



***A Year in Space for the
CUbesat MULtispectral Observing
System: CUMULOS***

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CUMULOS Mission Background

Goals: Fly commercial uncooled VIS, SWIR, LWIR cameras - Research nightlights/weather missions

CUMULOS is a hosted payload on the Integrated Solar Array and Reflectarray Antenna (ISARA) mission

- Engineering goals emphasized ConOps, calibration techniques, data pipeline, space performance of commercial cameras
- Science goals guided by past work with AeroCube color CMOS cameras, ISS photography, JAXA ALOS-2 compact infrared camera (microbolometer), and NOAA's VIIRS. CUMULOS sensor is designed to carry out "VIIRS-like" missions

Calibration Targets

- Gaining experience with on-orbit calibration and performance of CubeSat sensors was an important engineering goal
- Collected on bright stars, Moon, terrestrial calibration sites, multiple conjunction collections with VIIRS

Science Targets

- Urban Monitoring - nightlights at higher resolution than VIIRS using point-and-stare imaging to achieve sensitivity
- Fires and gas flares
- Maritime lights, fishing vessels, other ships
- Weather – airglow illuminated clouds using SWIR camera, moonlit clouds using VIS & SWIR cameras, cloud cover using LWIR microbolometer, conjunction collections with VIIRS

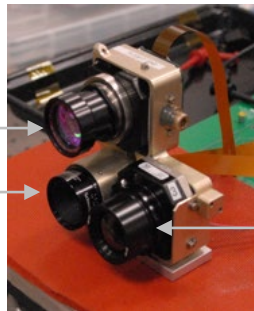
CUMULOS is our first IR CubeSat imaging payload, a pathfinder for commercial camera utility studies and CubeSat ConOps, and has pioneered new CubeSat nighttime remote sensing applications with all three cameras

CUMULOS Compact Payload – VIS, SWIR, LWIR

Flight camera hardware in lab

SWIR Camera
InGaAs 640x512
0.9-1.7µm
14-bit

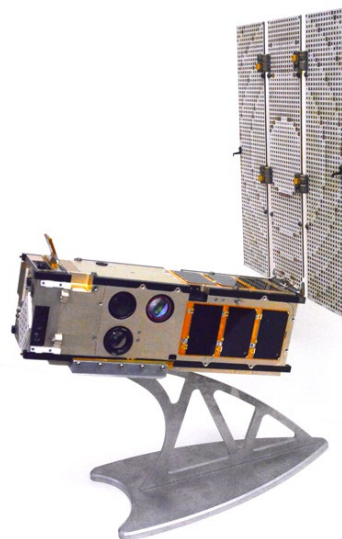
Visible Camera
Si 1280x1024
0.4-0.9µm
10-bit



SWIR - FLIR Tau SWIR 25
VIS – ON Semi CMOS
LWIR - FLIR Tau2 640

LWIR Camera
VOx Microbolometer
640x512
7.5-13.5 µm
14-bit

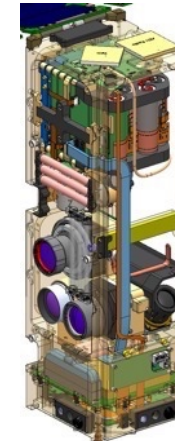
CUMULOS cameras on ISARA Engineering Model in lab and at SMALLSAT Conference 2018



ISARA Launched 12 Nov. 2017 on Cygnus Orbital ATK CRS OA-8



Boosted to final orbit from ISS 6 Dec. 2017 CUMULOS ops. began in June 2018 after 7 months of on-orbit storage



Fitting in the hosted payload

CUMULOS Camera Parameters

SATELLITE CAMERA	LENS F#	LENS FL (MM)	PIXEL PITCH (µM)	FPA PIXEL COUNT	NOMINAL ALTITUDE (KM)	GSD (M)	SWATH (KM)
CUMULOS VIS Si:CMOS	1.4	17.6	5.20	1280x1024	450	133	170 x 136
CUMULOS SWIR:InGaAs	1.4	25.0	25	640x512	450	450	288 x 230
CUMULOS LWIR:VOx	1.1	25.0	17	640x512	450	306	196 x 157

GSD, SWATH are minimums ignoring curvature of earth

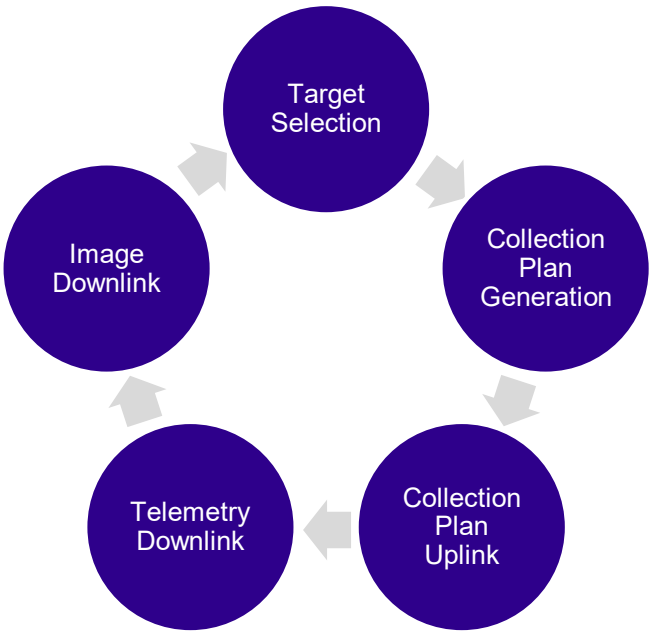
CUMULOS fits in ~ 1U of ISARA's 3U volume – 1st successful IR Earth imaging CubeSat payloads

CUMULOS Operations

Point and stare imaging at selected urban, environmental monitoring targets



MISSION CYCLE

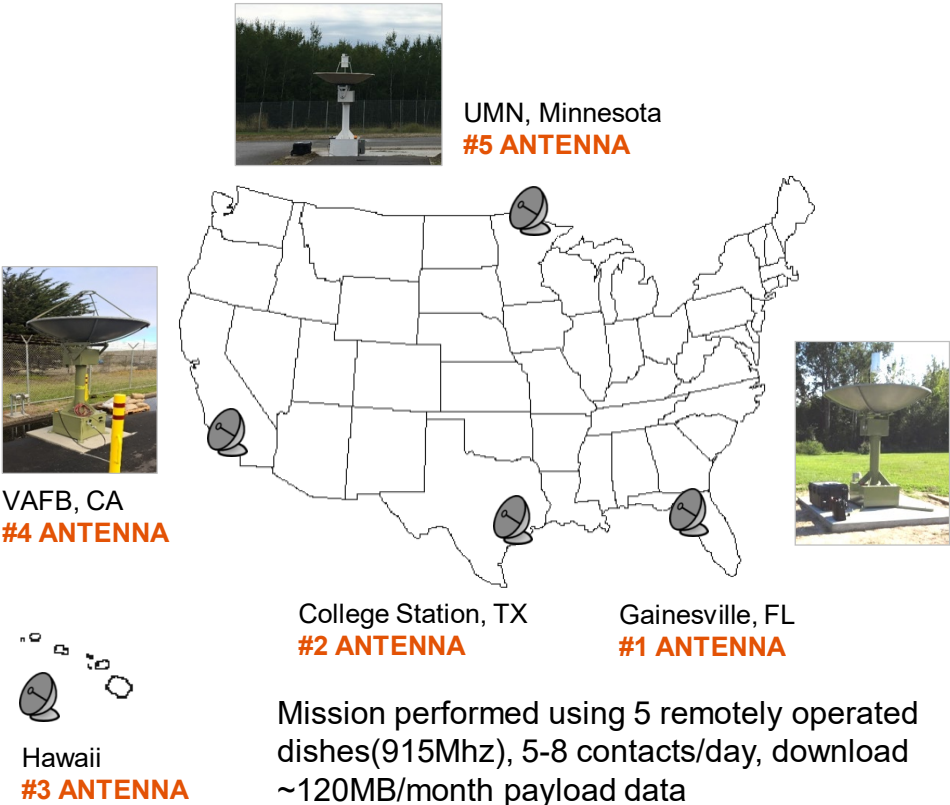


Mission Highly Automated - Operators involved in target selection, collection plan generation, anomaly resolution, ~ 2hr / collection activity

CONOPS

TIME	ACTIVITY
T-30M	System Startup
T-25M	ACS Initialization
T-30S	Imaging Start
T	Min Range to Target
T+30S	Imaging Stop
T+60S	ACS Shutdown
T+4H	Ready for next collection activity
T+3D	Image Downlink Complete

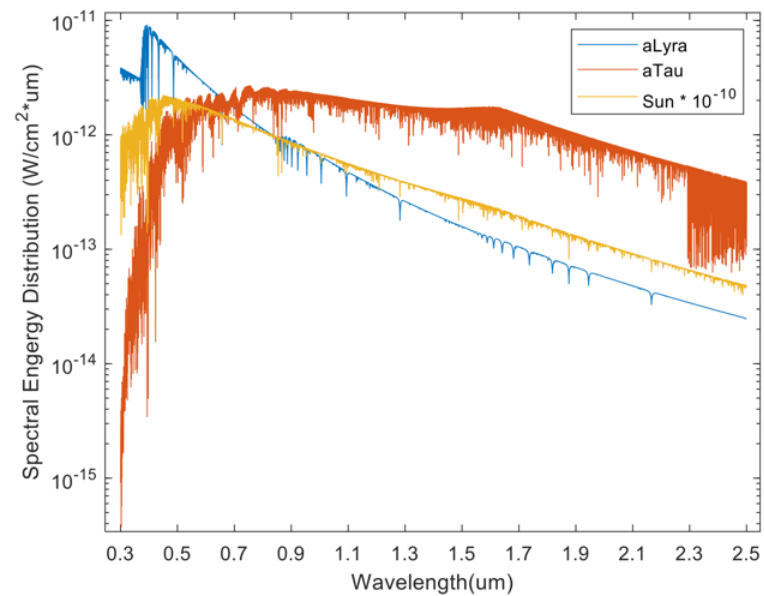
GROUND SEGMENT



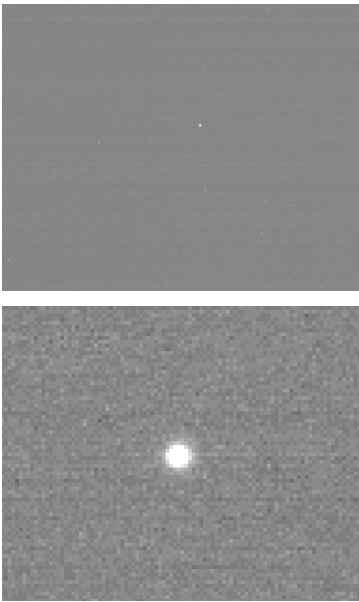
Targets selected (location, weather, lighting) – Satellite nominally tumbling, ACS initialized only for collection, Collections last ~ 1min, Satellite slews to maintain boresight vector, ~20 images collected with all three cameras, Process highly automated – Calibration / Georegistration pipeline is now validated. Pathfinder for our follow-on missions.

Celestial Calibration Targets – Stars

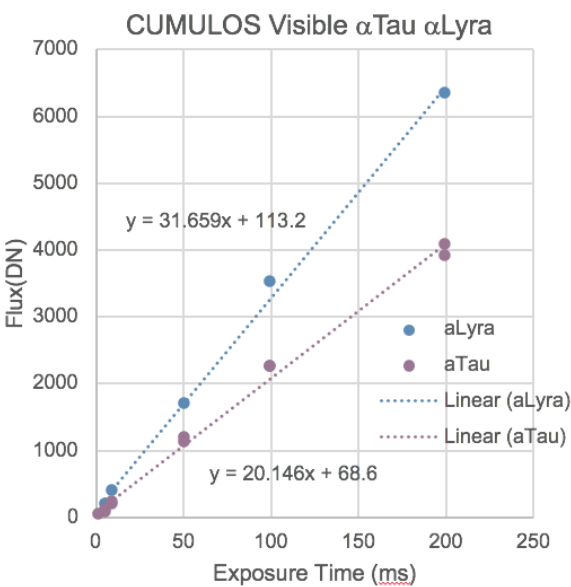
CUMULOS uses bright stars for calibration (for VIS and SWIR)



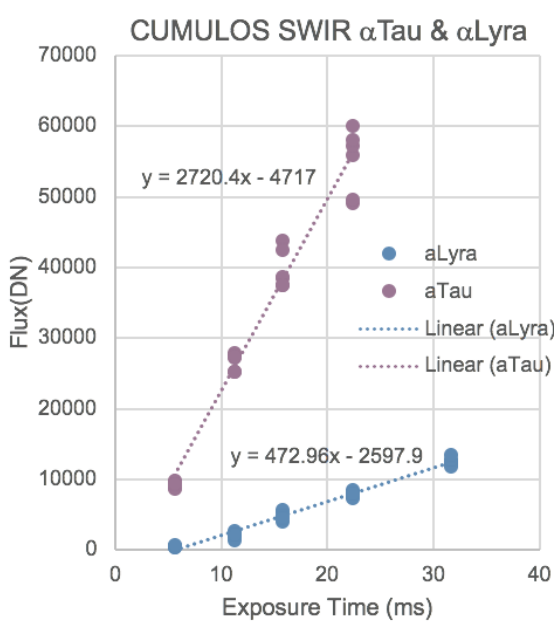
Stellar flux models for alpha Tau and alpha Lyra compared to the Sun. (Flux models are matched to ground-based observatory data.)



