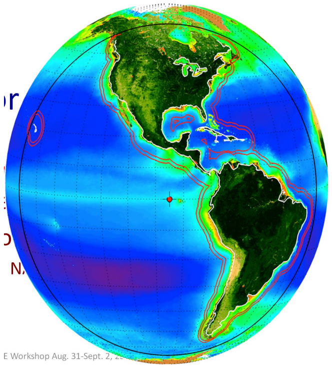
Ocean Color Science Working Group

Antonio Mannino

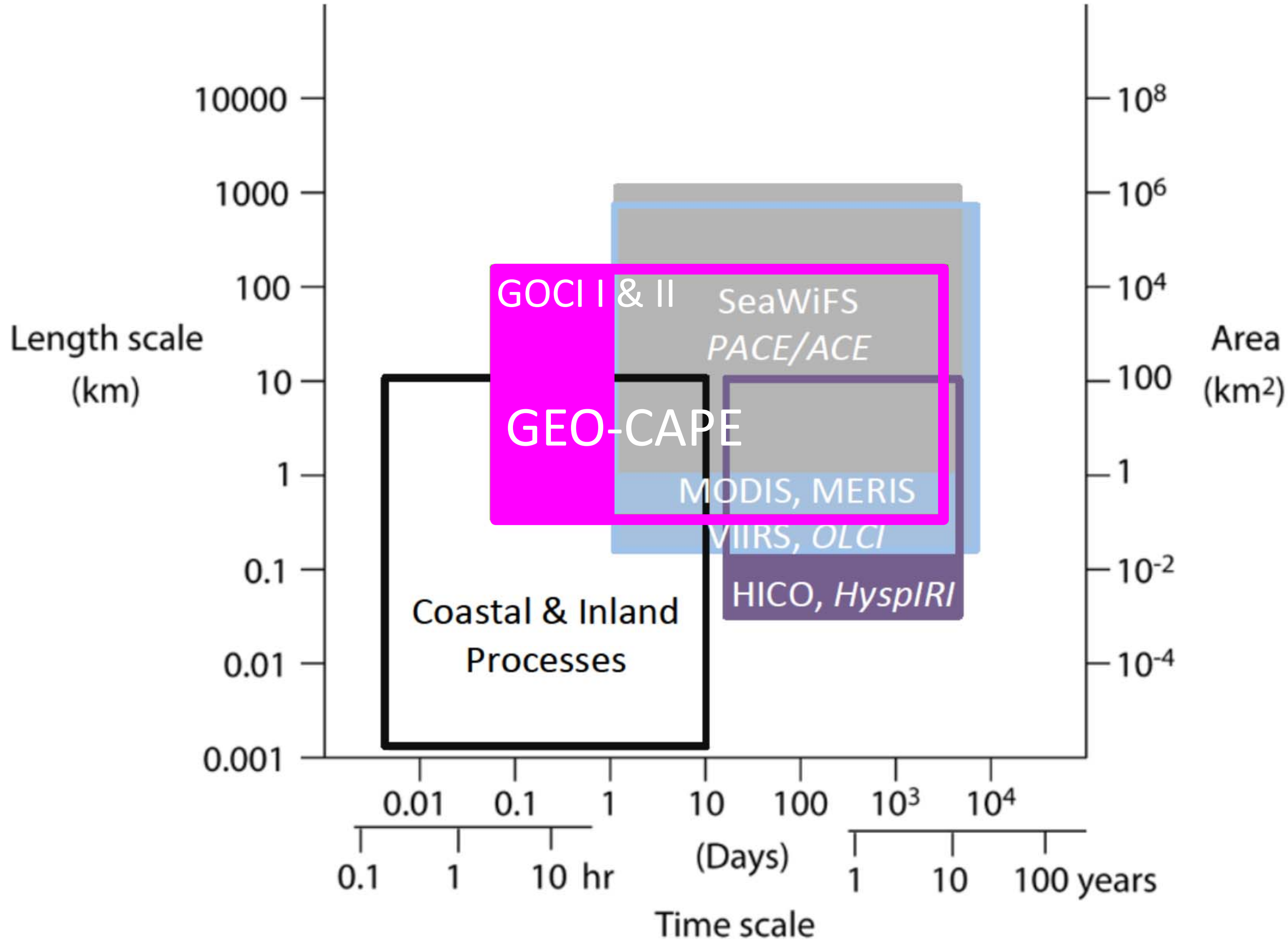
NASA GSFC



GEO-CAPE Oceans Activities

- **Science Working Group Activities**
  - Science Traceability Matrix
  - Applications Traceability Matrix
  - Science Value Matrix Development
  - White Papers
  - PI-led scientific investigations
  - Field Campaigns
    - Chesapeake Bay - July 2011 (CBODAQ)
    - Gulf of Mexico Experiment - September 2013 (GoMEX)
    - Korean coastal waters - May-June 2016 (KORUS-OC) - joint w/ KIOST
- **Recent Engineering Studies**
  - 2011 Pointing Study
  - 2014 Instrument Cost vs Capability study
  - 2015-2016 Functional 50-band filter wheel breadboard
  - 2015 Scheduling Study
- **Outreach**

Time & Space Scales of OC Missions



from Mouw et al., Remote Sens. Environ, In revision
Synthesis of 2012 Workshop for Remote Sensing of Coastal and Inland Waters

Modifications to STM

- Survey Threshold: <2 hours
- Geostationary orbit Threshold: 94°±2° W longitude; Baseline: 94°±1° W
- Threshold pointing stability <25% of pixel
- Threshold geolocation <50% of pixel
- Scanning Priority
  1. Survey of U.S. Coastal Waters
  2. Other coastal and large inland bodies of water
  3. Open ocean waters within FOR
- No consensus on spectral capability

Measurement & Instrument Requirements

	Threshold (minimum)	Baseline (goal)
Temporal Resolution Targeted Events	<1 hour	<0.5 hour
Survey Coastal U.S.	<2 hours	<1 hour
Spatial Resolution (nadir)	375 m x 375 m	250 m x 250 m
Spectral Range	345-1050 nm; 2 SWIR bands 1245 & 1640 nm	340-1100 nm; 3 SWIR bands 1245, 1640, 2135 nm
Scan Rate	>25,000 km^2/min	>50,000 km^2/min
Spectral Resolution	UV-VIS-NIR: ≤5 nm; 400-450nm: ≤0.8nm (NO_2); SWIR: ≤20-40 nm	UV-VIS: ≤0.75 nm; SWIR: ≤20-50 nm
Signal-to-Noise Ratio (SNR) @ Ltyp for 70° solar zenith angle	1000:1 for 350-800 nm (10nm FWHM); 600:1 for NIR (40nm FWHM); 250:1 & 180:1 for 1245 & 1640 nm (20 & 40nm FWHM); ≥500:1 NO_2	1500:1 for 350-800 nm; 100:1 for 2135nm (50nm FWHM); NIR, SWIR and NO_2 same as threshold

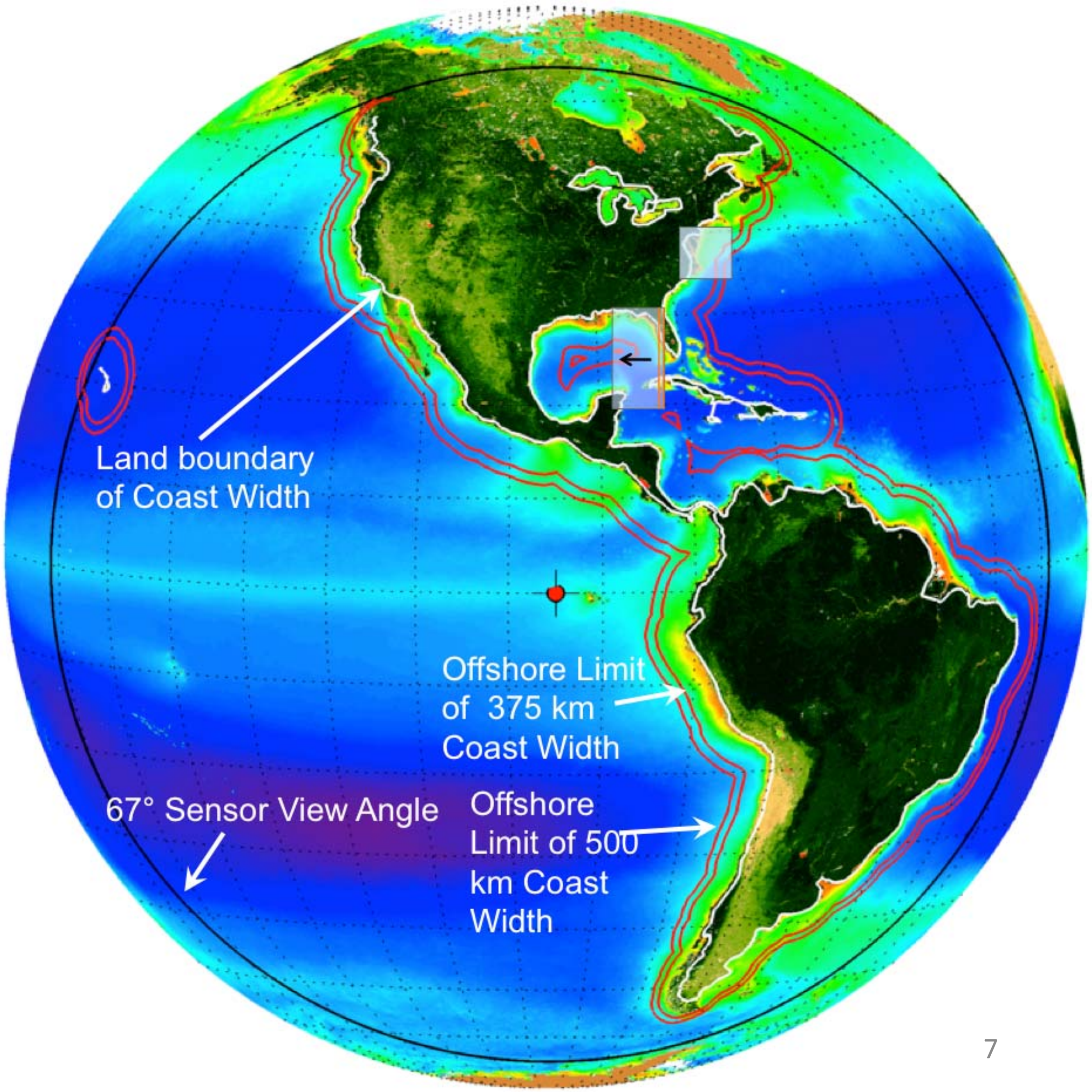
Competing Technical Challenges

Challenge: achieving an engineering solution for requirements that are in opposition to each other

- Spatial resolution
- Temporal resolution
- Spectral resolution
- Hyperspectral

Instrument concepts

- Filter radiometer (GOCI)
- Single slit spectrometer
- Multi-slit spectrometer
- Wide Field-of-View spectrometer



2014 Instrument capability vs cost study

1) IDL pre-costing (using NICM - mass, power, telemetry) to narrow instrument design options

- Select most viable instrument types for optical design lab

2) Optical Design Lab (ODL)

- Develop optical designs for new sensor concepts with a limited set of capability permutations (GSD, etc.).
- Select most viable designs for IDL study

3) Extended IDL study on Wide-Angle Spectrometer (WAS)

4) IDL study on Filter-wheel Radiometer (FR)

5) IRAD supported 2-day IDL re-fresh of GSFC concept

6) Architecture Scaling Study

- Scale IDL designs by capability trade space and cost these alternate designs using NICM.

