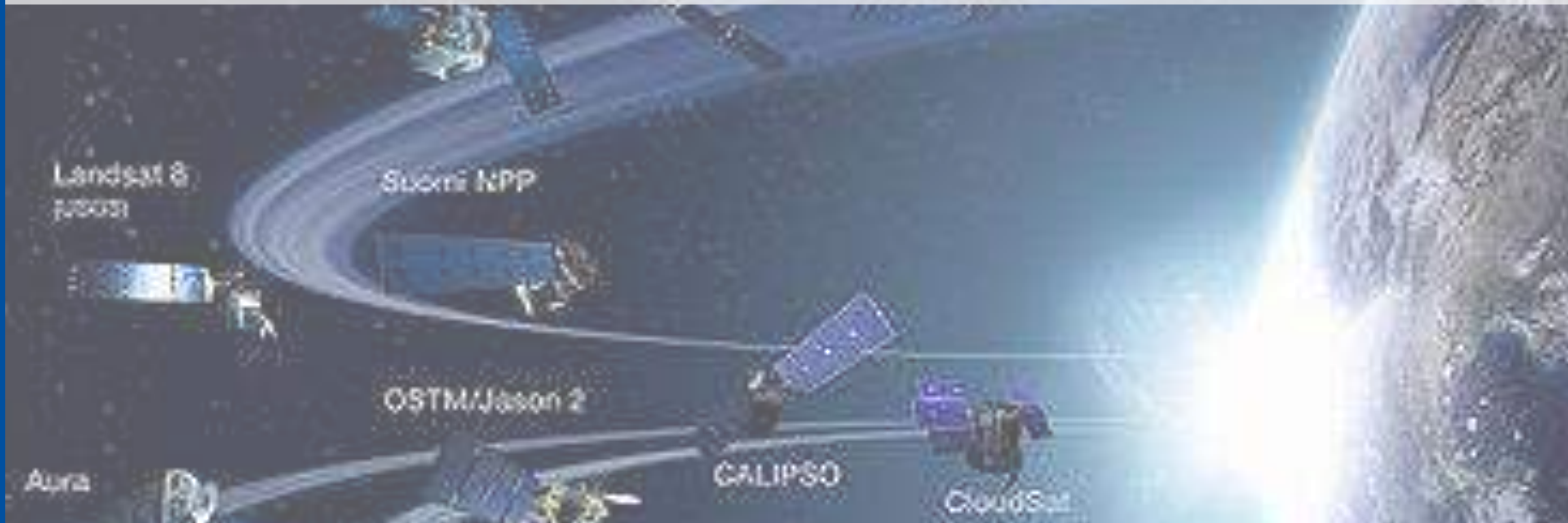
Mission Design Review –

NTNU SmallSat: a Hyperspectral imaging mission



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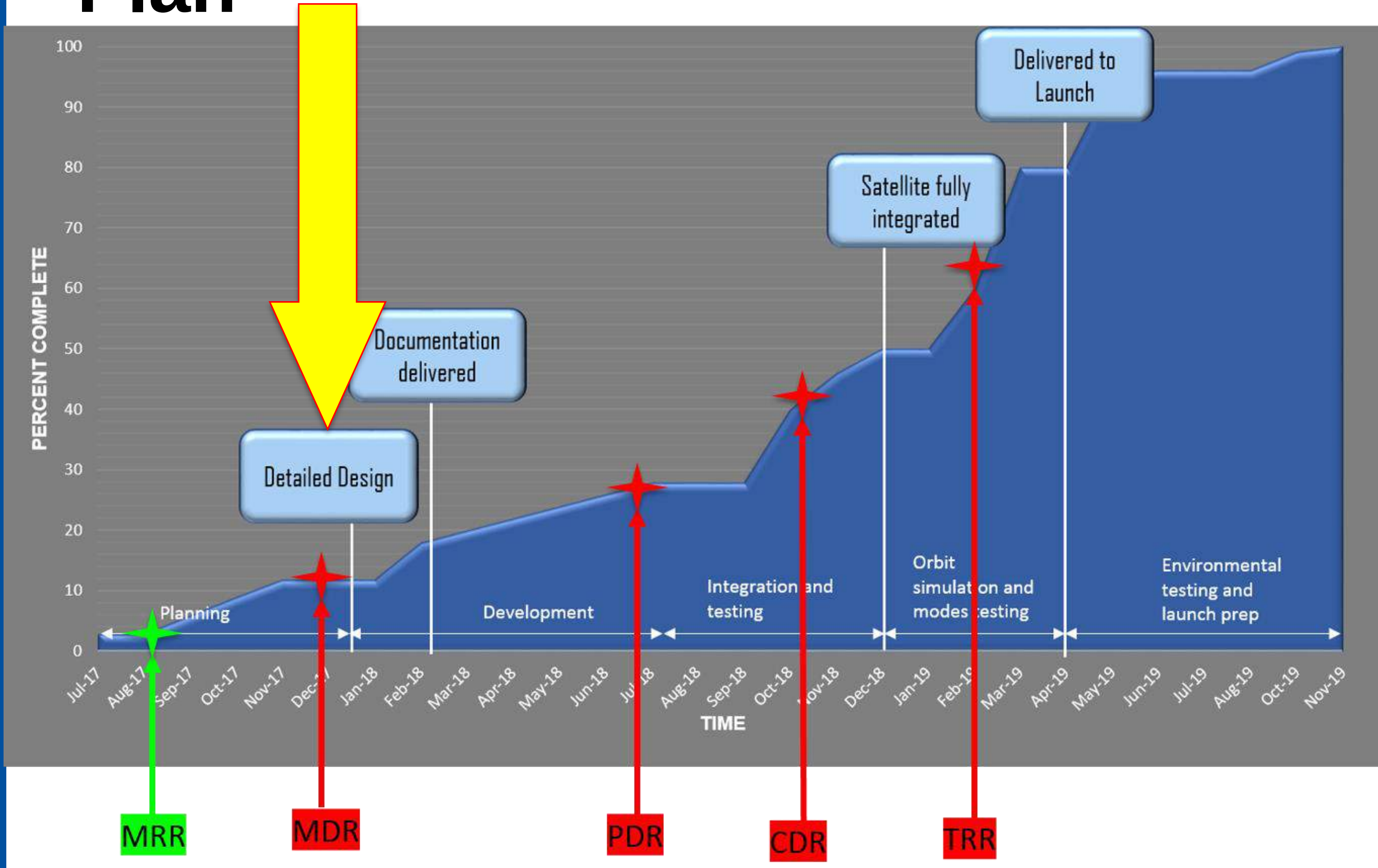
15/12/17

Plan


PERCENT COMPLETE
100
90
80
70
60
50
40
30
20
10
0
Delivered to Launch
Satellite fully integrated
Documentation delivered
Detailed Design
Planning
Development
Integration and testing
Orbit simulation and modes testing
Environmental testing and launch prep
Jul-17
Sep-17
Oct-17
Nov-17
Jan-18
Feb-18
Mar-18
Apr-18
May-18
Jun-18
Aug-18
Sep-18
Oct-18
Dec-18
Jan-19
Mar-19
Apr-19
May-19
Jun-19
Jul-19
Aug-19
Oct-19
Nov-19
TIME
MRR
MDR
PDR
CDR
TRR

Overview

- Science Objectives
  - Biology (species)
  - Locations
  - Sampling/Imaging Campaigns
- Technology Objectives
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  - Modeling
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  - Timeliness
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  - Link Budget
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  - Test pipeline
  - Calibration
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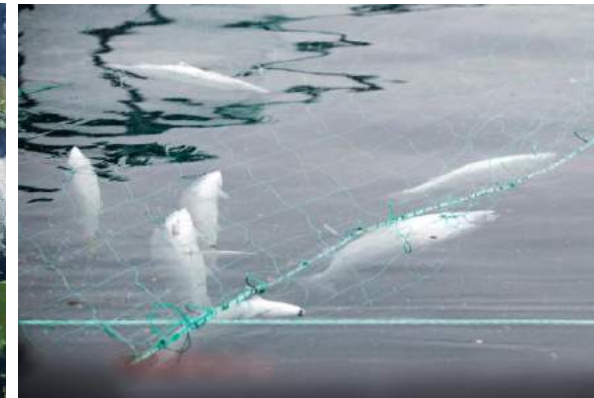
- Summary of proposals

Science Objectives

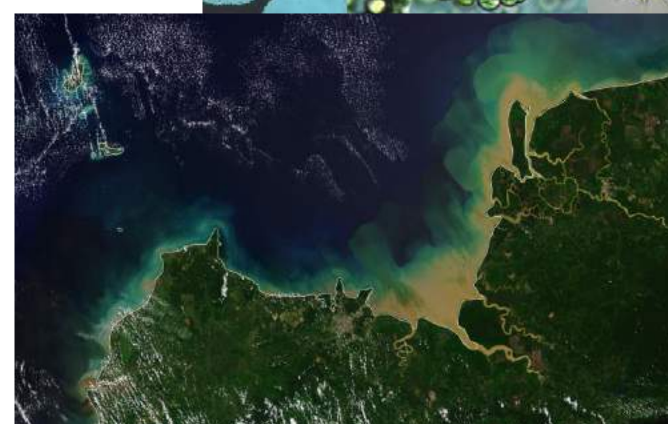
Background

- 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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Biology Available & Locations

Classes	Color	Location	Time of the year
Diatoms (mild)	Green-yellow	S to Mid-West Norway	March-June
Prymnesiophytes	Golden-Brown	All Norway	April-July
Raphidophytes/Dictyochophytes	Golden-Brown	South-West Norway	April-May
Cyanophytes (aka Cyanobacteria)	Reddish	Baltic/Skagerrak/South Norway	July-Sept
Species (Brown = TOXIC)	**Color**	**Probable Location**	**Time of the year**
Skeletonema Costatum	Golden-brown	Skagerrak	May-June
Chaetoceros convolutus	Golden-brown	Rogaland-Helgeland (S to N Norway)	March-April
Prymnesium Parvum	Golden	Hylsfjord in Ryfylke (S Norway)	July-August
Chrysochromulina polylepis	Brown	Skagerrak, W and Mid-Norway, Oster/Sørfjord	April-July
P. papilliferum	Golden	Hylsfjord in Ryfylke (South Norway)	July-August
Heterosigma akashiwo (raphidophyte)	Reddish	Osterfjord/Sørgjord (Bergen area)	April-May
Karenia mikimotoi (dinoflagellate)	Golden-brown	Skagerrak/Baltic	April-August
Karlodinium veneficum (dinoflagellate)	Golden-brown	Skagerrak/Baltic	April-August
Emiliania Huyxlei (very detectable)	Milky or brown	Along all Norwegian Coast	April-Sept
Pseudochatonella	Golden-brown	Baltic	April-August

Credit: Geir Johnsen et al. (1994)

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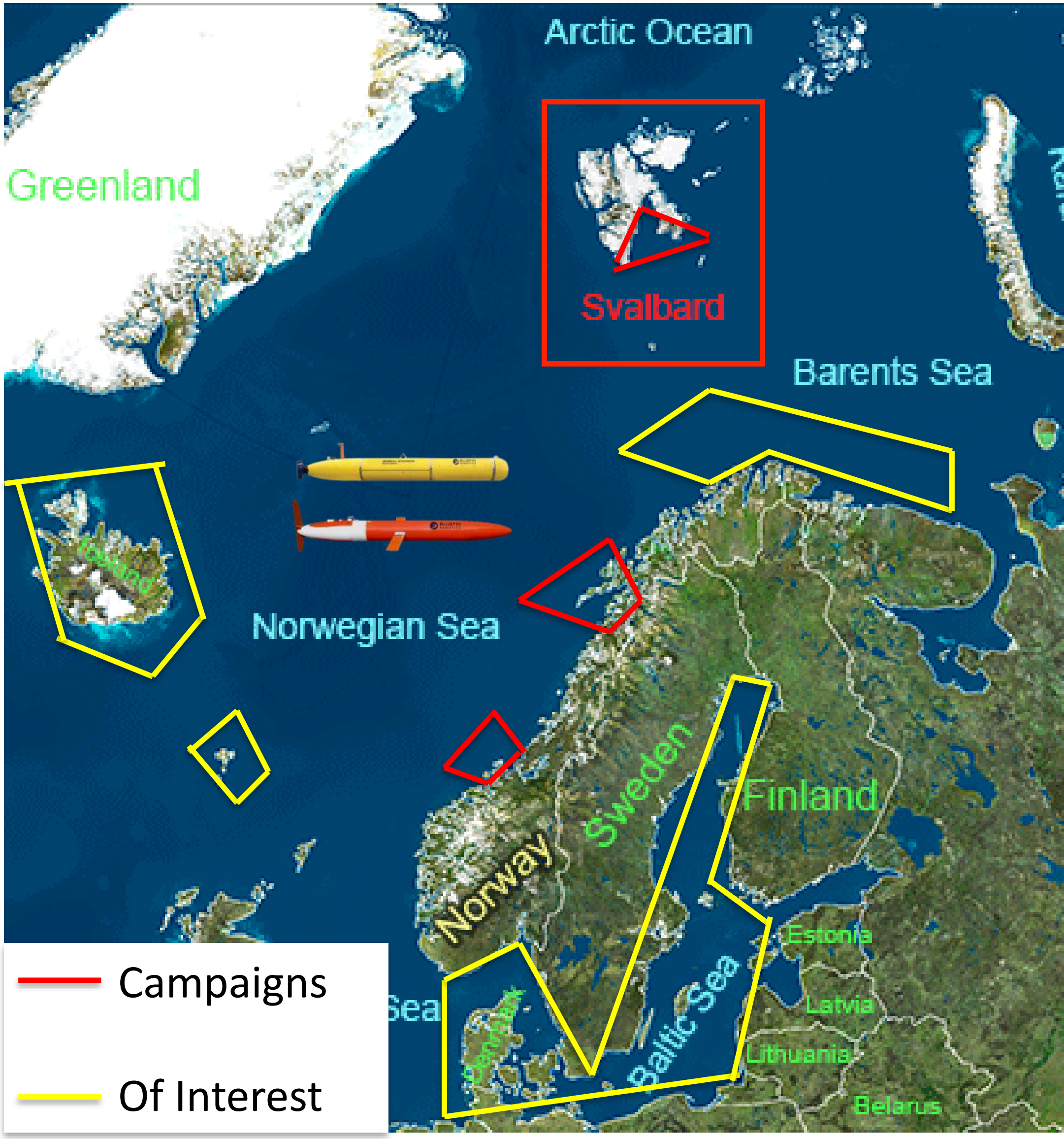
Science Requirements	
Biology	Shall detect with algal bloom and phytoplankton in Case 1 waters and 100x100 m^2 patches to determine chlorophyll-a, -b, -c3, -c4 concentrations
Biology	Detect algal blooms and phytoplankton in Case 2 waters and 100x100 m^2 patches to determine chlorophyll-a, -b, -c3, -c4 concentrations
Biology	Enable detection of HABs e.g. *Platymonas spp*., *Nitzschia closterium* and *Chlorella spp*. species at about 680-900 nm spectral range
Ocean Color	Detect other discolorations of oceans such as oil spills and river plumes
Ocean Color	If distinguishable, to detect fronts in fjords due to water and ocean currents (sun glint helps)
Ocean color	Enable flexibility of observing common phytoplankton concentrations skewing with spectra from 400-600 nm range to 600-700 nm range
Biology	Detect signatures below at least 2 m water depth
Biology	Able to detect bio-luminescent matter at night from space
Remote Sensing	Satellite shall cover main AUV campaigns in either Svalbard, Trondheim and at Frøya
Remote Sensing	In-situ validation of remote sensing data (sampling or fine-resolution) is necessary (with UAVs, USVs, AUVs, manual sampling)
Remote Sensing	Enable corrections for atmosphere, aerosols, air bubbles, sunglint, turbidity, diffracted second order light, water vapour, landscape distortions

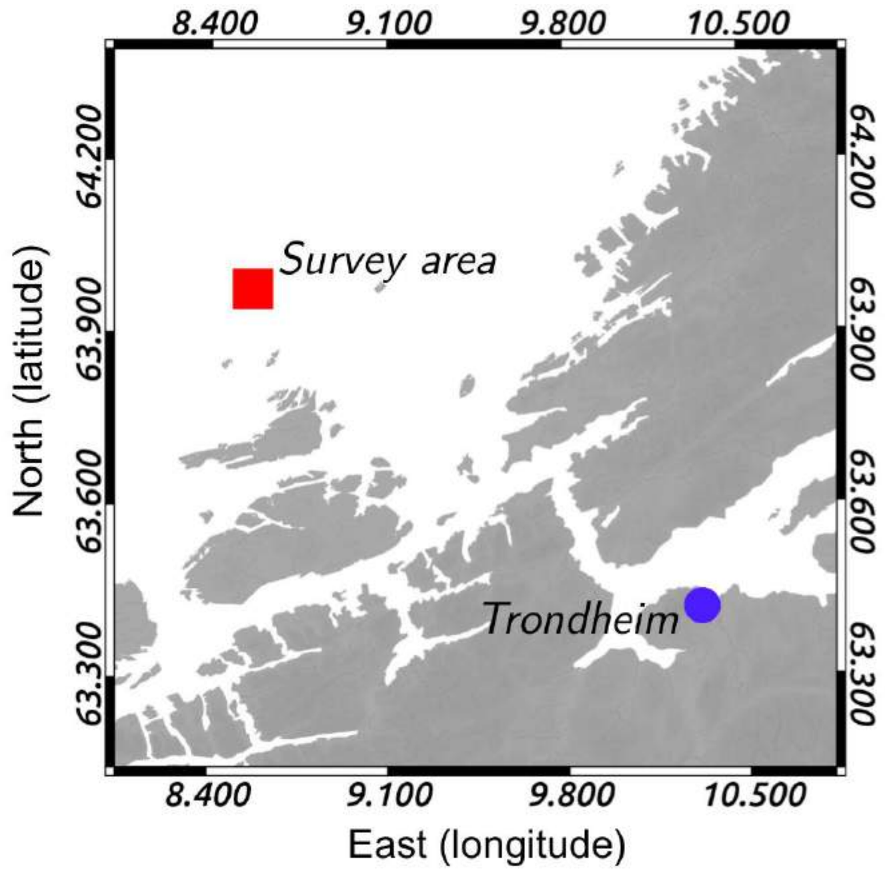
AUV Campaigns

- NTNU AUV Campaigns:
  - Frøya
  - Svalbard
  - Trondheimsfjord
  - Lofoten

- Interesting:
  - Barents Sea
  - Baltic
  - Faroe Islands
  - Iceland



AUV Campaigns



ENTiCE campaign. The project set out to map and understand the productive Frøyan archipelago.

