

Real-Time On-Board Processing Validation of MSPI Ground Camera Images

Paula J. Pingree, Thomas A. Werne, Dmitriy L. Bekker
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099
[First.MI.Last]@jpl.nasa.gov

Abstract— The Earth Sciences Decadal Survey identifies a multiangle, multispectral, high-accuracy polarization imager as one requirement for the Aerosol-Cloud-Ecosystem (ACE) mission. JPL has been developing a Multiangle SpectroPolarimetric Imager (MSPI) as a candidate to fill this need. A key technology development needed for MSPI is on-board signal processing to calculate polarimetry data as imaged by each of the 9 cameras forming the instrument. With funding from NASA’s Advanced Information Systems Technology (AIST) Program, JPL is solving the real-time data processing requirements to demonstrate, for the first time, how signal data at 95 Mbytes/sec over 16-channels for each of the 9 multiangle cameras in the spaceborne instrument can be reduced on-board to 0.45 Mbytes/sec. This will produce the intensity and polarization data needed to characterize aerosol and cloud microphysical properties. Using the Xilinx Virtex-5 FPGA including PowerPC440 processors we have implemented a least squares fitting algorithm that extracts intensity and polarimetric parameters in real-time, thereby substantially reducing the image data volume for spacecraft downlink without loss of science information.

The MSPI project consists of three phases: Ground-MSPI, Air-MSPI, and Space-MSPI. Ground-MSPI is a ground-based camera demonstration focused on characterizing the imager optics and performance. Air-MSPI will be an updated version of the ground system to be flown on an ER-2 aircraft in 2010. Lessons learned from the ground- and air-based demonstrations will be used in the design of the satellite-based Space-MSPI instrument. We have developed a modular demonstration system to test and verify the real-time processing of the FPGA-based on-board processing system first with simulated data, then with ground camera input via a Camera Link interface, and finally with the AirMSPI camera system. Collaborative efforts continue with the AirMSPI development team to integrate the OBP solution with their FPGA design. At this time we will showcase the results of our real-time OBP validation of MSPI ground camera images using the Virtex-5 FPGA.

TABLE OF CONTENTS

1	Introduction	1
2	Key Camera Design Features	2
	2.1 Photo-elastic Modulators	2
	2.2 Data Processing Algorithm Overview	2
3	On-Board Processing Implementation	3
4	Results	4
5	Future Work	5
6	Conclusion	5
	Acknowledgements	5
	References	5
	Biography	6

1 INTRODUCTION

The Multiangle SpectroPolarimetric Imager (MSPI) is an instrument concept in development at JPL to produce a highly accurate multiangle-multiwavelength polarimeter to measure cloud and aerosol properties as called for by the Aerosol-Cloud-Ecosystem (ACE) tier-2 mission concept in the Decadal Survey. This instrument has proposed 9 cameras (8-fixed and 1-gimballed), each of which must eventually process a raw video signal rate around 95 Mbytes/sec over 16-20 channels for space flight. A key technology development needed for MSPI is on-board processing to calculate polarimetry data as imaged by each of the 9 cameras forming the instrument.

In the MSPI design, a dual photoelastic modulator (PEM) assembly is integrated into a polarization-preserving 3-element reflector to provide both intensity and polarization imaging (Figure 1). A miniaturized focal-plane assembly consisting of spectral filters and patterned wire-grid polarizers provides color and polarimetric selection. A custom CMOS array with specialized signal acquisition, readout, and processing electronics captures the radiometric and polarimetric information.

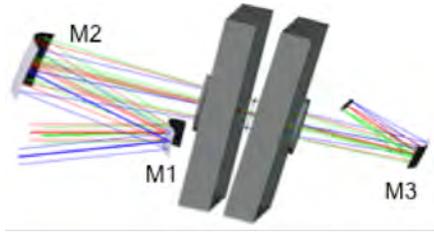


Figure 1. Side view of 3-mirror camera design with integrated dual-PEM [1].

