Development of an Ocean Radiometer for Carbon Assessment (ORCA) Prototype

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NASA/GSFC

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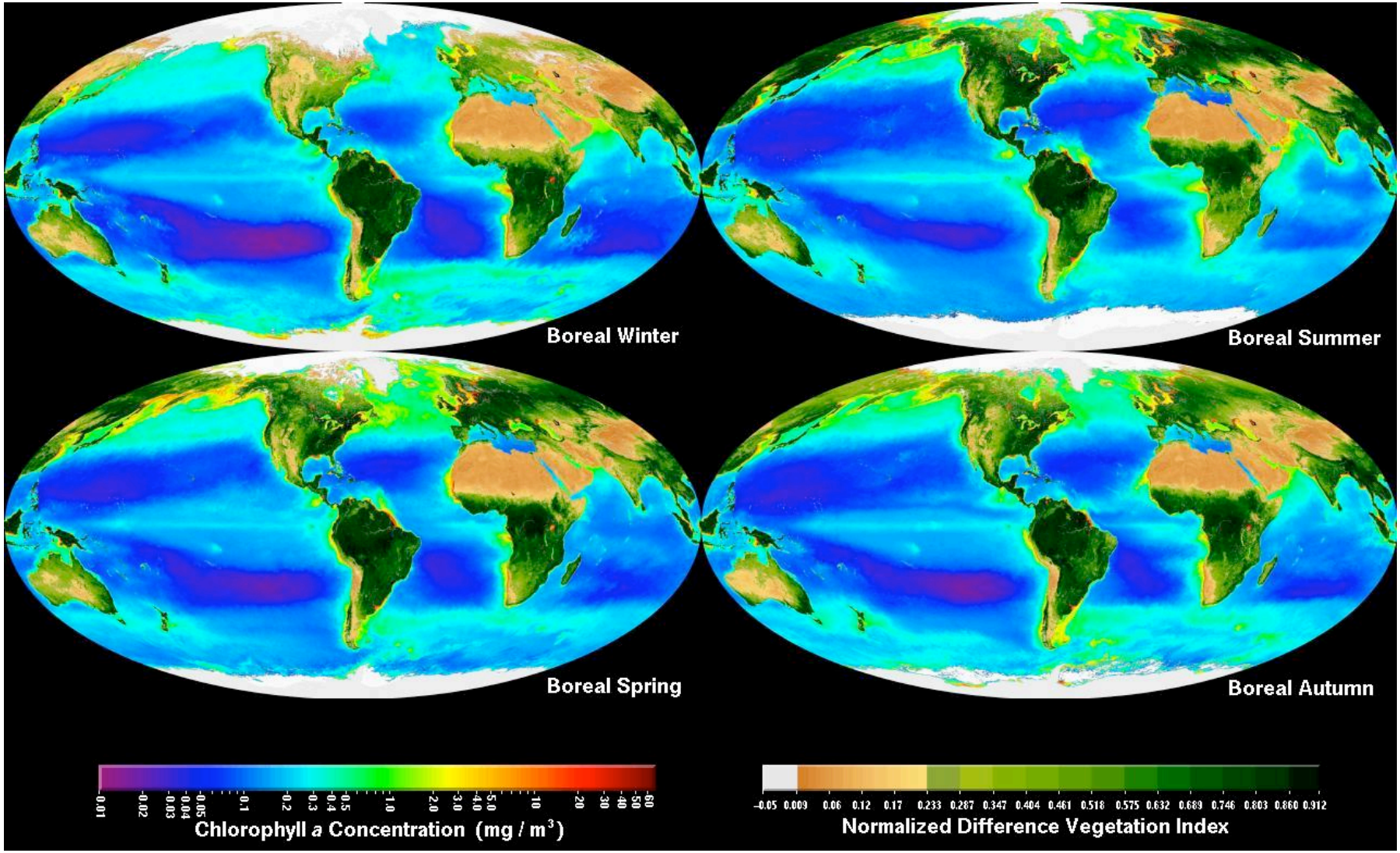
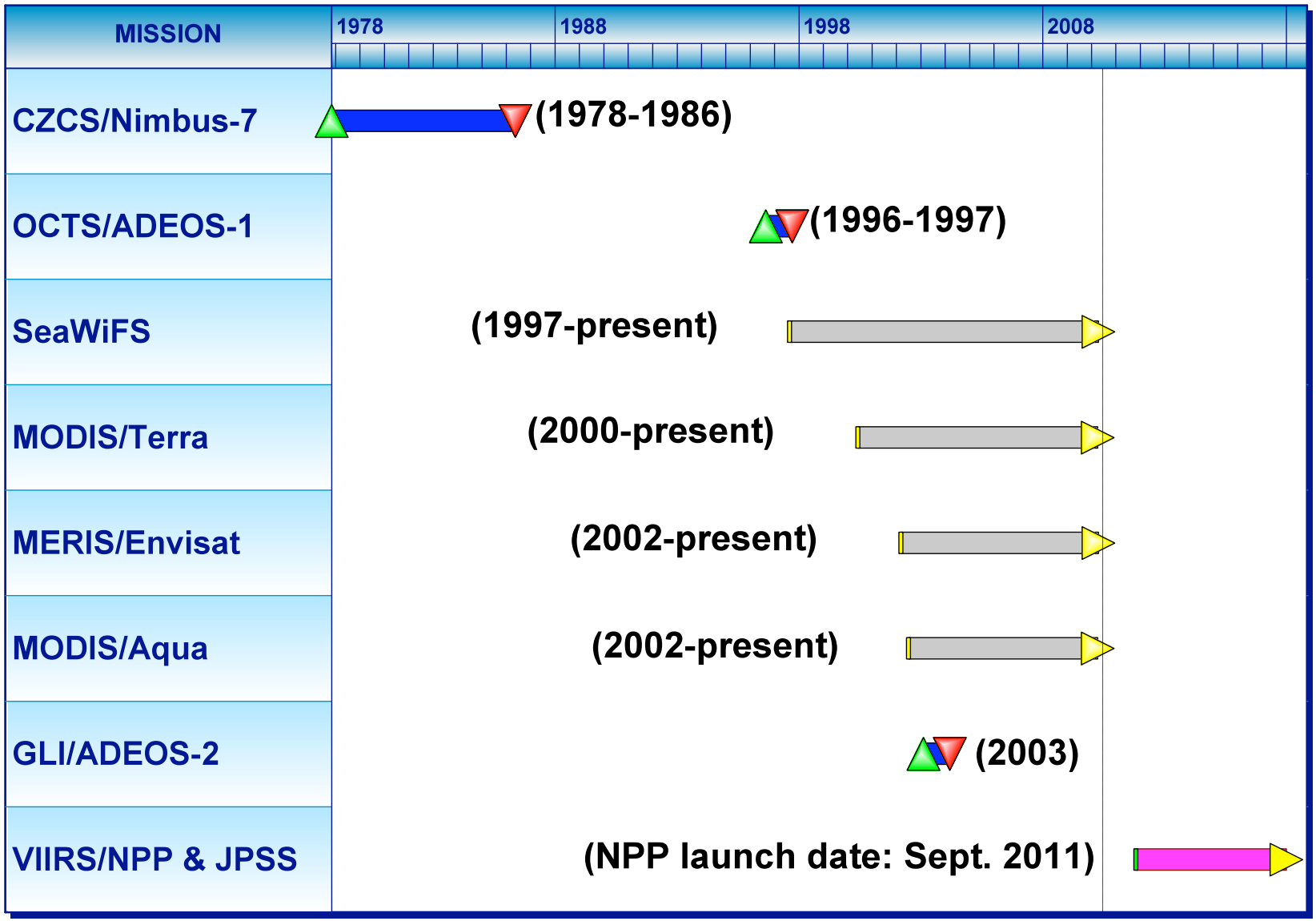
Global Biosphere Derived from SeaWiFS



Major Ocean Color Missions (1978-2016)

