SWEAT
Snow Water Equivalent with AlTimetry

Team Orange
Alpbach Summer School 2016
21th of July 2016
Outline

• Introduction
• Scientific objectives and requirements
• Measurement principle
• Payload
• System engineering
Outline

• Introduction

• Scientific objectives and requirements

• Measurement principle

• Payload

• System engineering
Snow Water Equivalent (SWE)

- Volume of water stored in a volume of snow
  - This is the relevant variable (storage) regarding snow

\[ SWE = h \times \frac{\rho_{\text{snow}}}{\rho_{\text{water}}} \]
Applications of SWE

• Prediction models
  – Hydrological
  – Climate
  – Numerical weather prediction models (e.g. ECMWF)
• Earth’s energy balance (albedo)
• Navigation (ships)
• Flood prediction
• Hydropower/dams
James Bay Project

• Series of hydroelectric power stations on the La Grande River, north of Canada

• Generating capacity 17000 MW
  – Revenue of ~ €4.85 billion
  – 1/3 of precipitation is snow

• €1,600,000,000 due to snow

(http://www.hydroquebec.com/production/centrale-hydroelectrique.html)
Available SWE products

• Observations
  – In-situ observations
  – Airborne (IceBridge)
  – Space missions (AMSR-E): RMSE of 11-32 cm

• Combined product: GlobSnow (& H-SAF) with a RMSE of 10-30 mm

→ Gap between accurate but sparse in-situ observations and global coarse-scale inaccurate observations
Scales of snow information

In-situ stations  SWEAT  AMSR-E

[Diagram showing scales and logos]
Users of GlobSnow

1. International organisations
   – World Health Organization (WHO)
   – Food and Agriculture Organisation (FAO)
   – Strategic Planning for Geoscience for a sustainable Earth (BRGM)
   – International Gorilla Conservation Program (IGCO)
   – Earth Science Advisory Committee (ESAC)
   – Centre of Terrestrial Carbon Dynamics (CTCD)
   – Laboratory for Climate Sciences and the Environment (LSCE)

2. Climate institutes such as the WCRP, ECMWF, EEA

3. National institutes
   – MeteoSwiss
   – Swiss Agency for the Environment, Forests and Landscapes
   – National Observatory of Athens
   – National Oceanography Centre, Southampton (NOCS)
   – Italian National Research Council (CNR)
   – Flemish Water Authority (AWZ), Belgium
   – Netherlands Ministry of Agriculture, Nature and Food Quality

4. Universities
   – University of Bremen
   – ...

Introduction – Scientific objectives & requirements – Measurement principle – Payloads – System engineering
Outline

• Introduction

• Scientific objectives and requirements

• Measurement principle

• Payload

• System engineering
Scientific objective 1: SWE from passive microwave algorithm

- Initial assumption
  - Grain size of snow
  - Radiative transfer model
  - Simulation of signal

- Observation of signal

\[
\text{Error} = |\text{simulated signal} - \text{observed signal}|
\]

Error < $\varepsilon$

- No
- Yes

Yes → SWE
Scientific objective 1: SWE from passive microwave algorithm

SO1: Improving estimation of global SWE from passive microwave products

Initial assumption
Grain size of snow
Radiative transfer model
Simulation of signal

Error = |simulated signal – observed signal|

Error < ε
No

Yes
Observation of signal

SWE from SWEAT

SWE
SO1: 50 shades of snow

(Libbrecht, 2005)
Scientific objective 2

SO2: Improve numerical snow and climate models
SO2: Snow in the energy balance

\[ Q_R = Q(1 - \alpha) + L_{in} + L_{out} \rightarrow \text{Climate models are sensitive to the albedo } \alpha \text{ (Furtado et al., 2014)} \]

Ice with snow: \( \alpha \approx 0.9 \)

Bare Ice: \( \alpha \approx 0.5 \)

Open ocean: \( \alpha \approx 0.06 \)

(Editied figure from NSIDC)
SO2: Climate Model

- Spatial resolution: ~100 km x 100 km grid
- Snow parameterisation: \( SCF = f(SWE) \)

\[
SCF = \min\left(1, \frac{SWE}{15}\right)
\]

(Dutra et al., 2010)

(Thackeray et al., 2015)
SO2: Improve Land Surface Models

- Shortwave radiation bias
- Similar to the expected changes due to climate change