MSPI is being developed [2] as a follow on to the Multi-angle Imaging SpectroRadiometer (MISR) [3], that has been operating since 2000 aboard NASA's Terra satellite. The first MSPI camera system developed is called LabMSPI consisting of a single 660-nm spectral band with channels having 0° and -45° polarizers, and no polarizer. LabMSPI was later upgraded to a multi-band version now known as GroundMSPI. The spectral bands of the GroundMSPI camera are 335, 380, 445, 470, 555, 660, 865, 935 nm where the bands at 470, 660 and 865 nm are polarimetric.

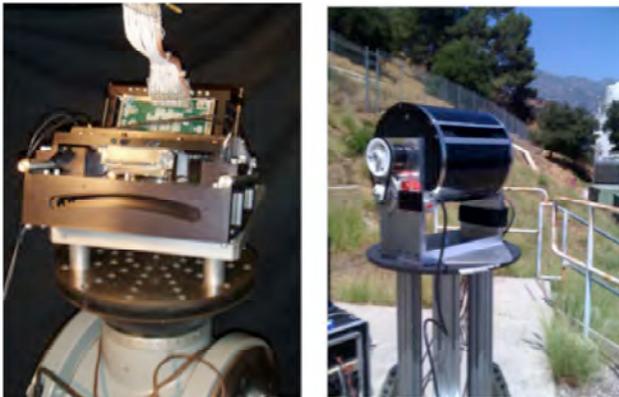


Figure 2. The assembled LabMSPI 660-nm camera (left), and the GroundMSPI multi-band camera deployed outdoors for field experiments at JPL (right).

AirMSPI is customized for flight on NASA's ER-2 high altitude aircraft. A comparison of MISR and planned MSPI characteristics is summarized in Table 1. The results presented in this paper were achieved with the GroundMSPI camera.

Instrument	Spatial resolution	Along-track angular range	Spectral range (nm)	Polarimetric uncertainty	Field of view
MISR	275 m – 1.1 km	70° fore- 70° aft	446-866	NA	$\pm 15^\circ$
MSPI	125 m – 2.2 km	70° fore- 70° aft	355-2130	± 0.005	$\pm 30^\circ$
AirMSPI	27.5 m – 110 m	70° fore- 70° aft	355-935	± 0.005	$\pm 15^\circ$
GroundMSPI	30 cm at 1 km distance	Horizon to horizon	355-935	± 0.005	$\pm 15^\circ$
LabMSPI	30 cm at 1 km distance	Horizon to horizon	660	± 0.005	$\pm 15^\circ$

Table 1. Instrument specification comparisons [1]

2 KEY CAMERA DESIGN FEATURES

2.1 Photo-elastic Modulators

The two photo-elastic modulators (PEMs) are included in the MSPI optical path to modulate the Q and U polarization components of the Stokes vector in order to achieve high accuracy in the “degree of linear polarization” (DOLP). One full cycle of the modulated polarization signal occurs in the time of one 40-msec frame, set by the beat frequency of the two PEMs. Each cycle of the modulation must be oversampled to create a hi-fidelity digital representation of the polarization components. The baseline is to sample the modulation 32 times per frame thereby creating 32 sub-frames per frame. Compared to the currently operational EOS Mission's MISR cameras, each with 4 spectral channels, the raw video data rate that must be handled by MSPI is increased by a factor of 256 (32x due to oversampling; 4x due to expansion of the number of channels, and 2x due to correlated double sampling to suppress read noise in the Si-CMOS readout).

A single 16-channel MSPI camera (one of nine) must process 95 Mbytes/sec of raw video data. A computationally intensive linear least-squares algorithm must also be applied to perform data reduction for video processing of the signal output from the photo-detector array. These data reductions can be performed (without sacrificing the information content of the camera product for science) based on how the calculations are implemented for digital signal processing in the Xilinx Virtex-5FXT FPGA. The result of the on-board processing algorithm is the reduction of dozens of samples acquired during a 40-msec frame to five parameters. Averaging cross-track and along-track pixels to reduce spatial resolution achieves further data reduction. The technology under development and described here is required to enable this process to occur in real-time, with the speed necessary to keep up with the MSPI data throughput.

