Why don’t all ocean color satellites measure hyperspectral radiances at meter-scales?

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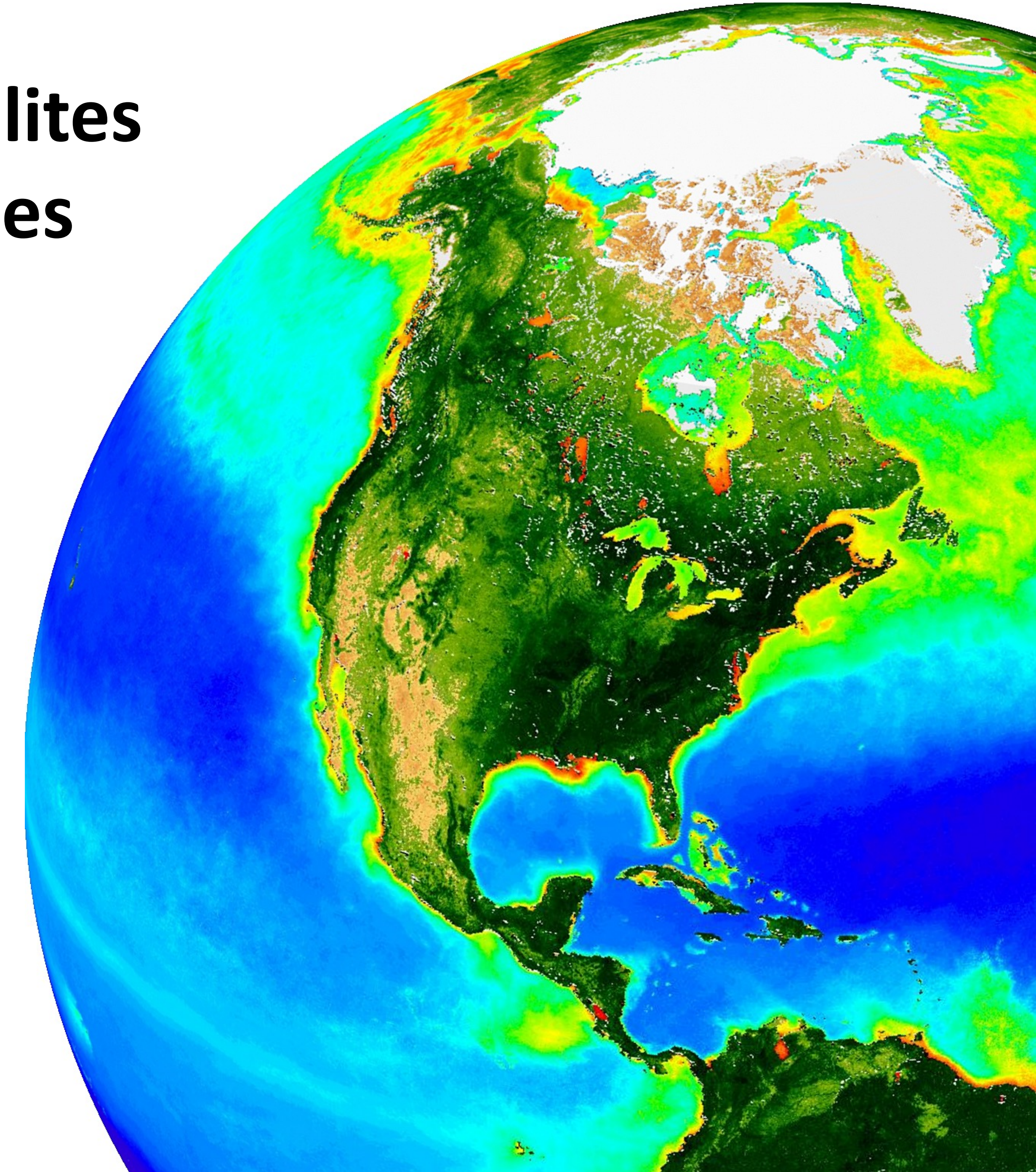
Acknowledgements: Gary Davis, Bryan Monosmith,
& **Curt Mobley**

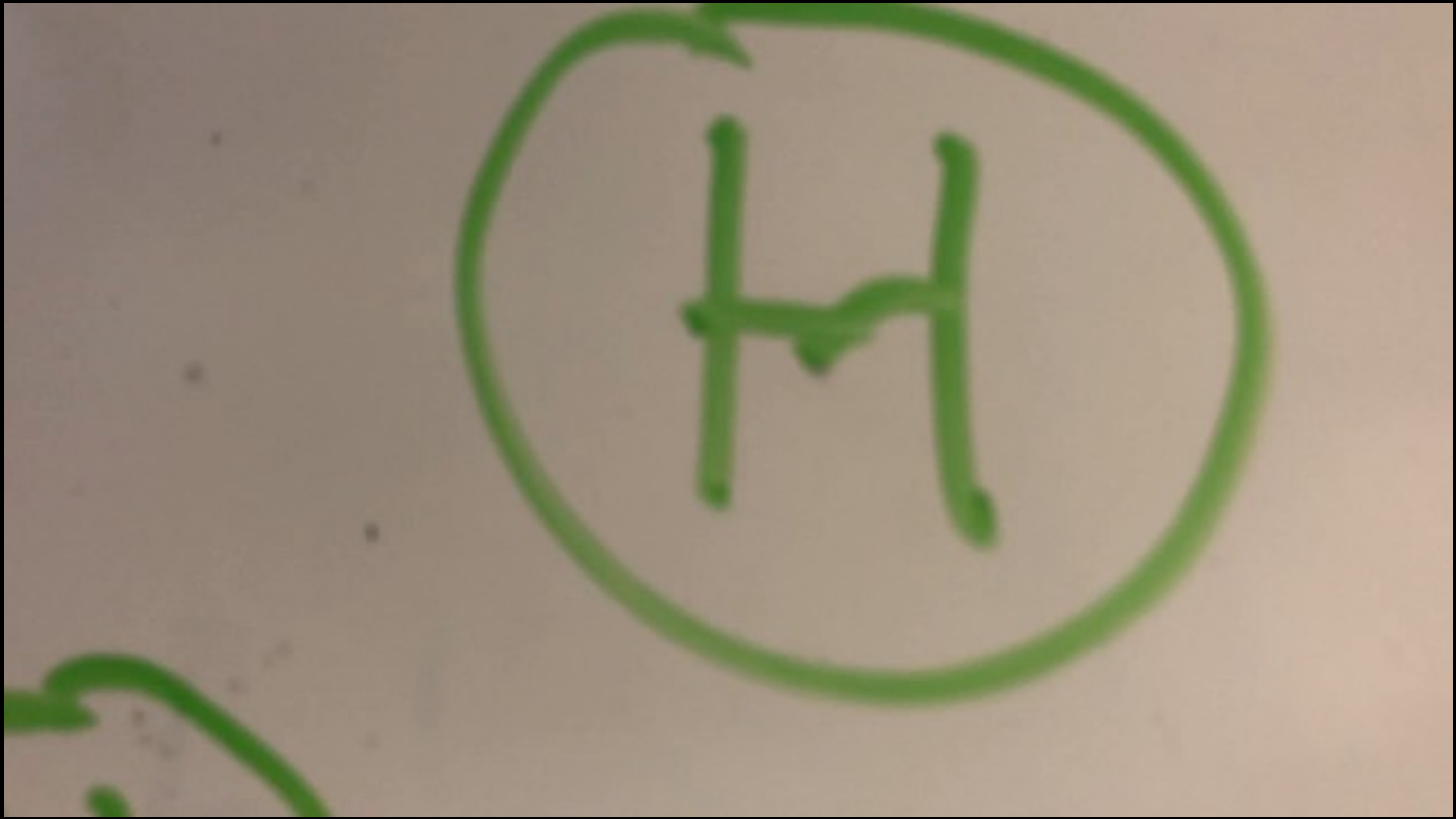
2023 Ocean Optics Summer Course



why include this talk?

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

1. use satellite data for your research & wish to understand engineering design choices
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


H

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

Contents

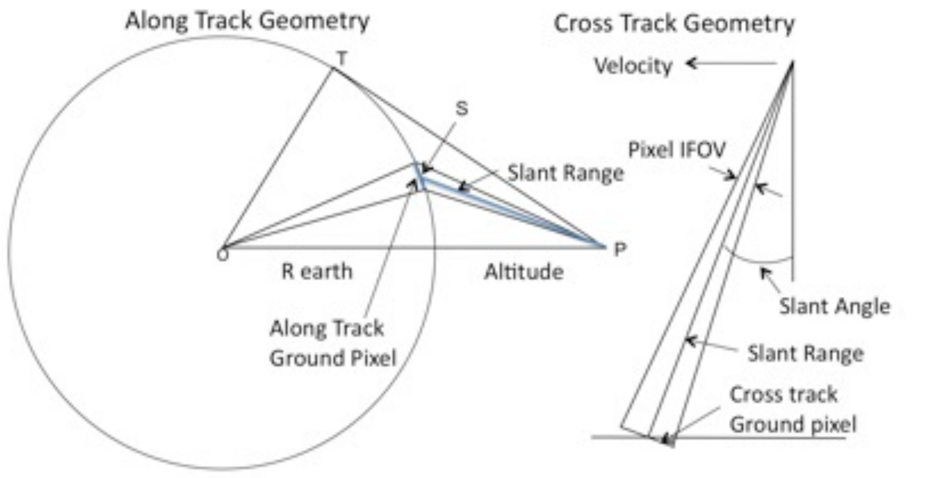
alternative title: the trade space within which you will work when creating an instrument design concept

Why don't all ocean color satellites measure hyperspectral radiances at meter-scales?

3 case studies:

(1) stationary satellite staring at 1 m^2 for 1 s
(2) moving satellite staring at 1 m^2
(3) moving satellite scanning side to side

satellite viewing geometry



What we will (hopefully) learn:

- how many photons leave a 1 m^2 of ocean surface
- how many photons from this patch reach the satellite detector
- ow many photons must the detector collect to achieve useful SNR

consider a satellite instrument with the following characteristics

Optical efficiency (OE)	= 0.66
Quantum efficiency (QE)	= 0.9
View angle	= 20 deg
Aperture	= 0.009 m (90 mm)
Altitude	= 650,000 m (650 km)
Slant Range	= 700,000 m (700 km)

solid angle of aperture (sensor) as seen from earth's surface = 1.3 e^{-14} sr

ground velocity = 6838 m s^{-1}

let's focus on a fluorescence channel:

Wavelength	= 0.678 um (678 nm)
Bandwidth ($\Delta\lambda$)	= 0.01 um (10 nm)
Typical TOA radiance	= 14.5 W m^{-2} um^{-1} sr^{-1}
Desired SNR	= 2000

$$SNR = \frac{N_{electrons}}{\sqrt{N_{electrons}}}$$

(oversimplification; assumes no dark current or noise)

consider a stationary satellite taking a quick peek at Earth

power reaching detector for 1 m² areal footprint & 1 s integration time:

$$P_{detector} = L \quad \Omega_{aperature} \quad Area_{surface} \quad OE \quad \Delta\lambda$$

$P_{detector}$	=	L	$\Omega_{aperature}$	$Area_{surface}$	OE	$\Delta\lambda$
$1.24e^{-15}$	=	14.5	$1.3e^{-14}$	1	0.66	0.01
W	=	$W\ m^{-2}\ sr^{-1}\ um^{-1}$	sr	m^2	(none)	um

photoelectrons reaching detector:

$$N_{electrons} = P_{detector} \quad t \quad QE \quad \lambda \quad h^{-1} \quad c^{-1}$$

$N_{electrons}$	=	$P_{detector}$	t	QE	λ	h^{-1}	c^{-1}
3812	=	$1.24e^{-15}$	1	0.9	0.678	$(6.63e^{-34})^{-1}$	$(3e^{14})^{-1}$
(none)	=	$J\ s^{-1}$	s	(none)	um	$J^{-1}\ s^{-1}$	$s\ um^{-1}$

integration time needs to be raised to 8 minutes to get SNR of ~ 1400

This is for top-of-atmosphere.

If we consider that the ocean contributes ~5% of this signal, then the number of photoelectrons from the ocean surface reaching the detector is ~190.

