PERSPECTIVES ON HYPERSPECTRAL REMOTE SENSING

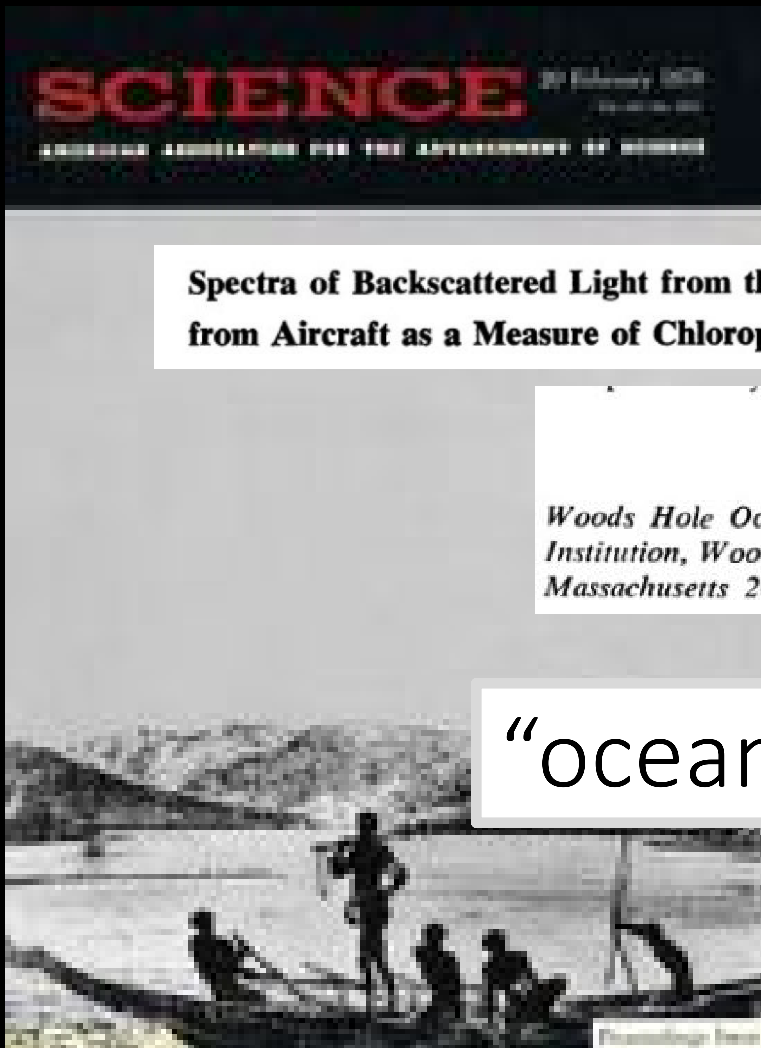
SLS 2026!

Jeremy Werdell
NASA Goddard Space Flight Center

13 July 2026

outline and goals

I will …	so you …
present the evolution of satellite instrument tech	understand how and why ocean color products evolved over time
share community thoughts on why “we need” hyperspectral information	know why we fought for it
explore why hyperspectral instruments differ	wrap your head around the vast consumer’s market
describe why OCI is what it is	learn how to best take advantage of it
provide examples of opportunities and gaps	get jazzed to take advantage of the opportunities and fill the gaps
run a “shark tank” exercise	develop intuition for the landscape of opportunities and challenges



Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration

George L. Clarke
Gifford C. Ewing
Carl J. Lorenzen
Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 20543

“ocean color”

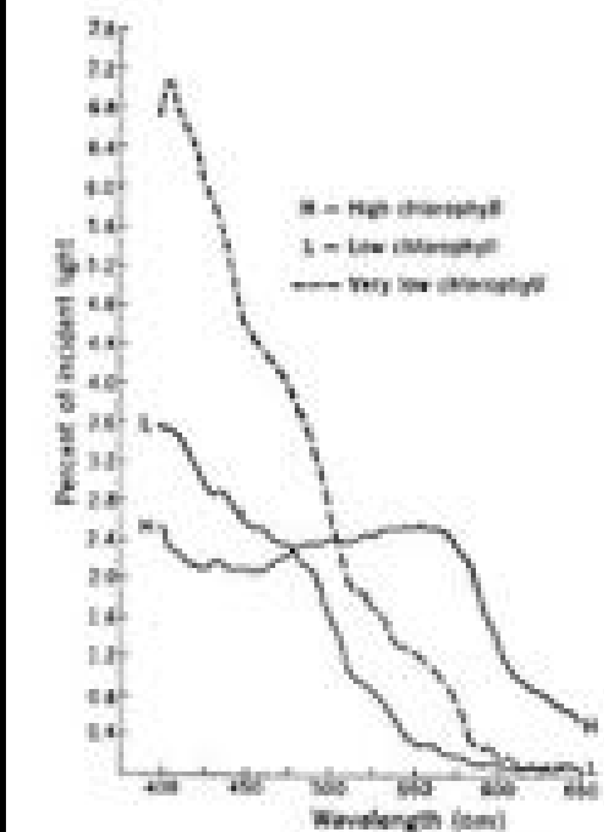
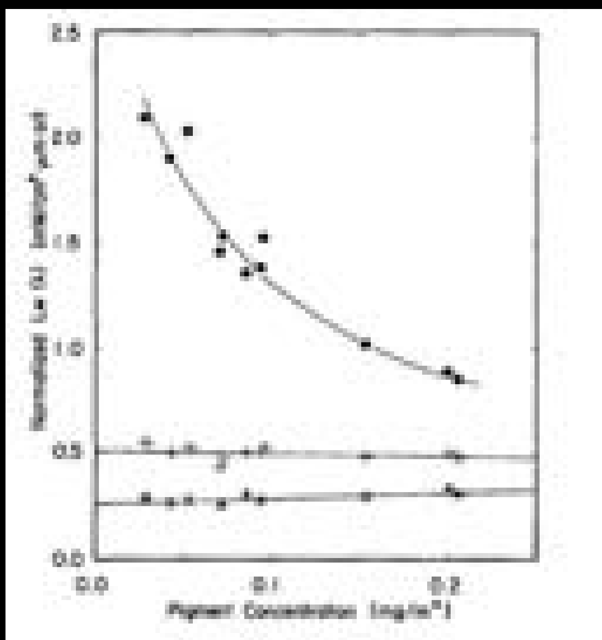


Fig. 3. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream.

Clear water radiances for atmospheric correction of coastal zone color scanner imagery

Howard R. Gordon and Dennis K. Clark

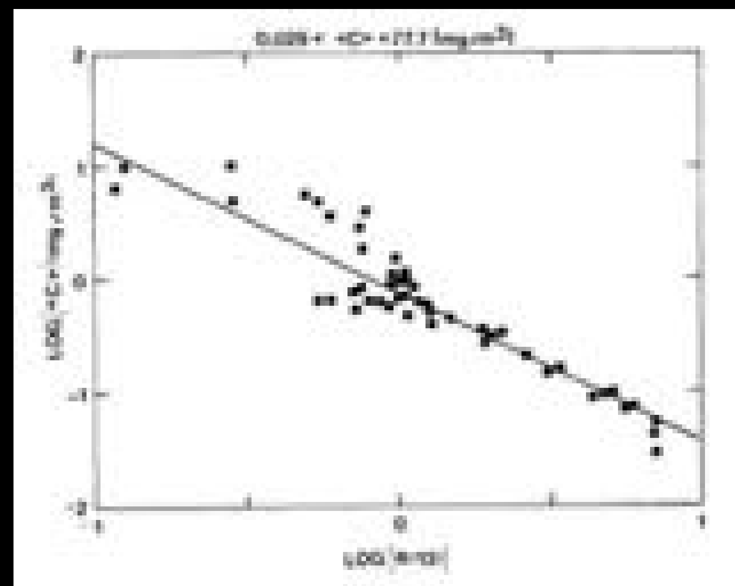
15 December 1981 / Vol. 20, No. 24 / APPLIED OPTICS 4175



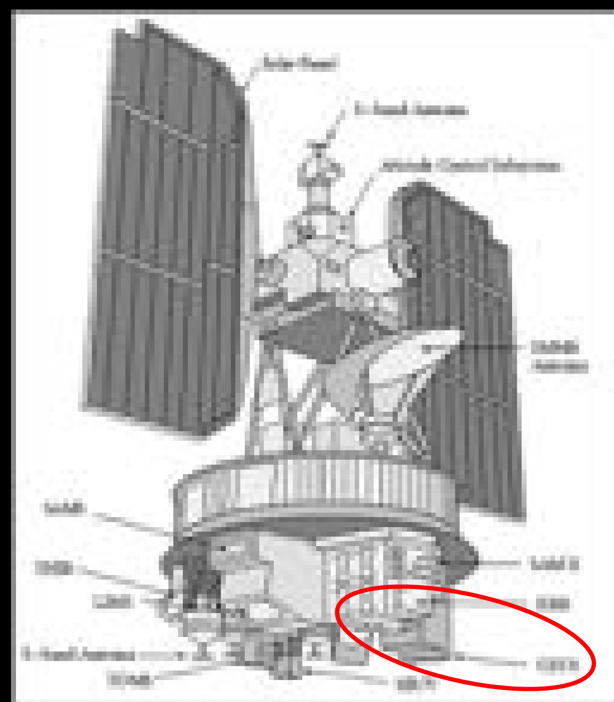
Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determinations and CZCS estimates

Howard R. Gordon, Dennis K. Clark, James W. Brown, Otis B. Brown, Robert H. Evans, and William W. Broenkow

20 APPLIED OPTICS / Vol. 22, No. 1 / 1 January 1983



Coastal Zone Color Scanner
1978-1986



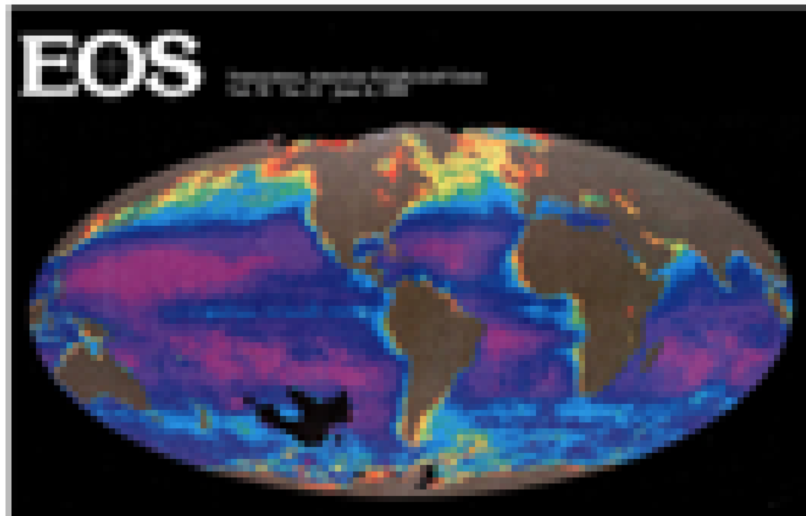
metric	CZCS
primary ocean bands (nm)	443, 520, 550, 670
○ chl-a + phaeopigments ○ diffuse attenuation at 490 nm	
nadir res.	825 m
nadir swath	1636 km discontinuous operation
tilt	$\pm 20^{o}$ in 2^{o} increments
det. per band	1
digitization	8 bits

NIMBUS 50

revolutionized perceptions of the ocean

Satellite Color Observations of the Phytoplankton Distribution in the Eastern Equatorial Pacific During the 1982–1983 El Niño

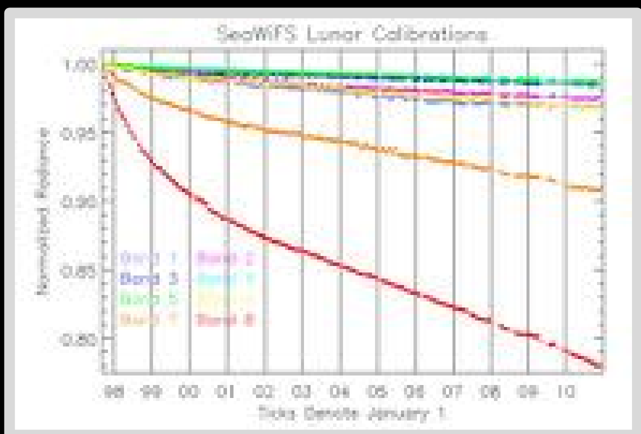
first ever look at global distribution of marine phytoplankton, ocean productivity



