CEOS Feasibility Study for Hyperspectral Sensors for SDB

Arnold G. Dekker

EOMAP SDB Day 7th June 2018-Herrsching

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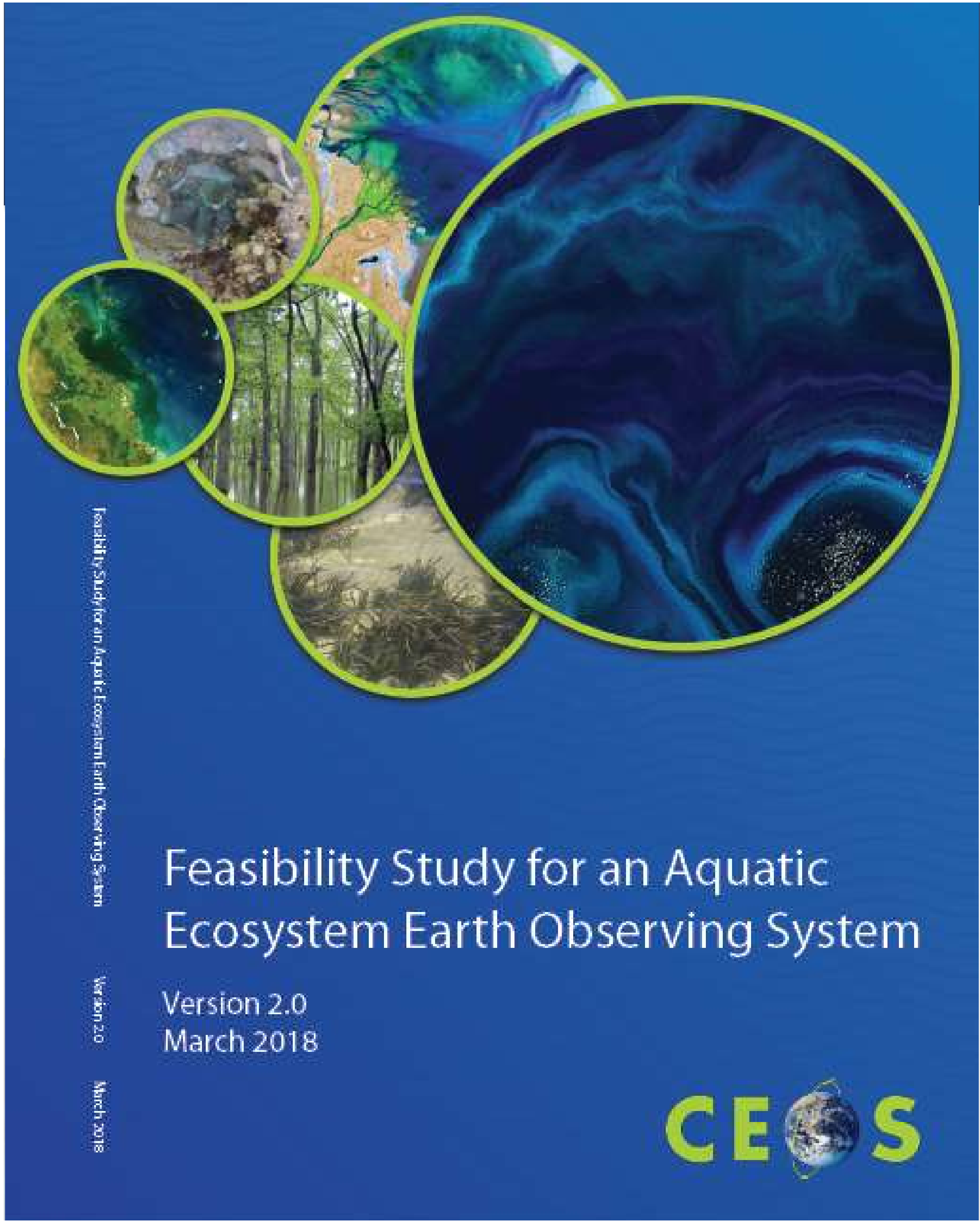


There are (a lot of) terrestrial, ocean and atmospheric sensors….. but none specifically for where ~60% of global population lives and ~60 Trillion U$ of GDP is produced………

Scope of the Feasibility Study Imaging Spectrometer for (non-Ocean) Aquatic Ecosystems

- **Determine the benefits and technological possibilities for designing a satellite mission focused on inland, near coastal waters, benthic and shallow water bathymetry applications**.

- Focus is on a **global mapping mission**

CEOS Team "Feasibility Study Imaging Spectrometer":

Lead: CSIRO - Arnold Dekker; Coordinator: ***DLR - Nicole Pinnel***

Members:

CNES	Marie-Jose Lefevre & Xavier Briottet (France)
DLR	***Peter Gege,*** Harald Krawczyk, Bingfried Pflug, Birgit Gerasch (Germany)
EOMAP	***Thomas Heege*** (Germany)
CNR	Federica Braga, Claudia Giardino & Vittorio Brando (Italy)
NASA	Kevin Turpie & Nima Pahlevan (USA)
CSA	Martin Bergeron & Maycira Costa (Canada)
USGS	Thomas Cecere (USA)
WaterInsight	Steef Peters (Netherlands)
TNO	Andy Court (Netherlands)
CSIRO	Hannelie Botha & Antonio Robles-Kelly (Australia)

Supporting sponsors:

(NSO)	Mark Loos & Joost Carpaaij (Netherlands)
(EC)	Astrid-Christine Koch & Catharina Bamps (European Commission)

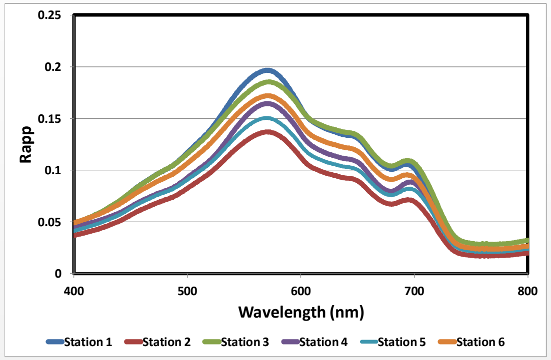
Table of Contents:

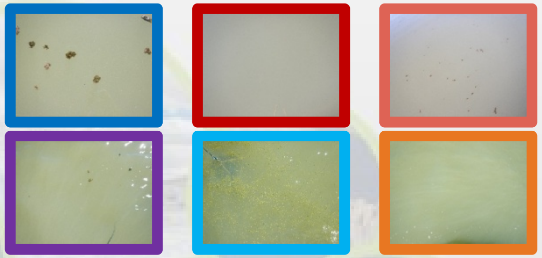
Feasibility Study for an Aquatic Ecosystem Earth Observation System

Available from: http://ceos.org/about-ceos/publications-2/

Inland waters not so simple: many different land-water boundaries; lakes at ~ - 408 to ~ + 6390 m altitude

