown on Proba-2.

<table>
<thead>
<tr>
<th>Orbital Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTAN</td>
<td>06:00 (AM)</td>
</tr>
<tr>
<td>a (km)</td>
<td>7100</td>
</tr>
<tr>
<td>e (deg)</td>
<td>0</td>
</tr>
<tr>
<td>i (deg)</td>
<td>98</td>
</tr>
<tr>
<td>w</td>
<td>0</td>
</tr>
</tbody>
</table>
3 PROBA - 2

- **Mission**

1. RAAN selected for 6:00 AM Local Time Ascending Node
### Mission

1. Launcher is **Rockot**
   - **Worst Case** separation rate of 8° per sec.
   - Inclination accuracy of 0.05°
   - Altitude accuracy of 12km
   - RAAN accuracy of 3.75° (≈15min LT)

2. Injected via the **Breeze upper stage**
3 PROBA - 2

Mission
3 PROBA - 2

- **Mission**
  1. Ground segment visibility
     - REDU
     - KIROUNA

<table>
<thead>
<tr>
<th></th>
<th>Mean # contact</th>
<th>Mean duration of contact</th>
<th>Mean contact per day</th>
<th>Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redu</td>
<td>5</td>
<td>8</td>
<td>35</td>
<td>11.5 hours</td>
</tr>
<tr>
<td>Kiruna</td>
<td>+/- / = ?</td>
<td>+/- / = ?</td>
<td>+/- / = ?</td>
<td>+/- / = ?</td>
</tr>
</tbody>
</table>
3 PROBA - 2

- **Mission**
  1. Ground segment visibility
    - REDU
    - KIROUNA

<table>
<thead>
<tr>
<th></th>
<th>Mean # contact</th>
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<tbody>
<tr>
<td>Redu</td>
<td>5</td>
<td>8</td>
<td>35</td>
<td>11.5 hours</td>
</tr>
<tr>
<td>Kiruna</td>
<td><strong>9.5</strong></td>
<td><strong>8</strong></td>
<td><strong>77</strong></td>
<td><strong>10 hours</strong></td>
</tr>
</tbody>
</table>
3 PROBA - 2

- **Mission**
  1. Scenario
     - LEOP
     - Commissioning (three months)
     - Nominal Operations

2. **Spacecraft Modes**
   - Separation
   - Safe
   - Imaging
   - Stand-by
3 PROBA - 2

- **Satellite Design - Configuration**
  1. Single H Structure
  2. Sun Shield
     - Standard STR
     - Bepi-Colombo STR
  3. High Unit Density
  4. Deployable Solar Panel (x2)
3 PROBA - 2

- **Satellite Design - Mechanics**
  1. Spacecraft Mass ≈ 120 kg

2. CoG Choice
   - Folded Configuration (LV requirement)
   - Deployed Configuration (GNC requirement)

<table>
<thead>
<tr>
<th>COG (mm)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>&lt; 15</td>
<td>-1 &lt; XY &lt; 1</td>
<td>-1 &lt; XZ &lt; 1</td>
</tr>
<tr>
<td>Y</td>
<td>-1 &lt; YX &lt; 1</td>
<td>&lt; 15</td>
<td>-1 &lt; YZ &lt; 1</td>
</tr>
<tr>
<td>Z</td>
<td>-1 &lt; ZX &lt; 1</td>
<td>-1 &lt; ZY &lt; 1</td>
<td>&lt; 8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COG (mm)</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>&lt; 20</td>
<td>&lt; 5</td>
<td>&lt; 400</td>
</tr>
<tr>
<td>Y</td>
<td>-1 &lt; YX &lt; 1</td>
<td>&lt; 15</td>
<td>-1 &lt; YZ &lt; 1</td>
</tr>
<tr>
<td>Z</td>
<td>-1 &lt; ZX &lt; 1</td>
<td>-1 &lt; ZY &lt; 1</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>
3 PROBA - 2

Satellite Design - Power

1. Power budget is positive, independently of the mode
   - Observation (w/o TX)
   - Observation with TX
   - Safe mode with TX (worst Beta-angle).