Feldman et al. 1984 and 1989

SeaWiFS
1997-2010

- lunar calibration
- system vicarious calibration

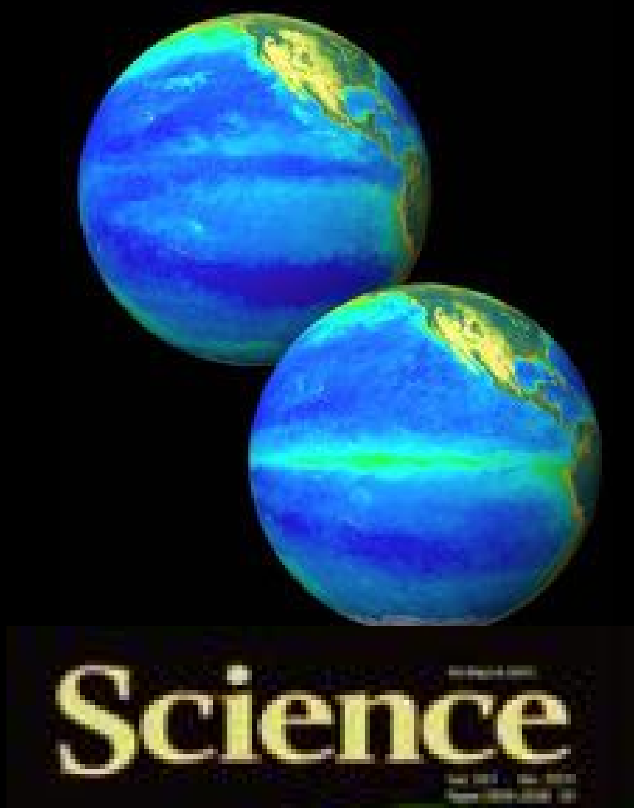


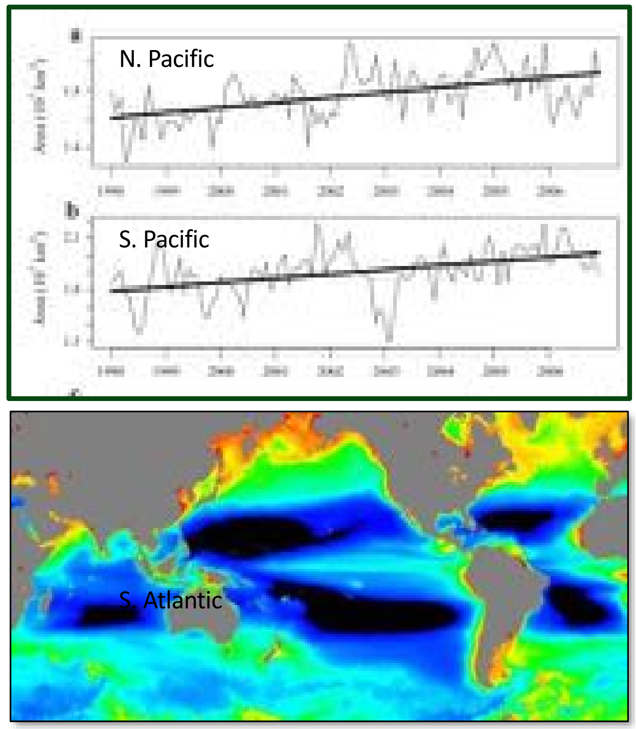
metric	CZCS	SeaWiFS
primary ocean bands (nm)	443, 520, 550, 670	412, 443, 490, 510, 555, 670, 765, 865
		+ aquatic inherent optical properties + carbon: POC, PIC + photosynthetically available radiation
nadir res.	825 m	1100 m
nadir swath	1636 km discontinuous operation	1500 km GAC (2-day global) 2875 km LAC
tilt	$\pm 20^{o}$ in 2^{o} increments	$\pm 20^{o}$
det. per band	1	4 (TDI) = 1
digitization	8 bits	10 bits GAC 12 bits LAC

- black pixel assumption revisited
- spectral inversion modeling
- coupled atmosphere-ocean retrievals
- wind speed dependent Sun glint mask
- ocean bidirectional reflectance

Biospheric Primary Production During an ENSO Transition

Michael J. Behrenfeld,[1*] James T. Randerson,[2] Charles R. McClain,[1] Gene C. Feldman,[1] Sietse O. Los,[3] Compton J. Tucker,[1] Paul G. Falkowski,[4] Christopher B. Field,[5] Robert Frouin,[6] Wayne E. Esaias,[1] Dorota D. Kolber,[4] Nathan H. Pollack[7]



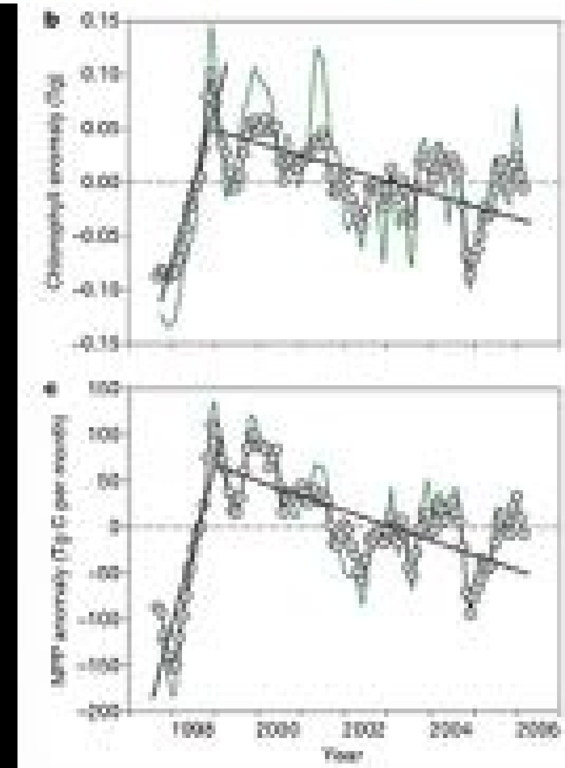


Polivina et al. 2008, Geophy. Res. Letters

Climate-driven trends in contemporary ocean productivity

nature

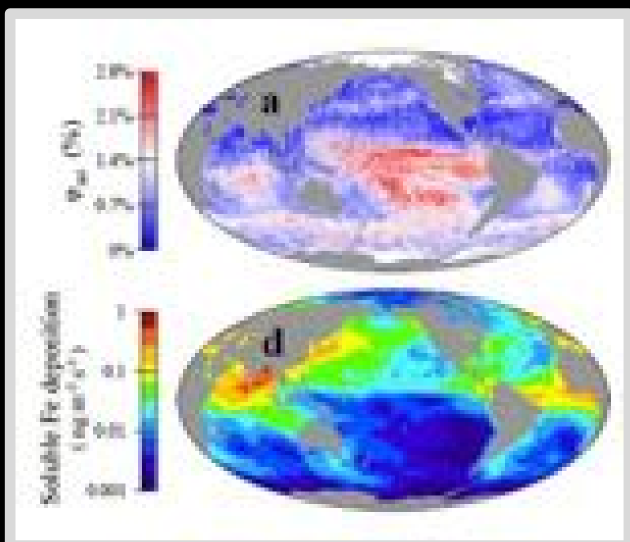
Michael J. Behrenfeld[1], Robert T. O'Malley[1], David A. Siegel[3], Charles R. McClain[4], Jorge L. Sarmiento[5], Gene C. Feldman[4], Allen J. Milligan[1], Paul G. Falkowski[6], Ricardo M. Letelier[2] & Emmanuel S. Boss[7]



MODIS
1999-present

- fluorescence band
- SWIR for turbid water
- 250 & 500 m atmosphere & land bands

Behrenfeld et al. 2009, BGS



metric	CZCS	SeaWiFS	MODIS
primary ocean bands (nm)	443, 520, 550, 670	412, 443, 490, 510, 555, 670, 765, 865	412, 443, 488, 531, 547, 667, 678, 748, 869, plus SWIR
nadir res.	825 m	1100 m	1000 m
nadir swath	1636 km discontinuous operation	1500 km GAC (2-day global) 2875 km LAC	2230 km (2-day global)
tilt	$\pm 20^{o}$ in 2^{o} increments	$\pm 20^{o}$	none
det. per band	1	4 (TDI) = 1	10
digitization	8 bits	10 bits GAC 12 bits LAC	12 bits

+ fluorescence line height
+ photosynthetic quantum yield
+ turbidity index

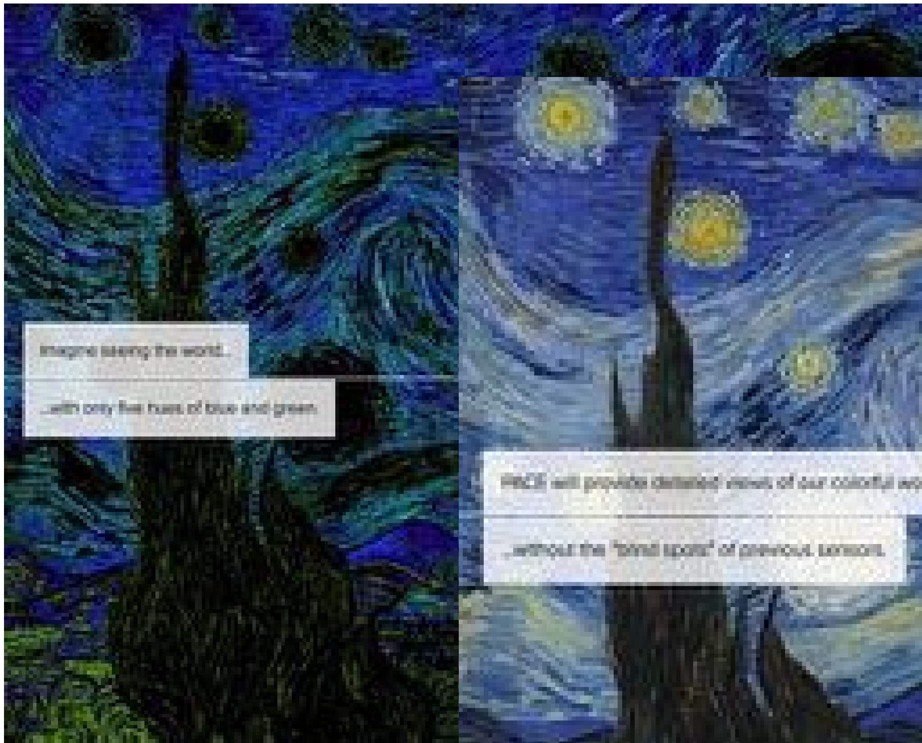
SGLI 2017-present

OLCI 2016-present

+ GOCI, HICO, MERIS, MOS, OCM, OSMI, SeaHaWK, VIIRS, others …

metric	CZCS	SeaWiFS	MODIS	SGLI	OLCI
primary ocean bands (nm)	443, 520, 550, 670	412, 443, 490, 510, 555, 670, 765, 865	412, 443, 488, 531, 547, 667, 678, 748, 869, plus SWIR	380, 412, 443, 490, 529, 566, 672(P), 763, 867(P), 1055, SWIR (IRS)	400, 412, 443, 490, 510, 560, 620, 665, 674, 682, 709, …, 765, …, 866, 1013
nadir res.	825 m	1100 m	1000 m	250 m full 1000 m red.	300 m full 1200 m red.
nadir swath	1636 km discontinuous operation	1500 km GAC (2-day global) 2875 km LAC	2230 km (2-day global)	1150 km (3+day global)	1270 km (3+day global)
tilt	$\pm 20^{o}$ in 2^{o} increments	$\pm 20^{o}$	none	none	none
det. per band	1	4 (TDI) = 1	10	pushbroom	pushbroom
digitization	8 bits	10 bits GAC 12 bits LAC	12 bits		

