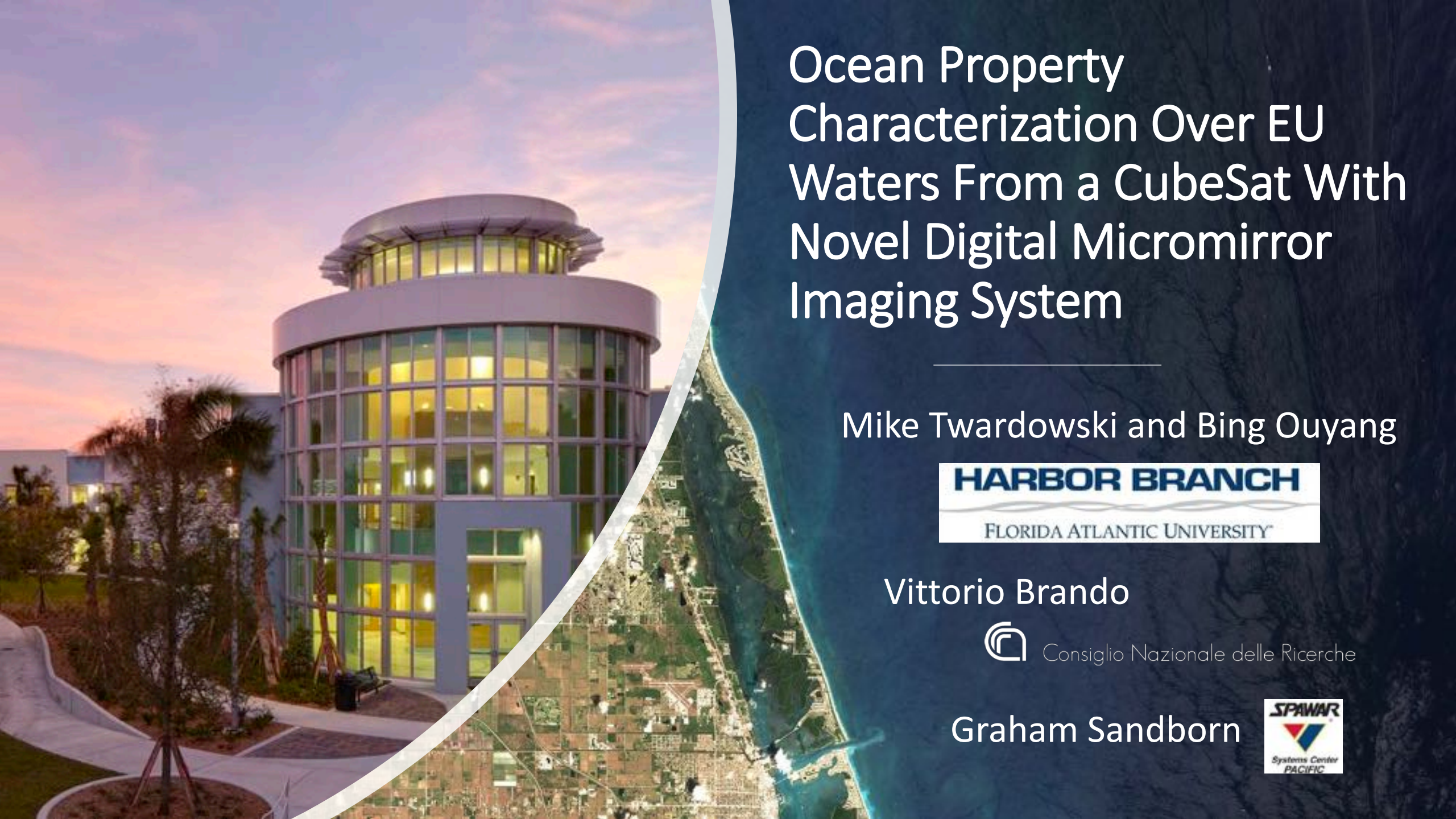

Ocean Property Characterization Over EU Waters From a CubeSat With Novel Digital Micromirror Imaging System

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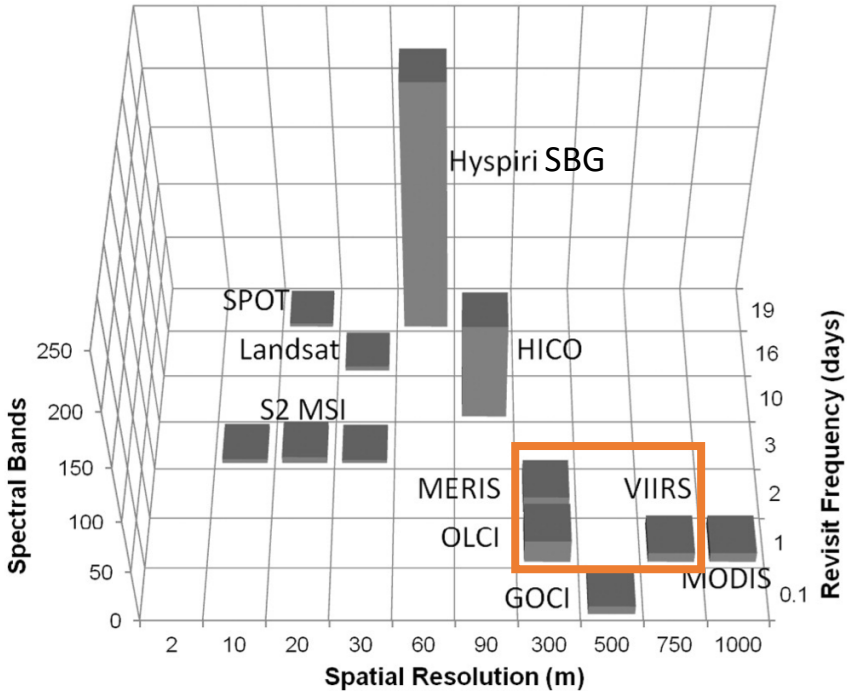
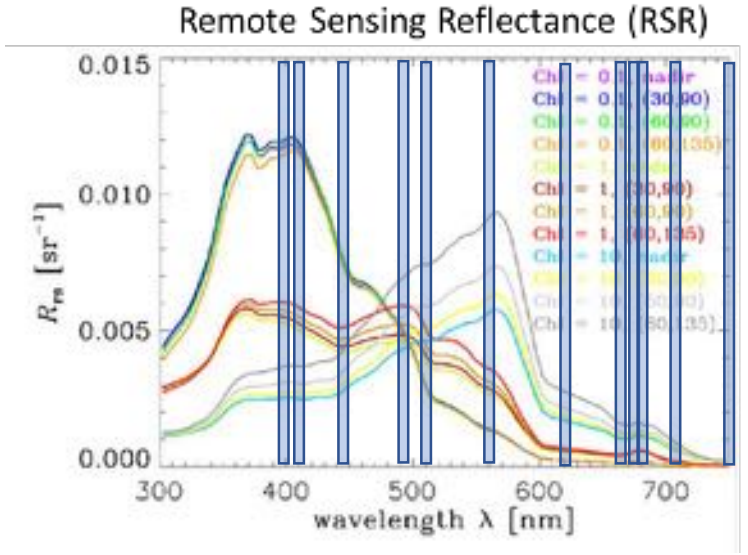
Graham Sandborn