- Validation: 10 Observations → SWEAT: 80 Observations

(Dutra et al., 2010)
Scientific objectives overview

• Main goals:
  1. Improving estimation of global SWE from passive microwave products
  2. Improve numerical snow and climate models

• Secondary goals:
  1. Improve understanding of relationship between microwave signals and snow evolution
  2. Reduce uncertainty in sea ice thickness measurements due to the snow pack
Scientific objectives overview

• Main goals:
  1. Improving estimation of global SWE from passive microwave products
  2. Improve numerical snow and climate models

• Secondary goals:
  1. Improve understanding of relationship between microwave signals and snow evolution
  2. Reduce uncertainty in sea ice thickness measurements due to the snow pack
Scientific requirements

1. SWE on sea ice
   - SR1.1 Temp. res. 3 d
   - SR1.2 Spat. res. 1 km
   - SR1.3 Coverage in polar regions
   - SR1.4 Accuracy 10 % for SWE > 0.3 m
   - SR1.5 Duration of 5 years

2. SWE on land
   - SR2.1 Temp. res. 3 d
   - SR2.2 Spat. res. 1 km
   - SR2.3 Coverage in polar regions
   - SR2.4 Accuracy 10 % for SWE > 0.3 m
   - SR2.5 Duration of 5 years
Scientific requirements

1. Temporal resolution: 3 days (ESA-GEWEX, 2015; Nghiem & Tsai, 2001)
2. Spatial resolution: 1 km (ESA-GEWEX, 2015; NRC, 2007)
3. SWE accuracy: (CoReH2O, 2012)
   - SWE > 0.3 m: 10%
   - SWE < 0.3 m: 3 cm
4. Coverage in polar regions
   - Snow on land
   - Arctic seas
5. Duration of 5 years: multiple-year statistics
How to measure SWE

**Emission**
- AMSR-E

- Coarse resolution
- Inaccurate

**Backscatter**
- CoReH2O

- Grain size
- Layering

**“Thickness”**
- SWEAT

- Direct link to SWE
Observation requirements

1. SWE on sea ice
   - SR1.1 Temp. res. 3 d
   - SR1.2 Spat. res. 1 km
   - SR1.3 Coverage in polar regions
   - SR1.4 Accuracy 10 % for SWE > 0.3 m
   - SR1.5 Duration of 5 years

2. SWE on land
   - SR2.1 Temp. res. 3 d
   - SR2.2 Spat. res. 1 km
   - SR2.3 Coverage in polar regions
   - SR2.4 Accuracy 10 % for SWE > 0.3 m
   - SR2.5 Duration of 5 years

1. Freeboard height
   - OR1.1 Vertical accuracy = 0.06 m relative to surface

2. Snow surface height
   - OR2.1 Vertical accuracy = 0.06 m relative to ground

3. Ground height
   - OR3.1 Vertical accuracy = 0.06 m relative to surface
Observation requirements

- Minimal absolute accuracy on SWE: 0.03 m (relative accuracy of 10 % for SWE > 0.3 m)

\[ h = SWE \frac{\rho_{H2O}}{\rho_{snow}} \]

- Maximum \( \rho_{snow} = 500 \text{ kg/m}^3 \) \( \Rightarrow \) \( h_{\text{min}} = 0.06 \text{ m} \)

\( \Rightarrow \) Determine snow height with accuracy of \( \pm 0.06 \text{ m} \)
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• Payload
• System engineering
New measurement principle from space

Ku-band (13 GHz)  Ka-band (37 GHz)

\[ \Delta t \approx \text{SWE} \]
New measurement principle from space

• Based on Leinss et al. (2015) and Guneriussen et al. (2001)

• Observable: \( SWE = h \times \rho \)

• Measurement: \( \Delta t = h \times \frac{n}{c} \)

• Refractive index \( n \): \( n^2 = 1 + 1.7\rho + 0.63\rho^2 \) (Maetzler, 1987)

Ground : sea ice freeboard, ice, land soil, rocks

Snow

Ku-band (13 GHz) Ka-band (37 GHz)

\( \Delta t \approx SWE \)
Ka-/Ku-band Penetration

Snow Depth from Ku/Ka-band height difference
(Guerreiro et al., 2016)

Ku-band reflection from snow-ice interface.
Corner Reflector as reference on above
(Willat et al., 2011)
Reliable SWE estimation is limited to:

