

Past, present and future of satellite Ocean Colour Radiometry (OCR)

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Lecture content

- ◆ Ocean colour radiometry (OCR) from space; are you kidding?
- ◆ Very basics of ocean colour sensors
 - ★ Basic principles, different types of sensors, ..
- ◆ Succinct history of passive ocean colour radiometry (OCR)
 - ★ From the “proof-of-concept” CZCS to currently on-orbit scientific and operational missions

◆ Future of satellite OCR:

There is need for better resolving

- ★ Long time scales: ensuring continuity of global observ. from LEO sensors
- ★ Small time scales: the geostationary vantage point
- ★ Ecosystems complexity: going hyper-spectral
- ★ Particle types: taking advantage of polarisation
- ★ The vertical structure: satellite-borne LIDARs
- ★ Local processes: high spatial resolution sensors

And making all this simpler and cheaper.. ?

Setting up of “the scene”: can this really work?

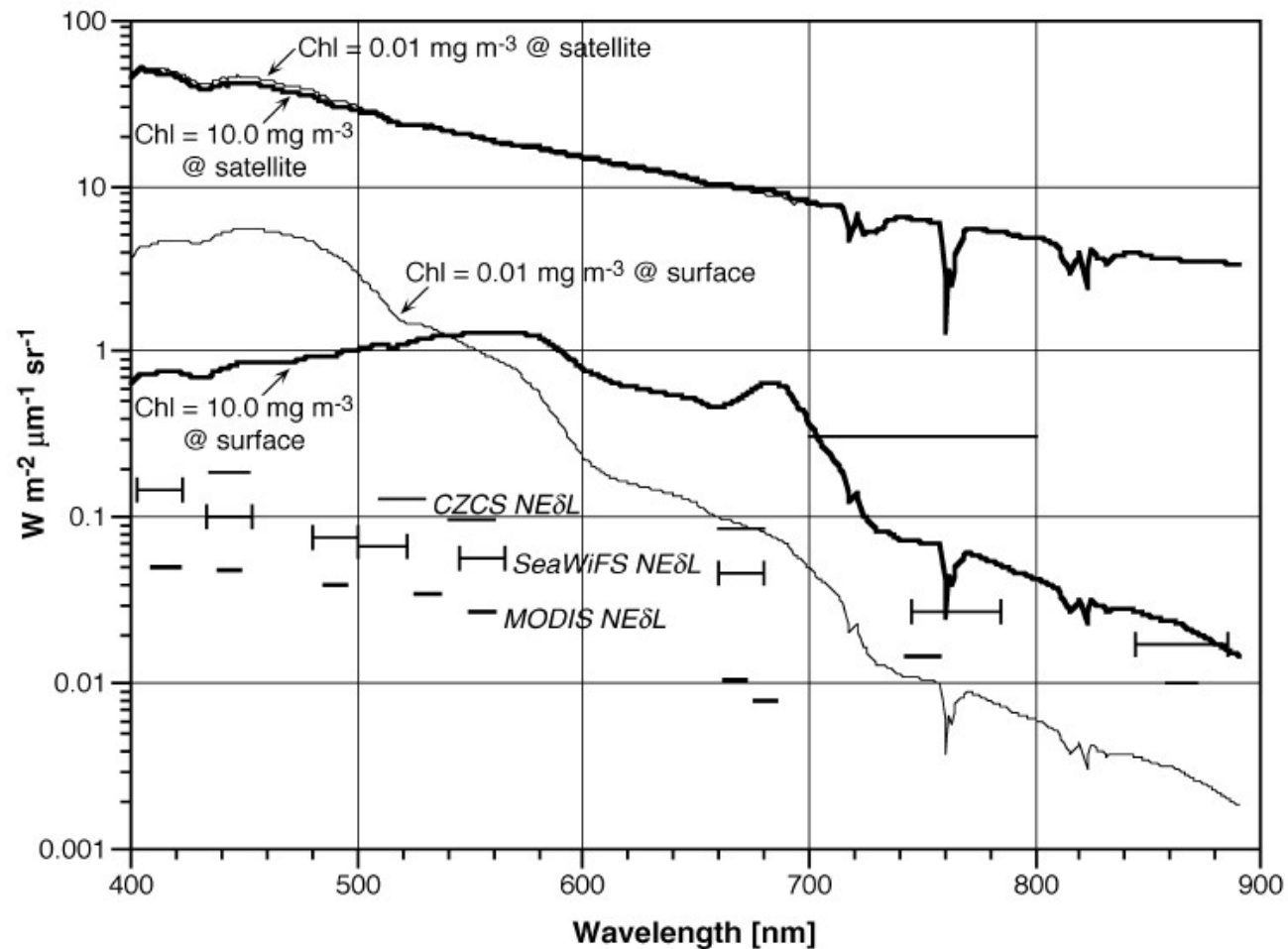


Figure 3 in Hooker SB et al., 1992. An overview of SeaWiFS and ocean color, NASA TM 104566, vol 1, NASA GSFC, Greenbelt, MD 20771

How it all started

George L. Clarke, Gifford C. Ewing and Carl J. Lorenzen, 1970. Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration, *Science* 167 (3921), 1119-1121.

DOI: 10.1126/science.167.3921.1119

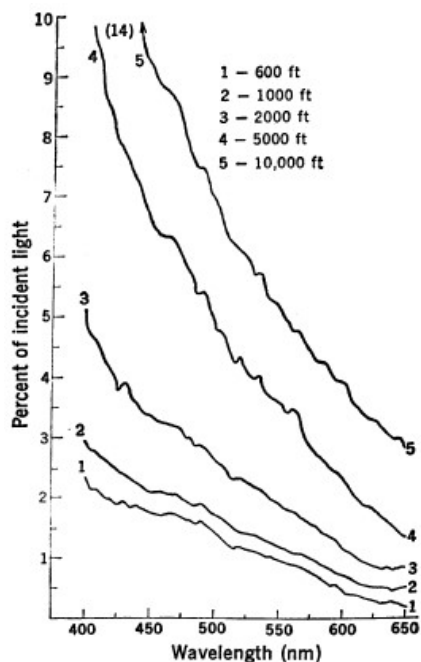


Fig. 1. Upwelling light as received at the indicated altitudes at Station S (Fig. 2) east of Cape Cod, 26 August 1968 between 1345 and 1512 hours, E.D.T.

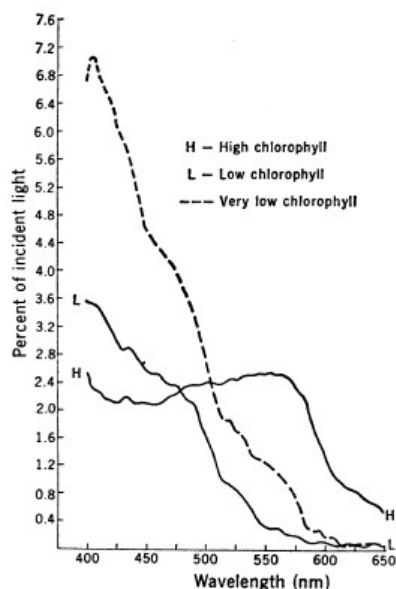


Fig. 3. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream.

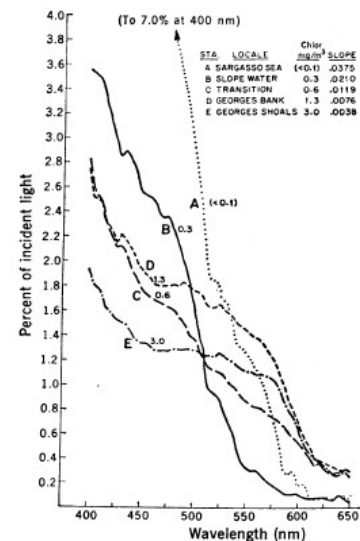


Fig. 4. Spectra of backscattered light measured from the aircraft at 305 m on 27 August 1968 at the following stations (Fig. 2) and times (all E.D.T.): Station A, 1238 hours; Station B, 1421 hours; Station C, 1428.5 hours; Station D, 1445 hours; Station E, 1315 hours. The spectrometer with polarizing filter was mounted at 53° tilt and directed away from the sun. Concentrations of chlorophyll a were measured from shipboard as follows: on 27 August, Station A, 1238 hours; on 28 August, Station B, 0600 hours; Station C, 0730 hours; Station D, 1230 hours.

How it all started

George L. Clarke, Gifford C. Ewing and Carl J. Lorenzen, 1970. Spectra of Backscattered Light from the Sea Obtained from Aircraft as a Measure of Chlorophyll Concentration, *Science* 167 (3921), 1119-1121. DOI: 10.1126/science.167.3921.1119

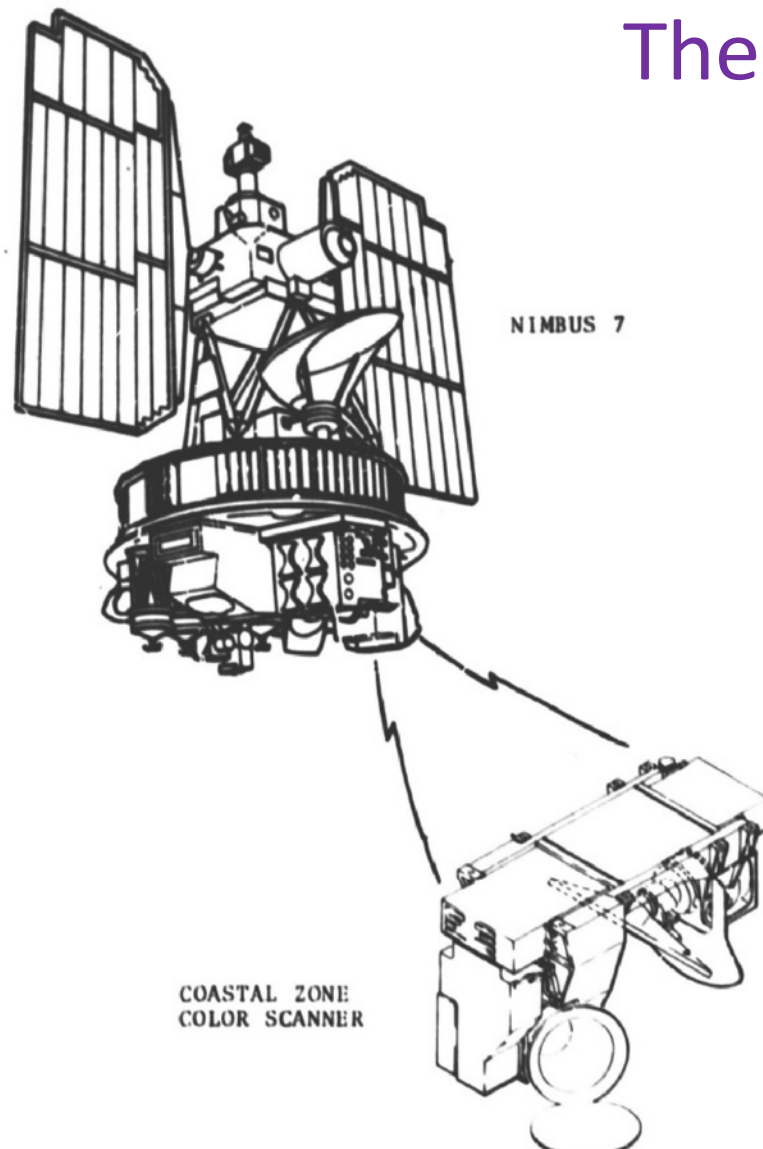
Abstract. Spectra of sun and skylight backscattered from the sea were obtained from a low-flying aircraft and were compared with measurements of chlorophyll concentration made from shipboard at the same localities and at nearly the same times. Increasing amounts of chlorophyll were found to be associated with a relative decrease in the blue portion of the spectra and an increase in the green. Anomalies in the spectra show that factors other than chlorophyll also affect the water color in some instances; these factors include other biochromes, suspended sediment, surface reflection, polarization, and air light.

Last sentence of the paper: If such interference can be eliminated, or identified and allowed for, spectrometric procedures from aircraft (and perhaps from satellites) will be of great value in the rapid investigation of oceanic conditions, including conditions important for biological productivity.

The “Coastal Zone Color Scanner”,

CZCS on NIMBUS 7

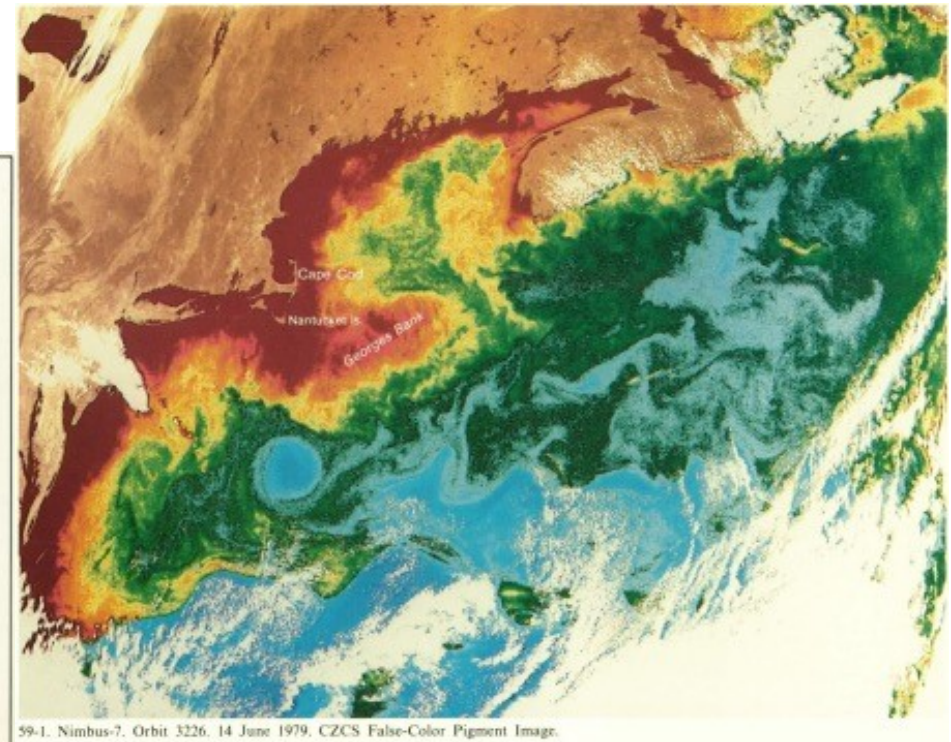
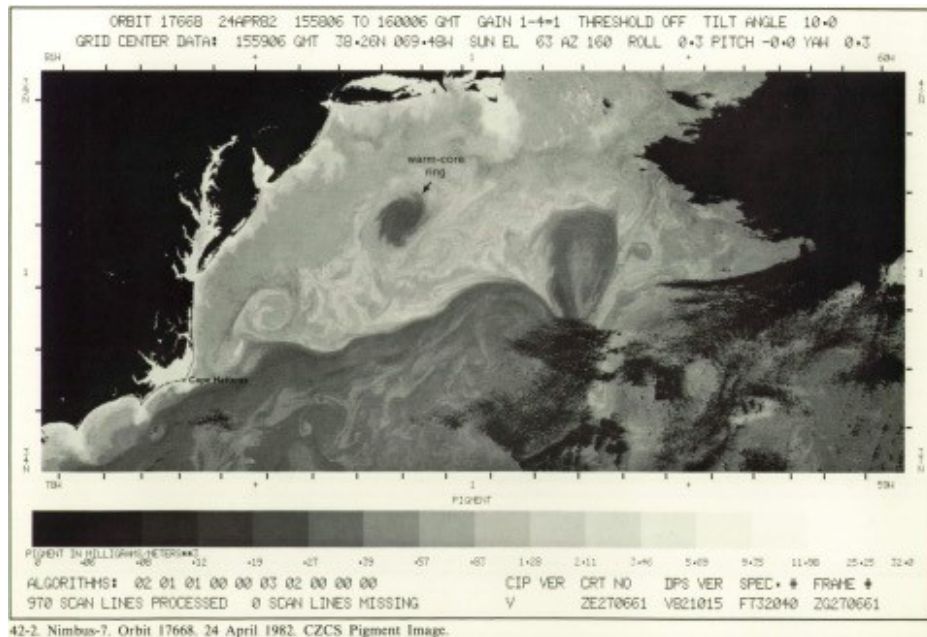
Launched October 1978



<u>Channel</u>	<u>Type</u>	<u>Spectral Range (μm)</u>	<u>Color</u>	<u>Function</u>
1	visible	0.433 - 0.453	purple	chlorophyll
2	visible	0.510 - 0.530	blue-green	reference
3	visible	0.540 - 0.560	yellow-green	sediments
4	visible	0.660 - 0.680	red	chlorophyll
5	Near IR	0.700 - 0.800	--	surface vegetation
6	IR	10.5 - 12.5	--	surface temperature

Illustration and Table taken from: Development of the Coastal Zone Color Scanner for Nimbus 7. Vol. 1: mission objectives and instrument description. Final report F78-11, Rev A, May 1979. NASA-CR-166720-Vol-1. Ball Aerospace Systems Div., Boulder. 76pp.

Initial CZCS imagery



From: NIMBUS-7 CZCS. Coastal Zone Color Scanner Imagery for Selected Coastal Regions. NASA report, 1984.

Available at: https://archive.org/details/NASA_NTRS_Archive_19880013063

See also: Hovis et al., 1980. Science 210, 60-63

And, guess what? it worked!