Example full frame and detail of a VIS camera star observation (50msec exposure of calibration star alpha Lyra).



VIS Camera Stellar Calibration Data



SWIR Camera Stellar Calibration Data

$$Flux = \frac{\int SE(\lambda)QE(\lambda)T(\lambda)d\lambda}{\int QE(\lambda)T(\lambda)d\lambda}$$

On orbit data (Flux), Data-informed stellar models (SE), detector quantum efficiency (QE), optics transmission (T)

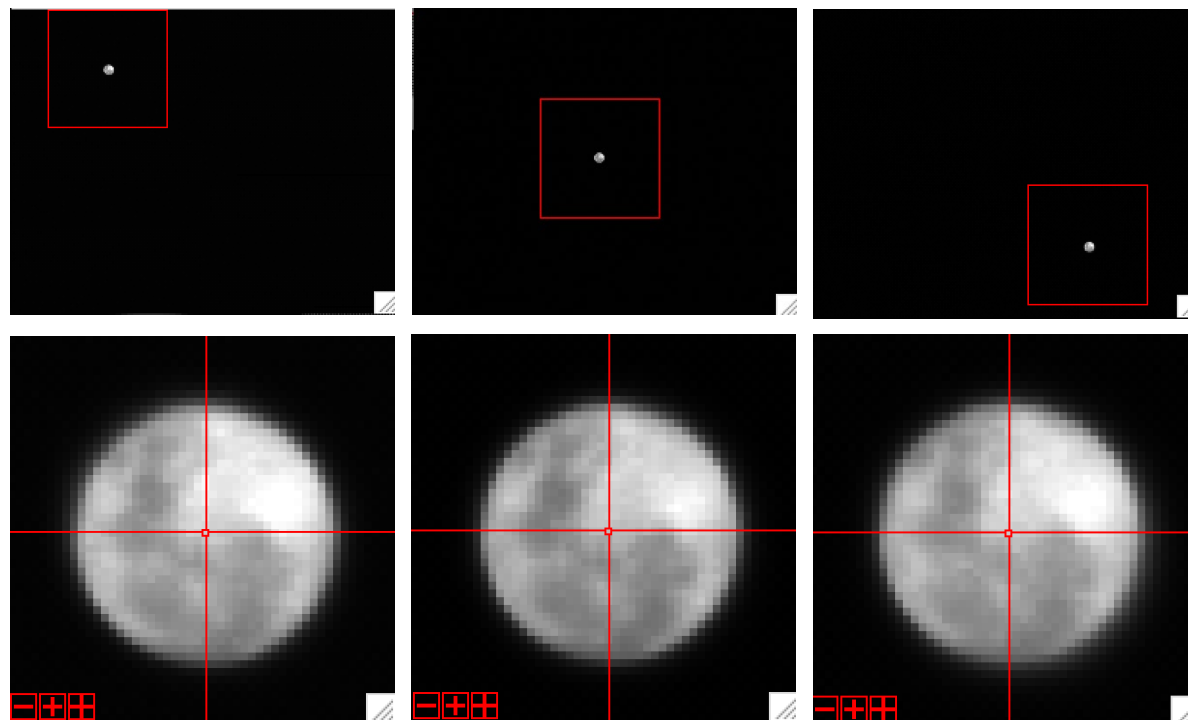


Sensor/ Star	DN/msec	W-cm ⁻² -sr ⁻¹	ph-sec ⁻¹ -cm ⁻² -sr ⁻¹
VIS/aTau	1	9.379x10 ⁻⁷	3.156x10 ¹²
VIS/aLyra	1	1.119x10 ⁻⁶	3.067x10 ¹²
SWIR/aTau	1	6.514x10 ⁻¹⁰	4.171x10 ⁹
SWIR/aLyra	1	6.850x10 ⁻¹⁰	4.033x10 ⁹

Celestial Calibration Targets - Moon

2019 Feb 19, 16:13 – Example Lunar Calibration Collect

ON-ORBIT LUNAR DITHER COLLECTION



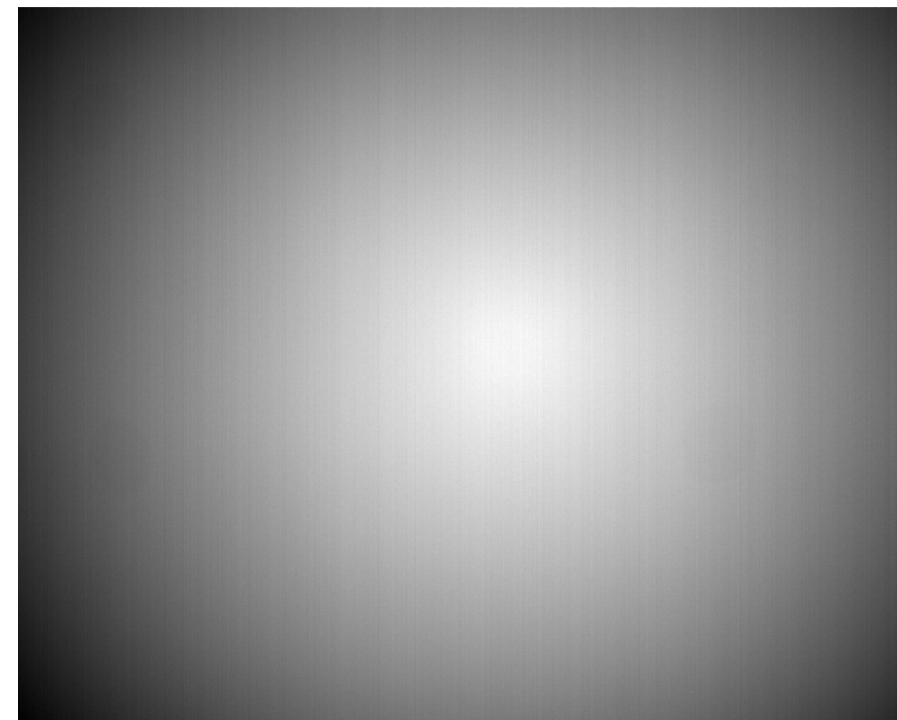
PEAK 577 DN

PEAK 805 DN

PEAK 642 DN

10 bit data values

GROUND FLAT FIELD CORRECTION

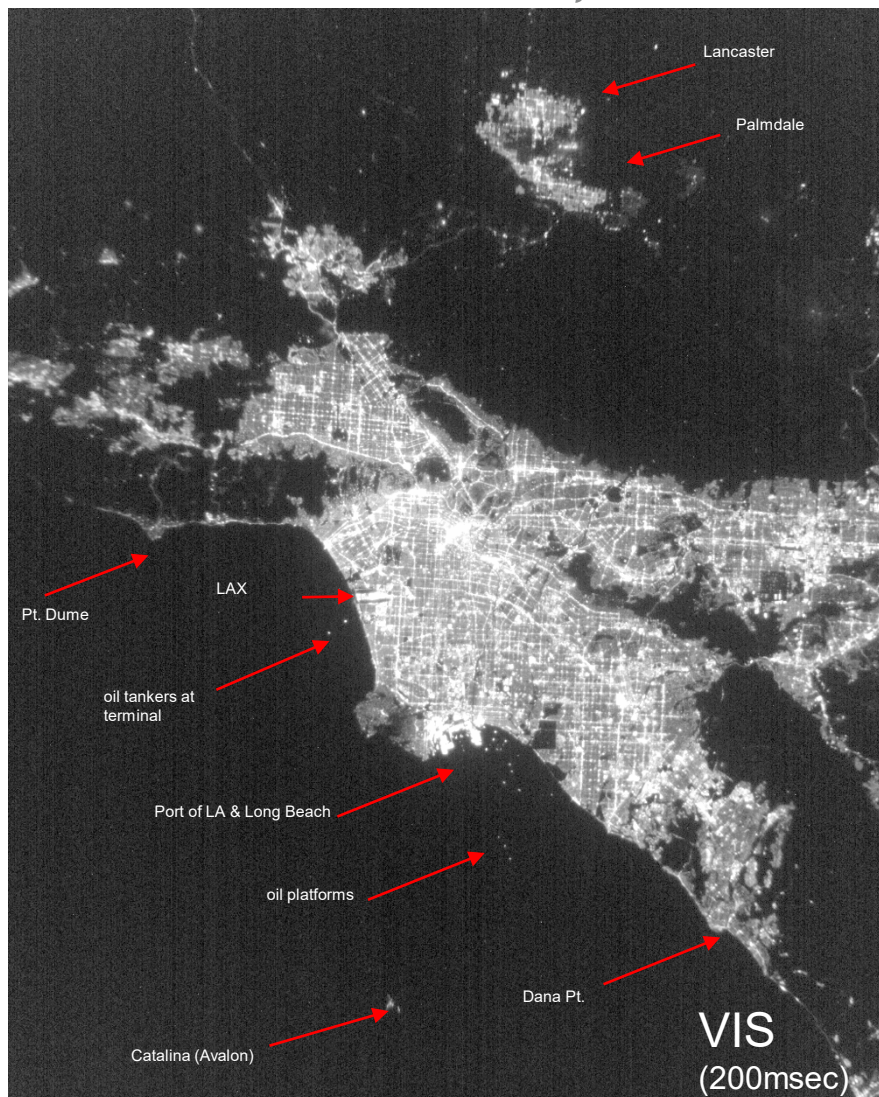


Moon observations used to validate ground calibration on-orbit. ROLO model lunar calibration work is underway.

Moon is imaged in upper left corner, center, lower right corner in VIS, LWIR frames taken at all exposure times and LWIR gains. Dark frames also taken. Details on calibration to be presented at next year's CALCON

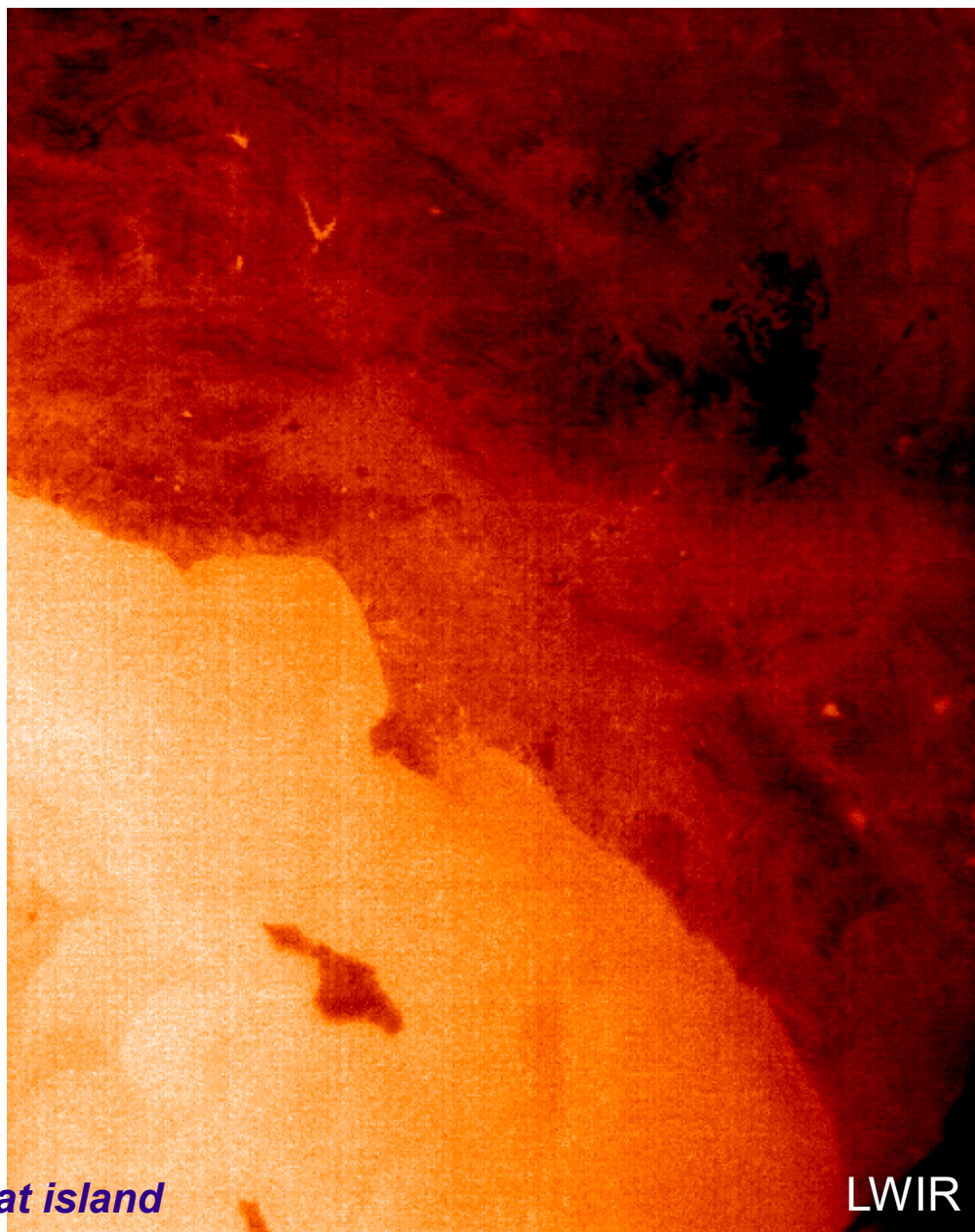
Urban Monitoring – Los Angeles Region – CUMULOS VIS & LWIR