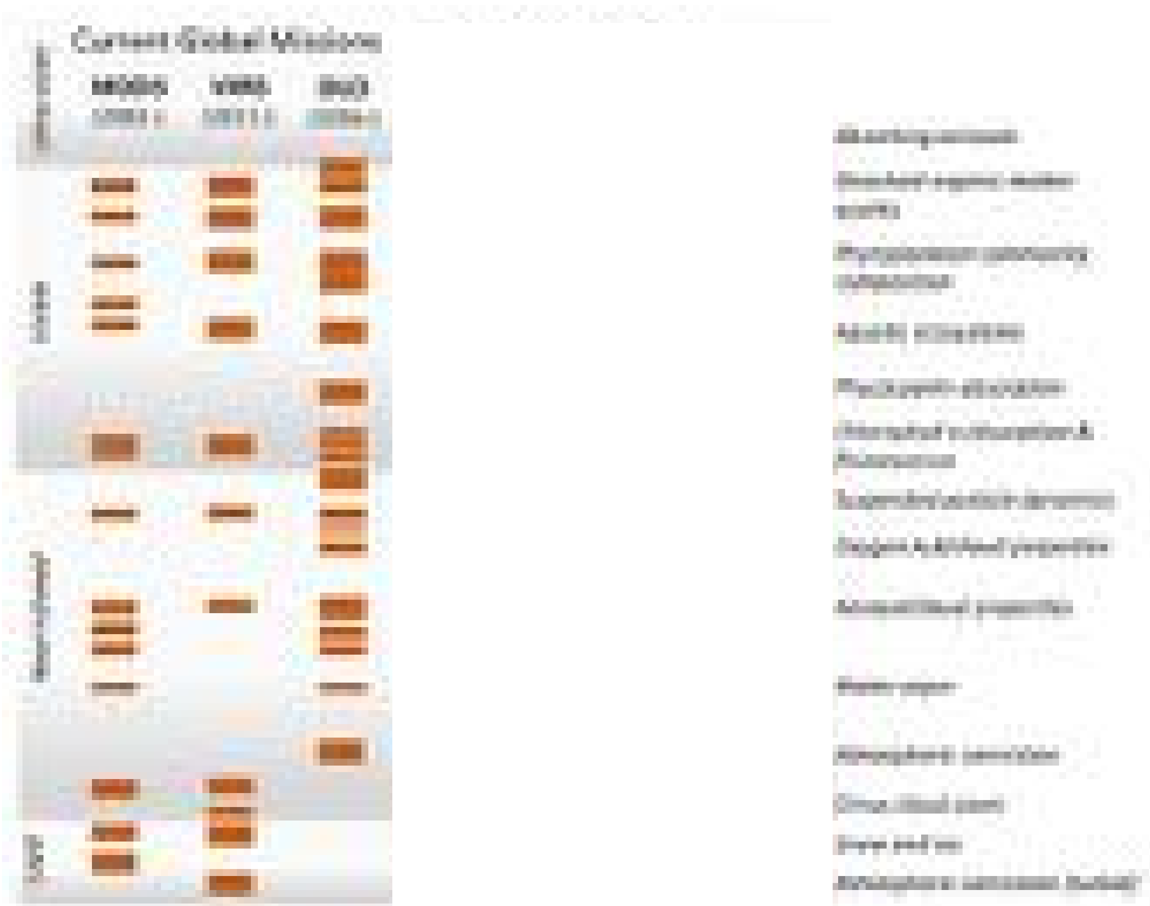
why hyperspectral?



5 hues of blue and green

5 hues across the visible spectrum

moving from multi-spectral radiometry to spectroscopy

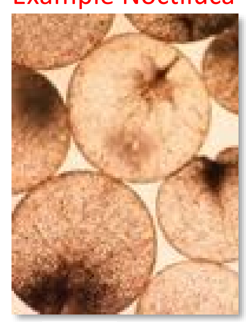


Dierssen et al. 2023, doi:10.1029/2023JG007574

Example diatom

Linda Armbrecht, abc.com.au

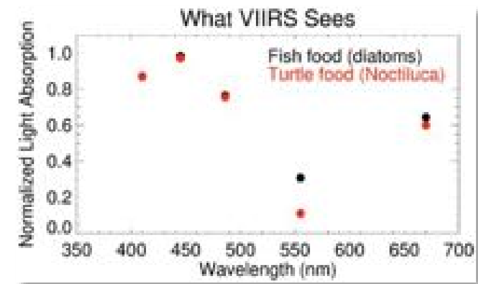
Example Noctiluca

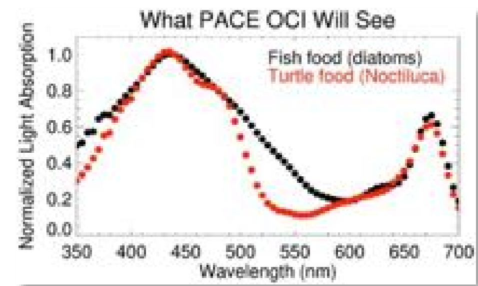


1 mm

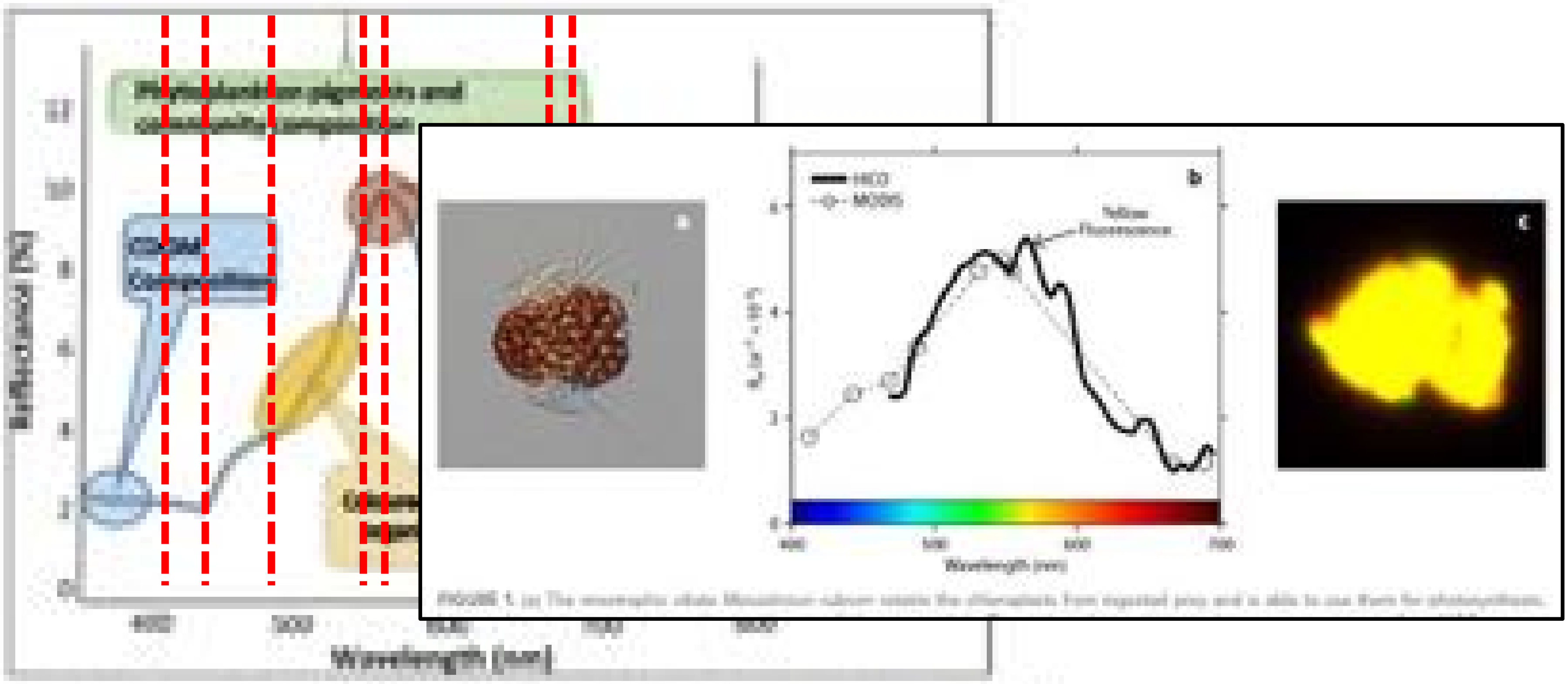
Joaquim Goes, LDEO

signals from the ocean are small & differentiating between constituents requires additional information relative to what we have today





why hyperspectral?



Dierssen et al. 2023, doi:10.1029/2023JG007574

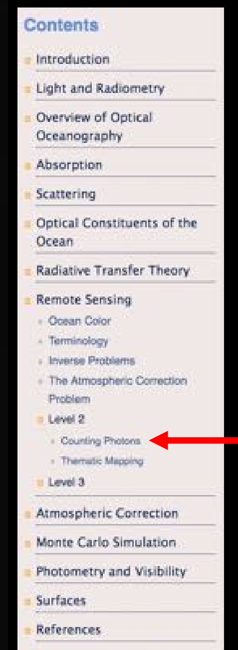
Dierssen et al. 2020, doi:10.5670/oceanog.2020.111

why hyperspectral?

	Aquatic Biogeochemistry	Aquatic Habitat Composition	Aquatic Biophysics
Historic	•Chlorophyll-a and Fluorescence Line Height •Particulate Inorganic and Organic Carbon (PIC, POC) •Net primary productivity (NPP) •Suspended Particulate Matter (SPM)	•Optical water types	•Diffuse light attenuation (K_d) •Photosynthetically Available Radiation (PAR) •Absorption due to CDOM and detritus (a_{dg}), phytoplankton (a_{ph}) •Particulate backscattering (b_{bp})
New	•Phytoplankton carbon •Ancillary pigment concentrations •Dissolved Organic Carbon (DOC) •CDOM Composition •Pollutants (oil, plastics)	•Floating vegetation composition •Benthic composition •Phytoplankton community composition •Wetland composition	•Absorption due to CDOM (a_g) and spectral slope coefficient •Absorption due to depigmented (detrital) particles (a_d) •Shallow water bathymetry & flooding

Dierssen et al. 2023, doi:10.1029/2023JG007574

chasing photons – considerations for making & maintaining useful satellite ocean color measurements



alternative title: the trade space within which you will work when creating an instrument design concept

current and future missions : it’s a consumers market

International Ocean Colour Coordinating Group

why PACE OCI is what it is (this applies to any instrument)

Extend key systematic **ocean** biological, ecological, & biogeochemical climate data records, as well as **cloud** & **aerosol climate data records**

Make **new global measurements of ocean color** that are essential for understanding the global carbon cycle & ocean ecosystem responses to a changing climate

Collect **global observations of aerosol & cloud properties**, focusing on reducing the largest uncertainties in climate & radiative forcing models of the Earth system

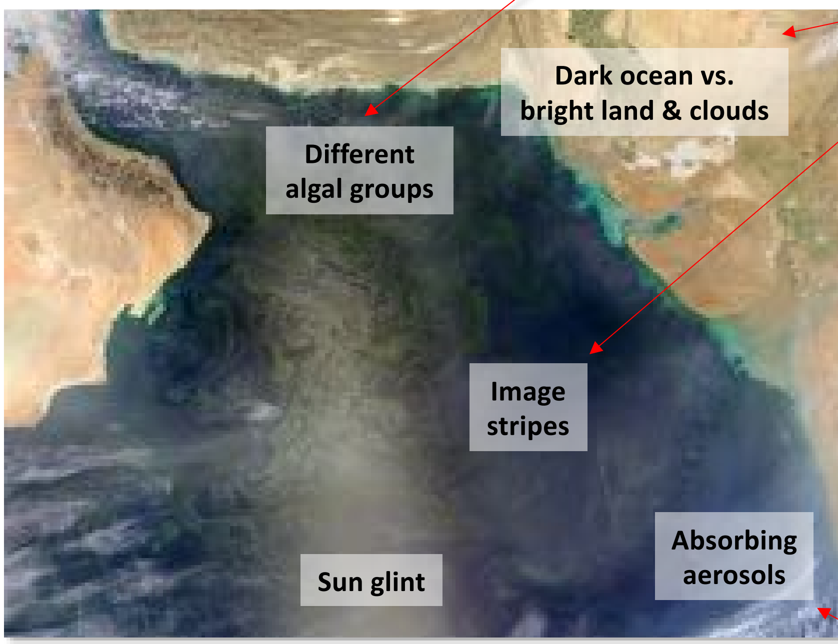
GSD of 1 ± 0.1 km^2 at nadir

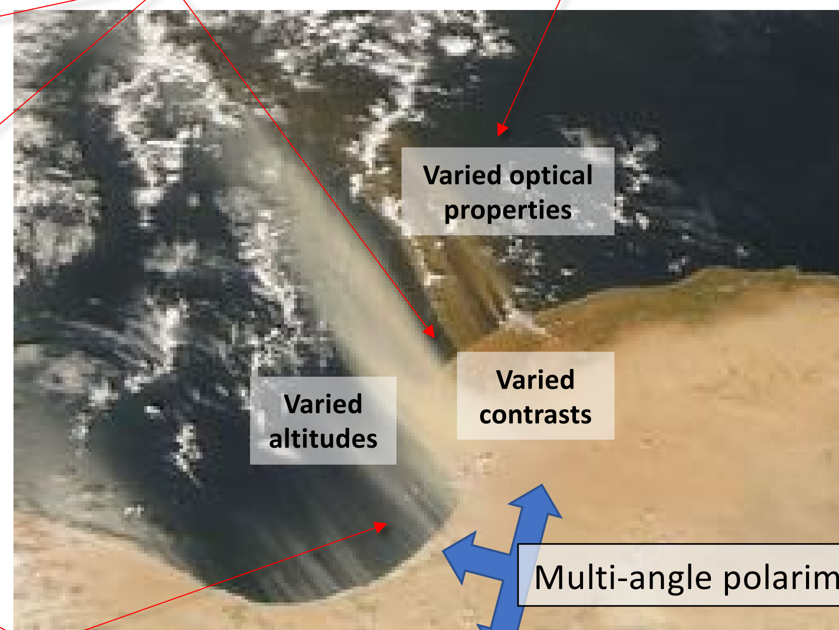
Twice-monthly lunar calibration & onboard solar calibration (daily, monthly, dim)

