The CubeSat Multispectral Observation System (CUMULOS)

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With advice and support from Richard Rudy, Ray Russell, Mike Owens, and Darren Rowen

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CUMULOS: 3 COTS cameras in a CubeSat

- **Visible camera** – 0.4 - 1.0 µm; φ=1.3 cm
- **SWIR camera** – 0.9 - 1.7 µm; φ=1.8 cm
- **LWIR camera** – 7.5 - 15.5 µm; φ=2.3 cm

• Primary Requirement:
  – To develop **optimal methods for the operation** of passively cooled COTS sensors and cameras and determine their **suitability to perform weather/environmental monitoring** missions

• No requirements on calibration accuracy or precision

• Orbit:
  • 450 x 720 km
  • 98° inclination
  • 10:30 local time descending node.
  • 20 day revisit
Activities: 3-mo. nominal mission, possible 3-mo. extension.

- Perform vicarious calibration of COTS payload. Compare performance to other Earth-observation assets.
- Study camera degradation as a function of time
- Observe human activity day and night: Urban heat islands and lights, land cover, river channels, ports, industrial operations, flares, fires. Characterize airglow illumination patterns

Data taking mode: Track-and-shoot
Actual FOV Alignment

Picosat lab test image 5/8/16
Primary Payload: The Integrated Solar Array and Reflectarray Antenna (ISARA)

- Goal: To demonstrate downlink data rates for CubeSats to >100 Mbps.
- NASA’s ISARA will transmit a Ka tone to ground station. Experiment consists on measuring antenna pattern.
- 3 Month-long mission – Launch 11/16
- NASA payload, Aerospace bus
- CUMULOS and ISARA
  - CUMULOS will be turned off while ISARA operates
  - CUMULOS does not impose any requirement on ISARA’s mission
  - Extensive tests to ensure “do no harm” to ISARA

http://www.nasa.gov/directorates/spacetech/small_spacecraft/isara_project.html
CUMULOS performance

Visible
0.60 μm
(AΩ=14 μm² sr)

<table>
<thead>
<tr>
<th>10^{-5}</th>
<th>10^{-4}</th>
<th>10^{-3}</th>
<th>10^{-2}</th>
<th>10^{-1}</th>
<th>10^0</th>
<th>10^1</th>
<th>10^2</th>
<th>10^3 W/m²/sr/um</th>
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</thead>
<tbody>
<tr>
<td>800 ms</td>
<td>0.11 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/N=10</td>
<td>S/N=160</td>
<td></td>
<td></td>
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SWIR
1.3 μm
(AΩ=319 μm² sr)

<table>
<thead>
<tr>
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<th>10^{-4}</th>
<th>10^{-3}</th>
<th>10^{-2}</th>
<th>10^{-1}</th>
<th>10^0</th>
<th>10^1</th>
<th>10^2</th>
<th>10^3 W/m²/sr/um</th>
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</thead>
<tbody>
<tr>
<td>32 ms</td>
<td>0.18 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S/N=10</td>
<td>S/N=430</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

LWIR
11 μm
(AΩ=239 μm² sr)

Antarctica | Cloud | Ice | Ocean | Cold Fire | Gas flare | No Atmos
---|---|---|---|---|---|---
-60 | -40 | 0 | 20 | 40 | 450 | 1600 (C)
±14 C | ±4 C | ±3 C | ±1 C | S/N=87 |
S/N=3 | S/N=13 | S/N=30 | S/N=500 | (5 m² source) |
(Saturation limit)
What did we do?

Will the cameras function in space?
What are the instrumental characteristics?
What level of radiometric precision/accuracy can we expect?

