



Studying the Earth at Night from CubeSats

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Outline

- Introduction – CubeSats are beginning to study nighttime lights and related missions – 3 papers in last year's SMALLSAT
 - *New resources add to DMSP OLS, VIIRS DNB, ISS NightPod capabilities*
 - *Color, higher resolution, different orbits, different overpass times*
 - *Our past work demonstrated point-and-stare imaging and showed examples of several cities and regions at 130-100-m resolution*
- AeroCube camera details, AC-4, AC-8 MFOV, AC-5, AC-8 NFOV
- New Nighttime Observations from CubeSats
 - *Persian Gulf, Los Angeles – Detecting change in urban regions, lighting at urban/wildland interface*
 - *Texas Gulf Coast and Singapore - Lightning and weather observations*
 - *East China Sea, Sea of Japan - Ship lights from CubeSats*
 - *Rio de Janeiro - Imaging in the South Atlantic Anomaly*
- Conclusions and Future Work

Acronyms: AeroCube (AC), Medium Field of View (MFOV), Narrow Field of View (NFOV), Visible Infrared Imaging Radiometer Suite (VIIRS), Day-night-band (DNB), International Space Station (ISS), Defense Meteorological Support Program (DMSP), Operational Line Scanner (OLS)

New work with cameras on Aerospace Corporation 1.5U CubeSats to image the Earth at Night and add to VIIRS and ISS photography results



Introduction - Nighttime Lights - a Potential CubeSat Mission

- The use of nighttime light signals for monitoring the global human footprint has been established by DMSP OLS and VIIRS DNB work
 - *City lights, transportation grids, urban growth and change, light pollution, natural gas flaring, biomass burning*
 - *Work with ISS photography & CubeSats shows utility of higher resolution*
 - *Past work “The Nightsat Mission Concept” proposed mission requirements*
- We are using existing Aerospace Corporation CubeSats with small on-board CMOS cameras to research nightlights imaging
 - *Demonstrate capabilities of CMOS cameras on different AeroCubes*
 - *Determine if and how CubeSats complement the VIIRS DNB capability*
 - Different orbits can sample early evening hours
 - Different spectral bands – (such as RGB color)
 - Higher resolution over a smaller field of view. We demonstrate point-and-stare imaging and show examples at 100-130-m resolution

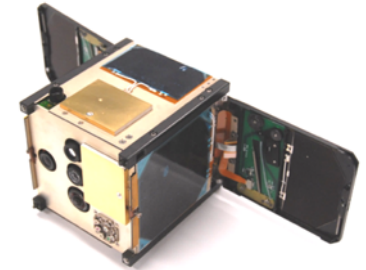
Measuring nighttime lights is a promising CubeSat mission. 3 papers last year on this topic (two with data). Existing CubeSat cameras approach Nightsat study requirements



AeroCube Camera Details: Specifications

AC-4 1U
AC-5 & 8 1.5U

| Satellite Camera | Lens F# | Lens FL (mm) | Pixel Pitch (μm) | Nominal Altitude (km) | GSD (m) |
|------------------|---------|--------------|-------------------------------|-----------------------|---------|
| AC-4, 8 (MFOV) | 2 | 3.40 | 2.80 | 600 | 494 |
| AC-5, 8 (NFOV) | 2 | 15.8 | 2.80 | 600 | 106 |



- 1600x1200 pixel 10-bit color RGB Bayer pattern CMOS arrays.
- Autoexposure was the only camera mode available for operations and images were downlinked using jpeg compression.
- The ON Semiconductor chips used are very compact, reasonably low-noise devices with decent low light sensitivity and have been reliably flown on many recent Aerospace Corporation CubeSats.

Cameras were not specially designed for nighttime measurements, but worked remarkably well. Other spacecraft details, including ACS, are documented in references.

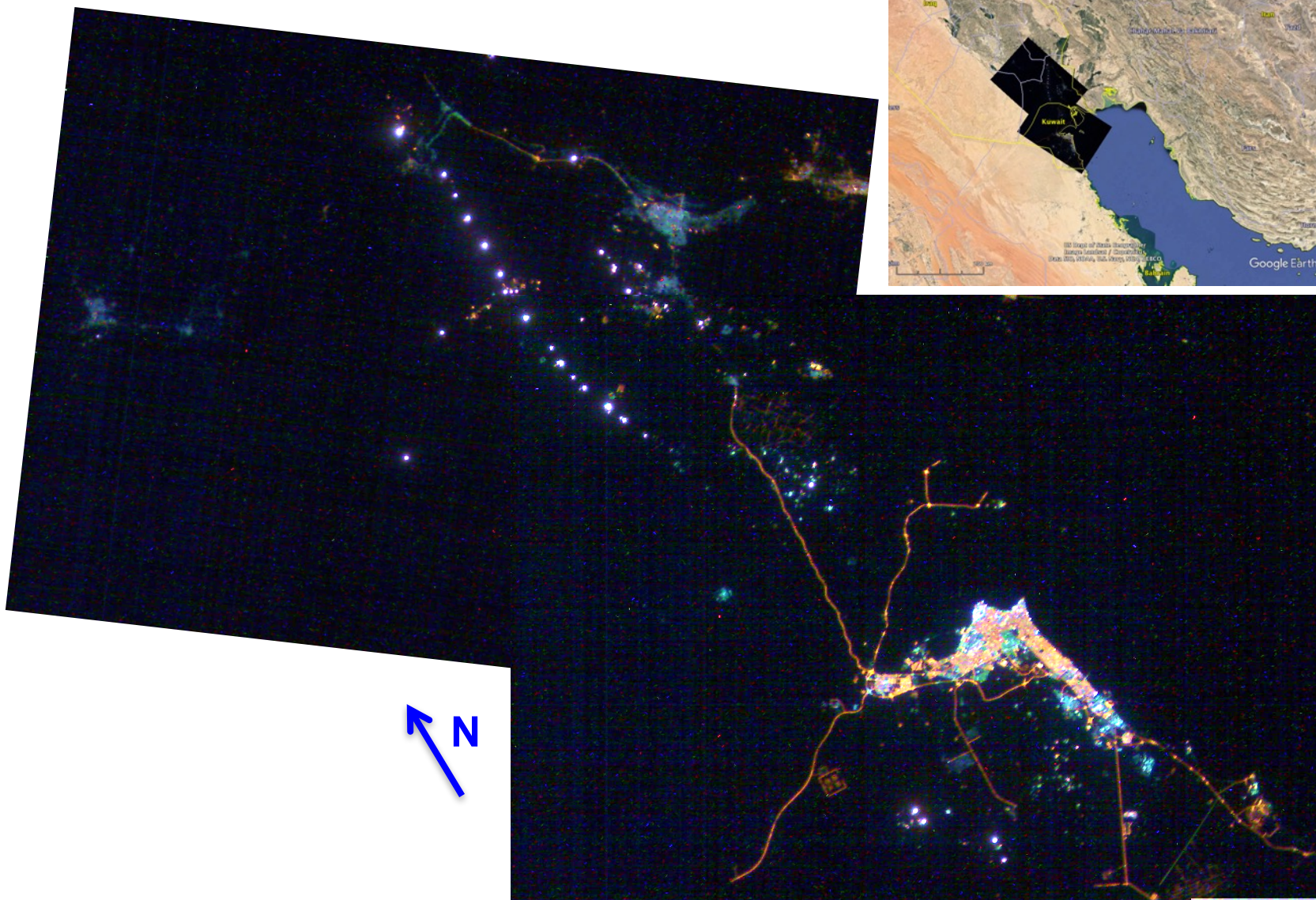


AeroCube Camera Details: Techniques for Nighttime Ops.

- “Point-and-stare” nighttime imaging from the AC-5 and AC-8 NFOV and MFOV cameras (talk last year demonstrated technique)
 - *Satellite is programmed to fly to a location, point and stay pointed while taking a number of camera frames, then after a delay, switch pointing to the next location and repeat. Must be done early in eclipse or use a rate gyro to maintain accurate Earth pointing*
 - *We show new examples using NFOV cameras to image the Persian Gulf, Los Angeles, and Brazil, and the Eastern Pacific Ocean using MFOV for wider area*
- Multi-pixel aggregation modes are used to image weather and lightning
 - *MFOV camera aggregated by 5x5 pixels to enable 7-8 minute collection of regional weather imagery. Examples shown from Texas and Singapore.*

Examples were chosen to highlight utility of higher resolution and color for change detection in urban regions, and to demonstrate staring observations of lightning and weather.