2.2 Data Processing Algorithm Overview

For a complete mathematical description of the data processing algorithm, see the journal articles in *Applied Optics* [1][2]. IEEE Aerospace Conference papers from

2009 and 2010 provide a concise overview of the algorithm with an emphasis on implementation details [4][5]. Summary information is provided here so that it can be related to the results presented in Section 3.

One of the goals of the MSPI instrument is to calculate polarimetric information about a target scene. Stokes vectors $\langle I, Q, U, V \rangle$ are used to describe the polarization state of incident light, where I is the intensity, Q and U quantify linear polarization at 0° and 45° , and V quantifies circular polarization. The particular quantities of interest are DOLP, which is defined as:

$$\text{DOLP} = \sqrt{(Q/I)^2 + (U/I)^2} = \sqrt{q^2 + u^2}$$

and the associated angle of linear polarization (AOLP) defined as:

$$\text{AOLP} = \frac{1}{2} \tan^{-1}(u/q)$$

where the normalized Stokes parameters are $q = Q/I$ and $u = U/I$.

The uncertainty specification on DOLP of $\leq 0.5\%$ is the most challenging aspect of the MSPI design. The MSPI camera measures intensity, I , at several wavelengths in the range shown in Table 1. Q and U are measured in a subset of the bands. The design takes advantage of the fact that the relative measurements q and u can be obtained with higher accuracy than Q or U [1].

3 ON-BOARD PROCESSING IMPLEMENTATION

GroundMSPI data acquisition is performed with a CameraLink frame grabber. Incoming data is time stamped and stored on an array of parallel hard disks. GroundMSPI data reduction via the described algorithm is applied in ground data processing. However, for the SpaceMSPI instrument this image data processing must be done on-board the instrument prior to spacecraft downlink due to on-orbit bandwidth constraints to the Earth-based ground stations.

We have developed an FPGA-based hardware/software co-processor system to implement the algorithm on a Xilinx Virtex-5 FPGA with embedded PowerPC440 processor. Details can be found in the 2010 IEEE Aerospace Conference paper [5]. In general, the algorithm used to process the polarization channels involves the following steps:

- In hardware, de-multiplex the incoming data stream. Use ancillary information provided about the PEM amplitudes and phases, and time stamps of the subframes within each frame to calculate a set of “basis functions”.

- In software, create the polarization measurement matrix B , comprised of the sampled basis functions, and calculate its pseudoinverse W .
- Load the W operator into hardware, and then apply it to the sampled measurements using matrix multiplication to retrieve the desired polarization parameter estimates.

The basis functions are analytic expressions (consisting of trigonometric and Bessel functions) of the PEM mean retardance amplitude, amplitude difference, the PEM average and difference frequencies, and the integration interval durations and sample locations within the frame. These sample times vary slightly from row to row.

The implementation of the MSPI OBP algorithm can be thought of as a self-updating multiply-and-accumulate process (which has critical hardware and software components). The processor accepts an input data stream that has been defined by the MSPI electronics and science data teams. The data stream is made up of packets of data; each packet corresponds to a simultaneous sampling of an entire row from the imager. Within each packet are three distinct sets of data: pixel information directly captured from the camera, phase information describing the relative temporal location of the sample within a low frequency PEM oscillation, and ancillary data—including debugging information, state variables describing the PEMs, etc.

Figure 3 shows a block diagram representation of our demonstration system to validate GroundMSPI real-time images using the Virtex-5 FXT FPGA to implement the on-board processing algorithm.

