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

David Antoine

Professor, Remote Sensing & Satellite Research Group
Curtin University, Perth, Australia

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?

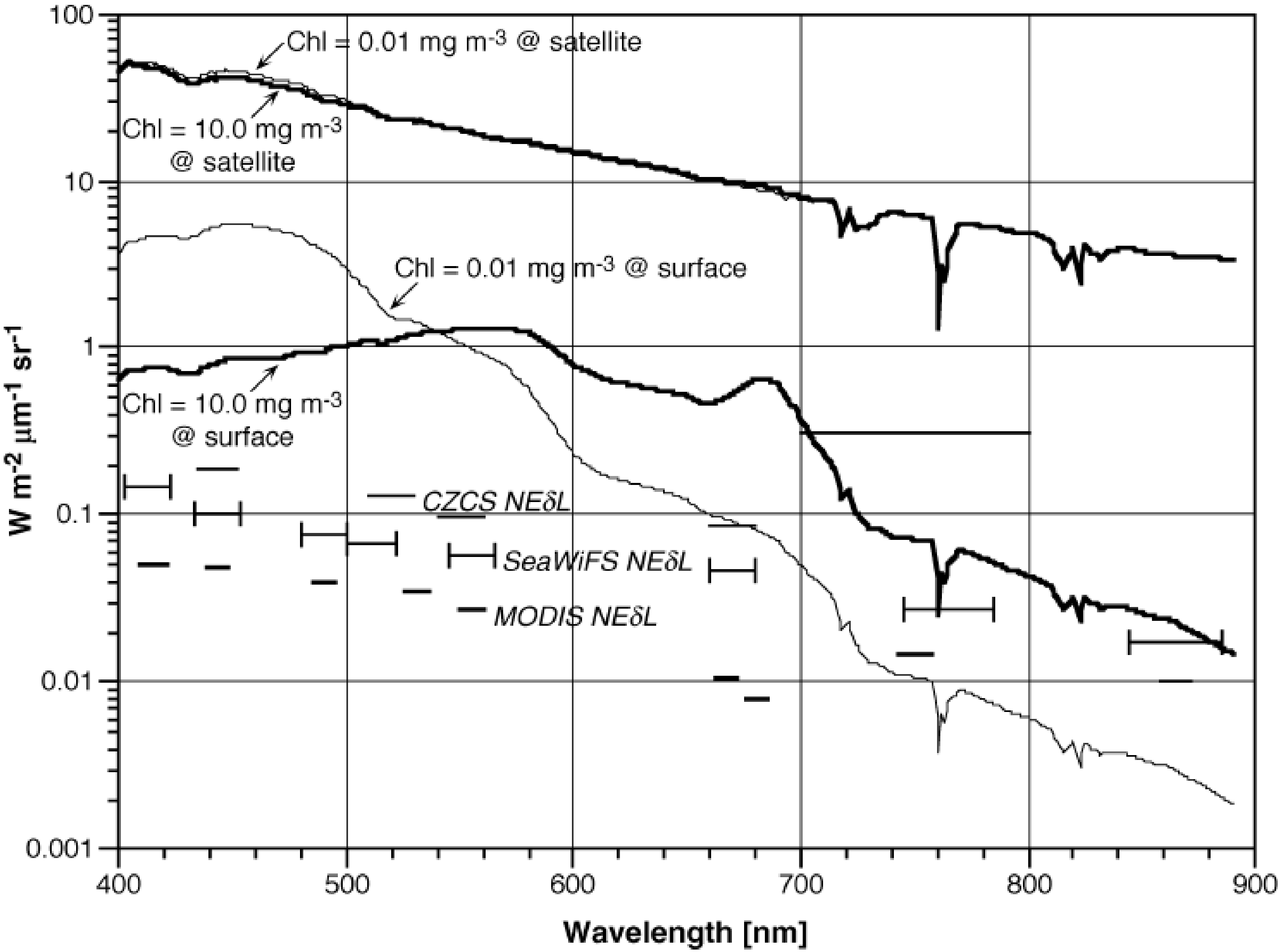


Figure 3 in Hooker SB et al., 1992. An overview of SeaWiFS and ocean color, NASA TM 104566, vol 1, NASA GSFC, Greenbelt, MD 20771

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

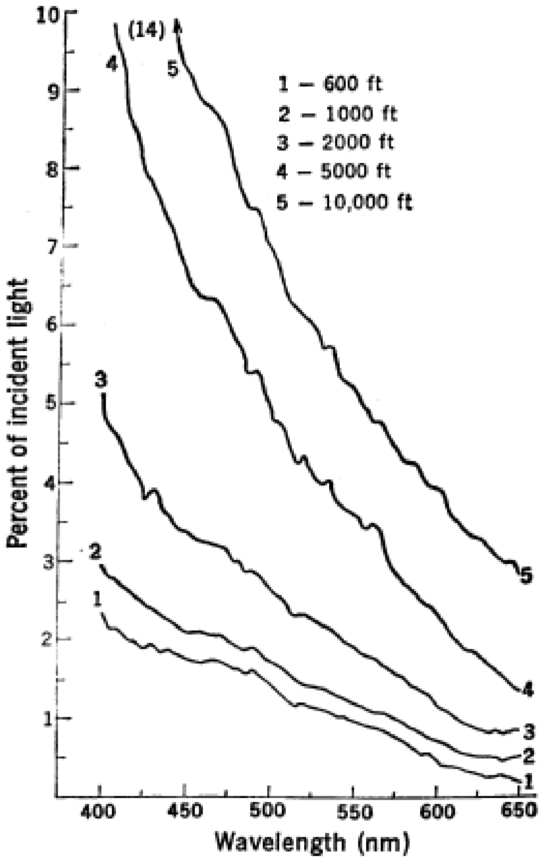


Fig. 1. Upwelling light as received at the indicated altitudes at Station S (Fig. 2) east of Cape Cod, 26 August 1968 between 1345 and 1512 hours, E.D.T.

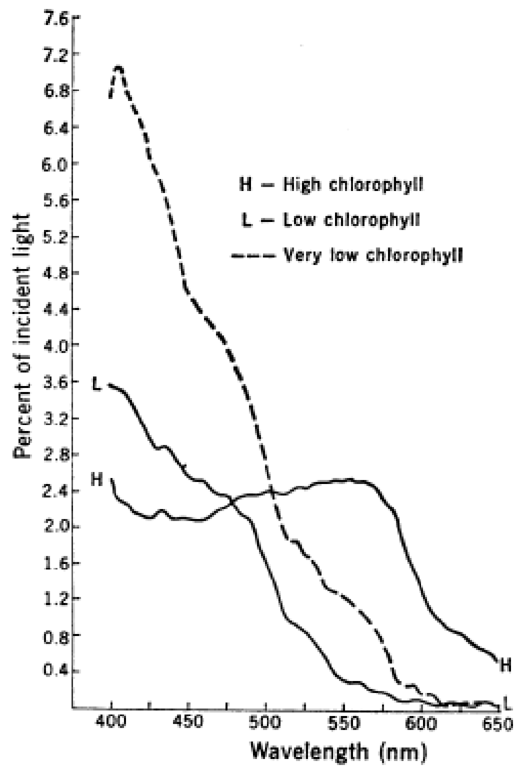


Fig. 3. Data from the high and low chlorophyll curves plotted as percentage of the incident light and compared with data taken on the same day from an area with very low chlorophyll concentration south of the Gulf Stream.

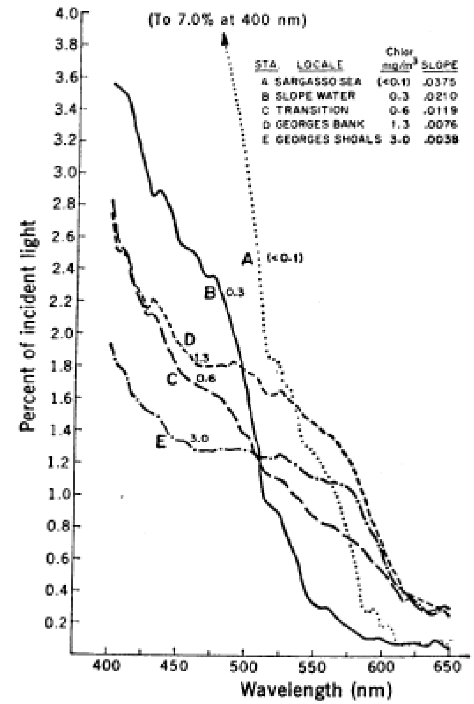


Fig. 4. Spectra of backscattered light measured from the aircraft at 305 m on 27 August 1968 at the following stations (Fig. 2) and times (all E.D.T.): Station A, 1238 hours; Station B, 1421 hours; Station C, 1428.5 hours; Station D, 1445 hours; Station E, 1315 hours. The spectrometer with polarizing 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

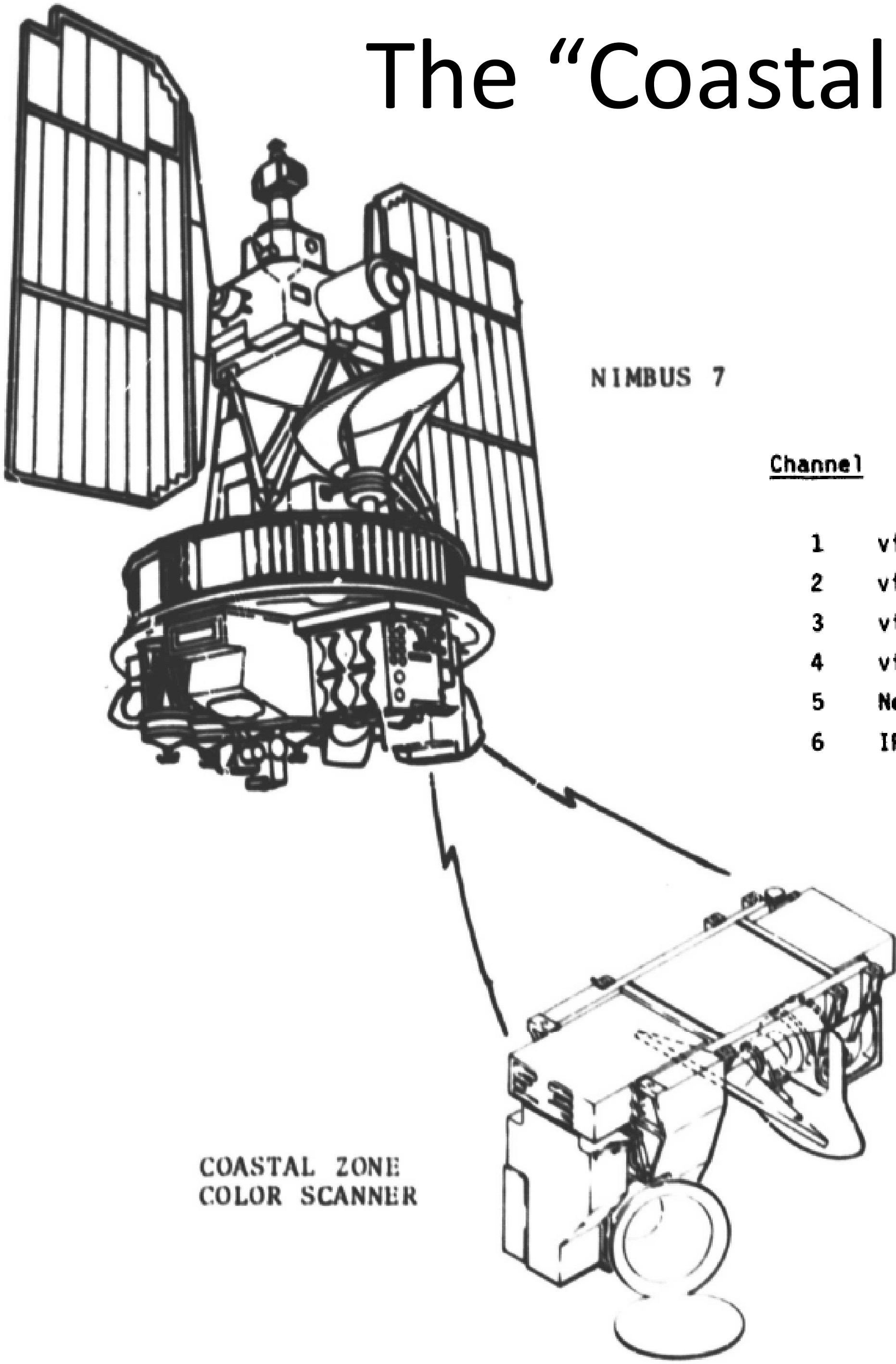
Abstract. *Spectra of sun and skylight backscattered from the sea were obtained from a low-flying aircraft and were compared with measurements of chlorophyll concentration made from shipboard at the same localities and at nearly the same times. Increasing amounts of chlorophyll were found to be associated 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

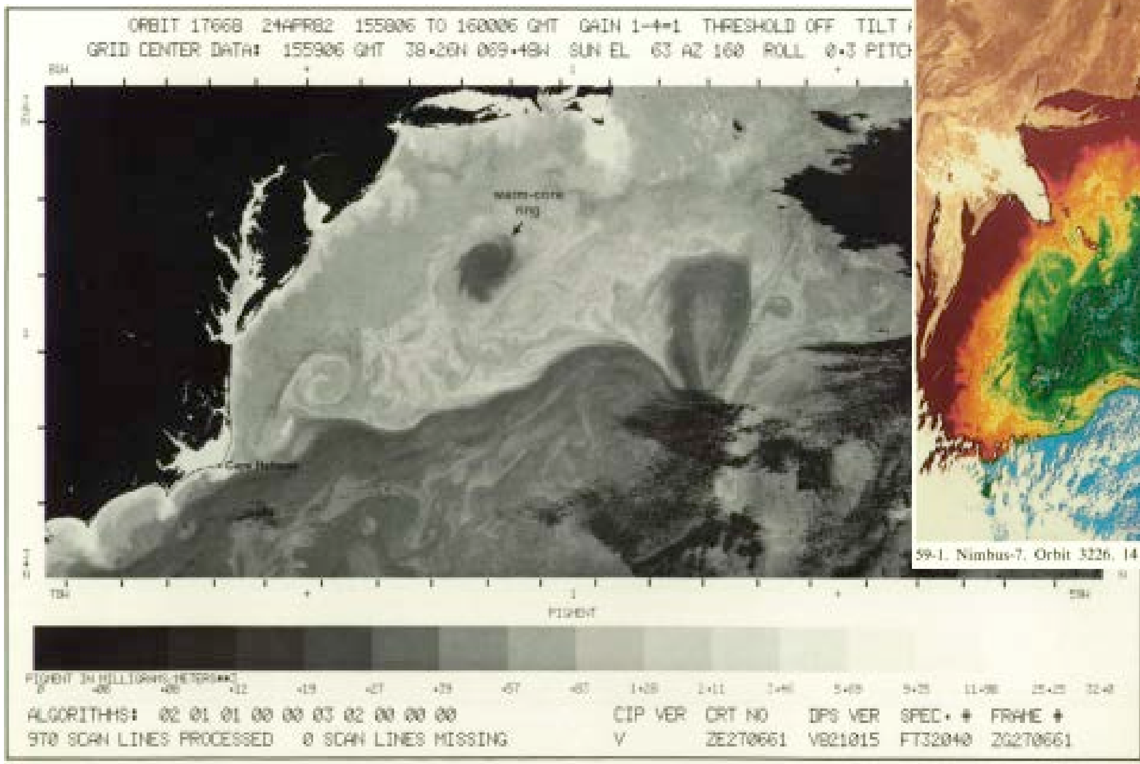
Launched October 1978



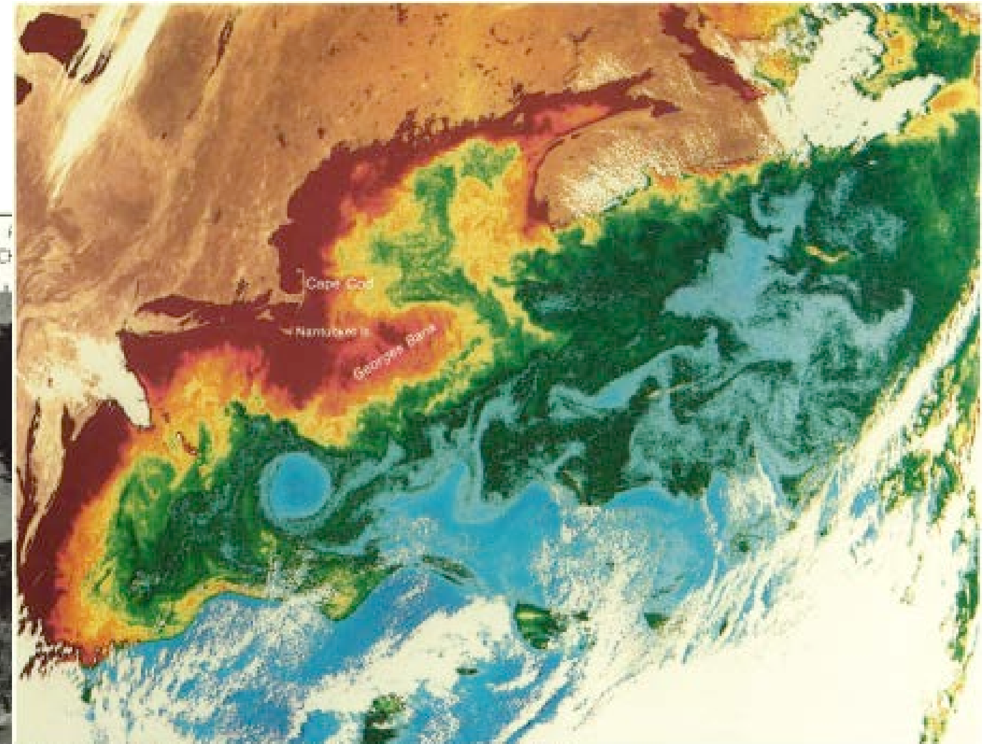
Channel	Type	Spectral Range (µm)	[illegible]	Function
1	visible	0.433 - 0.453	purple	chlorophyll
2	visible	0.510 - 0.530	blue-green	reference
3	visible	0.540 - 0.560	yellow-green	sediments
4	visible	0.660 - 0.680	red	chlorophyll
5	Near IR	0.700 - 0.800	--	surface vegatation
6	IR	10.5 - 12.5	--	surface 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



42-2. Nimbus-7. Orbit 17668. 24 April 1982. CZCS Pigment Image.



59-1. Nimbus-7. Orbit 3226. 14 June 1979. CZCS False-Color Pigment Image.

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!