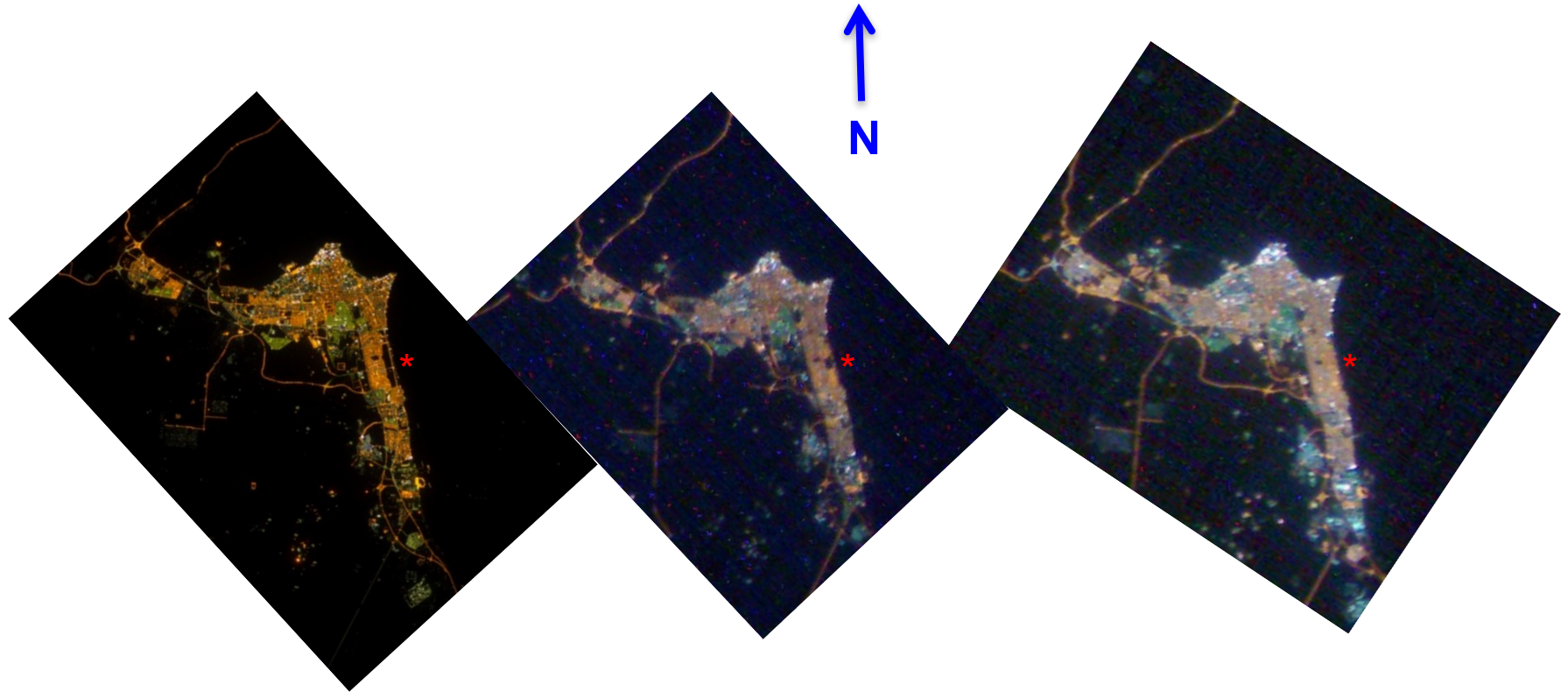
Two Frames: Rumaila Gas Flares and Kuwait City



*Two frames in a multi-point collection sequence 15 August 2016 22:26 UT
using AC-5 NFOV camera*



Kuwait City 2013 - 2016 : Comparison of ISS and AC-5



ISS Nightpod Nikon
with 180 mm Lens
~ 20 m GSD
12 Feb 2013

AeroCube-5
NFOV Camera
~ 130m GSD
11 May 2015

AeroCube-5
NFOV Camera
~ 130m GSD
15 Aug 2016

Development of coastal neighborhood evident in the sequence of ISS and AC-5 data. Other subtle changes also appear.

Kuwait City 2016 – 2017: Color Changes Noted



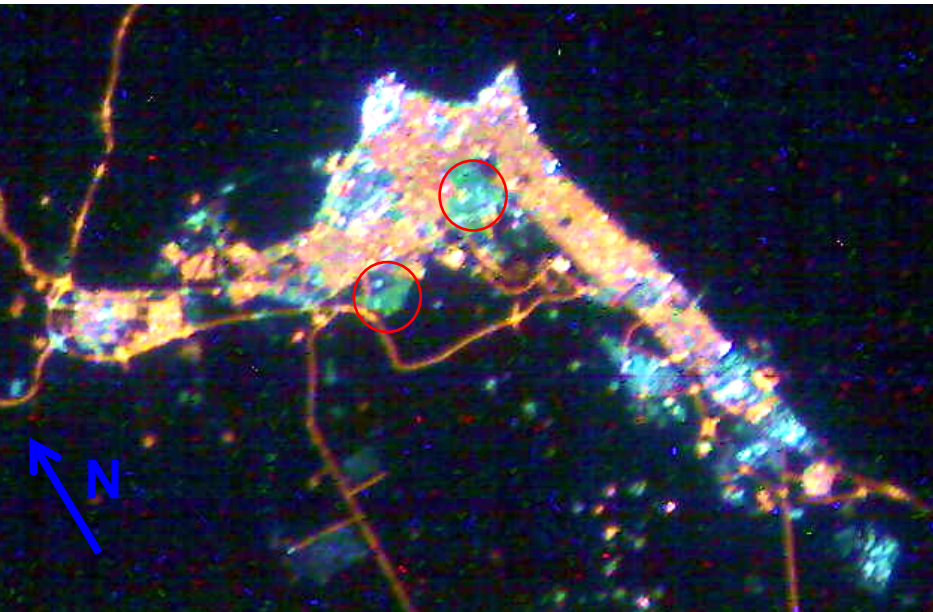
AeroCube-5 NFOV camera
~ 130m GSD 15 Aug 2016 red arrows mark
blue/green neighborhood lighting



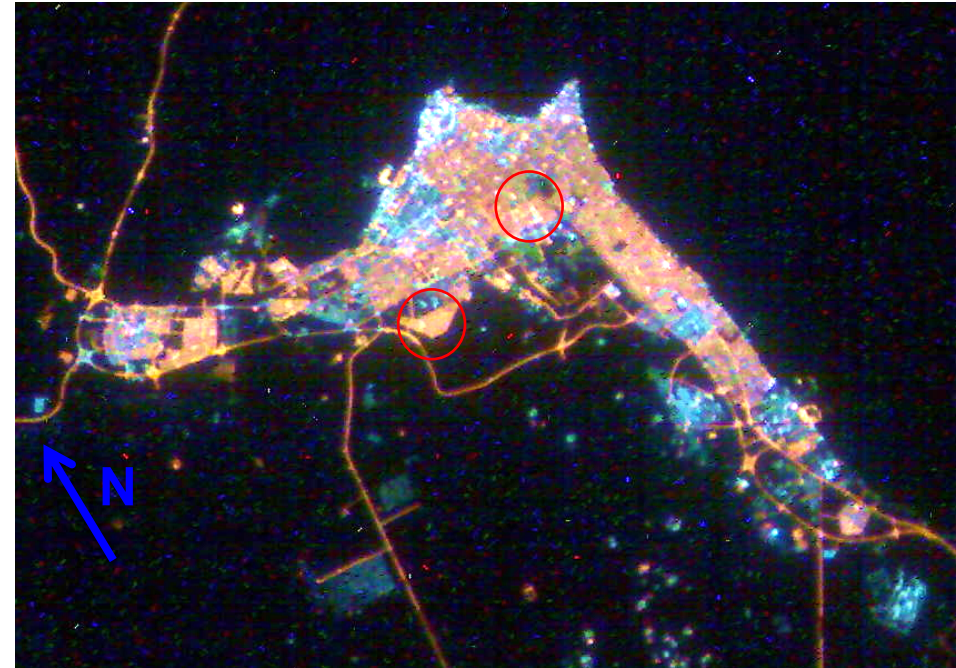
AeroCube-5 NFOV Camera (low altitude pass)
~ 90m GSD 18 May 2017 red arrows mark
blue/green to yellow change

A shift from blue/green (likely mercury vapor) to yellow (high pressure sodium) is noticeable in two regions. Elliptical orbit varies GSD and FOV.