Fronts & Internal Waves

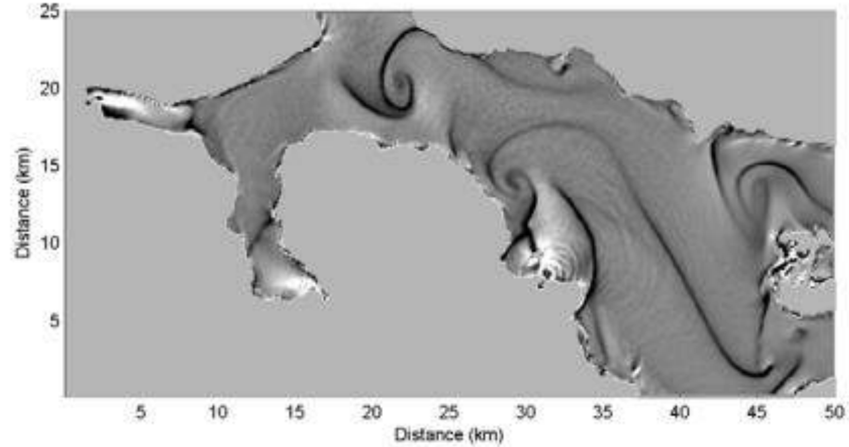
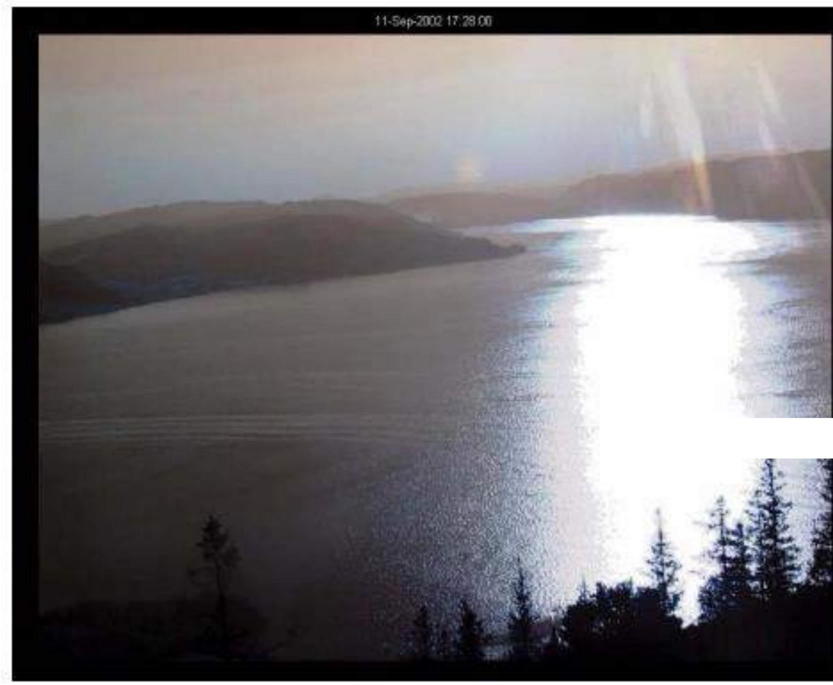


Figure 5.13 The surface horizontal divergence in the surface after 13 days.



Internal waves observed in the Cross Fjord, near the inlet of Gaulosen. The photo is

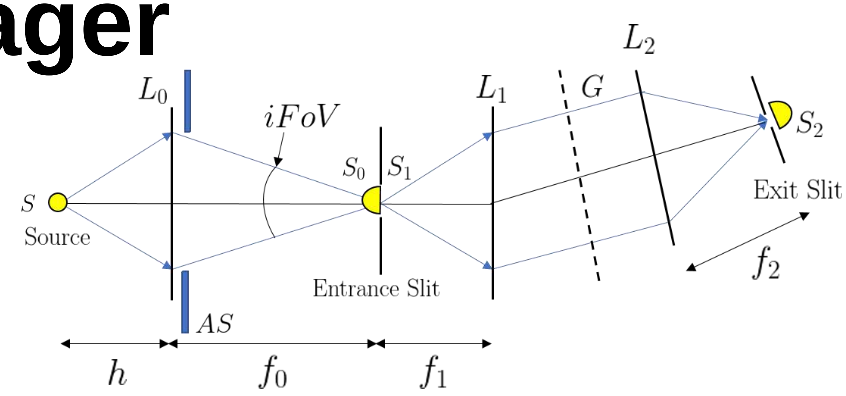
Credit: Ingrid Ellingsen (PhD Thesis, 2004)

Tech Demonstrator Objectives

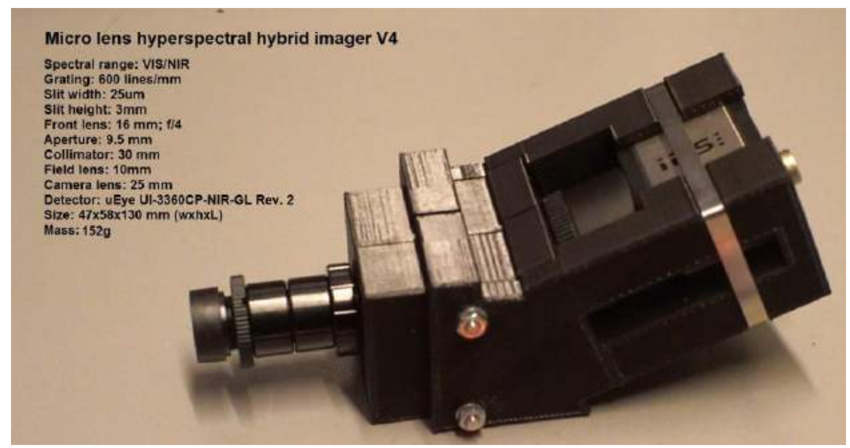
Hyperspectral Imager

HSI VERSION 4-1 SPECIFICATIONS

Spectral range	400-900 nm
Bandpass $\delta\lambda$	5 nm
Mass m	152 g
Size $w \times h \times L$	$47 \times 58 \times 130$ mm
$iFoV$	0.031°
Sampling	0.342 nm/pixel
Pixel size	5.5 μpixel
Binning	2×2
Grating	600 lines/mm
Usable bands	100
Sensor resolution	2048×1088 pixels
Number of effective pixels N	578 pixels
Dark current	125 e^-/s
Read-out noise (25 C°)	13 e^-



- Detector: uEye UI-3360CP-NIR-GL
- Slit: 25μmx 3 mm
- L0 front lens: f_0=16 mm; f/4 (flexible)



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

Requirements:

1. **Have to show *considerable* increase in spatial and spectral resolution for a small target area compared to existing space systems. GSD<50 m, Dx<300 m, DLambda=<5 nm**
2. **Onboard Processing (operational data) downlinked quickly**
3. **Autonomous coordination of systems for observation (comms.)**

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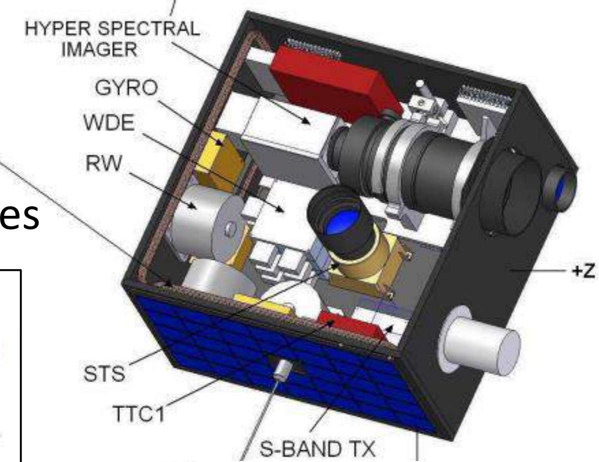
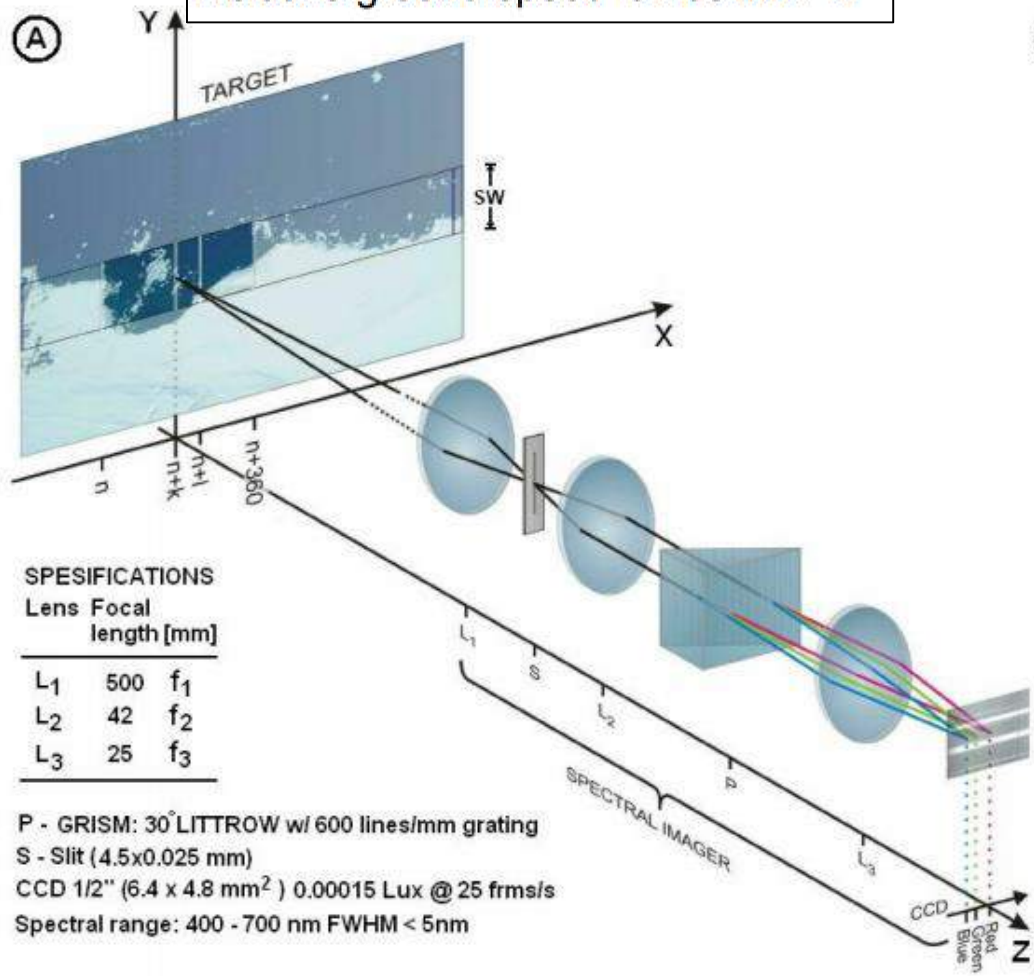
SVALBIRD

Credit: Fred Sigernes



Z = 700 km : Δx = 35.5 m Δy = 48.5
SW = 6.4 km with 500 mm telescope

Relative ground speed is 200 km / hr



Mission Requirements

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Mission Objectives

- Primary:
  - To provide real-time coastal ocean color mapping through Hyper-Spectral Imager (HSI) payload and on-demand autonomous coordination in a concert of robotic agents in vicinity of the Norwegian coast.
- Secondary:
  - Demonstrate competitive efficiency of HSI
  - Deliver scientific products to remote sensing, oceanography and biology communities
  - Monitor and predict dynamics of Harmful Algal Blooms (HABs) and prevent damage to fish farms
  - Monitor & track ground stations & vehicles and downlink data to ground autonomously
  - Demonstrate novel theory-to-practice optimal energy management and pointing control during slew maneuver in orbit
  - Build strong competence on and strengthen prospect of nano- and micro-satellite systems as supporting intelligent agents in integrated autonomous robotic systems for dedicated marine and maritime applications.
  - Describe the scientific methodology that will be adopted for the research, and coordinate the project plans with other ongoing research activities and NTNU and with engineering and scientific collaborators.

Mission Requirements

Level 0 mission statement

NTNU SmallSat mission will demonstrate proof-of-concept ocean color 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 30 x 30 km in an envelope of 100 km, in the Atlantic ocean
- Shall identify and track a ocean target area with 3 passes per day with 1 pass being direct overhead with >30 s 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 in approx. 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 3 months after deployment

- Sampling of target area shall not deviate more than 3.33 % error of 100 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 = 2 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 400-900 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 10:1
- Shall avoid clouds, saturation effects and sunglint

- Mission data shall be downlinked in max. 1 orbit after mission operations with >8 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 1 hr
- Space segment shall enable updates on mission planning
- Space segment shall support re-scheduling of planned events by ground command

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Operational Requirements & Constraints

Level 2 mission requirements

- Must enable initial mission plan update to start space segment operations and detumble with active control of magnetic field and gravity
- Shall enable sleep on/ off during on/ off HSI demands autonomously and on command

- S/C shall be in sun-synchronous orbit at h<550 km altitude, inclination of i<98 deg
- S/C shall have right ascension of ascending node Ω=80-110 deg or 250-290 deg
- Target shall be observed at approx. 60 deg N and 10 deg E
- Target area shall be mapped by push-broom scanning along-track and cross-track

- S/C shall enable <0.01 degrees relative pointing precision (2 sigma)
- Slew maneuver shall be prepared for and enabled 2 min prior to observing operations with slew rate of about 0.8 deg/s
- Shall point +20 deg to -20 deg from Nadir along-track with <1 deg/s pitch rate
- Avoidance of cloud cover and shadowing shall be enabled with flexible attitude control

- Must enable Ground Sampling Distance of GSD < 100 m to achieve at least effective spatial resolution of Δx<100 m through post-processing algorithms
- Shall utilize GPS for tracking, antenna pointing, slewing maneuver and image calibration
- Corrections for atmospheric distortions, turbidity, clouds shall be enabled for observations of target area with 750-1000 nm (NIR) bands
- Shall enable fine orbit & attitude knowledge for image calibration and discard non-valid pixels with 1 sigma deviation off the constraints for target area sampling errors
- Shall have Δx < 300 m and swath width of 30 km

- Shall enable downlinking data of <60 Mb spatially & spectrally compressed data and in 3 orbits
- Space segment shall support off/on payload operations during off-demand on command or observing hinderance autonomously
- Shall downlink data at least 1 Mb/s

- S/C must enable sleep during pass in South Atlantic Anomaly for 10 min
- Space segment shall support re-scheduling of planned events by ground command at e.g. target area coordinates, elevation, slant angle, slew rate
- Mission and orbit shall adhere to launch windows in spring or summer season and not deviate from observing primary objective with less than 3 weeks

Constraints (see later)

- Money
- Manpower
- Time
- Launch window
- Payload development
- Space policy

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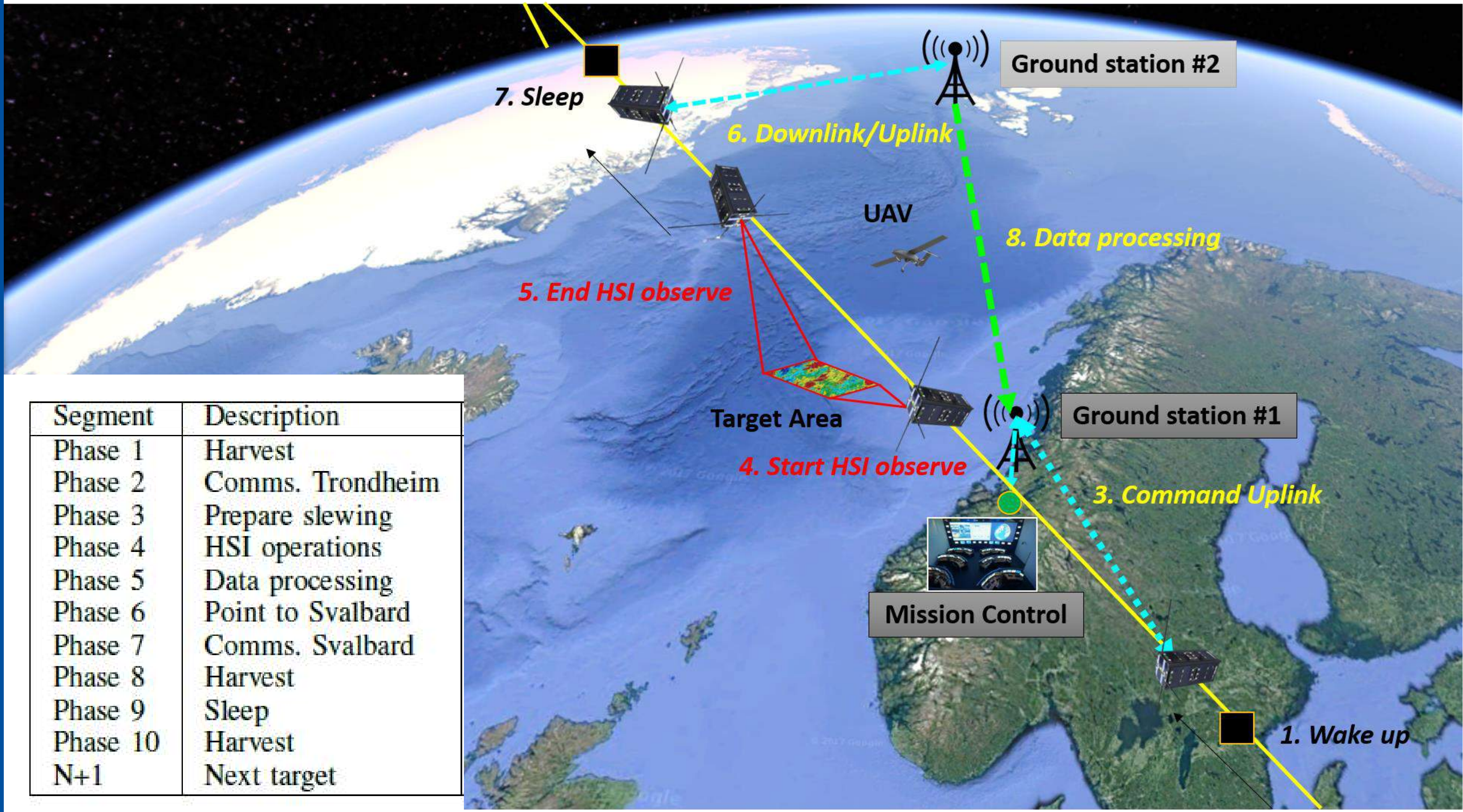
Concept of Operations

CONOPS 1 (DayTime Launch)



Segment	Description
Phase 1	Harvest
Phase 2	Comms. Trondheim
Phase 3	Prepare slewing
Phase 4	HSI operations
Phase 5	Data processing
Phase 6	Point to Svalbard
Phase 7	Comms. Svalbard
Phase 8	Harvest
Phase 9	Sleep
Phase 10	Harvest
N+1	Next target