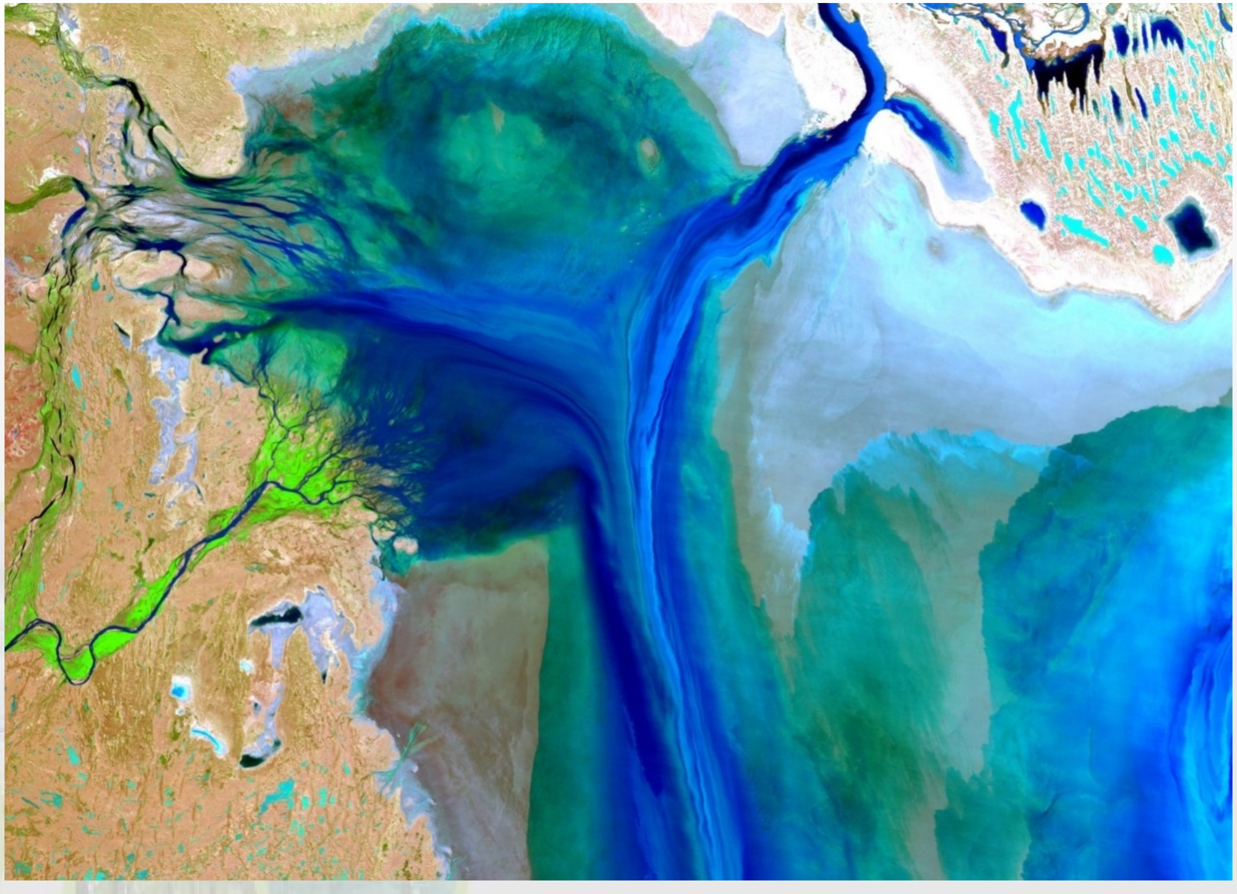
- Reflectance





Lake Burley Griffin spectroradiometric measurements by CSIRO (J. Anstee & H. Botha)

Salt lakes- not so simple
(Lake Eyre- Australia after floods)



Landsat image courtesy of USGS and GeoScience Australia

THE COLOUR OF COASTAL WATERS

images courtesy of CSIRO D. Blondeau-Patissier & T. Schroeder

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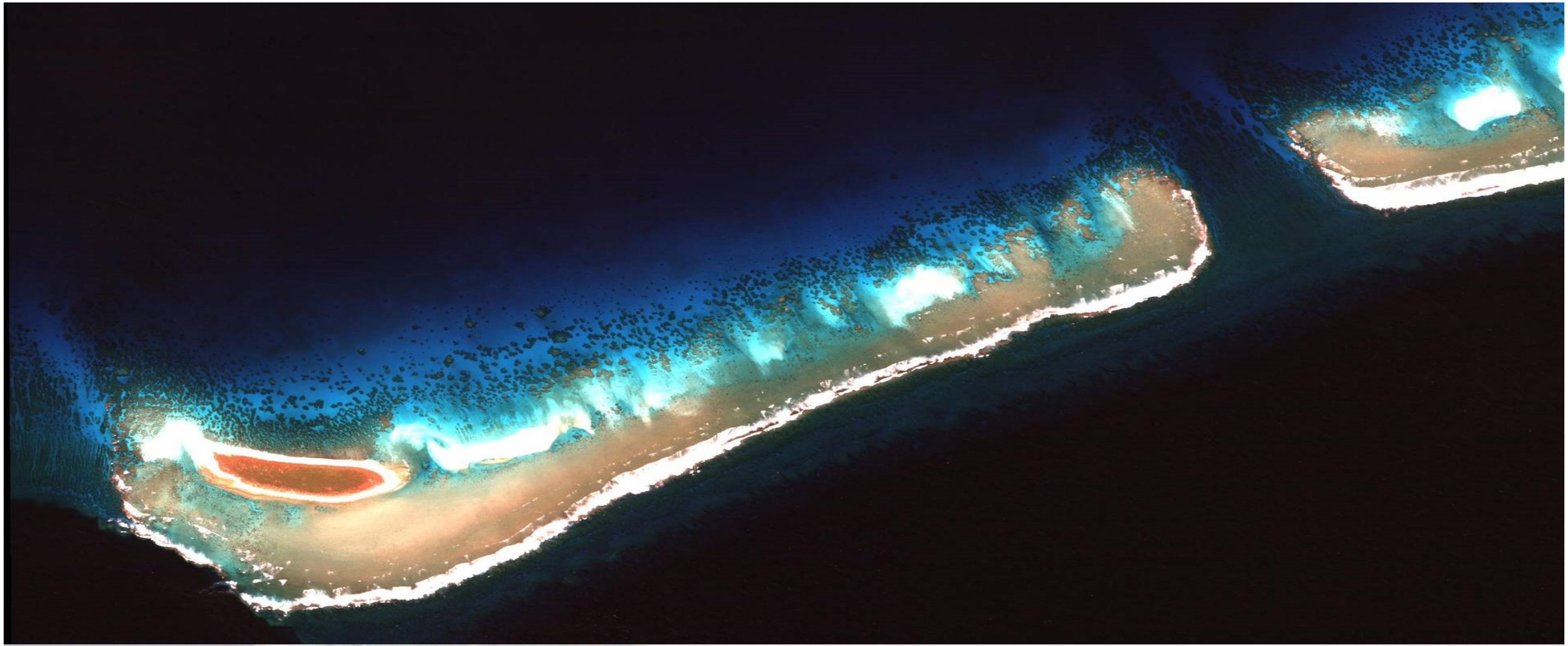
Coral reefs: not so simple:
Examples of coral reef habitat and sampling

images courtesy of CSIRO Aquatic Earth Observation -Oceans & Atmosphere



images courtesy of CSIRO Aquatic Earth Observation -Oceans & Atmosphere

Seagrass and intertidal: not so simple:

images courtesy of CSIRO Aquatic Earth Observation -Oceans & Atmosphere

End User Requirements

What do Managers Need from Optical Remote Sensing in Aquatic Ecosystems?

- Status, Condition and Trend & Anomalies:
  - **Status (survey, classify and map**)
    - o **what is where? (=99%of current remote sensing effort)**
      - **(is it absent when it should be present) or**
      - **(is it present when it should be absent?)**
  - **Condition:**
    - o **is it healthy?, is it stable?**
    - o **Is it stressed?**
  - **Trend:**
    - o **Is it getting worse or is it improving?**
      - **Remote Sensing can do hind casting and now casting**
      - **Model data fusion and data assimilation needed for forecasting**
  - **Anomalies:**
    - o **Normal (to be expected) or exceptional (indicating exceptional change from before? E.g. climate change indication?)**
- Bathymetry and topography

Variables that can be measured directly using EO in aquatic ecosystems

- Water Column Properties:
  - **Chlorophyll-a, Phaeophytin (all photosynthesizing orgs)**
  - **Cyanophycocyanin & CP-erythrin=>Cyanobacteria**
  - **Total Suspended Matter**
  - **Coloured Dissolved Organic Matter**
  - **Transparency/Turbidity/Vertical Attenuation of Light**
- 3-D Information (if the bottom is visible)
  - **Bathymetry (depth of substrate)**
  - **Bottom Relief (topography)**

R&D:

- Water Column Properties:
  - **Phytoplankton functional types**
  - **Particle size distributions**

Variables that can be measured directly using EO in aquatic ecosystems with bottom visibility

