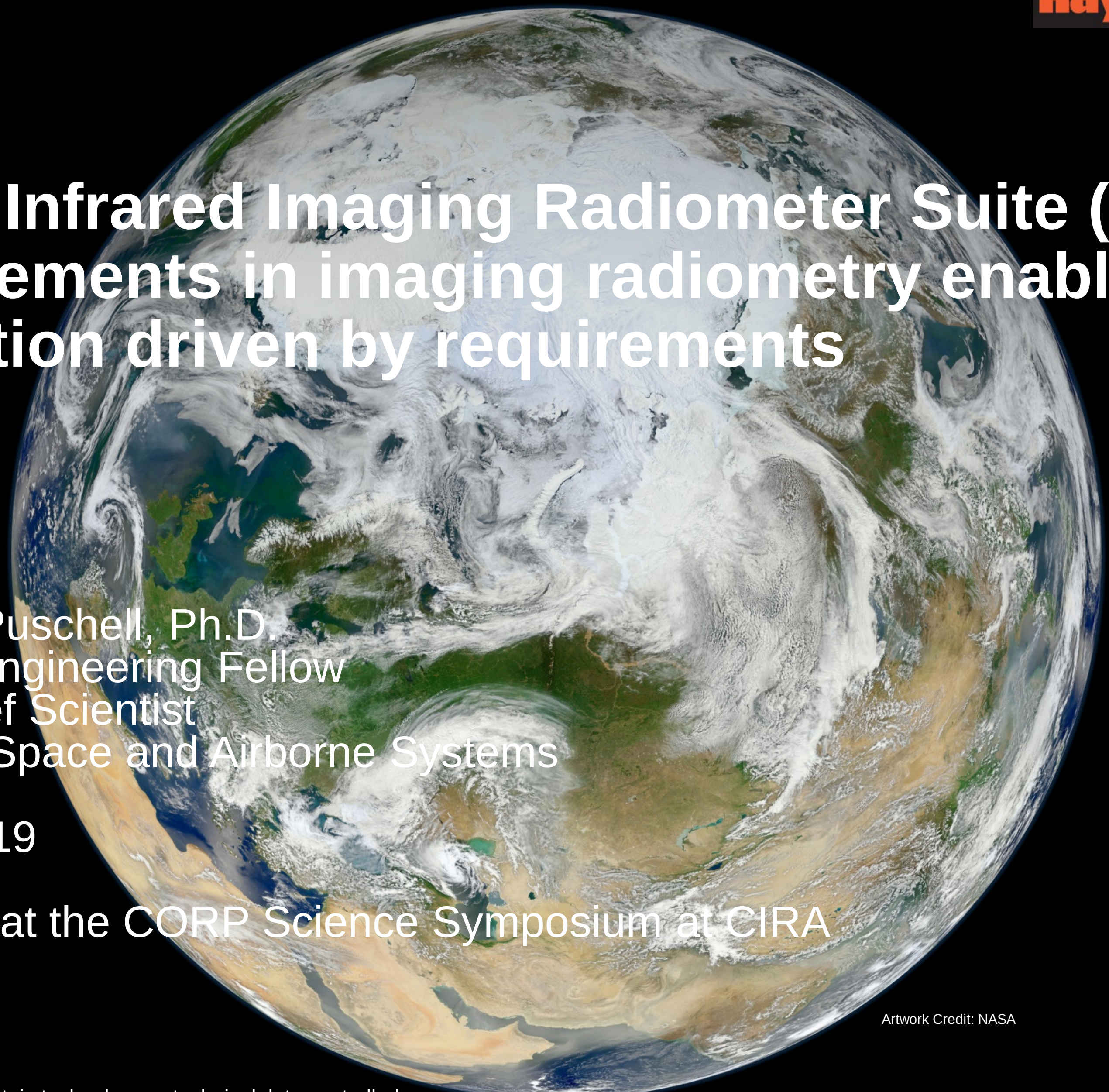


Visible Infrared Imaging Radiometer Suite (VIIRS): improvements in imaging radiometry enabled by innovation driven by requirements

Jeffery J. Puschell, Ph.D.
Principal Engineering Fellow
VIIRS Chief Scientist
Raytheon Space and Airborne Systems

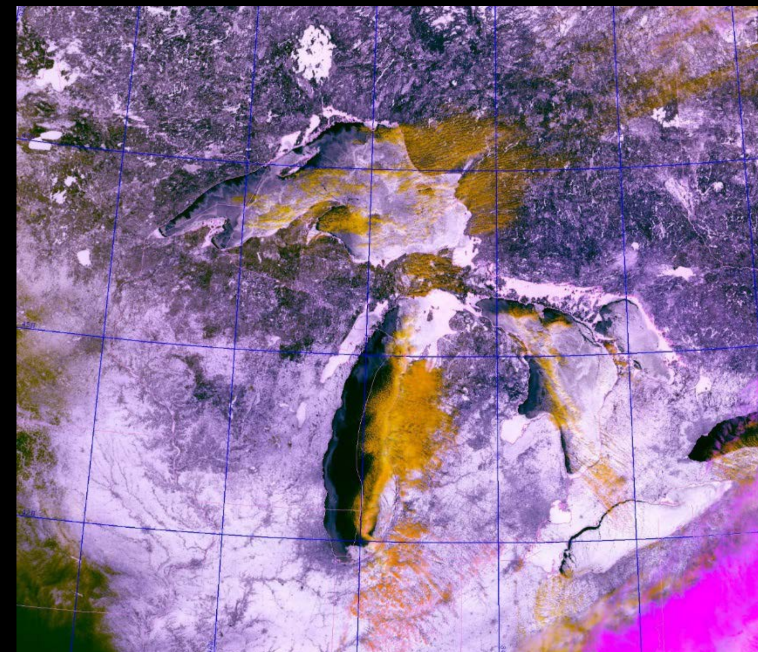
2016 July 19

Presented at the CORP Science Symposium at CIRA

Artwork Credit: NASA

Raytheon imagers in space have been changing the way we see the Earth for 50 years

Media provided by CIRA, NASA, NOAA and University of Wisconsin



Raytheon got into this business by building the first geosynchronous weather imagers and remote sensors with the University of Wisconsin

- Early legacy expertise in delivering infrared systems with superb infrared detectors built in-house in Goleta combined with the Hughes (now Boeing) pioneering expertise with GEO comm sats enabled us to enter the space-based imaging/remote sensing business
- First Instrument Launch – 1966 Dec 6
  - 10 Imaging Radiometers
  - 5 Atmospheric Sounders

First full earth color photo taken from GEO using ATS-3 on 1967 Nov 10

Multicolor Spin-Scan Cloud Camera
First GEO imager

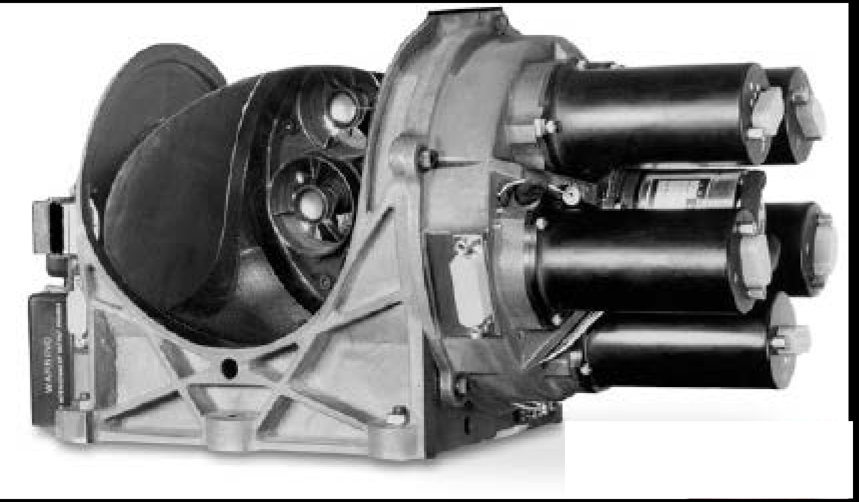
Visible/Infrared Spin-Scan Radiometer flew on GOES 1-7 and GMS 1-5

Vern Suomi
University of Wisconsin
Inventor of the Geosynchronous Weather Satellite

The path to VIIRS started with the Medium-Resolution Infrared Radiometer (MRIR)

Raytheon

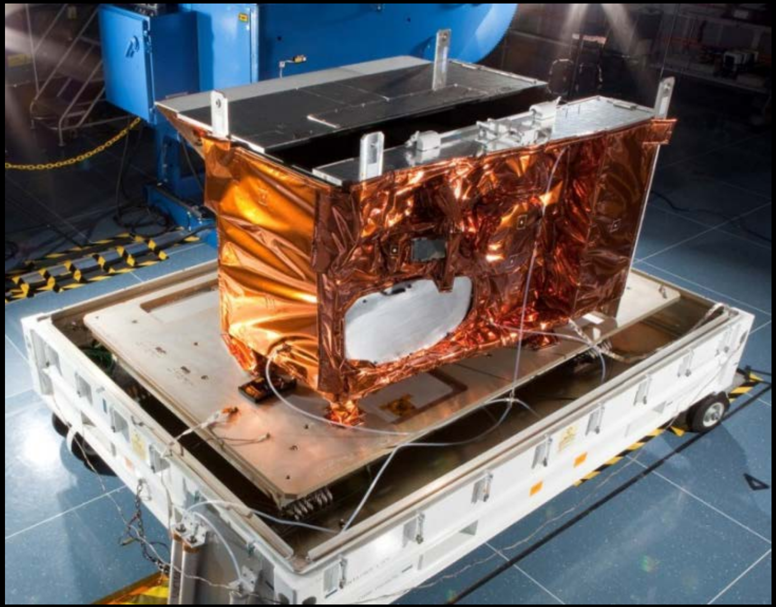
- MRIR was a five-channel scanning radiometer built for NASA’s Goddard Space Flight Center by Raytheon’s legacy Santa Barbara Research Center in the 1960s
- MRIR was the first instrument to measure sea surface temperature accurately from space and it pioneered data analysis and vicarious calibration techniques
- Unlike other instruments being flown at the time like the TIROS imagers, which were basically TV cameras in space, MRIR was a radiometer that provided data for understanding physics of the Earth’s surface and atmosphere



MEDIUM-RESOLUTION INFRARED RADIOMETER (MRIR)	
ORBIT:	1110 km, 108 min., sun synchronous (noon)
SCAN:	8 rpm cross-track rotating mirror
TELESCOPES (5):	4.4 cm dia., f/2.4 Cassegrain
SPECTRAL BANDS (5):	0.2 to 23 μm
DETECTORS (5):	Immersed and nonimmersed thermistor bolometers
RESOLUTION:	45 km
NEΔT (200K SCENE):	1.0 to 2.2K
LAUNCH DATES:	Nimbus 2: May 15, 1966 Nimbus 3: April 14, 1969

Visible Infrared Imaging Radiometer Suite (VIIRS) is the US operational environmental imager in polar orbit