2018 Oct 12 05:08 UT – No Moon, No Clouds



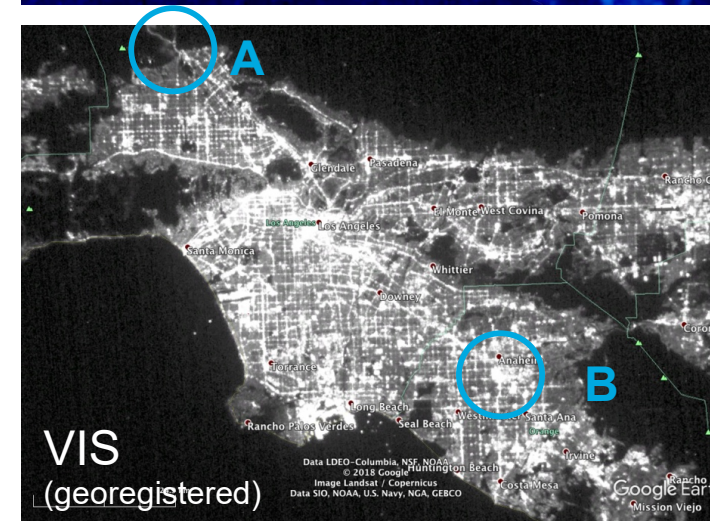
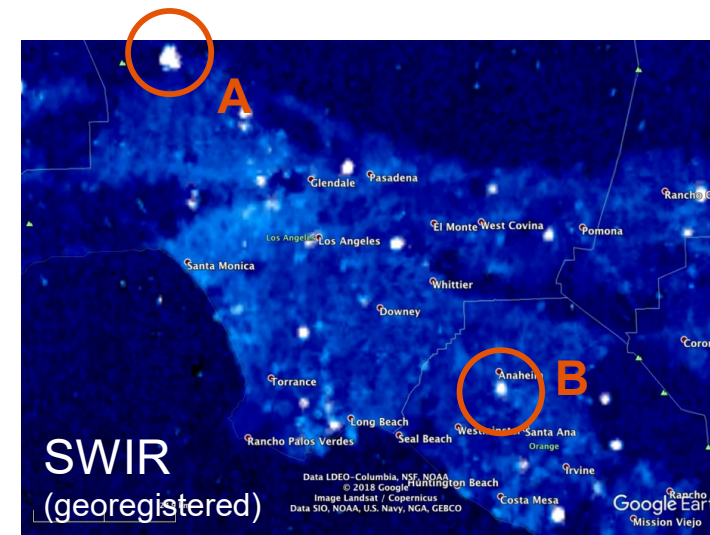
VIS image highlights urban grid at 130m resolution

LWIR shows thermal features from reservoirs, urban heat island



Urban Monitoring – Los Angeles Region – CUMULOS SWIR & VIS

2018 Oct 12 05:08 UT – No Moon

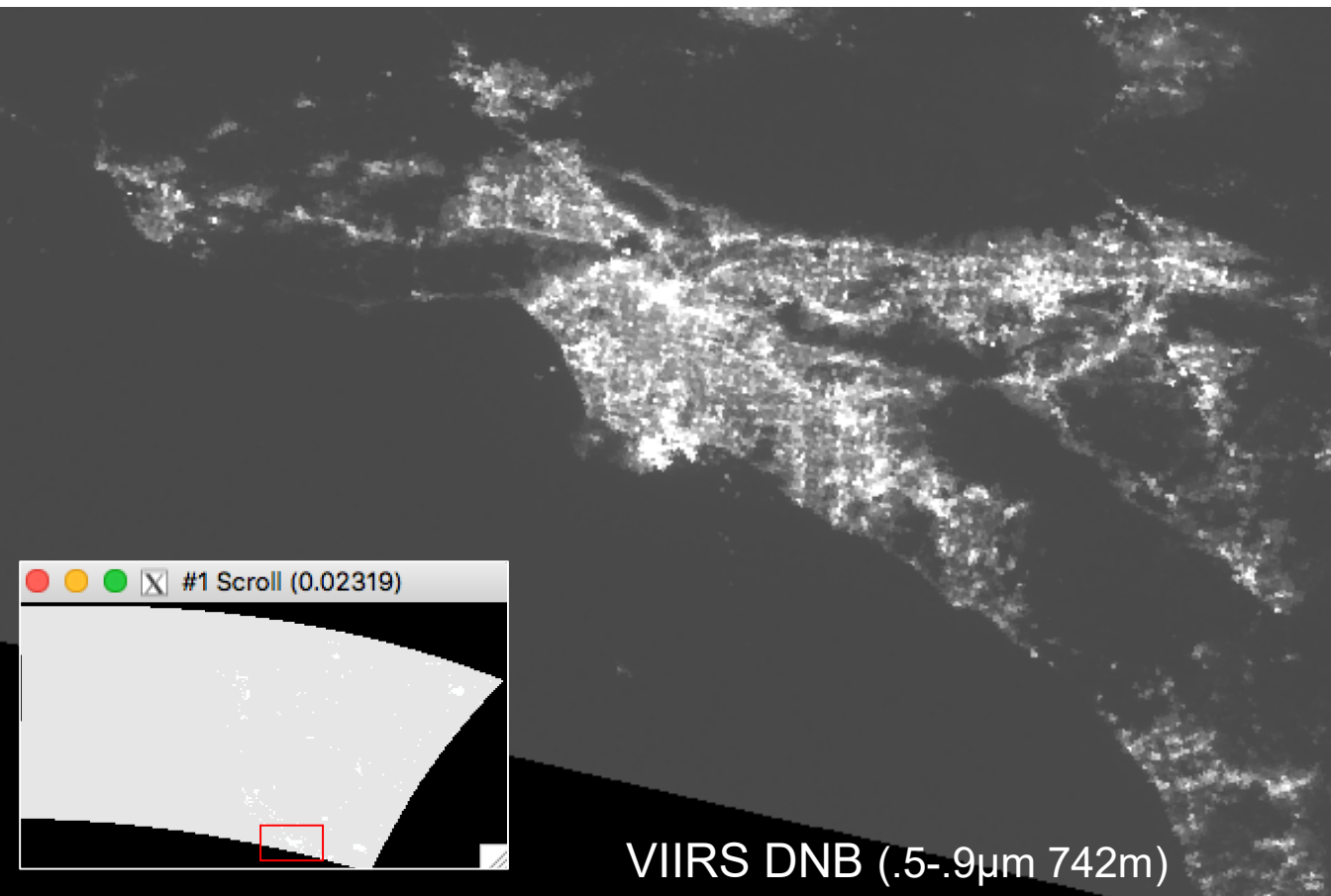


Georegistered data:
A) Landfill
B) Disneyland

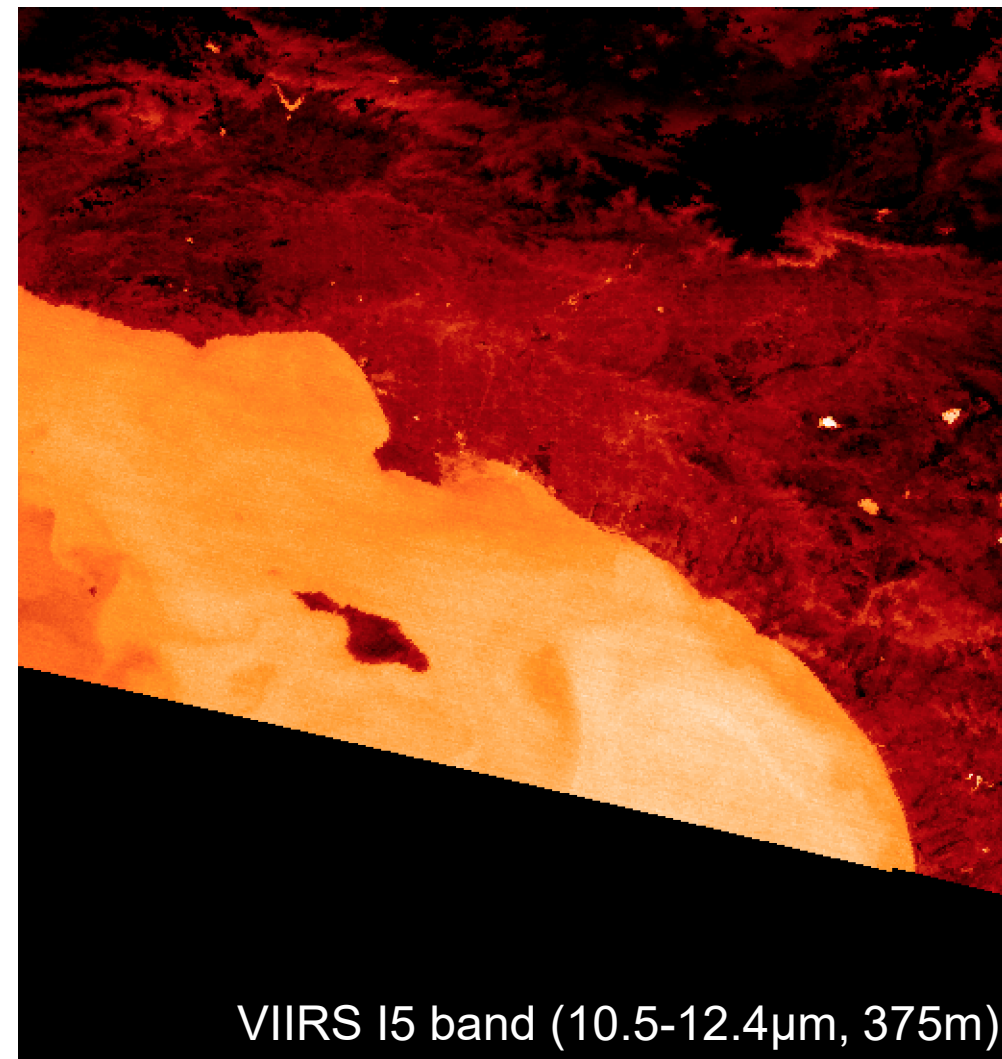
SWIR images “waste light” in the 0.9-1.7 μ m region, Highlights thermal sources (flares, stacks) and very bright light clusters

Urban Monitoring– VIIRS Comparison LA 12 Oct. 10:11 UT (>5 hours later)

Small portion of VIIRS 3000-km wide swath, LA still clear ~ 5 hours later during VIIRS



VIIRS DNB (.5-.9 μ m 742m)