Kuwait City 2016 – 2017: Color Changes- Detail



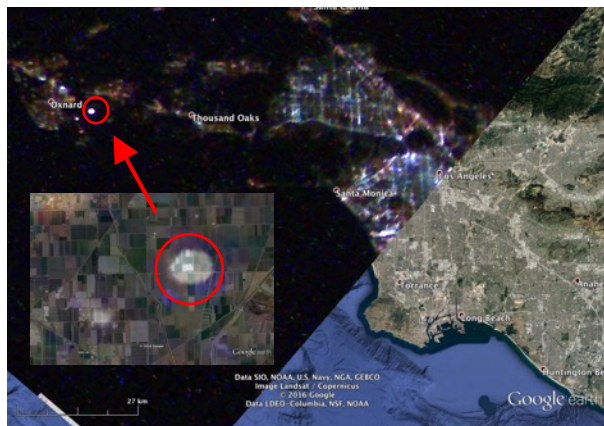
AeroCube-5 NFOV camera
~ 130m GSD 15 Aug 2016 red circles mark
blue/green neighborhood lighting



AeroCube-5 NFOV Camera (low altitude pass)
~ 90m GSD 18 May 2017 red circles mark
blue/green to yellow change

A shift from green (likely mercury vapor) to yellow (high pressure sodium) is noticeable in two regions. Elliptical orbit varies GSD and FOV.

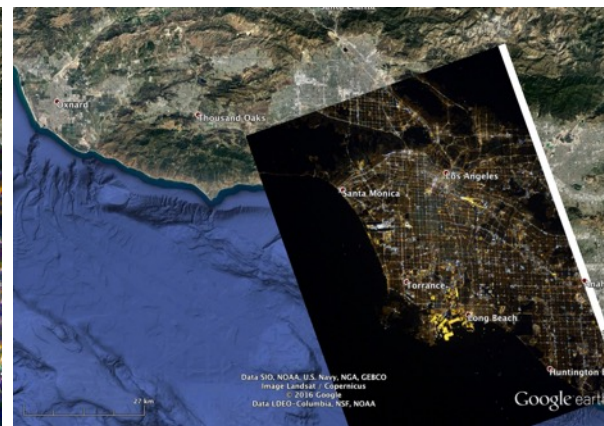
Los Angeles – Santa Monica Mountains Region



AC-5 19 Sept. 2015 – Exceedingly bright light source spotted near Oxnard. This turned out to be a seasonal greenhouse operation.



AC-5 22 August 2016 – Evolution from yellow sodium lights to blue-green LED lighting is one of many changes in LA lighting since 2010 ISS data



ISS photography 30 November 2010



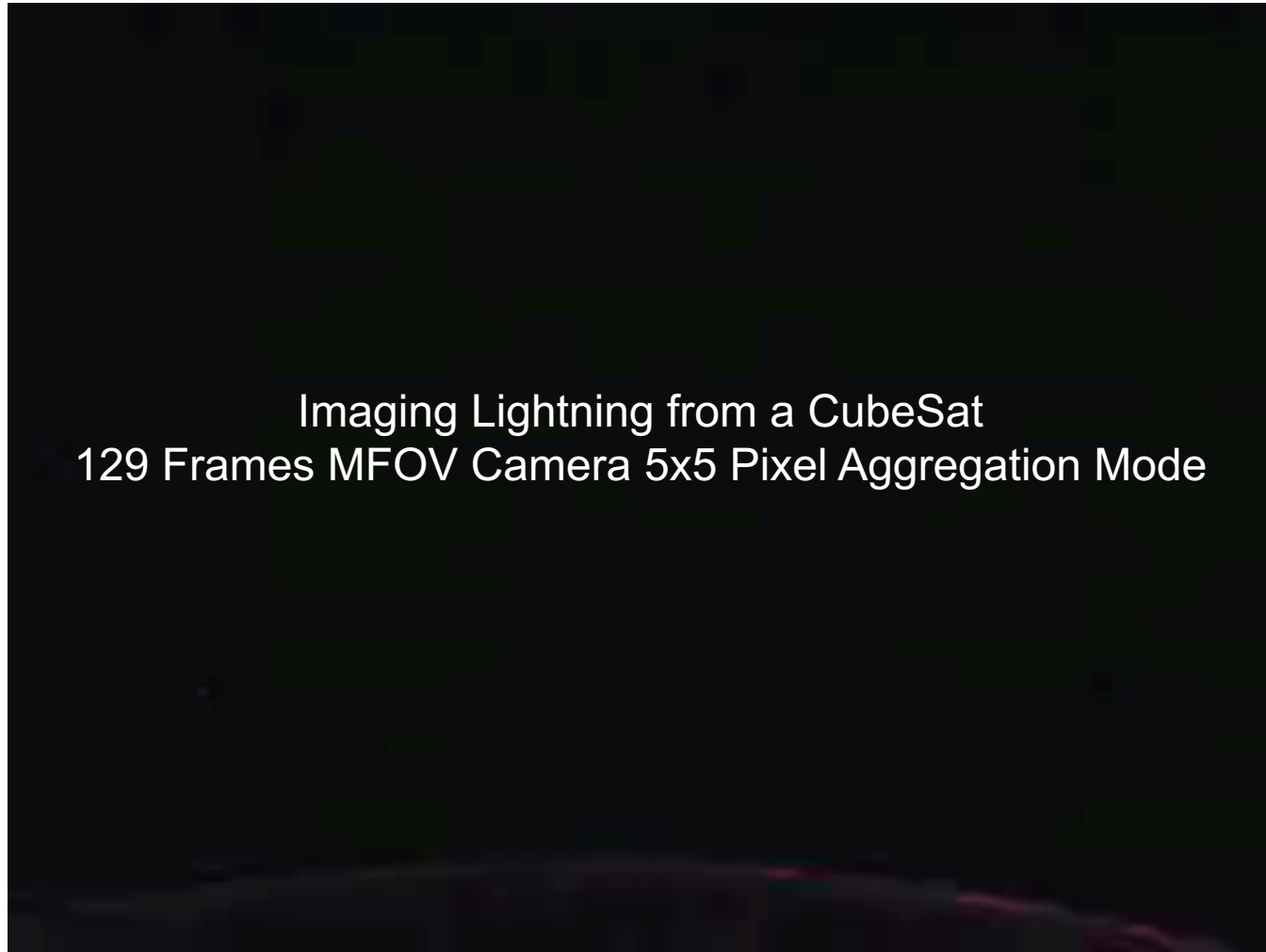
Southern California Region w/ overlays

Easily tasked CubeSat data provide more regional coverage than ISS, but at lower resolution - add color and improved resolution compared to VIIRS



Texas Flyby – Severe Weather Near Houston

Imaging Lightning from a CubeSat
129 Frames MFOV Camera 5x5 Pixel Aggregation Mode