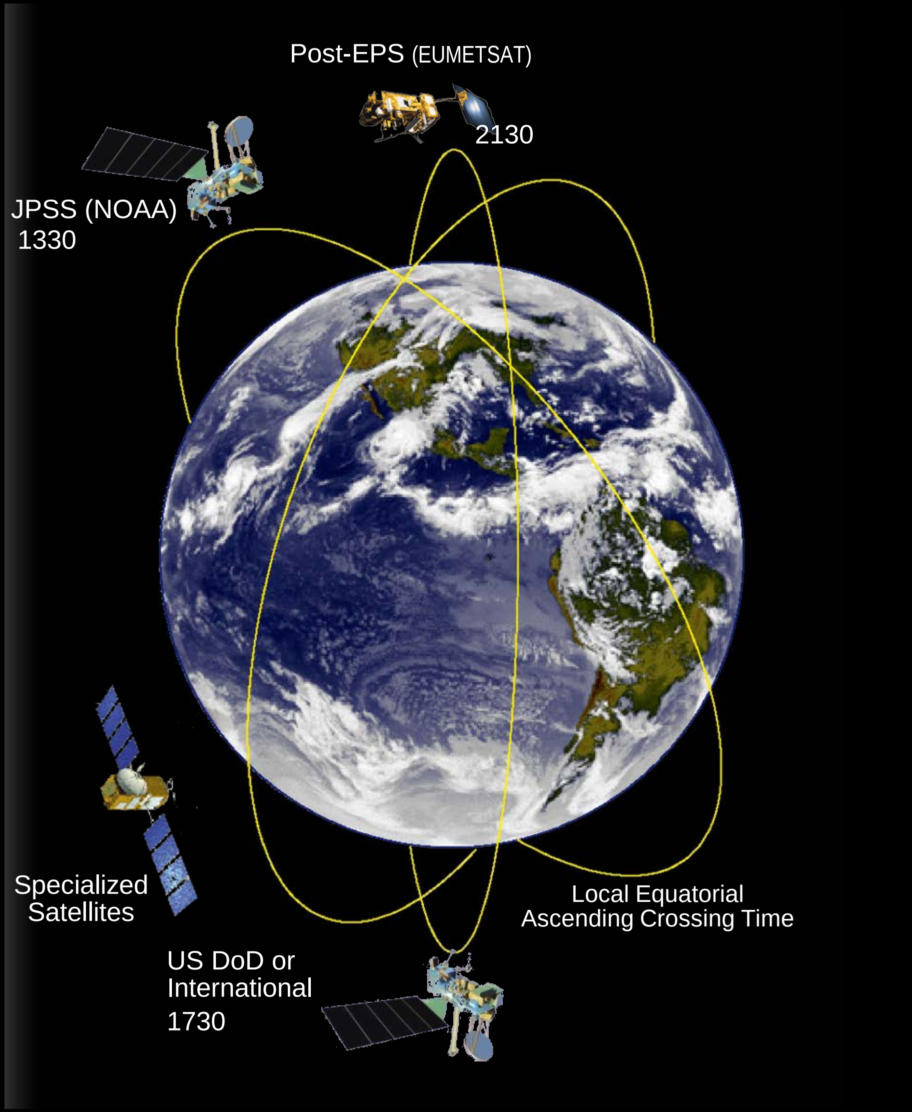
- Flight Unit 1 onboard the Suomi NPP satellite is performing well, providing high-quality visible/infrared Earth observations since 2011
- Flight Unit 2 has been delivered and Flight Unit 3 is being built now in El Segundo
- VIIRS provides higher spatial resolution data across a wider area than previous instruments
  - More complete global coverage, higher quality and more complete data
- A highly sensitive day/night band is improving weather forecasting around the world and providing new ways to observe the Earth from space
- VIIRS replaces four legacy sensors with a single instrument
  - Facilitates incorporation of new technology and response to changing requirements



VIIRS is a key instrument in the Joint Polar Satellite System (JPSS)

Raytheon

- JPSS mission
  - Provide national, operational, polar-orbiting remote-sensing capability
  - Incorporate new technologies from NASA into operations
  - Encourage international cooperation
- VIIRS collects visible/ infrared imagery and radiometric data
- VIIRS contributes to more environmental data products than any other JPSS sensor
- VIIRS has been observing Earth from the Suomi NPP satellite, a precursor to JPSS, since late 2011



VIIRS has 22 spectral bands that address a wide variety of Environmental Data Records (EDRs)

		Band No.	Wave-length (µm)	Horiz Sample Interval (km Downtrack x Crosstrack)		Driving EDRs	Radi-ance Range	Ltyp or Ttyp
				Nadir	End of Scan			
VIS/NIR FPA	Silicon PIN Diodes	M1	0.412	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols	Low High	44.9 155
VIS/NIR FPA	Silicon PIN Diodes	M2	0.445	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols	Low High	40 146
VIS/NIR FPA	Silicon PIN Diodes	M3	0.488	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols	Low High	32 123
VIS/NIR FPA	Silicon PIN Diodes	M4	0.555	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols	Low High	21 90
VIS/NIR FPA	Silicon PIN Diodes	I1	0.640	0.371 x 0.387	0.80 x 0.789	Imagery	Single	22
VIS/NIR FPA	Silicon PIN Diodes	M5	0.672	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols	Low High	10 68
VIS/NIR FPA	Silicon PIN Diodes	M6	0.746	0.742 x 0.776	1.60 x 1.58	Atmospheric Corr'n	Single	9.6
VIS/NIR FPA	Silicon PIN Diodes	I2	0.865	0.371 x 0.387	0.80 x 0.789	NDVI	Single	25
VIS/NIR FPA	Silicon PIN Diodes	M7	0.865	0.742 x 0.259	1.60 x 1.58	Ocean Color Aerosols	Low High	6.4 33.4
S/MWIR	PV HgCdTe (HCT)	M8	1.24	0.742 x 0.776	1.60 x 1.58	Cloud Particle Size	Single	5.4
S/MWIR	PV HgCdTe (HCT)	M9	1.378	0.742 x 0.776	1.60 x 1.58	Cirrus/Cloud Cover	Single	6
S/MWIR	PV HgCdTe (HCT)	I3	1.61	0.371 x 0.387	0.80 x 0.789	Binary Snow Map	Single	7.3
S/MWIR	PV HgCdTe (HCT)	M10	1.61	0.742 x 0.776	1.60 x 1.58	Snow Fraction	Single	7.3
S/MWIR	PV HgCdTe (HCT)	M11	2.25	0.742 x 0.776	1.60 x 1.58	Clouds	Single	0.12
S/MWIR	PV HgCdTe (HCT)	I4	3.74	0.371 x 0.387	0.80 x 0.789	Imagery Clouds	Single	270 K
S/MWIR	PV HgCdTe (HCT)	M12	3.70	0.742 x 0.776	1.60 x 1.58	SST	Single	270 K
S/MWIR	PV HgCdTe (HCT)	M13	4.05	0.742 x 0.259	1.60 x 1.58	SST Fires	Low High	300 K 380 K
LWIR	PV HCT	M14	8.55	0.742 x 0.776	1.60 x 1.58	Cloud Top Properties	Single	270 K
LWIR	PV HCT	M15	10.763	0.742 x 0.776	1.60 x 1.58	SST	Single	300 K
LWIR	PV HCT	I5	11.450	0.371 x 0.387	0.80 x 0.789	Cloud Imagery	Single	210 K
LWIR	PV HCT	M16	12.013	0.742 x 0.776	1.60 x 1.58	SST	Single	300 K

VIIRS global monitoring improves decision making on crucial international priorities

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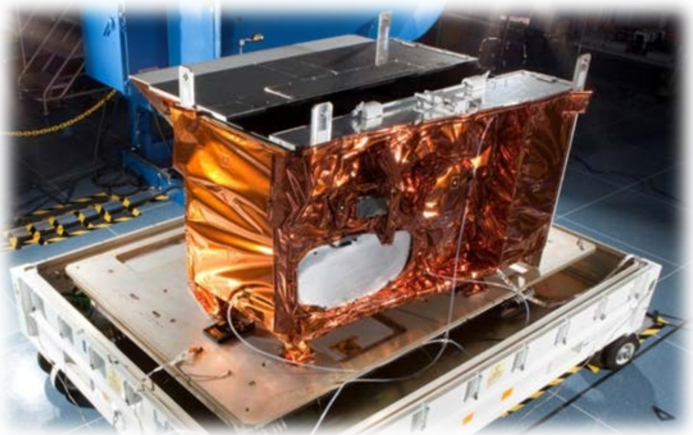
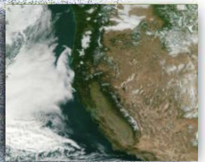
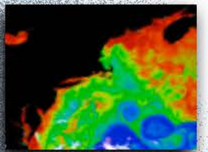


- Breaks through limitations of previous operational systems with more complete spectral and spatial coverage, sharper imagery, better sensitivity and better accuracy
- Benefits from substantial US research investment in NASA/NOAA research systems to enable new operational weather forecasting and other environmental data products
- Enables new ways to view Earth from space using calibrated low light imaging band with 100x better sensitivity and 8x better spatial resolution than previous system

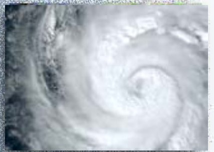
Data Products



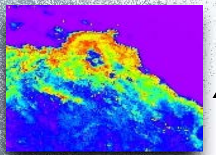
Imagery



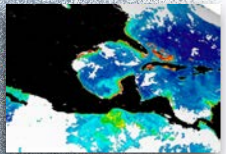
Sea Surface Temperature



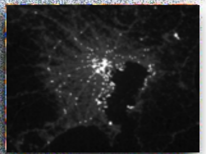
Clouds



Aerosols



Ocean Color



Low Light Visible Imaging

Benefits for Decision Makers

Improved Environmental Monitoring and Forecasting for Weather and Ecosystems

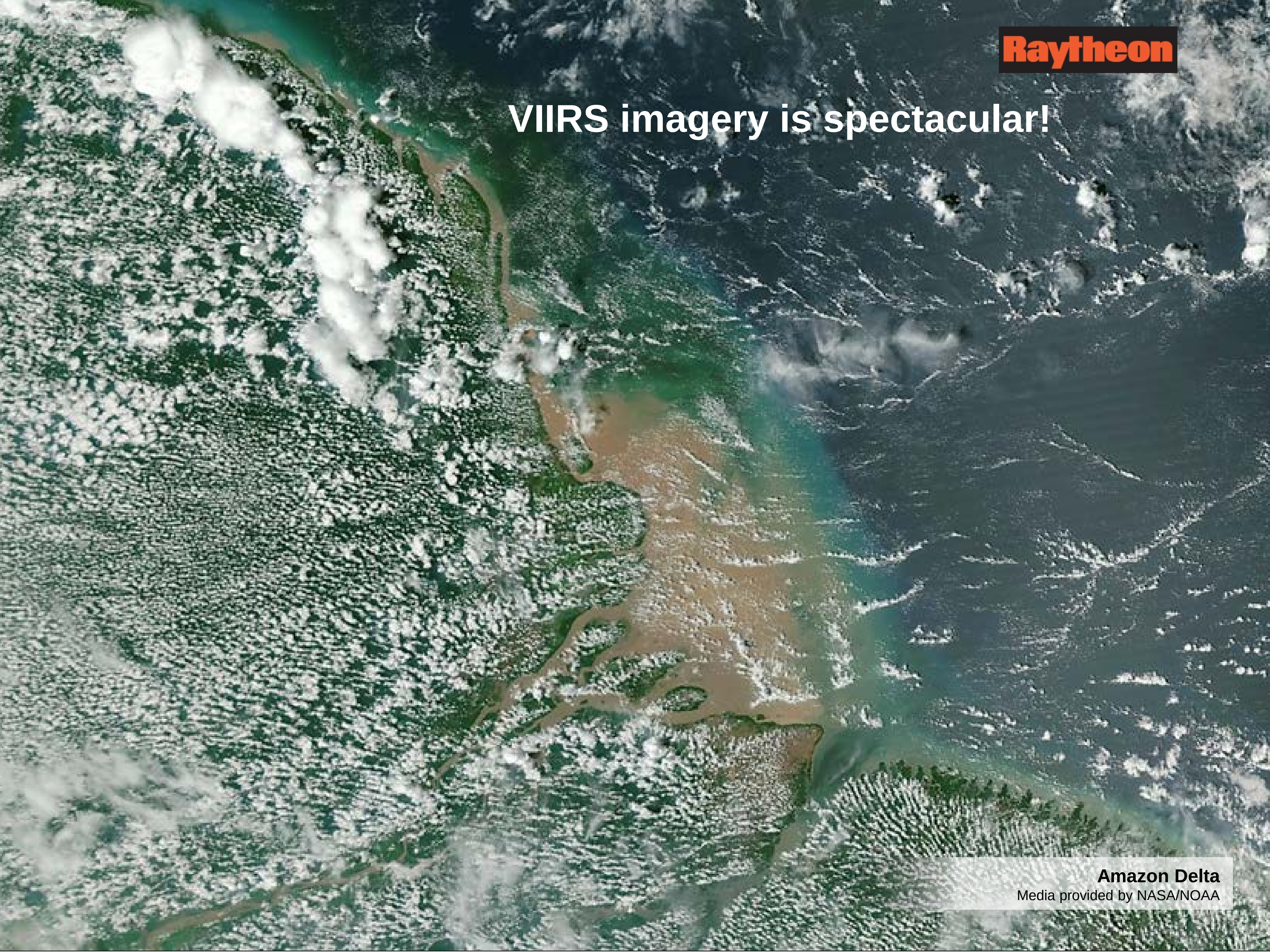
Natural Disasters: Earlier Warning and Faster Response

