Appears in Proc. International Workshop on Planning and Scheduling for Space, Moffett Field, CA, March 2013.

Onboard Mission Planning on the Intelligent Payload Experiment (IPEX) Cubesat Mission

Steve Chien [1], Joshua Doubleday[1], Daniel Tran [1],
John Bellardo[2], Craig Francis[2], Eric Baumgarten[2], Austin Williams [2],
Edmund Yee[2], Daniel Fluitt, [2] Eric Stanton [2], Jordi Piug-Suari[2]

[(1)] Jet Propulsion Laboratory, California Institute of Technology,
4800 Oak Grove Drive, Pasadena, CA, 91109-8099, USA, Email: {firstname.lastname}@jplnasa.gov
[(2)] California Polytechnic State University, San Luis Obispo, CA, Email:{bellardo,atwillia,jpuigsua}@calpoly.edu

Abstract

The Intelligent Payload Experiment (IPEX) is a cubesat manifested for launch in October 2013 that will flight validate autonomous operations for onboard instrument processing and product generation for the Intelligent Payload Module (IPM) of the Hyperspectral Infra-red Imager (HyspIRI) mission concept.

We first describe the ground and flight operations concept for HyspIRI IPM operations. We then describe the ground and flight operations concept for the IPEX mission and how that will validate HyspIRI IPM operations. We then detail the current status of the mission and outline the schedule for future development.

Introduction

Future space missions will produce immense amounts of data. A single image from the HiRise camera on the Mars Reconnaissance Orbiter (MRO) spacecraft is 16.4 Gigabits (uncompressed). The HyspIRI mission concept under study [HyspIRI] proposes to have two instruments - the HyspIRI thermal infrared imager (TIR) projected to produce 1.2 million pixels per second with 8 spectral bands at 4 and 7.5-12 microns per pixel and the HyspIRI visible shortwave infrared (VSWIR) projected to produce 300 thousand pixels per second with 220 spectral bands per pixel in the 0.4-2.5 micron range. Keeping up with these data rates would require efficient algorithms, streamlined data flows and careful systems engineering.

The HyspIRI mission concept baselines using Direct Broadcast technology [GSFC] to rapidly deliver this data to application users on the ground. However, in order to leverage the existing DB network, this downlink path is limited to approximately 10 million bits per second. The Intelligent Payload Module (IPM) proposed for HyspIRI is an onboard processing system intended to intelligently decide which data to downlink when, in order to maximize the utility of the DB system.

The HypsIRI IPM concept would involve both ground and flight automation (See Figure 0). On the ground, users would use Google Earth ™ to specify geographical and seasonal areas of interest. These requests would be automatically combined with predicted overflights to develop a schedule for onboard product generation and downlink [Chien et al. 2009]. Additionally onboard the

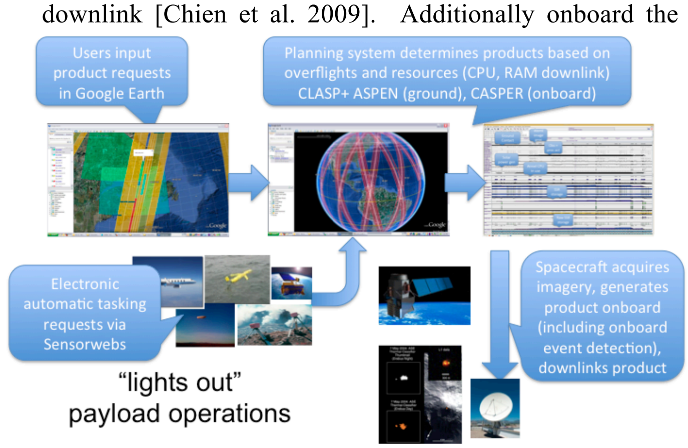

Figure 0: HyspIRI IPM Operations Concept

Portions of this work were carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

spacecraft, the instrument data would be analyzed to search for specific event or feature signatures such as a forest fire, volcanic eruption, or algal bloom. These detected signatures could generate alerts or products that would be merged on a priority basis to drive spacecraft operations.

IPEX Overview

IPEX is a 1 unit (1U) cubesat (Figure 1) [Chien et al. 2012] intended to flight validate technologies for onboard instrument processing and autonomous operations for NASA's Earth Science Technologies Office (ESTO).

