Plankton, Aerosol, Cloud, and ocean Ecosystems (PACE) Mission

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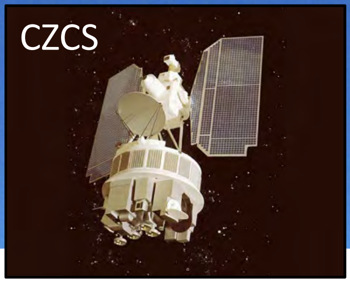
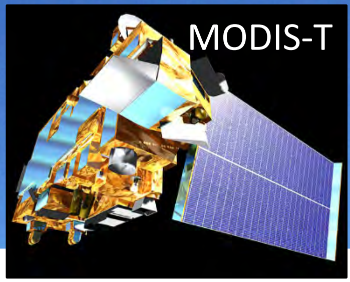
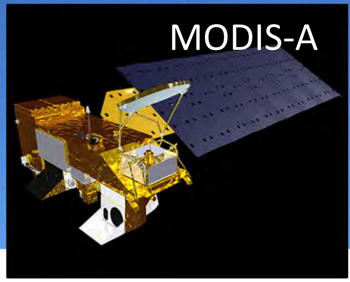
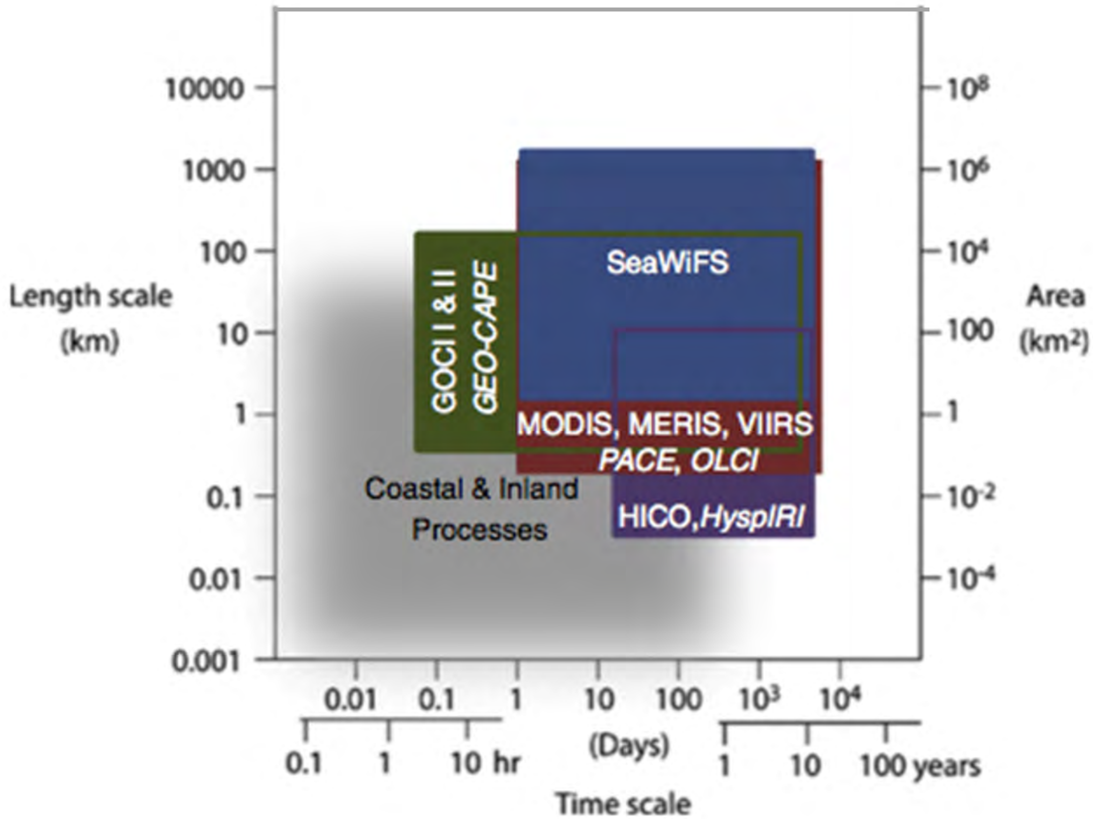
Ocean Color Legacy



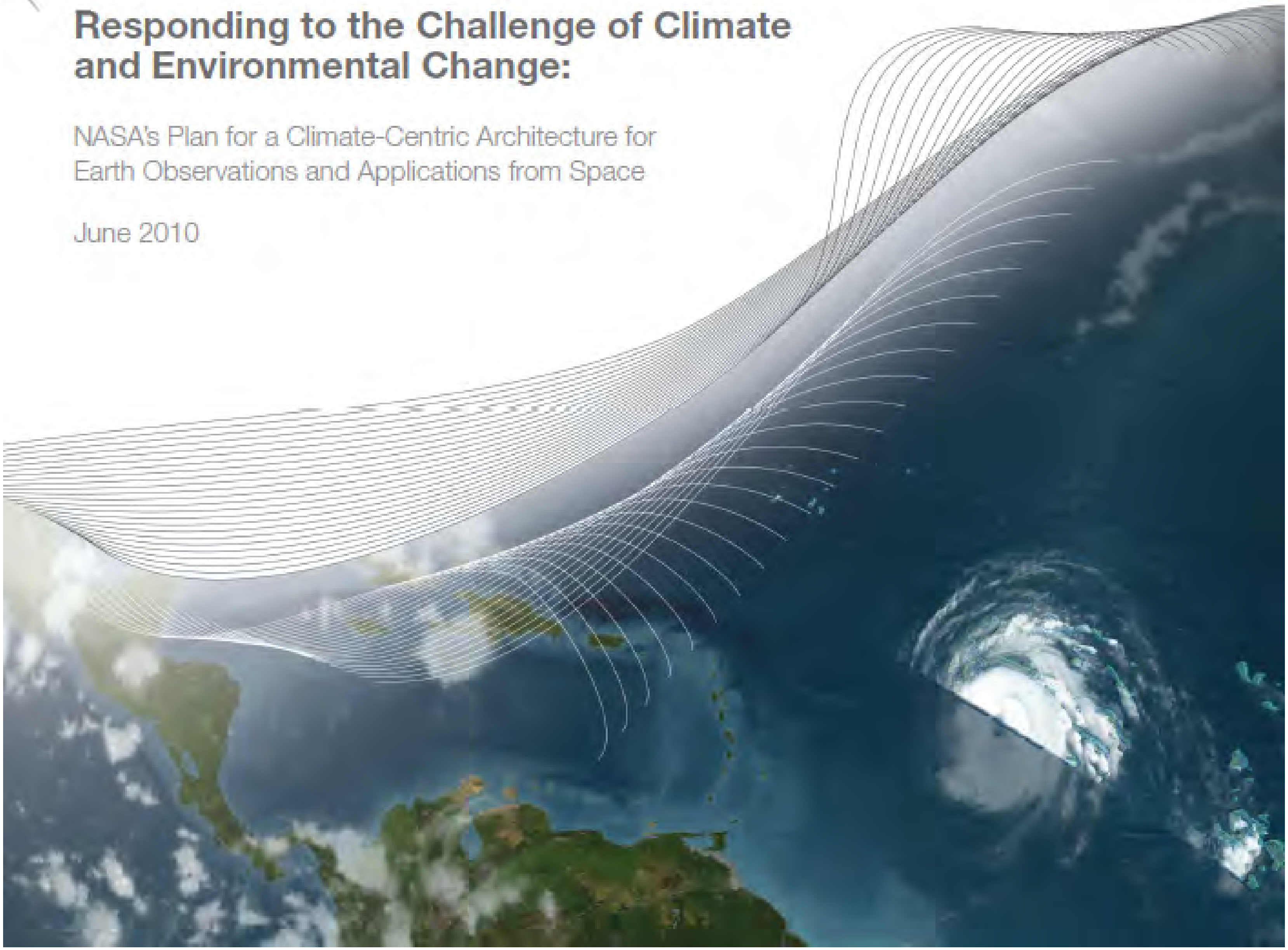






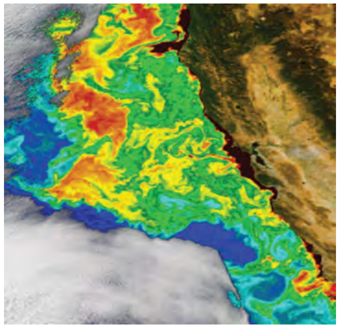
Mouw et al., Remote Sens. Environ, 2015

What is PACE ?