Input to Pre-costing - 2011 Informal RFI

		Raytheon GLIMR	Raytheon GOI	Ball MOS	GSFC COEDI	JPL COCOA	GSFC CEDI IDL Jan. 2010
GSD at nadir (m)		250 x 250	225 x 225	375 x 375	375 x 375	200 x 200	375 x 375
Spectral Range (multi- or hyper-spectral)		340-885 980-2200	340-885 980-2200	340-900 SWIR bands	340-1100 SWIR bands	350-1050 nm	340-1100 1.2-2.5
Spectral sampling & resolution (nm)		~5nm (HS) SWIR 20-50	~5nm (HS) SWIR 20-50	~5 nm	~0.4/0.8 nm SWIR 20-40	<5 nm multi-spectral	0.5 nm SWIR – 5
iFOV (E/W x N/S pixels)		1 x 8192	1 x 8192	1 x 2048	1 x 2048	2048 x 2048	1 x 2048
iFOV Stare Interval		4 sec	0.9 sec	4 sec	0.8 sec	0.2 sec	0.8 sec
SNR 1000 required	@443nm; 10nm FWHM; Ltyp = 45 W m^{-2} um^{-1} sr^{-1}	2310	2500	2320	1748	1000	2148
	@678nm; 10nm FWHM; Ltyp=8.66 W m^{-2} um^{-1} sr^{-1}	1150	1200	1866	1031	800	1195
Time to scan $3x10^5$ km^2 @ SNR & Ltyp listed above **Scan Rate** (km^2 min^{-1})		26.4 min 11,364	10.9 min 27,523	6.1 min 49,180	17.36 min 17,281	11.96 min 25,084	17.8 min 16,854
Geo design life (years)		3	3	3	3	2	3
Power CBE		360 W	390 W		220 W	50 W	392 W
Size CBE (length x width x height)		0.7 x 0.6 x 0.8 m	1.7 x 1.5 x 2.0 m	1.5 x 1.5 x 1.7 m	1.5 x 1.7 x 1.1 m	Cylinder 0.9m dia. x 1.3 m	2.1 x 0.95 x 2.8 m
Mass CBE (kg)		132 kg	283 kg	147 kg	220 kg	71 kg	548 kg

Thanks to Jeff Puschell (Raytheon), Tim Valle & Paula Wamsley (Ball), Richard Key (JPL)

2014 Instrument capability vs cost study

	Hyperspectral Spectrometers	Multi-spectral Filter Radiometer
Instrument Type	Single Slit, Multi-slit, Wide-Angle	Filter Wheel Instrument
Spatial Resolution	250, 375 & 500 m	250, 375 & 500 m
Spectral Resolution	0.4 and 2 nm	5 nm
Spectral Range	340-1050 nm	50 bands: 340-1050
SWIR Bands	1245, 1640, 2135 nm	1245, 1640, 2135 nm
SNR (UV-Vis; 10 nm bands)	1000	1000

		(SZA = 70Υ)				
λo - nm	Δλ - nm	W/m^2-Δλum-ster		Req'd		
Bands	FWHM	Ltyp	Lmax	SNR$_{req}$	Required Minimum Set of Multi-Spectral Bands[1]	NOTES
350	15	46.90	166.2	1,000		
360	15	45.40	175.6	1,000	Yes	
385	15	38.40	177.9	1,000	Yes	
388^	0.8	33.00	177.9	500		For estimating SNR for NO2 retrievals
412	10	49.50	281.1	1,000	Yes	
425	10	48.20	277.0	1,000		
443	10	45.00	271.3	1,000	Yes	
460	10	41.90	266.0	1,000		
475	10	38.20	261.3	1,000		
490	10	34.90	256.6	1,000	Yes	
510	10	29.00	250.3	1,000	Yes	
532	10	23.30	243.4	1,000		
555	10	18.50	224.9	1,000	Yes	
583	10	15.30	227.4	1,000		
617	10	12.20	216.7	1,000	Yes	
640	10	10.50	209.5	1,000		
655	10	9.57	204.7	1,000		
665	10	9.17	201.6	1,000	Yes	
678	10	8.66	197.5	1,000	Yes	
710	10	6.95	187.5	1,000	Yes	
748	10	5.60	175.5	600	Yes	
765	40	5.25	170.2	600	Yes	
820	15	3.93	152.9	600		
865	40	2.77	138.8	600	Yes	
1020	40	1.48	109.1	450	Yes	
1245*	20	0.582	56.10	250		
1640*	40	0.178	19.70	180		
2135*	50	0.040	5.35	100		

[1] **Additional bands between 360-1020nm desirable; SNR should not be an issue for the additional bands.**

^ Pixels can be aggregated up to 3x3 to achieve required SNR of 500:1 for atmospheric NO2 retrievals

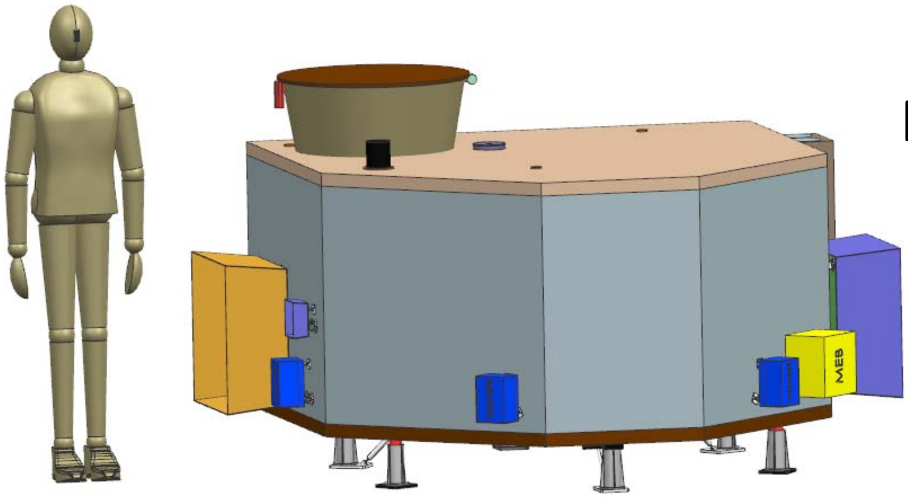
*** Pixels can be aggregated up to 2x2 to achieve required SNR**

2014 Instrument Study Cost Assumptions

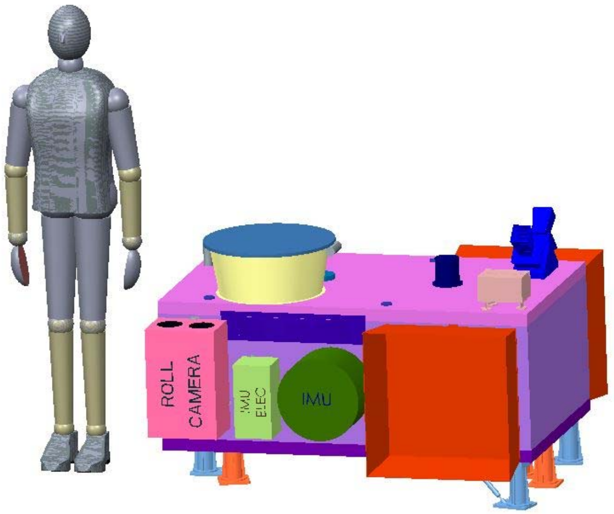
- **1 Flight Unit and Engineering Development Unit through PRICE-H**
- Engineering Test Units (ETUs) (10% of FU cost) and Component Spares covered by wrap factors
- Class C Mission (selective redundancy)
  - (Class B Parts – up-screening not included in cost estimate)
- 3 year design life (5-yr goal)
- Costs reported in FY2016 constant year dollars
- Instrument built by contractor
- Flight Software (FSW) Estimated using GSFC in-House bid rates
- SEER-H cost estimates for Detectors
- Schedule used: ATP: 12/17, CDR: 12/18, PER: 5/21; Launch 12/2023
- IDL study costs included HW and firmware to compensate for jitter and roll (star tracker, gyro, fast-steering mirror, passive struts, actuators and roll camera)
- **IDL provides instrument point design concepts with cost confidence level of 20-30% (rule of thumb to multiply by 1.5 to increase CL to 70%)**
  - **NICM system and sub-system versions provide 50% CL**

Instrument Relative Size

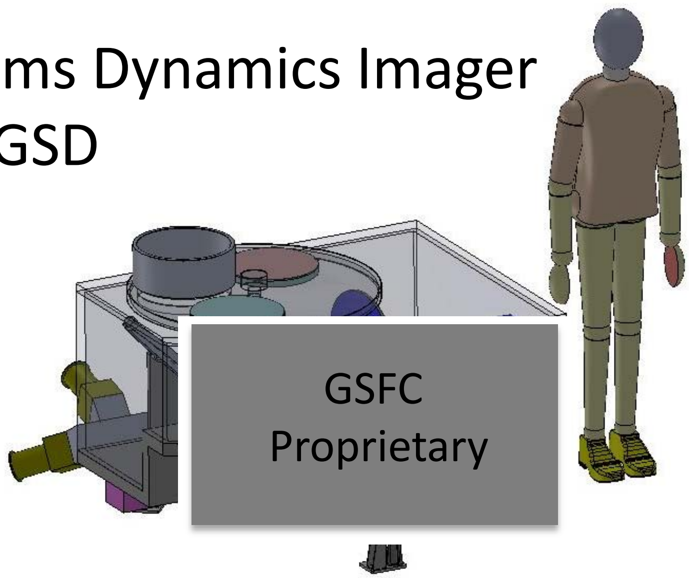
Wide-Angle Spectrometer (WAS) - 375m GSD