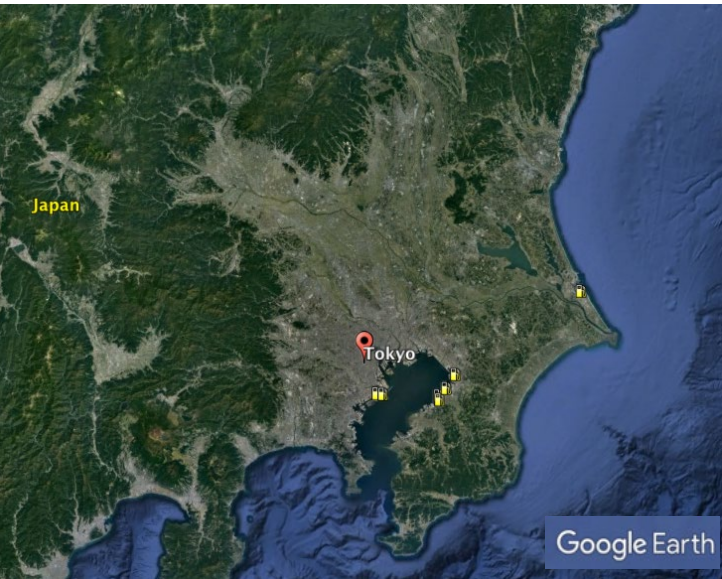
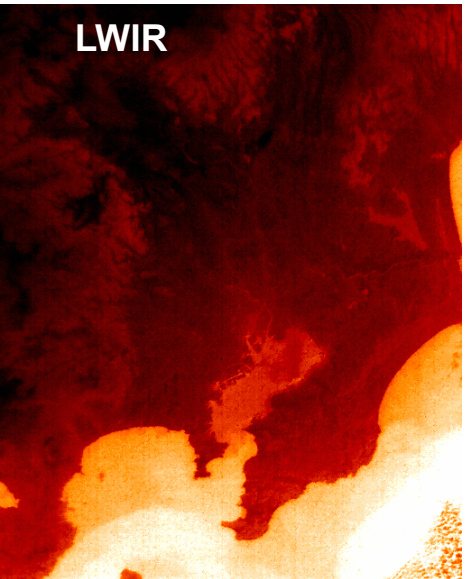
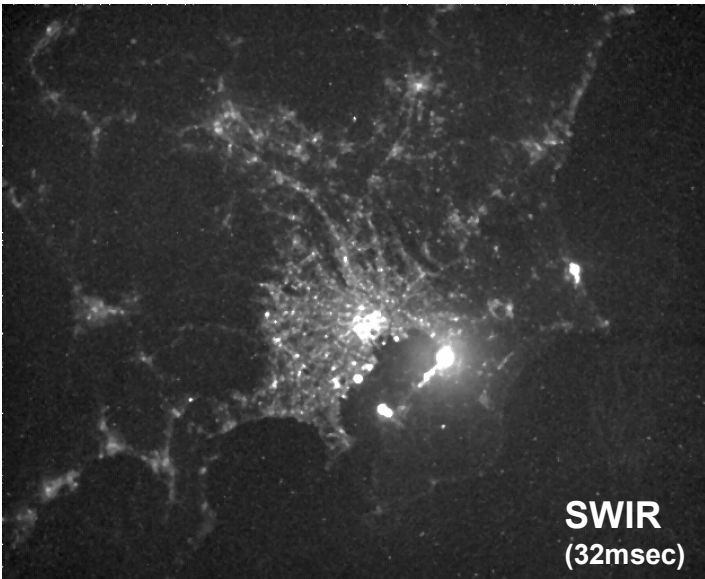
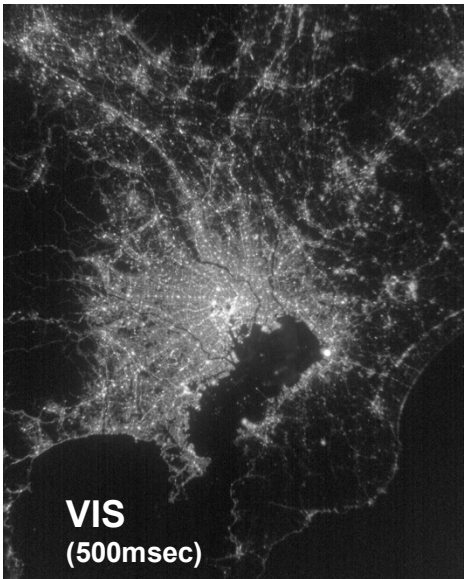
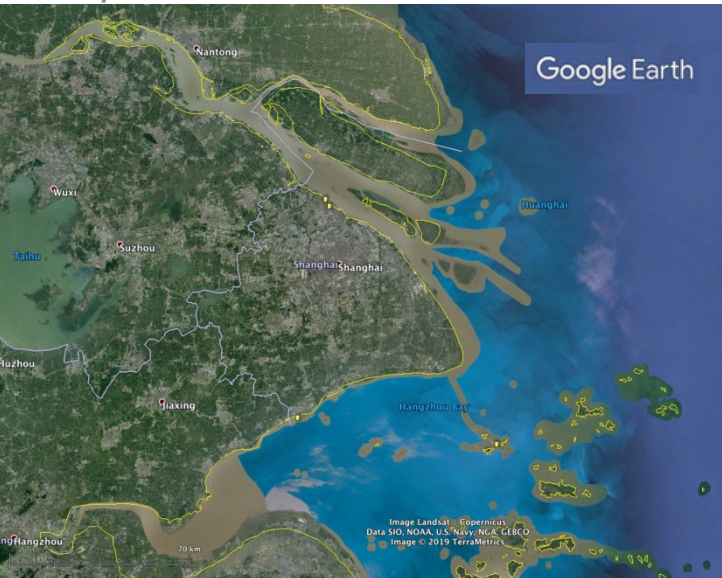
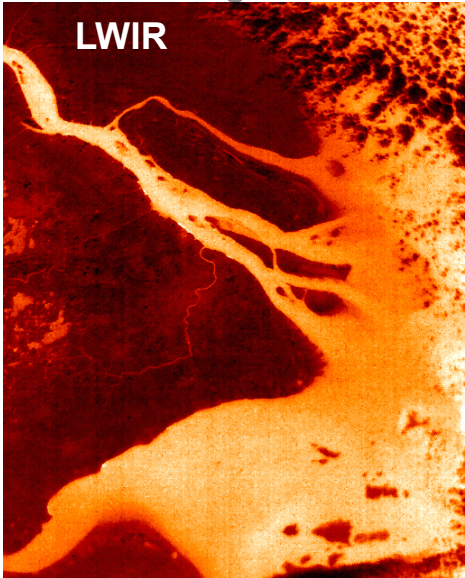
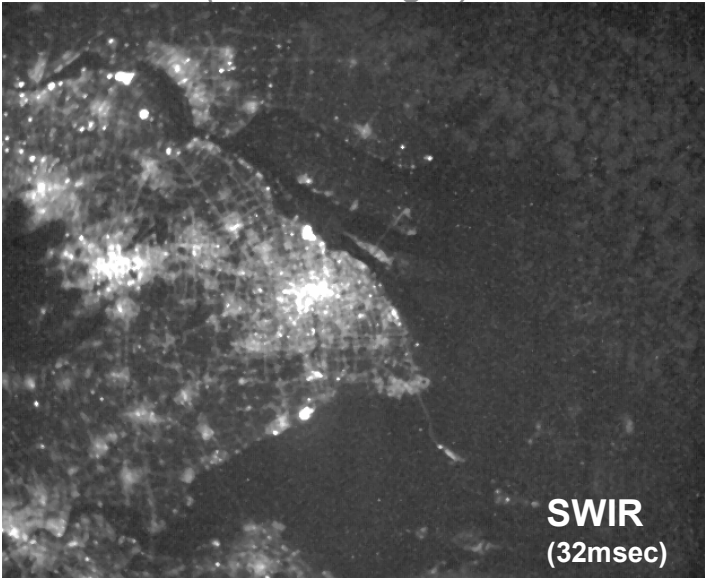
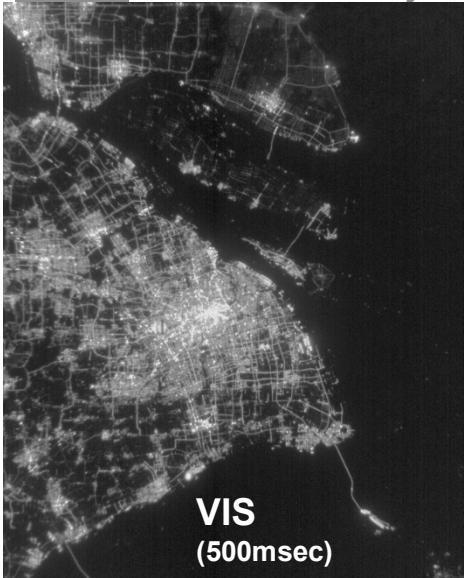
VIIRS I5 band (10.5-12.4 μ m, 375m)

VIIRS day-night-band resolution can't resolve urban grid, superior VIIRS LWIR performance is evident



Urban Monitoring – Global Cities Examples – Shanghai and Tokyo

Shanghai, 2018 December 13, 12:50 UT (moon 52.1° elevation, 177° azimuth, 32% illuminated),
Tokyo, 2019 February 6, 13:42 UT, (no moonlight) – cameras reveal urban grid, industrial hotspots, river and canal features

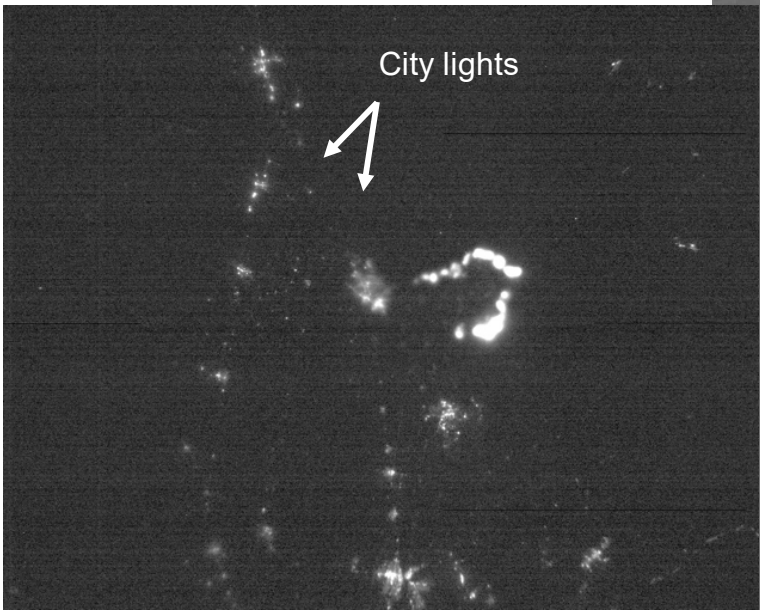




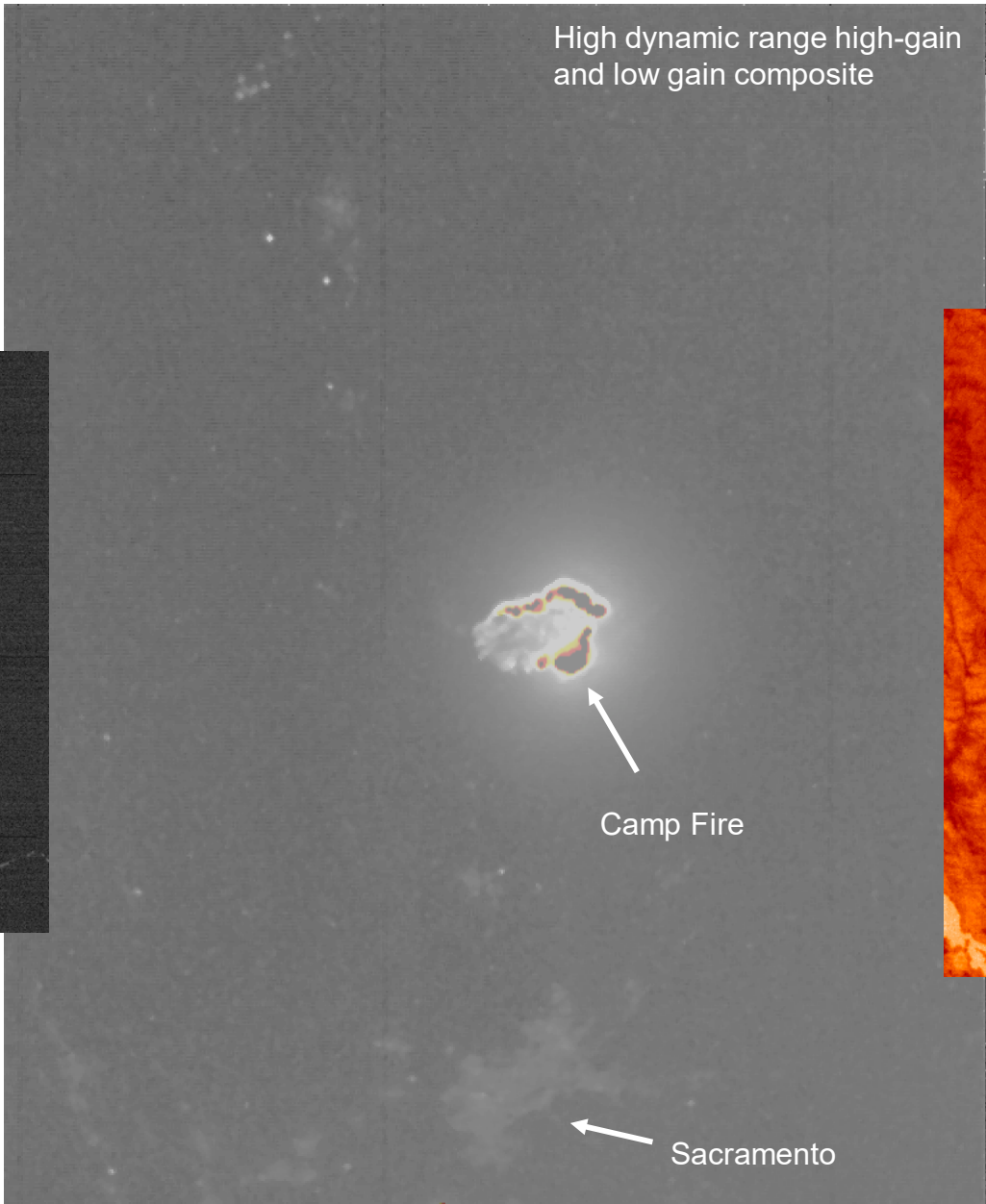
Fires - Chico, CA – “Camp” Fire SWIR (.9-1.7μm, 32 msec)

10 Nov 2018 10:48 UT
(moon down, no moonlight)

VIS (.4-.9μm, 200msec)

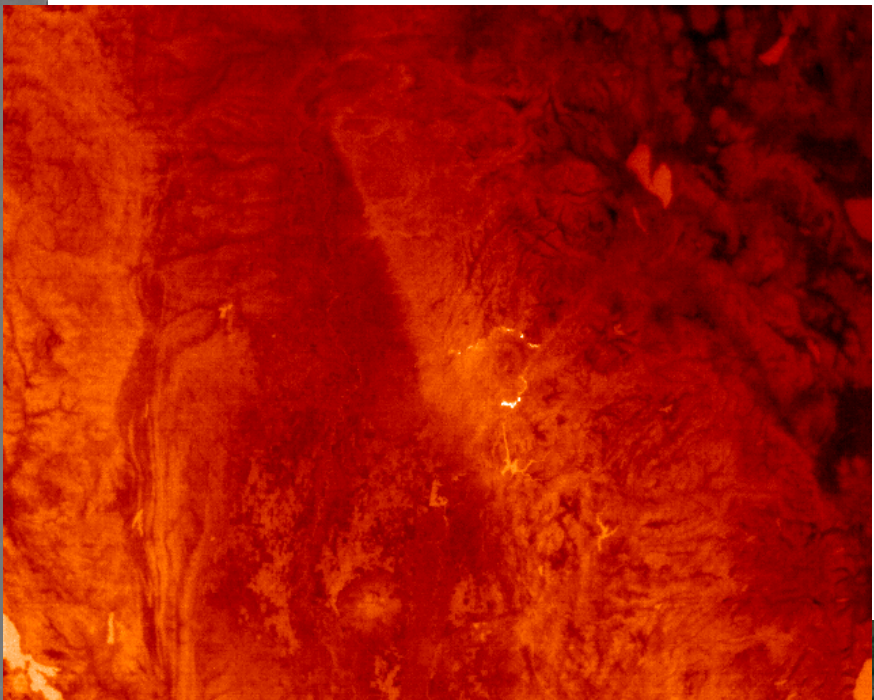


All three cameras detected the fire line and hotspots of this extreme fire. Using different gains and exposures enhances mapping of hot fire scenes. Cameras work well together.