*South-North Pass. 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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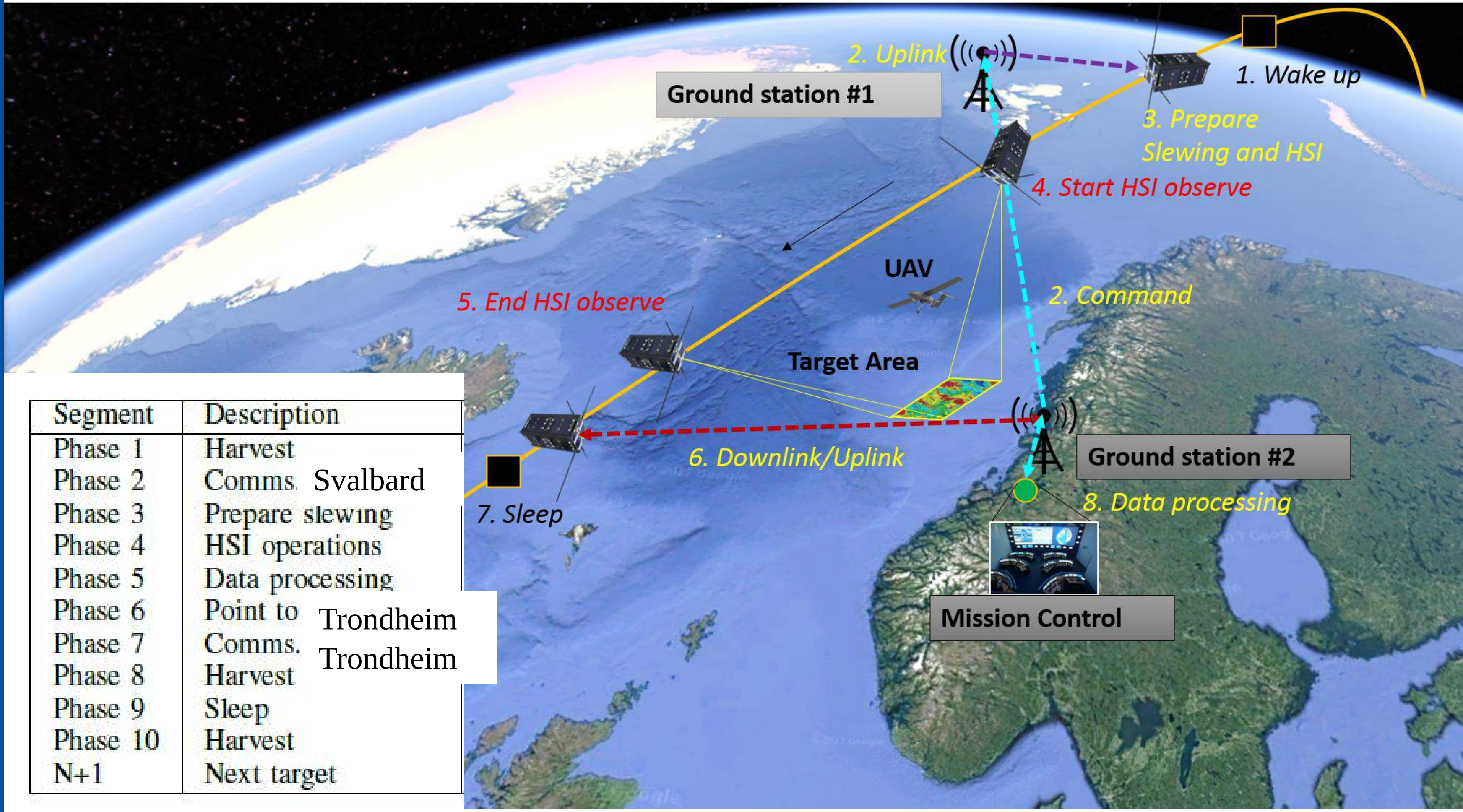
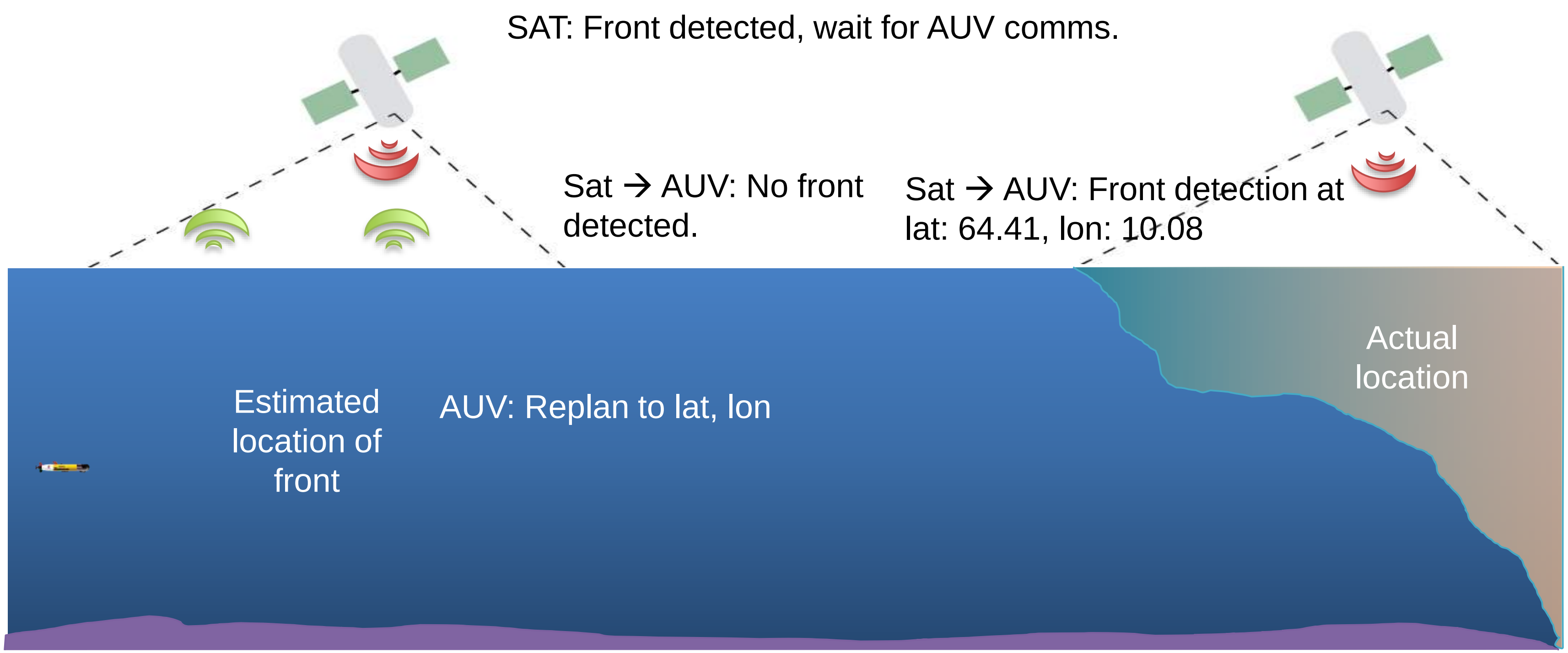
CONOPS 2 (NightTime Launch)



Segment	Description
Phase 1	Harvest
Phase 2	Comms. Svalbard
Phase 3	Prepare slewing
Phase 4	HSI operations
Phase 5	Data processing
Phase 6	Point to Trondheim
Phase 7	Comms. Trondheim
Phase 8	Harvest
Phase 9	Sleep
Phase 10	Harvest
N+1	Next target

*North-South pass. 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.*

Example: Adaptive and Data-Driven AUV – Satellite networked operations



Mission Architectures

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Details in excel spreadsheet

Mission Elements

Orange means changes to nominal

MISSION ELEMENT OPTIONS

Element	Option
A1	HSI mapping of the ocean; autonomous onboard processing of mission data, then transmitted after pass; ground commands on mission plan.
A2	HSI mapping of the ocean; autonomous onboard processing of mission data, then transmitted after pass; ground commands on mission plan; updates to other robotic agents.
A3	HSI mapping of the ocean; semi-raw downlinked mission data, then post-processed; ground commands on mission plan.
A4	HSI mapping of the ocean; semi-raw downlinked mission data, then post-processed; ground commands on mission plan; if satellite sees interesting signature → send out other air/surface agents directly
A5	HSI mapping of the ocean; autonomous onboard processing of mission data, then transmitted after pass; ground commanding on mission plan; autonomous coordinated robotic multi-agent observations
B1	No agents tracked from space
B2	Multi-agent targets tracked: USVs, UAVs, Ships, Buoys
C1	Oceanography through Hyperspectral imaging
D1	Small aperture HSI
D2	SDR
E1	2-6U size; 3-axis stabilization; spacecraft pointing; body-mounted solar panels; onboard GPS; onboard orbit control; ~~possibly micro propulsion~~
F1	SSO; 1-satellite
F2	(P)LEO; 1-satellite
~~G1~~	~~PSLV or Soyuz 9 (highly tradeable)~~
H1	Dedicated: NTNU; Commercial (e.g. KSAT)
I1	Store & dump data; TM/TC-transceiver; ≥2 ground stations; UHF-band uplink, X-band downlink
I2	Store & dump data; TM/TC-transceiver; ≥2 ground stations; UHF-band uplink, S-band downlink
I3	Store & dump data; TM/TC-transceiver; ≥2 ground stations; S-band uplink, X-band downlink
I4	Store & dump data; TM/TC-transceiver; ≥2 ground stations; S-band uplink, S-band downlink
I5	Store & dump data; TM/TC-transceiver; ≥2 ground stations; UHF-band uplink, X-band downlink; multi-agent cross-links in VHF/UHF
I6	Store & dump data; TM/TC-transceiver; ≥2 ground stations; UHF-band uplink, S-band downlink; multi-agent cross-links in VHF/UHF
I7	Store & dump data; TM/TC-transceiver; ≥2 ground stations; S-band uplink, X-band downlink; multi-agent cross-links in VHF/UHF
I8	Store & dump data; TM/TC-transceiver; ≥2 ground stations; S-band uplink, S-band downlink; multi-agent cross-links in VHF/UHF
J1	Fully automated ground stations; part-time operations on demand; Indirect updates on mission to/from other agents
J2	Fully automated ground stations; part-time operations on demand; Direct updates on mission to/from other agents

Compatible only with 6U

Rank	Mission Architecture
1	A3-B1-C1-D1-E1-F1-G1-H1-I2-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

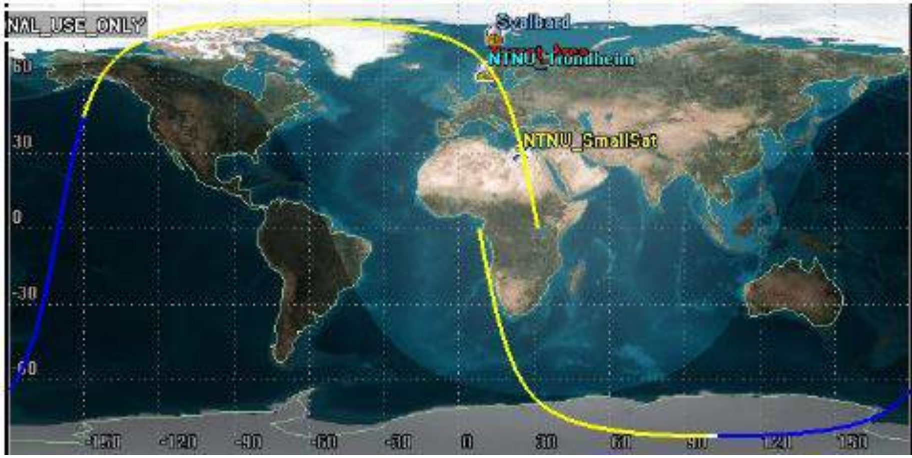
How chosen?

Mission Elements	System Driver 1	System Driver 2	System Driver 3	System Driver 4	System Driver 5	System Driver 6
A. Mission Concept	**Concept Complexity**	**Oceanography**	Lifetime	Comms. Power	**Cost**	**Mission Reliability**
B. Controllable Subjects	Concept Complexity	Oceanography	Lifetime	Comms. Power	Cost	**Mission Reliability**
C. Passive Subject	Concept Complexity	**Oceanography**	Lifetime	Comms. Power	Cost	**Mission Reliability**
D. Payload	Concept Complexity	**Oceanography**	Lifetime	Comms. Power	**Cost**	**Mission Reliability**
E. Spacecraft Bus	Concept Complexity	Oceanography	**Lifetime**	**Comms. Power**	**Cost**	**Mission Reliability**
F. Orbit	Concept Complexity	**Oceanography**	**Lifetime**	Comms. Power	**Cost**	**Mission Reliability**
G. Launch System	Concept Complexity	Oceanography	Lifetime	Comms. Power	**Cost**	Mission Reliability
H. Ground System	Concept Complexity	Oceanography	Lifetime	**Comms. Power**	**Cost**	**Mission Reliability**
I. Communications Architecture	Concept Complexity	Oceanography	Lifetime	**Comms. Power**	**Cost**	**Mission Reliability**
J. Mission Operations	Concept Complexity	**Oceanography**	Lifetime	Comms. Power	Cost	**Mission Reliability**

	Ratings here are 1-10, where 10 is the best. Note E1 and G1 do not have an impact yet	Complexity	Oceanography	Lifetime	Comms. Power	Cost	Mission Reliability	Weather Dependence	Design Sensitivity	Redundancy	Data Rate	Data Availability
A1	HSI mapping of the ocean with autonomous on-board processing of mission data, then transmitted after pass. Ground commands on mission plan.	8	6			6	8			5		9
A2	HSI mapping of the ocean with autonomous on-board processing of mission data, then transmitted after pass. Ground commands on mission plan. Updates to other robotic agents through mission control	6	7			5	8			8		9
A3	HSI mapping of the ocean with semi-raw downlinked mission data, then post-processed. Ground commands on mission plan.	10	6			6	9			5		8
A4	HSI mapping of the ocean with semi-raw downlinked mission data, then post-processed. Ground commands on mission plan. If satellite sees signature -> send out other agents directly	5	8			6	10			9		8
A5	HSI mapping of the ocean with autonomous on-board processing of mission data, then transmitted after pass. Ground commanding on mission plan. Fully autonomous coordinated robotic multi-agent observation with model update on-board S/C	5	9			3	10			10		10
B1	No agents except for space segment						5			5		
B2	Multi-agent targets: USVs, UAVs, Ships, Buoys						10			10		
C1	Oceanography through Hyperspectral light		10				8	3				
D1	Small aperture HSI		10			7	5	3	2		5	
E1	2-6U size; 3-axis stabilization; spacecraft pointing; body-mounted solar panels; onboard GPS; onboard orbit control; possibly micro-propulsion			0	0	0	0		0	0		

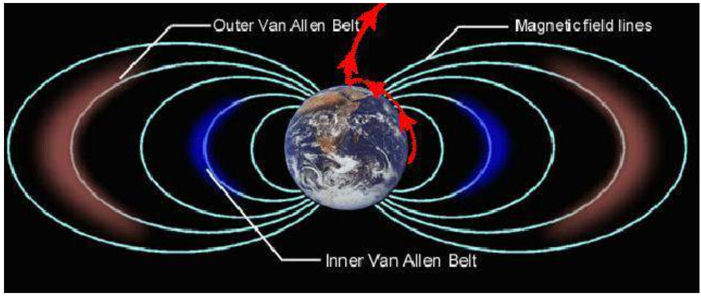
Orbit Analysis

Orbit Characteristics



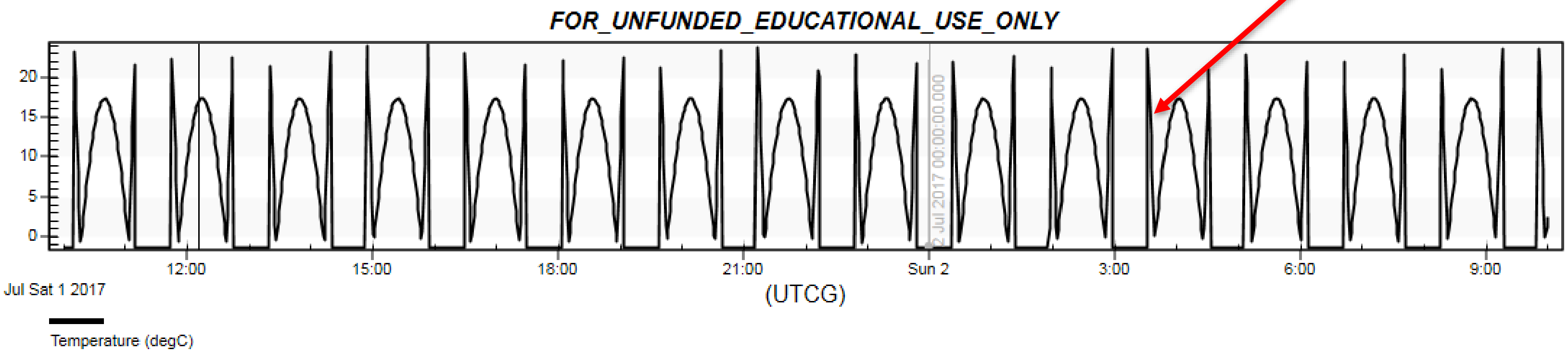
Parameter	Definition
Type	Sun-Synchronous
Altitude	500 km (450-550 km)
Semi-major axis	6878 km
Revisits to 1 Target	3
Inclination	97.31 deg
RAAN	83.3 or 228.3 deg (80-110 deg or 250-280 deg)
Repeat Cycle	6.91 days (107 cycles/day)
Orbital Period	95 min 39 s
Drift (Drag, SRP, gravity)	±100 m/day
Penumbra & Umbra	30 % of orbit

Space Environment

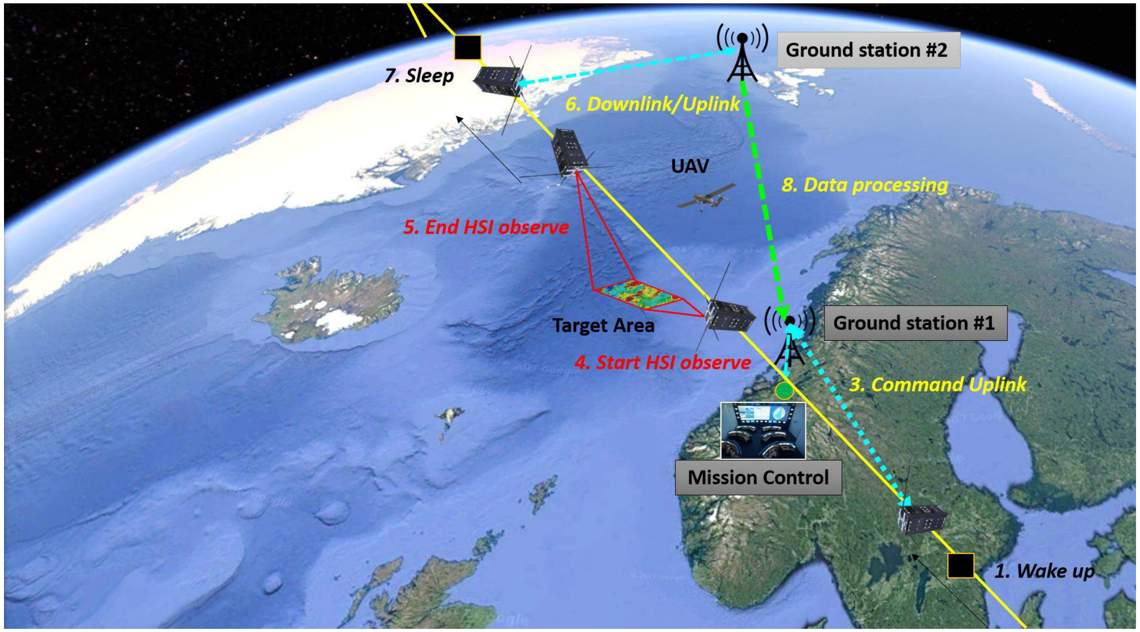


- S/C must survive for up to 3 years
- Thermal effects
  - All elements must sustain thermal gradients.
  - Data from other missions suggests that we can expect +20 C during sun illumination and -20 C during eclipse. The needed orbit will have around 30 min eclipse for every pass.
  - Terminators are of interest with gradients of 30 deg/s
- Radiation effects (TBD)
  - Total dose: 10kRad(=100Gy) or higher.
    Dose rate: 0.01 Gy/s or lower (ISO19683:2017(E))
- Impacts:
  - Bit flips
  - Optics & sensor performance degradation
    - Shot noise
    - Dark pixels
    - Optical efficieny (lamination)
    - Loss of focus (tolerances off)

Requirement: Determine tolerances and material that meets the thermal gradient loads at Sun terminator



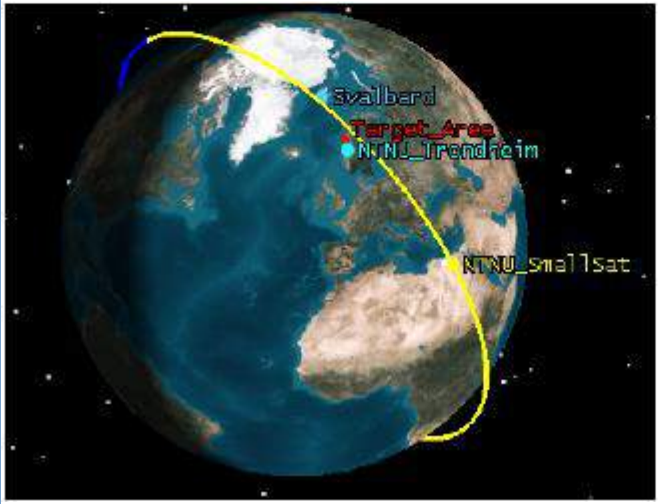
Mission Phases (Concept 1)



Segment	Description	Start (UTC)	Duration (s)
Phase 1	Harvest	09:37:10	5
Phase 2	Comms. Trondheim	09:37:15	125
Phase 3	Prepare slewing	09:39:20	115
Phase 4	HSI operations	09:41:15	54
Phase 5	Data processing	09:42:09	74
Phase 6	Point to Svalbard	09:43:25	20
Phase 7	Comms. Svalbard	09:43:45	270
Phase 8	Harvest	09:48:15	605
Phase 9	Sleep	09:59:20	2207
Phase 10	Harvest	10:36:07	2255
N+1	Next target	11:13:42	373

Concepts Revisited

Concept 1: RAAN=83.3 deg



REVISITS PER DAY (22 JUN 2020 07 AM - 23 JUN 2020 07 AM).
OBSERVER: NTNU TRONDHEIM WITH $\epsilon = 10°$, TOT. # OF PASSES: 6

