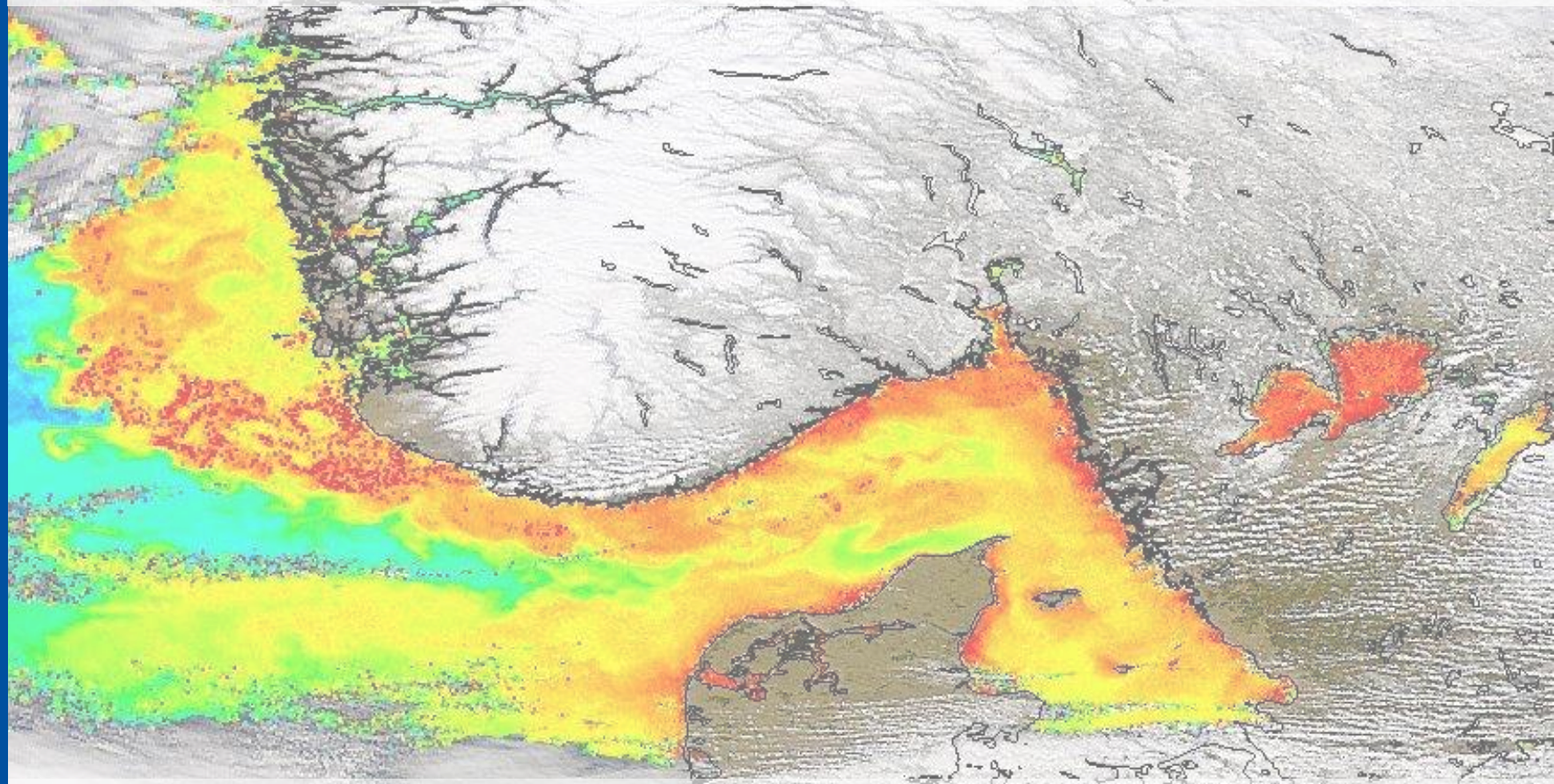
NTNU SmallSat: a Hyper-spectral imaging mission

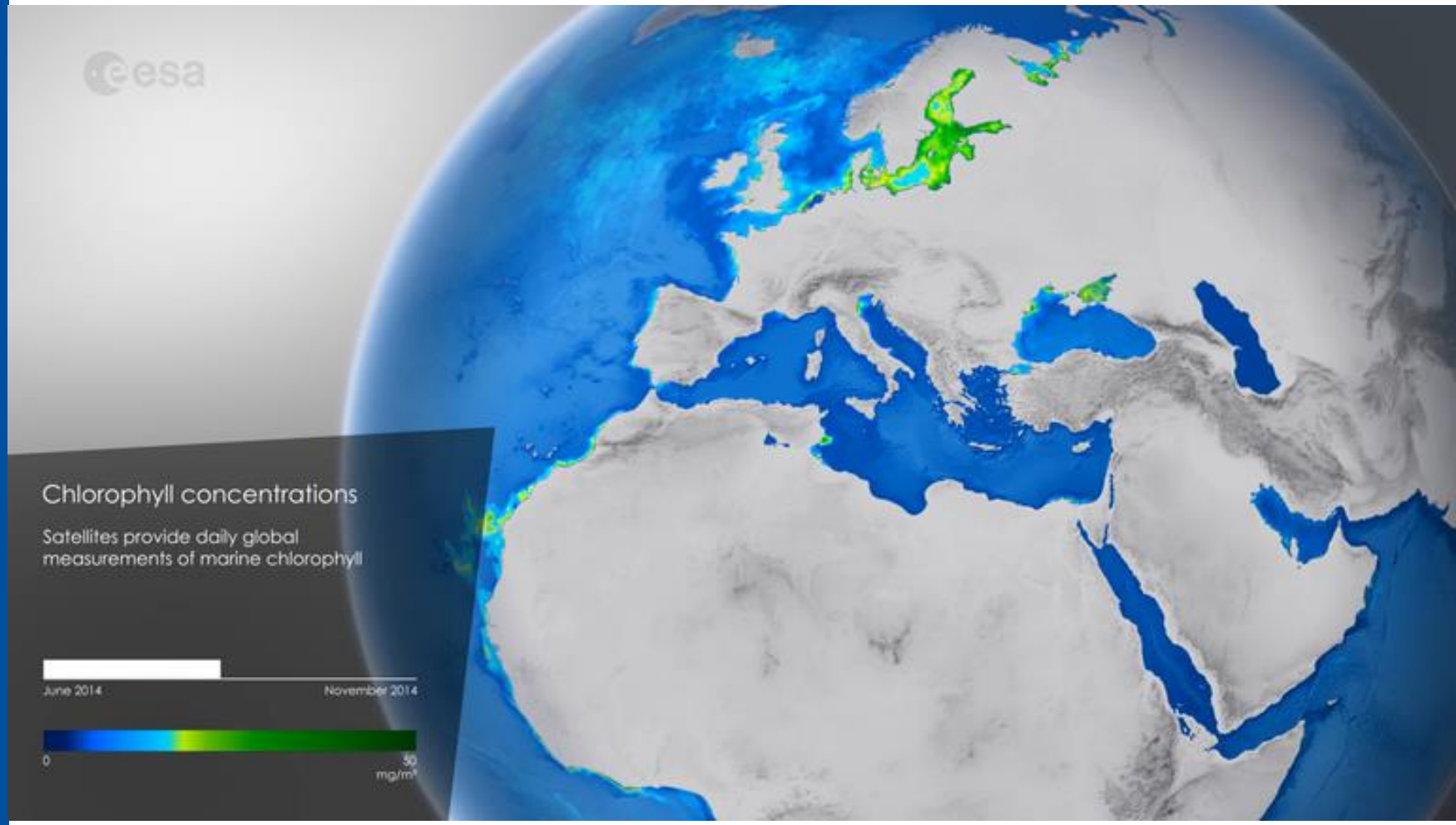
Mariusz E. Grøtte[1]



[1] *Center for Autonomous Marine Operations and Systems (AMOS), Department of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway*

Image: Chl-a concentrations off the coast of Norway. Credit: NASA

Chl-a concentration in the Baltic



Video credit: ESA. Data provided from Sentinel-3

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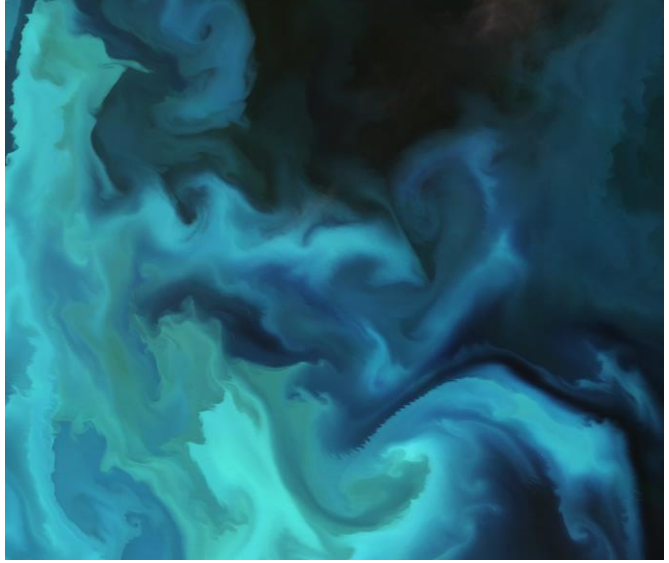
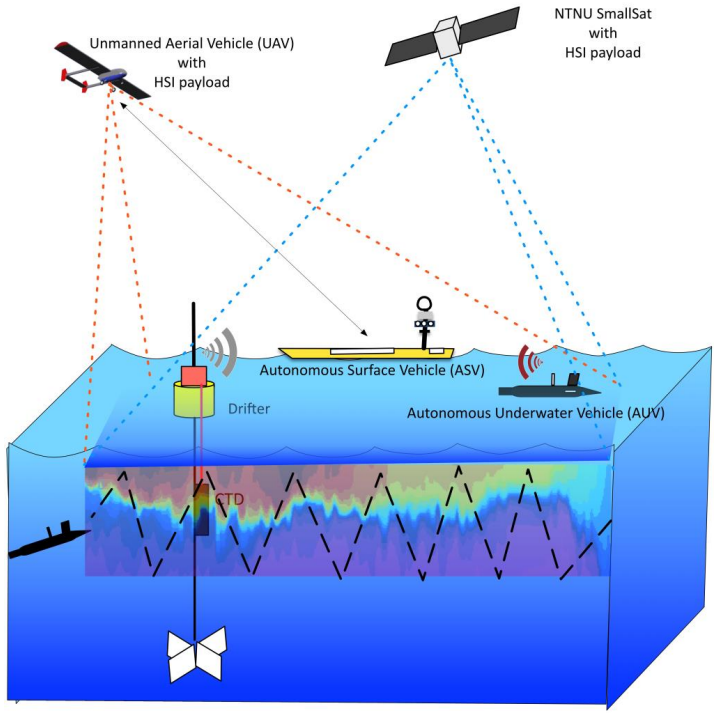
Overview

- Background & Motivation
- Hyperspectral Imager payload
- Mission Design
  - Success criteria & requirements
  - Mission architectures
  - Verification and testing plan
- Software & hardware
  - Data processing pipeline
  - PCB for HSI
- Mission Analysis
  - Orbit and target
  - Remote sensing
- Budgets
  - Data
  - Power
- Conclusions



Algal bloom; credit: ESA



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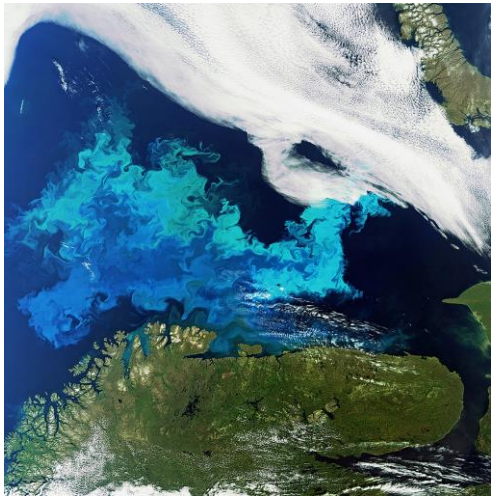
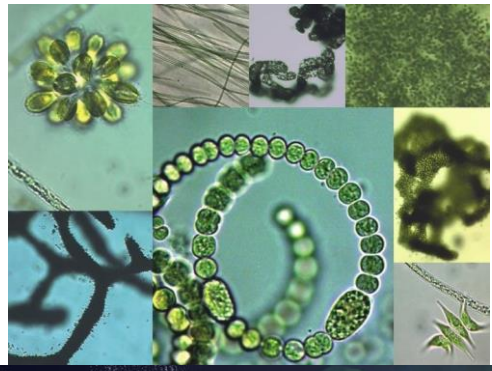
Background