SNR =~ 62

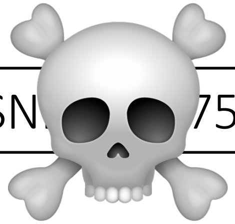
consider a moving satellite that stares at 1 m^2 at nadir

ground velocity = distance / time
$6838\ m\ s^{-1}$ = 1 m / t
integration time = 0.000146 s

repeat calculations with new integration time:

photoelectrons from ocean surface reaching detector = 0.028

SN[illegible]75



but, increase pixel size to 1 km^2 …
integration time increases by 3 orders of magnitude
area increases by 6 orders of magnitude

major reason why pushbroom instruments are attractive … SNR ~ 2900 for a 250 m pixel

repeat calculations with new area and integration time:

photoelectrons from ocean surface reaching detector ~ 28,000,000

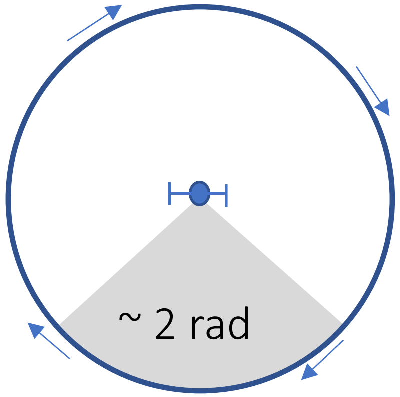
SNR =~ 23000

consider a moving satellite that scans from side-to-side

instantaneous field of view (IFOV) = pixel size / altitude
0.0014 rad = 1 km / 700 km

scanning instrument like SeaWiFS & PACE

a swath width of ~2 rad translates to ~1,400 pixels:
= swath width / IFOV
1,400 = 2 rad / 0.0014 rad



dividing the 28M photoelectrons by 1,400 pixels leaves ~19,900 photoelectrons from the ocean surface reaching the detector

useful duty cycle of of scan mirror is < 1/3, so really, we're talking about ~6,000 ocean surface photons

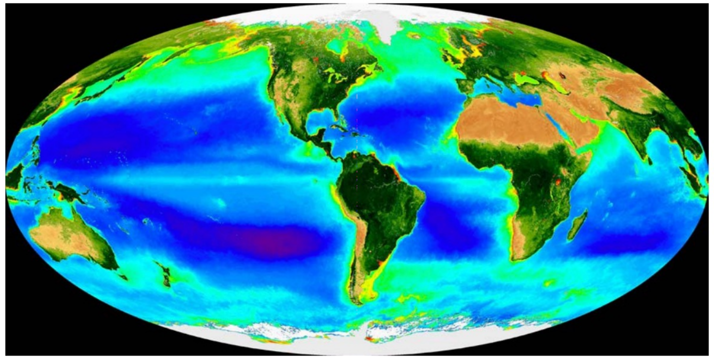
propagate this to TOA results in ~120,000 photons reach detector

SNR =~ 346

consider a moving satellite that scans from side-to-side

Requires >16x photons reaching the detector

Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) Mission Science Definition Team Report



October 16, 2012

λ	Band Width (nm)	Spatial Resol. (km^2)	L_{typ}	L_{max}	SNR-Spec
350	15	1	7.46	35.6	300
360	15	1	7.22	37.6	1000
385	15	1	6.11	38.1	1000
412	15	1	7.86	60.2	1000
425	15	1	6.95	58.5	1000
443	15	1	7.02	66.4	1000
460	15	1	6.83	72.4	1000
475	15	1	6.19	72.2	1000
490	15	1	5.31	68.6	1000
510	15	1	4.58	66.3	1000
532	15	1	3.92	65.1	1000
555	15	1	3.39	64.3	1000
583	15	1	2.81	62.4	1000
617	15	1	2.19	58.2	1000
640	10	1	1.90	56.4	1000
655	15	1	1.67	53.5	1000
665	10	1	1.60	53.6	1000
678	10	4	1.45	51.9	2000
710	15	1	1.19	48.9	1000
748	10	1	0.93	44.7	600
820	15	1	0.59	39.3	600
865	40	1	0.45	33.3	600
1240	20	1	0.088	15.8	250
1640	40	1	0.029	8.2	180
2130	50	1	0.008	2.2	15

useful duty cycle of of scan mirror is < 1/3, so really, we're talking about ~6,000 ocean surface photons

propagate this to TOA results in ~120,000 photons reach detector

SNR =~ 346

satellite instruments come in all shapes and sizes and have varying capabilities

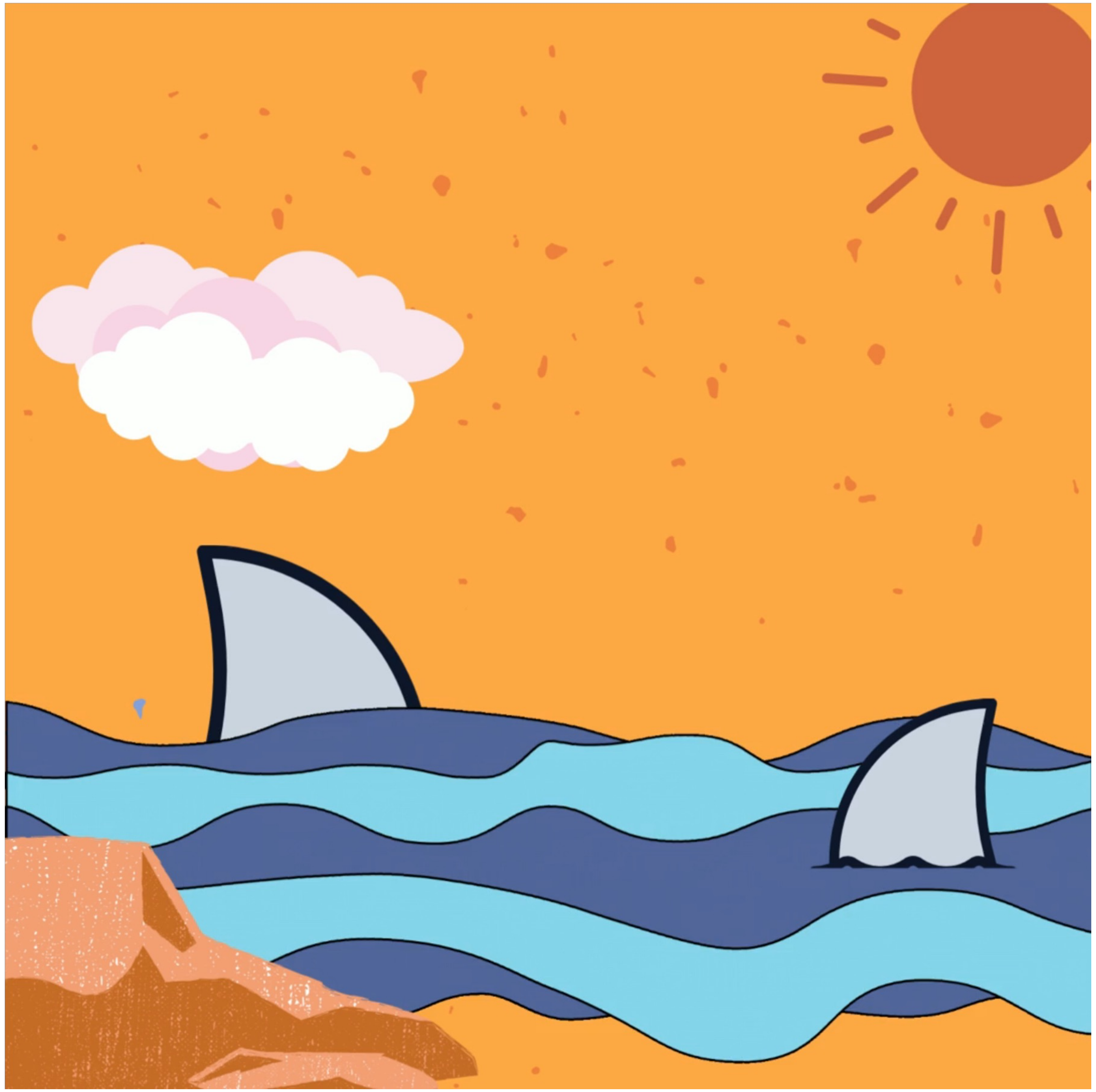
how does one choose what to use / build?

how would you design a mission to monitor coastal harmful algal blooms?

Optics Class
Class
Shark tank
exercise

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

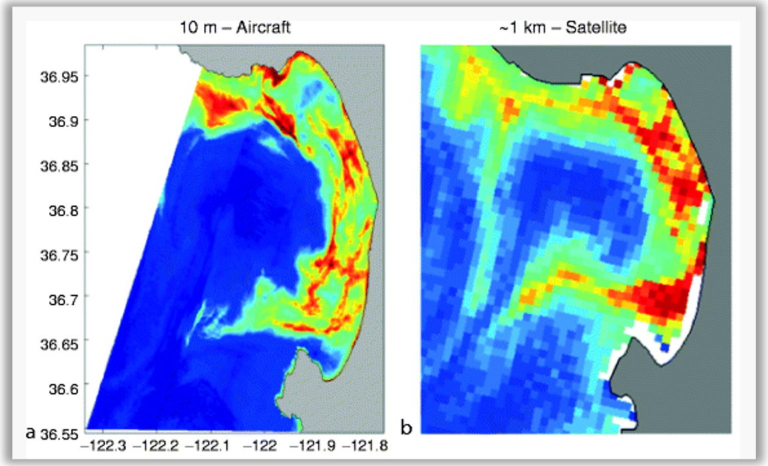
Ryan and Ivona
and Jeremy



Goal – build your own mission

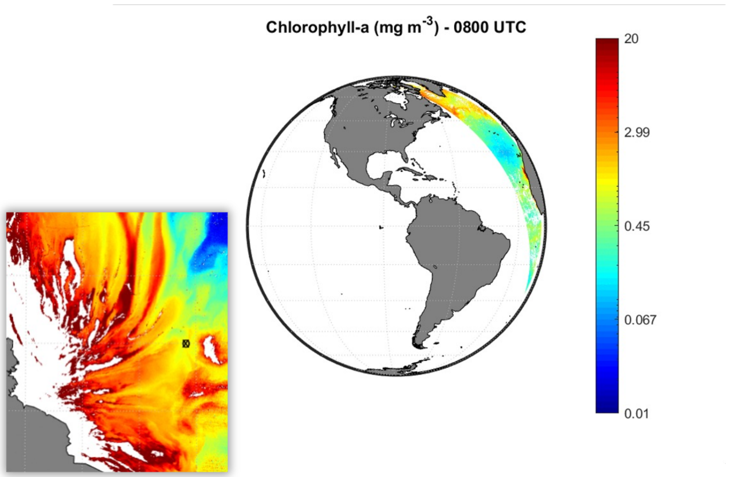
1. Find your team members (maybe groups of 5?)
2. Think about the assigned science question (coastal HABs)
3. Think what kind of space-based observation would you need to get data to address that question (you can copy already existing missions a bit)
4. Your budget its 100$ (and you are cost capped) – go shopping
5. Cool acronym (or yeah not a real mission)

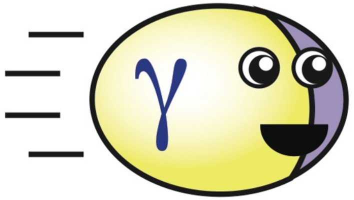
The battle over the happy photon

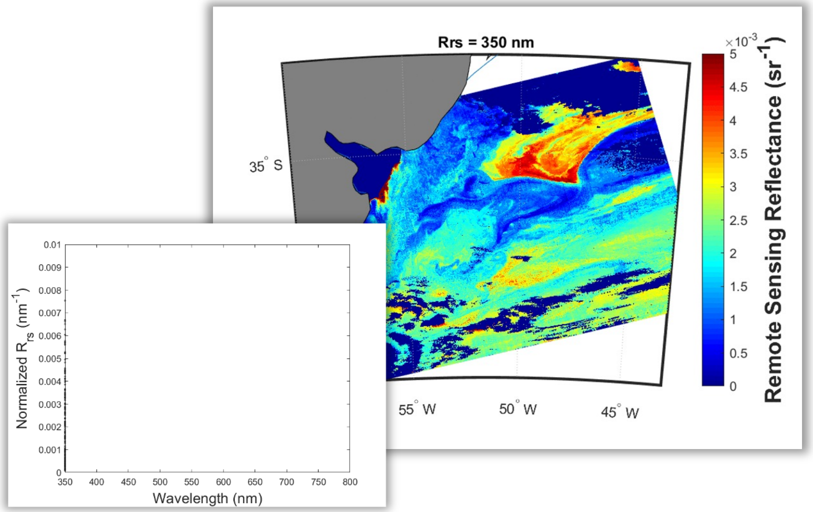


Spatial resolution

Temporal resolution

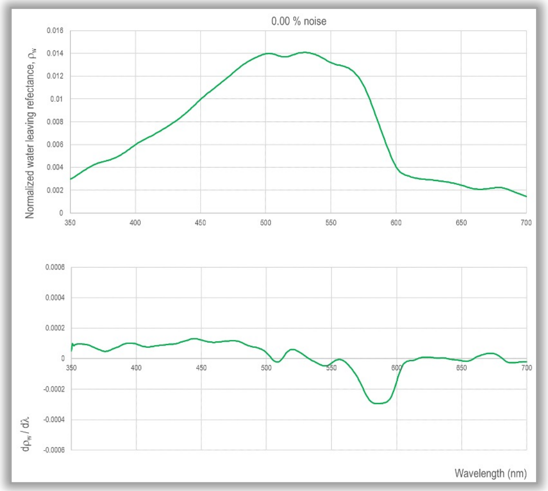


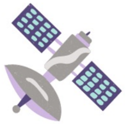




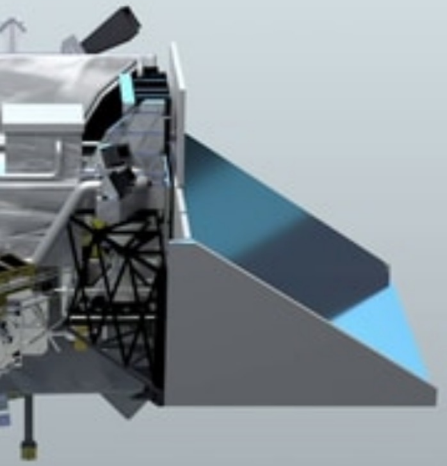
Spectral resolution

Signal to Noise





SATELLITE
Cafe



GRATUITY(AKA LAUNCH + SPACECRAFT) = 20%

OPEN :
MON-SUN
7 AM - 5 PM

123 Anywhere St.,
Any City, ST 12345

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
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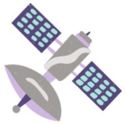