Responding to the Challenge of Climate
and Environmental Change:
NASA's Plan for a Climate-Centric Architecture for
Earth Observations and Applications from Space
June 2010

2.1.4 Climate Continuity Missions

Plankton, Aerosol, Cloud, and ocean Ecosystems (PACE), LRD 2018



The Pre-Aerosol, Clouds, and ocean Ecosystem (PACE) mission will make essential global ocean color measurements for understanding the carbon cycle and how it both affects and is affected by climate change, along with polarimetry measurements to provide extended data records on clouds and aerosols.

The PACE mission will extend key climate data records whose future was in jeopardy prior to the FY2011 budget request. Global ocean color measurements (SeaWiFS, MODIS), essential for understanding the carbon cycle and how it affects and is affected by climate change, will be made by a radiometer instrument on this mission. A polarimeter instrument will extend data records on aerosols and clouds using this approach begun by the French PARASOL mission …, as well as multi-spectral and multi-angle measurements (MISR).

New and continuing global observations of ocean ecology, biology, and chemistry are required to quantify aquatic carbon storage and ecosystem function in response to human activities and natural events. A key goal is improvement of climate-carbon and climate-ecology model prediction. The blend of atmospheric and oceanic requirements is critical as ocean biology is affected by deposition of aerosols onto the ocean, which in turn, produce aerosol precursors that influence climate.

Science Questions

What are the standing stocks & compositions of ocean ecosystems? How & why are they changing?

How & why are ocean biogeochemical cycles changing? How do they influence the Earth system?

How do physical oce
do ocean biological p

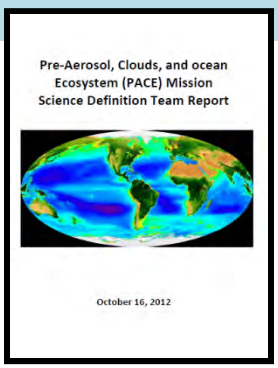
What is the distributi
how is their appeara

How do changes in c
health & welfare? What science based management strategies
need to be implemented to sustain our health & well-being?

What are the long-term changes in aerosol & cloud properties & how are these properties correlated with inter-annual climate oscillations?

What are the magnitudes & trends of direct radiative forcing & its anthropogenic component?

How do aerosols influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere?



2012 PACE Science Definition Team Report (274 pp)

The Mission

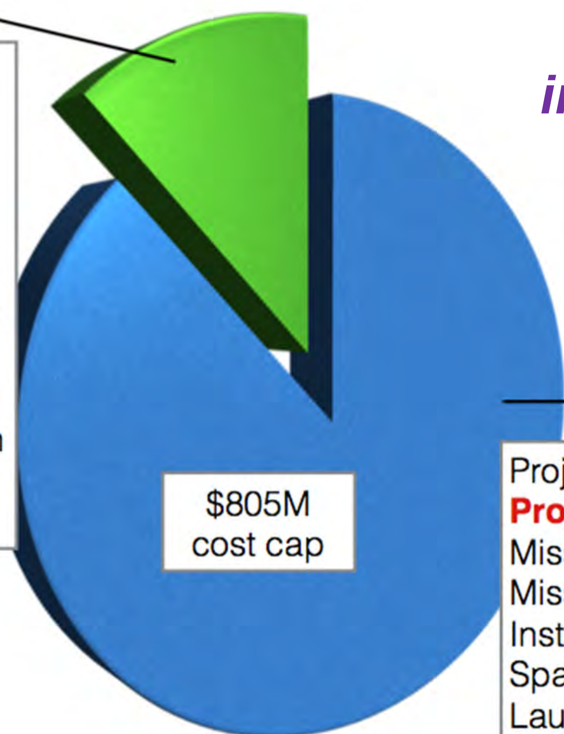
Dec 2014 HQ/ESD letter of direction for PACE mission

- Mission management, ocean color instrument, & science data processing at NASA GSFC
- Polarimeter (optional) to be contributed, procured, or directed

$100M HQ Science

Science Data Segment
Directed to the GSFC Ocean Biology Processing Group; co-located with the Project Science team

Competed Science Teams
(1) Science & algorithms
(2) Vicarious calibration & validation data collection



PACE may be the largest NASA investment this decade for ocean biogeochemistry - Deserves attention and support!

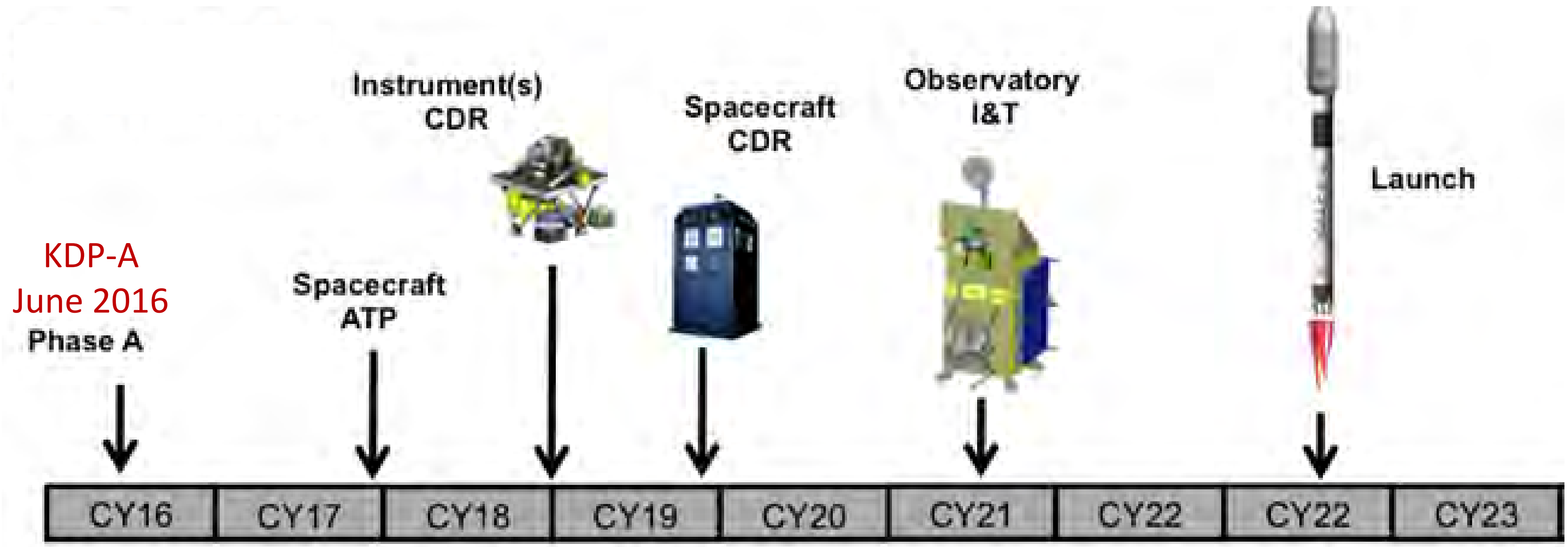
$705M Project

Project Management
Project Science
Mission Systems Engineering
Mission Safety & Assurance
Instrument Payload
Spacecraft
Launch Vehicle
Integration & Testing
MOC & Ground Systems
Others ...