Military Support: Sharper Imagery and Better Global Weather Forecasting for Mission Planning/Ops

Crucial Resources: Improved Ability to Protect Water Supply, Predict Electric Power Needs, Warn of Conditions Leading to Food Shortage

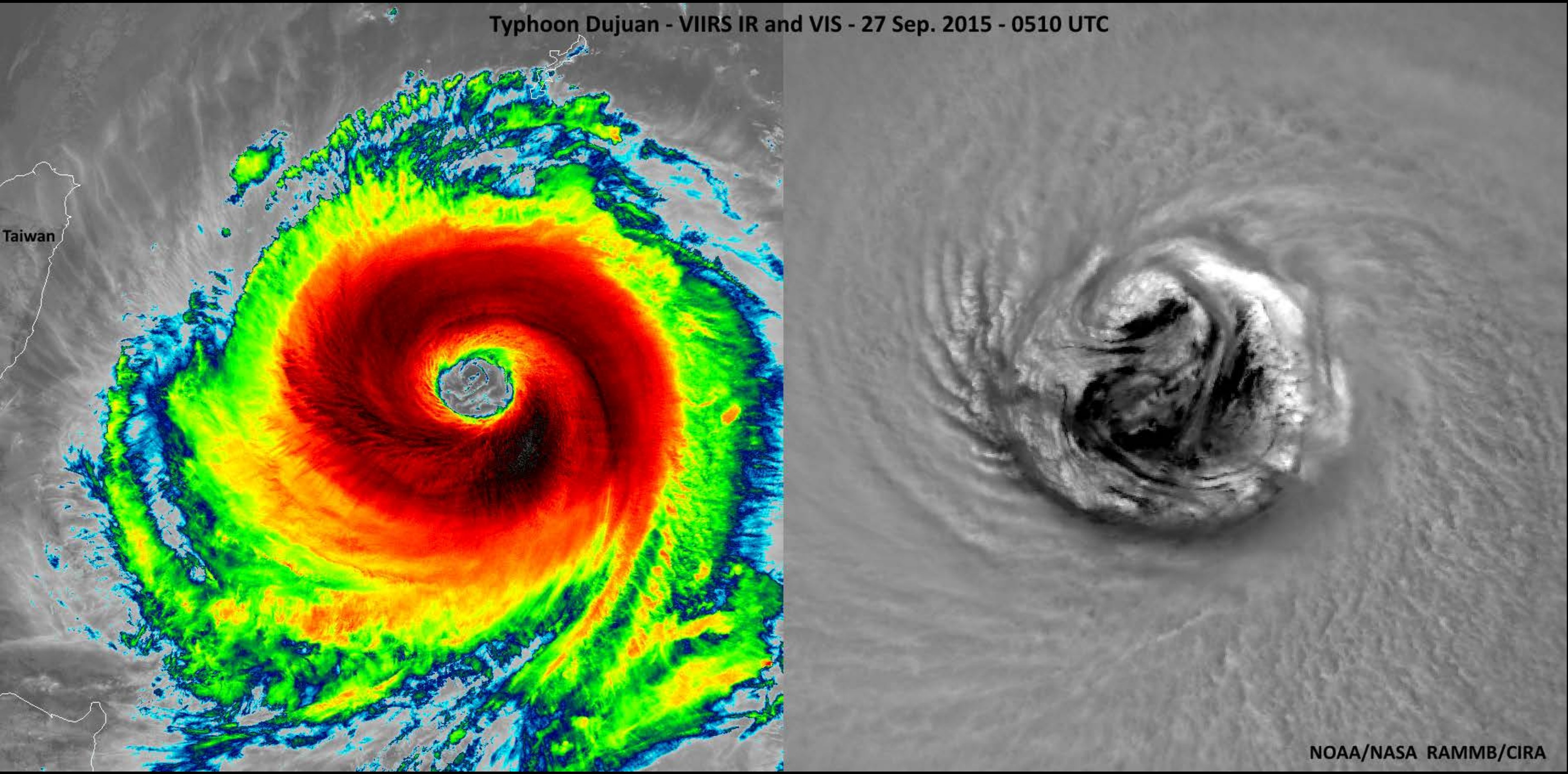
Public Health: Early Warning of Health Hazards

VIIRS imagery is spectacular!

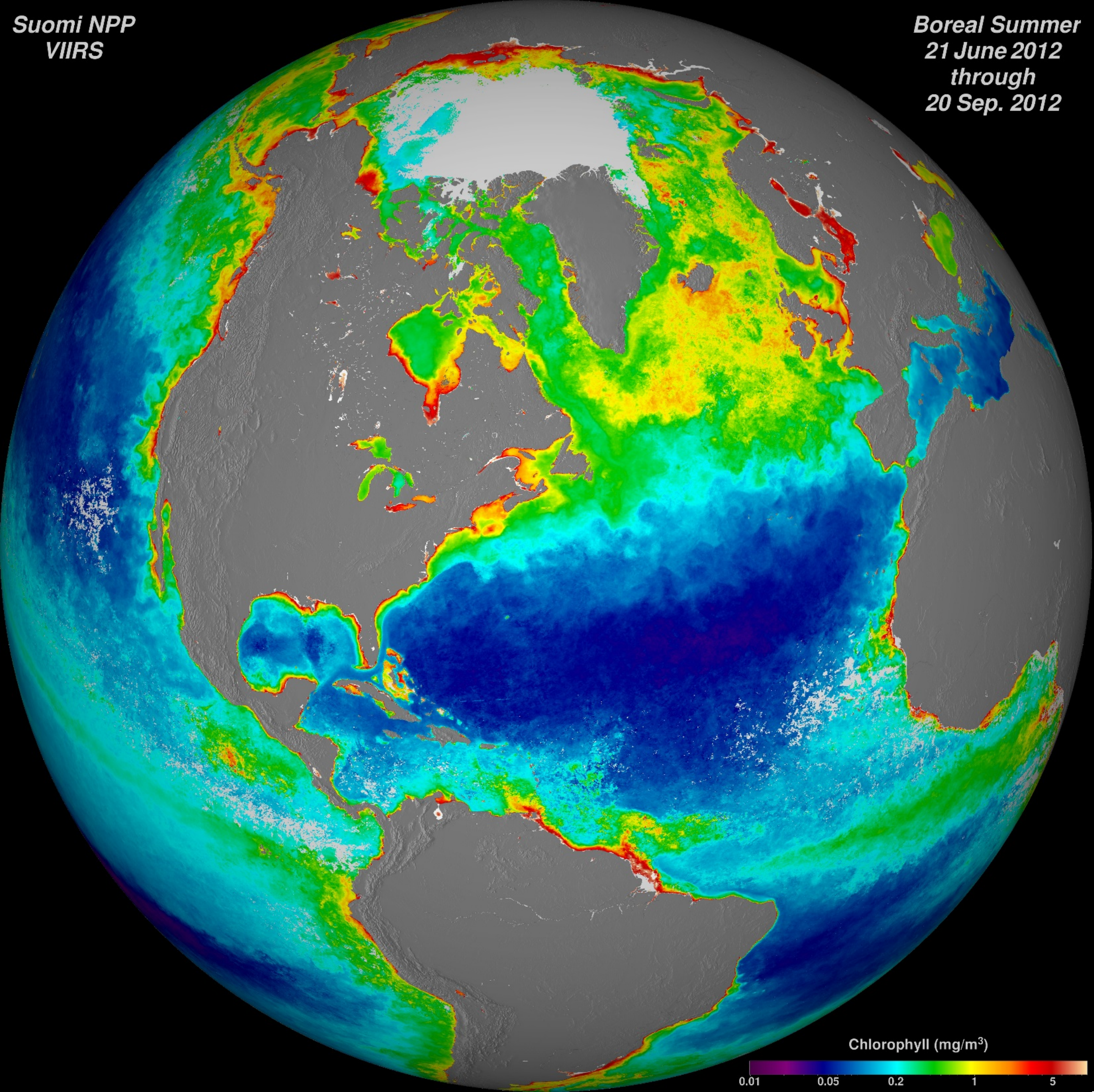


Amazon Delta
Media provided by NASA/NOAA

VIIRS' higher spatial resolution than other systems enables unprecedented insight into weather systems



Typhoon Dujuan approaching Taiwan on 2015 September 27
Credit: NOAA/NASA RAMMB/CIRA



