Next Generation LEO Ocean Color Satellites and their Cal-Val Requirements

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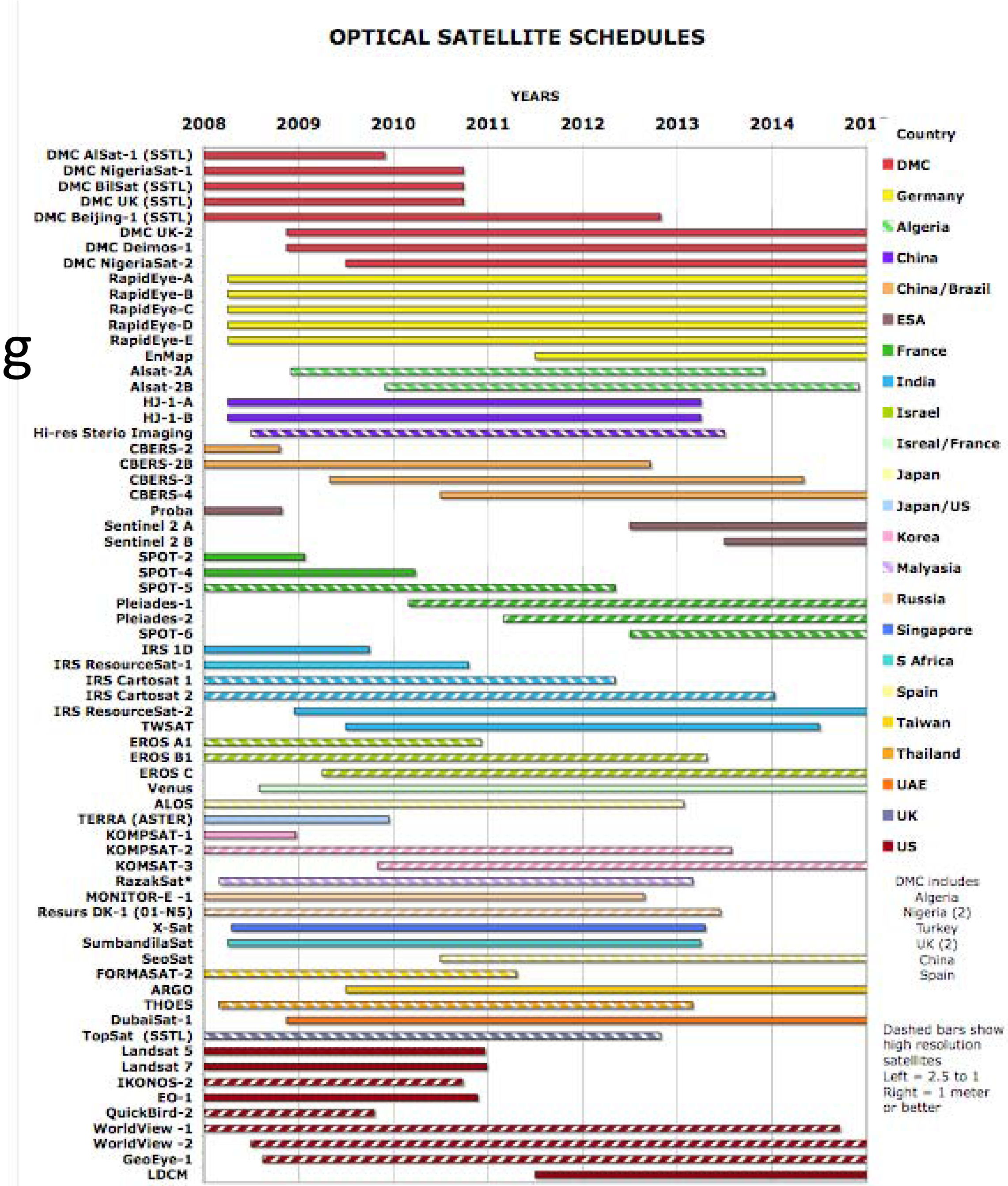
Small Satellite Constellations

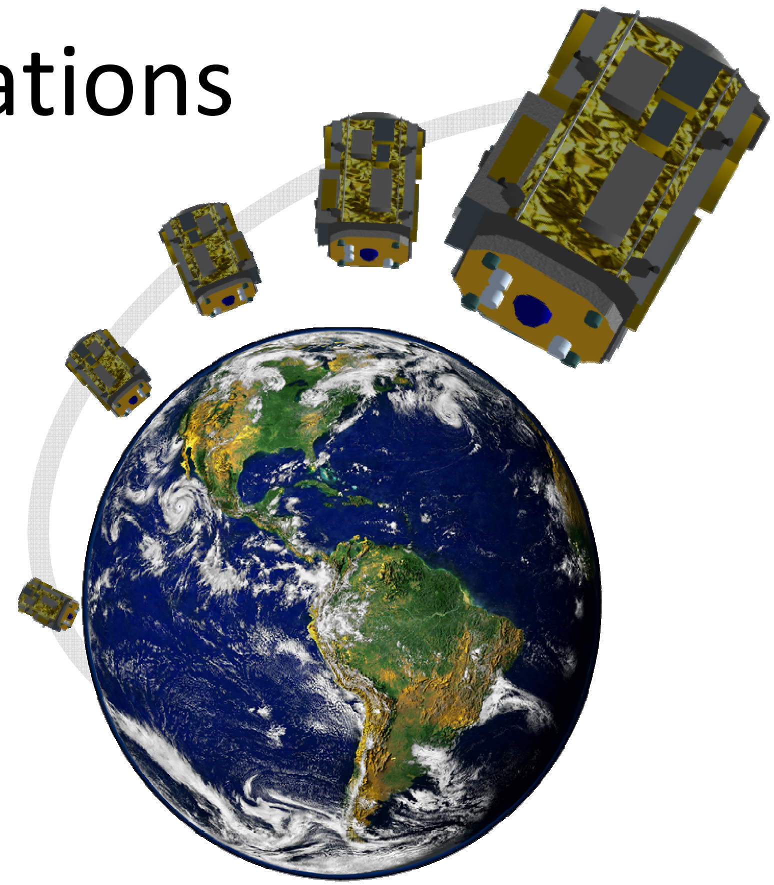
- ASPRS survey indicates by 2010 over 50 land imaging satellites with at a least a few Landsat bands will be in orbit with constellations becoming more common
  - Disaster Management Constellation
  - Rapid Eye
- Limited small satellite ocean imaging instruments examples possible next step