Mission Characteristics & Schedule

Characteristics

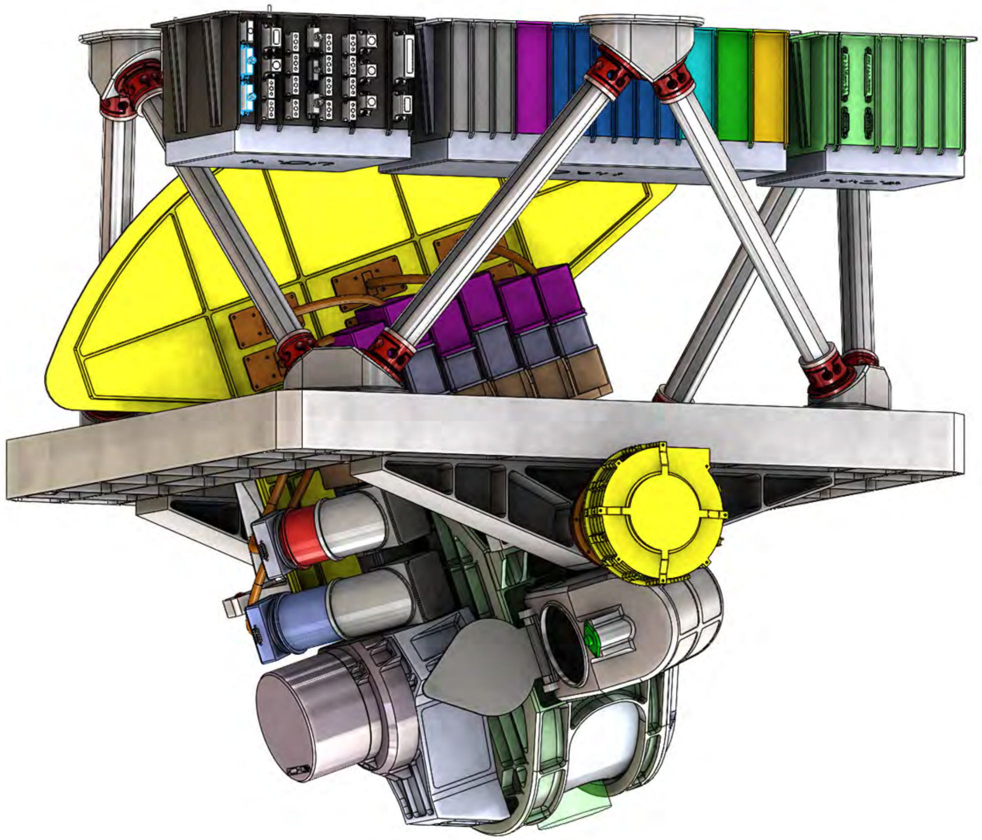
- "Design-to-cost" at 65% cost confidence
- Class C, 3 year mission, 10 years of fuel
- Sun synchronous polar orbit
- Equatorial crossing time: 11:00 - 13:00



Schedule

KDP = Key Decision Point   CDR = Critical Design Review   I&T = Integration & Testing

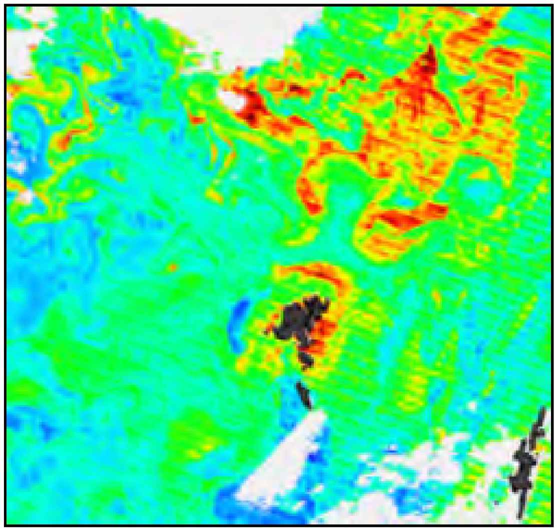
Ocean Color Instrument

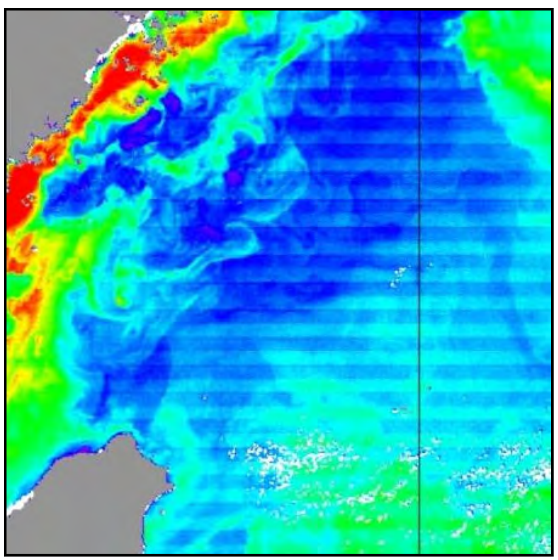


Characteristics

- Developed around 'lessons learned' from heritage sensors
- Deliver on ocean, aerosol, and cloud science objectives
- Tilt to avoid Sun glint
- Monthly lunar calibration
- 2-day global coverage
- Rotating scanner design
- 1 km resolution @ nadir
- High signal-to-noise ratios
- 5 nm resolution 350 - 890 nm
- SWIR bands @ 940, 1240, 1380, 1640, 2130, & 2250 nm
- *Potential*: Edge of scan spatial sampling, 315 nm UV limit, Spectral supersampling

Ocean Color Instrument





Objectives

- Highest quality global ocean color data at hyperspectral resolution from the UV to the NIR
- Continue & advance cloud and aerosol climate data record established by MODIS and VIIRS

Characteristics

- Time-delayed Integration used to achieve high SNR (SeaWiFS heritage)
- Scanning design and ‘single-detector system’ minimizes characterization challenges and simplifies lunar calibration
- *Threshold Requirement*: Striping artifacts ≤0.5% and correctable to noise levels
- *Threshold Requirement*: Accuracy / precision of water-leaving reflectances (unitless) of 20% or 0.004 for 350-395 nm, 5% or 0.001 for 400-700 nm, 10% or 0.002 for 700-900 nm

Ocean Color Product Suite

Measurement Class	Geophysical Parameters
Core Optical Variables	
radiometric quantities	$L_u(z,\lambda)$, $L_i(\lambda)$, $L_{sky}(\lambda)$, $E_d(z, \lambda)$, $E_s(\lambda)$, PAR(z)
apparent optical properties (AOPs)	$K_d(\lambda)$, K_{PAR}, Z_{eu}
inherent optical properties (IOPs)	$a(z,\lambda)$, $a_p(z,\lambda)$, $a_{ph}(z, \lambda)$, $a_d(z, \lambda)$, $a_{CDOM}(z, \lambda)$, $b_b(z, \lambda)$, $c(z, \lambda)$
Biogeochemical State Variables & Processes (Secondary Variables)	
phytoplankton pigment concentrations	Chl, accessory pigments, carotenoids
phytoplankton characteristics	C_{phyto}, taxonomic/functional groups, chlorophyll fluorescence
particle population characteristics	SPM, POC, PIC, PSDs
photobiochemical characteristics	DOC, CDOM fluorescence, MAAs, phycobili proteins
production	NPP, NCP
Synthesis & Modeling Variables (Tertiary Variables)	
Fluxes & ecosystems	C export, air-sea CO_2 exchange, land-ocean material exchange

Cloud & Aerosol Product Suite

Threshold requirements from HQ

Atmospheric Aerosol Measurements

a) Aerosol Optical Depth
   a. UV at 0.05 or 30% (total)
   b. VIS at 0.05 or 15% (total) over land
   c. VIS at 0.03 or 10% (total) over ocean

b) Fraction of total visible optical depth contributed by the fine mode aerosol over dark water to ±0.25.

Cloud Measurements

Cloud Layer Detection of 5-10% at a cloud optical depth of ~0.3 with dependence on surface type as a partial continuation of MODIS and VIIRS

a) Cloud Top Pressure
   a. Low cloud when optically thick and/or over dark surface at ≤50 hPa
   b. High cloud at >50 hPa.