SPAWAR
Systems Center
PACIFIC

European missions for Aquatic Earth Observation

Copernicus Sentinel 3 OLCI: global observer



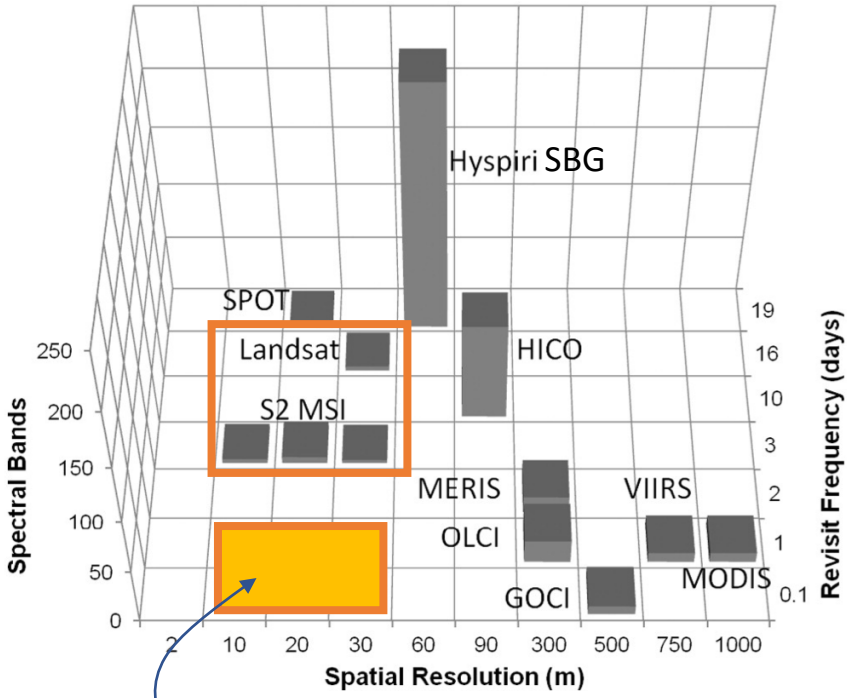


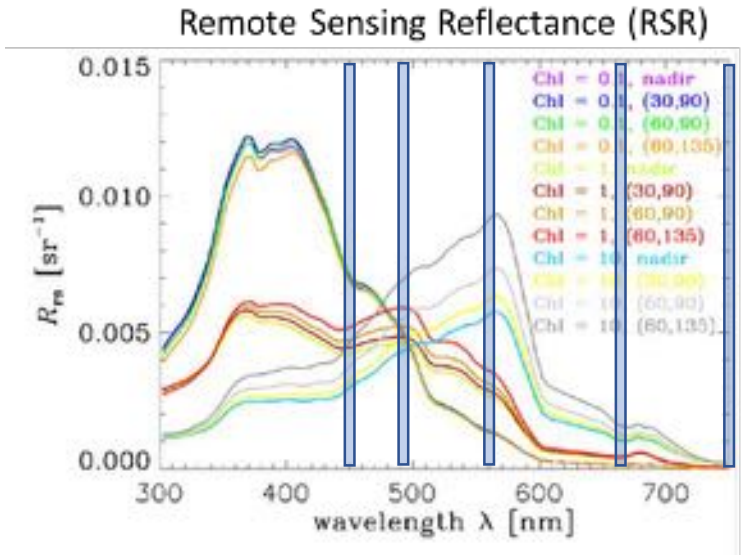
Mouw, Greb, Aurin, DiGiacomo, Lee, Twardowski, Binding, Hu, Ma, Moore, Moses, and Craig. 2015. Aquatic color radiometry remote sensing of coastal and inland waters: challenges and recommendations for future satellite missions. *RSE,* 160:15-30.

Hestir, Brando, Bresciani, Giardino, Matta, Villa, and Dekker. 2015. Measuring freshwater aquatic ecosystems: the need for a hyperspectral global mapping satellite mission. *RSE,* 167:181-195.

European missions for Aquatic Earth Observation

Copernicus Sentinel 2 MSI: fine scale/coastal





Critical region for coastal processes not currently being sampled…

Mouw, Greb, Aurin, DiGiacomo, Lee, Twardowski, Binding, Hu, Ma, Moore, Moses, and Craig. 2015. Aquatic color radiometry remote sensing of coastal and inland waters: challenges and recommendations for future satellite missions. *RSE,* 160:15-30.