- Köppen-Geiger climate zones with possible snow
- Sparse vegetation (MODIS land cover map)
- Slope $\leq 1^\circ$ due to altimeter principles (GMTED slope map)
Coverage

Legend
- Not measurable
- Potentially measurable

+ Antarctic region

60° N

+ Snow on sea ice

60° S

No slope and MODIS land cover information here
Airborne campaign

• Laser airborne campaign to complement the microwave measurements
  – When: First 2 winters, early, middle and late winter
  – Where:
    • Greenland
    • Arctic sea ice
    • Finland

• LVIS Laser (Icebridge) \((\text{Blair et al., 2011})\)
  – Swath: 2 km
  – Hor. resolution: 20 m
  – Accuracy: 6 cm
Calibration/validation of SWE

• Dedicated ground campaigns
  – In-situ measurements of
    • SWE
    • Density
    • Snow height
    • Snow microstructure
    • …
  – On land and sea-ice
  – In coordination with airborne laser altimetry
  – Example: CryoVex
Instrument requirements

Scientific requirements

1. SWE on sea ice
   - SR1.1 Temp. res. 3 d
   - SR1.2 Spat. res. 1 km
   - SR1.3 Coverage in polar regions
   - SR1.4 Accuracy 10 % for SWE > 0.3 m
   - SR1.5 Duration of 5 years

2. SWE on land
   - SR2.1 Temp. res. 3 d
   - SR2.2 Spat. res. 1 km
   - SR2.3 Coverage in polar regions
   - SR2.4 Accuracy 10 % for SWE > 0.3 m
   - SR2.5 Duration of 5 years

Observation requirements

1. Freeboard height
   - OR1.1 Vertical accuracy = 0.06 m relative to surface

2. Snow surface height
   - OR2.1 Vertical accuracy = 0.06 m relative to ground

3. Ground height
   - OR3.1 Vertical accuracy = 0.06 m relative to surface

Instrument requirements

1. Ku-band altimeter
   - IR1.1 Altimeter acc. = 70 ps

2. Ka-band altimeter
   - IR2.1 Altimeter acc. = 70 ps

3. Ku-band altimeter
   - IR3.1 Altimeter acc. = 70 ps
Instrument requirements

• Relative vertical accuracy = 0.06 m between Ka- and Ku-band
• But:
  – 0.03 m respectively
  – SNR and other uncertainties
  → Vertical accuracy = 0.01 m

• $\Delta t = \frac{2r}{c}$
  → Accuracy of 70 ps needed for 1 cm accuracy
Bonus products

- Sea ice freeboard: with the Ku-band
- Ice sheet elevation: with the Ku-band
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Payload Description

- Ku- and Ka-band altimeters
- Bistatic system
- Dual frequency
- Instruments calibrated on-board
- Parabolic antennas
Limitations of altimetry on slopes

- CryoSat limited to slopes below 0.4° (T. Parrinello, personal communication)
  - To overcome this: Swath Processing (Foresta et al., 2014; Gray et al., 2013)
  - Exploiting the full waveform of CryoSat SARIn mode data (the entire swath)
- Applicable to slopes between 0.5° and 2°
- 2 orders of magnitude more data

Introduction – Scientific objectives & requirements – Measurement principle – Payload – System engineering
Swath Processing

Petermann Glacier – standard processing - 1 track
Swath Processing

Petermann Glacier – swath processing - 1 track
Swath Processing

Petermann Glacier – standard processing
Swath Processing

Petermann Glacier – swath processing
Altimeter modes

Synthetic Aperture mode

Interferometric mode

Satellite motion

(i)

(ii)

(iii)
Altimeter modes

Synthetic Aperture mode

Use on: flat surfaces
• Ice sheet interior
• Sea-ice

Interferometric mode

Use on: surfaces with gentle slope
• Ice sheet margin
• Over land
• Coastal sea-ice
Ku-band altimeter

- **Function:** SO1 & SO3 → Measurement of the snow/ground interface
- **Heritage:** CryoSat-2/SIRAL
- **Frequency range:** ~13.2 to 13.7 GHz
- **Half angle:** 0.6°
- **Footprint:** 1.7 km