- ASPRS Land Imaging Satellite Survey by William Stoney



Benefits of LEO Small Satellite Constellations

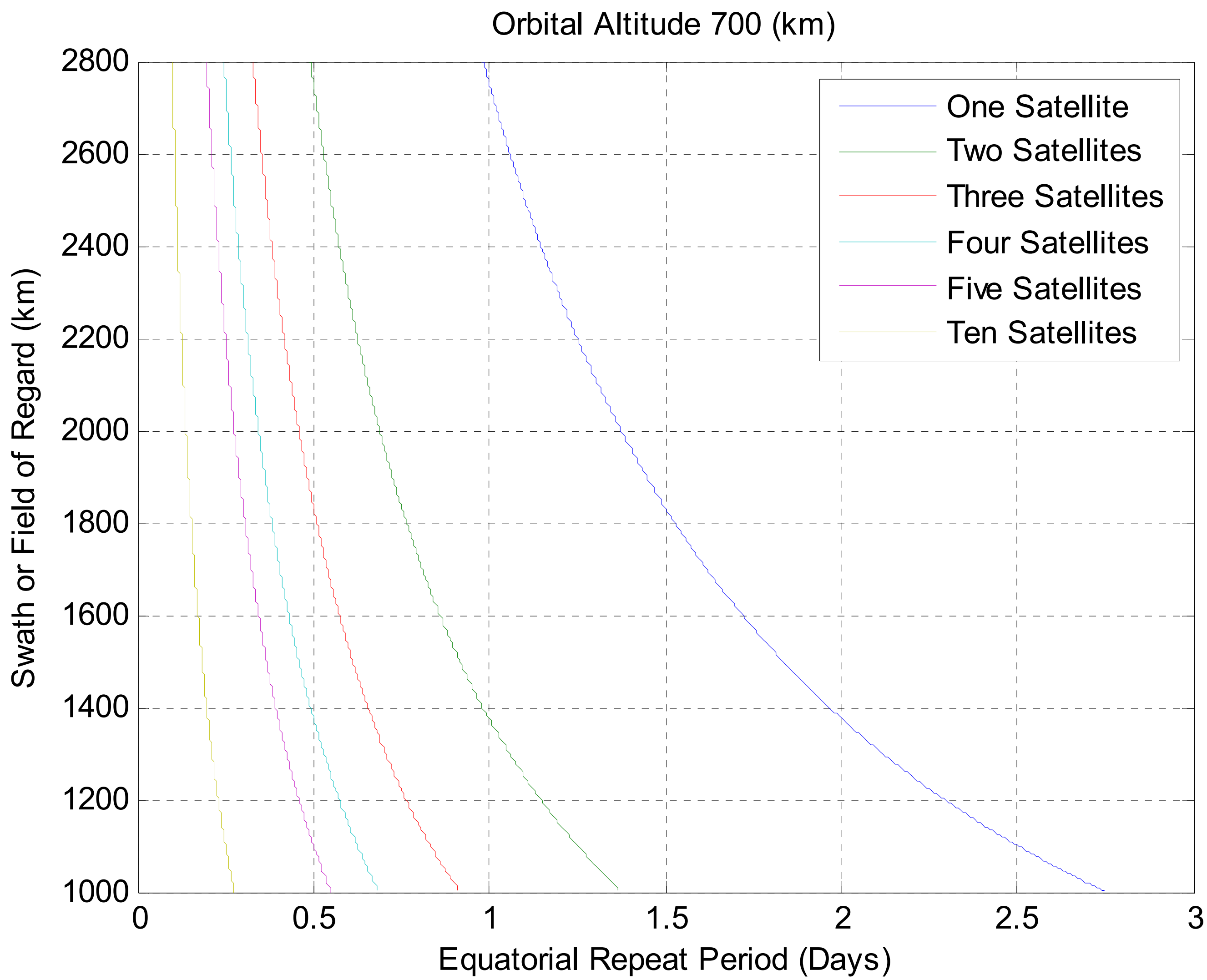
- Enhance performance
  - Global monitoring
  - Increased coverage
  - Increased revisit time
- Increased failure tolerance
- Amortization of non-recurring cost
- Launch cost reduction
- Recurring cost reduction



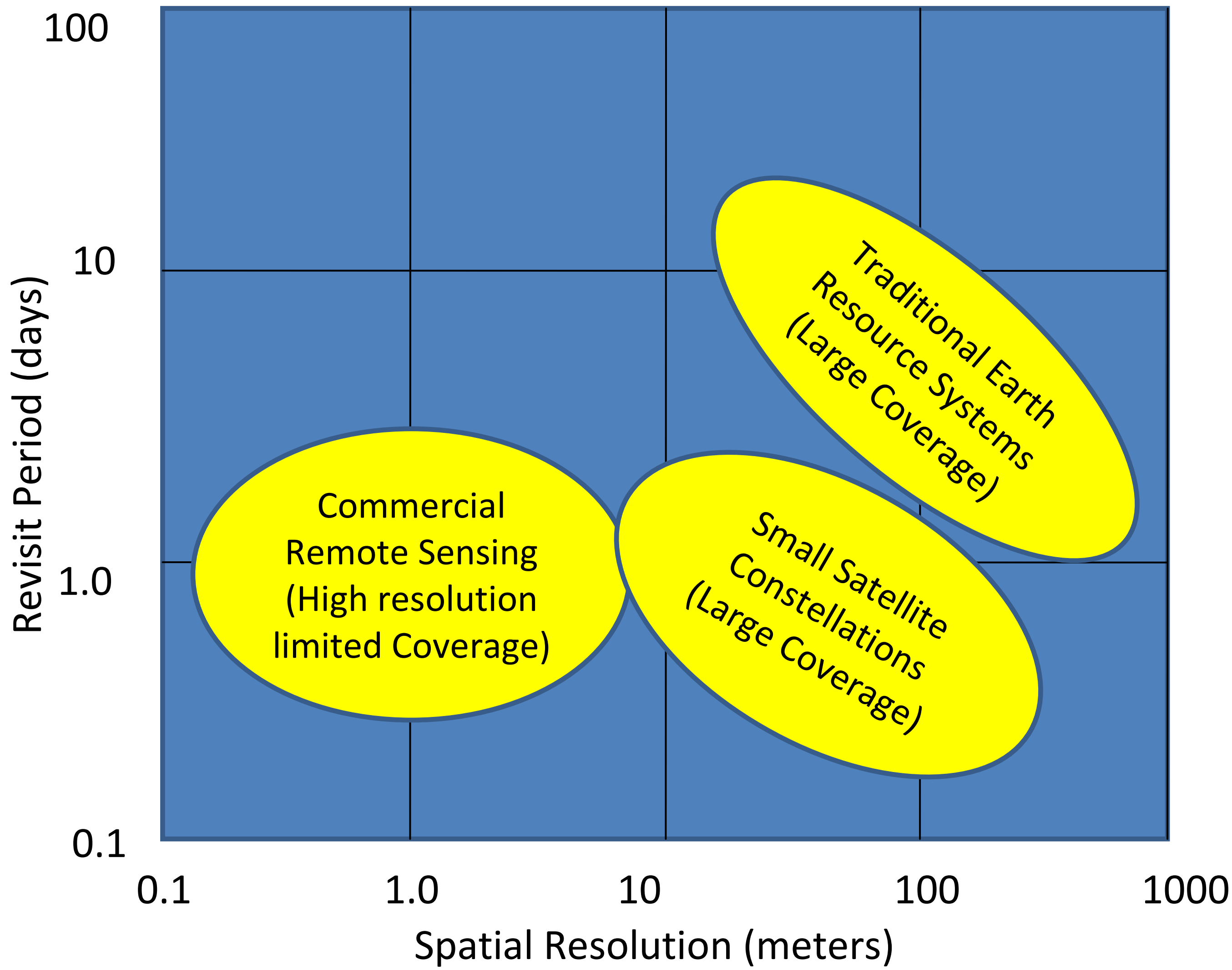
Small satellite constellation

Great potential to fill critical science data gaps that result from the high cost and long development cycles associated with traditional science missions

