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

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Acknowledgements:
Gary Davis, Bryan Monosmith, & Curt Mobley

PACE class @ UMBC
1-5 Aug 2022
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
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 & their interactions with the atmosphere under pervasive absorbing aerosols?
What measurements & data products? All of them.


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.
pushbroom vs. whiskbroom (scanner)

SeaWiFS
MODIS
VIIRS
PACE OCI

HICO
Landsat 8 OLI
MERIS
OLCI
GEO (geostationary) vs. LEO (polar, low earth orbit)
GEO (geostationary) vs. LEO (polar, low earth orbit)

35,786 km altitude
GEO (geostationary) vs. LEO (polar, low earth orbit)

35,786 km altitude

400-700 km altitude
different instruments & missions offer different capabilities

Landsat 8 OLI, 26 Oct 2016, Queensland, Australia

different algal groups (spectral bands)
dark ocean compared to bright targets
image artifacts
atmospheric correction (spectral bands + instrument performance)
temporal repeatability
contamination by Sun glint

ground sample distances
current & future missions – it’s a consumer’s market

<table>
<thead>
<tr>
<th>SENSOR / DATA LINK</th>
<th>AGENCY</th>
<th>SATELLITE</th>
<th>LAUNCH DATE</th>
<th>SWATH (KM)</th>
<th>SPATIAL RESOLUTION (M)</th>
<th>BANDS</th>
<th>SPECTRAL COVERAGE (NM)</th>
<th>SPECTRAL RESPONSE FUNCTION</th>
<th>EQUATORIAL CROSSING TIME</th>
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<tbody>
<tr>
<td>COCTS C2I</td>
<td>NSOAS/CAST (China)</td>
<td>Hy-1D</td>
<td>11 June 2020</td>
<td>3000 x 990</td>
<td>1100 x 50</td>
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<td>Sentinel-2A</td>
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<td>10/20/60</td>
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<td>Suomi NPP</td>
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<td>375 / 750</td>
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<td>402 - 11,800</td>
<td>SRF-link</td>
<td>13:30</td>
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<td>SATELLITE</td>
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<td>SWATH (KM)</td>
<td>SPATIAL RESOLUTION (M)</td>
<td># OF BANDS</td>
<td>SPECTRAL COVERAGE (NM)</td>
<td>ORBIT</td>
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<td>CZJ</td>
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<td>420 - 2450</td>
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<td>360 / 1</td>
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<td>400 - 1,010</td>
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<td>SABIA-MAR</td>
<td>CONAE</td>
<td>Multi-spectral Optical Camera</td>
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<td>200/2200</td>
<td>200/1100</td>
<td>16</td>
<td>380 - 11,800</td>
<td>Polar</td>
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<td>PACE</td>
<td>NASA</td>
<td>OCI</td>
<td>2023</td>
<td>2000</td>
<td>1000</td>
<td>HyperSpec (5 nm, 350-870nm) + 7 bands</td>
<td>350 - 2250 nm</td>
<td>Polar</td>
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<td></td>
<td>NASA</td>
<td>SPEXone</td>
<td>2023</td>
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<td>HyperSpec (2 nm)</td>
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<td>3000</td>
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<td>440-870 nm</td>
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<td>91</td>
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<td>NASA</td>
<td>Hyper-VNR / TIR</td>
<td>2026</td>
<td>-185</td>
<td>30</td>
<td>&gt;200</td>
<td>-180</td>
<td>60</td>
<td>100</td>
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<td>GLCMER</td>
<td>NASA</td>
<td>VNR-IMager / WFV4 sensor</td>
<td>&gt;2023</td>
<td>TBD</td>
<td>300</td>
<td>133</td>
<td>141</td>
<td>340-1040</td>
<td>Geostationary - Cont. US (490°W), Ar. Pacific, Caribbean</td>
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</tbody>
</table>
How to choose?

Plankton, Aerosol, Cloud, ocean Ecosystem
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 $1 \pm 0.1 \text{ km}^2$ 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

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

Spectral range goal of 320-865 @ 5 nm

Multi-angle polarimetry

Improve our understanding of how aerosols influence ocean ecosystems & biogeochemical cycles and how ocean biological & photochemical processes affect the atmosphere
OCEAN COLOR & THE OCEAN COLOR INSTRUMENT

OCEAN COLOR RETRIEVALS DRIVE OCI'S DESIGN & PERFORMANCE REQUIREMENTS

- Hyperspectral scanning radiometer
- (320) 340 – 890 nm, 5 nm resolution, 2.5 nm steps
- Plus, 940, 1038, 1250, 1378, 1615, 2130, and 2250 nm
- Single science pixel to mitigate image striping
- 1 – 2 day global coverage
- Ground pixel size of 1 km² at nadir
- ± 20° fore/aft tilt to avoid Sun glint
- Twice monthly lunar calibration
- Daily on-board solar calibration
- <0.5% total system error for VIS-NIR
- SNRs optimized for ocean color science
- Simulated top-of-atmosphere data available

* Developed primarily for mechanical processing assessments
Challenges

Atmospheric correction (L10)
Sun glint
Image artifacts
Spatial resolution
Conscientious use of the data
Solstices & equinoxes evaluated to determine extent of losses due to Sun Glint