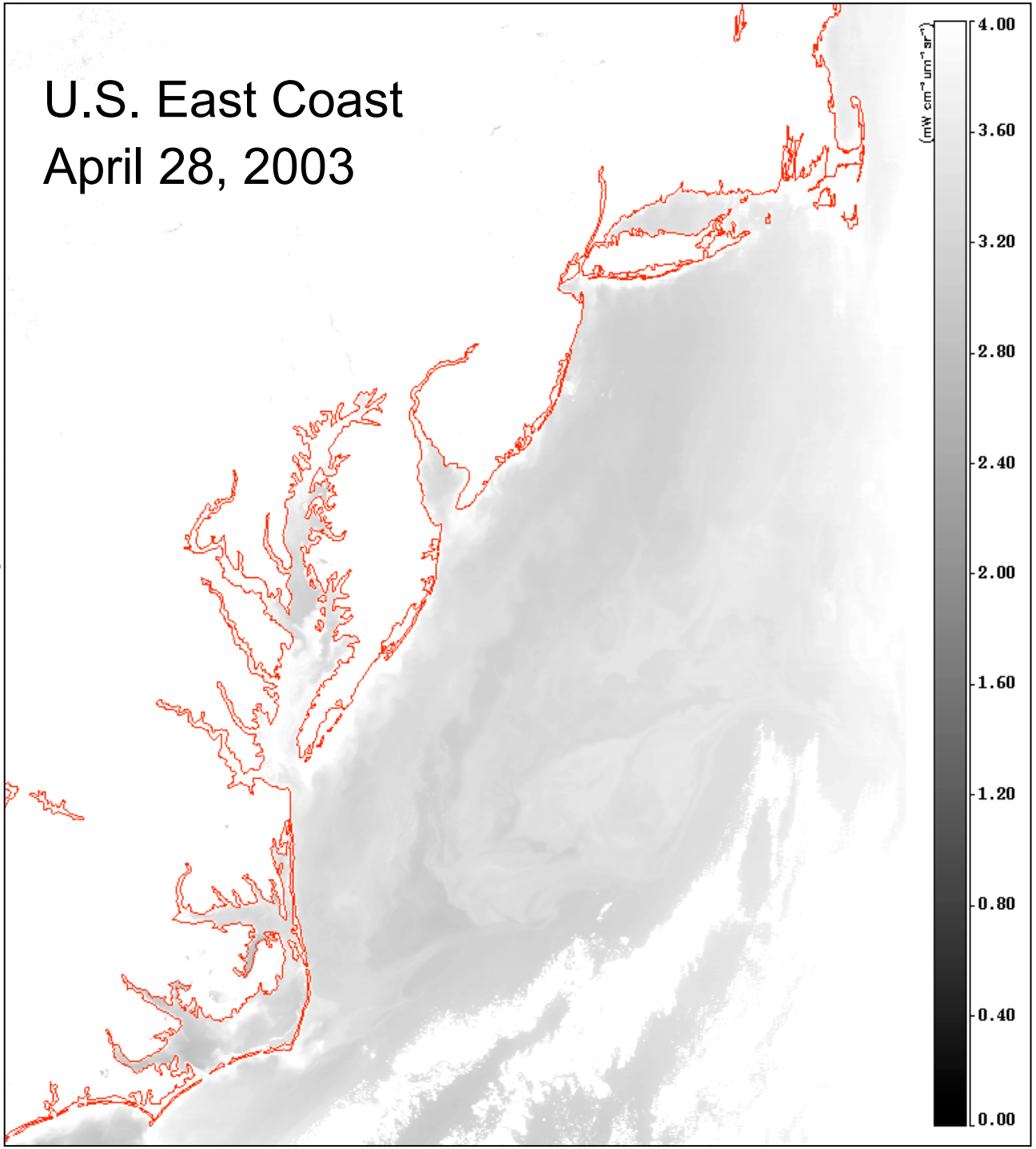


ESA Sentinel-3 & VIIRS/JPSS launch dates TBD.

Green wavelength
551 nm

Total top-of-the-atmosphere radiance

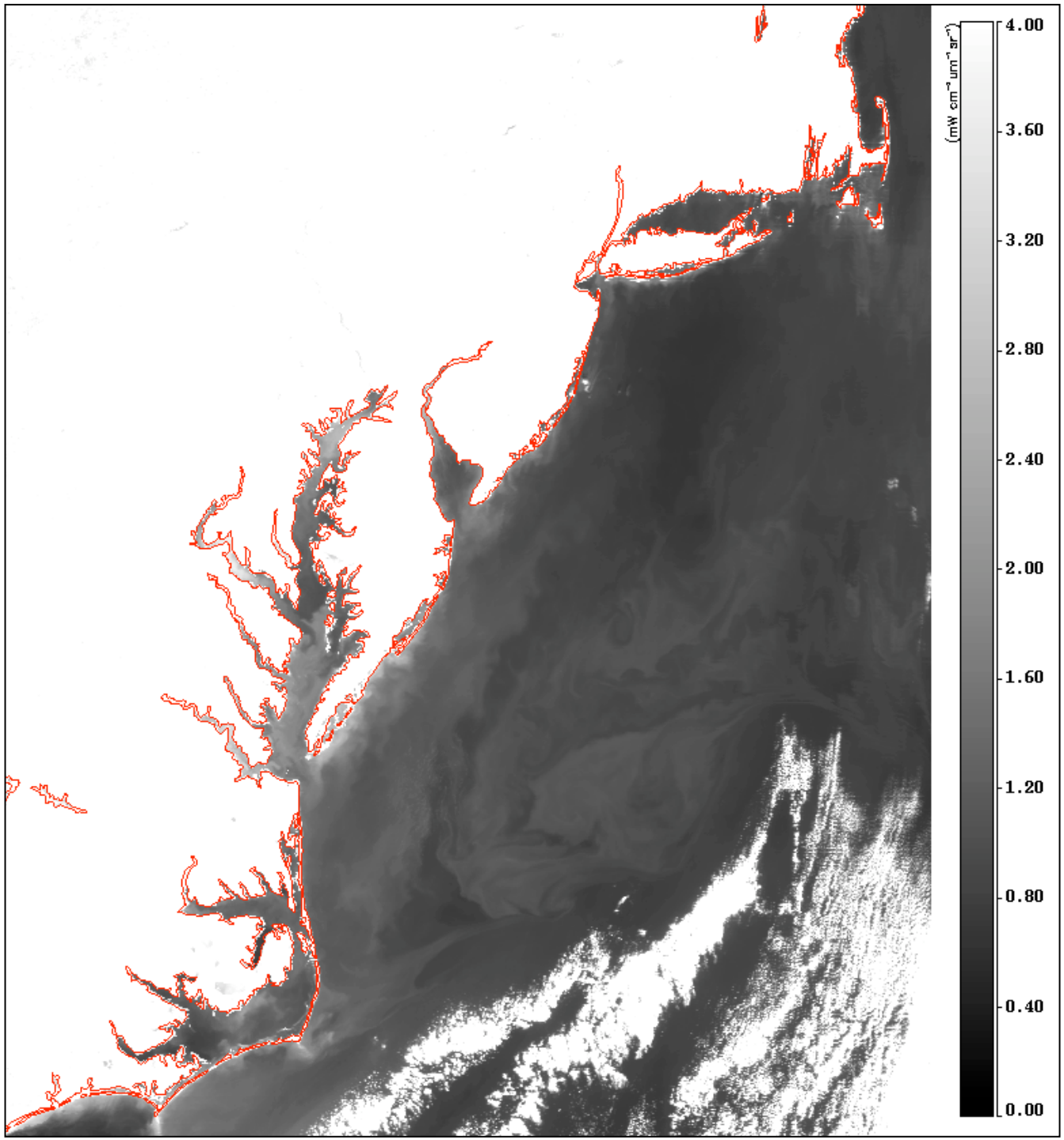
0 – 4 $mW/cm^2\ sr\ \mu m$



Green wavelength
551 nm

Total top-of-the-atmosphere radiance corrected for ozone absorption and Rayleigh (gas molecule) scattering

