SWEAT

Snow **W**ater **E**quivalent with **A**l**T**imetry

Team Orange

Alpbach Summer School 2016

21th of July 2016

Outline

- Introduction
- Scientific objectives and requirements
- Measurement principle
- Payload
- System engineering

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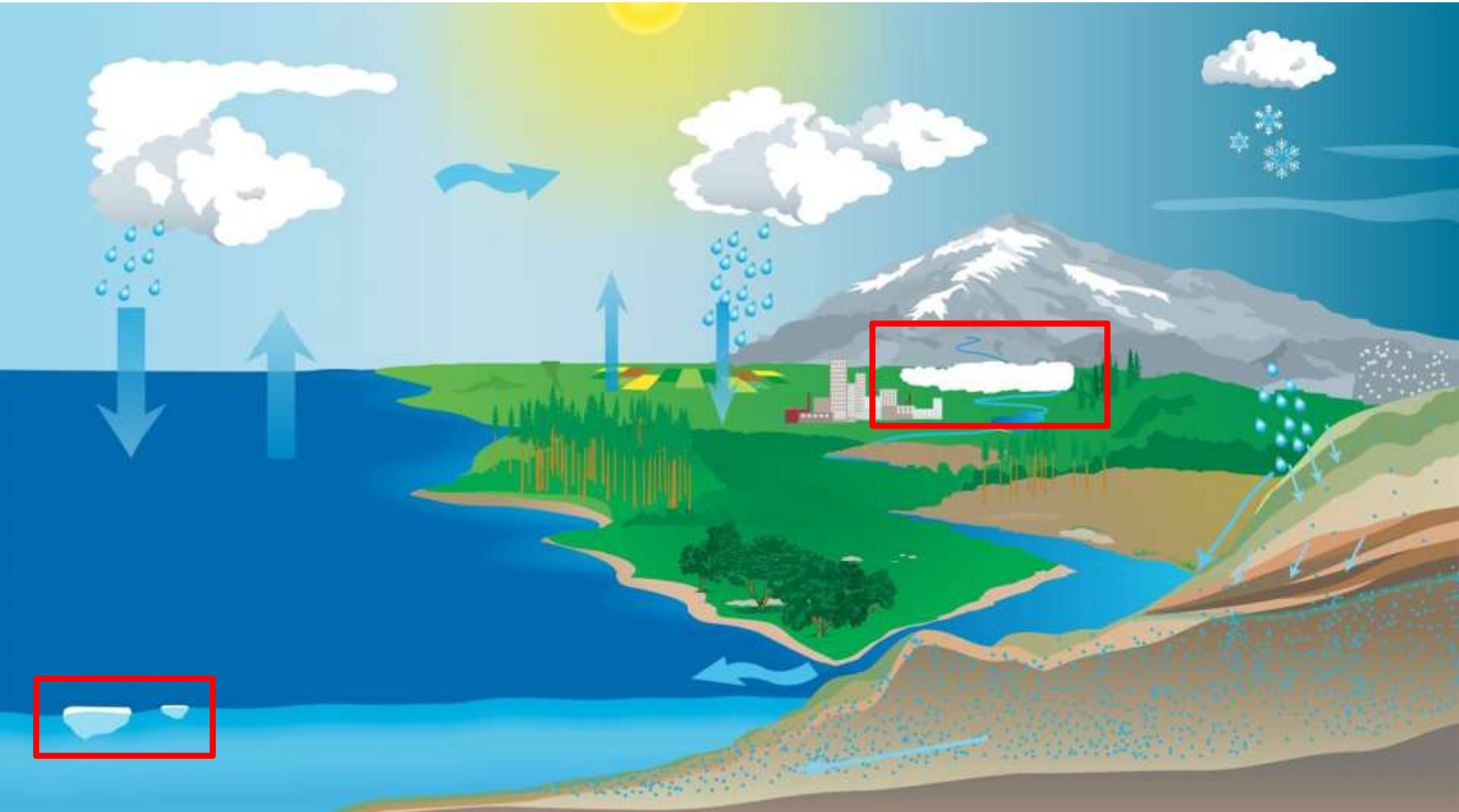
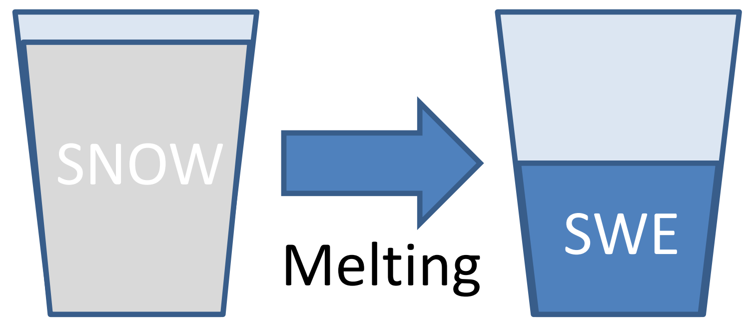
Global Water Cycle

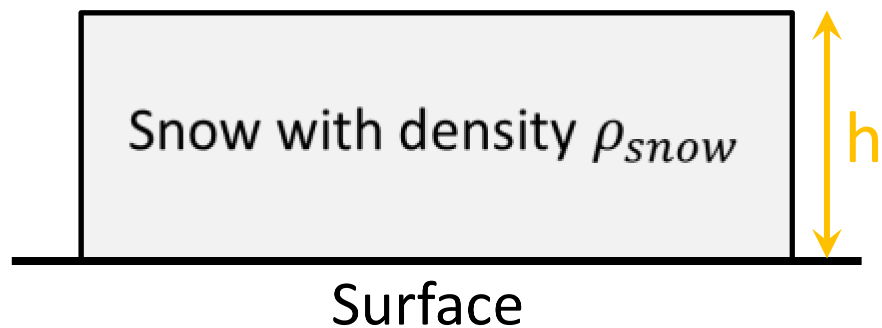


Snow Water Equivalent (SWE)

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

- $SWE = h * \frac{\rho_{snow}}{\rho_{water}}$





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)

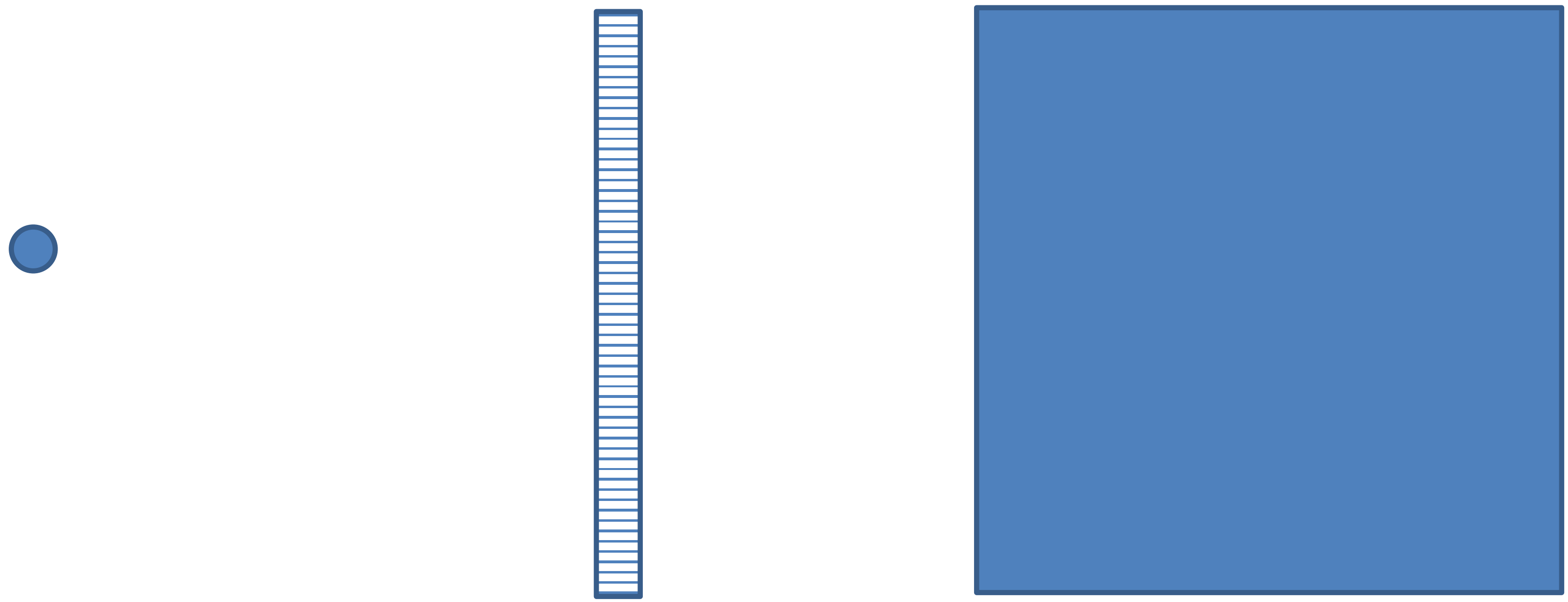
Available SWE products

- 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



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
   - ...

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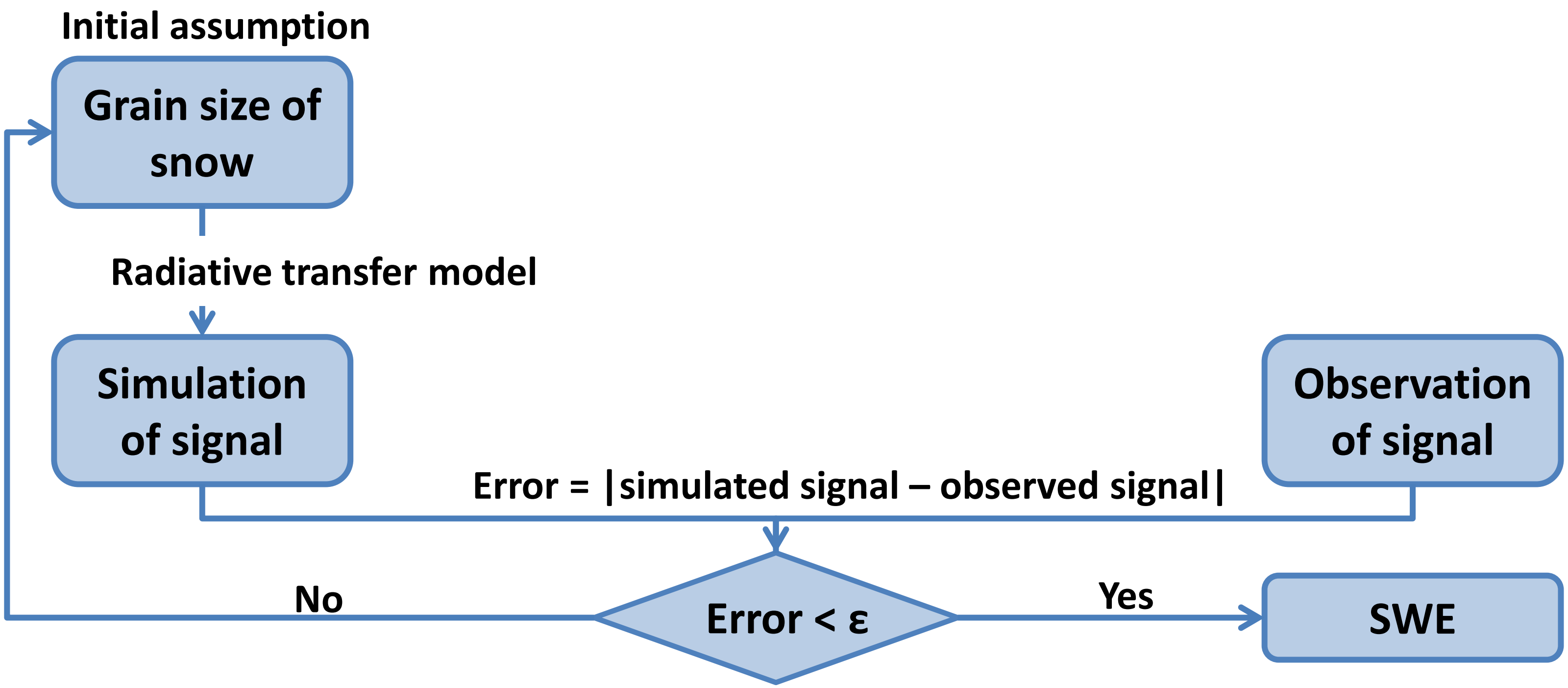
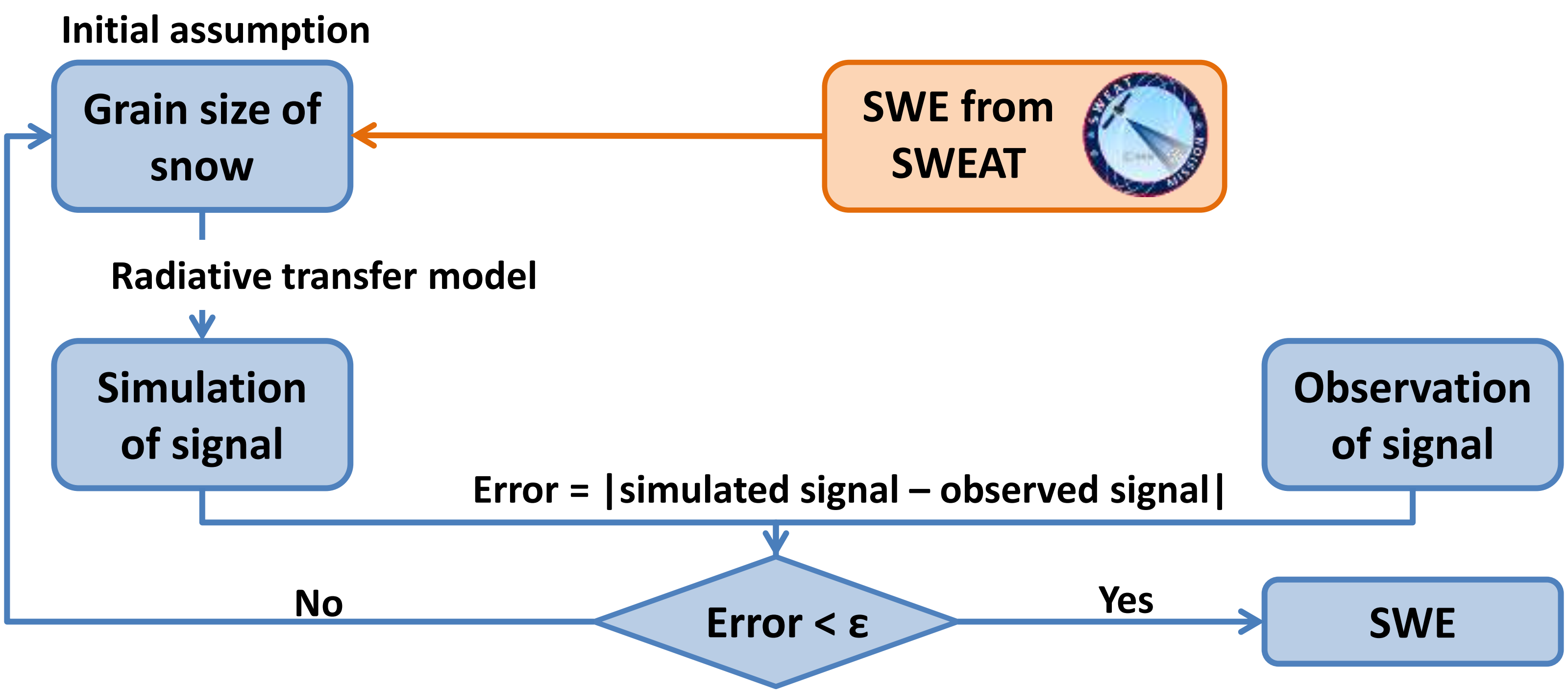
Scientific objective 1: SWE from passive microwave algorithm