Definition

Beta Angle = angle between the Sun-Earth vector and the orbital plane.

- $\beta = 90^\circ$ implies max sunlight time
- $\beta = 0^\circ$ implies min sunlight time
3 PROBA - 2

- Satellite Design - Power

- Beta angle = 0°
- Beta angle = 20°
- Beta angle = 50°
3 PROBA - 2

- **Satellite Design – Power**
  1. Battery DoD (Ah) in function of time
  2. Non Regulated bus 28V
3 PROBA - 2

- **Satellite Design - Power**

  1. Power budget while de-tumbling!

  2. Trade-off between:
     - Performance (GNC)
     - Time (LEOP schedule)
     - Battery Discharge (Higher DoD)

*Top: Incoming power (black), power consumption (red, and power to battery (green) [W]; Bottom: battery DoD [Ah]*)
3 PROBA - 2

- Satellite Design - Avionics
  1. System is **fully redundant**
  2. Data & Power centralized (**ADPMS**)

3. Interface Unit
   - AOCS Module
   - Deployment Module
   - Propulsion Module
   - Thermal Control Module

Source: eoportal
3 PROBA - 2

- **Satellite Design – AOCS**
  1. Low power resistojet (Xenon)
     - 15W for heater (x2)
     - 50s Isp (min)
     - 20mN Thrust
   - Total $\Delta V = 2m/s$

\[ \Delta u = V_{eq} \ln \left( \frac{mf}{me} \right) = V_{eq} \ln MR = Isp \ g_0 \ln MR \]
Satellite Design – AOCS

1. Sensors
   - 2 Star-tracker
   - 2 GPS RX
   - 2 Magnetor-Meter

2. Actuators
   - 4 Reaction Wheels
   - 3 dual-coil magneto-Torquer
3 PROBA - 2

GPS RX

⇒ Position determination
Magnetometer (2)

Measure continuously the Earth Magnetic field and determine itself where the North is.

⇒ Position determination
Star-Tracker (3)
• Takes pictures of stars
• Compare it with its internat catalog.
• Compute the satellite orientation/position

⇒ Orientation/Position
Magnetotorquer (4)

- Magnetic Coil
- Align itself to Magnetic lines

⇒ Orientation/Manoeuvre
Orientation/Manoeuvre

Accelerates or decelerates while momentum conservation implies the PROBA to rotate the other way.

⇒ Orientation/Manoeuvre
3 PROBA - V
3 PROBA - V

- **Mission**

1. Providing **Daily Vegetation Global Monitoring** Capability to Scientific Community

<table>
<thead>
<tr>
<th></th>
<th>Key Performance data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit</strong></td>
<td>Quasi SSO (slightly drifting LTDN – injection 10:45 AM)</td>
</tr>
<tr>
<td></td>
<td>$i = 98.73$ deg</td>
</tr>
<tr>
<td></td>
<td>$e = 0$</td>
</tr>
<tr>
<td></td>
<td>Altitude = 820km</td>
</tr>
<tr>
<td><strong>Mission Lifetime</strong></td>
<td>2.5 year</td>
</tr>
<tr>
<td><strong>Daily global coverage</strong></td>
<td>Latitudes 35° to 75°N</td>
</tr>
<tr>
<td></td>
<td>Latitudes 35° to 56°S</td>
</tr>
<tr>
<td><strong>Coverage after two days</strong></td>
<td>Latitudes between 75°N and 56°S</td>
</tr>
</tbody>
</table>
3 PROBA - V

- **Mission**
  1. RAAN selected for 10:45 Local Time Descending Node.
3 PROBA - V