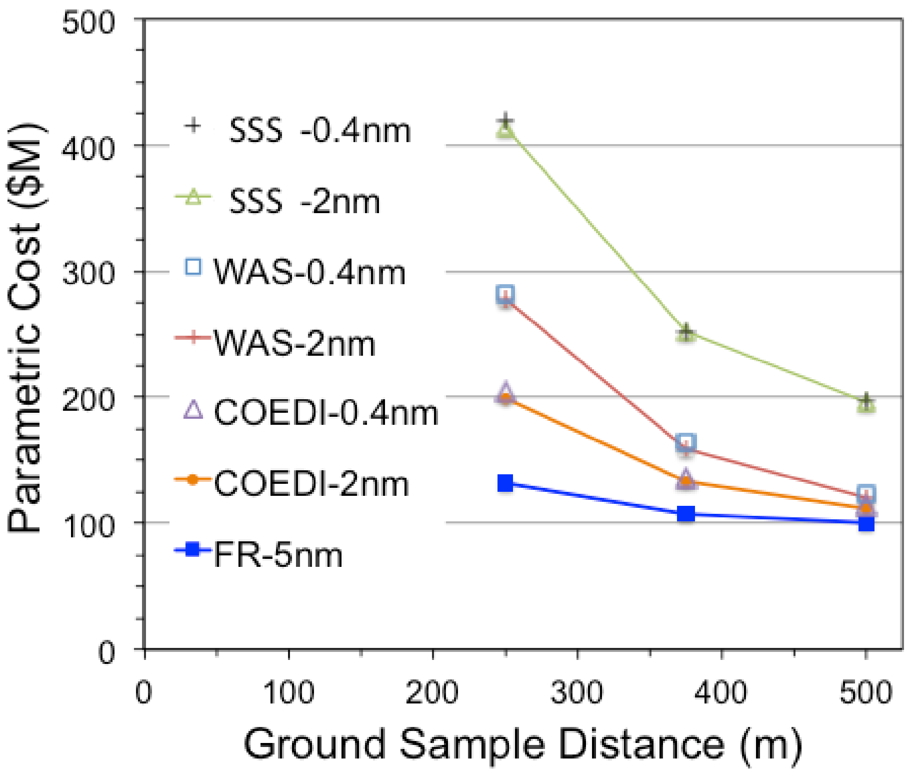
Filter Radiometer (FR) - 250m GSD



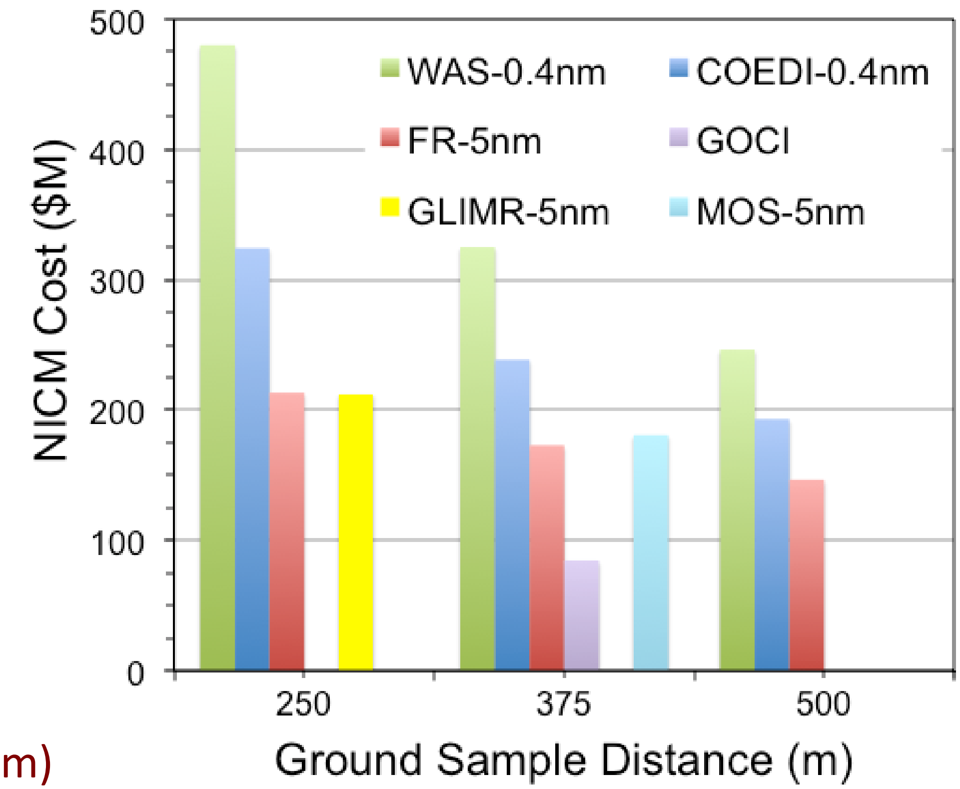
Coastal Ecosystems Dynamics Imager (COEDI) - 375m GSD



Instrument capability vs cost study



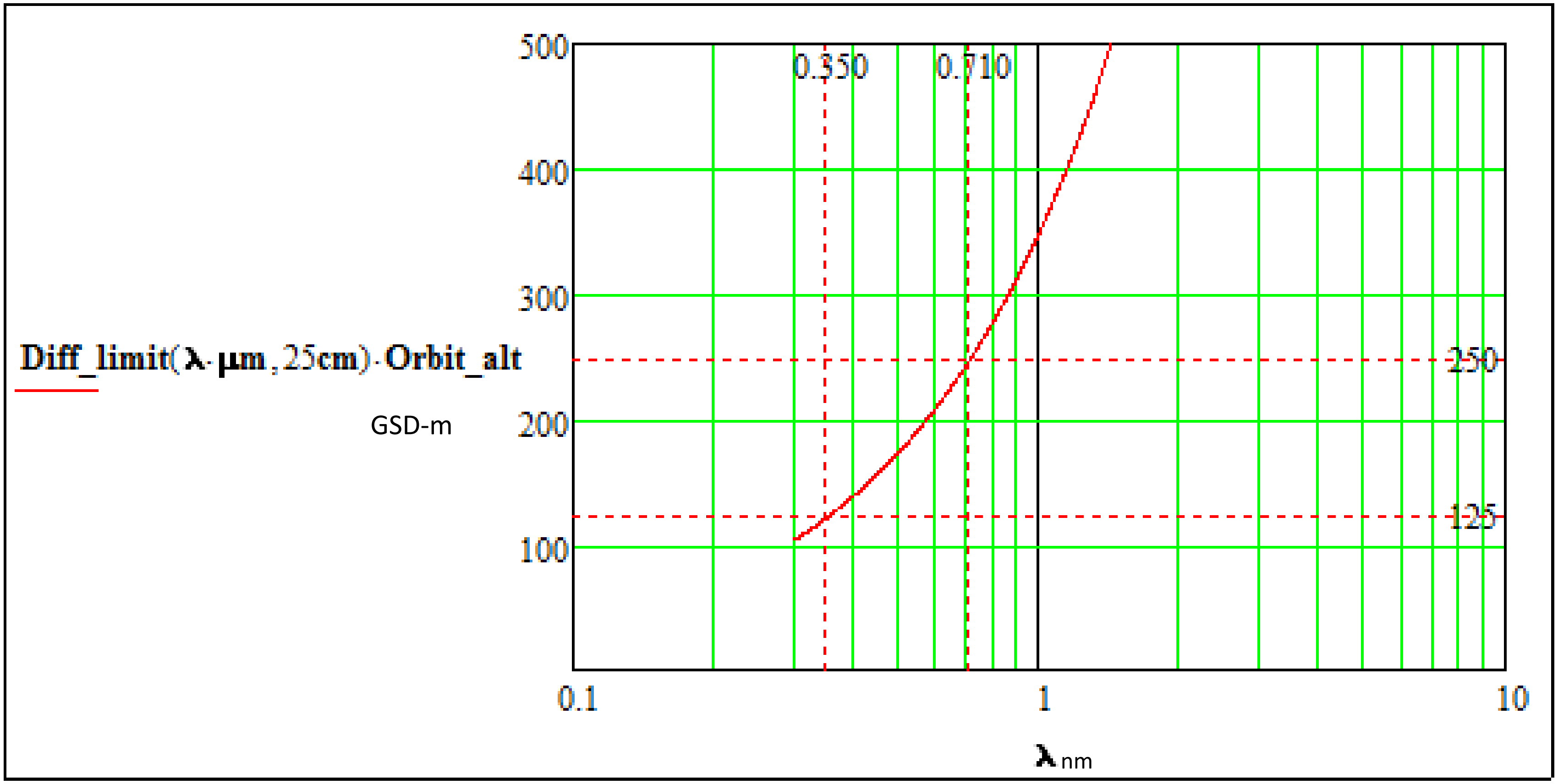
Spectral resolution: 0.4, 2, 5 nm
Nadir GSD: 250, 375, 500 m
SWIR: 3 bands



WAS = Wide Angle Spectrometer
FR = Filter Radiometer
SSS = single-slit spectrometer
COEDI = dual slit spectrometer (GSFC)
GLIMR = wide angle spectrometer (Raytheon)
MOS = 4-slit spectrometer (Ball)
GOCI = Korean/Astrium filter radiometer (360m)