- Benthic substratum
  - **Coastal: Seagrasses, macro-algae and associated substrates & freshwater: macrophytes and associated substrates**
    - **Extent**
    - **Main species differentiation: *if spectrally & spatially discriminable!***
    - **Density of cover; biomass**
  - **Coral Reef and associated substrates**
    - **Extent**
    - **Bleaching**
    - **Main substratum types (Live coral ,dead coral , seagrasses, macro-algae)-main species : *if spectrally & spatially discriminable!***
- Bathymetry

Variables that can be measured directly using EO in supra-to intertidal ecosystems

Intertidal rock platforms and beaches and mudflats

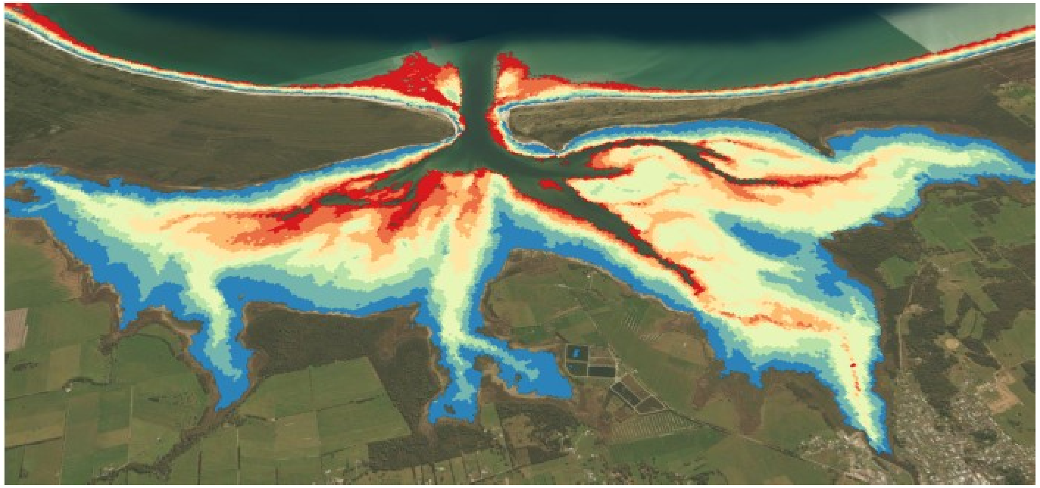
- **Seagrasses, macro-algae, benthic micro-algae and associated substrates & freshwater: macrophytes and associated substrates**
  - o **Extent**
  - o **Main species differentiation:** ***if spectrally & spatially discriminable!***
  - o **Density of cover; biomass**
- **Inter to Supratidal: saltmarsh, mangroves, floodplains**
  - o **Extent**
  - o **Main species differentiation:** ***if spectrally & spatially discriminable!***
  - o **Density of cover; biomass**

End User Requirements

- Generic end-user requirements are known
- Specific EO relevant end-user requirements are scattered across peer reviewed literature, grey literature or undetermined…………needs more work !
- Appendix A: The science and applications traceability matrix is a start but demonstrates the lack of systematic information:
  - the generic end-user needs are well defined.
  - The specific requirements that should translate into Earth Observing System specifications are poorly known………also for shallow water bathymetry

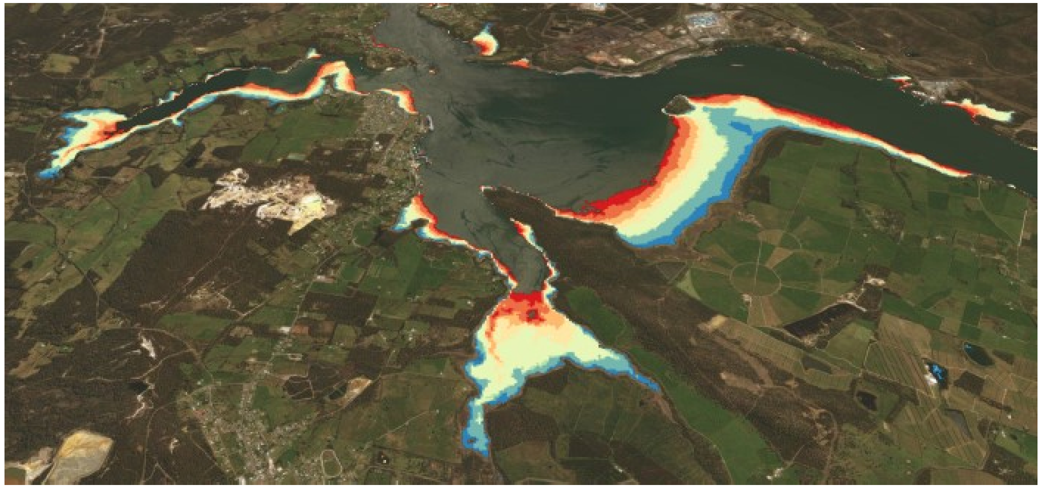
- ! Any help appreciated!: discussion publications, reports, brochures, podcasts, other media sources etc.

Duck Bay, Tas.



Extent of Exposed Intertidal Region
(% of the Observed Tidal Range)

- 0-10%
- 10-20%
- 20-30%
- 30-40%
- 40-50%
- 50-60%
- 60-70%
- 70-80%

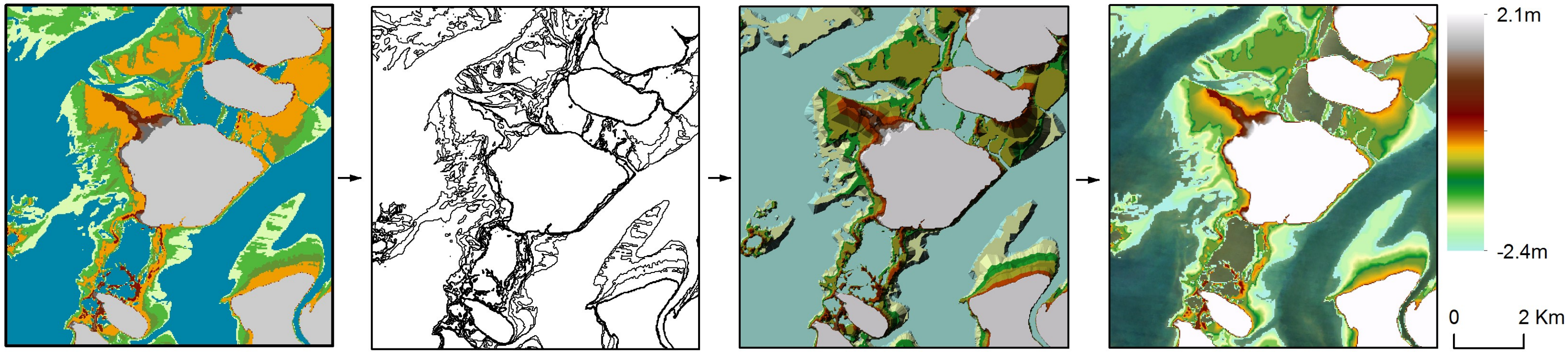


Tamar River, Tas.

Deriving a Digital Elevation Model

Tidal height attribution to each individual observation enable us to evaluate the distribution of the heights within each interval

Each distribution corresponds to the extents of the interval in the Relative Extents model



Relative Extents Model — Median Ensemble Elevation Contours — TIN — MSL Elevation Model

Median heights are used to attribute waterline contours at the boundaries of the intervals extents.

The uncertainty of the extent area is reflected in the standard deviation of the heights used to model the interval.

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From science and applications requirements to design specifications for an EO sensor

Measurement requirement (B= Baseline, T=Threshold)

- Levels/ranges of the desired aquatic ecosystem variable (e.g. concentration, spatial cover etc.)