Start-time (UTC)	Duration (min)
08:06:09	5.042
09:37:55	7.196
11:12:36	5.320
22:26:03	5.692
23:59:00	7.156
01:33:01	4.695
Max Duration	**7.196**
Min Duration	**4.695**

REVISITS PER DAY (22 JUN 2020 07 AM - 23 JUN 2020 07 AM).
OBSERVER: LONGYEARBYEN, WITH $\epsilon = 10°$, TOT. # OF PASSES: 10

Start-time (UTC)	Duration (min)
08:07:47	7.253
09:41:38	6.876
11:16:32	5.386
20:48:47	3.490
22:21:54	6.164
23:55:22	7.127
01:28:49	7.218
03:02:06	6.954
04:35:09	6.810
06:08:03	6.986
Max Duration	**7.253**
Min Duration	**3.490**

Concept 2: RAAN = 228.3 deg

REVISITS PER DAY (28 APR 2020 07 AM - 29 APR 2020 07 AM).
OBSERVER: NTNU TRONDHEIM WITH $\epsilon = 10°$, TOT. # OF PASSES: 6

Start-time (UTC)	Duration (min)
07:51:41	4.9
09:24:21	7.2
10:58:12	5.35
17:06:41	2.31
18:36:59	6.69
20:10:16	6.8
Max Duration	**7.21**
Min Duration	**2.31**

REVISITS PER DAY (28 APR 2020 07 AM - 29 APR 2020 07 AM).
OBSERVER: LONGYEARBYEN, WITH $\epsilon = 10°$, TOT. # OF PASSES: 10

Start-time (UTC)	Duration (min)
07:47:17	5.90
09:20:44	7.05
10:54:11	7.24
12:27:30	7.00
14:00:35	6.81
15:33:30	6.94
17:06:30	7.21
18:40:01	7.14
20:14:24	6.23
21:50:07	3.66
Max Duration	**7.24**
Min Duration	**3.66**

NTNU

Concepts Revisited: Observable Targets

Concept 1

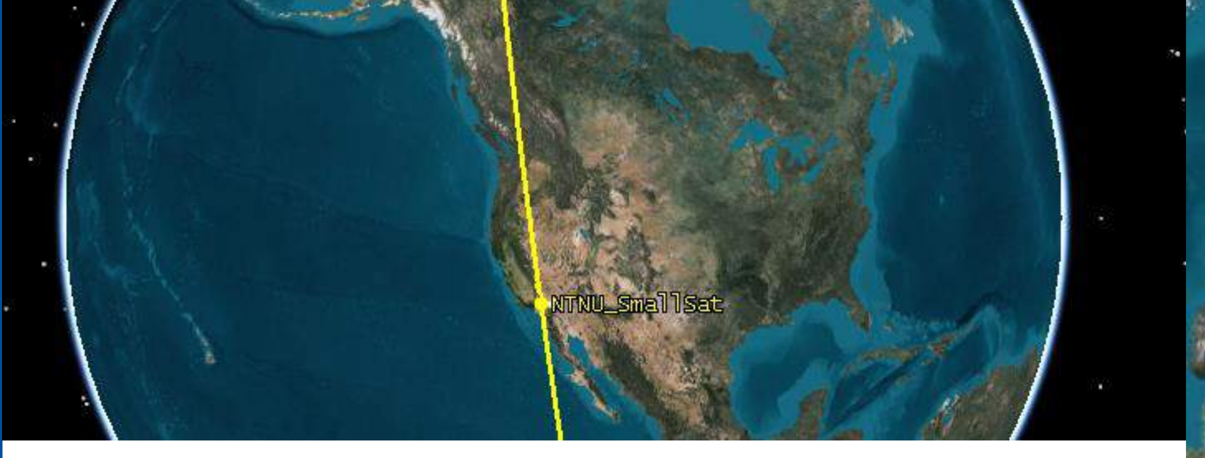
South-North Pass Observations on 22 June

#	Time (UTC)	Options	Ground Stations
1	08:09:00	Svalbard; Barents Sea; Trondheim (1st)	Svalbard (DOWN); Trondheim (UP)
2	09:39:10	Trondheim (2nd); Froya; Lofoten; Baltics; Svalbard	Svalbard (DOWN); Trondheim (UP); Porto (DOWN/UP)
3	10:51:20	Iceland; Faroe Islands; South Africa; Trondheim (3rd); Ireland; UK	Svalbard (DOWN); Trondheim (UP); Porto (UP)
4	12:40:00	West Africa; Iceland; Greenland	None
5	15:57:00	Lake Hudson	None
6	17:21:19	Mexico Gulf	None
7	18:59:00	Monterey Bay, CA	NASA Ames

Concept 2

North-South Pass Observations on 28 April 2020

#	Time (UTC)	Options	Ground Stations
1	07:51:30	Barents Sea; South Africa	Svalbard (UP); Trondheim (DOWN)
2	09:25:55	Svalbard; All Norway; Denmark	Svalbard (UP); Trondheim (DOWN)
3	11:02:30	Iceland; Faroe Islands; Azores (PT); Ireland; UK	Svalbard (UP); Porto (DOWN)
4	15:46:10	Lake Hudson	None
5	17:26:00	Monterey Bay	NASA Ames



Probability of Detection (Frøya)

Date (10:00 AM)*	Weather Conditions	Detection chance
1. April	Rainy, some sunshine	Low (<5 %)
2. April	Rainy	No chance (<1 %)
3. April	Cloudy	No chance (<1 %)
4. April	Rainy	No chance (<1 %)
5. April	Cloudy, some sunshine	Low (<5 %)
6. April	Rainy	No chance (<1 %)
7. April	Cloudy, some sunshine	Low (<5 %)
22. April	Cloudy, some sunshine	Low (<5 %)
23. April	Snow, some sunshine	Low (<5 %)
24. April	Sunny, some clouds	Medium (<10 %)
25. April	Sunny, some clouds	Medium (<10 %)
26. April	Rainy	No chance (<1 %)
27. April	Sunshine, some clouds	Medium (<10 %)
28. April	Sunshine, a few clouds	Medium (<15 %)

*Summer: higher chance of sunshine, but lower chance of detecting blooms
Data obtained from https://www.yr.no/

NTNU

Orbit 1 vs. Orbit 2

Elements	Pros/Cons	
	Orbit 1	Orbit 2
Operations Risk	+ (more uplink control at NTNU)	+ (more downlink control at NTNU)
Launch	+ (Available)	- (Not very available)
Coverage	+ (More available to Trondheim)	+ (In average a bit better)
Revisits to one Target	+ (3)	- (2)
# Targets	+ (More targets)	- (Dedicated to Norway)
Observing Norway	- (Passes Norway 3 times with good coverage)	+ (Fully available in one pass, Passes Norway 3 times, where 1 is great)
Constellation	+ (Easier for constellation of SmallSats)	- (Hard due to Launch)
Probability of detection	- (More dedicated)	+ (Higher probability in spring/summer)
SUM	**3**	**2**

Yellow: Critical (factor 2x)

Launchers

DETAIL	CONTAINERIZED			SATELLITE CLASS							
PAYLOAD TYPE	3U	6U	12U	50kg	100kg	150kg	200kg	300kg	450kg	750kg	1000kg
LENGTH (CM)	34.05	34.05	34.05	80	100	100	100	125	200	300	350
HEIGHT/DIA (CM)	10	10	22.63	40	50	60	80	100	150	200	200
WIDTH (CM)	10	22.63	22.63	40	50	60	80	100			
MASS (KG)	5	10	20	50	100	150	200	300	450	750	1000
PRICE-LEO	$295	$545	$995	$1,750	$3,950	$4,950	$5,950	$7,950	$17,500	$22,000	$28,000
PRICE-GTO	$915	$1,400	$2,750	$4,600	$8,400	$9,800	$11,200	$14,000	CALL	CALL	CALL

Pricing in thousands (USD)

NTNU

LAUNCH DETAIL			SATELLITE SIZE & AVAILABILITY							INQUIRE
Date	Orbit	Type	Cubesats	50kg	100kg	150	200kg	300kg	300kg+	Inquire
Q2 2018	450-500km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE
Q2 2018	550km SSO	Foreign	●	●	●	●	●	●	●	INQUIRE
Q2 2018	630km SSO	Foreign	●	●	●	●	●	●	●	INQUIRE
Q2 2018	220-420km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE
Q2 2018	450km SSO	Foreign	●	●	●	●	●	●	●	INQUIRE
Q2 2018	460km 45°	Foreign	●	●	●	●	●	●	●	INQUIRE
Q3 2018	550km SSO	Foreign	●	●	●	●	●	●	●	INQUIRE

Q4 2018	450-500km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖
Q4 2018	536km SSO	Foreign	●	●	●	●	●	●	●
Q1 2019	220-420km 52.6°	Foreign	●	⊖	⊖	⊖	⊖	⊖	⊖
Q2 2018	500km SSO	USA	●	⊖	⊖	⊖	⊖	⊖	⊖

Q2 2019	185 x 35,786km 27°	Foreign	●	●	●	●	●	●	●	INQUIRE >
Q2 2019	220-420km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE >
Q3 2019	450-500km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE >
Q4 2019	220-420km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE >
Q4 2019	450-500km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE >
Q4 2019	220-420km 52.6°	USA	●	⊖	⊖	⊖	⊖	⊖	⊖	INQUIRE >
Q4 2019	500km SSO	Foreign	●	●	●	●	●	●	●	INQUIRE >
Q4 2019	185 x 35,786km 27°	USA	●	●	●	●	●	●	●	INQUIRE >

Launchers Summary

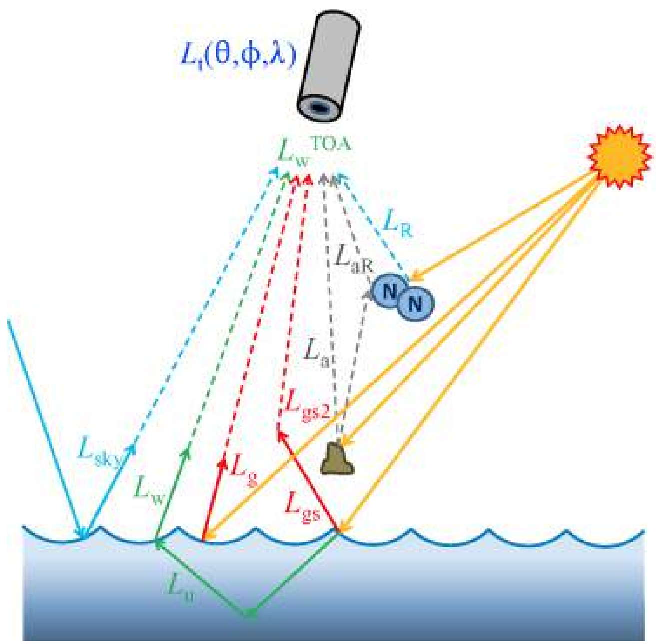
Date	Where	Orbit Type
Q2 2018	N/A (not US)	550 km SSO
Q2 2018	USA	500 km SSO
Q2 2018	N/A (not US)	450 km SSO
Q3 2018	N/A (not US)	550 km SSO
Q4 2018	N/A (not US)	536 km SSO
Q4 2019	N/A (not US)	500 km SSO
H2 2019	Russian	450-600 km SSO
Q4 2019	European	500-700 km SSO
Q4 2019	European	450-600 km SSO
Q1 2020	European	500-700 km SSO

Source: https://www.isispace.nl/launch-services/
http://spaceflight.com/schedule-pricing/

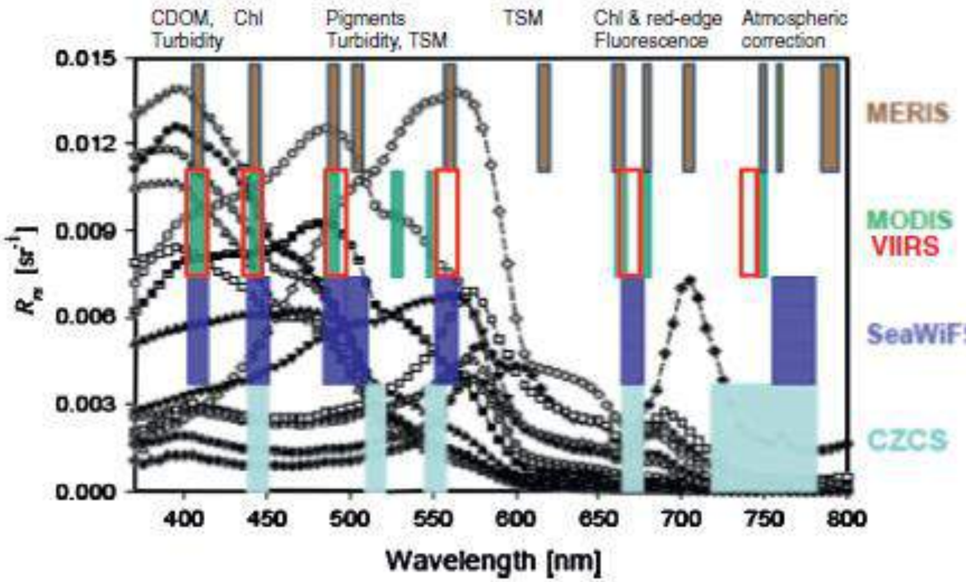
Remote Sensing

Remote sensing

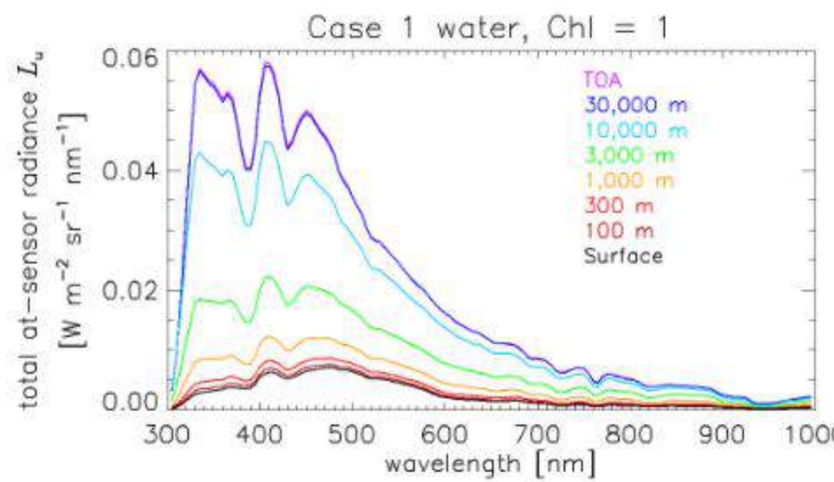
- What can be seen ToA
- Case 1 and Case 2 waters
  - Turbidity
  - CDM and SPM
- Atmospheric corrections



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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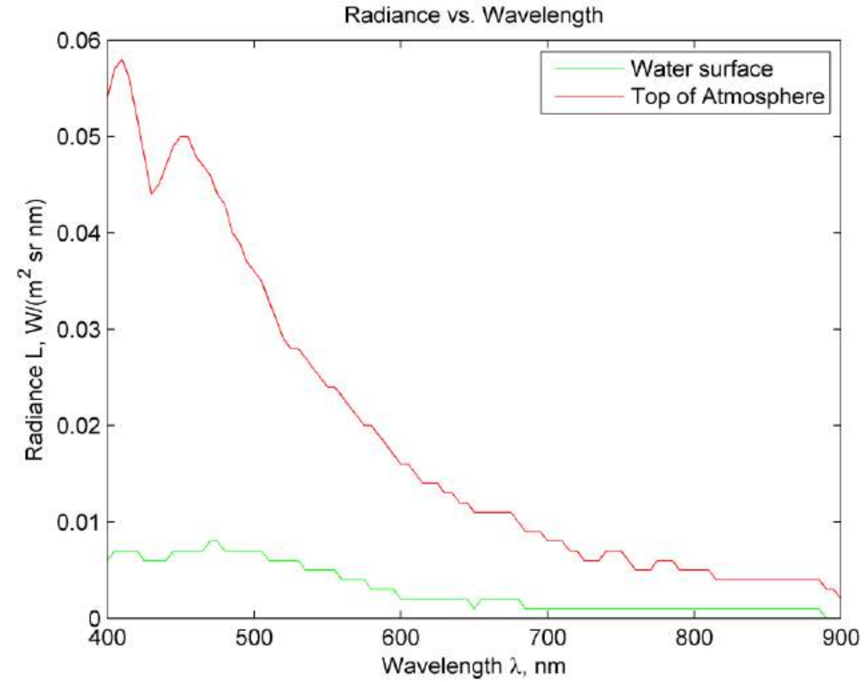
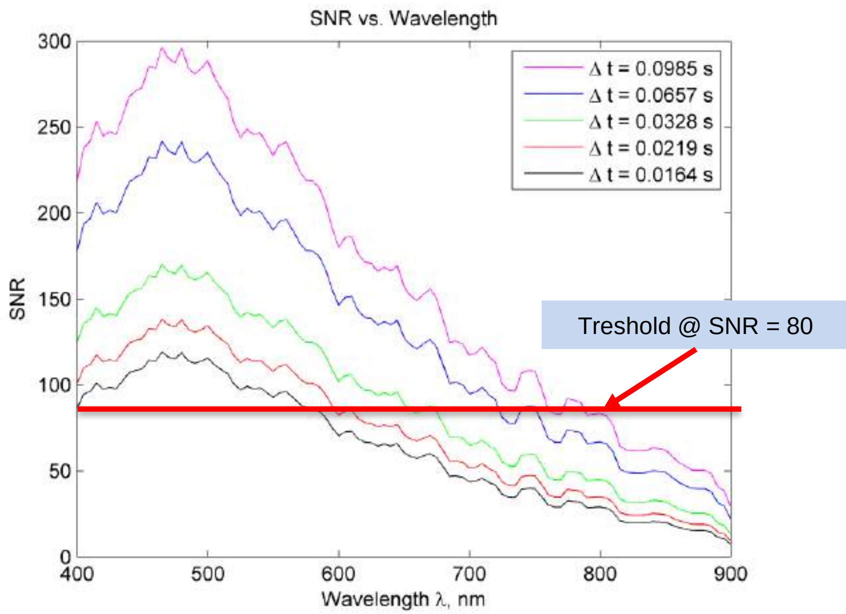
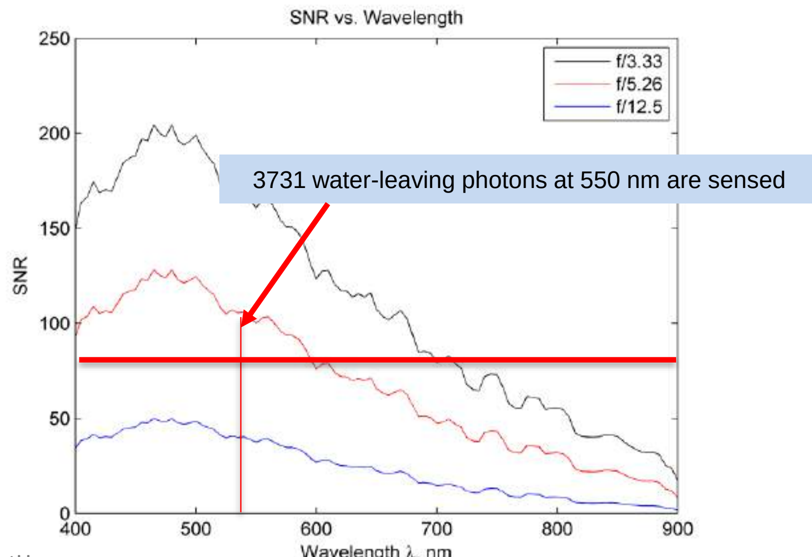
Sensitivity