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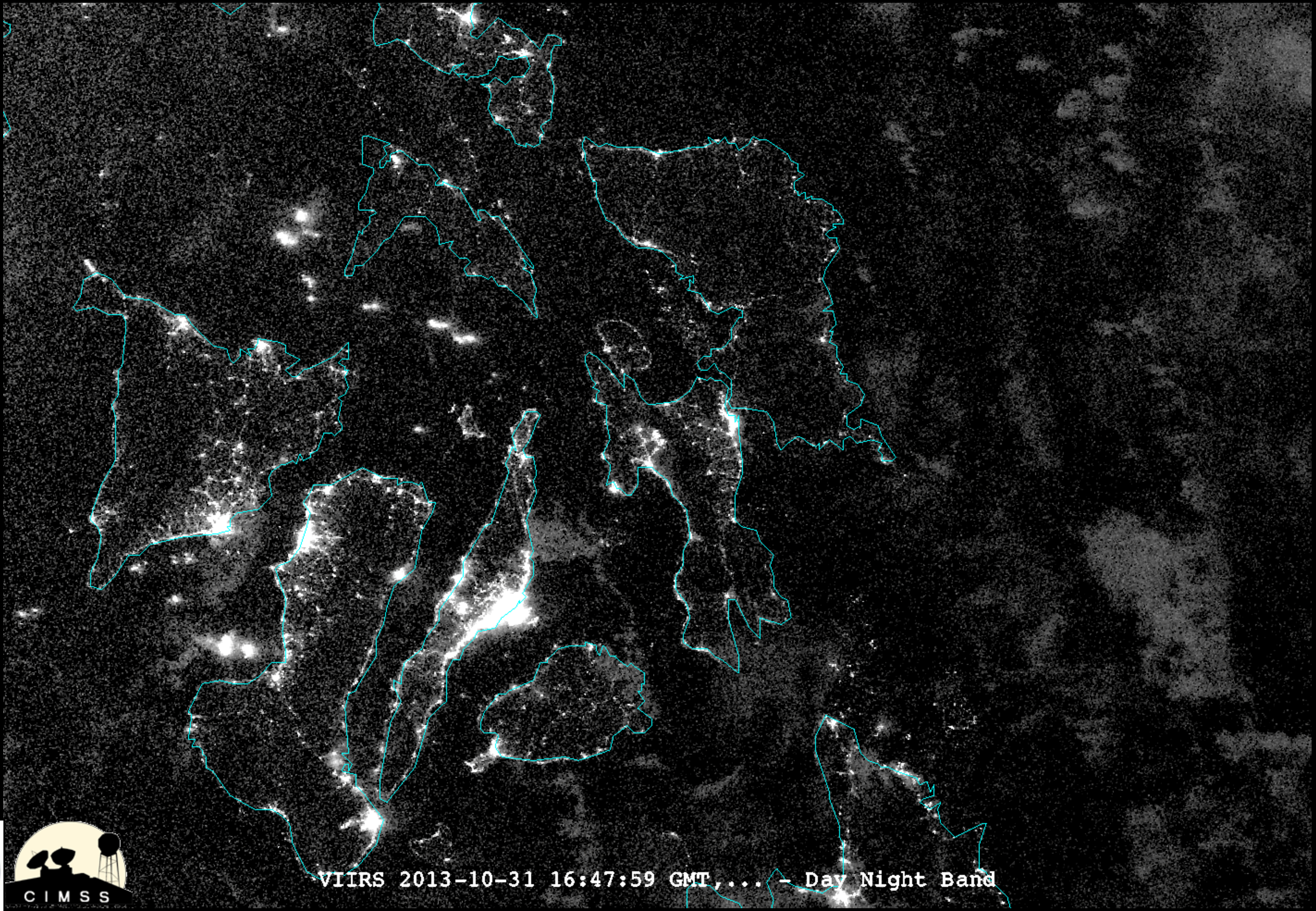
VIIRS data is used to monitor worldwide health of ocean and coastal ecosystems

Credit: NASA

VIIRS helps mitigate natural disasters worldwide, as illustrated by this observation of power outages caused by Super Typhoon Haiyan

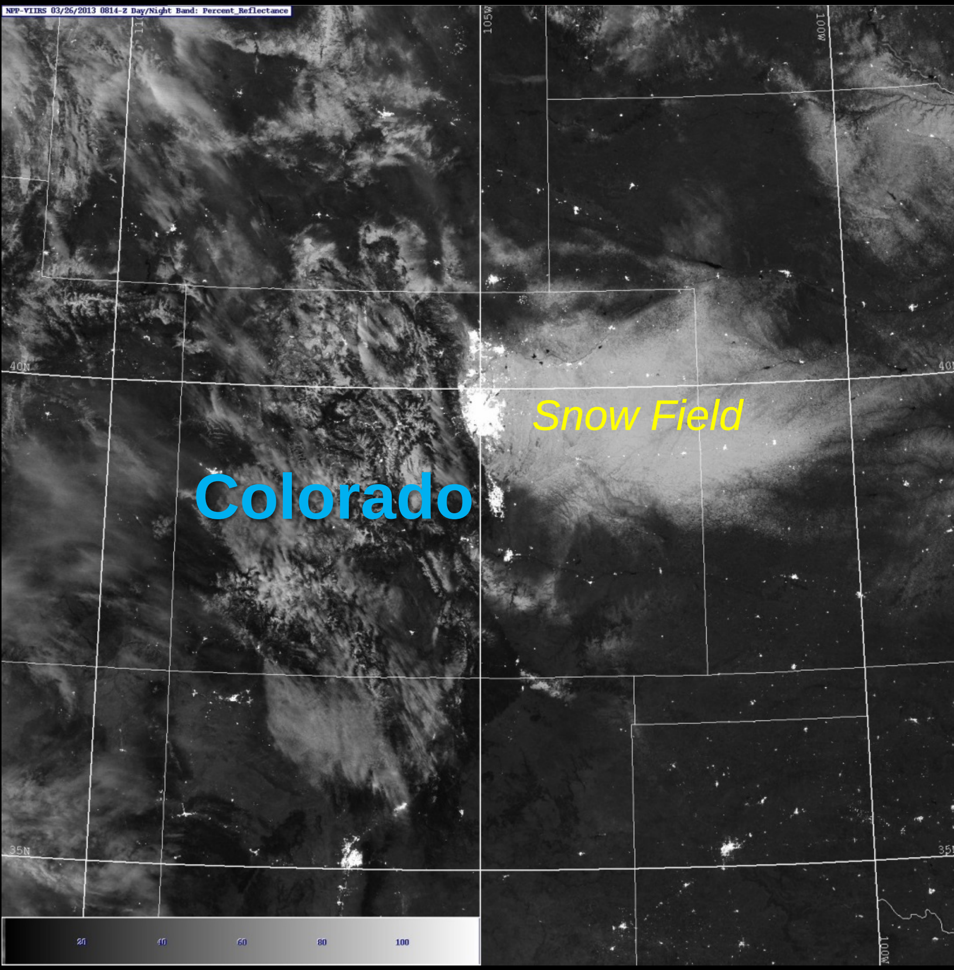
Raytheon

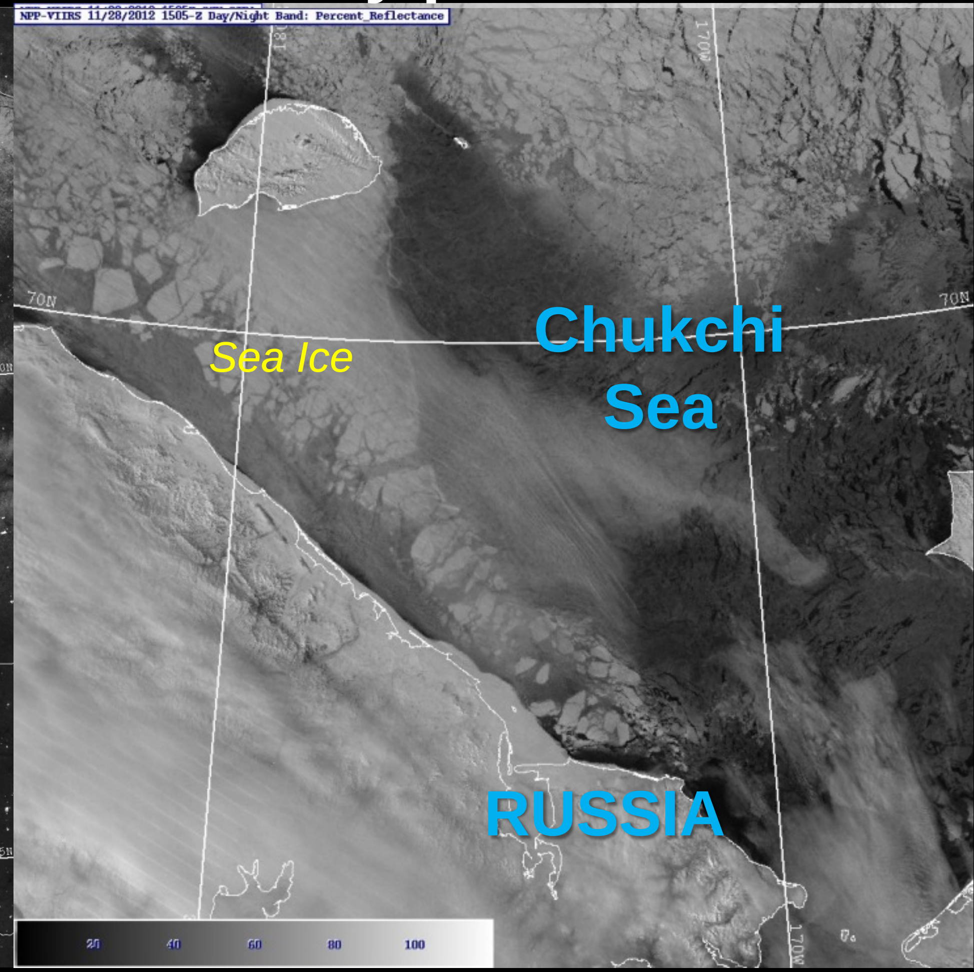


NOAA
CIMSS

VIIRS DNB imagery improves insight into conditions in the Arctic and other wintry places

Raytheon



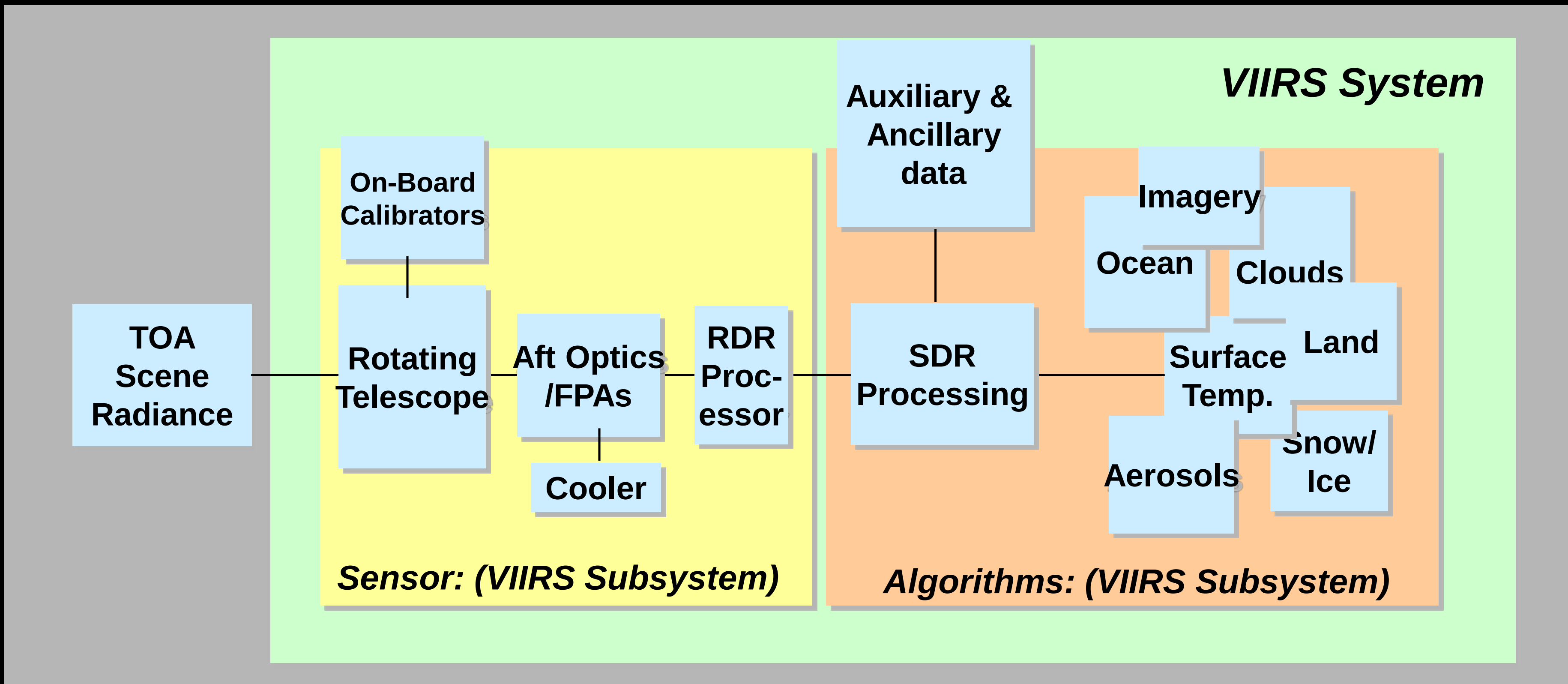


→ *Reveals features offering poor temperature contrast and/or obscured by optically thick (in the infrared) clouds*