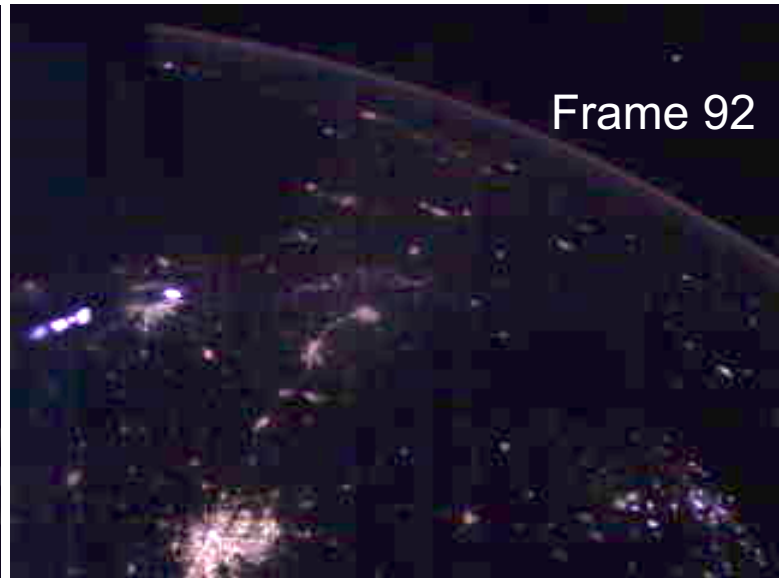
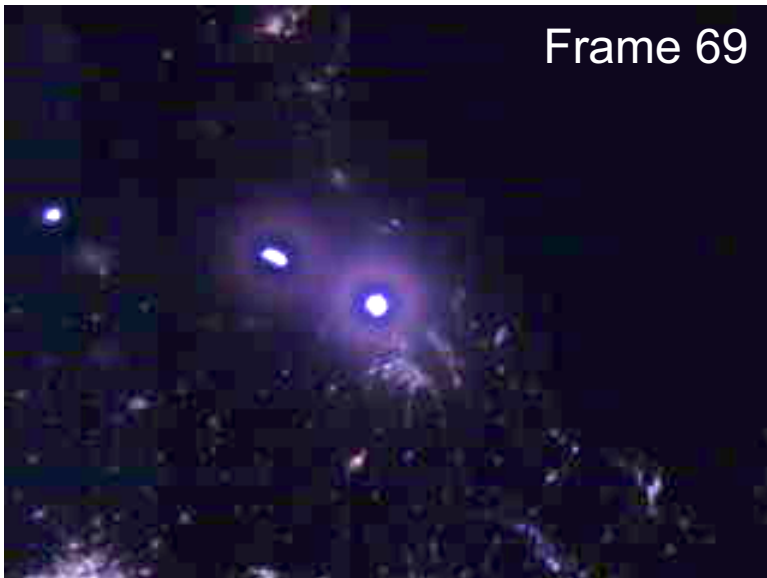
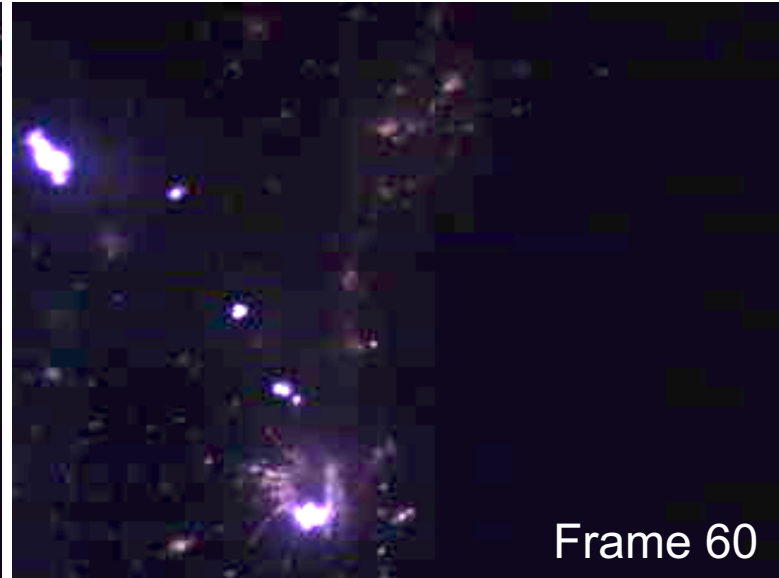
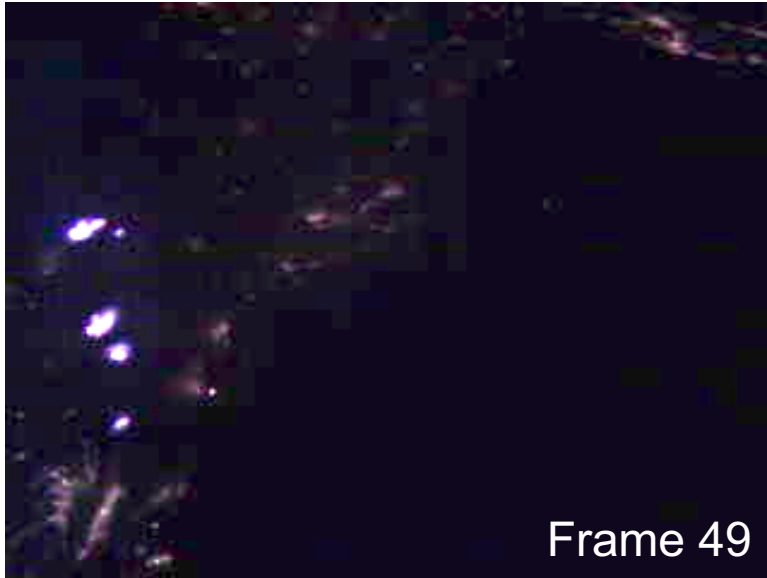


Click movie

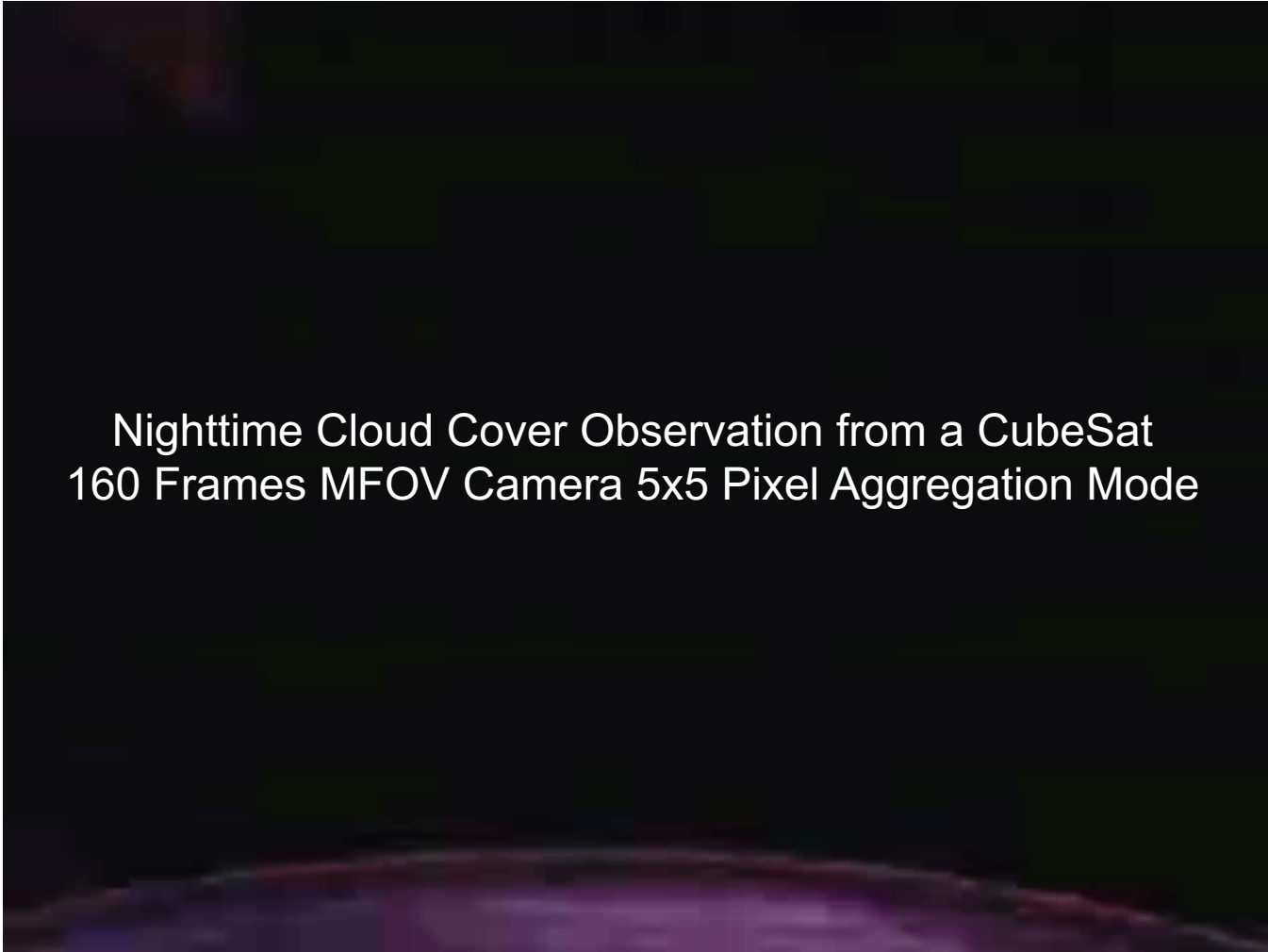
AC8C 27 March 2017 16:29:41UT Frame 1-129 New Moon



AC8-C 27 March 2017 16:29:41 UT. Four frames from a 129-frame sequence that images lightning activity from thunderstorms running northeast from Houston, TX