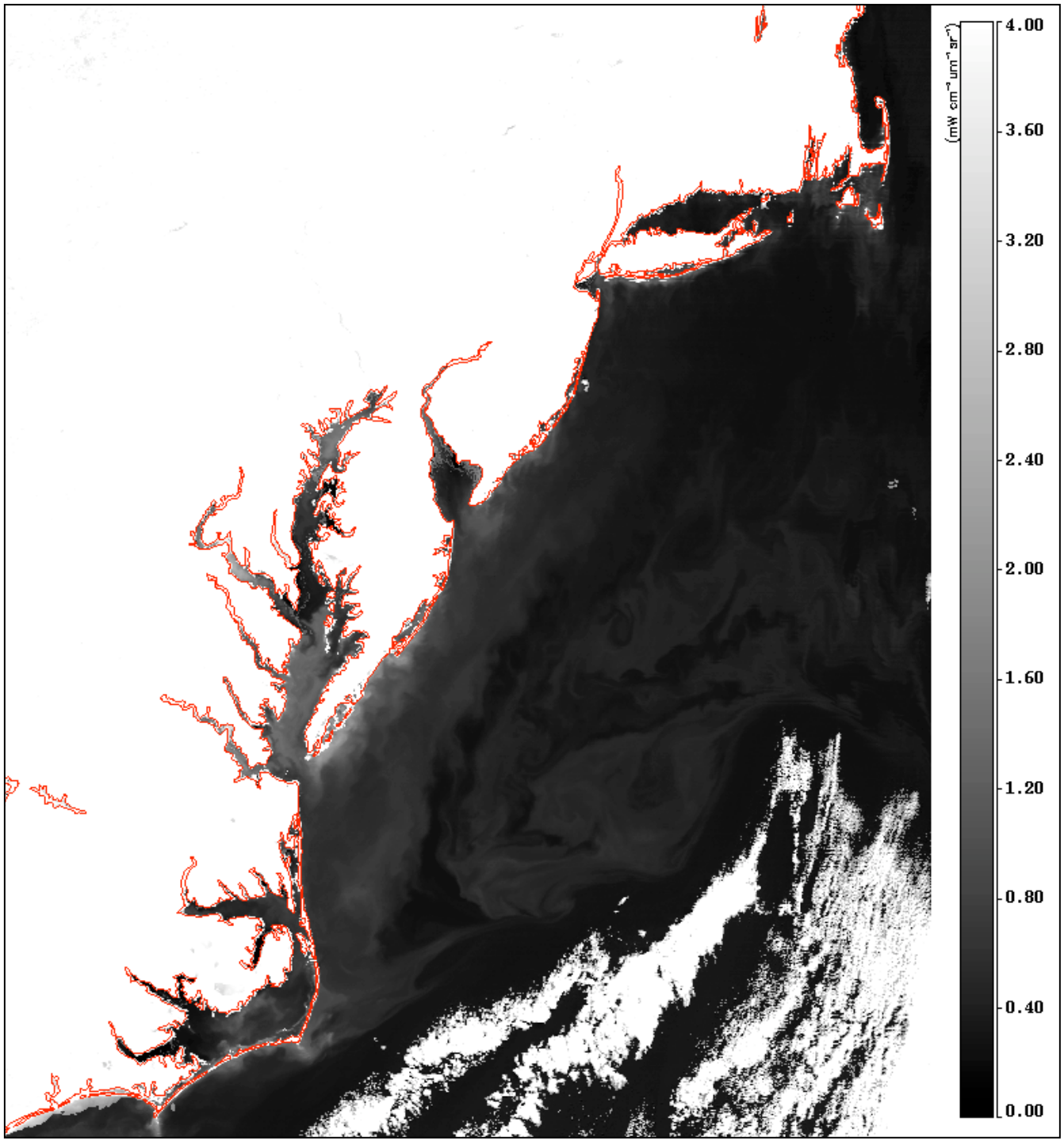
0 – 4 $mW/cm^2\ sr\ \mu m$



Green wavelength
551 nm

Total top-of-the-atmosphere radiance corrected for ozone absorption, Rayleigh & aerosol scattering