<table>
<thead>
<tr>
<th>Parameter Information:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass incl. 1.2 m antenna (kg)</td>
</tr>
<tr>
<td>Power / Output power (W)</td>
</tr>
<tr>
<td>Data rate (kbit/s)</td>
</tr>
<tr>
<td>PRF (kHz)</td>
</tr>
<tr>
<td>Pulse length (µs)</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
</tr>
<tr>
<td>Thermal operating range (°C)</td>
</tr>
</tbody>
</table>
Ka-band altimeter

- Function: SO2 → Measurement of the snow surface
- Heritage: SARAL/AltiKa
- Frequency range: ~ 35 to 37 GHz
- Half angle: 0.3°
- Footprint: 1.4 km

Parameter Information:

<table>
<thead>
<tr>
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<th>Value</th>
</tr>
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<td>Mass incl. 1.2 m antenna (kg)</td>
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<td>PRF (kHz)</td>
<td>4</td>
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<tr>
<td>Pulse length (µs)</td>
<td>110</td>
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<tr>
<td>Bandwidth (MHz)</td>
<td>500</td>
</tr>
<tr>
<td>Thermal operating range (°C)</td>
<td>-40 to +85</td>
</tr>
</tbody>
</table>
Calibration/validation for altimeter

- Active microwave transponders
  - ESA site in Svalbard (Fornari et al., 2013)
  - Gavdos, Greece (Hausleitner et al., 2012)

- Conventional sea-surface calibration (Mitchum, 2000)

- Cross-calibration with other altimeters
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System requirements

Instrument requirements

1. Ku-band altimeter
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System requirements

Instrument requirements

1. Ku-band altimeter
   IR1.1 Altimeter acc. = 70 ps

2. Ka-band altimeter
   IR2.1 Altimeter acc. = 70 ps

System requirements

1. Pointing accuracy
   SYR1.1 Pointing accuracy < 0.1°
   SYR1.2 Pointing stability < 0.005°

2. Thermal operating range
   SYR2.1 -35 °C < Top < -5 °C
   SYR2.2 -40 °C < Top < 85 °C
Mission profile

Introduction – Scientific objectives & requirements – Measurement principle – Payload – System engineering

5-YEARS OPERATION

Launch

3-day revisit time (SR1.1 & SR2.1)

De-orbit

Life-time of 5 years (SR1.5 & SR2.5)
Target orbit

- SR1.1 & SR2.1 → 3 days revisit time
- Limited number of orbits due to fast revisit time

Characteristics:
- Orbit height: 761.4 km
- Orbit period: 100.1 min
- Eccentricity: 0 - circular
- Rev/day: 14.37
- Repeating cycle: 43
- Maximum eclipse ratio: 35%
- Inclination: 90° - polar (SR1.3 & 2.3)
Target orbit
Target orbit

Coverage after 3 days of revisit time (i=92°) – CryoSat-2

→ 13.2% coverage of area of interest

Coverage after 3 days of revisit time (i=90°)
Spacecraft overview

- Solar array: 3.6 m x 3.6 m
- Radiator: 1.2 m
- Batteries: 2.2 m
- Thrusters: 2.5 m
- S-band: 2.3 m
- X-band: 2.5 m
- Ku/Ka antennas: 0.55 m
Attitude & Orbit Control System

- SYR1.1 → 3-axis control
- Sensors:
  - 3x star tracker (Terma HE-5AS) – cold redundancy
  - Sun sensor
  - 3-axis magnetometer
  - GPS/Galileo unit
  - Laser Retro-Reflectors
- Actuators:
  - 3x magneto torquer
  - 4x momentum wheel
  - 6x thrusters
Attitude & Orbit Control System

YAW MANEUVER

Model: Grace

β=74°

Model: Grace

β=0°
Thermal Control System

• Payload:
  – SYR2.1 & SYR2.2 → no active thermal control required
  – Radiator & heat pipes
  – Louvers

• Platform:
  – Heat pipes
  – Multi-layer insulation
  – Thermal coatings
  – Active heaters for batteries (20°C – 40°C)
# Power budget

