AUTONOMY FOR REMOTE SENSING - EXPERIENCES FROM THE IPEX CUBESAT

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ABSTRACT

The Intelligent Payload Experiment (IPEX) is a CubeSat mission to flight validate technologies for onboard instrument processing and autonomous operations for NASA's Earth Science Technologies Office (ESTO). Specifically IPEX is to demonstrate onboard instrument processing and product generation technologies for the Intelligent Payload Module (IPM) of the proposed Hyperspectral Infra-red Imager (HyspIRI) mission concept. Many proposed future missions, including HyspIRI, are slated to produce enormous volumes of data requiring either significant communication advancements or data reduction techniques. IPEX demonstrates several technologies for onboard data reduction, such as computer vision, image analysis, image processing and in general demonstrates general operations autonomy. We conclude this paper with a number of lessons learned through operations of this technology demonstration mission on a novel platform for NASA.

1 SPACECRAFT BACKGROUND

As a 1U cubesat, IPEX is approximately 10cm x 10cm x 10cm. To support the IPEX primary flight software, IPEX carries a 400MHz Atmel ARM9 CPU (no hardware floating point) with 128MB RAM, a few megabytes of radiation robust phase-change memory for essential software, 512MB NAND flash memory, and a 16 GB Micro SD card. IPEX utilizes the Linux operating system version 2.6.30, and a number of drivers and software executables for its base flight-software. All six sides of the IPEX spacecraft have solar panels for electrical power generation providing 1-1.5W power generation when not in eclipse, and roughly a 20 W-hr battery module to handle high-power operations and eclipses. For attitude control, the IPEX spacecraft uses passive magnetics to reduce tumbling of the CubeSat in low earth orbit to a predictable pattern in earth's magnetic field. Communications are handled via a radio tuned for amateur band UHF radio, amplified by 1 watt through an omnidirectional antenna of shape-memory alloy. The radio was initially configured for 9600 baud communication, with an option of easily increasing the rate should the link margin prove adequate. IPEX carries five OmniVision OV3642 cameras, each on a separate face of the spacecraft cube. Each camera is capable of producing images at 2048 x 1536 pixel resolution, 3 megapixels in size, with a finest instantaneous field of view of 0.024 degrees. With the IPEX orbit these cameras enable approximately 200m/pixel imagery of the Earth's surface at nadir.

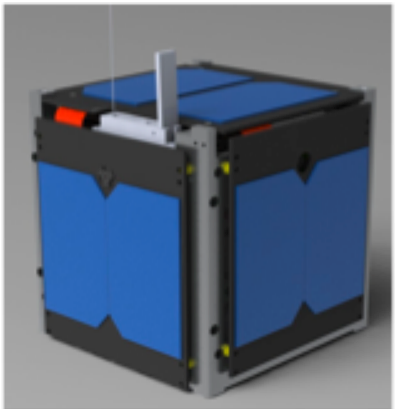

Figure 1 Rendered model of assembled and deployed IPEX spacecraft.

IPEX also carries a Gumstix Earth Storm computer-on-module which includes an 800 MHz ARM processor, 512MB RAM, 512 MB NAND flash, utilizing the Linux operating system[17]. The Gumstix utilizes slightly less than 1W power when powered. Power is controlled via flight software on the main Command and Data Handling (CDH) board. These two boards are linked via a 200kbit serial link over which Point-to-Point Protocol (PPP) is run to create a local area network and to transfer data files, commanding, and process logging.

2 IPEX GROUND AND FLIGHT OPERATIONS

The proposed HypsIRI IPM concept would involve both ground and flight automation. On the ground, users would use a geographic tool (e.g. 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 [18]. Additionally, onboard the 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 demonstrates technologies for both the ground and flight automation aspects of the proposed HyspIRI concept. The ground mission planning software for IPEX uses the CLASP planning system to determine the processing and downlink requests based on the projected overflight of the spacecraft[13,14,15]. Onboard the spacecraft, the CASPER planner manages spacecraft resources [16]. CASPER models 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. CASPER modifies IPEX operations in response to deviations from the modelled/predicted plan such as: battery state of charge deviations, activities taking longer or shorter than expected, or image products being larger or smaller than expected. CASPER also responds to onboard analysis of instrument data such as detection of features or events in imagery.

Onboard processing is used to detect data of little value (e.g. images of dark space) early in processing activity. This analysis saves 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 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, satcom for managing communication with the ground, datalogger for logging and archiving of telemetry and a sequence execution processes for real-time, time-based, and event-based commanding of the spacecraft.

3 IPEX ONBOARD INSTRUMENT PROCESSING

IPEX validates 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 [1,3]. Snow and ice products also use simple band processing formulae [4]. Thermal anomaly detection algorithms such as for volcano [5,6,7] and active fire mapping [8] also involve computationally efficient slope analysis of spectral signals. Finally, a wide range of vegetation indicators also involve difference ratios or similar computations [9].