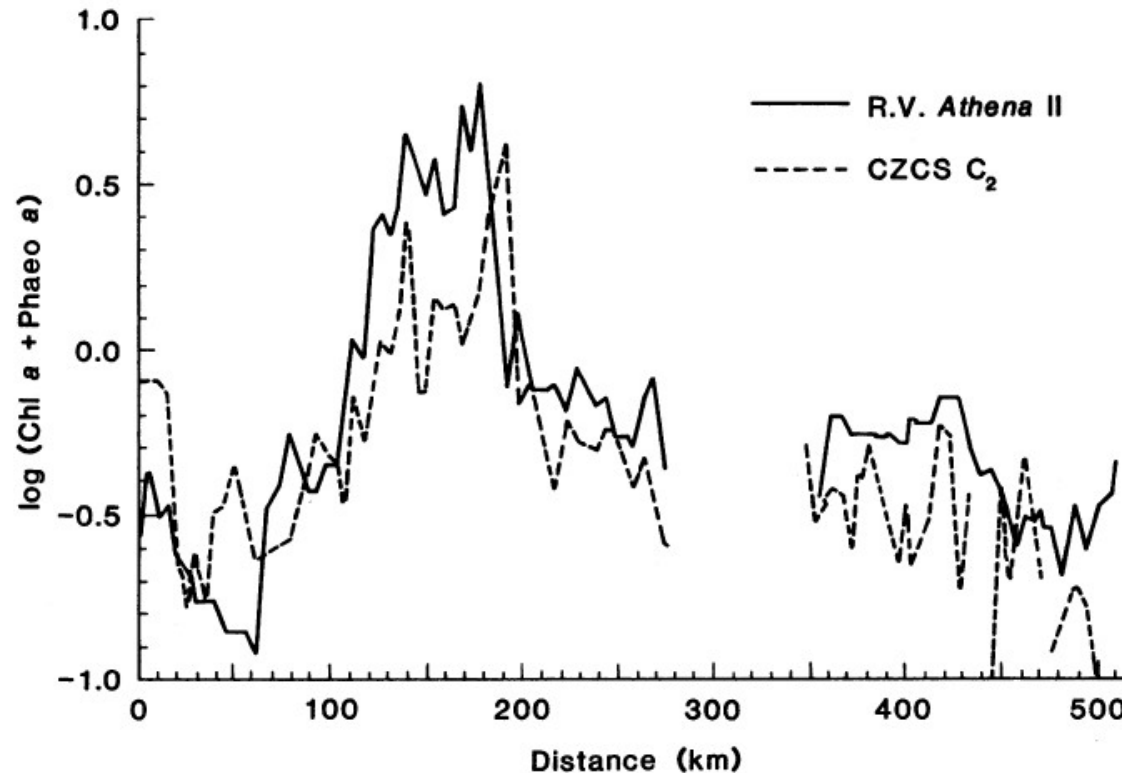
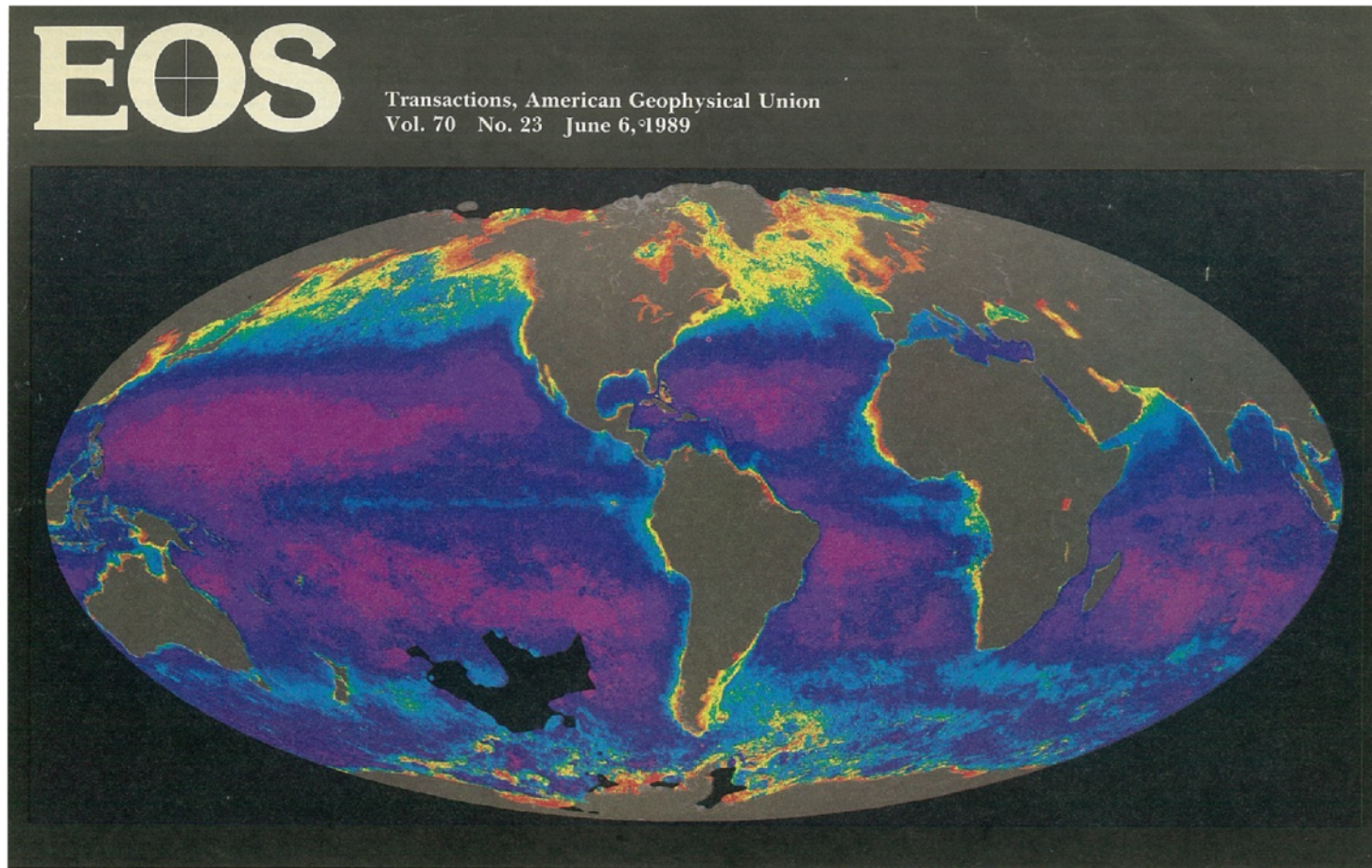


Fig. 3. Values of $C = (\text{Chl } a + \text{Phaeo } a)$ (in milligrams per cubic meter) from Fig. 2 (14 November 1978) compared with a track line of concentrations measured aboard the R.V. *Athena II* on 13 and 14 November 1978. The track line is superimposed on Fig. 2, and distance (above) runs from south to north. The estimated CZCS data have been subsampled to coincide with the ship samples for comparison.

Gordon et al., 1980. Science 210, 63-66

A milestone: first global data set



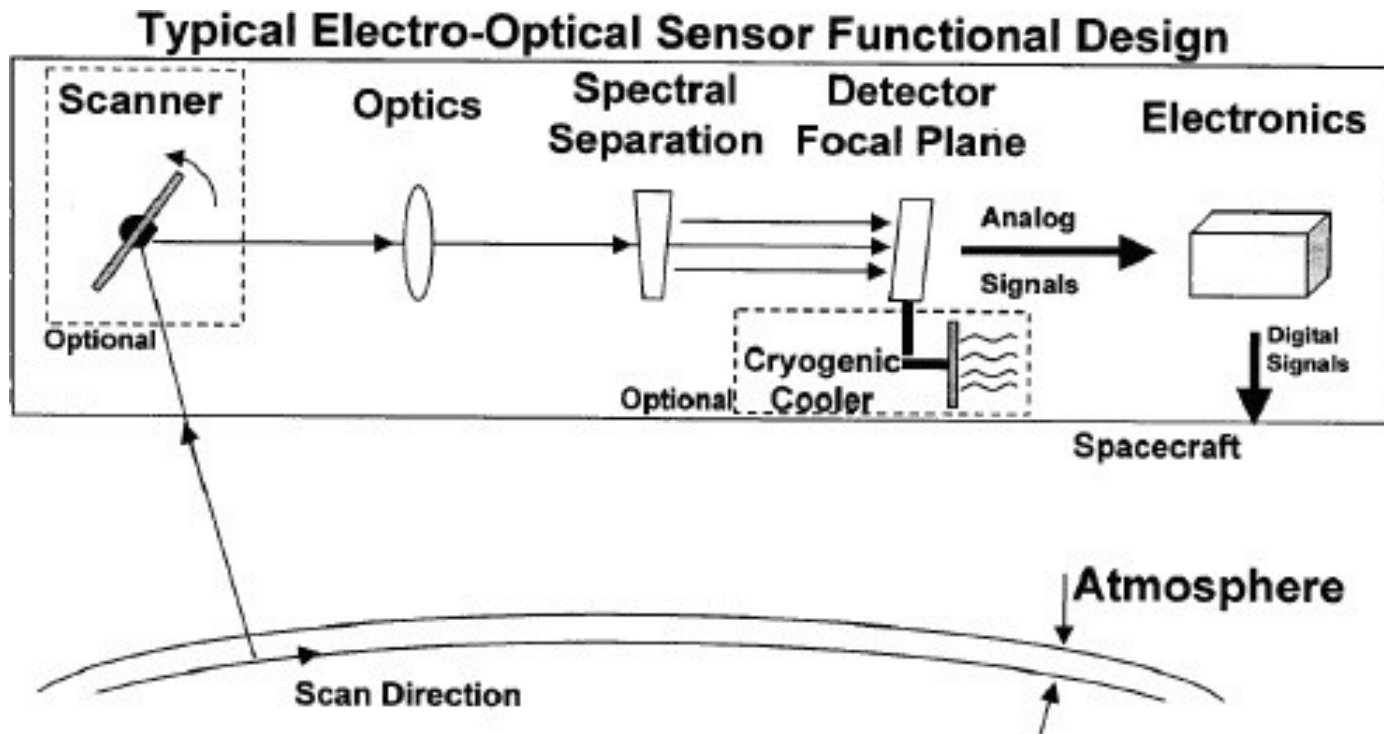
From: Feldman G.C., N. Kuring, C. Ng, W. Esaias, C. McClain, J. Elrod, N. Maynard, D. Endres, R. Evans, J. Brown, S. Walsh, M. Carle and G. Podesta, 1989. Ocean color : availability of the global data set. *EOS*, 70, 634.

What an “ocean colour sensor” does?

Steps to deliver OCR “imagery”:

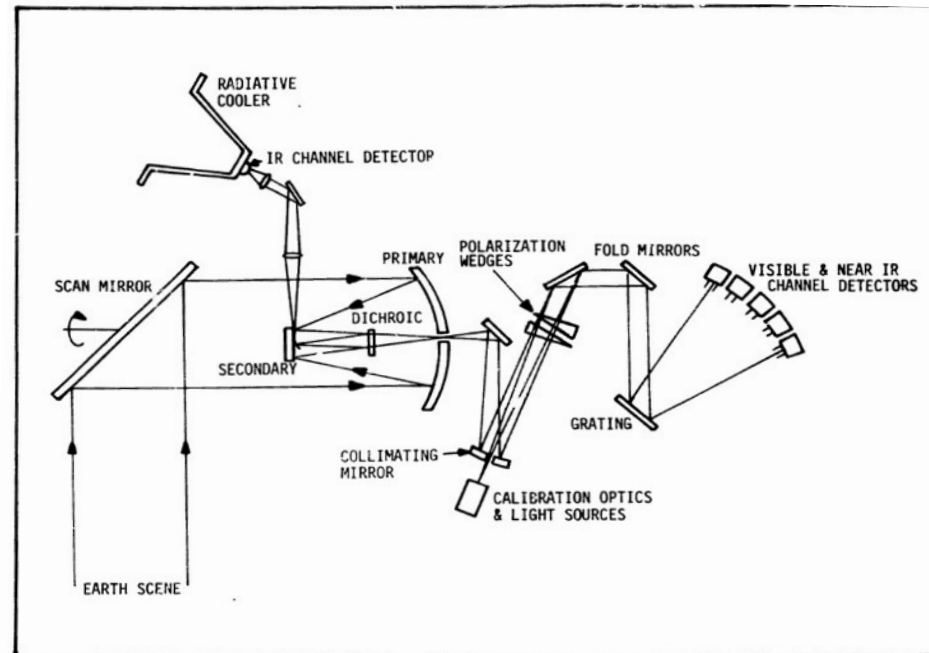
- ◆ Collecting light (photons): telescope, lenses, mirrors
- ◆ Making this insensitive to the polarisation state (within a few %): design, coatings, scramblers
- ◆ “Sorting” this in a number of spectral bands: filters, beam splitters, gratings
- ◆ Converting collected photons in an electric signal: detector(s)
- ◆ Converting this signal into bits: analog-to-digital conversion
- ◆ Sending those bits to the ground: transmission capability
- ◆ Doing the inverse path: from bits to radiances: calibration (pre-launch + onboard devices such as diffusers)
- ◆ Locating these information on the ground: satellite orbit / attitude control (precise orbit determination, gyroscopes, star trackers)

A simplified scheme



National Research Council. 2011. Assessing the Requirements for Sustained Ocean Color Research and Operations. Washington, DC: The National Academies Press. <https://doi.org/10.17226/13127>.

Example: the CZCS optical layout



The CZCS was a cross-track scanning radiometer

Illustration and Table taken from: Development of the Coastal Zone Color Scanner for Nimbus 7. Vol. 1: mission objectives and instrument description. Final report F78-11, Rev A, May 1979. NASA-CR-166720-Vol-1. Ball Aerospace Systems Div., Boulder. 76pp.

Another example: the MERIS optical layout

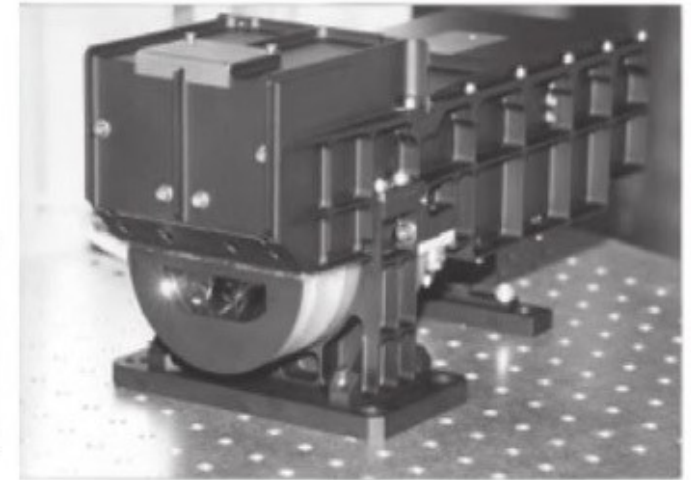
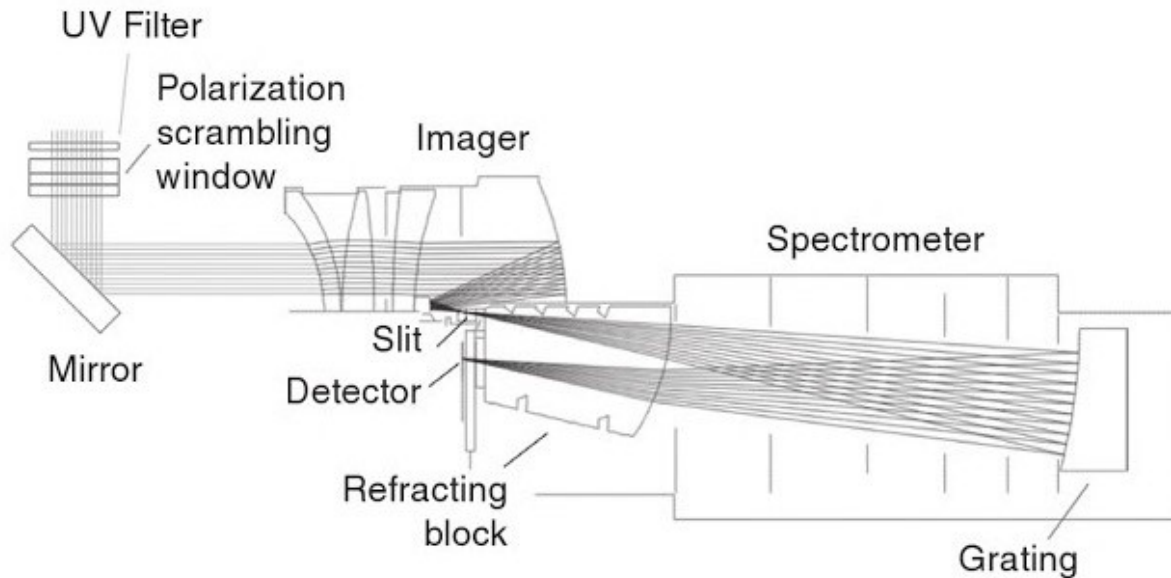
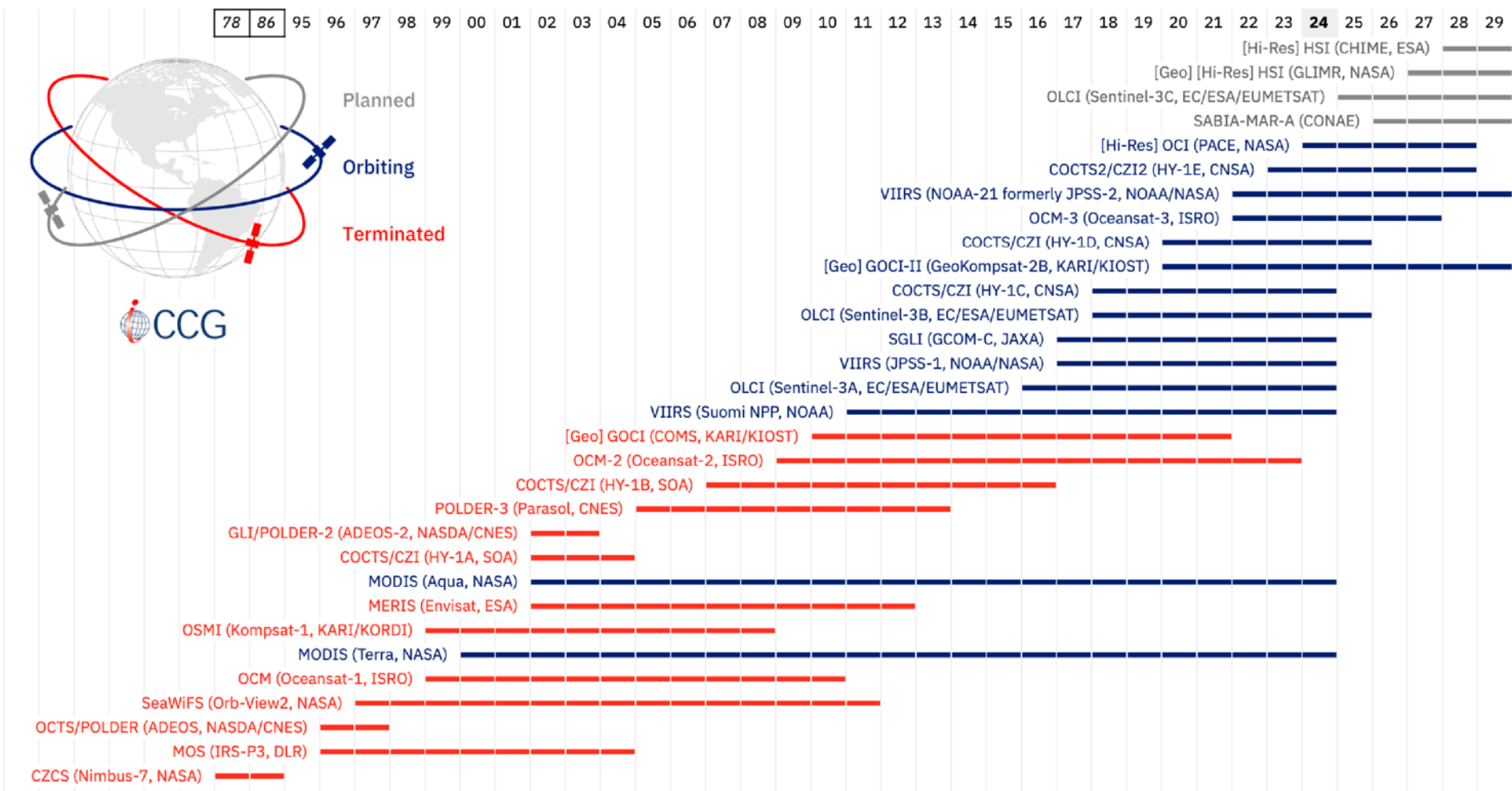


Figure 4.11 in: “Optical Payloads for Space Missions”, Shen-En Qian Ed., John Wiley & Sons, 26 Jan. 2016, 1008 pp.

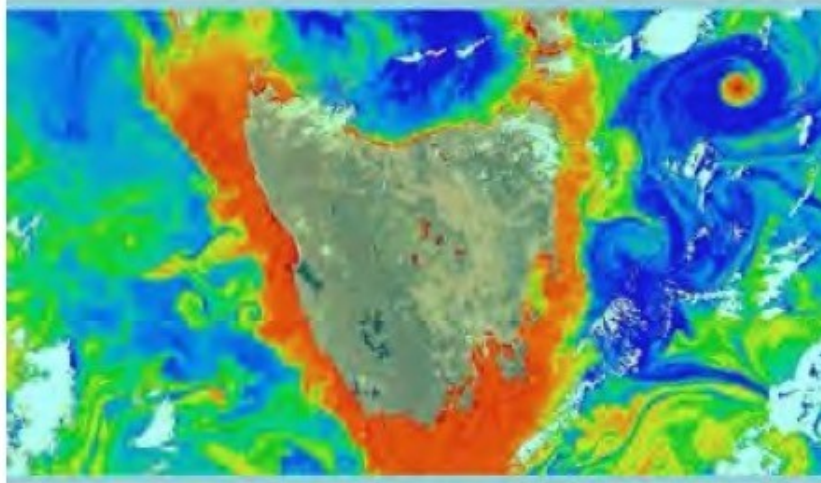
MERIS is a “push-broom” imaging spectrometer

See also: https://earthobservatory.nasa.gov/Features/EO1/eo1_2.php

What has happened since CZCS was launched?



THE COLOR OF THE ATMOSPHERE WITH THE OCEAN BELOW



A HISTORY OF NASA'S
OCEAN COLOR MISSIONS

JAMES ACKER

If you want to know all about the path from CZCS to SeaWiFS ,MODIS etc., this is what you need to read

Email to Jim Acker, who can tell you how to procure this book:

james.g.acker@nasa.gov

In which direction has this been going?