High dynamic range high-gain and low gain composite

LWIR (7.5-13.5)



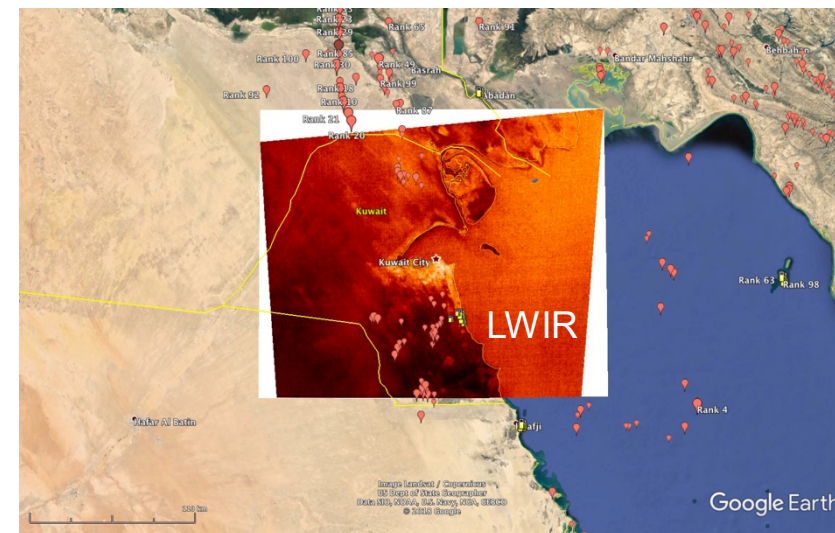
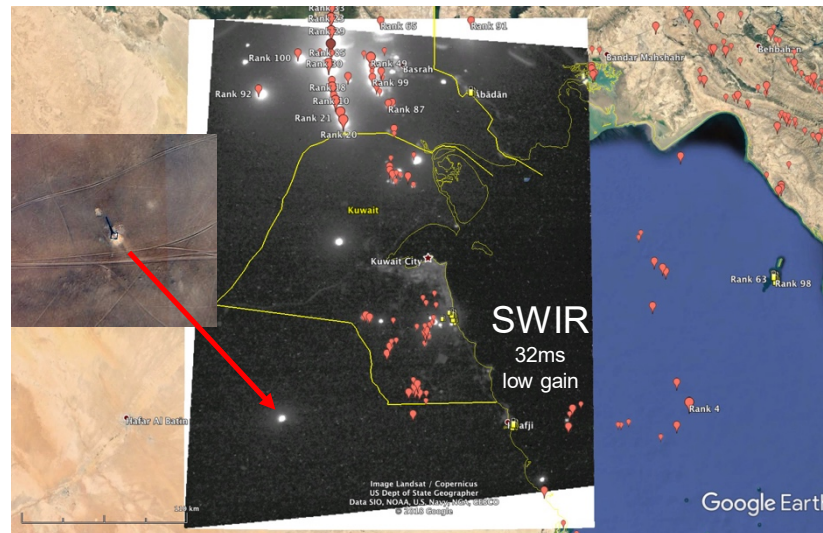
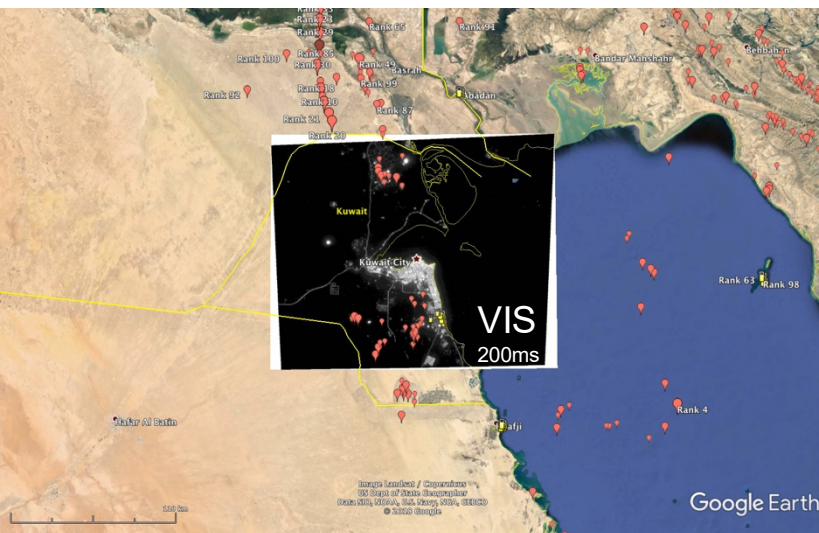
Modis hotspot map
11/10/2018 03:02 UT



Flares – CUMULOS Nighttime Kuwait Georegistered Imagery

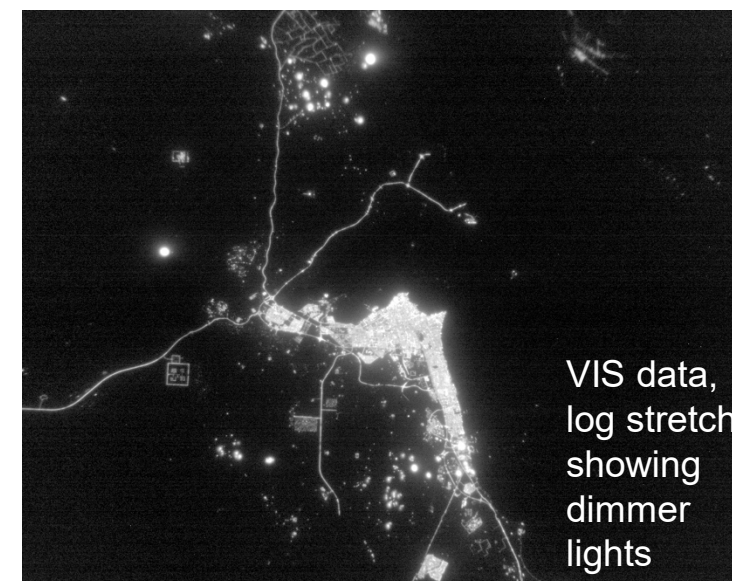
2018 Sep 17, 19:19 UT, Moon 12.5° elevation, 58% illuminated, no clouds are evident.

Pushpins are VIIRS-detected global flare product



- Gas flares are easily detected using the CUMULOS VIS (.4-.9 μ m) and SWIR (.9-1.7 μ m) cameras
- Only the largest hottest flare complexes show up as distinct point sources in the LWIR (7.5-13.5 μ m) camera
- VIIRS global natural gas flare product and Google Earth identifications provide highly useful "truth" data

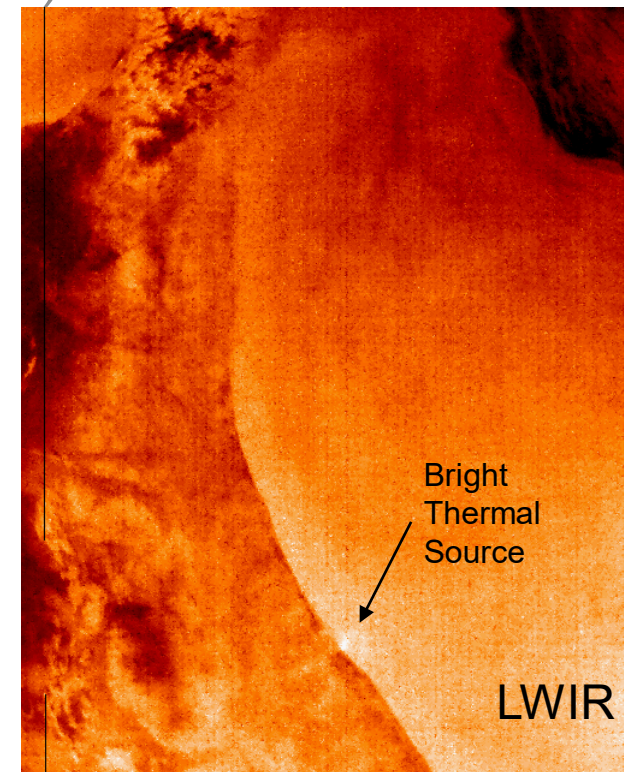
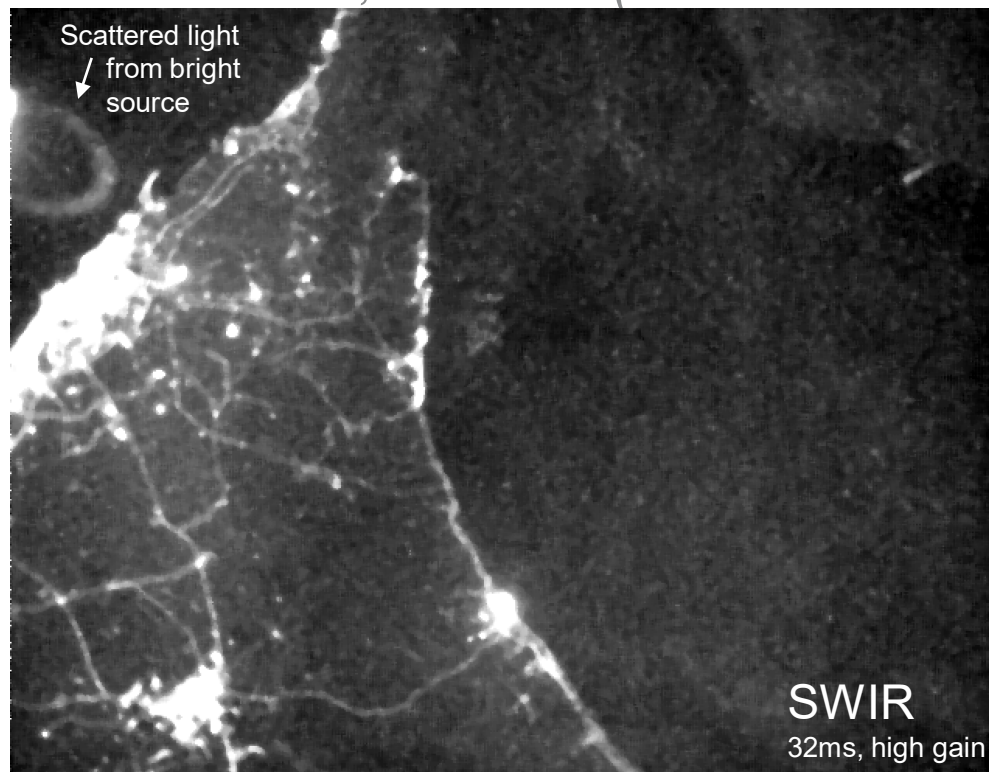
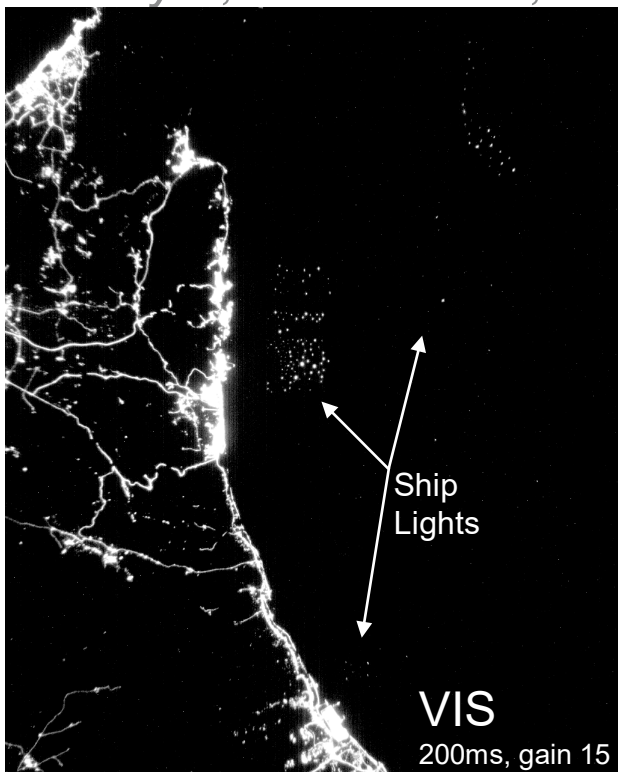
Global natural gas flares are interesting science targets and economic indicators as well as spatial fiducial points