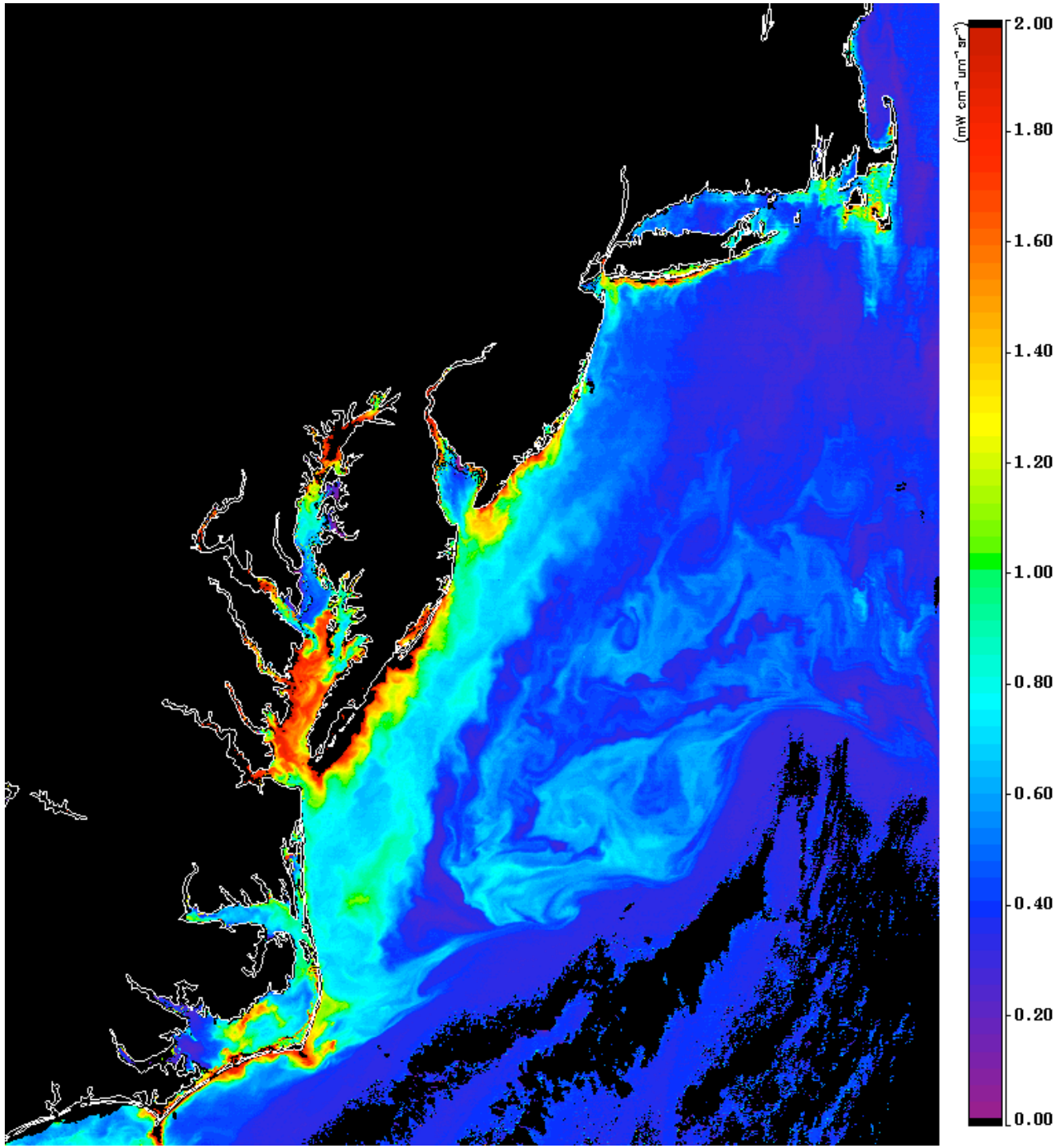
0 – 4 $mW/cm^2\ sr\ \mu m$



Green wavelength
551 nm

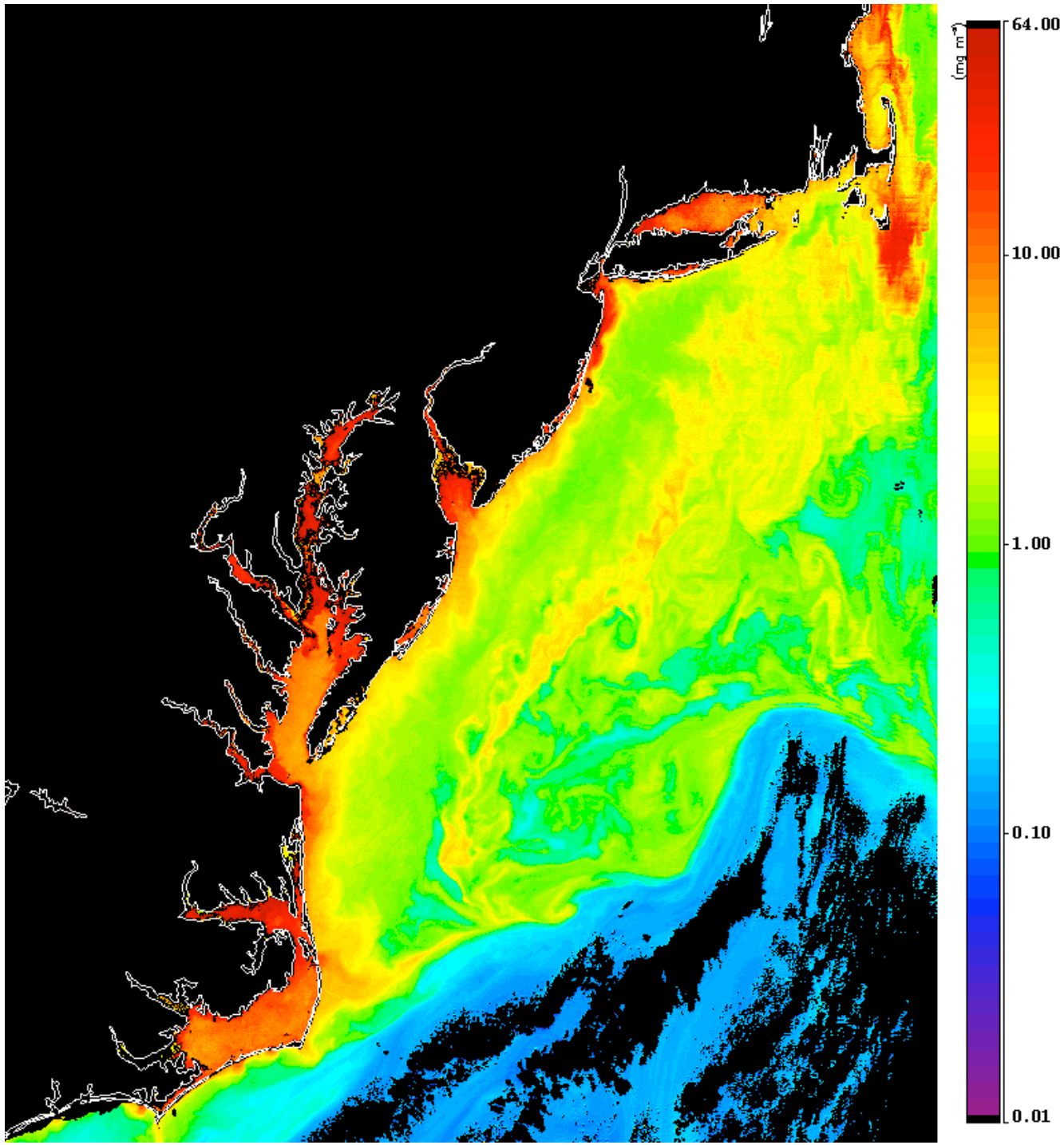
Normalized water-leaving radiance

$0 - 2\ {}^{mW}/_{cm^2\ sr\ \mu m}$



Chlorophyll-a concentration

0 – 64 mg / m^3



ACE Ocean Ecosystems STM

Goddard Space Flight Center

Category	Focused Questions*	Approach	Measurement Requirements	Instrument Requirements	Platform Requirements	Other Needs
Ocean Biology	•What are the standing stocks, composition, & productivity of ocean ecosystems? How and why are they changing? [OBB1]	Quantify phytoplankton pigments, optical properties, functional groups, primary productivity using bio-optical models & chlorophyll	of chlorophyll fluorescence	350 to 755 nm NR for 15 nm nds UV & visible uorescence bands 10, 748 nm centers) 10 to 40 nm width atmospheric correction bands at 748, 765, 820, 540, 2135 nm ic temporal stability nonstrated prelaunch) track swath °): sun glint avoidance ensitive (<1.0%) 1 km spatial resolution @ nadir UV to NIR bands design lifetime	Orbit permitting 2-day global coverage of ocean radiometer measurements Sun-synchronous orbit with crossing time between 10:30 a.m. & 1:30 p.m. Storage and download of full spectral and spatial data Monthly lunar calibration at 7° phase angle through Earth observing port	Global data sets from missions, models, or field observations: *Measurement Requirements* (1) Ozone (2) Total water vapor (3) Surface wind velocity (4) Surface barometric pressure (5) NO_2 concentration (6) Vicarious calibration & validation ** (7) Full prelaunch characterization (2% accuracy radiometric) *Science Requirements* (1) SST (2) SSH (3) PAR (4) UV (5) MLD (6) CO_2 (7) pH (8) Ocean circulation (9) Aerosol deposition (10) run-off loading in coastal zone
	•What are the material exchanges between land & ocean? How do they influence coastal ecosystems, biogeochemistry & habitats? How are they changing? [OBB1,2,3]	Estimate particle abundance, distribution (PSD), &	assessing instrument stray light			
	•How do aerosols & clouds influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere and Earth system? [OBB2]	Compare ACE observations with ground-based and model biological properties, exchange in the coastal physical properties (e.g. SST, SSH, etc), and dynamics, horizontal	atmospheric correction. Subsurface polarized return	sol vertical resolution face resolution rization misalignment sr^{-1} aerosol backscatter sensitivity at 532 nm after averaging ding transient response attering capability; Receiver m; 0-120 m. angles: 60° to 140° Angle resolution: 5° Degree of polarization: 1%		
	•How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics? [OBB1,2]	Combine ACE ocean observations with models to (1) air-sea exchange of dissolved materials, & (2) impacts on aerosol properties		**Measurements** algorithm testing ols development, ent comparisons		
	•What is the distribution of algal blooms and their relation to harmful algal and eutrophication events? How are these events changing? [OBB1,4]	Assess ocean radiant heating and feedbacks	Measure key phytoplankton groups across ocean biomes (coast/open ocean)	2, PSDs, IOPs, able Fe concentrations		
		Conduct field sea-truth measurements and in validate retrievals from to near-shore environ	improve model process parameterizations, e.g. particle fluxes	**tem Modeling** s such as NPP, IOPs, and ntrations.		

Ecosystem stocks & changes

Changes in ocean biogeochemical cycles

Coastal systems & land-ocean exchanges

Ocean-atmosphere interactions

Interaction of ocean physics & ecosystems

Phytoplankton blooms & eutrophication

* ACE focused questions are traceable to the four overarching science questions of NASA's Ocean Biology and Biogeochemistry Program [OBB1 to OBB4] as defined in the document: *Earth's Living Ocean: A Strategic Vision for the NASA Ocean Biological and Biogeochemistry Program* (under NRC review)

** See ACE Ocean Ecosystem white paper for specific vicarious calibration & validation requirements

ACE Ocean Ecosystems STM

Goddard Space Flight Center

Derived Products:

- Normalized water-leaving radiances
- Chlorophyll-a
- Diffuse attenuation coefficient (490 nm)
- Inherent optical properties (IOPs)
- Spectral diffuse attenuation coefficient
- Spectral remote sensing reflectance
- Primary production
- Calcite concentration
- Colored dissolved organic matter (CDOM)
- Photosynthetically available radiation (PAR)
- Fluorescence line height (FLH)
- Euphotic depth
- Total suspended matter (TSM)
- Trichodesium concentration
- Particle size distributions & composition
- Phytoplankton carbon
- Dissolved organic matter/carbon (DOM/DOC)
- Physiological properties (e.g., C:Chl, fluoresence quantum yields, growth rates)
- Taxonomic group distributions
- Export production
- Additional phytoplankton pigments (TBD)