Improved Coverage & Repeat Period



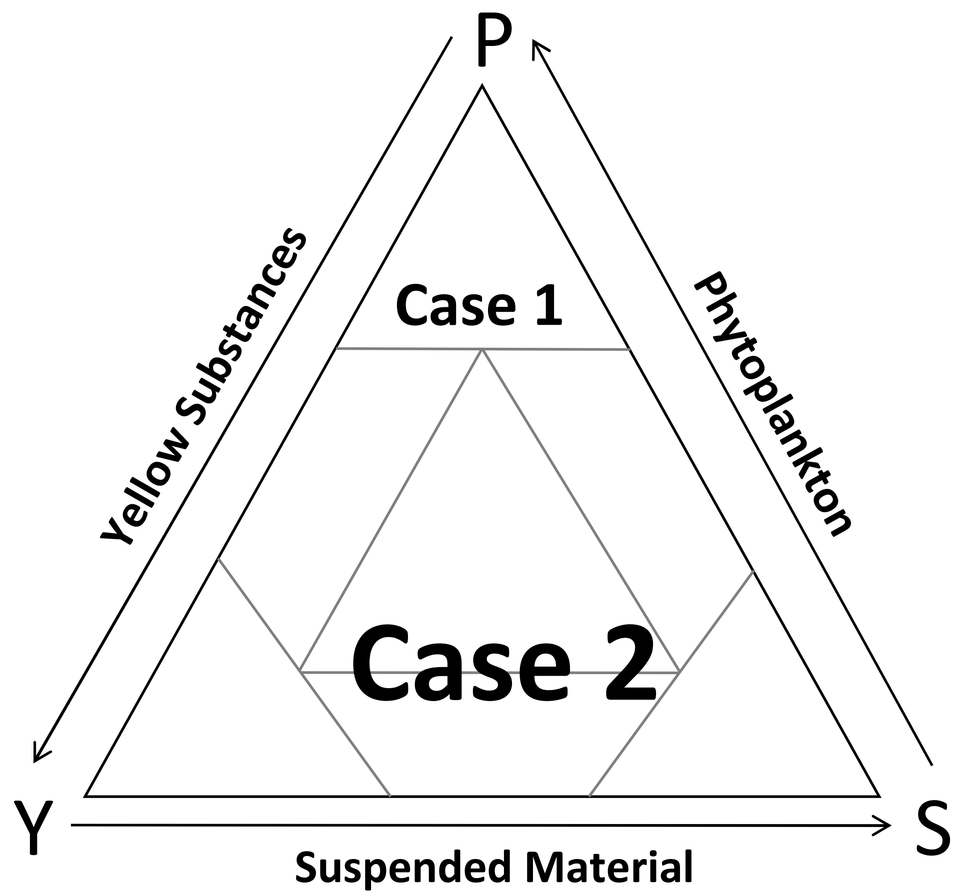
Unique Role for Small Satellite Constellations