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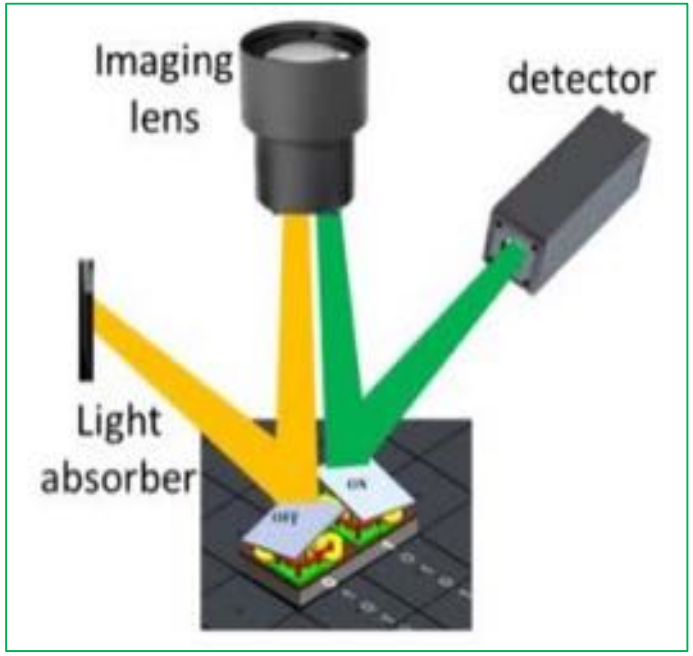
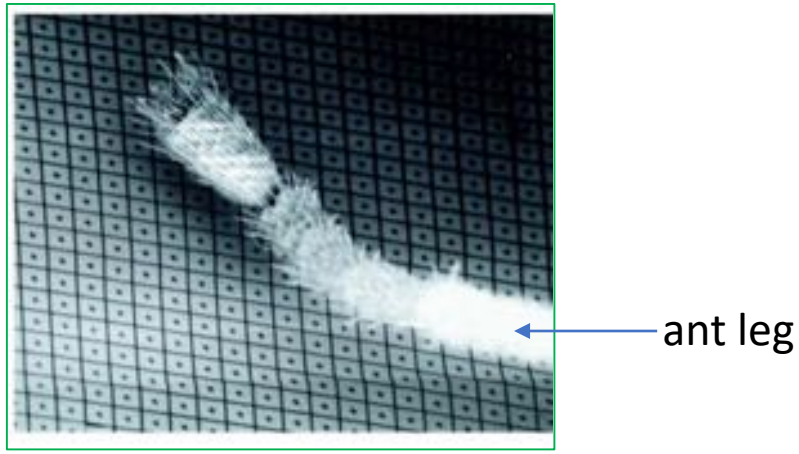
Intelligent image acquisition

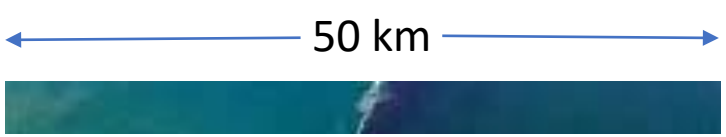
Digital Micromirror Device

- Array of millions of micromirrors
- Each mirror has binary reflection response
- Dither patterns (off/on patterns) can be adjusted at 40 kHz
- Allows highly flexible front end optical filtering

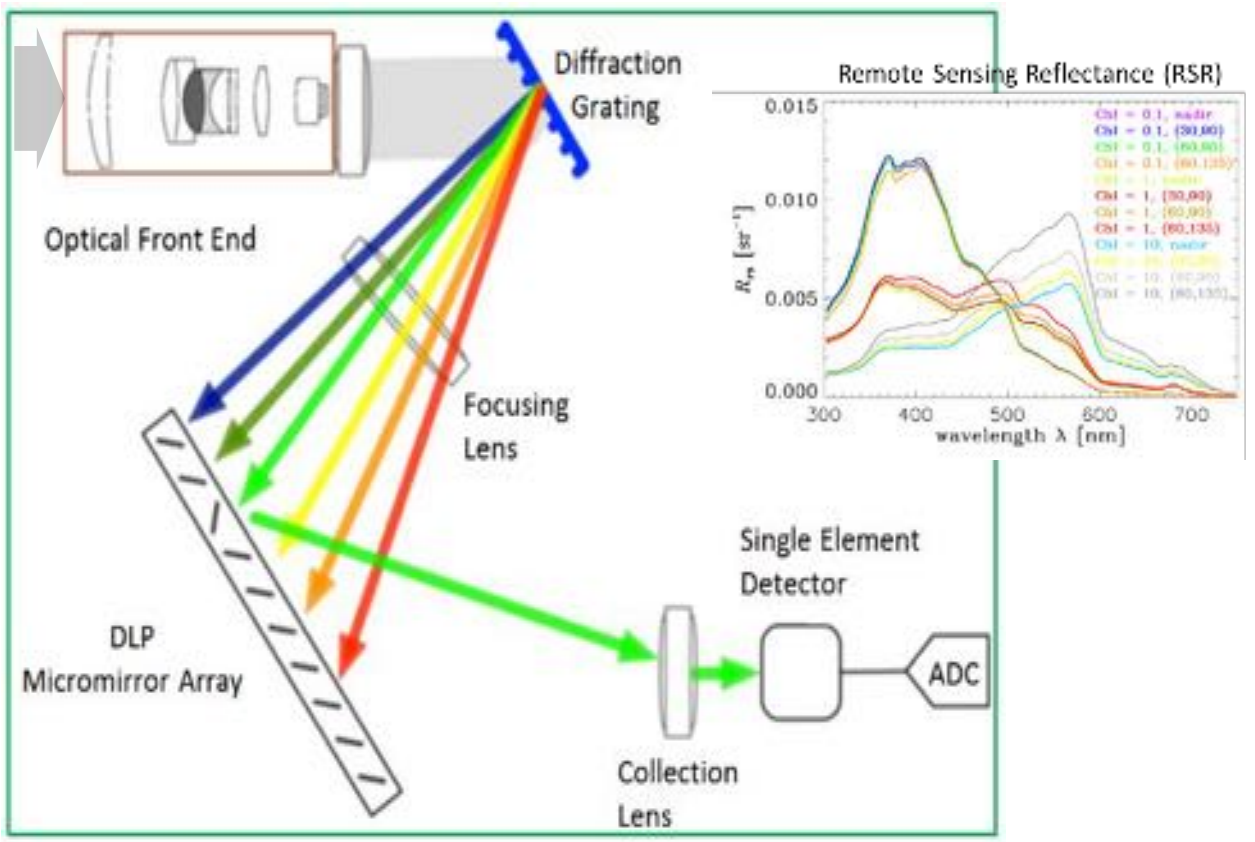




CubeSat DMD Imager Design



- Place a **Digital Micromirror Device (DMD)** in optical path
- Image a linear spatial scene onto the DMD in the vertical dimension *V*, hyperspectral bands in horizontal dimension *N* (i.e, **pushbroom imager**)
- Replace array detector with highly sensitive single detector (e.g., **PMT or APD**)
- **Decrease data loading** to $M << (V \times N)$
- Use **adaptive filter codebooks** (i.e., DMD dither patterns) to maintain SNR under different environment conditions
- **Image reconstructed at ground station** using complimentary codebook