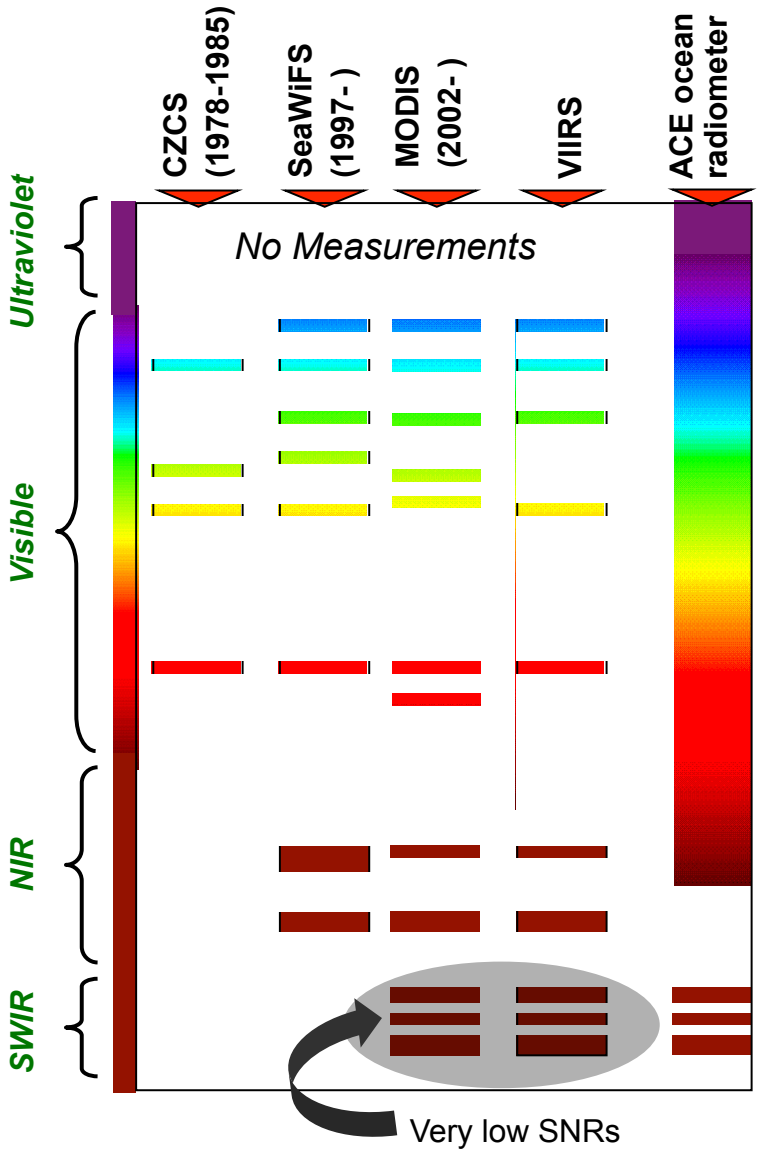
			•Maps to •Science •Question	Measurement Requirements	Instrument Requirements	Platform Requir'ts	Other Needs
		...omass, ...s, key ... and ...cal ...rescence	•1 •2 •6	Water-leaving radiances in near-ultraviolet, visible, & near-infrared for separation of absorbing & scattering constituents and calculation of chlorophyll fluorescence Total radiances in UV, NIR, and SWIR for atmospheric corrections Cloud radiances for assessing instrument stray light	**Ocean Radiometer** 5 nm resolution 350 to 755 nm 1000 – 1500 SNR for 15 nm aggregate bands UV & visible and 10 nm fluorescence bands (665, 678, 710, 748 nm centers) 10 to 40 nm width atmospheric correction bands at 748, 765, 820, 865, 1245, 1640, 2135 nm 0.1% radiometric temporal stability (1 month demonstrated prelaunch) ±±58.3° cross track swath Sensor tilt (±20°): sun glint avoidance Polarization insensitive (<1.0%) 1 km spatial resolution @ nadir No saturation in UV to NIR bands 5 year minimum design lifetime	Orbit permitting 2-day global coverage of ocean radiometer measurements Sun-synchronous orbit with crossing time between 10:30 a.m. & 1:30 p.m. Storage and download of full spectral and spatial data Monthly lunar calibration at 7° phase angle through Earth observing port	Global data sets from missions, models, or field observations: *Measurement Requirements* (1) Ozone (2) Total water vapor (3) Surface wind velocity (4) Surface barometric pressure (5) NO_2 concentration (6) Vicarious calibration & validation •** (7) Full prelaunch characterization (2% accuracy radiometric) *Science Requirements* (1) SST (2) SSH (3) PAR (4) UV (5) MLD (6) CO_2 (7) pH (8) Ocean circulation (9) Aerosol deposition (10) run-off loading in coastal zone
		...ssolved ...rishes	•2 •3				
		...emical ...es	•2 •4				
		...e, size ...acteristics	•3 •2				
		...ns in ...el fields ...ea CO_2	•2	High vertical resolution aerosol heights, optical thickness, & composition for atmospheric corrections Subsurface particle scattering & depth profile	**Lidar** 0.5 km aerosol vertical resolution 2 m sub-surface resolution < 0.3% polarization misalignment 0.0001 $km^{-1}sr^{-1}$ aerosol backscatter sensitivity at 532 nm after averaging < 4 ns e-folding transient response Brillouin scattering capability; Receiver FOVs: 0-60 m; 0-120 m.		
		...s with ...ata of ...ocean ...e, ...inds, ...tion (ML ...gence, etc)	•3 •4 •5 •6				
		...nosphere ...o evaluate ...ticulates, ...ses and ...oud	•4	Broad spatial coverage aerosol heights and single scatter albedo for atmospheric correction. Subsurface polarized return for typing oceanic particles	**Polarimeter** Observation angles: 60° to 140° Angle resolution: 5° Degree of polarization: 1%		
		...g and	•5	**Supporting Field & Laboratory Measurements** Primary production (NPP) measurement & round-robin algorithm testing Inherent optical properties (IOPs) instrument & protocols development, laboratory & field (coastal and open ocean) measurement comparisons Measure key phytoplankton groups across ocean biomes (coast/open ocean) Expanded global data sets of NPP, CDOM, DOM, pCO2, PSDs, IOPs, fluorescence, vertical organic particle fluxes, bio-available Fe concentrations		
	eutrophication events? How are these events changing? [OBB1,4]	Conduct field sea-truth measurements and modeling to validate retrievals from the pelagic to near-shore environments	•1 •2 •3 •4 •5 •6	**Ocean Biogeochemistry-Ecosystem Modeling** Expand model capabilities to assimilate variables such as NPP, IOPs, and phytoplankton species/functional group concentrations. Improve model process parameterizations, e.g., particle fluxes			

•*ACE focused questions are traceable to the four overarching science questions of NASA's Ocean Biology and Biogeochemistry Program [OBB1 to OBB4] as defined in the document: *Earth's Living Ocean: A Strategic Vision for the NASA Ocean Biological and Biogeochemistry Program* (under NRC review)

•**See ACE Ocean Ecosystem white paper for specific vicarious calibration & validation requirements

ACE Ocean Ecosystem Radiometer: Minimum Requirements

- 5 nm resolution 350 to 775 nm (functional group derivative analyses)
- 300 – 1000:1 SNR aggregate bands UV & visible
  - 300:1 for 350 nm @ Ltyp
  - 1000:1 for bands between 360- 710 nm @ Ltyps
  - 1400:1 SNR for 678 @ Ltyp (chlorophyll fluorescence band)
- 10 to 40 nm bandwidth aerosol correction bands at 748, 765, 820, 865, 1245, 1640, 2135 nm
  - 600:1 SNR for 748, 765, 820 & 865 nm @ Ltyps
  - 250:1 SNR at 1245 nm and 1640 nm, 100 SNR at 2135 @ Ltyps
- Stability
  - 0.1% radiometric stability knowledge (mission duration)
  - 0.1% radiometric stability (1 month prelaunch verification)
- 58.3^{o} cross track scanning
- Sensor tilt (±20^{o}) for glint avoidance
- Polarization: < 1.0% sensor radiometric sensitivity, < 0.2% prelaunch characterization accuracy
- < 2% prelaunch radiance calibration accuracy (minimum)
  - Goal: 0.5% prelaunch calibration accuracy
- 1 km spatial resolution @ nadir
- No saturation in UV to NIR bands
- 5 year minimum design lifetime