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Power (W)</th>
</tr>
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<tbody>
<tr>
<td><strong>Payload</strong></td>
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<tr>
<td>Ku-band</td>
<td>149</td>
</tr>
<tr>
<td>Ka-band</td>
<td>75</td>
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<tr>
<td><strong>Attitude &amp; Orbit Control System</strong></td>
<td>361</td>
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<tr>
<td><strong>Thermal control system</strong></td>
<td>5</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>115</td>
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<tr>
<td><strong>Telemetry, Tracking &amp; Control</strong></td>
<td></td>
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<tr>
<td>S-band receiver</td>
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<tr>
<td>S-band transmitter</td>
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<tr>
<td>X-band</td>
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<tr>
<td>Emergency UHF</td>
<td>1</td>
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<tr>
<td><strong>On-Board Data Handling</strong></td>
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</tr>
<tr>
<td><strong>Propulsion</strong></td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>779</td>
</tr>
<tr>
<td><strong>Total including system margin (20%)</strong></td>
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## Power budget

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Power (W)</th>
<th>Duty cycle per orbit (%)</th>
<th>Average power per orbit (W)</th>
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<td><strong>Payload</strong></td>
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<td>Ku-band</td>
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<td>40%</td>
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<td>Ka-band</td>
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<td>Attitude &amp; Orbit Control System</td>
<td>361</td>
<td>100%</td>
<td>361</td>
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<td><strong>Thermal control system</strong></td>
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<td>Thermal control system</td>
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<td>100%</td>
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<td><strong>Power</strong></td>
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<td>100%</td>
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<tr>
<td>S-band receiver</td>
<td>4</td>
<td>100%</td>
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<td>S-band transmitter</td>
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<td>X-band</td>
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<td><strong>On-Board Data Handling</strong></td>
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<td><strong>Propulsion</strong></td>
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<td>Propulsion</td>
<td>5</td>
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<tr>
<td><strong>Total</strong></td>
<td>779</td>
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<td>588.55</td>
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<tr>
<td>Total including system margin (20%)</td>
<td></td>
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<td>706.26</td>
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Power

• Solar arrays
  – Triple-junction GaAs solar cells
  – Efficiency end-of-life, including power control system: 20%
  – Total size & mass: 13 m² & 54 kg

• Batteries
  – Li-ion batteries
  – Redundancy
  – Capacity & mass: 110 Ah & 26 kg for each battery

• Power control system
# Mass budget

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass including margin (kg)</th>
</tr>
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<td>Ka-band</td>
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<td><strong>Thermal control system</strong></td>
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<td>Power</td>
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<td><strong>On-Board Data Handling</strong></td>
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<td><strong>Attitude &amp; Orbit Control System</strong></td>
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<td><strong>Total wet mass</strong></td>
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<td><strong>Launch adapter</strong></td>
<td>77</td>
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<tr>
<td><strong>Total launch mass</strong></td>
<td>843.28</td>
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</table>
Telemetry, Tracking & Control

• Payload: X-band
  – Downlink: 8.025 – 8.4 GHz, 10 - 300 Mbit/s

• Housekeeping: S-band
  – Uplink: 2.025 – 2.11 GHz, 64 – 1024 kbit/s
  – Downlink: 2.2 – 2.29 GHz, 1024 – 6250 kbit/s

• Emergency UHF

<table>
<thead>
<tr>
<th>Payload</th>
<th>Data volume per orbit (Mbit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ku</td>
<td>23776</td>
</tr>
<tr>
<td>Ka</td>
<td>63402</td>
</tr>
<tr>
<td>Total</td>
<td>87178</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spacecraft</th>
<th>Data volume per orbit (Mbit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housekeeping</td>
<td>872</td>
</tr>
<tr>
<td>Total</td>
<td>872</td>
</tr>
</tbody>
</table>
On-Board Data Handling

• Microprocessor: ERC32
  – Cryosat-2 heritage
  – Redundancy

• Mass memory:
  – Assumption: 3 orbits without ground station contact
  – 3.1 GB required
Propulsion

- Hydrazine thrusters
  - Attitude & orbit control
  - Collision avoidance
  - De-orbit
  - $I_{sp} = 225$ s

- Delta_V budget
  - De-orbit: 79 m/s
  - Fuel mass: 34 kg (including margins)
Propulsion

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DRAMA-2.0
Orbital Spacecraft Active Removal
Altitude vs. Time

Altitude [km]
Single averaged (over M)

Date
Perigee altitude
Apogee altitude
Launcher

• SWEAT
  – Launch mass: 843 kg
  – Volume: 20.1 m³

• Vega launcher:
  – Payload mass: 1430 kg
  – Volume inside fairing: 41.8 m³
Operations & ground segment