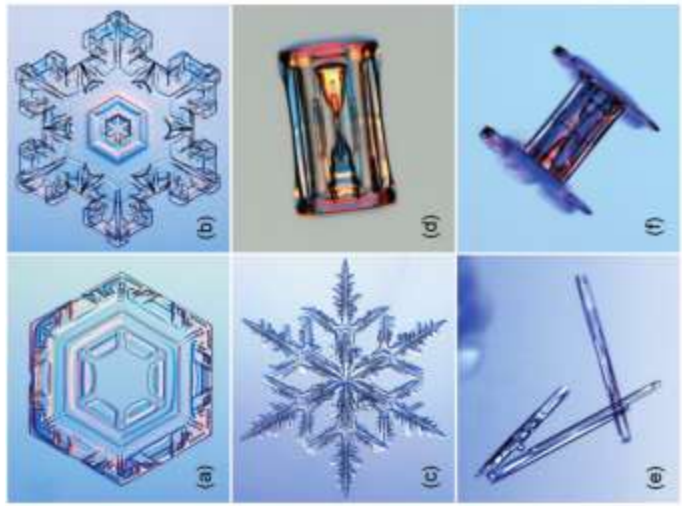


Scientific objective 1: SWE from passive microwave algorithm

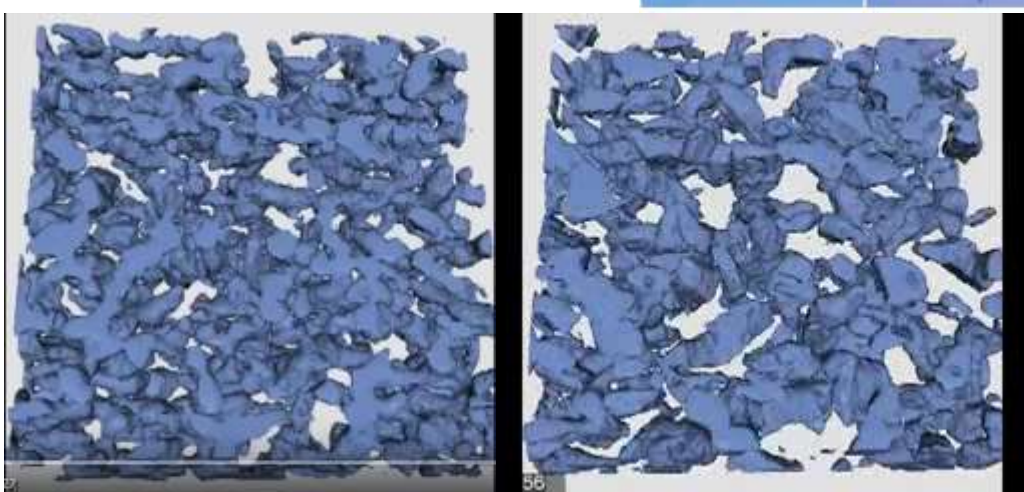
SO1: Improving estimation of global SWE from passive microwave products

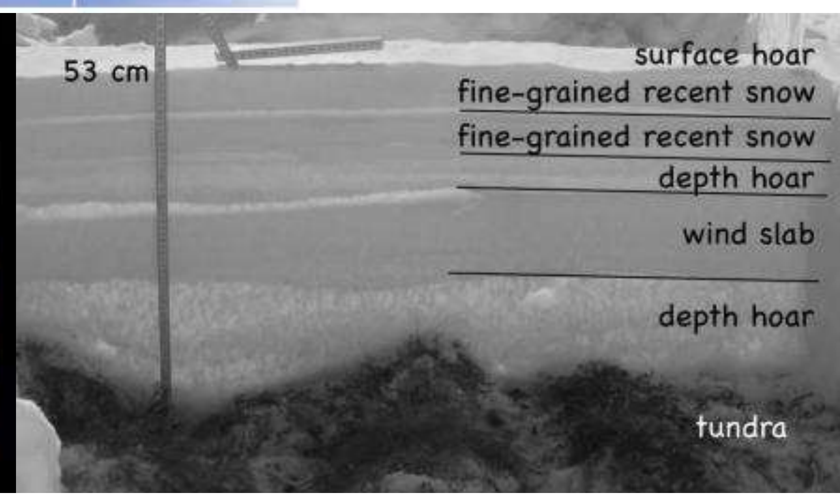


SO1: 50 shades of snow



(Libbrecht, 2005)

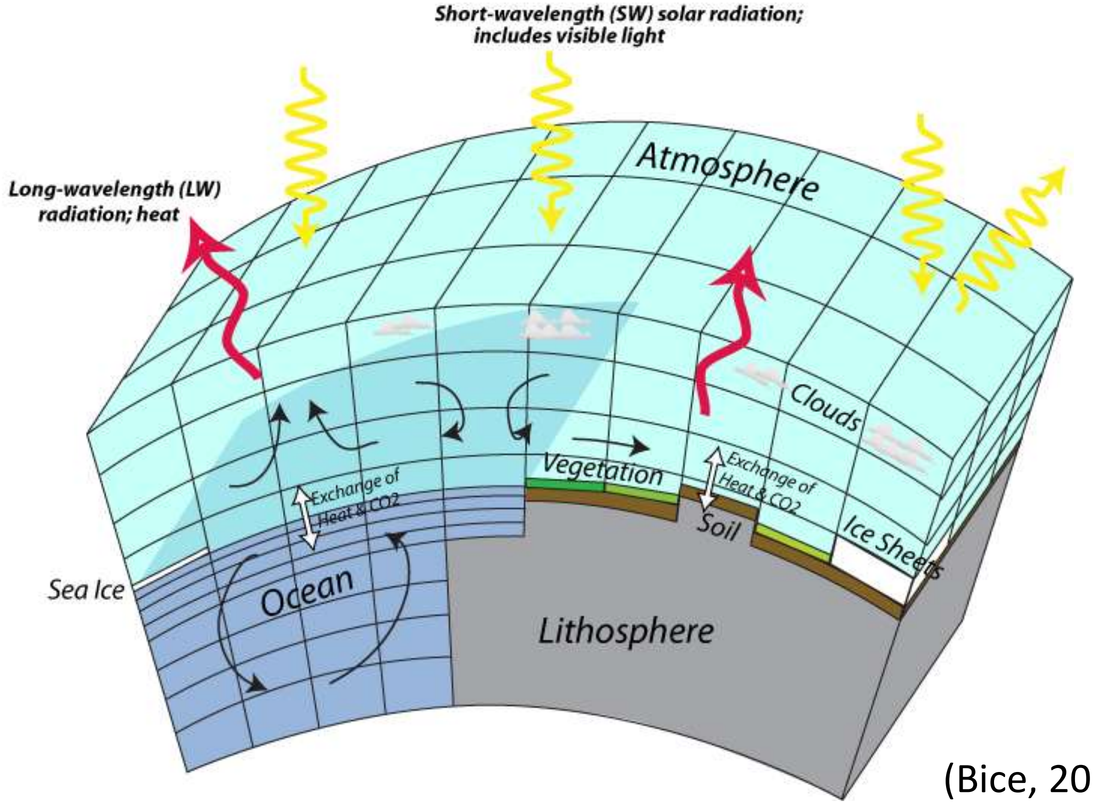




(https://youtu.be/A_BX6C9crBU) (http://blogs.scientificamerican.com/expeditions/files/2012/04/Fig8replace.jpg)

Scientific objective 2

SO2: Improve numerical snow and climate models

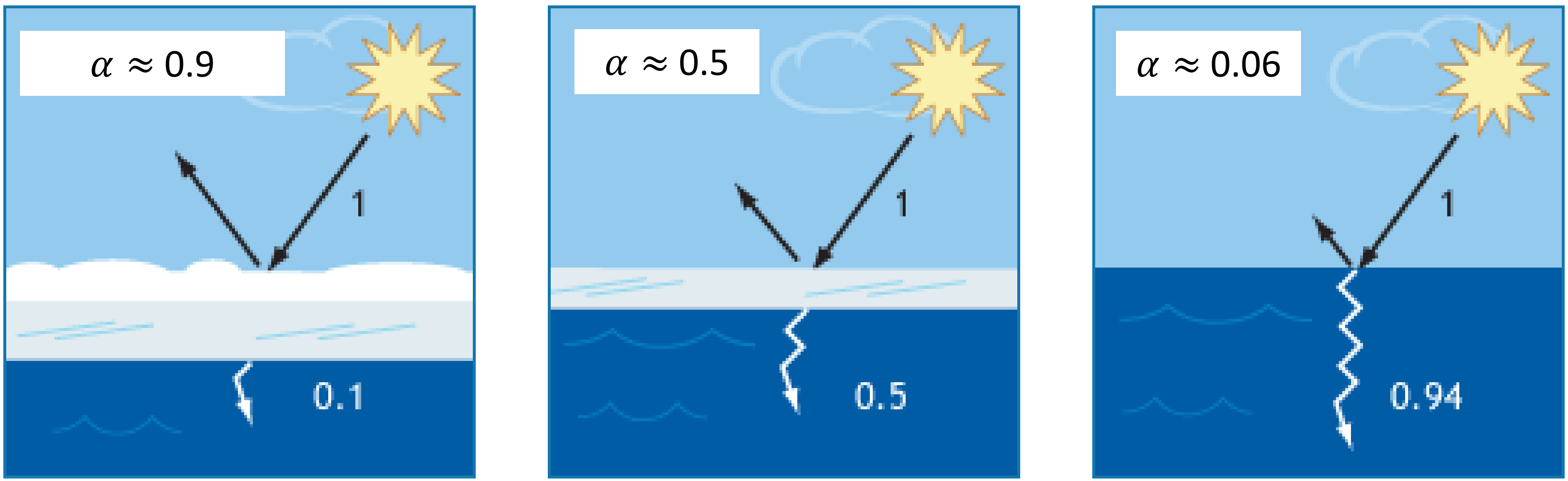


(Bice, 2016)

SO2: Snow in the energy balance

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

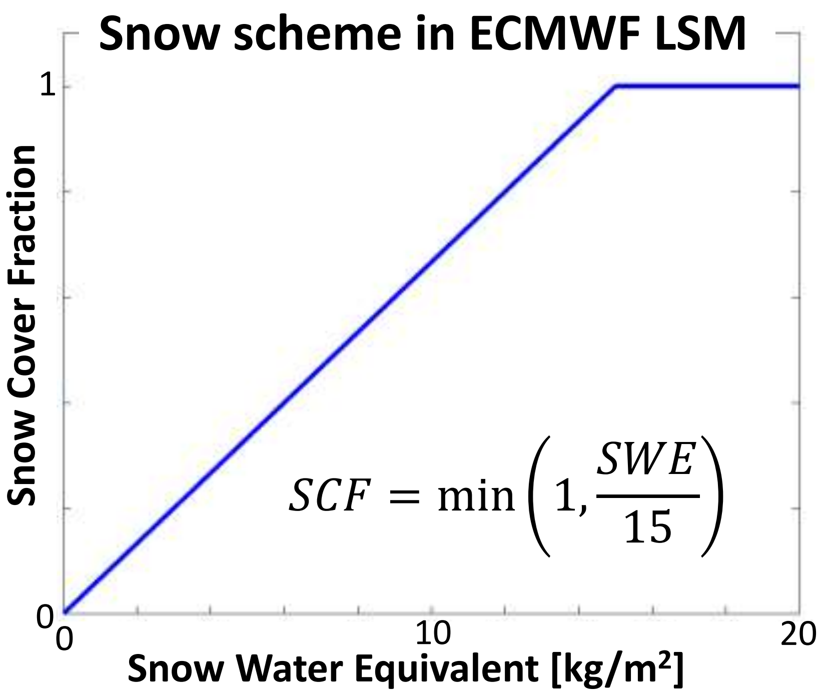
Ice with snow | **Bare Ice** | **Open ocean**