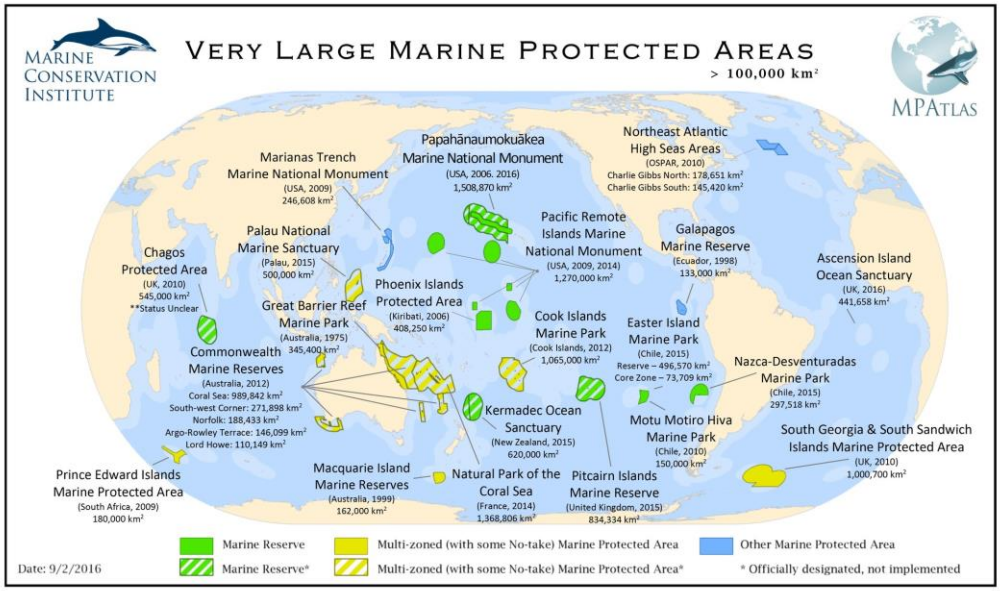
- Ocean Color
  - Algae; HABs
  - Phytoplankton
  - Cyanobacteria/toxins
  - River plumes/oil spill
- Norwegian fish farms
- Global climate change
- Marine habitats
- Microplastic (<5mm)



Algal bloom north of Finnmark; credit: ESA

Salmon (est. 900 tonnes) death; credit: IFinnmark





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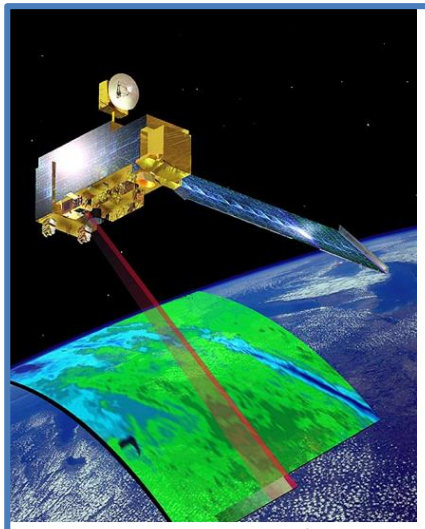
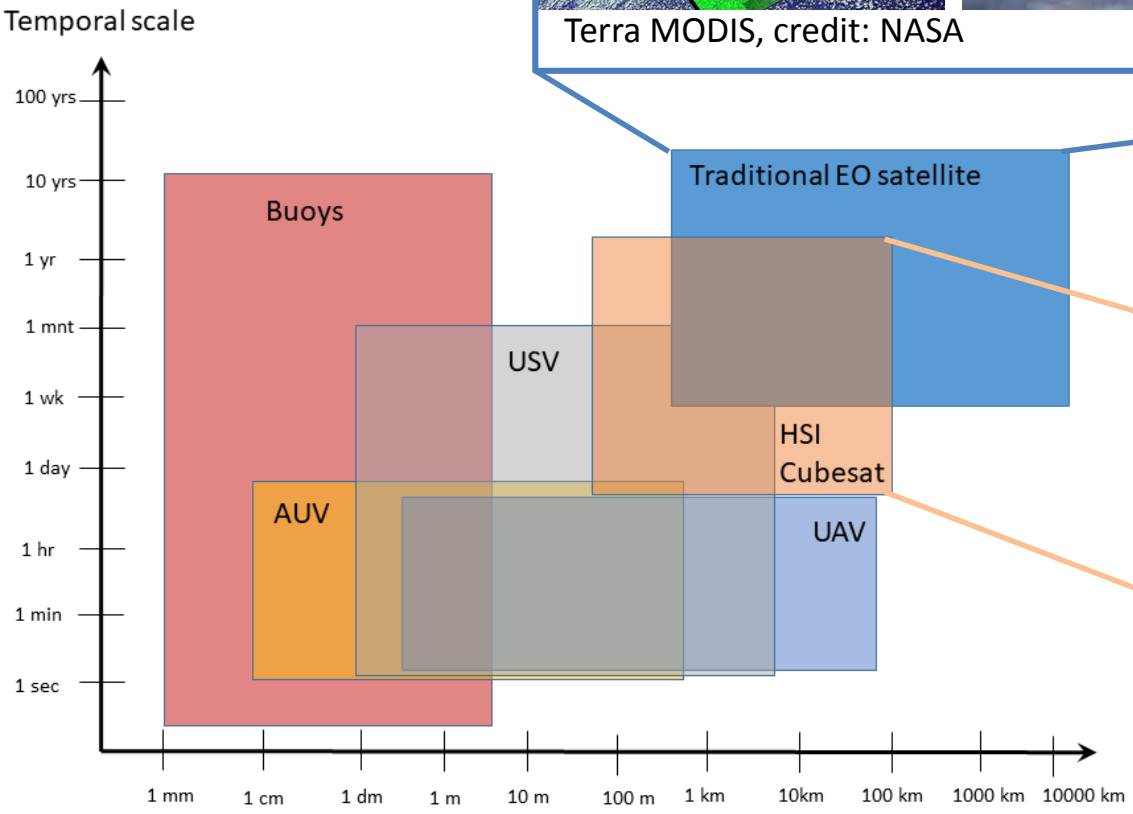
Motivation



Terra MODIS, credit: NASA

Sentinel 3, credit: ESA



CubeSats, credit: ESA

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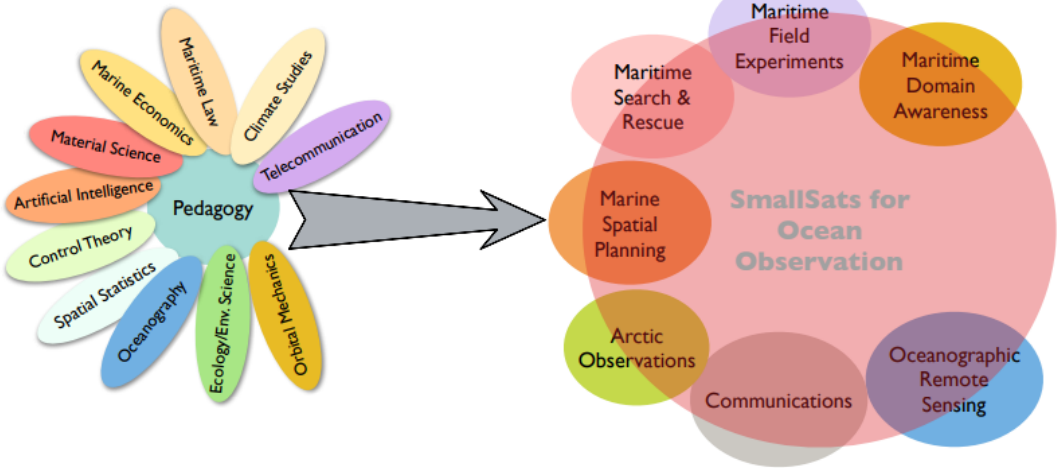
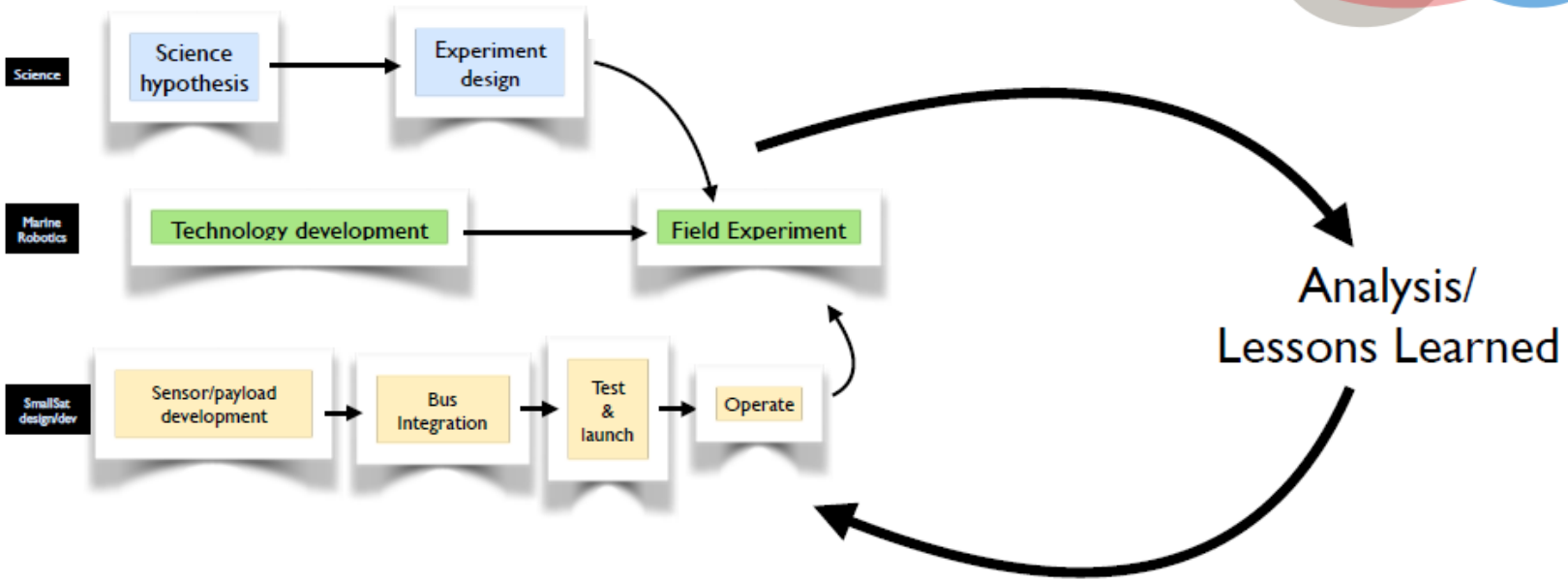
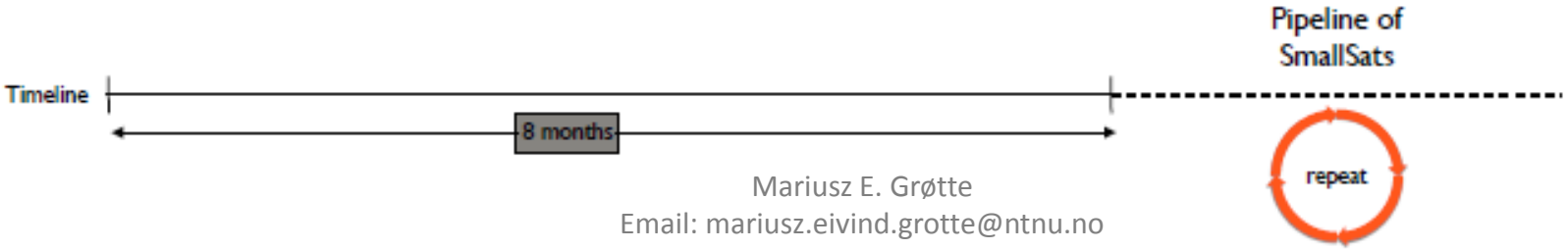
Roadmap







