Earth Remote Sensing Results from the CUbesat MULtispectral Observing System, CUMULOS

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Abstract

CUMULOS is a tiny three-camera VIS/SWIR/LWIR sensor system flying as a hosted payload on the NASA/JPL ISARA mission, a 3U CubeSat. The CUMULOS sensors provide a small-aperture, large field-of-view, remote sensing payload suitable for testing the performance of passively-cooled commercial sensors for weather and environmental monitoring missions. The CUMULOS consists of a 0.4-0.9 µm visible CMOS camera, a 0.9 -1.7 µm short-wave infrared InGaAs CMOS camera, and a 7.5-13.5 long-wave infrared VOx microbolometer camera. All three cameras and associated electronics fit into less than 1U of spacecraft volume and were accommodated on the ISARA mission on a non-interference basis. CUMULOS is designed for point-and-stare imaging and acquires almost simultaneous 3-band coverage of regions approximately 200 x 150 kilometers in size, at ground sample distances from 130 to 400 meters from an orbital altitude of 450km, 52° inclination. Remote sensing applications being investigated include: hotspot detection (including fires, gas flares, and volcanic activity), detection of nighttime lights, cloud cover detection, surface temperature characterization, and airglow phenomenology. Operational since June 2018, the sensors have taken sample daytime and nighttime cloud imagery including, notably, the detection of airglow-illuminated clouds by the SWIR camera operating in high-sensitivity mode. The LWIR microbolometer camera provides useful single-band cloud and earth surface thermal imagery. The visible camera can provide daytime pictures as well as high-sensitivity nightlights imagery. The combination of all three cameras working together has proven quite successful for characterizing nightlights and thermal hotspots in manner similar to the much larger VIIRS payload that flies on JPSS, and for researching compact sensor nighttime weather imaging possibilities. We present example results on nightlights mapping of urban areas and road networks, detection of gas flares and other industrial heat sources, detection of urban heat islands, and demonstrate how the combination of sensors work together to map light and thermal features of rapidly developing urban areas. CubeSats sensors, such as CUMULOS, can complement existing of larger space sensors, such as VIIRS, by acting as testbeds for new spectral bands, imaging at higher resolutions over smaller fields of view, and flying in different orbits to measure nightlights signatures at different times during the night. The CUMULOS is also an engineering test bed for developing techniques for the calibration of small sensors in space, demonstrating a calibration and georegistration data pipeline, and automating CubeSat remote sensing data collection. These experiences, lessons and procedures will be described as well.

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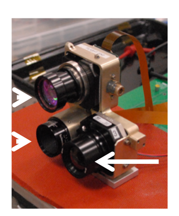
Abstract: CUMULOS, the Cubesat MULtispectral Observing System is a visible, short-wave infrared and long-wave infrared, 3-camera imaging system designed to research the use of commercial off-the-shelf (COTS) uncooled IR cameras in space for weather and environmental observations. The sensor system takes up less than 1U of volume, and flies in the NASA/JPL ISARA mission as a secondary payload. First operated in June after 6-months in space, initial results show impressive capabilities for cloud imaging and nighttime measurements of city lights and thermal features, such as oil industry gas flares and wildfires. The CUMULOS contains the first infrared CubeSat sensors flown by The Aerospace Corporation and is a pathfinder for others who are considering flying compact uncooled InGaAs IR cameras and VOx microbolometers on CubeSats for multiple missions.

The CUMULOS Payload on ISARA: CUMULOS was built by the Aerospace Corporation as an experimental payload hosted on the JPL-managed NASA Integrated Solar Array and Reflectarray Antenna (ISARA) mission. The Aerospace Corporation also built the ISARA mission spacecraft bus and operates the spacecraft via a multi-station ground network. The primary reflect array mission left over 1U of spacecraft volume available. CUMULOS was inserted on a non-interference basis and was not turned on until 6-months after launch following the successful completion of the ISARA primary mission operations.

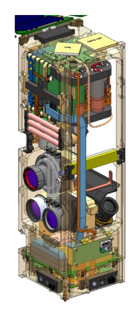


SWIR Camera InGaAs 640x512 0.9– 1.7μm

Visible Camera 1280x1024 0.4 – 0.9μm

LWIR Camera Microbolometer 640x512 7.5-13.5μm

Flight Hardware in lab

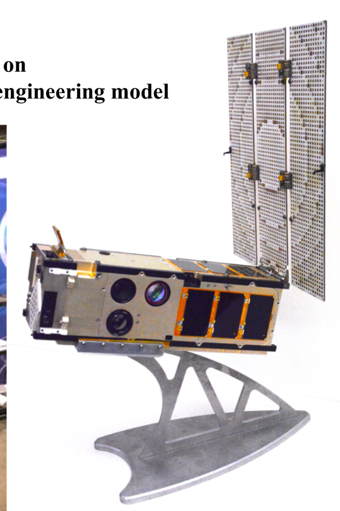


Fitting in the hosted payload

Launch 12 Nov. 2017 Cygnus Orbital ATK CRS OA-8

Boosted to final orbit from ISS 6 Dec. 2017

CUMULOS cameras on ISARA 3U CubeSat engineering model



CUMULOS Camera Parameters

Satellite Camera	Lens F#	Lens FL (mm)	Pixel Pitch (μm)	Nominal Altitude (km)	GSD (m)	Swath (km)
CUMULOS VIS	1.4	17.6	5.20	450	133	170 x 136
CUMULOS SWIR	1.4	25.0	25	450	450	288 x 230
CUMULOS LWIR	1.1	25.0	17	450	306	196 x 157