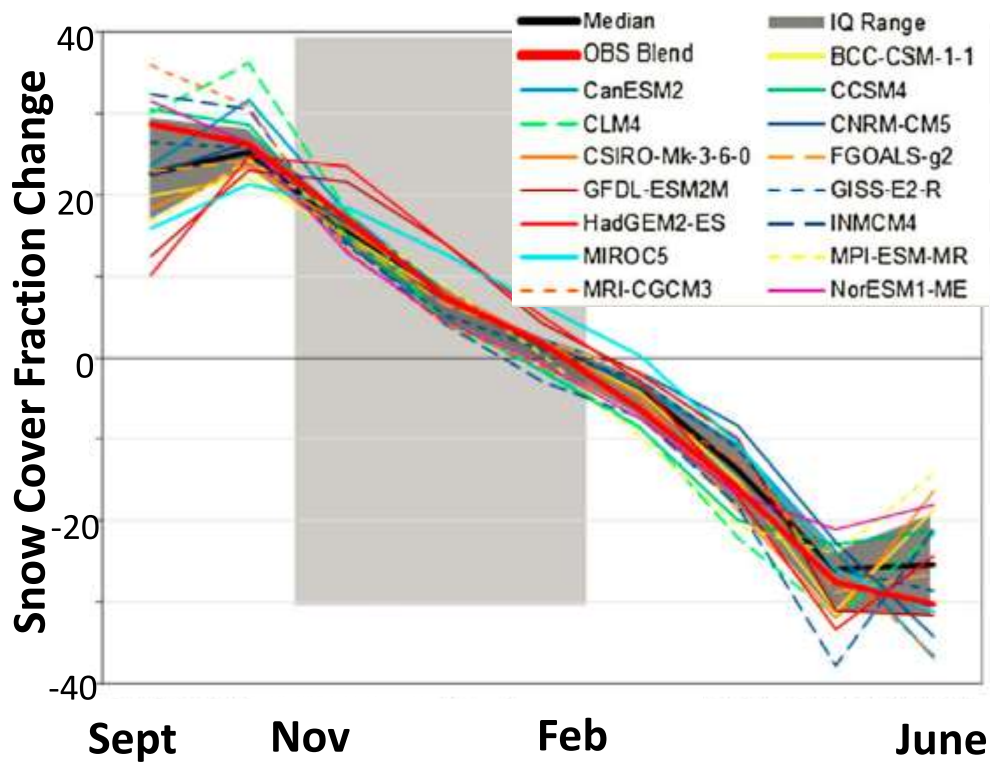
(Edited figure from NSIDC)

SO2: Climate Model

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

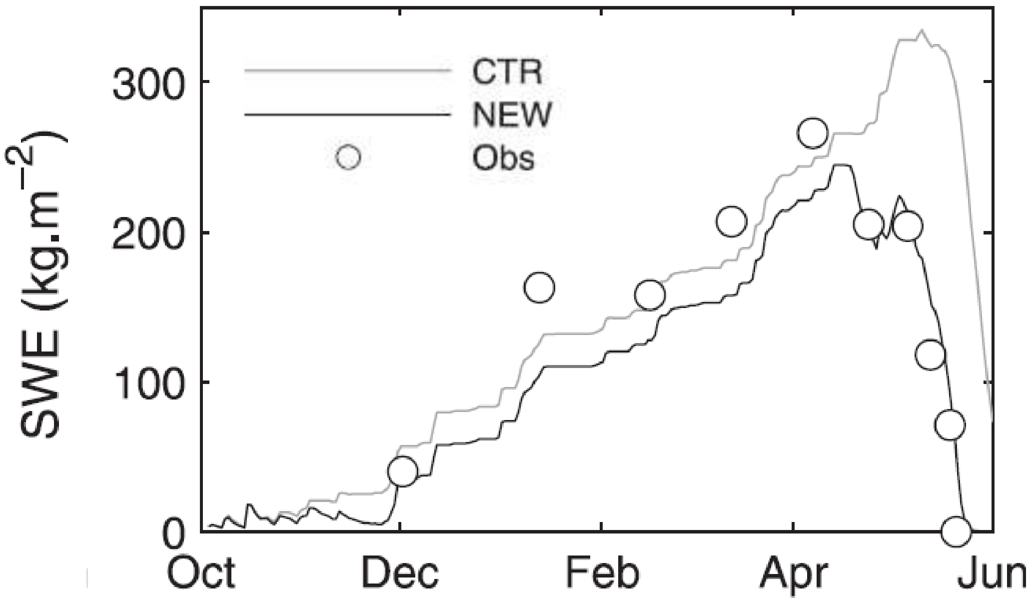


(Dutra et al., 2010)



(Thackeray et al., 2015)

SO2: Improve Land Surface Models



(Dutra et al., 2010)

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

- Validation: 10 Observations → SWEAT: 80 Observations

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

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  2. Improve numerical snow and climate models
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  2. Reduce uncertainty in sea ice thickness measurements due to the snow pack

SWE on sea ice

SWE on land

Scientific 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

Scientific requirements

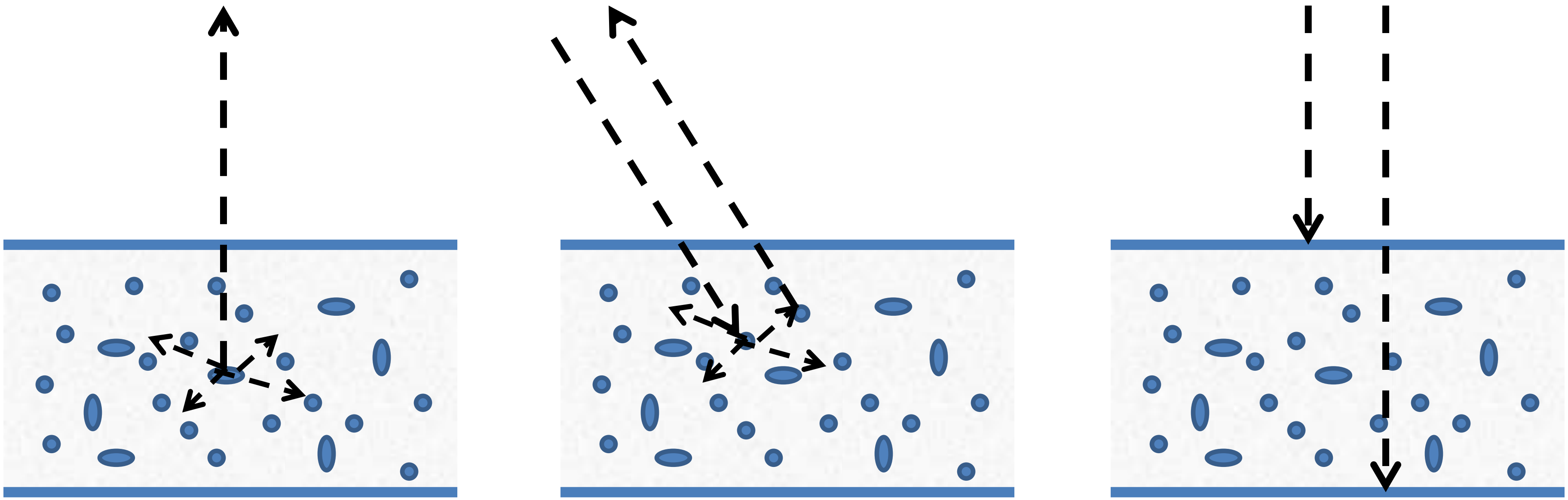
1. Temporal resolution: 3 days (ESA-GEWEX, 2015; Nghiem & Tsai, 2001)
2. Spatial resolution: 1 km (ESA-GEWEX, 2015; NRC, 2007)
3. SWE accuracy: (CoReH2O, 2012)
   – SWE > 0.3 m: 10%
   – SWE < 0.3 m: 3 cm
4. Coverage in polar regions
   – Snow on land
   – Arctic seas
5. Duration of 5 years: multiple-year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

How to measure SWE

Emission
- AMSR-E

Backscatter
- CoReH2O

"Thickness"
- SWEAT



- Coarse resolution
- Inaccurate

- Grain size
- Layering

- Direct link to SWE

Observation requirements

Scientific requirements

1. SWE on sea ice

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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

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 ρ_{snow} = 500 kg/m^3 → h_{min} = 0.06 m

→ Determine snow height with accuracy of ± 0.06 m

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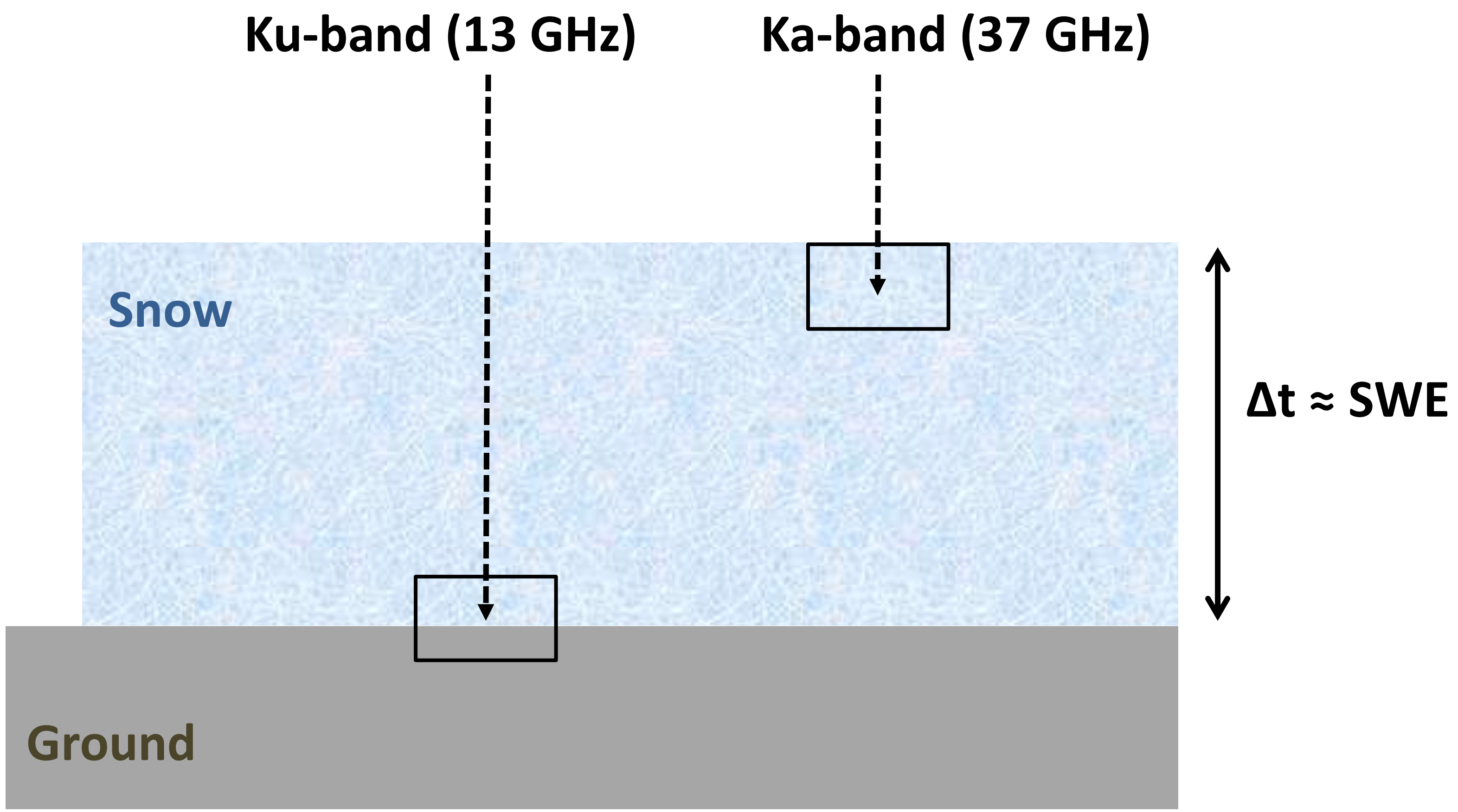
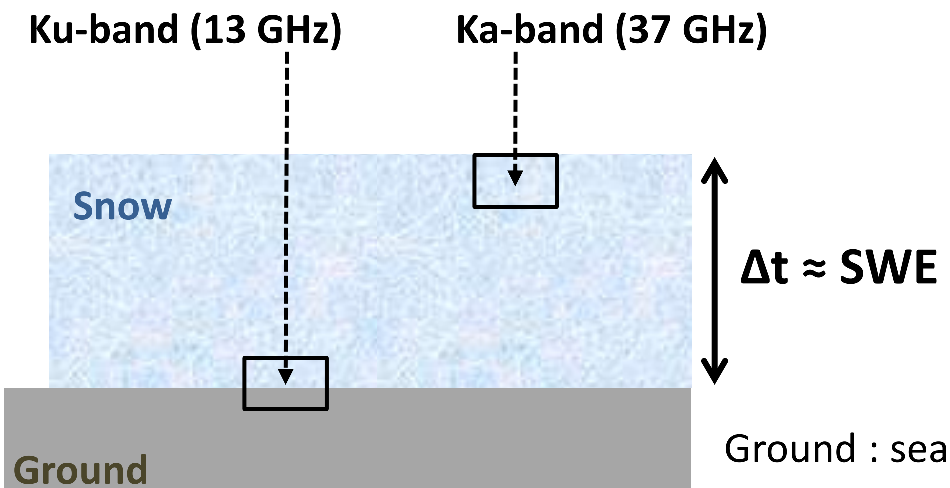
New measurement principle from space