Main drivers of the evolution of satellite OCR, from the lessons learned with the pioneers (CZCS):

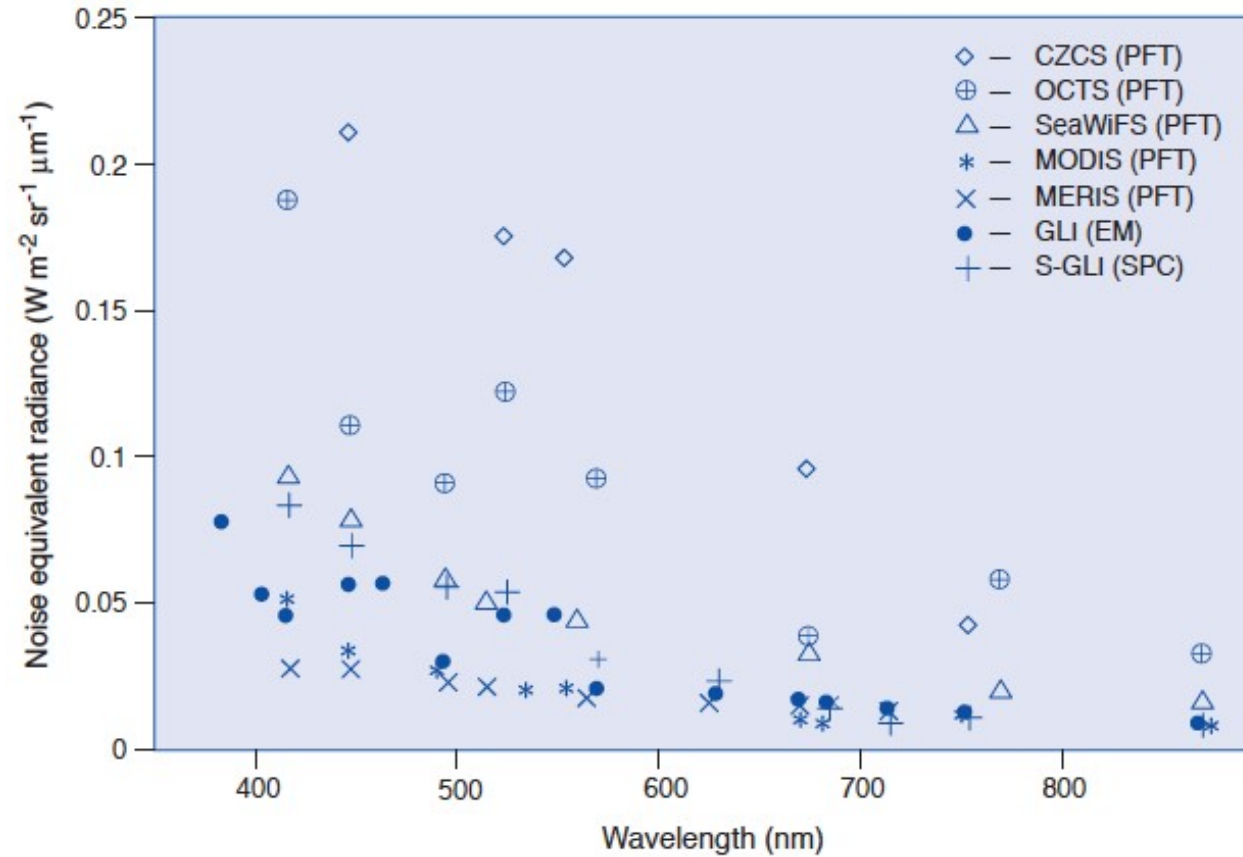
Technical/scientific rationale:

- ◆ Radiometric quality!! We need to see more than “nuances of blue and green”
- ◆ Spectral resolution: more bands!
- ◆ Calibration (absolute and temporal changes): the CZCS internal lamps failed to provide accurate control on temporal changes in calibration
- ◆ Vicarious calibration is needed as well
- ◆ We want global data sets
- ◆ We need to do more in coastal waters (the irony of the name “CZCS” is that it actually did more to reveal the global need for OCR than it did for coastal applications)
- ◆ We want to see deeper in the oceans

More “politically-driven”:

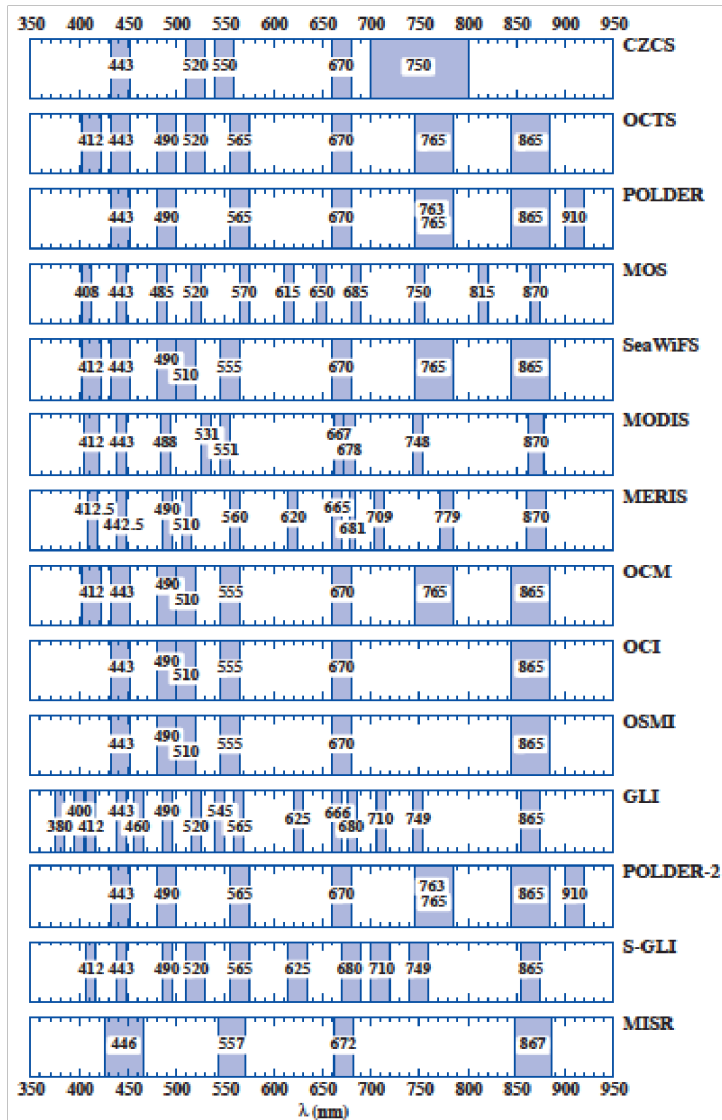
- ◆ Industry has to get contracts from Government / Space agencies to work.
- ◆ Countries want to demonstrate capability

Radiometric quality



From: IOCCG, 1998, Minimum Requirements for an Operational, Ocean-Colour Sensor for the Open Ocean, André Morel (Ed.), Reports of the International Ocean-Colour Coordinating Group, No. 1, IOCCG, Dartmouth, Canada.

Spectral resolution

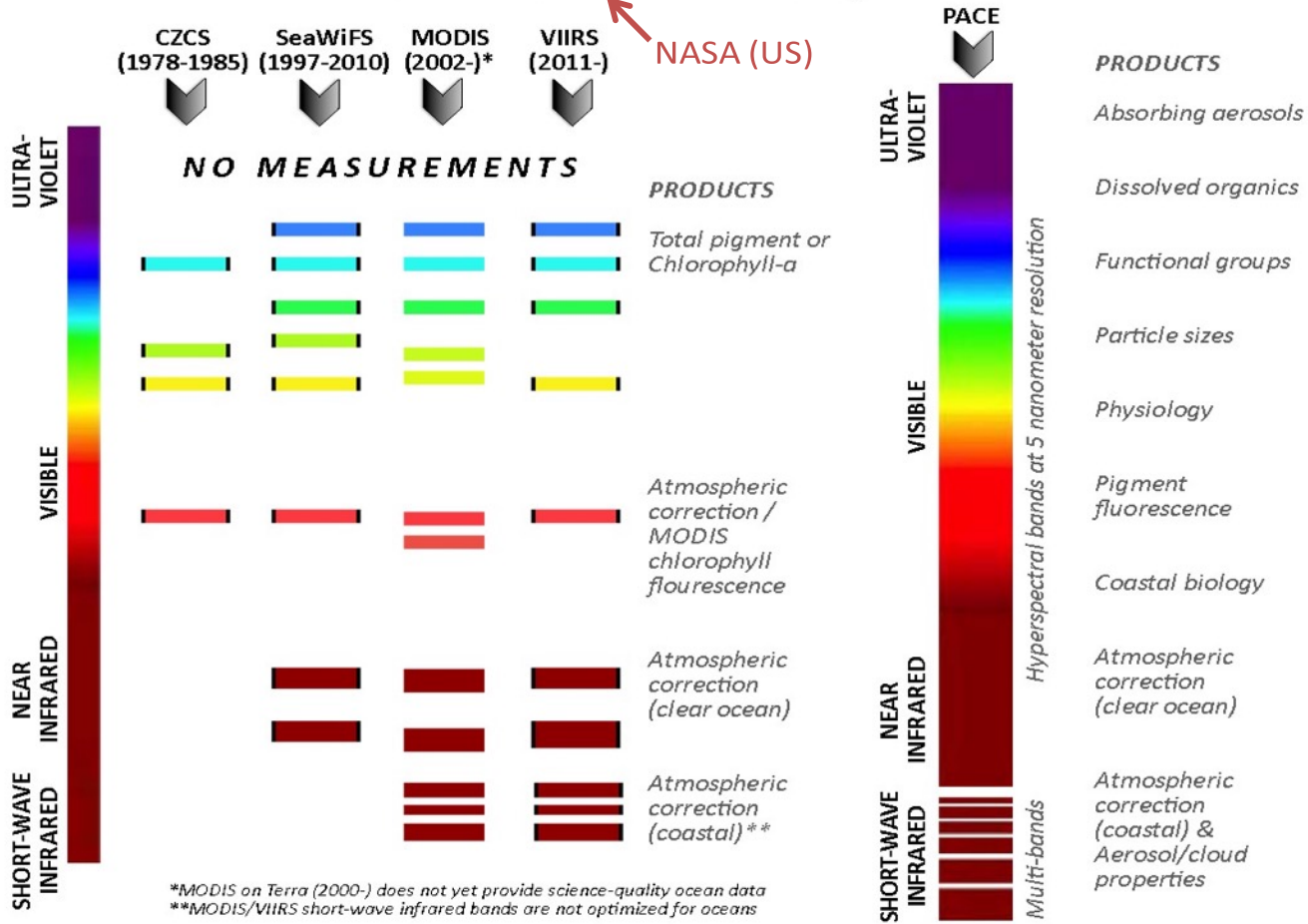


Adding bands to:

- Increase the confidence in derived products by better “classifying” reflectance spectra
- Improve atmospheric correction, generally, and more specifically for coastal and inland waters and when absorbing aerosols are present
- Allow better separation between CDOM and phytoplankton
- Quantify phytoplankton fluorescence
- Identify / quantify phytoplankton groups
- ...

From: IOCCG, 1998, Minimum Requirements for an Operational, Ocean-Colour Sensor for the Open Ocean, André Morel (Ed.), Reports of the International Ocean-Colour Coordinating Group, No. 1, IOCCG, Dartmouth, Canada.

SPECTRAL COVERAGE OCEAN COLOR HERITAGE SENSORS compared with PACE



Spectral resolution

<https://pace.oceansciences.org/science.htm>

Spatial resolution

Not so much change here, at least if we consider global ocean missions

Past and current:

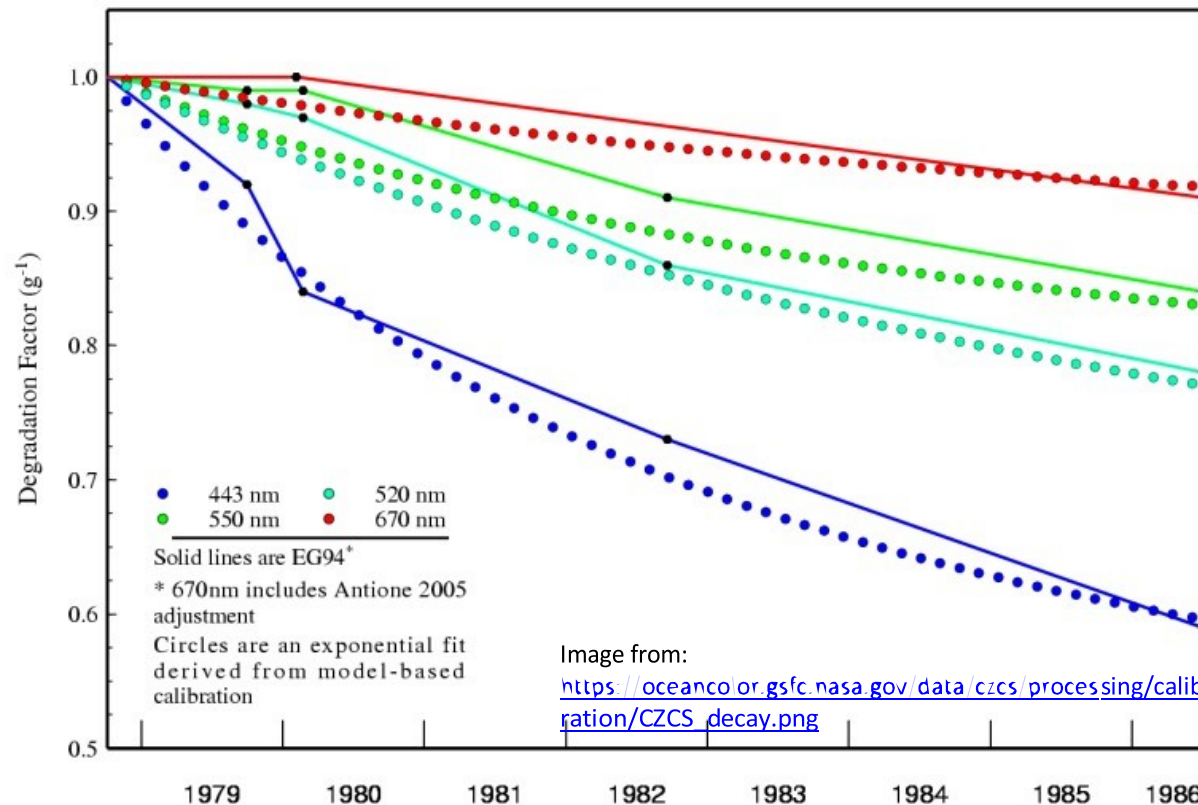
- ◆ CZCS: 825m
- ◆ SeaWiFS: 1km
- ◆ MERIS: 300m / 1.2 km
- ◆ MODIS: 250m (land), 1 km
- ◆ VIIRS: 750m
- ◆ OLCI: 300m / 1.2 km
- ◆ S-GLI: 250m / 1 km

Future:

- ◆ PACE: 1 km

Higher spatial resolution missions are now also used, whose purpose was not initially ocean colour however (later on in this lecture)

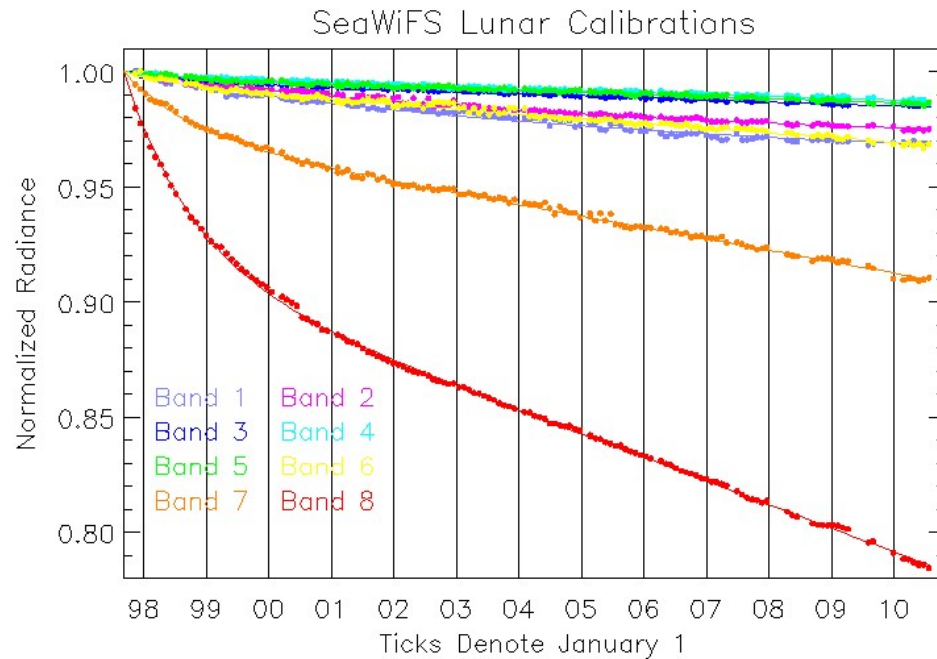
Calibration degradation: CZCS



See: Evans, R. H., and H. R. Gordon, 1994. *J. Geophys. Res.*, 99, 7293–7307.

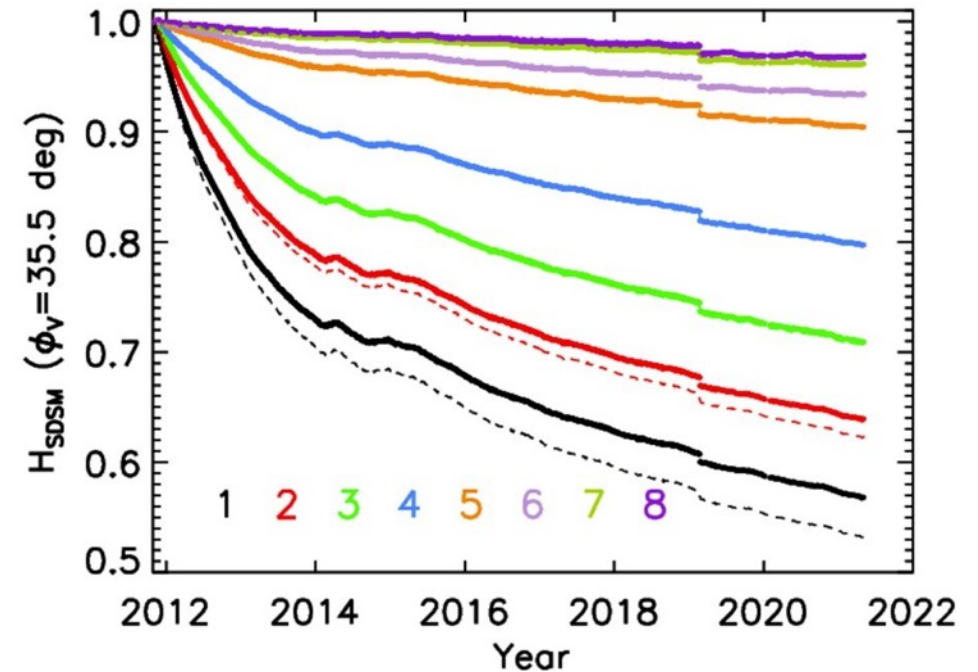
Antoine, D., Morel, A., Gordon, H.R., Banzon, V.F. and R.H. Evans, 2005. *Journal of Geophysical Research*, VOL. 110, C06009, doi:10.1029/2004JC002620

