Challenges and Recommendations for Remote Sensing of Optically Complex Waters

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Current state of aquatic visible remote sensing

- Almost all coastal and inland research and operational activities require aquatic color remote sensing capabilities that are not routinely available.
- Progress has been limited by the capability of the satellite sensors in orbit. To answer questions focused on coastal and inland waters, one is left to adapt existing capability to systems in which they were not intended.
- Despite these limitations, impressive progress has been made.
- The optical complexity requires improved spectral resolution while the physical processes acting require smaller spatial and temporal scales than are currently in orbit.

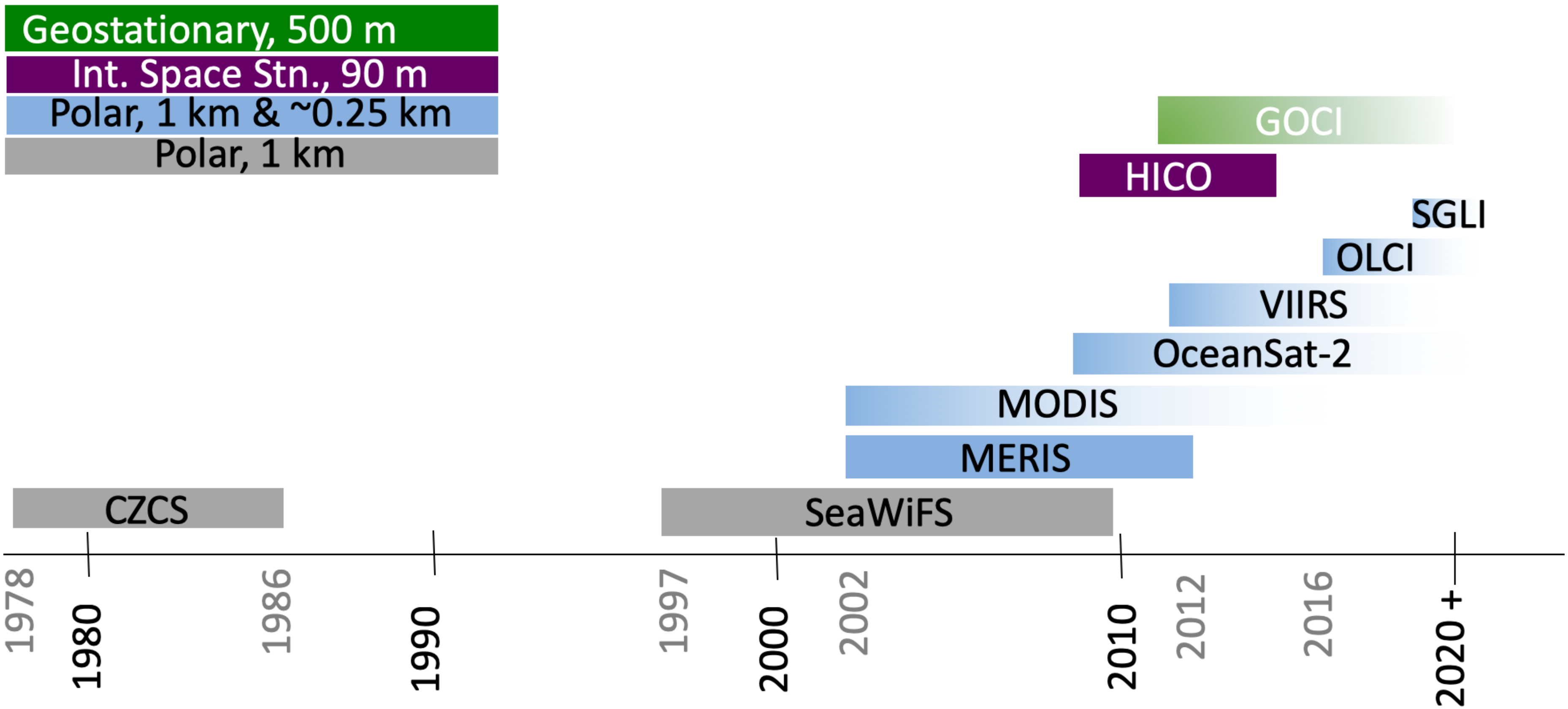
Sensors and satellite platforms that have been used and are available for inland, transitional and coastal waters