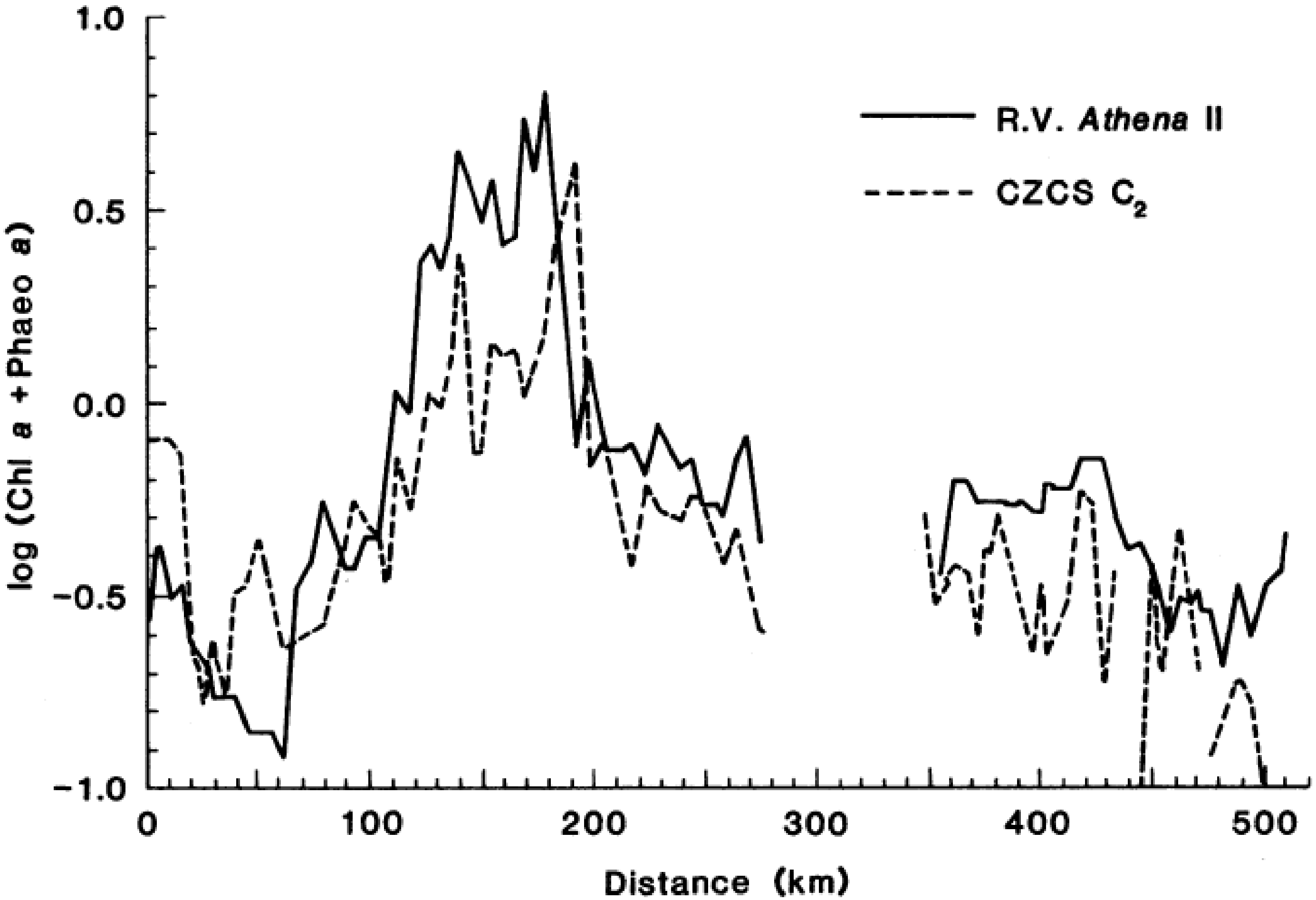
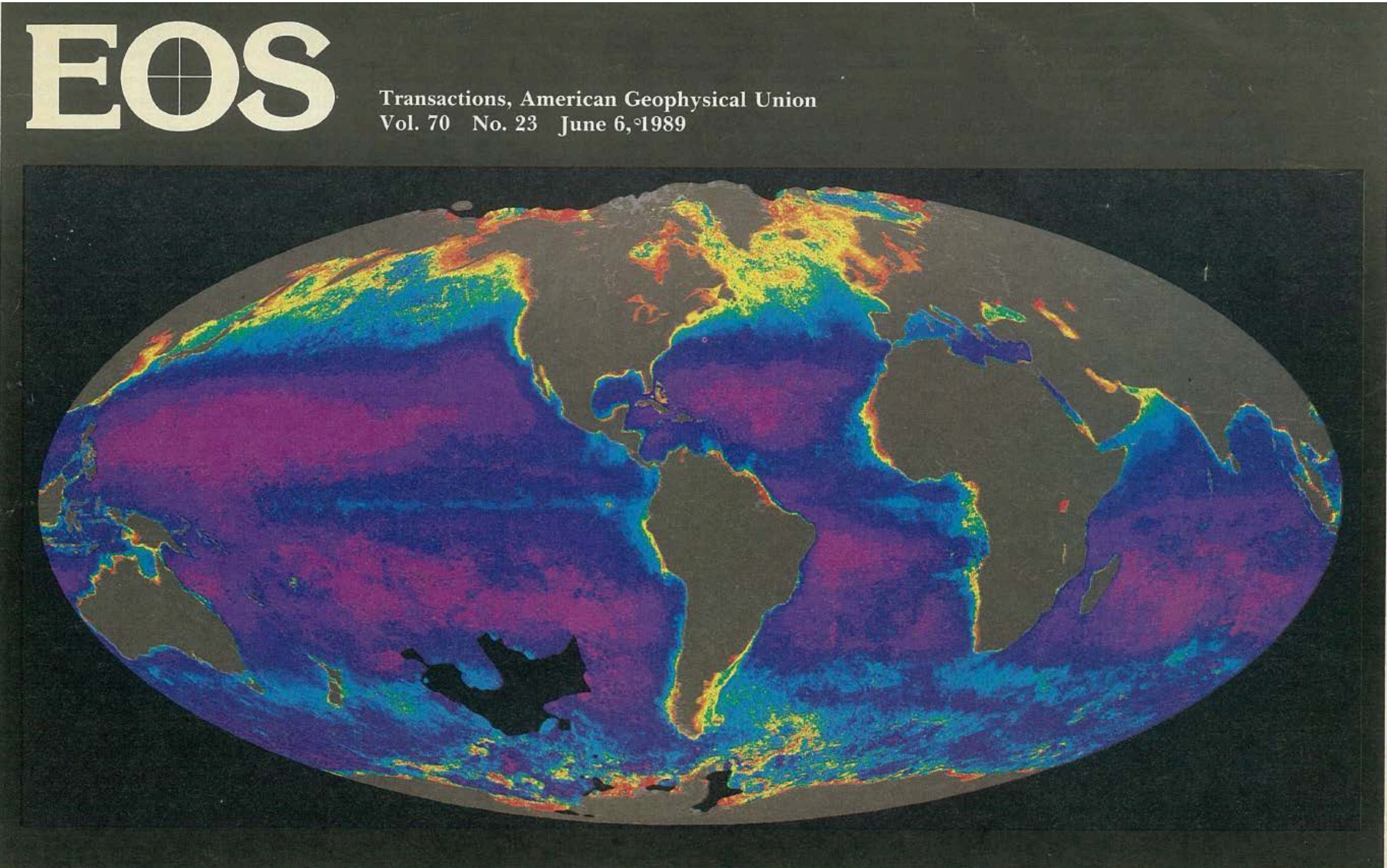


Fig. 3. Values of C = (Chl a + Phaeo a) (in milligrams per cubic meter) from Fig. 2 (14 November 1978) compared with a track line of concentrations measured aboard the R.V. *Athena II* on 13 and 14 November 1978. The track line is superimposed on Fig. 2, and distance (above) runs from south to north. 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



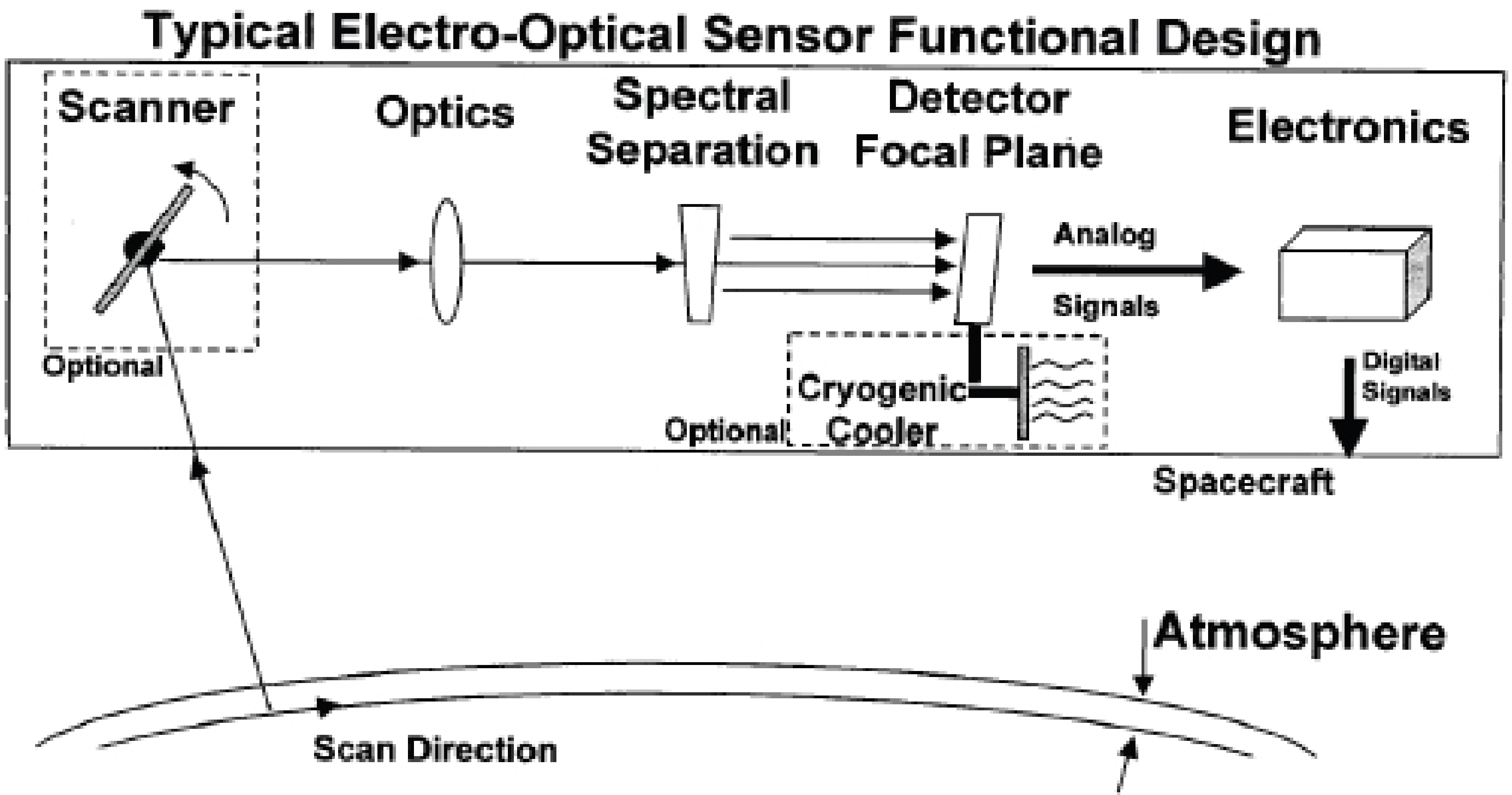
From: Feldman G.C., N. Kuring, C. Ng, W. Esaias, C. McClain, J. Elrod, N. Maynard, D. Endres, R. Evans, J. Brown, S. Walsh, M. Carle and G. Podesta, 1989. Ocean color : availability of the global data set. EOS, 70, 634.

What an "ocean colour sensor" does?

Steps to deliver OCR "imagery":

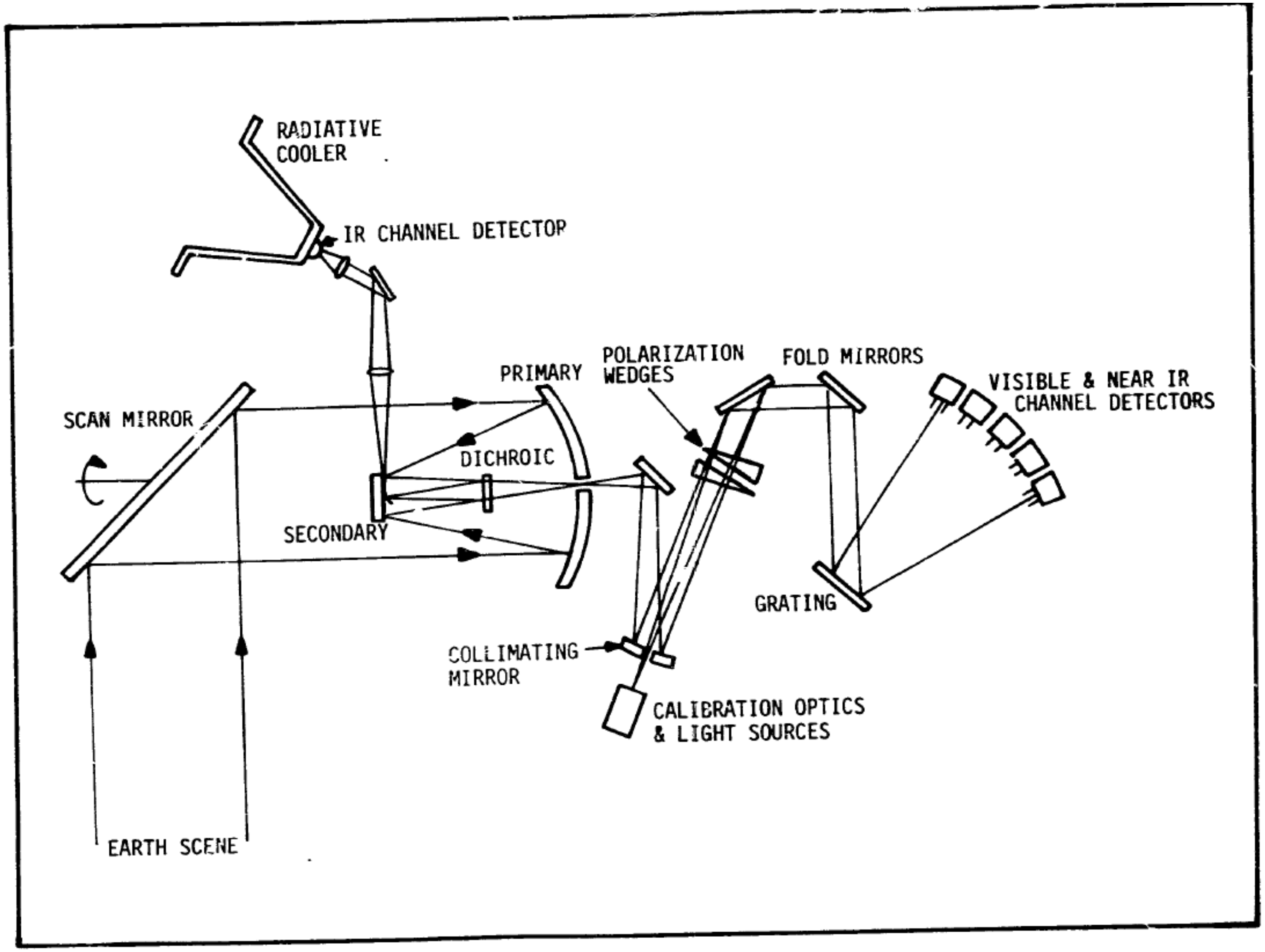
- Collecting light (photons): telescope, lenses, mirrors
- Making this insensitive to the polarisation state (within a few %): design, coatings, scramblers
- "Sorting" this in a number of spectral bands: filters, beam splitters, gratings
- Converting collected photons in an electric signal: detector(s)
- 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.

