A CubeSat approach to atmospheric motion vectors (AMVs) in the Midwave Infrared

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Motivation

• Earth Science Decadal Survey (2017) calls for 3D winds and heights in the planetary boundary layer (PBL) and free troposphere
  - Promotes the concept of a global wind monitoring capability composed of complementary active and passive components
  - Atmospheric Motion Vectors (AMVs) derived from the Compact Midwave Imaging System (CMIS) can contribute to the passive wind component (height assignment issues with current observations)

• Improve accuracy and precision of AMVs to improve numerical weather prediction and better understanding of PBL processes/interactions
  - Only small fraction retrieved from GOES/JPSS accepted due to errors in height assignment and correlated errors between along-track AMVs and cloud height

• Create low-Size, -Weight, and –Power (low-SWaP) capability promotes constellation in LEO to provide high resolution in time and space
CubeSat Concept

- Fly imagers on leading and trailing spacecraft to perform stereo calculations
- Accurate CMV/CGH requires cameras on two spacecraft several minutes apart to eliminate ambiguity in along-track direction between winds and cloud heights
- Estimated CMV/CGH Precision: ±0.5 m/s, ±200 m assuming ½-pixel relative geolocation accuracy
- Minimum detectable along-track CMVs: <1 m/s
Heritage from Previous AF Flights

MSIS Test Campaign
Integration: 16 Nov – 1 Dec 2013
Data Collection: 2 Dec – 20 Dec 2013
Objectives: Collection of Multi-spectral data of cloud and ground conditions needed to assess MSIS performance against METOC measurement requirements.
No midwave capability
Compact Midwave Imaging System (CMIS)

- Multi-spectral imager with bands at 2.25, 3.75, and 4.05 μm
  - Use 3.75 is primary band for stereo imaging
  - Use 2.25-μm to estimate/remove solar component from 3.75-μm band, optical thickness and equivalent droplet radius
  - Use 4.05-μm band for temperature estimation of clouds, SSTs, volcanic ash, fires
- 640 × 512 focal plane array
- Field of view: 53° cross-track

### Specifications

<table>
<thead>
<tr>
<th>Field</th>
<th>Number</th>
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<tbody>
<tr>
<td>Multi-Spectral</td>
<td>2.25, 3.75, 4.05 μm</td>
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<tr>
<td>Multi-Angle</td>
<td>22.5, 0, -22.5 views at 3.75 μm</td>
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<tr>
<td>Weight, Power</td>
<td>&lt; 3 kg, 7 W</td>
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<tr>
<td>Operating Temperature</td>
<td>150 K</td>
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<tr>
<td>NEdT</td>
<td>&lt; 1 K between 230 K and 400 K</td>
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CMIS Components

- Optics
  - APL lens design
  - Vendor lens fabrication
  - APL mechanical design and fabrication
- Stripe Filter
  - APL specification
  - Vendor fabrication
- Focal Plane Array
  - T2SL
  - Vendor-standard ROIC
- Cooler
  - APL specified mechanical interfaces
- Electronics
  - APL design
  - APL fabrication
Measured NEDT vs. Target Temperature for Flight Grade FPA (QGH2-HMW4-12)

NEDT < 1 K for temperatures above 230 K
Atmospheric Motion Vectors (GEO-LEO)

- Carr et al. (2018) describe capability to derive winds and cloud heights using MISR+GOES
- Demonstrate improved height assignment in LEO-GEO overlapped regions
- GOES-MISR retrievals for terrain provide estimated accuracies of $<0.5 \text{ m/s}$ for motion vectors and $<200 \text{ m}$ in height
- Develop a cost-effective solution (CMIS) for joint LEO-GEO wind and stereo height measurements

MISR-GOES retrieval error

• Differences between multi-satellite algorithm and only algorithm for single orbit
• Appears v-wind and height differences are correlated due to ambiguity between along-track winds and cloud heights
• Largest errors are 6-10 m/s for this single orbit
• Demonstrates the utility of two satellites for improving accuracy
MSIS Airborne Flight

MSIS Flight 2013-12-10
Aircraft motion compensation

- Aircraft motion skews features by 100s of pixels, making feature matching difficult.
- We use a high-rate IMU to compensate for aircraft attitude.
- Low aircraft altitude confounds direct comparison to space-based platform.
- Spacecraft motion will be much more benign.
Atmospheric Motion Vectors

13 September 2019

Fore: Overlap region (visible)

Fore: Radiance thresholded cloud mask

Fore: Clouds only

T+0 sec
Atmospheric Motion Vectors

Observed: predominantly southeastward cloud motion across fore-aft overlap region

T+58.7 sec
Case C, nadir-aft disparity

- Original pre-flight lab calibration model had remaining unaccounted off-axis error due to lens (barrel) distortion.
- Updating lens model by incorporating ground fiducials led to improved off-axis performance.
- Remaining disparity is due to height parallax.
Figure 108. Two dimensional height registration geometry used for error analysis.
The CMIS performance in an airborne environment and its measurement capability will be demonstrated on three dedicated NASA Gulfstream-3 flights out of LaRC flight facility, in Hampton.

Gulfstream-3 can accommodate both the nadir-viewing CMIS and a suite of previously flown visible and thermal-IR imagers equipped with GPS and IMU to provide needed complementary cloud measurements and critical position and attitude data for analysis.

One of the objectives for the flight demonstration is to cross-compare the CMIS airborne stereo retrievals with those constructed from VIIRS and GOES.
Summary and Conclusions

- Multi-platform and multi-angle imaging from space provides a cost-effective complement for day/night cloud-height detection and 3D wind retrieval
- Provides synergy with other systems (GEO imagers, LEO scatterometers, LEO imagers) for study of PBL processes/feedbacks
- Data analysis underway to define accuracies/precisions of CMV/CGH retrievals
- Software algorithms/techniques exist to create products for PBL science

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