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
dx	250 m







Requirement: SNR_water>10:1

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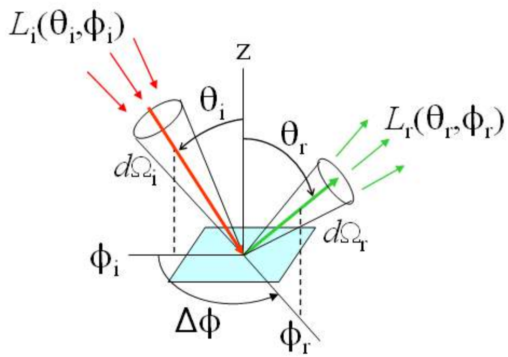
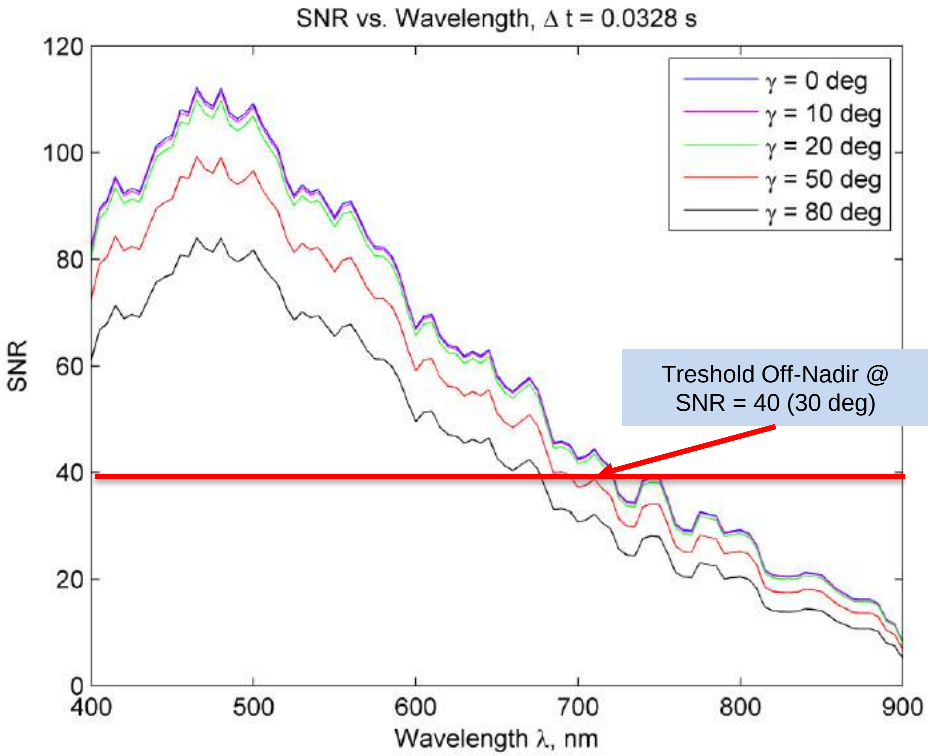
Viewing Angle Effects

- 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



Requirement: Total SNR off Nadir > 40:1 for all bands

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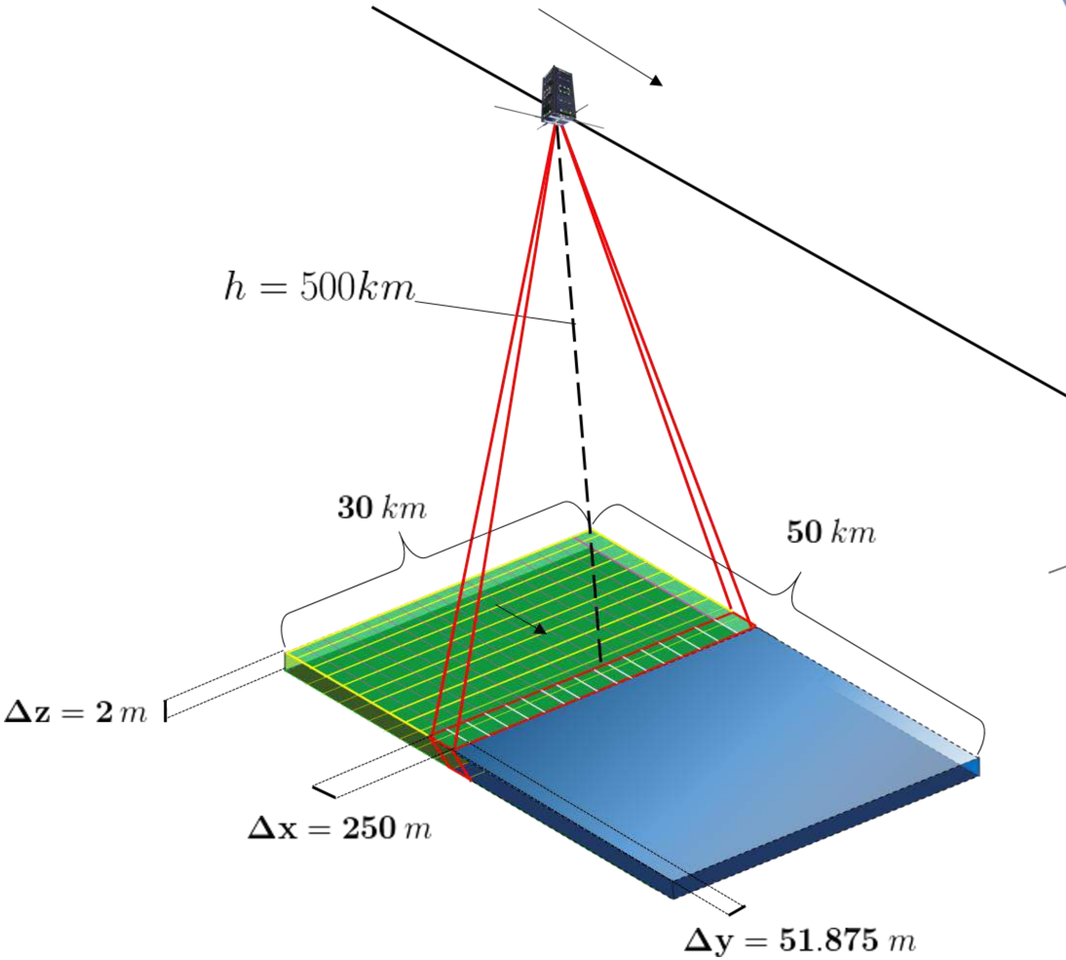
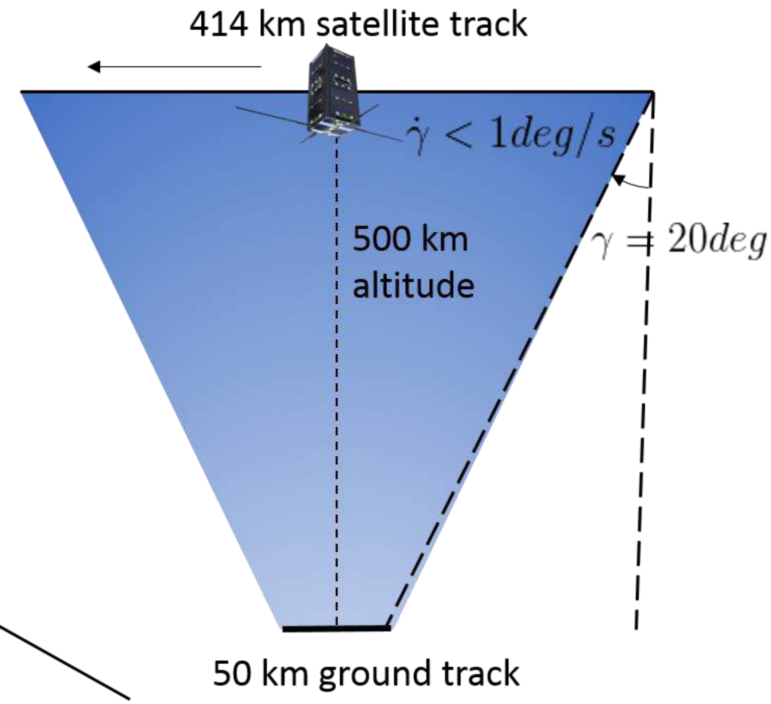
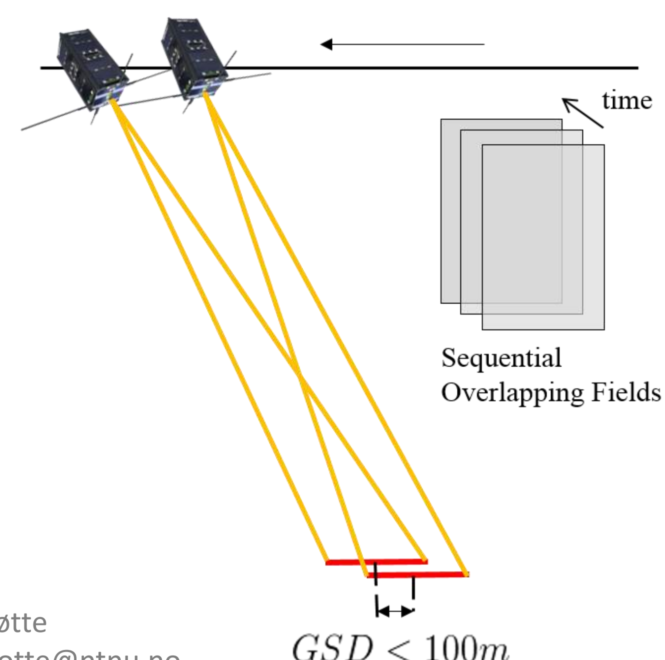
Mapping & Pointing Requirements

Sampling of Target







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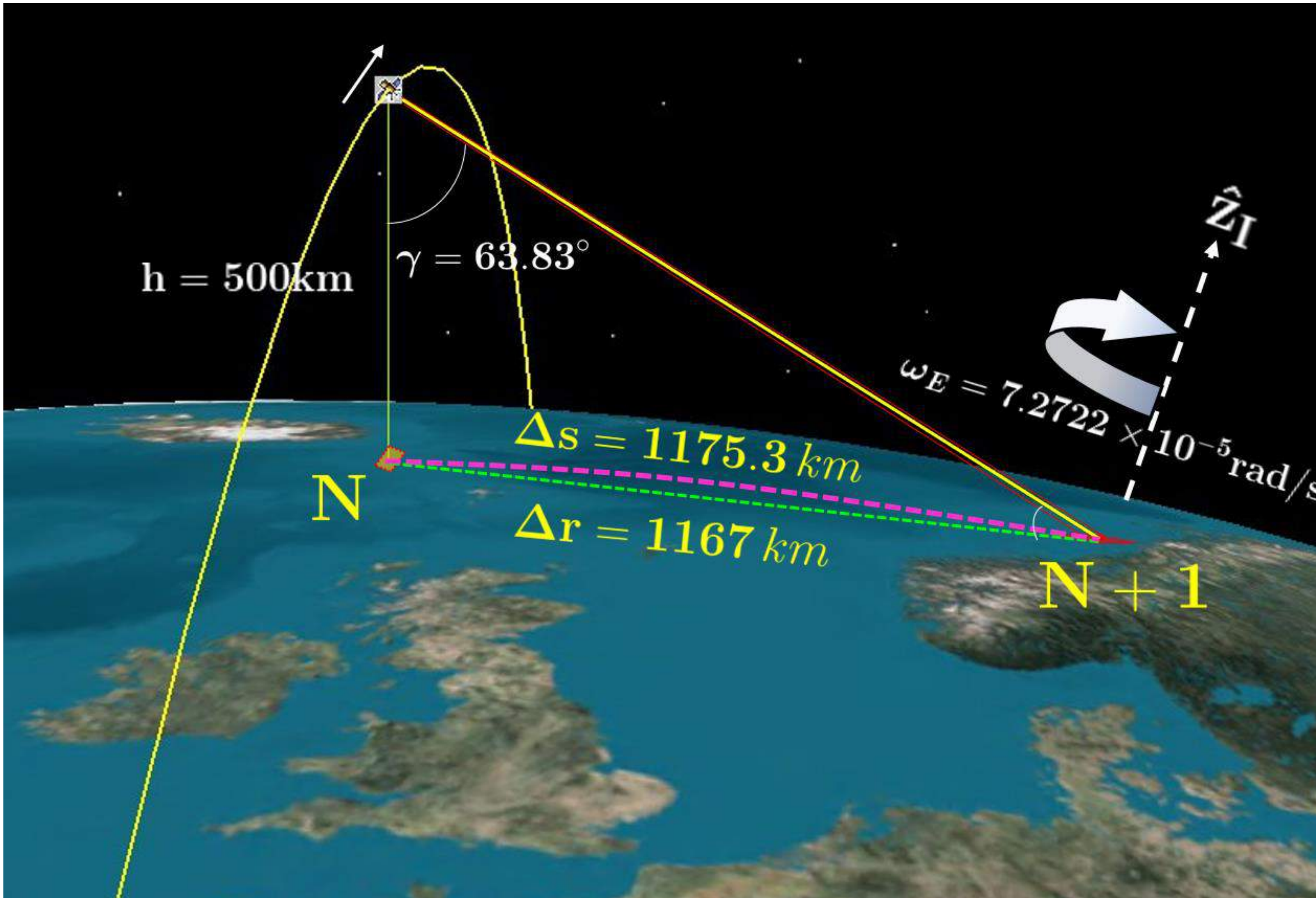
Cross-Track Slew Requirements



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

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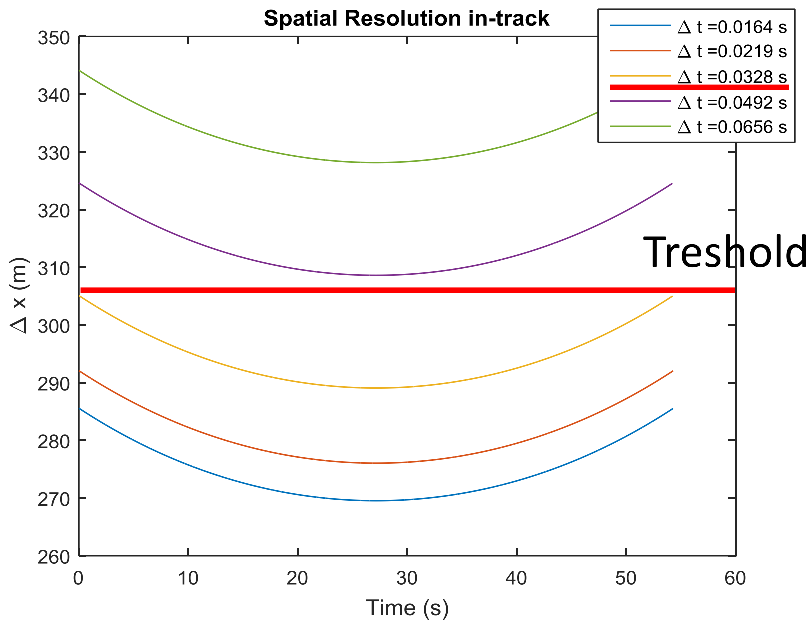
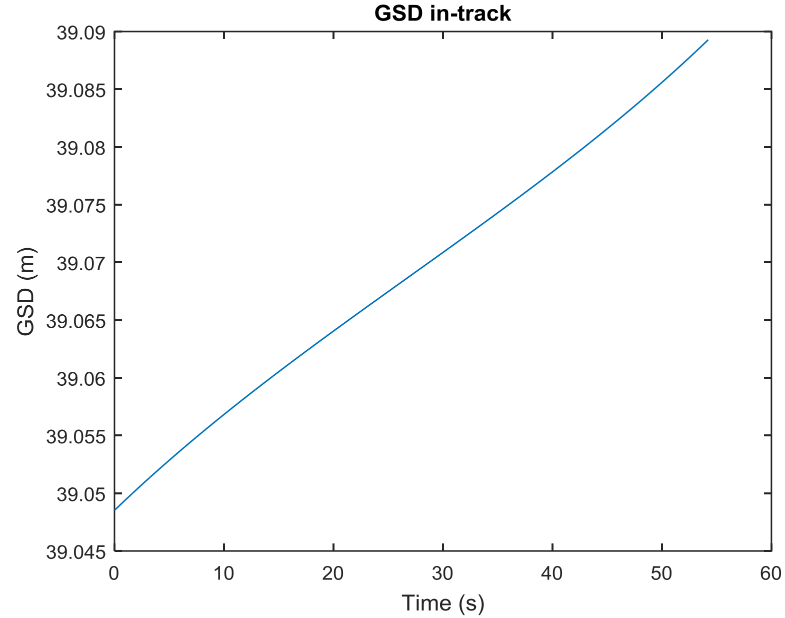
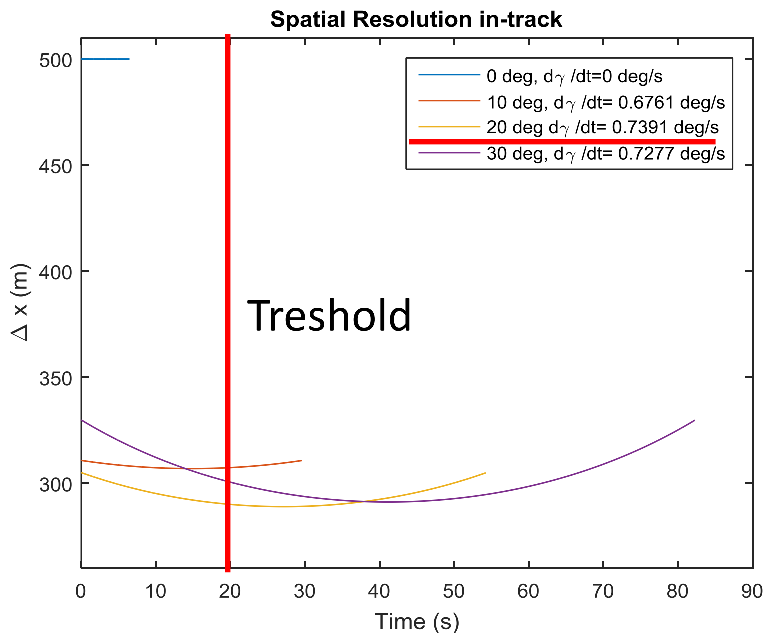
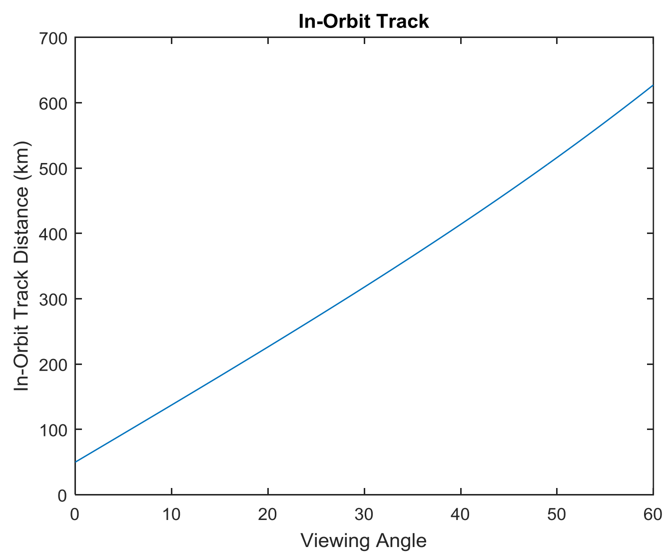
GSD and sampling calculations