Calibration degradation: SeaSTAR-SeaWiFS, SNPP-VIIRS



From

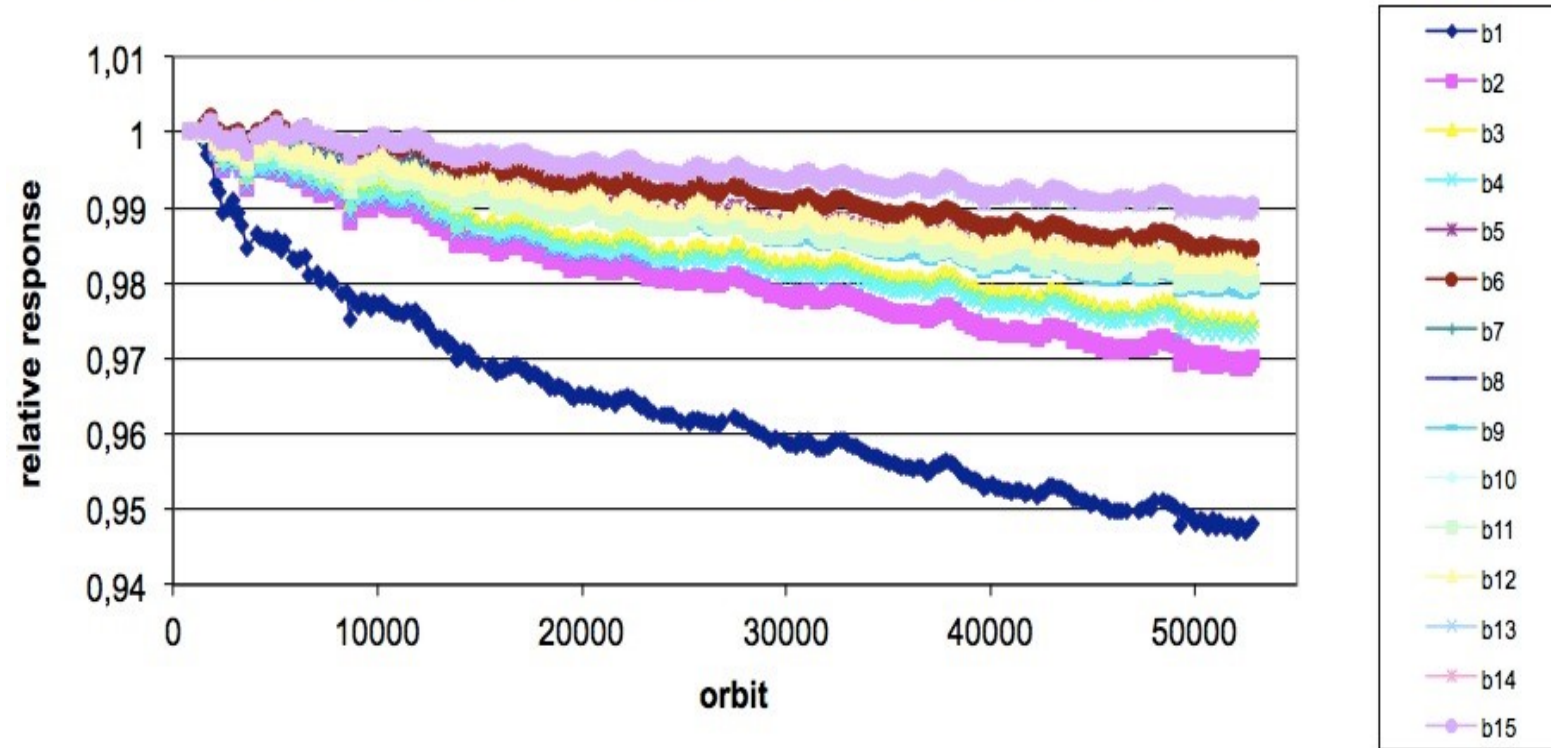
<https://oceancolor.gsfc.nasa.gov/reprocessing/r2009/seawifs/>



Sun, J.; Xiong, X.; Lei, N.; Li, S.; Twedt, K.; Angal, A. Ten Years of SNPP VIIRS Reflective Solar Bands On-Orbit Calibration and Performance. Remote Sens. 2021, 13, 2944. <https://doi.org/10.3390/rs13152944>

Calibration degradation: MERIS

MERIS Gain evolution wrt orbit 846, camera 5



From: Ludovic Bourg, ACRI-ST, Personal communication

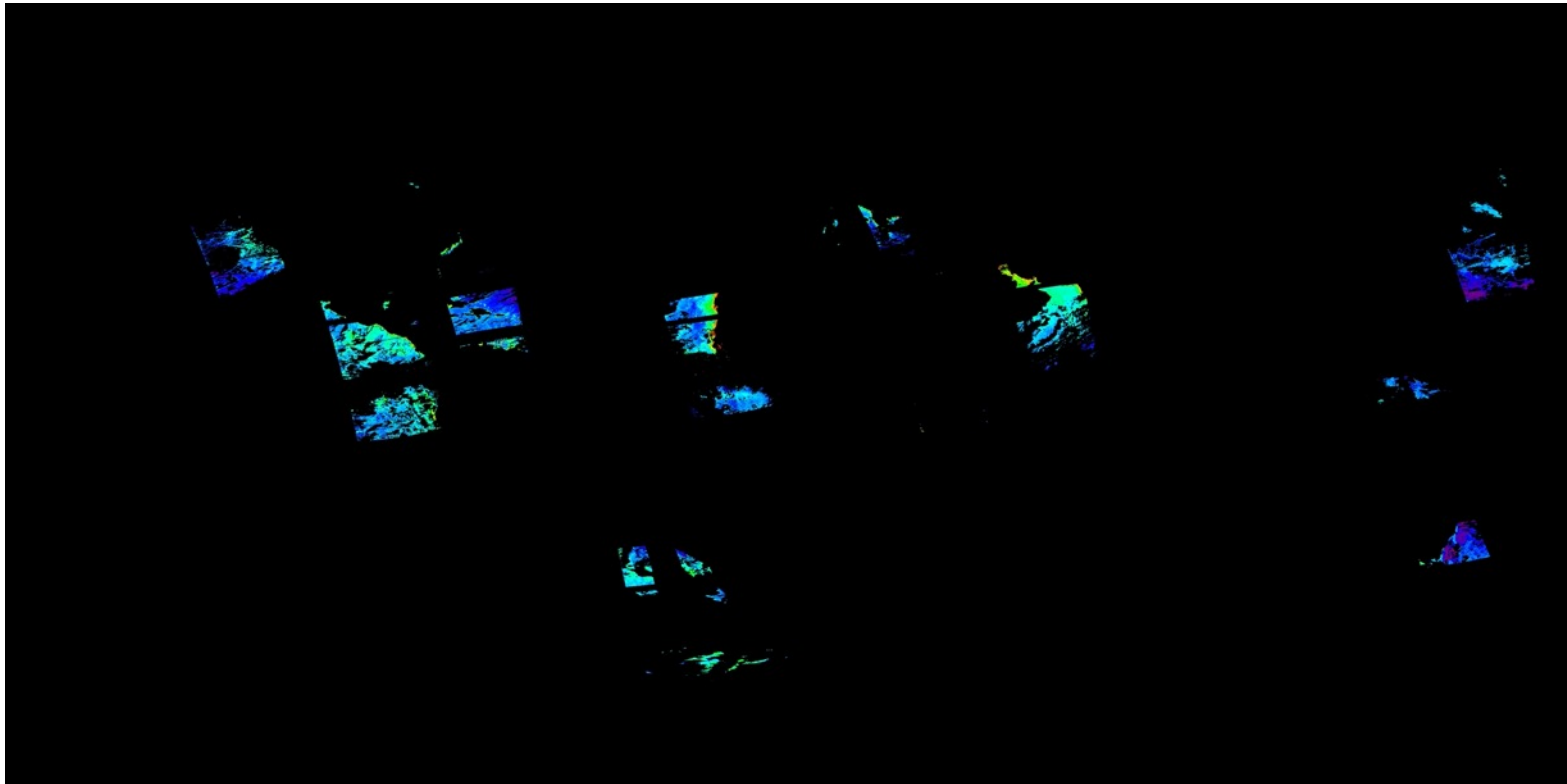
System Vicarious Calibration (SVC)

One requirement for satellite OCR is:

- Which errors can we tolerate on reflectances in the blue and green that we still can derive Chlorophyll within, say, $\pm 30\%$?
- The answer was: 5% in blue bands for an oligotrophic ocean (Gordon and Clark, 181. Appl. Opt. 20:4175-4180)
- It was rapidly realized that this requirement could not be met with pre-launch and onboard calibration capabilities only
- 5% at the L_w level means 0.5% at TOA
- Therefore, we need a process by which, overall, we eliminate biases in ocean color products (R_{rs}). Scatter (uncertainties) are not here considered.
- Basically: measure L_w as accurately as possible, add the atmospheric signal on top of it, and compare to the measured total signal at the “top of atmosphere” level (TOA), to obtain a “vicarious calibration gain”
- Do this on a number of “matchups”, and average the gains to end up with a “mission-average” gain.
- Beware: SVC does not addressing the temporal degradation issue

Global data sets

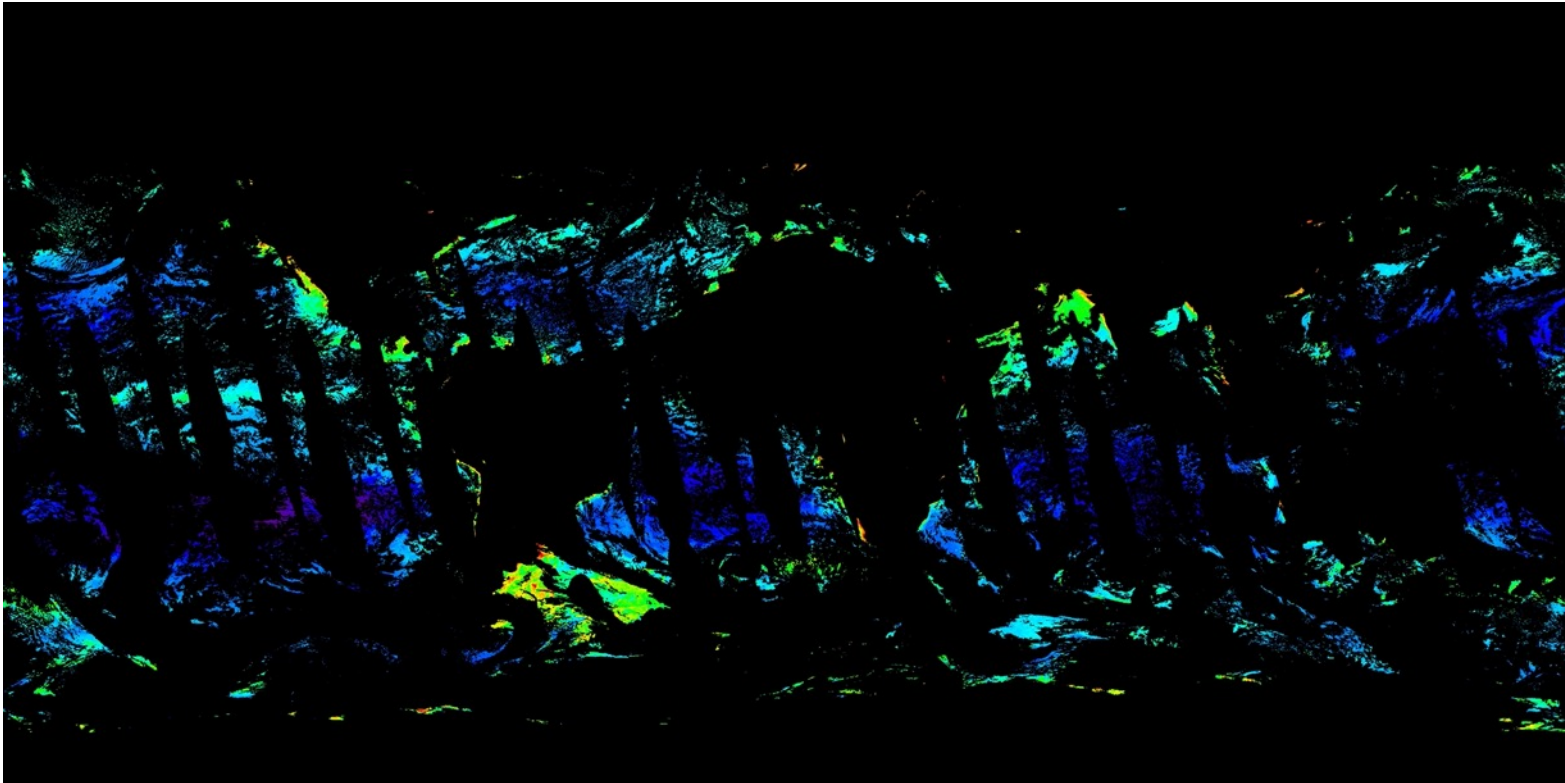
Going from intermittent to systematic sampling



https://oceancolor.gsfc.nasa.gov/cgi/l3/C1979032.L3m_DAY_CHL_chl_ocx_9km.nc.png?sub=img

Global data sets

Going from intermittent to systematic sampling

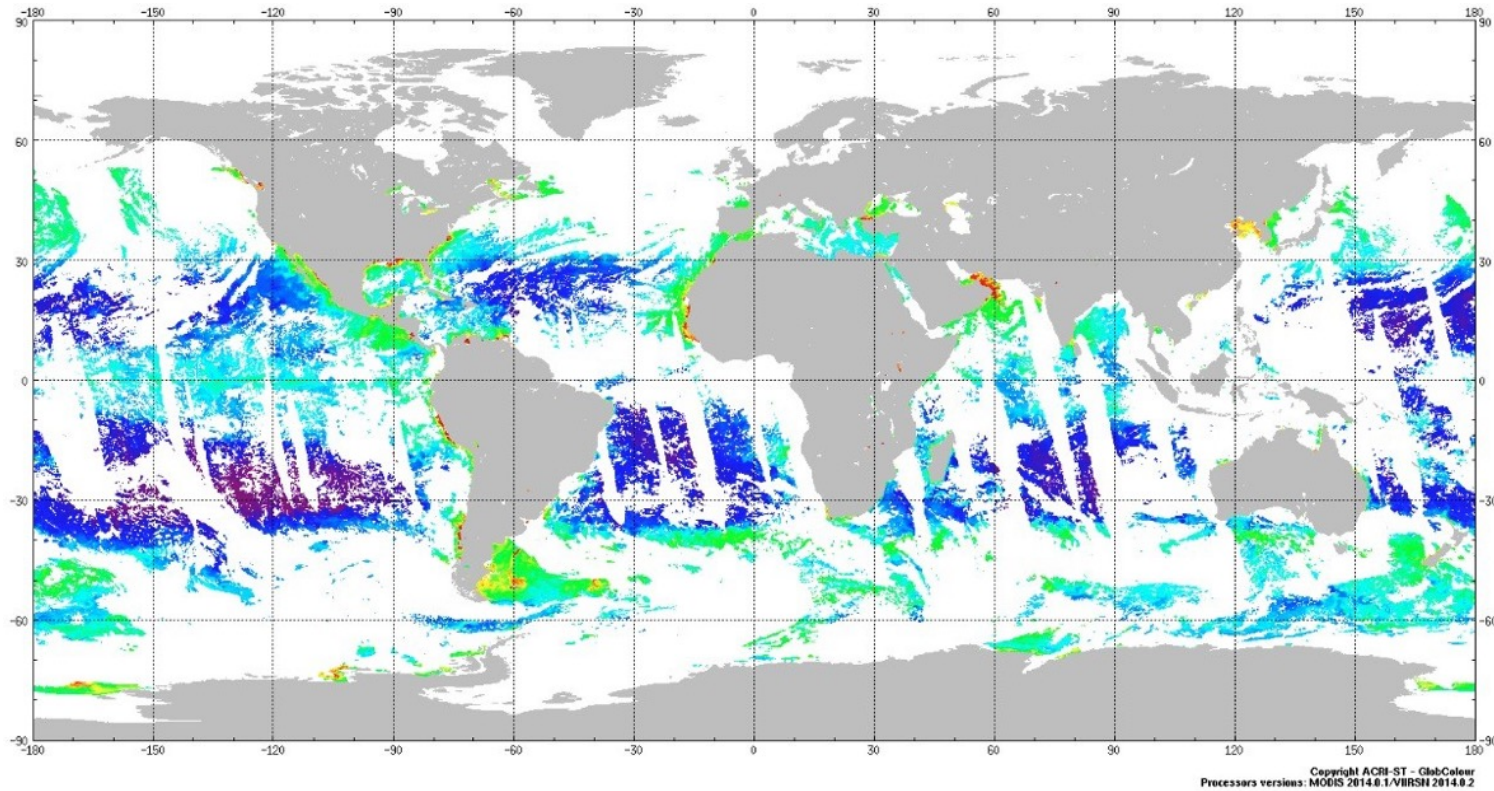


https://oceancolor.gsfc.nasa.gov/cgi/l3/C1979032.L3m_DAY_CHL_chl_ocx_9km.nc.png?sub=img

https://oceancolor.gsfc.nasa.gov/cgi/l3/V2012032.L3m_DAY_SNPP_CHL_chlor_a_9km.nc.png?sub=img

Global data sets

Merging data from multiple missions



https://oceancolor.gsfc.nasa.gov/cgi/l3/C1979032.L3m_DAY_CHL_chl_ocx_9km.nc.png?sub=img

https://oceancolor.gsfc.nasa.gov/cgi/l3/V2012032.L3m_DAY_SNPP_CHL_chlor_a_9km.nc.png?sub=img

http://hermes.acri.fr/images/data/GLOB/merged/day/2017/02/01/L3m_20170201_GLOB_25_AVW-MODVIR_CHL1_DAY_00.png

Global, multi-mission data sets

- The ESA Ocean Colour Climate Change Initiative (OC-CCI)

<https://climate.esa.int/en/projects/ocean-colour>

- The GlobCOLOUR data set

<https://www.globcolour.info>

https://data.marine.copernicus.eu/product/OCEANCOLOUR_GLO_BGC_L4_MY_009_104/services

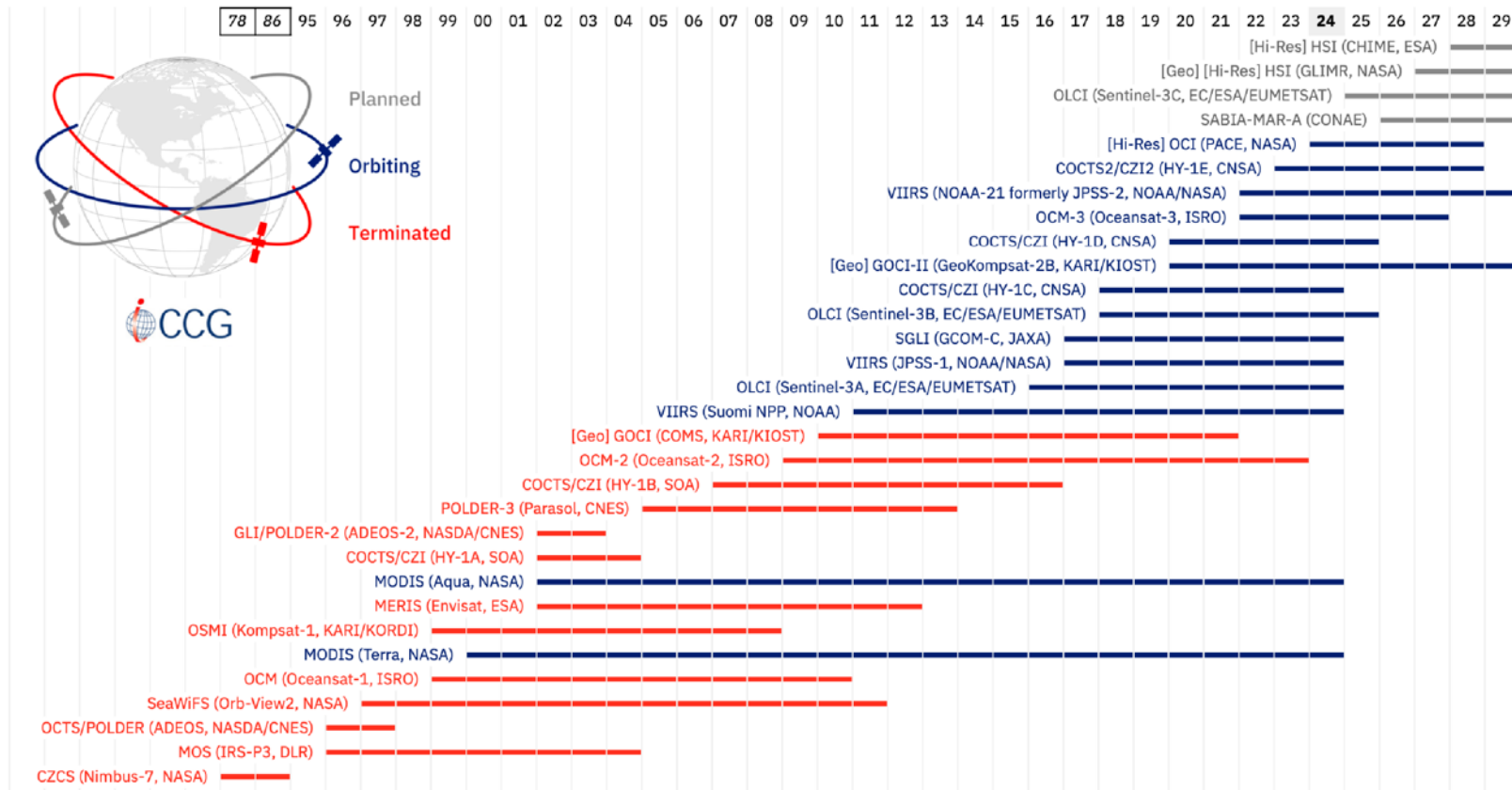
- The NASA's Ocean Biology Processing Group (OBPG)

<https://oceancolor.gsfc.nasa.gov>

What the future is made of?