GSD, SWATH are minimums ignoring curvature of earth

After the primary ISARA antenna mission goals were successfully concluded, CUMULOS was turned on for checkout on 10 June 2018. Initial tests showed successful operation of all three cameras.

CUMULOS Engineering Goals:

1) Develop appropriate ground calibration procedures for small CubeSat imaging payloads.
2) Develop in-space calibration procedures and ConOps, including stellar calibration, lunar measurements, dark scene correction, vicarious calibration and cross-satellite comparisons
3) Research streamlined imaging ConOps with a goal of automating data collection
4) Develop a radiometric and metric data pipeline using CubeSat imagery and star camera ADCS telemetry
5) Assess space worthiness and aging of compact payloads, electronics and optics

CUMULOS Science Goals:

1) Assess the utility and performance of the broadband microbolometer for weather context imaging (high, medium, low altitude clouds), water and terrain temperature discrimination, urban heat island detection, and ability to provide cloud cover knowledge and imagery for the other two cameras
2) Assess the utility and performance of the broadband SWIR camera for nighttime imaging, including cloud imaging via airglow and moonlight, detecting thermal sources such as gas flares, fires and volcanic activity and waste light from human lighting.
3) Assess the utility and performance of the broadband monochromatic VIS CMOS camera for day/night weather imaging and nighttime lights detection. Compare results to VIIRS, ISS digital photography, and color CubeSat camera results, as well as to the SWIR and LWIR CUMULOS cameras.

Initial Performance:

1) The microbolometer is functioning very well on orbit, including the shutter. Calibration target collections and cross satellite comparisons will establish performance metrics. Clouds are being imaged and assessed to study system sensitivity limits.
2) The SWIR camera is tuned for nighttime performance and is meeting or exceeding our expectations. We believe we're detecting reflected airglow signals. Daytime performance is better than expected with auto modes enabled.
3) The visible camera compares very well to VIIRS imagery of nightlight scenes. We will be making more detailed comparisons of nighttime cloud imagery between VIIRS and our SWIR and VIS cameras soon.

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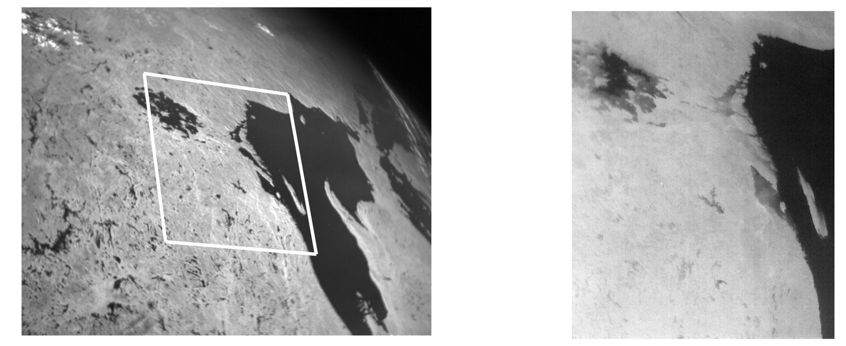
Daytime Weather Observations: The images below show CUMULOS data taken during early on-orbit operations. The first two images are a SWIR, LWIR infrared pair imaging Ontario and Lake Superior approximately centered on Thunder Bay Ontario. The larger FOV SWIR image shows a panoramic view of the glacial lakes and the Great Lakes all the way to the Earth limb. The smaller LWIR image highlights subtle thermal differences in the lakes, bays and inlets.