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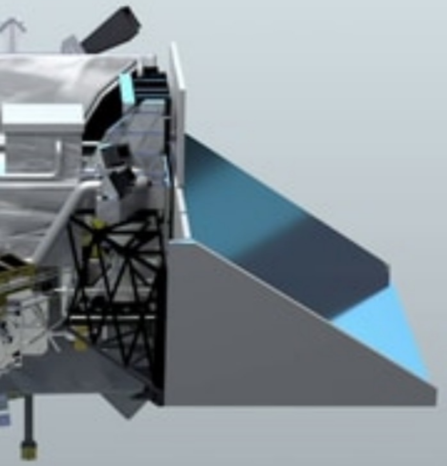

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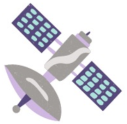

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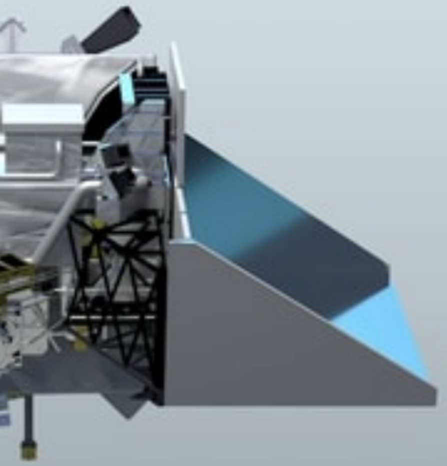

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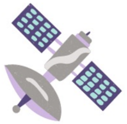

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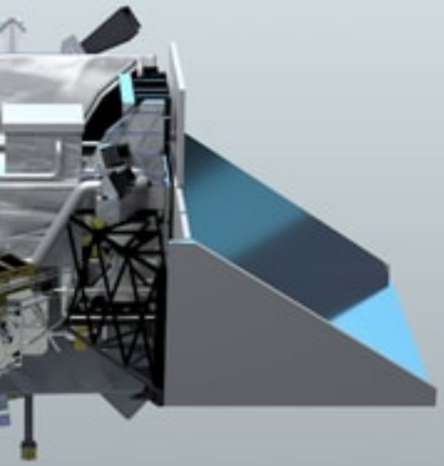

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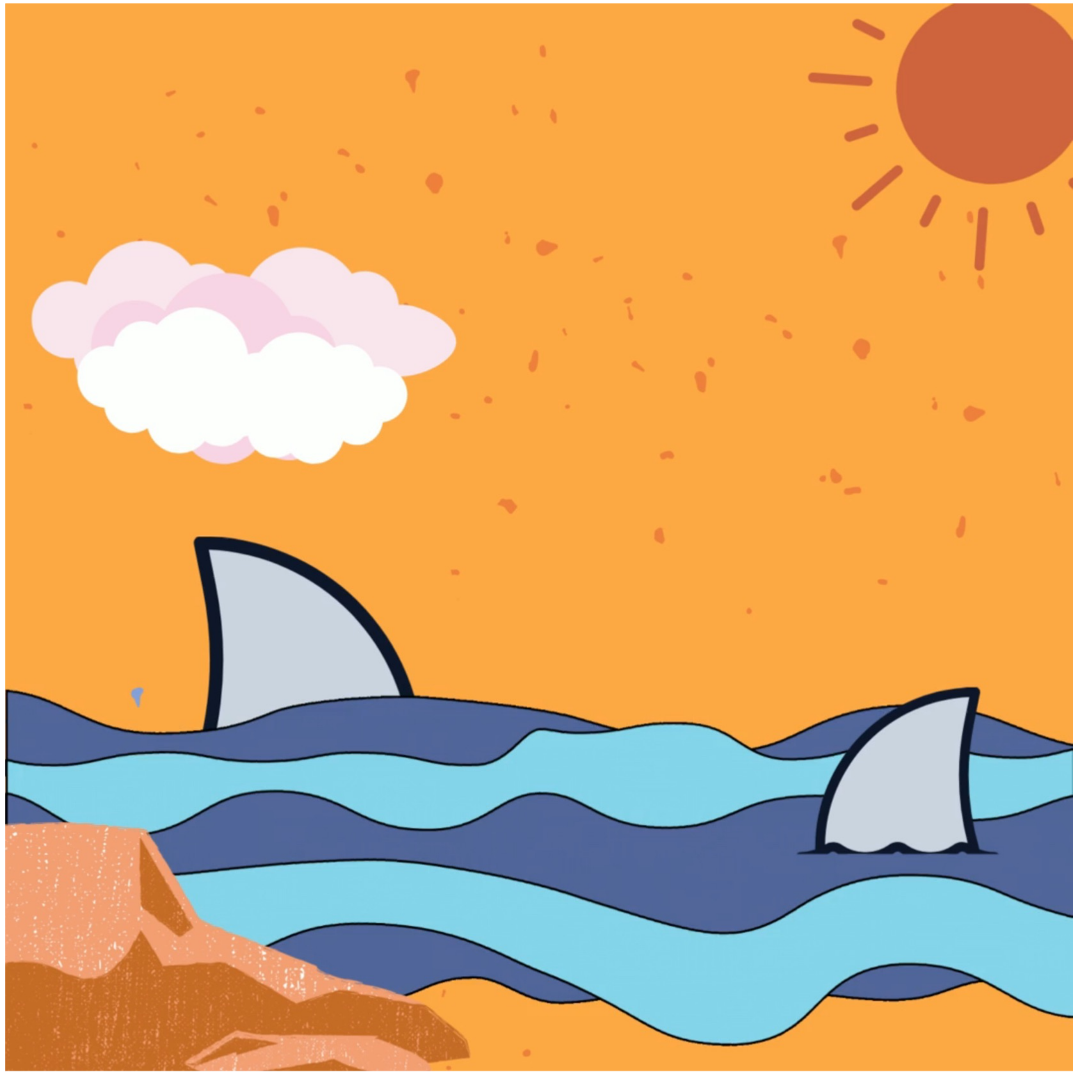
What if you go over the budget?

- Well – the review panel (or HQ) will decide.
- You fly or you get eaten by sharks.



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.

current & future missions – it's a consumer's market

SENSOR / DATA LINK	AGENCY	SATELLITE	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	BANDS	SPECTRAL COVERAGE (NM)	SPECTRAL RESPONSE FUNCTION	EQUATORIAL CROSSING TIME
COCTS CZI	NSOAS/CAST (China)	HY-1D	11 June 2020	3000 950	1100 50	10 4	402 - 12,500 433 - 885		13:30
COCTS CZI	NSOAS/CAST (China)	HY-1C	7 September 2018	3000 950	1100 50	10 4	402 - 12,500 433 - 885		10:30
GOCI-II Geostationary	KARI/KIOST (South Korea)	GeoKompsat-2B	18 February 2020	2500 x 2500	250	13	380 - 900	SRF-link	10 times/day
MODIS-Aqua	NASA (USA)	Aqua (EOS-PM1)	4 May 2002	2330	250/500/1000	36	405-14,385	SRF-link	13:30
MODIS-Terra	NASA (USA)	Terra (EOS-AM1)	18 Dec 1999	2330	250/500/1000	36	405-14,385	SRF-link	10:30
MSI	ESA	Sentinel-2A	23 June 2015	290	10/20/60	13	442-2202	SRF-link	10:30
MSI	ESA	Sentinel-2B	7 March 2017	290	10/20/60	13	442-2186	SRF-link	10:30
OCM-2	ISRO (India)	Oceansat-2 (India)	23 Sept 2009	1420	360/4000	8	400 - 900		12:00
OLCI	ESA/ EUMETSAT	Sentinel 3A	16 Feb 2016	1270	300/1200	21	400 - 1020	SRF-link	10:00
OLCI	ESA/ EUMETSAT	Sentinel 3B	25 April 2018	1270	300/1200	21	400 - 1020	SRF-link	10:00
SGLI	JAXA (Japan)	GCOM-C	23 Dec 2017	1150 - 1400	250/1000	19	375 - 12,500	SRF-link	10:30
VIIRS	NOAA (USA)	Suomi NPP	28 Oct 2011	3000	375 / 750	22	402 - 11,800	SRF-link	13:30
VIIRS	NOAA/NASA (USA)	JPSS-1/NOAA-20	18 Nov 2017	3000	370 / 740	22	402 - 11,800	SRF-link	13:30

SATELLITE	AGENCY	SENSOR / DATA LINK	LAUNCH DATE	SWATH (KM)	SPATIAL RESOLUTION (M)	# OF BANDS	SPECTRAL COVERAGE (NM)	ORBIT
HY-1E/F (China)	CNSA (China)	CZI	2021	2900 1000	1100 250	10 4	402 - 12,500 433 - 885	Polar
EnMAP	DLR (Germany)	HSI	2021-2022	30	30	242	420 - 2450	Polar
OCEANSAT-3	ISRO (India)	OCM-3	end-2021	1400	360 / 1	13	400 - 1,010	Polar
SABIA-MAR	CONAE	Multi-spectral Optical Camera	2023	200/2200	200/1100	16	380 - 11,800	Polar
PACE	NASA	OCI SPEXone HARP-2	2023	2000 100 1550	1000 2500 3000	Hyperspec (5 nm, 350-890nm + 7 bands NIR-SWIR) Hyperspec (2 nm) 4 bands	350-2250 nm 385-770 nm 440-870 nm	Polar
GISAT-1	ISRO (India)	MX-VNIR HyS-VNIR HyS-SWIR	12 August 2021	470 160 190	42 320 191	6 158 256	450-875 375-1000 900-2500	Geostationary (35.786 km) at 93.5°E
SBG	NASA	*Hyper-VSWIR *TIR-Imager	2026	~185 ~600	30 60-100	>200 ~8	380-2500	Polar
GLIMR	NASA	*VNIR-imager *WFOV-sensor	>2023	TBD	300 133	141	340-1040	Geostationary -Cont.US coasts, Amazon, Caribbean

IOCCG International Ocean Colour Coordinating Group


How to choose?
Plankton, Aerosol, Cloud, ocean Ecosystem

PACE will support studies of:

- ocean biology, ecology, & biogeochemistry
- atmospheric aerosols
- clouds
- land

Primary hyperspectral radiometer:

- Ocean Color Instrument (OCI) (GSFC)

2 contributed multi-angle polarimeters:

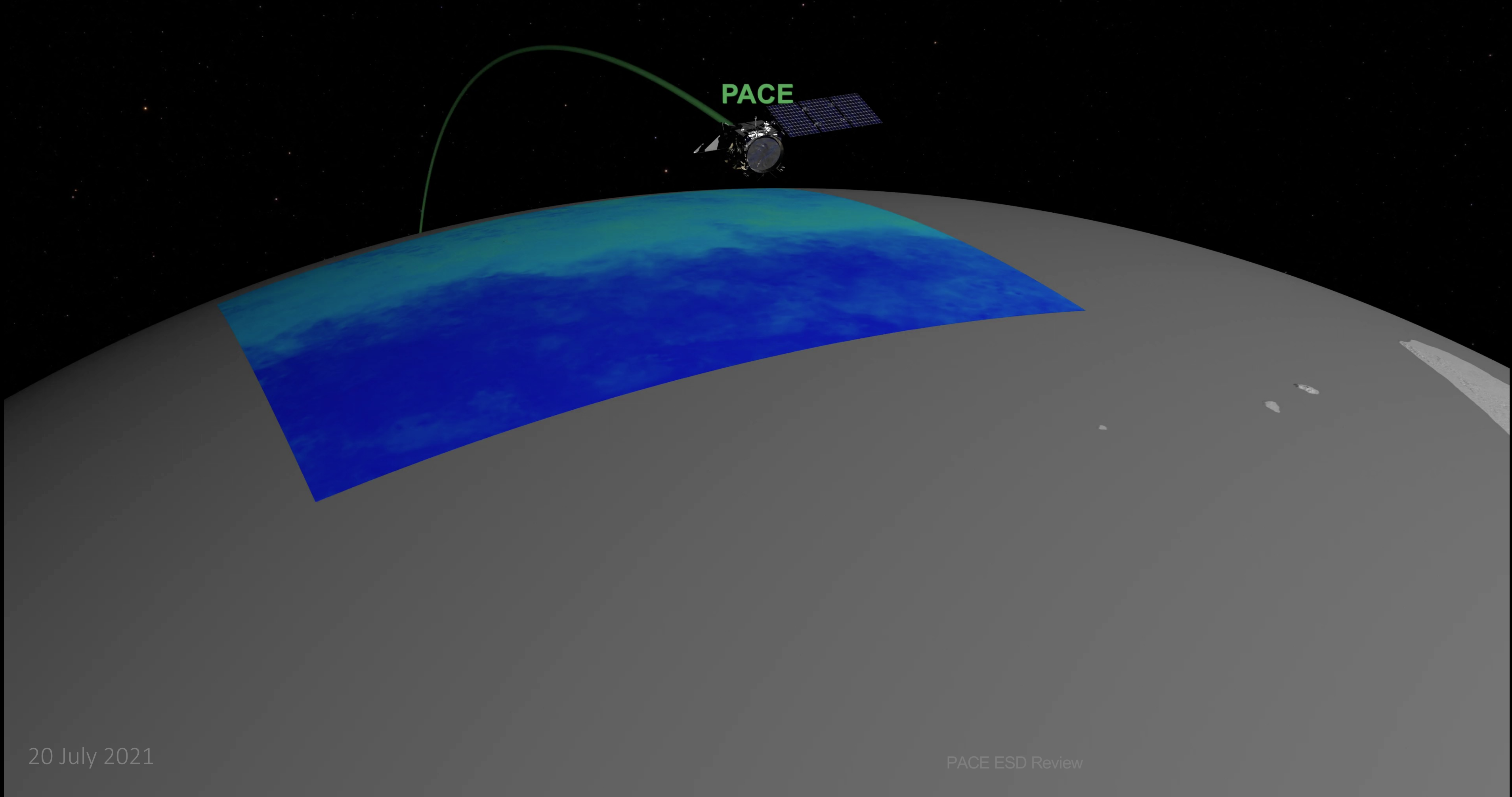
- HARP2 (UMBC)
- SPEXone (SRON/Airbus)

History:

- 2003-ish preliminary concept studies
- 2011 NASA Climate Change Initiative
- 2012 Science Definition Team
- 2014 first PACE science team
- 2015 mission directed to GSFC

Legacies:

- SeaWiFS, MODIS, VIIRS
- POLDER, MISR



Key characteristics:

- winter 2023/24 launch
- Falcon 9 from KSC/Cape Canaveral
- 676.5 km altitude
- polar, ascending, Sun synchronous orbit; 98^{o} inclination
- 13:00 local Equatorial crossing
- 3-yr design life; 10-yr propellant

PACE is NASA's next great investment in ocean color, cloud, and aerosol data records to enable continued and advanced insight into oceanographic and atmospheric responses to Earth's changing climate.

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

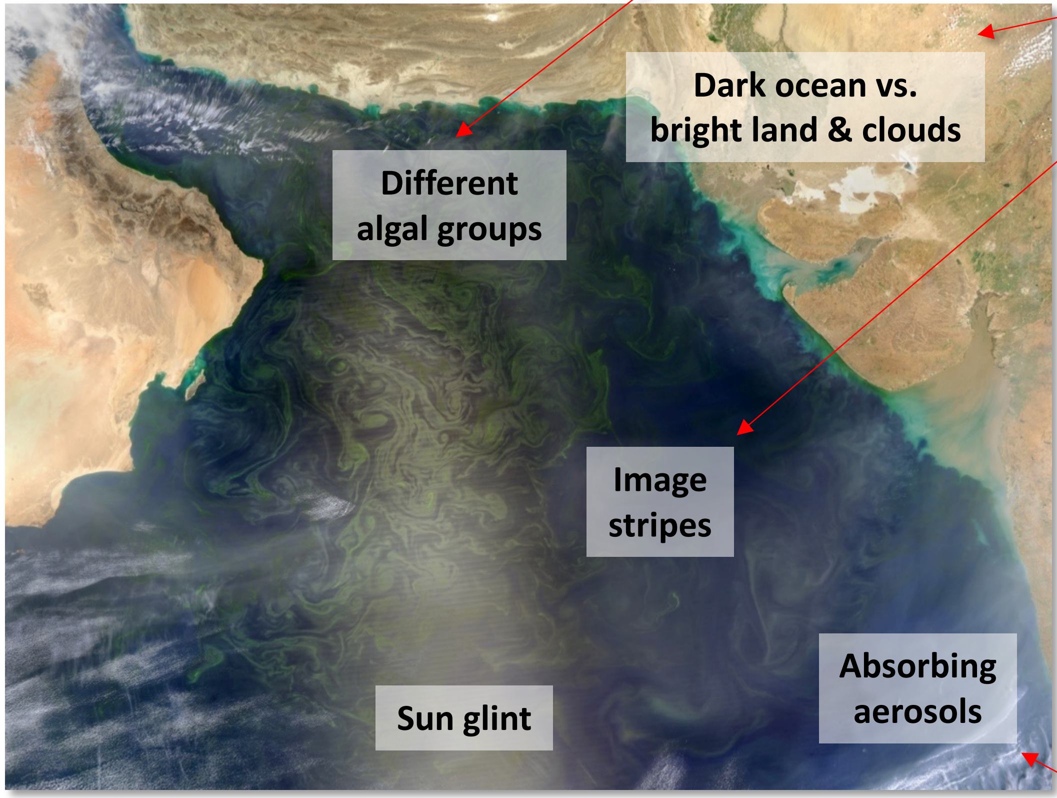
GSD of 1 ± 0.1 km² at nadir

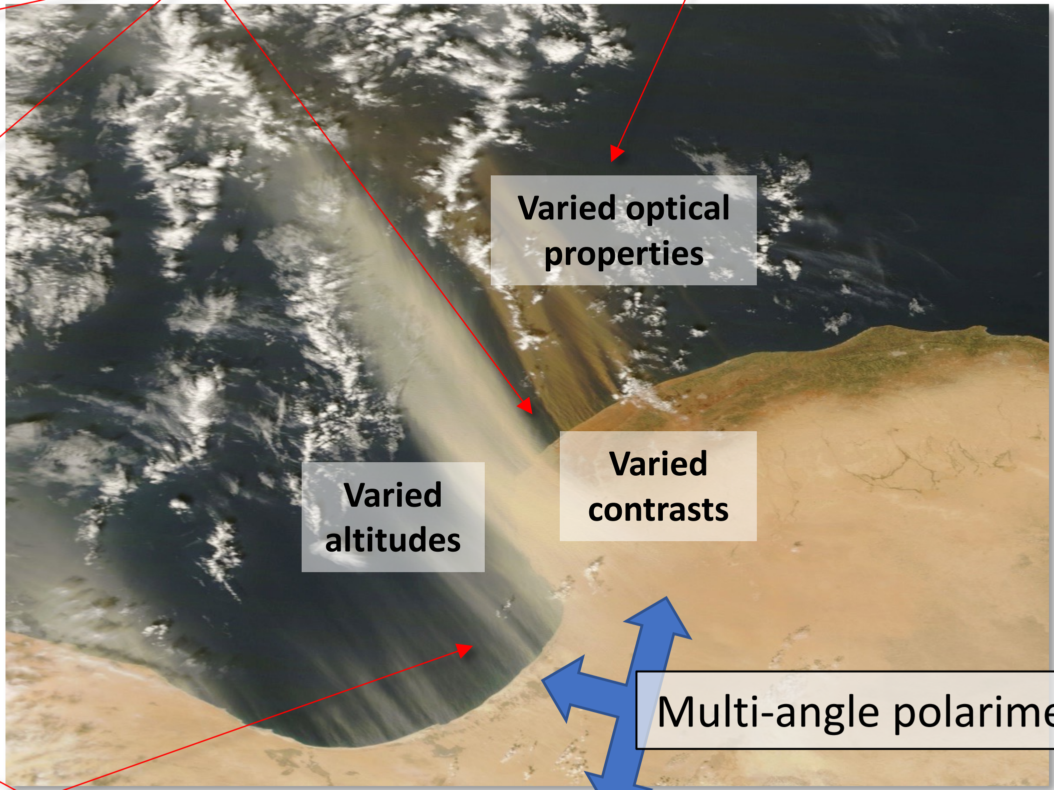
Twice-monthly lunar calibration & onboard solar calibration (daily, monthly, dim)