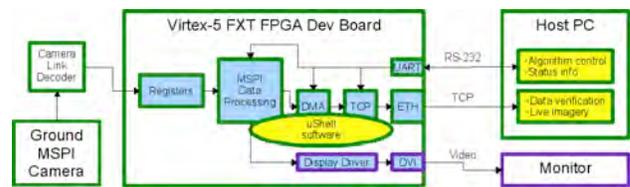


Figure 3. Demo System Block Diagram

The “MSPI Data Processing” block relies on floating-point matrix multiplication implemented from logic resources on the Virtex-5 FPGA. The V5FXT contains many embedded RAM blocks (BRAM) and dedicated hardware multipliers (DSP48), which are required for this real-time computation [6]. In our design, the logic surrounding BRAM blocks and DSP48 slices is running at 100 MHz, providing a high-speed link between these specialized FPGA resources and the rest of the system.

Prior to connecting to the GroundMSPI camera, we worked on validating CameraLink data capture into our FPGA

development board. This setup is shown in Figure 4. We used a CameraLink simulator to generate configurable frame patterns at a rate that is specified for the GroundMSPI camera. CameraLink data was de-serialized using a “breakout” box and fed directly into the Xilinx ML507 development board (hosting a Virtex-5 FPGA).

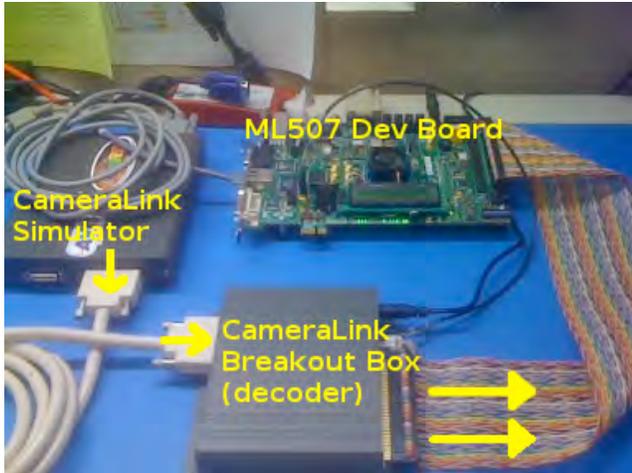


Figure 4. Demo System Hardware (ML507 and CameraLink Decoder)

Once this interface was verified, we substituted the CameraLink simulator with the GroundMSPI camera (shown in Figure 5). The OBP algorithm running on the FPGA performed real-time data processing of raw imagery from the GroundMSPI camera and then transferred the derived polarization parameters to the host pc (via Ethernet) for display / plotting using Matlab.

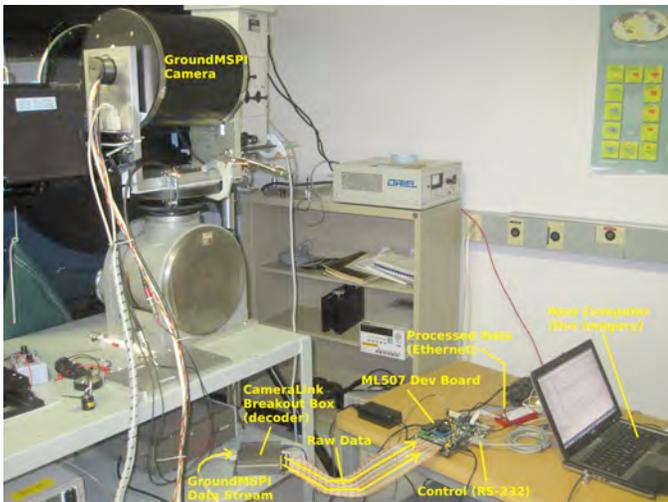


Figure 5. GroundMSPI Demo System Configuration

4 RESULTS

To demonstrate the functionality of the OBP algorithm operating on the GroundMSPI camera images, we performed two experiments:

1. Cover a portion of the camera aperture to see the estimated intensity, I , decrease.
2. Rotate a linear polarizer in front of the aperture to see the effect on estimated AOLP.