CUMULOS First Light - Imaging the Great Lakes
11 June 2018 01:10:03 UT

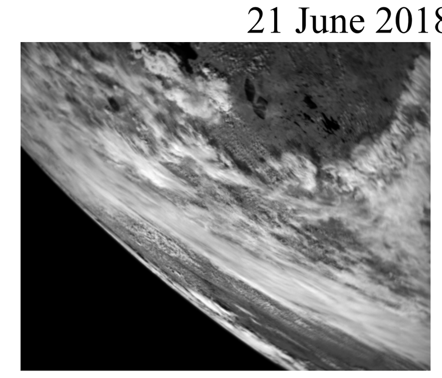


SWIR

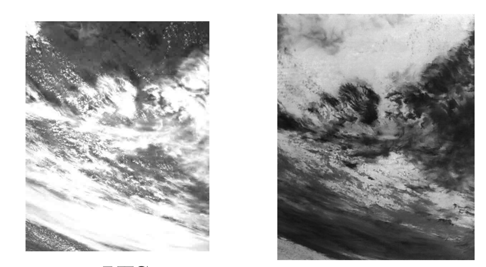
LWIR

The CUMULOS SWIR camera images late evening clouds, cloud shadows, earth surface and many water features with autogain features turned on. The LWIR camera (smaller FOV) images surface thermal features. These early test images were downloaded as jpegs and don't exhibit full sensor quality. The visible camera (not shown) was exposed at 1 msec and saturated.

CUMULOS Image Triplet over Minnesota
21 June 2018 - 21:20-21:22 UT



SWIR



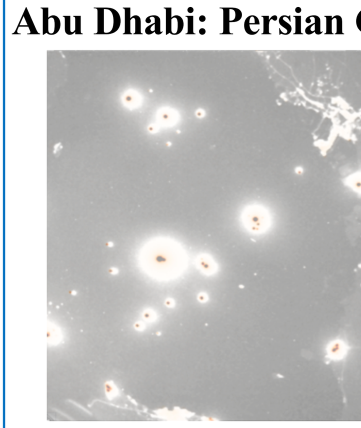
VIS

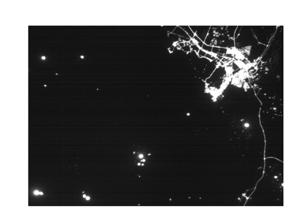
LWIR

During camera programming checkout we captured our first daytime image triplet from the SWIR, VIS and LWIR cameras. Here the weather imaging capabilities of the three cameras are shown viewing a common scene with high cloud structures. The microbolometer performs as expected and images colder cumulus cloud structures, including quite small cumulus clouds clusters detected in the other two cameras. Minnesota lake features are particularly evident in the SWIR image.

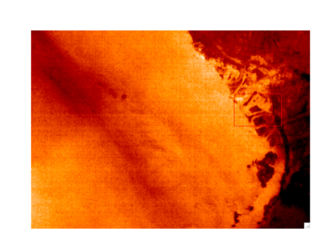
Nighttime Observations: We started our nighttime use of CUMULOS studying the bright cities and natural gas flares of the Persian Gulf. Nighttime images below show Abu Dhabi in the UAE and Kuwait City and surroundings imaged by CUMULOS. The SWIR and VIS cameras detect nighttime lights and bright gas flares. The thermal contrast between the warm Gulf waters, cooler land surfaces and the urban heat islands are clearly evident in the LWIR microbolometer data. The SWIR camera can saturate on the flare signals and its sensitivity is shown by detection of city lights and the airglow-illuminated desert surface in high gain mode.

Abu Dhabi: Persian Gulf Natural Gas Flares 16 July 19:08 UT





VIS

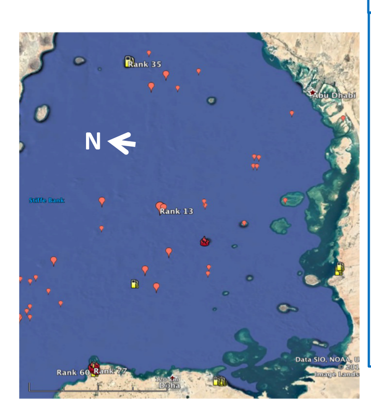


LWIR

< SWIR (high-gain + low-gain composite)

(Note: The camera images for this system checkout collect were not all pointed at exactly the same centroid)

No Moonlight

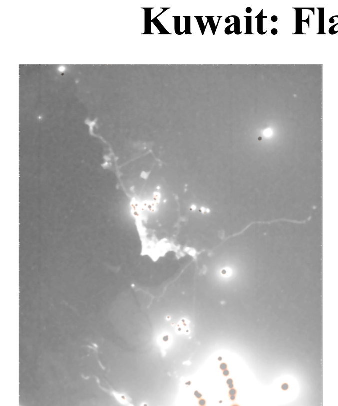


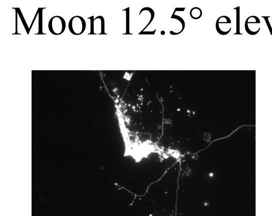
The large FOV SWIR sensor images the coasts of Abu Dhabi, Bahrain and Iran centered on a region of the Persian Gulf rich with natural gas flares. The CUMULOS SWIR sensor is tuned for nighttime use and is extremely sensitive, even detecting the surface reflection of the coastline areas an hour after the moon set. The brightest flares are saturated in high gain. The low gain SWIR (shown in negative contrast) pinpoints the hot flares. The visible sensor detects only city lights and flares. The LWIR sensors shows possible thin cloud cover in the region, not well-revealed in the impacted portion of the SWIR image. The LWIR is insensitive to most flares in this image, but does detect thermal activity at a desalinization plant and highlights the land/water thermal contrast.