Maritime – Boat Lights off of UAE in Gulf of Oman

2019 May 9, 22:44:34.16, Moonset 19:12 UT, no moon (frames not scaled)



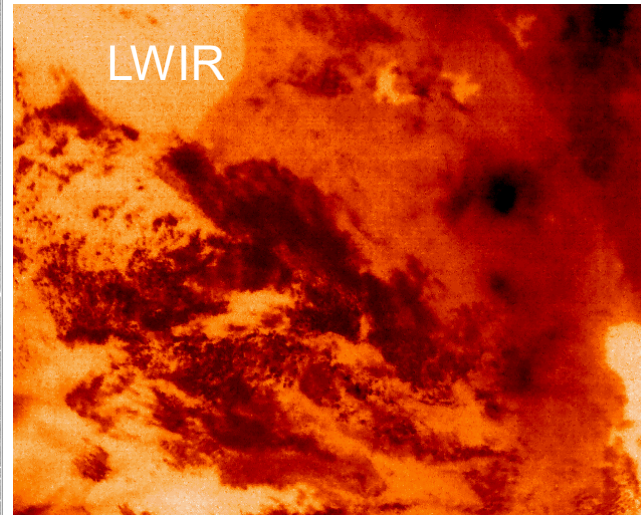
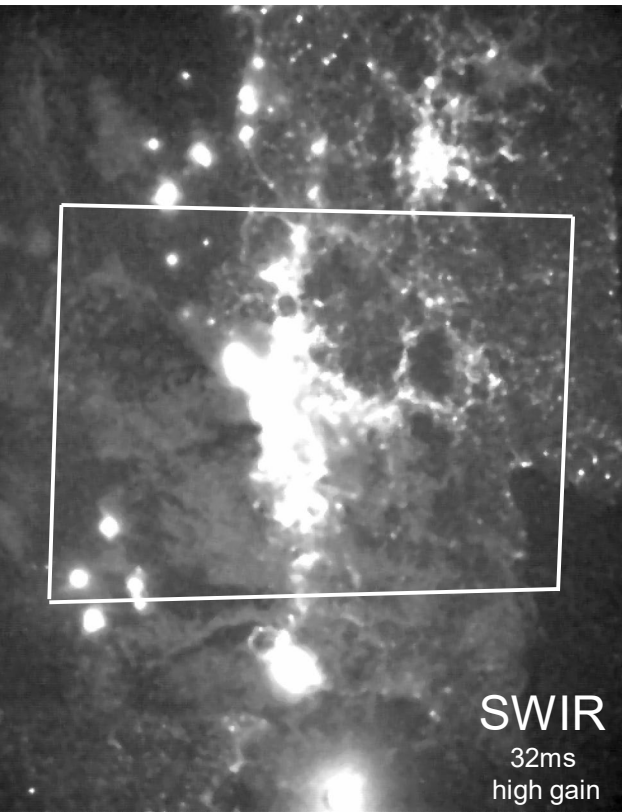
- Dozens of ship lights evident off of Fujairah, UAE and in Gulf of Oman outside of the strait of Hormuz
- Site chosen for study based on dense concentration of VIIRS boat detections
- Fish boats are often brightly lit as are oil tankers, goal of study is to show how CubeSats can inform VIIRS boat detection using higher resolution.

Cued by VIIRS detections, CUMULOS easily detects and resolves dense concentrations of closely spaced ship lights

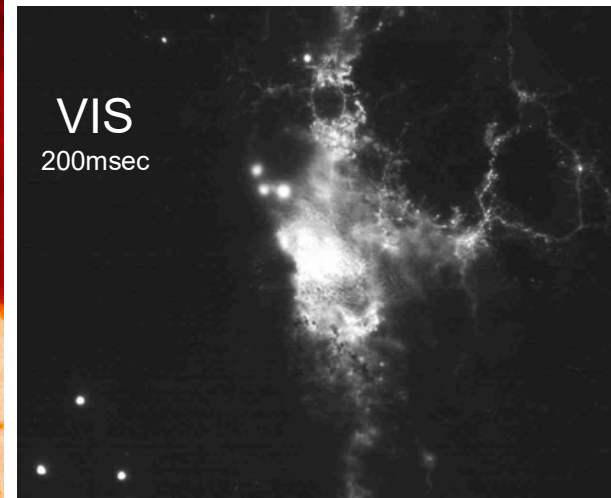


Weather – Airglow Illuminated Clouds – Jakarta, West Java region, Indonesia

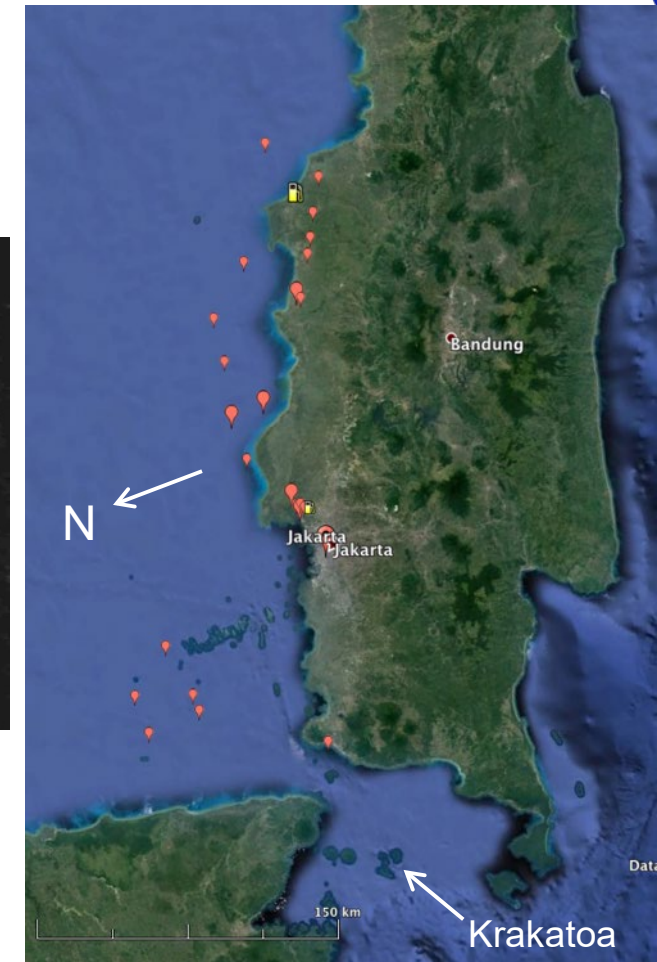
2018 Jul. 11, 15:55 UT - Moonset 09:02 UT, Moonrise, 21:54 UT. The lunar phase 4% waning crescent, no moonlight in this scene.



LWIR sees clouds in common with SWIR



VIS sees lights & flares in common with SWIR

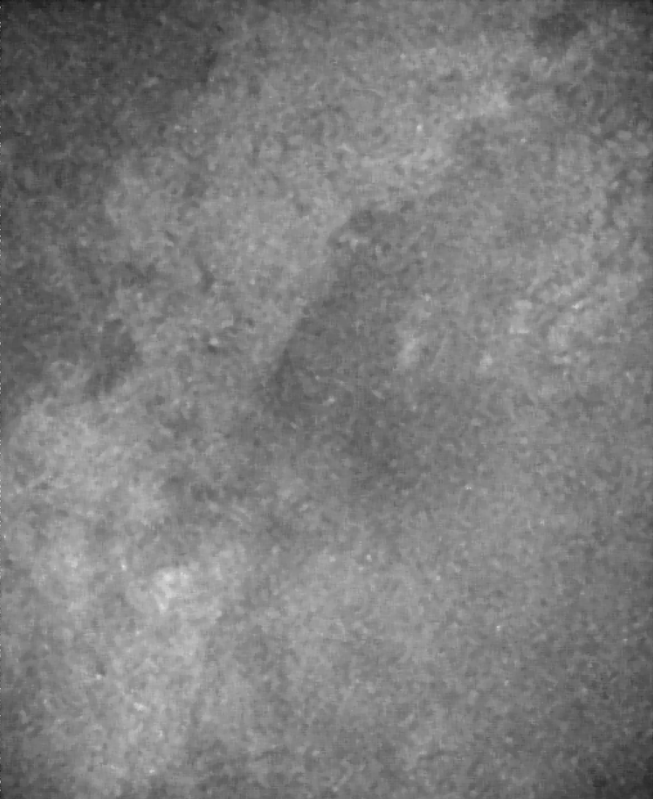


Context Map

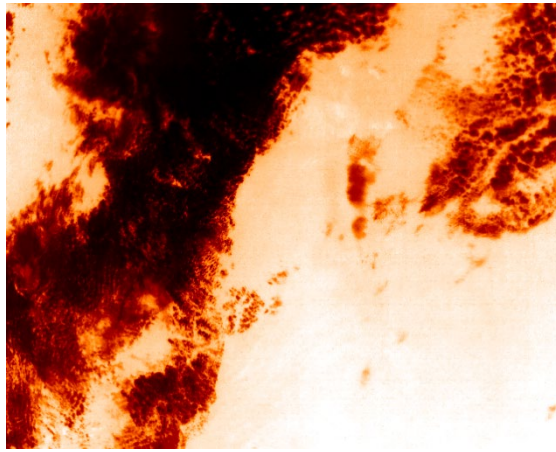
This complex nighttime scene features gas flares, nighttime lights, clouds, volcanic activity, ocean, and terrain. Airglow illuminated clouds are seen in high contrast over water in the SWIR .9-1.7μm band. Weather utility is being investigated with CUMULOS – VIIRS conjunctions.

Weather – Airglow Illuminated Clouds – Witjira, Australia Conjunction Collect

2018 Dec 11, 16:02:12.15 UT, moonset 12:51 UT, lunar phase 16% waxing crescent, no moonlight in scene



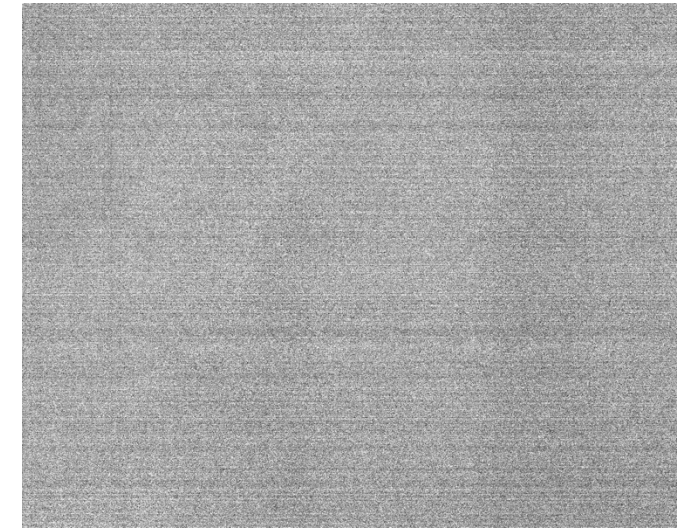
CUMULOS SWIR
(.9-1.7 μ m, 450m,
32ms, high gain)



CUMULOS LWIR
(7.5-13.5 μ m, 300m)

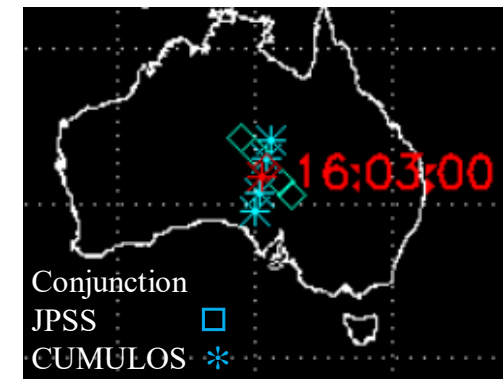


JPSS VIIRS DNB
(.5-.9 μ m, 742m)



CUMULOS VIS
(.4-.9 μ m, 130m, 500msec)

We are just beginning analysis of CUMULOS – VIIRS conjunctions collects – VIIRS DNB barely sees airglow-illuminated clouds. By operating in the SWIR, CUMULOS readily detects these clouds despite limitations imposed by the small optics and the 32msec integration time limit of the camera.





Conclusions

Intensive data collection phase has concluded for CUMULOS

- CUMULOS generated the highest resolution, radiometrically calibrated nightlights maps of urban, maritime, and global gas flaring regions taken to date, inspired by the “Nightsat Mission Concept” work of Elvidge et. al. and extensive research in recent years by DMSP and VIIRS experts
- CUMULOS took several observations of severe wildfires at night and demonstrated excellent performance at detecting intense fire lines with all three cameras, VIS, SWIR and LWIR
- CUMULOS flew uncooled infrared sensors and showcased their utility for cloud cover determination and airglow-only cloud detection
- CUMULOS has been a pioneering effort in the Aerospace Corporations CubeSat program, flying commercial IR cameras, developing on-orbit calibration procedures, and learning how to automate CubeSat operations and data pipelines. The stellar calibration effort using bright stars worked as conceived and should be a useful paradigm for others to follow for related missions.