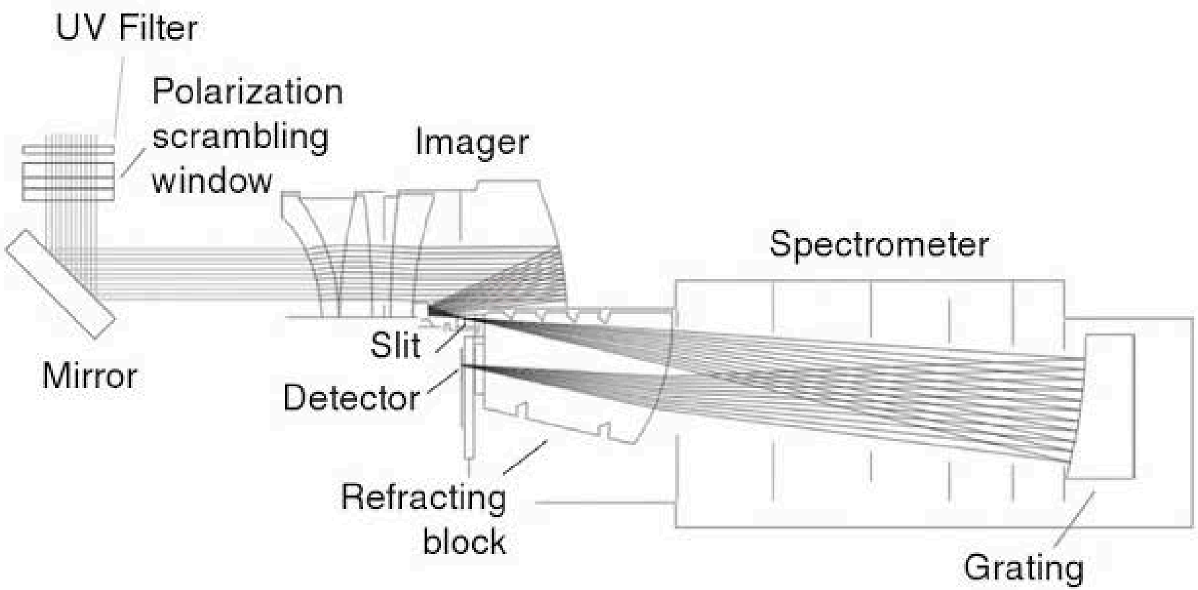
Example: the CZCS optical layout



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



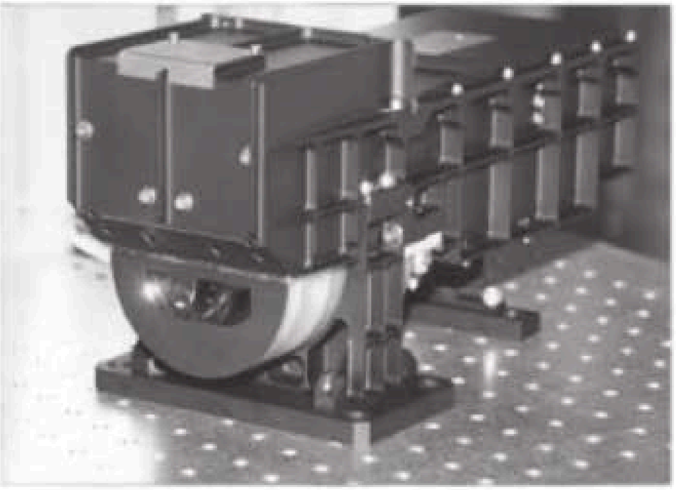


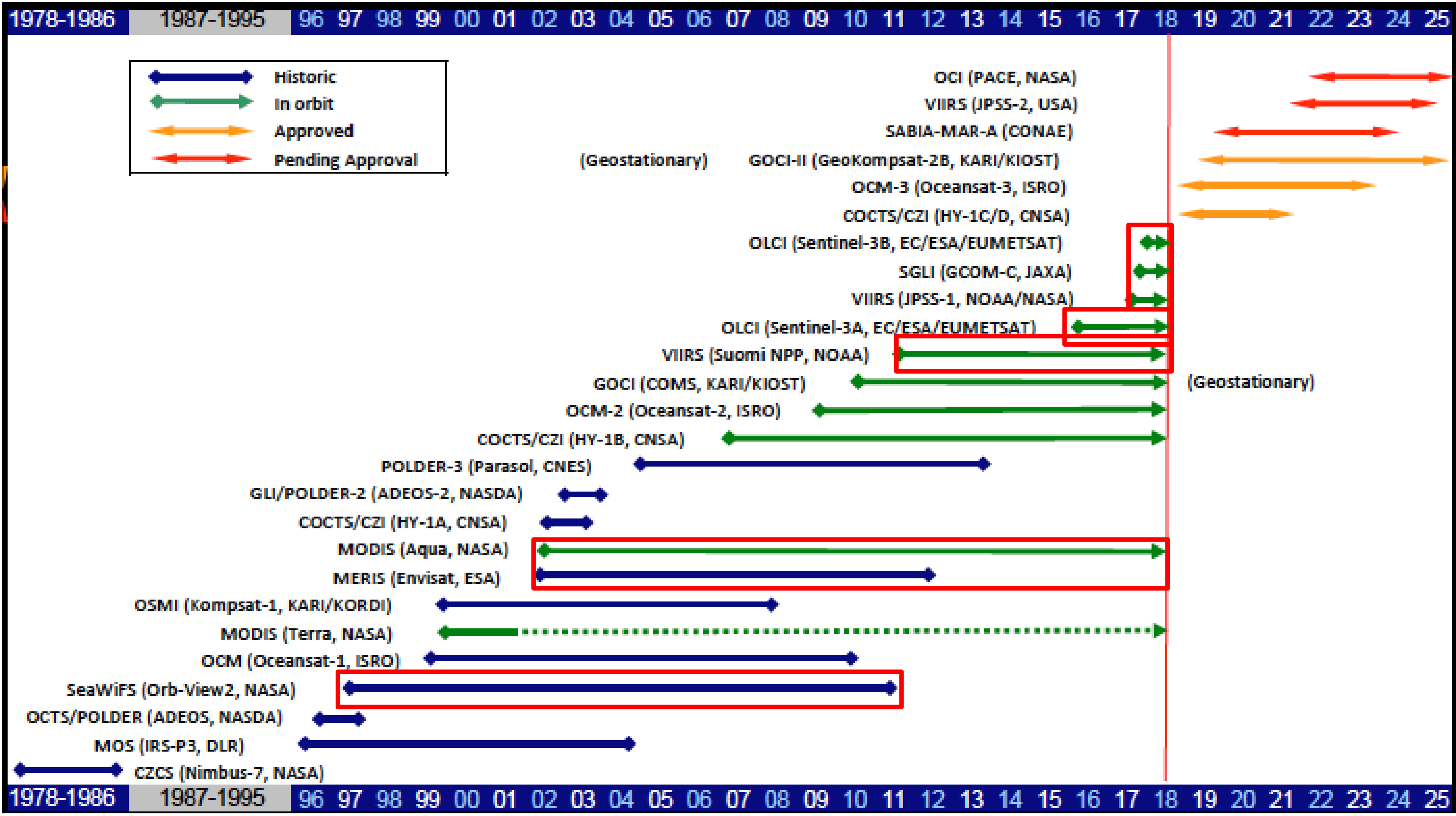
Figure 4.11 in: “Optical Payloads for Space Missions”, Shen-En Qian Ed., John Wiley & Sons, 26 Jan. 2016, 1008 pp.

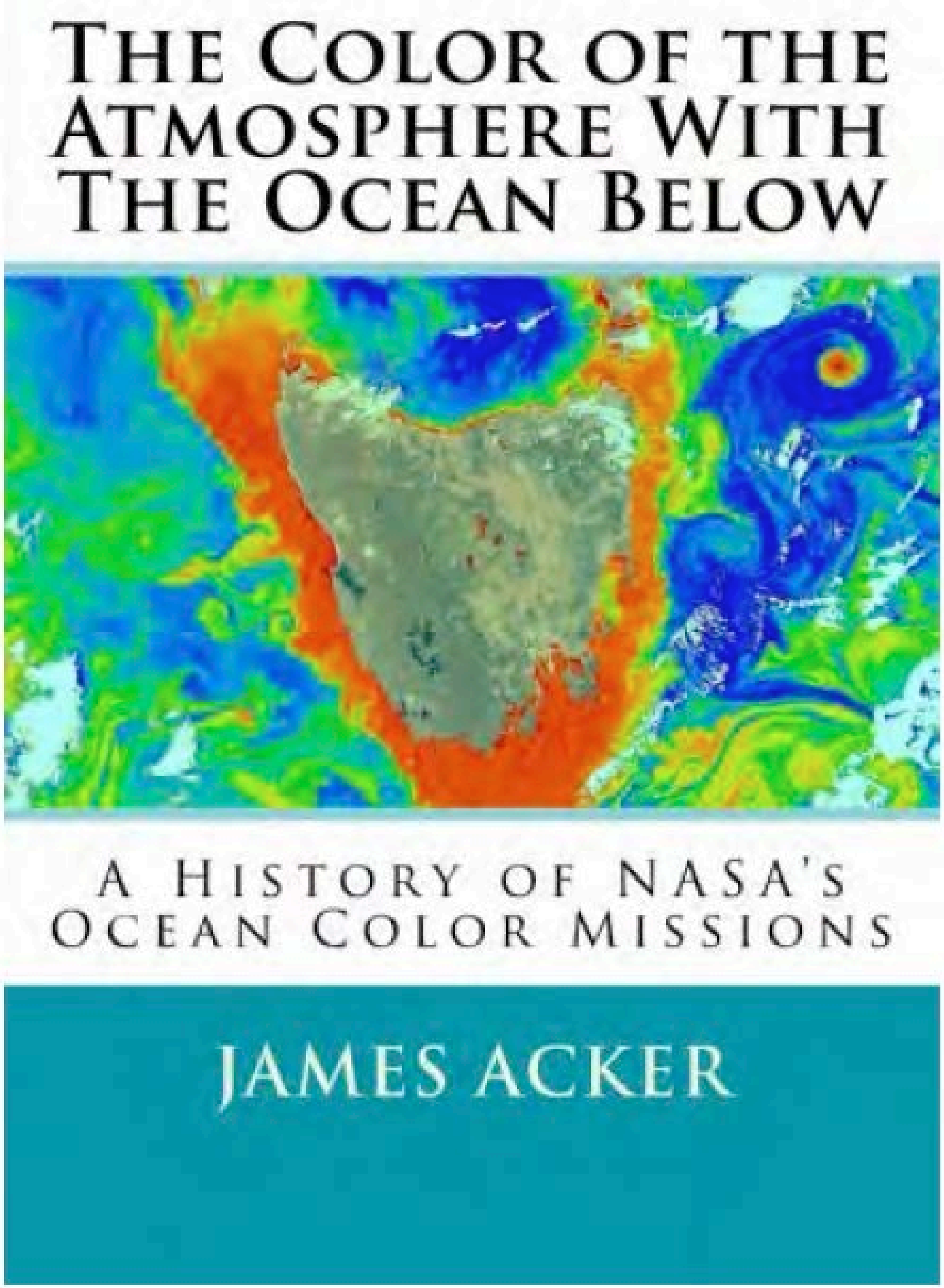
MERIS is a push-broom imaging spectrometer

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

What has happened since CZCS was launched?

Succinct history of passive satellite OCR





If you want to know it 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):

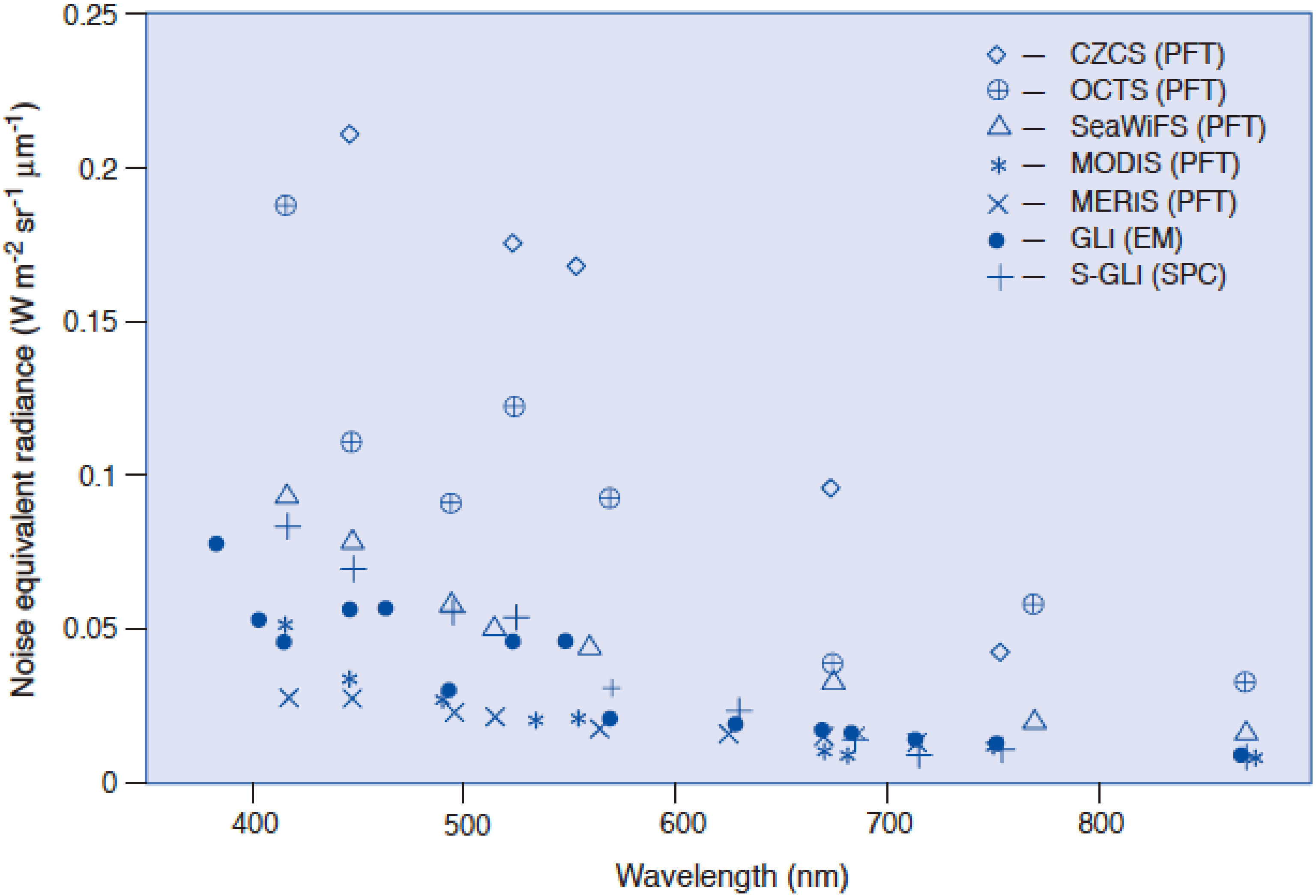
Technical/scientific rationale:

- 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)

More politically-driven:

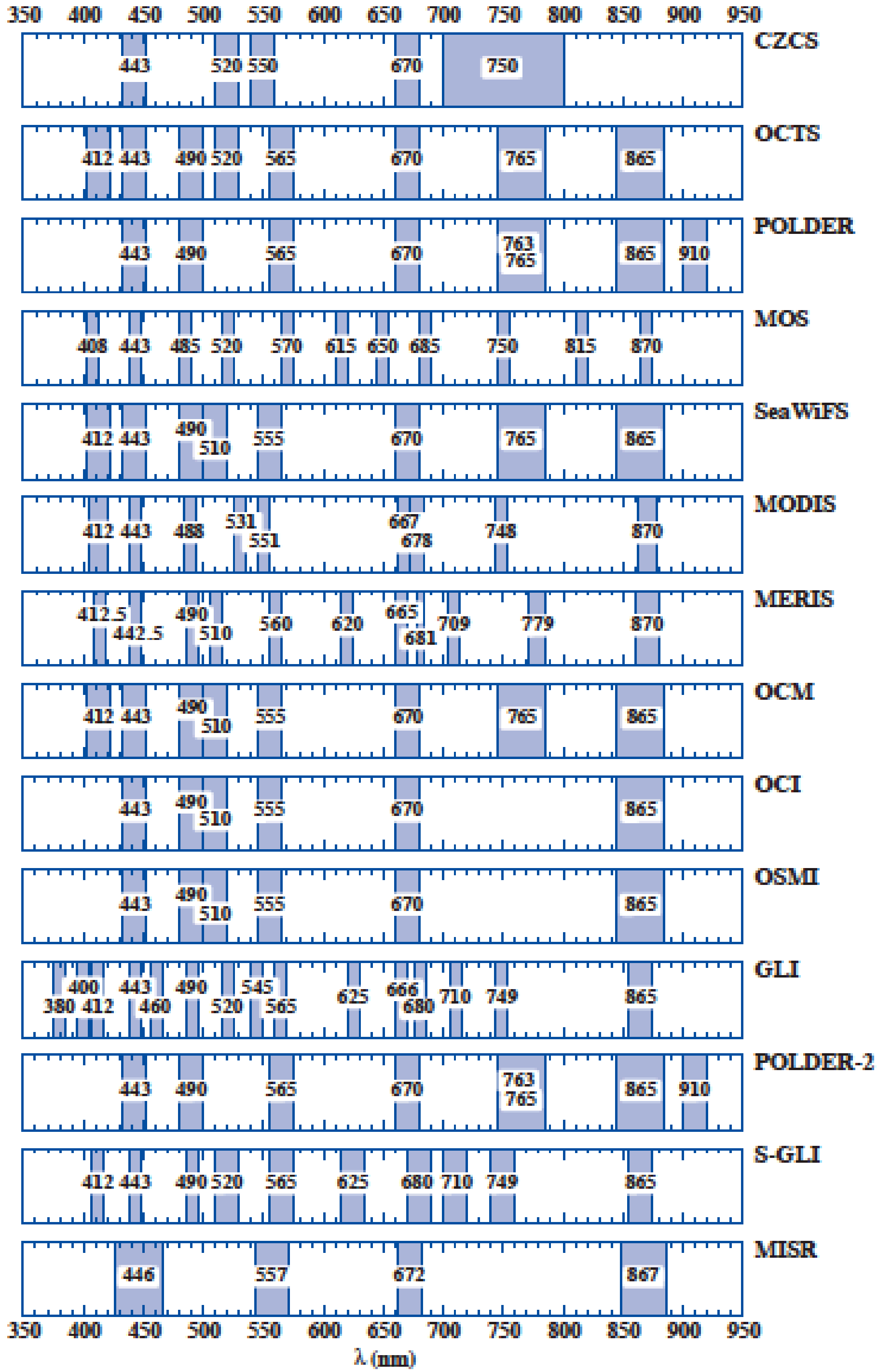
- Industry has to get contracts from Government / Space agencies to work.
- Countries want to demonstrate capability

Radiometric quality



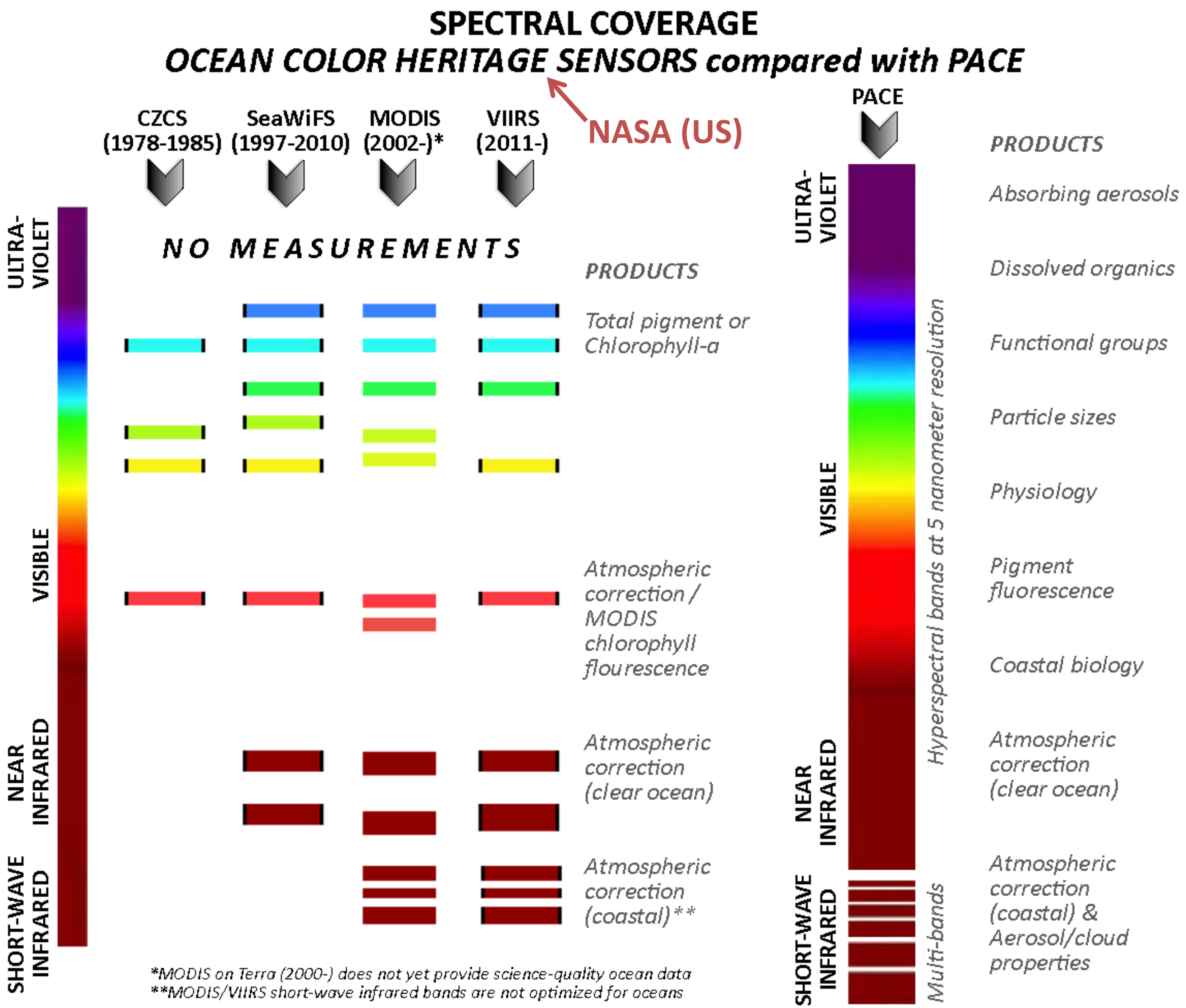
From: IOCCG, 1998, Minimum Requirements for an Operational, Ocean-Colour Sensor for the Open Ocean, André Morel (Ed.), Reports of the International Ocean-Colour Coordinating Group, No. 1, IOCCG, Dartmouth, Canada.