- **Mission**
  1. Launcher is **VEGA**
     - Semi-major axis accuracy of 15km
     - Inclination accuracy of 0.15 deg
     - Better than PSLV
       - Inclination accuracy of 0.2°
       - Altitude accuracy of 35km
  2. Launch site: **Kourou**
  3. Launch Date: **7th of May 2013**
3 PROBA - V

Mission

1. Ground station selection
   - Svalbard / Kiruna / Fairbanks – Payload data downlink
   - REDU for mission control

<table>
<thead>
<tr>
<th>Location</th>
<th>Svalbard</th>
<th>Redu</th>
<th>Kiruna</th>
<th>Alaska</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled by</td>
<td>KSAT</td>
<td>ESA</td>
<td>SSC</td>
<td>USN</td>
</tr>
<tr>
<td>Co-ordinates</td>
<td>78.13°N, 15.23°E</td>
<td>50.01°N, 5.14°E</td>
<td>67.85°N, 20.96°E</td>
<td>64.9°N, 147.9°W</td>
</tr>
<tr>
<td>Antenna diameter [m]</td>
<td>11/13</td>
<td>2.4</td>
<td>15/13</td>
<td>10</td>
</tr>
<tr>
<td>Bands available</td>
<td>S/X</td>
<td>S</td>
<td>S/X</td>
<td>S/X</td>
</tr>
<tr>
<td>Min Elevation [Deg]</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>EIRP [db]</td>
<td>64</td>
<td>72.5</td>
<td>71/69</td>
<td>24/37</td>
</tr>
<tr>
<td>G/T, sensitivity [db]</td>
<td>35.4</td>
<td>29 (S)</td>
<td>21.4/35.6</td>
<td>22/32</td>
</tr>
<tr>
<td>Altitude [m]</td>
<td>455</td>
<td>386.6</td>
<td>402</td>
<td>149</td>
</tr>
</tbody>
</table>

Source: ESA ESTRACK manual
3 PROBA - V

- **Mission**
  1. Ground station selection
     - Fairbanks & Kiruna overlap! No steerable antenna on board
     - Necessity to interrupt connection
3 PROBA - V

- **Satellite Design - Configuration**
  1. X-band antenna toward Nadir
  2. Solar Array on Velocity, Zenith & Anti Velocity
  3. Star Tracker looking as much as possible towards deep space
  4. Bottom board for LV interface
3 PROBA - V

- **Satellite Design - Structure**
  1. Single H structure
  2. Stiffening beams

3. **Honeycomb panels**
   - Aluminium core
   - Aluminium edge
   - Aluminium facesheet (Primary structure)
   - CFRP facesheet (Secondary structure)
3 PROBA - V

- **Satellite Design - Mechanics**

1. Spacecraft Mass = 148 kg with given margin philosophy

<table>
<thead>
<tr>
<th></th>
<th>Mass (w/o margin)</th>
<th>Margin</th>
<th>Mass w/ margin</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>5kg</td>
<td>5%</td>
<td>5.25kg</td>
<td>No modification</td>
</tr>
<tr>
<td>Unit 2</td>
<td>2kg</td>
<td>10%</td>
<td>2.2 kg</td>
<td>Modification</td>
</tr>
<tr>
<td>Unit 3</td>
<td>3kg</td>
<td>20%</td>
<td>3.6 kg</td>
<td>New development</td>
</tr>
<tr>
<td>TOTAL</td>
<td>10 kg</td>
<td></td>
<td>11.05 kg</td>
<td>w/o Sys Margin</td>
</tr>
</tbody>
</table>

|         | System Margin     | 20%    | 13.26kg        | w/ Sys Margin         |

2. Balance Mass of for CoG Location Requirement

<table>
<thead>
<tr>
<th>Launcher</th>
<th>Lateral Tolerance [mm]</th>
<th>Longitudinal Tolerance [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEGA</td>
<td>10</td>
<td>&lt; 500</td>
</tr>
</tbody>
</table>
3 PROBA - V

- Satellite Design - Power

1. Power budget approach could be:
   - Rely on Solar Array (SA) in Sun and on Battery in Eclipse
   - Rely on both Battery and SA when available.