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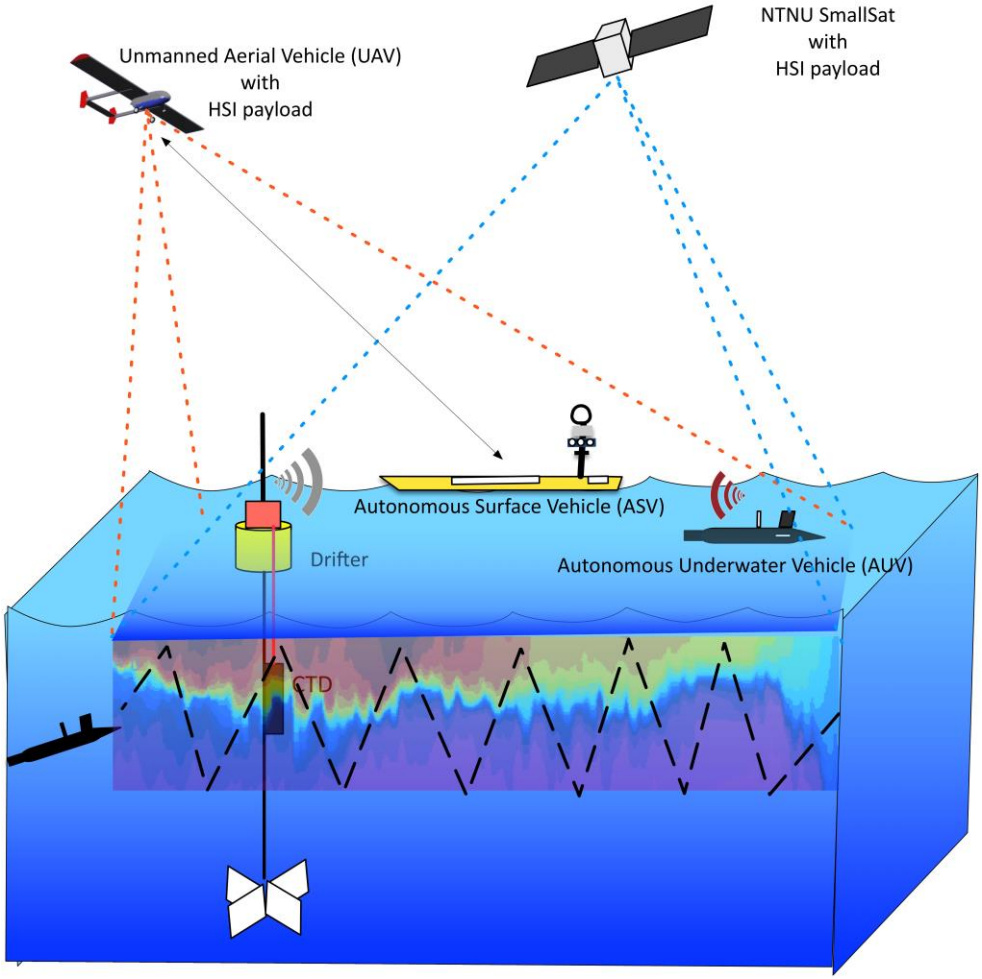
Vision: the Robotic Platform Architecture



- High spatio-temporal resolution for oceanographic observations
- De-conflicting time and space is critical
- Observations in hours not days → space segment

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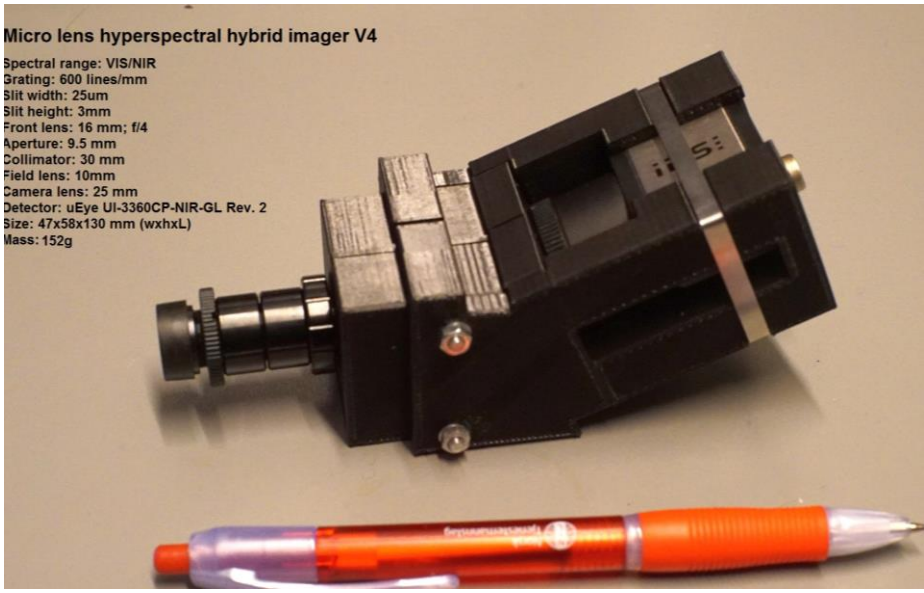
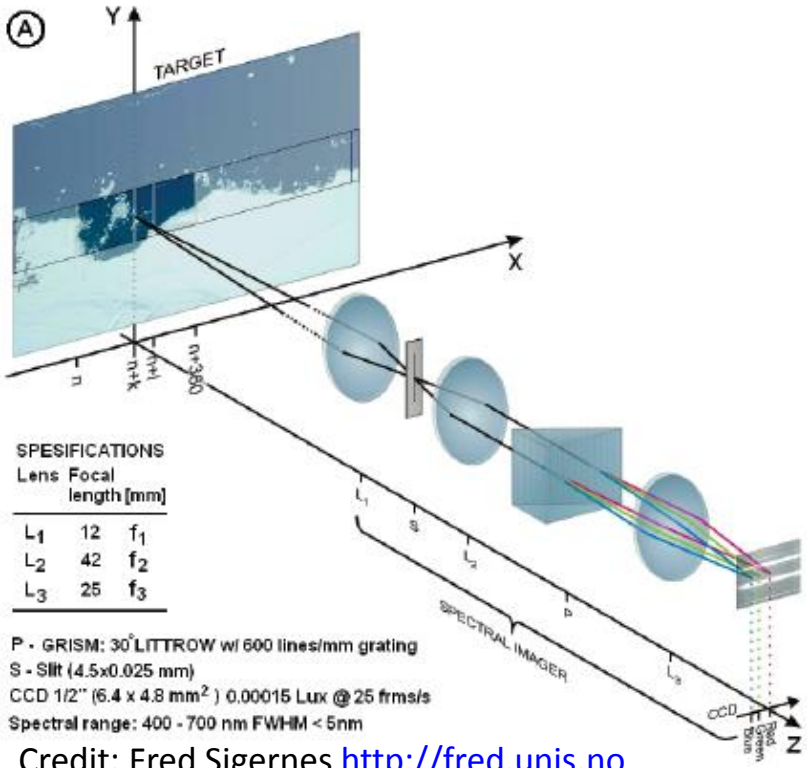
Hyperspectral Camera

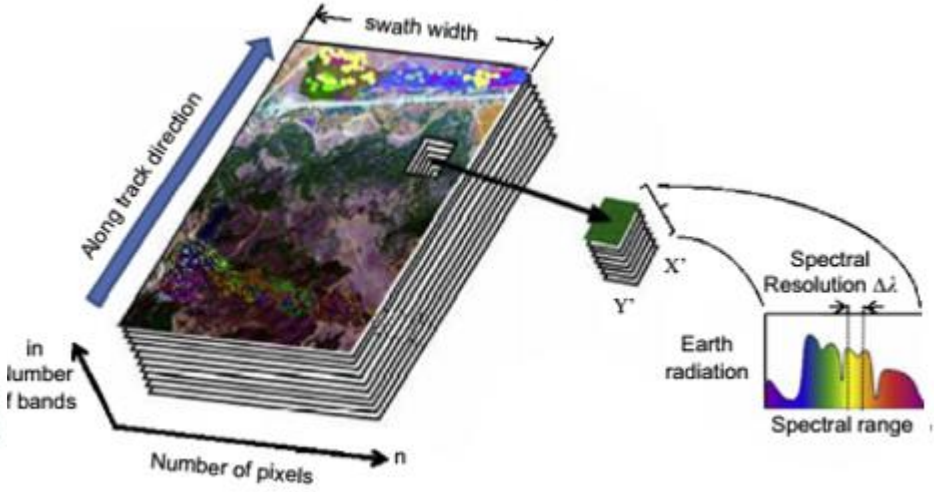
- Push-broom line scanner
- Spectral range: 400-900 nm
  - usable: 100 bands
  - spectral resolution of 5 nm
- Size: 1/3 U
- Mass: 152 g



HSI ver. 4, credit: Fred Sigernes http://fred.unis.no



Credit: Fred Sigernes http://fred.unis.no



Credit: M. Guelman, F. Ortenberg / Acta Astronautica 64 (2009) 1252 –1263

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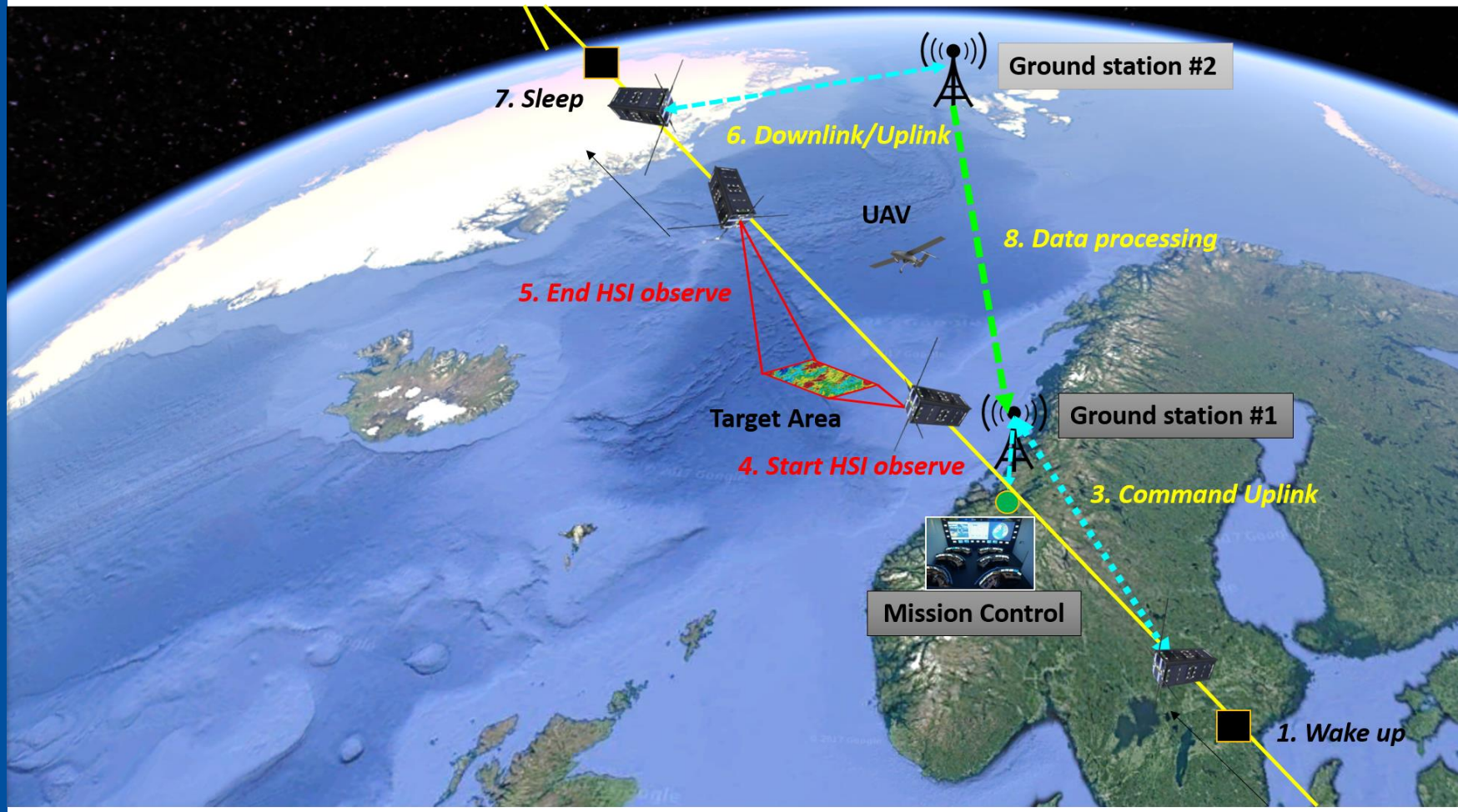
CONOPS



*Satellite is in retrograde **near-polar orbit** and is operational for imaging at about **1 min** during one direct overhead pass per day. Constellation is designed with baseline **2 revisits** per day. Norway has a large coastline and substantial responsibility for important ecosystem observations and maritime surveillance.*

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Mission Requirements

Level 0 mission statement

NTNU SmallSat mission will demonstrate proof-of-concept oceanographic observations through dedicated and targeted narrow field-of-view hyperspectral imaging

Level 0 – minimum success criteria

- S/C shall successfully launch, deploy and initialize operations in LEO
- Shall enable observe on meso-scale over ocean target area of about 50 x 30 km, giving a swath width of 30 km in the Atlantic ocean at viewing angle of <20 deg
- Shall identify and track a ocean target area with 3 passes per day with 1 pass being direct overhead with >3 min duration of pass
- Shall take images of target with 100 spectral bands in VISNIR that will include at least 3 detectable signature of scientific/ oceanographic content
- Ground user shall be able to download at least 10 on-board compressed images and telemetry data for direct interpretation during >2 min/day with coverage of approx. 3000 km slant range and ground elevation <30 deg
- Shall be operational for at least 3 months days with continuous operations mission updates during peak-season and target localization temporal resolution of between 1 day and 1 year