Singapore Flyby – Imaging Clouds and Lightning Over the Strait



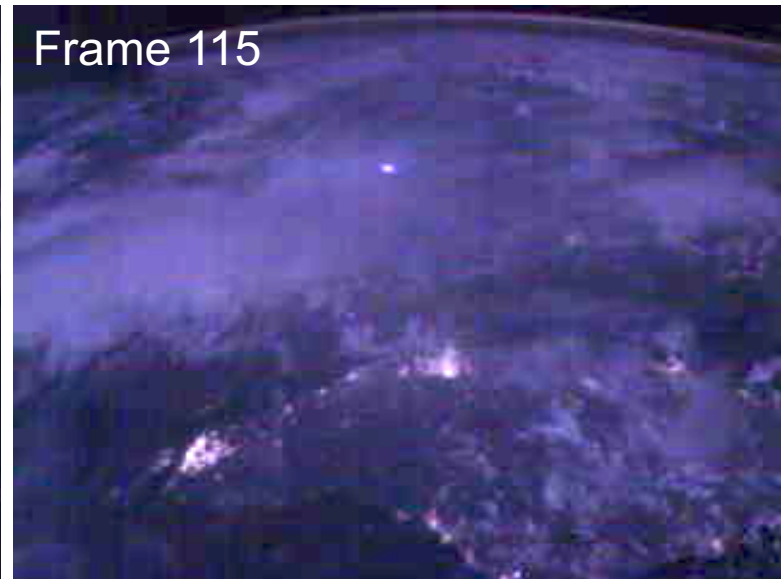
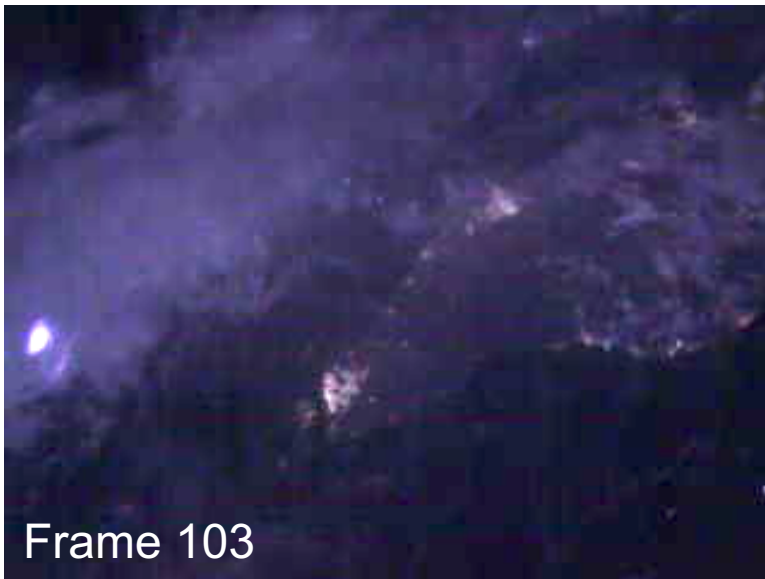
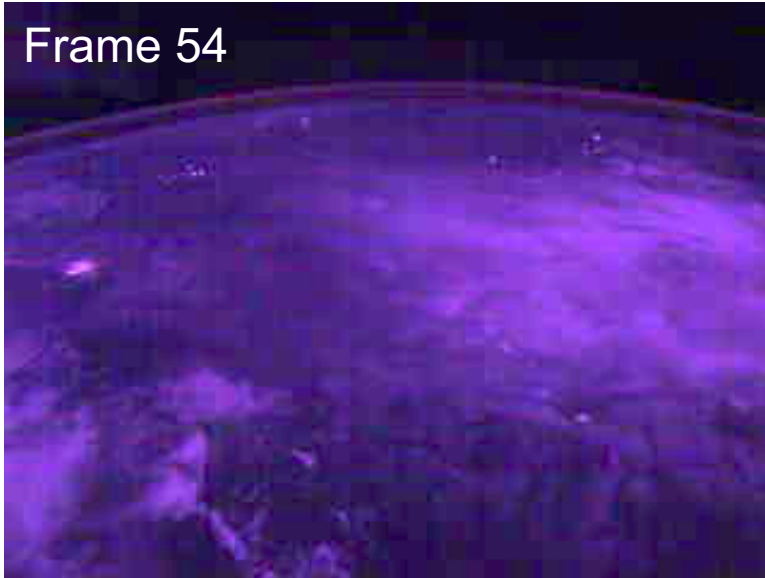
Nighttime Cloud Cover Observation from a CubeSat
160 Frames MFOV Camera 5x5 Pixel Aggregation Mode

Click movie

AC8C 12 April 2017 16:06:44UT Frame 1-160 Full Moon

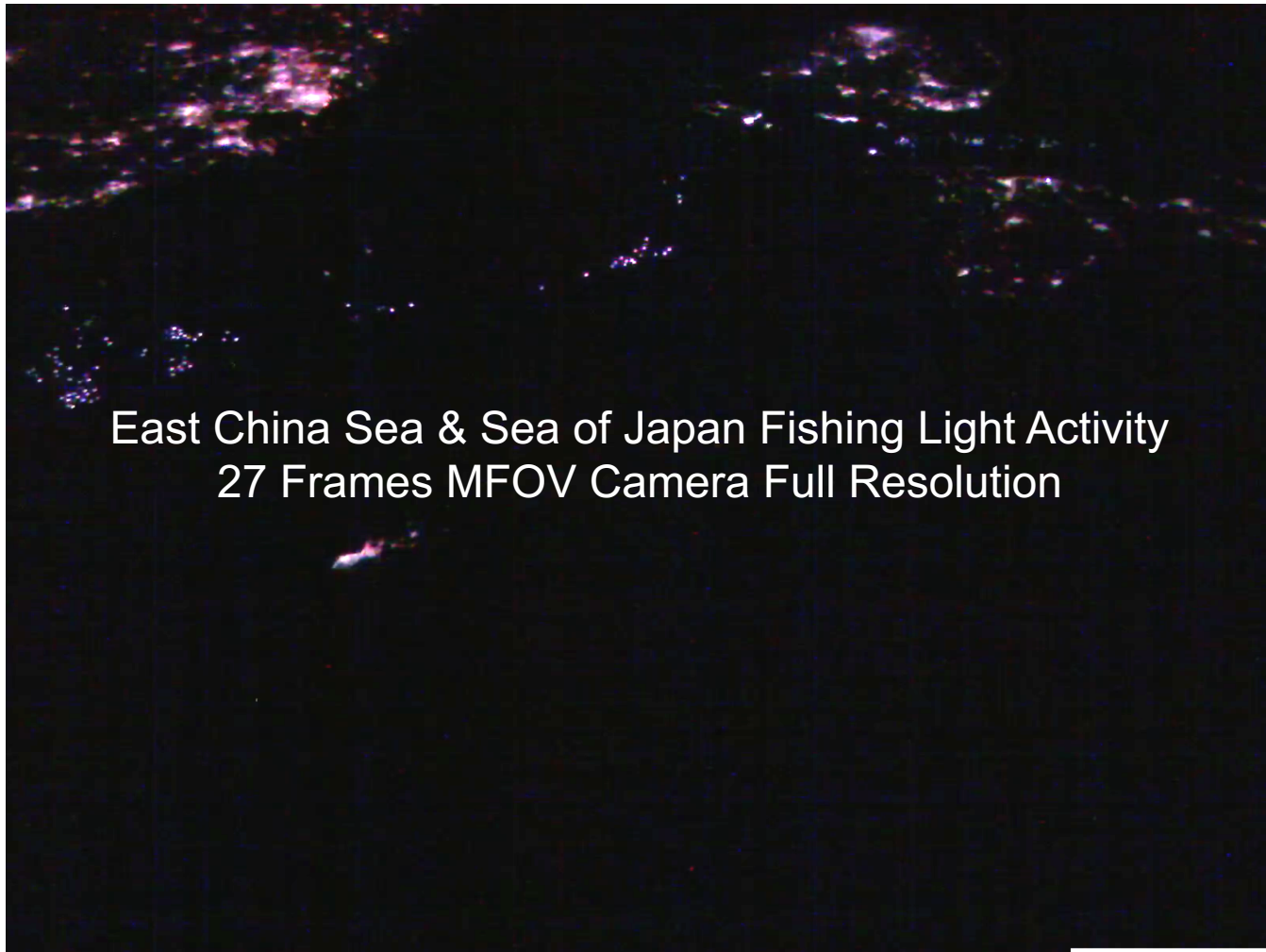


AC8-C 12 April 2017 16:06:44 UT. Four frames from a 160-frame sequence imaging the Indonesian archipelago, Singapore, the Strait of Malacca and the Malay peninsula.





Korea Flyby – Maritime Domain Awareness from a CubeSat

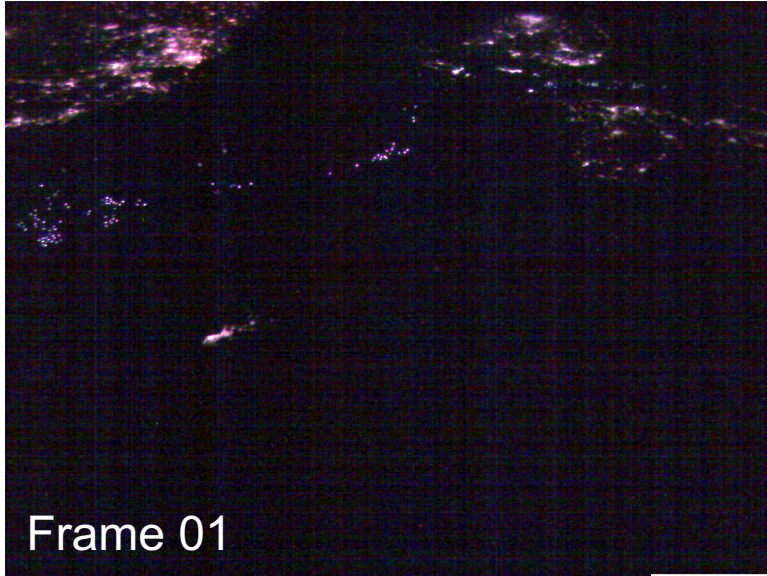


Click movie

AC-8D 29 April 2017 13:36:01 UT. 27-frame sequence covering the East China Sea traveling north over the Korean peninsula. 14% Moon had set