- Temporal resolution
- Spatial resolution
- Spectral resolution
- Radiometric resolution

- Geolocational accuracy
- Sunglint avoidance
- Polarisation sensitivity

Temporal resolution

Images courtesy of Adam Lewis GeoScience Australia

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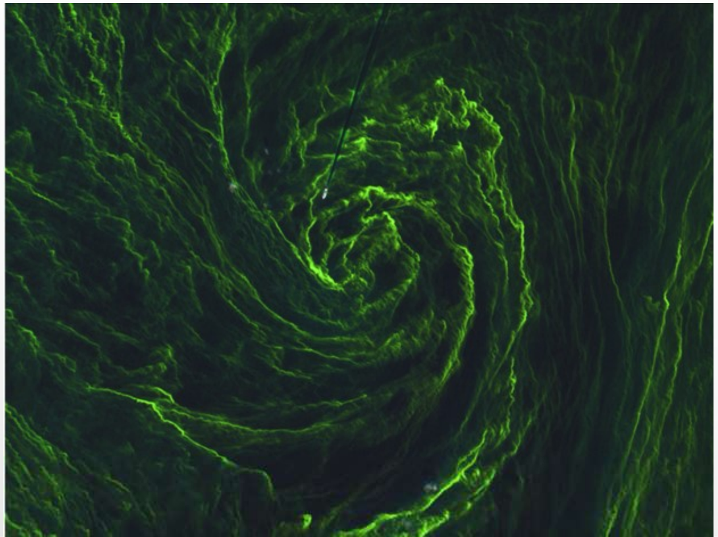
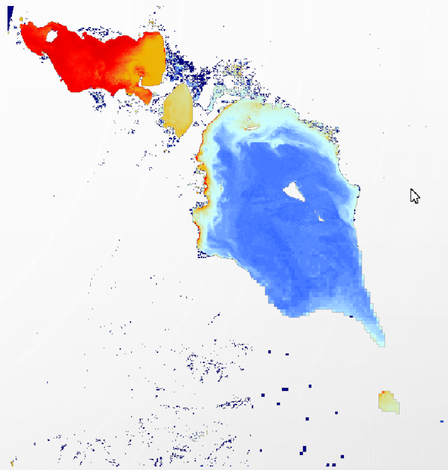
EXAMPLES OF SPACE-BASED IMAGES OF ALGAL BLOOMS





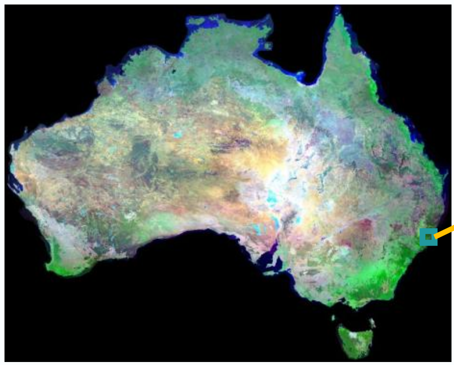
Images courtesy of ESA, Brockman consulting, Steve Greb; Mark Matthews

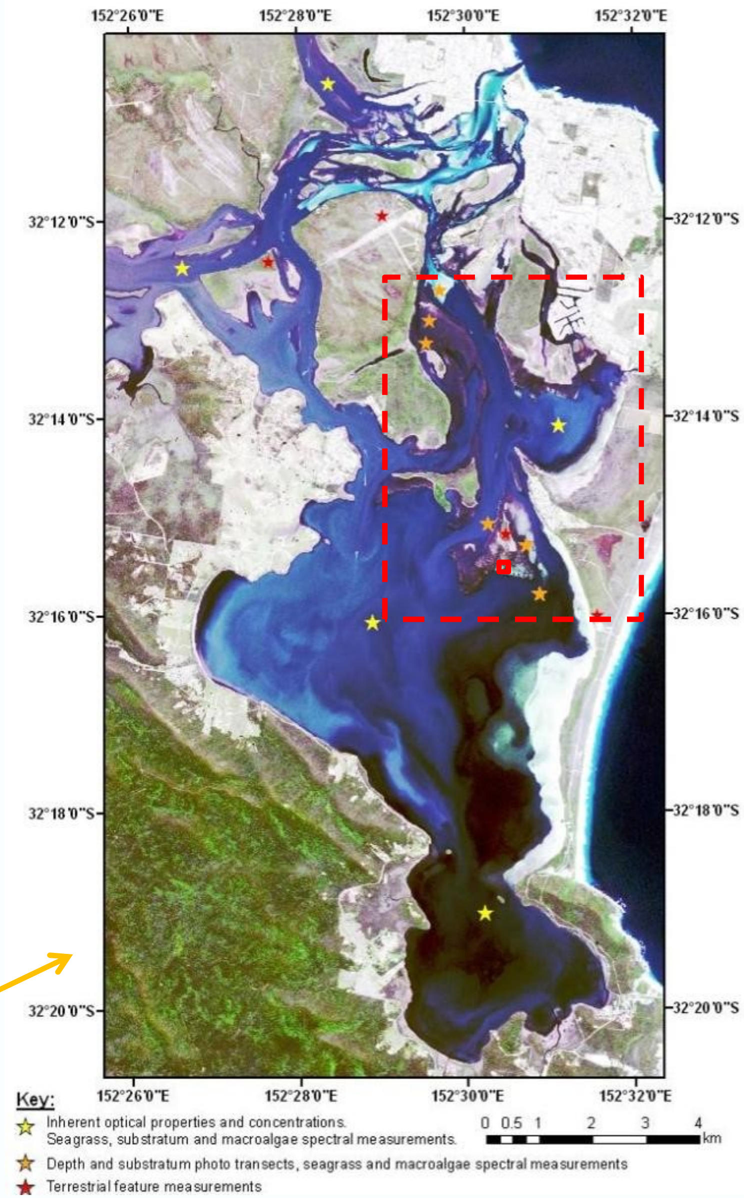
Spatial resolution

Spatial resolution

Study area

Wallis Lake, NSW central coast



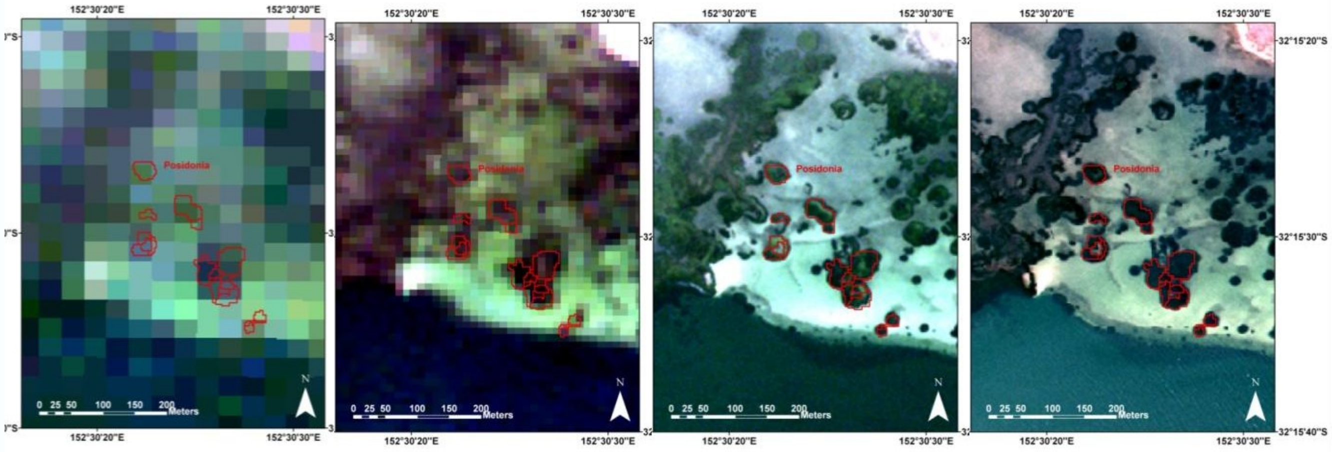


Effects of spatial resolution on feature discrimination: Question: which most suitable for a global mapping mission?

Low cost
Coarse detail

Higher cost
Fine detail

Landsat TM5 20 September 2008	ALOS 5 January 2007	QuickBird-2 20 September 2008	WorldView-2 10 August 2010



Spatial resolution:	**30m**	**10m**	**2.6m**	**1.6m**
Spectral Bands:	**4 VIS/NIR, 2 SWIR, 1 ThIR**	**4 VIS/NIR**	**4 VIS/NIR**	**8 VIS/NIR**

Spatial resolution for inland waters is a key driver for specifications

Table 6.2.