Level 1 mission requirements

- Shall detumble after separation with full mission operations support in <3 weeks
  - Ground shall identify S/C, generate TLE and estimate its initial state upon deployment from P-POD with 10% deviation to nominal orbit
    - Ground station shall track S/C over 6 months after deployment
- Sampling of target area shall not deviate more than 0.1 % error of 30 m
  - Target area shall have scientific content in an average 1:72 orbits and at least probability of detection of 1.39 % for 1 pass
    - Target shall have >5 % of its area covered by relevant content including at least Δz = 0.5 m ocean depth in summer season
- Target shall be observable by given movement (westwards) cross-track on previous/subsequent pass and min. elevation angle of 10 deg relative to S/C cross-track
  - Shall pass same the target location at same local time every day with drift less than 100 m per day westwards
    - Observation of target shall be enabled globally with uplink on mission plan 2 orbits prior to observation
- Shall have 100 spectral bands/channels available in 400-750 nm range
  - Images of oceanic/natural/biological content shall have spatial resolution of <100 m as well as maximum reflectance and brightness to distinguish content spectrally
    - Faintest detectable signature that is set to observe must be at SNR of 100:1
      - Shall avoid clouds, saturation effects and sunglint
- Mission data shall be downlinked in max. 1 orbit after mission operations with >3 min pr. pass
  - Model update of mission data shall happen in-orbit with geometric calibration
    - Shall have HSI operations and ground station availability in 1 pass with immediate image reconstruction and response
      - Shall downlink data to at least 1 ground station in Norway
- Space segment agent shall be coordinated with other robotic agents indirectly with response time of maximum 2 hrs
  - Space segment shall enable updates on mission planning
    - Space segment shall support re-scheduling of planned events by ground command

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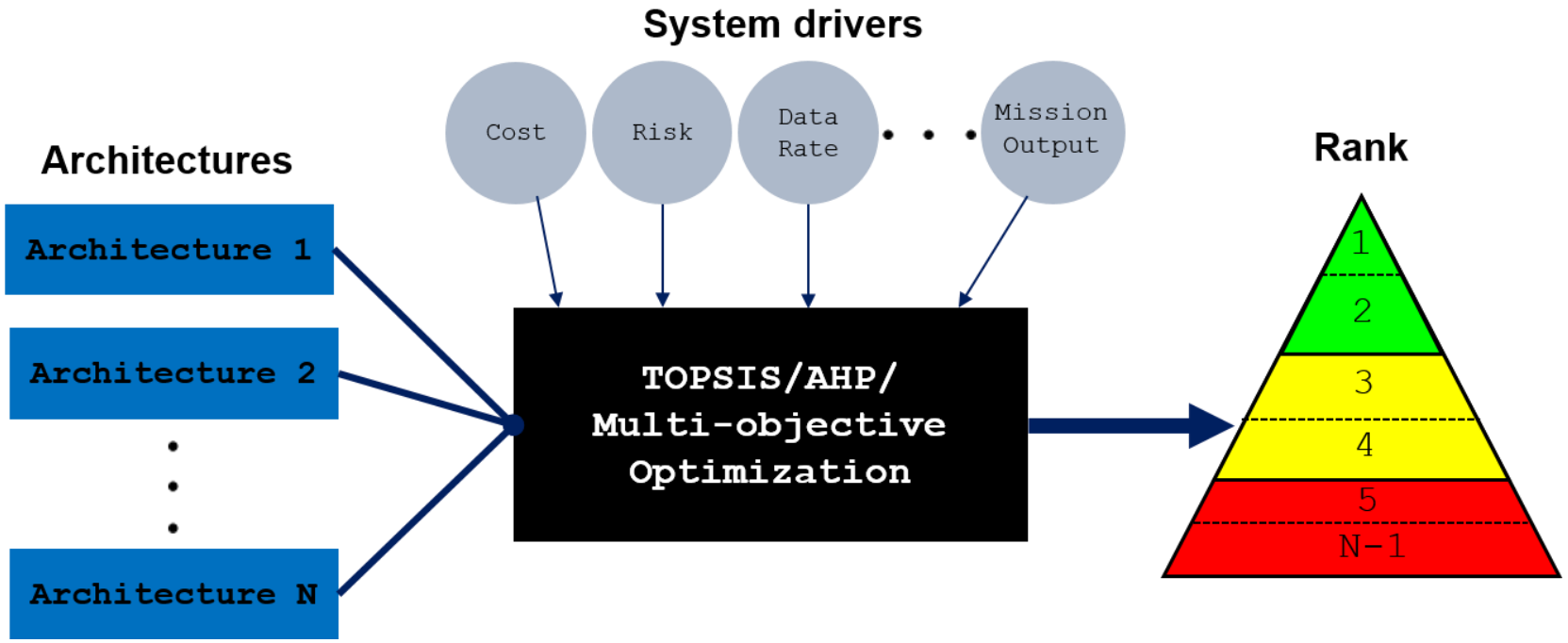
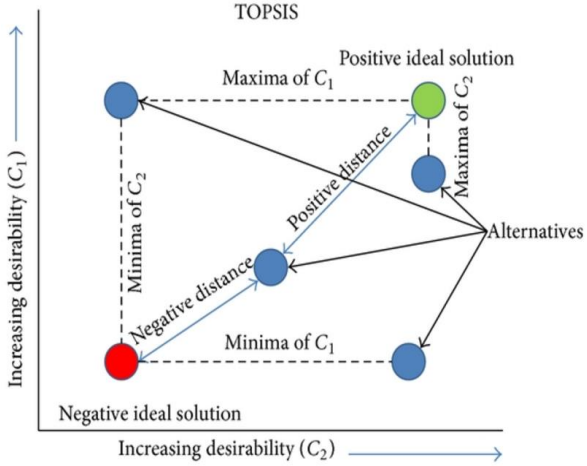
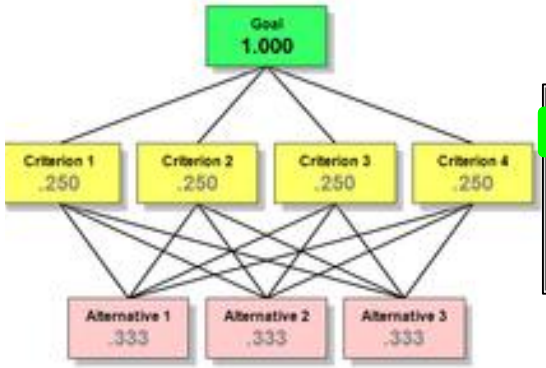
Trade-off Analysis







Rank	Mission Architecture
1	A3-B1-C1-D1-E1-F1-G1-H1-I1-J1
2	A1-B1-C1-D1-E1-F2-G1-H1-I2-J1
3	A3-B1-C1-D1-E1-F2-G1-H1-I1-J1
4	A3-B1-C1-D1-E1-F1-G1-H1-I2-J1
5	A2-B2-C1-D1-E1-F1-G1-H1-I6-J2

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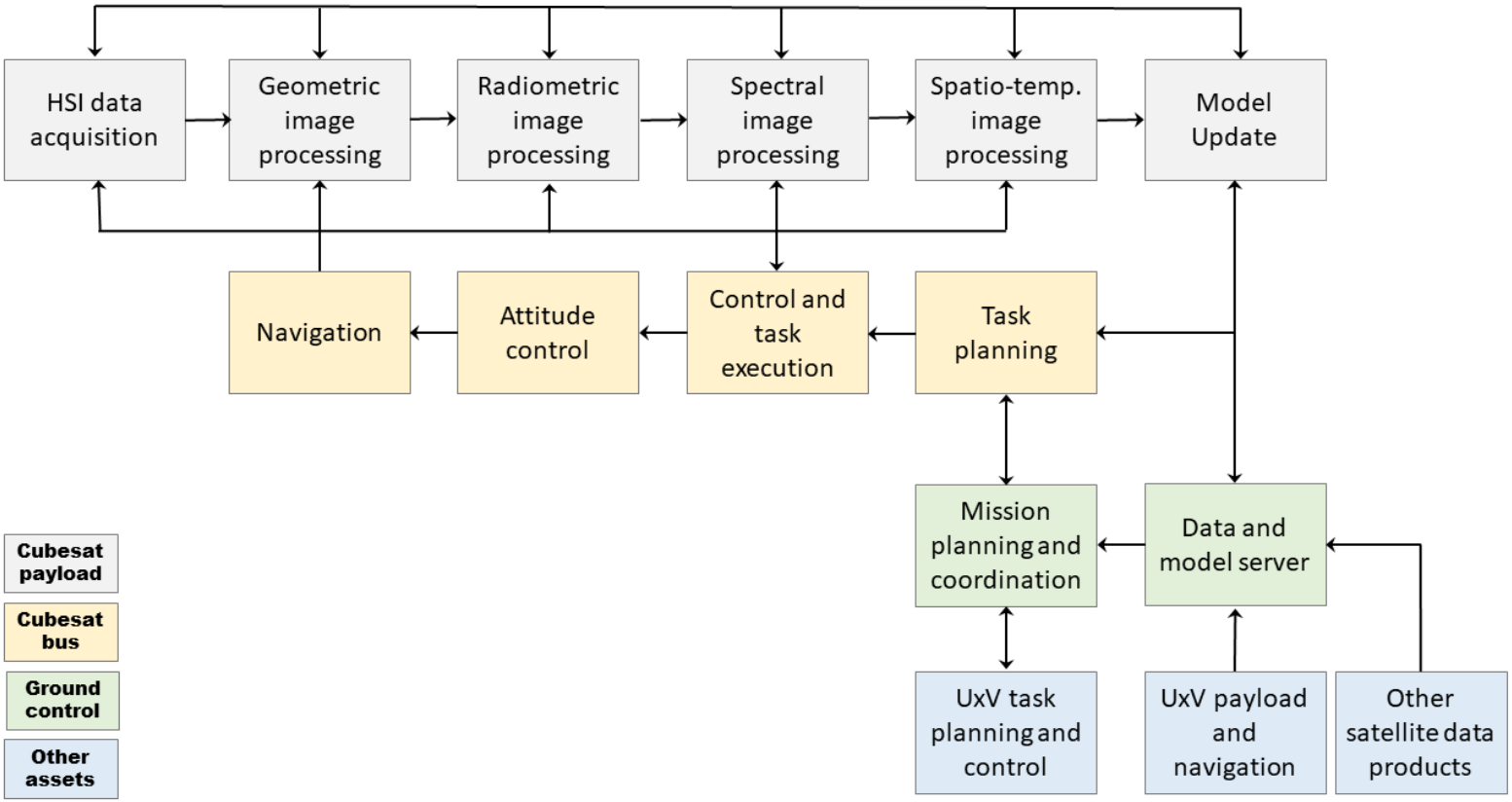
HSI Processing & Control