Spectral range from 350-865 @ 5 nm

940, 1038, 1250, 1378, 1615, 2130, 2260 nm

Instrument performance requirements



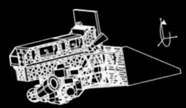


Multi-angle polarimetry

Tilt ± 20^o

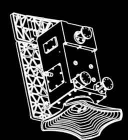
Spectral range goal of 320-865 @ 5 nm

Improve our understanding of how **aerosols influence ocean ecosystems & biogeochemical cycles** and how **ocean biological & photochemical processes affect the atmosphere**



OCI

340-890 nm in 2.5 nm steps
7 discrete SWIR: 940-2260 nm
1-2 day coverage; ±20° tilt; 1km
NASA Goddard Space Flight Center

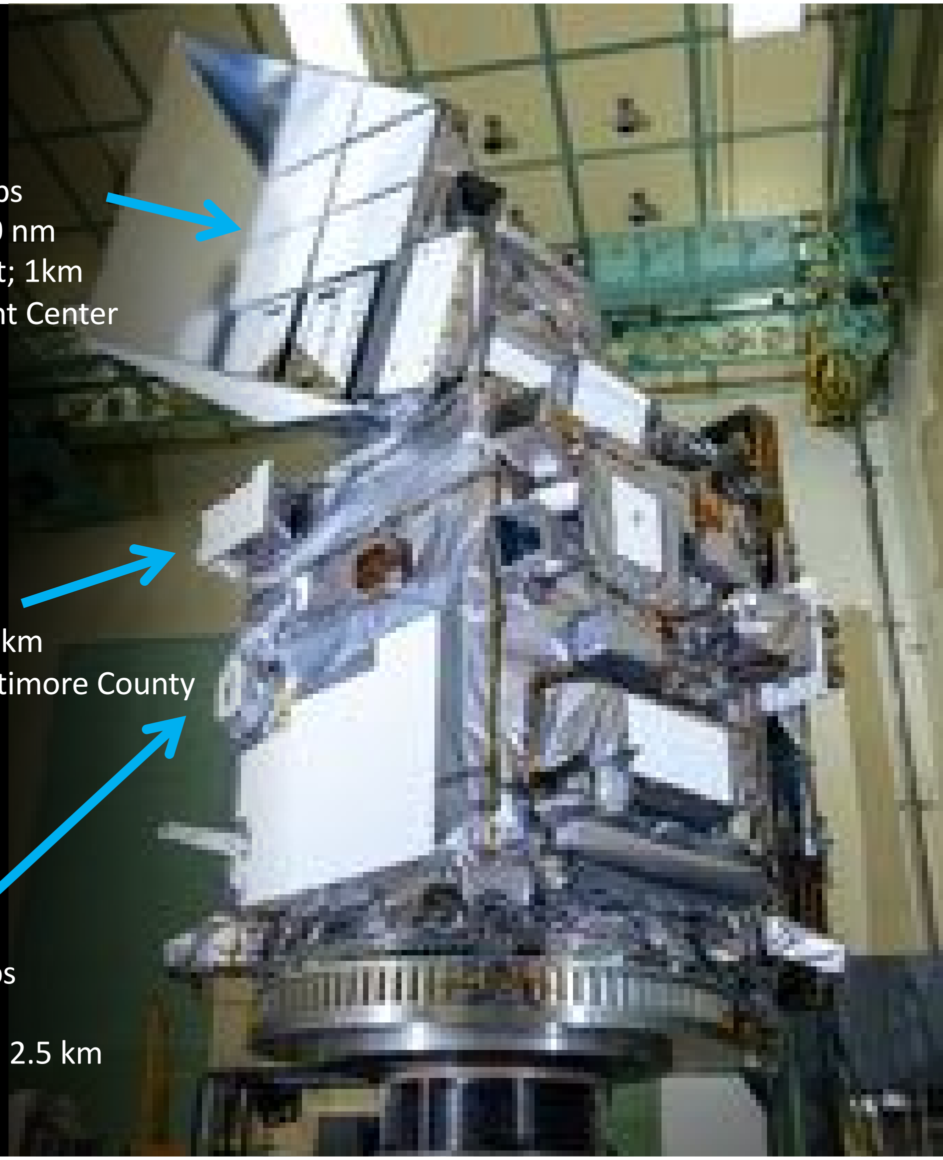


HARP2

440, 550, 670, 870 nm
10-60 viewing angles
wide swath polarimeter; 3 km
University of Maryland Baltimore County

SPEXone

380-770 nm in 2-4 nm steps
5 viewing angles
narrow swath polarimeter; 2.5 km
SRON, Airbus NL



PACE fills niches not currently addressed at home or abroad

No other current or planned hyper-spectral radiometer provides **1-2 day global** coverage

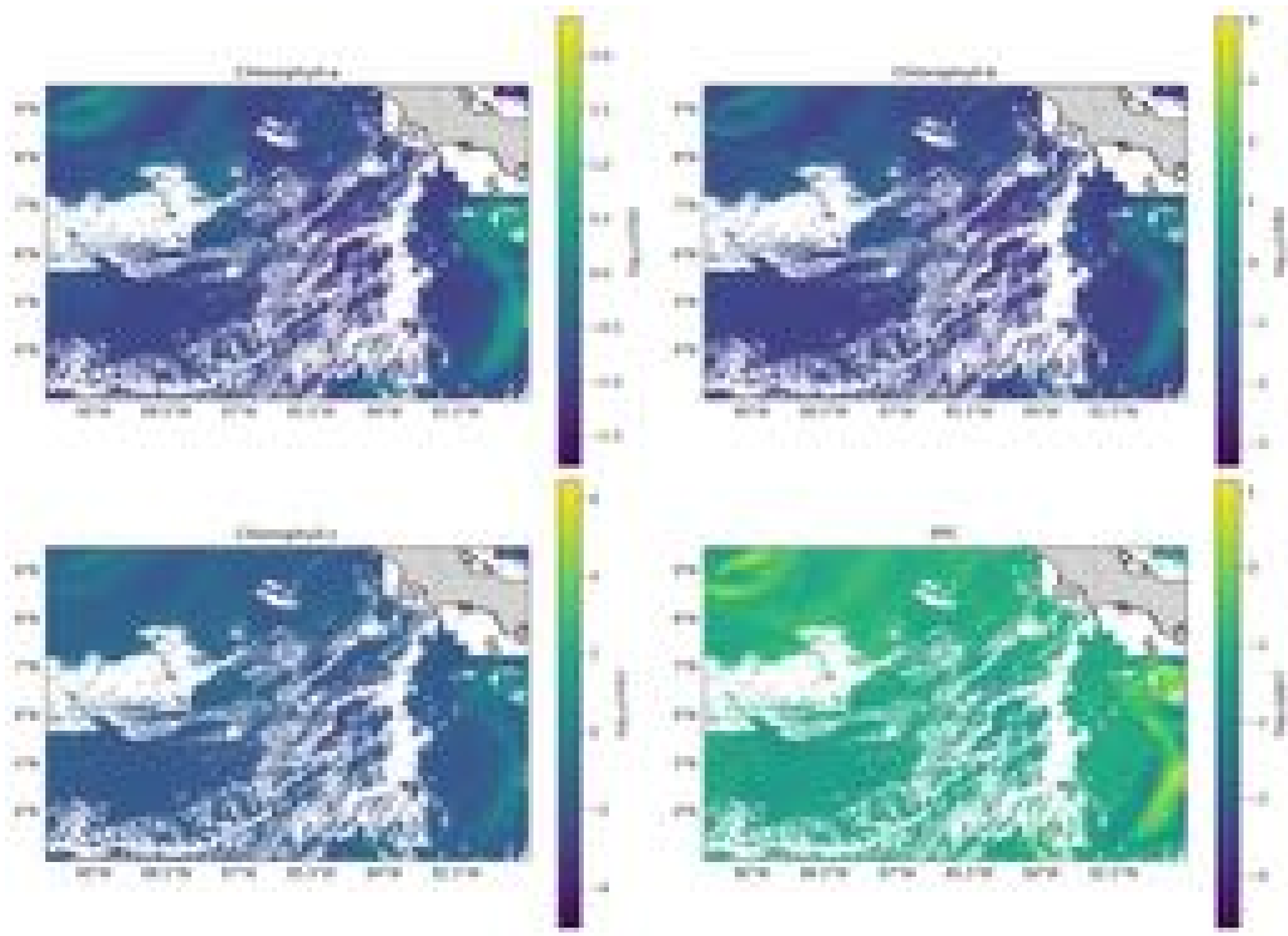
UV & two 2-µm bands realize atmospheric improvements over heritage instruments

Multi-angle polarimetry adds dimensions of information (as well as provides a pathfinder)

PACE key characteristics

polar, ascending, 98° inclination
13:00 local Equatorial crossing time
676.5 km altitude
6-9 hrs data latency