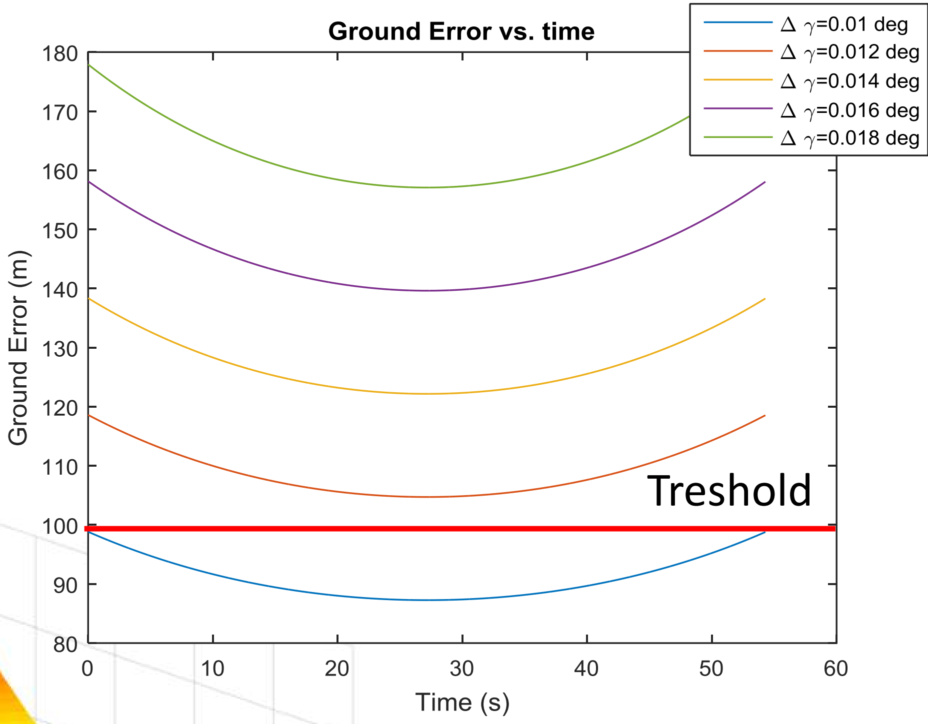


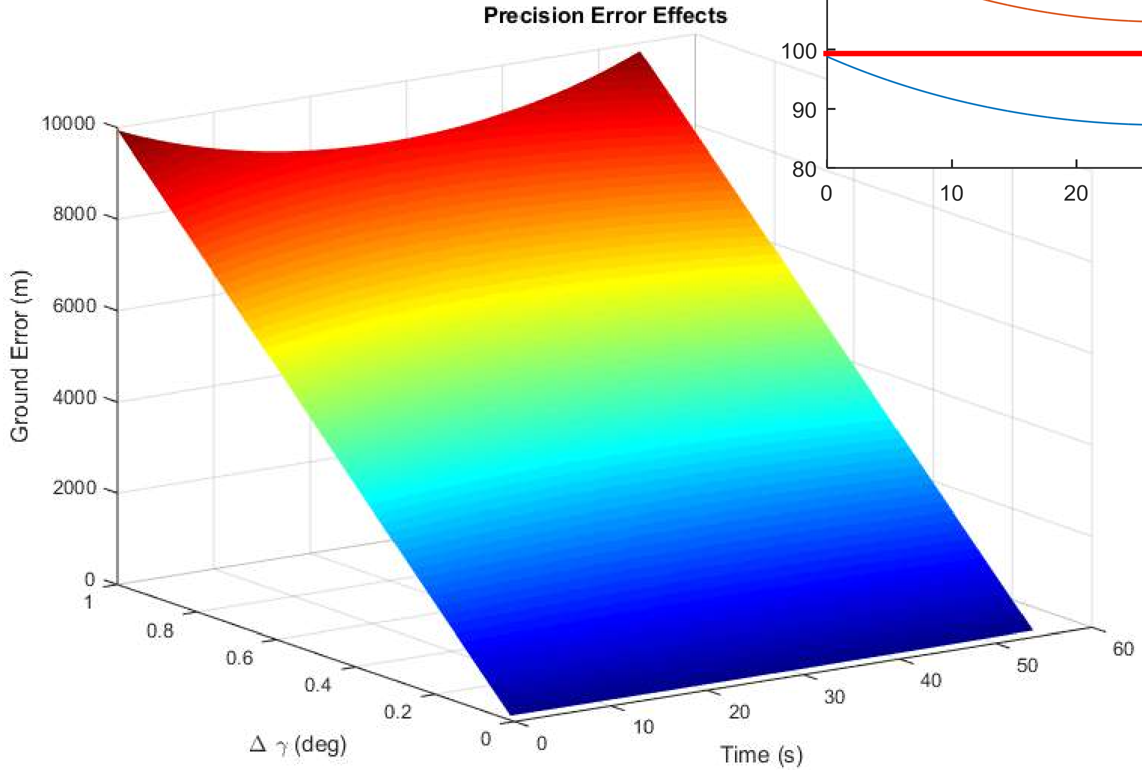


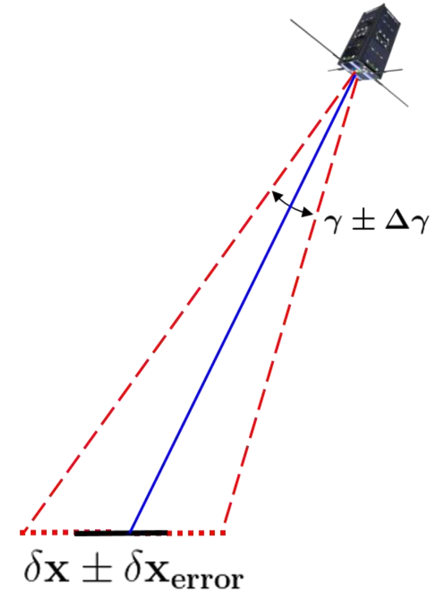


Precision Error

- 0.01° (2σ)
- Ground mapping sensitive to pointing







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Error Budget

Quote: «Pointing Accuracy should be 10%-20% of FoV», *Wertz & Larson: SMAD (1999)*

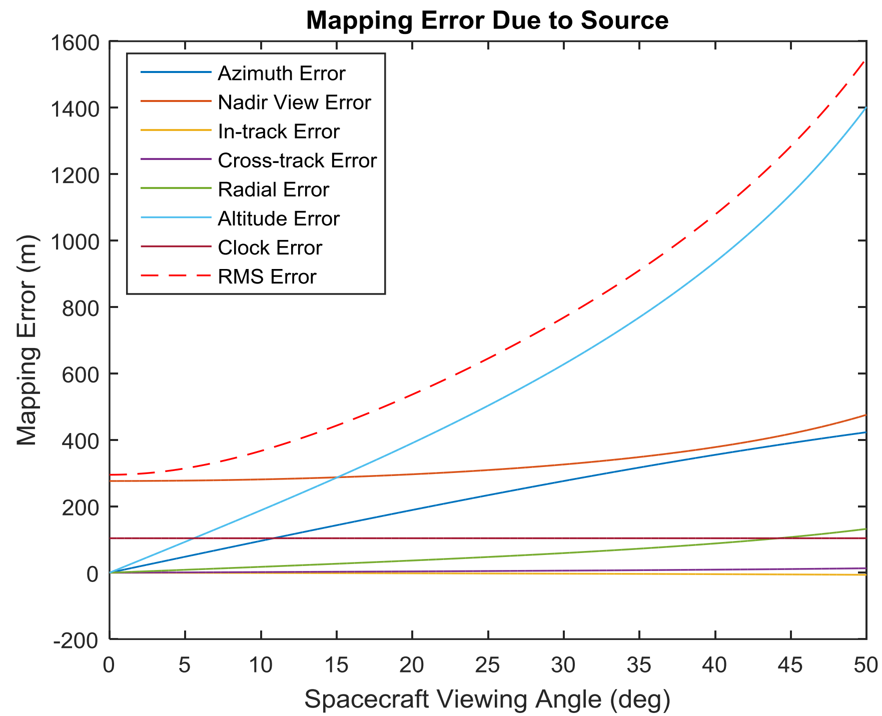
Accuracy Level	System
<10 deg	Gravity Gradient spacecraft, no attitude determination
<2 deg	Magnetometer only
<0.5 deg	Earth sensing, no oblateness corrections
<0.1 deg	General Earth sensing
<0.03 deg	High-accuracy Earth sensing
<0.01 deg	Star sensing

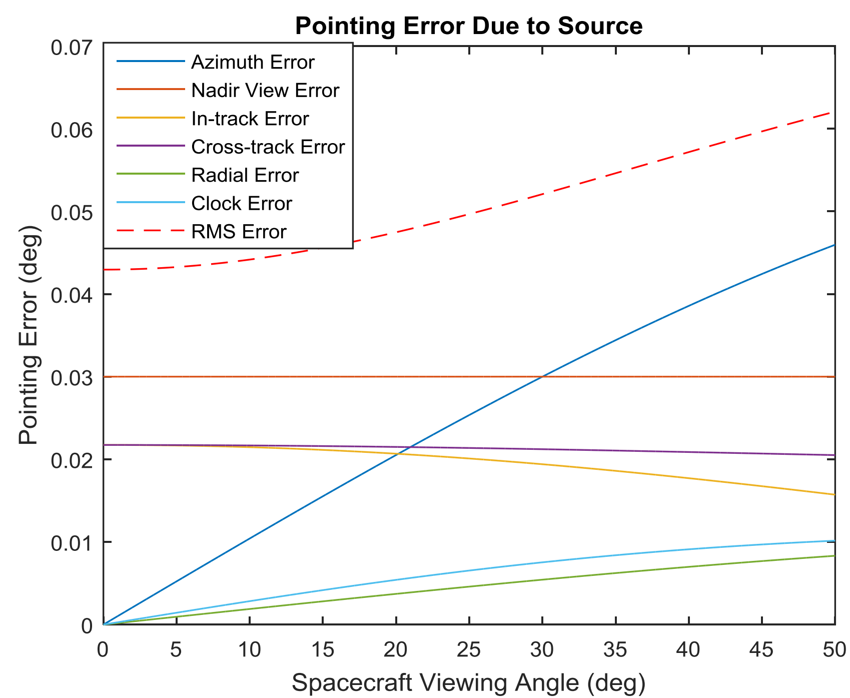
Sources of Mapping and Pointing Errors		
Spacecraft Position Errors:		
ΔI	In-or along-track	Displacement along the spacecraft's velocity vector
ΔC	Cross-track	Displacement normal to the spacecraft's orbit plane
ΔR_S	Radial	Displacement toward the center of the Earth (Nadir)
Sensing Axis Orientation Errors:		
$\Delta\eta$	Elevation	Error in angle of the sensing axis about Nadir
$\Delta\varphi$	Azimuth	Error in rotation of the sensing axis about Nadir
Other Errors:		
ΔR_T	Target Altitude	Uncertainty in the altitude of the observed object
ΔT	Clock Error	Uncertainty in the real observation time (results in uncertainty in the rotational position of the Earth)

Error Budget

Source	Error
Azimuth	0.06 deg
Nadir Angle	0.03 deg
In-Track	0.2 km
Cross-Track	0.2 km
Radial	0.1 km
Target Altitude	1 km (exag.)
S/C Clock	0.5 s

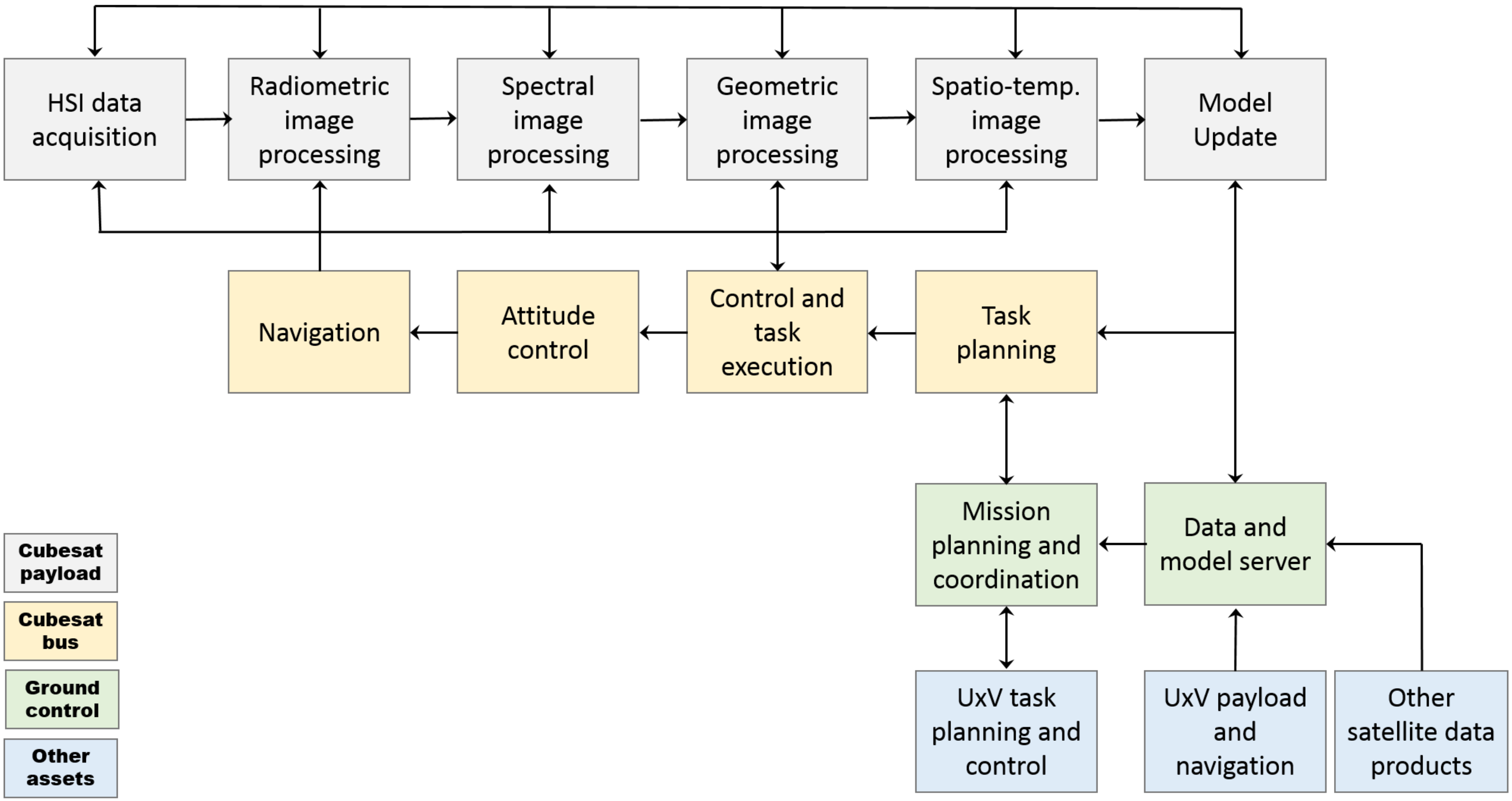
* Attitude determination error, instrument mounting error, stability over exposure time (mapping only), control error (pointing only)





Data Processing Requirements

Processing & control



Need to meet 3 firm requirements: data size, timeliness (processing time), data quality (Operational & Scientific)

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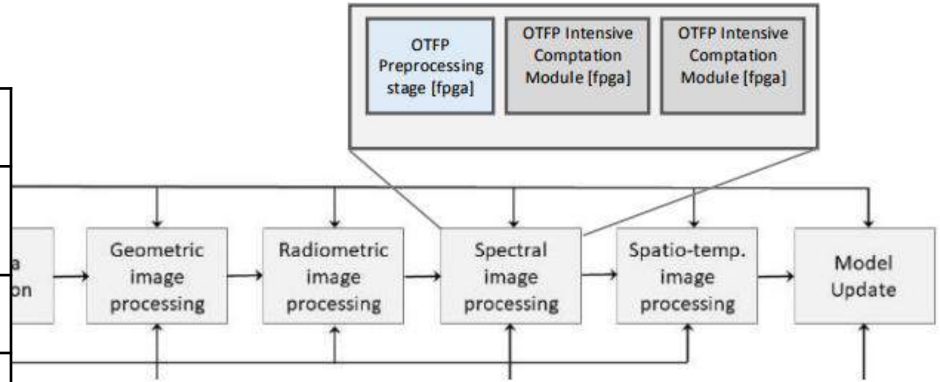
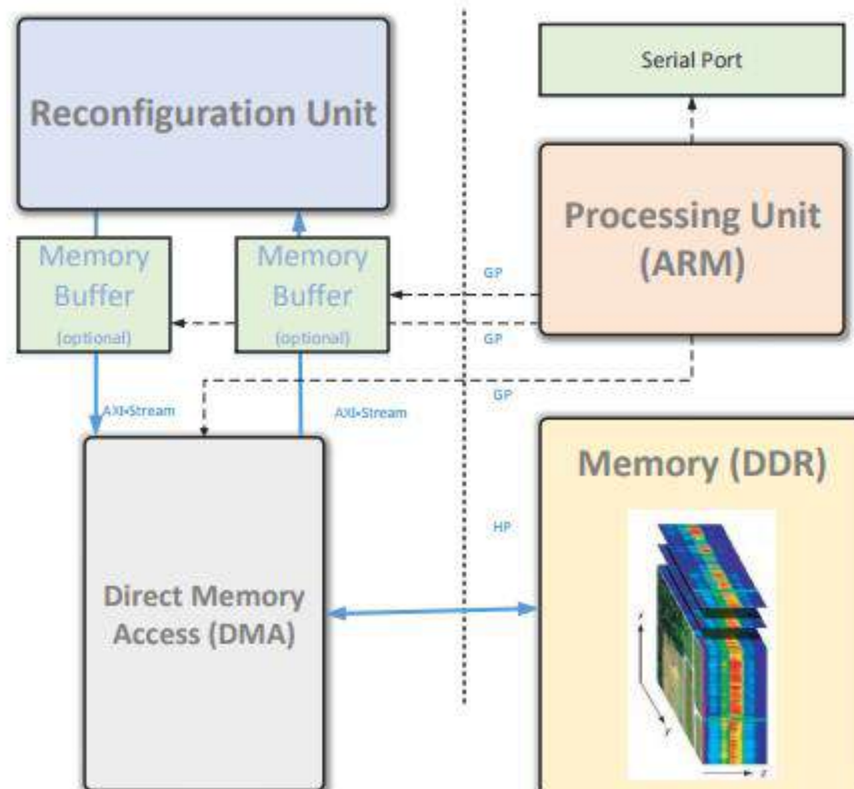
Data Processing

Algorithm	Application
JPEG2000	Spatial Compression (lossless)
PCA	Spectral compression
EMSC	Signature Detection
Anomaly Detection	Spectral compression & signature detection
2nd Order Derivatives	Spectral shape reconstruction
Standard atmospheric correction	Spectral compression & signature detection
LCMV beamforming	Signature detection
Spectral–Spatial Classification	Spectral-spatial compression & detection
Deconvolution	Pixel fusion
Super-resolution	Increase in spatial resolution





Bold: Baseline

Ask for references

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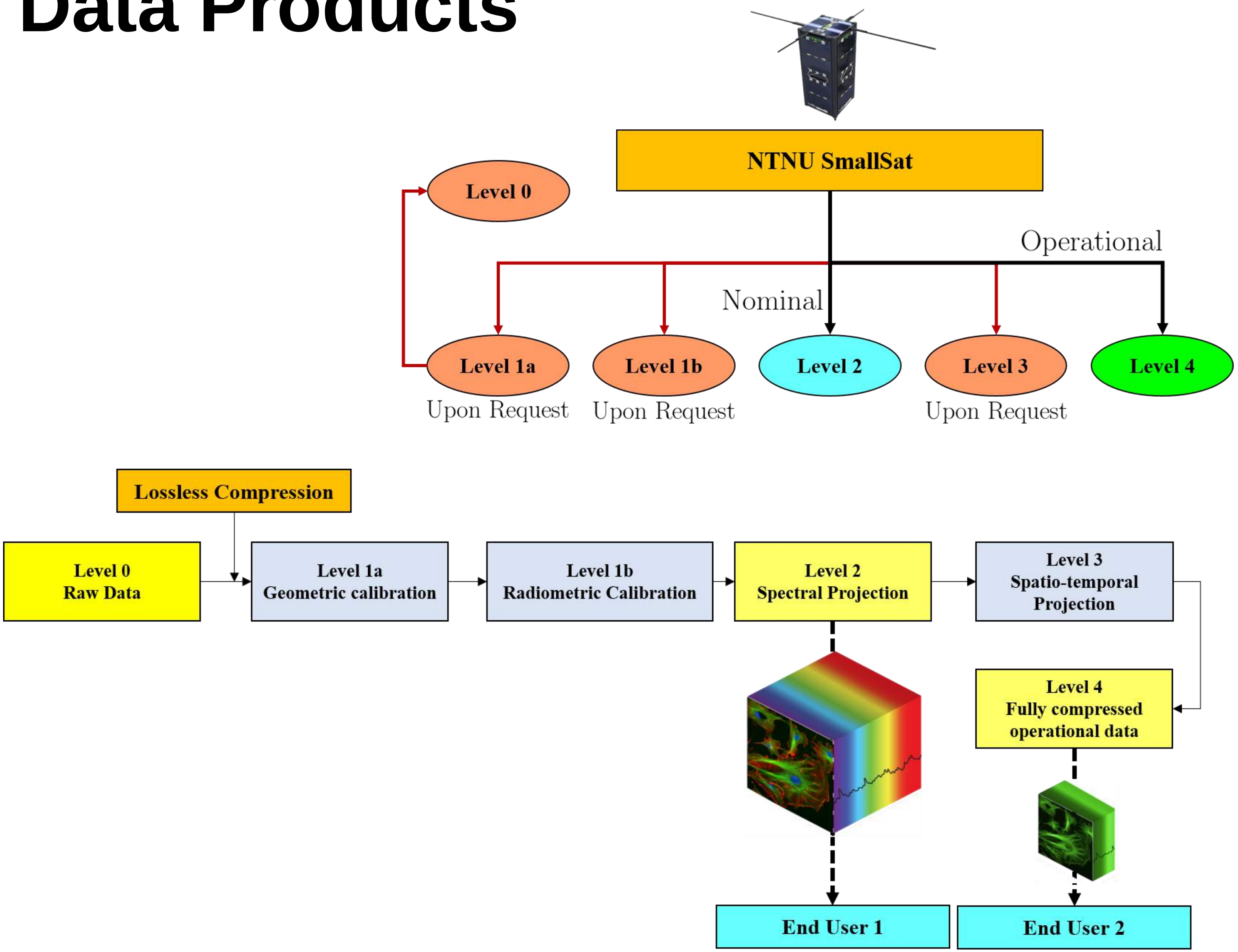
Data Products