Diffraction Limit and Optical Crosstalk

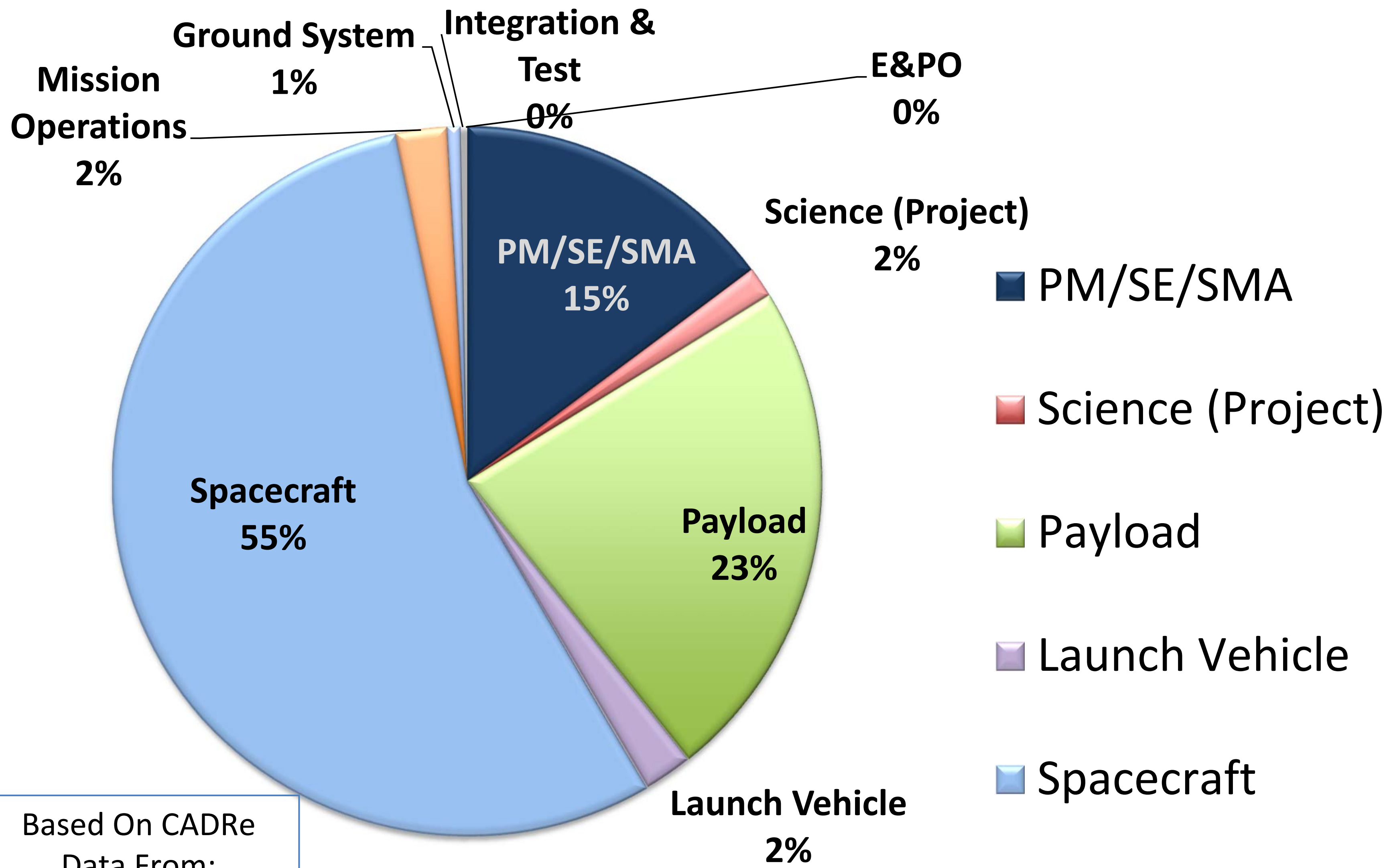
$$\mathbf{Diff\_limit}(\boldsymbol{\lambda}, \mathbf{D}) := 2.44 \cdot \frac{\boldsymbol{\lambda}}{\mathbf{D}}$$



Instrument Capability vs Cost

Instrument Type	Filter Radiometer FR		Wide Angle Spectrometer WAS	Multi-Slit Spectrometer COEDI	
Spatial Resolution	**250 m**	**375 m**	**375 m**	**375 m**	**250 m**
Spectral Resolution	5 nm	5 nm	0.4 nm	0.4 nm	0.4 nm
Spectral Range (nm) (2135 not req)	Multispectral (50) 340-1050; 1245, 1640, 2135	Multispectral (50) 340-1050; 1245, 1640, 2135	340-1050; 1245, 1640, 2135 nm	340-1050 1245,1640 nm	340-1050 1245,1640 nm
Scan Rate (km^2/min)	100,105	100,105	48,200	43,200	28,800
Mass CBE (kg)	190.4	126.3	309.4	202.8	358.6
Power CBE (W)	200.1	161.2	341.3	192.5	257.7
Volume (m x m x m)	1.5 x 1.46 x 1.02	1.0 x 0.97 x 0.68	2.6 x 1.8 x 1.5	1.5 x 1.7 x 1.1	2.2 x 2.5 x 1.7
Telemetry CBE (kbps)	15,900	10,600	23,832	23,854	35,765
NICM Cost ($M)	$213.4	$172.9	$325.2	$238.8	$308.0
Parametric Cost ($M)	**$131.7**	**$107.7**	**$165.2**	**$136.2**	**$200.1**
NICM Sub-System Cost ($M)	**$128.7**		**$179.3**		

Cost Breakdown of GOES N-P Missions



Based On CADRe
Data From:
GOES N-P

Courtesy of Bill Sluder

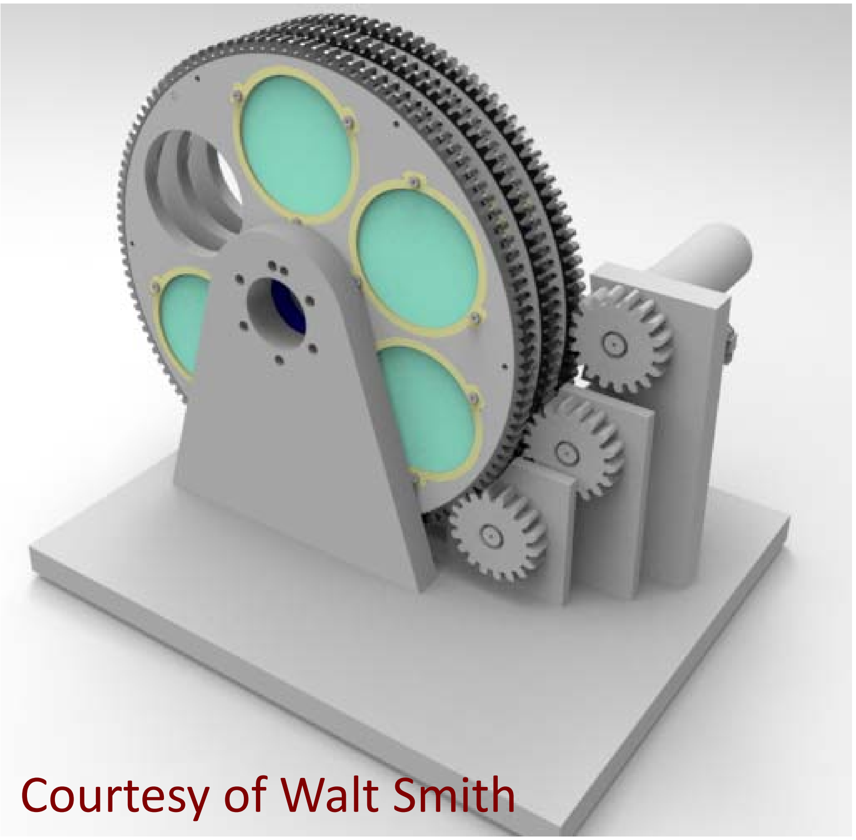
Cost Estimate for Ocean Color GEO-CAPE

WBS Element	Cost	Cost ($M)
Instrument	$133M * 1.5	200
Project Mngmt, Sys. Engr., & SMA*	10%*	60
Ground Sys. & Mission Ops.*	13%*	45
Host Fees (I&T, Launch, Data)	TBD	80
Science		65
Reserves	10%	45
TOTAL		**$495M**

* Cost % from recent LEO missions (should be lower for hosted mission)

Filter Wheel Breadboard Mechanism

- 50 filters into 10 wheels with 5 filters each. Each wheel has an open spot
- Each wheel is independently actuated but their positions are coordinated via computer
- Design should be modular, expandable and use commercial solutions if practical
- Not considered a high precision optical mechanism however the transition speed is fast
- Filter replicas made of glass are preferred
- Prototype “proof of concept” model is intended to operate in a shirt sleeve environment at STP conditions
- Index: 60° in 0.2 seconds, still for 2.0 seconds
- Life: 3 years operating 17 hours/24 hours