Spectral range from 350-865 @ 5 nm

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

Instrument performance requirements





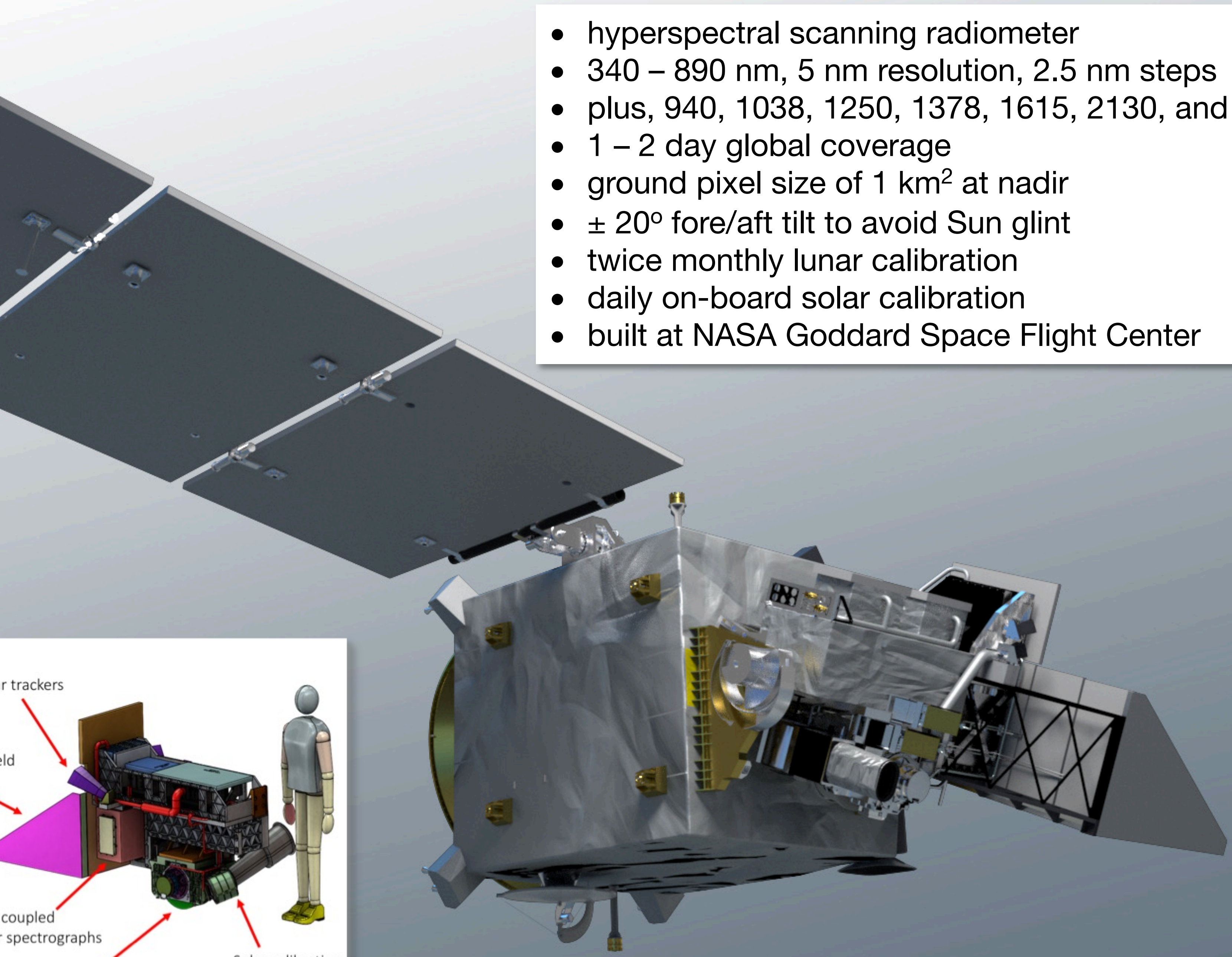
Multi-angle polarimetry

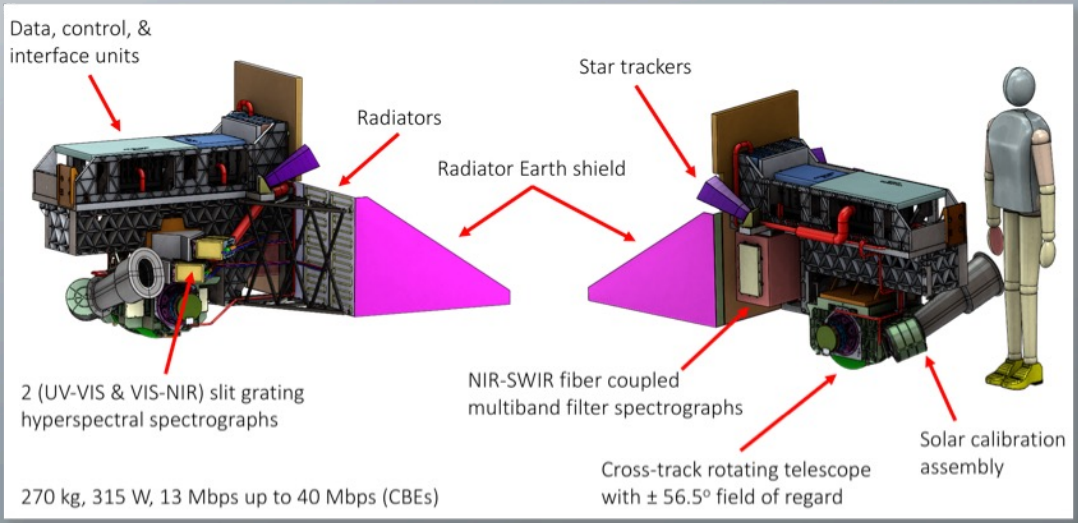
Tilt ± 20°

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**

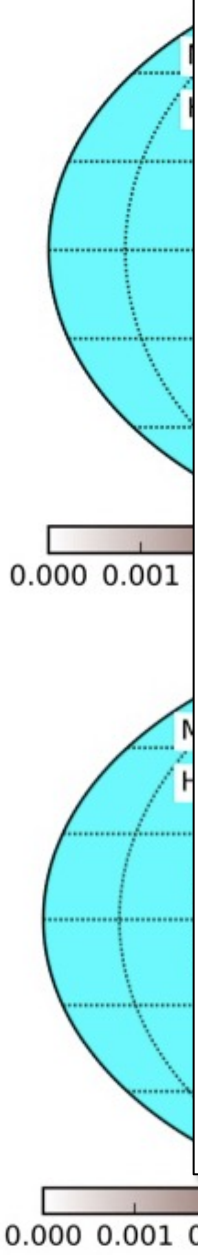
- hyperspectral scanning radiometer
- 340 – 890 nm, 5 nm resolution, 2.5 nm steps
- plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- 1 – 2 day global coverage
- ground pixel size of 1 km^2 at nadir
- ± 20° fore/aft tilt to avoid Sun glint
- twice monthly lunar calibration
- daily on-board solar calibration
- built at NASA Goddard Space Flight Center

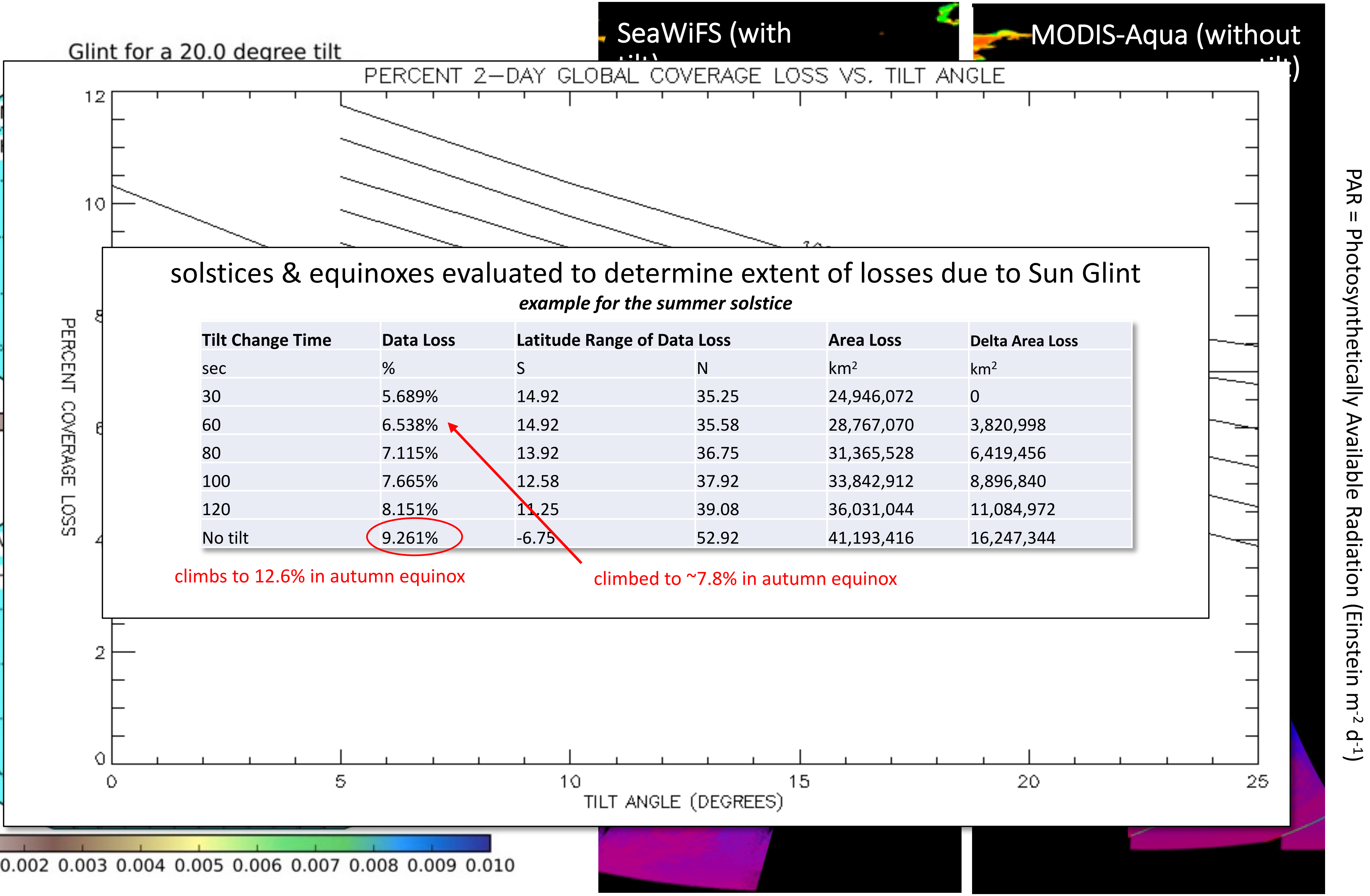




Challenges

Atmospheric correction (yesterday)
Sun glint
Image artifacts
Spectral resolution
Conscientious use of the data





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

example for the summer solstice

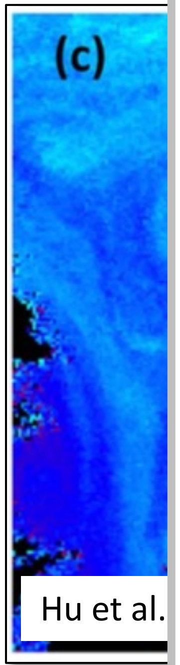
Tilt Change Time	Data Loss	Latitude Range of Data Loss		Area Loss	Delta Area Loss
sec	%	S	N	km²	km²
30	5.689%	14.92	35.25	24,946,072	0
60	6.538%	14.92	35.58	28,767,070	3,820,998
80	7.115%	13.92	36.75	31,365,528	6,419,456
100	7.665%	12.58	37.92	33,842,912	8,896,840
120	8.151%	11.25	39.08	36,031,044	11,084,972
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

image artifacts & instrument design

SeaWI
1



often

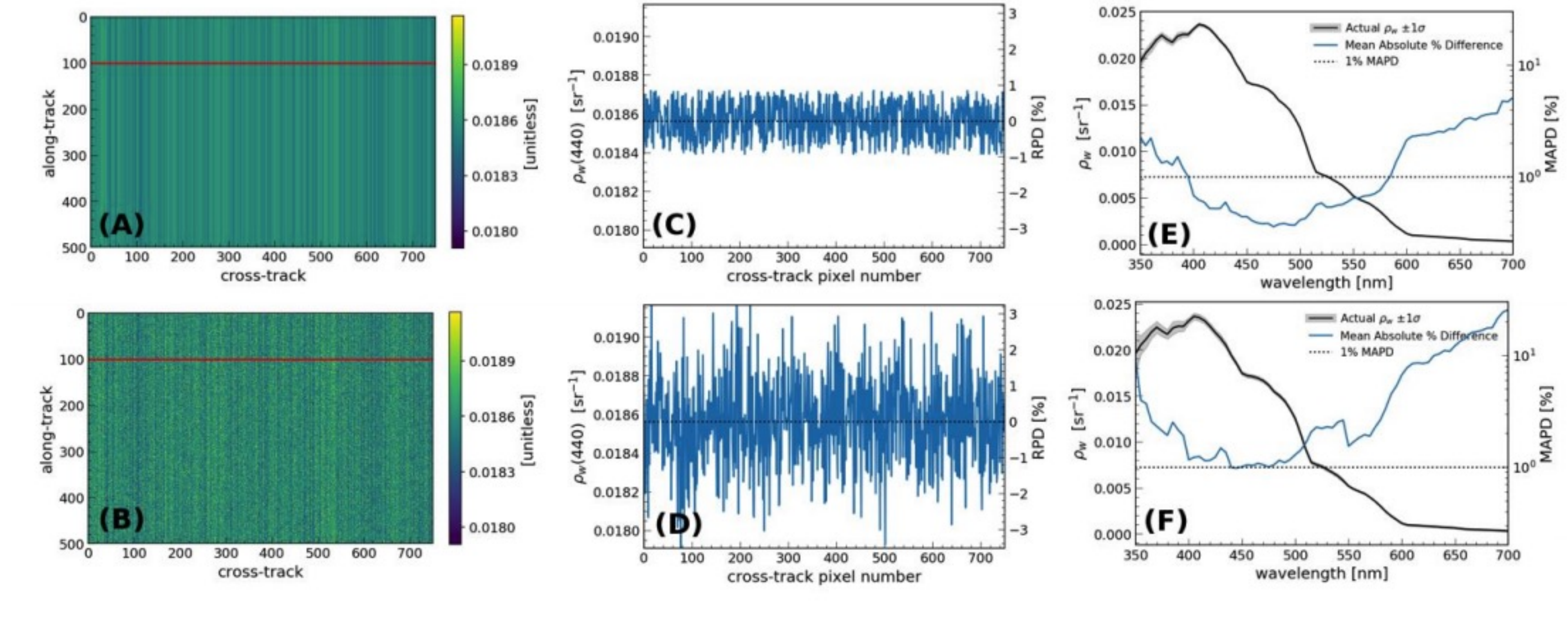
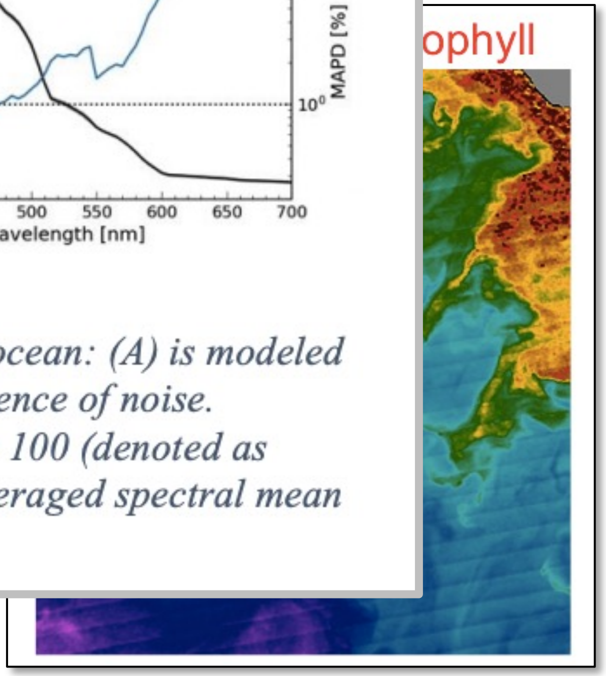
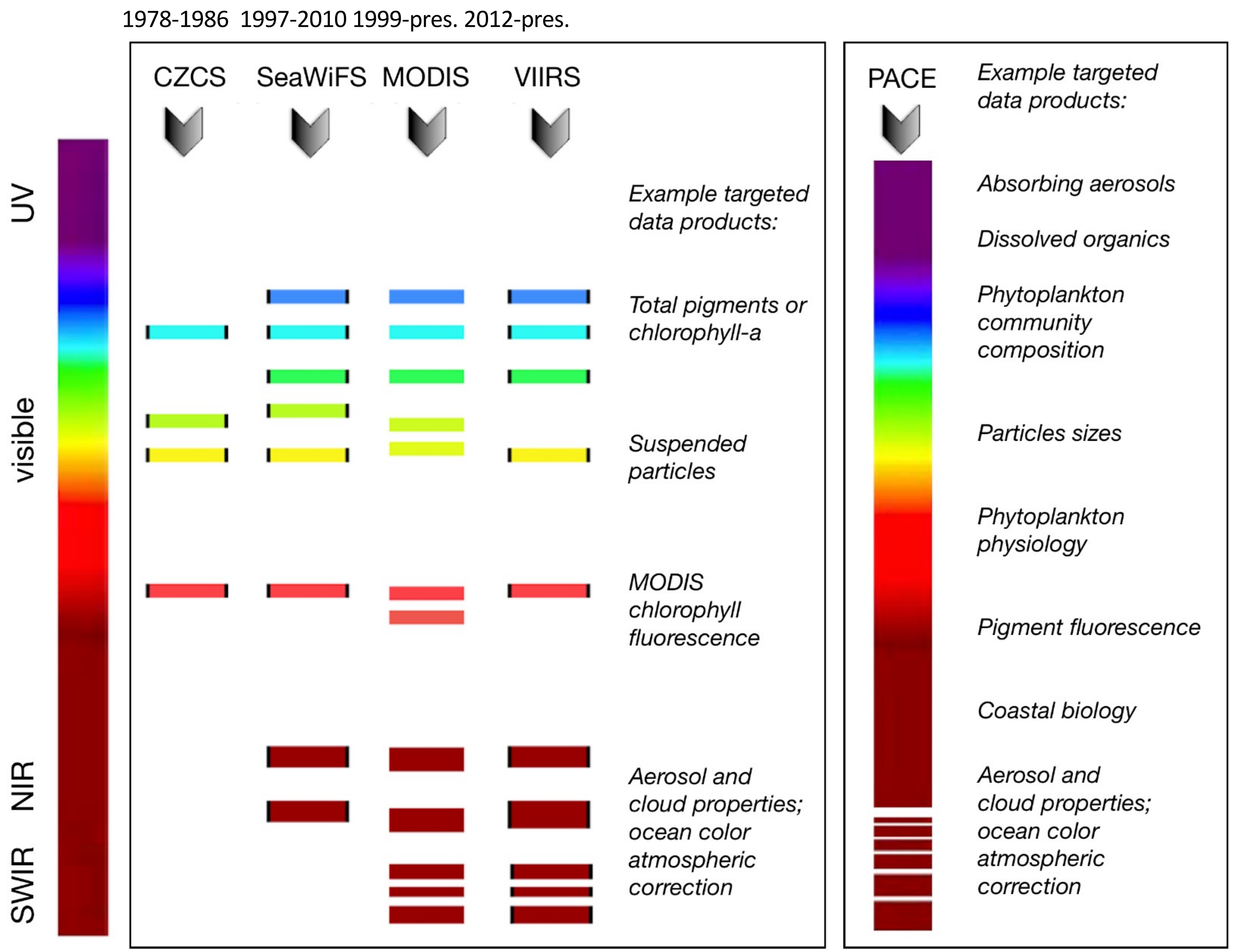