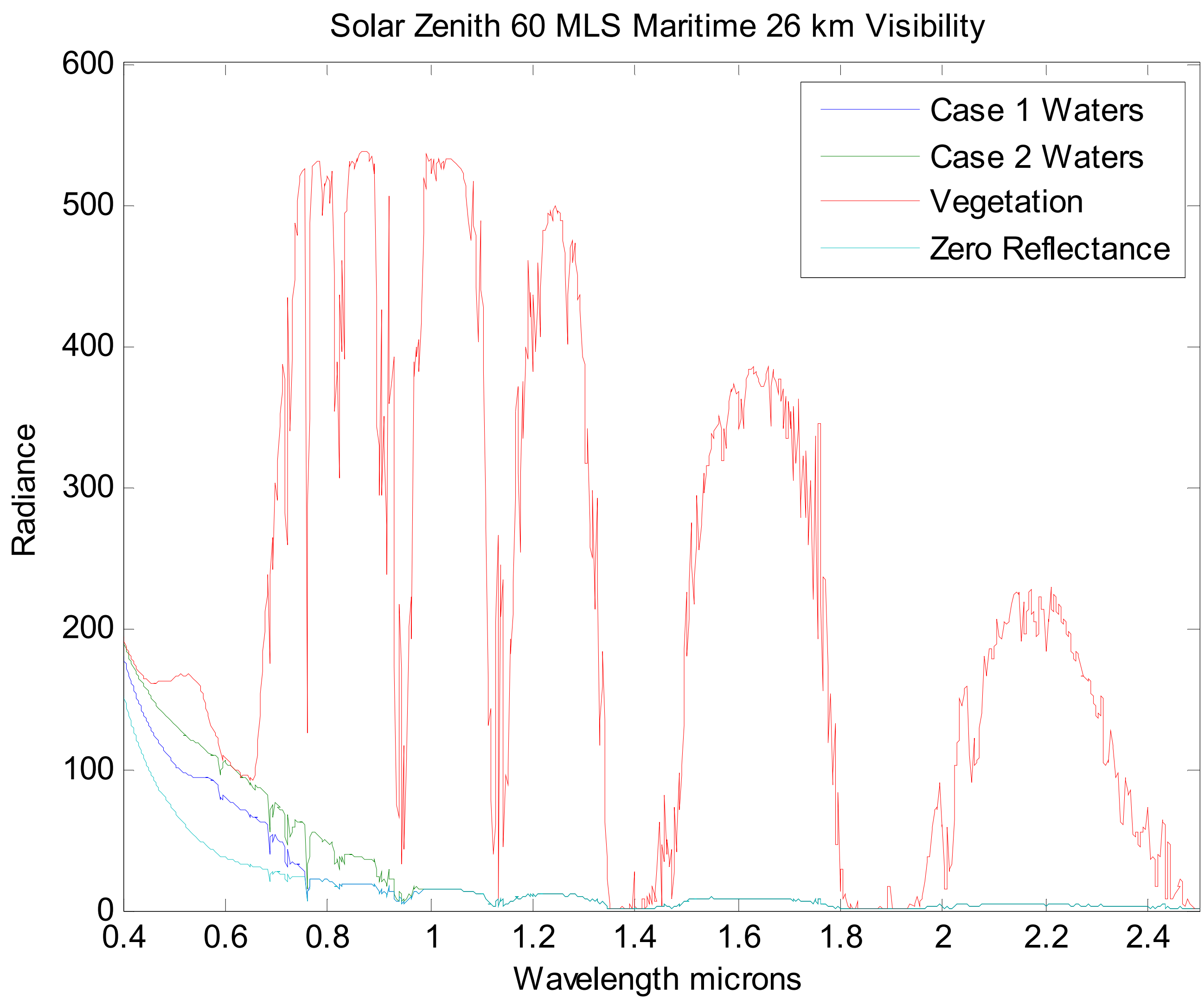
Ocean Color

Case 1 and Case 2 Waters

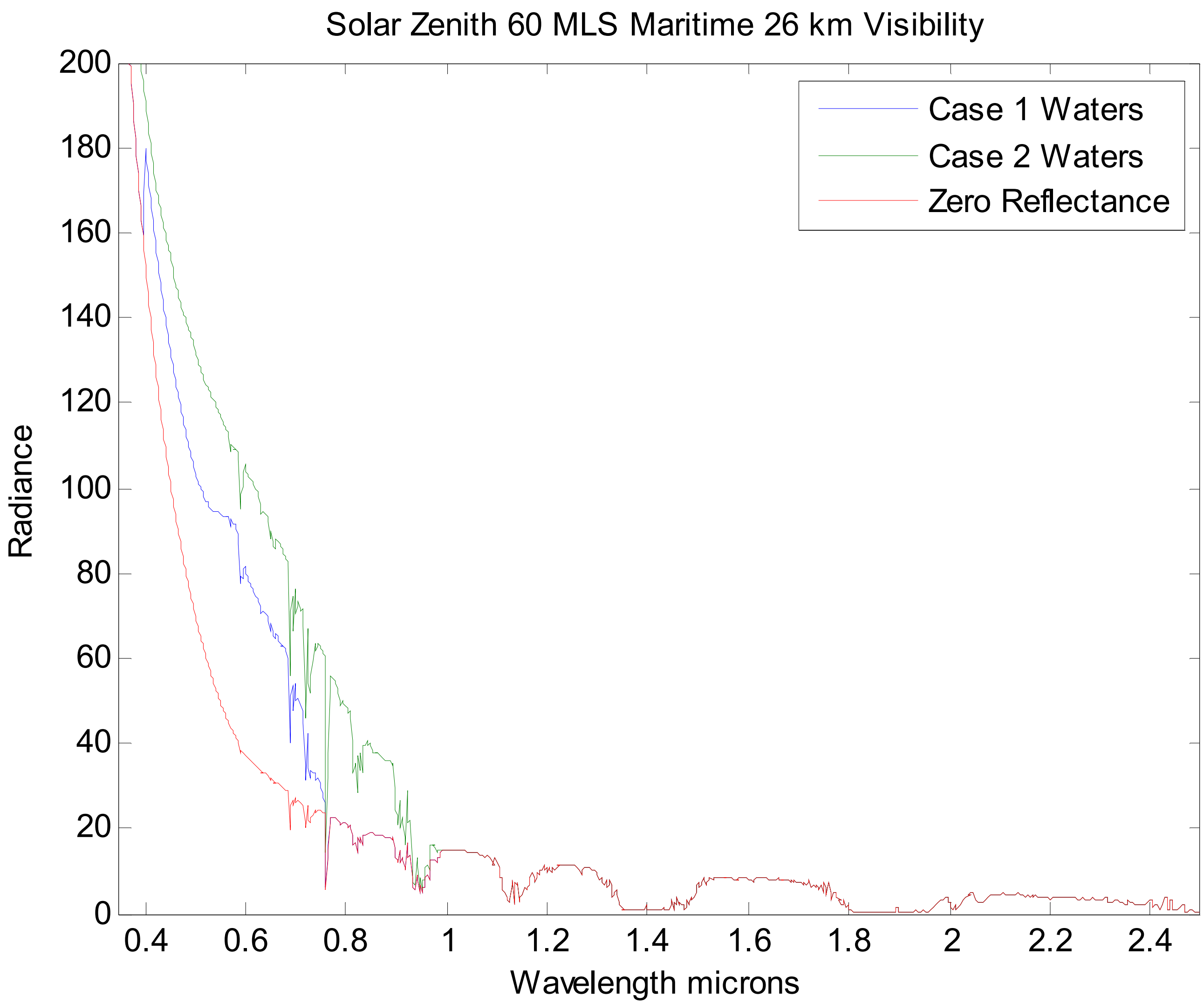
- Phytoplankton: Includes phytoplankton and other microscopic organisms, but for convenience called “phytoplankton” for the largest component.
- Suspended material (inorganic).
- Yellow substances: Includes colored, dissolved, organic substances and also include “detrital” particulate material, which generally has absorption characteristics similar to yellow substances.



Land and Water TOA Radiance



Water TOA Radiance



Importance of Coastal and Inland Waters

- Coastal zones represent about 8% of the ocean
  - Two thirds of the world's largest cities and 60% of the growing human population are within the coastal zone) and
  - Contributes to 14% of global ocean primary productivity
  - Provides 90% of the world fish catch
  - Provides largest sink of suspended river load.
- Inland waters
  - Provide drinking and irrigation water in many parts of the world

Modified IOCCG 2000 Report General Background Applications

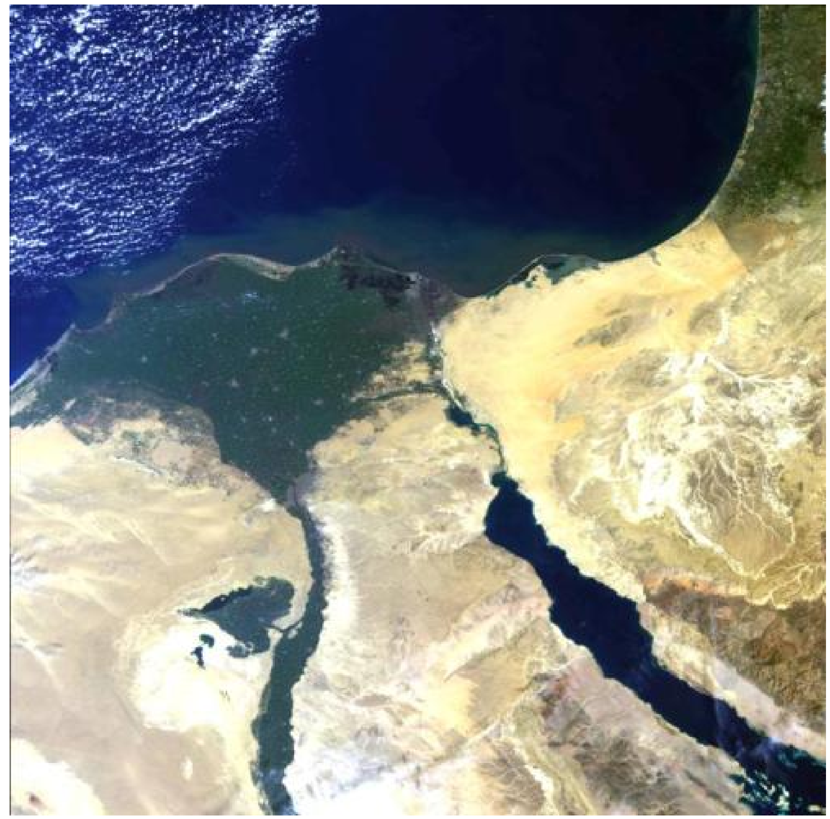
Land	Open Ocean Waters Case 1 Waters	Coastal and Inland Waters
Land use/Land Cover Change over time Disturbance/disease	Pigment concentration Bloom dynamics, productivity Carbon cycle, harmful algal blooms	Concentration of three components Bloom dynamics, productivity, sediment transport, coastal dynamics Carbon cycle, harmful algal blooms , water quality, aquaculture, fisheries, leisure activities