New measurement principle from space

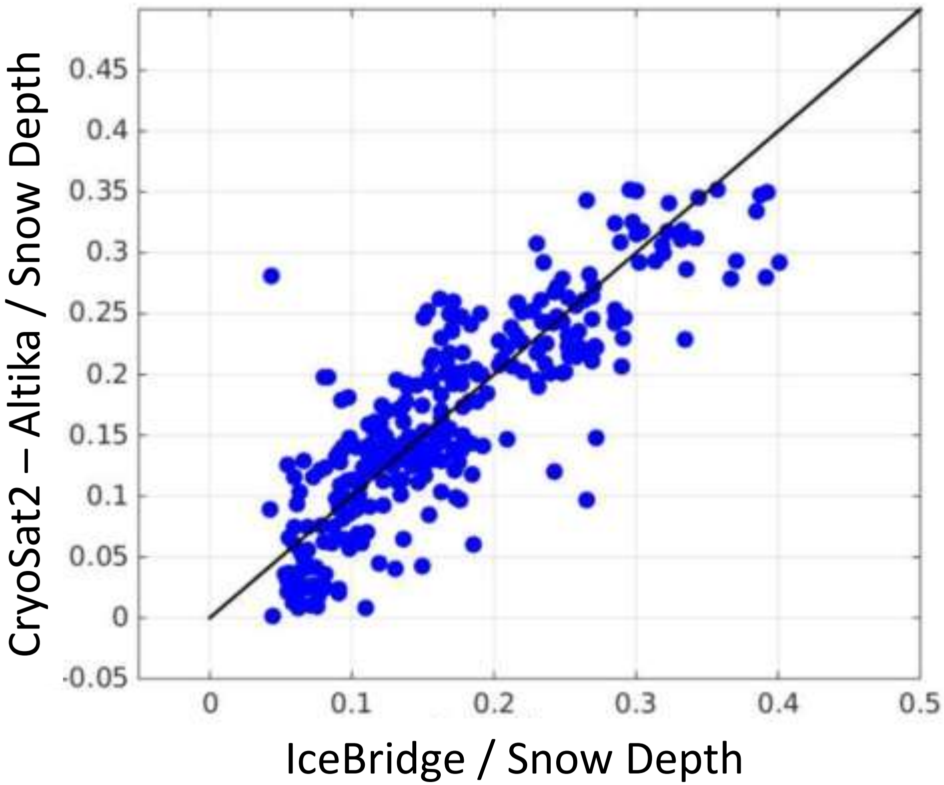
- Based on Leinss et al. (2015) and Guneriussen et al. (2001)
- Observable: $SWE = h * \rho$
- Measurement: $\Delta t = h * \frac{n}{c}$

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

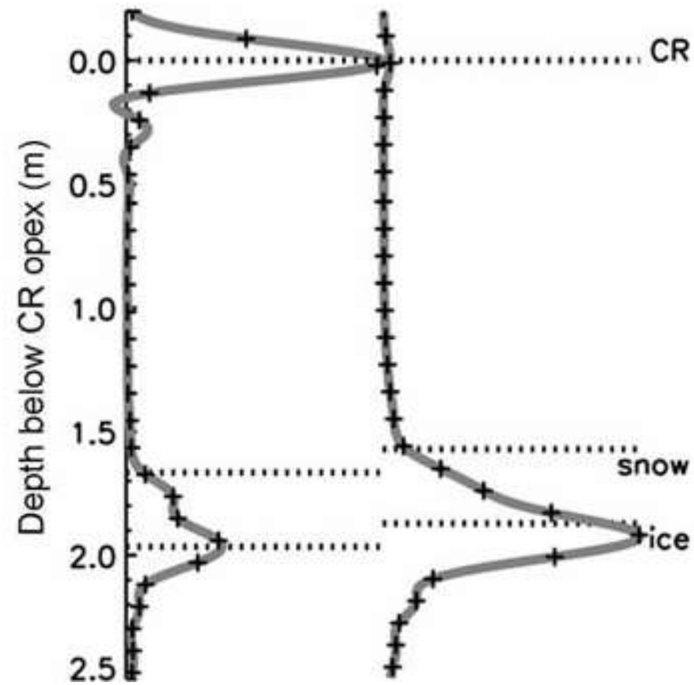


Ground : sea ice freeboard, ice, land soil, rocks

Ka-/Ku-band Penetration



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



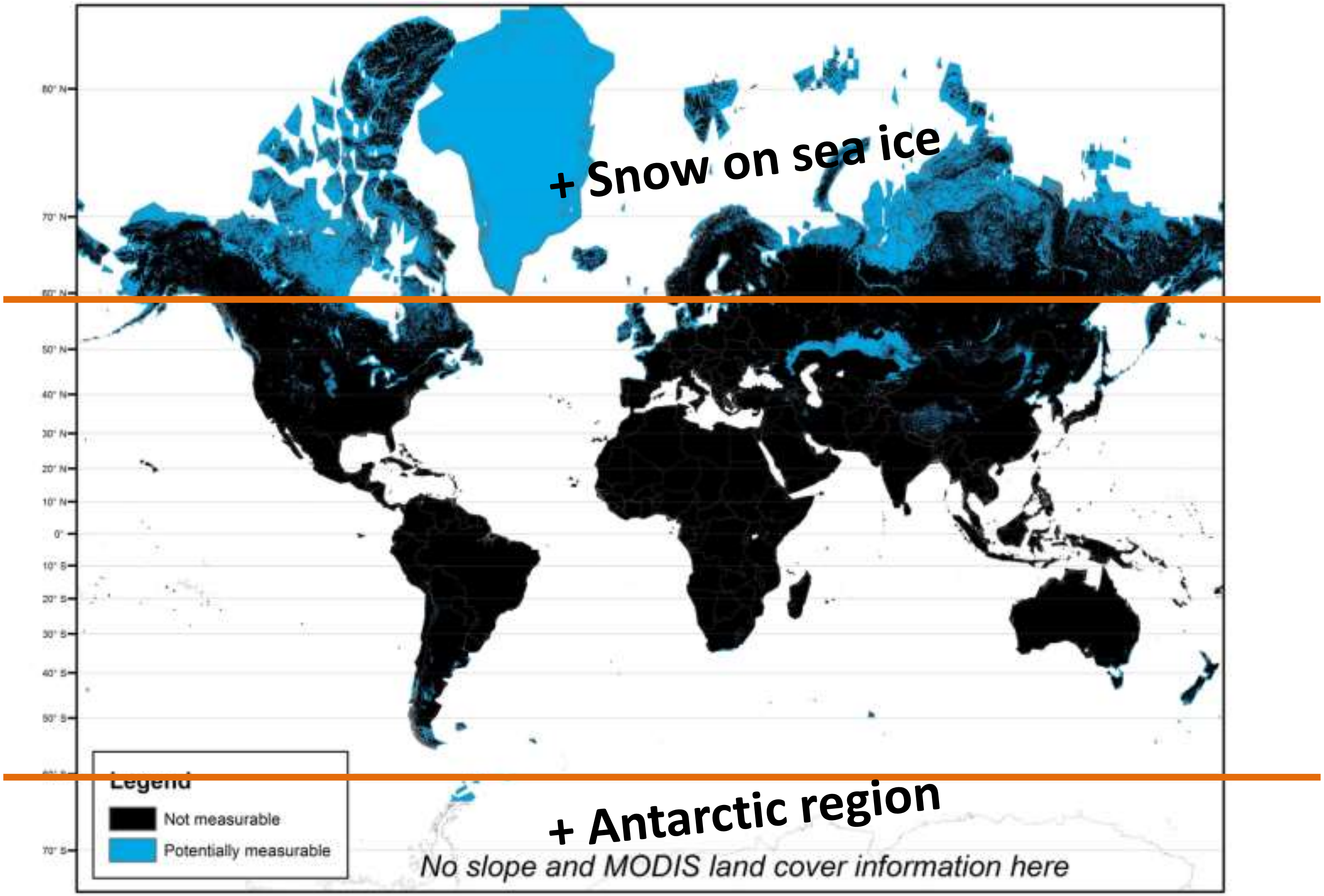
Ku-band reflection from snow-ice interface.
Corner Reflector as reference on above
(Willat et al., 2011)

Coverage

Reliable SWE estimation is limited to:

- Köppen-Geiger climate zones with possible snow
- Sparse vegetation (MODIS land cover map)
- Slope ≤ 1° due to altimeter principles (GMTED slope map)

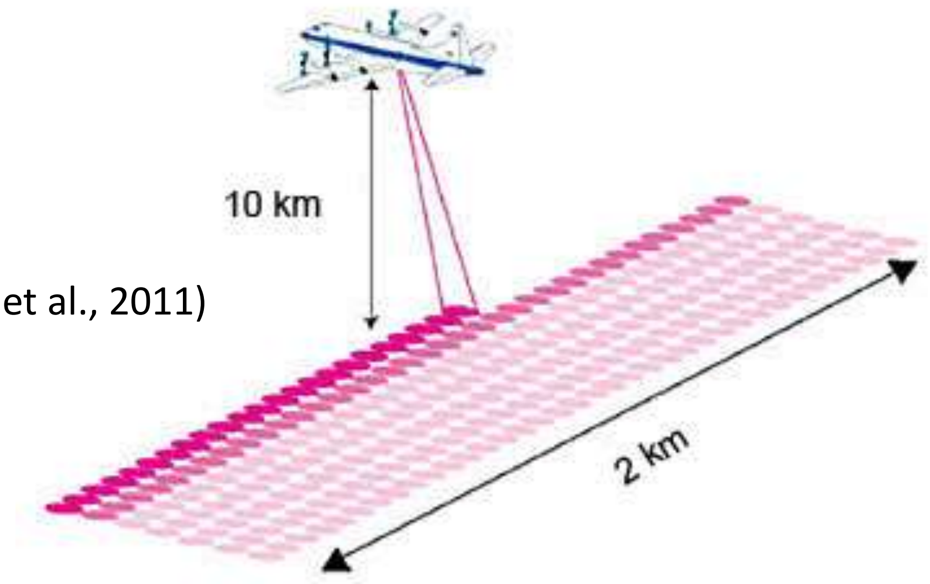
Coverage



+ Snow on sea ice
60° N
60° S
+ Antarctic region
Not measurable
Potentially measurable
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) (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

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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

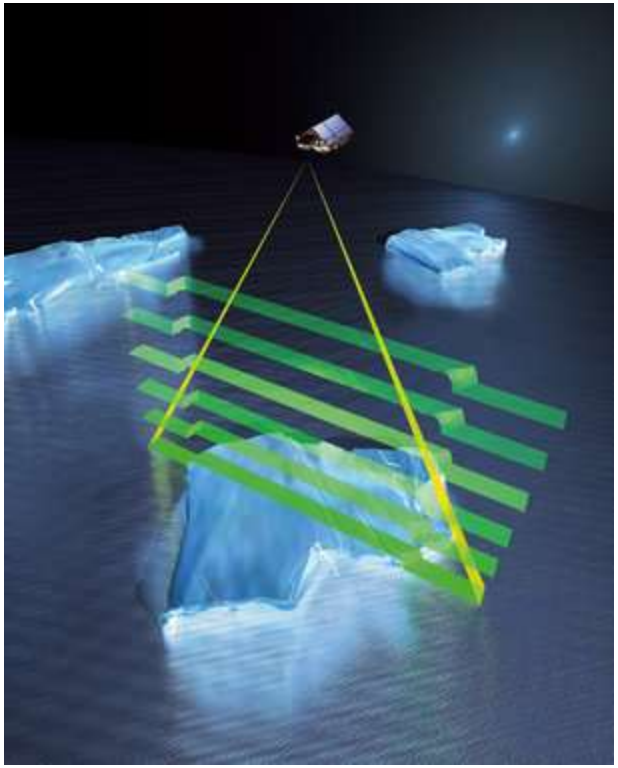
  → Vertical accuracy = 0.01 m

- $\Delta t = \frac{2\,r}{c}$

→ 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



(ESA CryoSat)

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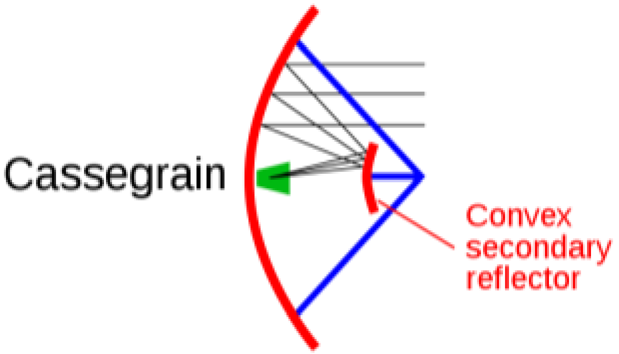
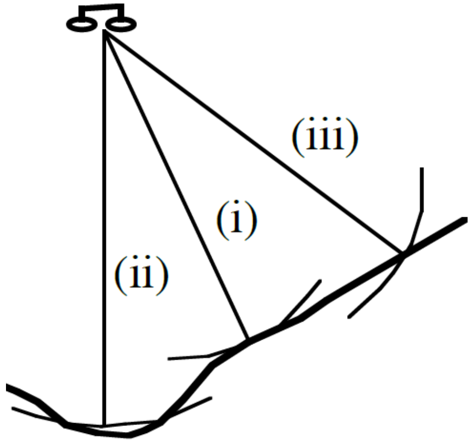
Payload Description