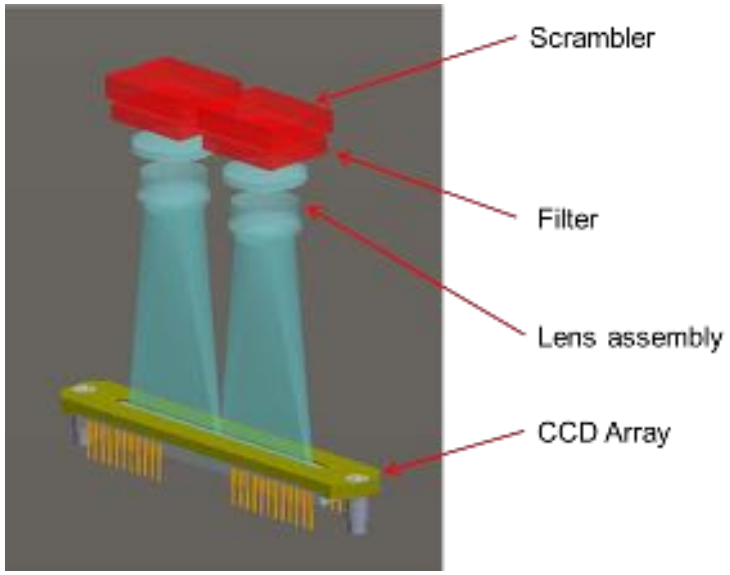


CubeSat DMD Imager Design

Key benefits with respect to current state-of-the-art (CCD/CMOS-based)

- Simpler, low SWaP-C optical design
- High spectral and spatial resolution possible
- A single PMT (or APD) detector with higher sensitivity, dynamic range (up to 2 orders higher), and SNR
- Interpixel non-uniformity errors, striping are avoided
- Front-end filtering to reduce redundant data loading with same SNR
- DMD dither pattern can be adapted in real time to optimize spatial-spectral resolution for a given scene
- DMD filtering can be used to mitigate blooming/saturation effects for bright land and cloud features adjacent to dark water
- Far less data volume transmitted with near-lossless compression

2-band schematic



CCD-based design

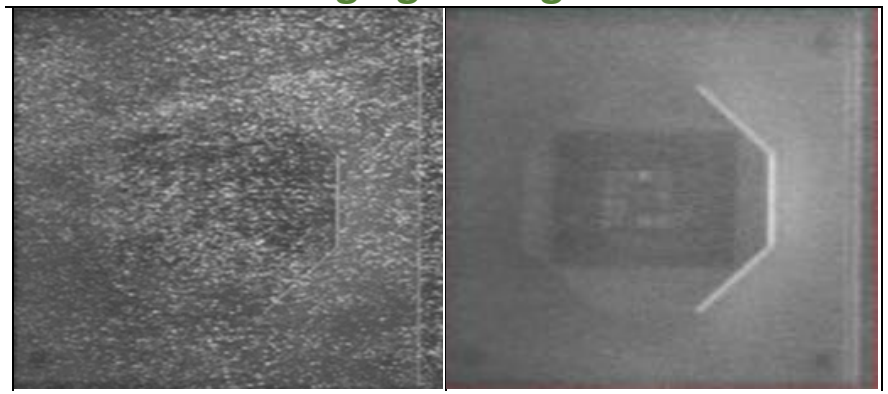
Hawkeye CubeSat imager

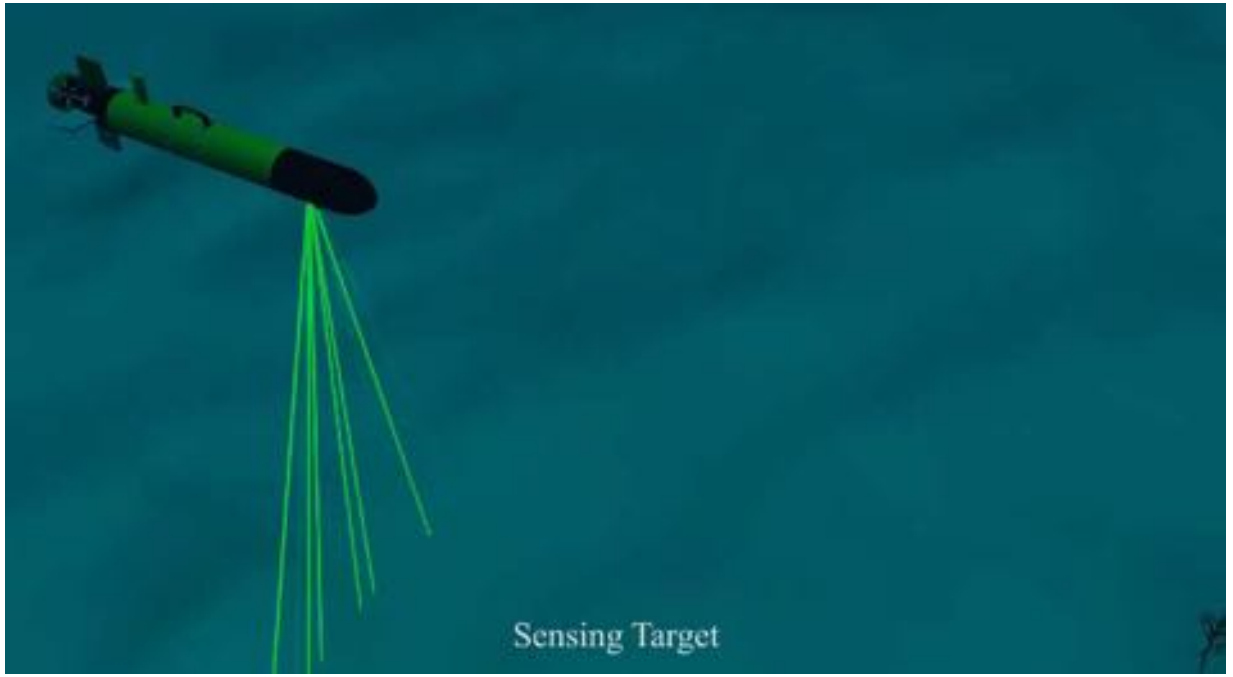
Cloudland Instruments

Compressive Sensing Algorithms

- Compressive Line Sensing (CLS): highly resource efficient technique
  - **Inspired by active CLS imager prototype previously developed for Navy and Air Force**
  - Senses each spatial-spectral "sheet" independently, jointly reconstructing a set of "sheets" for data cube
  - Imaging = *encoding/decoding*
  - DMD codebook applied adaptively, "on-the-fly"