ORCA Development Team

- **Science**
  - Chuck McClain, PI
  - Mike Behrenfeld (Oregon State U.)
    - Ocean Science Lead
  - Steve Brown (NIST)
    - System-level Test Lead
  - Jim Butler
    - sensor calibration
- **Engineering**
  - Leroy Sparr: Instrument Manager
  - Bryan Monosmith: Instrument Scientist
  - Mark Wilson: Optics Lead
  - Pete Shu: Detector Lead
  - Ken Blumenstock: Electro-mech. Lead
  - Manuel Quijada: Component & Subsystem Test Lead
  - Alan Holmes (private consultant)
    - SeaWiFS development lead

Other participants: Patrick Thompson (optical design), Gerhard Meister (ocean specifications), Brian Martin (instrument layout), Tim Madison (fabrication & alignment), Pete Petrone (component testing & alignment)

ORCA Development History

- NASA carbon program formulation: 2000-2001
  - Carbon cycle missions/sensors included an advanced ocean biology sensor
- ESSP formulation: 2003-2006
  - **PhyLM** (Physiology Lidar-Multispectral Mission): Ocean Biology Radiometer plus Aerosol Lidar
  - **OCEaNS** (Ocean Carbon, Ecosystems, and Near-Shore Mission: ocean biology radiometer, aerosol lidar, & polarimeter
  - 2 ISAL sessions (SeaWiFS-like filter radiometer, prism spectrometer)
- HQ Decadal Survey Mission Studies: 2006-2007
  - **GOCECP** (Global Ocean Carbon, Ecosystems, & Coastal Processes): Ocean Biology Radiometer only
    - ISAL session (3rd), grating spectrometer
  - **ACE** (Aerosol, Cloud, & Ecology): Ocean Biology Radiometer, Polarimeter, Aerosol Lidar, Cloud Radar
- 2008 IR&D Study: ORCA prototype development
  - Blue channel breadboard only (335-590 nm)
  - 3.3 FTEs & over $100K in procurements
- Instrument Incubator Program (FY09-11): ORCA prototype development
  - Red channel (570-885 nm) breadboard integration with blue channel
  - Scan mechanisms
  - System-level testing at NIST
- 2009 IR&D proposal: ORCA Shortwave-IR (SWIR) band development
  - Integration of two SWIR bands into ORCA prototype
  - 1.0 FTE & $55K in procurements
- ACE mission formulation (underway): Spectral band revisions
  - 26 recommended bands vs. 19 originally specified for ORCA
  - Instrument Design Lab (4th) completed in April 2009

ORCA IIP Objectives

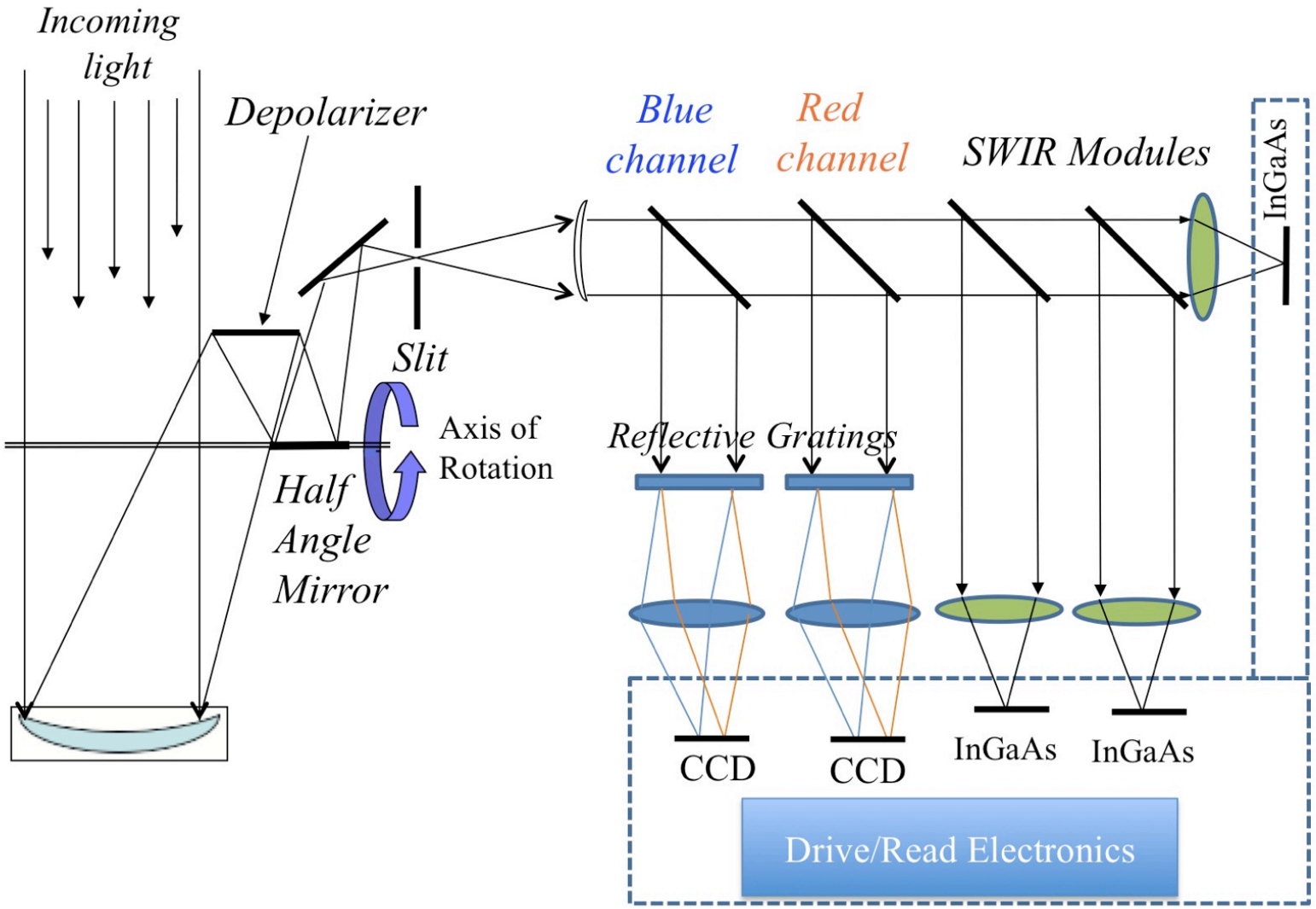
- **Primary Goals**
  - Refine component specifications and component test requirements/procedures to ensure compliance with desired performance.
    - perform component & subsystem level tests
  - Design & package ORCA in a flight-like configuration to evaluate:
    - overall design concept
    - component and system level performance
    - design challenges/deficiencies, e.g., polarization sensitivity, saturation radiances, image quality, and signal-to-noise
  - Conduct system-level calibration & characterization at the National Institute of Standards and Technology (NIST) to ensure:
    - Ensure test procedures and equipment are sufficiently mature to meet ocean performance specs.
    - Evaluate ORCA performance wrt ACE ocean radiometer performance specs.
- **Development Philosophy**
  - Emphasize data quality above design simplicity
  - Avoid new technology
    - Use established flight qualified components & technologies wherever possible.
      - Reduces development time and risk
    - Use successful heritage design concepts (e.g., SeaWiFS rotating telescope/half angle mirror)