As a 1U cubesat, IPEX is approximately 10cm x 10cm x 10cm. To support its primary flight software, IPEX carries a 400MHz Atmel ARM9 CPU (no hardware floating point) with 128MB RAM, 512MB flash memory, a 16 GB Micro SD card, and utilizes the Linux operating system. All six sides of the IPEX spacecraft will have solar panels for electrical power generation and is anticipated to have 1-1.5W power generation. The IPEX spacecraft will use passive magnetic attitude control to stabilize the CubeSat in low earth orbit. The spacecraft carries several batteries to enable operations in eclipse and continuous processing modes. IPEX will carry five Omnivision OV3642 cameras, each producing images at approximately 2048 x 1536 pixel resolution, 3 megapixels in size, with a finest instantaneous field of view of 0.024 degrees. With our currently manifested orbit we predict approximately 200m/pixel imagery of the Earth's surface at nadir. Figures 2 shows imagery from a balloon test flight in July 2012 acquired approximately 102,000 feet above sea level.

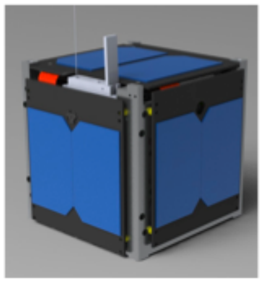

Figure 1: IPEX Model

IPEX will also carry a Gumstix Earth Storm computer-on-module [Gumstix 2013] which includes an 800 MHz ARM processor, 512MB RAM, 512 MB NAND flash, utilizing the Linux operating system. Current power benchmarks indicate that the Gumstix will utilize less than 1W power and will be on the majority of the time if not all of the time.

IPEX Ground and Flight Operations

IPEX is intended to demonstrate automated ground and flight operations of onboard autonomous processing of instrument data. In order to achieve this end, a range of capabilities and software are required.

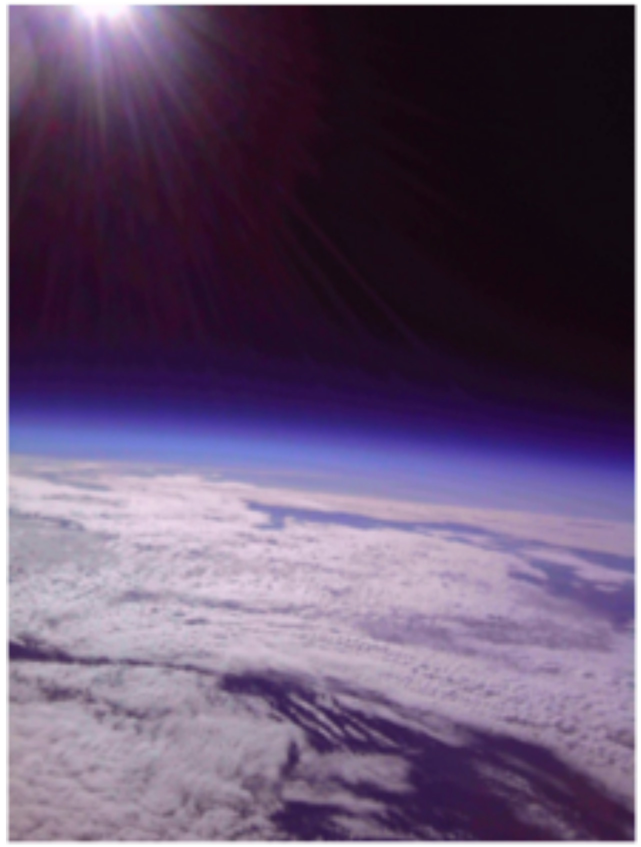

Figure 2: Image from July 2012 balloon test flight acquired approximately 102,000 feet asl

IPEX Ground Mission Planning

The ground mission planning software for IPEX uses the CLASP [Knight & Hu 2009, Rabideau et al. 2010, Knight et al. 2012] planning system to determine the processing and downlink requests based on the projected overflight of the spacecraft.

These requests are then handled in a priority-based fashion by the ASPEN [Rabideau et al. 1999] system to generate a baseline schedule for several days operations as a forward looking baseline schedule. ASPEN must manage the ground contact schedule, eclipse schedule, observation activities, and onboard image processing activities. The onboard image processing activities can involve a range of constraints including CPU usage, RAM usage, and downlink product size. The primary activities of image-acquisition and image-processing can also require significant data storage resources based on when the image is acquired versus when the Gumstix is powered on (thermal & power constrained) to process the image.