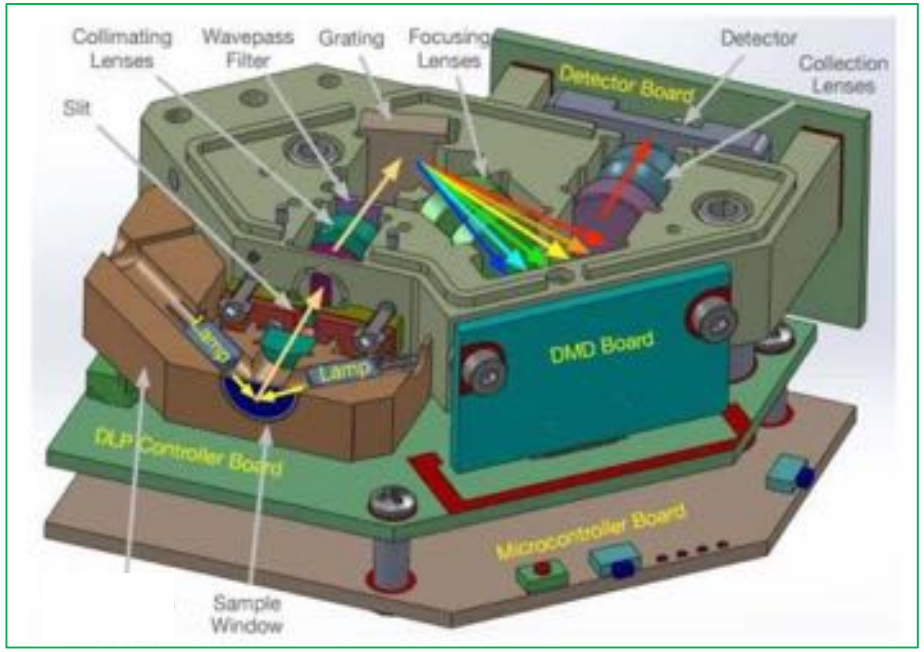
Underwater imaging through bubble screen



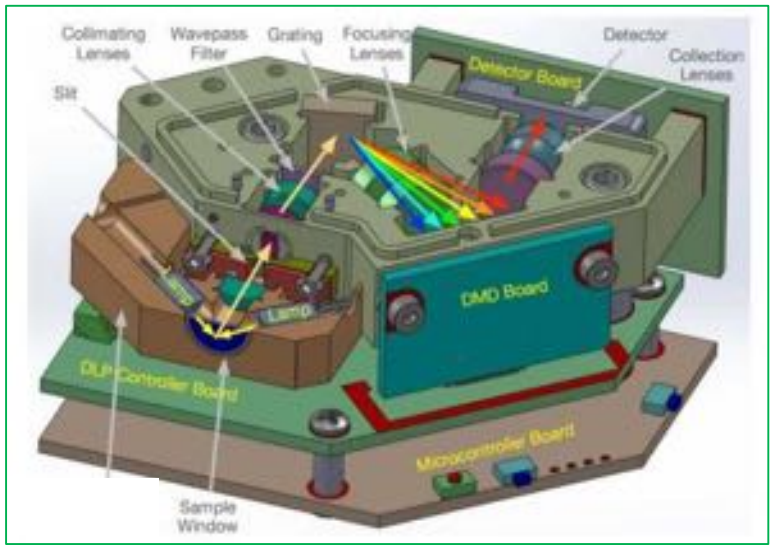


CubeSat DMD Imager – specs for Navy project

- Minimum SNR of 300 across all bands
- 350 to 900 nm spectral range, up to 1600 bands
- 20 m GSD over 50 km swath at 450 km altitude
- Equatorial orbit planned with ~90 min revisit
- Compressive sensing to optimize information content while achieving SNR
- Passive water-leaving radiance (L_w) detected, aka Remote Sensing Reflectance
  - Libraries of algorithms exist to derive a wide range of ocean water quality parameters