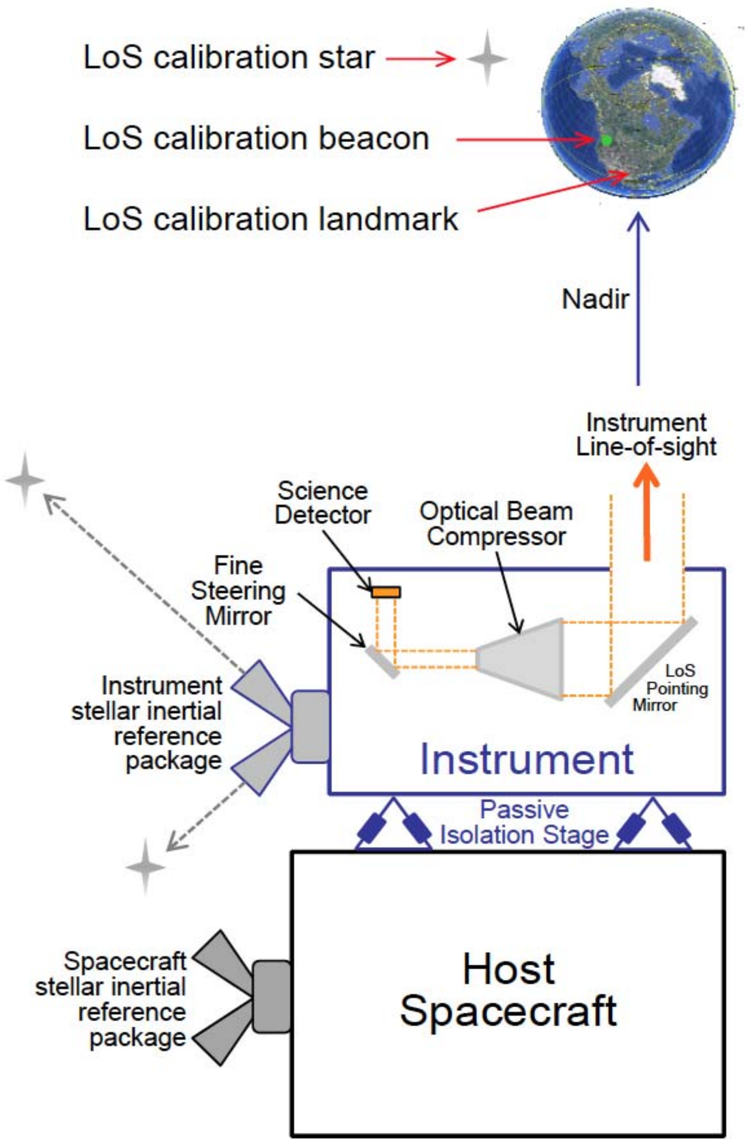


Courtesy of Walt Smith

Filter: 82 mm x 6 mm; 72 g;
94 mm radius
Wheel: 290 mm x 10 mm; 0.82 kg

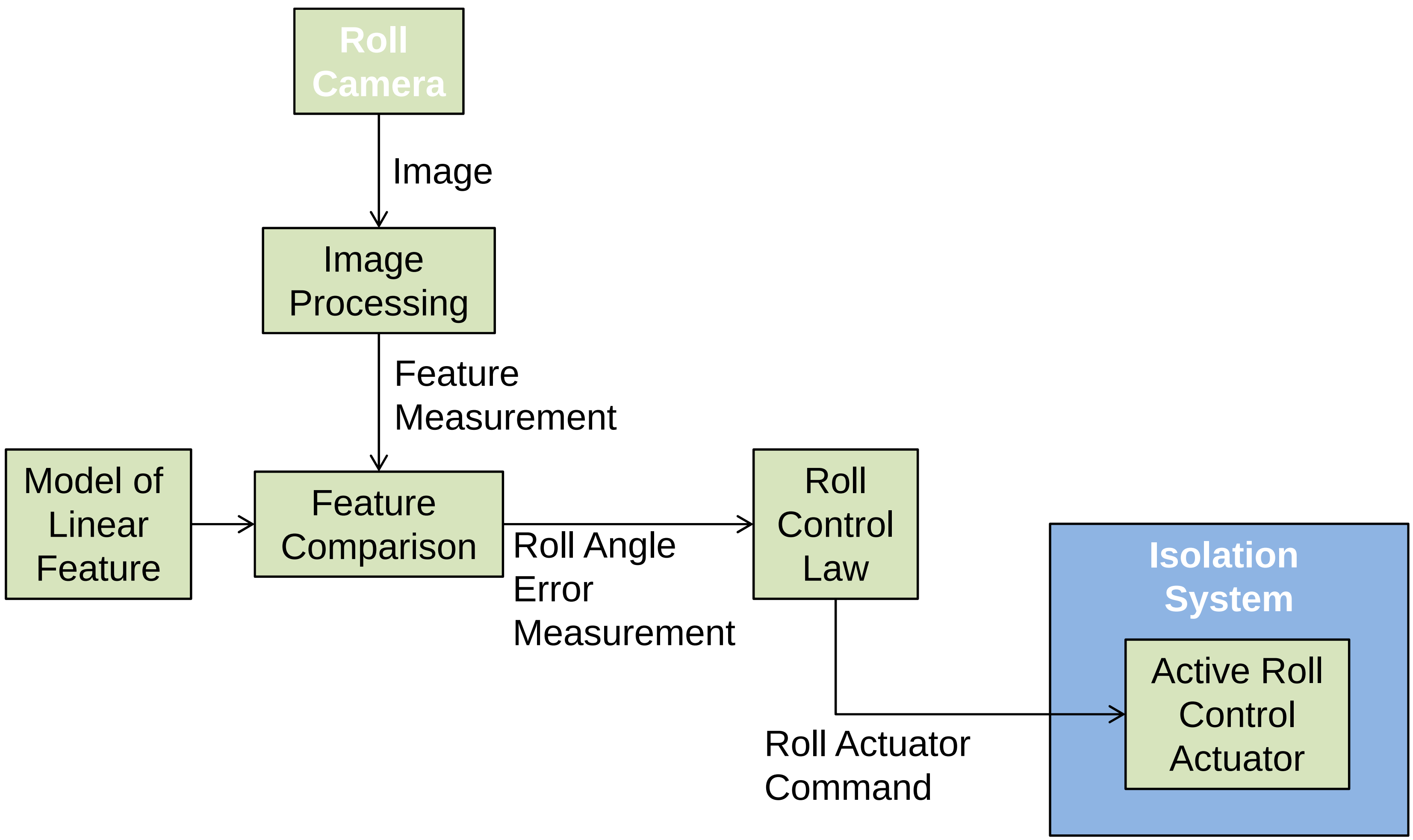
Pointing Study

- Passive isolation stage at the mechanical interface between the host SC and the instrument to minimize host spacecraft jitter imparted to instrument
- Instrument stellar inertial reference package (star tracker, gyro, attitude estimator) to achieve its LoS pointing knowledge requirements.
- Satellite ephemeris (position) measurements (GPS)
- Instrument entrance aperture pointing mirror with a 2 degree-of-freedom mount to place the instrument field of view on the desired target. Capable of pointing large mirrors over a large range of motion.
- Fine steering mirror to stabilize line of sight during science observations. Reduced sized and reduced range of motion (few degrees), but fast and precise (Note: Roll around the line-of-sight is uncontrollable. Spacecraft pointing errors that map into the instrument line of sight can not be corrected with pointing mirrors)
- Pointing calibrations strategies: Post observation landmark identification for geo location pointing reconstruction; Image the star background through the instrument to estimate instrument internal bias errors; Cal beacon on the ground to eliminate bias error; and Internal artificial star calibration source (i.e. a LED)



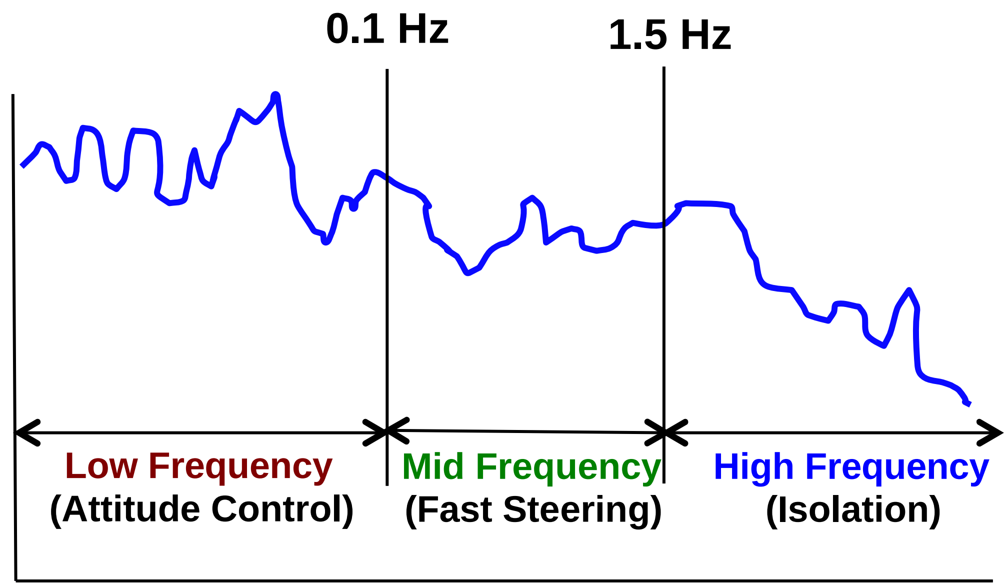
Courtesy of Eric Stoneking et al.

Roll Measurement Block Diagram



Disturbance Rejection Apportioned by Frequency

- Spacecraft attitude control rejects low-frequency disturbances (≤ 0.1 Hz)
- Jitter suppression system on instrument mount rejects high-frequency disturbances (1.5 Hz and above)



  - Active elements, plus passive rolloff due to inertia
- Active "fast steering loop" rejects mid-frequency disturbances (0.1 to 1.5 Hz)
  - Needs IMU sampled at >15 Hz
  - Actuation by either:
    - A fast steering mirror (baseline), or
    - By steering the scanning mirror, or
    - Active portion of the jitter suppression system

Courtesy of Eric Stoneking

Pointing Study

Pointing Accuracy Capability		
Window (sec)	Response to 160-arcsec Input (arcsec RMS)	Response to GOES Input (arcsec RMS)
0.5	0.284	0.270
1	0.278	0.269
2	0.274	0.269
5	0.271	0.269

Pointing Stability Capability		
Window (sec)	Response to 160-arcsec Input (arcsec RMS)	Response to GOES Input (arcsec RMS)
0.5	0.084	0.016
1	0.105	0.019
2	0.115	0.020
5	0.120	0.019

- 250 m GSD
- Accuracy requirement
  - Baseline: 0.36 arcsec
  - Threshold: 1.44 arcsed
- Stability requirement
  - Baseline: 0.14 arcsec
  - Threshold: 0.72 arcsec

Courtesy of Eric Stoneking et al.

FY15 Scheduling Study

Study Aims

- Optimize Acquisition of "Cloud Free" Scenes at Lowest Cost
- Scheduling of observations based on science priorities and cloud cover

NASA Ames Activities

Jeremy Frank et al.

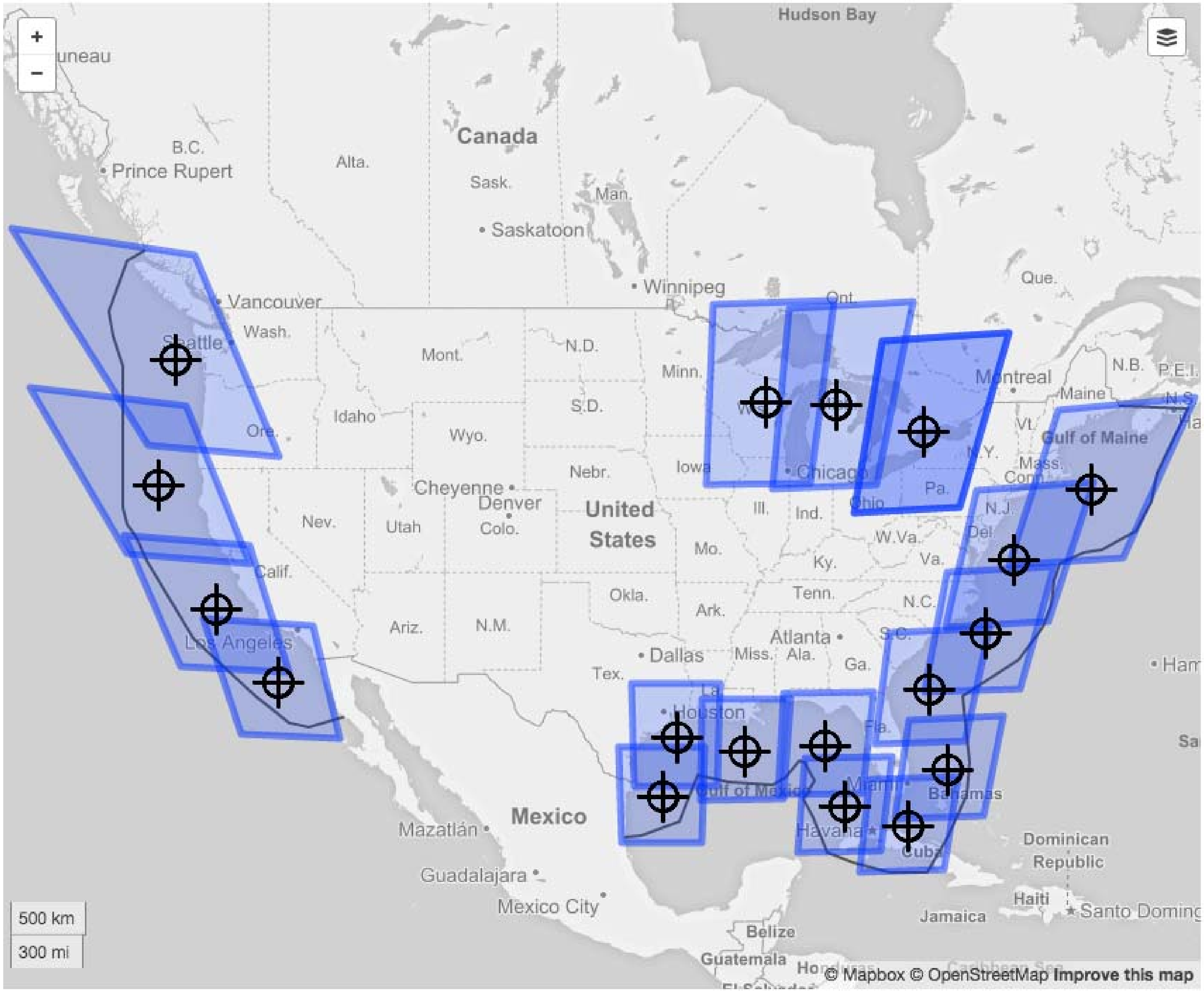
- Scene Layouts for FR and COEDI sensors (STK analysis)
  - GSD determination across sensor view angles
- Automated scheduler
  - Requires cloudiness predictions, cloudiness thresholds, scenes
  - Evaluation of automation technologies