Map of region imaged with VIIRS-detected flares

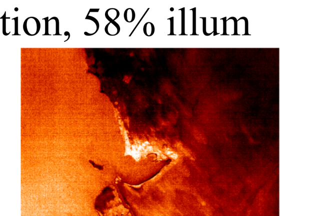
Kuwait: Flares, Lights, Heat Islands in 3 bands
17 Sept 2018 19:20 UT

Moon 12.5° elevation, 58% illum



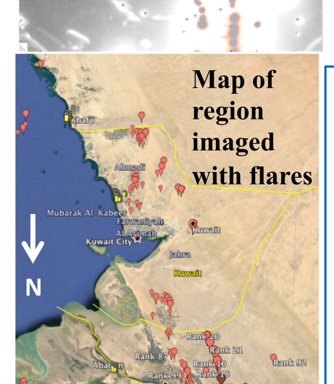


VIS



LWIR

< SWIR (high-gain + low-gain composite)



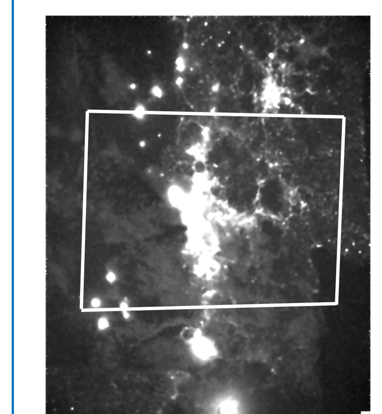
Map of region imaged with flares

The Kuwait/Iraq border region is imaged in a SWIR camera high gain + low gain composite. High-gain data saturates on signals from a double line of gas flares in the Rumaila oil field, detects waste light from Kuwait city and roadways, and sees weak, low elevation moonlight scattered from the desert. The low-gain data (shown in reverse contrast) pinpoints the gas flares. This high dynamic range data compliments the VIS camera imagery and aids in distinguishing hot thermal emissions from lights. The LWIR camera provides cloud context and highlights urban heat islands which closely match the development mapped by the VIS camera in these scenes. The 300-m GSD microbolometer only detects the brightest flares, although it does readily detect larger area thermal sources (such as fires).

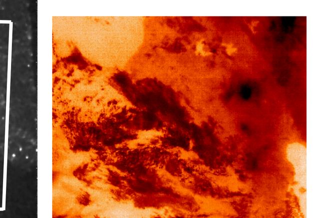
Nighttime Weather, Lights, Flares & Airglow Illuminated Clouds

The complex scene below of Jakarta, Indonesia and surroundings shows a number of features detected by CUMULOS. The SWIR camera detects lights and flares, including signals transmitted through cloud cover. It also detects weak airglow illuminated clouds which are most evident on the left hand side of the scene in contrast with the dark ocean. The brightest spot in the lower center is Krakatoa which is currently erupting. The LWIR microbolometer images cold cloud features in contrast with the warmer ocean. Ocean/land boundaries are evident as are cold highland volcano regions and three warm reservoirs in the upper part of the image. The visible camera with the smallest field of view sees gas flares, cloud obstructed lights from the Jakarta urban core and outlines of road networks, notably the ring of lights around Mt. Gede, a 2,958 m stratovolcano.

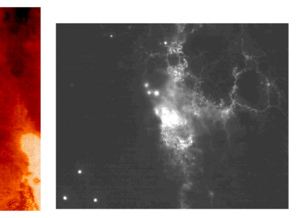
Jakarta Indonesia – Complex Nighttime Scene with no Moonlight
11 July 2018 15:55 UT



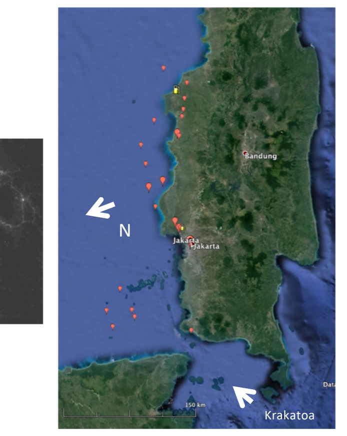
SWIR



LWIR



VIS



Java Map with flares

Moonset 09:02, Moonrise 21:54, Moon phase 4% waning crescent, so no moonlight in scene

Nighttime Fire Monitoring: The broadband VIS and SWIR bands of CUMULOS are highly responsive to the light emitted by wildfires and even the LWIR band responds to the very large hotspots of well developed wildfires. The images below highlight this capability and compare the fire pattern measured to-that measured by MODIS and VIIRS detection products. The Carr and "Camp" fires were two exceptionally large deadly fires in Southern California during the 2018 season. CUMULOS has demonstrated a highly sensitive fire monitoring satellite is achievable in a compact CubeSat form factor.