Sensor	Satellite	Resolution			
		Spectral (nm)	**Temporal (days)**	**Radiometric**	**Spatial (m)**
PACE	Worldview-3	450–800 (8)	1	14-bit	0.3
Quickbird	Quickbird	450–900 (5)	1–3.5	11-bit	0.7
SPOT 6	SPOT 6	455–890 (4)	01-May	12-bit	1.5
SPOT 7	SPOT 7	455–890 (4)	01-May	12-bit	1.5
IKONOS	LM900	445–928 (5)	1	11-bit	3
LISS 4	IRS-P6	520–680 (3)	5	10-bit	5.8
HRG	SPOT 5	480–1750 (5)	02-Mar	8-bit	10
ETM	Landsat 7	450–2350 (8)	16	8-bit	10
Aster	Terra	520–1165 (14)	16	8-bit	15
OLI	Landsat 8	435–2294 (9)	16	12-bit	15
CHRIS	Proba-1	415–1050 (19)	7	12-bit	18
LISS 3	IRS-P6	520–1700 (4)	24	7-bit	23.5
Hyperion	EO-1	400–2500 (220)	16	12-bit	30
ALI	EO-2	430–2350(9)	16	11-bit	30
HICO	ISS	300–1000 (87)	3	14-bit	100
TIRS	Landsat 8	1060–1251 (2)	16	12-bit	100
MODIS	Terra/Aqua	405–14,385 (36)	16	12-bit	250
MERIS FS	Envisat	390–1040 (15)	3	16-bit	260
OCM	IRS-P4	400–900(8)	2	12-bit	360
VIIRS	NPP and JPSS	402–11,800 (22)	1	12-bit	370
WiFS	SeaWiFS	402–885 (8)	2	10-bit	1000
AVHRR 3	NOAA-18	580–1250 (6)	1	12-bit	1100
MERIS RR	Envisat	390–1040 (15)	3	17-bit	1200
SEVIRI	METEOSAT	400–1600 (4) 3900–13,400 (8)	0.001	10 bit	1000 3000
MCI	Sentinel 2	425–1405 (13)	2 systems 5 days	12 bit	Oct-60
OLCI	Sentinel 3	400–1020 (21)	3 systems <2 days	16 bit	300