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



Limitations of altimetry on slopes

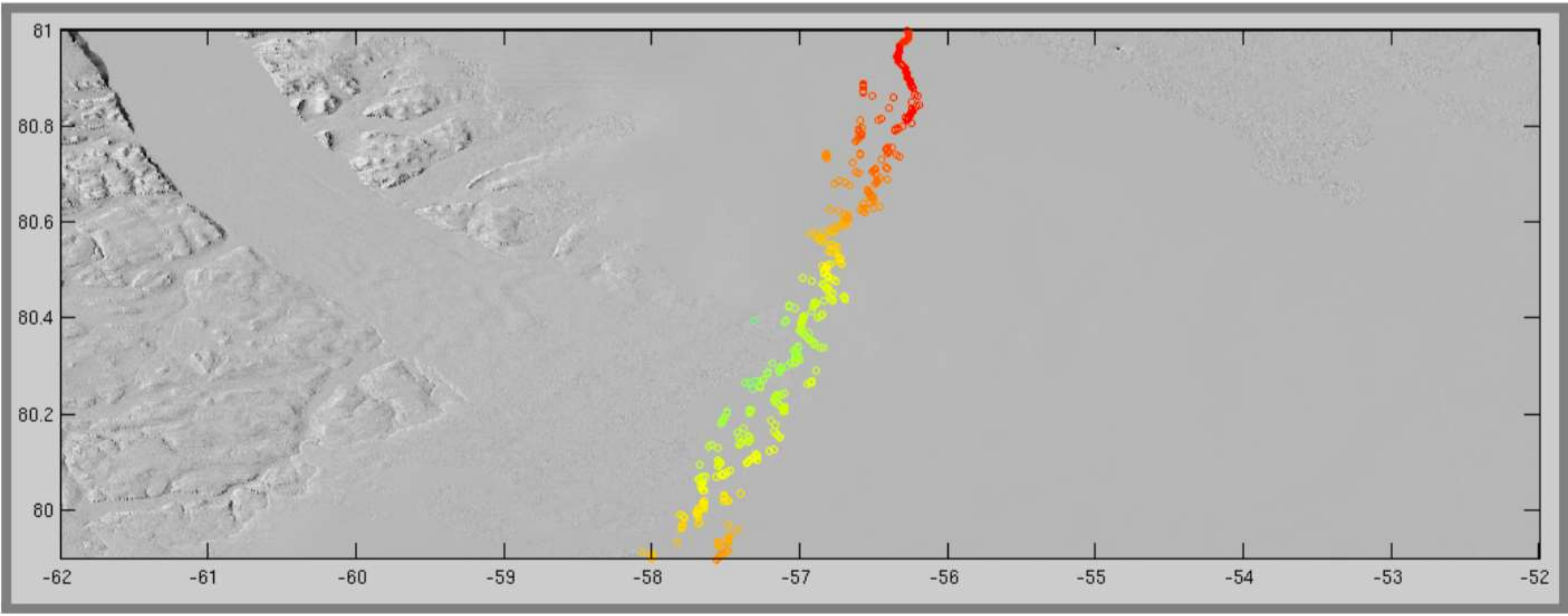
- CryoSat limited to slopes below 0.4° (T. Parrinello, personal communication)
  - To overcome this: Swath Processing (Foresta et al., 2014; Gray et al., 2013)
  - Exploiting the full waveform of CryoSat SARIn mode data (the entire swath)
- Applicable to slopes between 0.5° and 2°
- 2 orders of magnitude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



Across track echo location (Interferometry)

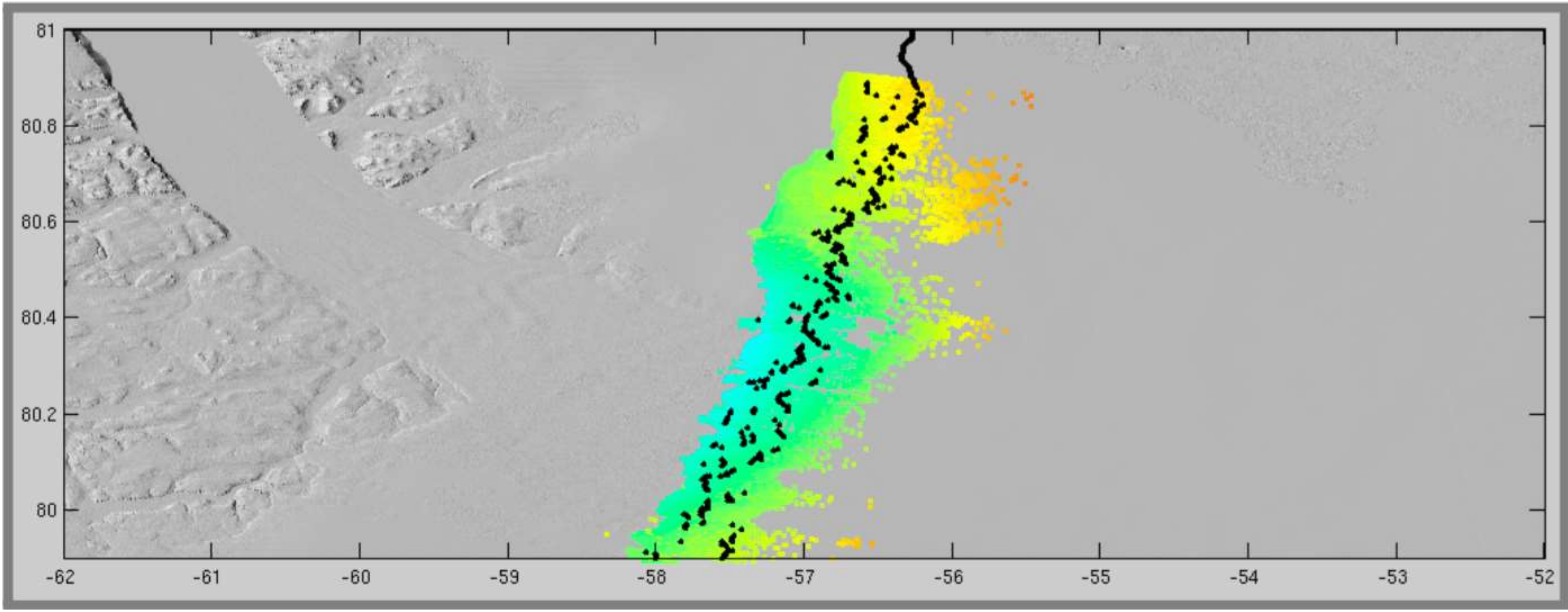
Swath Processing

Petermann Glacier – standard processing - 1 track



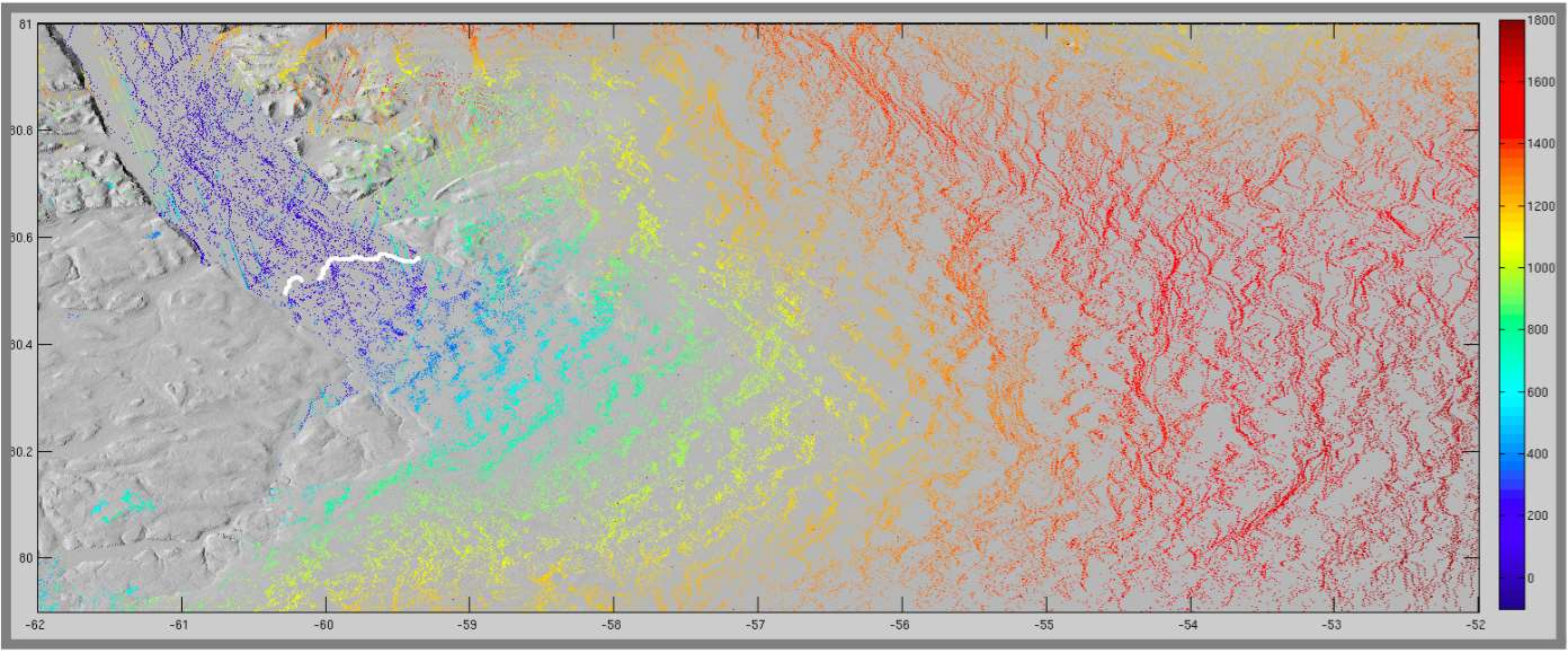
Swath Processing

Petermann Glacier – swath processing - 1 track



Swath Processing

Petermann Glacier – standard processing



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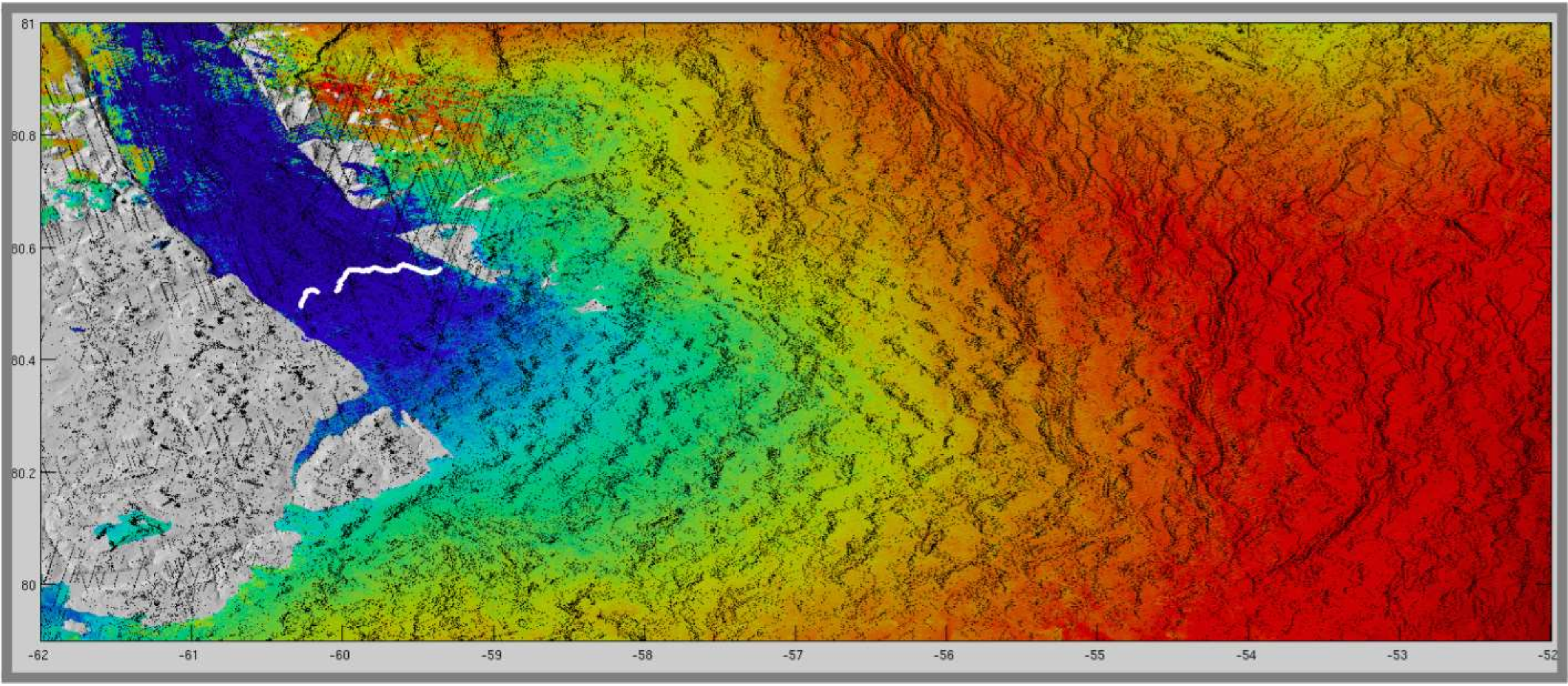
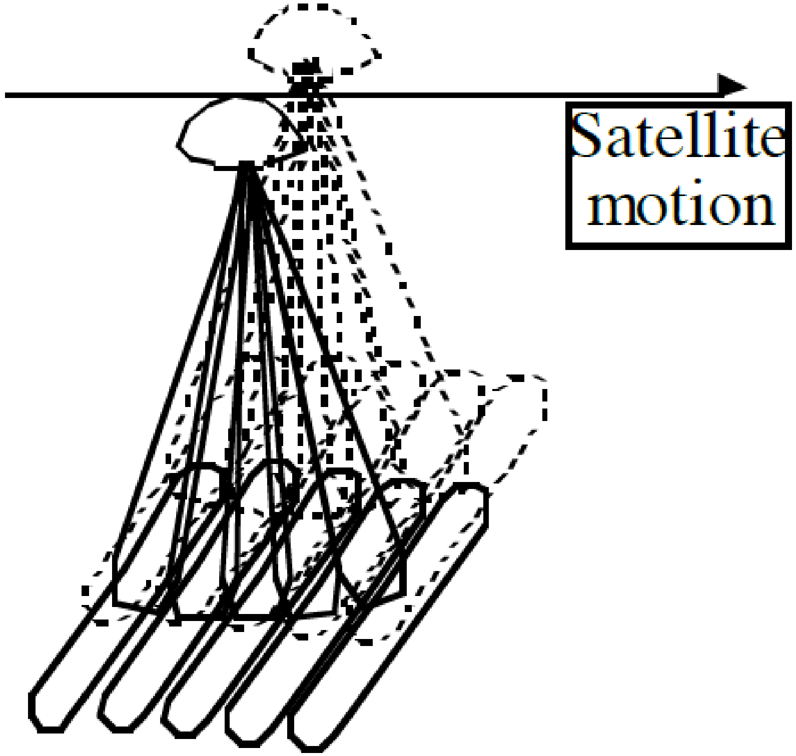
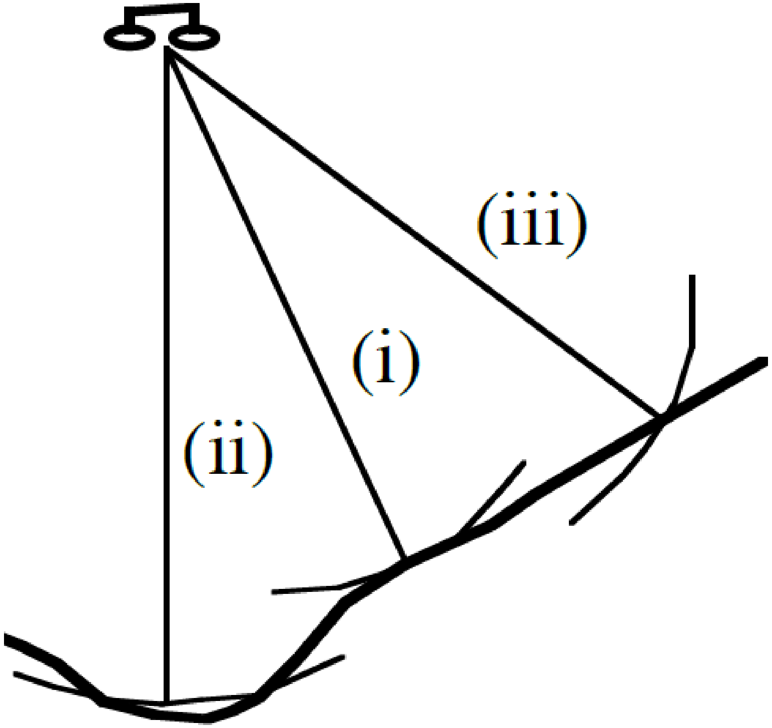