Ground sampling distance requirements showing resolvable size class and total cumulative number and area coverage of the world's lakes (based on assumptions using Verpoorter et al. (2014) dataset). (Courtesy E.L. Hestir & Mark Matthews)

Size Class	Required GSD*	% Total Area	Total number	
≥ 10 km^2	1054 m	44	25,976	Focus of current and future OC sensors
≥ 1 km^2	333 m	60	353,552	
≥ 0.1 km^2	105 m	80	4,123,552	
≥ 0.01 km^2	33 m	90	27,523,552	Focus of this study
≥ 0.002 km^2	15 m	100	117,423,552	

*Calculated using a box of 3 x 3 pixels sufficient to resolve the specified lake size

Ground sampling distance requirements showing the resolvable river width class and cumulative number of total river reaches of the world's rivers from Pavelsky et al. (2012) dataset.

River Reach Size Class (width)	Required GSD*	Total number of reaches	Percent of total reaches	
1.5 km	500	2,877	< 0.1%	
≥ 1 km	333	8,483	<1%	
≥ 0.5 km	167	35,420	1%	Focus of current and future OC sensors
≥ 0.1 km	33	382,466	12%	Focus of this study
≥ 0.05 km	17	766,303	24%	Focus of this study
≥ 0.01 km	3	2,576,452	81%	

*Calculated using a box of 3 x 1 pixels sufficient to resolve the width of the river reach

Spatial resolution

What is optimal spatial resolution for satellite derived shallow water bathymetry?

Taking into account spectral, radiometric and temporal resolution requirements as well?

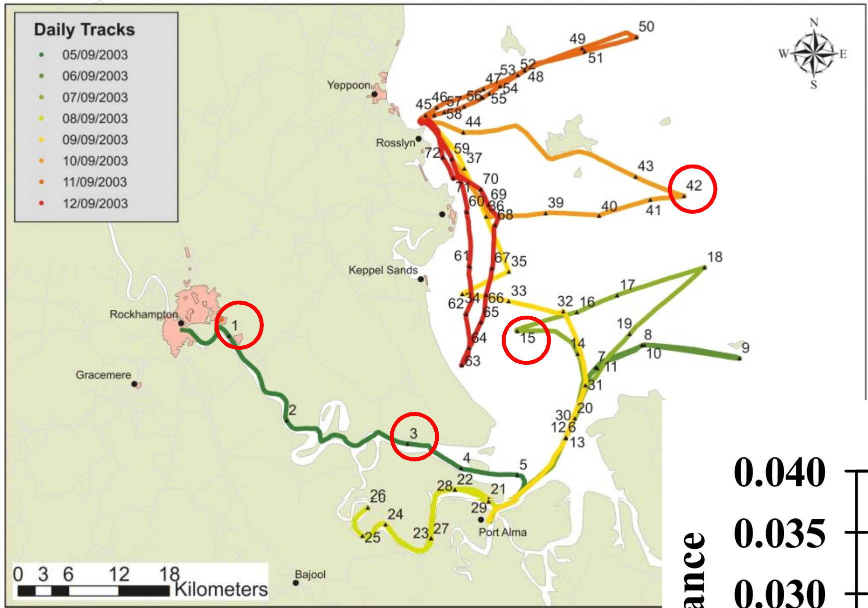
Spatial resolution

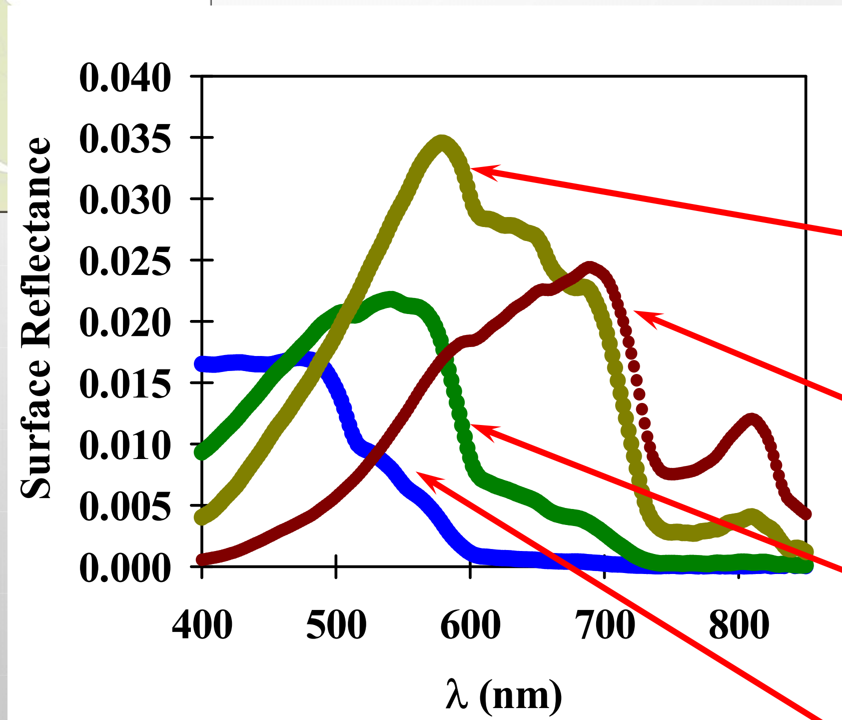
Spectral resolution

September 03:

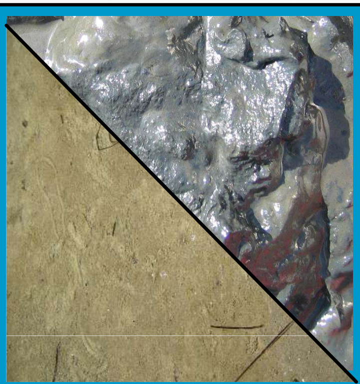
Extensive spatial sampling of IOP and AOP during a 8-day cruise

→ **a system of high variable water types**



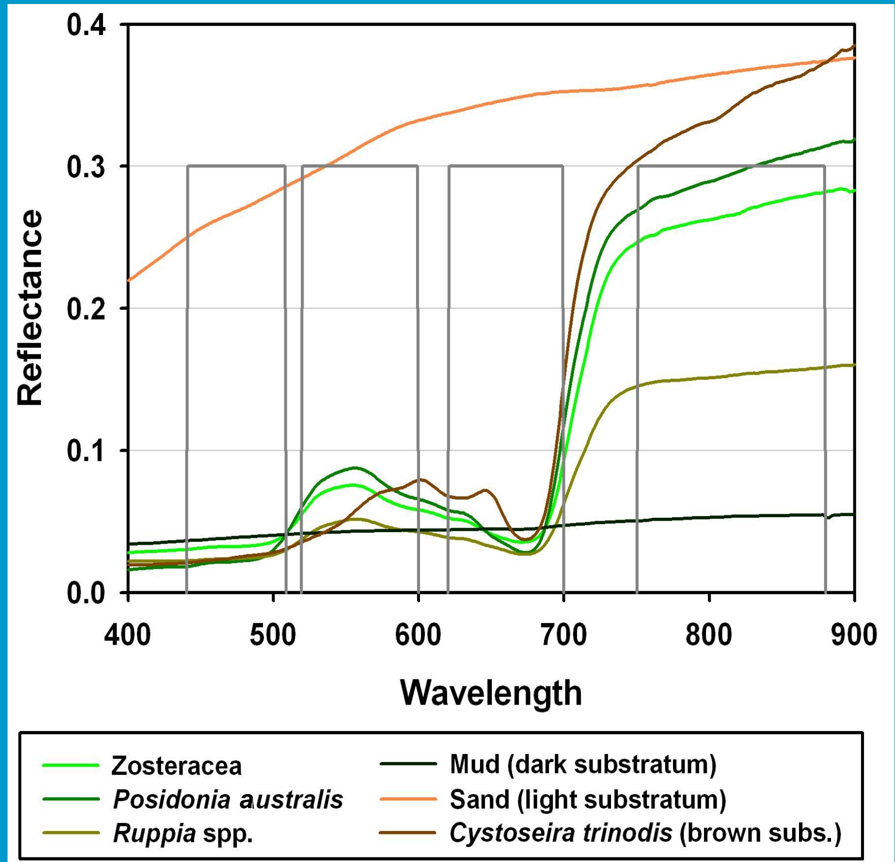


Optical properties of the benthic substratum in Wallis Lake NSW



Sand and mud

Zosteraceae



Posidonia australis

Ruppia megacarpa

Using Bio-optical modelling across coral reef/seagrass/macro-algae/estuarine/freshwater ecosystems (the physics based approach)

