Multiangle SpectroPolarimetric Imager (MSPI) On-Board Processing Technology Development and In-Flight Validation for the ACE Decadal Survey Mission

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Outline

1. Introduction
2. On-board Processing
3. In-Flight Validation Plan
4. Conclusions

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ACE [1]

Name Aerosol-Cloud-Ecosystems (ACE)

Mission Tier II Earth Sciences Decadal Survey

Description Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry

Goal *The primary goal of the Aerosol Cloud Ecosystems (ACE) mission is to reduce uncertainty about climate forcing in aerosol-cloud interactions and ocean ecosystem carbon dioxide (CO_2) uptake. Aerosol-cloud interaction is the largest uncertainty in current climate models.*

Instruments

- Multibeam cross-track dual-wavelength lidar
- Cross-track scanning cloud radar
- *Multiangle, multi-wavelength polarimeter*
- Multiband, cross-track visible-UV spectrometer

[1] From: "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," National Academies Press 2007.

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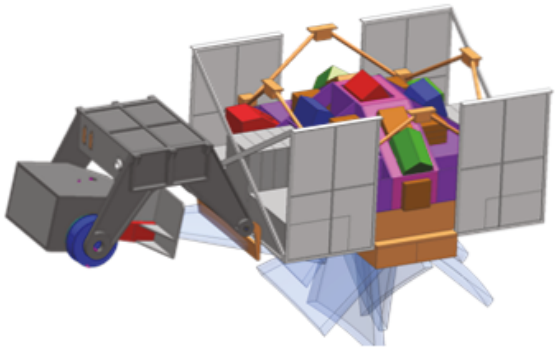
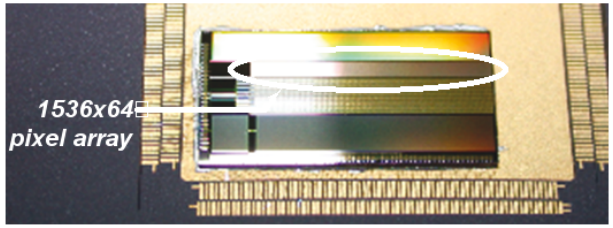
MSPI

- Multiangle SpectroPolarimetric Imager (MSPI)
  - 1536-pixel line-array, pushbroom camera
  - Eight fixed, one gimballed camera
  - 16 channels per camera (both spectral and polarimetric)
- Highly accurate degree of linear polarization (DOLP) estimation
  - Dual, beating photoelastic modulators (PEMs)
  - Pattern polarizers on imager
  - Spectral filters on imager
- Heritage from Multiangle Imaging SpectroRadiometer (MISR)



MSPI Instrument



MSPI CMOS Pixel Array

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Requirements

- Each camera (nine total) produces about 95 MB/s of video data
- This data rate is much too high to downlink all the raw data
- One solution is to perform polarimetric estimation on the instrument
- Processing must be done in real-time
- Since there are multiple cameras on MSPI, each processor must be low-power
- The processor needs to be reprogrammable, in the event updates are desired mid-mission
- This parameter estimation is necessary—it would be performed in ground-processing anyway
- Although the motivations are the same, this is data extraction, not compression

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MSPI Algorithm

- MSPI's goal is to compute polarization estimates (Stokes vector <I,Q,U,V>), DOLP and angle-of-linear-polarization (AOLP)
- A series expansion of the PEM action shows that, to first order, they modulate the linear components of polarization (Q and U) onto a complicated periodic waveform.
- The desired parameters can be extracted by inverting the modulation
  - Use measured parameters to compute the modulation waveform
  - Apply the inverse operation
- Specific rows in the pixel array are covered with pattern polarizers

660nm I	no polarizer
660nm I_0	horizontal polarizer
660nm I_{45}	45° polarizer

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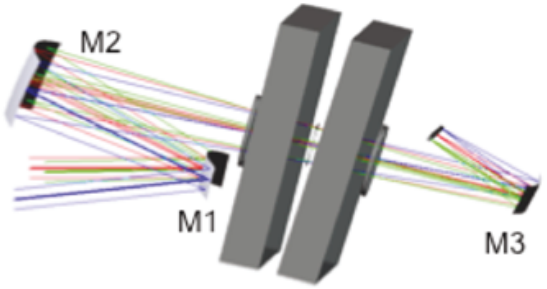
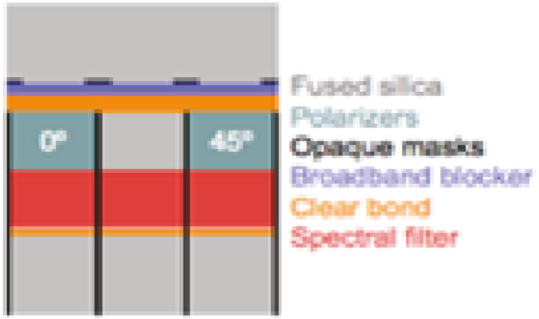
MSPI Algorithm