Overall Goal: Demonstrate prototype meets/exceeds ACE ocean performance specs

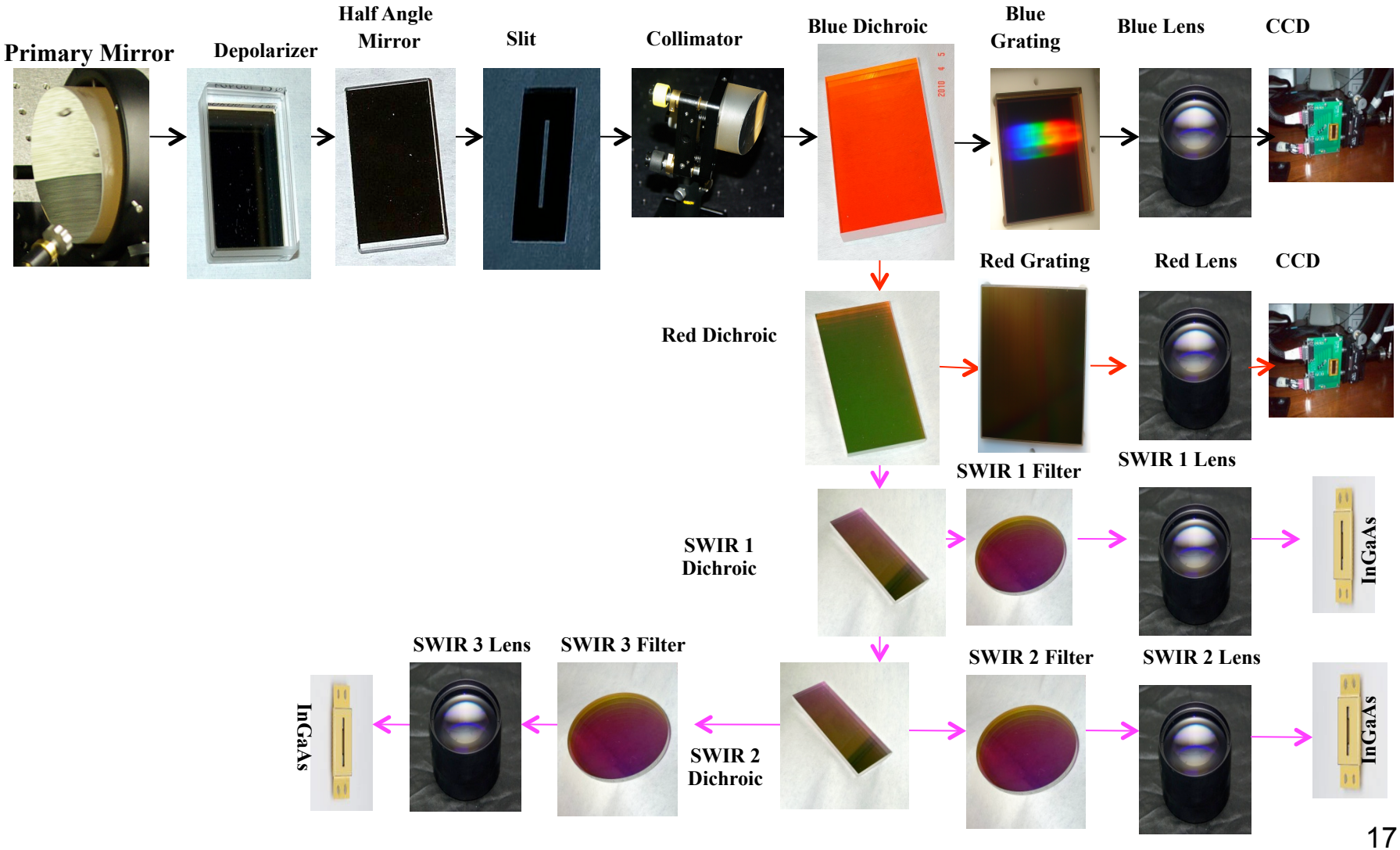
Accomplishments to Date

- **Optical design completed**
  - 3 SWIR bands added with internal funding
  - Stray light analyses conducted
- **All optical components purchased and tested**
  - Component testing at GSFC
  - All components meet or exceed specifications
- **Electromechanical devices purchased and tested**
- **All structural components designed, fabricated, & painted**
- **ORCA development laboratory established in Bldg. 28**
  - Equipped for fabrication, alignment, and preliminary testing
- **System assembled & fit checked**
- **System performance requirements & test protocols drafted**