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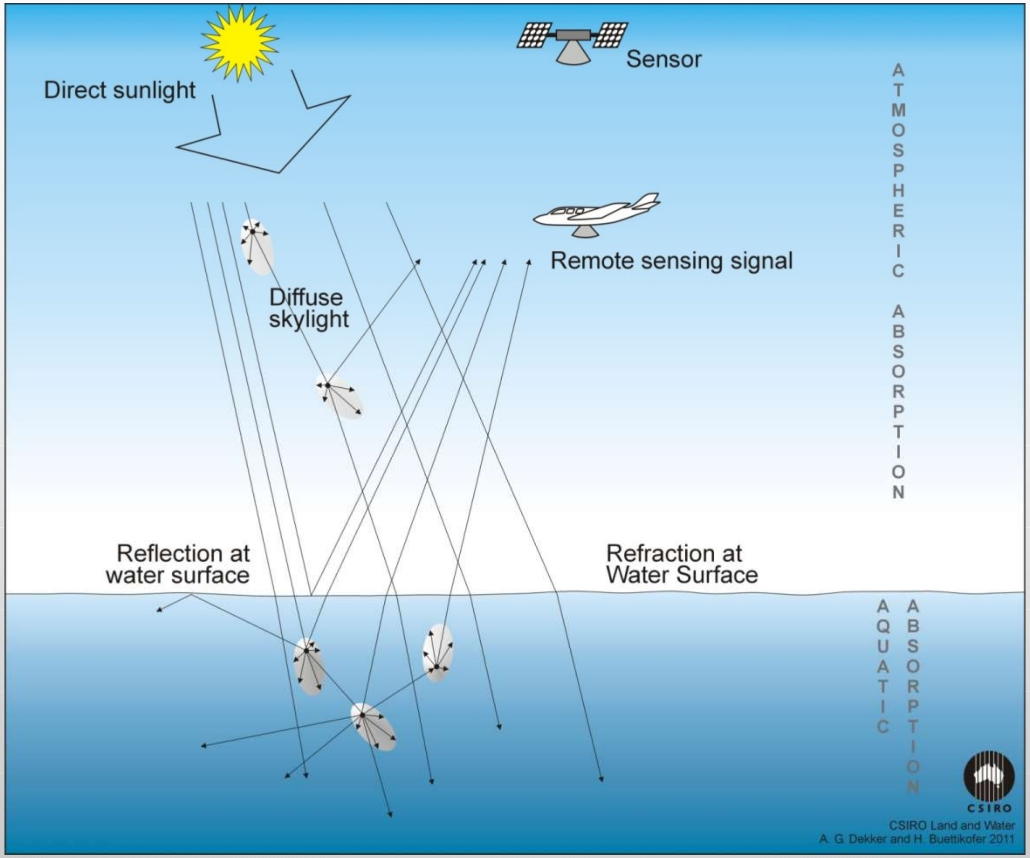
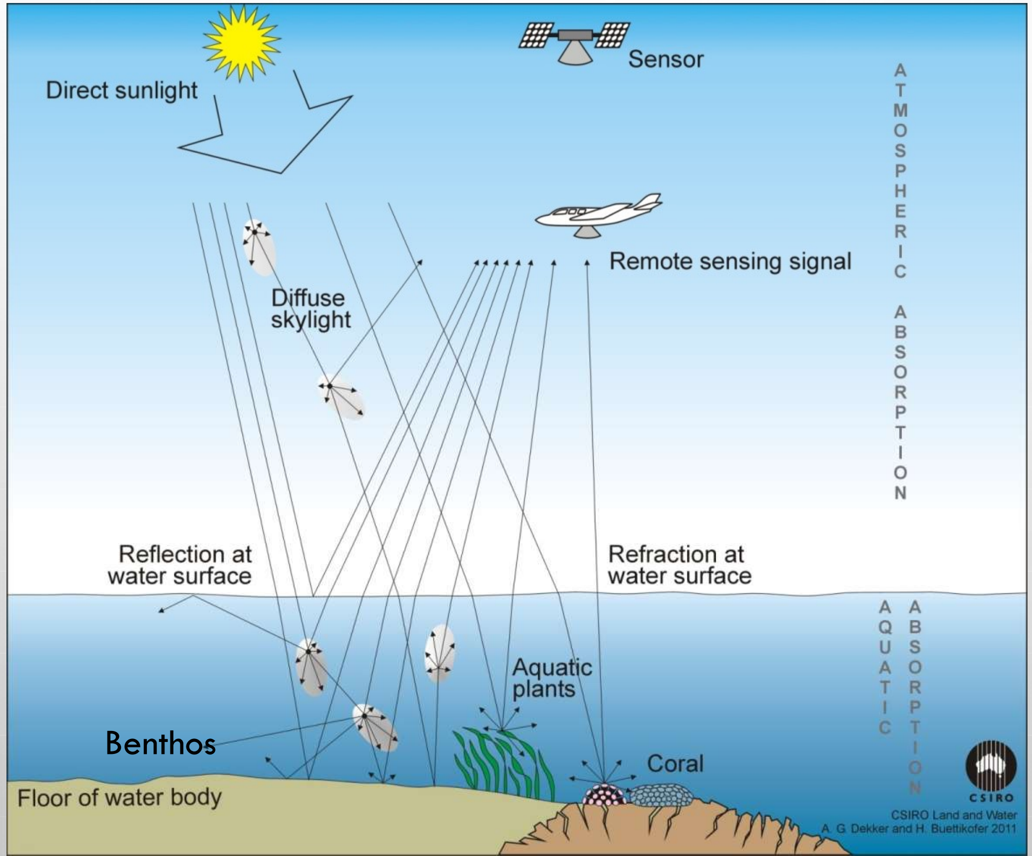
THE CONCEPTUAL PHYSICS-BASED MODEL FOR OPTICALLY DEEP WATERS



CSIRO

THE CONCEPTUAL PHYSICS-BASED MODEL FOR OPTICALLY SHALLOW WATERS (......OPTICALLY DEEP ON THE RIGHT)



Summary spectral bands & resolution from: (i) multiple types of simulations, (2) spectral pigment features (from phytoplankton, macrophytes and other benthos), and algorithm requirements

Centre	FWHM	Water quality and benthic characterisation related application	
[nm]	[nm]		
+/-380	15	CDOM (Mannino et al., 2014) ; NAP; PFT (Wolanin et al., 2016); mycosporin-like amino acids (Dupuoy et al., (2008)	1
+/-412	5 to 8	CDOM (Mannino et al., 2014); PFT (Wolanin et al., 2016)	2
+/-425	5 to 8	CDOM ; Blue Chl-a absorption reference band ; NAP; PFT (Wolanin et al., 2016)	3
+/-440	5 to 8	CDOM (Mannino et al., 2014); Blue Chl-a absorption maximum; PFT (Wolanin et al., 2016)	4
467	5 to 8	Band required to separate Pheaocystis from diatoms (Astoreca et al., 2009); Blue Chl-a absorption band reference band; Accessory pigments	5
+/-475	5 to 8	Accessory pigments ; Blue Chl-a absorption band reference band ; PFT (Wolanin et al., 2016), NAP;	6
+/-490	5 to 8	Blue Chl band-ratio algorithm; PFT (Wolanin et al., 2016), Accessory pigments	7
+/-510	5 to 8	Blue Chl band-ratio algorithm ; NAP ;	8
+/-532	5 to 8	PFT & carotenoids (Wolanin et al., 2016); NAP	9
+/-542	5 to 8	NAP	10
555	5 to 8	NAP (as most algal pigments absorptions are low); Cyanophycoerythrin reference band PFT (Wolanin et al., 2016)	11
565	5 to 8	CPE in vivo absorption maximum and possibly fluorescence (Dierssen et al., 2015)	12