CIRA

Miller et al. 2013, Satellite Meteorology Conference, Vienna, Austria

VIIRS was designed as an end-to-end system to meet NPOESS EDR requirements - system performance was verified with a testbed supported by hardware demos



- EDRs Drove Algorithm and RDR Requirements
- Sensor Specification derived from EDRs with testbed
- Sensor performance verified by PDR & Phase II Hardware Risk-Reduction Demonstrations and Analyses
- EDR performance verified by testbed with sensor model

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VIIRS responds successfully to enhanced performance requirements from previous operational and research sensors

Operational Sensors

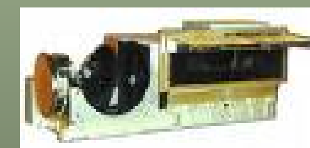
OLS

74 kg
2 bands

- High Spatial Resolution
- Day/Night Band
- Minimize Pixel Growth Across Scan

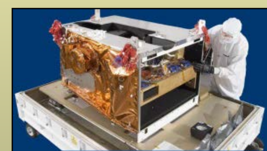
- Radiometric Accuracy
- SST Band Continuity

AVHRR



33 kg
5 bands

VIIRS



OMM

EM

270 kg
22 bands

Research Sensors

MODIS

220 kg
36 bands

- Band Selection/Continuity
- Thin Cirrus Band
- Solar Diffuser
- Calibration Lessons Learned

- Ocean Color Bands
- Rotating Telescope

SeaWiFS

45 kg
8 bands

VIIRS combines technology developed in MODIS and SeaWiFS with innovation to meet enhanced performance requirements demanded by NPOESS

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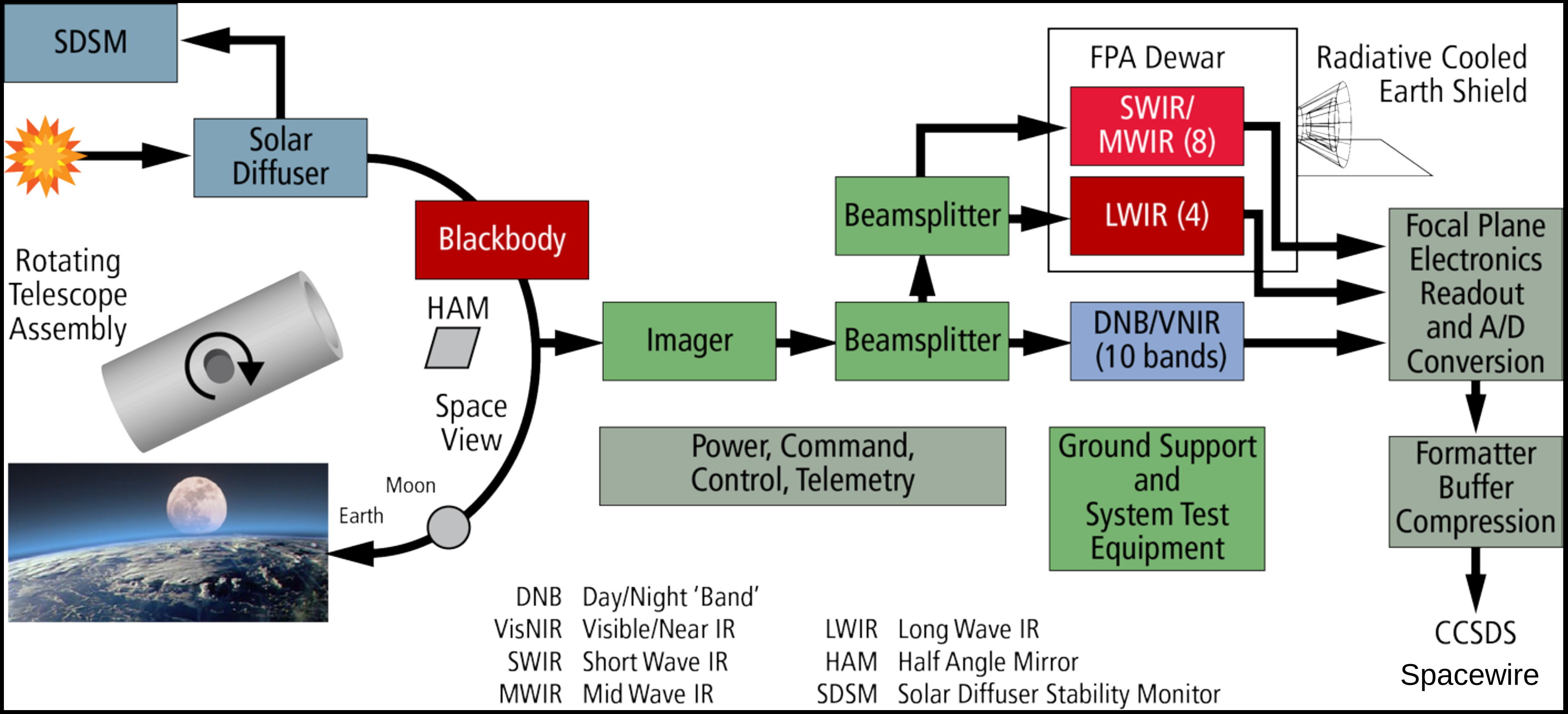
Dimensions:	137 x 149 x 89 cm^3
Mass:	270 kg
Power:	184 W
Data Rate:	11.4 peak/9.1avg Mbps



VIIRS improvements are enabled by design and engineering innovations driven by requirements

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Requirements

- “Constant” spatial resolution across the full swath
- 375-m resolution thermal infrared imagery
- Full spectrum radiometric calibration
- High contrast imagery even in the terminator orbit
- 750-m resolution, high sensitivity low light imagery

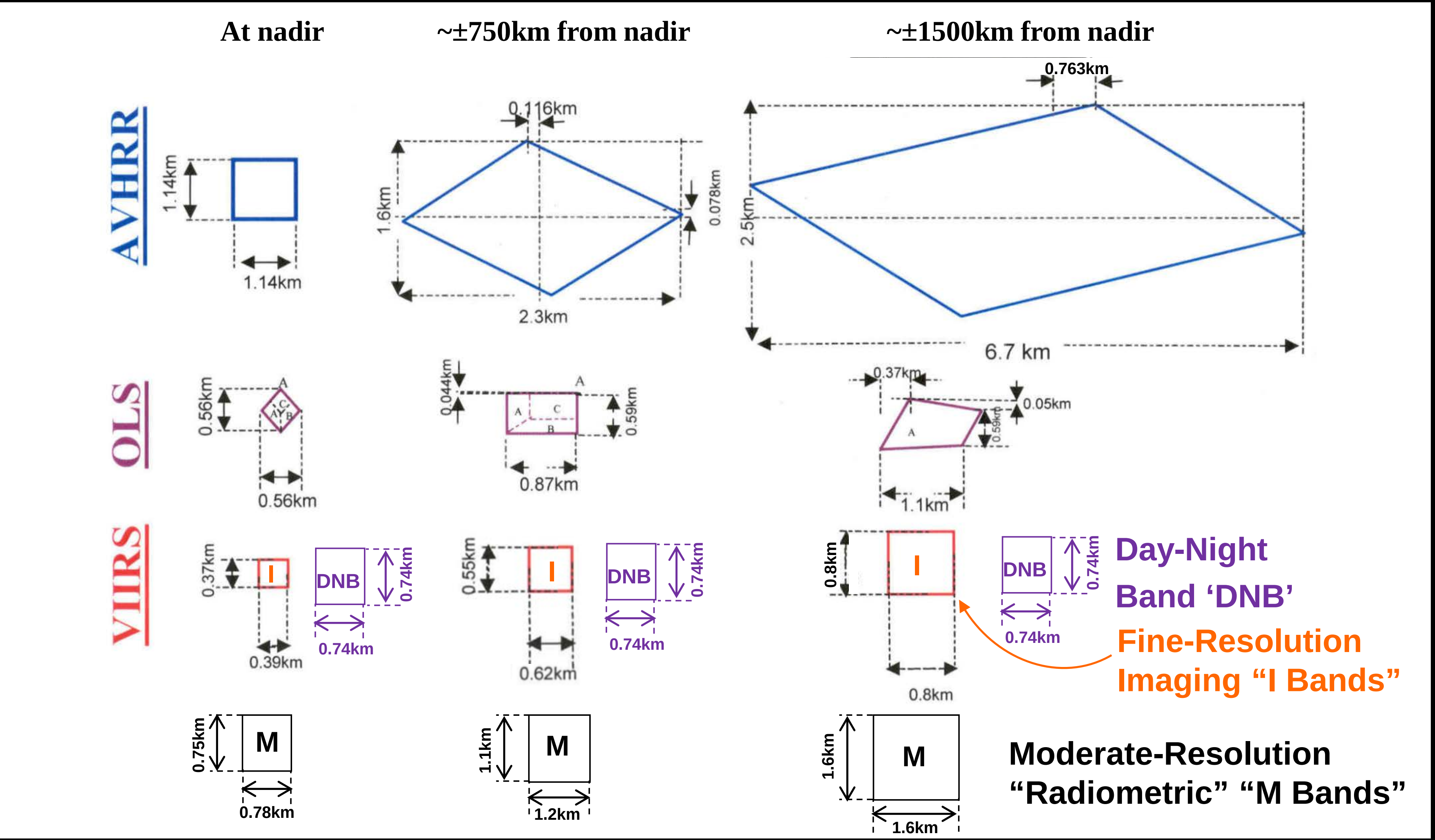
Innovations

- Oversampling and variable aggregation of detector samples
- PV HgCdTe detector technology for LWIR to improve sensitivity
- MODIS flight proven calibration technology brought to operational practice
- Rotating telescope scanner to minimize straylight
- High sensitivity CCD detector technology with TDI to improve SNR and oversampling with 32 aggregation modes

Improvements

- Greatly reduced pixel growth at edge of scan
- Much sharper thermal infrared imagery with better sensitivity
- Well calibrated bands across full spectral range
- High sensitivity calibrated Day Night Band (DNB) with nearly constant pixel size across the swath