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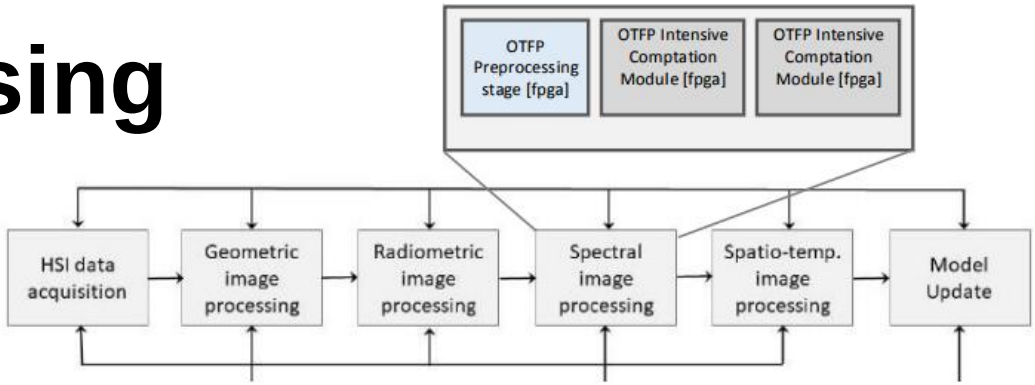
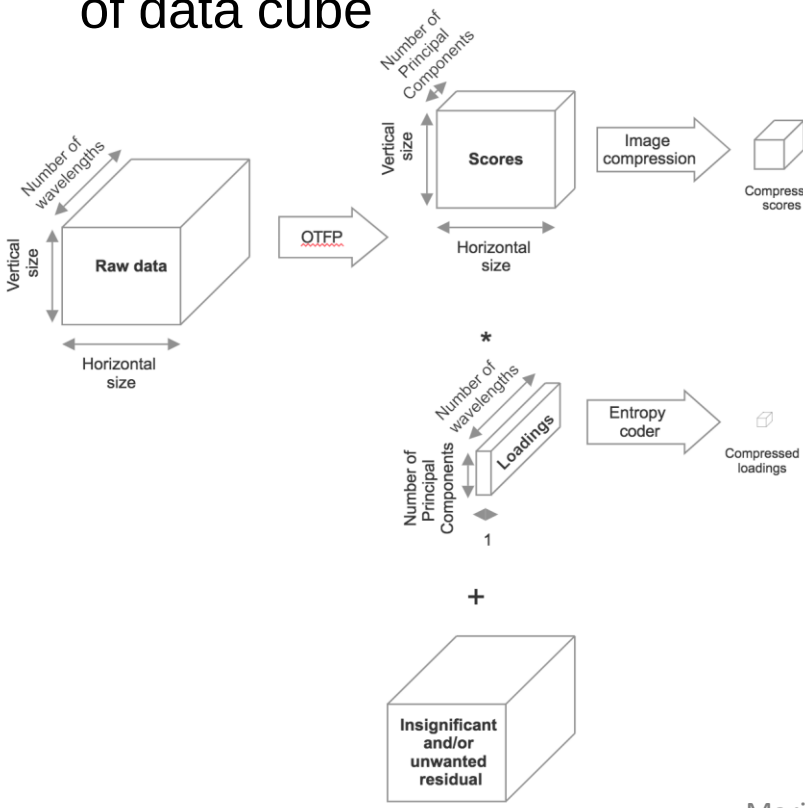
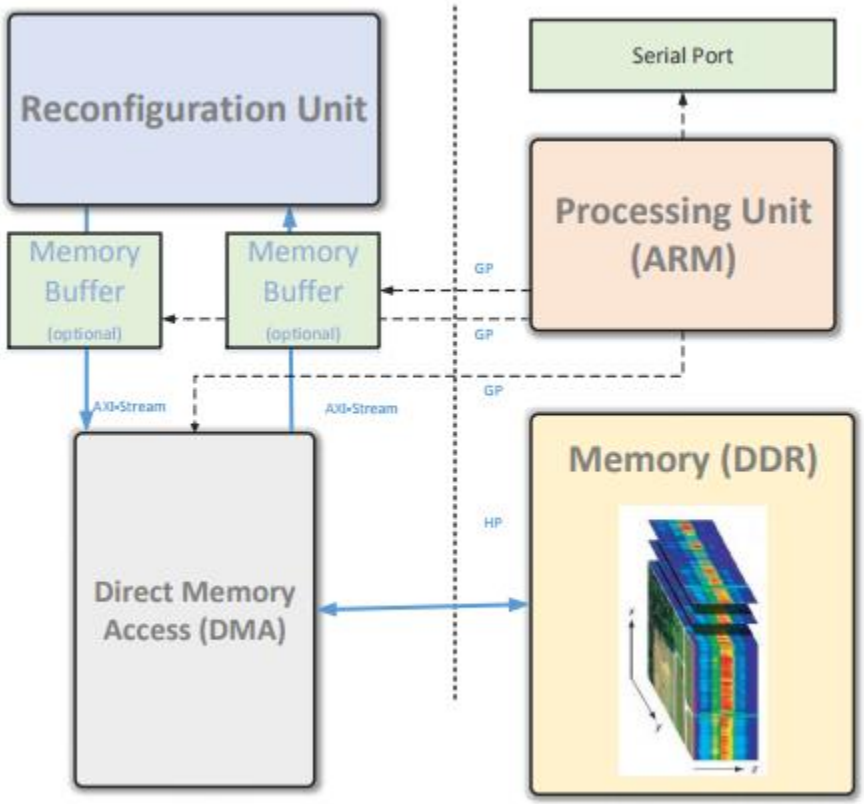
Data Processing

- Spectral + spatial + geometric compression
- OTFP
- Principal components of data cube







Credit left bottom: Idletechs

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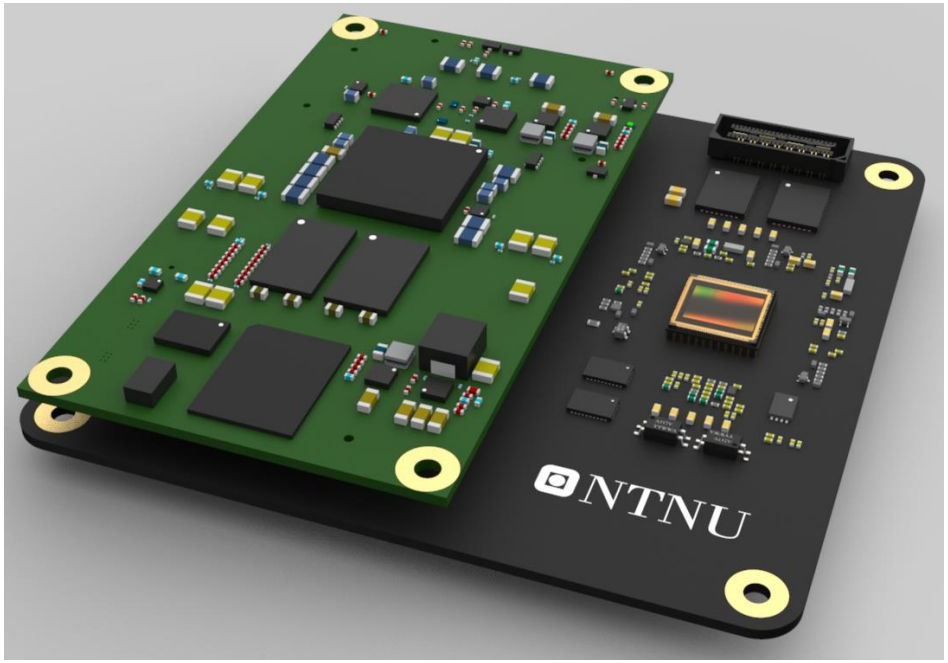
Payload Electronics

- ARM/FPGA Computer
- Based on Zynq7000 FPGA
- Inexpensive automotive parts
- NIR enhanced image sensor
- Power consumption < 3W
- Up to 100fps, 12-bit resolution
- Supports multiple protocols
- Low cost



Render of version 1, currently in development
Credit: Julian Veisdal @ Moonwearables Inc.

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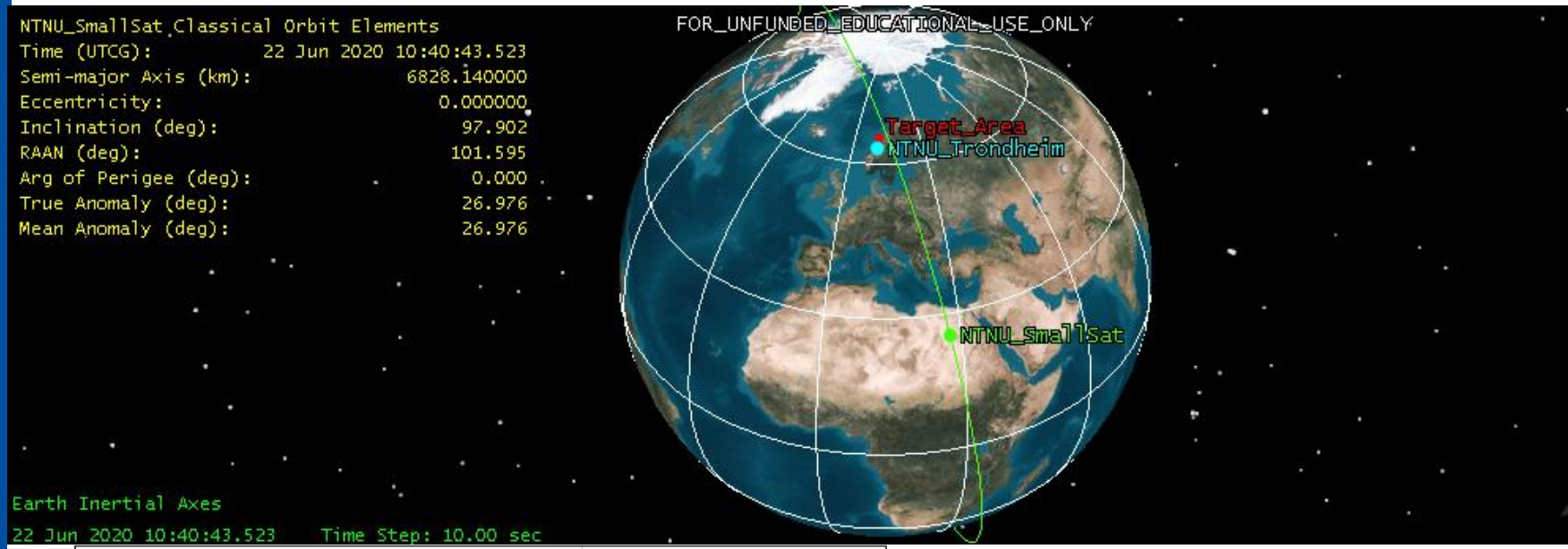
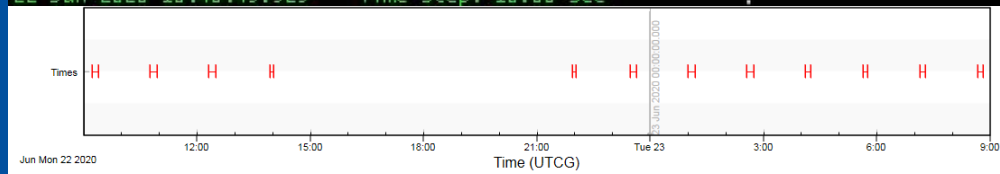
Mission Analysis

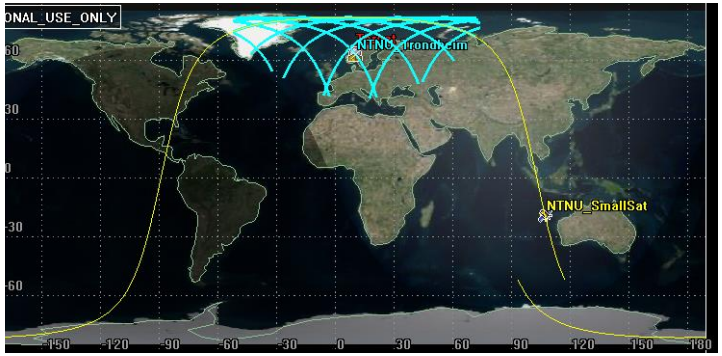




Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	22 Jun 2020 09:13:28.141	22 Jun 2020 09:23:47.520	619.379
2	22 Jun 2020 10:45:33.192	22 Jun 2020 10:56:40.450	667.258
3	22 Jun 2020 12:19:18.869	22 Jun 2020 12:29:26.733	607.864
4	22 Jun 2020 13:55:47.777	22 Jun 2020 14:01:19.933	332.156
5	22 Jun 2020 21:56:07.881	22 Jun 2020 22:01:49.471	341.590
6	22 Jun 2020 23:28:08.793	22 Jun 2020 23:38:16.484	607.691
7	23 Jun 2020 01:00:56.124	23 Jun 2020 01:12:09.342	673.218
8	23 Jun 2020 02:33:48.854	23 Jun 2020 02:44:15.283	626.429
9	23 Jun 2020 04:06:27.791	23 Jun 2020 04:15:06.699	518.909
10	23 Jun 2020 05:38:23.841	23 Jun 2020 05:45:41.883	438.042
11	23 Jun 2020 07:09:18.405	23 Jun 2020 07:17:17.005	478.600
12	23 Jun 2020 08:40:01.739	23 Jun 2020 08:49:46.440	584.701

Global Statistics

Min Duration	4	22 Jun 2020 13:55:47.777	22 Jun 2020 14:01:19.933	332.156
Max Duration	7	23 Jun 2020 01:00:56.124	23 Jun 2020 01:12:09.342	673.218