Altimeter modes

Synthetic Aperture mode

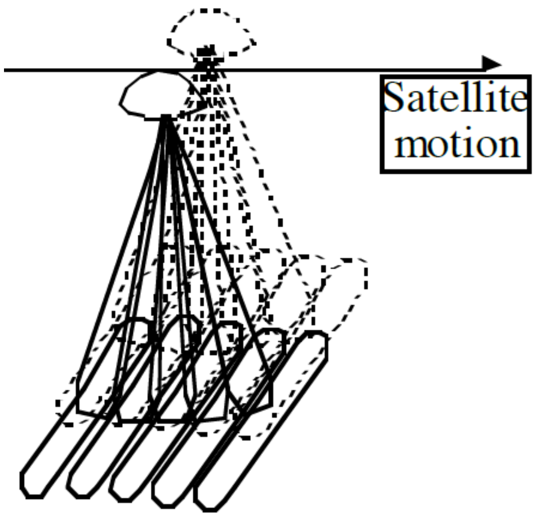


Interferometric mode



Altimeter modes

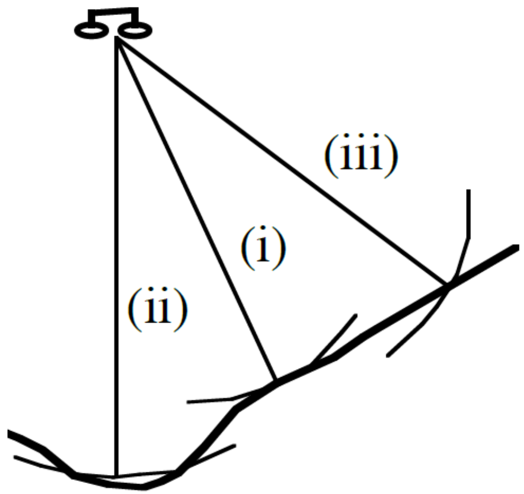
Synthetic Aperture mode



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

Parameter Information:	
Mass incl. 1.2 m antenna (kg)	96
Power / Output power (W)	149/25
Data rate (kbit/s)	12
PRF (kHz)	17.8
Pulse length (µs)	50
Bandwidth (MHz)	320
Thermal operating range (°C)	-35 to -5

Ka-band altimeter

- Function: SO_2 → Measurement of the snow surface
- Heritage: SARAL/AltiKa
- Frequency range: ~ 35 to 37 GHz
- Half angle: 0.3°
- Footprint: 1.4 km

Parameter Information:	
Mass incl. 1.2 m antenna (kg)	45
Power / Output power (W)	75 / 2
Data rate (kbit/s)	43
PRF (kHz)	4
Pulse length (µs)	110
Bandwidth (MHz)	500
Thermal operating range (°C)	-40 to +85

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

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System requirements

Instrument requirements

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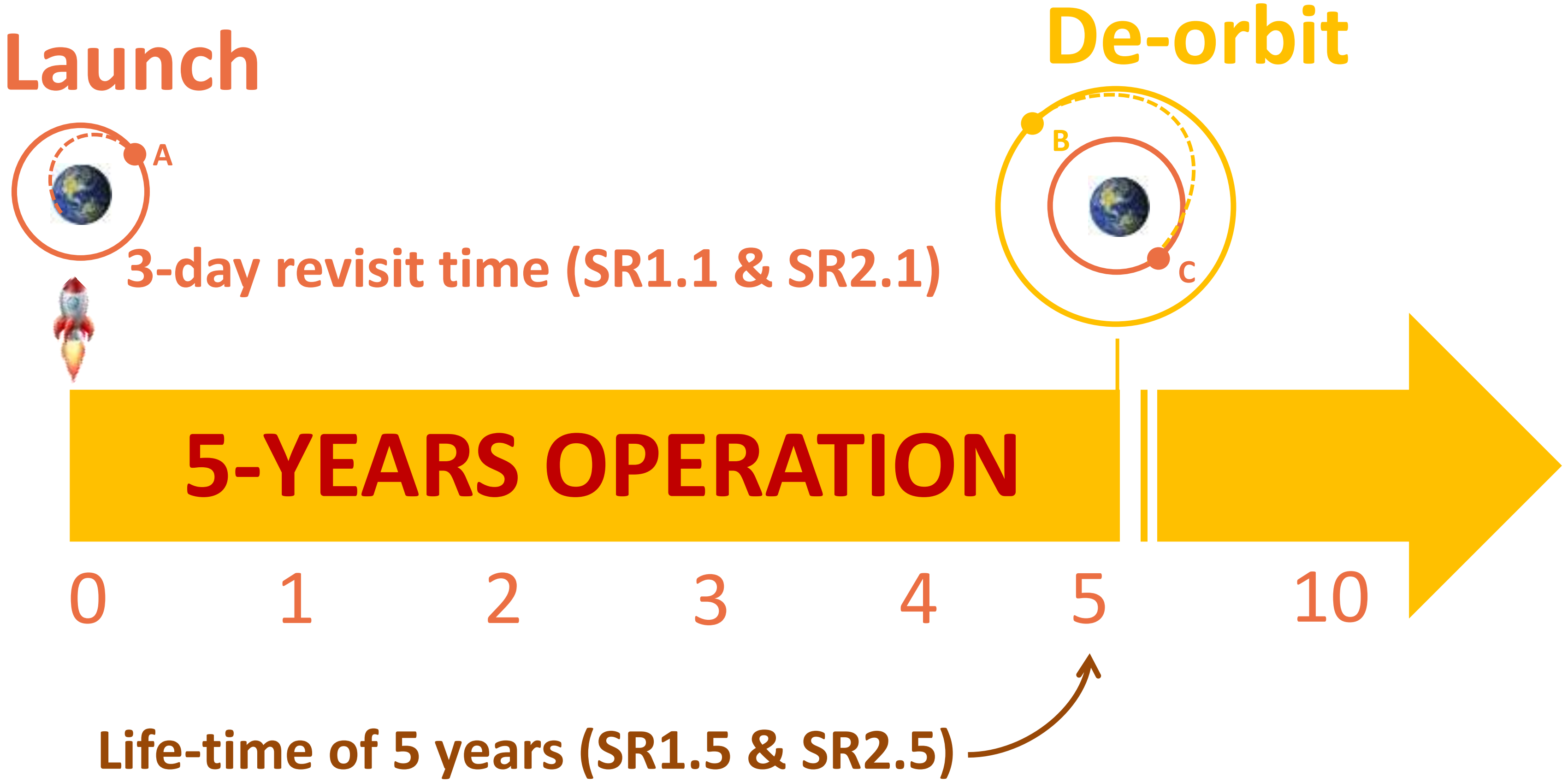
2. Ka-band altimeter
   - IR2.1 Altimeter acc. = 70 ps

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

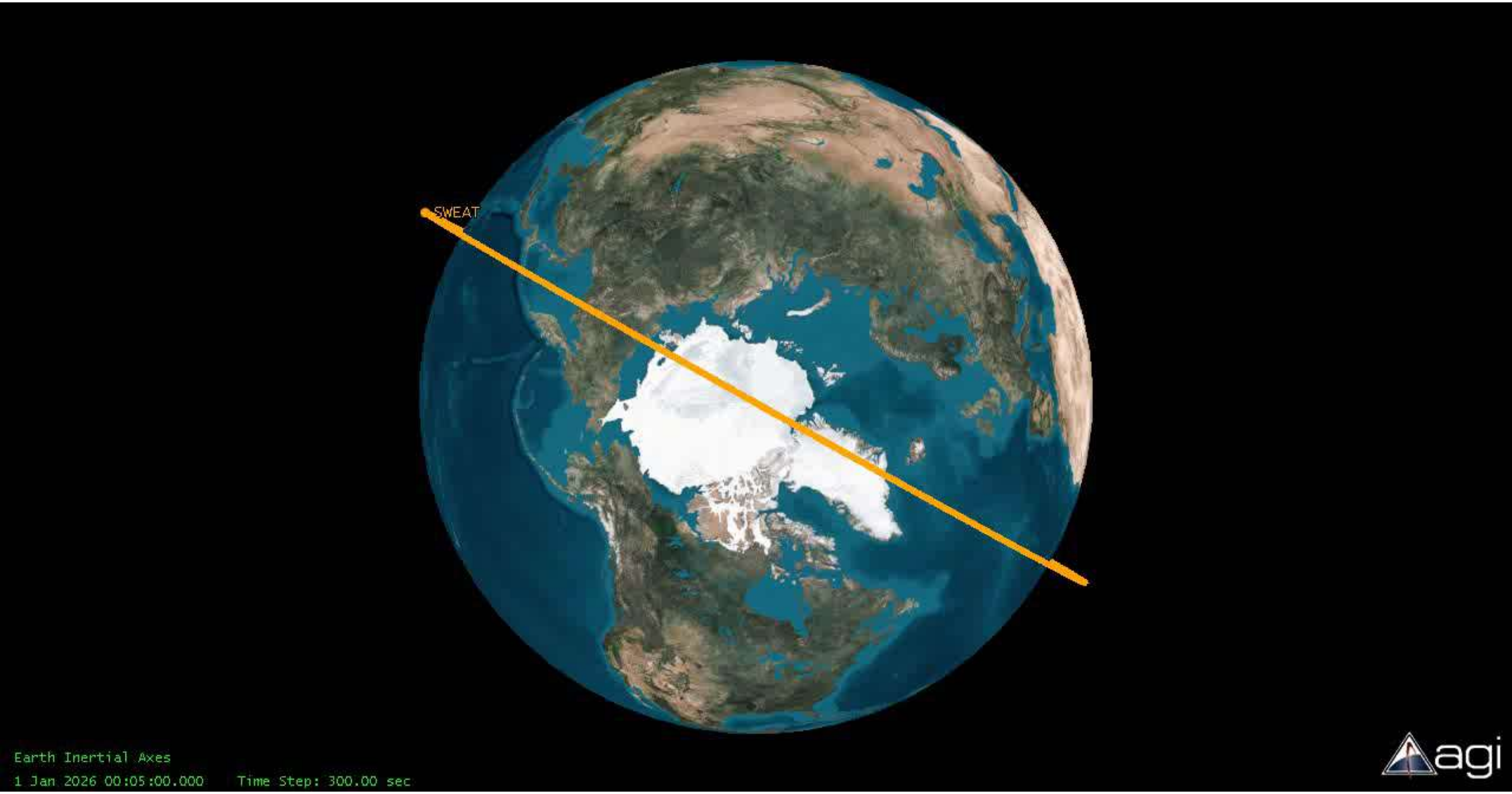


Target orbit

- 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)

(Rev/day and Repeating cycle: 2.99 days revisit time)