terrestrial
atmospheric
aquatic

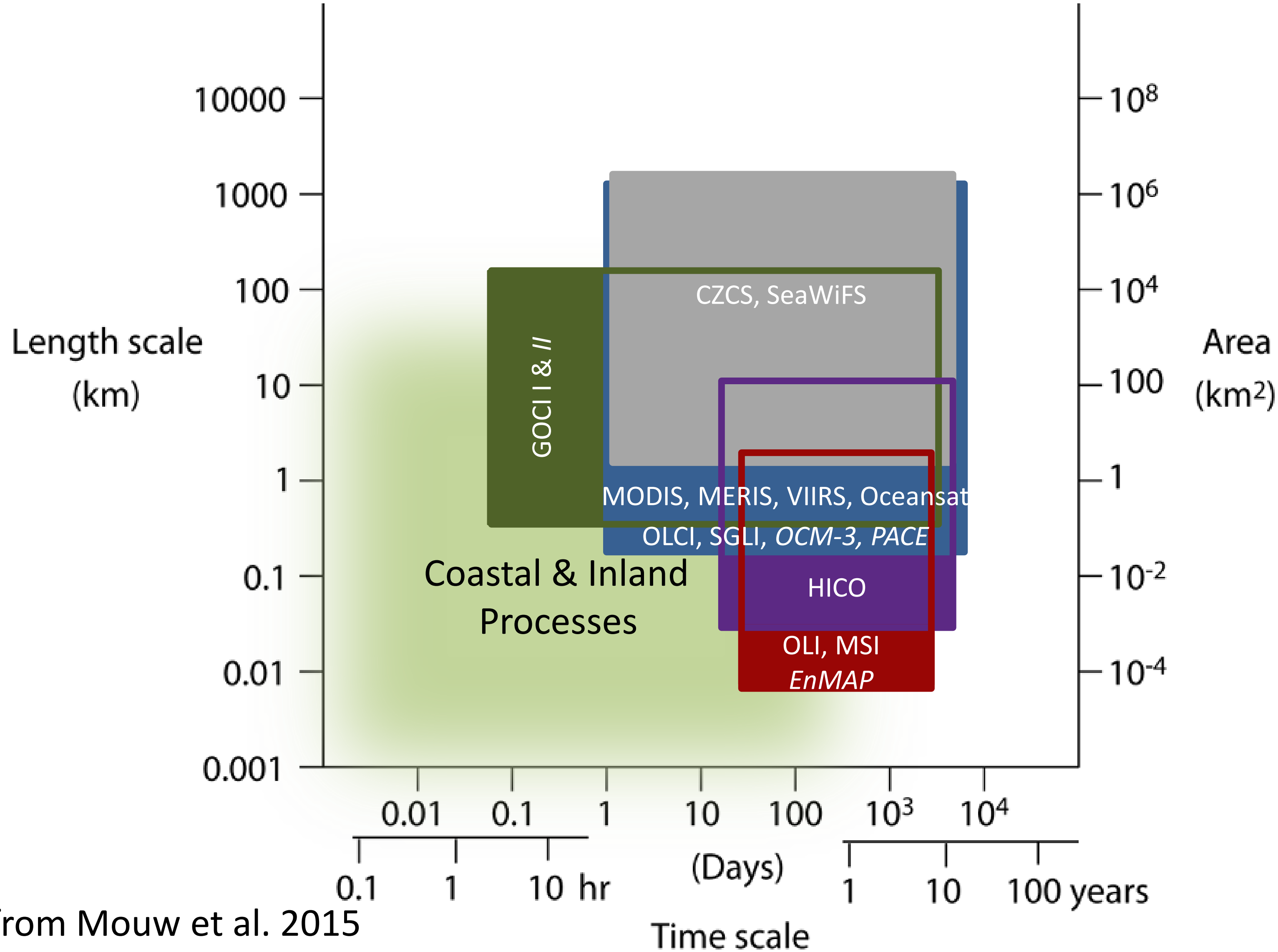
Tyler et al. 2016

Current Missions



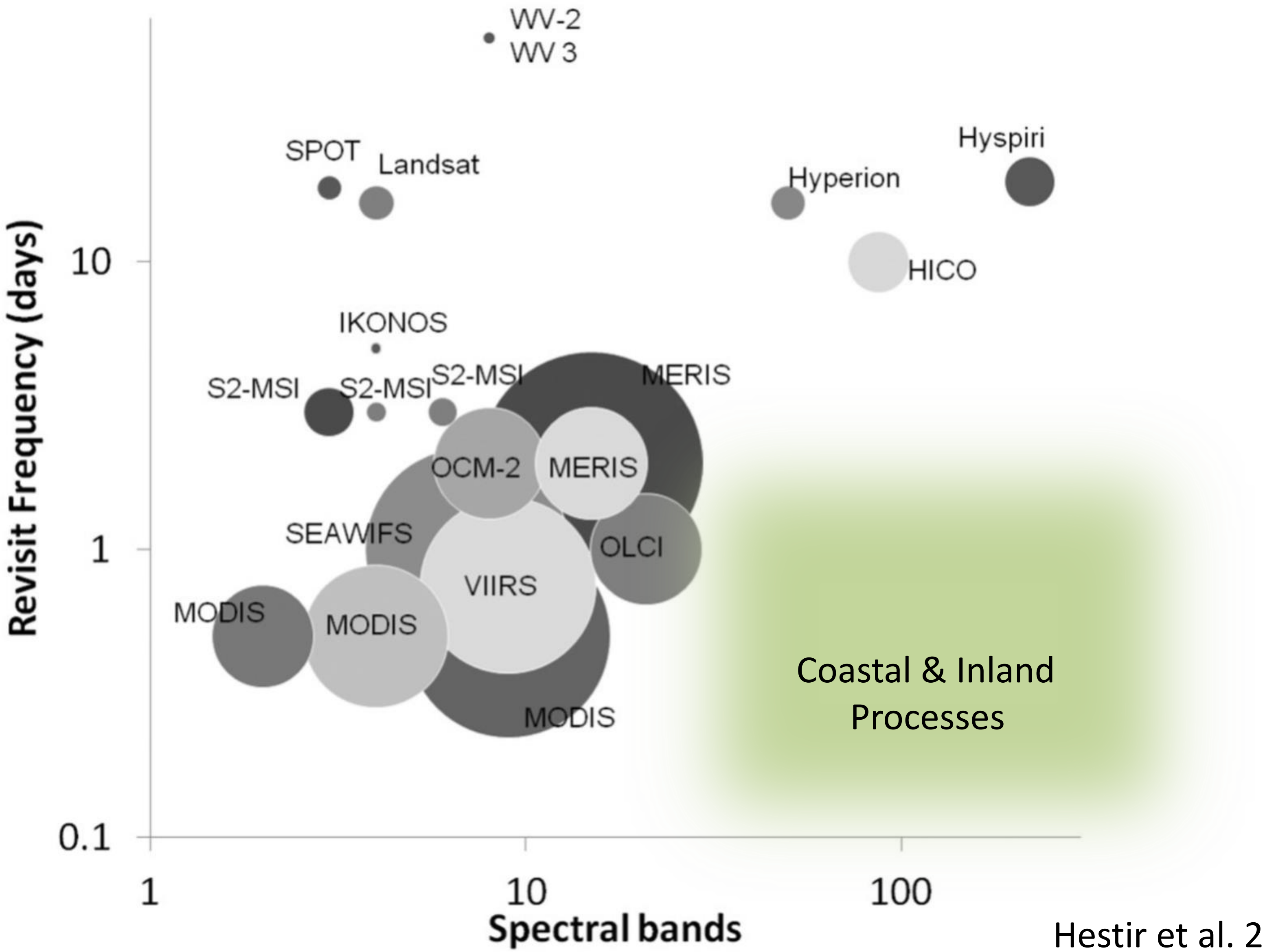
Mouw et al. in IOCCG, in review