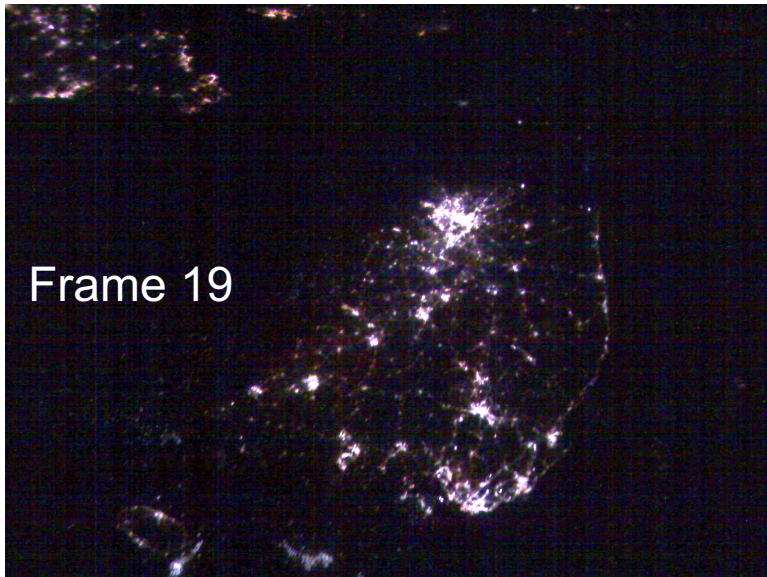
AC-8D MFOV camera full-resolution 29 April 2017 13:36:01 UT. Four frames from 27-frame sequence covering the East China Sea traveling north over the Korean peninsula



Frame 01



Frame 11



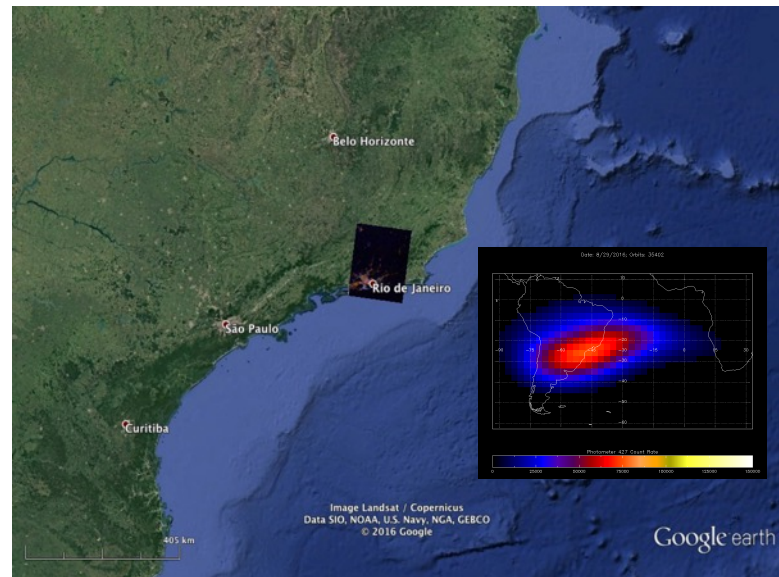
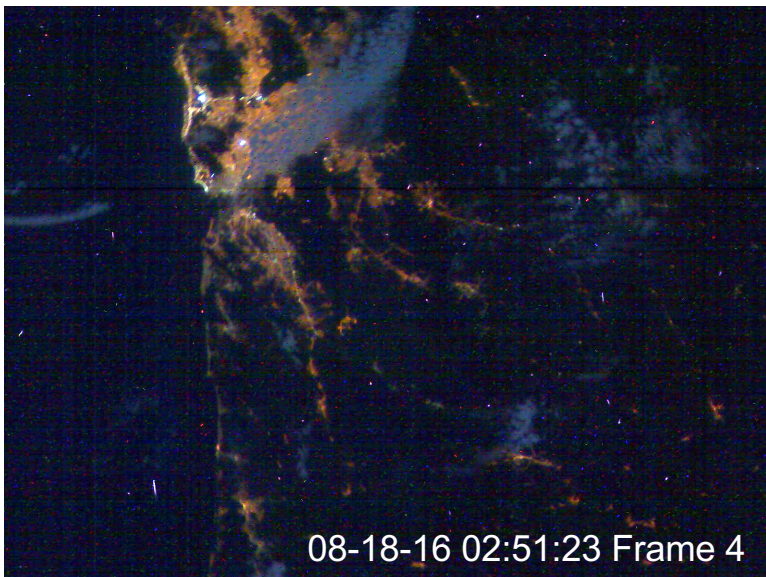
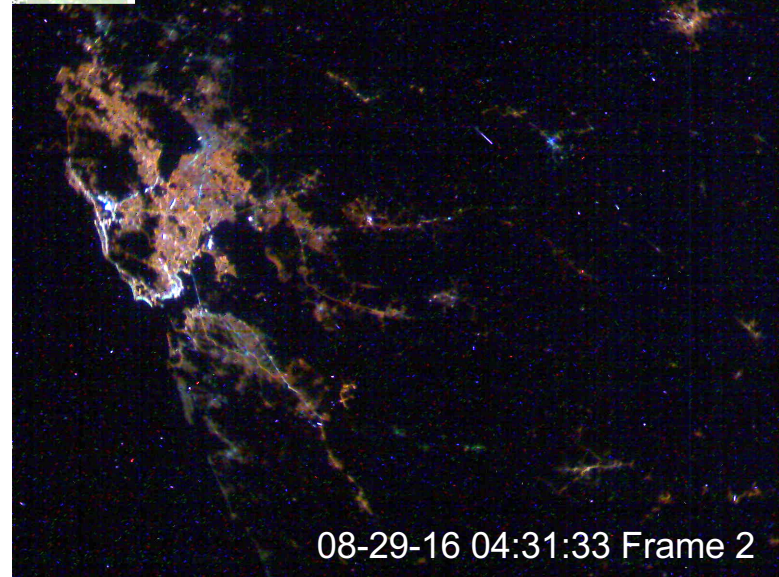
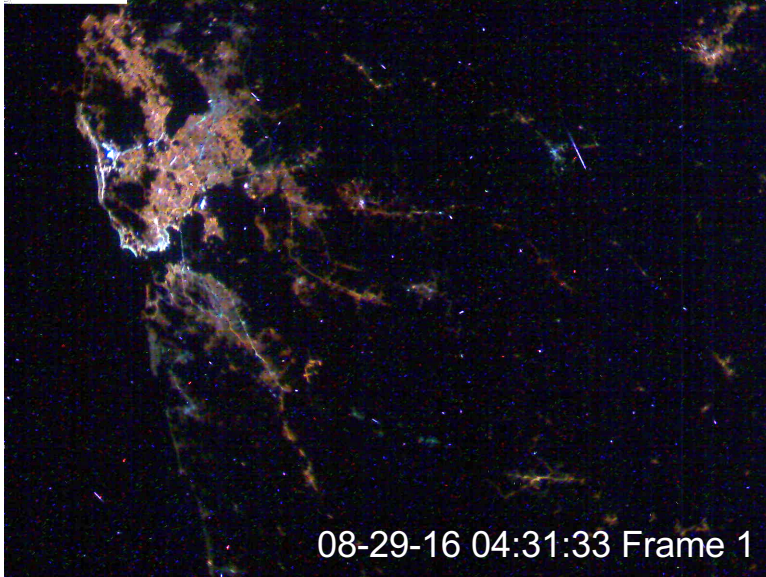
Frame 19



Frame 25



Imaging Rio in the South Atlantic Anomaly





Future Sensors (near term)

| Satellite Camera | Lens F# | Lens FL (mm) | Pixel Pitch (μm) | Nominal Altitude (km) | GSD (m) |
|------------------|---------|--------------|-------------------------------|-----------------------|---------|
| AC-7 (high res) | 1.9 | 34.9 | 1.67 | 500 | 24 |
| CUMULOS VIS | 1.4 | 17.6 | 5.20 | 500 | 148 |
| CUMULOS SWIR | 1.4 | 25.0 | 25 | 500 | 500 |
| CUMULOS LWIR | 1.1 | 25.0 | 17 | 500 | 340 |

- New camera payloads will add to our ability to research the Earth at night from CubeSat platforms.
- 2 NASA Optical Communication and Sensor Demonstration CubeSats (aka AC-7)
- CUMULOS (the CUBesat MULTispectral Observation System) which is hosted on the NASA ISARA (Integrated Solar Array and Reflectarray Antenna) CubeSat
- These were originally scheduled to launch on a Falcon-9 v1.1 rocket along with Formosat-5 and a number of other CubeSat payloads.
- The AC-7 satellites and ISARA are now scheduled to launch 11 October, 2017. After 6 weeks at the ISS they will be boosted to a 500 km orbit and deployed.