What are the advantages & disadvantages of these approaches?
3 PROBA - V

- **Satellite Design - Power**

  1. Power budget approach could be:
     - Rely on Solar Array (SA) in Sun and on Battery in Eclipse
     - Rely on both Battery and SA when available.

<table>
<thead>
<tr>
<th></th>
<th>IMAGING</th>
<th>X-BAND</th>
<th>STD-BY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDHU</td>
<td>20W</td>
<td>20W</td>
<td>20W</td>
</tr>
<tr>
<td>COM</td>
<td>5W</td>
<td>40W</td>
<td>5W</td>
</tr>
<tr>
<td>PAYLOAD</td>
<td>32W</td>
<td>5W</td>
<td>5W</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>85 W</td>
<td>120 W</td>
<td>40W</td>
</tr>
<tr>
<td>Sys Marg</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>90W</td>
<td>125W</td>
<td>45W</td>
</tr>
</tbody>
</table>

*Typical power budget*
3 PROBA - V

- Satellite Design - Power

1. Power > 0 (consumption) & Power < 0 (recharge)
3 PROBA - V

- Satellite Design – RF COM
  - Downlink (S-Band) – 2235 MHz
    - Data rate = 142kbps (BPSK modulation)
    - Symbol rate = 329 ksps (Convolutional-Reed Solomon Coding)

- Two things to look at:
  - Flux margin (avoid too much power received on grd)
  - Telemetry Recovery margin (avoid too little power to read the telemetry) (Eb/N0)

- Good practice = 3 dB
Satellite Design – RF COM

1. How to make quick check for Flux Density?
   - +Power @ Transmitter (dBW)
   - - Circuit Loss (3dB)
   - +S/C Gain of Antenna (dBi)
   - - 10*LOG(4*π*(slant_km*1000)^2)

   \[
   = \text{Power Flux @ G/S (dBW/m}^2\text{)}
   \]
   - -10*LOG(bit_rate_kbps)+6+30

   \[
   = \text{Power Flux Density @ G/S (dBW/m}^2/4\text{kHz) shall be < Required}
   \]
3 PROBA - V

- **Satellite Design – RF COM**

1. How to make quick check for TM Recovery margin?
   - +Power @ Transmitter (dBW)
   - - Circuit Loss (3dB)
   - +S/C Gain of Antenna (dBi)
   - - Path Loss (dB) - Atmosphere & Polarization mismatch (1dB)
   - + G/T of the Antenna (dB/K)
   - - Boltzmann constant (dBW/HzK)
   
   = C/N0 (carrier to noise ratio) (dBHz)
   - - TM Demodulation Loss (dB) depends on complexity
   - - TM BitRate (dBHz)

- Eb/N0 (dB) shall be > Required
3 PROBA - V

- **Satellite Design – RF COM**
  1. Downlink (S-Band) – 2235 MHz
     - Data rate = 142kbps (BPSK modulation)
     - Symbol rate = 329 ksps (Convolutional-Reed Solomon Coding)
  2. Uplink (S-Band) – 2058 MHz
     - Data rate = 64kbps
     - Carrier Recovery margin of 20dB
     - Telecommand Recovery margin of 6dB
3 PROBA - V

- Satellite Design – Memory
  1. Memory
     - Mass Memory size = 90Gbit
     - Required < 55 Gbit
     - Total Generated < 230 Gbit
  2. Ground contact
     - 20 contact per day – 8 skipped (assumption)
     - Max time delay = 3,2 hours
3 PROBA - V

- **Satellite Design – AOCS**
  1. **Guidance**
     = *determination of the desired path of travel from the satellite's current location to a designated target*
  2. **Navigation**
     = *determination of the satellite’s location, velocity and attitude*
  3. **Control**
     = *manipulation of the forces needed to track guidance commands while maintaining satellite stability*
3 Phase A

What are the typical sources of error?
3 Phase A

- What are the typical pointing requirement one usually finds?
3 Phase A

How much deviation does it give on ground if the satellite flies at 800 km?

