Real-Time Data Products and the Intelligent Payload Module

Daniel Mandl - NASA/GSFC
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HyspIRI-SBG Workshop

HyspIRI Mission Study

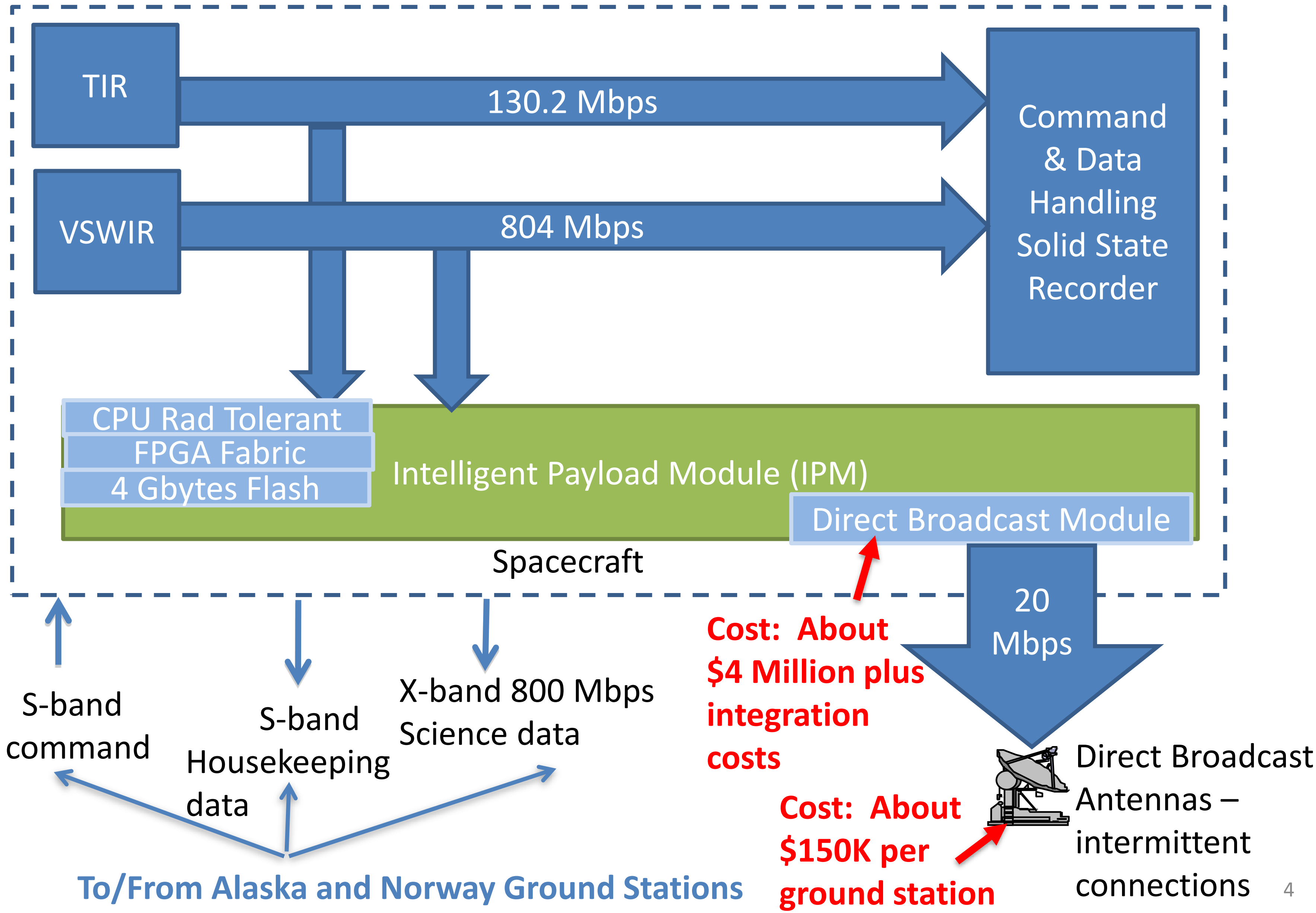
Intelligent Payload Module(IPM)

- Consists of
  - Onboard radiation hardened or tolerant processor
    - CPU and Field Programmable Gate Array fabric to realtime processing
  - For HyspIRI, onboard processing fast enough and enough memory and field programmable gate array gates to band strip selected bands at 4 Gbps and possibly perform radiometric correction, atmospheric correction and georeferencing/Orthorectification/co-registration at that speed
  - Non-volatile storage separate from SC solid state recorder
  - Communication link to ground separate from SC communication systems for rapid interface to ground
- Provide quick look products in realtime or near realtime
  - Subset of VSWIR and/or TIR bands
  - Level 3 products
  - Intelligent triggering to detect and initiate transmission to the ground of selected features, disturbances, disasters etc.
- Separate from SC Command and Data Handling processor but connected so that key telemetry information can be shared