aquatic photosynthetic pigments: full spectrum optimization



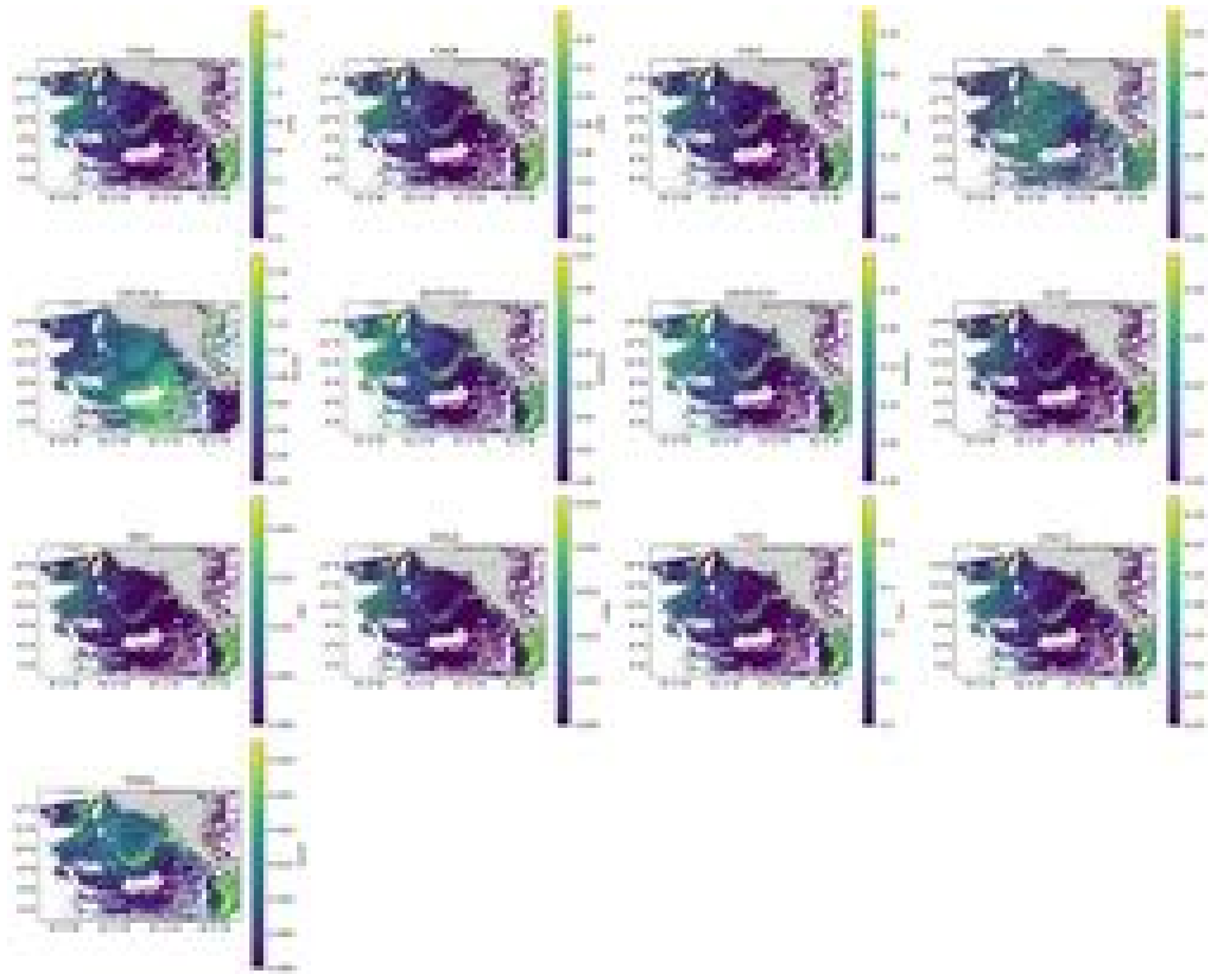
GPig applied to PACE OCI

Chase et al. 2024
Chase et al. 2020
Chase et al. 2017

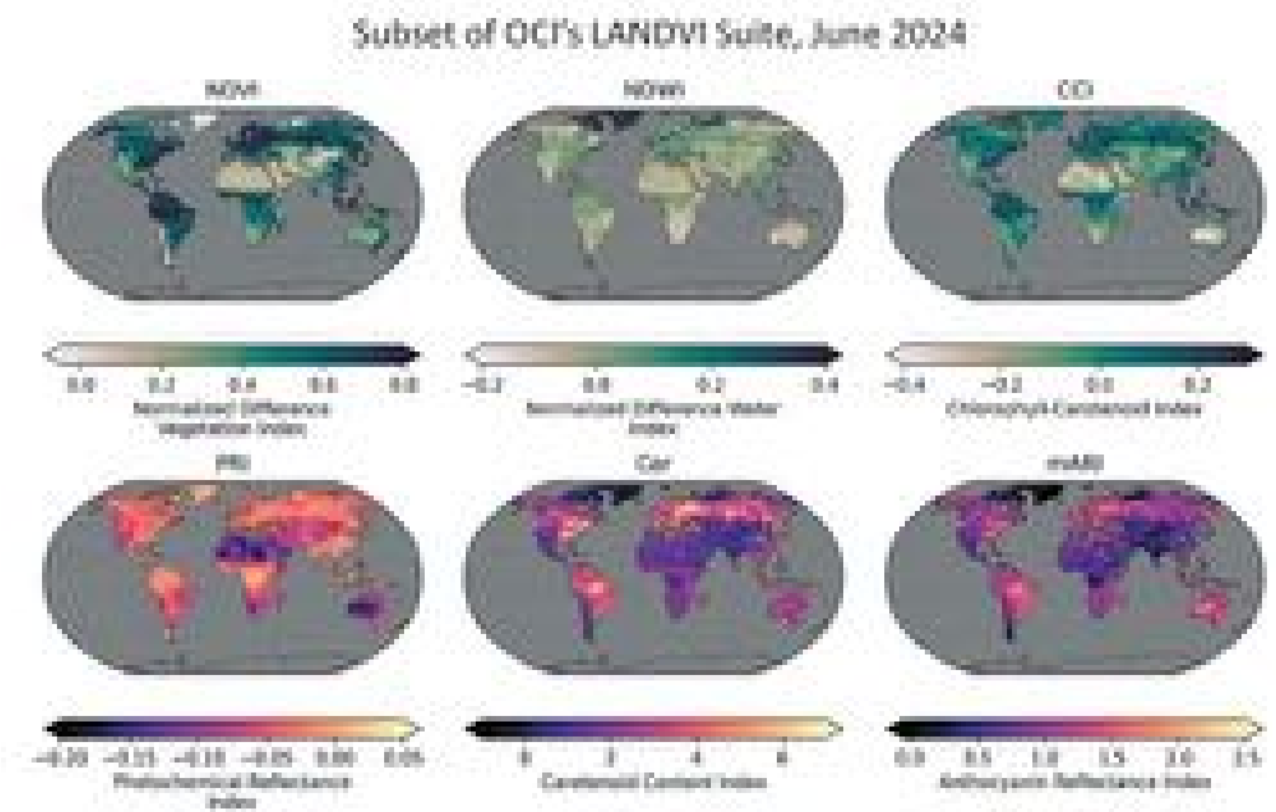
photosynthetic pigments: spectral derivatives

SDP applied to PACE OCI

Kramer et al. 2024
Kramer et al. 2022
Kramer and Siegel 2019
Catlett and Siegel 2018



additional value offered by the full UV-NIR spectrum



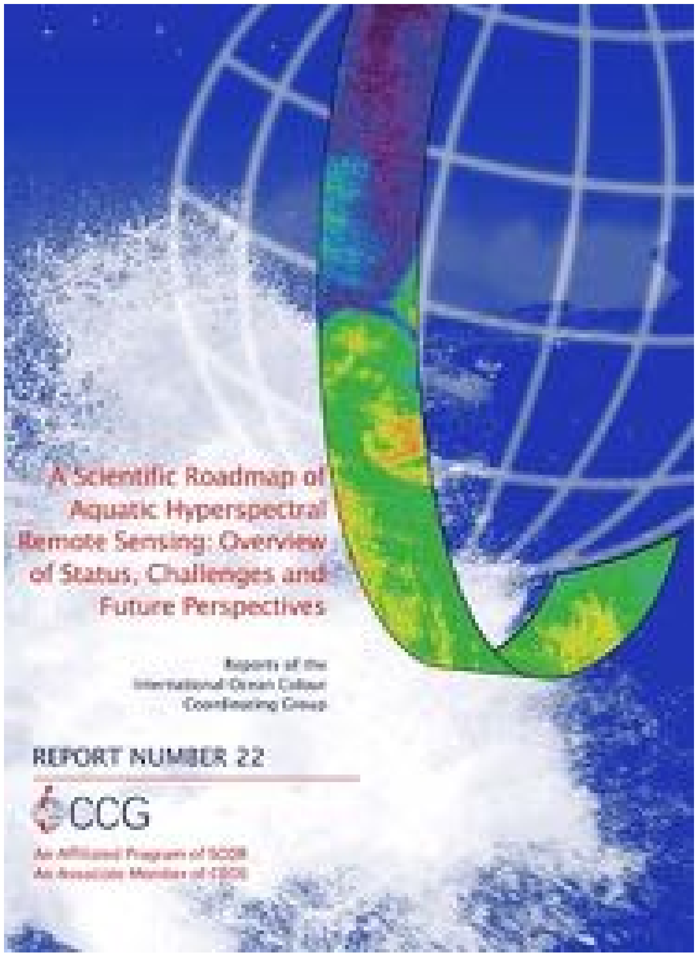
Vegetation Indices from OCI
(4-5 more available)

Caplan and Huemmrich 2025

NDVI: 645, 859 nm
NDWI: 859, 1250 nm
CCI: 530, 1618 nm
PRI: 530, 570 nm
Car: 495, 705, 800 nm
mARI: 550, 705, 800 nm

a non-exhaustive list of algorithms being implemented for PACE

familiar name	product	PI	PACE POC
SOP	photosynthetic pigments -> PCCs	Kramer	Cetinić
Gpig	photosynthetic pigments -> PCCs	Chase	Cetinić
aquatic fluorescence	fluorescence properties	Frankenberg	Cetinić
AFAI	floating algae	Hu, Barnes	Ibrahim
PIC	particulate inorganic carbon	Mitchell	Cetinić
QAA	spectral Kd, IOPs	Shoemaker	McKinna
ZTT	spectral IOPs	Moore	McKinna
alternative Kd	spectral Kd	Frouin	McKinna
CI	cyanobacteria index	Seegers	Seegers
Aquaverse	WQ for coastal / inland waters	O'Shea	Seegers
HMV	WQ for coastal / inland waters	Liu	Seegers
MAPP	aerosol, ocean and land properties	Stamnes	Allen
MAIAC	aerosol and surface properties	Lyapustin	Caplan, Sayer
GRASP	aerosol, ocean and land properties	Dubovik	Gao
volumetric 3D clouds	3D cloud reconstruction	Foley	Foley
Greenland cryo	Greenland ice/BC deposition	Ottaviani	Caplan
ocean surface refractive index	Ocean surface refractive index	Ottaviani	Knobelspiesse
ISOFIT	atmospheric correction	Thompson, JPL	Caplan
SWRE	shortwave radiation effect	Cairns	Cairns
terrestrial GPP	terrestrial GPP	Huemmrich	Caplan



<u>practical topics to be addressed by the TF</u>:

- what is the **current status of**, and what are the limitations of, aircraft- and satellite-borne passive hyperspectral remote sensing?
- regarding addressing emerging science questions, what are the **current gaps**?
- what **further (algorithmic, modeling) progress** towards these questions may be gained from hyperspectral remote sensing, particularly from satellites?
- what is the current status of critical **calibration and validation efforts** to support the above, including uncertainties characterizations, and what are the gaps?

A Scientific Roadmap of Aquatic Hyperspectral Remote Sensing: Overview of Status, Challenges and Future Perspectives

Chapter 5

Ana Dogliotti, Astrid Bracher, Jeremy Werdell, Malik Chami, Maycira Costa, Heidi Dierssen, Claudia Giardino, Toru Hirawake, Chuanmin Hu, Amir Ibrahim, Wonkook Kim, Emanuele Organelli, Shaoling Shang, Fang Shen

Summary and Key Recommendations for Actions

1) Technology & Sensor Development

- Prioritize **high spectral and spatial resolutions (<30m), enhanced signal-to-noise satellites** for coastal/inland.
- Systematic combine data from **multiple satellite types, including commercial** (hyperspectral, multispectral, atmospheric/land).
- Hyperspectral missions (e.g., PRISMA, EnMAP) must be strategically transitioned into **operational platforms** for **long-term monitoring of costal/inland**.
- Maintain and expand hyperspectral **airborne, drone, and autonomous platforms** for testing and validation of new missions and fine-scale mapping.

Continuity for global missions (e.g., OCI) too!

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Summary and Key Recommendations for Actions

2) Targeted Investment in Calibration and Validation Infrastructure

- Improve and expand **water, benthic, and floating matter observing networks** (floats, gliders, uncrewed vehicles, above water) with hyperspectral radiometers for both algorithm development and validation
- Improve **vicarious calibration** using spectrally consistent methods to separate true instrument calibration errors from atmospheric effects, thereby improving the atmospheric correction itself.

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A Scientific Roadmap of Aquatic Hyperspectral Remote Sensing: Overview of Status, Challenges and Future Perspectives

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Summary and Key Recommendations for Actions

3) Advance algorithms and products

- Improve **atmospheric correction** methods including adjacency effects, coupled ocean-atmosphere inversion, AI + physics approaches, and use of UV/SWIR, polarization, and multi-angle data to further refine the separation of water and atmospheric signals.
- **Transition robust hyperspectral products** into operations (e.g., PFT, IOPs, DOC, benthic and floating matter).
- Apply **data fusion** (hyperspectral, acoustics, lidar, polarimetry) for complex habitats.
- Incorporate **uncertainty quantification** in all products to ensure reliability and international harmonization.

how does one choose what to use / build?

my prediction is that >50% of you will someday:

1. **use satellite data for your research and wish to understand engineering design choices** (== shake your fist at the clouds and shout "*why are there so many options and differences across instruments?*")

2. serve as members of space agency Science Definition Teams (or equivalent, e.g., 2017 Decadal Survey "designated observable" teams)

3. serve on satellite mission review boards or proposal panels

4. write proposals for new missions (or field campaigns or instruments)

5. build something that requires trade space and a fixed budget

SLS Class Shark Tank exercise

(aka build a mission with your new co-PIs)

Jeremy (courtesy of Ivona and Ryan)

how would you design a mission to monitor coastal harmful algal blooms & their interactions with the atmosphere under pervasive absorbing aerosols?

goal : build your own mission

1. find your team members (maybe groups of 5?)
2. think about the assigned science question (coastal HABs + abs aer)
3. think what kind of space-based observation would you need to get data to address that question (you can copy existing missions a bit)
4. stay under a budget of 100$ (you are cost-capped) – go shopping
5. develop a cool acronym (or, yeah, it's not a real mission)

What measurements & data products?