Data Budget

DATA SIZE 1 IMAGE PACKET

Option	Format	Size
1	Raw A (1 frame)	1600×580 pixels $\times$ 16 bits/pixel $\times$ 1 frame = 14.848 Mbit
2	Raw A (JPEG2000)	1600×580 pixels $\times$ 3 bits/pixel $\times$ 1 frame = 2.784 Mbit
3	Raw B (1653 frames)	$1653 \times 1600 \times 580$ pixels $\times$ 12 bits/pixel = 24.5437 Gbit
4	Raw B (JPEG 2000)	$1653 \times 1600 \times 580$ pixels $\times$ 3 bits/pixel = 4.603 Gbit
5	Raw C (Raw B deconvoluted)	500×580 pixels $\times$ 100 channels $\times$ 16 bits/(pixel $\times$ channel) = 464 Mbit
6	Raw C (with JPEG2000)	500×580 pixels $\times$ 100 channels $\times$ 3 bits/(pixel $\times$ channel) = 87 Mbit
7	Compressed (spectrally)	500×580 pixels $\times$ 20 components $\times$ 24 bits/pixel = 139.2 Mbit
8	Compressed (spectrally + JPEG2000)	500×580 pixels $\times$ 20 components $\times$ 3 bits/pixel = 17.4 Mbit
9	TM/TC & geometric data (NavData)	7 Mbit

Downlink to Ground Station at ε=10 deg

Option	Format	Size	UHF-band 100 kbps	S-band 1 Mbps	X-band 10 Mbps
1	Raw A (1 frame)	21.848 Mbit	3.6413 min	21.848 s	2.1848 s
2	Raw A (JPEG2000)	9.784 Mbit	1.631 min	9.784 s	0.9784 s
3	Raw B (1653 frames) + NavData	24.5507 Gbit	68.1964 hrs	6.8196 hrs	40.9178 min
4	Raw B (JPEG2000) + NavData	4.607 Gbit	12.7972 hrs	1.27972 hrs	7.6783 min
5	Raw C (Raw B deconvoluted) + NavData	471 Mbit	1.3083 hrs	7.85 min	47.1 s
6	Raw C (with JPEG2000) + NavData	94 Mbit	15.667 min	1.5667 min	9.4 s
7	Compressed (spectrally) + NavData	146.2 Mbit	24.3666 min	2.4367 min	14.62 s
8	Compressed (spectrally + JPEG2000) + NavData	24.4 Mbit	4.0667 min	24.4 s	2.44 s

Needs to be stored onboard and consecutively downlinked

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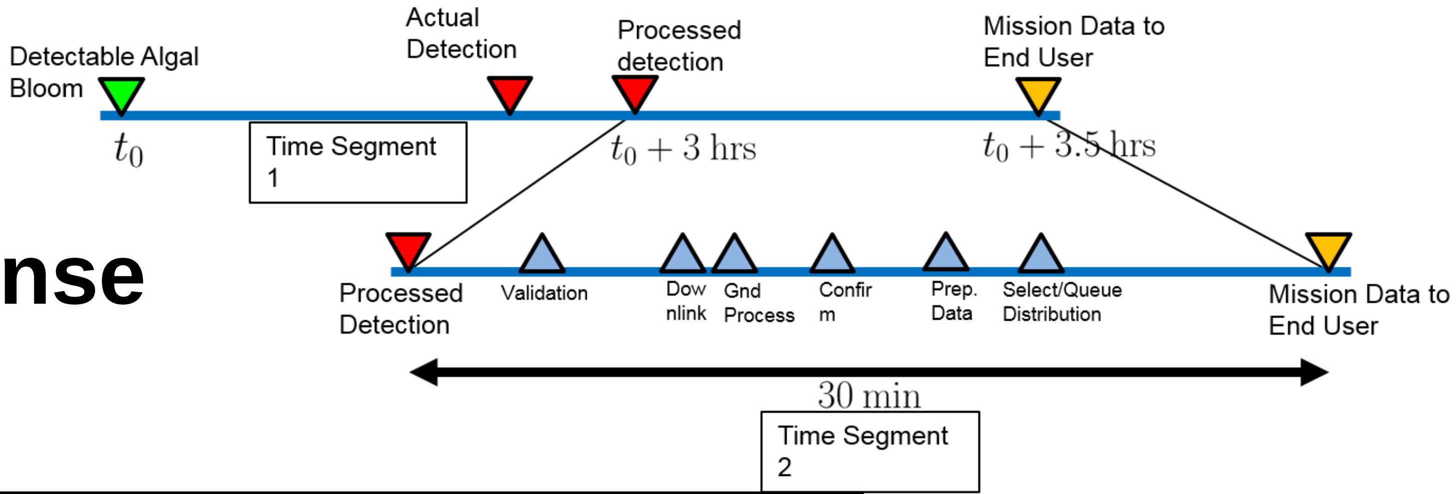
Response Time



Time Segment 1 Requirements		
Time to Actual Detection	2 Orbits prior to Remote detection	3 hrs
	Pushbroom scanning and HSI operations given SNR>50:1 at view angle = 20 deg	54 s
Time Segment 2 Requirements		
Time from Detection to Data Delivery	Initial Validation (processing time given detection)	2 min
	Downlink (S-band)	2 min
	Obit and Attitude Determination	5 min
	Ground Look Point Determination	2 min
	Completion of Ground Processing	3 min
	Confirmation of Algal Bloom (Chl-a or –b)	3 min
	Data Preparation (Sorting, formatting, internal routing)	2 min
	Queuing for User Distribution (Sorting, distribution, Queue Processing)	3 min
	Distribution to End User (Network Mgmt., Channel Rates)	2 min
	Margin	5 min
Total		30 min

Communications Architecture

Ground Stations

- Baseline:
  - KSAT Svalbard (only S-band uplink and downlink)
  - NTNU (UHF/VHF uplink or S-band downlink)

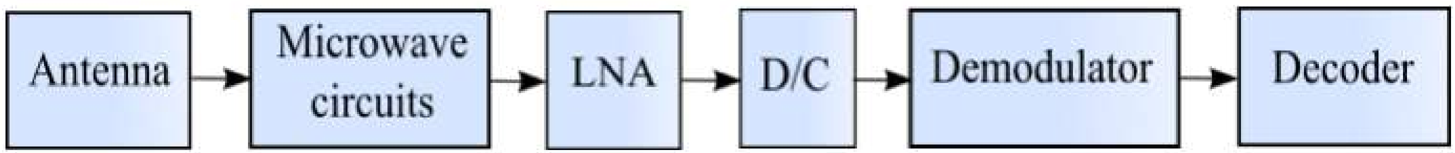
- Additional:
  - University of Porto
  - Gran Canaria
  - Mountain View High School
  - GomSpace/Tyvak/UTIAS + others (upon selection)

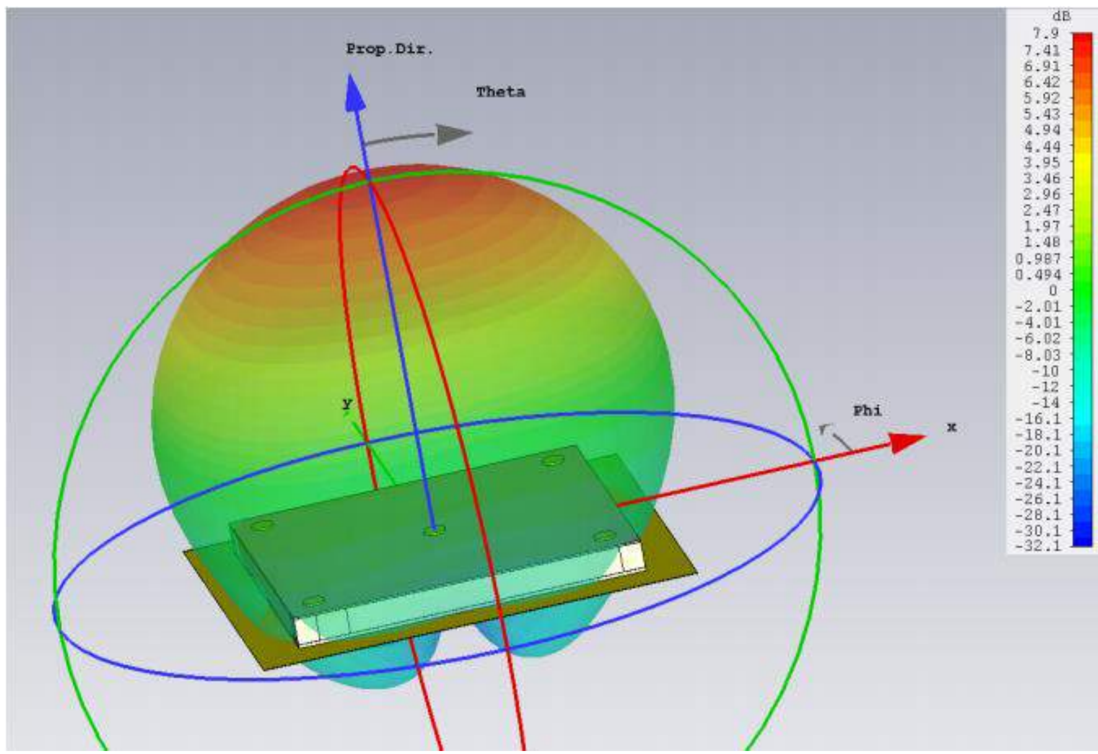
- Proposal for Concept 2: must have S-band uplink capability or uplink 1 orbit prior to acquisition
  - UHF antenna at KHO, Longyearbyen if not?
- Concept 1 is fine
- Pointing accuracy relaxed (1 deg) – i.e. not all ADCS turned on peak performance

KSAT & ISIS S-band Downlink

	Units	KSAT ground station	ISIS ground station
Size[1]	[m]	3.,7	2[2]
Gain	[dB]	64 dB[3]	31.35 dB[4]
Frequency band	[MHz]	2200-2300	2200 - 2500
Polarisation	-	RHCP/LHCP	Circular
G/T	[dB/K]	12.6	~4.9[5]
Beamwidth	[°]	-	5.1
EIRP	[dBW]	44.8	-
Height	[m]	-	3.3
Width	[m]	-	5.97
Weight	[Kg]	-	165

Downlink Architecture





S-band patch antenna. Credit: GomSpace

Link Budget

A: S-band Downlink (GOMspace + KSAT);
B: S-band Uplink (GOMspace + KSAT); and
C: S-band Downlink (GOMspace + ISIS)

	A	B	C
TX			
Power input (W)	0.48	-	26.8
Antenna gain (dB)	7.90	-	7.90
Losses (dB)	1.00	-	1.00
EIRP (dBm)	33.7	74.8	33.7
Propagation Losses			
Free space loss (dB)	163.88	163.48	163.88
Atmospheric loss (dB)	4.73	4.73	4.73
Other losses (dB)	4.00	4.00	4.00
Total propagation losses (dB)	172.6	172.2	172.6
RX			
Antenna gain (dB)	63.99	7.70	31.35
Losses (dB)	1.00	1.00	1.00
LNA gain (dB)	0.00	39.00	0.00
Noise figure (dB)	7.06	24.19	8.06
Bandwidth (MHz)	2	2	2
Link Quality			
Carrier power (dBm)	-75.91	-51.70	-108.56
Noise power (dBm)	-128.53	-111.40	-127.53
Signal to Noise ratio (dB)	52.62	59.69	18.97
Margin (dB)	45.13	52.20	11.48

Assuming h=500 km; elevation angle = 10 deg

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Payload

Hyperspectral Imager Versions

Part	Dimensions	Description
HSI ver. 4-1		
$f_0/\#$	$f_0/4$	f-number front lens
$A_0(L_0)$	4 mm	Aperture front lens
L_0	14 mm	Front lens diameter
f_0	16 mm	Focal length front lens
w	0.025 mm	Entrance slit width
z	3 mm	Entrance slit height
S_1	10 mm	Field lens aperture
$f_1/\#$	$f_1/3.33$	f-number collimator lens
$A_1(L_1)$	9 mm	Aperture collimator lens
f_1	30 mm	Focal length collimator
G	25×25 mm^2	Grating area
$f_2/\#$	$f_2/2.5$	f-number detector lens
$A_2(L_2)$	10 mm	Aperture detector lens
f_2	25 mm	Focal length detector lens
HSI ver. 4-2		
$A_0(L_0)$	12.5 mm	Aperture front lens
f_0	50 mm	Focal length front lens
HSI ver. 5		
$f_0/\#$	$f_0/2.8$	f-number front lens
$A_0(L_0)$	3.714 mm	Aperture front lens
f_0	10.4 mm	Focal length front lens
w	0.075 mm	Aperture front lens

Suggestion: add another RGB camera to validate HSI images

→ Better spatial resolution

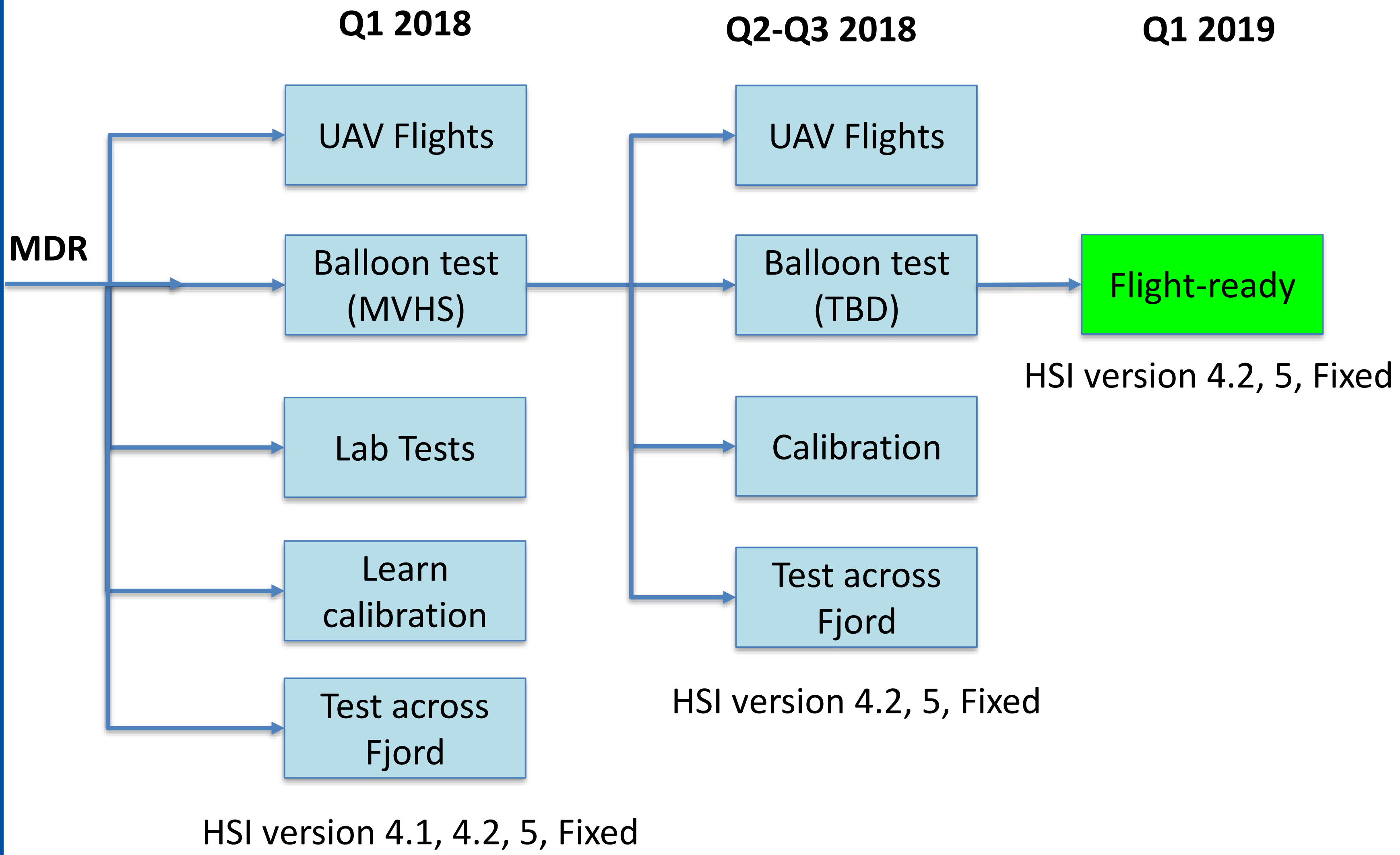
→ More light in, worse spatial resolution

Manufacturing Pipeline

	Version 1	Version 2	Version 3
Timeline	Early 2018	Summer 2018	Early 2019
Goal	• Get the entire processing chain up and running with image capture and on-board processing. • Perform drone and ballon tests and decide on final optics.	• Create a flight ready design that is the correct size, has the correct connections to the bus and has parts that can last in low-earth orbit.	• Flight approved hardware. Correct everything that we found in testing the Version 2 design.
Method	• Use off-the-shelf FGPA processing board combined with a custom PCB carrier plate for power supply, image sensor, SD-card for storage and USB debug/ streaming capabilities. • Optics can be swapped out and multiple different versions can be tested on the same prototype.	• Custom made PCB with the FPGA and other components. • Vertical image sensor for horizontal optics to reduce space. • Completely adhere to the CubeSat ISO-17770 standard. • Perform all the required tests like "Shake and bake". • Develop with feedback from bus-provider.	• Correct all the bugs found in the testing of Version 2. • Perform all tests necessary for official flight approval. • Fully characterize flight ready hardware.
Assumptions	• Optics have been tested and validated with off-the-shelf camera.	• Known bus provider • Optics have been decided • Known mechanical limitations and power budget.	• Tests have been performed on Version 2. • All requirements are known.
Estimated Cost	US$ 1500	US$ 3500	US$ 3 500+

Key point: All the different versions are based on more or less the same hardware architecture. Meaning most of the development time will be spent on PCB/production design and testing/verification. Credit: Julian Veisdal (Moon Labs)

Testing Pipeline



Calibration

1. Monochromatic light source (550 nm)
2. Sky (blue)
3. Black body type source of light emitting radiance.
4. Diffuse source of light - even illumination (not focused)
5. Closing lid
6. Source of light (clean room) and subtract the noise to see signal response

- The extra noise coming from microbubbles (Rayleigh scattering) needs to be characterized.
  - Most likely random
- Ultimately ground truth vs. HSI images from space
  - HICO data
  - STK
  - Our HIS
- Solar and Lunar Calibration (radiometric stability)