• Mission control centre: ESOC

• Estrack ground stations located close to poles:
  – Troll, Antarctica
  – Svalbard, Norway
  – Prince Albert, Canada
Operations & ground segment

Introduction – Scientific objectives & requirements – Measurement principle – Payload – **System engineering**

Prince Albert (Canada)  Svalbard (Norway)

Troll (Antarctica)
Operations & ground segment

- Required downlink time per orbit:
  - Payload: 15 min
  - Housekeeping: 3 min
- Mean total access time per orbit: 23 min

<table>
<thead>
<tr>
<th></th>
<th>S-band up</th>
<th>S-band down</th>
<th>X-band down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range [GHz]</td>
<td>2.025-2.210</td>
<td>2.2-2.29</td>
<td>8.085-8.4</td>
</tr>
<tr>
<td>Data rate [bit/s]</td>
<td>(64-1024)k</td>
<td>(1024-6250)k</td>
<td>(10-500)M</td>
</tr>
<tr>
<td>Transmit power [W]</td>
<td>5000</td>
<td>2.2</td>
<td>5</td>
</tr>
<tr>
<td>EB/EN (Svalbard) [dB]</td>
<td>60.8</td>
<td>29.5</td>
<td>23.3</td>
</tr>
</tbody>
</table>

Introduction – Scientific objectives & requirements – Measurement principle – Payload – System engineering
Development schedule

Phase 0-A-B1
- MDR
- PDR
- SRR

Phase B2-C-D
- PDR
- CDR
- QR

Phase E
- Mission Operation (5 years)

Phase F
- Disposal Phase (5 years)

Envisaged Launch (2026)

2 to 3 years maximum

5 to 6 years

Space Surveillance Awareness
(15 years earlier than required)
Risk assessment

• Ku-band altimeter
  - TRL = 6
  - Heritage: Cryosat-2

• Ka-band altimeter
  - TRL = 6
  - Heritage: SARAL

• No other critical technology identified
## Risk assessment

<table>
<thead>
<tr>
<th>Event</th>
<th>Severity</th>
<th>Likelihood</th>
<th>Total Risk</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obsolescence</td>
<td>3</td>
<td>B</td>
<td>6</td>
<td>Longer phase 0-A-B1</td>
</tr>
<tr>
<td>Something not built to specifications</td>
<td>3</td>
<td>B</td>
<td>6</td>
<td>Severity could range from development delays to impaired data gathering</td>
</tr>
<tr>
<td>AOCS fails</td>
<td>4</td>
<td>B</td>
<td>8</td>
<td>Redundant system</td>
</tr>
<tr>
<td>Development of hydrological models reduce scientific value</td>
<td>4</td>
<td>A</td>
<td>4</td>
<td>No known missions are currently planned to investigate SWE in the same way as SWEAT</td>
</tr>
</tbody>
</table>
## ROM cost breakdown

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (M €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Instrument development (before start))</td>
<td>15</td>
</tr>
<tr>
<td>Industrial cost spacecraft (Heritage Cryosat)</td>
<td>100</td>
</tr>
<tr>
<td>Payload</td>
<td>80</td>
</tr>
<tr>
<td>Vega Launcher</td>
<td>45</td>
</tr>
<tr>
<td>Scientific data processing (high data rating processing intensive)</td>
<td>35</td>
</tr>
<tr>
<td>Operational cost</td>
<td>45</td>
</tr>
<tr>
<td>Airplane campaign</td>
<td>1</td>
</tr>
<tr>
<td>Project Team (10% of industrial cost + scientific data processing + operational cost)</td>
<td>25</td>
</tr>
<tr>
<td>Contingency (15 % of industrial cost + scientific data processing + operational cost + project team)</td>
<td>43</td>
</tr>
<tr>
<td><strong>Overall cost</strong></td>
<td><strong>389</strong></td>
</tr>
</tbody>
</table>
Outreach & education possibilities

- Public theme day to improve awareness of SWE
- Involve students in engineering process
- Mascot & promotional merchandising (e.g. paper model)
- Communication via social networks
- Distribute downlinked data via internet (free data access)
Summary

• Snow Water Equivalent (SWE) is very important in hydrological and climate processes

• SWEAT:
  – Measuring SWE directly from space at high spatiotemporal resolution
  – Generating data to improve current SWE products
  – Using a novel technological combination of Ku- and Ka-band radar altimeters
Thank you for your attention
Go Team Orange!