Figure 6 shows three overlaid snapshots from the first experiment. In this experiment, we began data capture with the aperture unblocked, then covered a portion of the aperture with a block, then passed a narrow obstruction across the entire aperture.

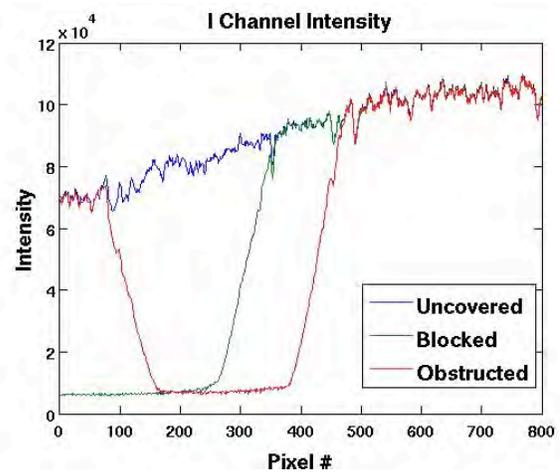


Figure 6. Experiment 1: Intensity validation

The first snapshot (blue) is of the unblocked aperture. This shows the nominal camera intensity estimate. Evidently, when the camera images a light source, the image intensity is around $8e4$. The second image (green) shows the intensity after covering the left-side of aperture with a block. Clearly, this is visible in the processed data, since the image intensity drops to about $5e3$. The third snapshot (red) is with the narrow obstruction in front of the aperture. This also shows the correct behavior, since the intensity is at the blocked level near the obstruction and at the nominal level away from the obstruction. Thus the experimental results agree with the expected results.

Figure 7 shows two snapshots from the second experiment. In this experiment, we began data capture with a linear polarizer between the camera and light source oriented in an arbitrary direction. Midway through the data collection we rotated the polarizer to a different orientation, approximately 90 degrees from the initial state. The blue data shows the computed angle of polarization at the beginning of data collection, and the red data shows the same quantity after rotation. The experimental results match exactly with our expectation, including agreement with the amount of applied rotation.

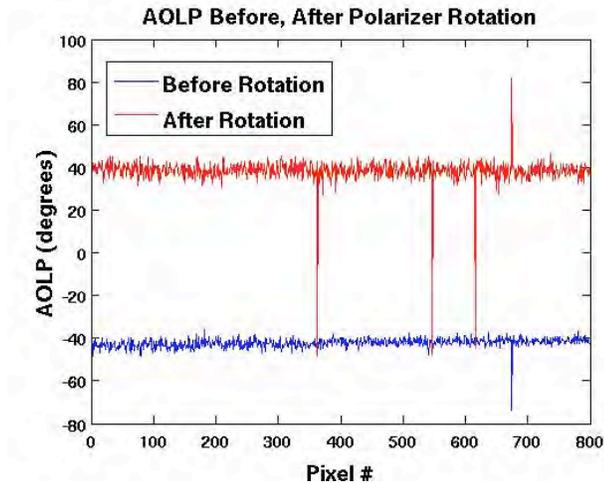


Figure 7. Experiment 2: AOLP validation

5 FUTURE WORK

We are currently estimating the polarimetric parameters for only the 660nm band in the camera, while the camera produces polarimetric information in two additional bands (470nm and 865nm). We need to spend a little time to modify the processor to compute estimates for these bands as well. The required alterations involve increasing the depth of FIFOs within the processor and producing multiple sets of pseudo-inverse operators.

Pixel-readout timing is quasi-static in the ground camera, but will be changing on a per-frame basis in the airborne camera. We need to work to alter the implementation details to handle this detail. Primarily, the necessary changes are limited to software (e.g. building a predictive pseudo-inverse operator), but there are some potential complicating issues in hardware as well (controlling the number of subframes per frame).