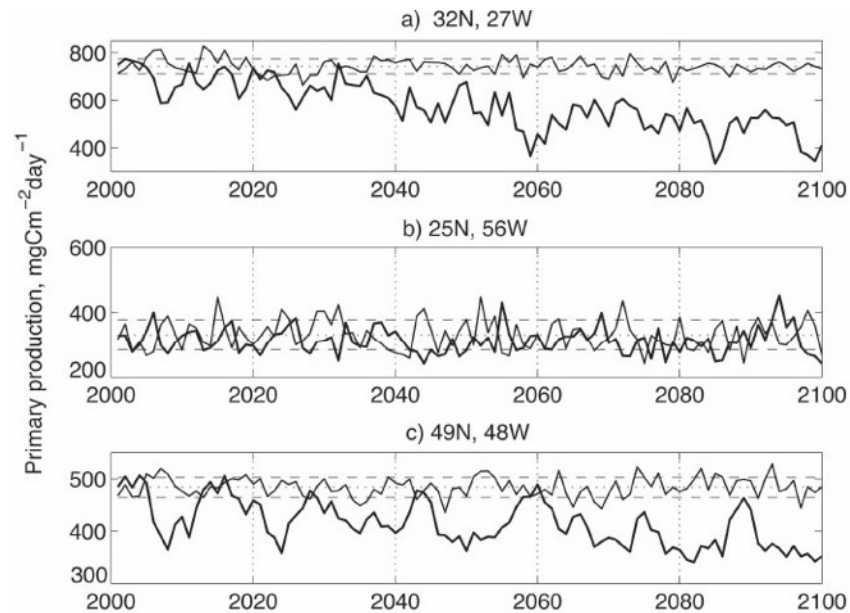
What the future is made of?

1) A bit more of the same: Ensuring continuity in the global OCR record



“Climate Change detectability”

Henson et al., 2010, Biogeosciences, 7, 621–640



Their fig. 7 (example from the GFDL model)

Their work:

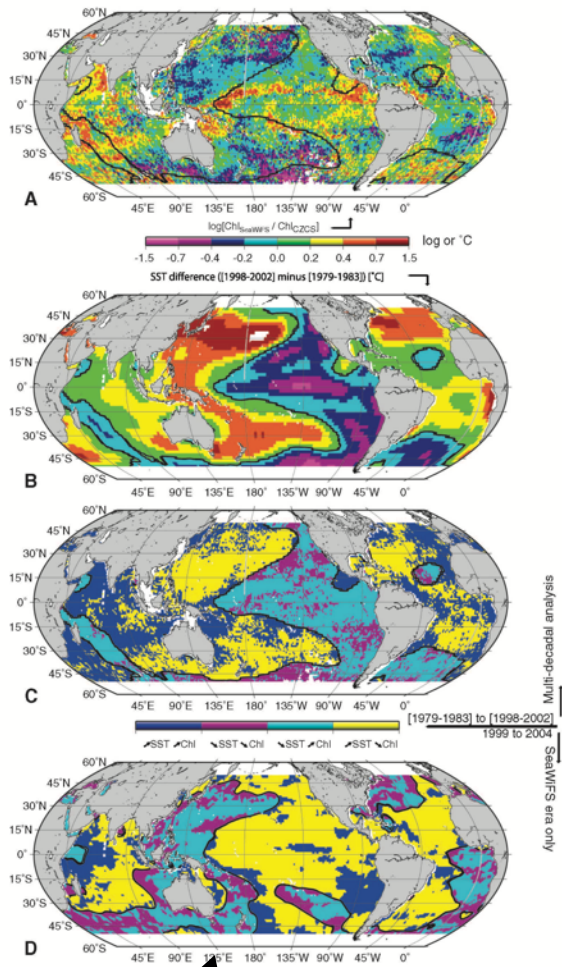
- Running 3 global coupled ocean-ecosystem models (GFDL MOM-4/TOPAZ, IPSL NEMO/PISCES, NCAR physical model/CCM-3) over 2001-2100.
- Comparing Chl and production in reference runs and “climate change runs” with the IPCC AR4 A2 scenario

Their conclusions:

- Detection of climate change-driven trends in the satellite data is confounded by the relatively short time series and large interannual and decadal variability.
- Thus, recent observed changes in chlorophyll, primary production and the size of the oligotrophic gyres cannot be unequivocally attributed to the impact of global climate change.
- Analysis of modeled chlorophyll and primary production from 2001–2100 suggests that, on average, the climate change-driven trend will not be unambiguously separable from decadal variability until 2055.
- Because the magnitude of natural variability in chlorophyll and primary production is larger than, or similar to, the global warming trend, a consistent, decades-long data record must be established if the impact of climate change on ocean productivity is to be definitively detected

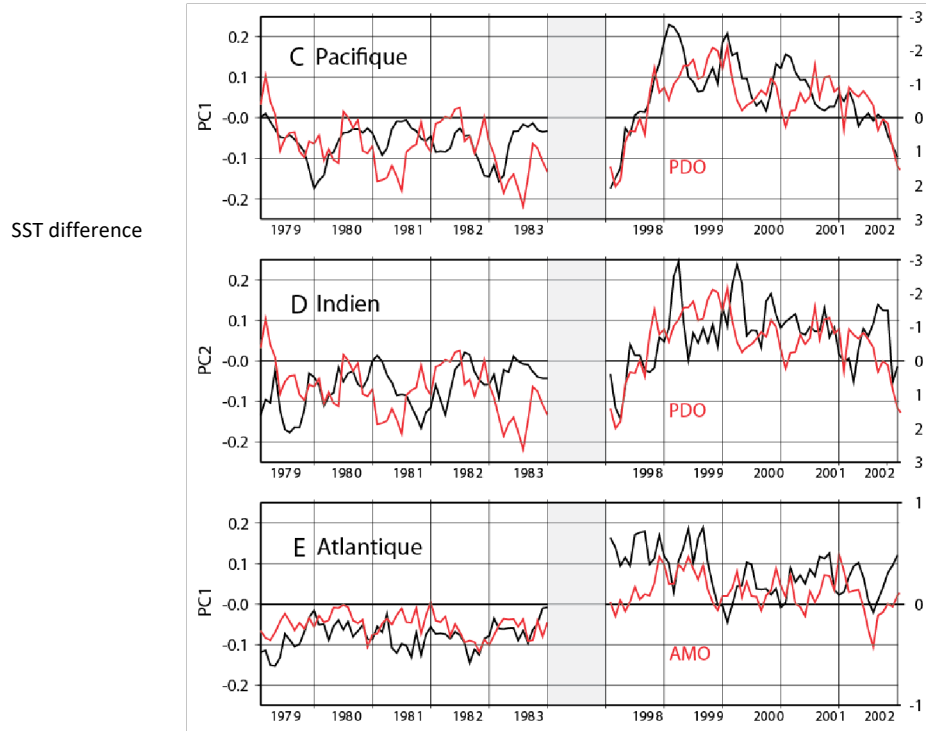
Martinez et al., Science, Vol 326, 27 Nov 2009

“Climate-Driven Basin-Scale Decadal Oscillations of Oceanic Phytoplankton”



Behrenfeld et al., 2006, Nature

Martinez, E., D. Antoine, F. D’Ortenzio, B. Gentili (2009). Climate-Driven Basin-Scale Decadal Oscillations of Oceanic Phytoplankton. Science 326, 1253; doi: 10.1126/science.1177012



Chl-SST temporal covariability from multivariate EOFs (black curve, left axis) for 3 oceanic basins. PDO and AMO are superimposed (right

Abundance & distribution of phytoplankton in the Pacific & Atlantic depend on decadal oscillations of physical properties in these basins.

What the future is made of?

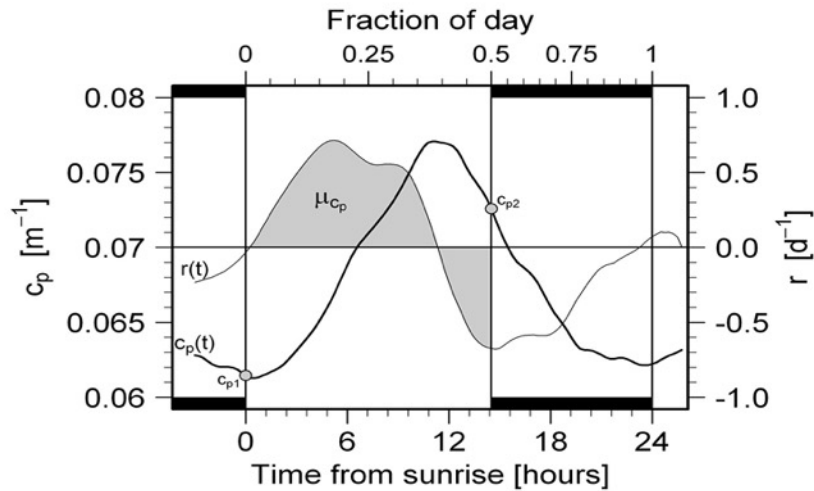
2) OCR sensors on geostationary orbits

- ◆ Current missions have one major drawback: they observe the ocean at best once a day, always at the same time
 - ◆ The resulting “repeat” is, at best, of a few days, exceptionally less
 - ◆ Many processes occur at temporal scales largely inferior to the day(s)
 - ◆ Obtaining full spatial coverage of a given area, e.g., an ocean basin, requires accumulating data over long periods of time (a week for instance): this is “blurring” the spatio-temporal variability
- There is an obvious mismatch between how the oceans vary and how we observe them from space
- Hence the idea of putting ocean colour sensors on geostationary orbits

Advantages of the GEO orbit

1. Within a range of conditions of observation (solar & view angles, clouds, ...), the diel dynamics of the ocean will be accessible. The 1st objective in this case is to study the ocean ecosystem functioning at the diurnal scale. The diurnal cycle of photosynthesis / respiration .. generates a diel cycle in the particulate pool, hence of the optical properties and of the recorded signal
2. In the above conditions and also when a little less observations will be available over a day, the 2nd group of objectives is related to observation & understanding of rapidly evolving phenomena (river outflows, aerosol plumes, phytoplankton blooms, (sub)meso-scale features ..). These phenomena are not necessarily linked to the biological functioning, and rather under the influence of physical forcings
3. When the conditions of observation do not allow the diel changes to be sampled, there is still the capability to dramatically improve coverage, with at least one observation of good quality per day in many areas. This is of tremendous importance for all operational uses, from data assimilation into coupled biological-physical 3D models to services in coastal zones

Diurnal cycles of ocean properties

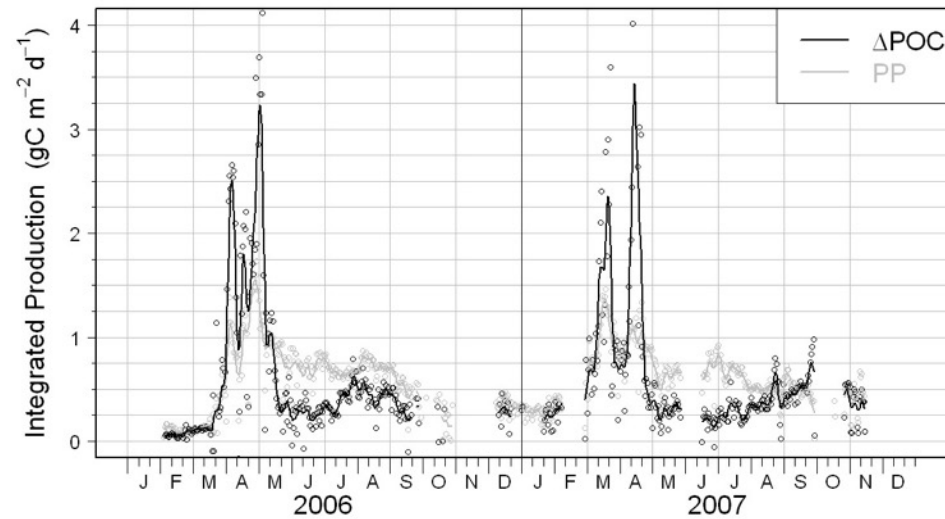


Possible to go from Δc_p to ΔPOC .
 After integration over the productive layer, one gets an estimate of “primary production”

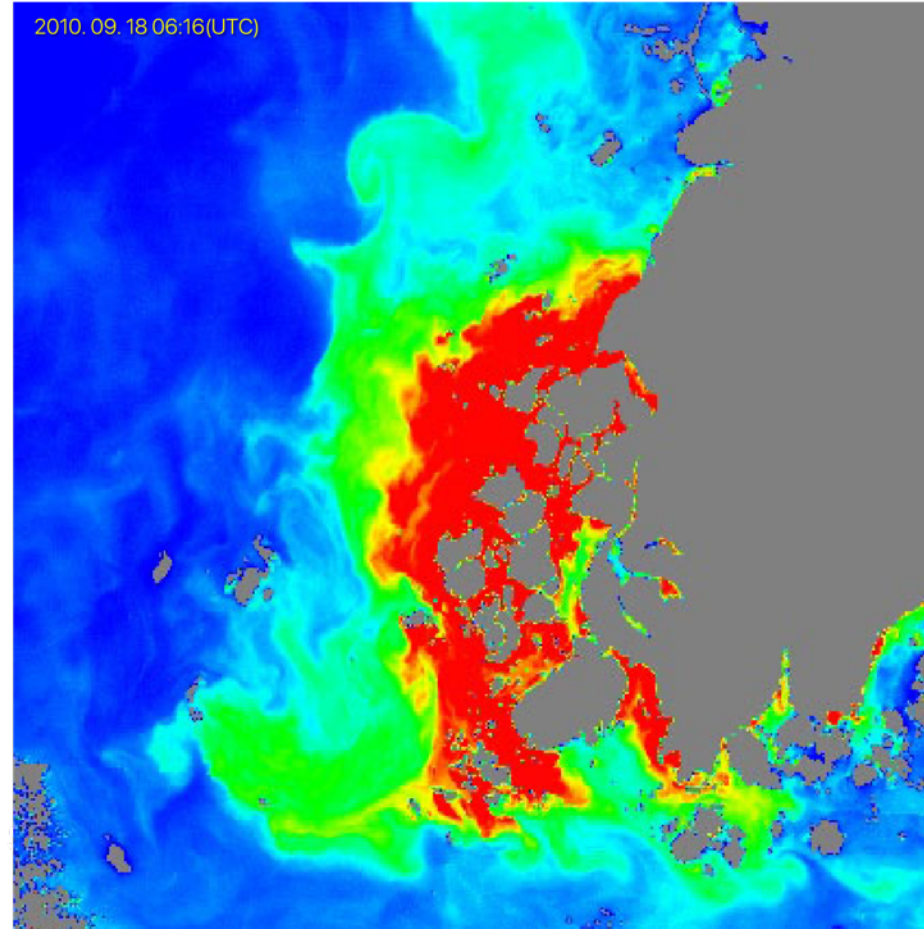
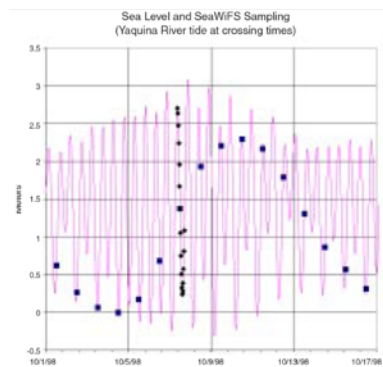
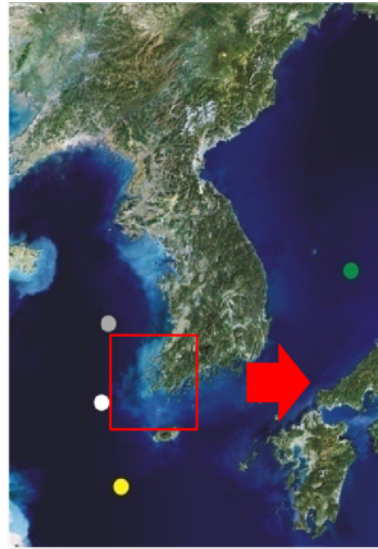


From Gernez, Antoine and Huot, 2011, L&O, 56, 17-36

Can be potentially used to derive ocean primary production



Advantages of the GEO orbit



Courtesy from Joo-Hyung Ryu, KIOST

Advantages of the GEO orbit

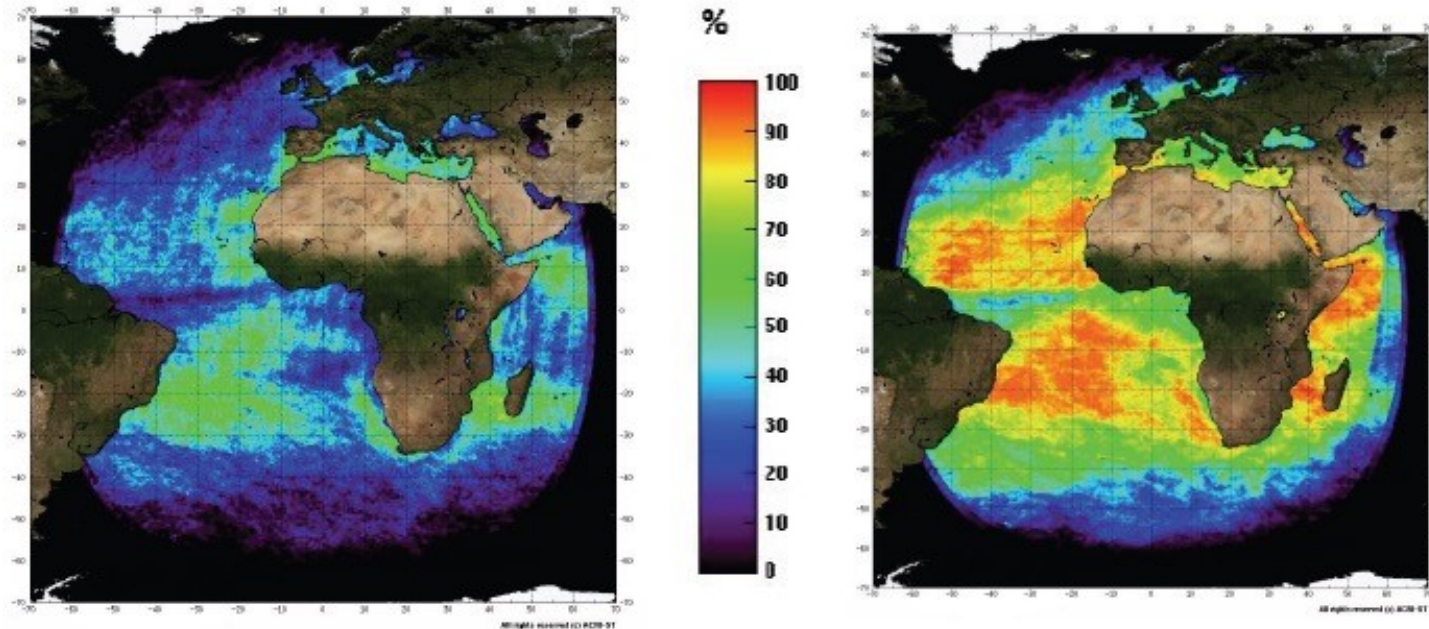


Figure A.1.3. 1 Example of monthly data availability in March for two mission configurations: constellation of two Sentinel-3 alone (left), and complemented by a GEO with 1 hour revisit (right). A realistic cloud coverage is taken into account (MSG data for year 2007) as well as geometrical constraints (air mass < 5 , glint reflectance smaller than $5 \cdot 10^{-4}$). For a given pixel, availability must be understood as at least one clear observation per day (50% means there is at least one daily data for half of the days in the month). The observation area is constrained by the MSG observation area (MSG clouds).

Taken from the "GeOCAPI" proposal to ESA

Main challenges of the GEO orbit

The sensor is at ~36,000km from the Earth, instead of being at about 700km in the case of Low-Earth Orbit (LEO) sensors

- If the same at-the-ground spatial resolution is aimed at, the instantaneous field of view is much smaller (the solid angle is much smaller).
- This might be an issue for the signal-to-noise!
- However, because of the GEO position, the sensor can “stare” and, therefore, the integration time can be much longer than for a LEO sensor. At the end, similar SNRs to LEO sensors are reachable (~1000 in the blue)
- Pointing stability is however another big challenge
- High latitudes are not covered
- Other challenges are more of a “political” nature: launching to the GEO orbit is expensive.