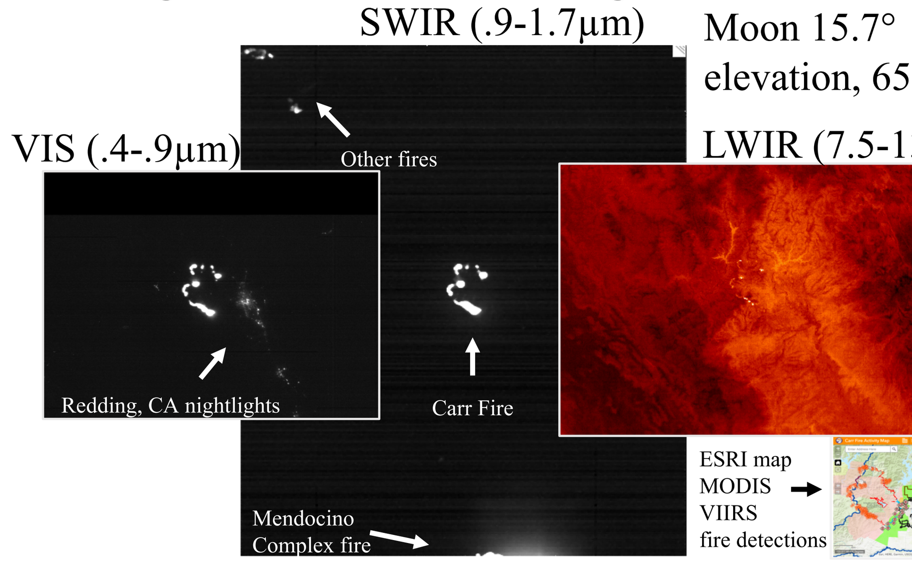
Redding, CA – "Carr Fire"– 3 August 2018 08:04 UT

SWIR (.9-1.7μm)

Moon 15.7° elevation, 65% illum.

VIS (.4-.9μm)

LWIR (7.5-13.5)



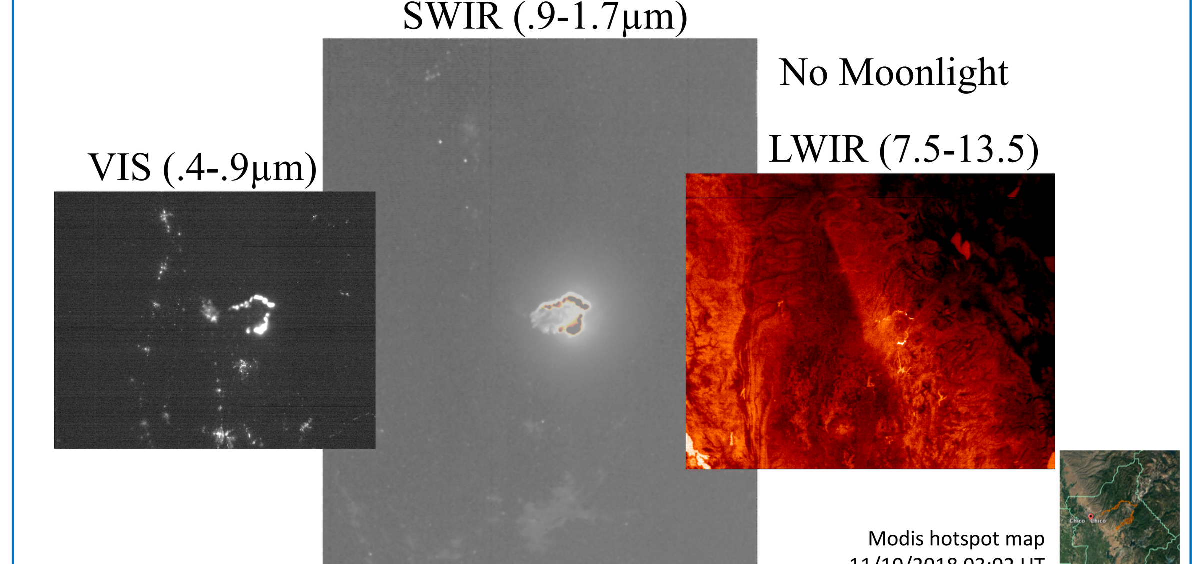
Chico, CA – "Camp" Fire – 10 Nov 2018 10:48 UT

SWIR (.9-1.7μm)

No Moonlight

VIS (.4-.9μm)

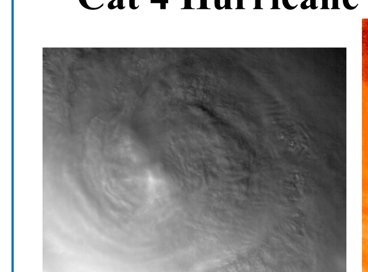
LWIR (7.5-13.5)



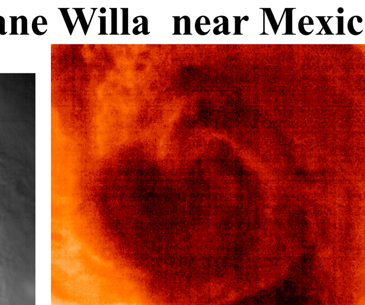
Modis hotspot map 11/10/2018 03:02 UT

Storm Imaging: CUMULOS was tasked continuously during hurricane system to image storms. The twilight image below highlights the capability of the VIS and LWIR cameras.