		reference band PFT (Wolanin et al., 2016)	
565	5 to 8	CPE in vivo absorption maximum and possibly fluorescence (Dierssen et al., 2015)	12
+/-583	5 to 8	CPE and CPC reference band; chlorophylls a,b and c (Johnsen et al., 1994); CPE fluorescence (Dierssen et al., 2015)	13
+/-594	5 to 8	PFT (Wolanin et al., 2016)	14
+/-615	5 to 8	CPC in vivo absorption maximum (Hunter et al., 2010)-avoiding chlorophyll- c	15
624	5 to 8	CPC in vivo absorption maximum (Dekker, 1993; Simis 2007), suspended sediment, PFT(Wolanin et al., 2016); chlorophyll c (Johnsen et al., 1994)	16
631	5 to 8	PFT (Wolanin et al., 2016)	17
+/-640	5 to 8	NAP, CPC reference band	18
649	5 to 8	Chl-b in vivo absorption maximum (Johnsen et al., 1994)	19
665	5 to 8	FLH baseline (Gower et al., 1999; Gilerson et al., 2008)	20
676	5 to 8	Red Chl-a in vivo absorption maximum (Johnsen et al., 1994)	21
683	5	Chlorophyll fluorescence (FLH) band (Gower et al., 1999; Gilerson et al., 2008)	22
+/-700	5 to 8	HABs detection; NAP in highly turbid water; reference band for 2 or 3 band Chl-a algorithms	23
+/-710	5 to 8	FLH baseline (Gower et al., 2005); HABs detection; NAP in highly turbid water; reference band for 2 or 3 band Chl-a algorithms	24
+/-748	15	NAP in highly turbid water (Ruddick et al., 2006) ; FLH baseline band (Gilerson et al., 2008)	25
+/-775	15	NAP in highly turbid water (Ruddick et al., 2006);	26

Recommended spectral bands for atmospheric correction purposes as well as Non Algal Particulate matter concentration estimation.

centre [nm]	FWHM [nm]	Atmospheric characterisation and air-water interface effect removal bands	
+/- 360	8	To constrain the SWIR-based aerosol model over turbid waters	1
+/- 368	8	To constrain the SWIR-based aerosol model over turbid waters	2
+/-412	8	NO2	
+/-520	8	Aerosol retrieval	3
+/-575	8	Chappuis band for O3 absorption(Gorshelev et al.(2014)	4
+/-605	8	Chappuis band for O3 absorption (Gorshelev et al.(2014)	5
+/-620	8	Aerosol retrieval	
+/-709	8	Aerosol retrieval	
+/-740	8	Sun glint removal	
+/- 761	3	Sun glint removal	6
+/-775	16	Aerosol retrieval; water vapour reference band	7
+/-820	16	Water vapour absorption	8
+/-865	16	Aerosol retrieval; water vapour reference band; sunglint removal; (Dogliotti et al., 2015)	9
+/-940	16	Water vapour absorption	10
+/-1020	16	water vapour reference band	11
+/-1050	16	water vapour reference band	12
+/-1130	16	Water vapour absorption	13
+/-1135	16	Water vapour reference band	14
+/- 1380	16	Cirrus clouds	15

Spatial resolution

Temporal resolution

Temporal resolution requirements

1. Within hours such as algal blooms, flood events with associated influxes of high nutrient, high coloured dissolved organic matter and suspended sediment loads into reservoirs, estuaries or coastal seas or with tidal or wind driven events.
2. Within days such as pollution events, dredging effects etc.
3. Within weeks such as coral bleaching events (Healthy coloured coral -> bleached coral -> dead coral or recovered coral).
4. Seasonally to yearly to longer term such as successions of phytoplankton functional types or emergence, florescence and decay of macrophytes.
5. For bathymetry???...............

CEOS Report : "Feasibility Study for an Aquatic Ecosystem Earth Observation System: Summary

1. Spectral and spatial resolution are the core sensor priorities

- Spectral
  - ~26 bands in the 380-780 nm wavelength range for retrieving the aquatic ecosystem variables
  - ~15 spectral bands between 360-380 nm and 780-1400 nm for removing atmospheric and air-water interface effects.
  - These requirements are very close to defining an imaging spectrometer with spectral bands between 360 and 1000 nm (suitable for Si based detectors), possibly augmented by a SWIR imaging spectrometer.
- Spatial-
  - ~17 m pixels resolves ~25% of river reaches globally
  - ~33 m pixels resolves the vast majority of water bodies (lakes, reservoirs, lagoons, estuaries etc.) large than 0.2 ha
  - Still maintains radiometric sensitivity

2. Radiometric resolution and range and temporal resolution need to be as high as is technologically and financially possible.
3. A high temporal resolution could be obtained by a constellation of Earth observing sensors e.g. in a various low earth orbits augmented by high spatial resolution geostationary sensors.

(green)	Meets threshold requirements
(yellow)	Suitable for some applications - but does not meet one or more requirements
(orange)	Commercial data costs
(grey)	Unsuitable

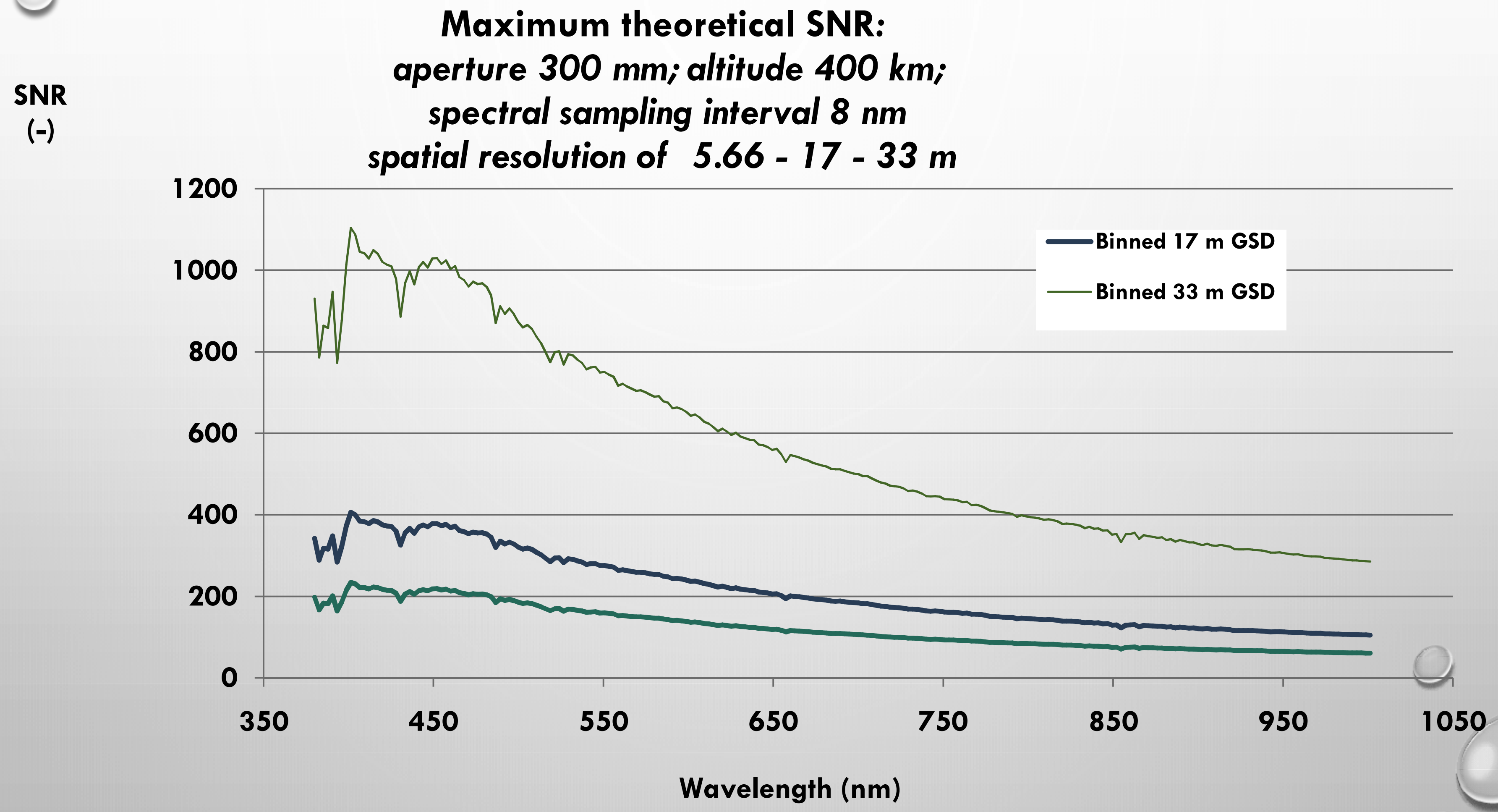
Data currency	Sensor functional type	Sensor Functional Type (= Optical and Nearby Infrared)	Spatial Resolution (= Pixel size)	Spectral bands (water-relevant spectral range (360—1000 nm)	SNR	Revisit frequency cycle (once every x days)	Raw Data Cost per km^2 [USD]	Launch Date
Future	Hyper-spectral Satellite	EnMap	30 m	90		Programmable (once per 4 days)	Free	2020
		PRISMA	20 m spectral–2.5 m B&W	66		25 days/pointing-7 days	Free	2018
		HyspIRI	30	60		16	Free	2022
Future	Hyper-spectral Int.Space Station	HISUI	20 * 30 m pixels	60		orbit between 51 degrees North and South resulting in a 3 to 5 days cadence	Free	2018
Future	Hyper-spectral Int.Space Station	DESIS	30 m	235		orbit between 51 degrees North and South resulting in a 3 to 5 days cadence	Free or Commercial?	2018