Reports and Monographs of the International Ocean-Colour Coordinating Group

An Affiliated Program of the Scientific Committee on Oceanic Research (SCOR)
An Associated Member of the (CEOS)

IOCCG Report Number 12, 2012

Ocean-Colour Observations from a Geostationary Orbit

Edited by:

David Antoine, Laboratoire d'Océanographie de Villefranche (LOV-CNRS),
Villefranche-sur-mer, France)

Report of an IOCCG working group on Ocean-Colour Observations from a Geostationary Orbit, chaired by David Antoine, and based on contributions from (in alphabetical order):

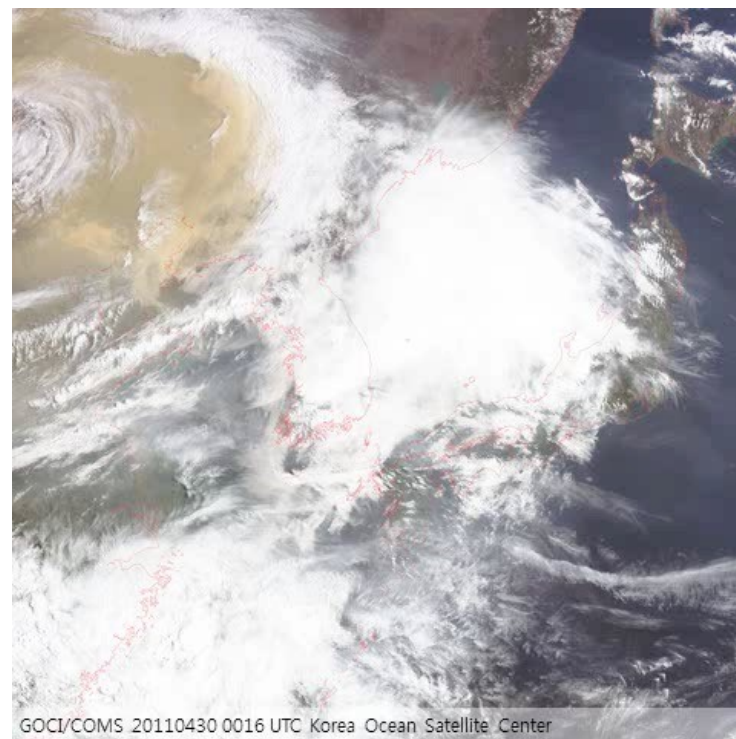
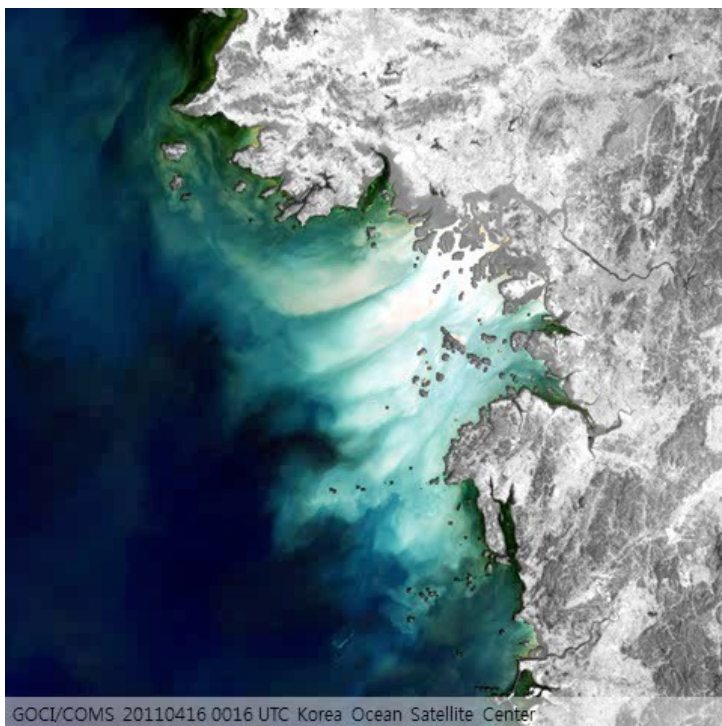
Yu-Hwan Ahn	Korea Institute of Ocean Science and Technology (KIOST)
David Antoine	Laboratoire d'Océanographie de Villefranche, France
Jean-Loup Bézy	ESA/ESTEC, The Netherlands
Prakash Chauhan	Indian Space Research Organisation (ISRO), India
Curtiss Davis	Oregon State University (OSU), USA
Paul DiGiacomo	National Oceanic and Atmospheric Administration, USA
Xianqiang He	State Key Lab of Satellite Ocean Environment Dynamics, China
Joji Ishizaka	Nagoya University, Japan
Hiroshi Kobayashi	University of Yamanashi, Japan
Anne Lifermann	Centre National d'Etudes Spatiales (CNES), France
Antonio Mannino	National Aeronautics and Space Administration (NASA), USA
Constant Mazeran	ACRI-ST, Sophia Antipolis, France
Kevin Ruddick	Management Unit of the North Sea Mathematical Models (MUMM), Belgium

Series Editor: Veneta Stuart

OCR from the GEO orbit

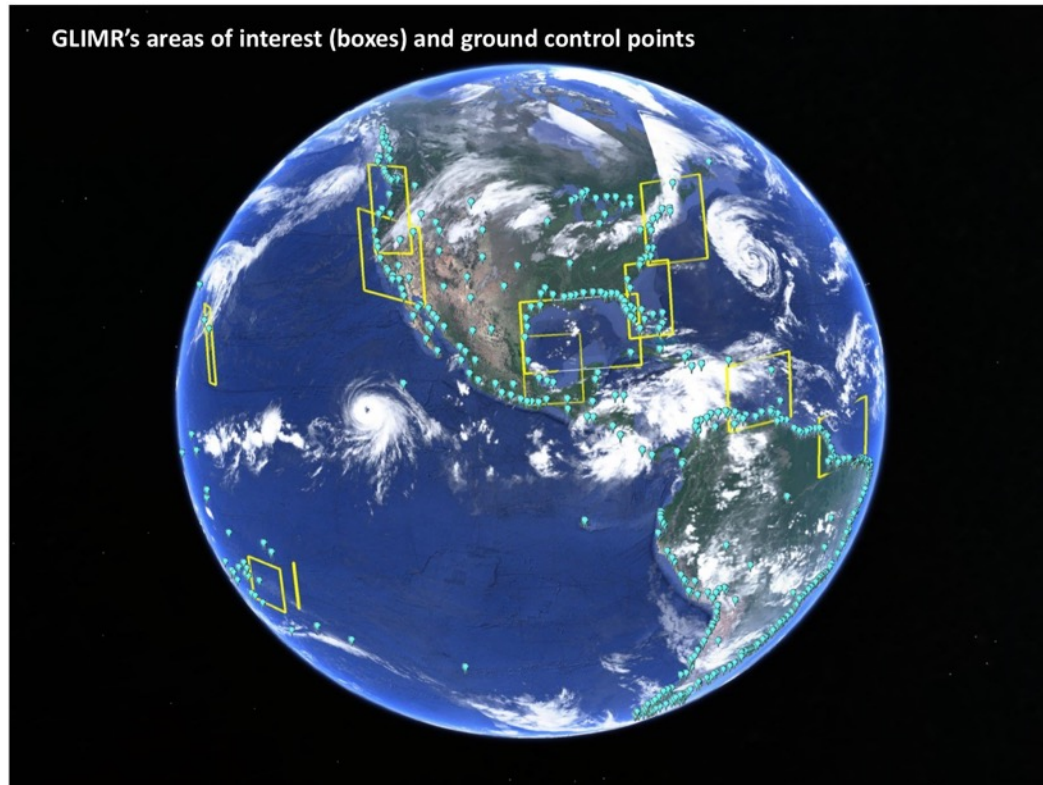
Do we have plans?

There are already two OCR sensors on a GEO orbit: the Korean “Geostationary Ocean Colour Instrument” (GOCI) and GOCI-II



OCR from the GEO orbit

Do we have plans?



Geosynchronous Littoral Imaging and Monitoring Radiometer (**GLIMR**)

Pis:

Joe Salisbury (UNH),
Antonio Mannino (NASA)

The two main science goals of GLIMR are to:

1. Understand the processes contributing to rapid changes in phytoplankton growth rate and community composition.
2. Quantify how high frequency fluxes of sediments, organic matter, and other materials between and within coastal ecosystems regulate the productivity and health of coastal ecosystems.

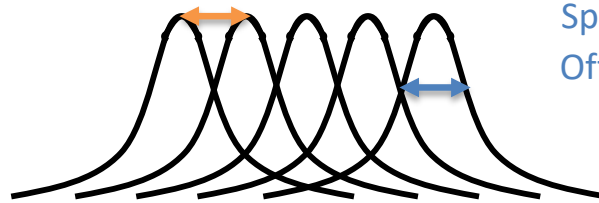
<https://eosps.nasa.gov/missions/geosynchronous-littoral-imaging-and-monitoring-radiometer-evi-5>

What the future is made of?

3) Going hyperspectral

→ Means “continuous” observations from the near UV to near IR at a high spectral resolution; always some “averaging” or “smoothing”, however

Spectral resolution



Spectral sampling

Often defined at the “full-width-half-maximum” (FWHM)

- Basic assumption is that we can derive more information on ocean ecosystems from using a richer spectral information, as compared to the few spectral bands of most current OCR sensors
- Instruments have to be designed in such a way that radiance is measured from the near UV to the near IR with, e.g., a 3nm resolution. Need a spectro-radiometer. That’s actually what MERIS was and what OLCI is (only a subset of bands is aggregated and transmitted to ground, however).

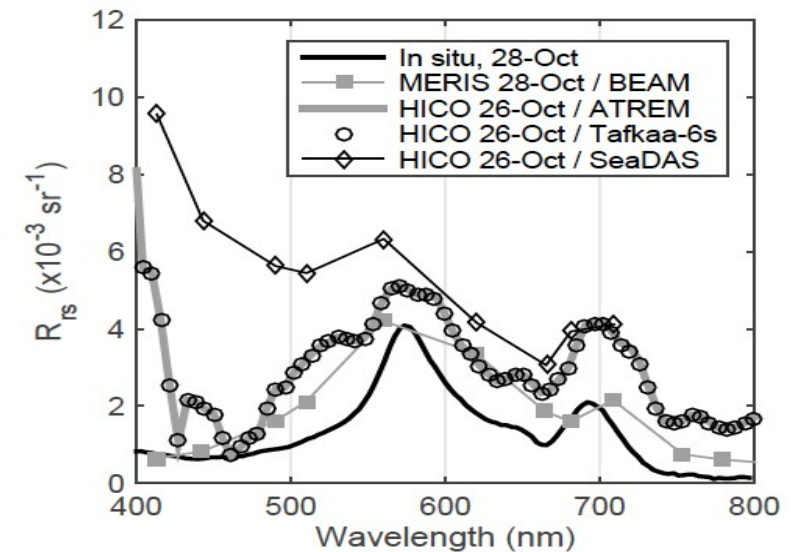
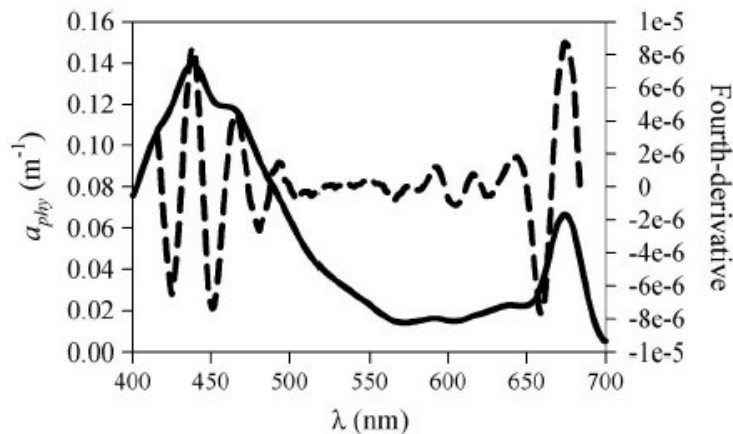
What the future is made of?

3) Going hyperspectral

→ Going hyperspectral is an attempt to solve ill-posed problems by bringing more (supposedly) independent observations

→ Typical problems that are tackled with hyperspectral RS:

- Bathymetry in shallow and clear waters
- Phytoplankton functional types
- HABs



Ryan et al., 2014. Remote Sens, 6, 1007-1025;
doi:10.3390/rs6021007

What the future is made of?

3) Going hyperspectral

→ Current / scheduled hyperspectral sensors

HyspIRI	NASA	VSWIR instrument	>2022	145	60	10 nm contiguous bands	380 - 2500	LEO, Sun Sync.
https://hyspiri.jpl.nasa.gov								
EnMAP	DLR (Germany)	HSI	2019	30	30	242	420 - 2450	Polar
http://www.enmap.org								
PACE	NASA	OCI	2022/2023	2000	1000	hyperspectral (5 nm from 350 to 890 nm + 6 in NIR-SWIR)	350-2250 nm	Polar
https://pace.gsfc.nasa.gov								

<https://ioccg.org/resources/missions-instruments/>



National Aeronautics and
Space Administration

PACE

Plankton, Aerosol, Cloud,
ocean Ecosystem

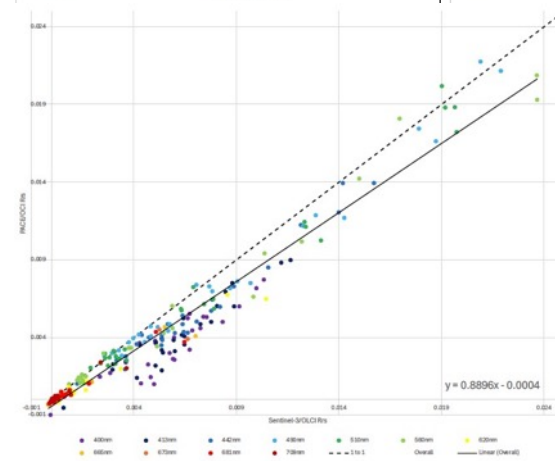
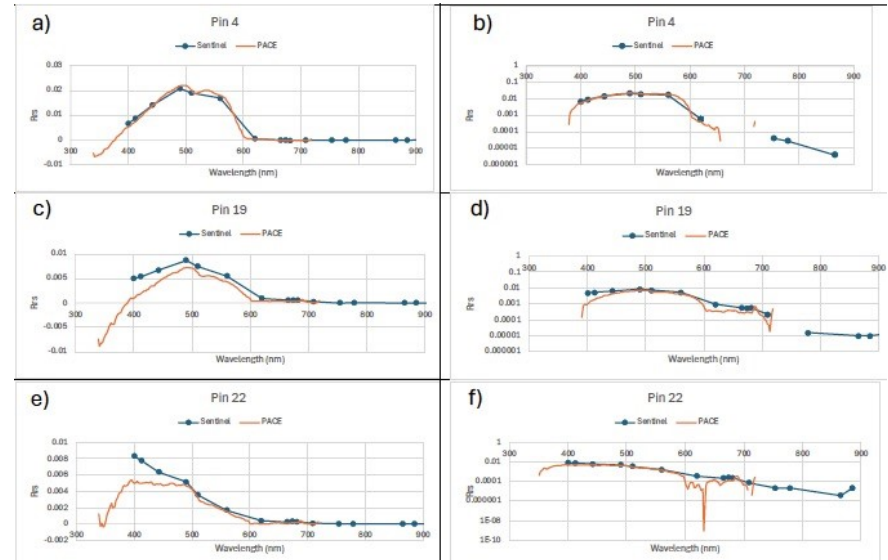
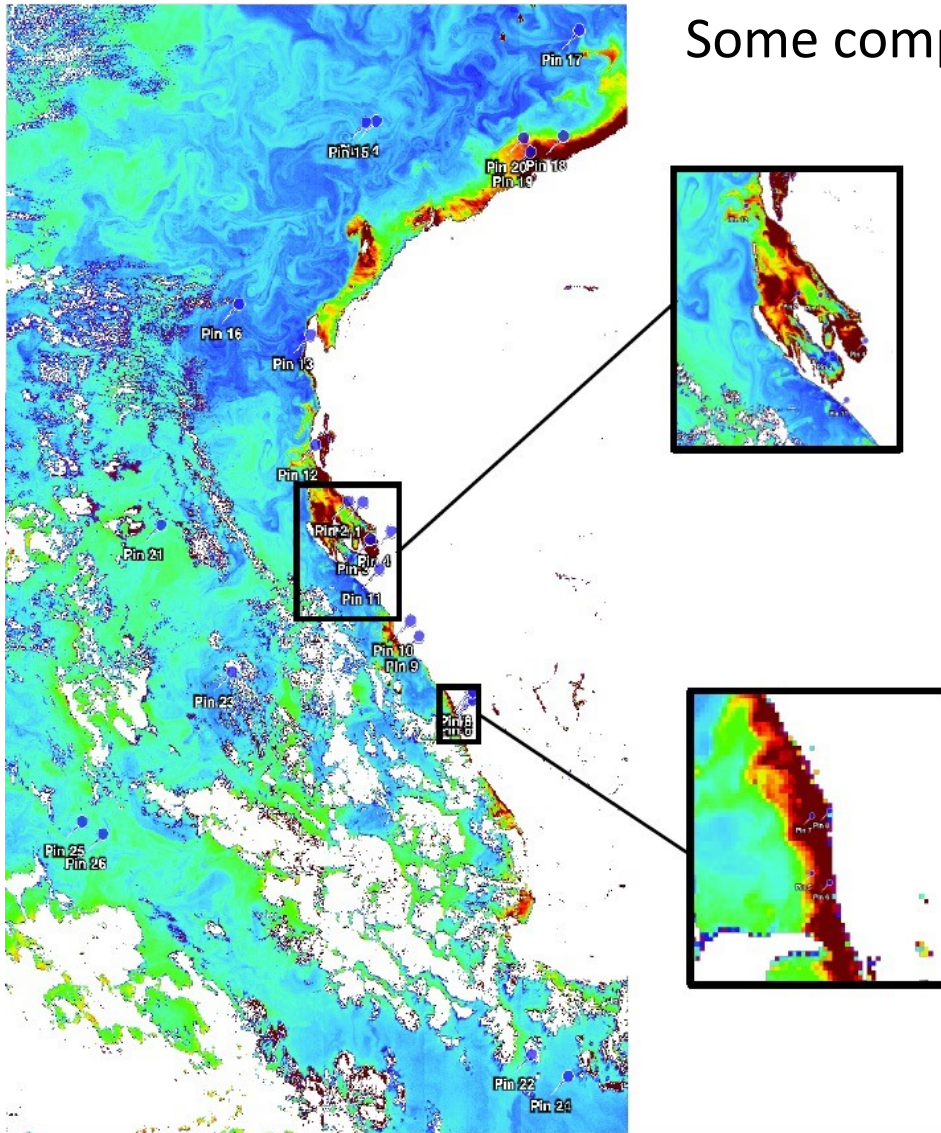


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<https://pace.oceansciences.org>

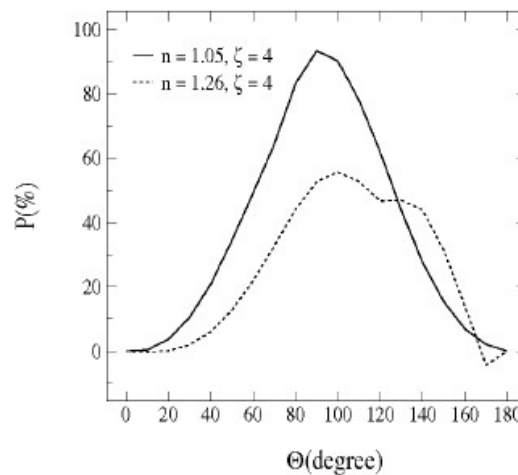
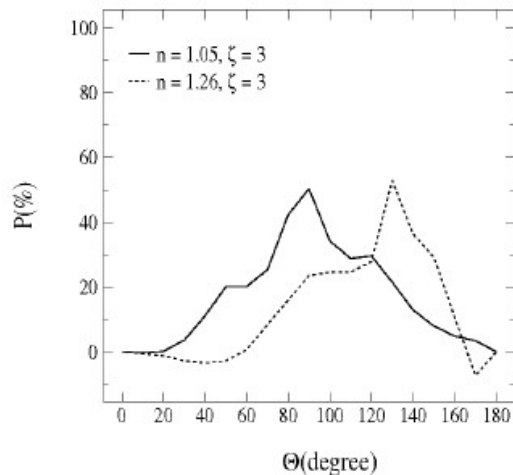
Some comparison PACE/OCI vs S3A/OLCI



What the future is made of?