<table>
<thead>
<tr>
<th>Priority</th>
<th>Task</th>
<th>Vis</th>
<th>SWIR</th>
<th>LWIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Learn to use cameras</td>
<td>1/28/16</td>
<td>1/28/16</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>Focus the cameras</td>
<td>2/8/16</td>
<td>1/28/16</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>MTF changes with TVC</td>
<td>N/A</td>
<td>11/10/15</td>
<td>8/26/15</td>
</tr>
<tr>
<td>1</td>
<td>Measure gain</td>
<td>2/12/16</td>
<td>11/16/15</td>
<td>10/15/15</td>
</tr>
<tr>
<td>1</td>
<td>Obtain Flats</td>
<td>2/12/16</td>
<td>10/22/15, 10/27/15</td>
<td>10/15/15</td>
</tr>
<tr>
<td>1</td>
<td>Measure Dark Current</td>
<td>2/10/16, 2/11/16</td>
<td>10/5/15, 11/2/15</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Measure Read Noise</td>
<td>2/10/16</td>
<td>10/5/15</td>
<td>10/15/15</td>
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<tr>
<td>2</td>
<td>Obtain Radiom. coeffs</td>
<td>2/12/16</td>
<td>11/2/15</td>
<td>12/9/15</td>
</tr>
<tr>
<td>2</td>
<td>Derive Bad pixel mask</td>
<td>2/10/16</td>
<td>10/22/15, 10/27/15</td>
<td>8/6/15</td>
</tr>
<tr>
<td>2</td>
<td>Determine command rate</td>
<td>8/15/16</td>
<td>TBD</td>
<td>8/15/16</td>
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<tr>
<td>2</td>
<td>Derive signal model</td>
<td>3/10/16</td>
<td>3/15/16</td>
<td>5/2/15</td>
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<tr>
<td>2</td>
<td>Alignment Flight PostVibe</td>
<td>2/9/16</td>
<td>2/9/16</td>
<td>2/9/16</td>
</tr>
<tr>
<td>2</td>
<td>Alignment Flight PreVibe</td>
<td>2/3/16</td>
<td>2/3/16</td>
<td>2/3/16</td>
</tr>
<tr>
<td>3</td>
<td>Measure Field Distortion</td>
<td>2/16/16</td>
<td>2/16/16</td>
<td>10/20/15</td>
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<tr>
<td>3</td>
<td>Measure PSF</td>
<td>2/18/16</td>
<td>2/18/16</td>
<td>2/17/16</td>
</tr>
<tr>
<td>3</td>
<td>Alignment Qual PreVibe</td>
<td>2/4/16</td>
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<tr>
<td>3</td>
<td>Alignment Qual PostVibe</td>
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<td>2/10/16</td>
<td>2/10/16</td>
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<tr>
<td>3</td>
<td>Alignment Flight Integrated PostVibe</td>
<td>5/18/16</td>
<td>5/18/16</td>
<td>5/18/16</td>
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</tbody>
</table>
Visible Camera

• **Characteristics**
  – CMOS chip (Aptina MT9M001C12STM) – Similar chips flown
    • 1280 x 1024 pixels
    • 5.2-µm pixels = 180 m at 600 km
    • 10-bit monochrome - 40 e/DN - Saturation at 725 DN
    • RN: 27 e/pix (25 C)
    • Dark Current: 13 e/sec/pix (25 C)

• **Optics**
  – f/1.4 17.6 mm, 6-element lens (Schneider Xenoplan 27-1991417 – Flown in space).
  – Point Spread Function:
    • Documentation: Q=FWHM/pix=1.3 \(\rightarrow\) 230 m (If diffraction limited at 650 nm, \(\lambda/D=27 \mu\text{rad}\); \(Q=0.175\))

• **Spectral Range**: 0.4-0.8 µm
Visible Camera, cont.

• **Operational Characteristics**
  – Exposure times from 0.11 ms to 900 ms
  – Changeable multiplicative gains to ADC: 1 -15
  – Controllable Image Corrections
    • Black subtraction: Temperature dependent bias subtraction

• **Pixel Response Non-Uniformities (PRNU or ‘Flat errors’)**
  – Integrating sphere observations, average of 6 illuminations with 64 images each.
  – ~40% gain variation along image field (σ=12%)
  – Per pixel uncertainty in the PRNU is 0.1%

Flat field observations
Visible Camera, cont.

• Preliminary radiometric calibration on the ground, using a 660 C BB observed at 26’10” with a 1” diameter aperture.

• Aperture photometry of irradiance source transformed to a radiance value.

• Radiometric coefficient (W cm\(^{-2}\) \(\mu\text{m}^{-1}\) sr\(^{-1}\) per ct sec\(^{-1}\)) error: ±3%
SWIR Camera

• Characteristics
  – FLIR Tau SWIR 25 - 43-00039-22-A5
    • InGaAs chip
    • 640 x 512 pixels
    • 25-µm pixels = 600 m at 600 km
    • 14-bit monochrome

• Optics:
  – StingRay SR2145-A01 – Space qualified
    • f/1.4 25 mm
  – Point Spread Function:
    • Documentation: Q=0.52 -> 312 m (If diffraction limited at 1.3 µm, λ/D=72.8 µrad ; Q=0.07)

• Spectral Range: 0.9-1.7 µm

<table>
<thead>
<tr>
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<th>Low</th>
<th>High</th>
</tr>
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<tbody>
<tr>
<td>Gain</td>
<td>124.4 e/DN</td>
<td>1.7 e/DN</td>
</tr>
<tr>
<td>RN (25 C)</td>
<td>1,000 e/pix</td>
<td>70 e/pix</td>
</tr>
<tr>
<td>DC (T=0 sec; 25 C)</td>
<td>6,100 DN/pix</td>
<td>1,100 DN/pix</td>
</tr>
<tr>
<td>Well-Depth</td>
<td>1.3 Me</td>
<td>18 Ke</td>
</tr>
<tr>
<td>Saturation</td>
<td>~4,000 DN</td>
<td>~9,000 DN</td>
</tr>
<tr>
<td>(after DC subtraction)</td>
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</tbody>
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Far-field focus test image
SWIR Camera, cont.