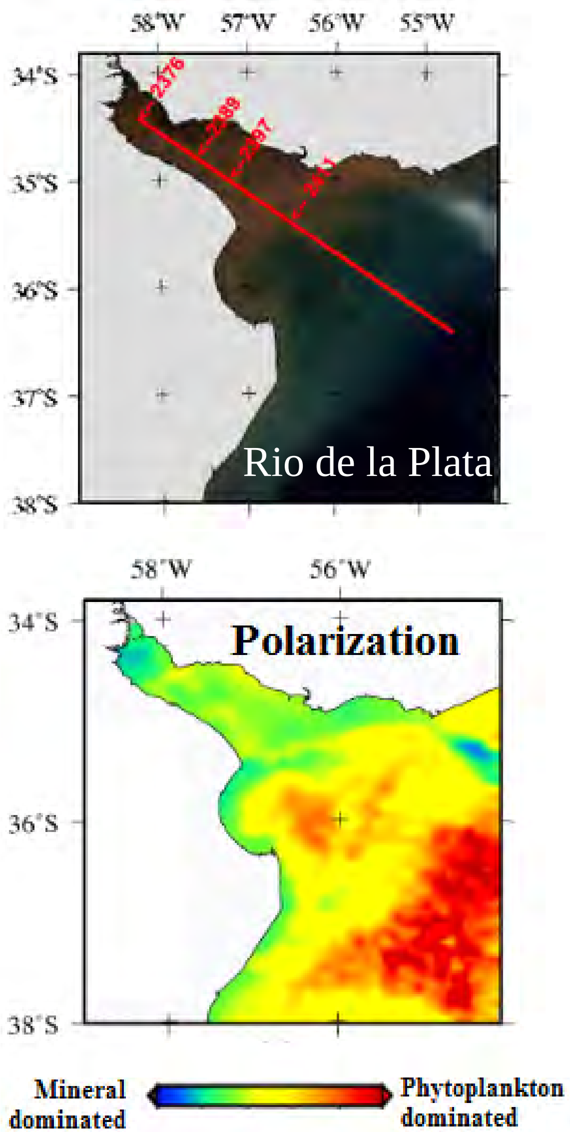
b) Cloud Water Path as a function of optical depth, effective radius and surface
   a. ~30% for liquid clouds
      ~50% for ice clouds

c) Optical Thickness as a function of optical depth, effective radius, wavelength and surface
   a. ~20% for liquid clouds with small sub-pixel heterogeneity
      ~30% for ice clouds

d) Effective Radius with upper layer weighting
   a. ~20% for liquid clouds with small sub-pixel heterogeneity
      ~30% for ice clouds

Shortwave Radiative Effect at ~10 Wm^{-2} TOA

Polarimeter



Loisel et al., 2008 Optics Express

Instrument

- Multi-angle polarimeter
- 2-3 day global coverage
- 4 km resolution @ nadir

Data Products

- Single scattering albedo (aerosol absorption)
- Aerosol layer height
- Effective radius (aerosol size)
- Real refractive index (aerosol composition)
- Imaginary refractive index (absorbing aerosols)

Targets

- Characterize aerosol particle types & sizes
- Reduce uncertainty in aerosol characterizations for input in global climate forcing models
- Improve ocean color atmospheric corrections and thus ocean products
- *Classification of ocean particles (??)*

Additional Capabilities

1. **Ocean Color Instrument:** Global ocean color, clouds & aerosols science

2. **Polarimeter:** Enhanced clouds & aerosols science, plus advanced ocean color atmospheric correction

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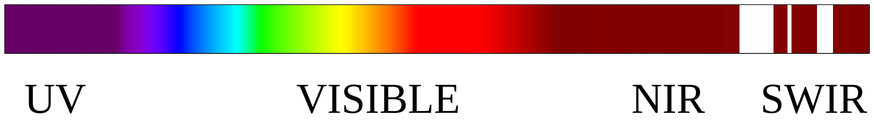
3. **High spatial resolution imager (GSD < 100 m):** Coastal ocean & small-scale atmospheric science

4. **Support for NASA Earth Venture class instrument**

5. **Direct broadcast of science data**

Thinking Forward



advancing ocean data products

- atmospheric corrections
- phytoplankton community composition
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
- phytoplankton physiology
- net primary production
- carbon fluxes and export

UV spectral anchoring, hyperspectral NIR, polarimetry, simultaneous O3, spectral 'supersampling'

Marker pigments: derivative analyses, spectral matching algorithms

Near-UV separation of pigment and cDOM absorption

Particulate backscattering spectral slope

Iron stress from fluorescence quantum yield, spectral supersampling of fluorescence band, phytoplankon pigment absorption spectra

Integrated approach:

- nutrient stressors
- community composition
- phytoplankton biomass
- pigment absorption spectra
- improved cDOM = improved pigment

Pre-launch studies are needed to mature approaches for achieving these science targets

Thinking Forward

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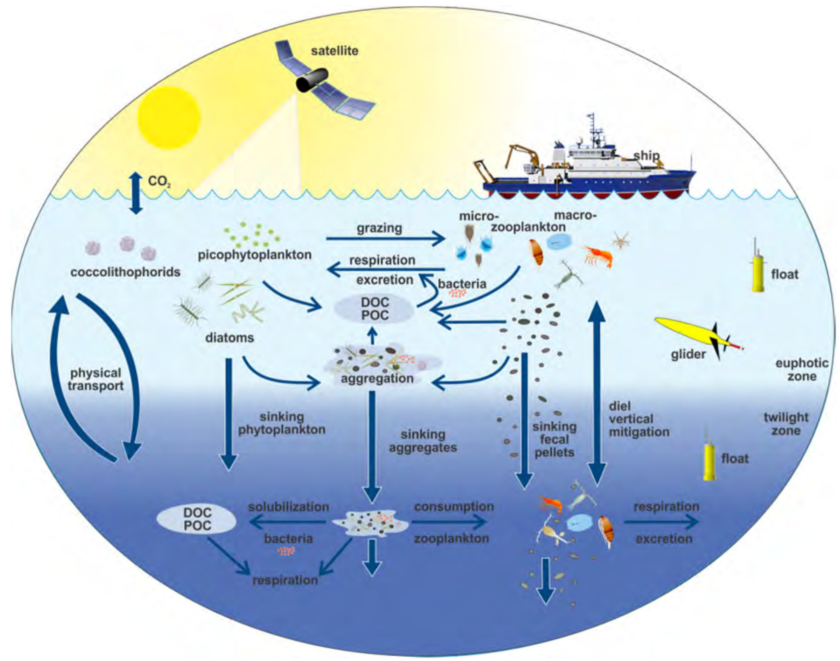


EXPORTS

Can carbon export and fate within the twilight zone be predicted from surface ocean NPP and ecosystem properties characterized by PACE?

EXport **P**rocesses in the **O**cean from **R**emo**T**e **S**ensing (2017 - 2024)

Vicarious Calibration & Data Validation

- Vicarious Calibration and Data Validation (*in situ*)
  - FY15 – 17: ROSES 2014 A.3
    - Issued jointly between OBB and ESTO
    - Allows lead time for concepts to mature prior to launch
    - Identifies technical development needs/risks for the approaches selected
  - FY18 – 21: ROSES 2017 (4 years)
    - Selects best approach and hardware (pre-launch) or further risk reduction on instrumentation, if needed, for:
      - Vicarious calibration of ocean color data products
      - Validation of all data products – *in situ*
      - Calibration/validation of polarimetry data products (TBD)
  - FY22 – 25: ROSES 2021 (4 years)
    - Perform cal/val during mission operations
    - Includes airborne and *in situ* measurements
    - Continue every year during mission extensions

Science Teams
Pre-launch and Post-launch

- Pre-launch Science Teams
  - FY15 – 17: ROSES 2013 A.25
    - Covers IOPs and Atmospheric Correction
    - Achieves consensus and develops community-endorsed paths forward for the sensor retrievals for the full spectrum of components within a given measurement suite
  - FY18 – 21: ROSES 2017 (4 years)
    - Allows lead time for scientific algorithm development prior to launch
    - Initiates interface between instrument developers and OBPG; OBPG and algorithm developers
    - Supports applications research along with research activities