(give it in 2-sigma & 3-sigma confidence)
How do you think it can compare to a 6U cubesat flying at 500 km?
3 PROBA - V

- Launched on the 07/05/2013 from Kourou
4 CASE STUDY
3 SOLAR OCCULTATION MISSION
3 SOLAR OCCULTATION MISSION

- **Mission**

1. ESA asks you to put **two spacecrafts** in High Elliptical Orbit (HEO) with 20 hours period so that one can occult the Sun while the other one collects picture of its Corona (scientific purpose)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit type</td>
<td>HEO</td>
</tr>
<tr>
<td>Perigee altitude</td>
<td>600km</td>
</tr>
<tr>
<td>Apogee altitude</td>
<td>60,000km</td>
</tr>
<tr>
<td>Inclination</td>
<td>59°</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.8</td>
</tr>
</tbody>
</table>
What are the advantages and disadvantages of such an orbit?
### What would you put in your spacecraft?

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Aluminum (density = 2700 kg/m³)</td>
</tr>
<tr>
<td></td>
<td>CFRP (density = 1800 kg/m³)</td>
</tr>
<tr>
<td></td>
<td>Invar (density = 8000 kg/m³)</td>
</tr>
<tr>
<td>Thermal</td>
<td>Passive OR Active ?</td>
</tr>
<tr>
<td>Mechanism</td>
<td>Body Mounted OR Deployable SA?</td>
</tr>
<tr>
<td>Power</td>
<td>Large OR Small SA ?</td>
</tr>
<tr>
<td></td>
<td>Large OR Small Battery?</td>
</tr>
<tr>
<td>GNC</td>
<td>Sensor? + Why ?</td>
</tr>
<tr>
<td></td>
<td>Actuator? + Why?</td>
</tr>
<tr>
<td>RF</td>
<td>High/Low Gain COM Antenna?</td>
</tr>
</tbody>
</table>
How would you Launch the two spacecrafts so that they reach the same orbit?

(Two Launches? One Launch?)
(Together? Separated?)
3 SOLAR OCCULTATION MISSION

- Welcome in Phase A!
3 Phase A... And the usual problems

STACK (SC1+SC2)

Spacecraft 1 (SC1) & Spacecraft 2 (SC2)
3 Phase A… And the usual problems

1. Mass Budget
   - “Total dry mass including I/F ring with L/V shall be less than 360kg for SC1 and 300kg for SC2”.
   - Current estimate: SC1 = 375kg & SC2 = 270kg

2. Power Budget
   - “Total maximum power consumption shall be less than 300W (with margins) for both spacecrafts”
   - Current estimate: SC1 = 350W & SC2 = 250W
3 Phase A... And the usual problems

1. Link Budget

   “The SC1 shall be able to downlink data at a symbol rates of 2Msps”

   “Both SC shall be able to receive TC data at a symbol rates of 64ksps”

   Current estimation with 2.4 meter antenna (REDU)
   - Downlink not closed for 2Msps (@apogee) for S/C1
   - Uplink not closed for 64ksps (@apogee) for neither SC...
3 Phase A

- What can we do?
3 Phase A

- **For Information**
  1. SC1 has two propulsion subsystems
     - 2x8 thrusters to raise orbit (Mono-propellant)
     - Sixteen thruster for GNC and FF (Cold Gas)
  2. SC2 does not have any propulsion
  3. Monopropellant shall be maintained above 10°C (always) and thus currently consumes 90W just for heating.
  4. Monopropellant thrusters shall be pre-heated to give their maximum performance (1N and 202 sec of Isp)
  5. Monopropellant sub-system weight 27kg
  6. Payload is currently kept warm constantly (40W)
3 Phase A