Figure 4.5: Subplots (A) and (B) show simulated pushbroom images of $\rho_w(440)$ for a uniform ocean: (A) is modeled with 0.1% miscalibration error, and (B) is modeled with 0.1% miscalibration error in the presence of noise. Subplots (C) and (D) show variability in $\rho_w(440)$ along a cross-track 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).

detector
show
ean color
ore
calibrate)



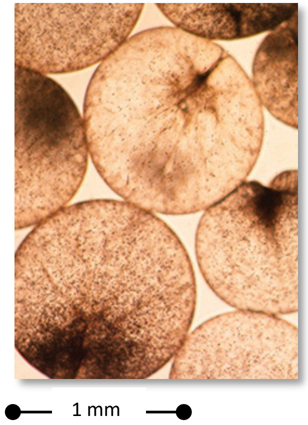
moving from multi-spectral radiometry to spectroscopy



Example diatom

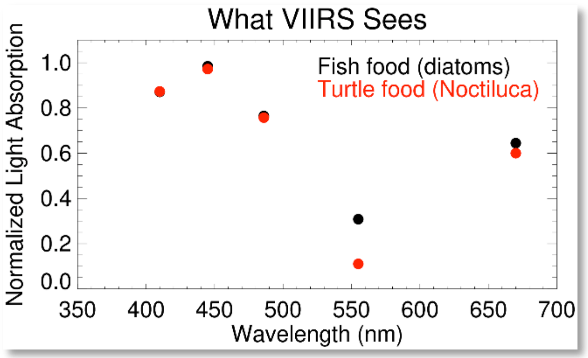
Linda Armbrecht, abc.com.au

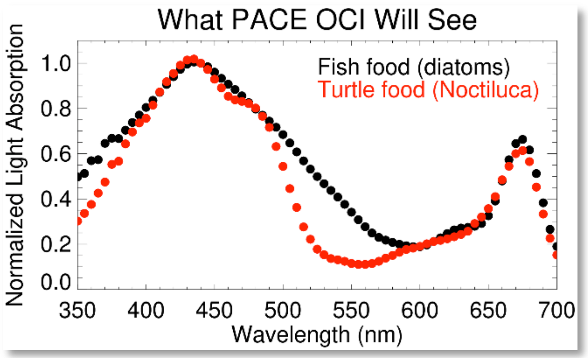
Example Noctiluca

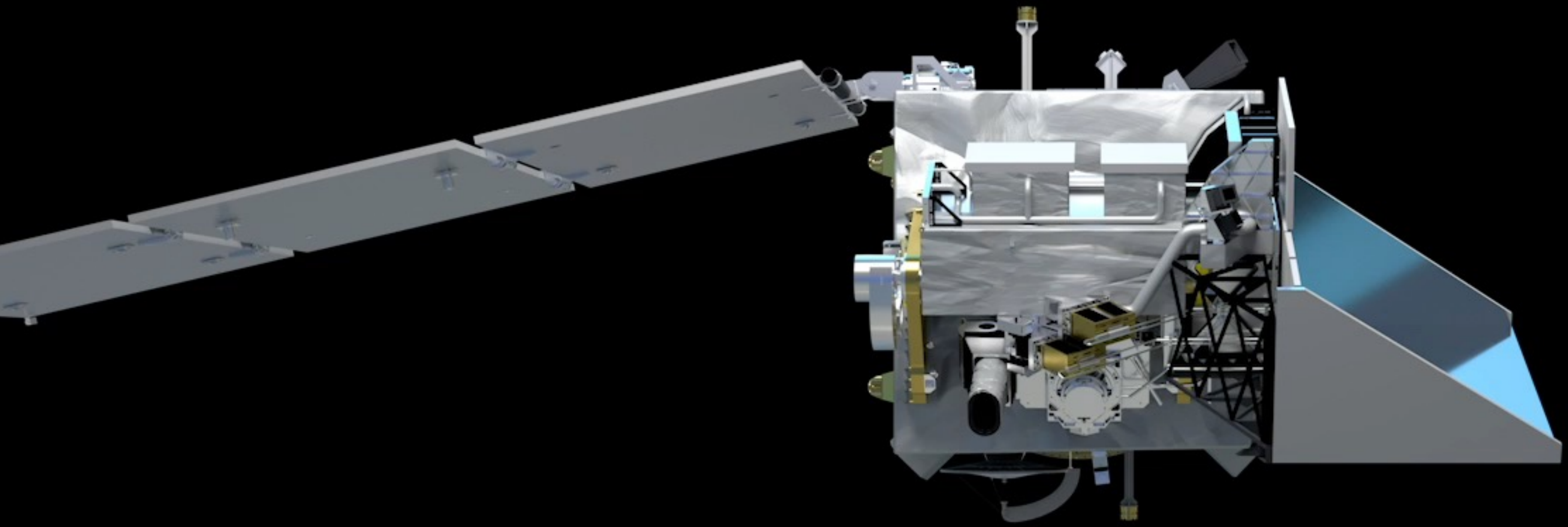


Joaquim Goes, LDEO

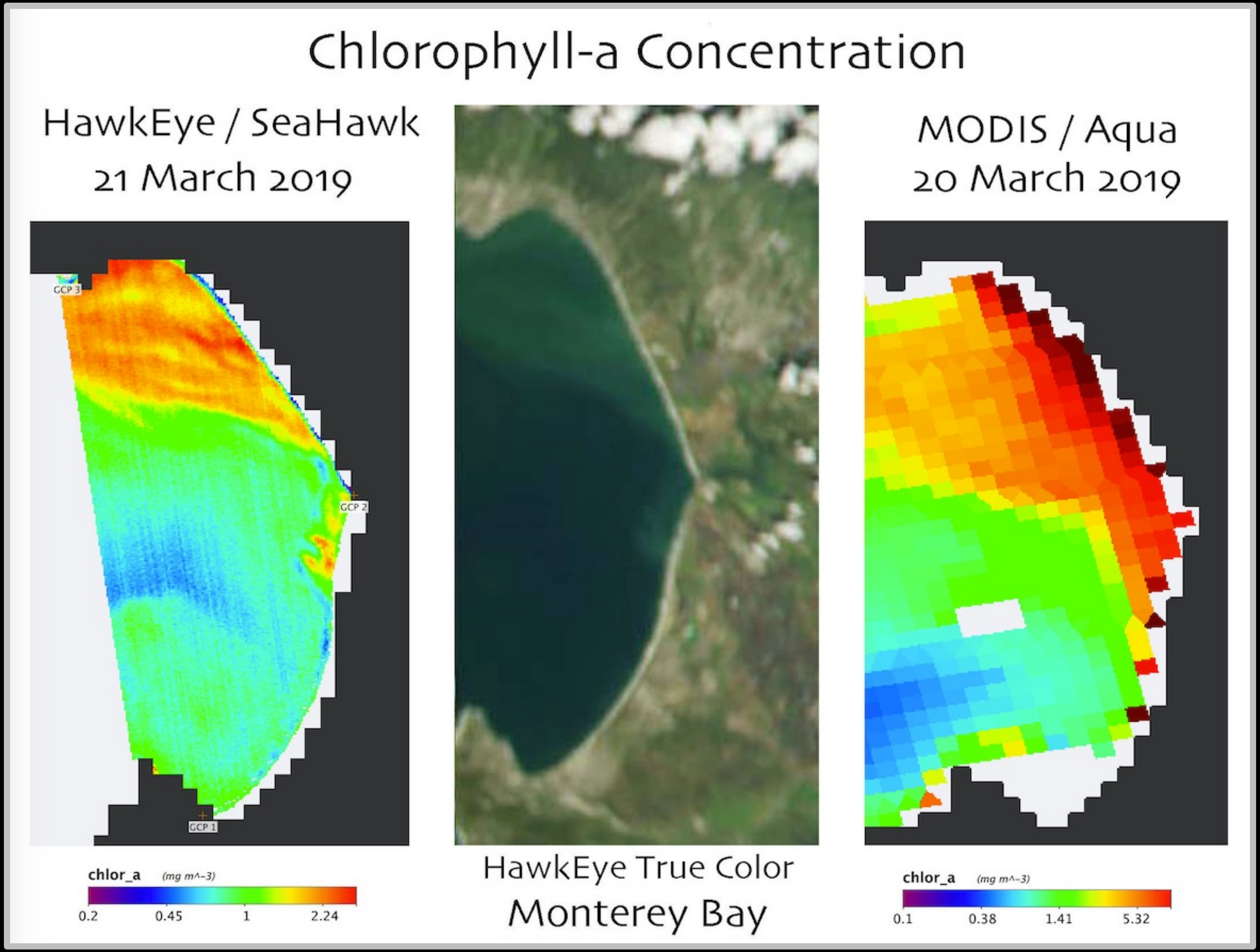
signals from the ocean are small & differentiating between constituents requires additional information relative to what we have today