VIIRS spatial sampling approach greatly reduces pixel growth at edge of scan



VIIRS detector sample sizes were selected to meet requirements at end of scan

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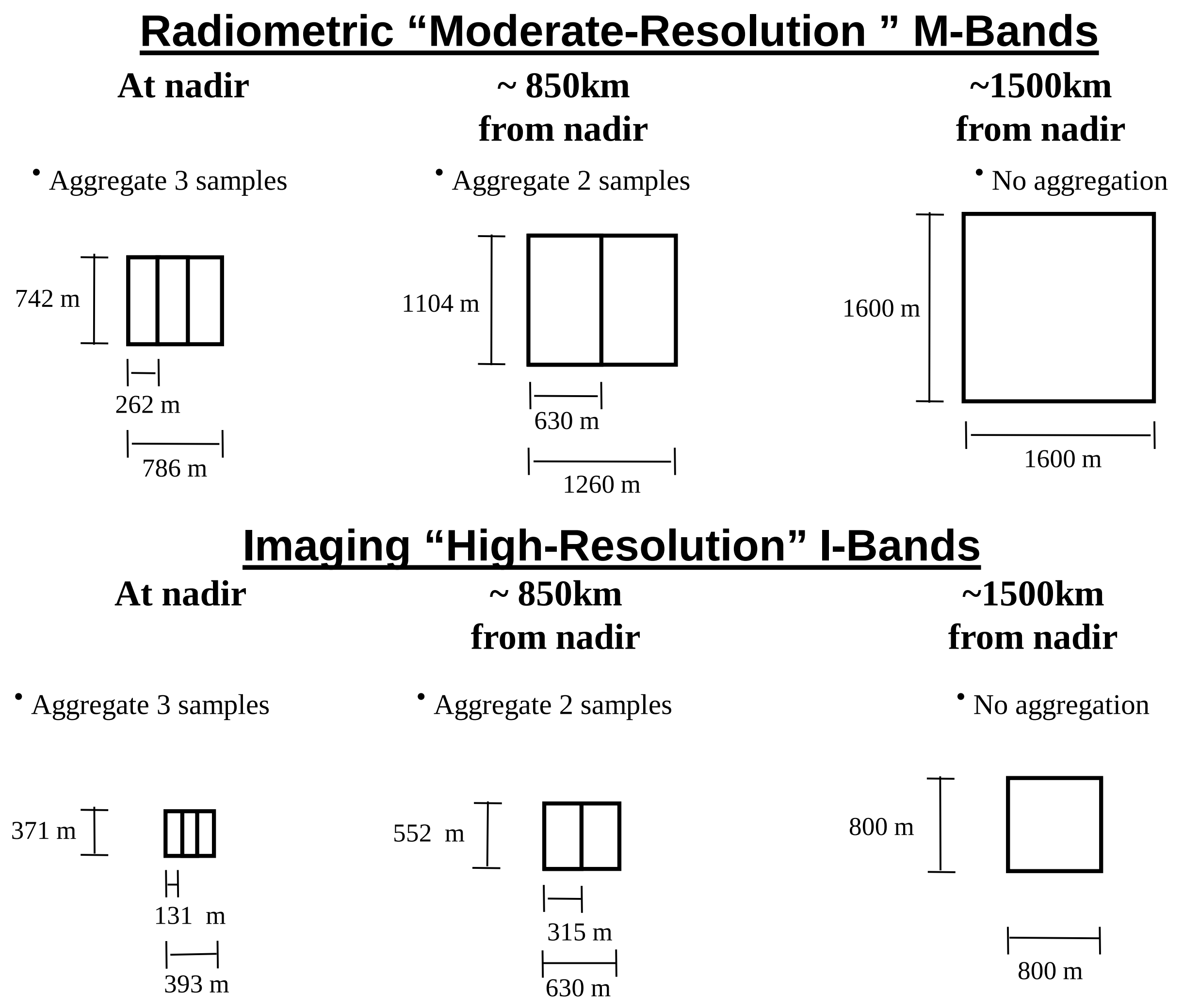
On-board aggregation of detector samples into pixels reduces downlink data rate



Exact sample size in the scan direction varies by spectral band. Values shown here are typical.

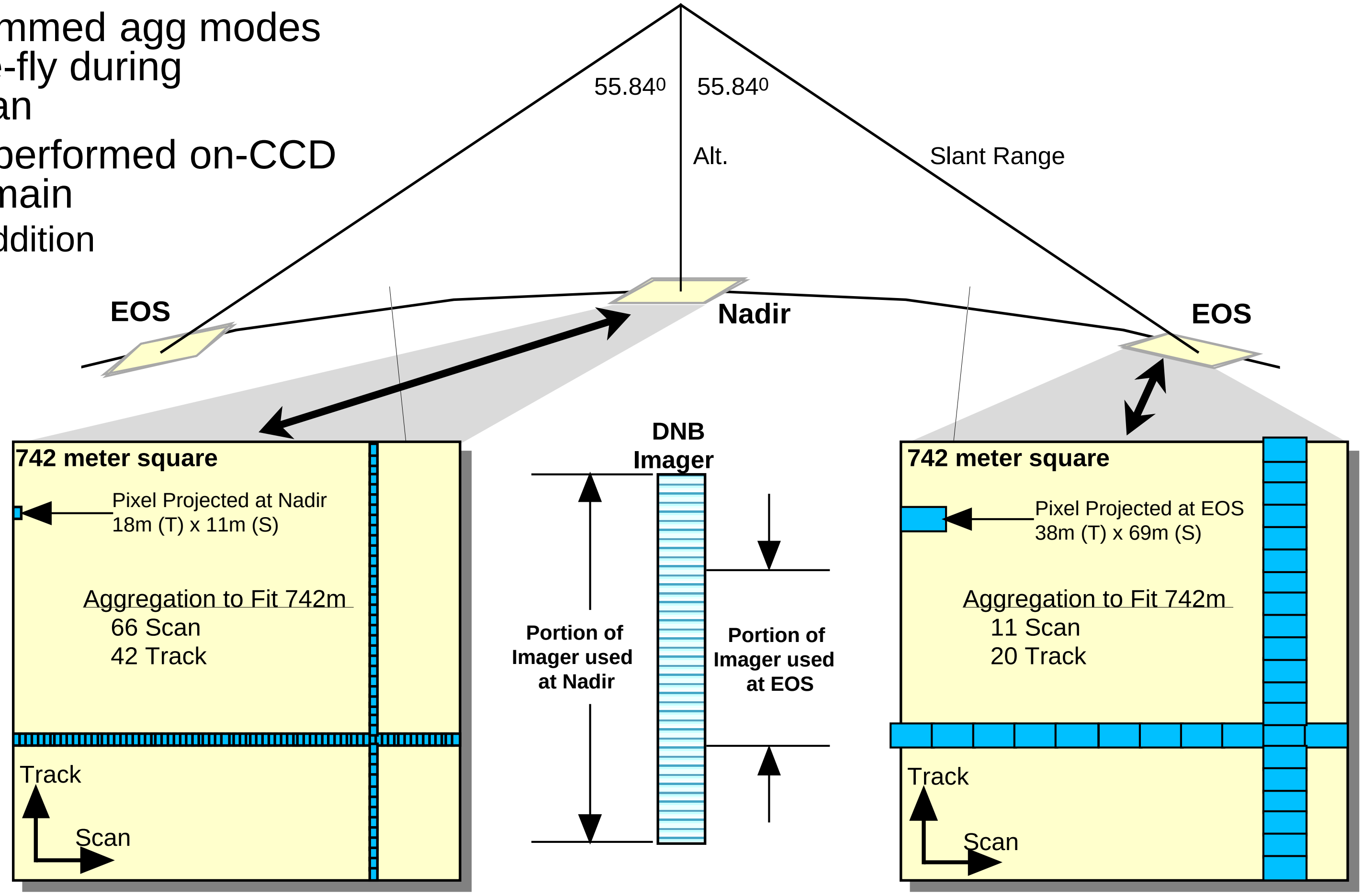
*Schueler, C. 1997, "Dual-use Sensor Design for Enhanced Spatioradiometric Performance," US Patent 5,682,034

VIIRS DNB uses variable aggregation across scan to improve SNR and maintain nearly constant pixel size

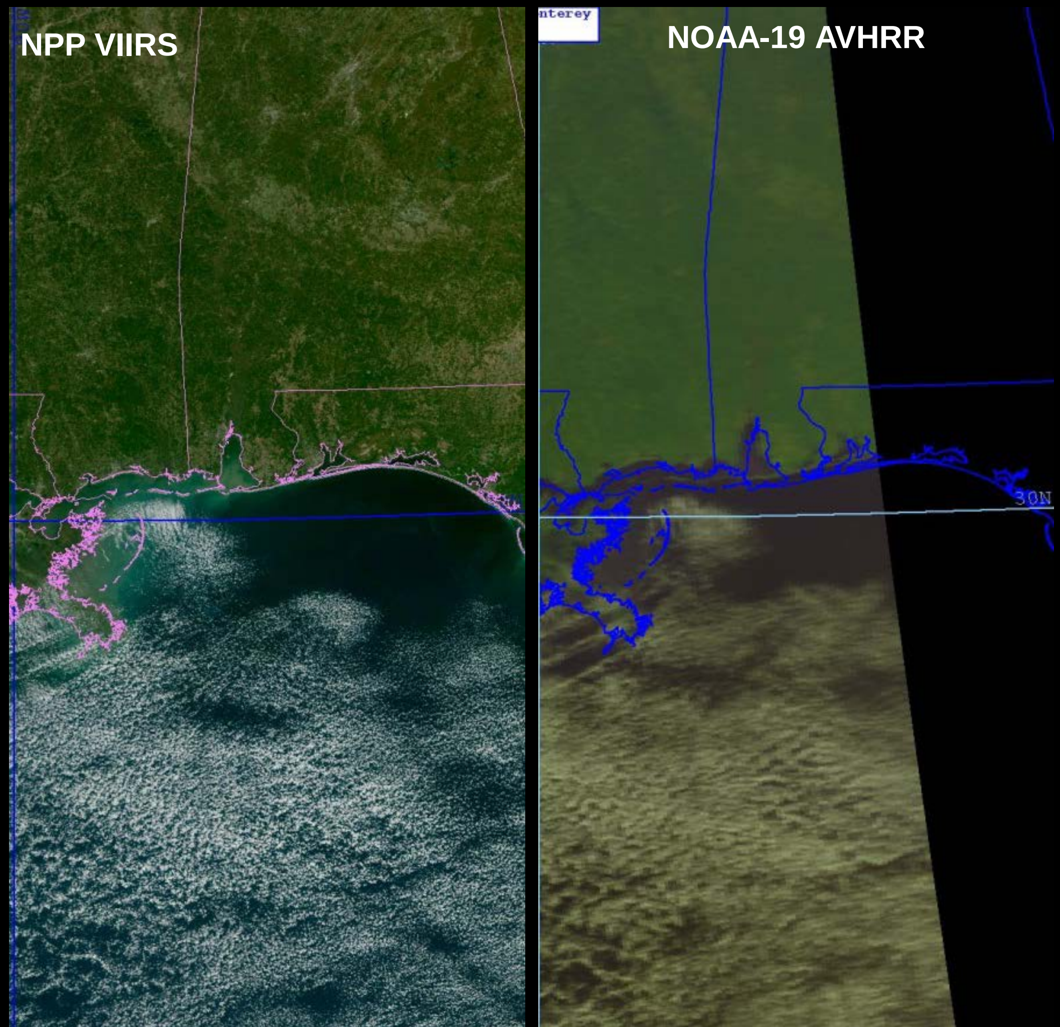
Raytheon

- Variable aggregation provides near-constant HSI throughout scan
  - 32 preprogrammed agg modes cycled on-the-fly during earthview scan
  - Aggregation performed on-CCD in charge domain
    - Noiseless addition