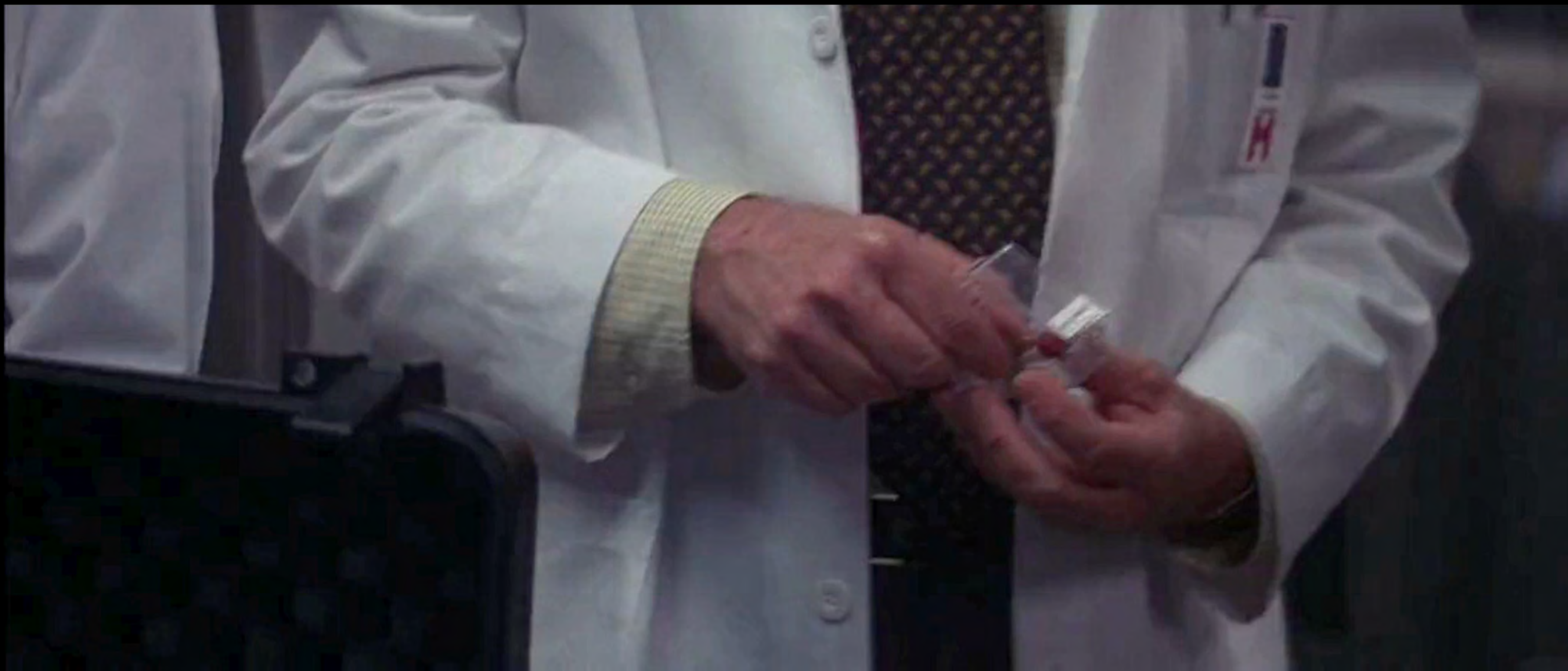
- At-launch Science Teams
  - FY22 – 25: ROSES 2021 (4 years)
    - Pre-launch algorithms and post-launch competed science/applications for ocean color instrument's aerosol, cloud, ocean science, plus aerosol and clouds from polarimeter (TBD)

- Post-launch Competed Science - options
  - Competed through ROSES 2025
  - After launch, joint funding between EOS project, R&A, and PACE mission budget, exploring additional funding from Applied Sciences
  - Mission contribution TBD
  - Continue during mission extensions

The PACE 'Family Tree'

A Consistent Theme with Many Names:

- Advanced ocean color sensor enabling improved 2º and 3º science products
- Parallel Cloud & Aerosol measurements supporting disciplinary science and recognizing ocean-atmosphere scientific and radiometric interdependencies



Satellite data live longer than satellites….

… PACE is a mission we can grow into!

Questions & Discussion

pace.gsfc.nasa.gov

Thank you !

Clouds & Aerosol Particle Data Products

Threshold data products from HQ

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Shortwave Radiative Effect at ~10 Wm^{-2} TOA

multi-angle polarimetry

Advanced cloud & aerosol data products

single scattering albedo
aerosol layer height
effective radius
real refractive index
imaginary refractive index

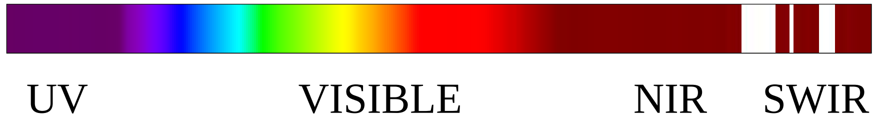
Desired capabilities of a polarimeter

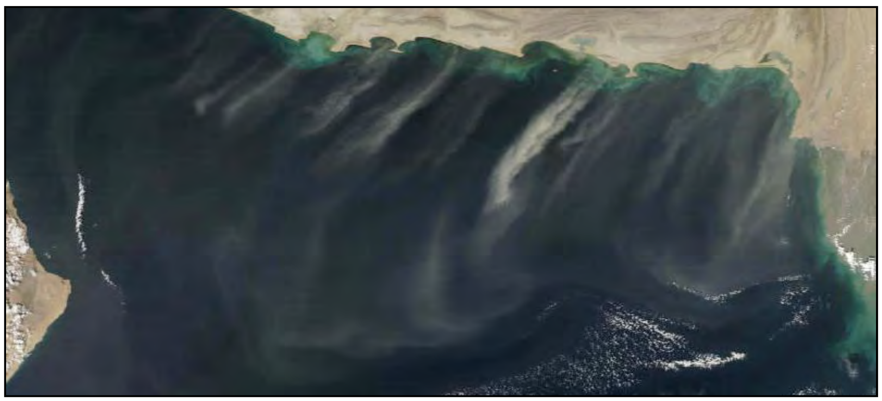
Rationale for prioritization	Priority	Minimum Capability	Enhanced Capability
PACE is a climate-science mission. Global polarimetry will: (1) Reduce uncertainties in aerosol characterizations for input into global climate forcing (e.g., IPCC) models; and (2) Improve ocean color atmospheric correction, thus improving understanding of global ocean ecosystems and carbon cycles	1a	**% ground coverage of OCI Swath** Not specified *Target: 50%*	**% ground coverage of OCI Swath** Not specified *Target 90%*
	1b	**Swath width** ±15-25°	**Swath width** ±30°
The utility of the measurements degrades when uncertainties exceed 1%	2	**DOLP uncertainty** <0.01	**DOLP uncertainty** <0.005
Spectral resolution, number of polarized bands, and angular range (# of scattering angles) all dictate what derived products can be produced	3a	**Spectral channels** >4 over 400-1600 nm + 2200 nm only if sparse angular sampling	**Spectral channels** Minimum + 940 nm or O2 A-band and 1378 or 1880 nm
	3b	**Angular range** ±50° at satellite in all bands	**Angular range** ±55° at satellite in all bands
Multiangular capabilities enhance the ability to estimate many cloud and aerosol properties	4a	**Number of angles** 5-6 for clouds	**Number of angles** ~50 for cloud bows
	4b	**Number of angles** 4 for aerosols	**Number of angles** 10 for aerosols
4 km is adequate for climate science		**Pixel size / Spatial resolution** 5 km	**Pixel size / Spatial resolution** 1 km
All concepts meet the radiometric and SNR requirements		**Radiometric uncertainty** 5%	**Radiometric uncertainty** 3%
		SNR Not specified	**SNR** Not specified

Draft Level-1 Threshold Science Requirements

Threshold Requirement	Rationale
≤ 1000 m GSD at nadir	Provides adequate spatial resolution for global oceanographic & atmospheric climate-related studies
Sun synchronous, polar orbit w/ local 11:00 to 13:00 Equatorial crossing time	Maximizes the illumination of the ocean & minimizes the pathlength of the atmosphere to be removed through ocean color atmospheric correction
2-day to solar & sensor zenith ≤ 75^o & ≤ 60^o	Yields acceptable fraction of clear-sky scenes to allow global-scale computations at monthly, seasonal, & annual timescales
±20^o to avoid Sun glint	Maximizes spatial coverage given that ocean color data products cannot be reliably acquired in the presence of Sun glint
Monthly lunar calibration through Earth view port w/ illumination of all science detectors	Required to achieve radiometric stability of 0.1% at the top of the atmosphere, which is necessary to detect trends in geophysical variables
Striping artifacts ≤ 0.5% for calibrated top-of-atmosphere radiances	Spatial & temporal analyses of geophysical data products cannot tolerate image artifacts; 0.5% mis-calibration at the top-of-the atmosphere leads to 5% uncertainty in water-leaving reflectances
350-800 nm @ 5 nm	Required to reveal oceanographic & atmospheric constituents that cannot currently be resolved by heritage instruments
940, 1240, 1378, 1640, 2130, and 2250 nm	Required to continue time-series of heritage cloud & aerosol products from MODIS & VIIRS, & to support ocean color atmospheric correction