Modified IOCCG 2000 Report General Background Phenomenology

Land	Open Ocean Waters Case 1 Waters	Coastal and Inland Waters
Spatial scales ~10 m Time scales ~10-100 d Strong gradients Most of signal from target	Spatial scale ~1 km Time scales ~1-2 d Weak gradients Most of signal from atmosphere NIR can be assumed to be black	Spatial scale ~30-300 m Time scales ~0.2-2 d Weak and strong gradients Most of signal from atmosphere NIR typically not black

SeaWifs and MERIS

SeaWiFs true color Outer Banks of North Carolina



MERIS true color Nile Delta image

Modified IOCCG 2000 General Background

Land	Open Ocean Waters Case 1 Waters	Coastal and Inland Waters
Sensor Requirements		
Broad spectral bands Wide dynamic range Low signal-to-noise (~100) Moderate radiometry (~2-5%)	Narrow spectral bands Narrow dynamic range High signal-to-noise (Goal ~500) Excellent radiometry (<2%) Visible-Near Infrared (~7-10 bands) Vicarious calibration (Lunar cals)	Narrow spectral bands Narrow dynamic range High signal-to-noise (Goal >1000) Excellent radiometry (<2%) Ultraviolet-Short Wave Infrared (~10-20 bands) Vicarious calibration (Lunar cals) Stray light
Techniques		
Cluster classification	Atmospheric correction	Atmospheric correction/Modeling

Satellite Ocean Imagers

Imager	Country	Satellite	GSD (meters)	Swath (km)	Repeat Frequency	# Bands	Radiometric Resolution (Bits)
SeaWifs	USA	SeaStar	1100	2801 LAC 1502 GAC	1 day	8	10
MODIS	USA	Aqua/Terra	250,500,1km	2330	1 – 2 days	36	12
MERIS	Europe	Envisat-1	300	1150	3 days	15	12
OCM	India	Oceansat-1	350	1420	2 days	8	12
GLI	Japan	ADEOS-2	250, 1km	1600	4 days	36	12
OCI	Taiwan	ROCSAT-1	807	701	Non-polar orbit	6	10
CZI/COCTS	China	HAIYANG-1B	500m, 1.1km	500/1400	3 – 7 days	4/10	10/12
MMRS	Argentina	SOC-C	5, 175	90, 360	9 days	5	8

NOAA Operational Specifications for Satellite Ocean Color Measurement.

Nominal threshold and goal specifications for GEO-CAPE ocean color imaging based on threshold and objective requirements for coastal ocean color as documented in National Ocean Service Environmental Satellite Requirements DRAFT February 8, 2005, with later review and endorsement by members of the Coastal Ocean Applications and Science Team (COAST). Some updates made August 2008, including addition of SWIR bands to threshold.

Nominal Threshold Channel Center Wavelenth (um)	Nominal Threshold Resolution (um)	Nominal Threshold Signal to Noise	GOAL Channel Center Wavelength (um)	GOAL Resolution (um)	Nominal Goal Signal to Noise
0.412	0.02	300 to 1 all channels	0.345	0.02	900 to 1 all channels
0.443	0.02		0.380	0.02	
0.490	0.02		0.407 through 0.987	0.01	
0.510	0.02		0.507	0.05	
0.555	0.02		1.000	0.04	
0.580	0.02		1.240	0.03	
0.620	0.02		1.380	0.03	
0.645	0.01		1.640	0.03	
0.667	0.01		2.130	0.05	
0.678	0.01		11.200 (2 km)	0.8	
0.709	0.01		12.300 (2 km)	1	
0.750	0.02	Nominal Thresold Horiz. Resolution: 300 m; 3 hr refresh rate			Nominal Goal Horiz. Resolution: 30 m except for LW IR Channels; 1 hr refresh rate
0.865	0.02				
1.240	0.03				
1.640	0.03				
2.130	0.05				

Ocean Color Imagers Compared with Land Imagers

- Benefits from increased repeat time (Coastal fraction of day)
- Coarser resolutions (100's of meters) will meet most applications but with much higher SNRs
- Requires better radiometry (1-2%)
  - Sub-kilometer features
- Coastal will benefit from SWIR and UV channels
  - Optically complex case 2 waters (UV-SWIR)
  - Atmospheric correction approaches more complex than ocean color missions
    - Absorbing aerosols (UV channels)
    - Dark water assumption benefits from SWIR bands
- Geolocation can not depend on GCPs

Spectral Band Requirements/Sensor Trades

High Quantum Efficiency Detectors

Band	λ (nm) Wavelength	Ltyp† Radiance	Lmax† Radiance	FWHM (nm)	SNR SeaWifs
1	345	90	270	20	
2	360	75	300	20	
3	380	72.2	330	20	
4	412	82.5	480	20	930
5	443	77.5	560	20	1030
6	460	69	585	20	
7	490	62.5	575	20	1140
8	510	47.5	540	20	925
9	555	35	540	20	820
10	595	27	505	20	
11	620	19	480	20	
12	667	15	430	10 (20 SeaWifs)	890
13	678	14	425	10	
14	748	9	360	10	560
15	865	5.2	270	40	430
16	1240	1.2	125	30	
17	1375	6		30	
18	1640	0.5	73	30	
19	2130	0.16	30	50	

Silicon Detectors

Exotic Detectors

Units	$W/m^2 \cdot \mu m \cdot ster$

Geo vs LEO Constellations

- GEO
  - Provides the rapid revisit over a limited region
  - Telescope size becomes large for higher spatial resolution and thermal data sets
  - Single instrument calibration
- LEO constellations
  - Provides worldwide access
  - Rapid revisits with at several times a day will require a large number of satellites or a few very agile ones
  - Intra-constellation calibration critical