h=500 km, duration = 11.12 min

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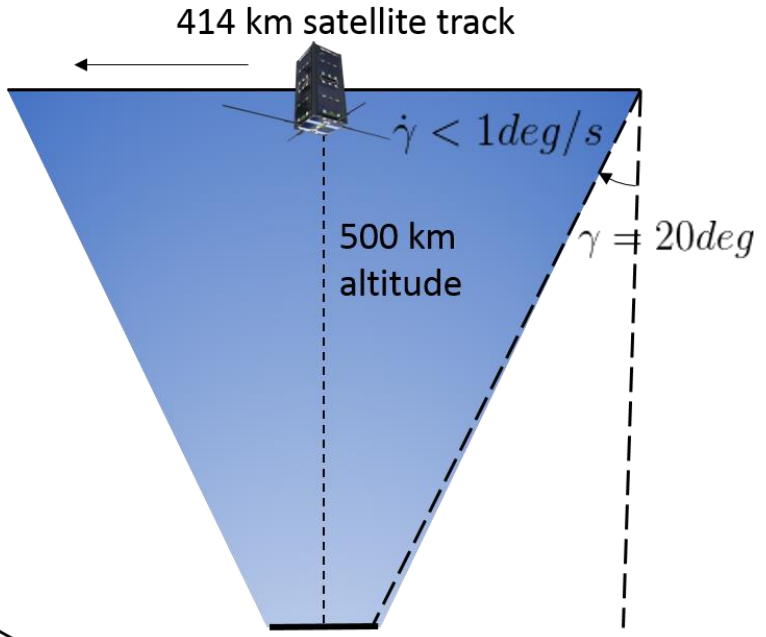
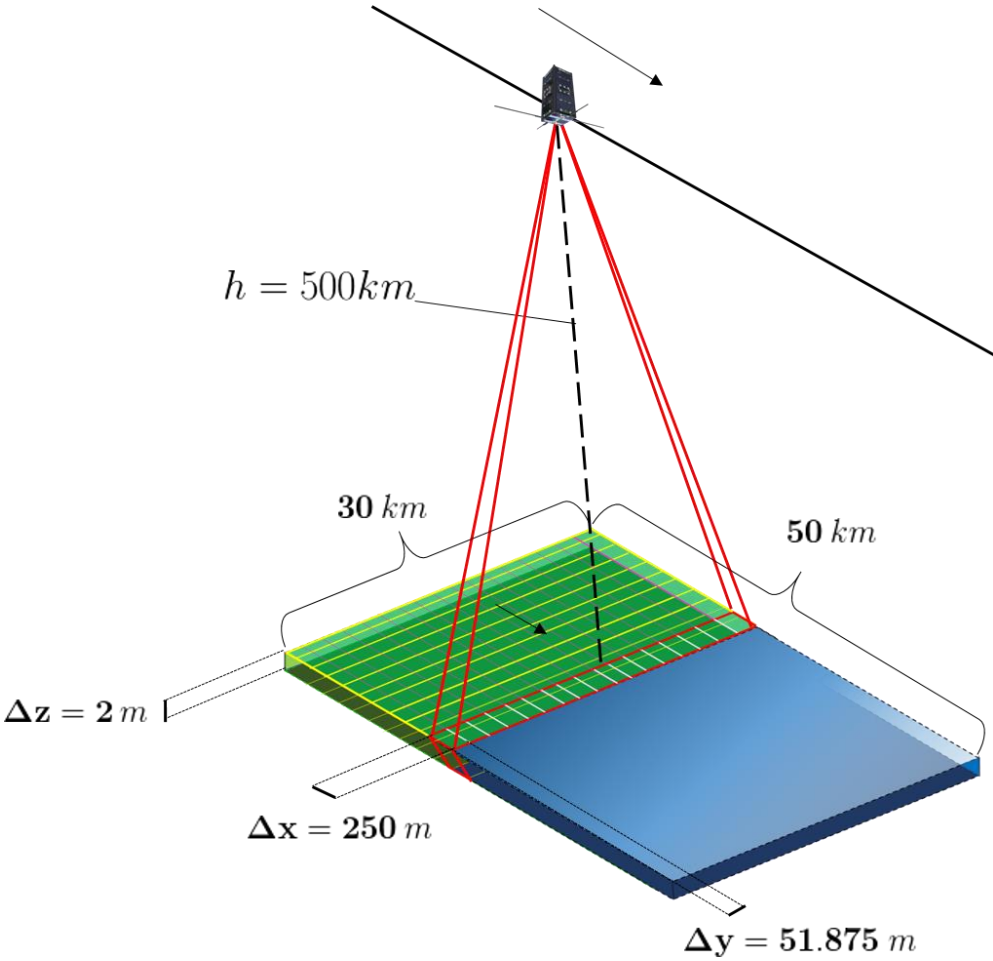
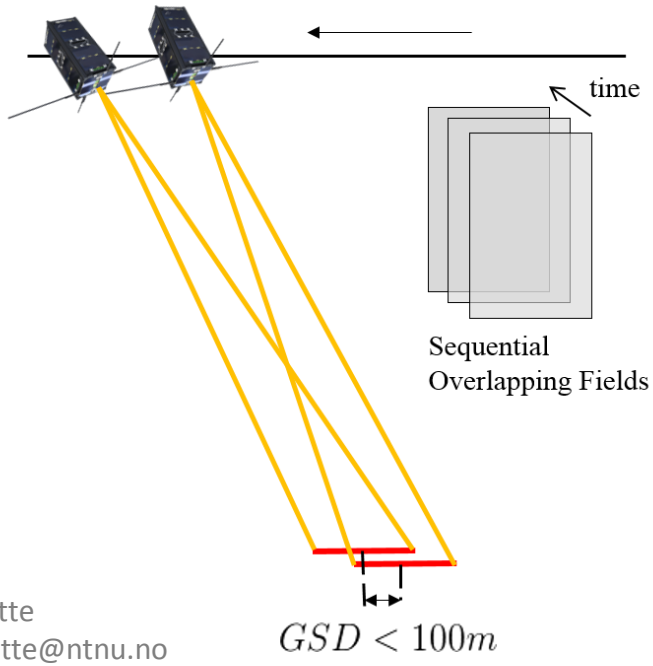
Sampling of Target







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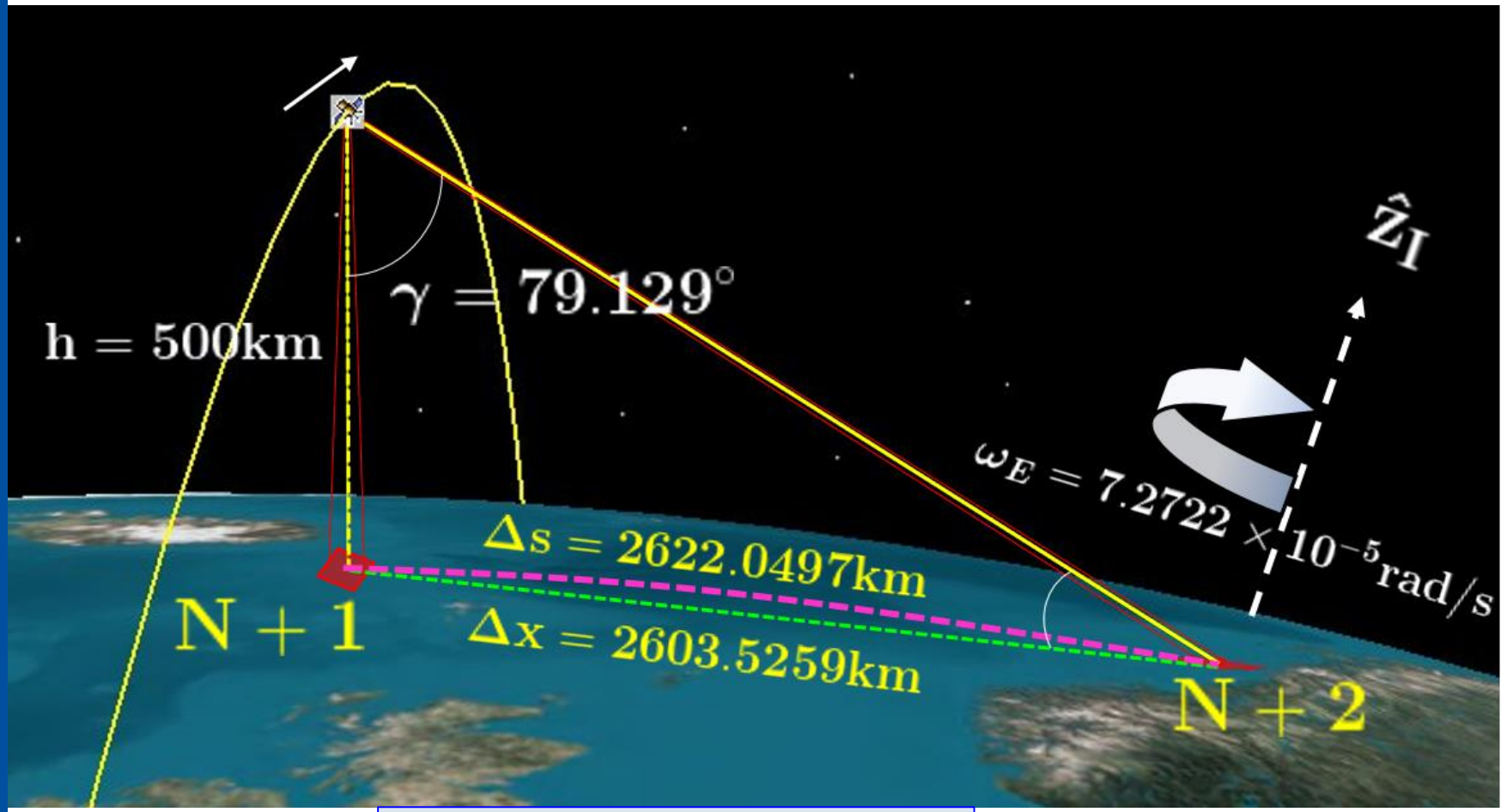
Cross-Track Slew Requirements



Θ = 20 deg wrt. Nadir along-track
$\dot{\gamma}$ = <1 deg/s, $\dot{\theta}$ = 0.7361 deg/s

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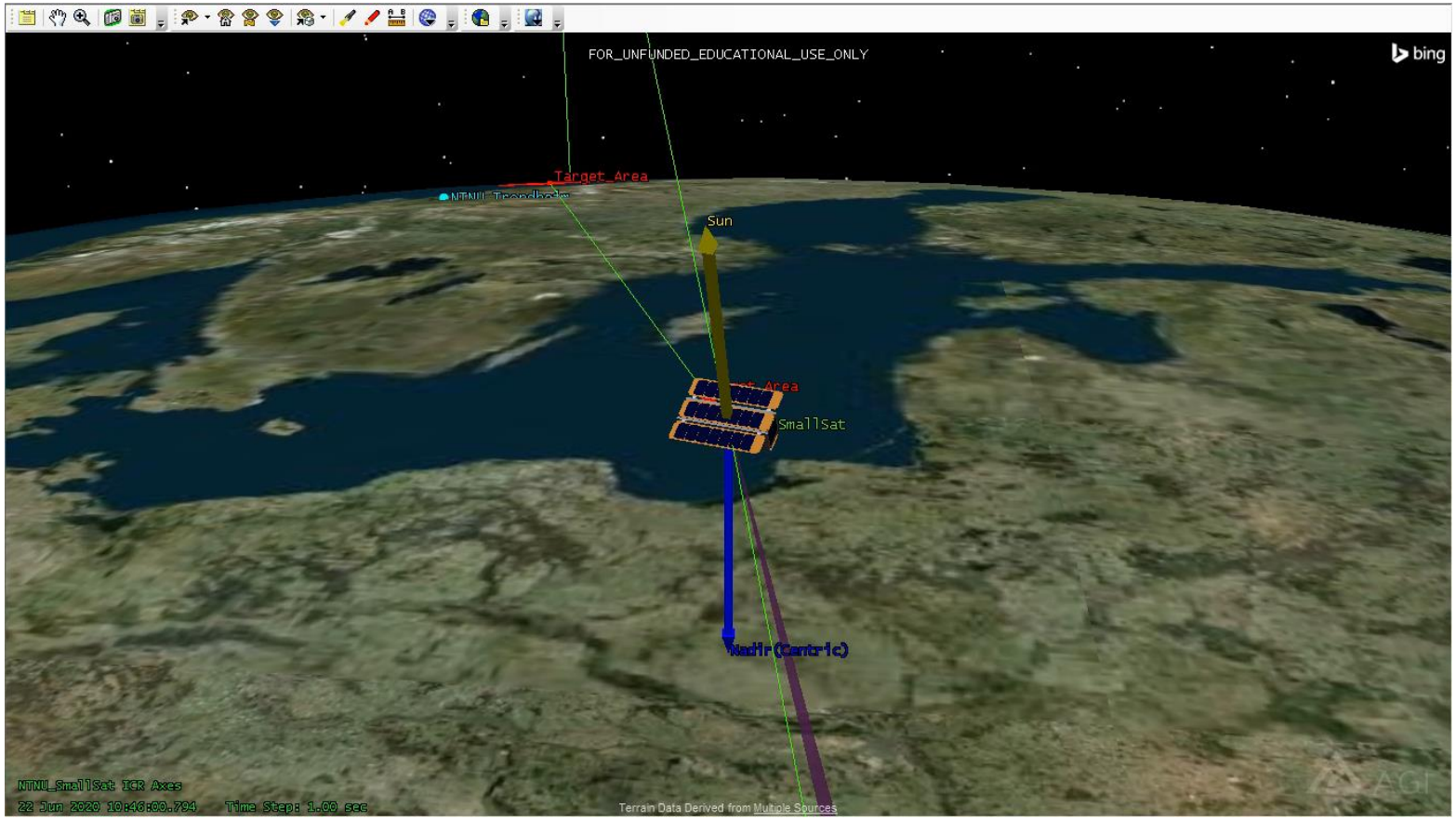
Slew Maneuver

- YPR sequence
- Constrained optimal slew maneuver
- $\dot{\gamma}_x$ = 1 deg/s, adaptive step size control