4) OCR sensors recording the polarisation state

- Basically, the idea is to introduce an additional, independent, piece of information in the inversion problem: polarisation
- Polarisation is highly dependent on the particle composition (so: index of refraction) and particle size distribution (PSD) and particle shape
- The main aims are 1) to better identify aerosols in order to improve atmospheric corrections and, 2) to discriminate between mineral and biogenic particles in the ocean (coastal zones)



From Loisel et al., 2008, Optics Express, 16(17), 12905-12918

Degree of polarisation as a function of n and the PSD (slope parameter ζ).

Polarisation:

Past / current / future sensors with a polarisation capability

Past:

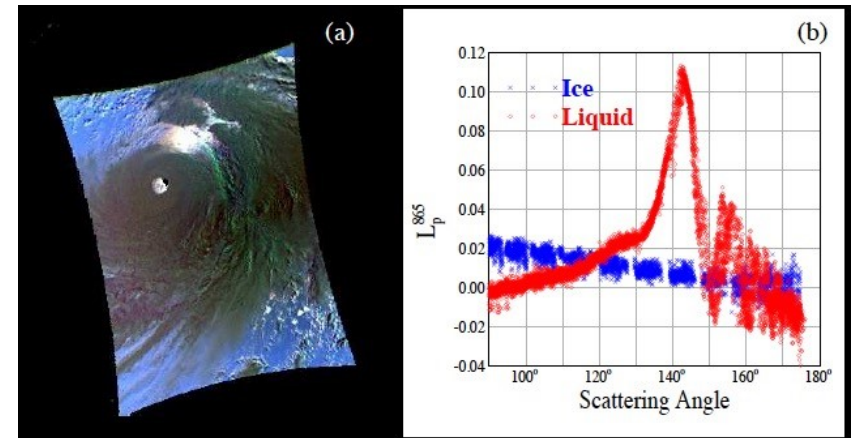
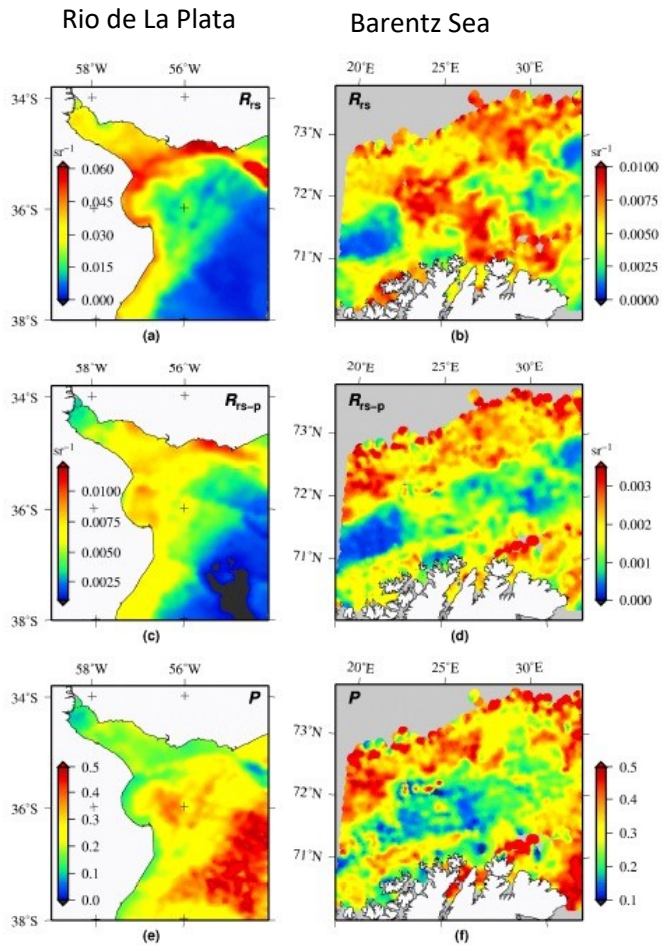
- ◆ POLDER 1, 2, 3 (CNES)
- ◆ MISR (NASA)

Present:

- ◆ S-GLI (JAXA)
- ◆ PACE (NASA)

Future

- ◆ 3MI (EUMETSAT)



POLDER observations used for cloud studies.

From Riedi et al., 2010. Atmos. Chem. Phys., 10, 11851–11865, doi:10.5194/acp-10-11851-2010

From Loisel et al., 2008, Optics Express, 16(17), 12905-12918 Using POLDER observations

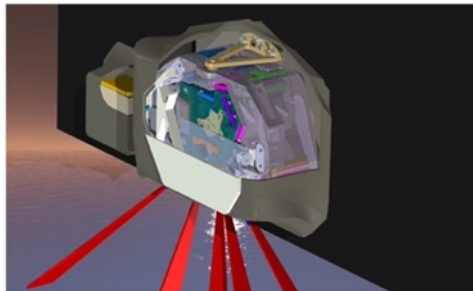
Polarisation

The NASA PACE mission carries 2 polarimeters

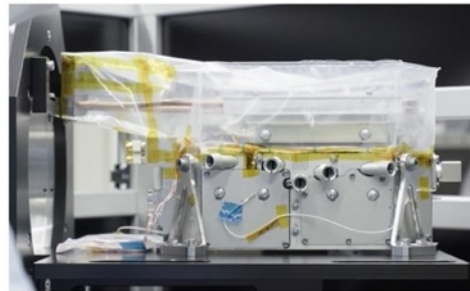
SPEXone Polarimeter

PACE's SPEXone instrument is a multi-angle polarimeter. It measures the intensity, Degree of Linear Polarization (DoLP) and Angle of Linear Polarization (AoLP) of sunlight reflected back from Earth's atmosphere, land surface, and ocean. The focus of the SPEXone development is to achieve a very high accuracy of DoLP measurements, which facilitates accurate characterization of aerosols in the atmosphere.

Aerosols are small solid or liquid particles suspended in the air that affect climate directly through interaction with solar radiation. Aerosols affect climate indirectly by changing the micro- and macro-physical properties of clouds. According to the Intergovernmental Panel on Climate Change, aerosols are the largest source of error in quantifying the radiative forcing of climate change. SPEXone will enable measurements of optical and micro-physical properties of aerosols with unprecedented detail and accuracy.



Artist's impression of SPEXone instrument in space - ©Airbus Defence and Space Netherlands & SRON Netherlands Institute for Space Research



SPEXone instrument in SRON clean room - ©Airbus Defence and Space Netherlands & SRON Netherlands Institute for Space Research.

HARP2 Polarimeter

HARP2 (Hyper-Angular Rainbow Polarimeter #2) is a wide angle imaging polarimeter designed to measure aerosol particles and clouds, as well as properties of land and water surfaces. The amount and type of particles in suspension in the atmosphere are relevant to applications pertaining to health effects, cloud life cycle and precipitation, climate, etc. HARP2 will combine data from multiple along track viewing angles (up to 60), four spectral bands in the visible and near infrared ranges, and three angles of linear polarization to measure the microphysical properties of the atmospheric particles including their size distribution, amount, refractive indices and particle shape.

HARP2 is a contributed instrument to the PACE mission, designed and built by UMBC's [Earth and Space Institute](#).



<https://pace.oceansciences.org/spexone.htm>

<https://pace.oceansciences.org/harp2.htm>

What the future is made of?

5) Satellite-borne LIDARs

- ◆ Passive ocean colour allows accessing a signal whose 90% comes from depths $< \sim 1/K_d$ (Gordon and McLuney, 1975, Applied Optics 14(2))
- ◆ In the clearest waters, this is about 20 m in the blue; otherwise, just a few meters
- ◆ We know, however that the vertical structure in the upper layers is important as well, and not necessarily uniform
- ◆ Hence the idea that LIDARs could help, because they are precisely designed to resolve vertical structures
- ◆ Satellite LIDARs have been essentially used for atmospheric purposes, however. Ocean LIDARs have been rather deployed from ships or aircrafts, with a variety of applications but, most often, for bathymetry determination

Satellite-borne LIDARs

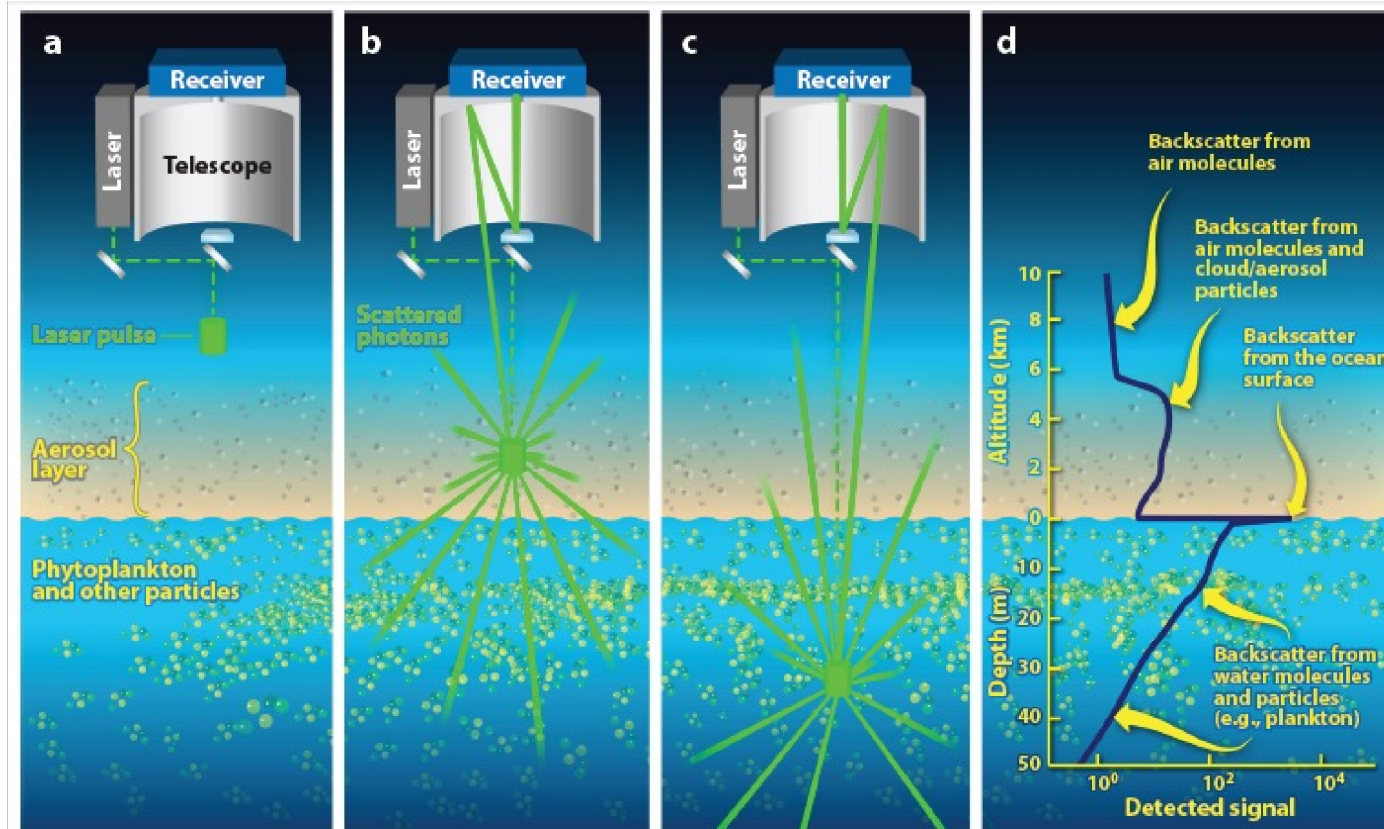
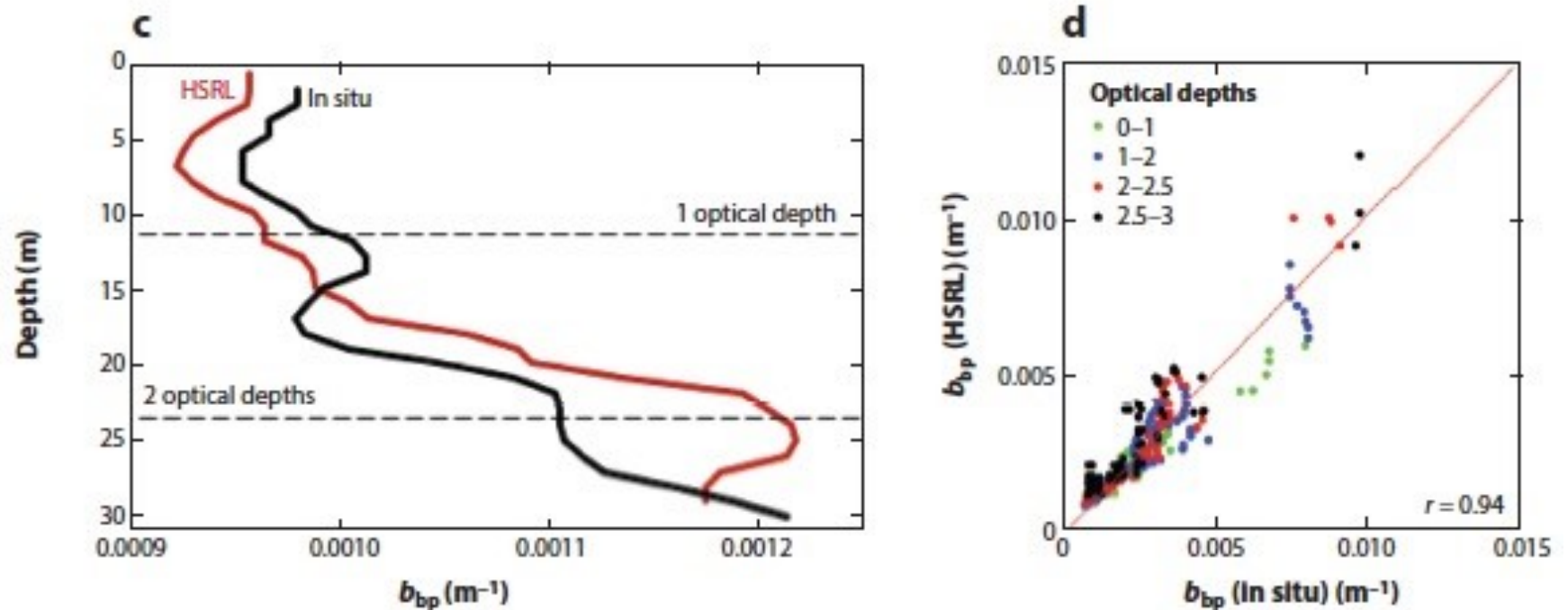


Figure 1 in Hostetler et al., 2018, Spaceborne Lidar in the Study of Marine Systems, Annual Review of Marine Science, 10:121–47. <https://doi.org/10.1146/annurev-marine-121916-063335>

Satellite-borne LIDARs for the ocean

Main advantage: they resolve information on the vertical



From Figure 4 in Hostetler et al., 2018, Spaceborne Lidar in the Study of Marine Systems, Annual Review of Marine Science, 10:121–47. <https://doi.org/10.1146/annurev-marine-121916-063335>

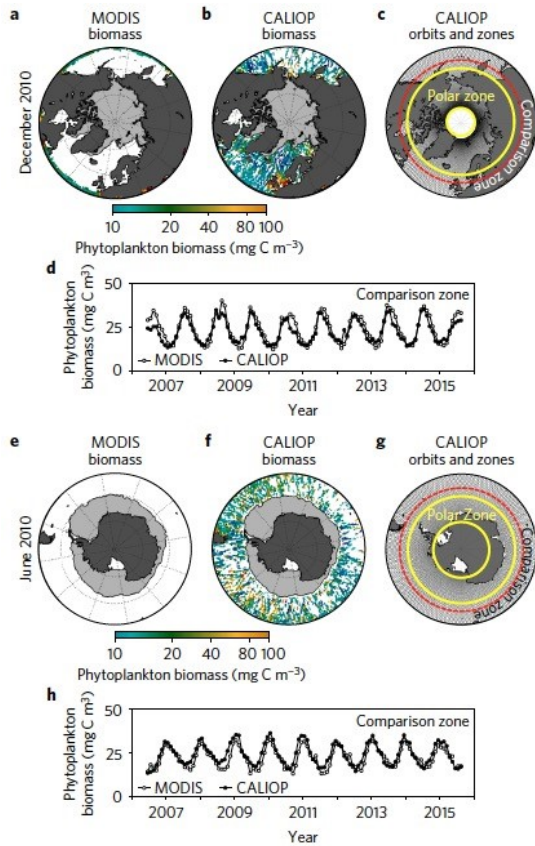


Figure 1 | Phytoplankton biomass observations from CALIOP and MODIS. **a**, MODIS phytoplankton biomass retrievals poleward of 45° latitude (white: no data) for northern latitudes (December 2010). **b**, CALIOP phytoplankton biomass retrievals for December 2010. **c**, Black lines: CALIOP orbit tracks poleward of 45° latitude. The red dashed ring demarks the 45°–55° ‘comparison zone’. Yellow rings demark the north polar zone (60°–81.5° latitude). **d**, 2006–2015 monthly mean phytoplankton biomass for the north ‘comparison zone’. **e–h**, As in **a–d**, respectively, but for southern latitudes during June 2010 (south polar zone in **f**: 60°–75°). Grey shading: ice cover in panels **a,b** and **e,f**.

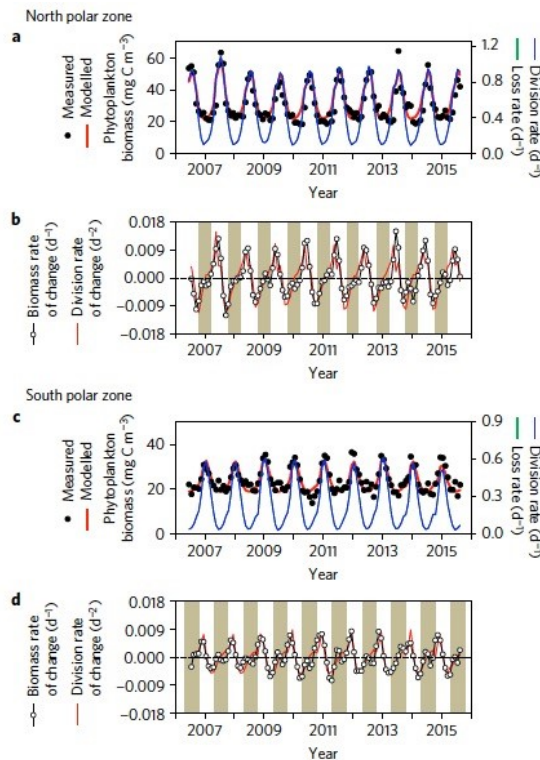


Figure 2 | Polar phytoplankton cycles. **a,c**, Black symbols: CALIOP monthly mean phytoplankton biomass (C). Blue line: phytoplankton division rates (μ). Green line: phytoplankton loss rates (l , which are indistinguishable from μ). Red line: calculated C time series from model predictions of $d\mu/dt$ (Methods). **b,d**, Open symbols, black line: biomass rates of change (r) calculated from CALIOP observations (equation (2)). Red line: modelled $d\mu/dt$ (equations (1) and (3)). Statistics on relationships between r and $d\mu/dt$ are: $r^2 = 0.63$, $n = 110$, $p < 0.001$ (**b**) and $r^2 = 0.71$, $n = 110$, $p < 0.001$ (**d**). Vertical tan bars: months with no MODIS data.

From: Behrenfeld et al., 2017, Nature Geosciences, 10, doi: 10.1038/NGEO2861

Satellite-borne LIDARs for the ocean

Other interesting feature: they work night and day

What the future is made of?