Source: Jacobson, et al., 2010, AMS 6th Annual Symposium on Future National Operational Environmental Satellite Systems, 349

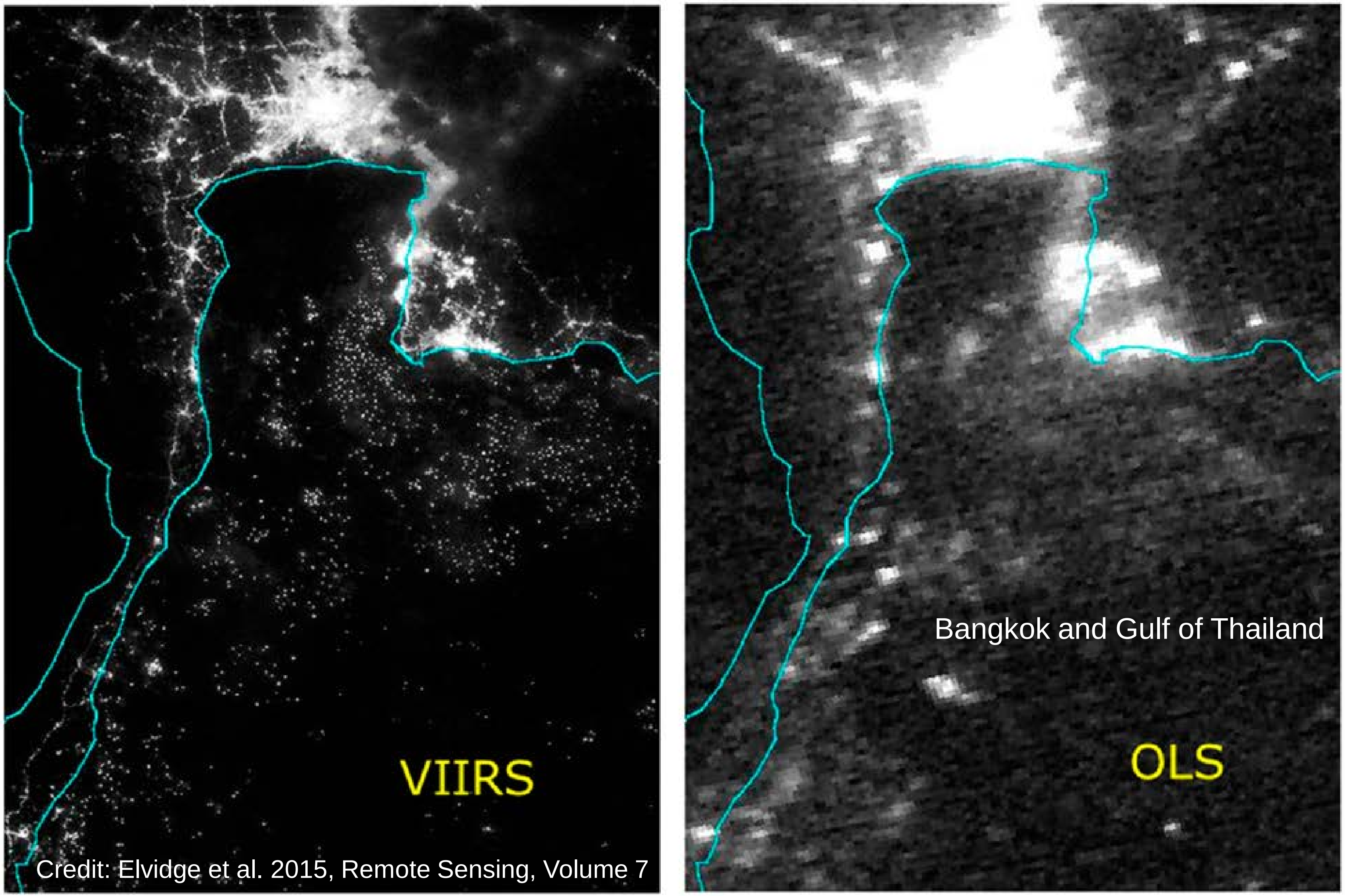


VIIRS spectral coverage and spatial resolution are much better than AVHRR, enabling remarkably superior data products



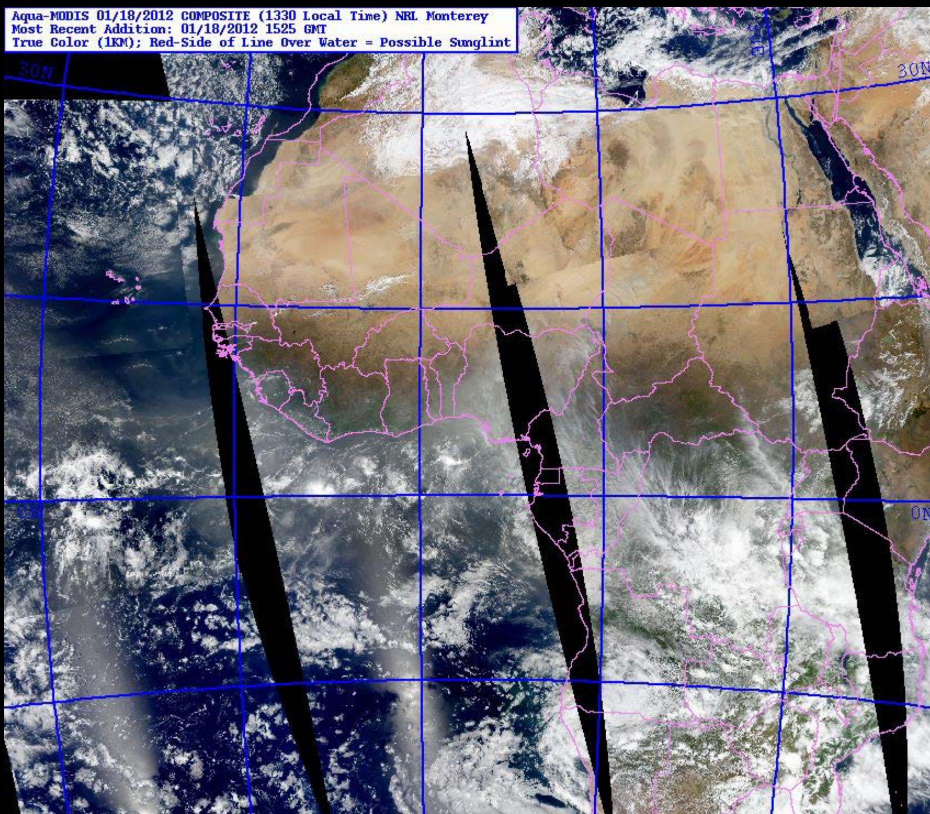
Credit: NRL-Monterey and NOAA

VIIRS DNB offers much better sensitivity and spatial resolution than DMSP OLS



Credit: Elvidge et al. 2015, Remote Sensing, Volume 7

VIIRS eliminates the MODIS coverage gaps between passes over equatorial regions!