Spectral resolution



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



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

Spatial resolution

Not so much change here, at least if we consider “truly ocean” missions

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 not used, whose purpose was not initially ocean color however (later on in this lecture)

Calibration degradation: CZCS

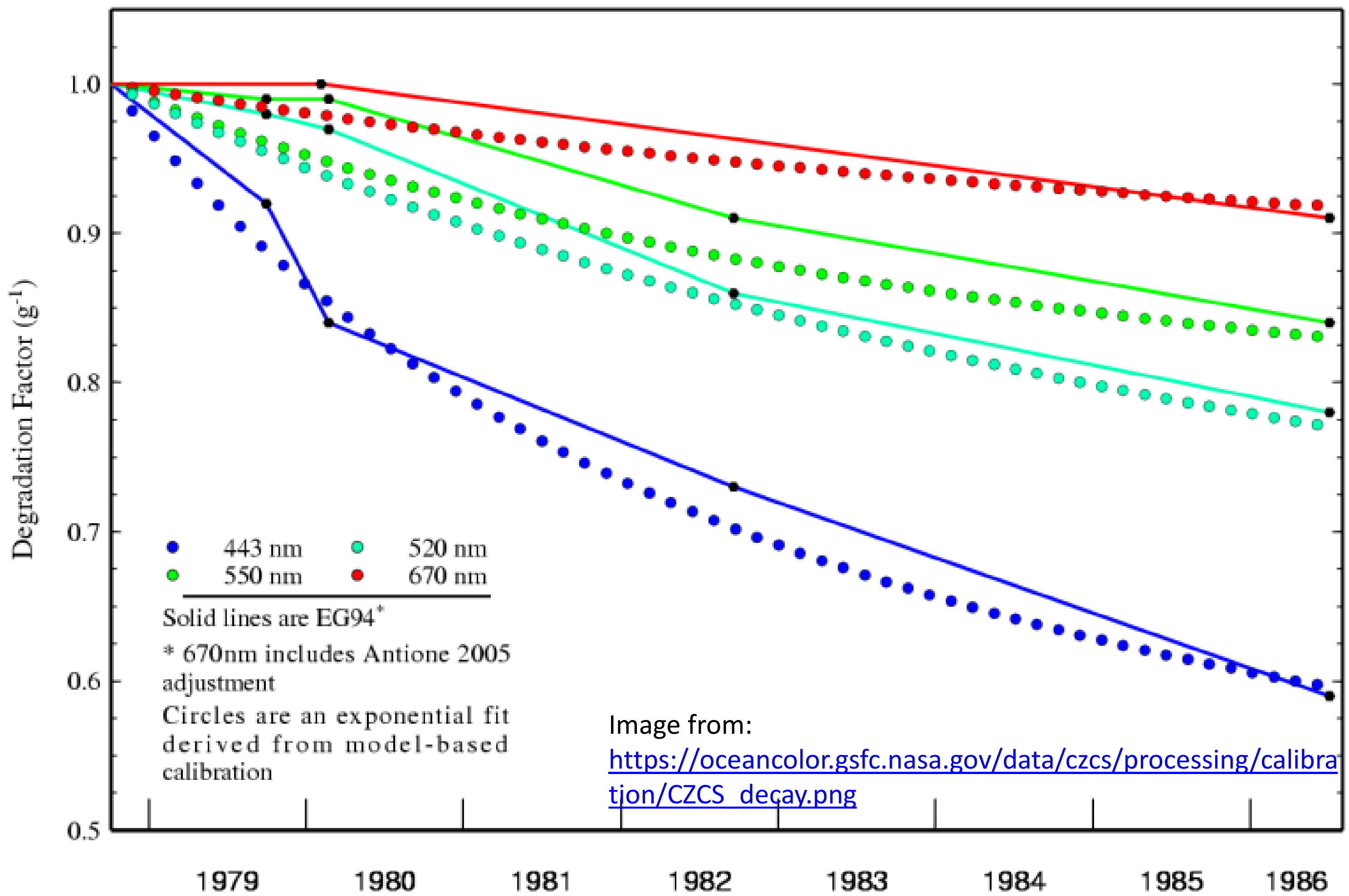
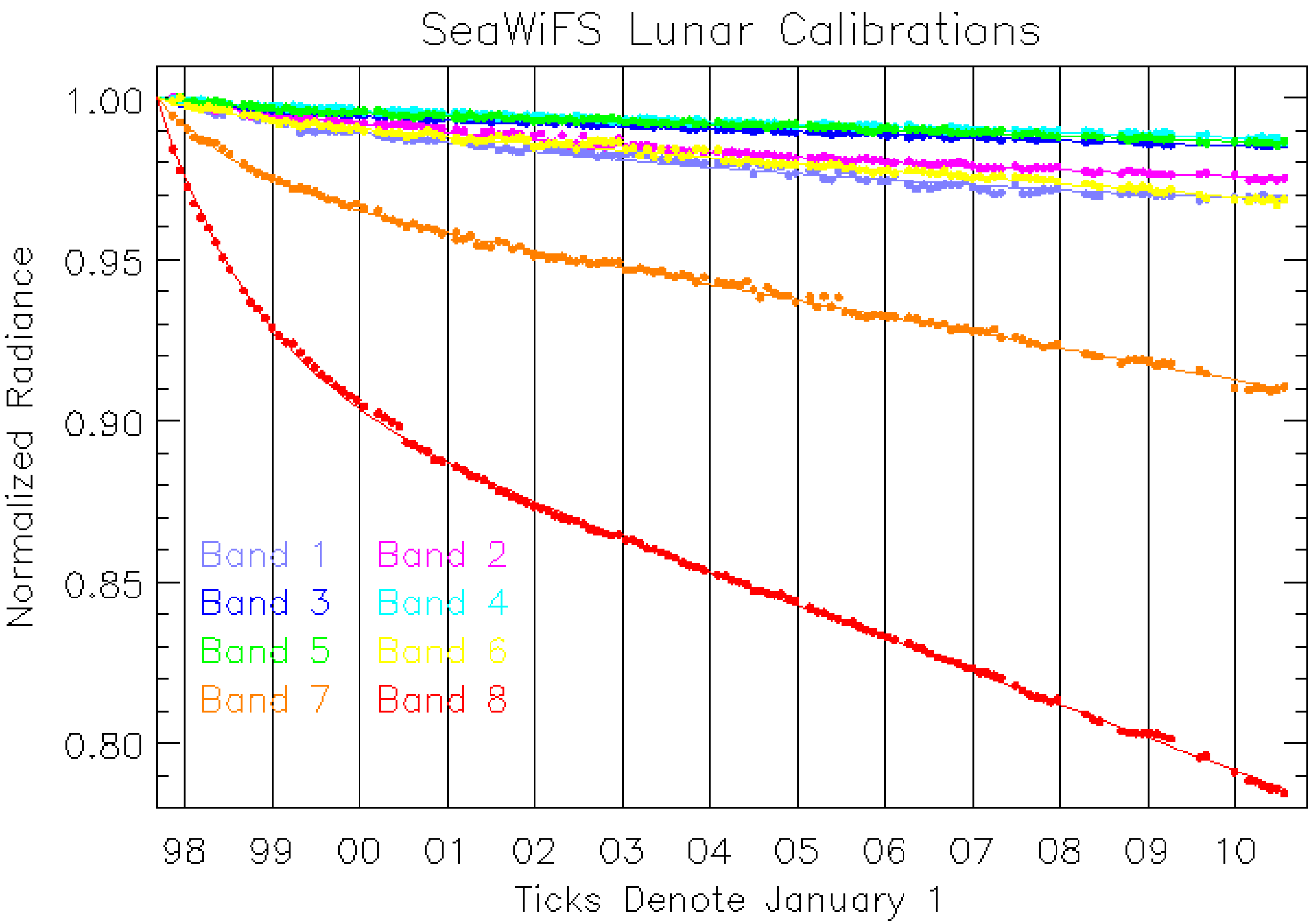


Image from:
https://oceancolor.gsfc.nasa.gov/data/czcs/processing/calibration/CZCS_decay.png

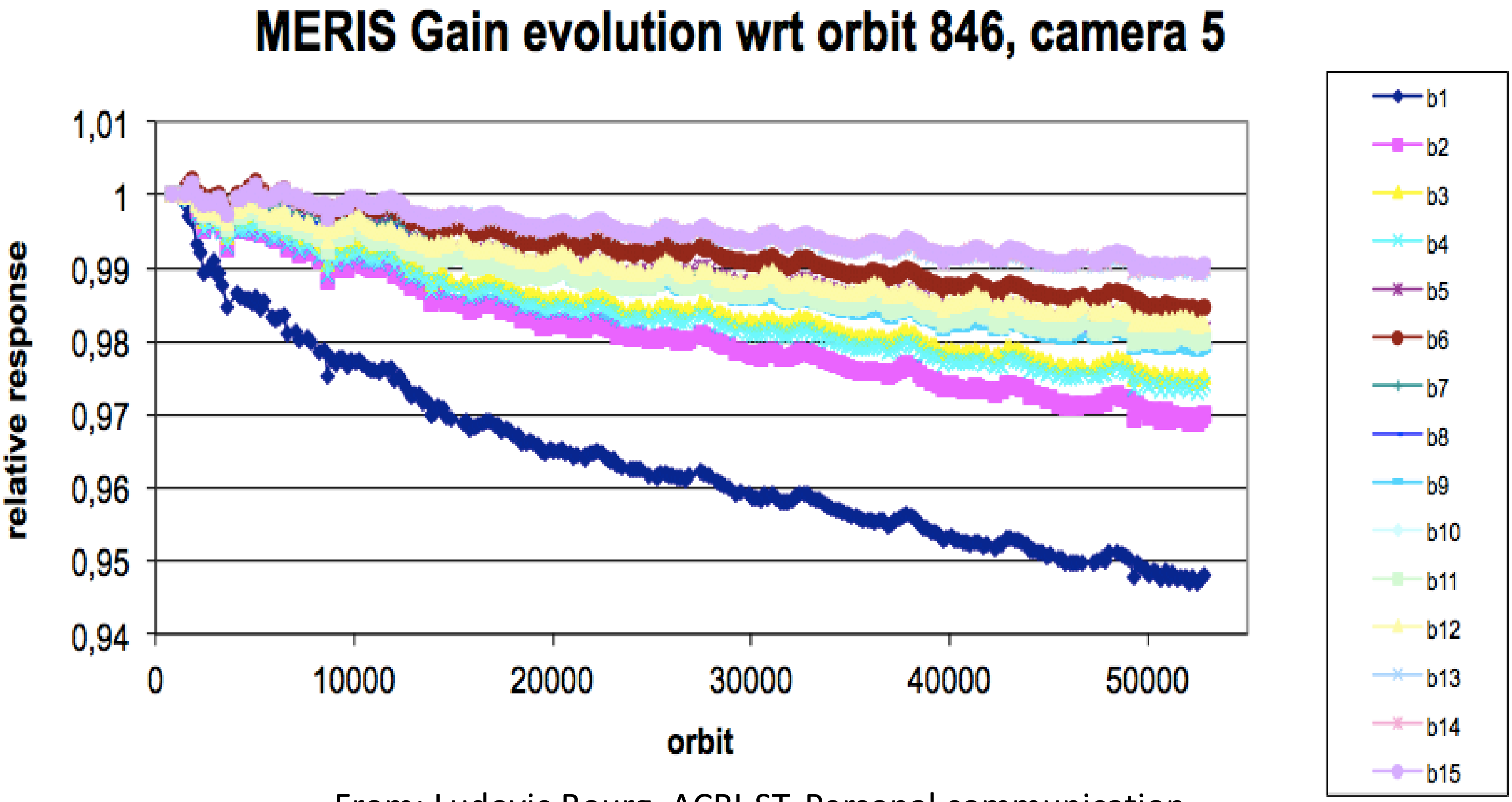
See: Evans, R. H., and H. R. Gordon, 1994. J. Geophys. Res., 99, 7293–7307.
And
Antoine, D., Morel, A., Gordon, H.R., Banzon, V.F. and R.H. Evans, 2005. Journal of Geophysical Research, VOL. 110, C06009, doi:10.1029/2004JC002620

Calibration degradation: SeaWiFS



From https://oceancolor.gsfc.nasa.gov/reprocessing/r2009/seawifs/

Calibration degradation: MERIS



From: Ludovic Bourg, ACRI-ST, Personal communication

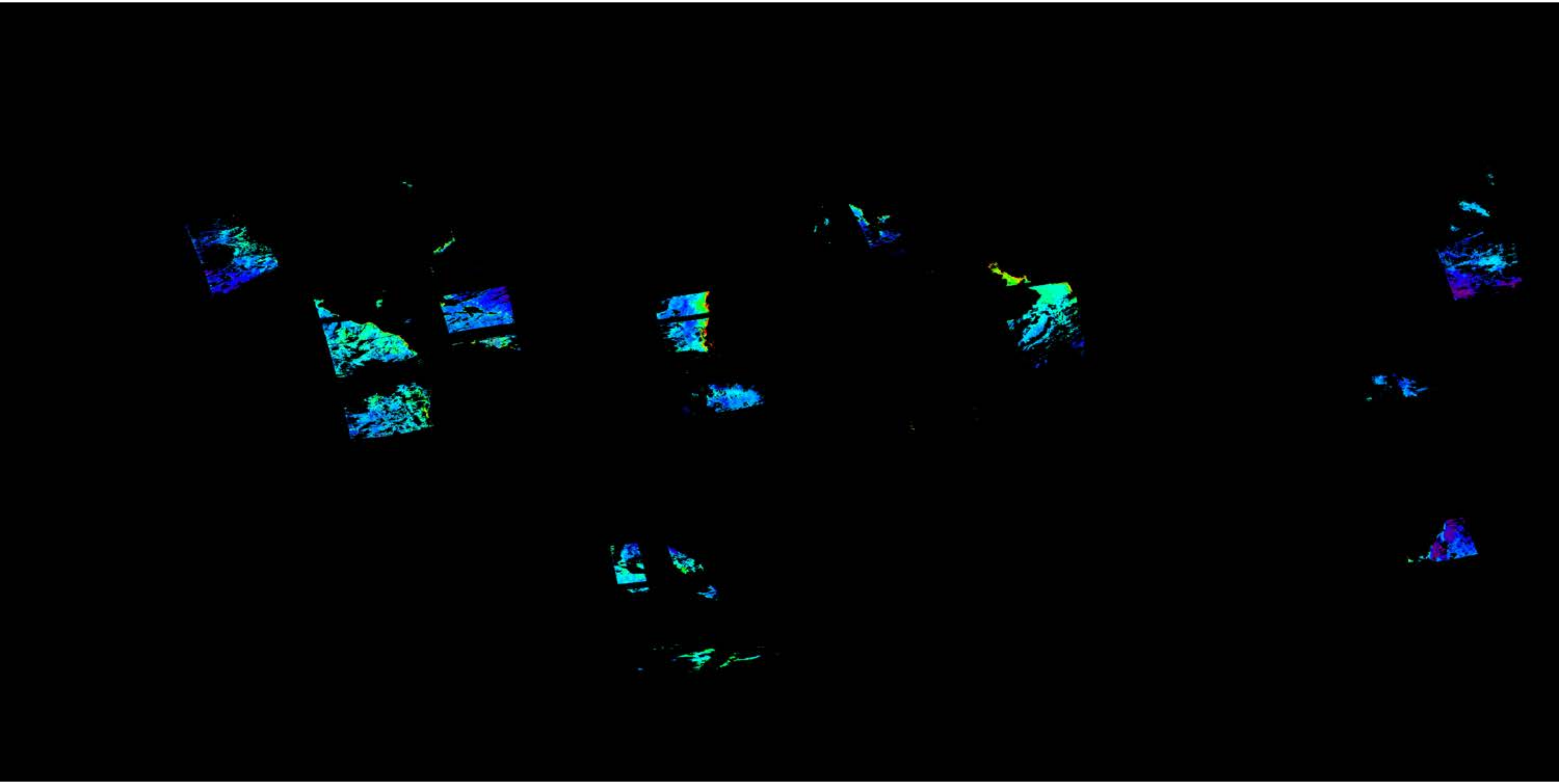
System Vicarious Calibration

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, ±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 Lw as accurately as possible, add the atmospheric signal on top of it, and compare to the measured total signal at the "top of atmosphere" evel (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: that's not addressing the temporal degradation issue