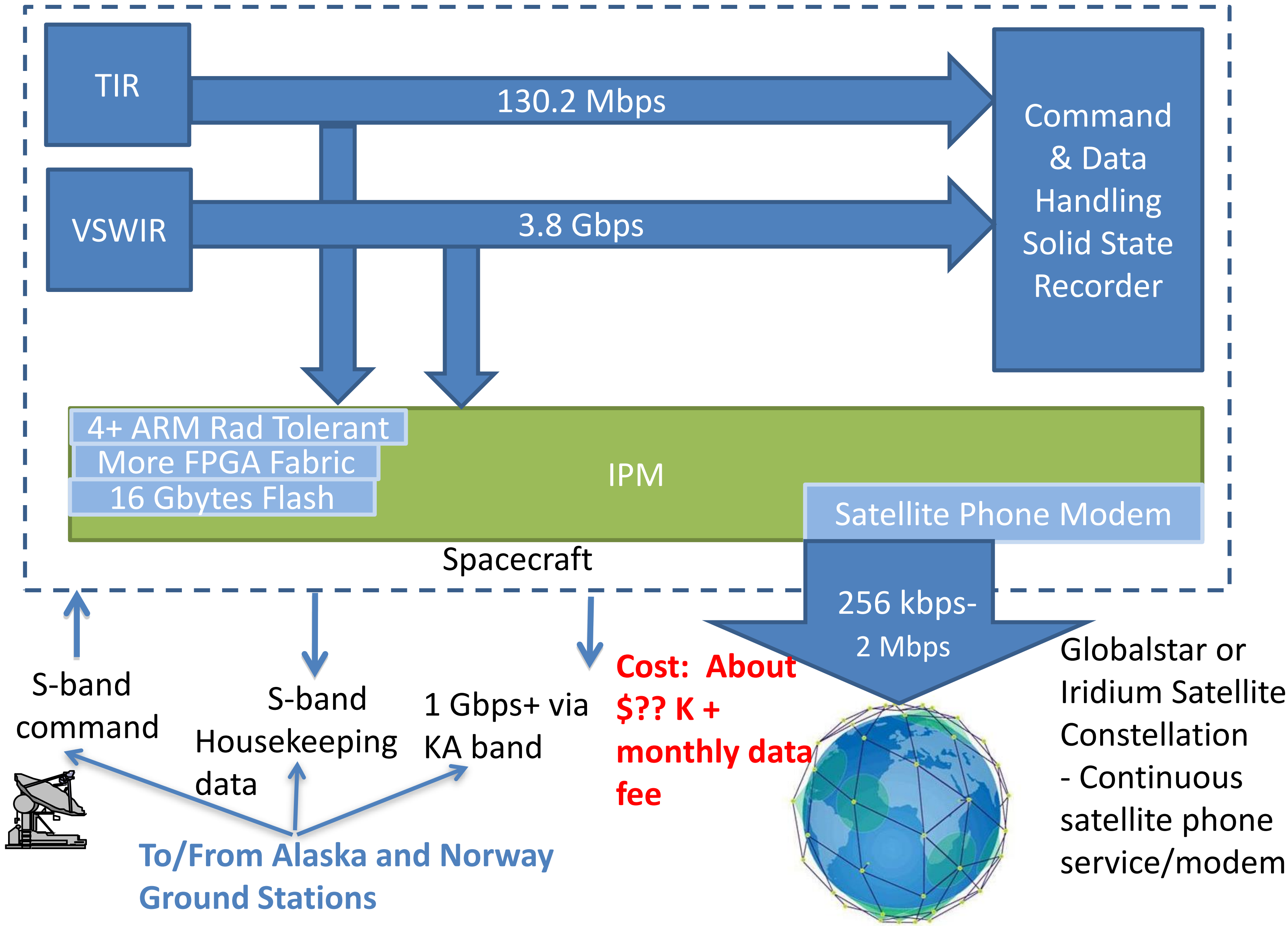
Responsive to HyspIRI Science Questions

- Cross cutting
- Disasters (Fires, Floods, Volcanoes etc) for first responders and others with low latency needs
- Contemporaneous measurements with field campaigns
- Quicklook science data and products
- Continuous monitoring for desired features and selected actions when detected

Original HyspIRI Low Latency Data Flow Operations Concept and Some Rough Cost Estimates/Guesses



More Recent HyspIRI Low Latency Data Flow Operations Concept



Platforms Used to Experiment with IPM Onboard Processing (GSFC + JPL)