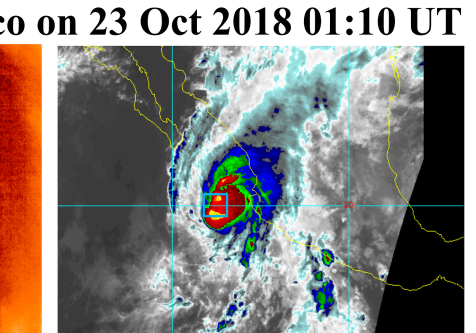
Cat 4 Hurricane Willa near Mexico on 23 Oct 2018 01:10 UT



VIS 01:10:47.14 UT



LWIR 01:10:36.24 UT



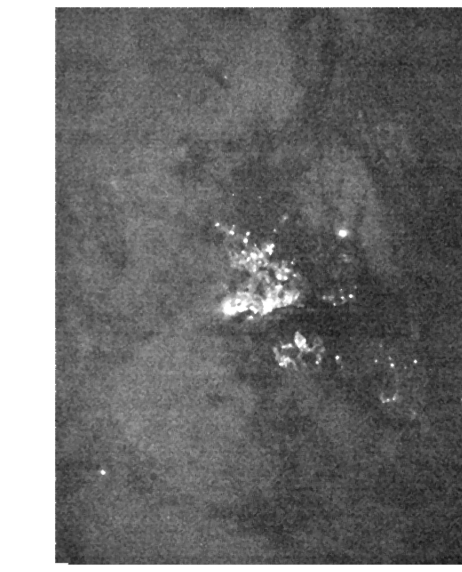
GOES-15 IR 01:15 UT

blue box ~ CUMULOS FOV

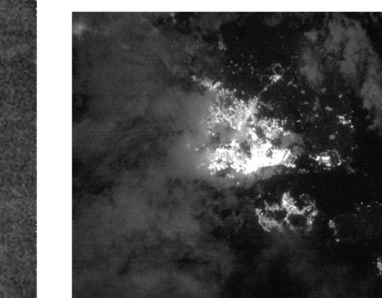
CUMULOS VIS and LWIR imagery of hurricane Willa taken right after local sunset (sun was -7° elevation relative to sea level). The high-altitude storm clouds were still solar illuminated at a very low sun angle. These images show the high-resolution low-light capability of the CUMULOS VIS sensor over its limited FOV. No VIIRS low-light sensor had an overpass near this time and the last GOES VIS image was tasked at 00:30 UT. The CUMULOS microbolometer is barely able to image the very cold temperature clouds in the eye region which range from -60° to -80°C. Future mosaic weather imaging collections with CUMUOS to will be desirable to expand area coverage.

Nighttime Weather, Urban Lights, and Ships in the Singapore Strait and Java Sea: The Singapore region appears in a break in the clouds in these SWIR, VIS and LWIR images from the CUMULOS sensors. Economic development in neighboring regions of Malaysia and Indonesia is evident in the visible imagery of urban lights and port infrastructure. Baseline imaging of rapidly changing areas like Singapore helps quantify growth and change. Moored ships in the Singapore straits are evident. Clouds obscure other ships and the Malacca strait. Also shown is a separate experiment imaging a dense concentrations of fishing boats in the Java sea.

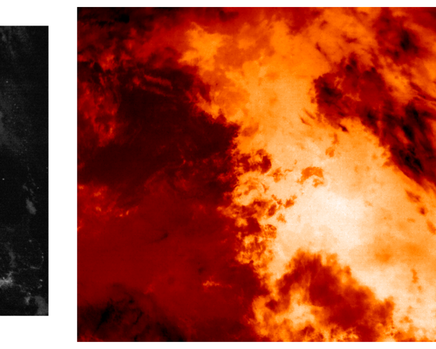
CUMULOS - Singapore Region
2018 Sep 19 13:12 UT - Moon at 67.9° elevation, 74% illum.