- **Operational Characteristics**
  - *Exposure times from 0.2 ms to 32 ms*
  - *High and Low gains*
  - *Controllable Image corrections*
    - PRNU gain
    - Pixel offset
    - Exposure dependent dark current correction
    - Bad pixel replacement
  - *Pixel Response Non-Uniformities:*

  - **Non-Uniformity Correction (NUC)**
  - **Flat field observations, with factory corrections**
  - **Flat field observations, without factory corrections**
SWIR Camera, cont.

- Radiometric measurements
  - **Target:**
    - Irradiance source 200 C BB
    - Observed at 26' with a 0.185” diameter aperture.
  - *High gain response is not linear with time.*
LWIR Camera

- **Characteristics**
  - *FLIR Tau 640 46640025H-FPNLX*
    - VOx Bolometer
    - 640 x 512 pixels
    - 17-µm pixels
    - 14-bit monochrome
  - **Optics:**
    - *f/1.1 25 mm*
    - **Point Spread Function:**
      - Documentation: $Q=0.92 \rightarrow 374 \text{ m}$ (If diffraction limited at 10 µm, $\lambda/D=440 \mu\text{rad}$; $Q=0.6$)
  - **Spectral Range:** 7.5 - 15.5 µm

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Graphic: FLIR Tau 2 Product Specification
• Operational Characteristics
  – Fixed frame rates: 40 ms or 33 ms
  – Time constant: 10 ms.
  – High and Low gains
  – Controllable Image corrections
    • Mechanical shutter provides blank image to perform PRNU correction
    • “Temperature stabilization, column correction”
    • 1/f Noise correction
    • Bad pixel replacement
  – Pixel Response Non-Uniformities

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain @ 30 C</td>
<td>7.1 DN/K</td>
<td>52.2 DN/K</td>
</tr>
<tr>
<td>Saturation</td>
<td>12,000 DN</td>
<td>14,000 DN</td>
</tr>
<tr>
<td>415 C</td>
<td>125 C</td>
<td></td>
</tr>
<tr>
<td>NEAT @ 30 C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Documentation</td>
<td>181.5 mK</td>
<td>60.5 mK</td>
</tr>
<tr>
<td>Measured within frame</td>
<td>271 mK</td>
<td>88 mK</td>
</tr>
<tr>
<td>Measured F2F</td>
<td>3 K</td>
<td>4 K</td>
</tr>
</tbody>
</table>

Multiple observations of -3.5C flat source in vacuum.
Procedure:
• Take shutter calibration
• Take multiple images within < 1 second
Measuring the camera response:
• Observations in a thermal-vac chamber.
• Multiple observations at a given flat source.
• Procedure:
  • Turn camera on
  • Take shutter calibration
  • Take 3 images within < 1 second
  • Turn camera off
  • Change target temperature

**Target Temperatures**

**Derived count-temperature relationship**

**Default count-temperature relationship**

**LWIR—Low**

**LWIR—High**

**Pixel error**
Calibration

Note: Ground-based radiometric calibration is inadequate.

For the reflective bands (Vis and SWIR):

- The final output is a radiance flux density ($W \text{ cm}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$).
- But we measure integrated flux ($W \text{ cm}^{-2} \text{sr}^{-1}$).
- The error in the determined radiance flux density depends on the target spectrum, calibrator spectrum, and errors in the filter band.
- Target spectra are ~5500 K “blackbodies”, but calibration spectra are much colder.

<table>
<thead>
<tr>
<th>Vis</th>
<th>Default</th>
<th>Custom</th>
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<tbody>
<tr>
<td>Flat</td>
<td>12%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Radiometry (Random)</td>
<td>3%</td>
<td>3%</td>
</tr>
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<table>
<thead>
<tr>
<th>SWIR</th>
<th>High Gain/Default</th>
<th>Low Gain/Default</th>
<th>High Gain/Custom</th>
<th>Low Gain/Custom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat</td>
<td>6%</td>
<td>8%</td>
<td>0.2%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Radiometry (Random)</td>
<td>3%</td>
<td>5%</td>
<td>2%</td>
<td>5%</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>LWIR</th>
<th>High Gain/Default (30 C)</th>
<th>Low Gain/Default (30 C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame to Frame</td>
<td>7%</td>
<td>2%</td>
</tr>
<tr>
<td>Radiometry</td>
<td>±4°C</td>
<td>±3°C</td>
</tr>
</tbody>
</table>
Summary

- S/C to launch 11/2016
- CUMULOS mission will begin after ISARA ends (L+3 months).
- CUMULOS will demonstrate the capabilities and limits of different COTS detector architectures
- On-board vicarious calibration will be needed. Anchored to other instruments such as VIIRS and AIRS
- Preliminary Lessons:
  - *Quoted specs are NEVER specific for the device at hand.*
  - *Most early work involves re-writing the software to read the cameras*
  - *The discovery of undocumented features is the rule. Little to no help from manufacturers*
  - *Significant performance improvements are gained by measuring PRNU on the ground.*

The authors wish to acknowledge the U.S. Air Force Space and Missile Systems Center Advanced Development Directorate (SMC/AD), and The Aerospace Corporation Multi-Program Acquisition Capability Enhancement Program (MPACE), for their support of the CUMULOS payload.