IPEX Onboard Planning

Onboard the spacecraft, the CASPER [Chien et al. 2000] planner will be used to manage spacecraft resources. CASPER will model all of the same resources and constraints as ASPEN but will be able to modify IPEX operations in response to deviations from the ground predicted plan such as: using more or less power than expected, activities taking longer or shorter than expected, or image products being larger or smaller than expected. CASPER will also be able to respond to onboard analysis of instrument data such as detection of features or events in imagery. Onboard processing will also be used to detect data of little value (e.g. images of dark space) early in processing activity. This analysis will save processing time, data-storage, and energy that would have been spent processing these less interesting images. In response, CASPER can schedule follow-on acquisitions from event or feature detection, or previously unscheduled lower priority data acquisition goals.

The CASPER model for IPEX represents a number of software processing workflows and a number of operations constraints.

The basic processing flow of the IPEX spacecraft is as follows.

1. Acquire imagery with a camera (ideally of a ground specified target area)
2. Process the image with a preliminary assessment quite which scores the image as likely of the Earth
3. Process the image on the Atmel processor with a range of selected image processing algorithms
4. Process the image on the Gumstix processor with a range of selected onboard algorithms.
5. Compare the generated products to determine if the products vary.

Additionally, at each earth contact, the spacecraft will perform a number of actions.

1. Downlink engineering telemetry since the last ground contact
2. Downlink statistics on onboard processing (images acquired, images processed, runtimes, comparison results).
3. Downlink a small subset of the images and/or products for ground validation

The CASPER model for IPEX contains a number of resources including: the communications system, power, battery state of charge (energy), several data stores (Atmel SD flash, Gumstix flash, Gumstix SD flash), Atmel and Gumstix CPU resources, and camera resources.

The CASPER IPEX model also contains a number of activities including power generation (via solar panels), acquiring images, processing images using various algorithms, conversion of image formats, ground contacts, cleaning up file systems, solar view, eclipse, and activities pertaining to downlink.

CASPER onboard generally schedules ground-requested imaging, and onboard generated imaging requests and associated image processing along with each set of images acquired. CASPER onboard receives imaging time windows within which IPEX is allowed to image. This is to account for the constraint that when the IPEX payload board is powered (e.g. camera or gumstix usage) noise from this card reduces the ability of IPEX to receive uplinked signals.

IPEX Command and Data Handling

The base flight software on IPEX is based on extensions and adaptation of the Linux operating system. The well-known System V *init* process is used directly to start, and restart if necessary, the principal components of the flight software: system manager for health monitoring, watchdog, beacon for real-time distribution of telemetry, datalogger for logging and archiving of telemetry and a sequence execution processes for real-time, time-based, and event-based commanding of the spacecraft.

IPEX Onboard Instrument Processing

IPEX will be validating a wide range of onboard instrument processing algorithms. The vast majority are variations of pixel mathematics, e.g. normalized difference ratios, band ratios, and similar products. For example, many flooding (surface water extent) classifications are based on band ratios [Brakenridge et al. 2005, Ip et al. 2006, Carroll et al. 2009]. Snow and ice products also use simple band processing formulae [MODIS]. Thermal anomaly detection algorithms such as for volcano [Wright et al. 2003, 2004, Davies et al. 2006] and active fire mapping [Justice et al. 2002] also involve computationally efficient slope analysis of spectral signals. Finally, a wide range of vegetation indicators also involve difference ratios or similar computations [Perry and Roberts 2008].

IPEX will also fly more computationally complex image processing technologies. These include: Support Vector Machine Learning Techniques [Cortes and Vapnik 1995, Doggett et al. 2006], spectral unmixing techniques [Bornstein et al. 2011], and TextureCam [Thompson et al. 2012] Random Decision forest classification techniques.

IPEX is expected to have an extremely limited downlink data rate (less than 9600 bits per second). As a result, most of the IPEX onboard processing validation will come from running algorithms on the same images on the Atmel and Gumstix, and comparing the results. Only in cases where the results do not compare will full images be likely to be downlinked.

IPEX Status

The IPEX spacecraft bus design and development is led by Cal Poly San Luis Obispo and is mostly complete. Originally IPEX was intended to fly the SpaceCube Mini processor package [Flatley 2009] unfortunately schedule issues required the switch to the Gumstix. Many elements of the spacecraft such as the CPU/system board and structure are complete. Many other elements such as the payload interface board are mostly complete with minor revisions expected. As this paper is written the engineering test unit (ETU) has completed assembly and is awaiting vibration testing.