6 CONCLUSION

This paper presents the results of on-board processing of GroundMSPI camera images using the Xilinx Virtex-5 FPGA. We implemented a least-squares fitting algorithm that extracts intensity and polarimetric parameters in real-time, thereby substantially reducing the image data volume for spacecraft downlink without loss of science information. Using our demonstration system, integrated to the GroundMSPI camera via a Camera Link interface, we performed two validation experiments. The results from these experiments show that the OBP algorithm is processing image data correctly.

ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

- [1] Diner, D.J., A. Davis, B. Hancock, S. Geier, B. Rheingans, V. Jovanovic, M. Bull, D. Rider, R.A. Chipman, A-B Mahler, and S. McClain (2010). First results from a dual photoelastic modulator-based polarimetric camera. *Appl. Opt.*
- [2] Diner, D.J., A. Davis, B. Hancock, G. Gutt, R.A. Chipman, and B. Cairns (2007). Dual photoelastic modulator-based polarimetric imaging concept for aerosol remote sensing. *Appl. Opt.* **46**, 8428-8445.
- [3] Diner, D.J., J.C. Beckert, T.H. Reilly, C.J. Bruegge, J.E. Conel, R.A. Kahn, J.V. Martonchik, T.P. Ackerman, R. Davies, S.A.W. Gerstl, H.R. Gordon, J-P. Muller, R.B. Myneni, P.J. Sellers, B. Pinty, and M. Verstraete (1998). Multi-angle Imaging SpectroRadiometer (MISR) instrument description and experiment overview. *IEEE Trans. Geosci. Remote Sens.* **36**, 1072-1087.
- [4] Norton, C.D., T.A. Werne, P.J. Pingree, and S. Geier, "An Evaluation of the Xilinx Virtex-4 FPGA for On-Board Processing in an Advanced Imaging System," *Aerospace Conference, 2009 IEEE*, pp. 1-9, March 2009.
- [5] Werne, T.A., D.L. Bekker, and P.J. Pingree, "Real-Time Data Processing for an Advanced Imaging System Using the Xilinx Virtex-5 FPGA," *Aerospace Conference, 2010 IEEE*, March 2010.

- [6] “Virtex-5 FXT FPGAs,” <http://www.xilinx.com/products/virtex5/fxt.htm>, Xilinx, Inc., San Jose, CA, 2008.

BIOGRAPHY



Paula Pingree is Supervisor of the Flight Instrument electronics group in the Instruments and Science Data Systems Division at JPL, and Principal Investigator for the AIST “Optimizing MSPI Design for the ACE Mission” technology task. She has been a key contributor to the design, integration, test and operation of several JPL flight projects including Cassini, Mars Global Surveyor, Deep Space 1, and Deep Impact. Most recently she led the Electronics development for the Microwave Radiometer instrument on the Juno spacecraft planned for a 2011 launch to Jupiter. Ms. Pingree has a Bachelor of Engineering degree in Electrical Engineering from Stevens Institute of Technology in Hoboken, NJ, and a Master of Science in Electrical Engineering from California State University Northridge. She is a member of IEEE.



Thomas Werne is a Staff Engineer in the Instrument Flight and GSE Software group in the Instrument Software and Science Data Systems Section at JPL. He is currently working on implementing FPGA-based technology for Smart Payload applications. Thomas has Bachelor of Science degrees in Electrical Engineering and Mathematics, a Master of Electrical and Computer Engineering from Rose-Hulman Institute of Technology in Terre Haute, IN, and is currently enrolled as a Ph.D. Student in Control and Dynamical Systems at Caltech. He is a member of IEEE.



Dmitriy Bekker is a Staff Engineer in the Instrument Flight and GSE Software group in the Instrument Software and Science Data Systems Section at JPL. He is currently working on FPGA-based data acquisition and processing design for multiple prototype science instruments. His areas of interests include FPGAs, embedded systems, digital signal processing, and system architecture. Dmitriy received his M.S. and B.S. degrees in Computer Engineering from Rochester Institute of Technology in 2007.