Global data sets

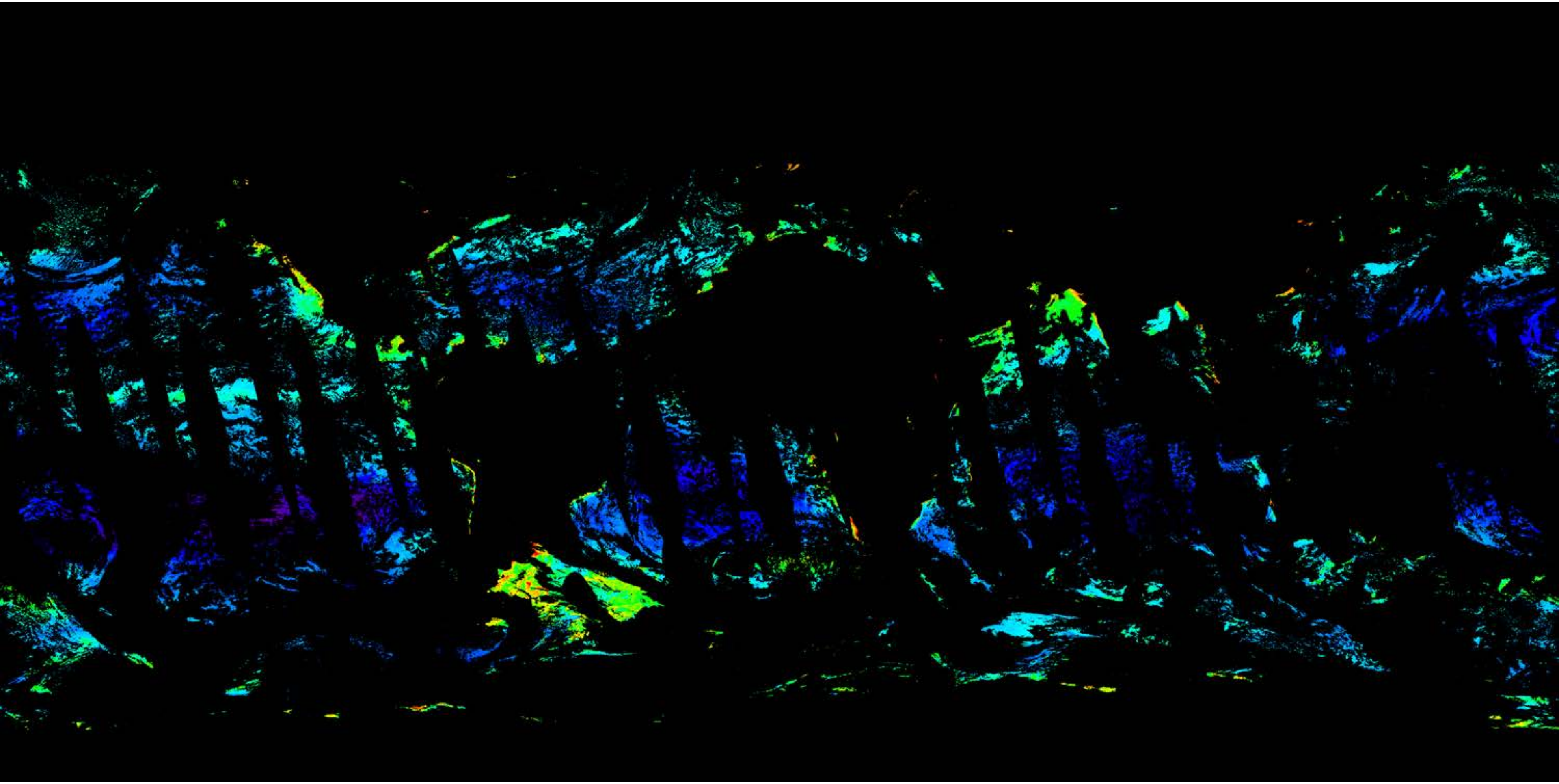
Going from intermittent to systematic sampling



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

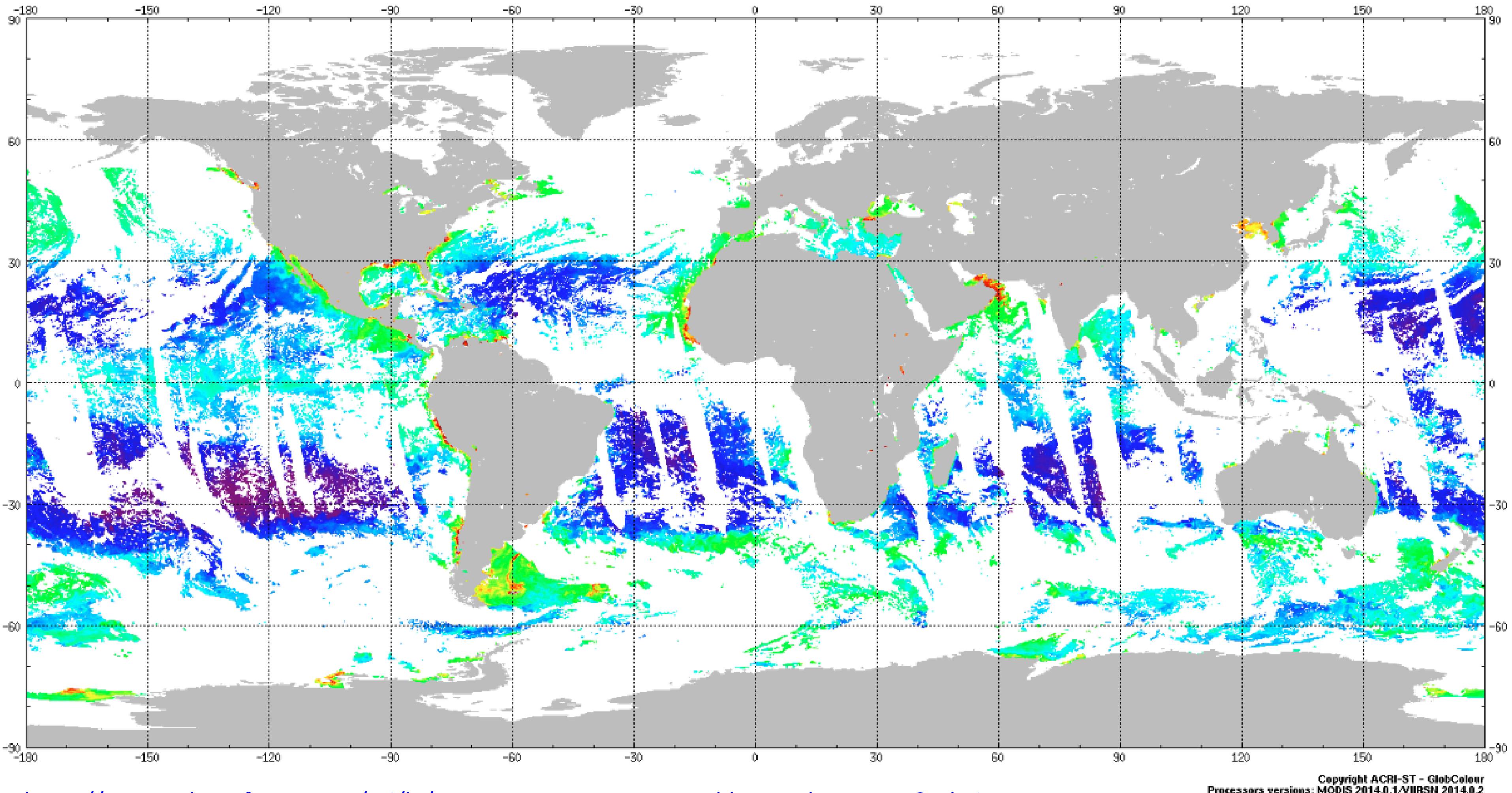


https://oceancolor.gsfc.nasa.gov/cgi/l3/C1979032.L3m_DAY_CHL_chl_ocx_9km.nc.png?sub=img

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

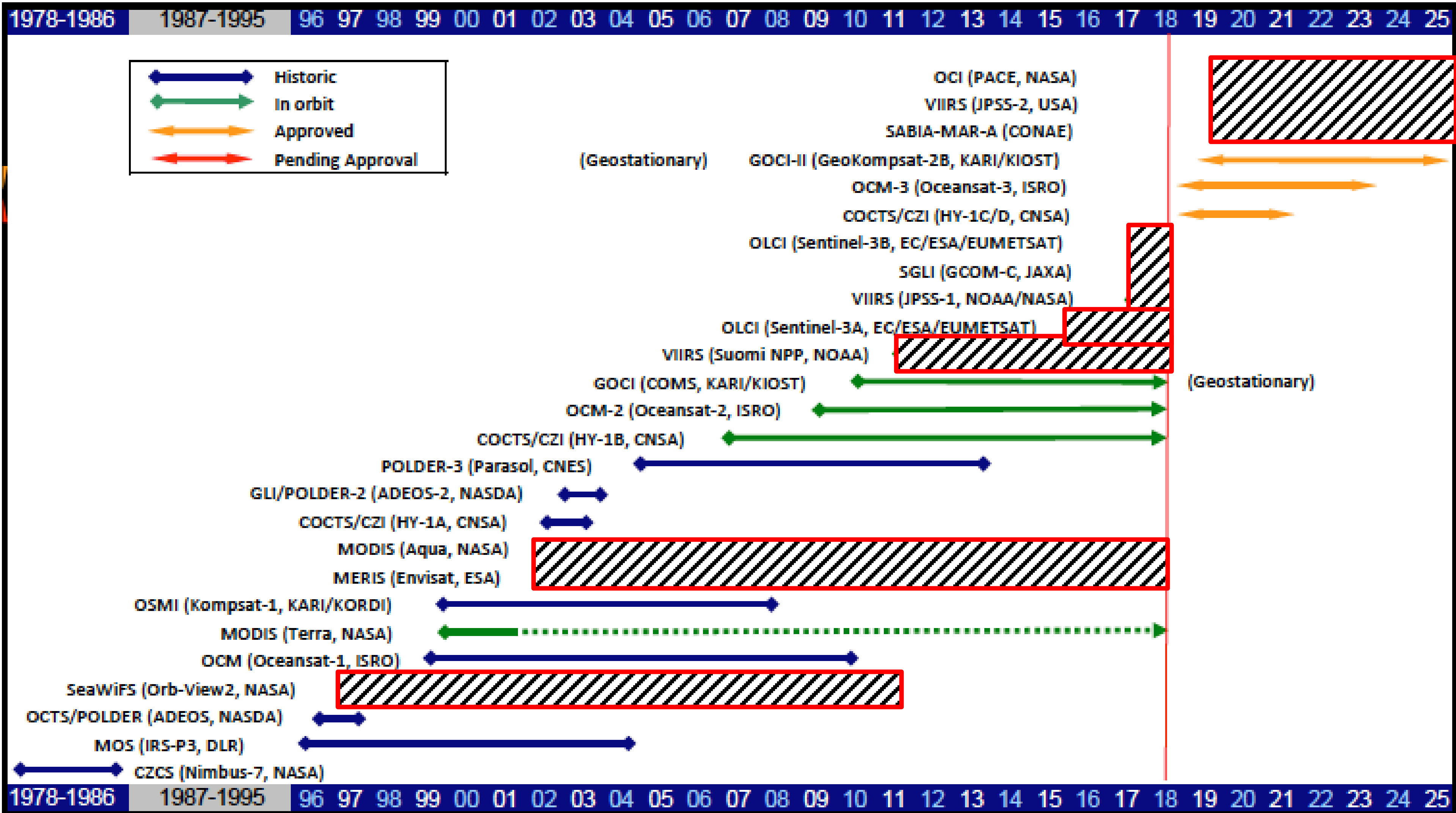
http://hermes.acri.fr/images/data/GLOB/merged/day/2017/02/01/L3m_20170201__GLOB_25_AVW-MODVIR_CHL1_DAY_00.png

What the future is made of?

What the future is made of?

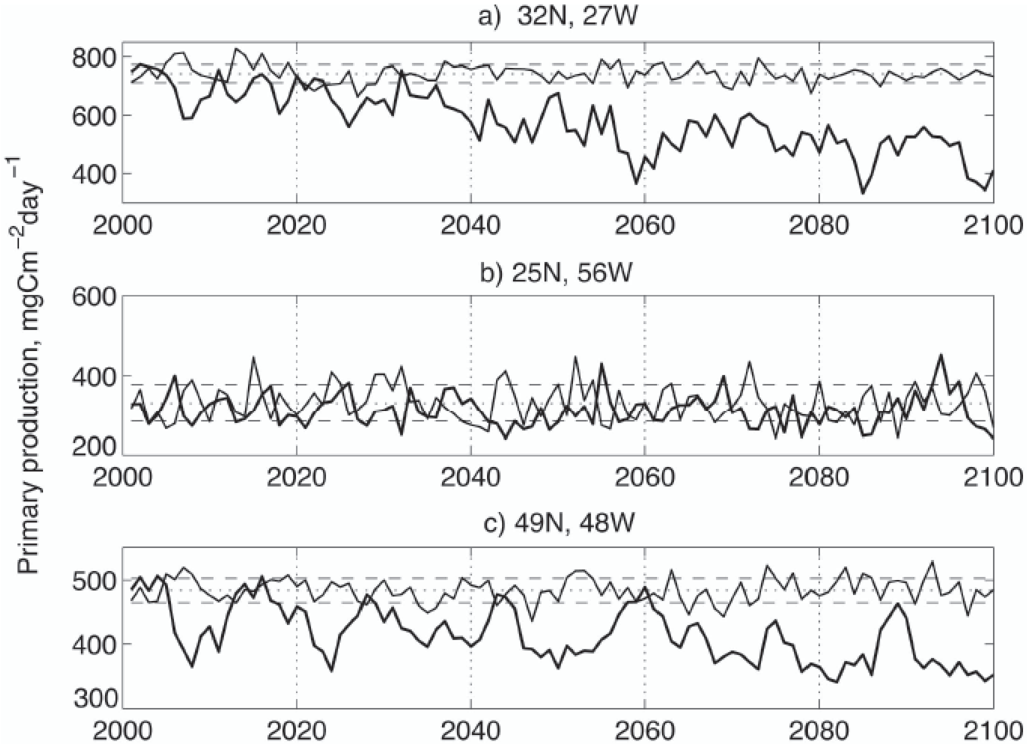
1) A bit more of the same

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.

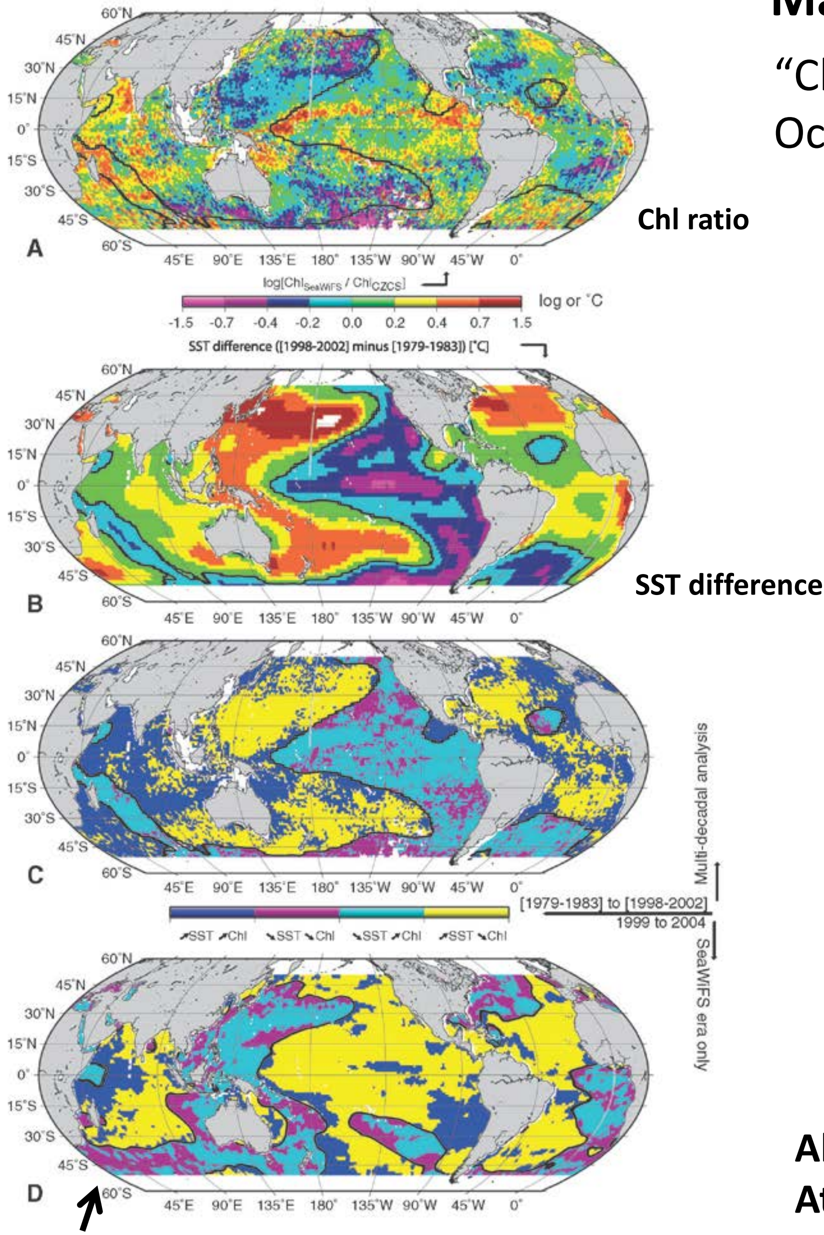
•Thus, **recent observed changes** in chlorophyll, primary production and the size of the oligotrophic gyres **cannot be unequivocally attributed to the impact of global climate change**.

•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**.