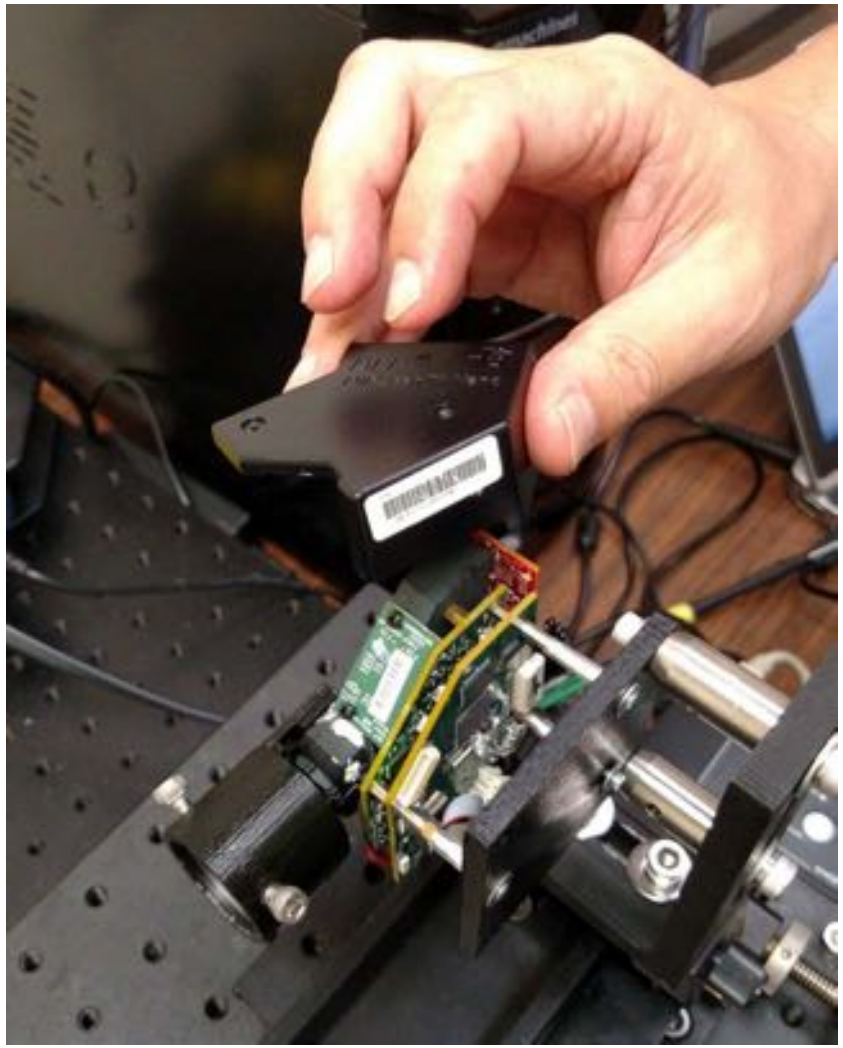


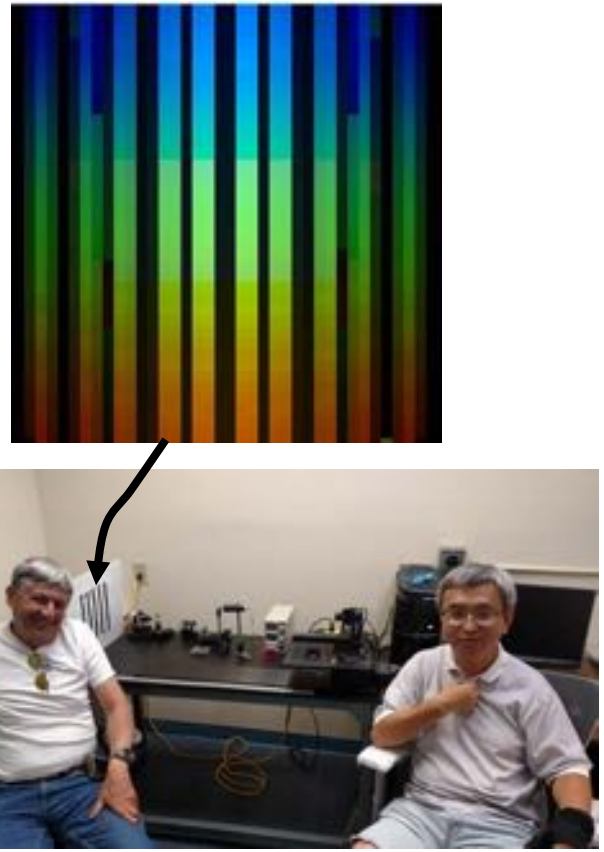
Mission/Payload Sensor



<u>FY19</u>: 854 x 480 pixel DMD

6.2 x 5.8 x 3.6 cm^3



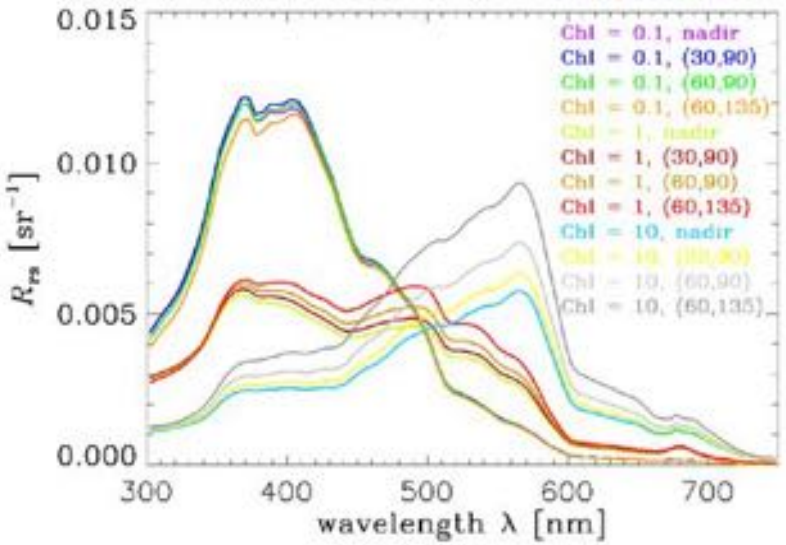


<u>FY20</u>:

2560 x 1600 pixel DMD

Science Products – Ocean Properties

Remote Sensing Reflectance (RSR)



- Fundamental optical properties of water
  - absorption
  - backscattering

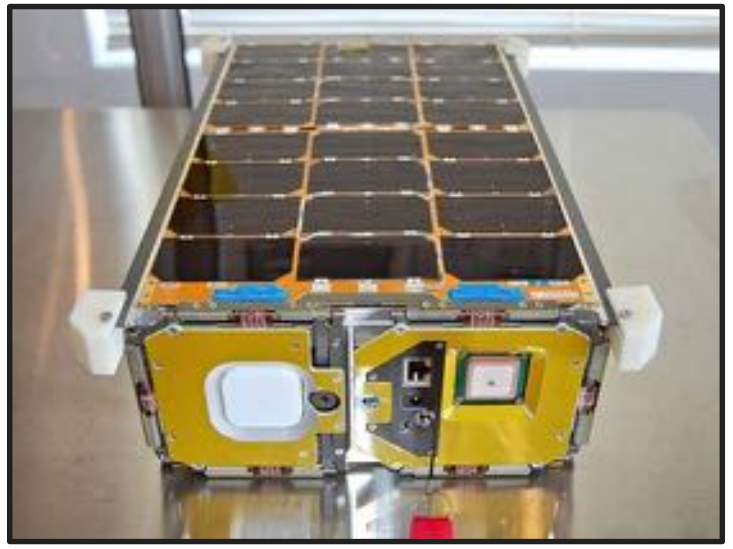
Imaging, visibility, Electro-Optical ID applications