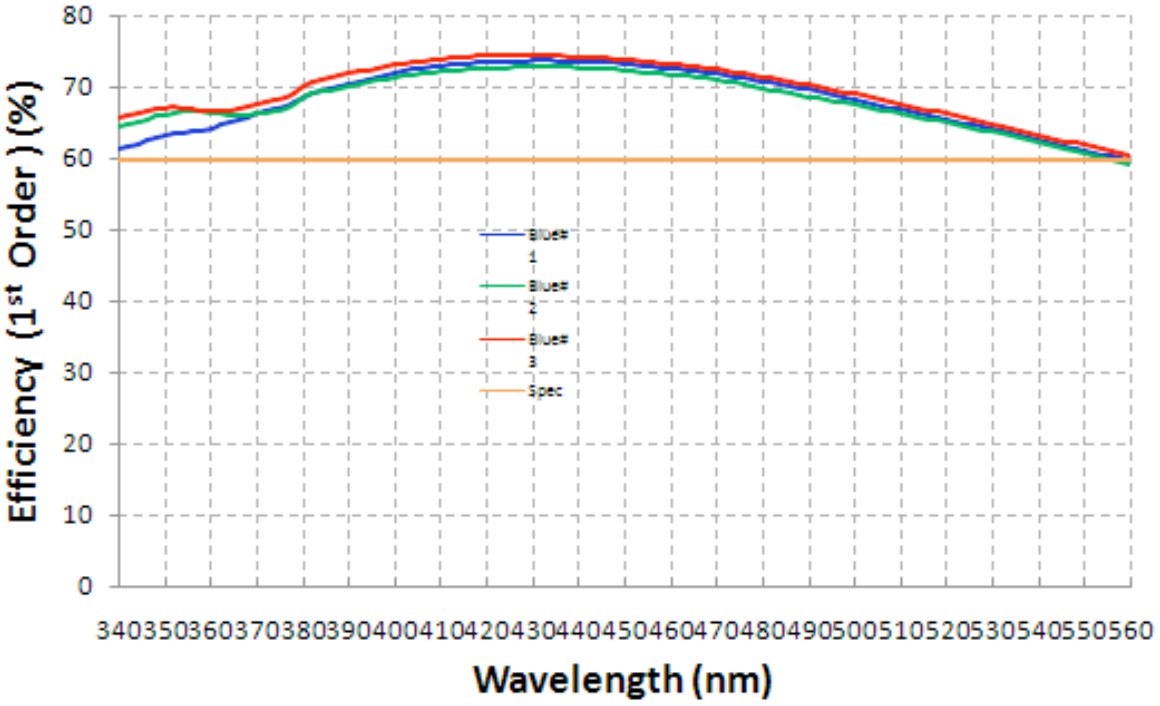
ORCA Functional Schematic



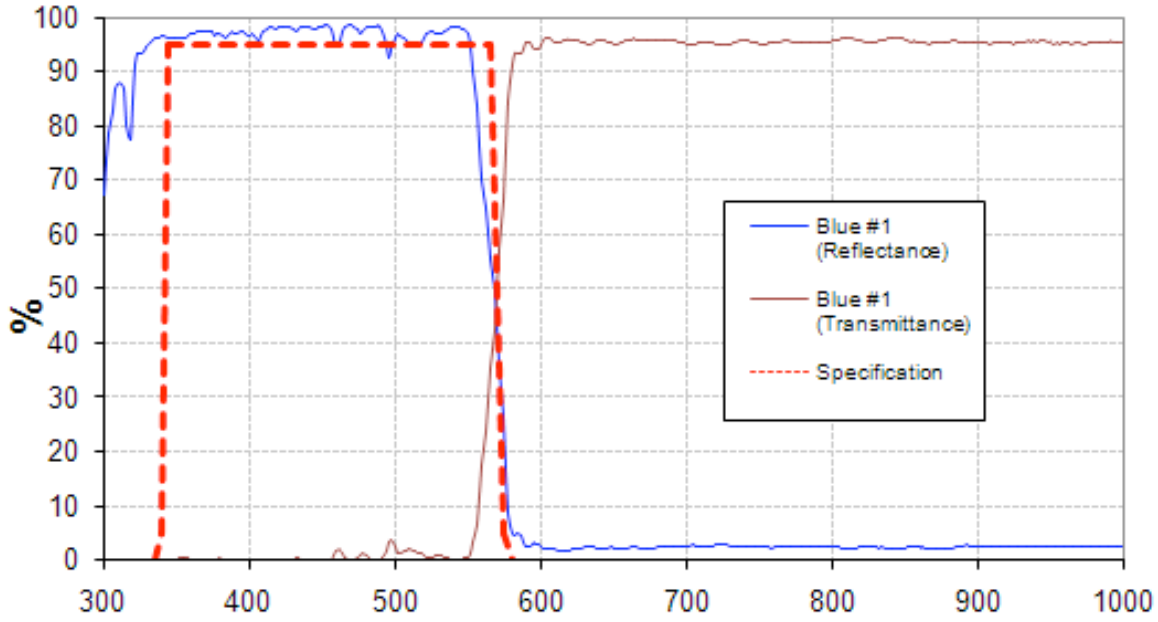
ORCA Components



Optical Component Performance



Blue Grating Efficiencies



Blue Dichroic Reflectance & Transmittance

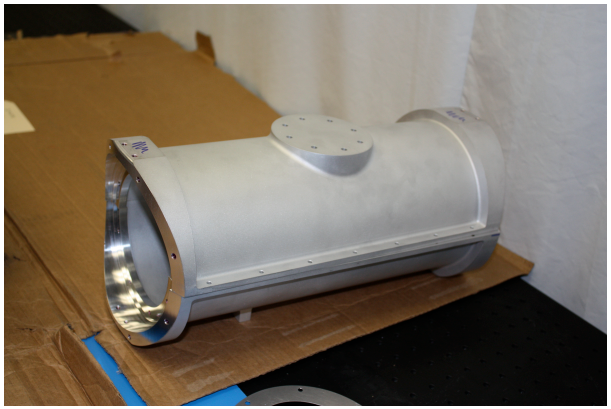
[illegible]	[illegible]	Ltyp	Lmax	ACE SNR-spec	ORCA SNR-model	SeaWiFS SNR	MODIS SNR
350	15	7.46	35.6	300	2020		
360	15	7.22	37.6	1000	2225		
385	15	6.11	38.1	1000	2370		
412	15	7.86	60.2	1000	3156	897	1861
425	15	6.95	58.5	1000	3006		
443	15	7.02	66.4	1000	3048	967	2487
460	15	6.83	72.4	1000	3062		
475	15	6.19	72.2	1000	2960		
490	15	5.31	68.6	1000	2740	1010	2672
510	15	4.58	66.3	1000	2575	1000	
532	15	3.92	65.1	1000	2192		2155
555	15	3.39	64.3	1000	2011	870	2271
583	15	2.81	62.4	1000	2203		
617	15	2.19	58.2	1000	2010		
640	10	1.90	56.4	1000	1660		
655	15	1.67	53.5	1000	1830		
665	10	1.60	53.6	1000	1562	570	1839
678	10	1.45	51.9	1400	1510		2070
710	15	1.19	48.9	1000	1616		
748	10	0.93	44.7	600	1305		1311
765	40	0.83	43.0	600	2512	522	
820	15	0.59	39.3	600	1200		
865	40	0.45	33.3	600	1640	364	1285
1245	20	0.088	15.8	250	415		51
1640	40	0.029	8.2	250	273		39
2135	50	0.008	2.2	100	146		24
Wavelength units: nm, Radiance units: mW/cm^2 nm str							

ORCA SNRs:

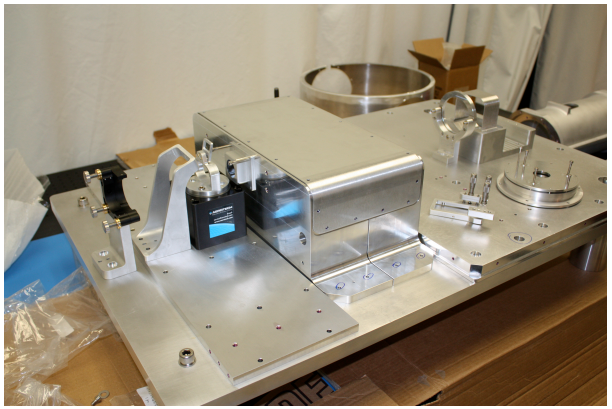
- measured optical component parameters
- vendor detector array performance characteristics (conservative values used)

ORCA exceeds ACE ocean radiometer SNR specs at all wavelengths.

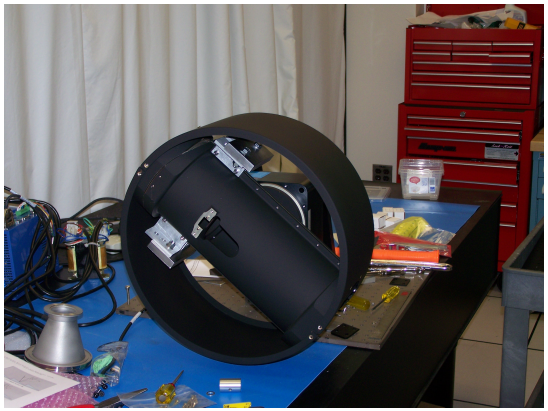
ORCA: Fabrication & Alignment



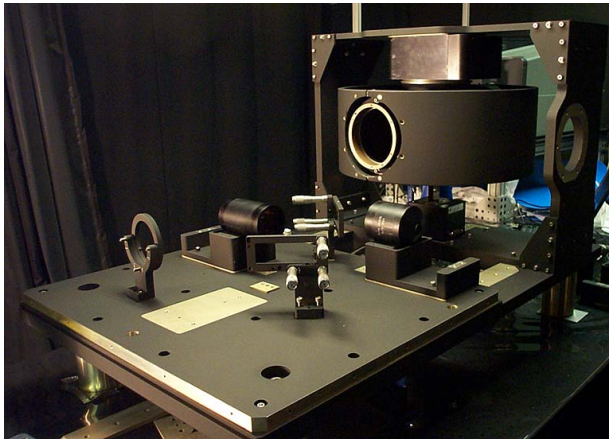
Telescope Housing



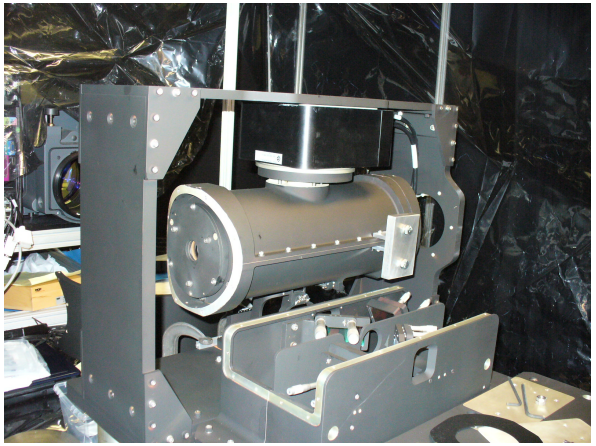
Optical Bench



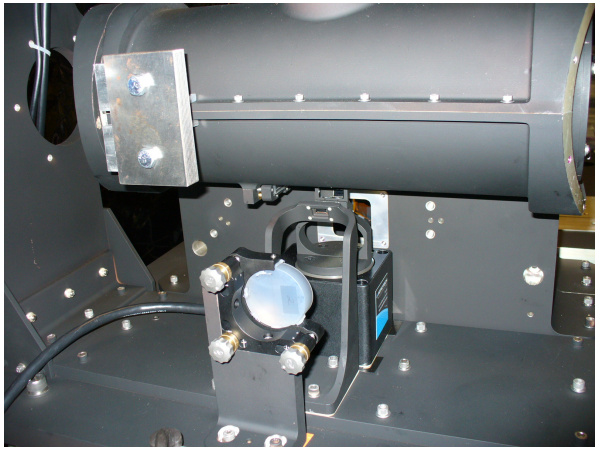
Telescope Static Balance



Telescope & Shield



Telescope & Spectrographs



Collimator

Path to Flight-like ORCA Prototype

- **Current IIP support**
  - Complete fabrication & alignment
  - Complete data acquisition & analysis software
  - Complete optical system testing at GSFC & NIST
- **Future funding (TBD)**
  - Purchase & integrate **flight-like CCDs** (blue & red channels) **and linear arrays** (SWIR bands)
    - CCDs and linear arrays are custom manufactured
  - Design & integrate flight-like electronics and data system
  - Verify synchronization of rotating telescope, half-angle mirror, and focal plane electronics readouts at flight data rates (6 Hz scan rate, full swath)
  - Design, build, & test solar diffuser/spectral calibrator apparatus