Spatial and Temporal Resolution



Updated from Mouw et al. 2015

Spectral and Temporal Resolution



Hestir et al. 2015

H4 Imaging

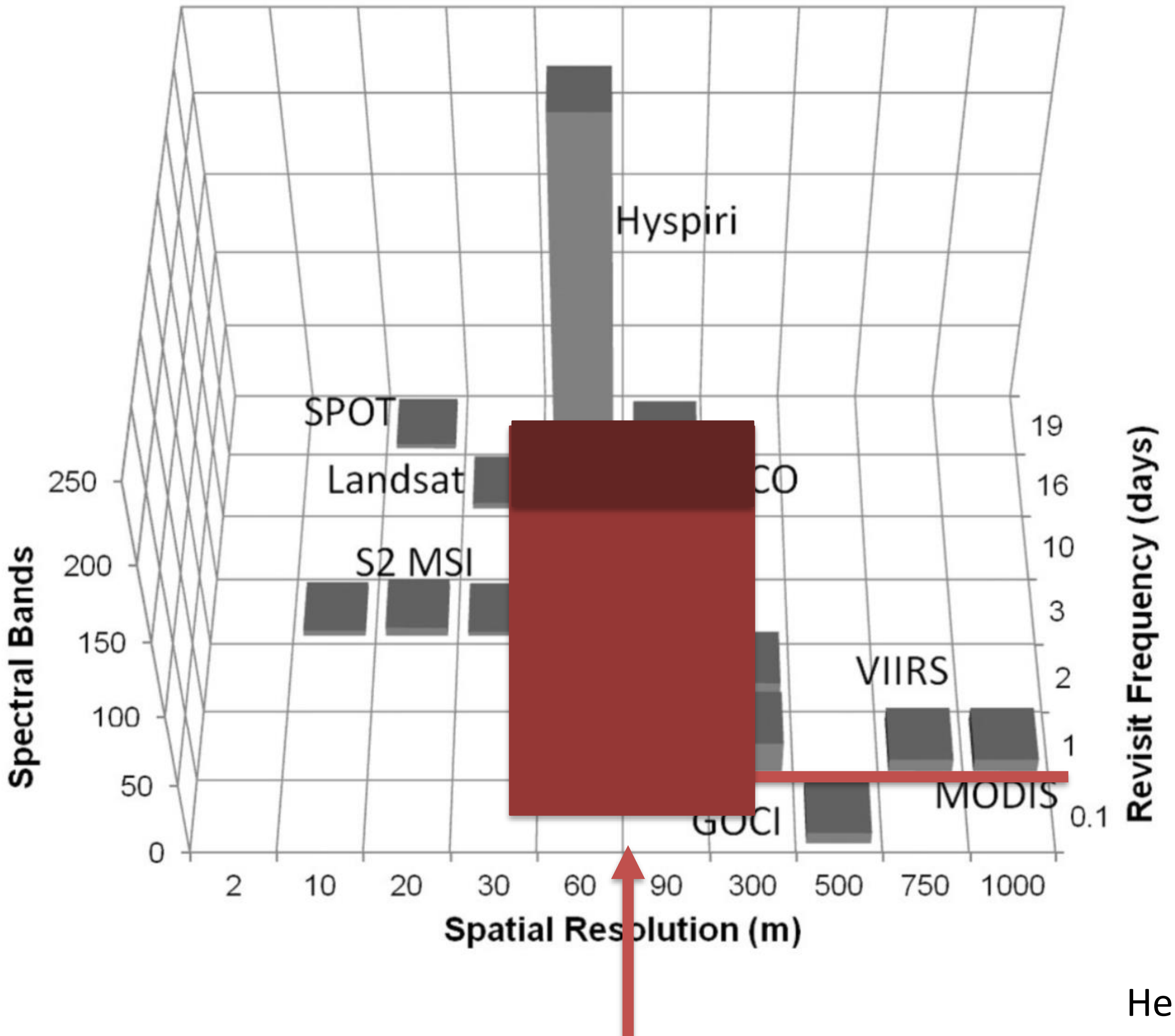
Current and planned satellites are not designed to observe parameters that change rapidly with extreme tides, salinity, temperatures, storms, pollution, or physical habitat destruction over scales relevant to human activity.