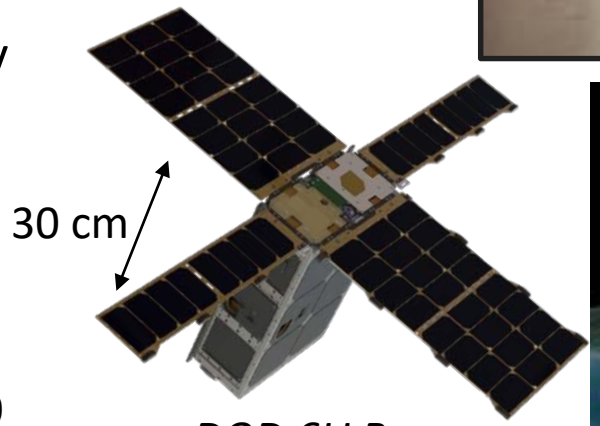
- Biogeochemical properties
  - Suspended Particulate Matter (SPM)
  - Chromophoric DOM
  - Chlorophyll
  - Algal pigment composition
  - Particulate organic carbon (POC)
  - Primary productivity
  - Etc…

Ecosystem monitoring, ocean health, hazard impacts

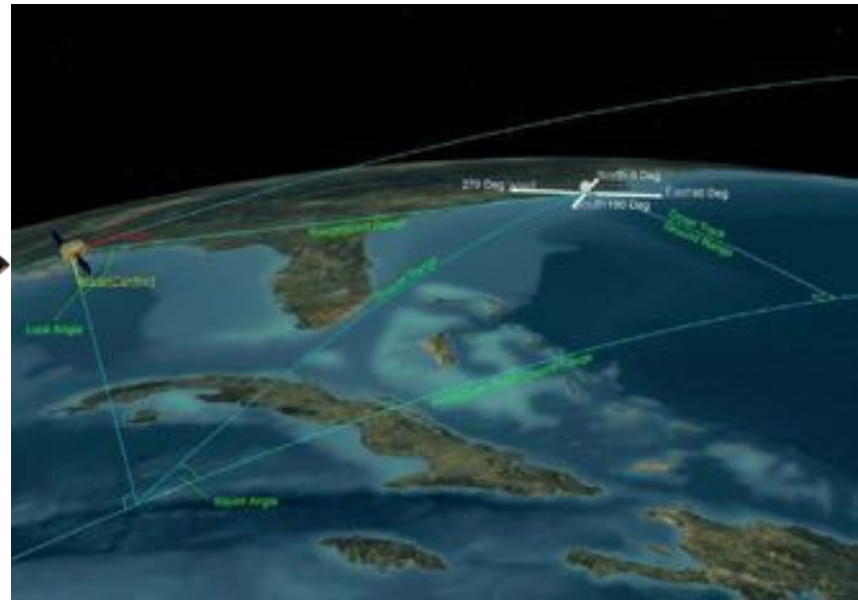
SPAWAR Systems Center Pacific Launch Program

- Phase A simulation and testing
  - Thermal vacuum, vibration, radiation, etc
  - Power budgets
- Material and hardware durability/reliability assessment
- Integration design with 6U bus
- Simulate and test data downlink
  - ~1 Mbps over ~5 min/orbit
- **Developing optical comm downlink with 120 Mbps capability**
- **Also developing optical comms in space for real-time downlink from anywhere in orbit**