Geostationary Coastal and Air Pollution Events (GEO-CAPE)

Geosynchronous Earth orbit with 3 instruments:

1. UV-Vis-NIR wide area spectrometer:

- 0.5 nm bands from 340 – 1240 nm, SNR > 1000:1
- N & S America from 45°S to 50°N
- Hourly (O3,NO2,CH20,SO2, Aerosols)
- 7 km nadir spatial resolution
- land and shallow water

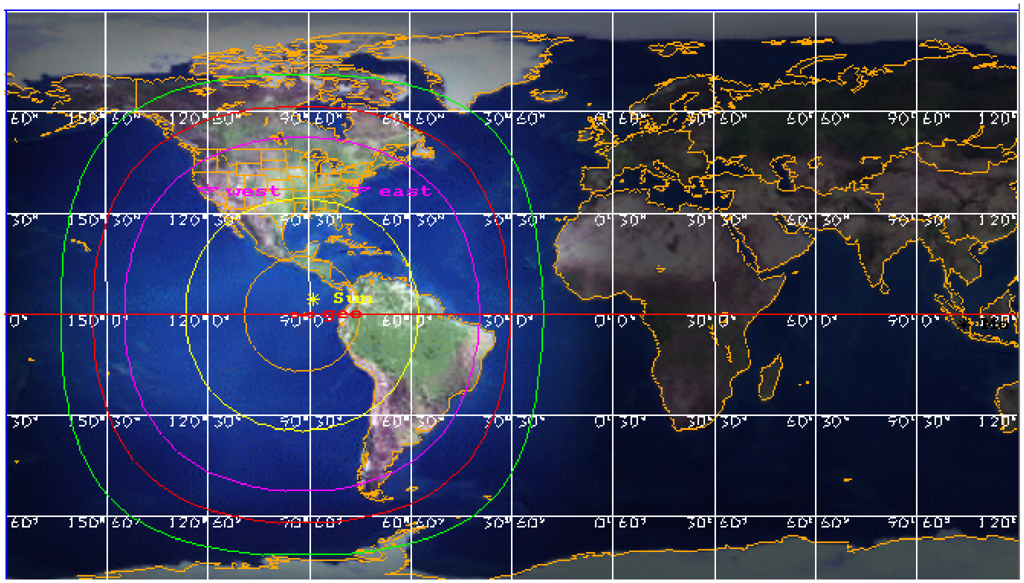
2. Event-Imaging Science Measurement:

- Spectral range, near IR to UV
- 250 – 500 m spatial resolution, 300 km FOV steerable over land and shallow water

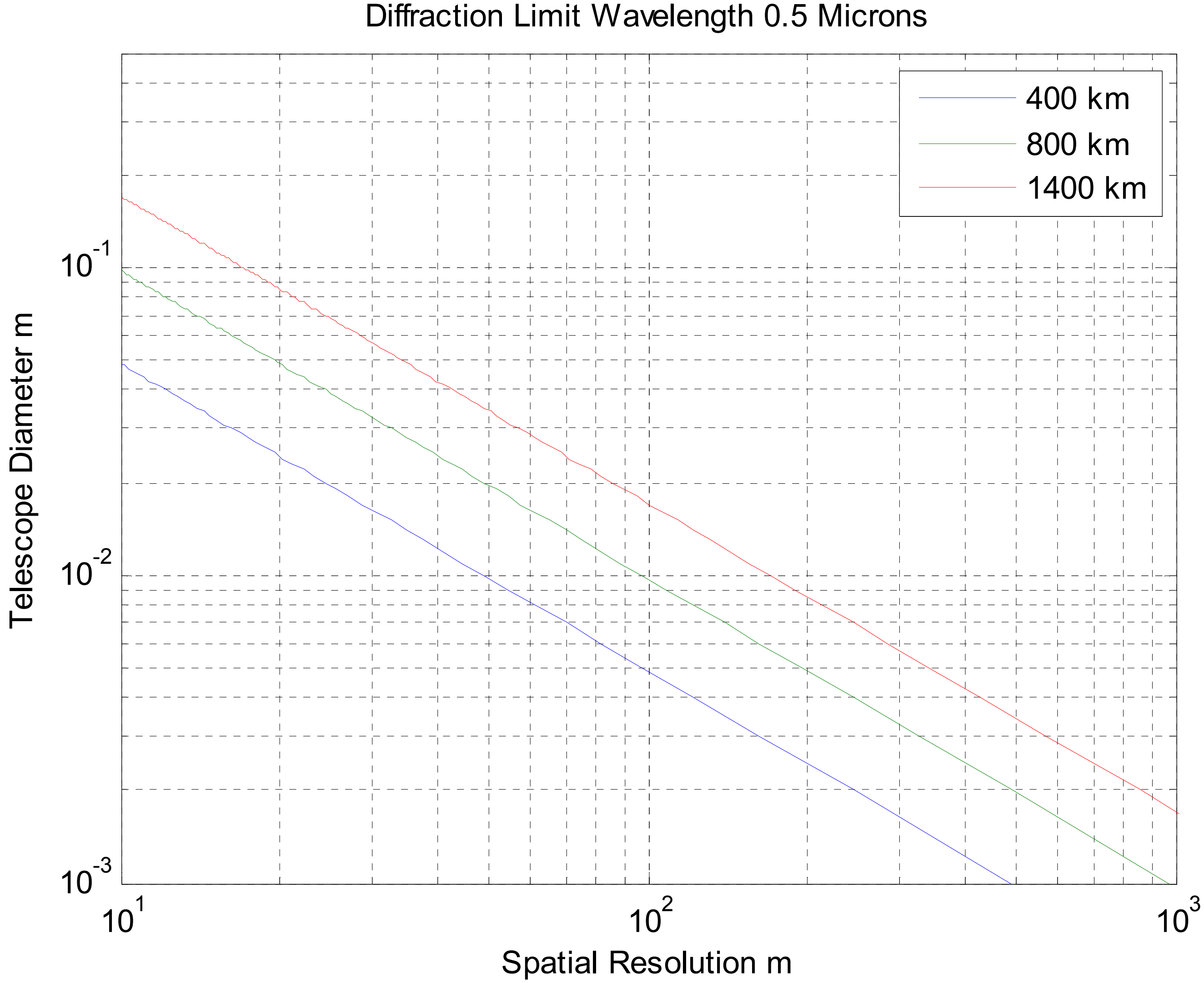
3. Thermal and near IR Correlation Science Measurement:

- CO observations

- Recommended launch date 2013-2016
- Gather sciences identifying human versus natural sources of aerosols and ozone precursors
- Track air pollution transport