Coming next – a higher resolution color camera on AC-7 B,C and CUMULOS, a 3-camera VIS/SWIR/LWIR sensor



References

- Elvidge, C. D., Ziskin, D., Baugh, K. E., Tuttle, B. T., Ghosh, T., Pack, D. W., Erwin, E. H., Zhizhin, M., "A Fifteen Year Record of Global Natural Gas Flaring Derived from Satellite Data", *Energies*, vol. 2, no. 3, 2009.
- Elvidge, C.D, Zhizhin, M., Baugh, K., Hsu, F.-C., Ghosh, T., "Methods for Global Survey of Natural Gas Flaring from Visible Infrared Imaging Radiometer Suite Data", *Energies*, vol. 9, January 2016.
- Miller, S.D, Mill, S.P., Elvidge, C.D., Lindsey, D. T., Lee, T.F., Hawkins, J.D., "Suomi Satellite Brings to Light a Unique Frontier of Nighttime Environmental Sensing Capabilities", *Proceedings of the National Academy of Sciences*, vol. 109, no. 39, September, 2012.
- Miller, S.D., Straka III, W., Mills, S., Elvidge, C., Lee, T., Solbrig, J., Walther, A., Heidinger, A., Weiss, S., "Illuminating the Capabilities of the Suomi National Polar-Orbiting Partnership (NPP) Visible Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band", *Remote Sensing*, vol. 5, 2013.
- Elvidge, C.D.; Hsu, F.-C.; Baugh, K.; Ghosh, T., "Why VIIRS data are superior to DMSP for mapping nighttime lights", *Proceedings of the Asia-Pacific Advanced Network v. 35*, 2013.
- Elvidge, Christopher D., Mikhail Zhizhin, Feng-Chi Hsu, and Kimberly E. Baugh. "VIIRS nightfire: Satellite pyrometry at night." *Remote Sensing* 5, no. 9 (2013): 4423-4449.
- Elvidge, C.D.; Hsu, F.-C.; Baugh, K.; Ghosh, T., "National Trends in Satellite Observed Lighting: 1992–2012", In *Global Urban Monitoring and Assessment through Earth Observation*; Weng, Q., Ed.; CRC Press: Boca Raton, FL, USA, pp. 97–120, 2014.
- Kyba, C.C.M., Garz, S. Kuechly, H., De Miguel, S.A., Zamorano, J., Fischer, J., Hölker, F., "High-Resolution Imagery of Earth at Night: New Sources, Opportunities and Challenges", *Remote Sensing*, vol. 7, 1-23, January 2015.
- De Miguel, S.A.; Castaño, J.G.; Zamorano, J.; Kyba, C.C.M.; Pascual, S.; Ángeles, M.; Cayuela, L.; Martin Martinez, G.; Caltner, P., "Atlas of astronaut photos of Earth at night" *Astronomy and Geophysics*, vol. 55, no. 4 August 2014. This helpful Atlas to nighttime ISS photography is described by Kyba et. al. in reference 11 and online at: <http://www.citiesatnight.org>, and <http://www.nightcitiesiss.org/>
- Pack, D.W., Hardy, B.S. "CubeSat Nighttime Lights" *Proceedings of the AIAA/USU Conference on Small Satellites*, CubeSat Session IV: LEO Missions, SSC16-WK-44. 2016. <http://digitalcommons.usu.edu/smallsat/2016/S4LEOMis/1/>
- Elvidge, C.D, Cinzano, P., Pettit, D.R., Arvesen, J., Sutton, P., Small, C., Nemani, R., Longcore, T., Rich, C., Safran, J., Weeks, J, Ebener, S. "The Nightsat Mission Concept", *International Journal of Remote Sensing*, vol. 28, No. 12, May 2007.
- Rowen, D and Dolphus, R. 3-axis attitude determination and control of the AeroCube-4 cubesats. In *AIAA/USU Conference on Small Satellites*, 10th Annual CubeSat Developers' Workshop, 2013.
- Gangestad, J.W., Rowen, D.W. and Hardy, B.S., "Forest Fires, Sun glint, and a Solar Eclipse: Responsive Remote Sensing with AeroCube-4", *Geoscience and Remote Sensing Symposium (IGARSS)*, IEEE, Quebec City, Canada, July 2014.
- Gangestad, J.W., Rowen, D.W. and Hardy, B.S., "Along for the Ride: Experience with Flexible Mission Design for CubeSats", *Proceedings of the AIAA/AAS Astrodynamics Specialist Conference, SPACE Conferences and Exposition*, San Diego, CA, August, 2014.
- Gangestad, J.W., Rowen, D.W., Hardy, B.S. and Hinkley, D.A., "Flying in a Cloud of CubeSats: Lessons Learned from AeroCube-4, -5 and -6", *Proceedings of the 65 International Astronautical Congress*, Toronto, Canada, September, 2014.



References (continued)

- All photographs taken from the International Space Station and their meta data are available at “The Gateway to Astronaut Photography of Earth”, which is run by NASA: <http://eol.jsc.nasa.gov>.
- (Longcore et al., unpublished analysis of VIIRS data).
- Aubé, M., J. Roby, and M. Kocifaj. 2013. Evaluating potential spectral impacts of various artificial lights on melatonin suppression, photosynthesis, and star visibility. *PLoS ONE* 8:e67798.
- Falchi, F., P. Cinzano, D. Duriscoe, C. C. Kyba, C. D. Elvidge, K. Baugh, B. A. Portnov, N. A. Rybnikova, and R. Furgoni. The new world atlas of artificial night sky brightness. *Science Advances* 2:e1600377. 2016.
- Baugh, K.; Hsu, F.-C.; Elvidge, C.D.; Zhizhin, M. Nighttime lights compositing using the VIIRS day-night band: Preliminary results. *Proc. Asia Pac. Adv. Netw* **2013**, 35, 70–86.
- Elvidge, C.D.; Zhizhin, M.; Baugh, K.; Hsu, F.-C. Automatic Boat Identification System for VIIRS Low Light Imaging Data. *Remote Sens.* **2015**, 7, 3020-3036.
- Vernov, S.N.; Gorchakov, E.V.; Shavrin, P.I.; Sharvina, K.N. Radiation Belts in the Region of the South-Atlantic Magnetic Anomaly. *Space Sci. Rev.* 1967, 7, 490–533.
- Joint Polar Satellite System Visible Infrared Imaging Radiometer Suite Sensor Data Records Algorithm Theoretical Basis Document (ATBD) See: S-NPP/JPSS Science Documents. <http://www.star.nesdis.noaa.gov/jpss/Docs.php>, https://ncc.nesdis.noaa.gov/documents/documentation/ATBD-VIIRS-RadiometricCal_20131212.pdf
- Janson, S.W., Welle, R., Rose, T., Rowen, D., Hinkley, D., Hardy, B. La Lumondiere, S., Maul, G., Werner, N. “The NASA Optical Communication and Sensors Demonstration Program: Preflight Update”, Proceedings of the 29th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, USA, August, 2015.
- Ardila, D., Pack, D.W., "The Cubesat Multispectral Observation System (CUMULOS)." *Conference on Characterization and Radiometric Calibration for Remote Sensing*, (2016). <http://digitalcommons.usu.edu/calcon/CALCON2016/all2016content/27/>
- Pack, D.W., et. al. “The Aerospace Corporation CubeSat Remote Sensing Imagers” *Proceedings of the AIAA/USU Conference on Small Satellites*, 2017.
- Manzoni, G., Brama, Y.L., Zhang, M. 2016. “Athenoxat-1, Night Vision Experiments in LEO” *Proceedings of the AIAA/USU Conference on Small Satellites*, CubeSat Session IV: LEO Missions, SSC-16-WK-07. <http://digitalcommons.usu.edu/smallsat/2016/S4LEOMis/6/> .
- Walczak, K. 2016. “NITESat: A People-Powered Science Mission” Proceedings of the AIAA/USU Conference on Small Satellites, Poster Session III. <http://digitalcommons.usu.edu/smallsat/2016/Poster3/8/>
- Sakamoto, Yuji, Yukihiro Takahashi, Kazuya Yoshida, K. Fukuda, T. Nakano, S. Batazzo, T. Fukuhara, and J. Kurihara. "Development of the microsatellite RISING-2 by Tohoku University and Hokkaido University." In Proceedings of the 61st International Aeronautical Congress, No. IAC-10-B4, vol. 2. 2010.
- T. Kuwahara, K. Yoshida, Y. Sakamoto, Y. Tomioka, K. Fukuda, M. Fukuyama, Y. Shibuya "International Scientific Micro-satellite RISESat based on Space Plug and Play Avionics," in 26th Annual AIAA/USU Conference on Small Satellites, Logan, 2012.