- For Information
What do we need to update if the Power consumption is modified?
3 Phase A – Electrical Architecture

1. Power Generation & Storage
   - Solar Array
   - Battery

2. Power Conditioning Distribution Unit (not displayed)

3. Connections
   - Safe & Arm
   - Umbilical Connection
3 Phase A – Solar Array Sizing

1. Main components
   - Cells Series (TBD)
   - String Parallel (TBD)
   - Section (TBD strings)

2. Secondary components (not displayed)
   - Shunt Selection
   - Dump Resistor
3 Phase A – Solar Array Sizing

1. **Main components**
   - Cells Series (TBD)
   - String Parallel (TBD)
   - Section (TBD strings)

2. **Secondary components (not displayed)**
   - Shunt Selection
   - Dump Resistor

How can we calculate this?
3 Phase A – Solar Array Sizing
3 Phase A – Solar Array Sizing

- **Solar Array Design (3G28%)**
  1. Evaluate the degradation?
    - Coverglass thickness
  2. Degradation of Electrical Parameters
  3. Degradation of Temp. Coefficient

### Table: Coverglass thickness (μm) vs. Electrical Parameters

<table>
<thead>
<tr>
<th>Coverglass thickness (μm)</th>
<th>Pmax [W/cm²]</th>
<th>Voc [V/cm²]</th>
<th>Isc [A/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5.11E+17</td>
<td>5.99E+17</td>
<td>7.12E+17</td>
</tr>
<tr>
<td>25.4</td>
<td>7.64E+14</td>
<td>8.93E+14</td>
<td>8.43E+14</td>
</tr>
<tr>
<td>76.2</td>
<td>1.52E+14</td>
<td>1.76E+14</td>
<td>1.35E+14</td>
</tr>
<tr>
<td>152.4</td>
<td>7.81E+13</td>
<td>9.99E+13</td>
<td>6.48E+13</td>
</tr>
<tr>
<td>304.8</td>
<td>4.16E+13</td>
<td>4.75E+13</td>
<td>3.27E+13</td>
</tr>
<tr>
<td>508.0</td>
<td>2.55E+13</td>
<td>2.88E+13</td>
<td>1.94E+13</td>
</tr>
<tr>
<td>762.0</td>
<td>1.64E+13</td>
<td>1.86E+13</td>
<td>1.16E+13</td>
</tr>
<tr>
<td>1524.0</td>
<td>2.06E+12</td>
<td>9.37E+12</td>
<td>5.43E+12</td>
</tr>
</tbody>
</table>

### Table: 3G-28% cell: Electrical Parameters drifts irradiation

<table>
<thead>
<tr>
<th>EP</th>
<th>BoL</th>
<th>2.00E+13</th>
<th>7.00E+13</th>
<th>2.50E+14</th>
<th>5.00E+14</th>
<th>1.00E+15</th>
<th>3.00E+15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc</td>
<td>2650</td>
<td>0.99</td>
<td>0.97</td>
<td>0.95</td>
<td>0.94</td>
<td>0.92</td>
<td>0.9</td>
</tr>
<tr>
<td>Isc</td>
<td>498</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
<td>0.98</td>
<td>0.96</td>
<td>0.87</td>
</tr>
<tr>
<td>Vmp</td>
<td>2366</td>
<td>0.99</td>
<td>0.99</td>
<td>0.94</td>
<td>0.93</td>
<td>0.92</td>
<td>0.9</td>
</tr>
<tr>
<td>Imp</td>
<td>480</td>
<td>0.99</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td>0.95</td>
<td>0.84</td>
</tr>
<tr>
<td>Pmp</td>
<td>1135</td>
<td>0.98</td>
<td>0.97</td>
<td>0.92</td>
<td>0.91</td>
<td>0.87</td>
<td>0.76</td>
</tr>
</tbody>
</table>