NEXT STEPS

- 1) Scale optics and focal plane size and fly a 50m resolution VIS camera combined with newer IR cameras in a CUMULOS follow-on sensor that could be hosted in a 6U class payload, this time with LaserCom!**
“AltoCUMULOS” – Goal would be to prototype a global energy usage, human footprint, urban mapping mission.
- 2) Study feasibility and optimum design for a larger format CubeSat DNB mission – nighttime weather focused.**

Acknowledgements



This research was funded by
The Aerospace Corporation's Independent
Research and Development program.

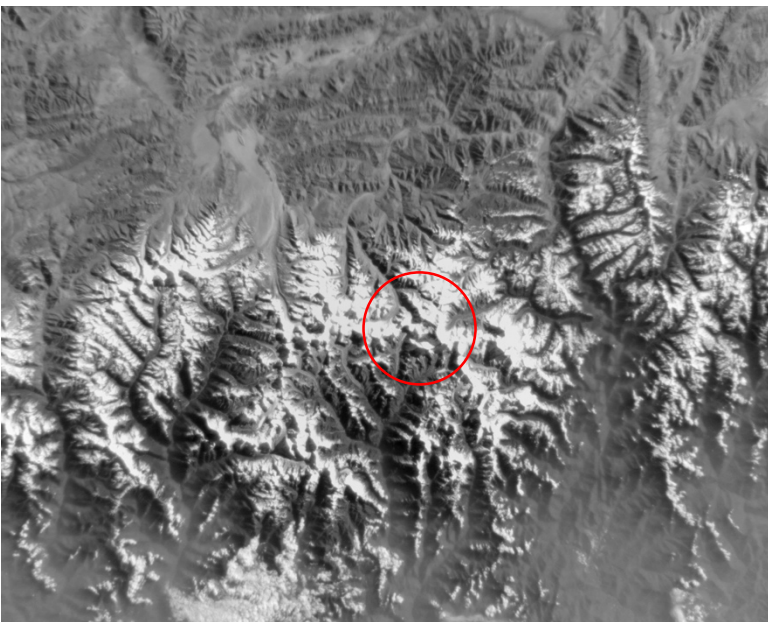
We thank NASA AMES and JPL for the
opportunity to fly the CUMULOS payload
on the ISARA mission!

Bonus Charts

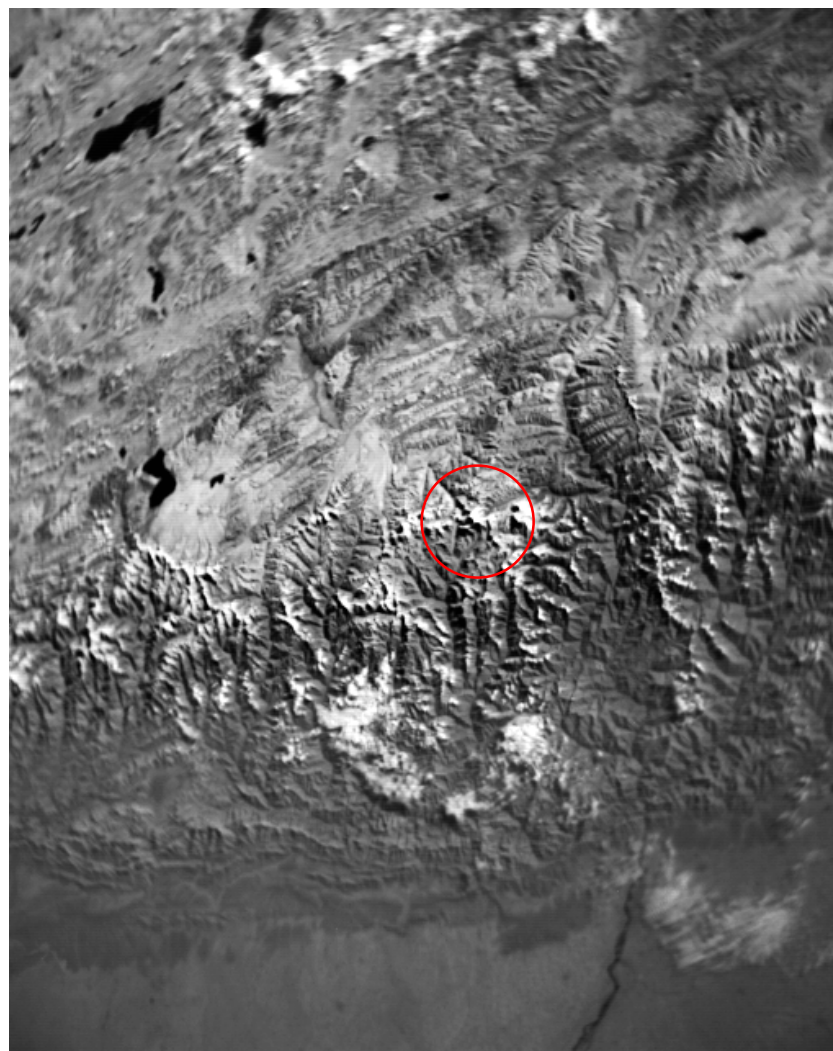


Daytime Observation - Mount Everest Region and the Himalayas

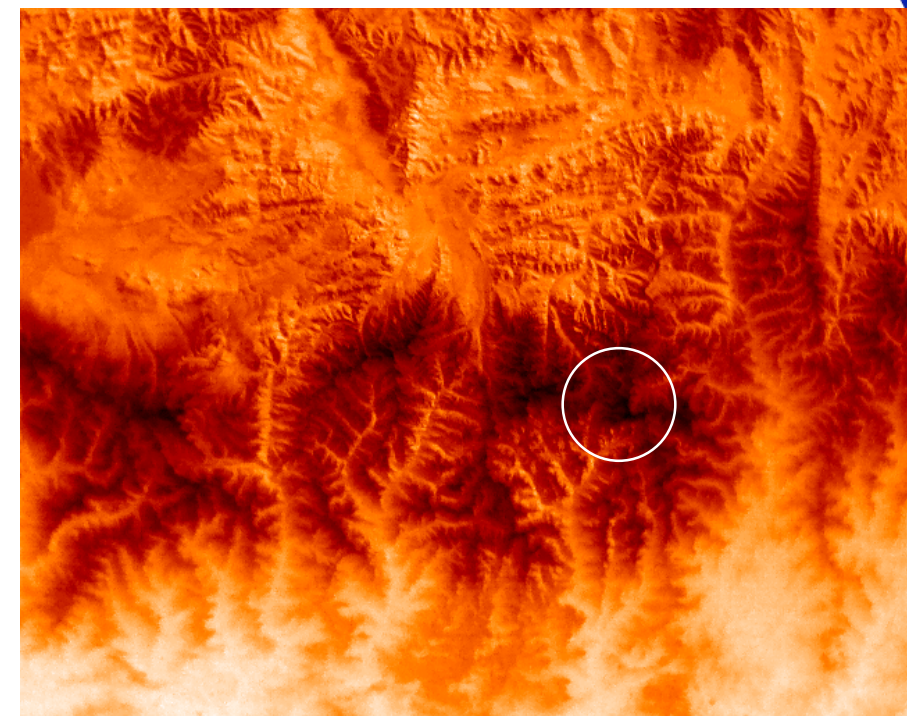
2019 May 20, 01:42 UT



VIS



SWIR

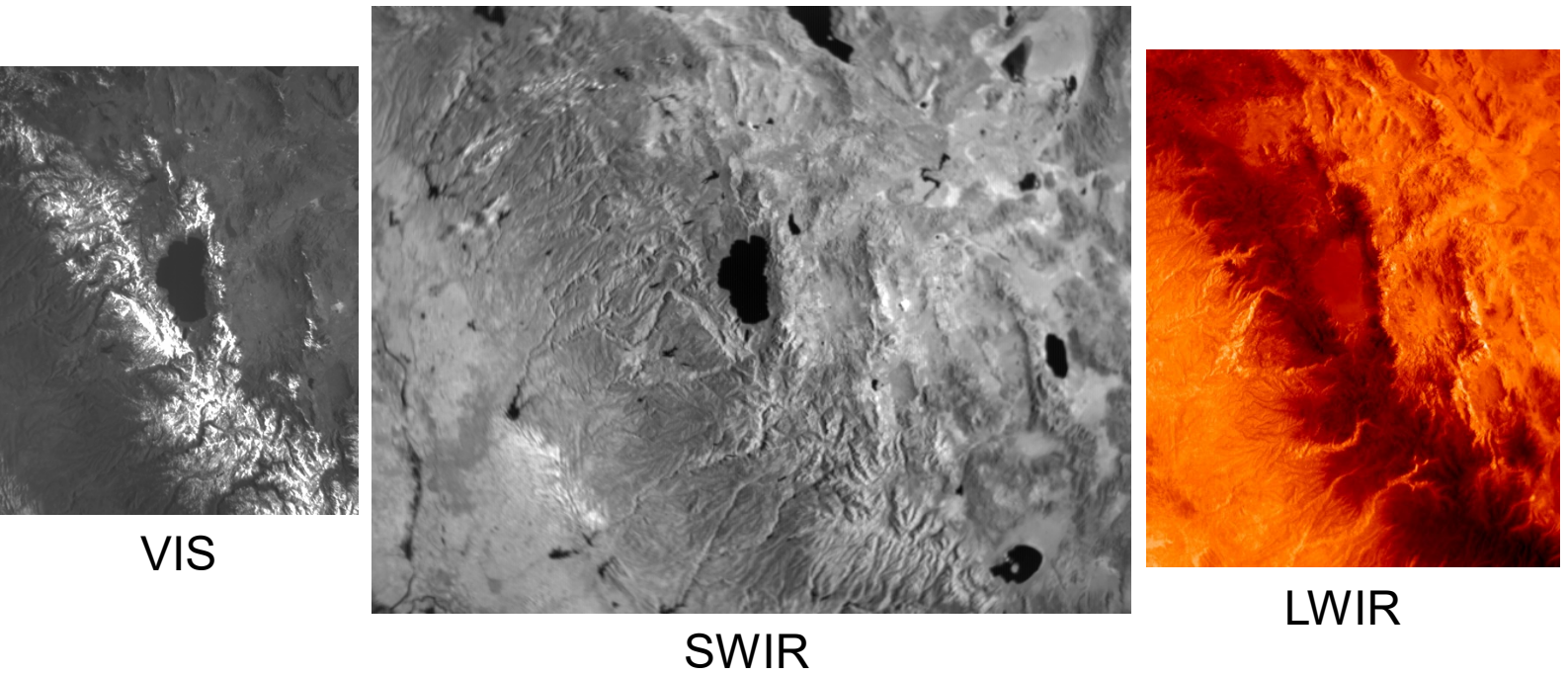


LWIR



IR Calibration High Altitude Lake - Lake Tahoe, California

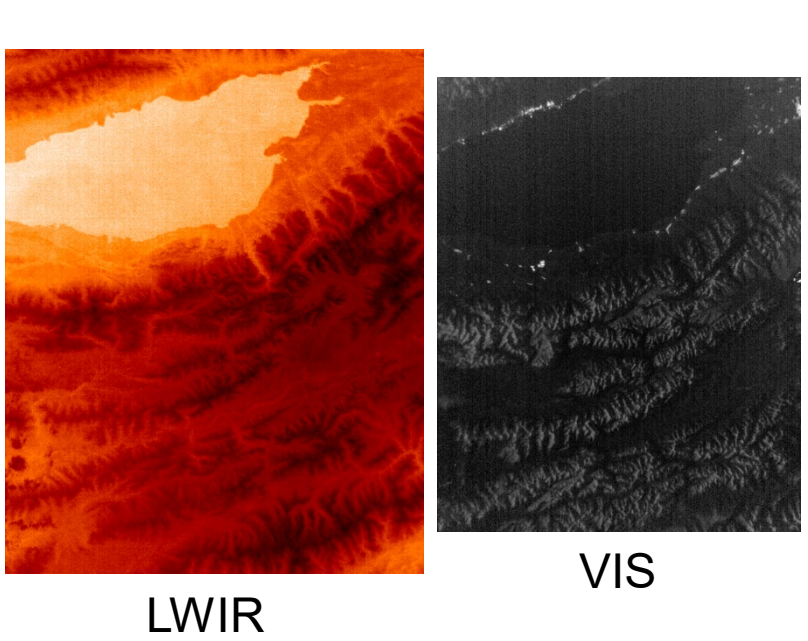
2019 Apr 29, 15:40 UT, just after sunrise



Daytime – Sun 29° elev.
(Lake Tahoe is an instrumented IR calibration site)