All of them.

What instruments? Active? Passive?

Both.

Spectral – what wavelengths? Thermal?

Yes please! UV-to-SWIR plus thermal.

Spectral – what resolution?

Hyperspectral, of course.

What spatial footprint?

The smaller the better. 10 m!

What repeatability?

Daily global, duh. Phytos are transient.

What allowable image quality?

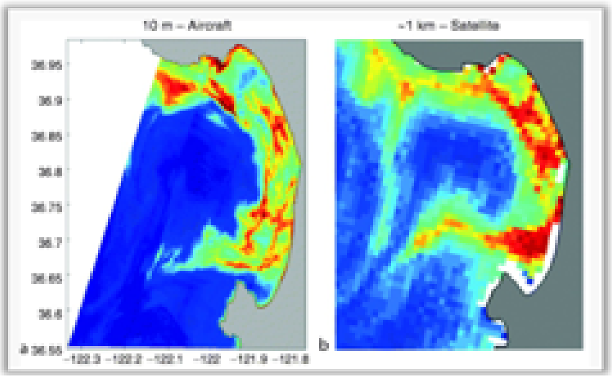
High SNRs, no image artifacts.

What temporal stability?

Change is bad.

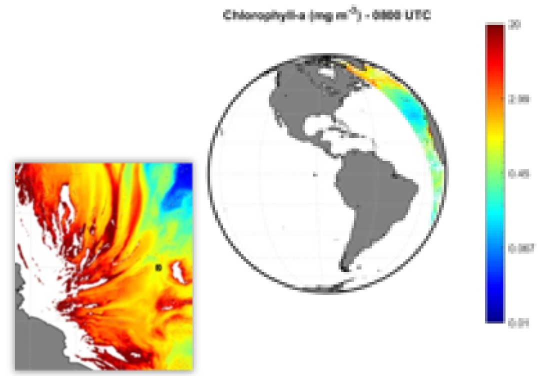
You can't have this mission
(from orbit alone anyway).

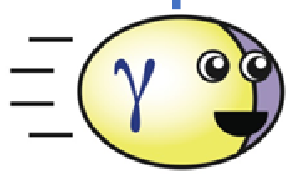
the battle over the happy photon

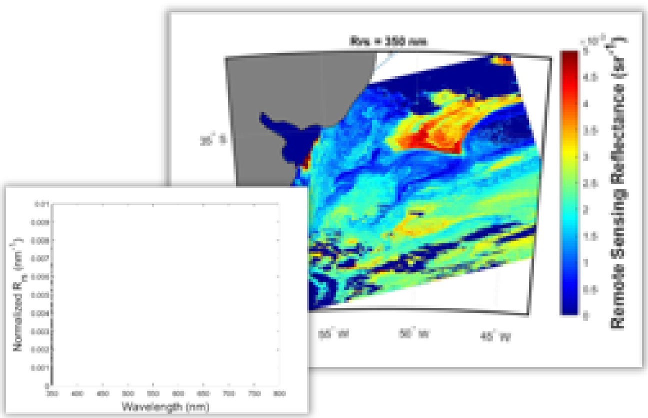


spatial resolution

temporal resolution

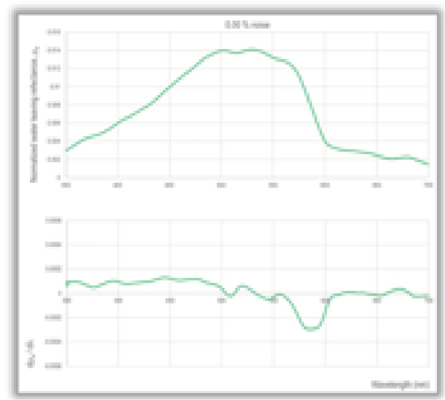






spectral resolution

signal to Noise



INSTRUMENTS (VIS)

multispectral (10) radiometer	$35
HYPERSPECTRAL radiometer	$55
multispectral (3) radiometer	$25
Hyperspec, multiangle polarimeter	$45
lidar, single channel	$50
instrument yet to be invented	$80
multispec (4), multiangle polarimeter	$40

SPATIAL RES

1 km (radiometer)	$25
300 m (radiometer)	$40
1 km (polarimeter)	$50
10 m (radiometer)	$65
2-3 km (radiometer)	$25

TEMPORAL RES

DAILY	$25
7-10 DAYS	$10
MULTIPLE TIMES A DAY (GEO)	$35
MULTIPLE TIMES A DAY (constellation)	$20

ADD ONS

SWIR	$10
UV	$10
THERMAL	$15
additional bands in vis	$2
additional angles	$4
more than occasional artifact	-$7
low SNR (lower than pace instr)	-$15
higher-than-planned SNR at spec. range	-$5
Calibration (MORE reliable): On board calibrator	$5
Calibration (LESS reliable): Cross calibrate with existing sensors	-$5

what if you go over budget?

this includes schedule slips because
time does indeed equal money

the review panel (who debriefs HQ)
or HQ (alone) will decide your fate …

1. they give you money

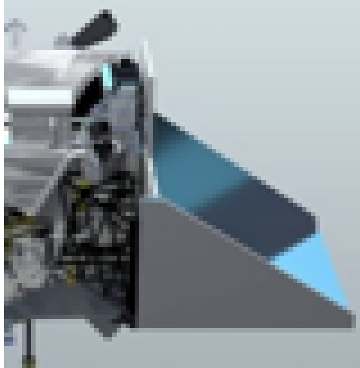
2. they cancel you

3. you get put on a shelf

4. you get eaten by sharks

SATELLITE

Cafe



GRATUITY(AKA LAUNCH + SPACECRAFT) = 20%

OPEN | MON-SUN 7 AM - 5 PM

INSTRUMENTS (VIS)

multispectral (10) radiometer	$35
HYPERSPECTRAL radiometer	$55
multispectral (3) radiometer	$25
Hyperspec, multiangle polarimeter	$45
lidar, single channel	$50
instrument yet to be invented	$80
multispec (4), multiangle polarimeter	$40

SPATIAL RES

1 km (radiometer)	$25
300 m (radiometer)	$40
1 km (polarimeter)	$50
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2-3 km (radiometer)	$25

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What measurements & data products?

All of them.

What instruments? Active? Passive?

Both.

Spectral – what wavelengths? Thermal?

Yes please! UV-to-~~SWIR plus thermal.~~

Spectral – what resolution?

Hyperspectral, of course.

What spatial footprint?

The smaller the better. 10 m!

What repeatability?

Daily global, duh. Phytos are transient.

What allowable image quality?

High SNRs, no image artifacts.

What temporal stability?

Change is bad.

You can't have this mission
(from orbit alone anyway).

You have neither the budget …
… nor the technology.

And certain aspects of the design are in conflict with each other.

So … we make compromises based on overarching science objectives.

Course	Option	Jeremy	Ivona
Award		$100	$100
Launch		$20	$20
instrument	3 wl	$25	$25
spatial	300	$40	$40
temporal	daily	$25	$25
add on	low SNR	-$15	-$15
add on	surprising SNR	-$5	-$5
add on	x-cal	-$5	-$5