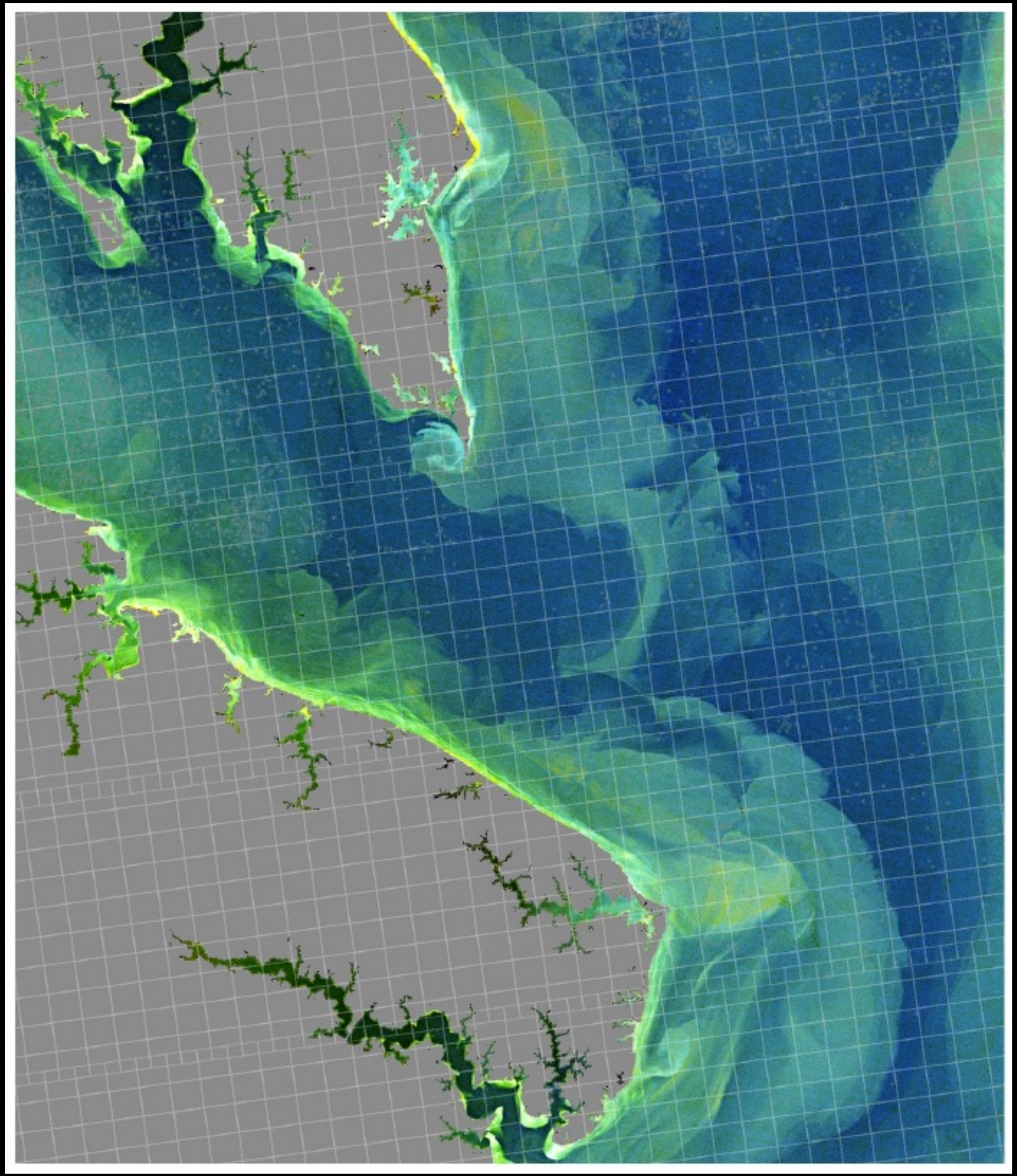




all that said …



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

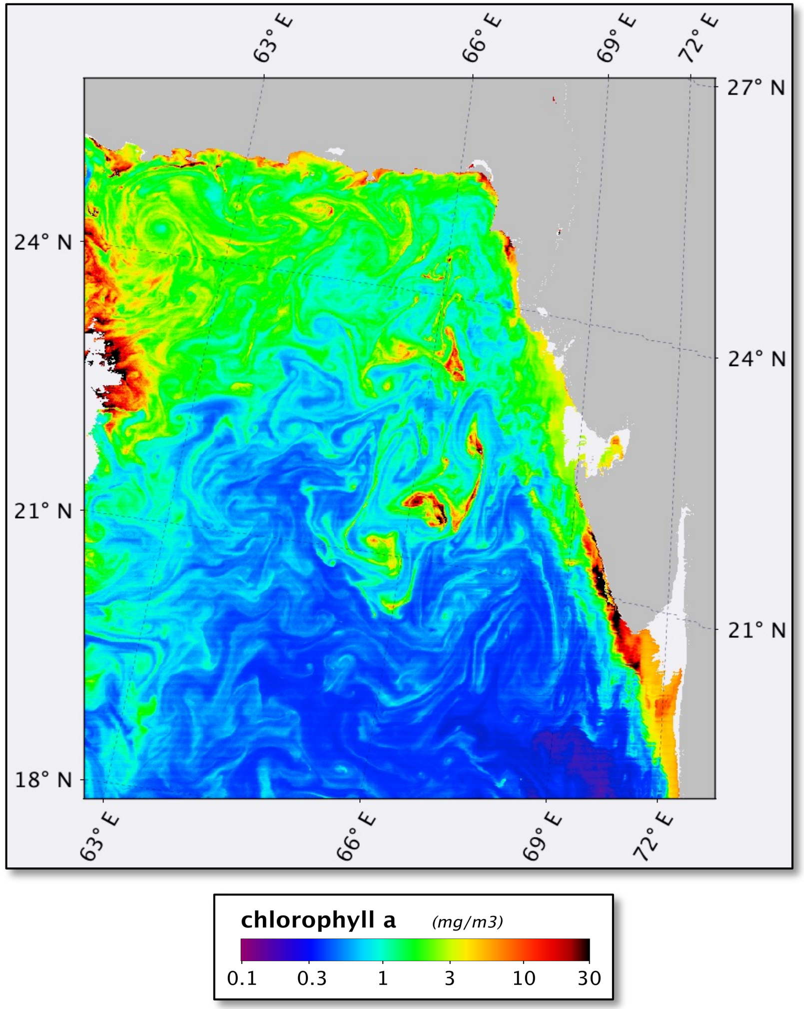


NEVER GIVE UP

Never Stop Trying to Exceed Your Limits. We Need the Entertainment.

understand how data processing changes the "answers"

For your consideration:
- horizontal resolution
- temporal resolution
- vertical resolution



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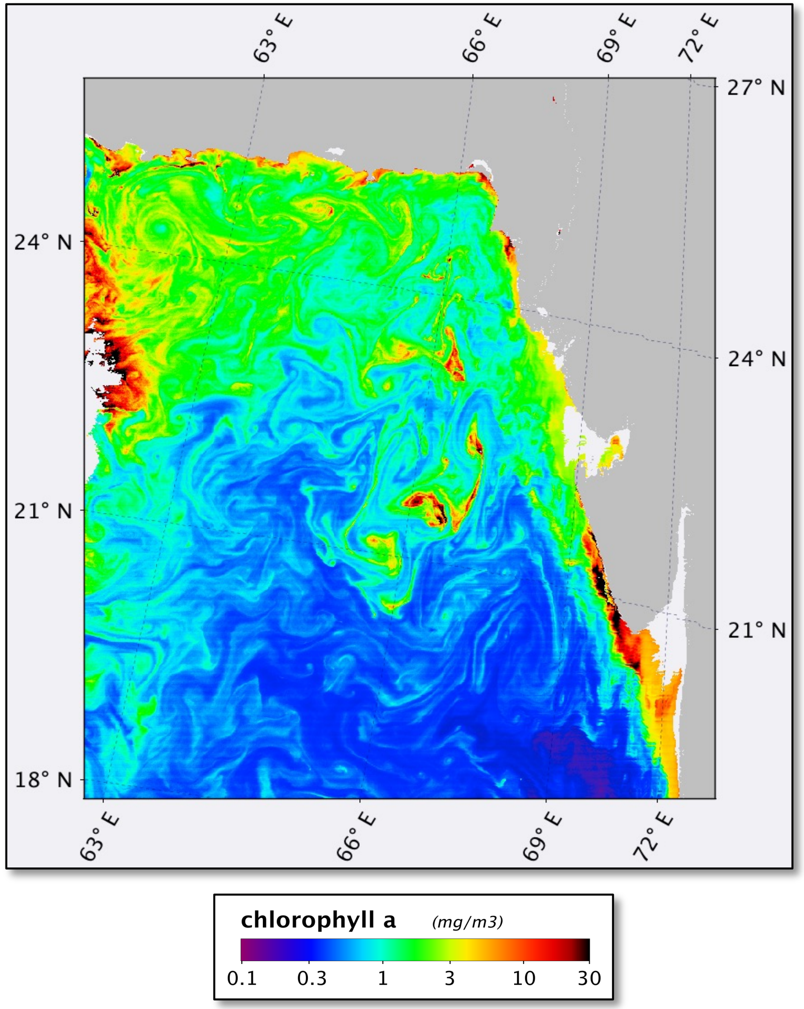

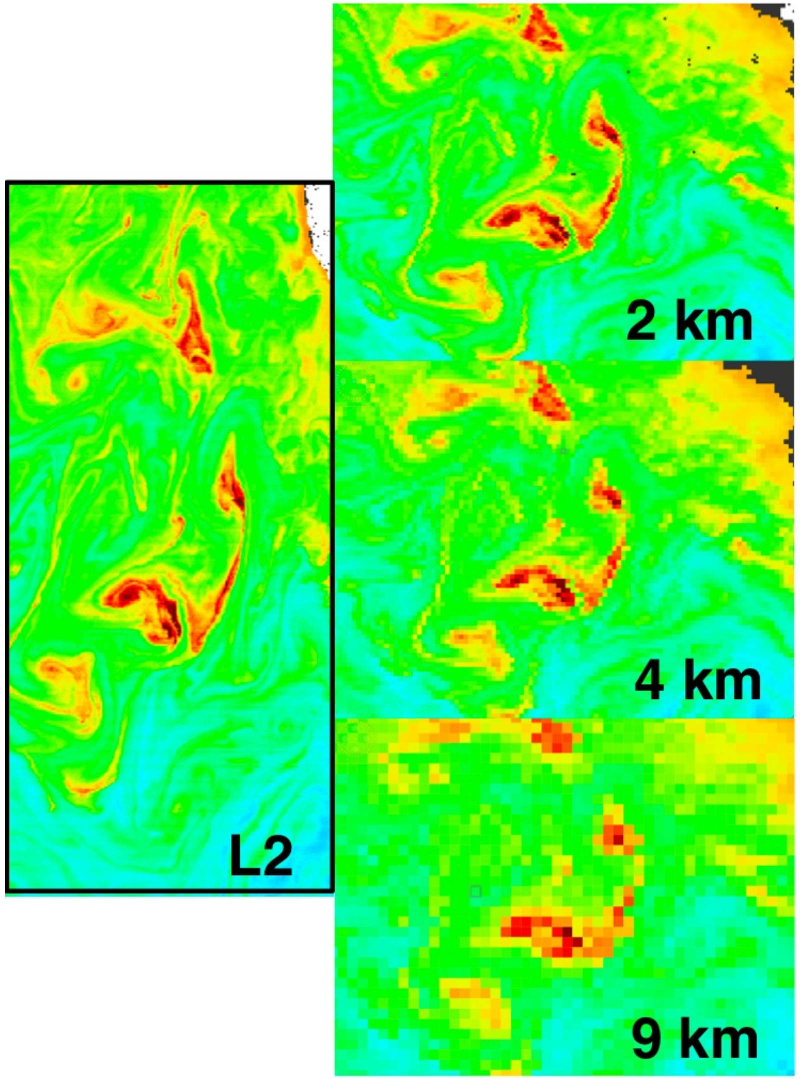

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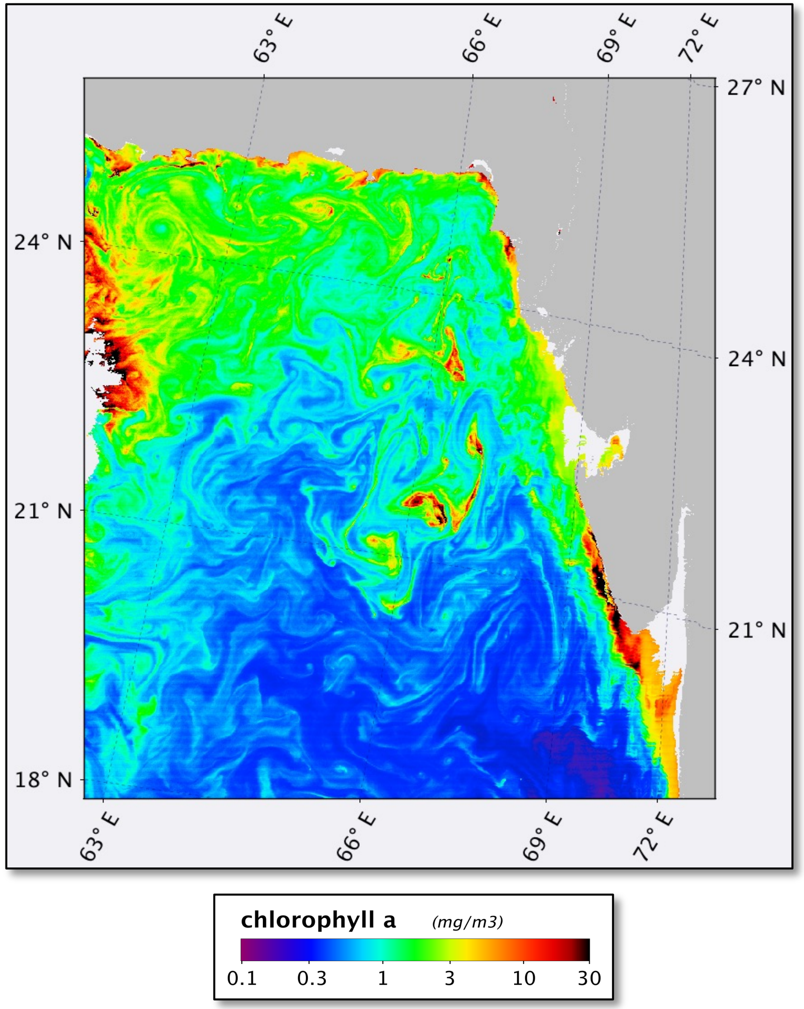