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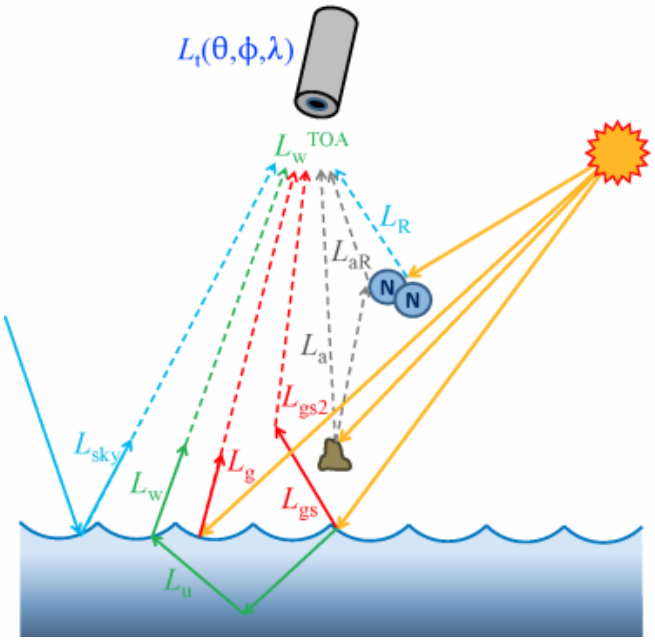
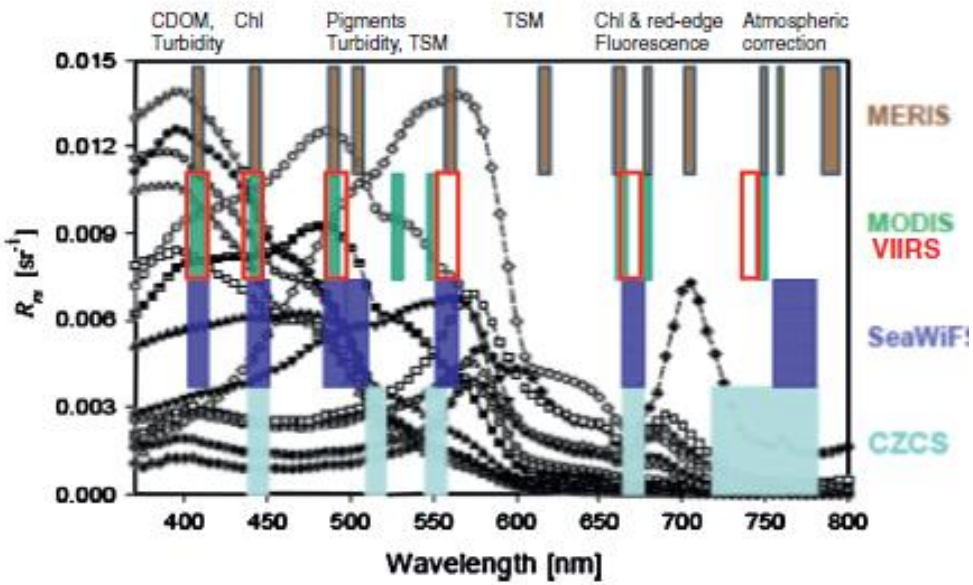
Remote sensing

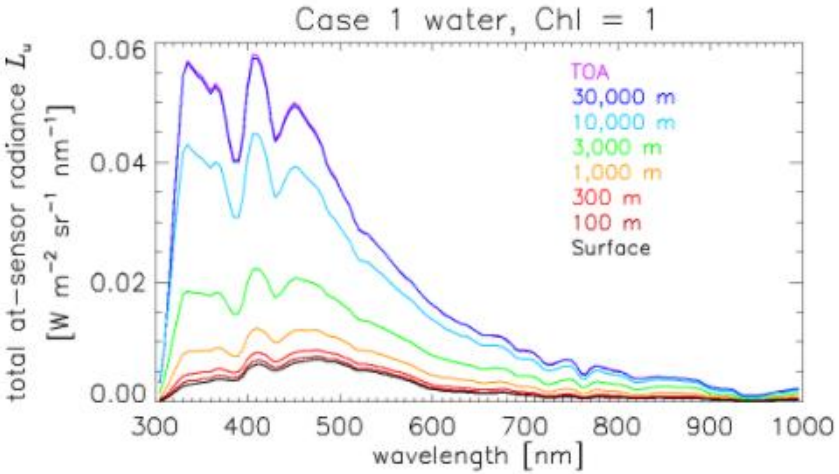
- What can be seen ToA
- Case 1 and Case 2 waters
  - Turbidity
  - CDM and SPM
- Atmospheric corrections



Credit: Mobley et al. (2016)



Credit: Blondeau-Patissier et al., Progress in Oceanography, 123:123–144, 2014



Ref: http://www.oceanopticsbook.info/

$$L_t = L_R + [L_a + L_{aR}] + L_g^{TOA} + L_{sky}^{TOA} + L_{wc}^{TOA} + L_w^{TOA}$$

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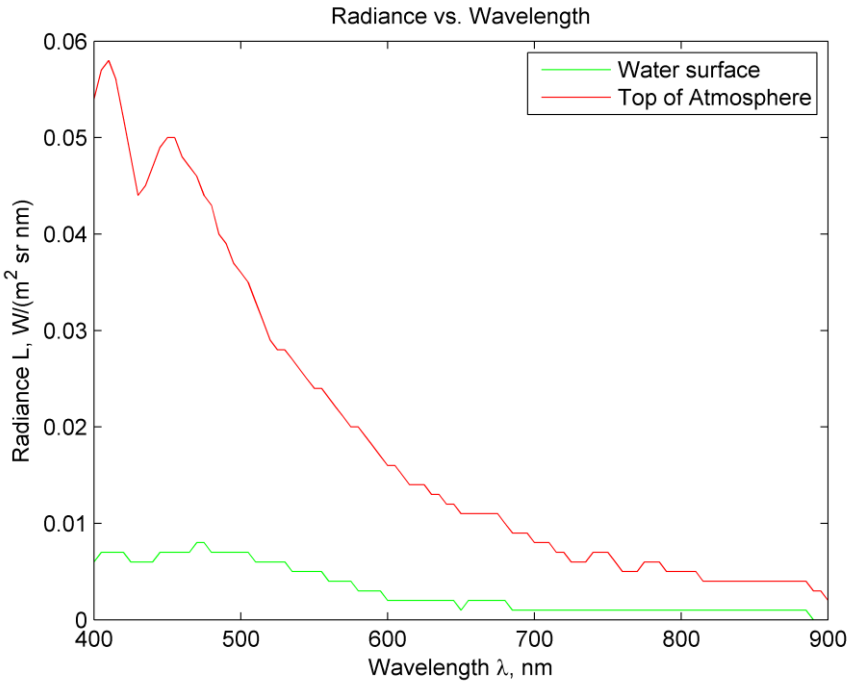
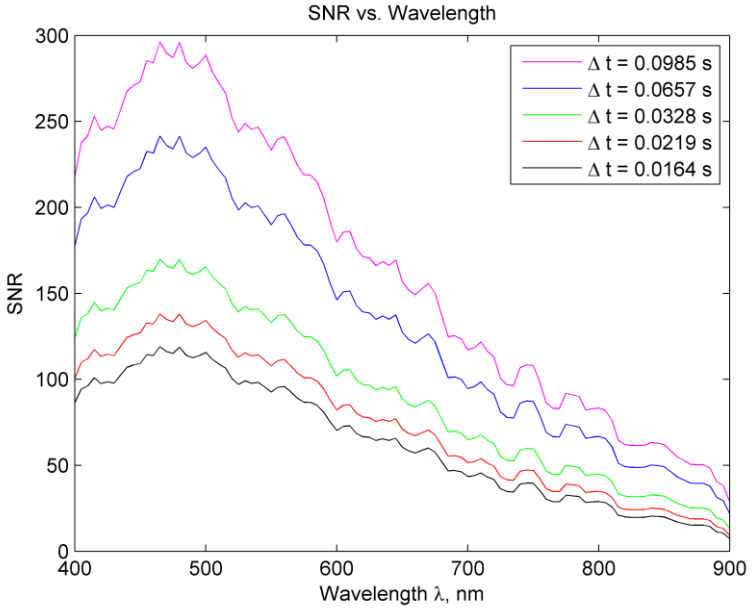
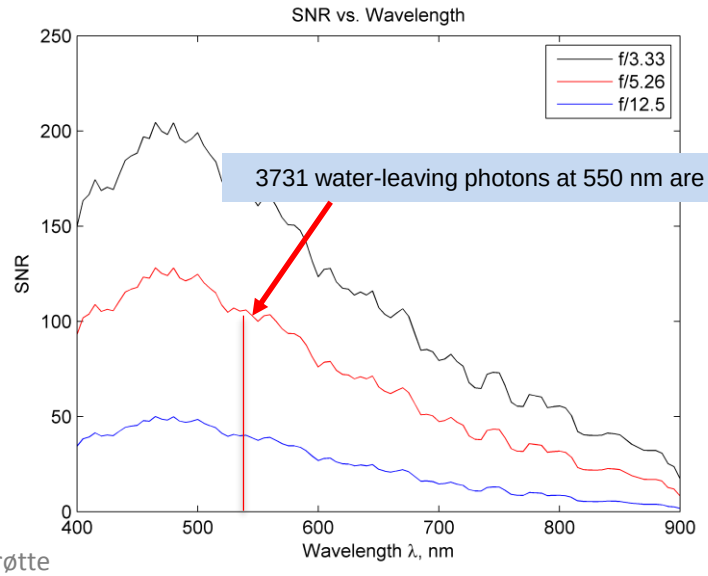
Sensitivity

Humidity	56%
Solar Zenith Angle	45^0
Surface wind speed	6 m/s
Viewing angle	0^0
Chl-a concentration	1 mg/m^3
Water	Case 1
f_0	50 mm
f/#	5.5
h	500 km
Δx	250 m







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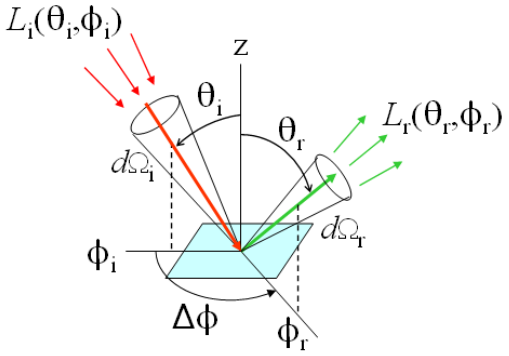
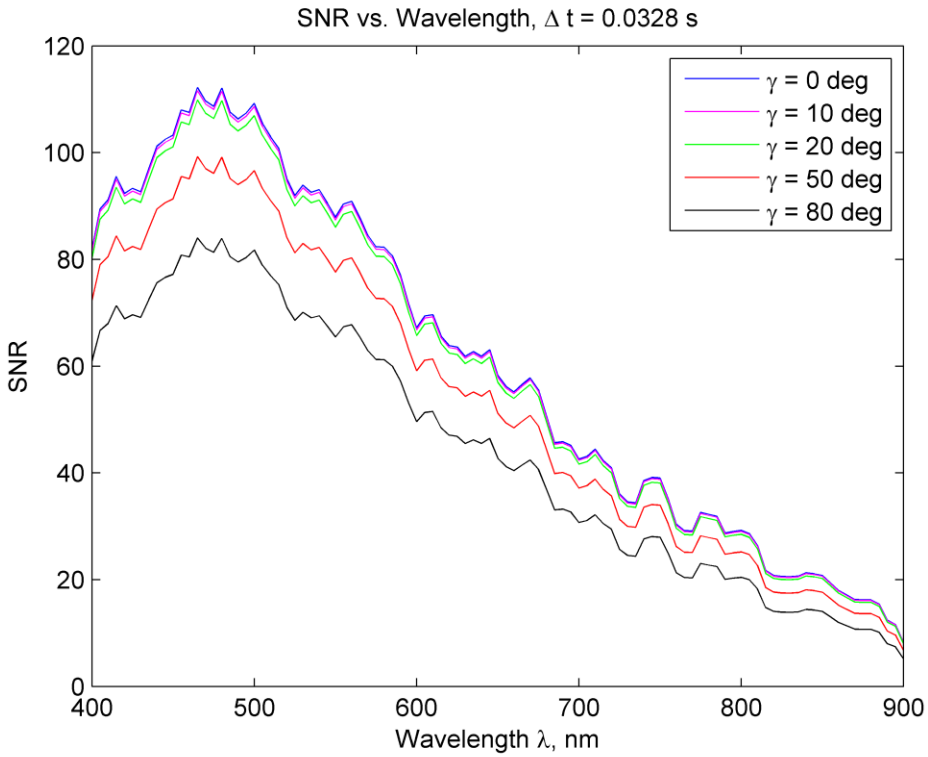
Viewing Angle Effects

- Lambertian BRDF: $p(\phi) = \frac{2}{3\pi^2}(sin\phi + (\pi - \phi)cos\phi)$



- Slant range increases
  - Spatial resolution worsens
  - Added distortions
- Less water-leaving photons reaching sensor
- Exposure time matters for GSD