Target orbit



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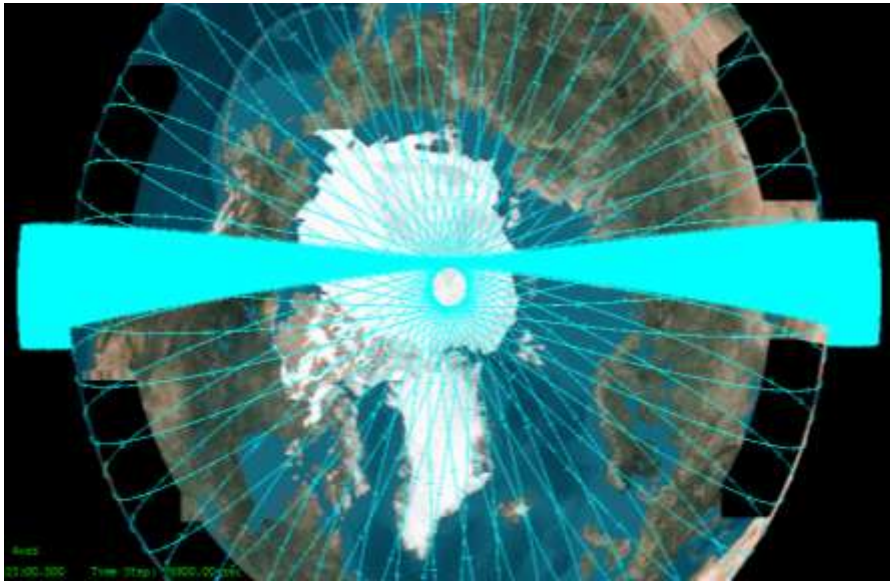
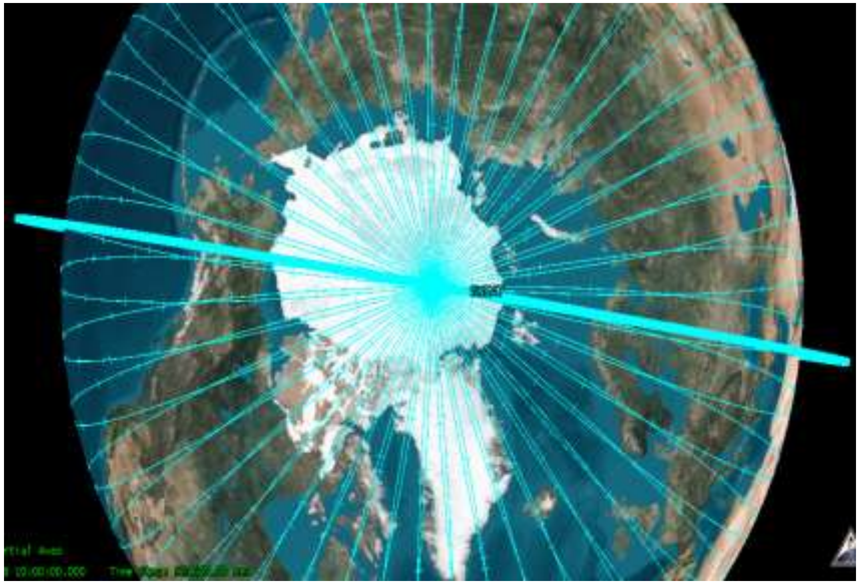


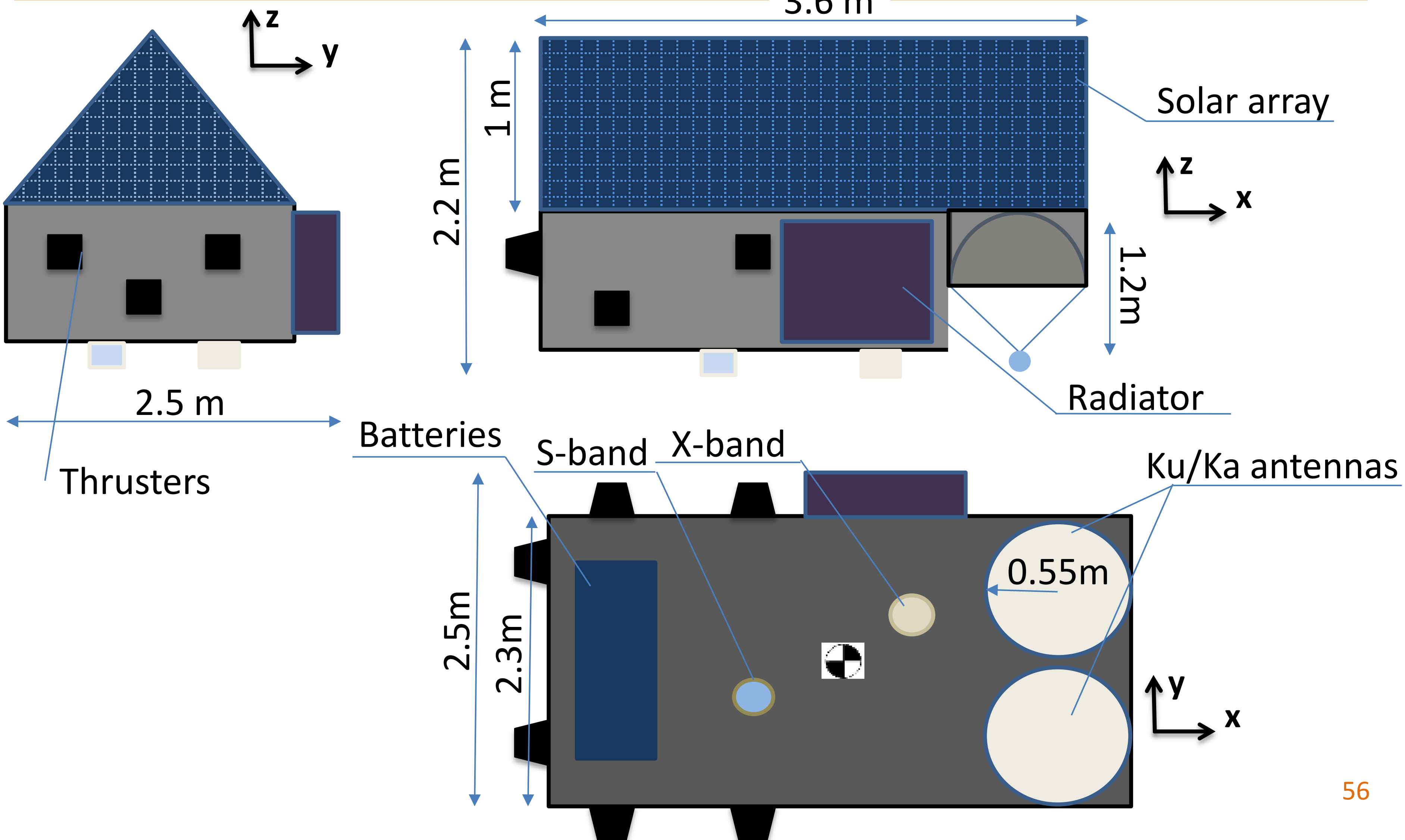
Coverage after 3 days of revisit time (i=92°) – CryoSat-2



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

→ 13.2% coverage of area of interest

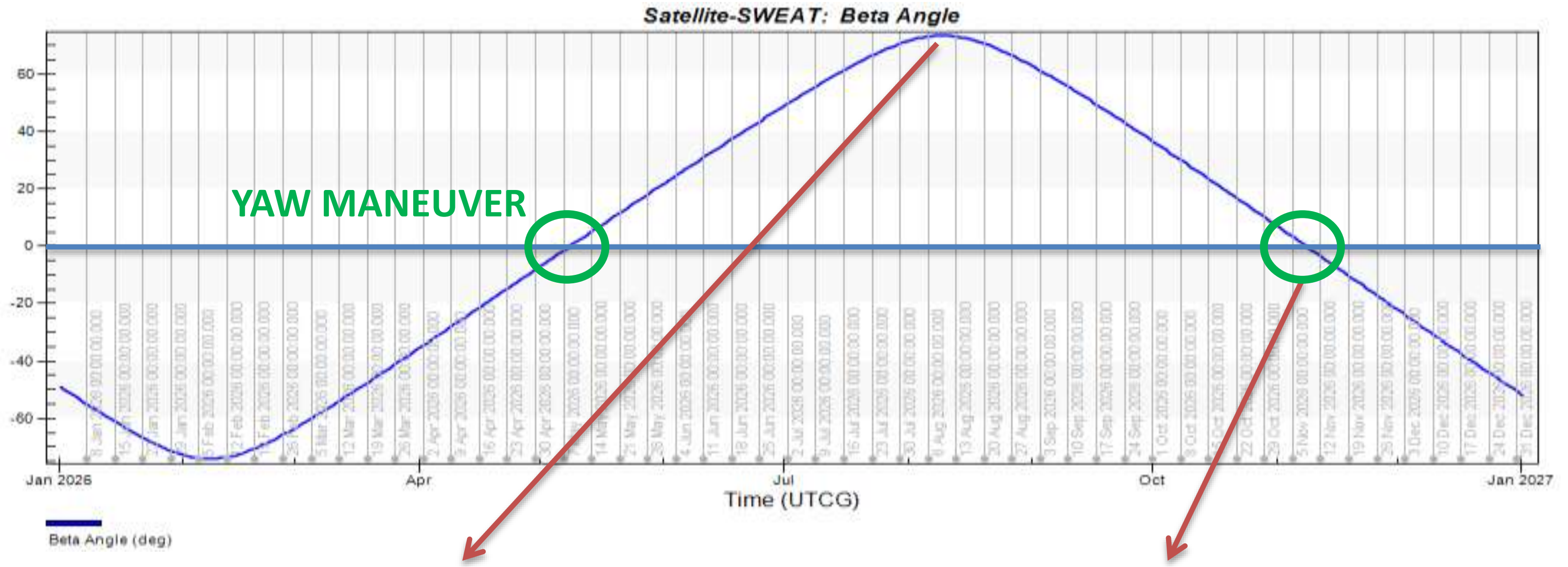
Spacecraft overview

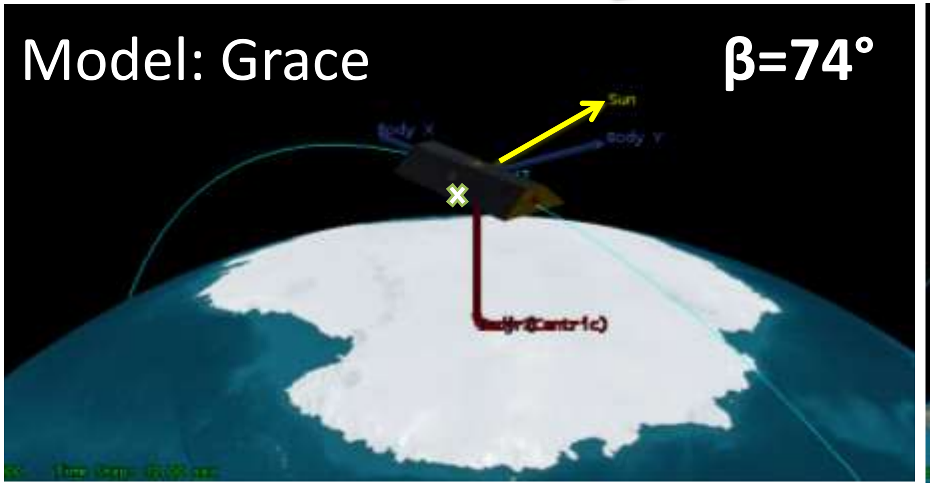


Attitude & Orbit Control System

- 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





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

Subsystem	Power (W)
Payload	
Ku-band	149
Ka-band	75
Attitude & Orbit Control System	361
Thermal control system	5
Power	115
Telemetry, Tracking & Control	
S-band receiver	4
S-band transmitter	14
X-band	45
Emergency UHF	1
On-Board Data Handling	5
Propulsion	5
Total	779
Total including system margin (20%)	

Power budget

Subsystem	Power (W)	Duty cycle per orbit (%)	Average power per orbit (W)
Payload			
Ku-band	149	40%	59.6
Ka-band	75	40%	30
Attitude & Orbit Control System	361	100%	361
Thermal control system	5	100%	5
Power	115	100%	115
Telemetry, Tracking & Control			
S-band receiver	4	100%	4
S-band transmitter	14	25%	3.5
X-band	45	25%	11.25
Emergency UHF	1	100%	1
On-Board Data Handling	5	100%	5
Propulsion	5	100%	5
Total	779		588.55
Total including system margin (20%)			706.26

Power

- Solar arrays
  - Triple-junction GaAs solar cells
  - Efficiency end-of-life, including power control system: 20%
  - Total size & mass: 13 m^2 & 54 kg
- Batteries
  - Li-ion batteries
  - Redundancy
  - Capacity & mass: 110 Ah & 26 kg for each battery
- Power control system

Mass budget

Subsystem	Mass including margin (kg)
Payload	
Ku-band	96
Ka-band	45
Structure	50
Thermal control system	13
Power	186
Telemetry, Tracking & Control	50
On-Board Data Handling	2
Attitude & Orbit Control System	168
Propulsion	0.23
Total dry mass	610.23
Total dry mass including system margin (20%)	732.68
Propellant	34
Total wet mass	766.28
Launch adapter	77
Total launch mass	843.28