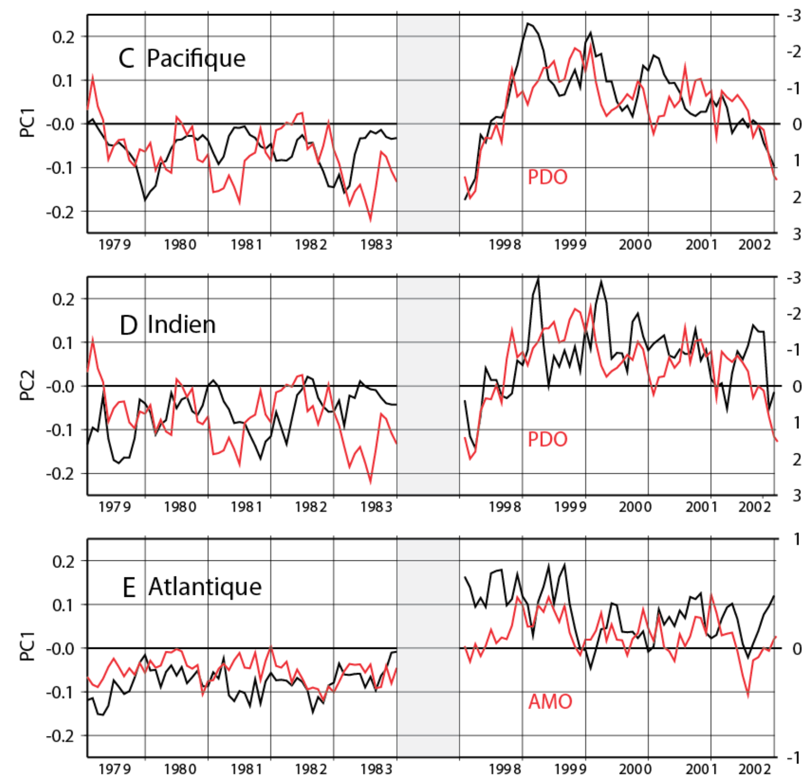
•Because the magnitude of natural variability in chlorophyll and primary production is larger than, or similar to, the global warming trend, **a consistent, decades-long data record must be established** if the impact of climate change on ocean productivity is to be definitively detected

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

"Climate-Driven Basin-Scale Decadal Oscillations of Oceanic Phytoplankton"



Behrenfeld et al., 2006, Nature



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

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

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

Global, multi-mission data sets

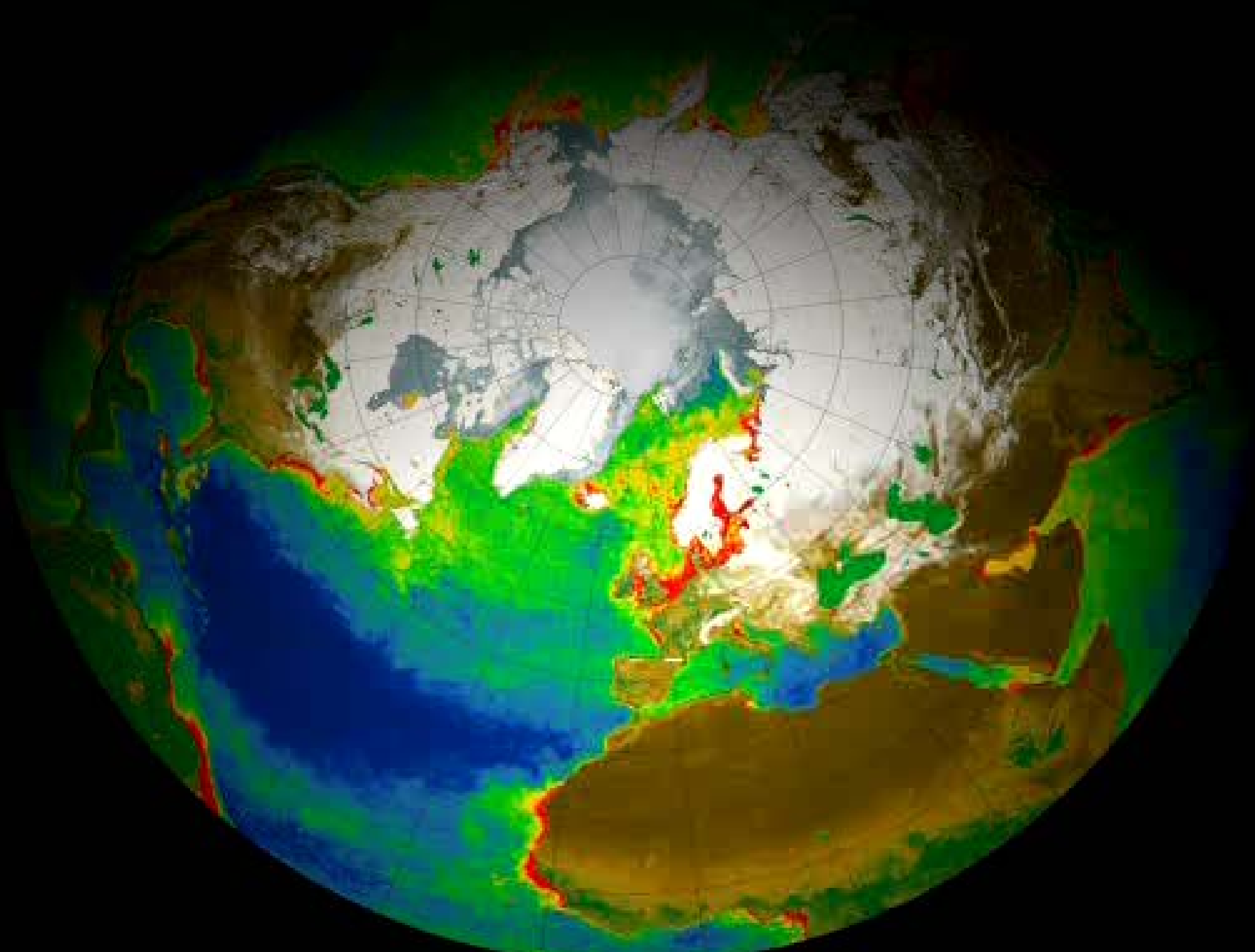
- The ESA Ocean Colour Climate Change Initiative (OC-CCI)

  http://www.esa-oceancolour-cci.org

  http://www.esa-oceancolour-cci.org/?q=products%20description

- The GlobCOLOUR data set (http://globcolour.info)
- The NASA's Ocean Biology Processing Group (OBPG)

  https://oceancolor.gsfc.nasa.gov



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

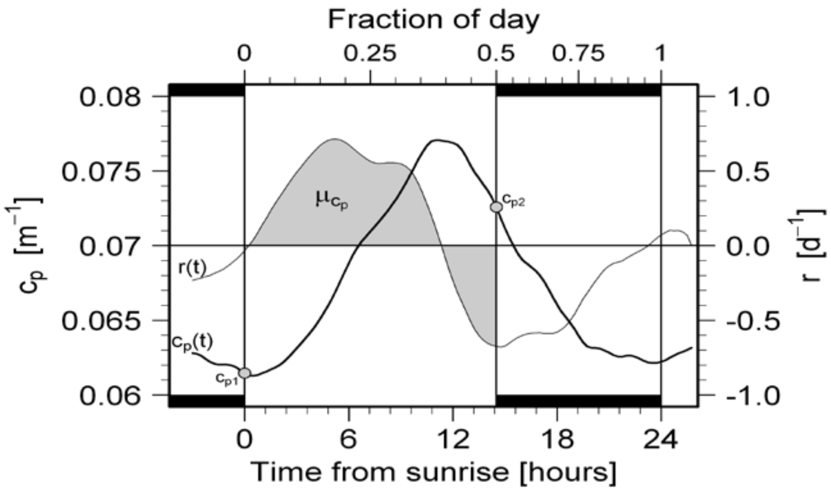
Advantages of the GEO orbit

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

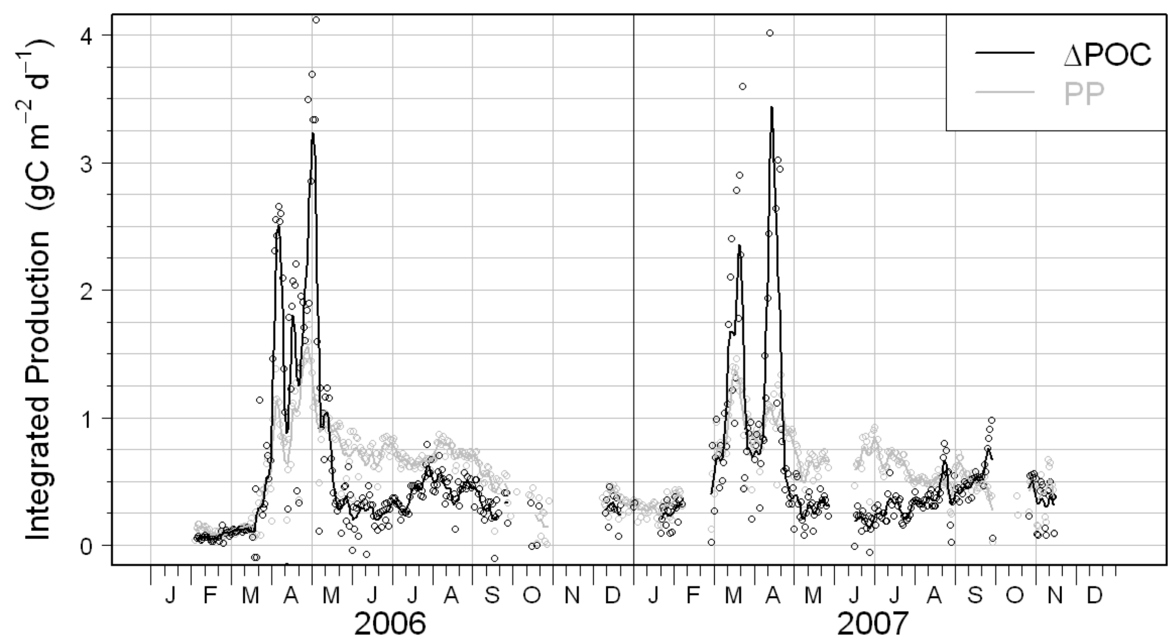
Diurnal cycles of ocean properties



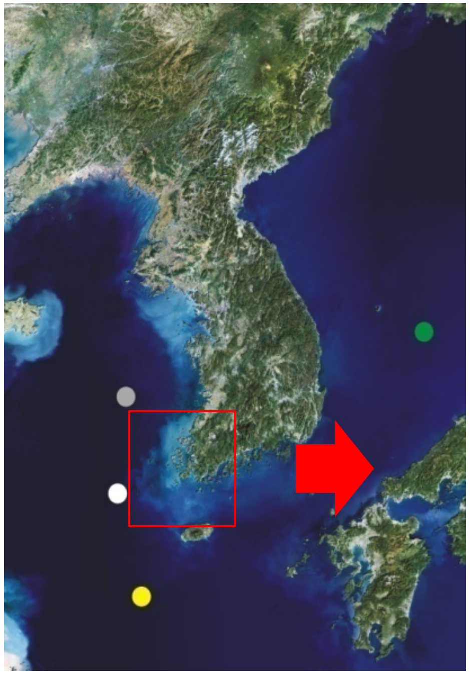
Possible to go from Δc_p to ΔPOC.
After integration over the productive layer, one gets an estimate of "primary production"

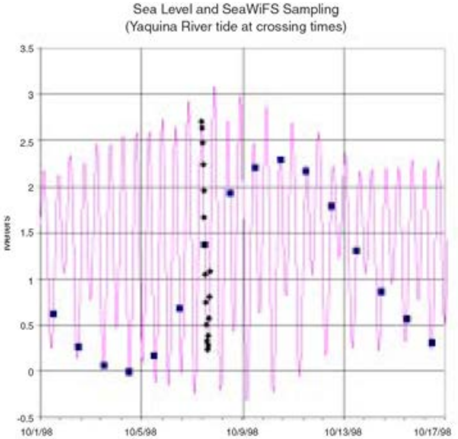
From Gernez, Antoine and Huot, 2011, L&O, 56, 17-36

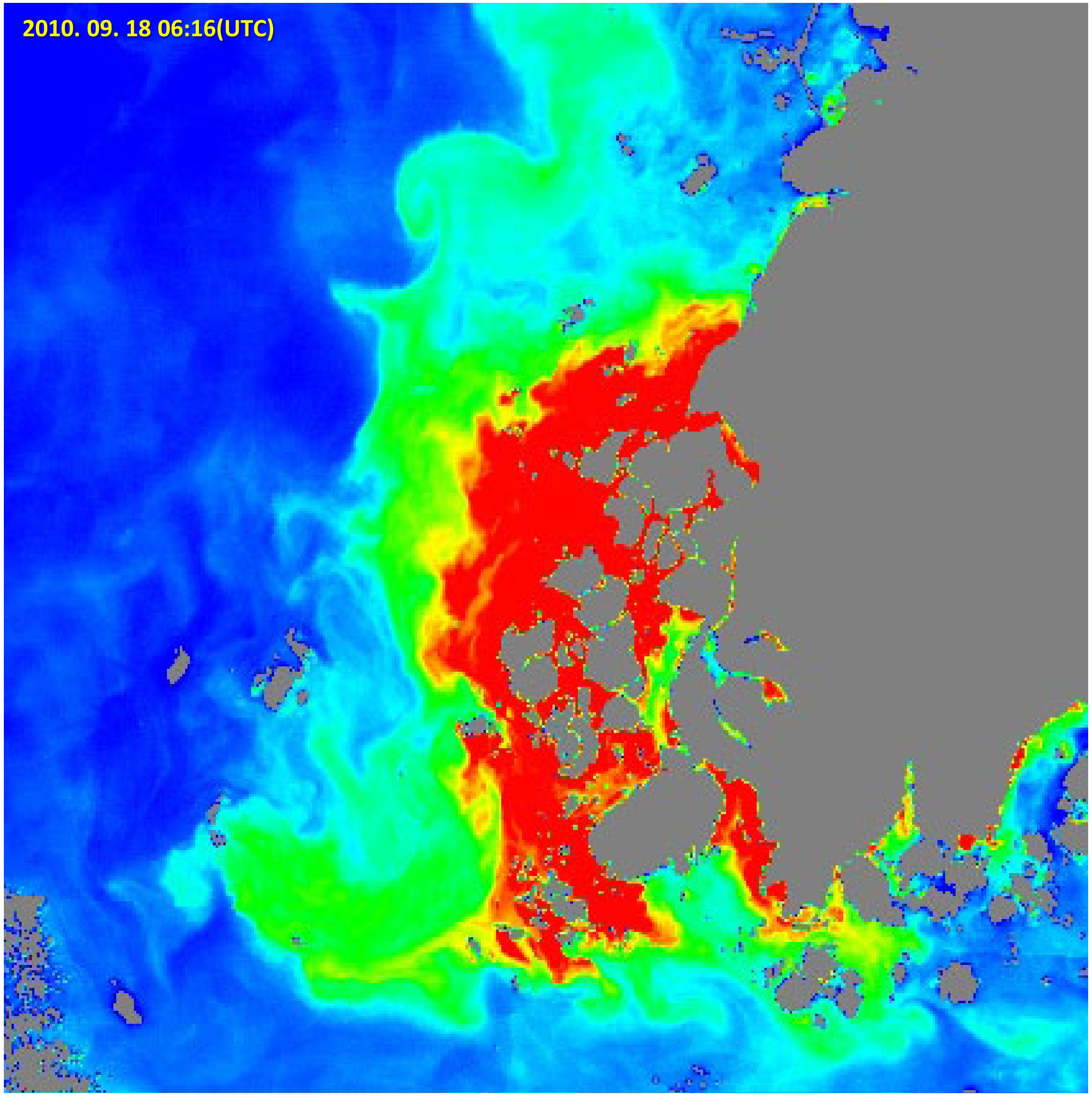
Can be potentially used to derive ocean primary production



Advantages of the GEO orbit







Courtesy from Joo-Hyung Ryu, KIOST

Advantages of the GEO orbit

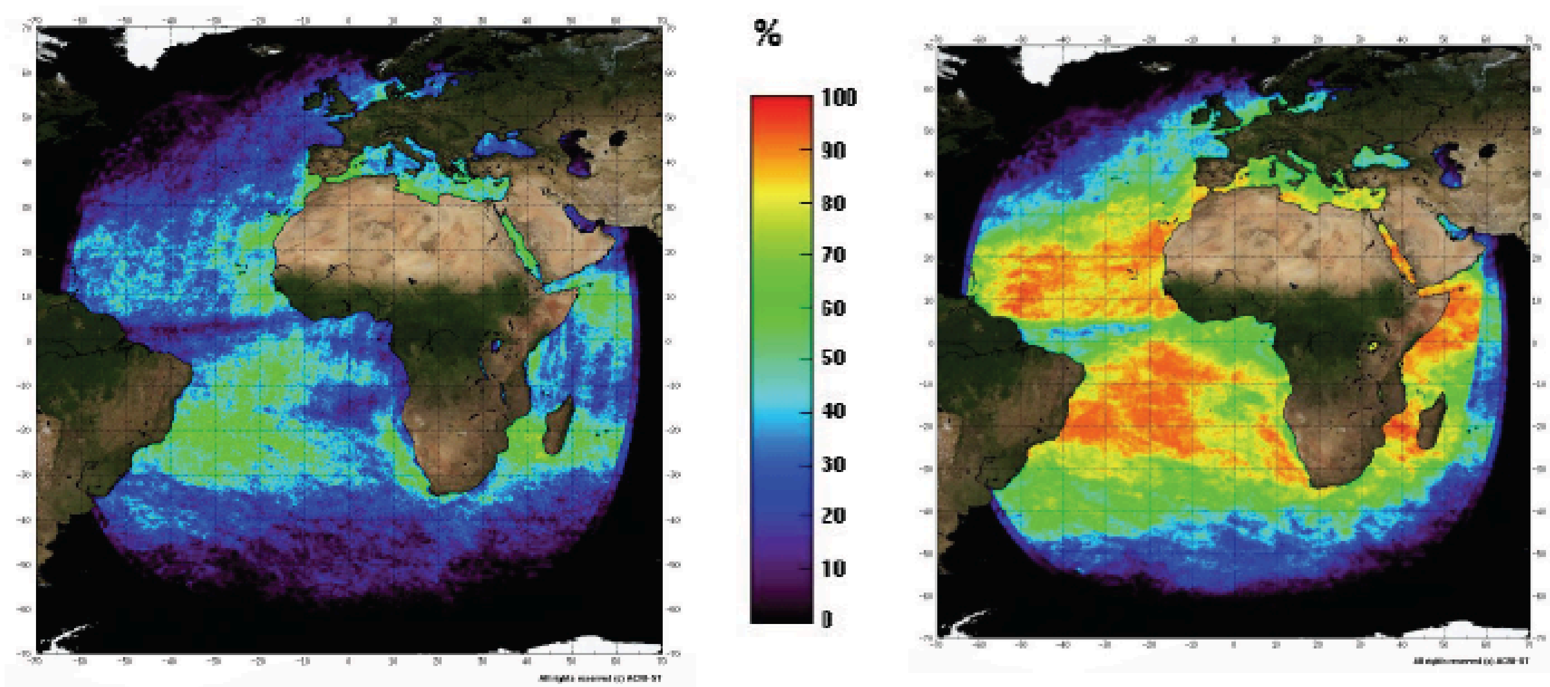


Figure A.1.3. 1 Example of monthly data availability in March for two mission configurations: constellation of two Sentinel-3 alone (left), and complemented by a GEO with 1 hour revisit (right). A realistic cloud coverage is taken into account (MSG data for year 2007) as well as geometrical constraints (air mass < 5, glint reflectance smaller than 5 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

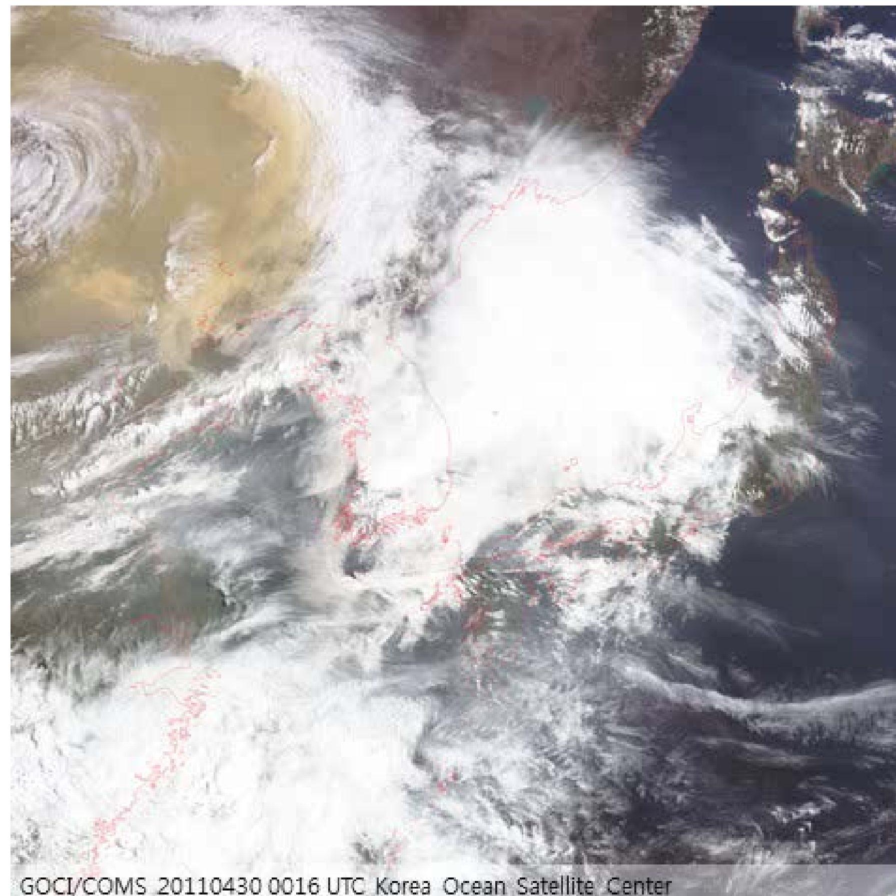
→ High latitudes are not covered

→ Other challenges are more of a "political" nature: launching to the GEO orbit is expensive.