GSFC study Elements - http://geocape.herokuapp.com

Karen Moe, Dan Mandl, Jacqueline LeMoigne, Stuart Fry & Pat Cappelaere

- Smart cloud forecasting
- On-board cloud detection
- Ground/on-board scheduling with Robust Executive

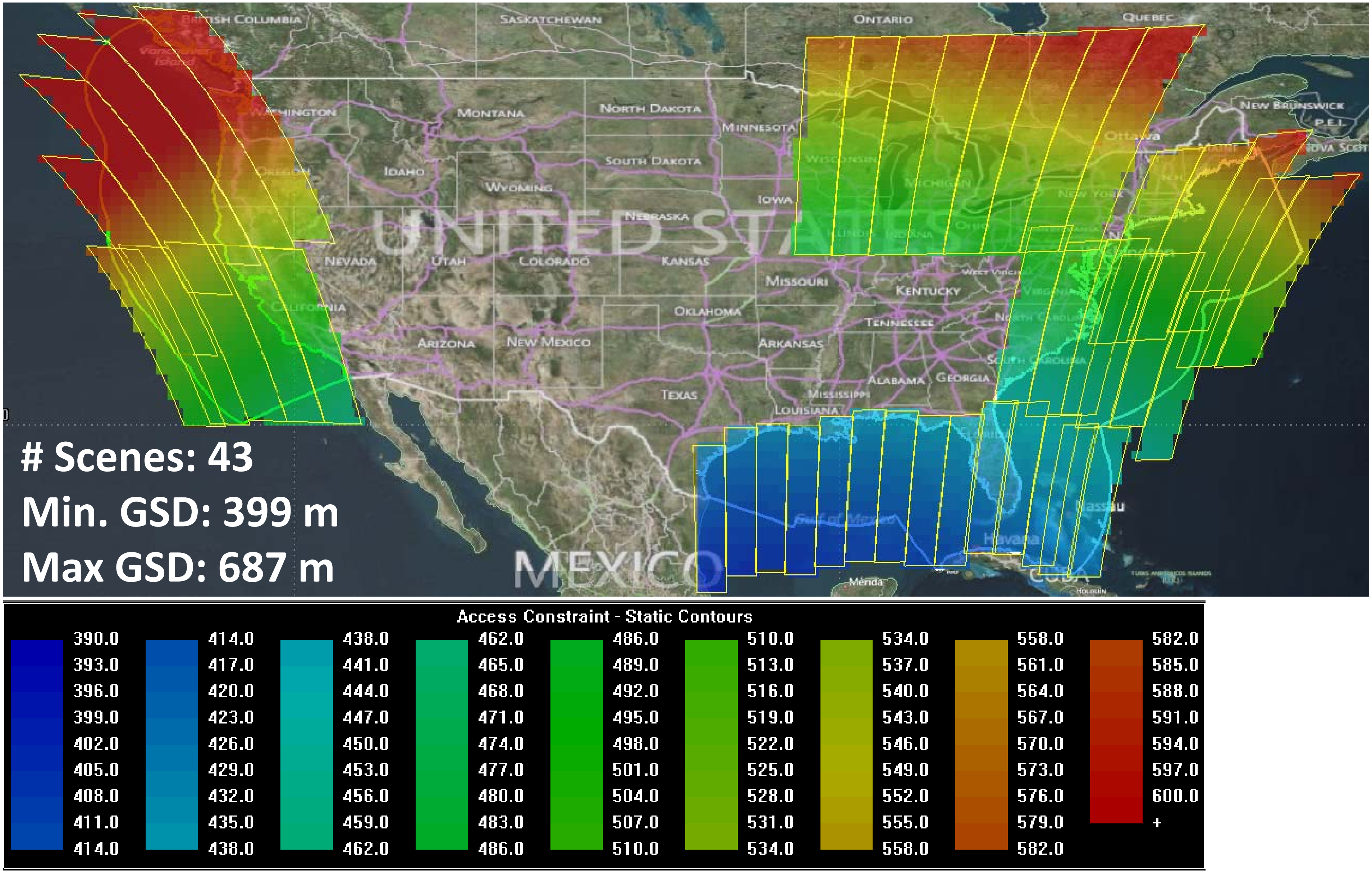
Strawman 18 Coastal/Lakes Survey Scenes Using FR



~45min to scan CONUS coastal waters

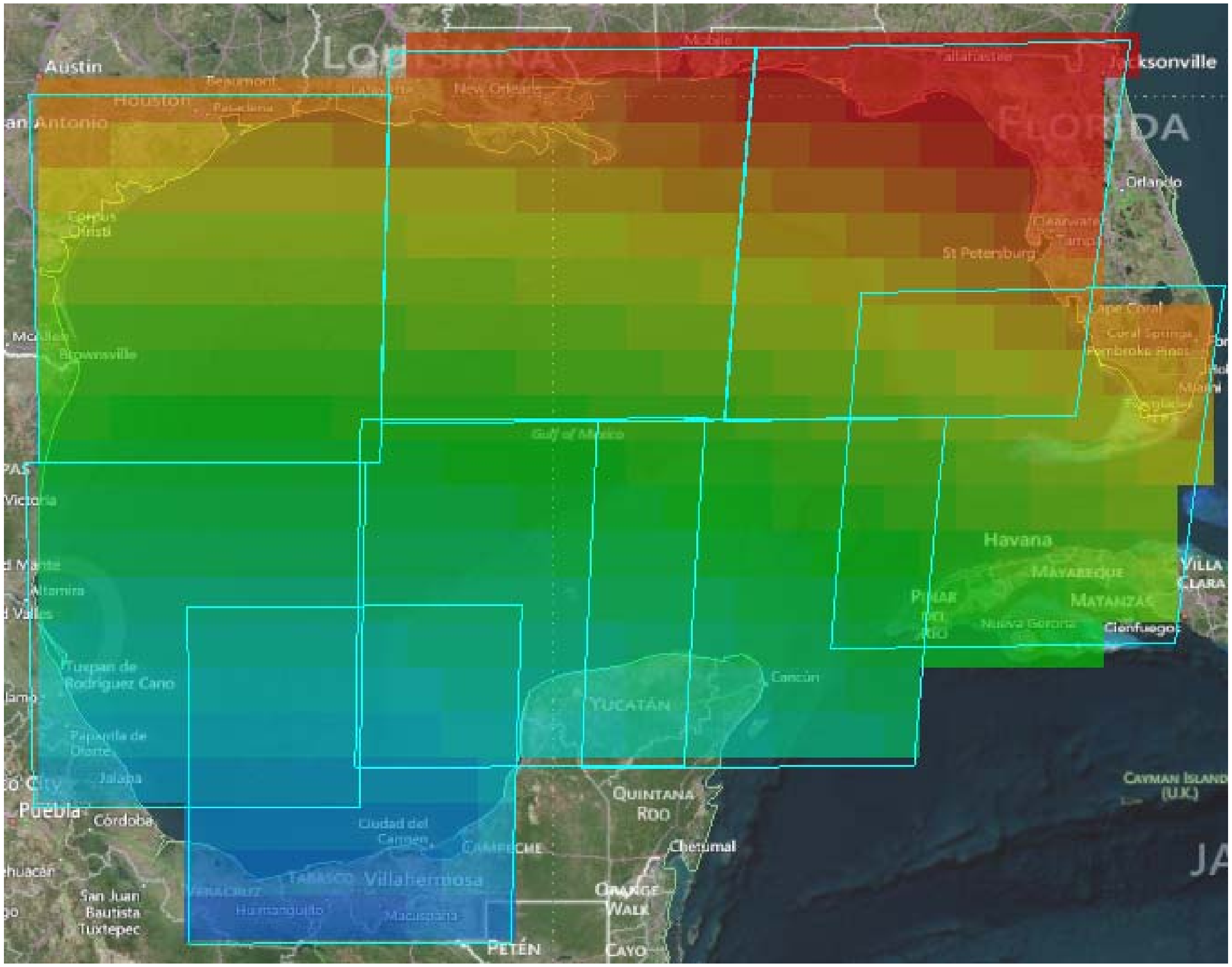
Source: GSFC analysis via GUI Editor, assuming spherical Earth – Satellite at 95W

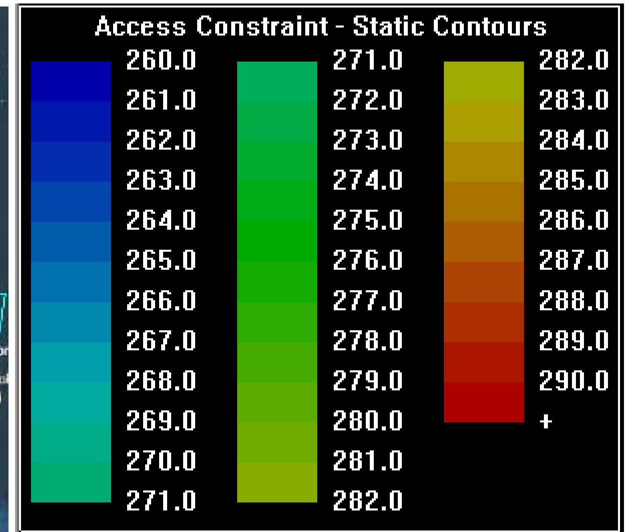
COEDI - 375m GSD, 500km coverage



Courtesy of Jeremy Frank et al.