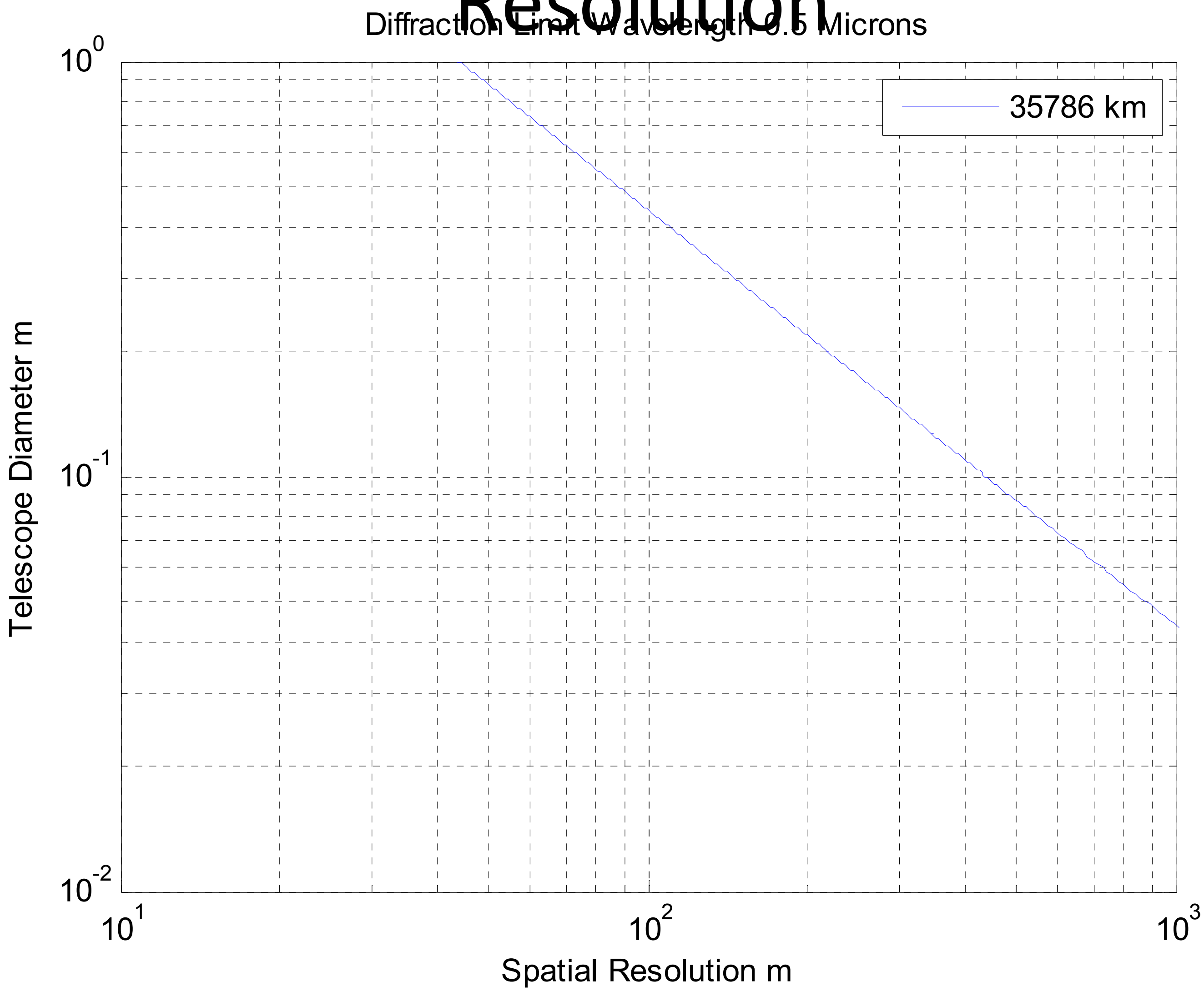


LEO Telescope Diameter Spatial Resolution



Small telescopes meet spatial resolution needs

GEO Telescope Diameter Spatial Resolution



Spatial resolution will be limited by practical telescope size

Limits GEO use

Possible Coastal Ocean Color Mission Level Objectives

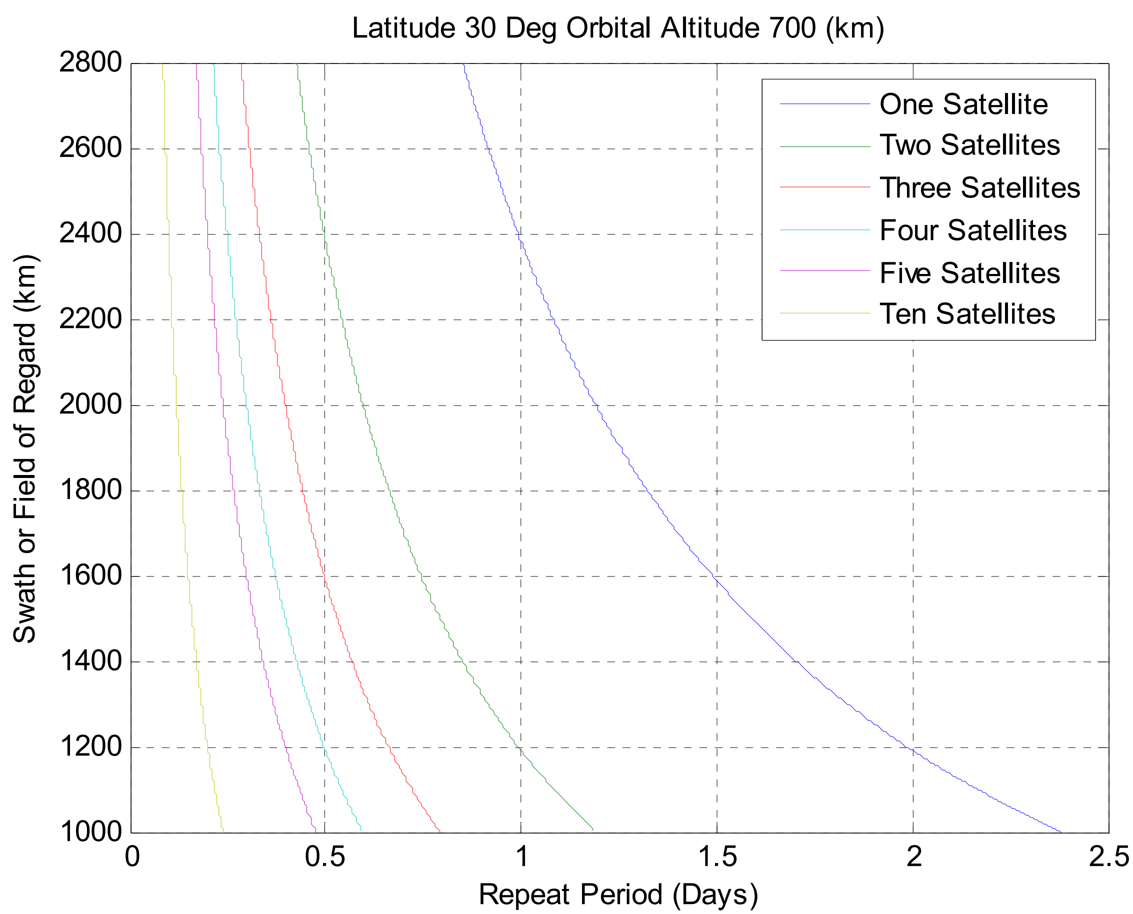
Mission Parameter	Range
Mission Lifetime	5 years
Global Coverage	0.2-1days
Orbit	Sun-synchronous (LEO)
Sensor Tilt	± 20 deg (fore and aft of satellite track)
On-Orbit Calibration	Monthly lunar (a near-full moon viewing) calibration capability
Ground Sample Distance	<300 m (coastal regions)
Geopositional Accuracy	0.1 pixels (rms) (~30 m)
Coastal Ocean Color Bands	UV-VNIR-SWIR ~20 bands