Thinking Forward





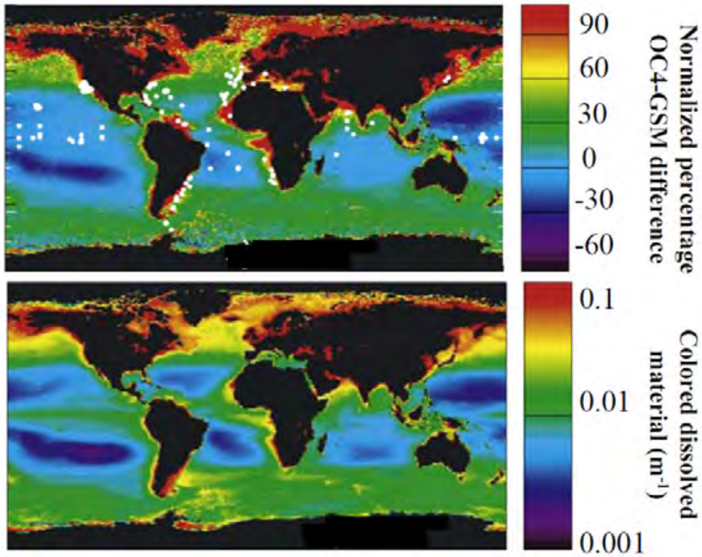
advancing ocean data products

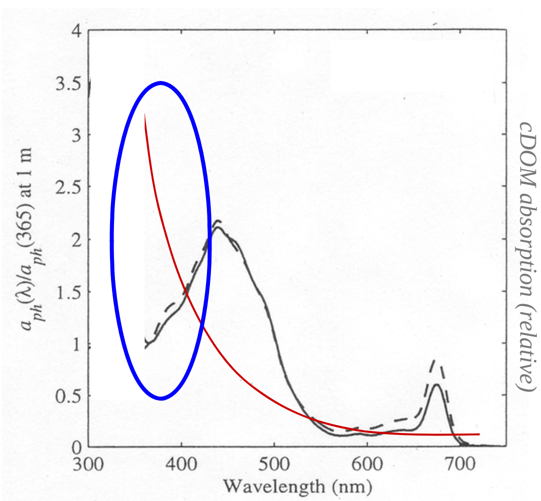
- atmospheric corrections
  - SWIR bands for coastal regions
  - NIR + UV anchoring
  - polarimeter for aerosol types and heights
- phytoplankton community structure
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
- phytoplankton community composition
- phytoplankton physiology
- net primary production
- carbon fluxes and export

Thinking Forward

Siegel et al., 2005

NPP impact ~ 15 Pg C y^{-1}



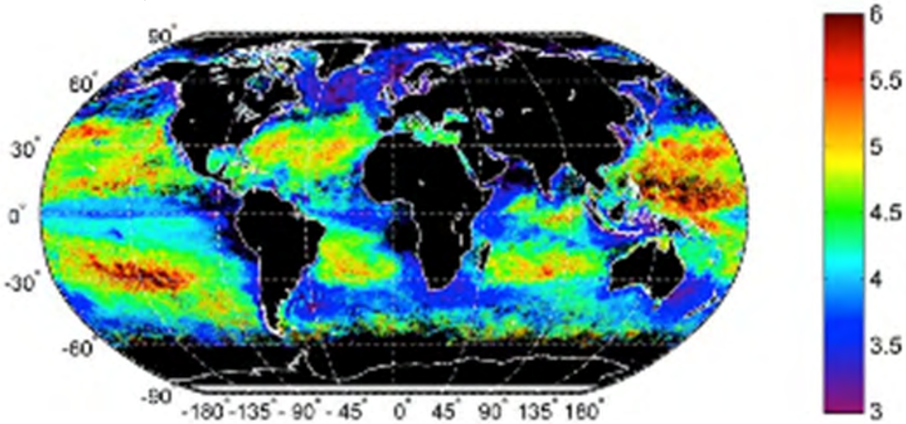


advancing ocean data products

- atmospheric corrections
- phytoplankton community structure
- dissolved carbon pools
  - ➢ UV bands improve cDOM assessments
- phytoplankton and total particulate carbon biomass
- phytoplankton community composition
- phytoplankton physiology
- net primary production
- carbon fluxes and export

Thinking Forward

Slope of the Particle Size Distribution

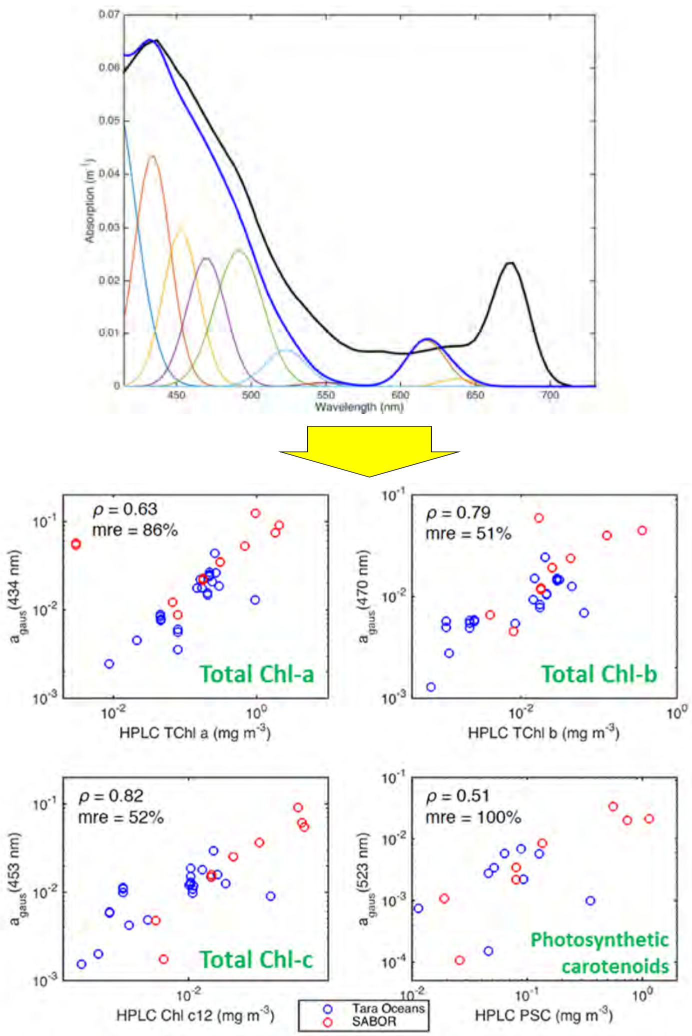


Kostadinov et al., 2009

advancing ocean data products

- atmospheric corrections
- phytoplankton community structure
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
    - particulate backscattering and backscattering spectral slope
- phytoplankton community composition
- phytoplankton physiology
- net primary production
- carbon fluxes and export

Thinking Forward

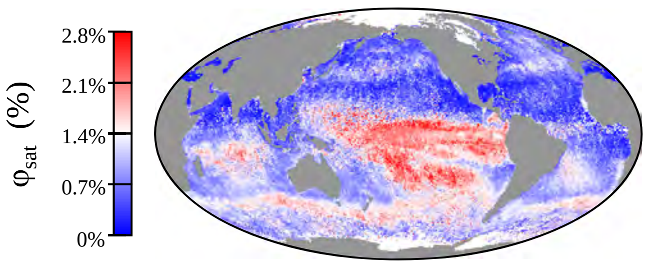


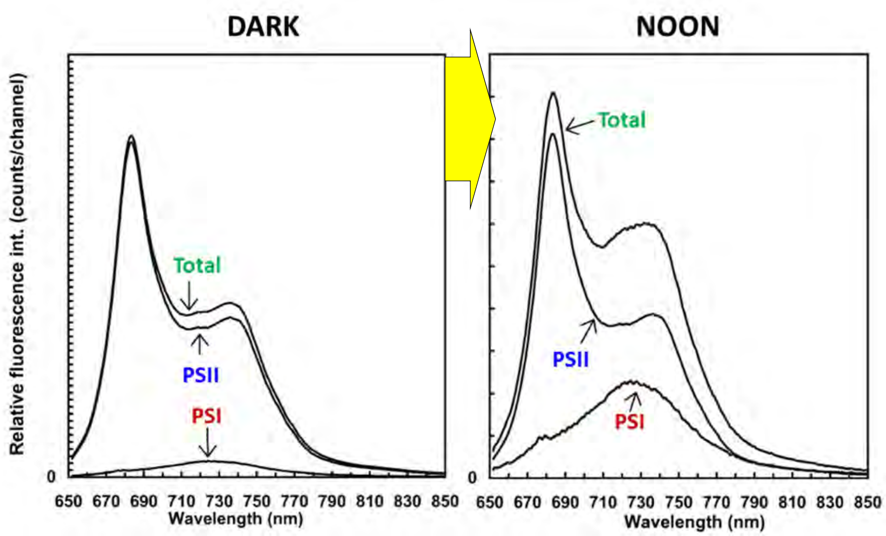
Chase et al., 2013

advancing ocean data products

- atmospheric corrections
- phytoplankton community structure
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
- phytoplankton community composition
  - ➢ Particle size distribution
  - ➢ Marker pigments
    - o Derivative analyses
    - o Spectral matching algorithms
- phytoplankton physiology
- net primary production
- carbon fluxes and export