FR - 250 m GSD



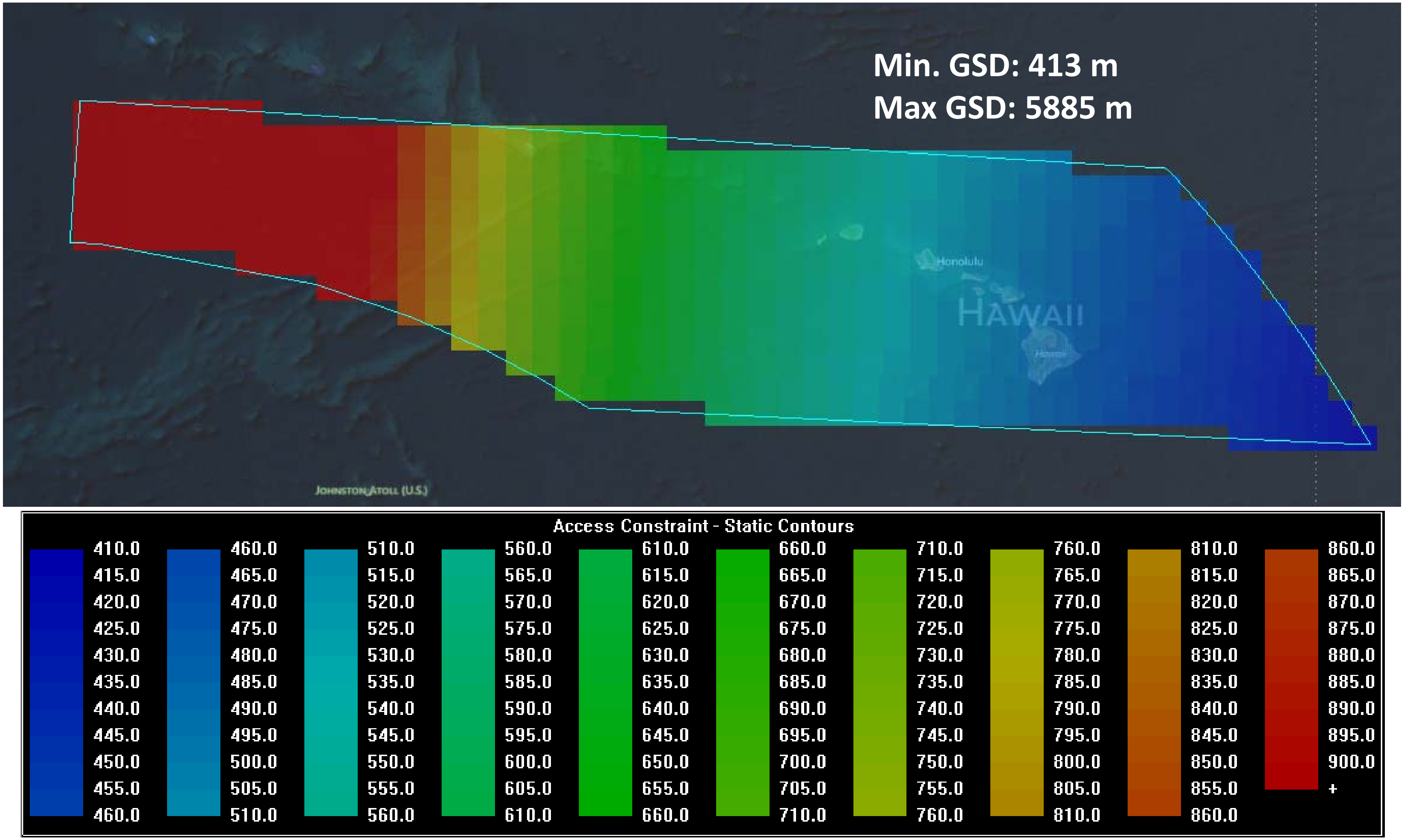


Min. GSD: 262 m

Max GSD: 295 m

Courtesy of Jeremy Frank et al.

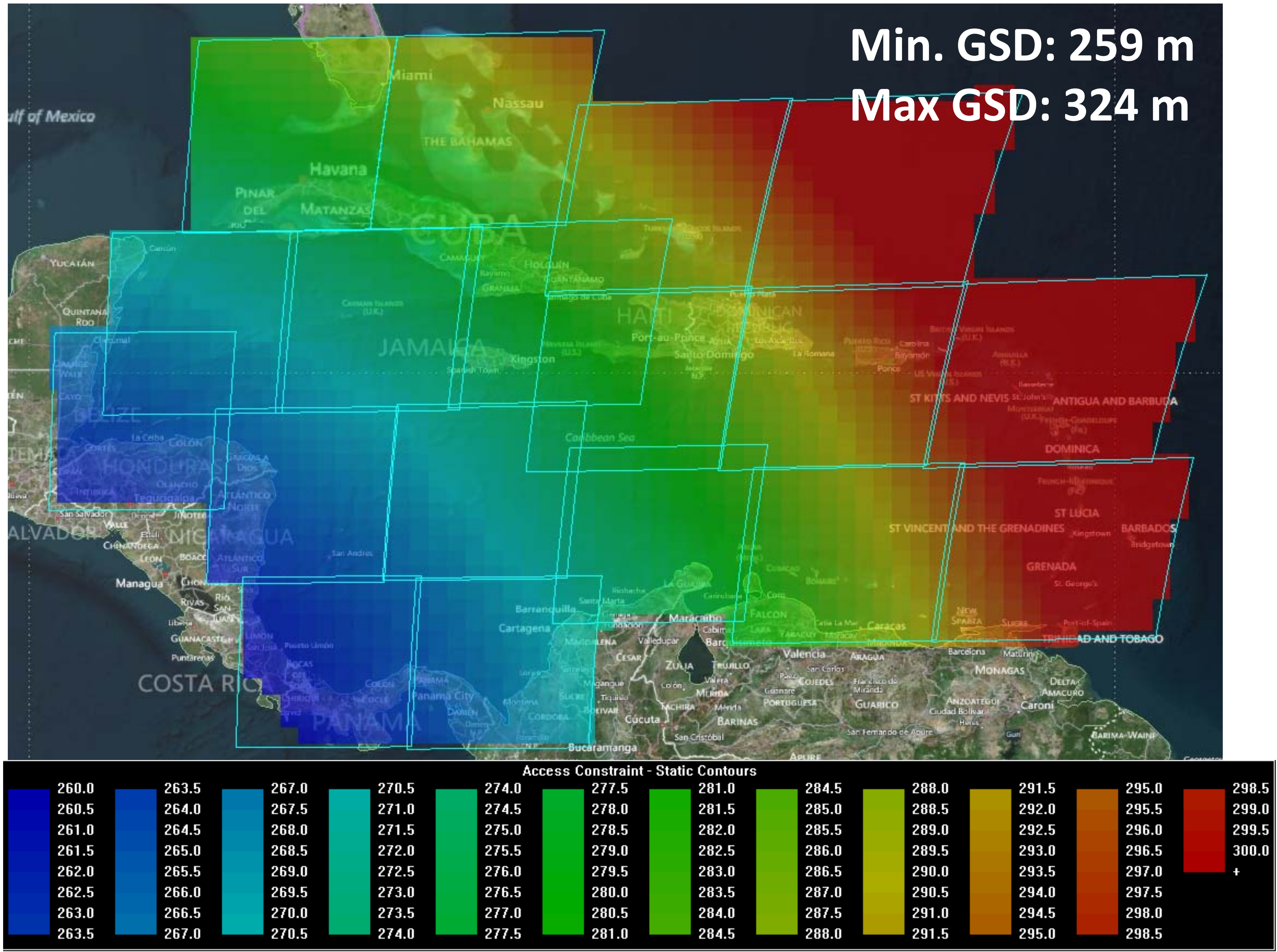
FR Scenes over Hawaii



Air Mass of 4 to 5; OC retrievals feasible from 95W

Courtesy of Jeremy Frank et al.

FR Scenes over Caribbean



Courtesy of Jeremy Frank et al.

FY15 Scheduling Study

- Scene Layout (U.S. Coastal waters + Great Lakes, 375 to 500 km ocean boundary/coverage)
  - Filter Radiometer
    - 4096 x 4069 pixels (250m GSD nadir)
    - 512 x 512 km footprint at nadir
  - COEDI
    - 375m: 2048 x 1 pixels, 768 km footprint N-S
- Automated scheduler
  - Requires cloudiness predictions, cloudiness thresholds, set of scenes
  - Evaluation of automation technologies

	Threshold	Baseline
US Survey	0.9	0.5
RSIs	0.7	0.3
Critical Target Science (HAB or oil spill)	1	0.6
Experimental Target (cruise, etc.)	0.8	0.4
Open Ocean	0.2	0.1