IPEX is also flying more computationally complex image processing technologies. These include: support vector machine classifiers [10,2], the TextureCam random forest classifier [12,19,20], spectral unmixing techniques [11,21], and onboard discovery through image salience analysis [22].

4 LESSONS

4.1 Operations Contingency Plans

The notional IPEX con-ops involved a regular uplink of ground generated schedule of observation requests and schedule of ground contacts to IPEX – the later to minimize electrical noise from cameras and the auxiliary processor while utilizing the radio link. Through the hardware development phase it became apparent that the radio link had very little margin, particularly at the spacecraft receive side.

Resolving a ground loop and employing a few other EMI mitigations provided enough confidence in the communication system to proceed with the mission. Contingencies were added to the con-ops in case radio communication wasn't reliable: should the ground stations be unable to successfully transmit any commands to IPEX (e.g. send-file command) but successfully receive beacon telemetry from the spacecraft, IPEX was configured to randomly schedule a 45 minute window of processing time every 12 hours, effectively allowing the onboard autonomous system "idle time" to schedule low-priority jobs for collecting and/or process images. Additional processing time can be added via ground commands.

In operations the uplink margin indeed proved limited. In practice a "good" pass would successfully transmit from ground 20-30 packets, or 1-2kilobytes, which could translate to 50-300kB of retrieved files. However most passes through the duration of the mission had a net retrieval of <50kB of data per pass, and uplinking 1kB of command data was a challenge.

In order to maximize the uplink bandwidth, the number of specific scheduled observation-requests – at the cost of ~100 bytes each – was minimized and instead predominantly schedules-of-ground-contacts uploaded – at a cost of 80 bytes per interval or 200-400 bytes per day – to provide the onboard autonomous system up to 22 hours per day of operations. While the resulting autonomously generated "idle" observations were not geographically targeted, it did allow a bulk of observations on the order of 100-200 per day as compared to approximately 10 targeted observations per day from the random 45 minute windows.

Ultimately this hybridized use of the contingency operations concept of purely idle observations, and the limited uplink to expand the allowed idle time, allowed us to reach our mission success criteria of 10000 observation products ahead of schedule.

4.2 Preloading Utilities

With excess data storage onboard, and the limited communications that manifested, it would have been advantageous to have a larger super-set of software preloaded on the spacecraft, allowing for in-flight adaptations without uploading new software images. For example, with a number of image products downlinked and evaluated, it was found that sun-glint images were difficult to classify. Had the texture-cam training executable been onboard to retrain on existing onboard images against highly-compressed uplinked class-masks, an improved sun-glint filter may have been feasible. Retrained forests were far to large generate on ground and uplink.

4.3 Fault-Handling (reboot)

IPEX responds to faults by performing a full hardware power cycle. Early in the mission the time between reboots was up to 27 days. As the mission wore on reboots became more frequent. The longest uptime since July 2014 is 140 hours with most uptimes less than 70 hours. The reason for every reboot has not been determined, however some reboots were due to latch-up events as indicated by abnormally high current draw. Additional reboots correlate with an increase in class M and X solar flare activity. IPEX experienced 3-4 times the average CubeSat radiation due to its orbit, which causes it to clip the Van Allen Belts twice per revolution.

4.4 Passive magnetic attitude stabilization

Our model of spacecraft attitude and camera pointing never developed due to insufficient magnetic dipole measured at final spacecraft assembly. However telemetry from solar panels and temperature gauges indicates that our spin rate was dampened by magnetic hysteresis material and was low enough for clear images, as originally designed.

4.5 Hardware does not maintain itself

IPEX was fortunate to have manifested on a relatively high orbit that should last many years, far outlasting the expected (and realized) life of the spacecraft hardware, and unfortunately outlasting funding for maintenance and staffing of ground-station operations. While IPEX was a demonstration of autonomy, rotors, antennas and amplifiers subjected to outdoor weather conditions cannot service themselves. Many potential passes of IPEX were either missed or executed less than ideally due to the ground-stations being operated on a best-effort pro-bono basis and not having funding/staffing dedicated to maintaining the systems.

4.6 Plan for extended mission lifetime

The initial contingency plans proved successful. IPEX was able to meet its success criteria ahead of schedule, however long term maintenance was a lower priority. As a result maintenance activities that needed to occur on a 6 or 12 month timescale were designed as ground in the loop. This proved limiting when IPEX went weeks without ground commanding.

5 SUMMATION

IPEX launched in Dec 2013 and despite some early hardware anomalies, went on to quickly achieve its baseline automation mission ahead of schedule. While IPEX no longer communicates as of February 2015, we have captured a number of lessons from this mission to be applied to future low-cost autonomous missions.

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