Thinking Forward





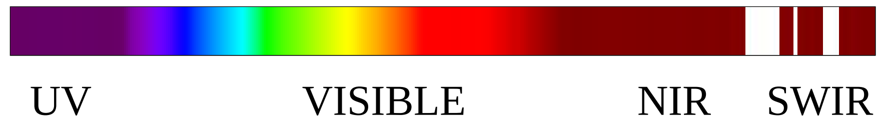
- Detached chlorophyll complexes
- Altered ratio of PSI:PSII

advancing ocean data products

- atmospheric corrections
- phytoplankton community structure
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
- phytoplankton community composition
- phytoplankton physiology
    - ➢ specific nutrient stressors
- net primary production
- carbon fluxes and export

Franck et al 2002 **Milligan et al. 2012**

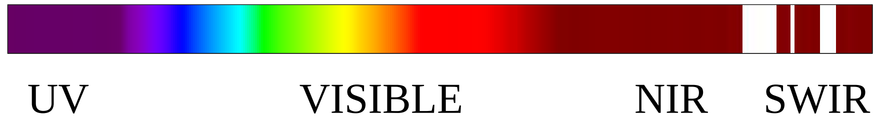
Thinking Forward

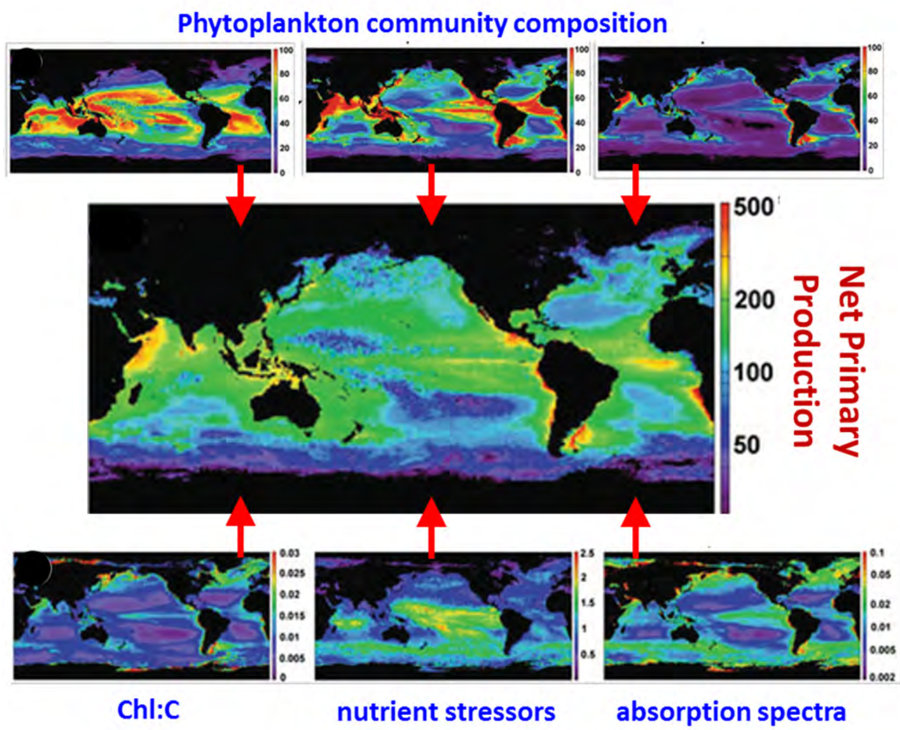


advancing ocean data products

- atmospheric corrections
- phytoplankton community structure
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
- phytoplankton community composition
- phytoplankton physiology
  - ➢ specific nutrient stressors
  - ➢ photophysiology
    - o phytoplankton carbon +
    - o pigment absorption spectra +
    - o underwater light field +
    - o mixing depth
- net primary production
- carbon fluxes and export

Thinking Forward



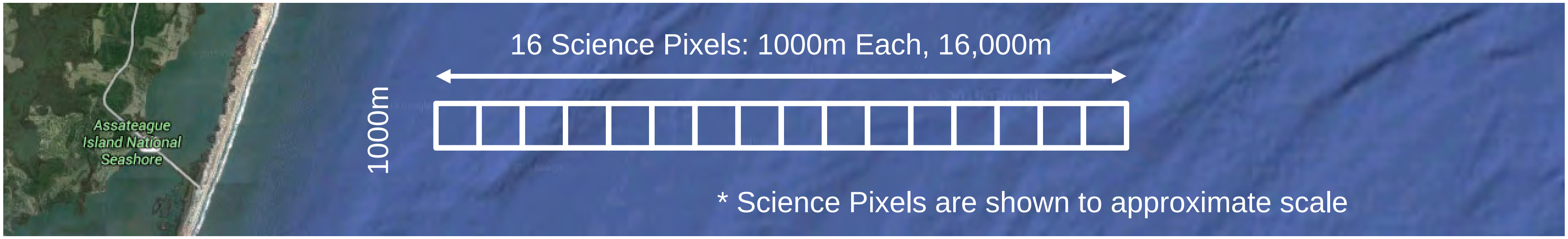


advancing ocean data products

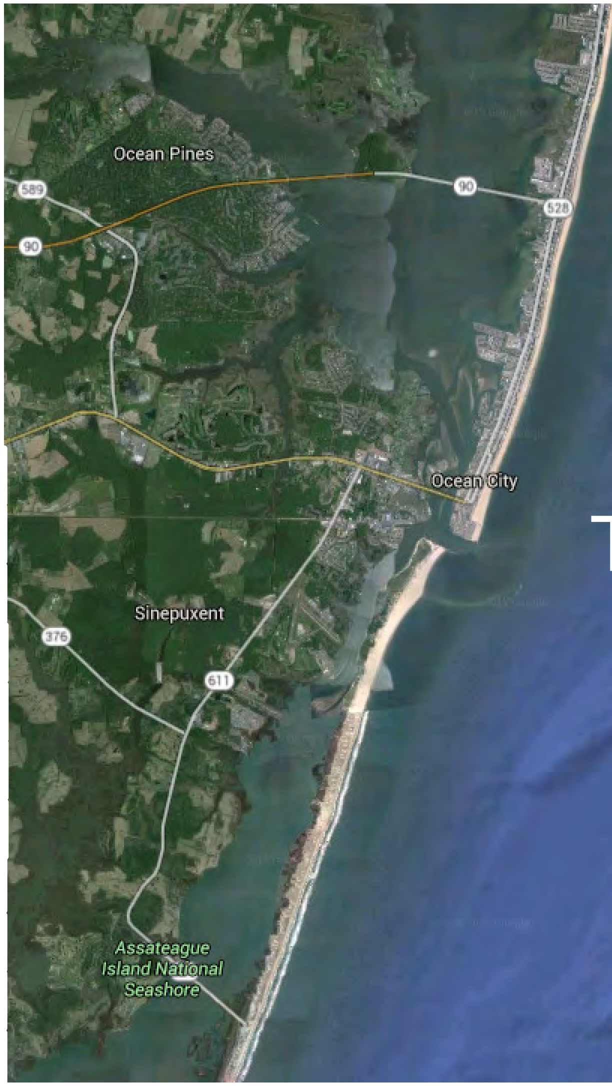
- atmospheric corrections
- phytoplankton community structure
- dissolved carbon pools
- phytoplankton and total particulate carbon biomass
- phytoplankton community composition
- phytoplankton physiology
- net primary production
  - ➢ integrating expanded retrieval suite
- carbon fluxes and export

OCI Telescope Ground Coverage

- 1 Science Pixel = 1000m x 1000m at Nadir
- OCI optics projects 16 science pixels onto a slit. The slit is re-imaged onto detectors (CCDs and SWIR detectors)
- This is 16,000m x 1000m of ground area
- If you stop the telescope from rotating, the optics will only see 16 science pixels on the ground.