### Table: 3G-28% cell: Temperature Coefficients drifts irradiation

<table>
<thead>
<tr>
<th>TC</th>
<th>BoL</th>
<th>2.00E+13</th>
<th>7.00E+13</th>
<th>5.00E+14</th>
<th>1.00E+15</th>
<th>3.00E+15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voc (mV/K)</td>
<td>-5.96</td>
<td>-6.01</td>
<td>-6.11</td>
<td>-6.15</td>
<td>-6.25</td>
<td>-6.46</td>
</tr>
<tr>
<td>Isc (mV/K)</td>
<td>0.340</td>
<td>0.298</td>
<td>0.298</td>
<td>0.340</td>
<td>0.370</td>
<td>0.340</td>
</tr>
<tr>
<td>Vmp (mV/K)</td>
<td>-6.01</td>
<td>-6.42</td>
<td>-6.45</td>
<td>-6.26</td>
<td>-6.35</td>
<td>-6.59</td>
</tr>
<tr>
<td>Imp (mW/K)</td>
<td>0.316</td>
<td>0.248</td>
<td>0.219</td>
<td>0.220</td>
<td>0.250</td>
<td>0.220</td>
</tr>
<tr>
<td>Pmp (mW/K)</td>
<td>-2.54</td>
<td>-2.60</td>
<td>-2.69</td>
<td>-2.66</td>
<td>-2.59</td>
<td>-2.42</td>
</tr>
</tbody>
</table>
3 Phase A – Solar Array Sizing

- What happens to the P_max at EoL?

Consider both radiation and thermal effect
3 Phase A – Solar Array Sizing

- Example using 3G28%
  1. Evaluate the degradation?
    - Coverglass thickness

- Degradation of Electrical Parameters

- Degradation of Temp. Coefficient
3 Phase A – Solar Array Sizing

2. Evaluate the number of cells?
   - Consider worst case (EoL + Hot temperature ≈ 100°C)
   - Max battery voltage to be provided (e.g. 28V)

<table>
<thead>
<tr>
<th>Description</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harness voltage drop (incl. connectors)</td>
<td>&lt; 1 V</td>
</tr>
<tr>
<td>Solar Array connectors &amp; protections (e.g. diodes)</td>
<td>&lt; 1 V</td>
</tr>
<tr>
<td>Maximum Battery Voltage</td>
<td>28 V</td>
</tr>
<tr>
<td>Minimum solar cell strings voltage required</td>
<td>28+1+1=30 V</td>
</tr>
<tr>
<td>Additional voltage margin</td>
<td>1 V</td>
</tr>
<tr>
<td>Required solar string voltage</td>
<td>31 V</td>
</tr>
<tr>
<td>EoL cell voltage @ 100°C</td>
<td>1,8 V</td>
</tr>
<tr>
<td>Required amount of cell to cells in one string to achieve voltage</td>
<td>18 Cells</td>
</tr>
</tbody>
</table>
### 3 Phase A – Solar Array Sizing

#### Evaluate the number of strings?

- Max current allowed by PDHU (e.g. 20A) @BOL
- Compute current available at EOL, knowing that \( \frac{di}{dT} < 0 \) and accounting for Minimum Solar Cste \( (\frac{di}{dC} > 0) \)

<table>
<thead>
<tr>
<th>Description</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assuming best case = direct illumination, BOL, hot case</td>
<td>-</td>
</tr>
<tr>
<td>BOL string current</td>
<td>0.5 A</td>
</tr>
<tr>
<td><strong>BOL maximum amount of string</strong></td>
<td>40 strings</td>
</tr>
<tr>
<td>Assuming worst case = 10% shading, low solar constant, cold case</td>
<td>-</td>
</tr>
<tr>
<td>EOL degradation factor</td>
<td>90%</td>
</tr>
<tr>
<td>EOL string current</td>
<td>0.45 A</td>
</tr>
<tr>
<td>Shading degradation (10% of 40 strings shaded)</td>
<td>4 strings</td>
</tr>
<tr>
<td><strong>Total current available at EOL</strong></td>
<td>16.2 A</td>
</tr>
</tbody>
</table>
3 Phase A – Solar Array Sizing