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

Payload	Data volume per orbit (Mbit)
Ku	23776
Ka	63402
Total	**87178**

Spacecraft	Data volume per orbit (Mbit)
Housekeeping	872
Total	**872**

On-Board Data Handling

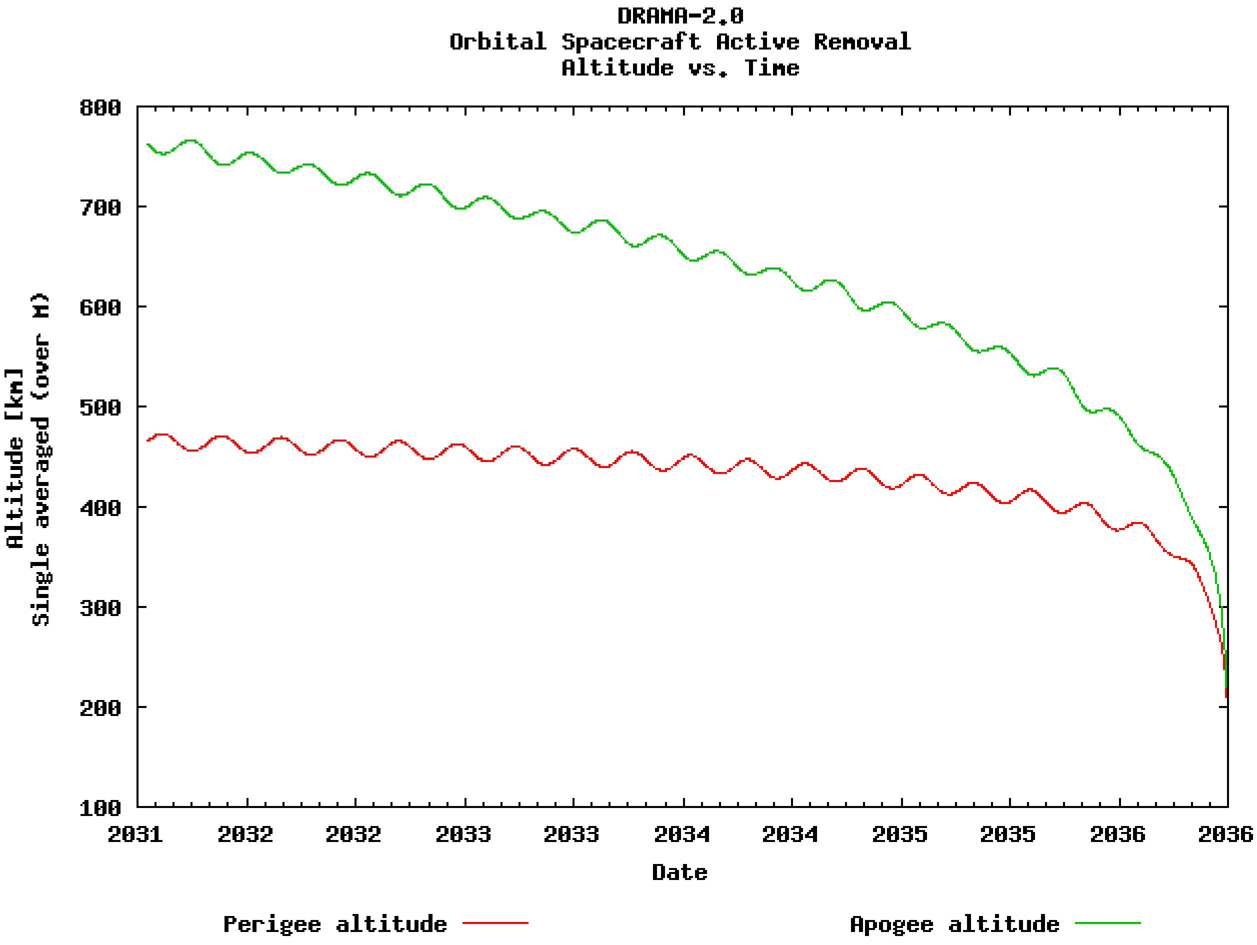
- Microprocessor: ERC32
  - Cryosat-2 heritage
  - Redundancy

- Mass memory:
  - Assumption: 3 orbits without ground station contact
  - 3.1 GB required

Propulsion

- Hydrazine thrusters
  - Attitude & orbit control
  - Collision avoidance
  - De-orbit
  - Isp = 225 s
- Delta_V budget
  - De-orbit: 79 m/s
  - Fuel mass: 34 kg (including margins)

Propulsion


DRAMA-2.0
Orbital Spacecraft Active Removal
Altitude vs. Time
Altitude [km]
Single averaged (over M)
800
700
600
500
400
300
200
100
2031
2032
2032
2033
2033
2034
2034
2035
2035
2036
2036
Date
Perigee altitude
Apogee altitude

Launcher

- SWEAT
  - Launch mass: 843 kg
  - Volume: 20.1 m^3
- Vega launcher:
  - Payload mass: 1430 kg
  - Volume inside fairing: 41.8 m^3

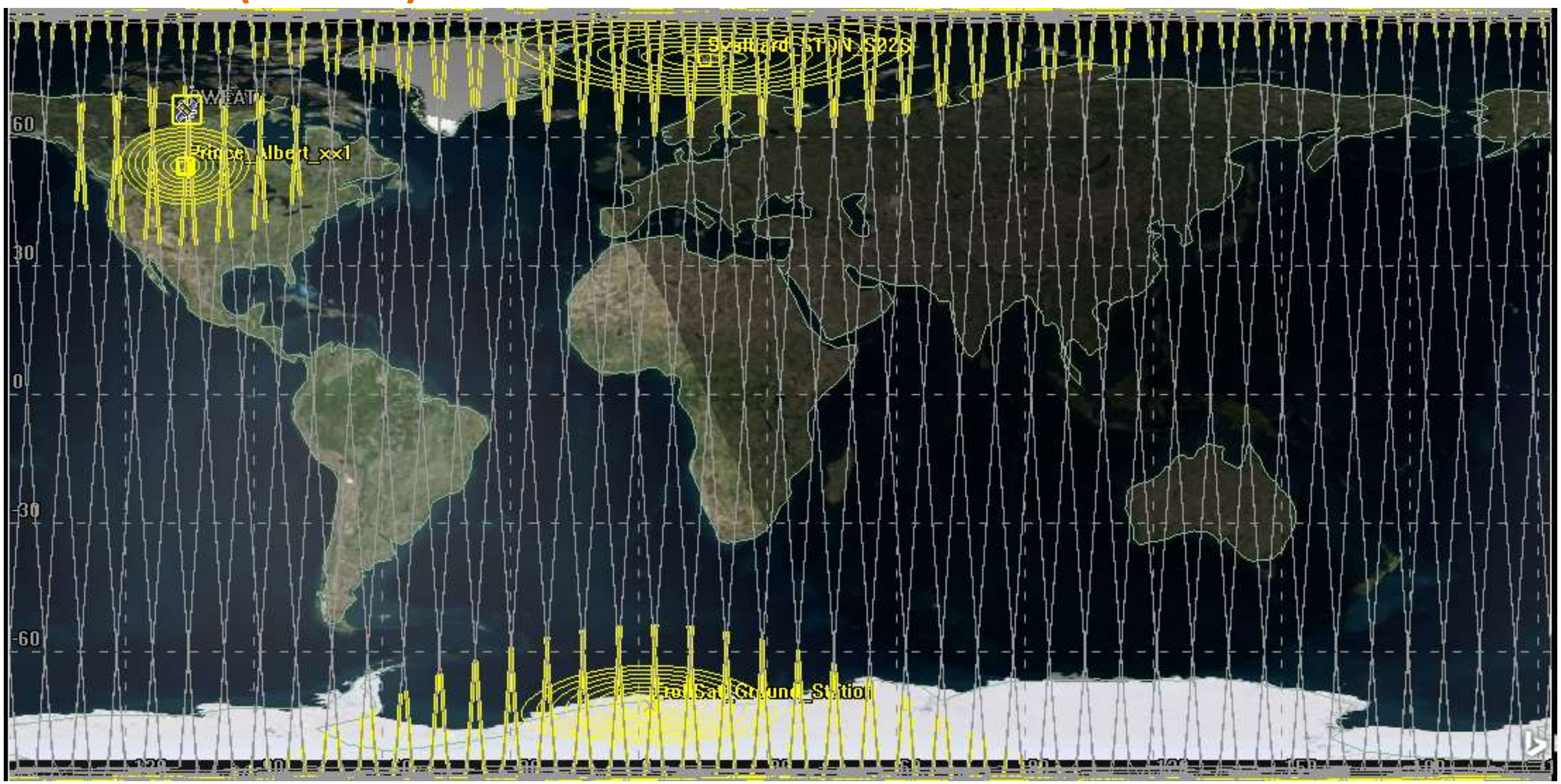
SWEAT

Operations & ground segment

- Mission control centre: ESOC
- Estrack ground stations located close to poles:
  - Troll, Antarctica
  - Svalbard, Norway
  - Prince Albert, Canada

Operations & ground segment

Prince Albert (Canada) **Svalbard (Norway)**



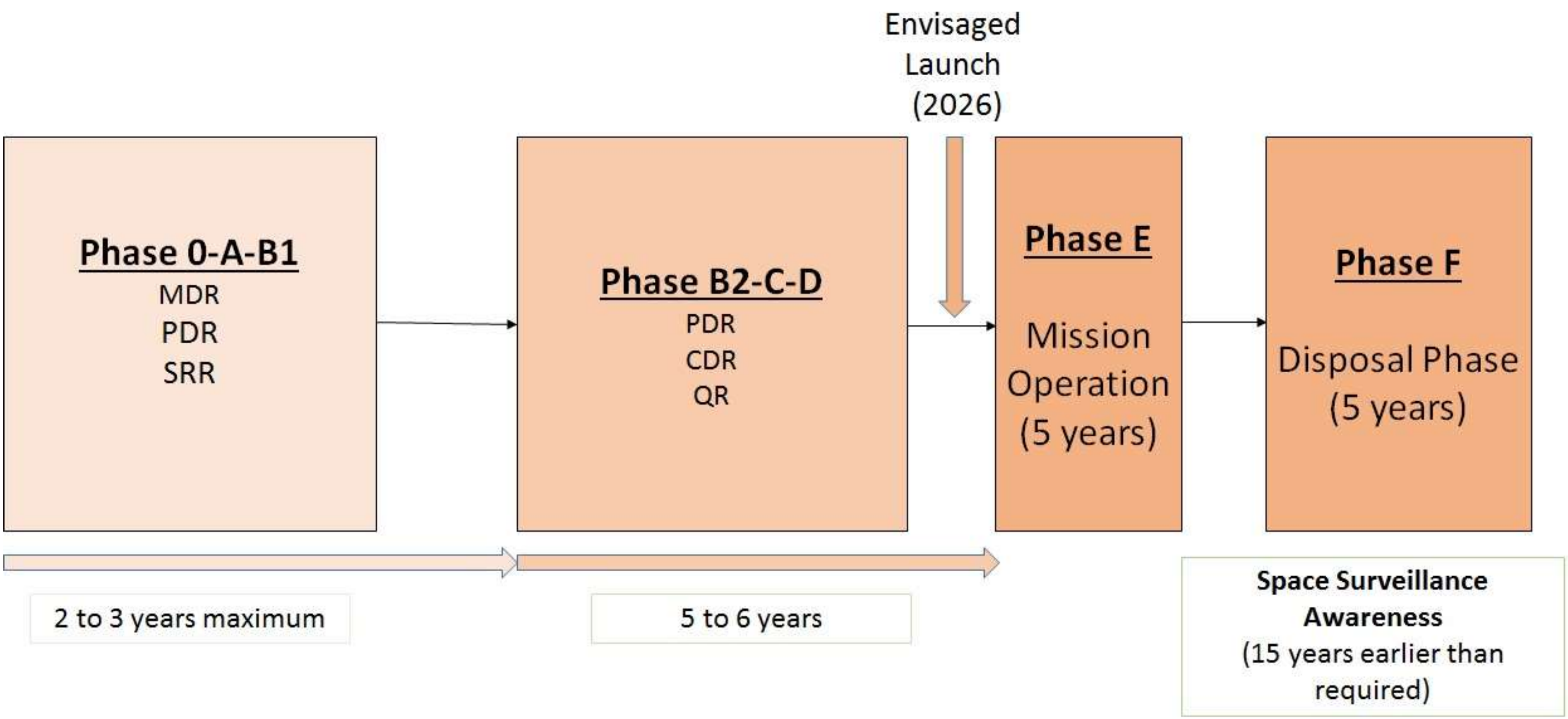
Troll (Antarctica)

Operations & ground segment

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

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

Development schedule



Risk assessment

- Ku-band altimeter
  - TRL = 6
  - Heritage: Cryosat-2
- Ka-band altimeter
  - TRL = 6
  - Heritage: SARAL

- No other critical technology identified

Low	Severe
Moderate	Critical

Risk assessment

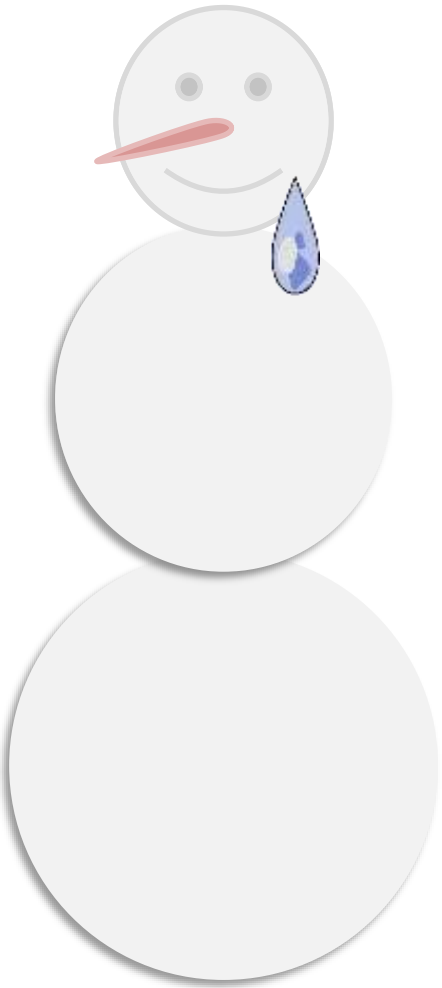
Event	Severity	Likelihood	Total Risk	Mitigation
Obsolescence	3	B	6	Longer phase 0-A-B1
Something not built to specifications	3	B	6	Severity could range from development delays to impaired data gathering
AOCS fails	4	B	8	Redundant system
Development of hydrological models reduce scientific value	4	A	4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

ROM cost breakdown

Item	Cost (M €)
(Instrument development (before start))	15
Industrial cost spacecraft (Heritage Cryosat)	100
Payload	80
Vega Launcher	45
Scientific data processing (high data rating processing intensive)	35
Operational cost	45
Airplane campaign	1
Project Team (10% of industrial cost + scientific data processing + operational cost)	25
Contingency (15 % of industrial cost + scientific data processing + operational cost + project team)	43
Overall cost	**389**

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!