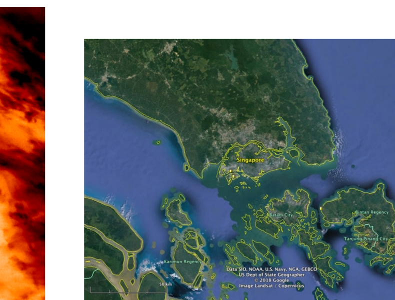
SWIR



VIS

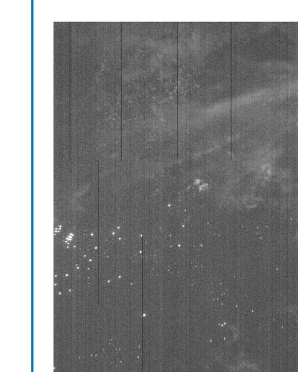


LWIR

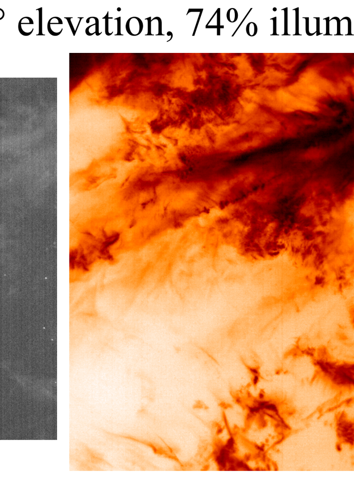


Map of Region

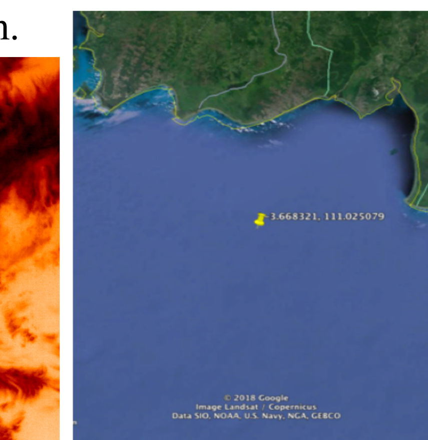
CUMULOS – Java Sea Boat Detection 2018 Oct 19 13:15 UT
Moon at 67.9° elevation, 74% illum.



VIS

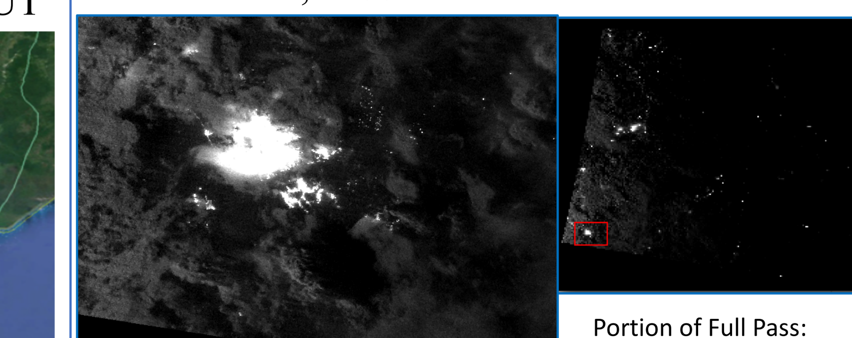


LWIR



Southern Borneo Coast

VIIRS DNB - Singapore Comparison
2018 Sep 19 17:39 UT - Moon at 18.8° elevation, 75% illum. > 4 hours later



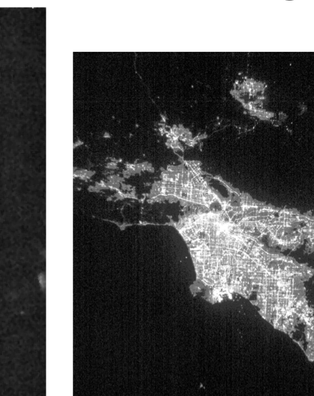
Suomi NPP VIIRS DNB Singapore detail

Portion of Full Pass: Singapore was on the edge of this S-NPP pass. Red box shows rough comparison of CubeSat FOV

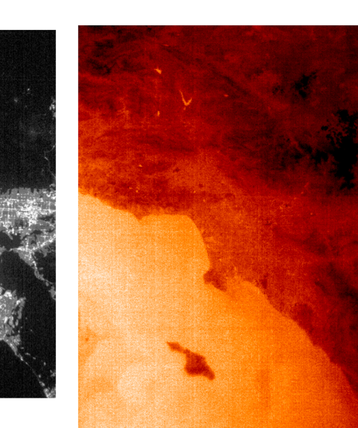
Characterizing Urban Geography and Light Pollution: The Los Angeles region is imaged on a mostly clear night in these SWIR, VIS and LWIR images from the CUMULOS sensors. The SWIR image highlights hotspots and concentrations of waste light in the .9-1.7 μm region. The VIS image clearly shows the major street grids in LA and is stretched to reveal dim urban interface and coastal lights present in Malibu, Palos Verdes and the Hollywood Hills. Baseline imaging at higher than VIIRS resolution of rapidly changing areas helps maps urban and infrastructure growth and change. A Color image from from the high res. camera AC-7C (NASA's OCSD) is inset. These data highlight the potential of CubeSat cameras in characterizing development and light pollution in urban regions with both pan. and color cameras and performing VIIRS-like missions at higher resolutions.