IR Calibration High Altitude Lake - Issyk Kul, Kyrgyzstan

2019 May 14, 21:00 UT

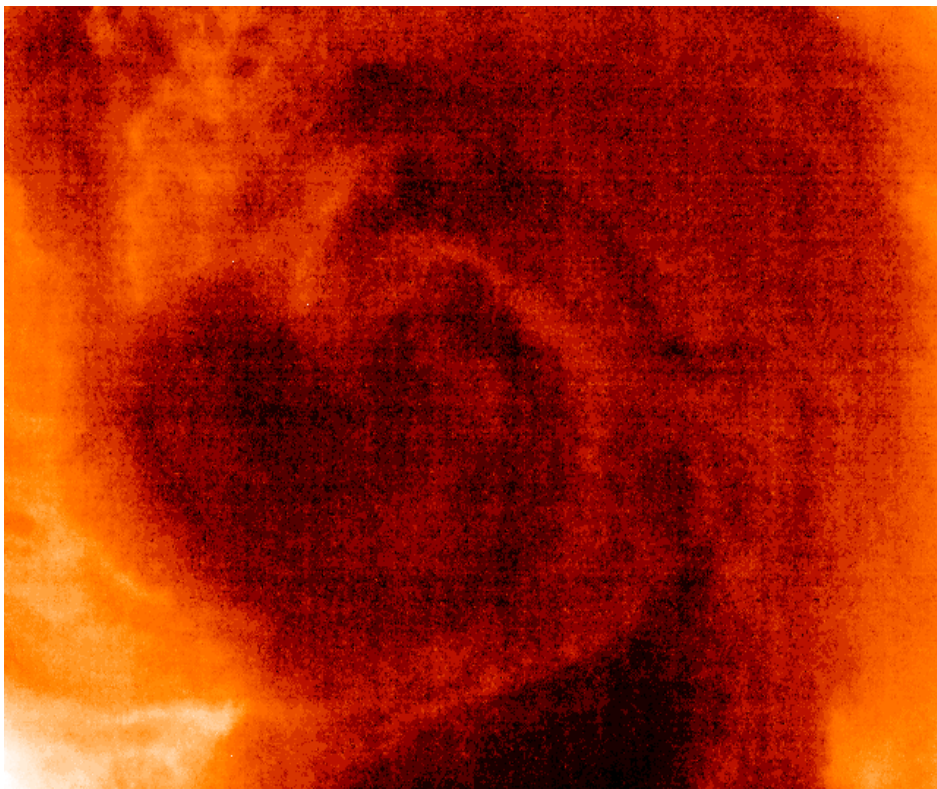


Nighttime – Moon 14.2° elev., 80% illum.
(VIIRS conjunction data collection)

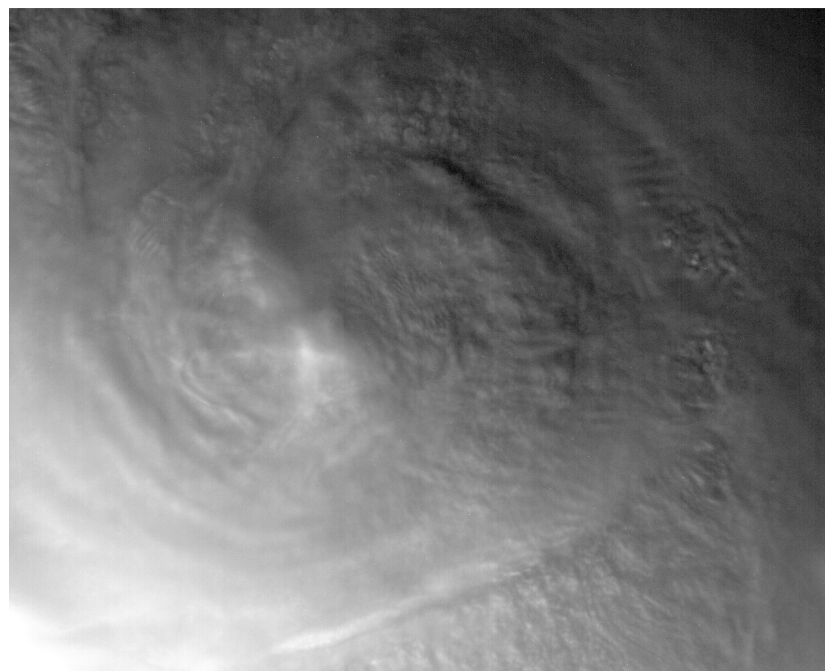
High altitude lake data to be exploited to understand microbolometer performance

Weather - Hurricane Willa – CUMULOS Observation of High Cold Clouds

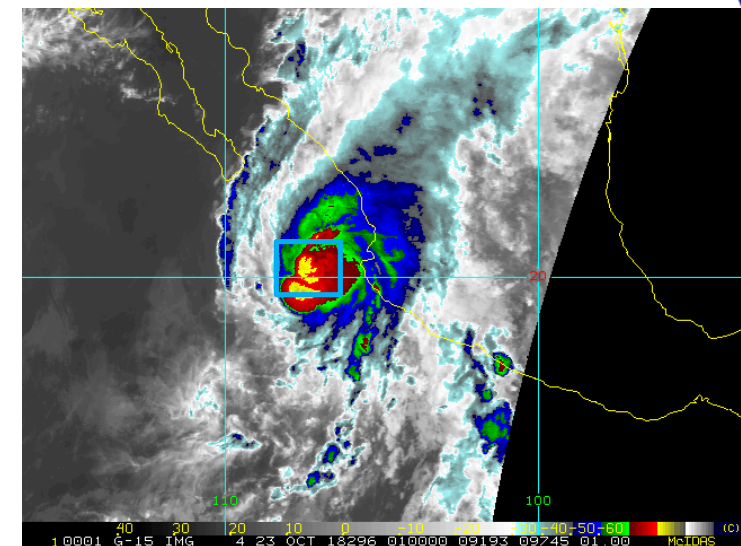
2018 Oct 23 01:11 UT



CUMULOS LWIR



CUMULOS VIS

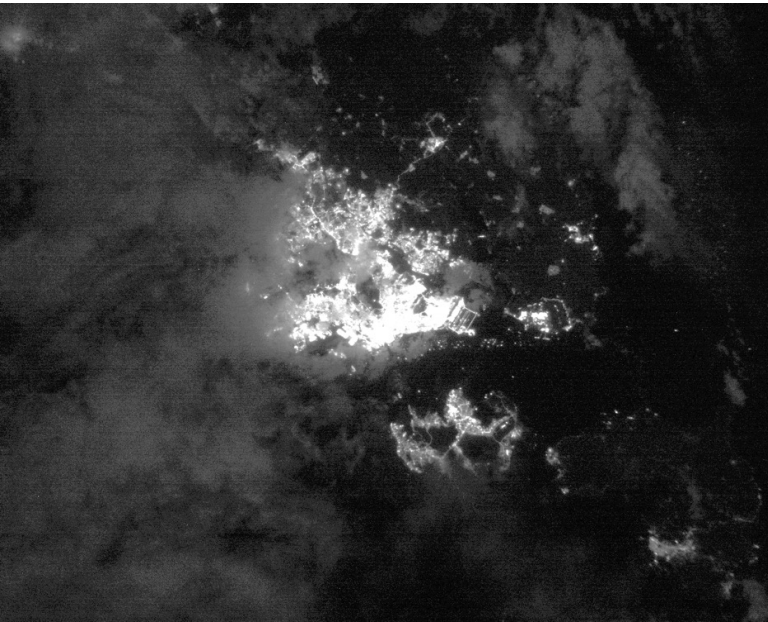


GOES 15 thermal image of Hurricane Willa 2018 Oct 23, 01:15 UT. Blue box outlines the approximate CUMULOS snapshot region.

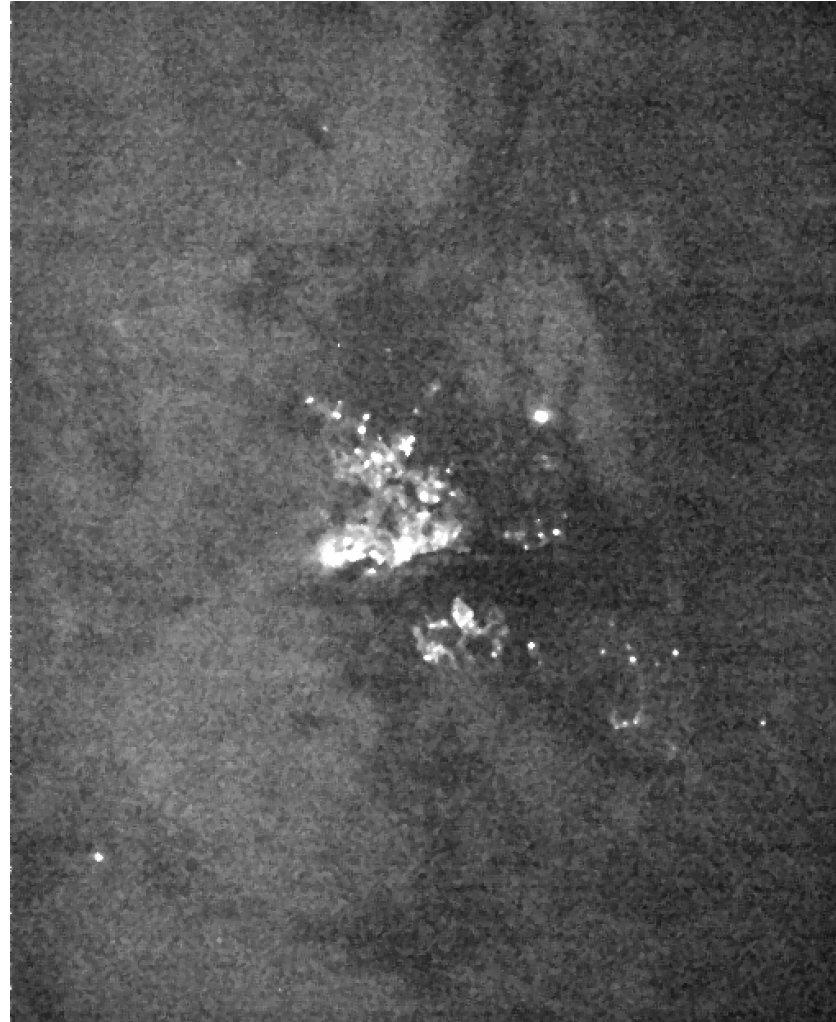
Detecting structure on the high, cold clouds forming the eye of a tropical cyclone is a challenging test of the uncooled LWIR microbolometer's performance

Urban Monitoring – Maritime – Weather: Singapore – Lights, Boats and Weather

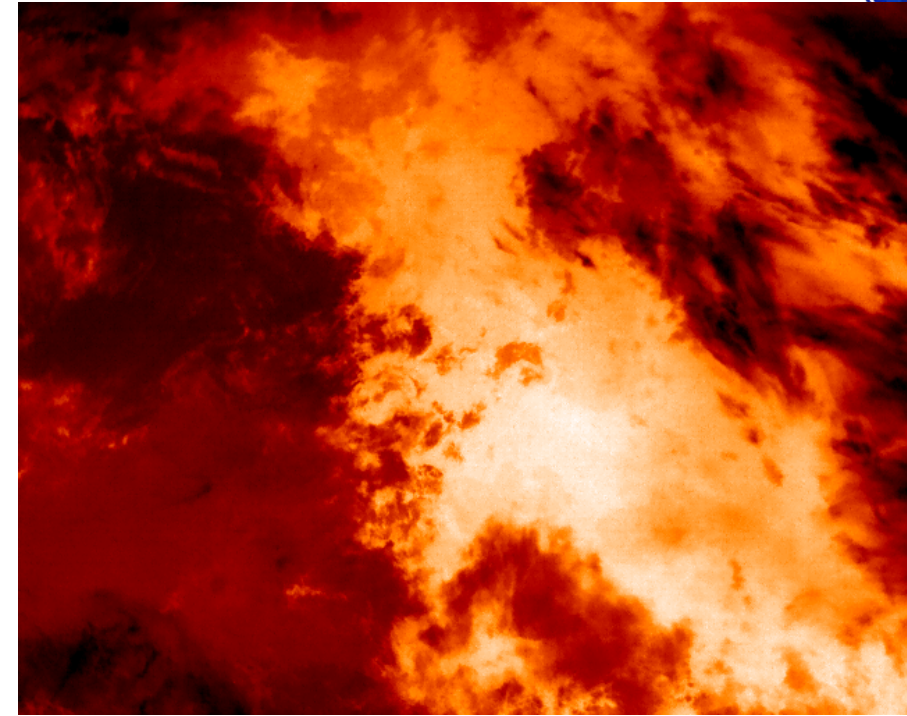
2018 Sep 19 13:12



VIS

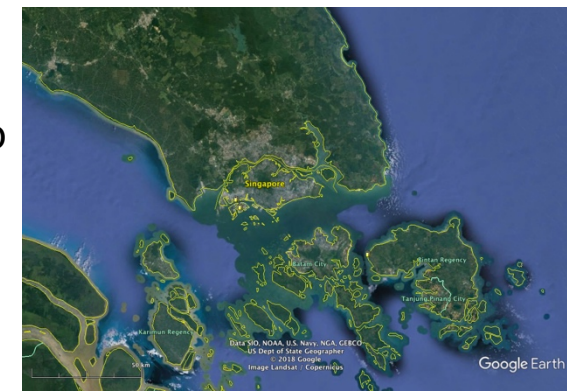


SWIR



LWIR

Context Map



The lights of Singapore reveal themselves through a break in the clouds – VIS data is stretched to show moonlit clouds