The ground and flight autonomy software is developed by JPL and has been assembled in a set of software spirals. The first versions of the ASPEN planning model were developed in the summer of 2011. An updated version of the CASPER software is being integrated with the Cal Poly flight software in the summer of 2012. Roughly a dozen of the image processing algorithms are currently operating on the Atmel and Gumstix processors. Current efforts are focused on increasing the fidelity of the operations models, implementing safeguards to avoid deadlock and other software issues, and closer integration with the Cal Poly flight software.

We have tested most elements of the IPEX hardware and software on two balloon launches the 28th July 2012 and 9th December 2012. These flights were a high end-to-end test of the commanding software, image acquisition, telemetry, and hardware in a near space environment. These flights also enabled acquisition of test imagery in near space like conditions with the flight cameras.

IPEX is manifested for a October 2013 launch. This launch has an associated May 2013 launch integration delivery. Our engineering test unit is in environmental testing. A number of remaining hardware issues should be resolved before construction of the flight unit in late Spring 2013. Software is currently in extended duration tests. Final flight hardware is scheduled for delivery in mid June.

Related Work, Future Work, and Conclusions

The Remote Agent controlled the Deep Space One spacecraft for approximately two days in 1999 [Muscettola et al. 1998]. The Autonomous Sciencecraft on the Earth Observing One (ASE) spacecraft has pioneered onboard instrument data analysis [Chien et al. 2005]. In particular ASE highlighted onboard product generation for volcanology [Davies et al. 2006], flooding [Ip et al. 2006], and cryosphere [Doggett et al. 2006] disciplines. However, ASE did not have to deal with high data rate streams that will challenge IPEX and the proposed HyspIRI mission and HyspIRI Intelligent Payload Module.

Onboard the Mars Exploration Rovers, the WATCH software enables automatic processing of imagery to track dust devils and cloud features [Castano et al. 2008]. More recently, the AEGIS software enables onboard retargeting for targets of geological interest [Estlin et al. 2012].

We have described the IPEX mission to flight validate autonomous operations and onboard instrument processing. The IPEX cubesat will also demonstrate low cost, autonomous ground and flight mission operations enabling end users to specify image processing and product requests.

References

B. Bornstein, R. Castano, S. Chien, D. Thompson, B. Bue, “Spectral segmentation and endmember detection onboard spacecraft,” IEEE WHISPERS Workshop, Lisbon, Portugal, June 2011.

G.R. Brakenridge and E. Anderson, MODIS-based flood detection, mapping, and measurement: the potential for operational hydrological applications. In: Transboundary Floods, Proc. of NATO Advanced Research Workshop, Baile Felix – Oradea, Romania, May 4-8, 2005.

M. Carroll, Townshend, J., DiMiceli, C., Noojipady, P., Sohlberg, R. (2009), A New Global Raster Water Mask at 250 Meter Resolution. International Journal of Digital Earth, December 2009.

A. Castano, A. Fukunaga, J. Biesiadecki, L. Neakrase, P. Whelley, R. Greeley, M. Lemmon, R. Castano, S. Chien, “Automatic detection of dust devils and clouds at Mars,” *Machine Vision and Applications*, October 2008, vol. 19, No. 5-6, pp. 467-482.

C. Cortes and V. Vapnik, "Support-Vector Networks", Machine Learning, 20, 1995.

S. Chien, R. Knight, A. Stechert, R. Sherwood, and G. Rabideau, "Using Iterative Repair to Improve the Responsiveness of Planning and Scheduling," *Proceedings of the Fifth International Conference on Artificial Intelligence Planning and Scheduling*, Breckenridge, CO, April 2000.

S. Chien, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, D. Mandl, S. Frye, B. Trout, S. Shulman, D. Boyer, “Using Autonomy Flight Software to Improve Science Return on Earth Observing One, *Journal of Aerospace Computing, Information, & Communication*, April 2005, AIAA.

S. Chien, D. Silverman, A. Davies, D. Mandl, Onboard Science Processing Concepts for the HyspIRI Mission, *IEEE Intelligent Systems*, November/December 2009 (vol. 24 no. 6), pp. 12-19.

S. Chien, J. Doubleday, K. Ortega, T. Flatley, G. Crum, A. Geist, M. Lin, A. Williams, J. Bellardo, J. Puig-Suari, E. Stanton, E. Yee, “Onboard Processing and Autonomous Operations on the IPEX Cubesat Mission,” Intl Symposium on Space Artificial Intelligence, Robotics, and Automation for Space, Turin, Italy, Sep 2012.