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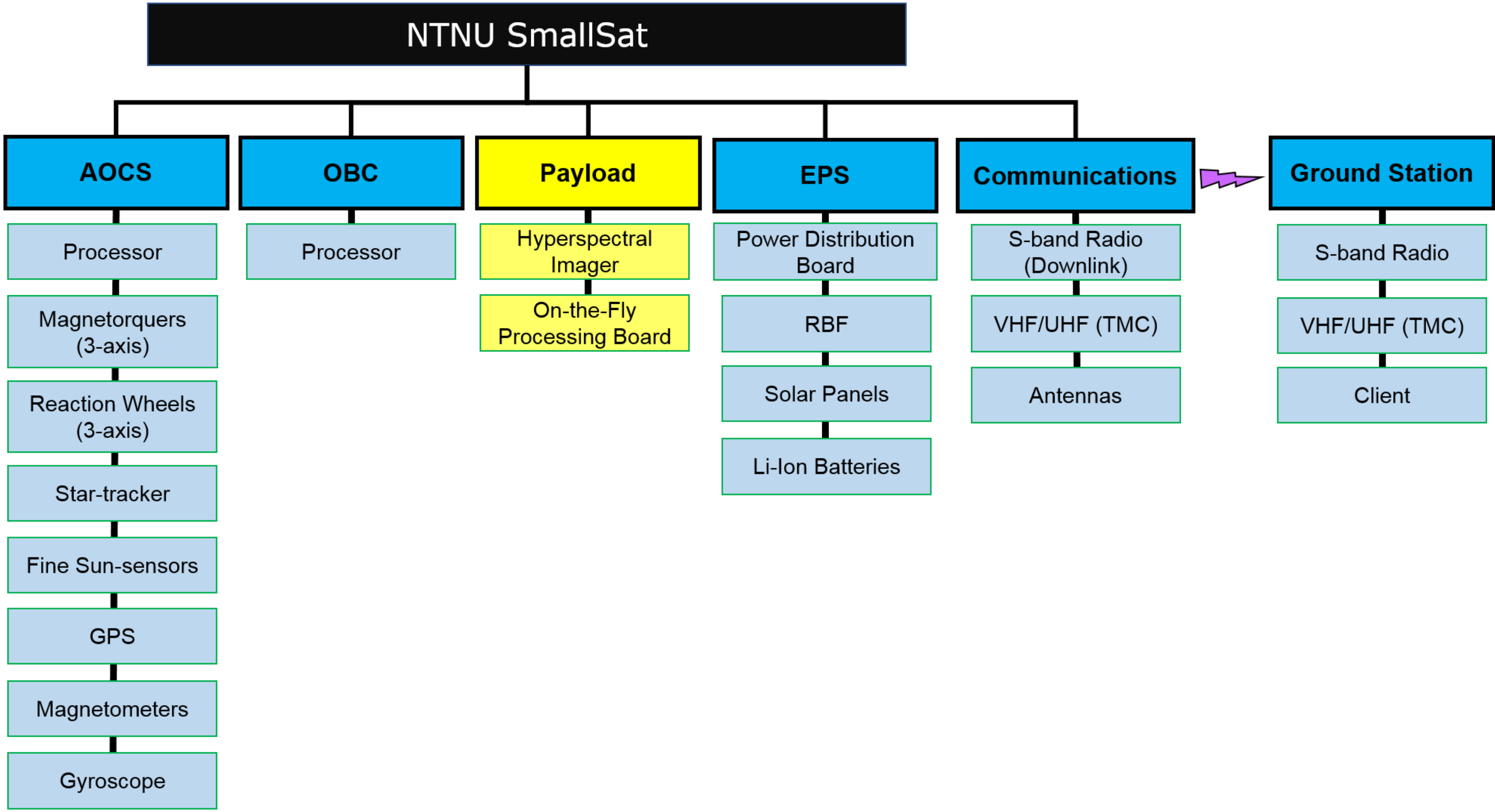
Systems Design

Product Tree



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Mass Budget

Details in excel spreadsheet

MASS BUDGET IN GRAMS

Subsystem	Mass 3U, g (+20 %)	Mass 6U, g (+20 %)
HSI	480	480
Structure	291.36	1272
Stack rods	73.8	147.6
Mechanisms	36	72
Wires & cables	120	240
Reaction Wheels	1128	1128
Star-tracker	336	672
Fine Sun Sensor	10.8	21.6
Magnetorquers	129.6	187.2
ADCS	124.8	134.4
Antenna S-band	132	132
Antenna UHF/VHF	36	108
Radio S-band	78.36	78.36
Radio UHF/VHF	29.4	29.4
GPS	28.8	28.8
OBC	112.8	112.8
EPS	120	120
Batteries	324	600
Solar Panels	448.8	909.6
SDR	N/A	250.8
Total	3910.92	6724.56

Ref: Survey of COTS from Gomspace, Hyperion Technologies, Clydespace
https://gomspace.com/
https://www.clyde.space/
http://hyperiontechnologies.nl

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Details in excel spreadsheet

Power Budget

POWER CONSUMPTION OF SUBSYSTEMS

Subsystem	Avg., W (+30 %)	Peak, W (+30 %)
HSI	3.9	10.4
Mechanisms	0	0.017
TT&C	0.065	0.13
Reaction Wheels	0.663	3.315
Star-tracker	0.91	1.3
Fine Sun Sensor	0.052	0.052
Magnetorquers	0.78	0.78
ADCS	0.306	1.255
Antenna S-band	0.78	13.91
Antenna UHF/VHF	0.78	13.91
Radio S-band	17.16	18.72
Radio UHF/VHF	5.304	5.304
GPS	1.5015	1.56
OBC	0.221	1.17
EPS	0.0975	0.195
Batteries	0.0052	0.0052

Ref: Survey of COTS from Gomspace, Hyperion Technologies, Clydespace
https://gomspace.com/
https://www.clyde.space/
http://hyperiontechnologies.nl

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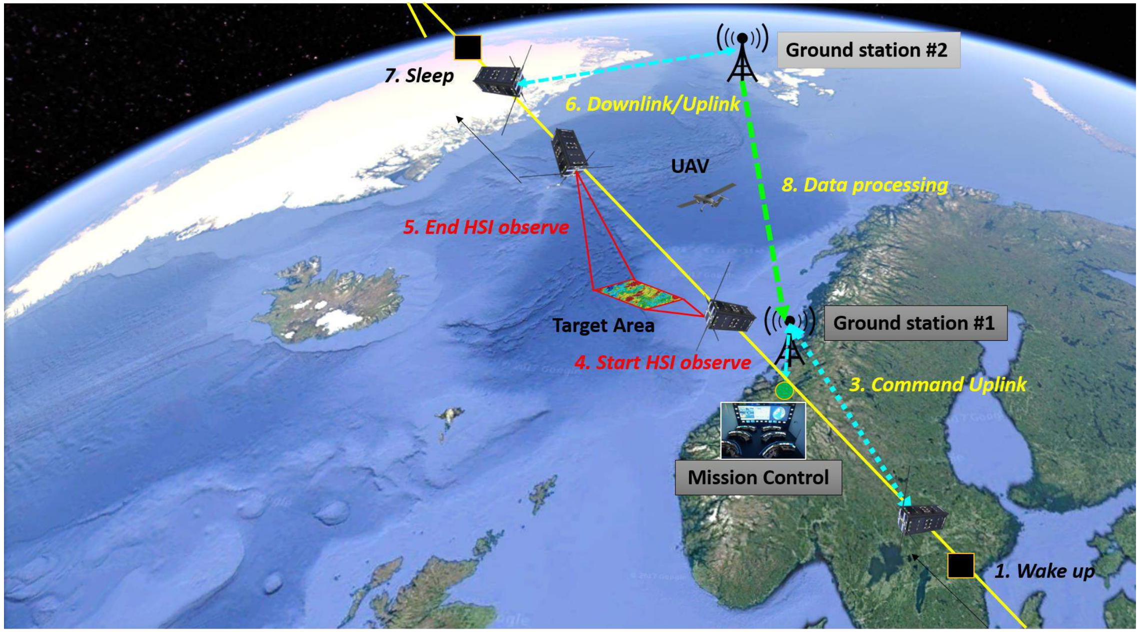
Mission Phases (Concept 1)



Segment	Description	Start (UTC)	Duration (s)
Phase 1	Harvest	09:37:10	5
Phase 2	Comms. Trondheim	09:37:15	125
Phase 3	Prepare slewing	09:39:20	115
Phase 4	HSI operations	09:41:15	54
Phase 5	Data processing	09:42:09	74
Phase 6	Point to Svalbard	09:43:25	20
Phase 7	Comms. Svalbard	09:43:45	270
Phase 8	Harvest	09:48:15	605
Phase 9	Sleep	09:59:20	2207
Phase 10	Harvest	10:36:07	2255
N+1	Next target	11:13:42	373

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Details in excel spreadsheet

- Assuming battery discharge at 70 % capacity;
- 1 image per orbit

ENERGY BUDGET FOR 3U

Mission segment	Duty Cycle (s)	Power in (W)	Power in (Wh)	Power Consumed (Wh)	Start Power (Wh)	End Power (Wh)
Phase 1	5	7.36	0.0102	0.010	26.95	26.95
Phase 2	125	3.68	0.1278	0.953	26.95	26.13
Phase 3	115	2.208	0.0705	0.366	26.13	25.83
Phase 4	54	2.208	0.0331	0.301	25.83	25.56
Phase 5	74	3.68	0.0756	0.240	25.56	25.40
Phase 6	20	3.68	0.0204	0.158	25.40	25.26
Phase 7	270	2.208	0.1656	2.950	25.26	22.48
Phase 8	605	7.36	1.2369	1.078	22.48	22.63
Phase 9	2207	0.00	0.00	3.578	22.63	19.06
Phase 10	2255	7.36	4.6102	4.018	19.06	19.65
Phase N+1 (target)	373		0.3173	1.869	19.65	18.10
Phase N+1 (rest)	5357		6.0332	11.781	18.10	12.35

Battery capacity = 2600 mAh, Max solar power = 7.36 W, Min solar power = 2.208 W

ENERGY BUDGET FOR 6U

Mission segment	Duty Cycle (s)	Power in (W)	Power in (Wh)	Power Consumed (Wh)	Start Power (Wh)	End Power (Wh)
Phase 1	5	14.72	0.02	0.01	53.90	53.90
Phase 2	125	7.36	0.26	1.05	53.90	53.10
Phase 3	115	4.42	0.14	0.46	53.10	52.78
Phase 4	54	4.42	0.07	0.53	52.78	52.32
Phase 5	74	7.36	0.15	0.28	52.32	52.19
Phase 6	20	7.36	0.04	0.17	52.19	52.06
Phase 7	270	4.42	0.33	3.14	52.06	49.25
Phase 8	605	14.72	2.47	1.51	49.25	50.21
Phase 9	2207	0.00	0.00	5.03	50.21	45.19
Phase 10	2255	14.72	9.22	5.62	45.19	48.79
Phase N+1 (target)	373		0.63	2.34	48.79	47.09
Phase N+1 (rest)	5357		12.07	17.81	47.09	41.35

Battery capacity = 5200 mAh, Max solar power = 14.72 W, Min solar power = 4.42 W

Cost Estimates

Details in excel spreadsheet

FY17$		
Subsystem	**Cost Low MNOK**	**Cost High MNOK**
Hardware (3U)	1.887	2.641
Software & Support	0.694	0.971
Launch & Prep	2.244	2.692
Operations	1.000	1.400
Training (1 week)	0.428	0.599
Total	**6.253**	**8.303**
Hardware (6U)	3.709	5.192
Software & Support	0.694	0.971
Launch	4.263	5.115
Operations	1.000	1.400
Training (1 week)	0.428	0.599
Total	**10.094**	**13.277**

Ref: http://spaceflight.com/schedule-pricing/ ; https://www.cubesatshop.com/ ; NASA ARC; GomSpace

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3U vs. 6U

Element	3U CubeSat	6U CubeSat
Energy Budget	✗	✓
Image flexibility (N+2)*	✗	✓
Mapping Precision	✗	✓
Launch costs	✓	✗
Operations costs	✗	✓
Hardware costs	✓	✗
Software costs	✓	✗
SDR Mission*	✗	✓
Lifetime	✗	✓

* Not possible for 3U CubeSat

Conclusions

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Orbits

- Orbit Concept 1: More available for launch, easier for constellation design
- Orbit Concept 2: Higher mission utility and meets scientific & political objectives
- Need Spring/Summer observations
- Low chances of detection off Norway – motivates a constellation of SmallSats to meet scientific objectives

Payload

- Need to test and validate performance in next year – flight ready by Q1 2019
- Manufacturing pipeline within schedule for launch in 2019/20
- TBD on HSI design

Data Processing

- Compressed data and science data may be downlinked (Level 4 & Level 2 respectively)
- Raw data must be stored and consecutively downlinked (Level 1a)
- Spatial compression after each frame taken (per exposure)?
- If deconvolution is applied after each frame, then also raw images may be downlinked immediately
  - Need to determine if deconvolution is reversible

Communications Architecture

- NTNU (UHF & S-band)
- KSAT Svalbard (S-band) only
- Renders Orbit Concept 2 difficult for immediate response architecture
- S-band uplink also?

Systems Design

- 3U: Overall cheaper, but loss of mapping precision and lack of power for flexibility
- 6U: More costly, higher power, higher precision and accommodates **SDR** as secondary payload
- Ready to commence systems engineering to meet mission and systems requirements
- Next milestone: PDR

Verdict: FEASIBLE

Will be useful/capable of supporting AUV campaigns for monitoring & mapping of coastal areas

Challenges: Payload, Launcher and S/C bus

S/C size: 3U good enough, 6U better

IOCCG (based on the experiences form CZCS):
«The uncertainty in the (normalized) water-leaving radiance retrieved from the sensor in oligotrophic waters at 443 nm should not exceed 5%, and uncertainty in Chlorophyll should be ±30%.»

This should be the goal for any ocean color sensor. It is not achievable without applying radiometric and system vicarious calibration.

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Summary of S/C Requirements

Element	Requirement
Target Area	30x30 km^2
Detection Subjects	HABs, phytoplankton, oil, plumes
Orbit	500 km SSO (RAAN ca. 83.3 or 228.3 deg)
Launch	Preferably before April 2019
Thermal	Withstand 30 degrees C/s
Radiation	Optical coating to withstand radiation effects of 10kRad
Spectral Range	400-900 nm (5 nm resolution)
Spatial Resolution	<300 m
GSD	<50 m
Image Resolution	<100 m
Data Levels (Nominal)	Level 4 and Level 2
Data Levels (Upon Request)	Level 0, 1a, 1b, 3
Mapping Knowledge	<100 m
Pointing Accuracy	<0.01 deg (1 deg for downlink)
Orbit Knowledge	<10 m
Energy	>14 Wh for one pass
Radio-link	S-band (down), UHF (up), S-band (up?)
Ground Stations	NTNU (UHF+S-band), KSAT (S-band)
Cost	<10 MNOK (13 MNOK for 6U)

Hyperspectral Imager requirements

DATA PROCESSING REQUIREMENTS

Parameter	Value
Optical along-track resolution δx	250-266.044 m
Optical cross-track resolution Δy	51.9-55.2 m
Numer of pixels in Swath Width N_p	580
Exposure time Δt	0.0328 s
Spatial resolution Δx	300-305.085 m
GSD	39 m
Image resolution (after deconvolution)	500 $\times$ 580 pixels
Principal Components	$\leq$ 20
HSI observation time $[t_{\text{HSI},0}, t_{\text{HSI},f}]$	[0, 54.34] s
Processing time $[t_{\text{process},0}, t_{\text{process},f}]$	[54.34, 115] s
S-band downlink time $[t_{\text{comms},0}, t_{\text{comms},f}]$	[115, 175] s
Downlink time for raw data	unlimited
Nominal data format	Level 2
Operational data format	Level 4
Optional data formats	Levels 1a, 1b, 3
Format of data to Radio	CAN/RS422

Summary of suggestions

- 3U or 6U?
  - Cost vs. (precision + flexibility)
- UHF comms. with UAV or AUV (mother asset) or S-band with mission operations
- S-band uplink?
- Optics
  - Increase aperture
  - Increase sensitivity
  - Increase SNR
  - Increase spatial res. Vs. spectral res
  - Start testing asap
  - Add another RGB camera to validate HSI images
- Onboard processing to be validated
  - Deconvolution after each frame taken (exposure)
  - Spatial Compression after each frame taken (exposure)
  - Reduction in data size – more real-time processing and power consumed
- SDR capability? Must go up to 6U

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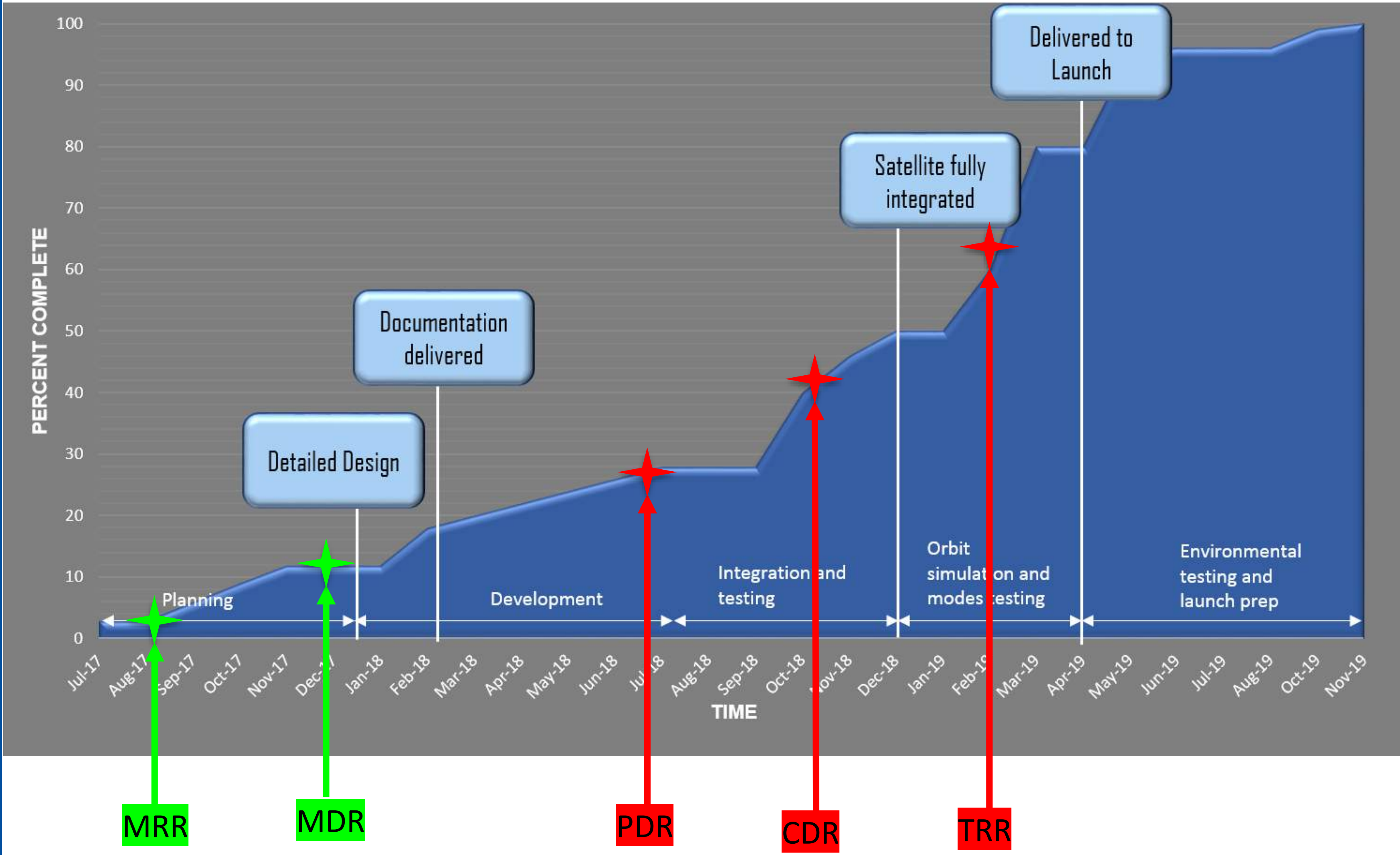
Verification, Validation and Testing



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