Los Angeles Region Urban Monitoring – CUMULOS 2018 Oct 12 05:08 UT – No Moon

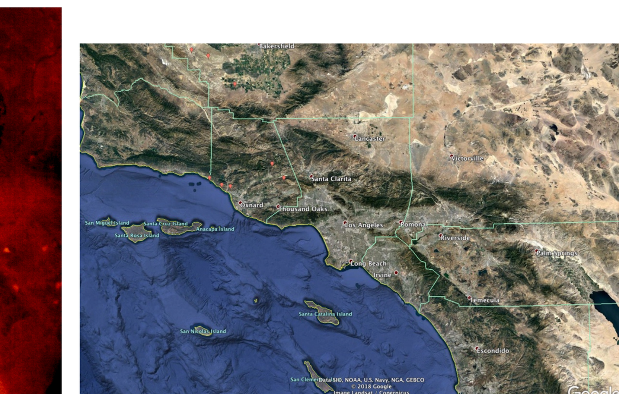
SWIR



VIS (stretched for dim lights)



LWIR



Map of LA Region

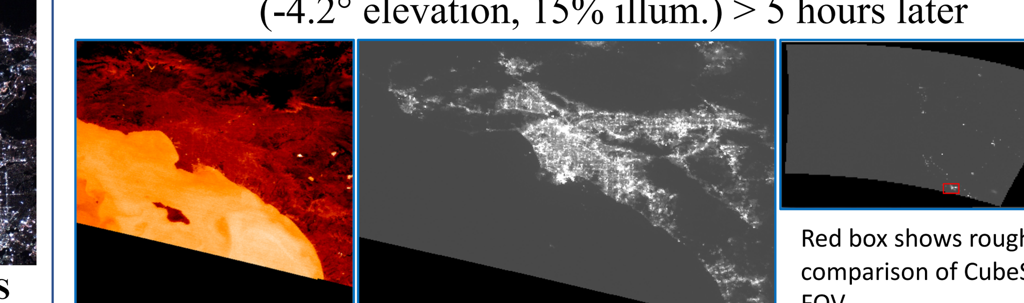
Los Angeles: Color Nighttime CubeSat Imagery

AeroCube 7C

Aerocube-7C, NASA's OCSD CubeSat, can be tasked when not engaged in its primary missions. Its 40-m color capability can assist with urban monitoring research and compliments the CUMULOS. The image shown is from 26 Sep at 03:47:28 UT and shows light fog obscuring the west side of Los Angeles and color from the city lights of LA. We are just beginning to task this sensor.

AeroCube 7-C VIS

VIIRS - Same Night Comparison
2018 Oct 12 10:11 UT- No Moon (-4.2° elevation, 15% illum.) > 5 hours later



VIIRS I-5 (10.5-12.4 μm)

VIIRS DNB

Red box shows rough comparison of CubeSat FOV

CONCLUSIONS: CUMULOS was built to investigate COTS camera operations in space, CubeSat calibration ConOps, and to study VIIRS-like environmental monitoring missions in a CubeSat form. The concept was to sacrifice swath width, while exceeding VIIRS resolution in the visible and closely matching it in the infrared SWIR and LWIR channels using the most sensitive COTS cameras readily available. Sensitivity is achieved through point-and-stare imaging. The CUMULOS camera suite is being used to research higher resolution urban and infrastructure monitoring, oil industry flare activity, fire and volcanic activity detection, boat light detection, and weather coverage augmentation using CubeSat platforms. CUMULOS and related satellites serve as pathfinders for future constellations of mission capable CubeSats. We have: 1) shown that mission capabilities can be achieved for bright nightlights target detection in quite small CubeSat form factors, 2) demonstrated SWIR airglow-illuminated nighttime cloud imaging from space, and high dynamic range detection of hot thermal sources such as fires and flares, and 3) shown that tiny COTS microbolometers deployed on CubeSats can provide useful cloud context imagery, are sufficient for qualitative cloud imaging purposes, and are also able to detect urban heat islands and bright fire thermal emissions. Detailed study and validation of our sensors calibration is in progress, using stars, the moon, ground targets and conjunction collections with VIIRS. This effort will give confidence in the design of future mission capable CubeSat sensors with COTS or custom-designed compact VIS, SWIR and LWIR camera systems. The capabilities of CUMULOS demonstrated to date match or exceed our expectations for a 1U sized multipurpose VIS, SWIR, LWIR imaging system.. We hope the CUMULOS prototype inspires others to fly small, capable CubeSat sensors to enhance monitoring of the human nightlights footprint, provide additional platforms to monitor thermal emission sources such as fires, and volcanic activity, and potentially to enhance weather monitoring via proliferated lower cost sensors.

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AEROSPACE

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