A.G. Davies S. Chien, V. Baker, T. Doggett, J. Dohm, R. Greeley, F. Ip, R. Castaňo, B. Cichy, G. Rabideau, D. Tran and R. Sherwood, “Monitoring Active Volcanism with the Autonomous Sciencecraft Experiment (ASE) on EO-1,” Remote Sensing of Environment, vol. 101, no. 4, 2006, pp. 427–446.

T. Doggett,, R. Greeley, A. G. Davies, S. Chien, B. Cichy, R. Castano, K. Williams, V. Baker, J. Dohm and F. Ip (2006) Autonomous On-Board Detection of Cryospheric Change. *Remote Sensing of Environment*, Vol. 101, Issue 4, pp. 447-462.

T. Estlin, B. Bornstein, D. Gaines, R. C. Anderson, D. Thompson, M. Burl, R. Castaño, M. Judd, AEGIS Automated Targeting for the MER Opportunity Rover, ACM Transactions on Intelligent Systems and Technology, V. 3, No. 3, 2012.

T. Flatley, SpaceCube Processor, <http://hyspiri.jpl.nasa.gov/downloads/public/2.9%20Flatley%20-%20OnBoard%20Processing%20Technology.pdf

Goddard Space Flight Center, http://directreadout.sci.gsfc.nasa.gov/

Gumstix Earth Storm, https://www.gumstix.com/store/product_info.php?products_id=264

HyspIRI Mission, http://hyspiri.jpl.nasa.gov

F. Ip, J. Dohm, V. Baker, T. Doggett, A. Davies, R. Castano, S. Chien, B. Cichy, R. Greeley, R. Sherwood, D. Tran, G. Rabideau, Flood detection and monitoring with the Autonomous Sciencecraft Experiment onboard EO-1, Remote Sensing of Environment, Volume 101, Issue 4, 30 April 2006, Pages 463-481.

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D.P., Descloitres, J., Alleaume, S., Petitcolin, F., Kaufman, Y. 2002. The MODIS fire products. Remote Sensing of Environment 83:244-262.

R. Knight, D. Mclaren, S. Hu, “Planning Coverage Campaigns for Mission Design and Analysis: CLASP for the proposed DESDyni Mission,” Proceedings International Symposium on Artificial Intelligence, Robotics, and Automation for Space, Turin, Italy, September 2012.

R. Knight and S. Hu. "Compressed Large-scale Activity Scheduling and Planning (CLASP)," Proceedings of the Sixth International Workshop in Planning and Scheduling for Space (IWPSS-2009), July 19th-21st, Pasadena, California, 2009.

MODIS Snow Ice Web site, http://modis-snow-ice.gsfc.nasa.gov/

N. Muscettola, P. Nayak, B. Pell, B. Williams, “**Remote agent: To boldly go where no AI system has gone before**, Artificial Intelligence, 1998 – Elsevier.

E. Perry and D. Roberts, “Sensitivity of Narrow-Band and Broad-Band Indices for Assessing Nitrogen Availability and Water Stress in an Annual Crop, Agronomy Journal, vol. 100 Issue 4, 2008, pp. 1211-1219.

G. Rabideau, S. Chien, D. Mclaren, R. Knight, S. Anwar, G. Mehall, “A Tool for Scheduling THEMIS Observations, International Symposium on Space Artificial Intelligence, Robotics, and Automation for Space, Sapporo, Japan, August 2010.

G. Rabideau, R. Knight, S. Chien, A. Fukunaga, A. Govindjee, "Iterative Repair Planning for Spacecraft Operations in the ASPEN System," *International Symposium on Artificial Intelligence Robotics and Automation in Space*, Noordwijk, The Netherlands, June 1999.

D. R. Thompson, A. Allwood, D. Bekker, N. A. Cabrol, T. Estlin, T. Fuchs, K. L. Wagstaff, "TextureCam: Autonomous image analysis for astrobiology survey," Lunar and Planetary Sciences Conference, Houston, TX, (2012).

Wright, R., Flynn, L. P., Garbeil, H., Harris, A., & Pilger, E. (2003). Automated volcanic eruption detection using MODIS. Remote Sensing of Environment, 82, 135– 155.

Wright, R., Flynn, L. P., Garbeil, H., Harris, A. J. L., & Pilger, E. (2004). MODVOLC: Near-real-time thermal monitoring of global volcanism. Journal of Volcanology and Geothermal Research, 135, 29–49.