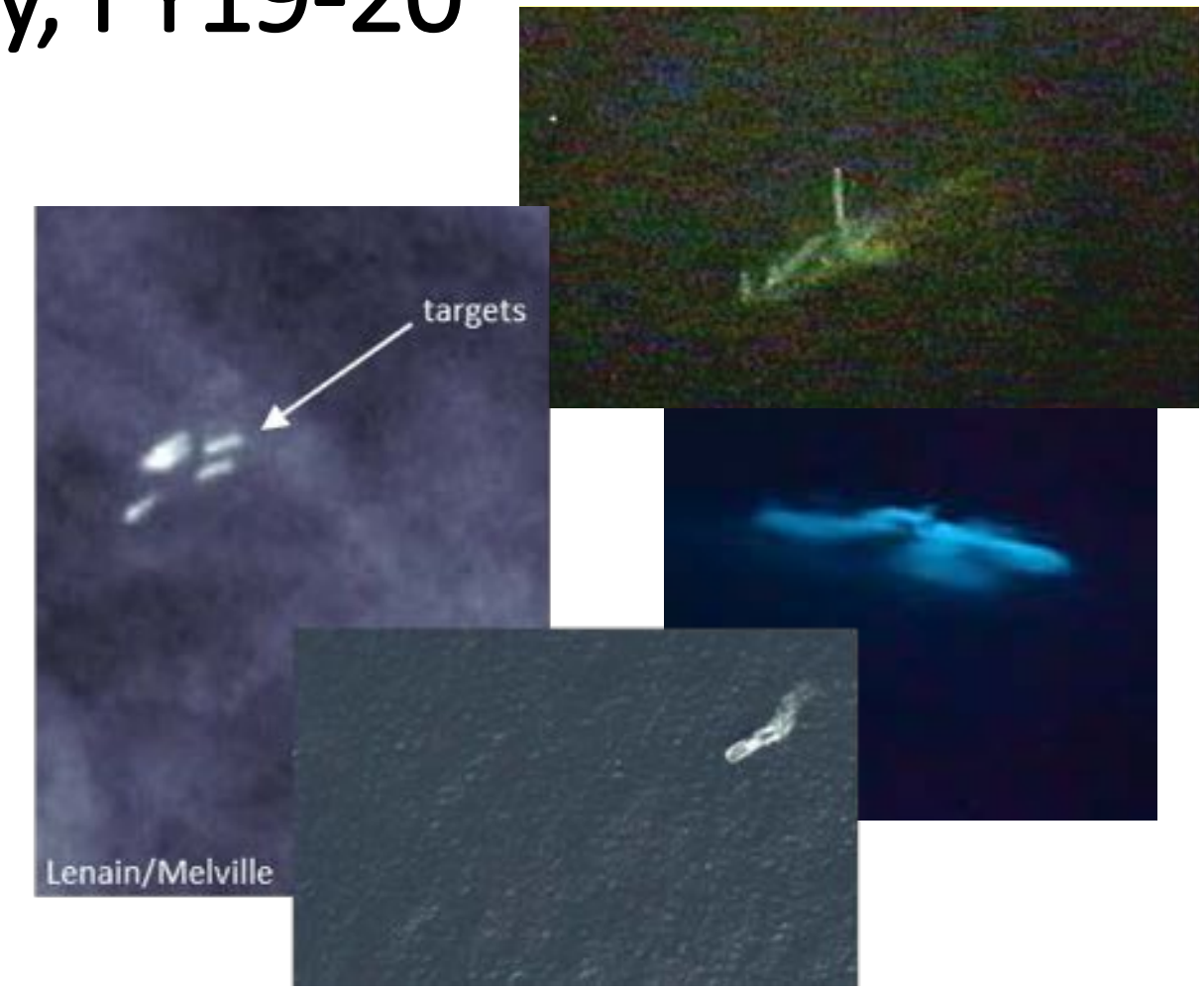


DOD 6U Bus Pumpkin



Development of bioluminescence and thermal imagers in review at Navy, FY19-20

- For persistent surveillance
- Same DMD front end optical filtering technique
  - For **bioluminescence**, full 2D scene imaged onto DMD at 490 nm
  - For **thermal**, full 2D scene imaged onto DMD at MWIR
  - Sparse background monitoring switches to intensive monitoring protocol with object detection
  - Testing proposed from geostationary orbit on CubeSats (~2 m GSD) and HAPS drones (~40 cm GSD)



Testing on HAPS with SSC-Pacific currently in review…

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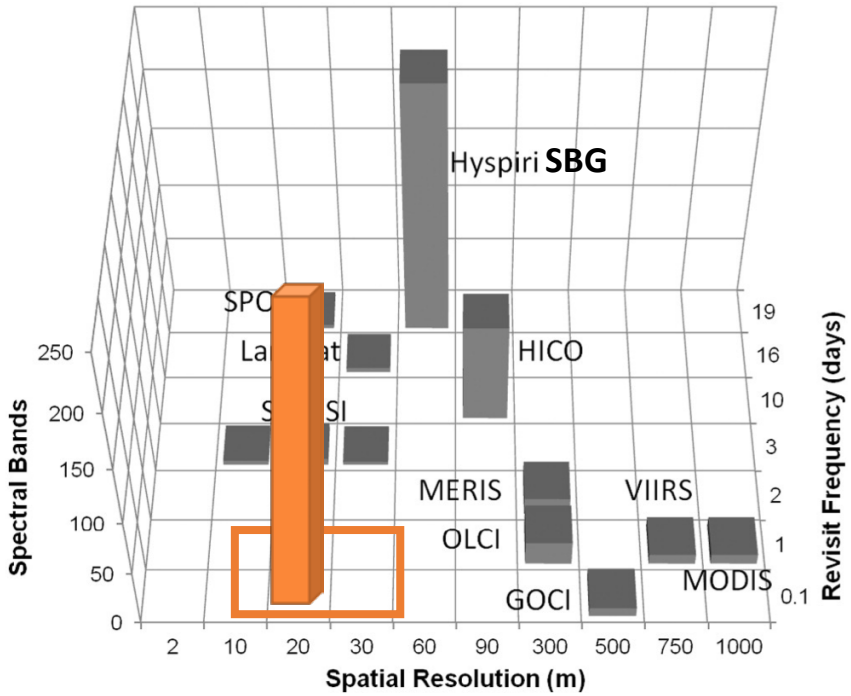
OCEAN & ATMOSPHERE
RESEARCH

European missions for Aquatic Earth Observation

a new observation class on the horizon?



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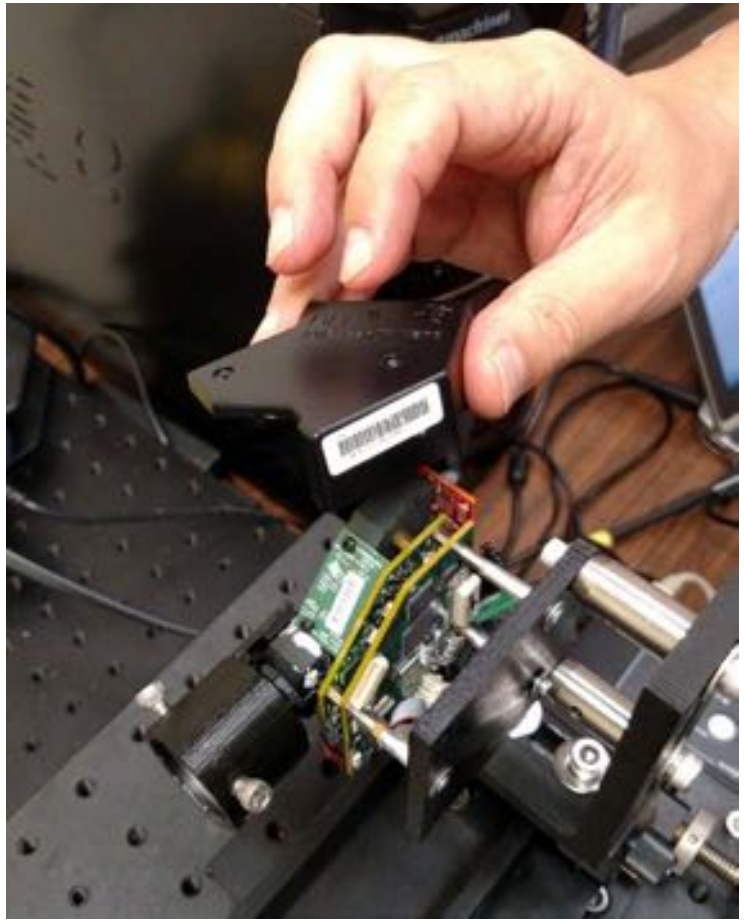
Summary

- Currently developing hyperspectral DMD imager
  - 854 x 480 DMD increased to 2560 x 1600 in FY20
  - Phase B CubeSat deployment in equatorial orbit, FY21
- Flight operations testing at SSC-Pacific
- Navy support for bioluminescence and thermal imagers in review
  - Phase A testing on HAPS drones
- **Interested in contributing a DMD imager for monitoring EU waters**
- **Postdoc opportunities**



Thank You

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