- How do we know that it is enough to have 40 strings?
3 Phase A – Battery Sizing

1. Main components
   - Cells Series (TBD)
   - String Parallel (TBD)

2. Secondary components
   - Internat heaters
   - Thermistors
3 Phase A – Battery Sizing

1. Main components
   - Cells Series (TBD)
   - String Parallel (TBD)

2. Secondary components
   - Internat heaters
   - Thermistors

How can we calculate this?
3 Phase A – Battery Sizing

1. Evaluate the number of cells?
   - Check Nominal non regulated bus voltage requirement (28V)
   - Find Cells characteristics (e.g. 4V End of Charge - EoL)
   - Combine 7 cells in series to create the voltage
3 Phase A – Battery Sizing

2. Battery shall be used for
   2. Detumbling
   3. Eclipse
   4. Support

3. Evaluate the number of strings?
   - $\text{Capacity}_{\text{used}} = \text{Power} \times \text{Time}$
   - $\text{Capacity}_{\text{required}} = \frac{\text{Capacity}_{\text{Used}}}{(1-\text{DoD}_{\text{Allowed}})}$
   - Capacity of 1 string = $\text{Nb}_{\text{Cells}} \times \text{Capacity}_{\text{Cell}}$
   - One String Failure Tolerance

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Used Capacity (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detumbling</td>
<td>200</td>
</tr>
<tr>
<td>Eclipse</td>
<td>120</td>
</tr>
<tr>
<td>Long Eclipse</td>
<td>665</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>DoD choice</th>
<th>Required Capacity (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detumbling</td>
<td>20%</td>
<td>240</td>
</tr>
<tr>
<td>Eclipse</td>
<td>20%</td>
<td>148</td>
</tr>
<tr>
<td>Long Eclipse</td>
<td>60%</td>
<td>1064</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Nb}_{\text{Cells}}$</td>
<td>7</td>
</tr>
<tr>
<td>$\text{Capacity}_{\text{Cell}}$</td>
<td>5.4 Wh</td>
</tr>
<tr>
<td>Capacity 1 string</td>
<td>37.8 Wh</td>
</tr>
</tbody>
</table>

29 (+1) Strings
3 WHERE ARE WE NOW?

1. Mass Budget
   - “Total dry mass including I/F ring with L/V shall be less than 360kg for SC1 and 300kg for SC2”.

2. Power Budget
   - “Total maximum power consumption shall be less than 300W (with margins) for both spacecrafts”
3 WHERE ARE WE NOW?

1. Link Budget
   - “The SC1 shall be able to downlink data at a symbol rates of 2Msps”

   - “Both SC shall be able to receive TC data at a symbol rates of 64ksps”

   - Current estimation:
     - Downlink not closed for 2Msps (@apogee) for S/C1
     - Uplink not closed for 64ksps (@apogee) for neither SC...
3 Phase A

- What can we do?
3 We have modified requirement

1. Link Budget
   - “The SC I shall be able to downlink data at a symbol rates of 256ksps and 2Msps”
   - “Both SC shall be able to receive TC data at a symbol rates of 64ksps”

Note: REDU antenna of 15 meter diameter is now considered. Operational cost has been increased.
4 CONCLUSION

Summarizing
4 CONCLUSION

1. Follows the Project Life Cycle
   - Starts with Mission Concept
   - Prepares System Requirements
   - System Designs based on Technical & Programmatic Trade-Offs
   - Prepare sub-system & unit requirement + analysis
   - Link all levels together (= unit requirement verifying sub-system requirement, themselves verifying system requirements)
   - Manufacture the S/C
   - Verify Requirements (Review of Design / Analysis / Test)
   - Launch it!

2. Iterative Multi-disciplinary approach + Massive Communication