6) High spatial resolution sensors

- ◆ The “Satellite OCR” realm is essentially made of moderate (medium) spatial resolution sensors. Sub-satellite resolution in the hectometre domain: basically 250 m to 1 km
- ◆ This is totally fine for most regional to global applications
- ◆ This is not necessarily adapted to observing / studying more local phenomena, in particular in coastal environments
- ◆ There is accordingly an increased interest in using high spatial resolution sensors
- ◆ Most of these, however, have not been specifically designed for ocean colour research and applications
- ◆ “A bit” of work is needed to apply those to the marine environment

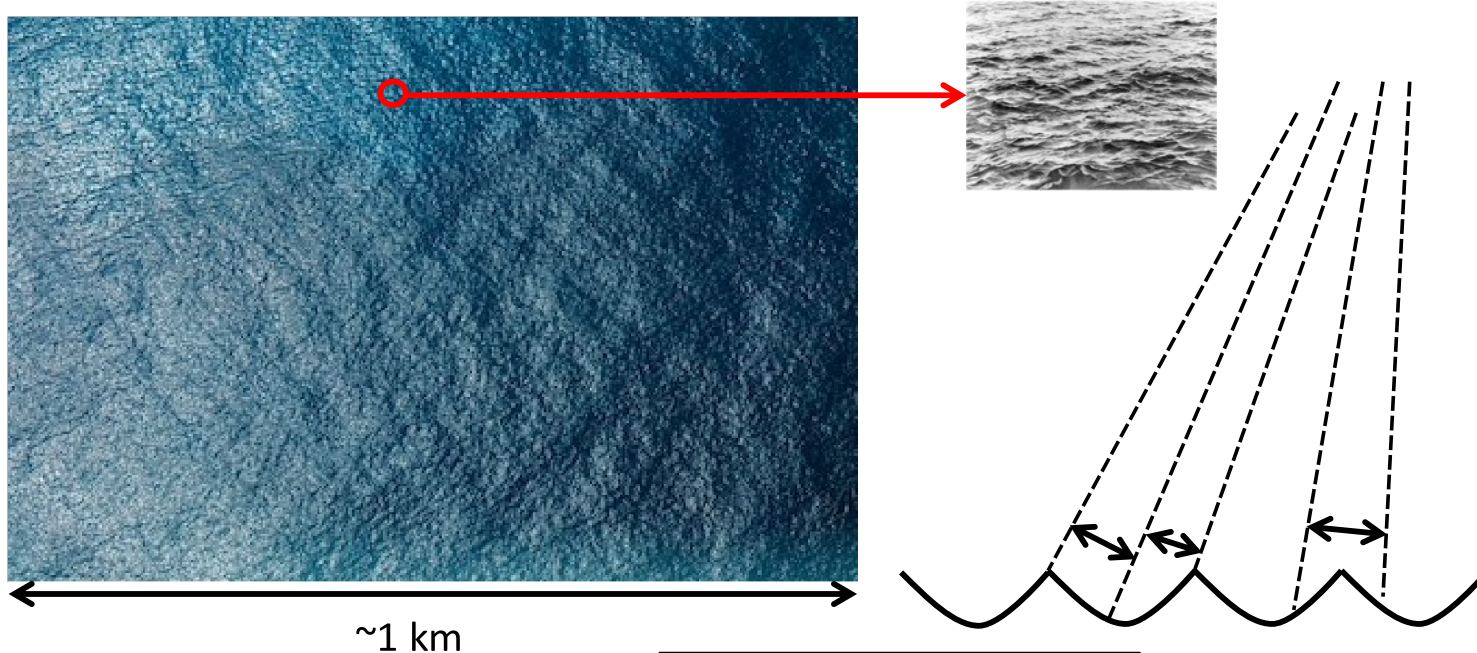


ESA Sentinel2/MSI instrument

High spatial resolution sensors: Some issues to consider

- ◆ High spatial resolution inevitably means lower SNR: how much “lower” is acceptable to still be useful for ocean applications ?
- ◆ When is it that the radiometric quality (SNR) is so much degraded that the quantitative aspect of satellite OCR is lost?
- ◆ High spatial resolution also means that the way we model surface effects no longer holds, e.g., the slope of the interface may differ for each pixel
- ◆ The above may sometimes be an advantage?
- ◆ Shadows
- ◆ Because most uses of the high spatial resolution observations are for the coastal environment: atmospheric corrections becomes more complex, at least more difficult to achieve properly

High spatial resolution sensors: surface effects



~1 km

Valid for medium resolution sensors

$$p(\theta_s, \theta_v, \Delta\phi) = \frac{1}{\pi \sigma^2} \exp\left(\frac{-\tan^2(\beta)}{\sigma^2}\right)$$

$$\sigma^2 = 0.003 + 5.12 \cdot 10^{-3} W$$

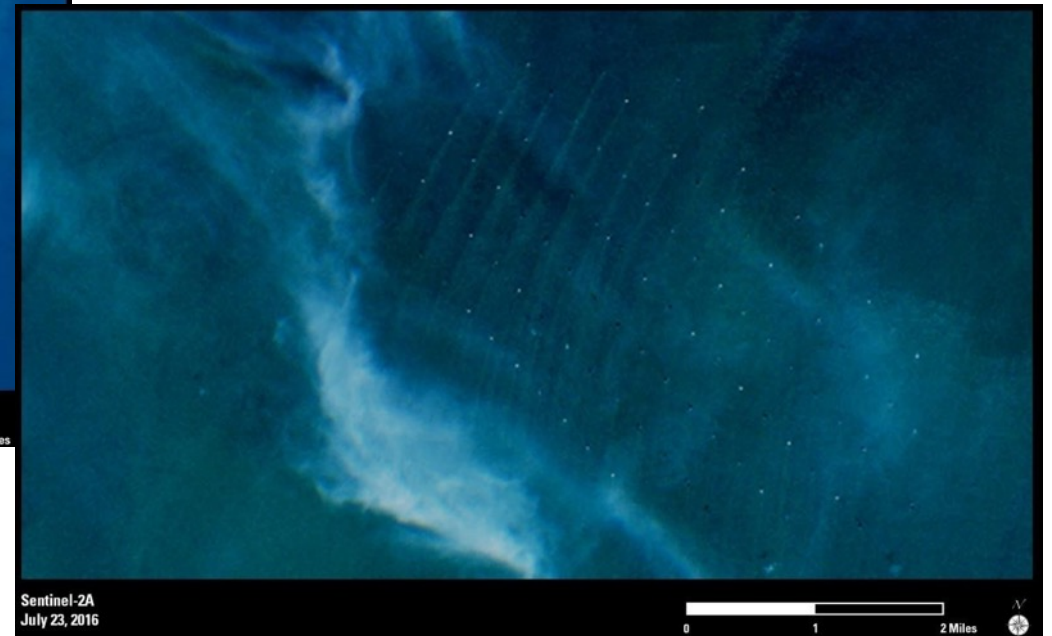
$$\rho_G = \pi \rho_F p(\theta_s, \theta_v, \Delta\phi) / (4 \cos(\theta_v) \cos(\theta_s) \cos^4(\beta)) T(\theta_v) T(\theta_s)$$

Cox C. and W. Munk, 1954. Statistics of the sea surface derived from sun glitter. J. Mar. Res., 13, 198-227.

Examples of observations from high spatial resolution sensors



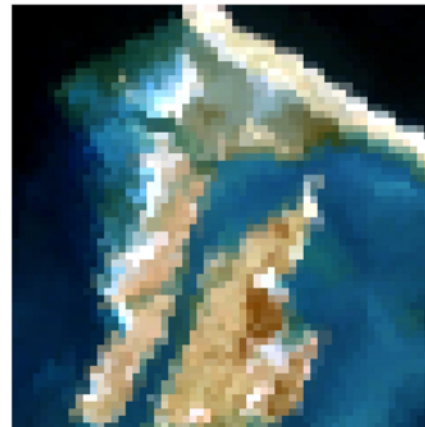
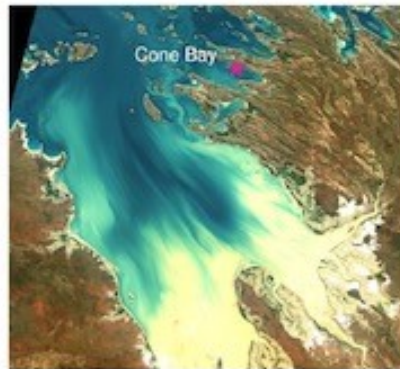
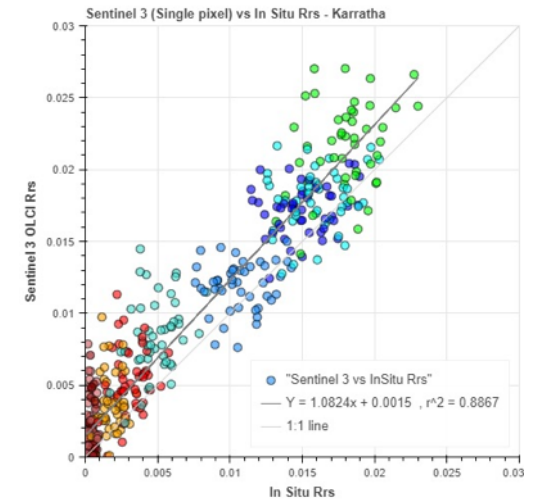
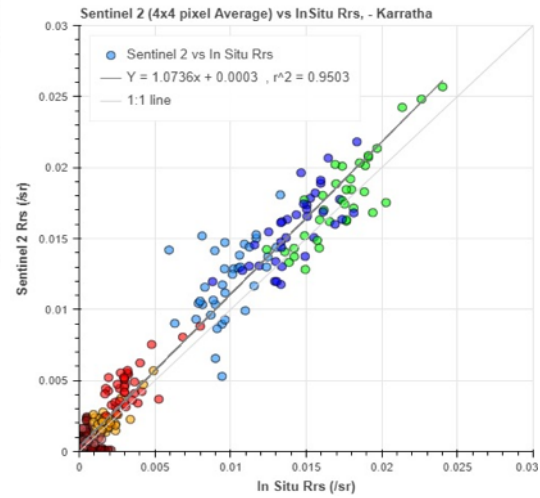
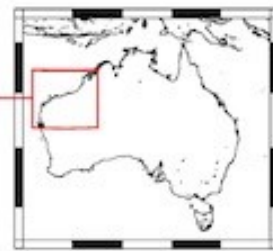
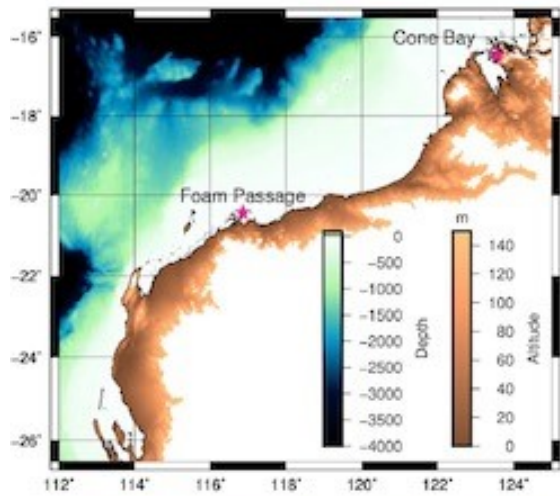
Landsat 8 shows a sediment plume in the North Sea near England on June 30, 2016. Credit: USGS/NASA Landsat Program.



Sentinel-2A shows a sediment plume in the North Sea near England on July 23, 2016. Credit: ESA Sentinel-2.



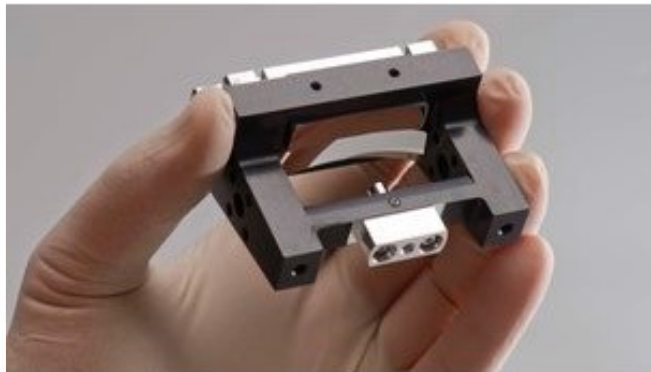
Example using S2/MSI



What the future is made of?

7) Cube sats.. “and the like”

HAND-SIZED HYPERSPECTRAL CAMERA TO FLY ON ESA'S NEXT CUBESAT



Mini-TMA telescope

8 January 2018 Colour equals information, so the more spectral bands an Earth-observing satellite sees, the greater quantity of environmental findings returned to its homeworld. Now ESA is ready to fly a hand-sized hyperspectral imager – small enough to fit on its next nanosatellite.

Observing in 45 visible and near-infrared spectral bands, the HyperScout instrument will be launched on 2 February, aboard ESA's cereal box-sized GomX-4B nanosatellite.

Hyperspectral instruments divide up the light they receive into many narrow, adjacent wavelengths to reveal spectral signatures of particular features, crops or materials, providing valuable data for fields such as mineralogy, agricultural forecasting and environmental monitoring.

http://www.esa.int/Our_Activities/Space_Engineering_Technology/Hand-sized_hyperspectral_camera_to_fly_on_ESA_s_next_CubeSat
and
http://www.esa.int/Our_Activities/Space_Engineering_Technology/Hyperspectral_imaging_by_CubeSat_on_the_way

What the future is made of?

7) Cube sats.. “and the like”

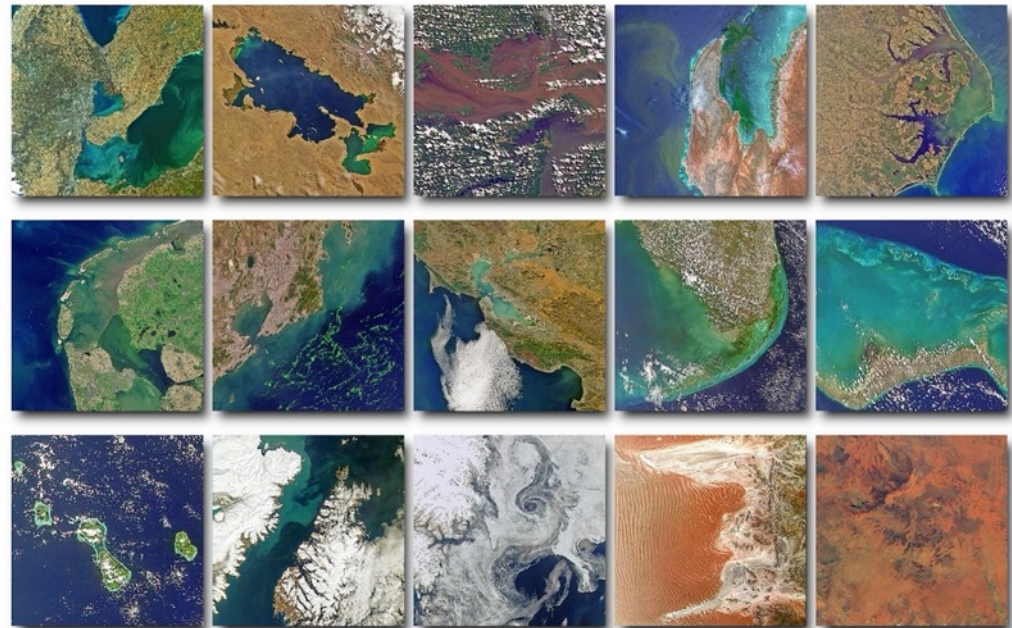
<https://uncw.edu/socon/index.html>

SeaHawk-1 Ocean Color Cubesat is now OPERATIONAL

MORE UPDATES COMING SOON



Hawkeye image gallery



<https://www.earthdata.nasa.gov/learn/articles/seahawk-hawkeye-ocean-color>

Proudly West Australian

An entire spacecraft on a single circuit board

Cost-effective manufacturing, rapid iterative prototyping, and far greater payload capacity.

Other 1U Cubesats

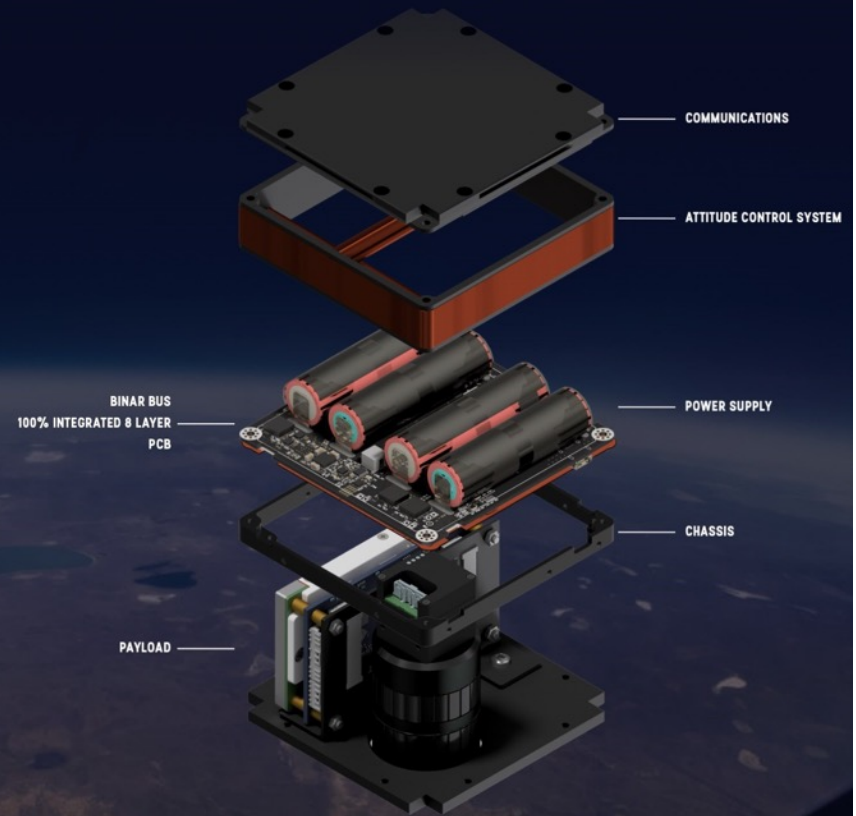
Binar 1U Cubesat

BUS SIZE

BUS SIZE

PAYLOAD CAPACITY

PAYLOAD CAPACITY

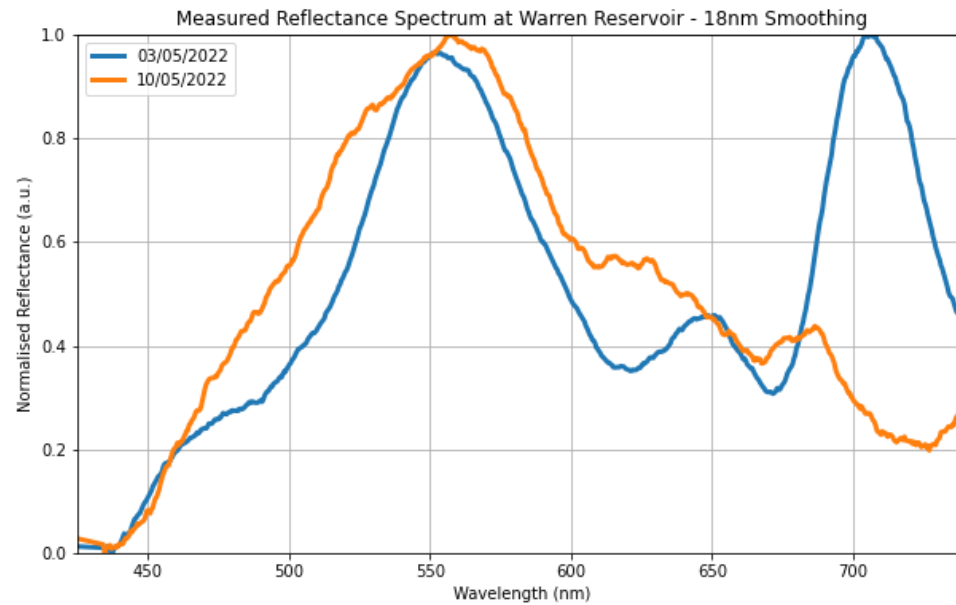


<https://www.binarspace.com>



CSIRO and SA Water demonstrate cyanobacteria detection with sensor technology that is bound for space.

May 24th, 2022



<https://research.csiro.au/laboratory-for-satelliteoptics/csiro-and-sa-water-demonstrationcyanobacteria-detection-with-sensor-technology-that-is-bound-for-space/>

Thanks for your attention



Image ©: ESA/ATG Medialab