**Table:**

<table>
<thead>
<tr>
<th>Tilt Change Time</th>
<th>Data Loss (%)</th>
<th>Latitude Range of Data Loss</th>
<th>Area Loss (km²)</th>
<th>Delta Area Loss (km²)</th>
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</thead>
<tbody>
<tr>
<td>30 sec</td>
<td>5.689</td>
<td>14.92 - 35.25</td>
<td>24,946,072</td>
<td>0</td>
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<tr>
<td>60 sec</td>
<td>6.538</td>
<td>14.92 - 35.58</td>
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<tr>
<td>80 sec</td>
<td>7.115</td>
<td>13.92 - 36.75</td>
<td>31,365,528</td>
<td>6,419,456</td>
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<tr>
<td>120 sec</td>
<td>8.151</td>
<td>11.25 - 39.08</td>
<td>36,031,044</td>
<td>11,084,972</td>
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<tr>
<td>No tilt</td>
<td>9.261</td>
<td>-6.75 - 52.92</td>
<td>41,193,416</td>
<td>16,247,344</td>
</tr>
</tbody>
</table>

**Notes:**
- Example for the summer solstice
- Climbs to 12.6% in autumn equinox
- Climbed to ~7.8% in autumn equinox
SeaWIFS (rotating telescope)

MERIS (pushbroom)

Hu et al. (2012)

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

often smaller science pixels

(30-300 m)

often larger science pixels

(1 km)

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).
moving from multi-spectral radiometry to spectroscopy

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

Example diatom

Example Noctiluca

What VIIRS Sees

What PACE OCI Will See

1 mm
Landsat OLI image with MODIS-Aqua grid shown (Franz et al. 2015)
For your consideration:
- horizontal resolution
- temporal resolution
- vertical resolution

understand how data processing changes the “answers”
understand how data processing changes the “answers”

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

understand how data processing changes the “answers”
For your consideration:
- horizontal resolution
- temporal resolution
- vertical resolution

understand how data processing changes the “answers”

first optical depth
0.37 = \exp(-K_d z)
-1 = -K_d z

Estimation of the Depth of Sunlight Penetration in the Sea for Remote Sensing
Howard R. Gordon and W. R. McCluney
February 1976 / Vol. 14, No. 2 / APPLIED OPTICS 413
For your consideration:
- horizontal resolution
- temporal resolution
- vertical resolution

understand how data processing changes the “answers”
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
Why don’t all ocean color satellites measure hyperspectral radiances at meter-scales?

3 case studies:

(1) stationary satellite staring at $1 \text{ m}^2$ for $1 \text{ s}$
(2) moving satellite staring at $1 \text{ m}^2$
(3) moving satellite scanning side to side

What we will (hopefully) learn:

• how many photons leave a $1 \text{ m}^2$ of ocean surface
• how many photons from this patch reach the satellite detector
• how 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)

let’s focus on a fluorescence channel:

Wavelength = 0.678 um (678 nm)  
Bandwidth (Δλ) = 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**:

\[
P_{\text{detector}} = L \Omega_{\text{aperture}} A_{\text{surface}} OE \Delta \lambda
\]

\[
\begin{align*}
1.24 \times 10^{-15} &= 14.5 \\ W &= W \text{ m}^{-2} \text{ sr}^{-1} \text{ um}^{-1} \\ 1.3 \times 10^{-14} &= 1 \\ 0.66 &= 0.01
\end{align*}
\]

photoelectrons reaching detector:

\[
N_{\text{electrons}} = P_{\text{detector}} t \text{ QE} \lambda h^{-1} c^{-1}
\]

\[
\begin{align*}
3812 &= 1.24 \times 10^{-15} \\ 1 &= 0.9 \\ 0.678 &= (6.63 \times 10^{-34})^{-1} \\ (\text{none}) &= (3 \times 10^{14})^{-1} \\
(\text{none}) &= J \text{ s}^{-1} \\ (\text{none}) &= \text{um} \\ J^{-1} &= \text{s}^{-1} \\ \text{s}^{-1} &= \text{um}^{-1}
\end{align*}
\]

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

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

SNR ~ 2900 for a 250 m pixel

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

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

\[
\text{instantaneous field of view (IFOV)} = \frac{\text{pixel size}}{\text{altitude}}
\]

\[
0.0014 \text{ rad} = \frac{1 \text{ km}}{700 \text{ km}}
\]

a swath width of \(\sim 2\) rad translates to \(\sim 1,400\) pixels:

\[
= \frac{\text{swath width}}{\text{IFOV}}
\]

\[
1,400 = \frac{2 \text{ rad}}{0.0014 \text{ rad}}
\]

dividing the 28M photoelectrons by 1,400 pixels leaves \(\sim 19,900\) photoelectrons from the ocean surface reaching the detector

useful duty cycle of of scan mirror is < 1/3, so really, we’re talking about \(\sim 6,000\) ocean surface photons

propagate this to TOA results in \(\sim 120,000\) photons reach detector

\[\text{SNR} = \sim 346\]
Consider a moving satellite that scans from side-to-side. The useful duty cycle of the 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. The SNR is ~346. Requires >16x photons reaching the detector.
NEVER GIVE UP

NEVER STOP TRYING TO EXCEED YOUR LIMITS. WE NEED THE ENTERTAINMENT.