Required Ocean Color Mission Level Trade Studies

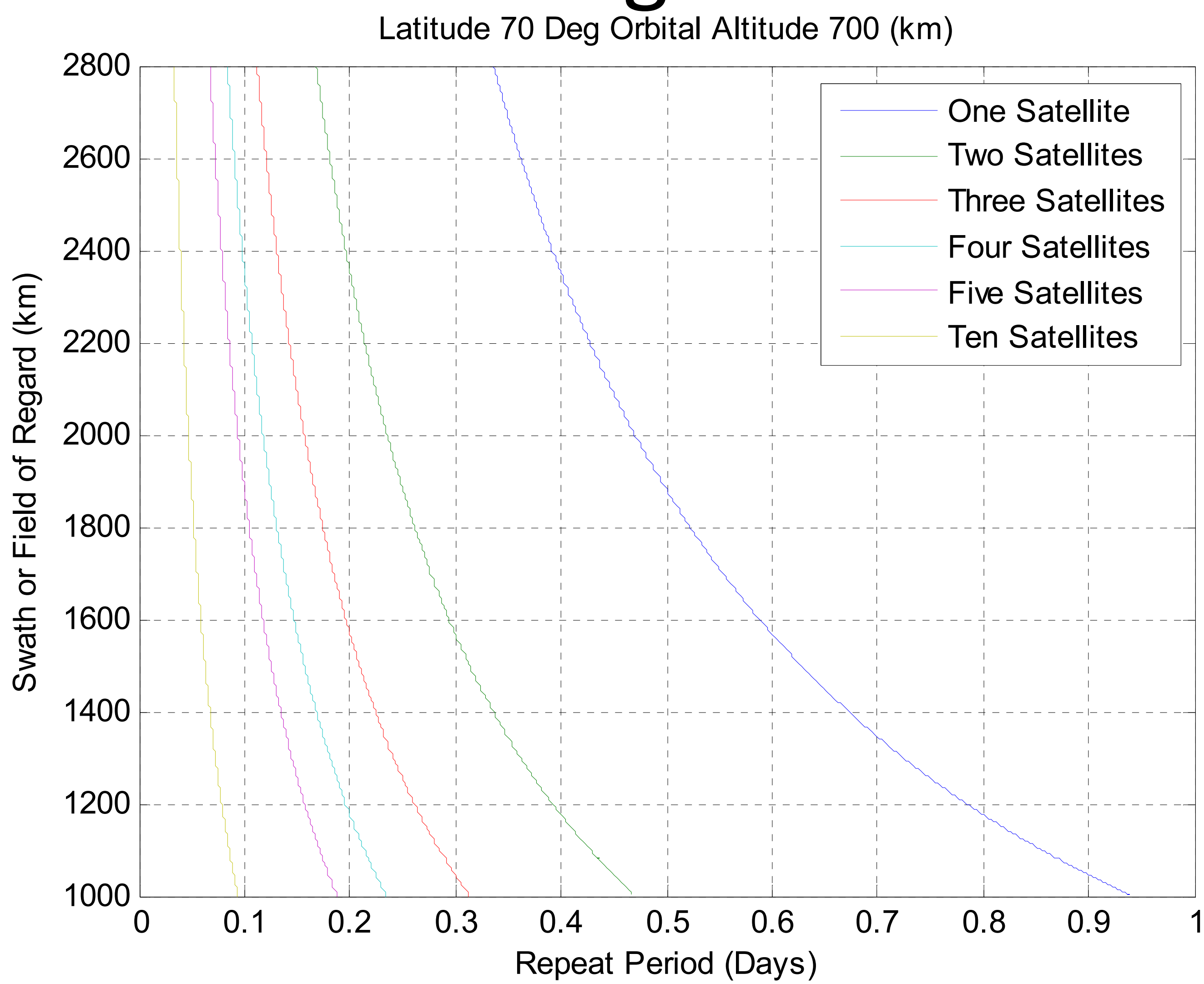
- Mission Architecture
  - Constellation
  - Nadir looking vs. agile
- Spatial Resolution
  - Cost vs. resolution
- Modes of operation
  - Local Area Coverage (LAC) direct broadcast
  - Global Area Coverage (GAC)

LEO Constellation Repeat Period
30 Deg Lat

- Large swaths and several satellites required for desired repeat period



LEO Constellation Repeat Period 70 Deg Lat



Coastal Ocean Color Instrument Architecture Comments

- Wide Field of View may require multiple modules (spectral and field of regard)
  - UV, VNIR and SWIR may be different instruments
- Pushbroom architectures with proven heritage do exist
  - Hyperspectral VNIR (MERIS-like)
  - Multispectral (Advanced Land Imager, Multispectral Thermal Imager) VNIR-SWIR

Shot Noise SNR

- High SNR requirements generally requires a shot noise limited system
- SNR~1000 requires 1E6 electrons!
- First order analysis shows SNRs >500 are achievable for 300 m GSD, for few cm optics at 700 km for typical radiances

$$SNR \approx \sqrt{\frac{\pi\,\gamma\,GSD^3 D^2 L\,T\,n\,\Delta\lambda\,TDI}{4v_g R^2\,hc/\lambda}}$$

$D - Telescope\ Diameter$

$L - Band\ Spectral\ Radiance$

$T - System\ Band\ Transmission$

$R - Orbital\ Altitude$

$\lambda - Wavelength$

$\Delta\lambda - Band\ Spectral\ Bandwidth$

$n - Quantum\ Efficiency$

Calibration/Validation

- Critical for long term systematic studies and applications
- All systems within a constellation need to be on the same coordinate system and radiometric scale
  - Vicarious calibrations
  - Monthly lunar calibrations
  - Limited on-board calibration to keep coast down

Summary and Conclusions

- A Coastal Ocean Color mission based on a LEO constellation is a possible next Earth imaging system
  - Global coverage
  - Repeat times with several satellites can approach GEO systems
  - A cost effective "Rapid Eye Like" mission
  - Payload risk reduction efforts required to bound costs
  - Thermal additions easier than GEO
    - Microbolometer