RSI and other scheduling study criteria

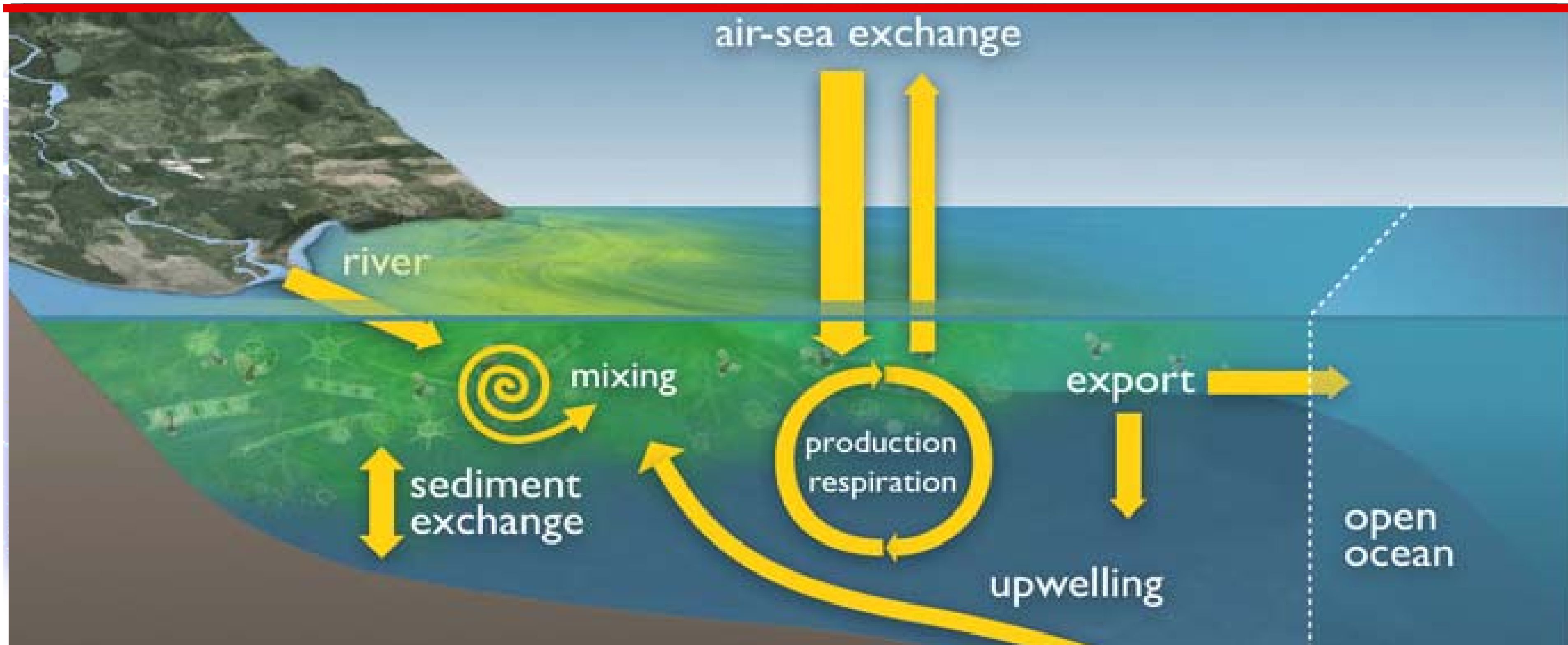
- 1) consider the following Regions of Special Interest (RSI):
- (a) Amazon and
- (b) Orinoco River plumes and adjacent ocean, (c) Puerto Rico,
- (d) remainder of the Gulf of Mexico and
- (e) Caribbean,
- (f) western South America and
- (g) south eastern South America (off Uruguay and Argentina);

science drivers are terrestrial material fluxes and impacts to coastal ocean ecology and biogeochemistry and phytoplankton blooms (Peruvian upwelling and Patagonian shelf

scoring from Highest to Lowest priority

- Threshold critical target science including HABs and oil spills
- Threshold Survey of U.S. coastal waters (including the Great Lakes)
- Threshold experimental target science (research cruise); for this study you can assume none or invent your own (2 week cruise in a coastal or open ocean location)
- Threshold RSIs (3 RSIs per day)
- Baseline critical target science including HABs and oil spills
- Baseline Survey of U.S. coastal waters (including the Great Lakes)
- Baseline RSIs (3 RSIs per day or more per prioritization)
- Baseline experimental target science (research cruise); for this study you can assume none or invent your own
- Threshold open ocean (any region beyond the coastal coverage (early morning/late in the day of GEO-CAPE). Scene location can be chosen based on minimum cloud cover.
- Baseline open ocean (any region beyond the coastal coverage (early morning/late in the day of GEO-CAPE). Scene location can be chosen based on minimum cloud cover.

GEO-CAPE APPLICATIONS Objectives in Coastal Areas



Hazards/Disasters | Water Resources | Oceans/Lakes | Ecological Forecasting | Air Quality/Human Health | Climate

- Post-storm Assessments (e.g., flood detection); sediment transport (navigation)
- Detection and tracking of oil spills, and other disasters
- Water Quality Indicators and management of water resources in lakes and coastal waters
- Better monitoring, predictions and early-warnings for HABs ; fisheries management
- Air Quality in Coastal Cities, and impacts of anthropogenic air pollution on human health
- Mapping and assessment of carbon dynamics, sources and fluxes & integration into climate models

Overall: Improve assimilation of satellite data into operational models to (i) assess/improve management of coastal resources , and (ii) improve forecasting/predictions.

Applications Traceability Matrix

Agency	Applications	Satellite products	Spatial requirements	Temporal requirements
				daily
				– 3hrs
				aily
				ecified
				ecified
				WQ), ly- nal ing)

Applications Identified

- Habitat Quality/Assessment/Mapping
- Water Quality
- Fisheries Management
- Ecological Models
- Ecological Forecasting
- Sustainability
- Research
- Human Health
- Pollution Tracking
- HABs
- Current Trajectory
- Visibility
- Sustainability

FY14 & FY15 Science Studies

- 22 unique funded studies (>$1.7M in science study grants)
  - Temporal resolution
    - Arnone, Lee, Hu, Laney/Sosik, Muller-Karger/Toro-Farmer, Salisbury, Sosik/Lohrenz, Tufillaro/Davis,
  - Spatial resolution
    - Arnone, Ackleson, Laney/Sosik, Mannino, Salisbury, Tufillaro/Davis
  - Atmospheric correction, BRDF, Sun-sensor geometry, clouds
    - Ahmad, Arnone, Gatebe, Hu, Lee, Muller-Karger/Toro-Farmer, Pahlevan, Tzortziou
  - Algorithms using UV, hyperspectral and/or high spectral resolution
    - Hu, Mannino/Tzortziou, Sosik/Lohrenz, Tufillaro/Davis,
  - Interdisciplinary white paper
    - Jordan/Tzortziou
  - Airborne data analysis
    - Davis, Hu

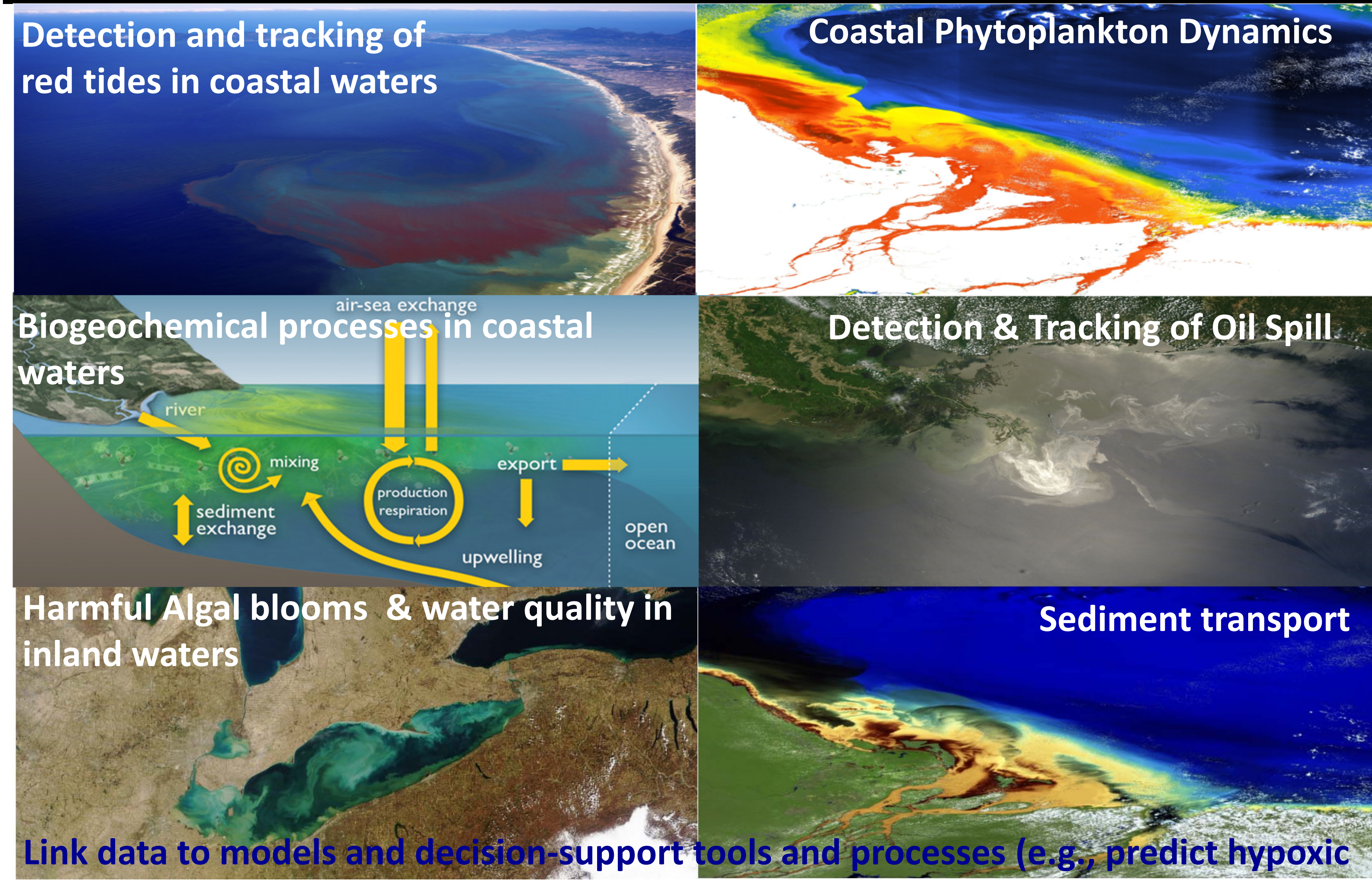
Outreach

- Splinter session on geo ocean color & presentation on GEO-CAPE at International Ocean Color Science Meeting (May 2013)
- NASA Ocean Color Research Team Meeting (May 2014)
- Ocean Optics Conference Town Hall (Nov. 2014)
- HyspIRI Meeting (June 2015)
- NASA OCRT update (June 2015)
- International Ocean Color Science Meeting (June 2015)
  - Breakout session on geo ocean color & presentation on GEO-CAPE
- Planned Town Hall at CERF (Nov. 2015)

Summary

- Over 70 GEO-CAPE oceans relevant publications by Oceans SWG members
- Continuing collaboration with Korean GOCI team
  - GOCI processing within SeaDAS 7 enabled
  - Distribution of GOCI L1 and NASA standard products awaiting Korean ministry approval (NASA USPI award)

Beyond PACE: Future Measurements for Coastal and Applications Research



Link data to models and decision-support tools and processes (e.g., predict hypoxic regions, fisheries mngmt, ocean acidification, water-quality forecasting)

How to sell the mission to stakeholders?

- Ecosystem Health Index
- Global constellation of Geo ocean color
- Synergy with PACE and other OC missions
- Synergy with TEMPO

Ocean Science Working Group

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*** New Members since 2013**