Meets baseline requirements	
Meets threshold requirement	1 Highly suited
Suitable for some application	2 Suitable
Commercial data costs	3 Potential
Unsuitable	4 Not suitable

Data currency	Sensor functional type	Sensor Functional Type (= Optical and Nearby Infrared)	Water-quality variables (freshwater, coastal and ocean): *Note based on spectral capability only*						Macrophytes, macro-algae, seagrasses and corals *Note based on spectral capability only*			Shallow water bathymetry *Note based on spectral capability only*
			CHL	CYP	TSM	CDOM	Kd	Turb SD	Emergent	Floating leaved	Submersed	
Future	Hyper-spectral Satellite	EnMap	1	1	1	1	1	1	1	1	1	1
		PRISMA	1	1	1	1	1	1	1	1	1	1
		HyspIRI	1	1	1	1	1	1	1	1	1	1
Future	Hyper-spectral Int.Space Station	HISUI	1	1	1	1	1	1	1	1	1	1
Future	Hyper-spectral Int.Space Station	DESIS	1	1	1	1	1	1	1	1	1	1

TRADE-OFF RESOLUTIONS

Higher spatial resolution = lower radiometric resolution=less depth penetration



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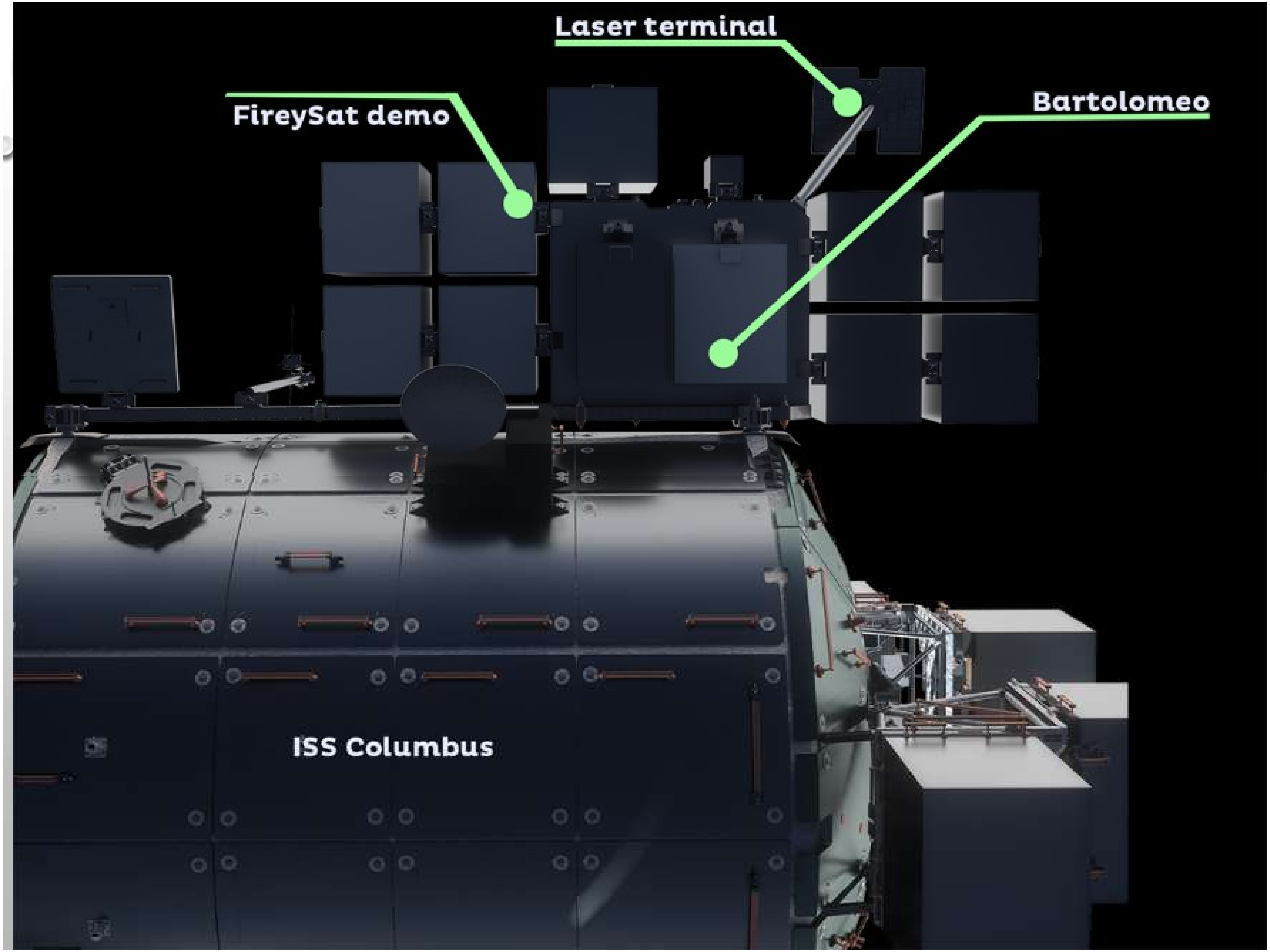
FINER SPATIAL RESOLUTION = LESS PHOTONS
FINER SPECTRAL RESOLUTION = LESS PHOTONS

LESS PHOTONS MEANS REDUCED RADIOMETRIC RESOLUTION=>
LESS DEPTH INTERVALS

- Finer spatial resolution = lower radiometric resolution= less depth penetration but improved identification of smaller benthic features and less water column concentration composition discrimination
- Coarser spatial resolution = higher radiometric resolution=deeper depth penetration but reduced identification of smaller benthic features and improved water column concentration composition discrimination.
- Finer spectral resolution=> higher depth penetration although counteracted by lower radiometric resolution=> lower depth penetration but improved benthic cover and water column concentration composition discrimination.
- Coarser spectral resolution=> higher radiometric resolution => better depth penetration but counteracted by less depth penetration due to broader spectral bands and less detailed benthic cover and water column concentration composition discrimination

e.g. Worldview-3 : high spatial , coarse spectral (~50 nm wide bands)=> medium radiometric resolution

On the International Space Station-the AIRBUS Bartolomeo Module can host payloads. We are working with FireySat on acquiring funding for a swarm of satellites with appropriate specifications- possibility for dedicated shallow water bathymetry satellites: DESIS on ISS (ready for use January 2019) could be a excellent precursor.


Laser terminal
FireySat demo
Bartolomeo
ISS Columbus

What are (future) shallow water bathymetry satellite sensor requirements?

See: http://ceos.org/about-ceos/publications-2/

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