$15 left to spend

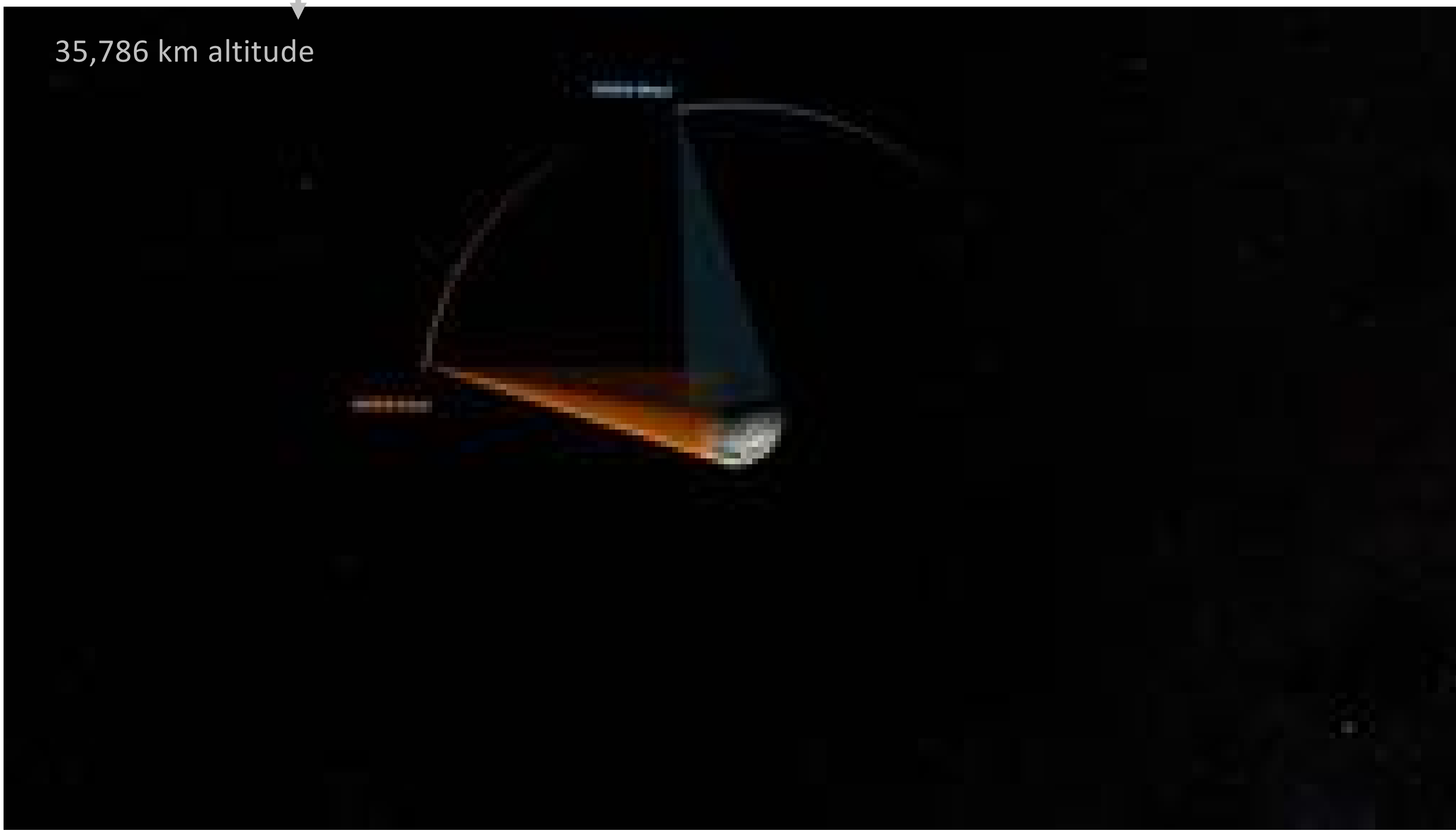

persevere …

persevere …

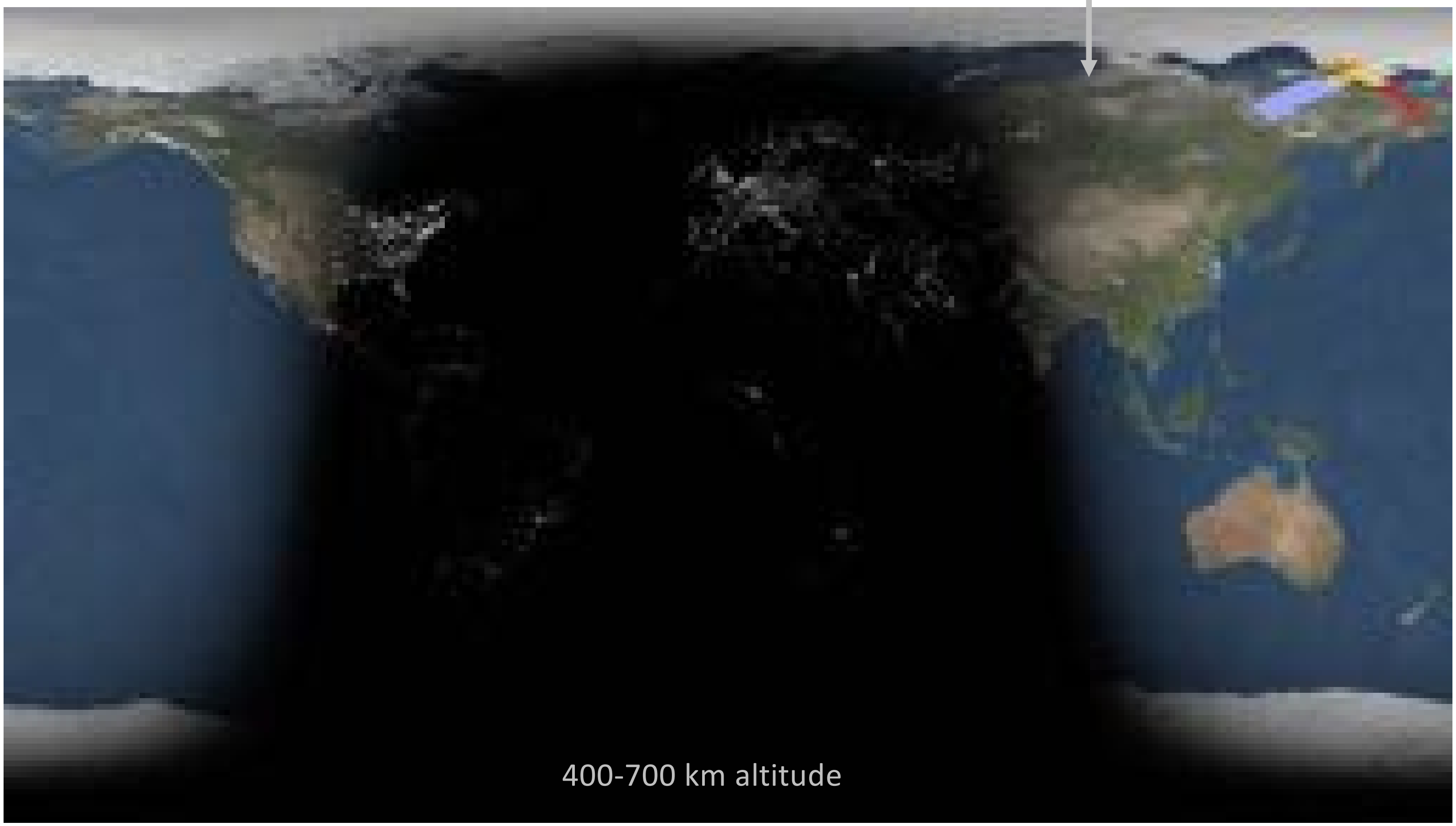
… and collaborate

#NASAESABakeoff

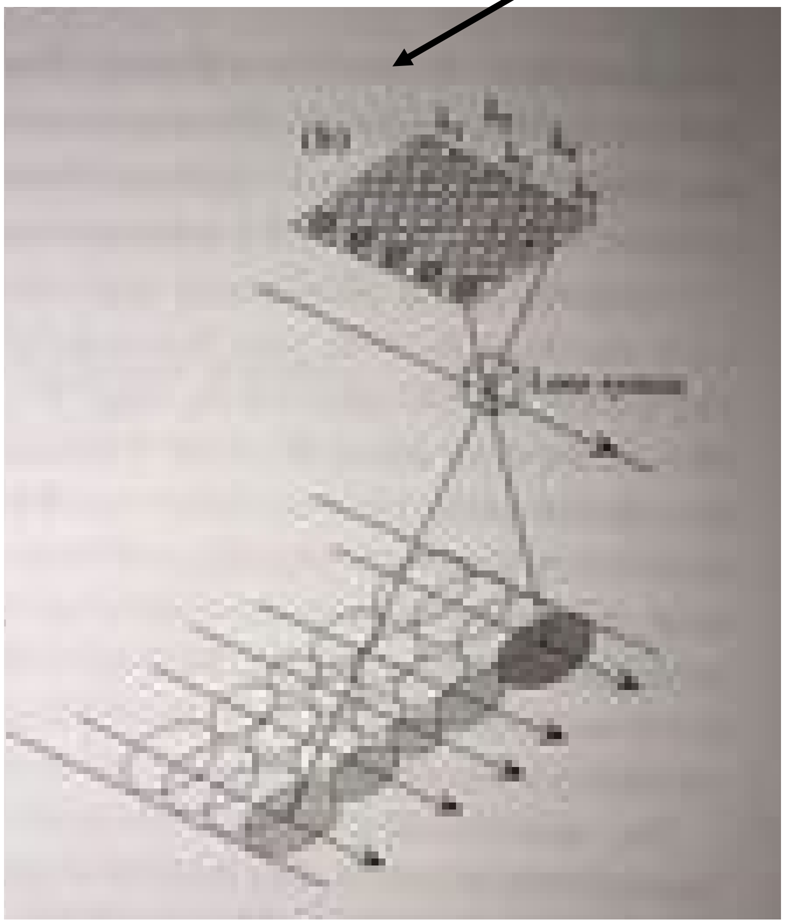
GEO (geostationary) vs. LEO (polar, low earth orbit)

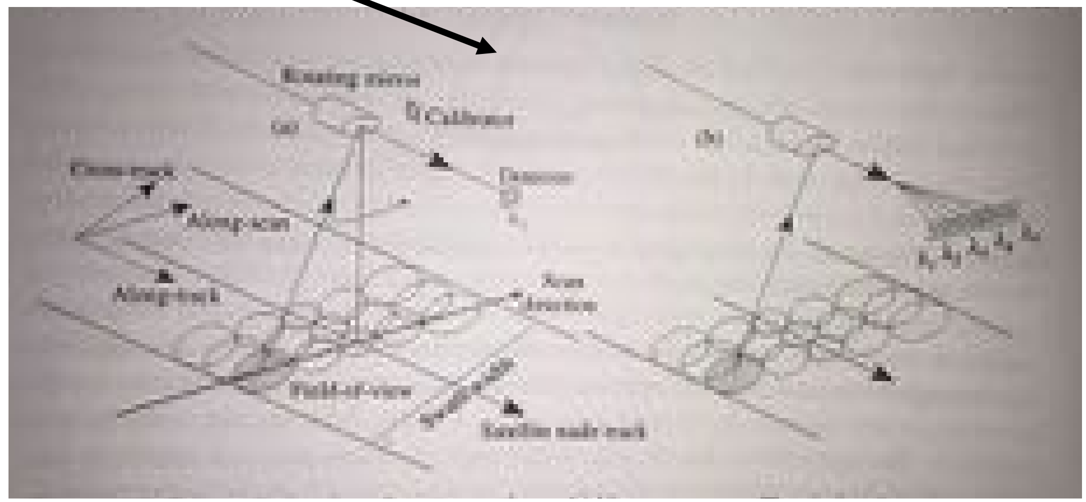


GEO (geostationary) vs. LEO (polar, low earth orbit)



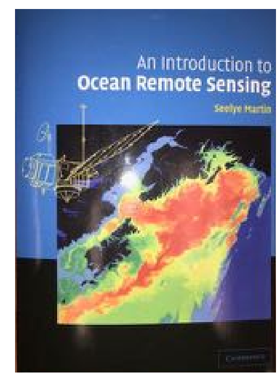
pushbroom vs. whiskbroom (scanner)

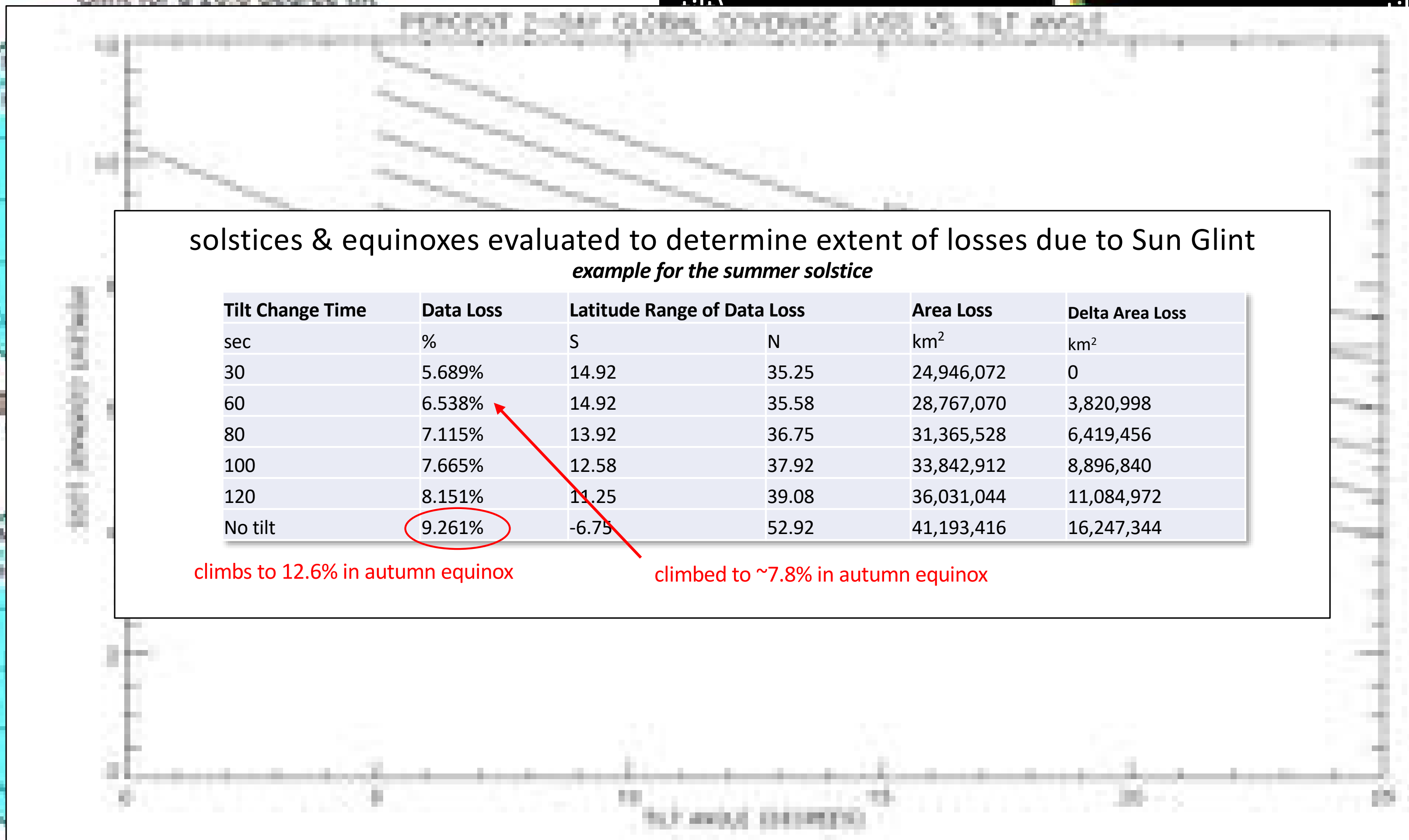




HICO
Landsat 8 OLI
MERIS
OLCI

SeaWiFS
MODIS
VIIRS
PACE OCI





solstices & equinoxes evaluated to determine extent of losses due to Sun Glint

example for the summer solstice

Tilt Change Time	Data Loss	Latitude Range of Data Loss		Area Loss	Delta Area Loss
sec	%	S	N	km^2	km^2
30	5.689%	14.92	35.25	24,946,072	0
60	6.538%	14.92	35.58	28,767,070	3,820,998
80	7.115%	13.92	36.75	31,365,528	6,419,456
100	7.665%	12.58	37.92	33,842,912	8,896,840
120	8.151%	11.25	39.08	36,031,044	11,084,972
No tilt	9.261%	-6.75	52.92	41,193,416	16,247,344