OCR from the GEO orbit

Do we have plans?

There is already one OCR sensor on a GEO orbit: the Korean "Geostationary Ocean Colour Instrument" (**GOCI**)



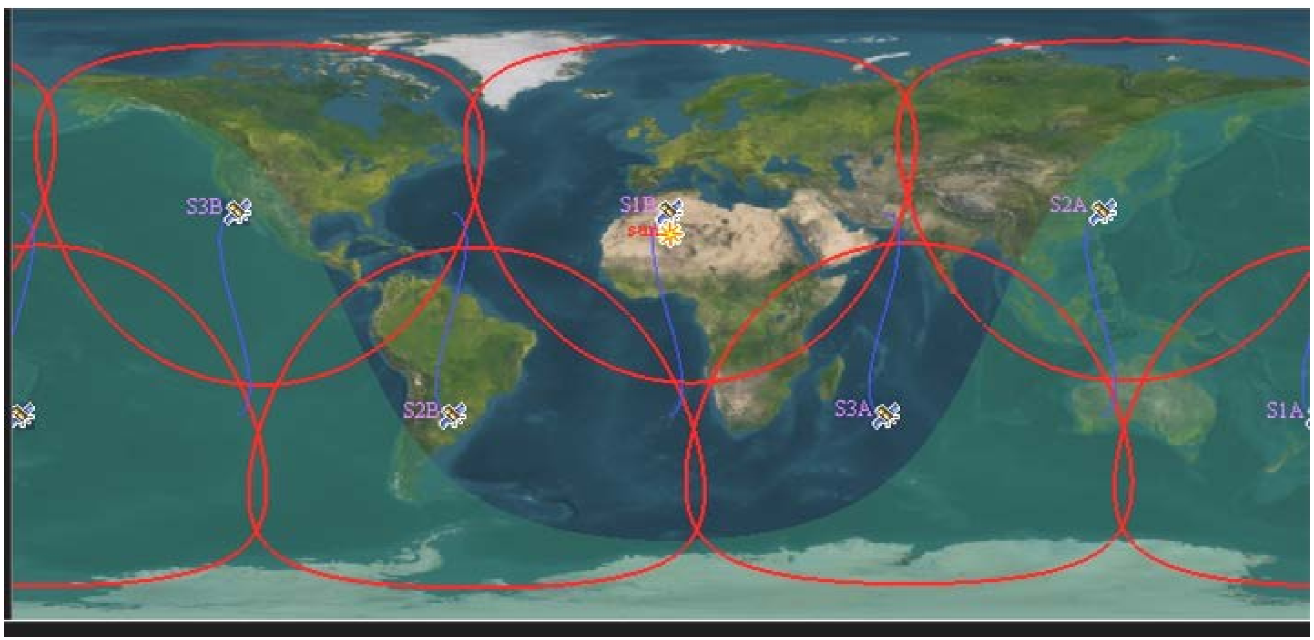
OCR from the GEO orbit

Do we have plans?

GeoKompsat 2B	KARI/KIOST (South Korea)	GOCI-II	March 2019	1200 x 1500 TBD	250/1000	13	412 - 1240 TBD	Geostationary
GISAT-1	ISRO (India)	HYSI-VNIR	* (planned)	250	320	60	400-870	Geostationary (35.786 km) at 93.5°E
GEO-CAPE	NASA	Coastal Ocean Color Imaging Spec (Name TBD)	>2022	TBD	250 - 375	155 TBD	340-2160	Geostationary

Highly uncertain fate, actually

From http://ioccg.org/resources/missions-instruments/scheduled-ocean-colour-sensors/



From the 2016 “GeOCAPI” mission proposal to ESA. © LOV, CNES

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)

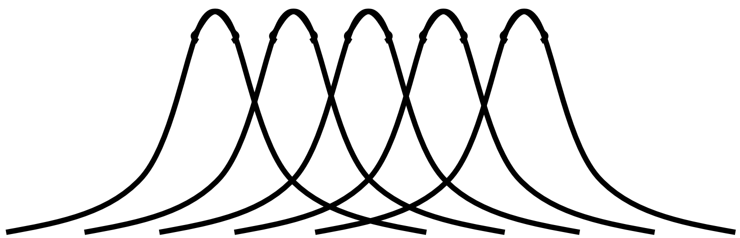
Report of an IOCCG working group on Ocean-Colour Observations from a Geostationary Orbit, chaired by David Antoine, and based on contributions from (in alphabetical order):

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: Venetia Stuart

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



→ 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

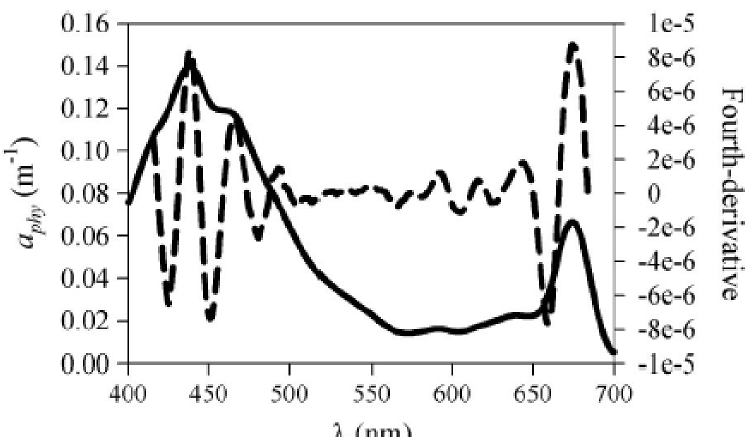
→ Instruments have to be designed in such a way that radiance is measured from the near UV to the near IR with, e.g., a 3nm resolution. Need a spectro-radiometer. That's actually what MERIS was and what OLCI is (only a subset of bands is aggregated and transmitted to ground, however).

What the future is made of?
3) Going hyperspectral

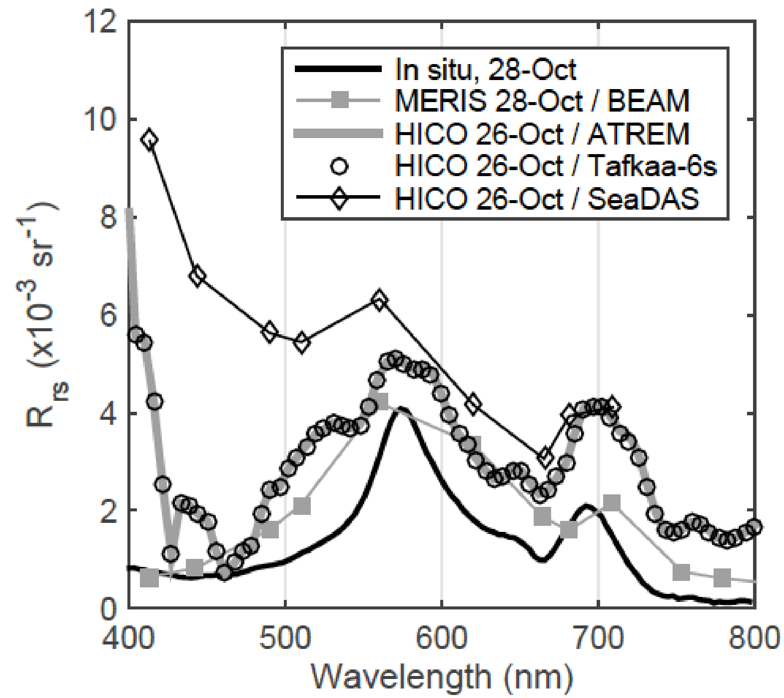
→ Going hyperspectral is an attempt to solve ill-posed problems by bringing more (supposedly) independent observations

→ Typical problems that are tackled with hyperspectral RS:

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



Organelli, E. , A. Bricaud, D. Antoine and J. Uitz, 2013. *Applied Optics*, 52, 2257-2273.



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

HICO	ONR, DOD and NASA	JEM-EF Int. Space Stn.	18/09/09 - 4/12/14	50 km Selected coastal scenes	100	124	380 - 1000	51.6o, 15.8 orbits p/d

http://hico.coas.oregonstate.edu

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

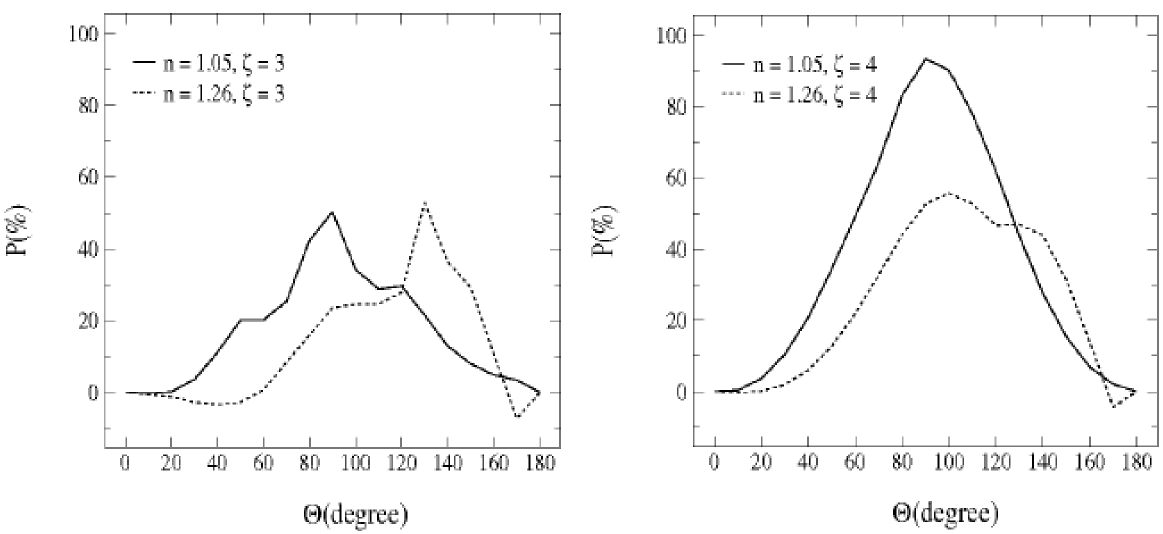
https://pace.gsfc.nasa.gov

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)

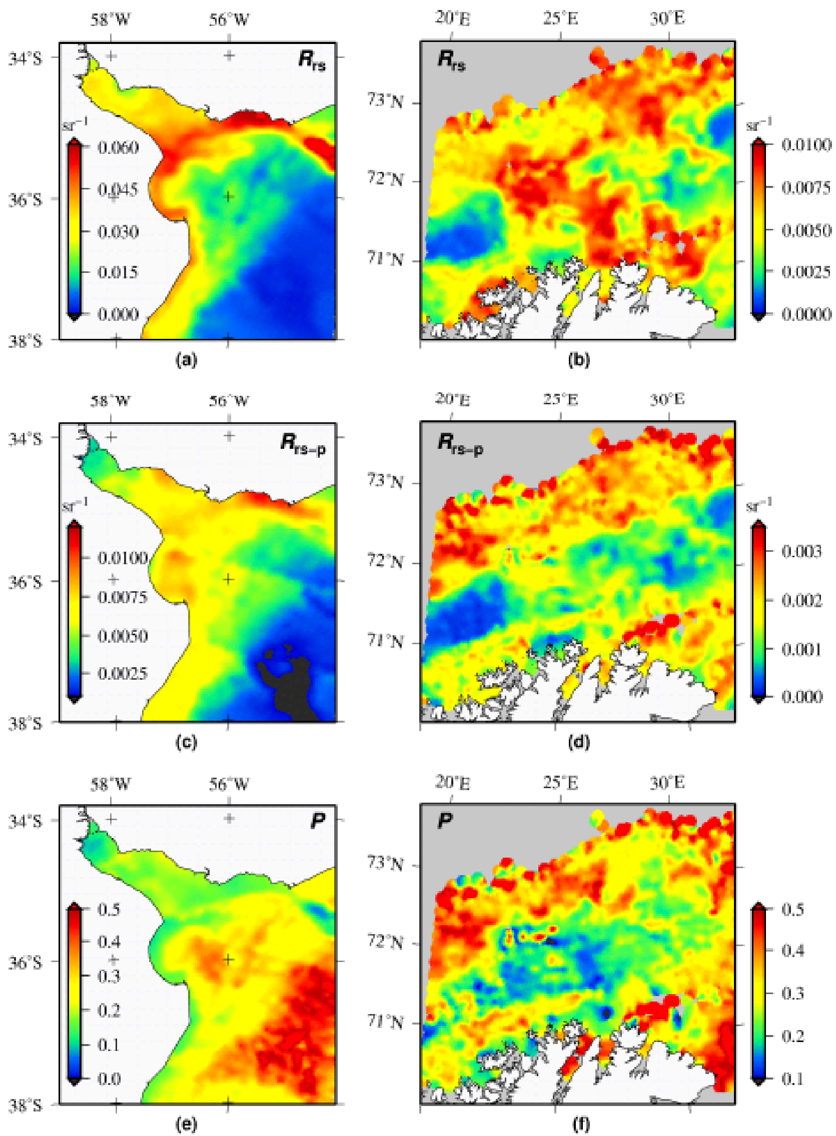


From Loisel et al., 2008, Optics Express, 16(17), 12905-12918

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

Polarisation:

Rio de La Plata | Barentz Sea



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

Using POLDER observations

Past / current / future sensors with a polarisation capability

Past:

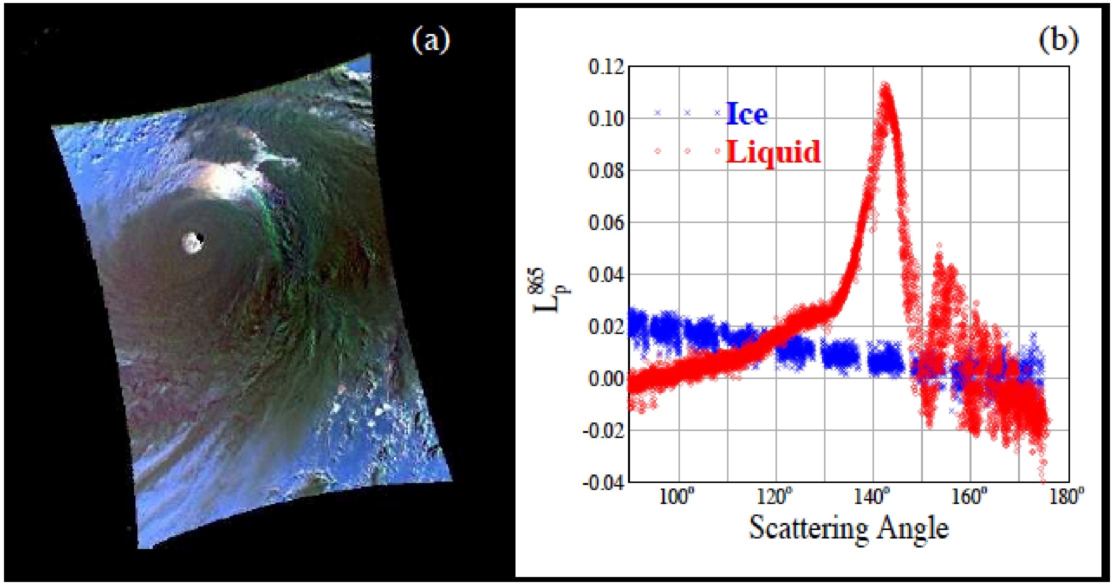
- POLDER 1, 2, 3 (CNES)
- MISR (NASA)

Present:

- S-GLI (JAXA)

Future

- 3MI (EUMETSAT)
- PACE (NASA)



POLDER observations used for cloud studies.
From Riedi et al., 2010. Atmos. Chem. Phys., 10, 11851–11865, doi:10.5194/acp-10-11851-2010

The 2018 AGU Fall Meeting will be held from 10-14 December 2018 in Washington, D.C.

Session ID: 44332
Session Title: OS002. Advancing the use of multi-angle polarimetry for ocean-color remote-sensing applications

Session Description: Satellite ocean color revolutionized our understanding of Earth's oceans. Ocean color utilizes the intensity and spectral variation of light scattered upward from beneath the ocean surface to derive optical properties and constituent concentrations. Contemporary ocean color radiometers rely on scalar treatment of light, thus neglecting its polarization components. Polarized light carries information that is currently underutilized in ocean color. Multi-angle polarimeters have been successful in improving our understanding of aerosol and cloud properties, and several satellite missions are planned to host advanced multi-angle polarimeters - including NASA's Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) mission. With the increasing availability of airborne and satellite polarimeters, and recent advancements in technology, radiative transfer, and in-situ systems, it is time to fully assess the value of multi-angle polarimetry for ocean color applications. This session will showcase results that contribute to this assessment. Papers highlighting airborne, satellite, in-situ, and radiative transfer analyses are welcome.

Conveners: Jeremy Werdell (NASA GSFC), Paula Bontempi (NASA HQ), Bryan Franz (NASA GSFC), and Amir Ibrahim (NASA GSFC)

What the future is made of?