Acknowledgments

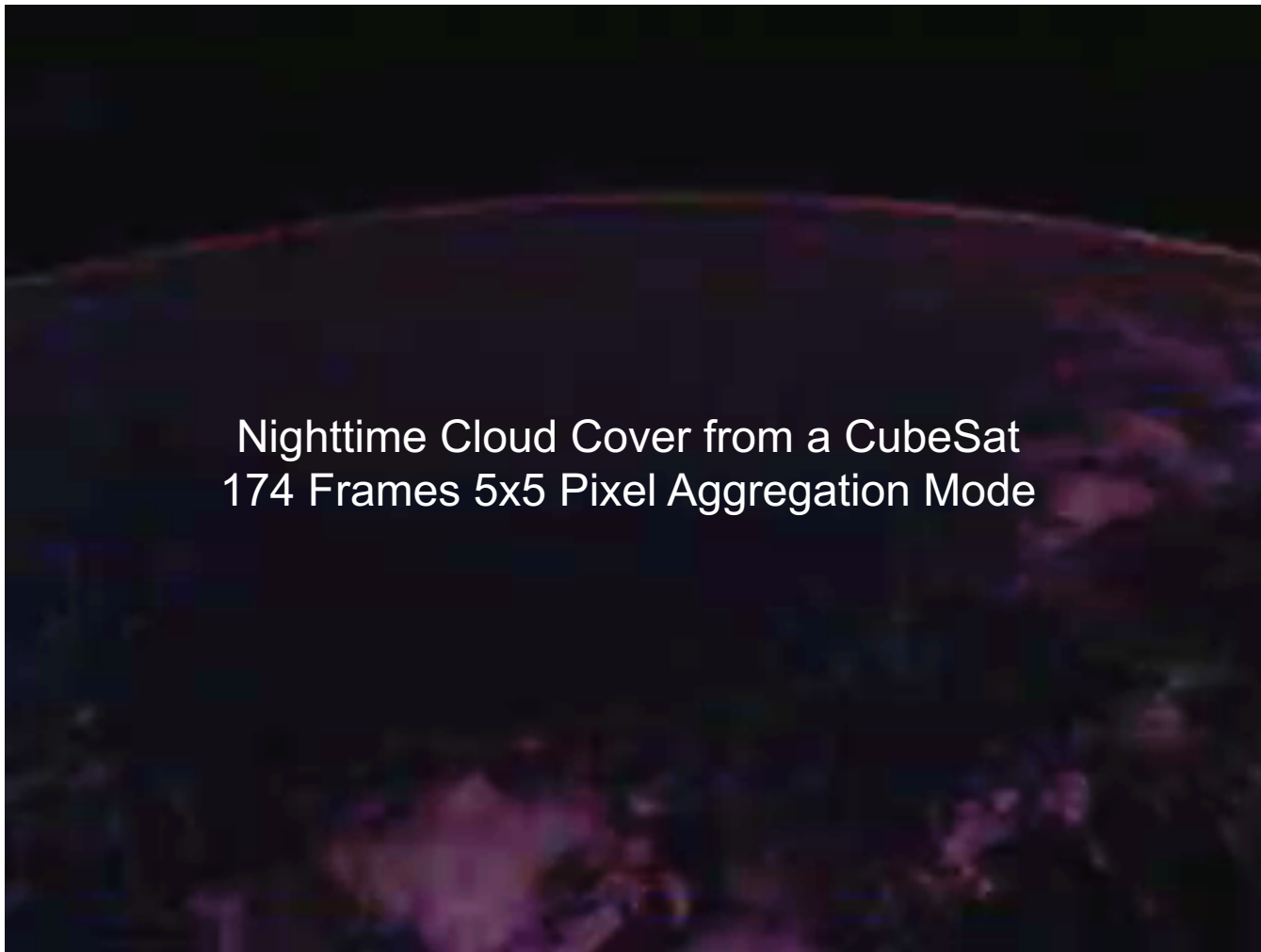
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Extra Slides





Persian Gulf Flyby – Lights, Clouds, Lightning, Flares



Click movie

AC8C 7 May 2017 04:39:57 UT Frame 1-174



Pearl River Delta Flyby – Lightning Over the South China Sea

Demonstration of LEO Lightning Flash Rate Measurement
142 Frames 5x5 Pixel Aggregation Mode



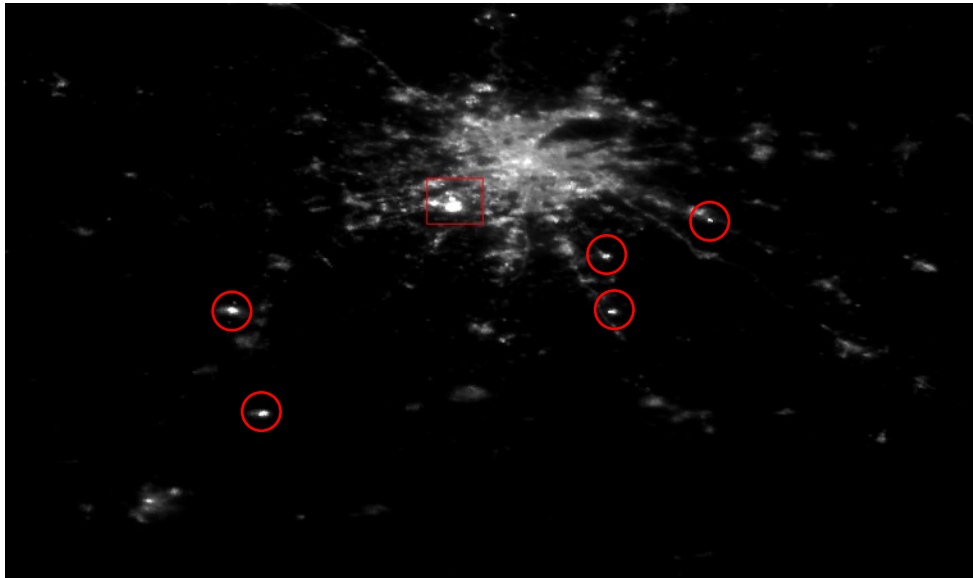
Click movie

AC8C 21 April 2017 18:19:17 UT Frames 1-142

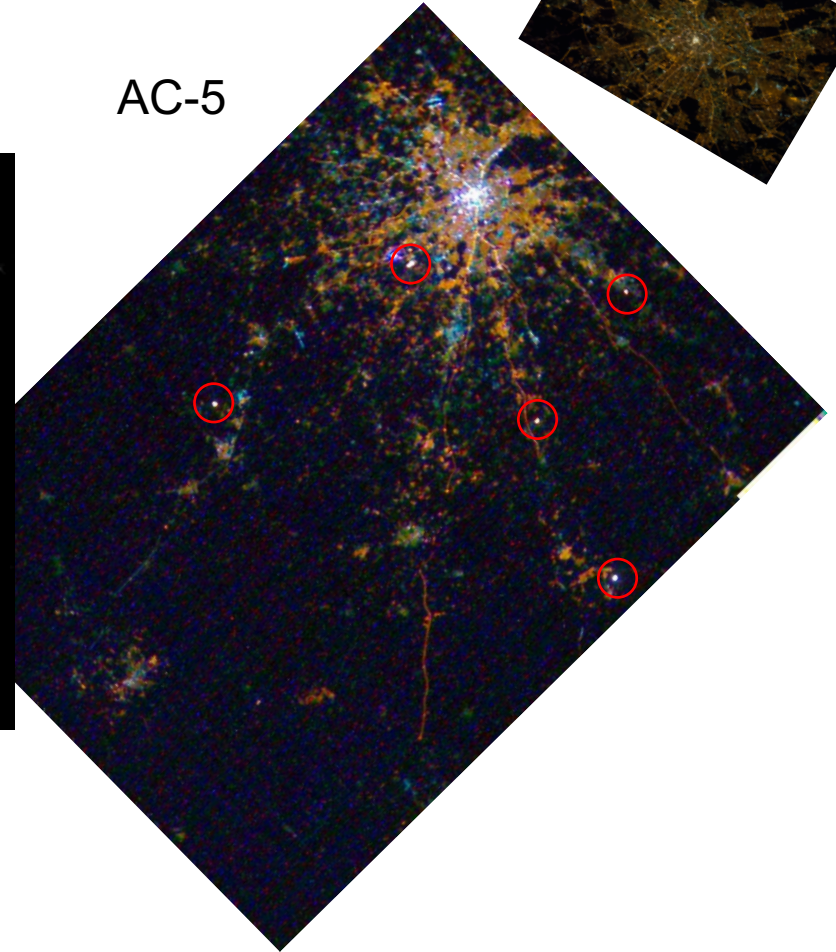
Moscow



VIIRS



AC-5



ISS



Greenhouse Complex is brightest source