Making these observations requires a new generation of satellite sensors able to sample with these combined characteristics:

1) Spatial resolution on the order of 30 to 100-m pixels or smaller
2) Spectral resolution on the order of 5 nm in the visible and 10 nm in the short-wave infrared spectrum (or at least two or more bands at 1,030, 1,240, 1,630, 2,125, and/or 2,260 nm) for atmospheric correction and aquatic and vegetation assessments
3) Radiometric quality with signal to noise ratios (SNR) above 800 (relative to signal levels typical of the open ocean), 14-bit digitization, absolute radiometric calibration <2%, relative calibration of 0.2%, polarization sensitivity <1%, high radiometric stability and linearity, and operations designed to minimize sun glint
4) Temporal resolution of hours to days

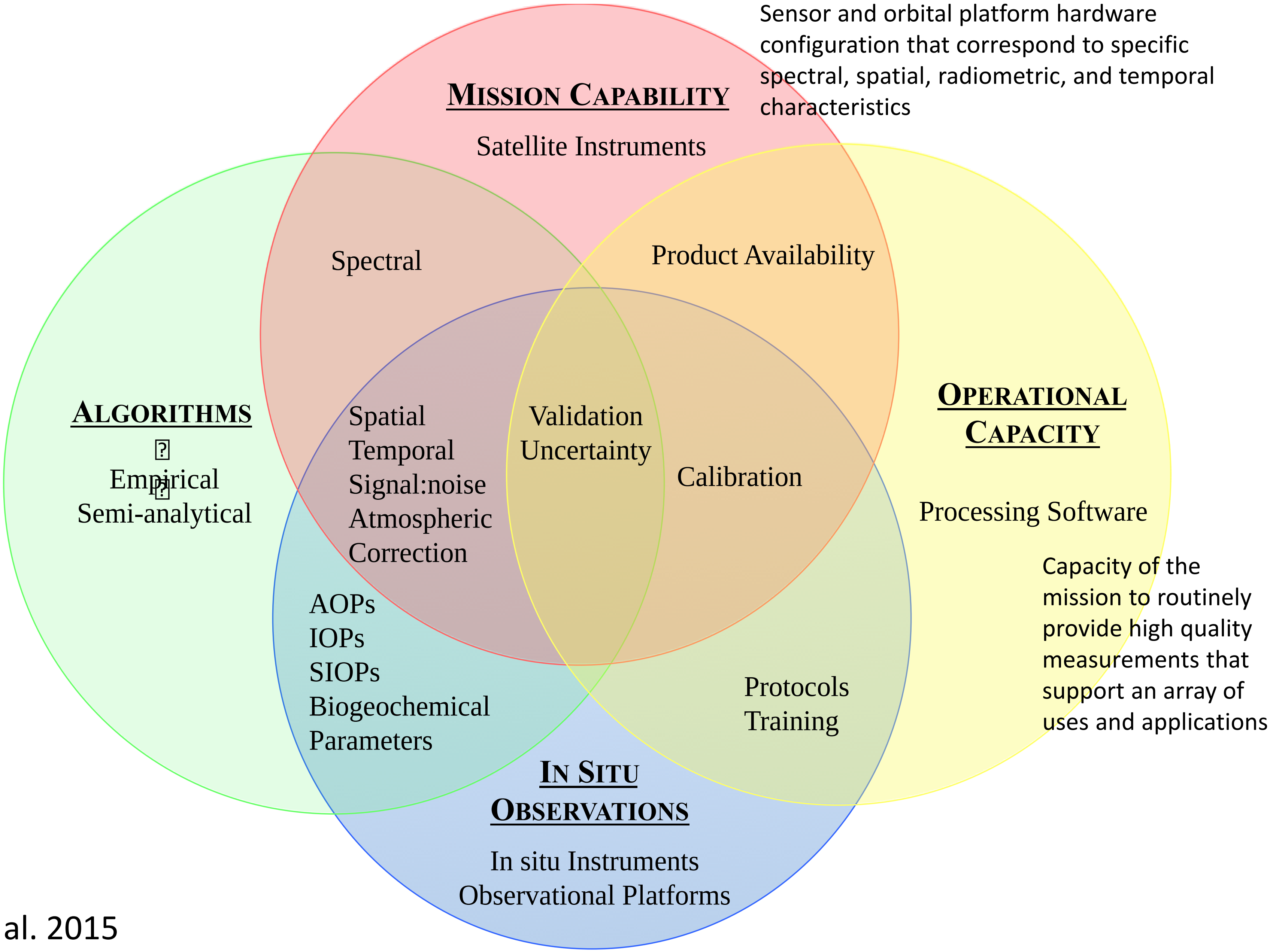
Muller-Karger et al., 2017

Spatial, Spectral and Temporal Resolution



Hestir et al. 2015

Fundamental Elements of Satellite Remote Sensing



Mouw et al. 2015

Mission Capability

Previous/Existing	Desired	Needed
300 m – 1 km, multispectral, polar orbiting.	100 – 500 m, polar orbiting and geostationary with greater spectral resolution and coverage, wide dynamic range and high signal to noise to allow for detection across broad parameter ranges.	Investment in geostationary and coastal/inland focused missions to optimize coverage, resolution and availability of new and improved measurements.

Mouw et al. 2015

Algorithms

Previous/Existing	Desired	Needed
Multiple approaches optimized to different datasets for various regions.	A menu of algorithm choices with clear information about their respective strengths and limitations.	• Coordinated algorithm comparison to condense and clarify strengths and limitations and identify fit for purpose options. • Research into biogeochemical property variability and relationships with optical properties.

Mouw et al. 2015

In Situ Observations

Previous/Existing	Desired	Needed
• Non-coordinated, multi-agency efforts with data going to many different data repositories, if any and often with limited public data access. • Some coincident observations but not all minimum required observations.	• Limited number of centralized publically-available data repositories ensuring access to consistent high quality data. • Protocols that cover a dynamic range of variability. • At minimum, collect coincident observations of the standard suite of parameters; if possible collect a broader suite of data products.	• Invest in technology development to address instrumentation gaps; such as sensors designed for high turbidity waters, and hyperspectral b_b. • Clear, consistent and coordinated data sharing policies across agencies. • Update protocols. • Investment in sustaining and increasing observation networks.

Mouw et al. 2015

Standard *In Situ* Observations

Recommended standard in situ observations for algorithm development, refinement and validation.