5) Satellite-borne LIDARs

- Passive ocean colour allows accessing a signal whose 90% comes from depths < ~$1/K_d$ (Gordon and McLuney, 1975)
- In the clearest waters, this is about 20m 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

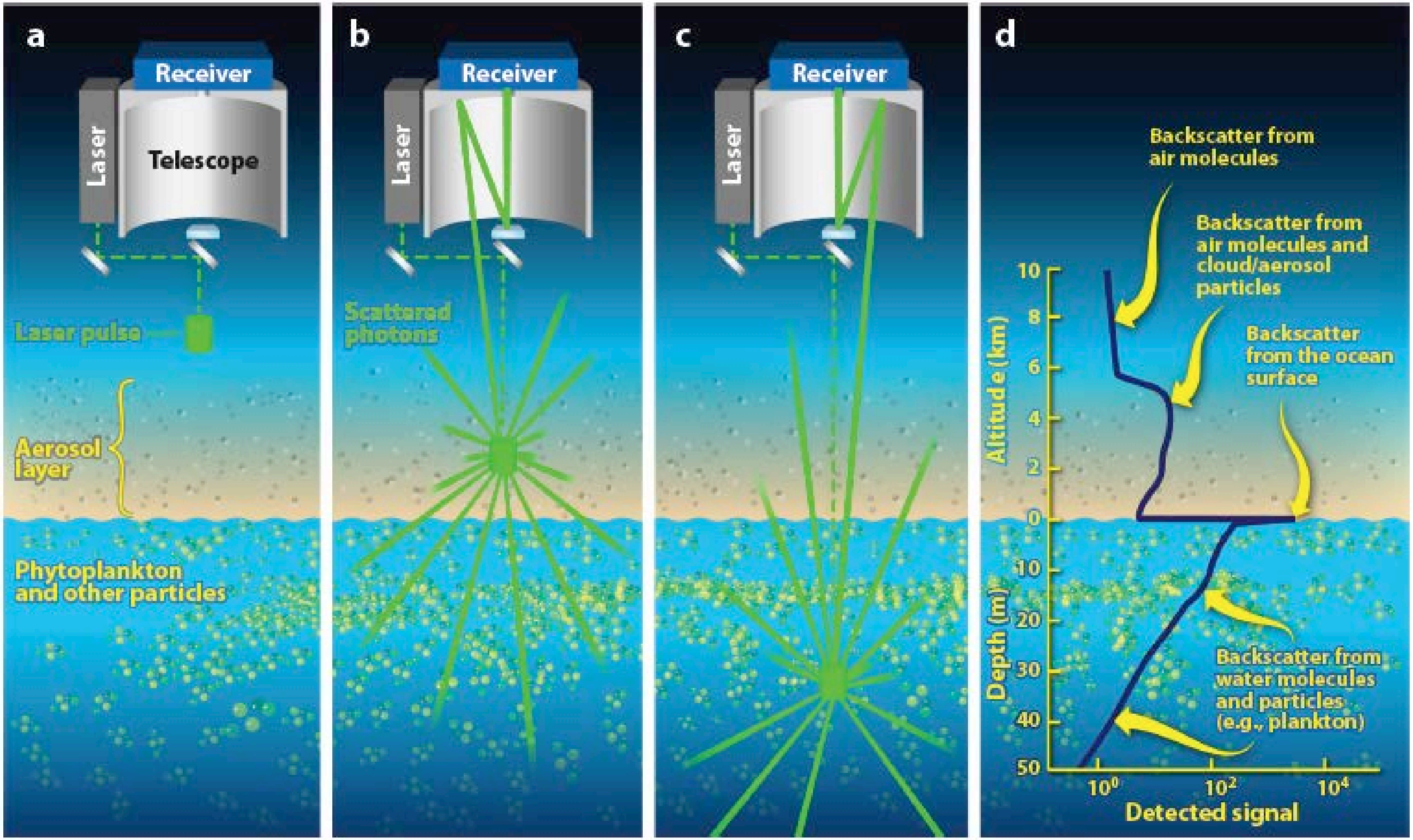
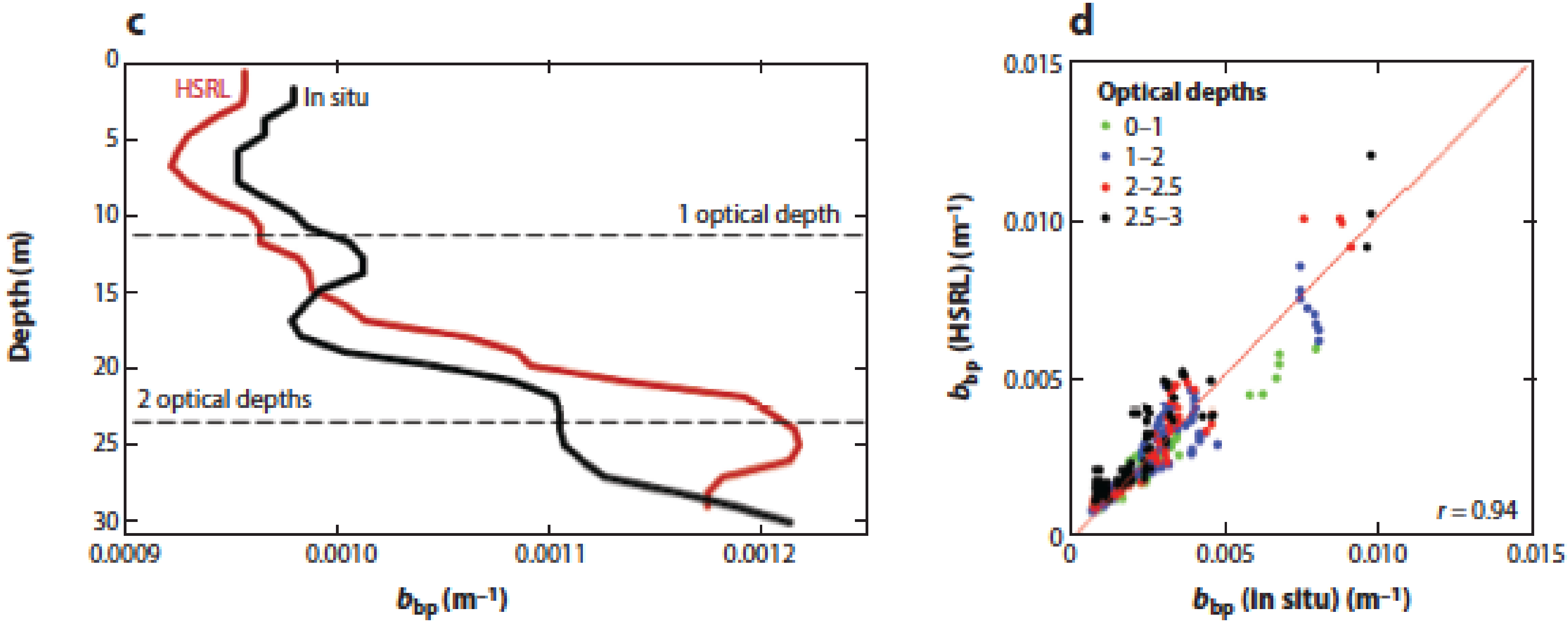


Figure 1 in Hostetler et al., 2018, Spaceborne Lidar in the Study of Marine Systems, *Annual Review of Marine Science*, 10:121–47. https://doi.org/10.1146/annurev-marine-121916-063335

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

Satellite-borne LIDARs for the ocean

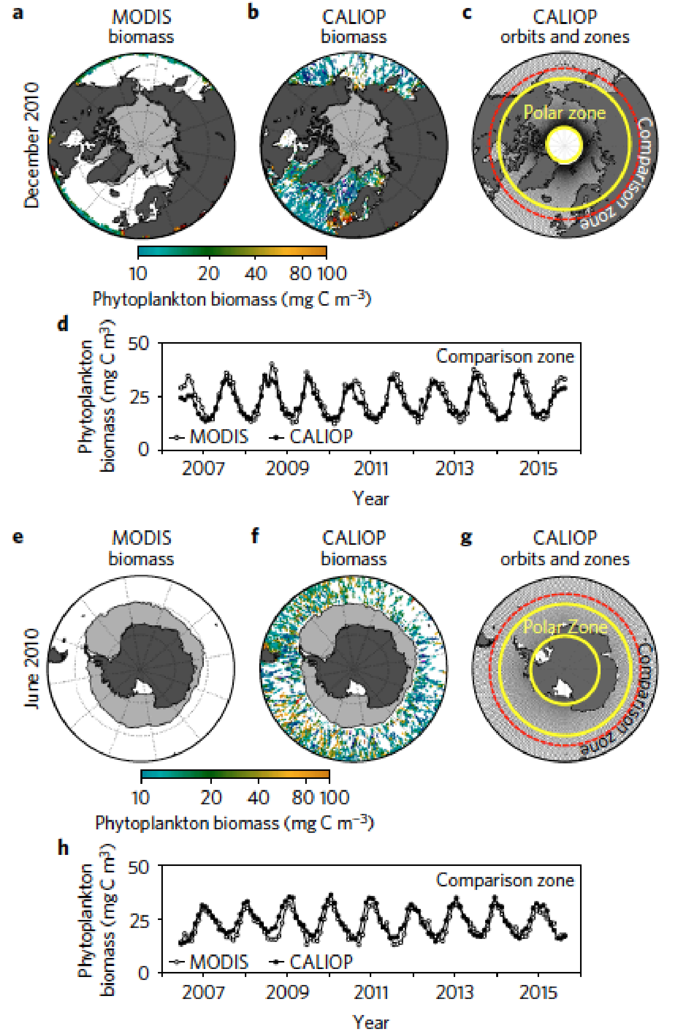


Figure 1 | Phytoplankton biomass observations from CALIOP and MODIS. **a**, MODIS phytoplankton biomass retrievals poleward of 45° latitude (white: no data) for northern latitudes (December 2010). **b**, CALIOP phytoplankton biomass retrievals for December 2010. **c**, Black lines: CALIOP orbit tracks 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**.

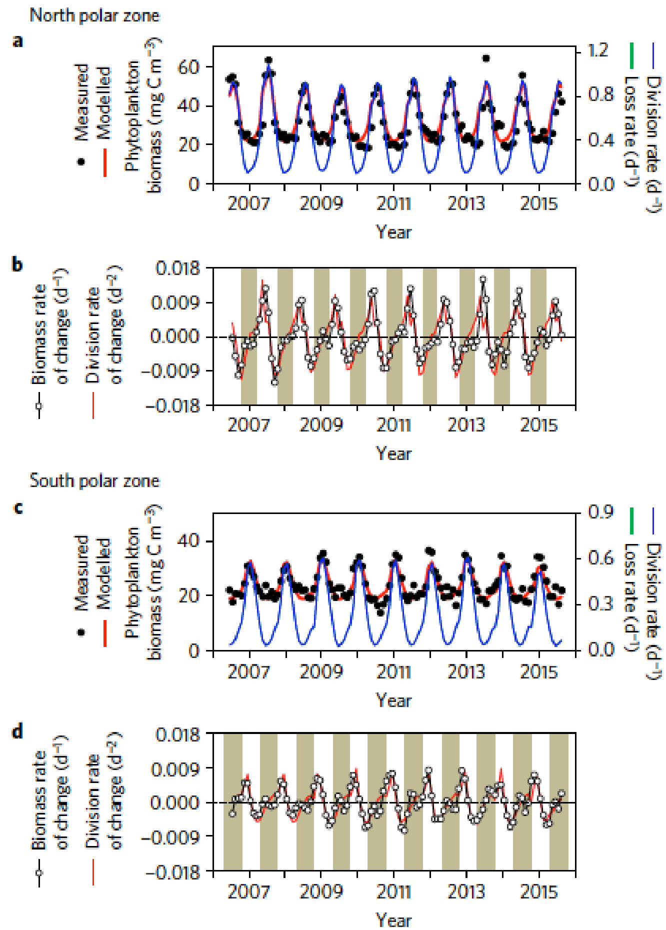


Figure 2 | Polar phytoplankton cycles. **a**,**c**, Black symbols: CALIOP monthly mean phytoplankton biomass (*C*). Blue line: phytoplankton division rates (μ). Green line: phytoplankton loss rates (*l*, which are indistinguishable from μ). Red line: calculated *C* time series from model predictions 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.

Other interesting feature: they work night and day

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

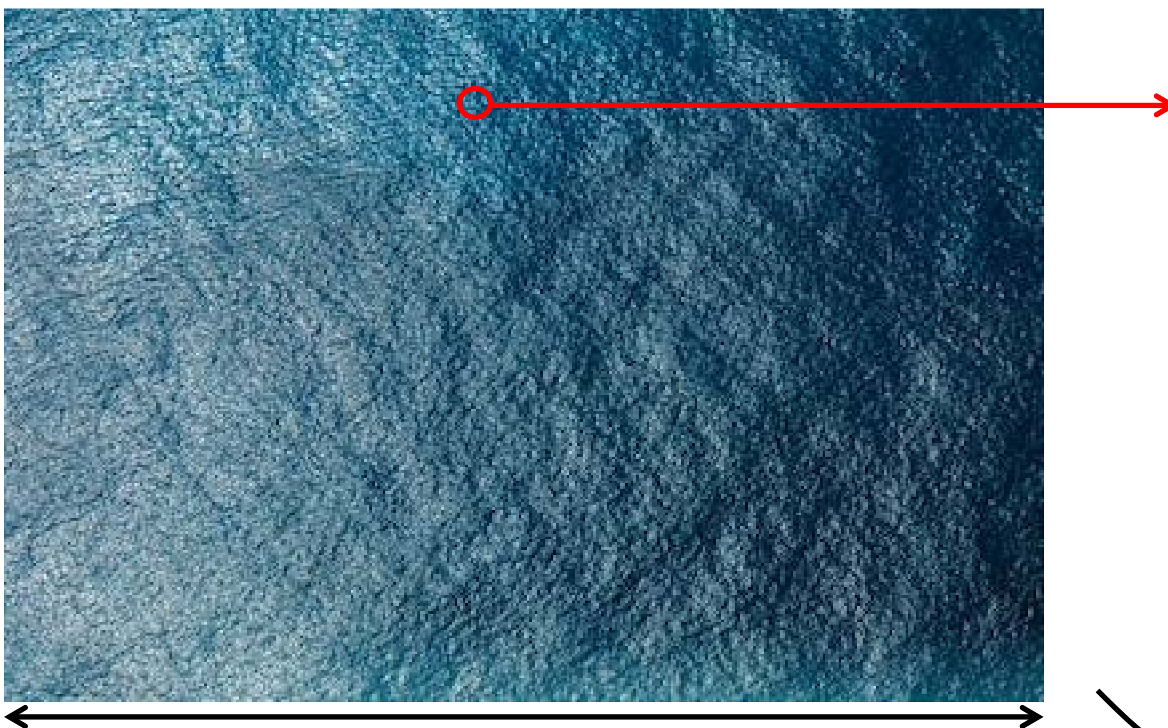
What the future is made of?
6) High spatial resolution sensors

- The “Satellite OCR” realm is essentially made of moderate (medium) spatial resolution sensors. Sub-satellite resolution in the hectometric domain: basically 250m to 1km
- 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
- Mot 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

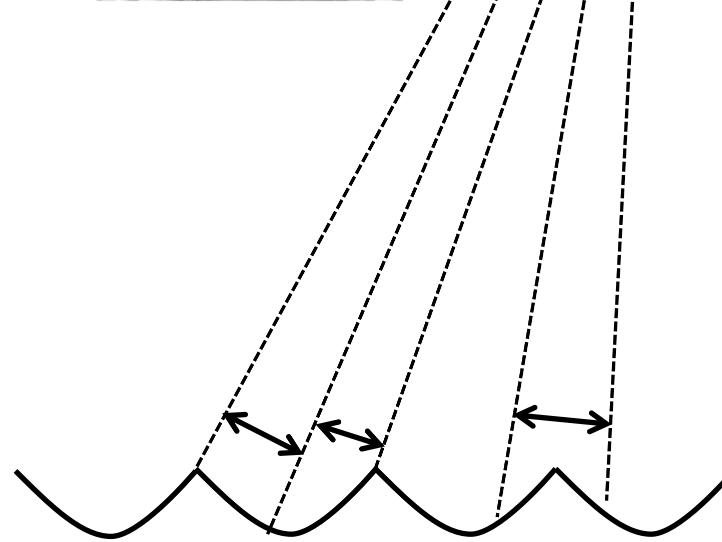
High spatial resolution sensors: Some issues to consider

- 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: the issues with atmospheric corrections become of paramount importance

High spatial resolution sensors: Surface effects



~1 km



Valid for medium resolution sensors

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

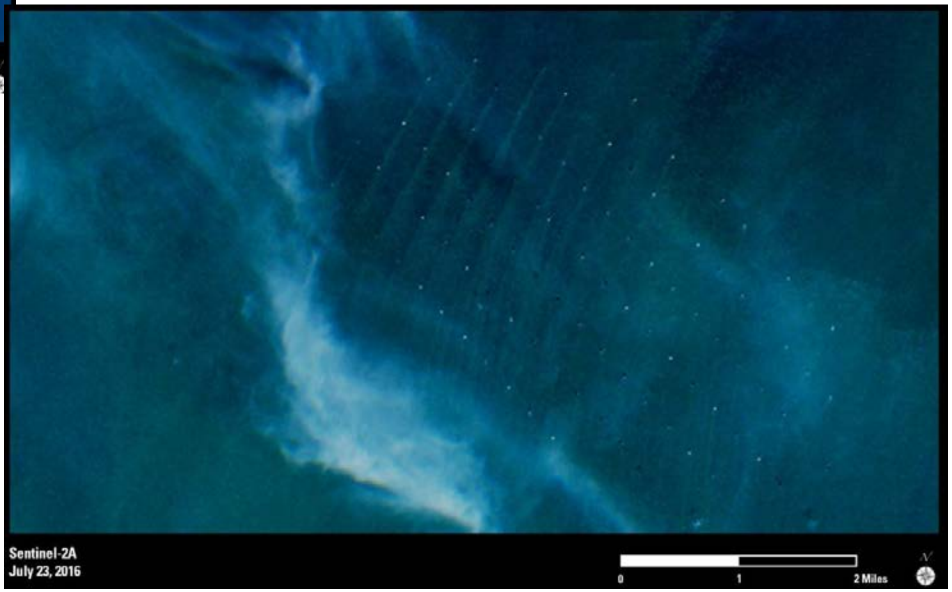
$$\sigma^2 = 0.003 + 5.12\ 10^{-3}\ W$$

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

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.



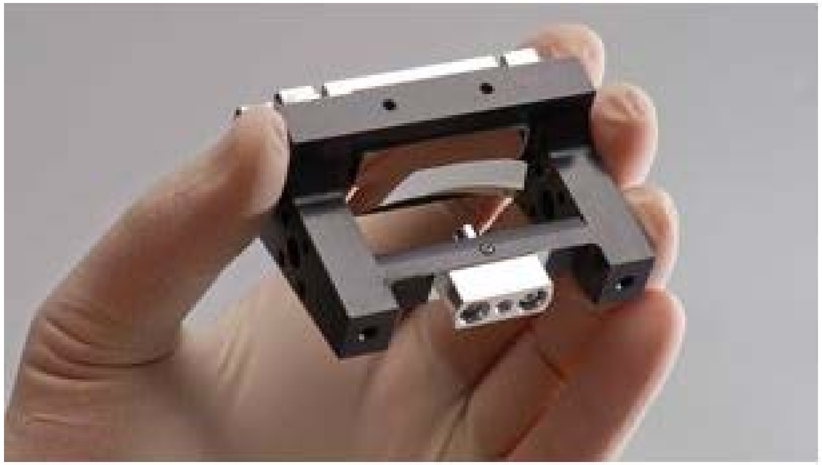
Sentinel-2A shows a sediment plume in the North Sea near England on July 23, 2016. Credit: ESA Sentinel-2.

R

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

Thanks for your attention

Image ©: ESA/ATG Medialab