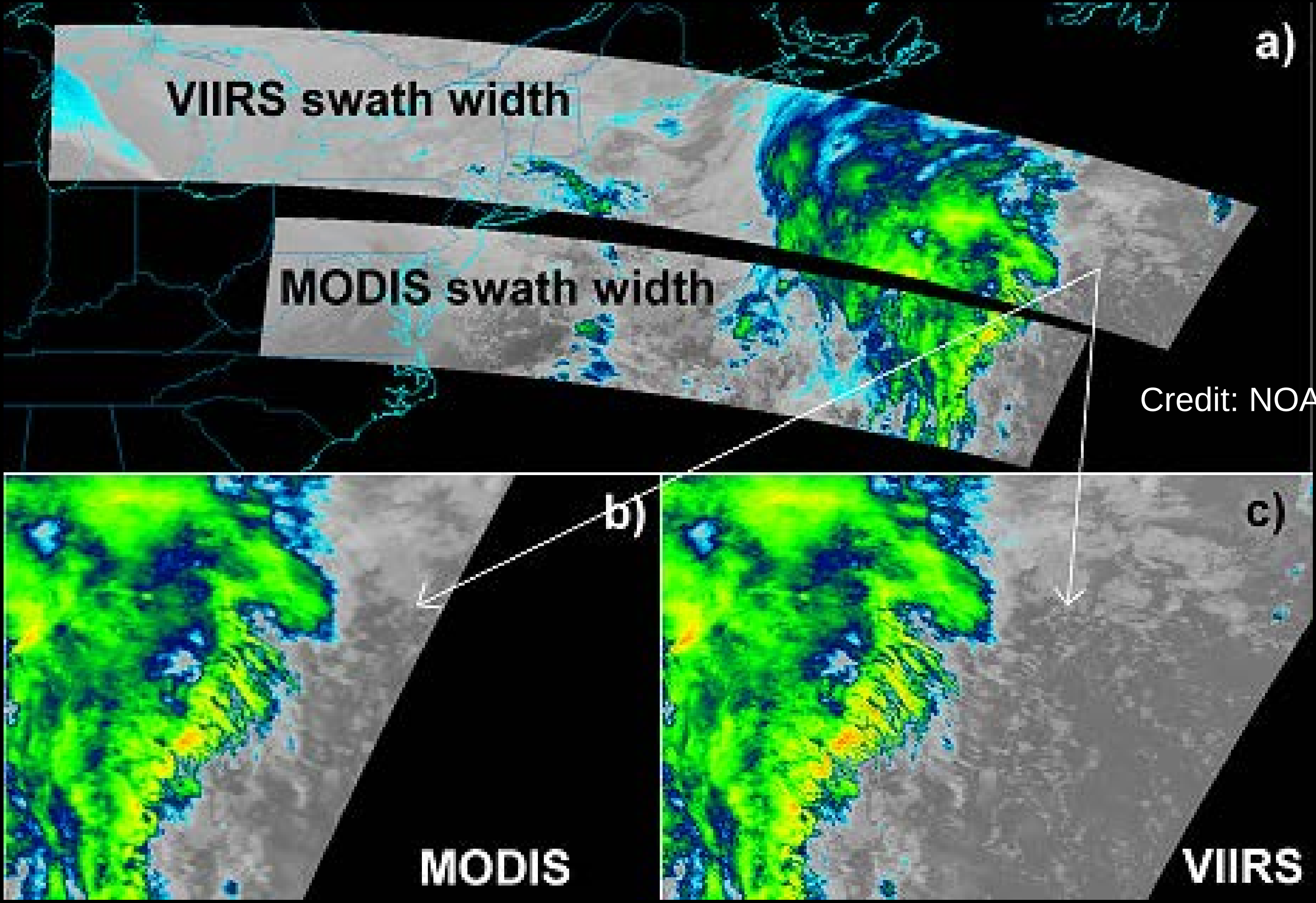


MODIS

VIIRS

Credit: NRL-Monterey and NASA

VIIRS offers wider swath and higher spatial resolution than MODIS



Credit: NOAA

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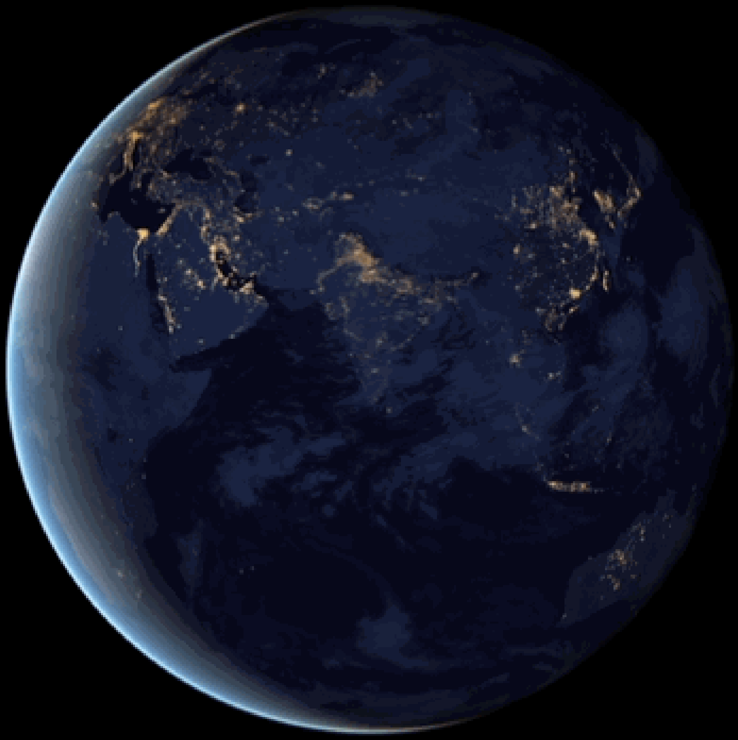
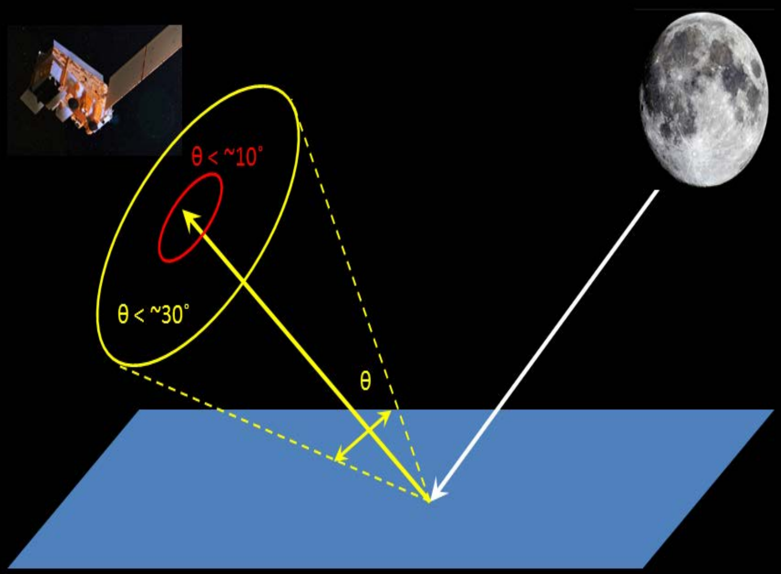
The Best is yet to come!

Innovations in the user community will increase the value of VIIRS immeasurably! One example is new applications of the VIIRS DNB, with much of that work being led by Dr. Steve Miller at CIRA



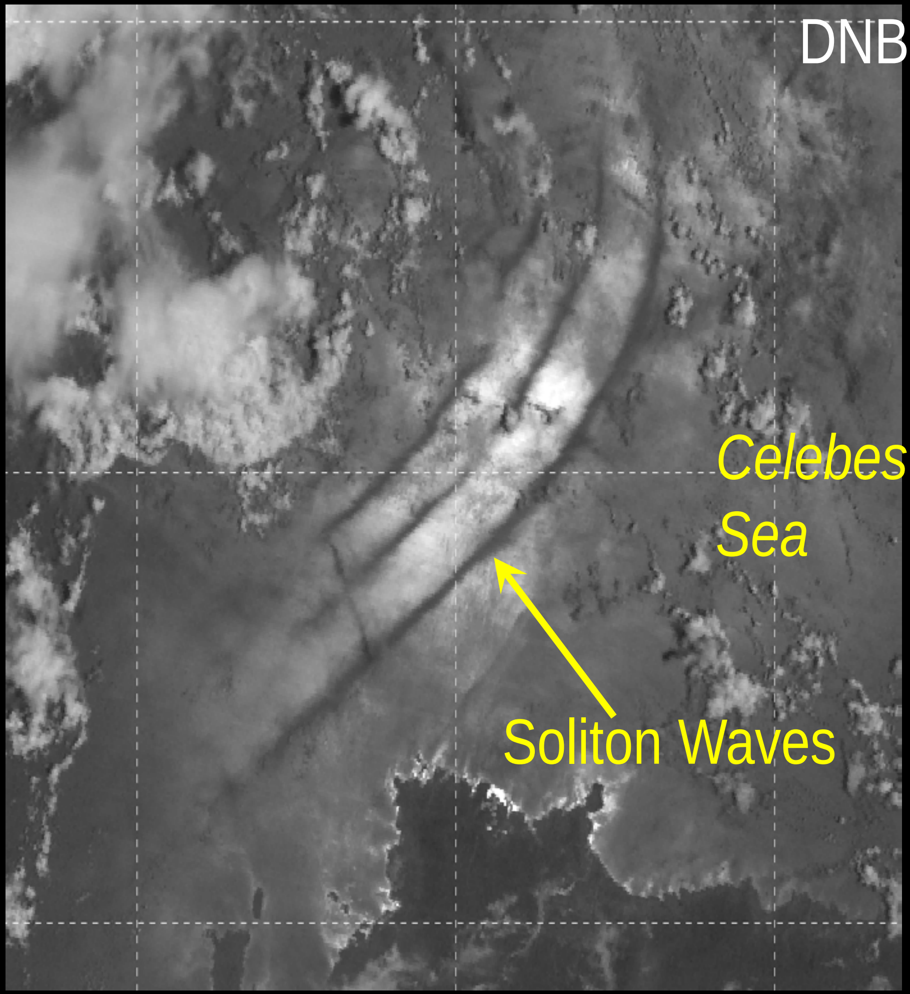
Artwork Credit: NASA/NOAA

Moon Glint



→ Near mirror reflection geometry reveals information about surface properties.

<u>*Uses*</u>: ocean surface properties (currents, boundaries, winds, slicks, ship wakes), and cloud heights via lunar shadows



Credit: CIRA

What does the future hold?

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Possible Instrument Types and Nominal Performance Requirements for Future NOAA Environmental Remote Sensing Systems

INSTRUMENT TYPES	SUBSET OF NOMINAL PERFORMANCE REQUIREMENTS
Moderate resolution imagers or imager suites offering performance similar to current imagers such as VIIRS, MODIS and ABI with high value improvements	~25 spectral channels across the ~0.35–14 µm spectral region, 375 m spatial resolution at nadir in LEO, up to 2 km infrared spatial resolution in GEO, maintain global spatial coverage rates of VIIRS and ABI, enables spatial and spectral access needed to maintain legacy products for VIIRS, MODIS and ABI, while adding spectral bands needed for water vapor measurements in LEO and bands needed for future imaging spectroradiometers addressing coastal water imaging, NEdT (250 K) in each emissive spectral channel of 0.1 K, SNR for typical top-of-the-atmosphere radiance in each 385–710 nm ocean/coastal water signal reference band at SeaWiFS spatial resolution of ~1.1 km of ~1000 (~600 for atmospheric correction reference bands at 748–865 nm and ~300 for 1240–2130 SWIR bands), day-night band characteristics similar to or better than VIIRS DNB
Hyperspectral imagers with ability to produce both imaging and sounding data	~1300 spectral channels across the ~0.35–15.5 µm spectral region, 375 m spatial resolution at nadir, maintain global spatial coverage rates of VIIRS and ABI, enables spatial and spectral access needed to maintain legacy products for VIIRS, MODIS and ABI, while adding spectral range needed for future imaging spectroradiometers addressing coastal water imaging, spectral sampling of λ/dλ ~ 1000 for emissive region and dλ ~ 10 nm in reflective region, NEdT (250 K) in each emissive spectral channel of 0.1 K, SNR for typical top-of-the-atmosphere radiance in each spectrally aggregated 385–710 nm ocean/coastal water signal reference band at SeaWiFS spatial resolution of ~1.1 km of ~1000 (~600 for atmospheric correction reference bands at 748–865 nm and ~300 for 1240–2130 SWIR bands)

Requirements derived from performance of current systems with plausible improvements such as extending spectral range to the UV to benefit aerosol, coastal water and ocean imaging and high value enhancements that improve spatial resolution and sensitivity of IR sounding

AVIS: Advanced Visible-infrared Imaging Spectroradiometer

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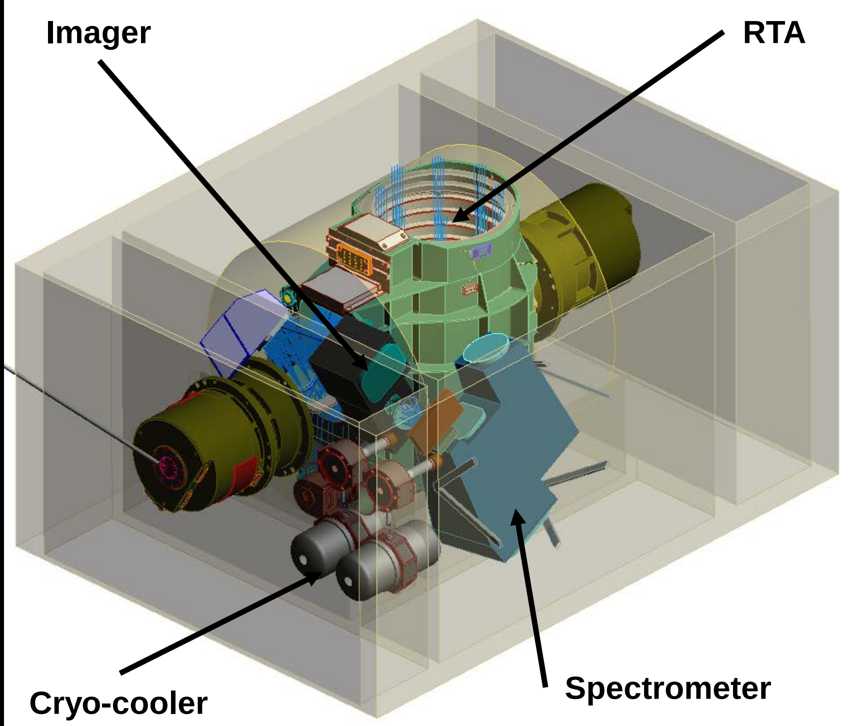

Notional illustration

- Wide field of view (~1.66 deg along track), high spatial resolution (375 m) imaging spectrometer covering 380-14800 nm spectral region with 10 nm effective spectral samples
- Same Rotating Telescope Assembly (RTA) as VIIRS, but with a 2x shorter focal length and 2x wider along track field of view to enable slower scan rate thereby improving sensitivity without giving up spatial sampling and calibration advantages of VIIRS architecture
- Operates in sun-synchronous orbit at 833 km altitude with 1330 crossing time, providing data across a ~3000 km (~1870 mi) swath
- 18.5 cm effective diameter off axis f/3.1 telescope with a reflective triplet spectrometer using a prism for the UV-SWIR and gratings for the MWIR-LWIR and LWIR-VLWIR
- 192 (cross track/spectral) x 1344 (along track) UV-SWIR detector array and 575 x 1344 MWIR-LWIR and 555 x 1344 LWIR-VLWIR detector arrays

Raytheon

Innovation continues! Thanks for your kind attention!