climbs to 12.6% in autumn equinox

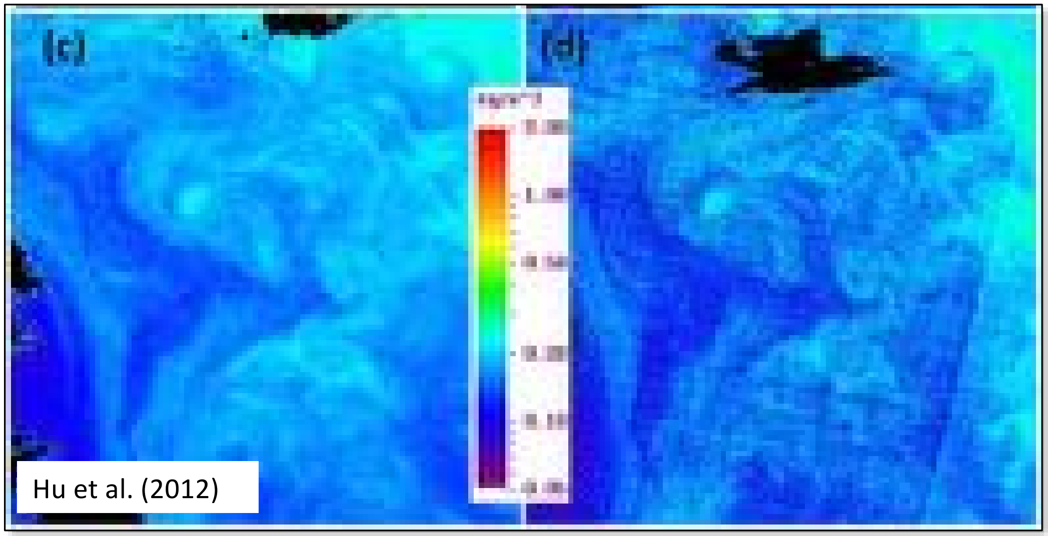
climbed to ~7.8% in autumn equinox

PAR = Photosynthetically Available Radiation (Einstein m^{-2} d^{-1})

image artifacts & instrument design

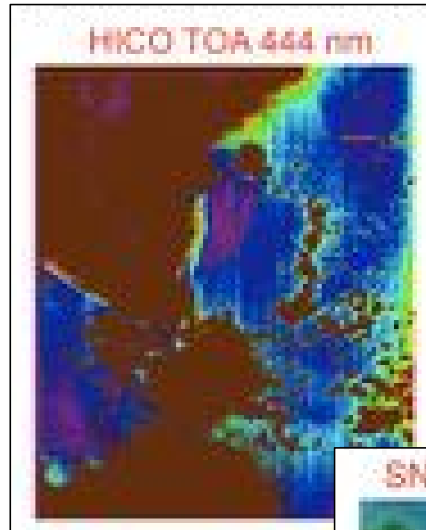
SeaWIFS (rotating telescope)
1 science detector

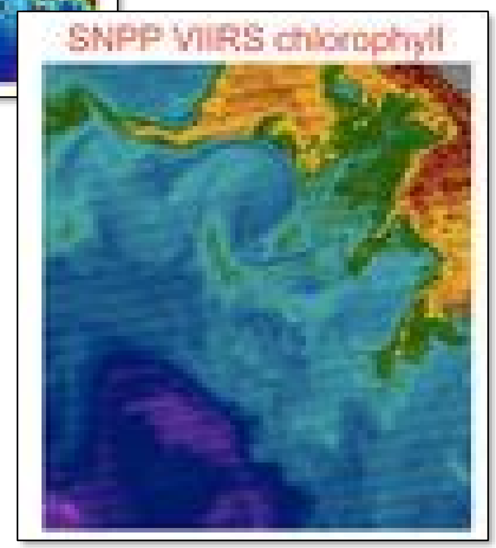
MERIS (pushbroom)
multiple science detectors



often larger science pixels
(1 km)

often smaller science pixels
(30-300 m)

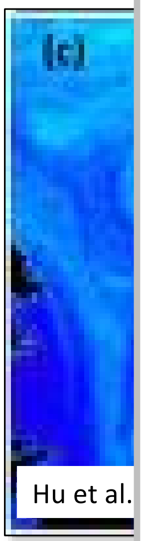




all multiple detector instruments show stripes in ocean color imagery (more detectors to calibrate)

image artifacts and instrument design

SeaWI
1



often

detector
show
ean color
ore
calibrate)

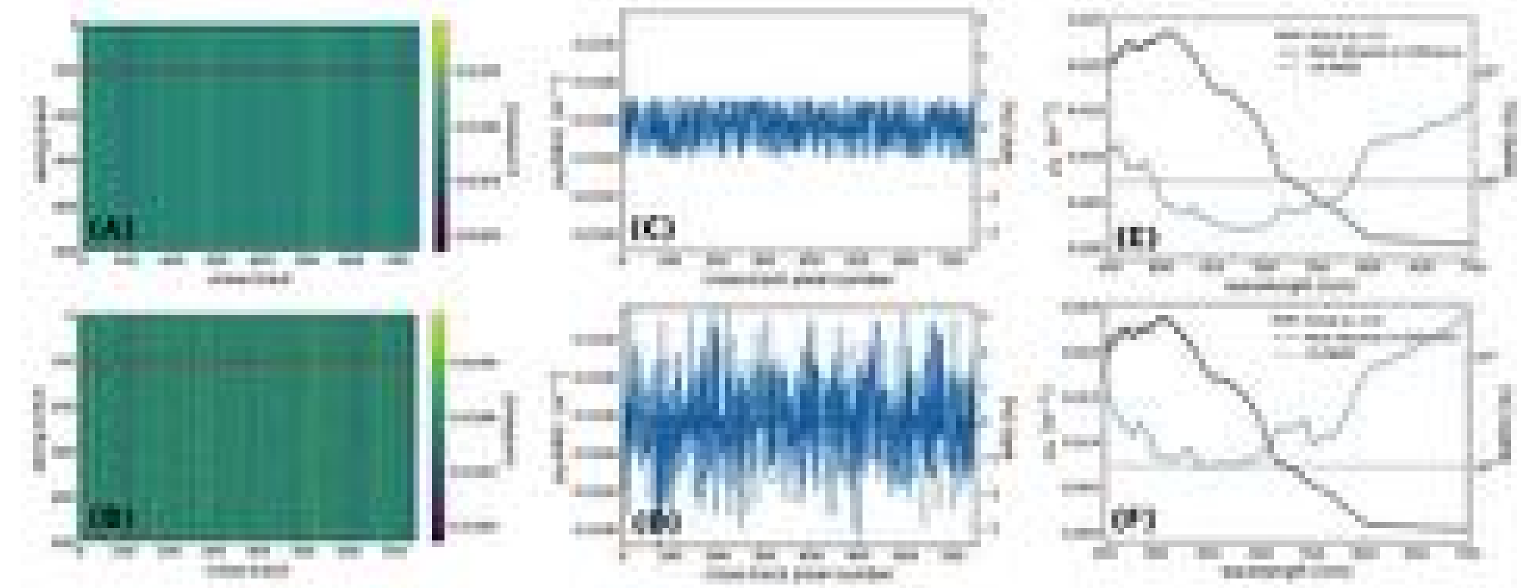
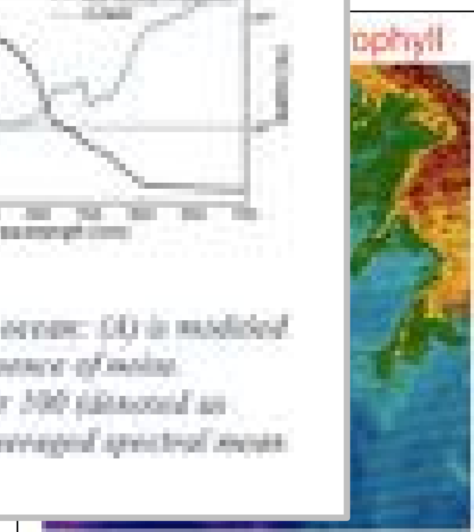
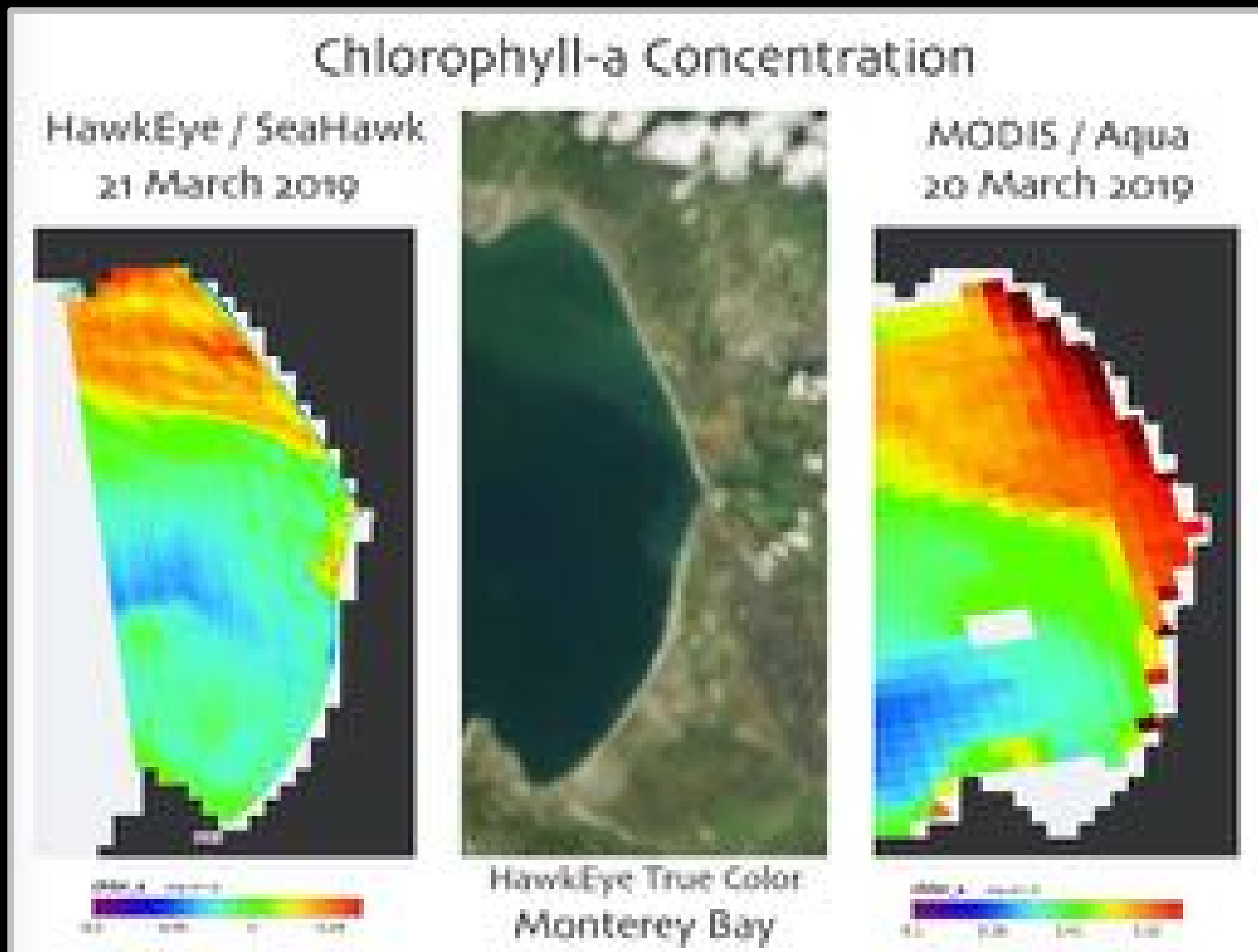


Figure 4.1: Subplots (A) and (B) show simulated pushbroom images of $\rho_w(440)$ for a uniform ocean: (A) is modeled with 0.1% miscalibration error, and (B) is modeled with 0.1% miscalibration error in the presence of noise. Subplots (C) and (D) show variability in $\rho_w(440)$ along a cross-track transect for scan number 100 (denoted as redlines in subplots (A) and (B)). Subplots (E) and (F) show the true $\rho_w(\lambda)$ and the transect-averaged spectral mean absolute percent differences (MAPD).



all that said ...



Landsat OLI image with MODIS-Aqua grid shown (Franz et al. 2015)