- In a *frame* (beat-period), there are N *subframes* (integration periods, or samples)
- For each pixel, collect a frame of subframes samples into a vector $v =< I_{45,1}, \ldots, I_{45,N} >$
- Denote the desired unknown quantities for that frame by another vector $x =< I, \nabla I, U, \nabla U >$
- Then $v = Bx$, where B is an operator consisting of samples of the basis functions
- Perform least-squares to solve for the unknowns $x = B^{\dagger} v$, where $B^{\dagger} = \left(B^T B\right)^{-1} B^T$



MSPI Optical Path & PEMs



MSPI Imager X-Section

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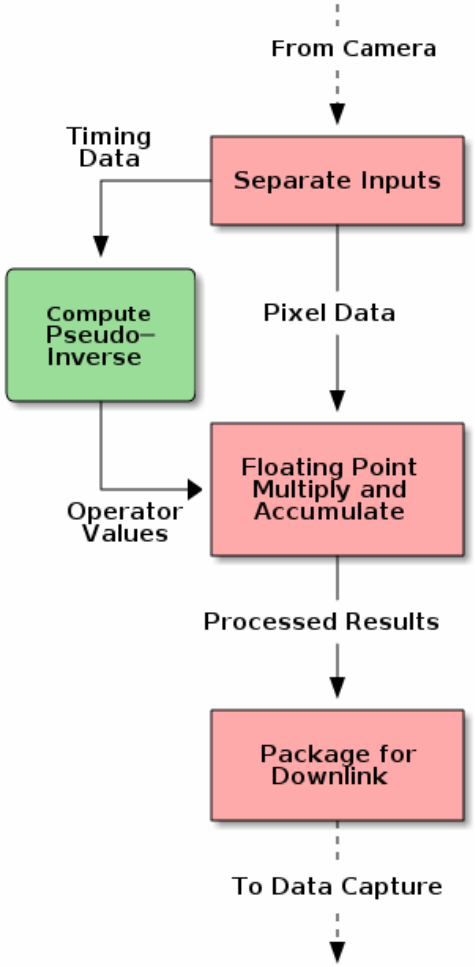
Implementation

- We built a mixed HW/SW implementation of the MSPI OBP algorithm on a Xilinx Virtex-5 FPGA
  - Ample reprogrammable logic: speed-critical tasks
  - PowerPC 440, Microblaze processors: complex tasks
  - Rad-hard-by-design equivalent available
- The algorithm is real-time adaptive, predictive, floating-point multiply-and-accumulate (MAC)

  Processor Computes & updates operators, applies prediction algorithm

  Hardware Separates pixel and timing data, performs MAC
- Device utilization is approximately 20%
- Processing errors are order of machine-ε



Processing Scheme

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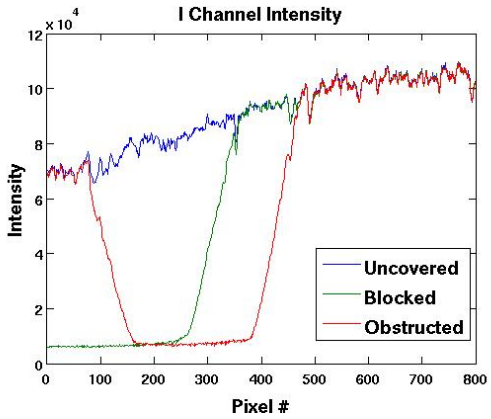
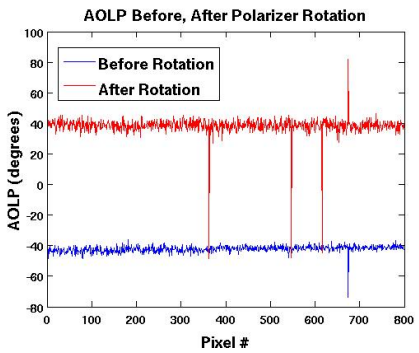
Laboratory Results