	Minimum parameters	Additional parameters
AOPs	$R_{rs}(\lambda)$, $K_d(\lambda)$, Z_{eu} (or $Z_{10\%}$)	
IOPs	$a(\lambda)$, $a_{CDOM}(\lambda)$, $a_{NAP}(\lambda)$, $a_{ph}(\lambda)$, $b_{bp}(\lambda)$	$b_{bp,NAP}(\lambda)$, $b_{bp,ph}(\lambda)$
Biogeochemical	[Chl], TSM, POM, PIM, DOM, DIM	HPLC pigments, primary productivity

*Spectral parameters should be observed at the highest spectral resolution allowed by the instrumentation or at 2–5 nm increments.

Mouw et al. 2015

Operational Capacity

Previous/Existing	Desired	Needed
• Global - open ocean mission /product heritage. • Tailored products available for some regions and applications. • Support and training often geared more to expert users. • Limited access to some satellite color data streams, especially in NRT mode. Mouw et al. 2015	• Routine and sustained delivery of high-quality operational color data in NRT and delayed modes for coastal and inland waters. • Development of merged/blended remote sensing and integrated remote sensing-in situ (information) products. • Development of robust color-derived proxies and indicators. • Optimal algorithms identified for most/all coastal and inland regions with limitations and uncertainties clearly indicated.	• Ongoing coordinated field observations for each coastal/inland region to ensure continual validation. • Identification of best performing practices and approaches and continual evaluation as new approaches are developed. • Facilitate user data/product access and utilization, including development of application portals. • Expanded user outreach and training. • Free, open and timely access (NRT and delayed modes) to all satellite color data streams. • Implement user-driven community of practice for remote sensing of coastal and inland water to facilitate communication, best practices and harmonization efforts.

Prioritized Implementation

<table>
<tr><th>Priority</th><th>Immediate</th><th>Near-term</th><th>Long-term</th></tr>
<tr><td>1</td><td>In Situ Observations: Establish limited number of centralized publically available data repositories.

Operational Capacity: Provide more training opportunities for non-specialists.</td><td>In Situ Observations: Invest in data collection in complex waters and the characterization of MSIOP variability.

Operational Capacity: Work to ensure free, open and timely (NRT or other) access to all satellite color data streams.</td><td>Mission Capability: Ensure satellite mission capability with flexibility to handle appropriate sensitivity, spectral, spatial and temporal scales found in coastal and inland systems. Move toward sensor agnostic designs with greater spectral resolution and coverage that could be resampled for various applications.</td></tr>
<tr><td>2</td><td>In Situ Observations: Establish standard measurements for any in situ campaign supporting remote sensing. Update community (NASA et al.) protocols to include consideration of the dynamic range of properties encountered in these systems and extend to include biogeochemical properties.</td><td>Operational Capacity: Identify best practices and approaches for use of color remote sensing data in applications. Develop decision support information and tools for algorithm and product selection. Develop application portals to facilitate access and fit for purpose use of color remote sensing data and derived products.</td><td></td></tr>
<tr><td>3</td><td>Operational Capacity: Establishment of a user-driven community of practice for remote sensing of coastal and inland waters to link freshwater and marine, satellite and in situ data, data providers and users, science and societal considerations, to work collaboratively with IOCCG, space agencies et al.</td><td>Algorithms: Perform an algorithm intercomparison for consolidation and/or simplification of algorithm choices.

In Situ Observations: Create a ‘NOMAD-like’ dataset/s with coincident observations for the inland/coastal waters.</td><td>Mouw et al. 2015</td></tr>
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Recommendations - Future Satellite Missions

- ***Mission Capability:*** Ensure planned geostationary missions proceed.
- ***In Situ Observations:*** Data sets should be as comprehensive as possible (temporal, spatial, cover large dynamic ranges), moved toward autonomous platforms, protocol improvement, centralized database regardless of agency.
- ***Algorithms:*** A comparison exercise to document algorithms fit for use, in addition to consolidation and simplification of the range of algorithm options. Place focus on product continuity rather than algorithm continuity.
- ***Operational Capacity:*** Provide greater training opportunities at broad audience event. Panel of experts to provide recommendations on the 'fit for application'. Develop application portals and accompanying decision support tools

Mouw et al. 2015

Resources / Acknowledgements

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