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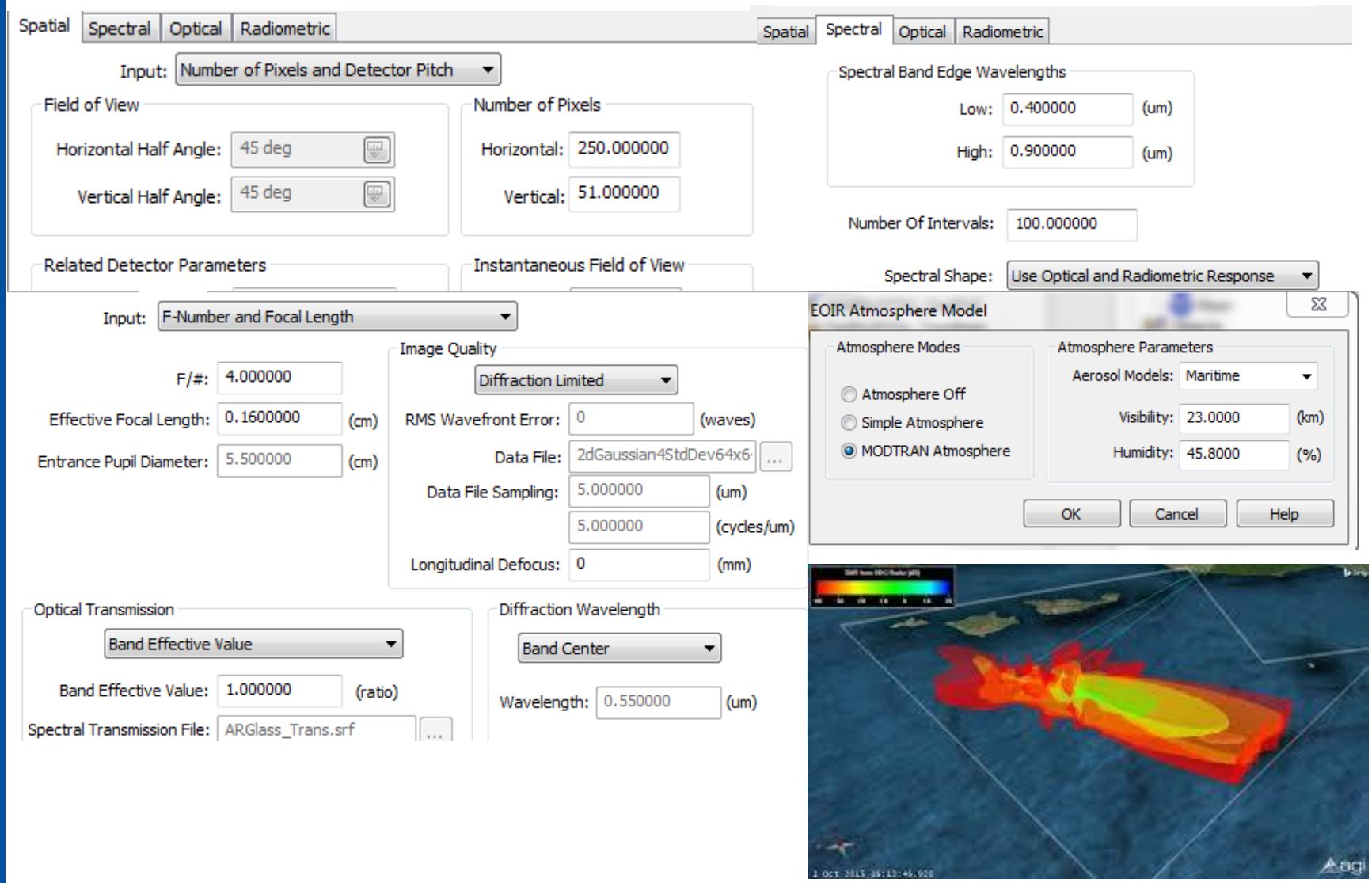
EOIR Tool in STK



Volumetric area, credit: AGI

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Preliminary Data Budget

Estimation of size of one target measurement packet:

Format	Size
Uncompressed	500 × 600 pixels × 100 channels 12 bits/(pixel × channel) = 360 Mb
Compressed (spectrally)	500 × 600 pixels × 20 components 24 bits/pixel = 144 Mb
Compressed (spectrally + JPEG2000)	500 × 600 pixels × 20 components 3 bits/pixel = 18 Mb

Format	Size	UHF/VHF-band 200 kb/s	S-band 2 Mb/s	X-band 10 Mb/s
Uncompressed	360 Mb	30 min	3 min	36 s
Compressed (spectrally)	144 Mb	12 min	1.2 min	14.4 s
Compressed (spectrally + JPEG2000)	18 Mb	1.5 min	9 s	1.8 s

- Attitude log information @ 100 Hz gives additional 1-2 MB
- Telemetry: 5 Mb

  → **Approx. 25 Mbit total**

- Time available for downlink: minimum 3 min available in one day with Ground station ε=30º

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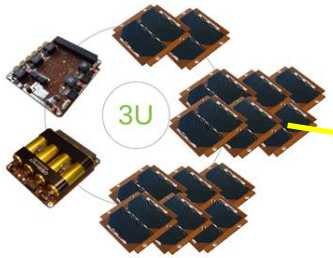
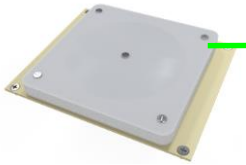
Potential Satellite Platform

- 3U CubeSat
- Flight Planner
- ADCS
  - Magnetorquers
  - Reaction wheels
  - Fine sunsensors
  - Gyroscope
  - Magnetometers
  - GPS
  - Star-tracker
- S-band patch antenna
- Linux/FreeRTOS
- CAN/I²C/SPI
- (SDR)
- CSP Routing



Solar panels + EPS + batteries

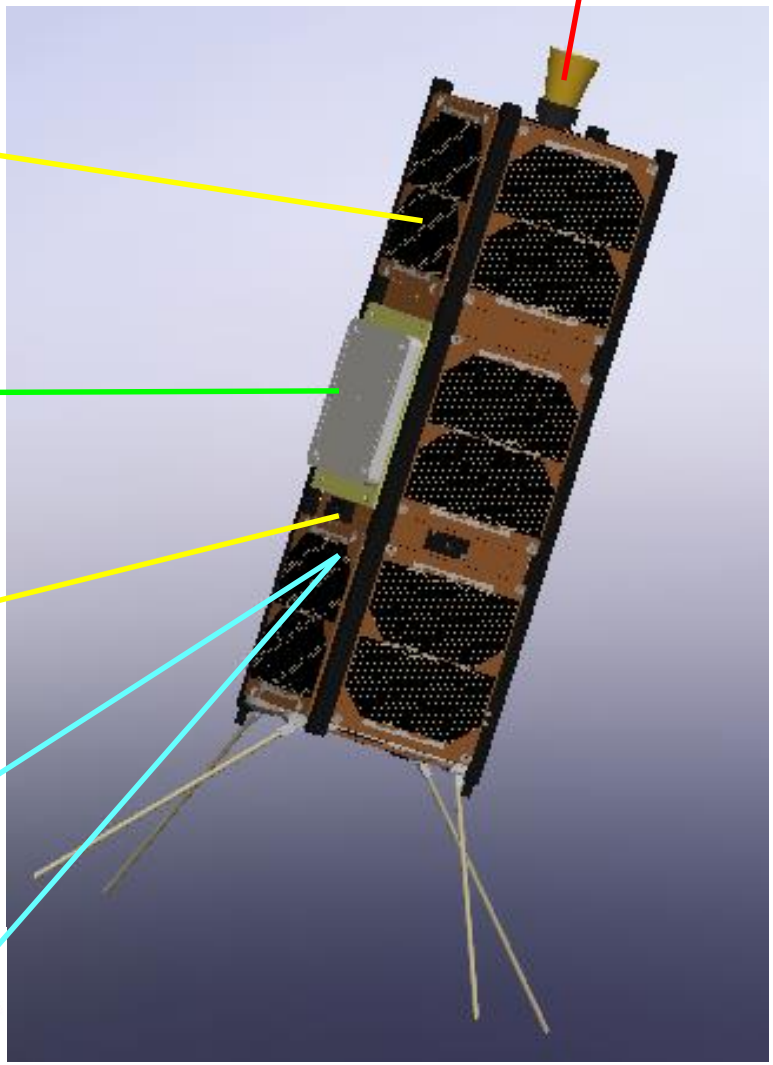

S-band antenna


Fine Sun Sensor


GPS


NanoDock ADCS-6


NanoCam C1U


Credit: Gomspace

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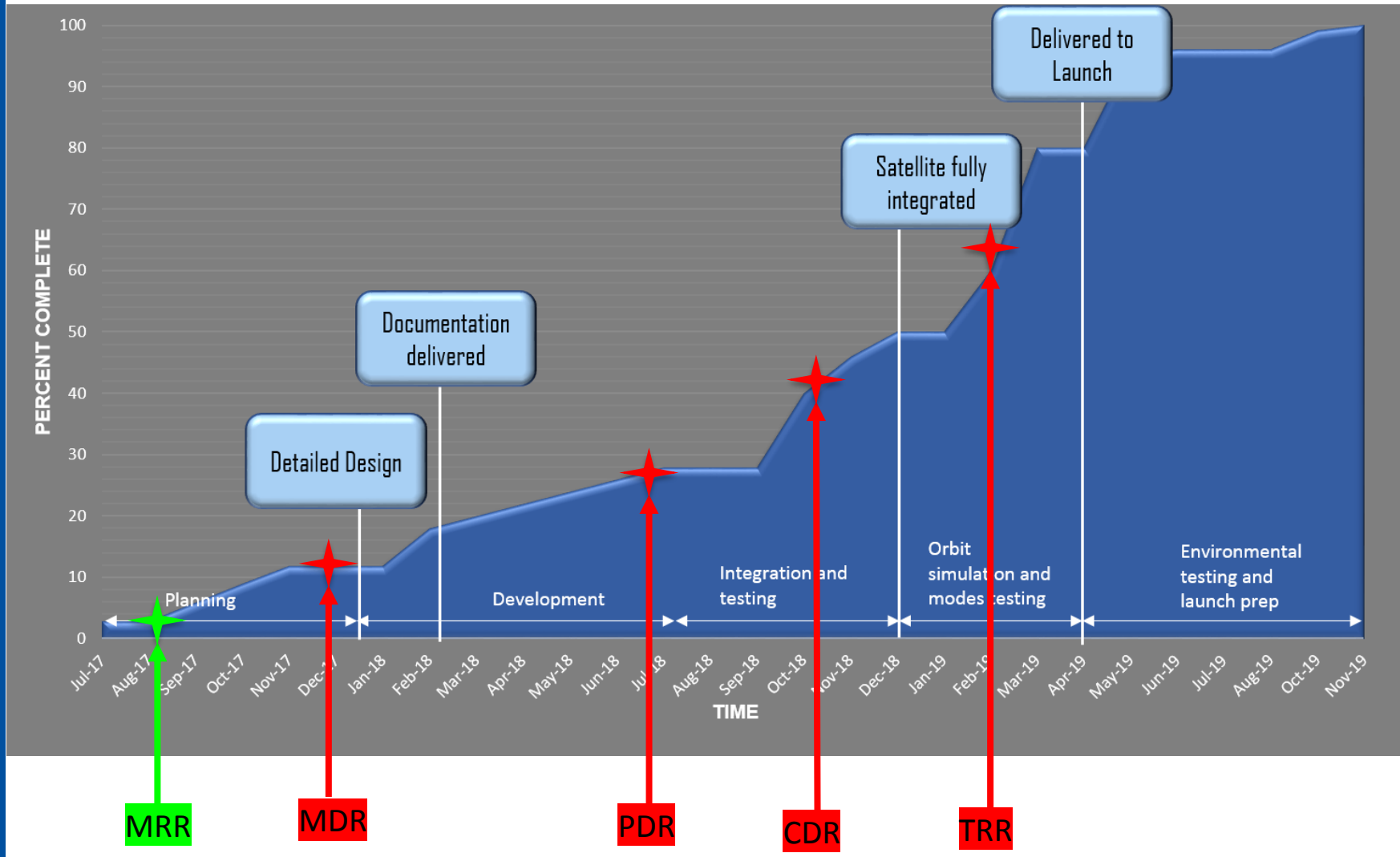
Verification, Validation and Testing



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NORSAT Satellite Series

- Norsat-1 (Operational)
  - AIS-payload
  - Langmuir probe for plasma measurements
  - Total solar irradiation instrument
  - S/C bus built by UTIAS SFL
- Norsat-2 (Operational)
  - AIS-payload
  - VDES communication payload to test two-way VHF communication for marine/shipping applications
  - S/C bus built by UTIAS SFL
- Norsat-3
  - Planned and “firm”, but currently little official info on its payload and platform.
- Norsat-4
  - Currently phase A study.
  - Our HIS and SDR-proposals will be evaluated as payload candidates.

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Conclusions & Future Work

- Currently on mission-design (Phase A)
  - Full architecture will be fully defined
  - Iteration on mission requirements
  - Feasibility studies on HSI payload and slew-maneuver studies
  - Thermal tests to be done (FEA and H/W)
  - Comms. architecture
  - Need to establish feasibility of viewing target at angles (do we get the desired signal?)
  - 6U/3U CubeSat?
- Mission Design Review on 15th December
- HSI payload for UAVs is to be integrated in SmallSat
- If first two missions are successful → a pipeline of SmallSats will support coordinated oceanographic observations.
  - Space segment shall provide higher temporal and spatial resolution.

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Collaborators

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Norsk Romsenter
NORWEGIAN SPACE CENTRE

AMES RESEARCH CENTER

NASA

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FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

UNIS
UNIS - The University Centre in Svalbard