- We have demonstrated a preliminary version of the algorithm in a laboratory setting

  Source Integrating sphere
  Polarizer Rotatable linear polarizer
- FPGA processes polarimetric data collected from the MSPI camera
- A PC captures the output processed data and displays the resulting parameter estimates in real-time using Matlab.
- Correctly detects obstructions in the intensity estimates
- Correctly detects a 90° rotation of the polarizer in AOLP



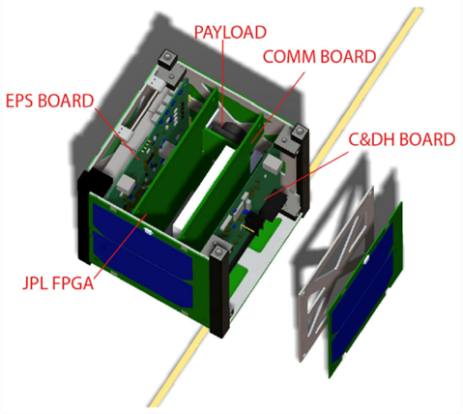
Intensity



AOLP

M-Cubed

- University of Michigan's Multipurpose Minisatellite (M-Cubed)
- CubeSat (10cm x 10cm x 10cm)
- Primary mission: capture high-resolution (1280x1024) images of the Earth and downlink
- Developed by students
  - 16 undergraduates, 11 graduate students
  - Primarily commercial off-the-shelf (COTS) hardware
  - Flight heritage from University of Michigan's Radio Aurora Explorer (RAX): launch Nov. 2010
- Operated over ham-radio from University of Michigan



M-Cubed

Primary Payload

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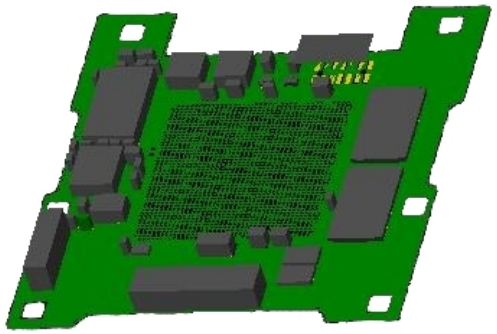
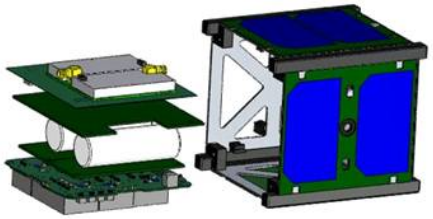
COVE

- CubeSat On-board processing Validation Experiment (COVE)
- Validate:
  - MSPI algorithm—process an M-Cubed image
  - Space-qualified Xilinx Virtex-5 Field-Programmable Gate Array (FPGA)
- Synergistic task combining M-Cubed and JPL MSPI OBP development work
  - Implement MSPI OBP algorithm on an FPGA in a secondary payload onboard M-Cubed
  - Monitor current, voltage, temperature of FPGA during operation
  - Ability to reprogram FPGA in flight to serve as a future test platform
- Selected for launch as secondary payload on NPOESS Preparatory Project (NPP) mission



COVE Processing Board



M-Cubed + COVE

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Validation Aboard M-Cubed

- The MSPI algorithm requires the MSPI camera to generate science
- We are not trying to collect scientific results
- M-Cubed uses a COTS camera, not the special MSPI camera
- From the algorithm's point-of-view, the input is just a data-stream
- Modify the MSPI processor slightly to accept M-Cubed data format
- Downlink raw and processed M-Cubed camera data and compare on the ground
- This will allow us to *validate* the processor *in space*
- The FPGA is reprogrammable in flight
  - If a bug is discovered, we can patch it and try again
  - Other camera-based instruments can potentially upload designs and validate as well

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Conclusions

- As a candidate for the Earth Science Decadal Survey ACE mission, JPL is developing MSPI, the Multiangle SpectroPolarimetric Imager
- Downlinking the complete MSPI data stream is not feasible; rather, processing needs to be done onboard
- To meet this challenge, JPL has designed and implemented a Xilinx Virtex-5 FPGA-based solution that will perform real-time onboard polarimetric parameter estimation
- JPL is working with the University of Michigan to fly a version of the algorithm onboard the M-Cubed CubeSat to verify both the algorithm and the FPGA
- Launch as secondary payload aboard NPP scheduled for Fall 2011

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