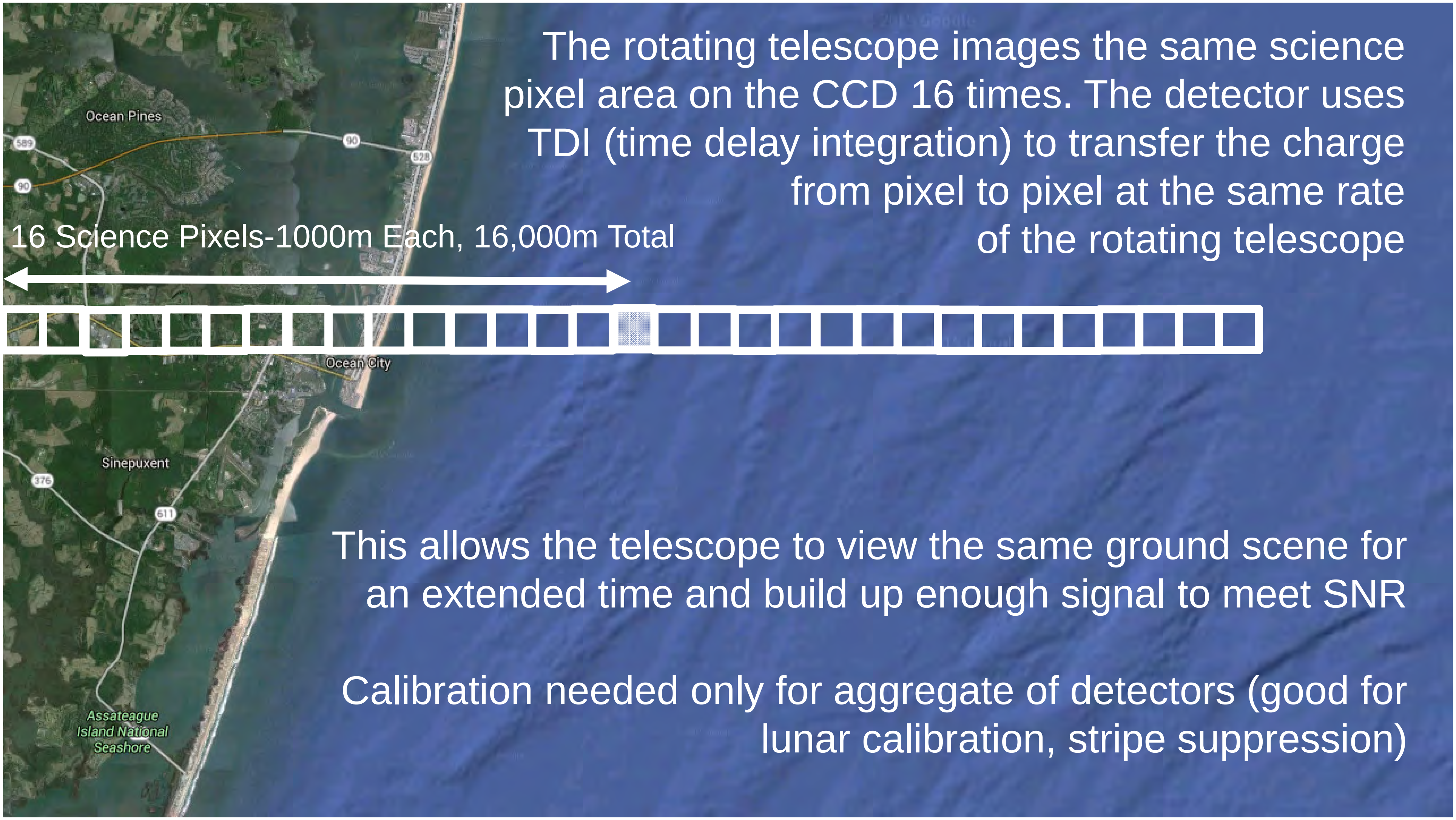
OCI Rotating Telescope Ground Coverage



The rotating telescope moves the image of the 16 science pixels across the ground to cover the full field of regard

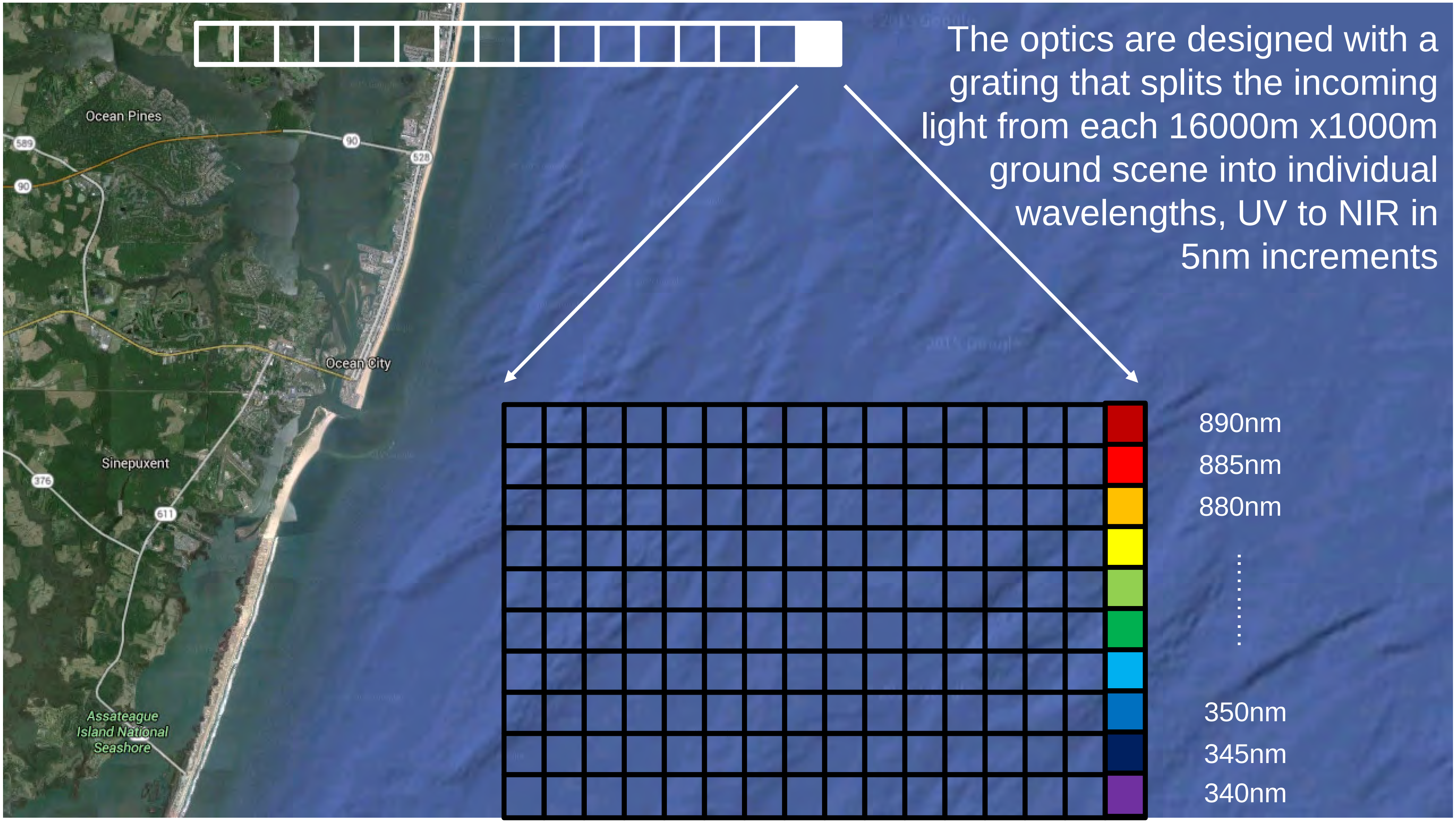
The telescope rotates fast enough so there are no gaps in coverage in the along track direction between scans (scan progression determined by spacecraft speed, upward in this example)

OCI Time Delay Integration



SeaWiFS used TDI with 4 photodiodes

OCI -Time Delay Integration - Hyperspectral



The optics are designed with a grating that splits the incoming light from each 16000m x1000m ground scene into individual wavelengths, UV to NIR in 5nm increments