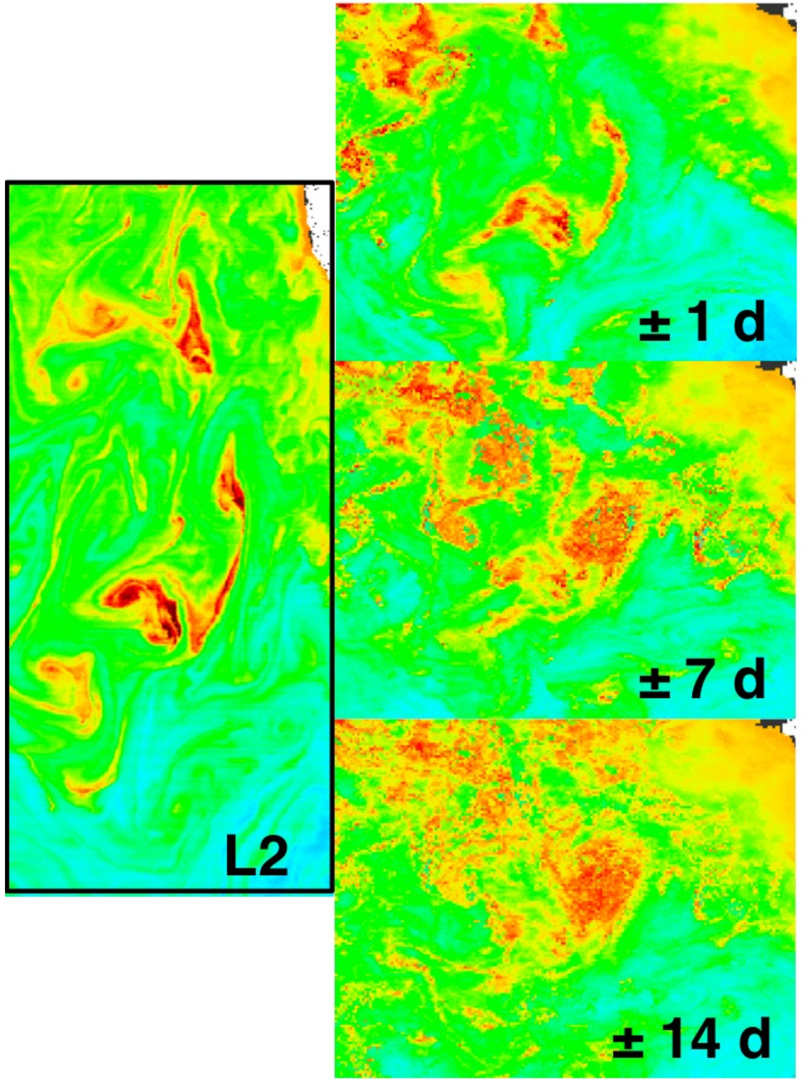

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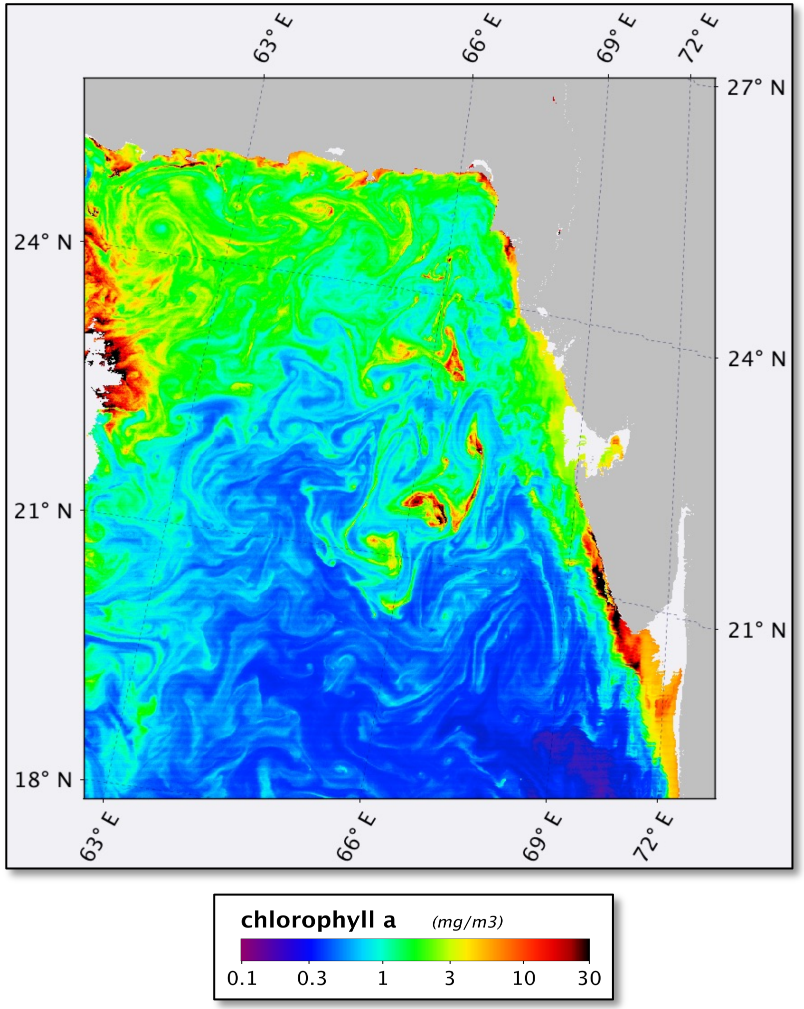

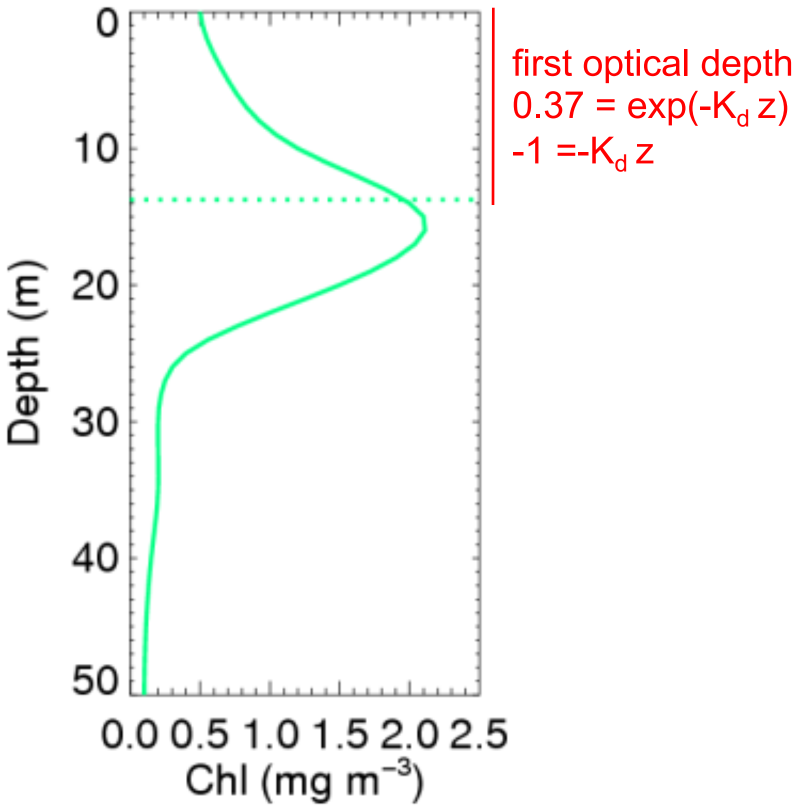

Estimation of the Depth of Sunlight Penetration in the Sea for Remote Sensing

Howard R. Gordon and W. R. McCluney

February 1975 / Vol. 14, No. 2 / APPLIED OPTICS 413

understand how data processing changes the “answers”

For your consideration:
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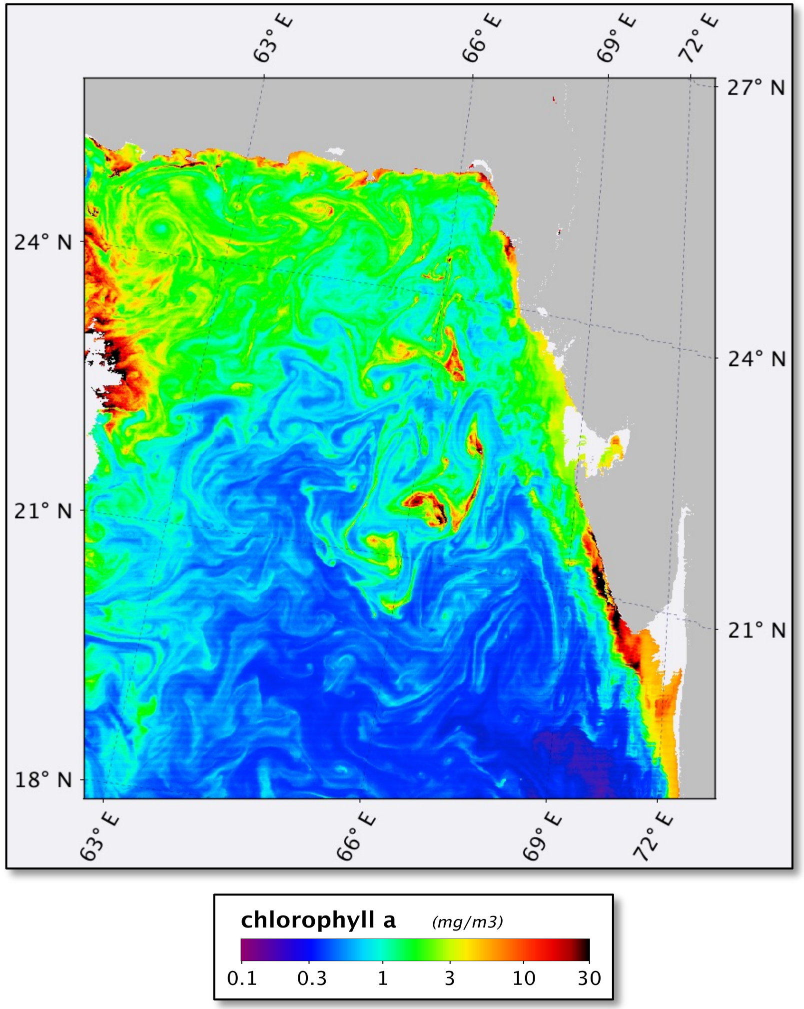
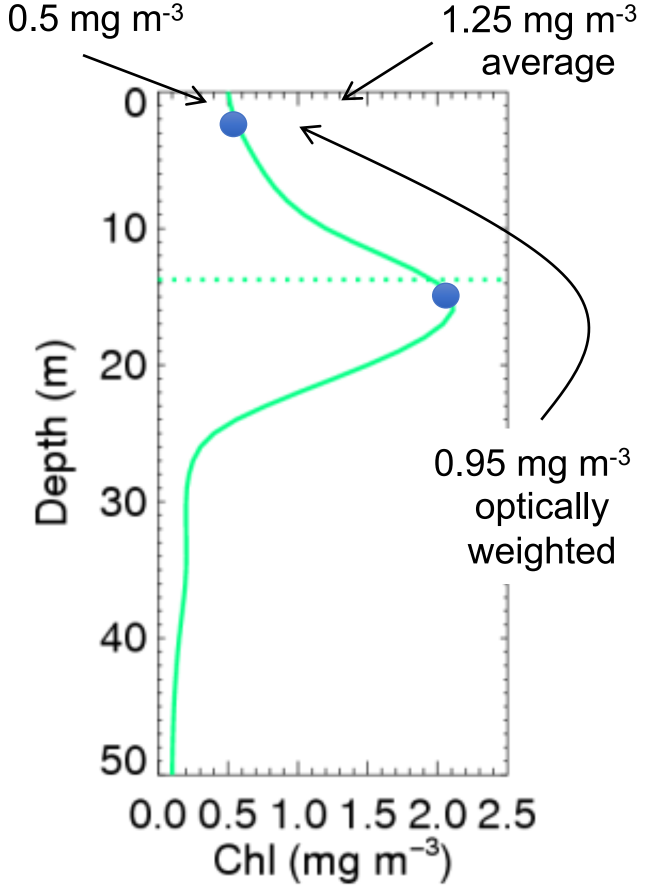
- temporal resolution
- vertical resolution





Theoretical derivation of the depth average of remotely sensed optical parameters

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#8803 - $15.00 USD
Received 15 September 2005; revised 20 October 2005; accepted 24 October 2005
31 October 2005 / Vol. 13, No. 22 / OPTICS EXPRESS 9052

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persevere …

… and collaborate

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