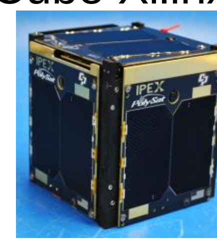
AMS, USFS King Air B200
Tilera TilePro/SpaceCube
(Maestro Proxy)

Contract MD 500C
ChaiV640, TilePro

ISS Optical Window
(SpaceCube Xilinx FPGA)

Intelligent
Payload
Module

USFS Cessna Citation
AMS, Tilera TilePro/SpaceCube
(Maestro Proxy)



IPEX Cubesat(Gumstix)

DJI M600 Drone
Piccolo,
NanoHyperspec
(ARM/CSP)

NASA Cessna 206H
ChaiV640, TilePro/SpaceCube

EO-1/ ASE/ CASPER/Mongoose

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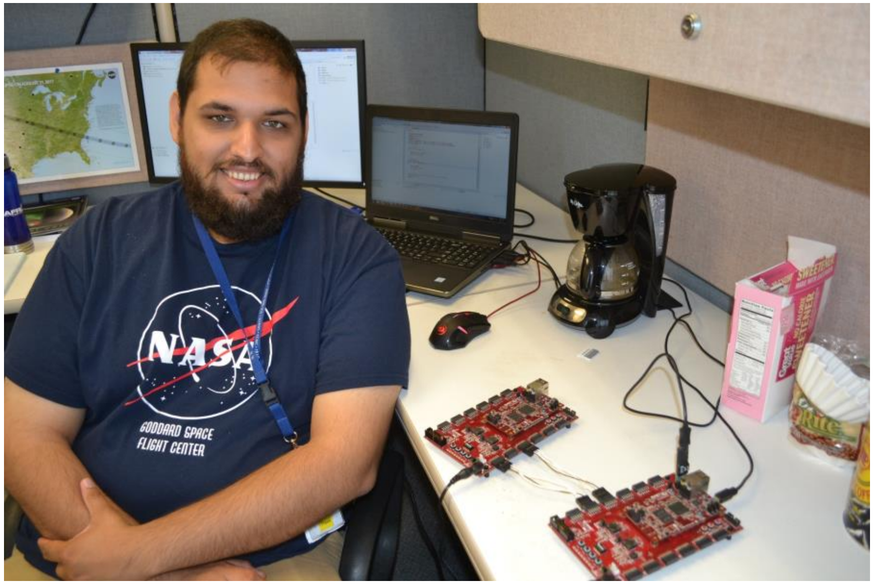
Demo of 4 Gbps Throughput for IPM Using FPGA



- Travis Wise demos field programmable gate array (FPGA) data thoughput of 4 Gbps with 5 LVDS twisted pair using 2 MicroZeds – 6-22-17
- Each LVDS carries 800 Mbps
- Issue with completing Level 1 Radiometric correction due to not enough fabric memory on the smaller MicroZed. Alleviated by newer larger fabric/on-fabric memory
- Use MicroZed because there is a space rated board called CHREC Space Processor (CSP) which sells for $20-80K depending on quality of components
- Higher performance boards exist in commercial world and also more radiation hardened boards (SpaceCube) also exist but are more expensive
- For comparison: EO-1 took 20 minutes to create small onboard products with Mongoose processor

Some Viable IPM Processors for Space

Onboard Processor	FPGA/CPU Type	CPU Memory (DDR)	Fabric Memory Block Ram	Non-volatile storage	Cost of Flight Unit	Date TRL 7-9	Comment
CHREC Space Processor	Xynq/2 ARMs (667 Mhz)	1 Gbyte DDR2	612Kbyte	4 Gbyte	$20-80K	now	radiation tolerant
SpaceCube 2 (Defense)	2 x V5 rad tol 4 PowerPCs 400 Mhz	4 x 512 MB DDR2	2 x 1341 Kbytes	2 x 4 Gbytes	$500K	now	Radiation tolerant
SpaceCube 2 (Radhard)	Virtex 5 softcore- N x Microblaze 75Mhz	4 x 512 MB DDR2	2 x 1341 Kbytes	2 x 4 Gbytes	$600K	now	Radiation hardened
SpaceCube 3	Kintex- /hardcore 4 PowerPC 1.2-1.8 Ghz	4Gbytes Processor/2 Gbytes FPGA-DDR3	4.75 Mbytes	1 x 16 Gbytes	??	TRL 6 2019 TRL 7-8 2020	Full missio grade-rad tol-meet RT req
SpaceCube 3	Kintex- HPSC hardcore – 8 ARMs 1.2-1.8 Ghz	4Gbytes Processor/2 Gbytes FPGA-DDR3	4.75 Mbytes	1 x 16 Gbytes	??	2021+	Full mission grade-meet RT req

Similar to Virtex 7

Virtex 5

Virtex 8

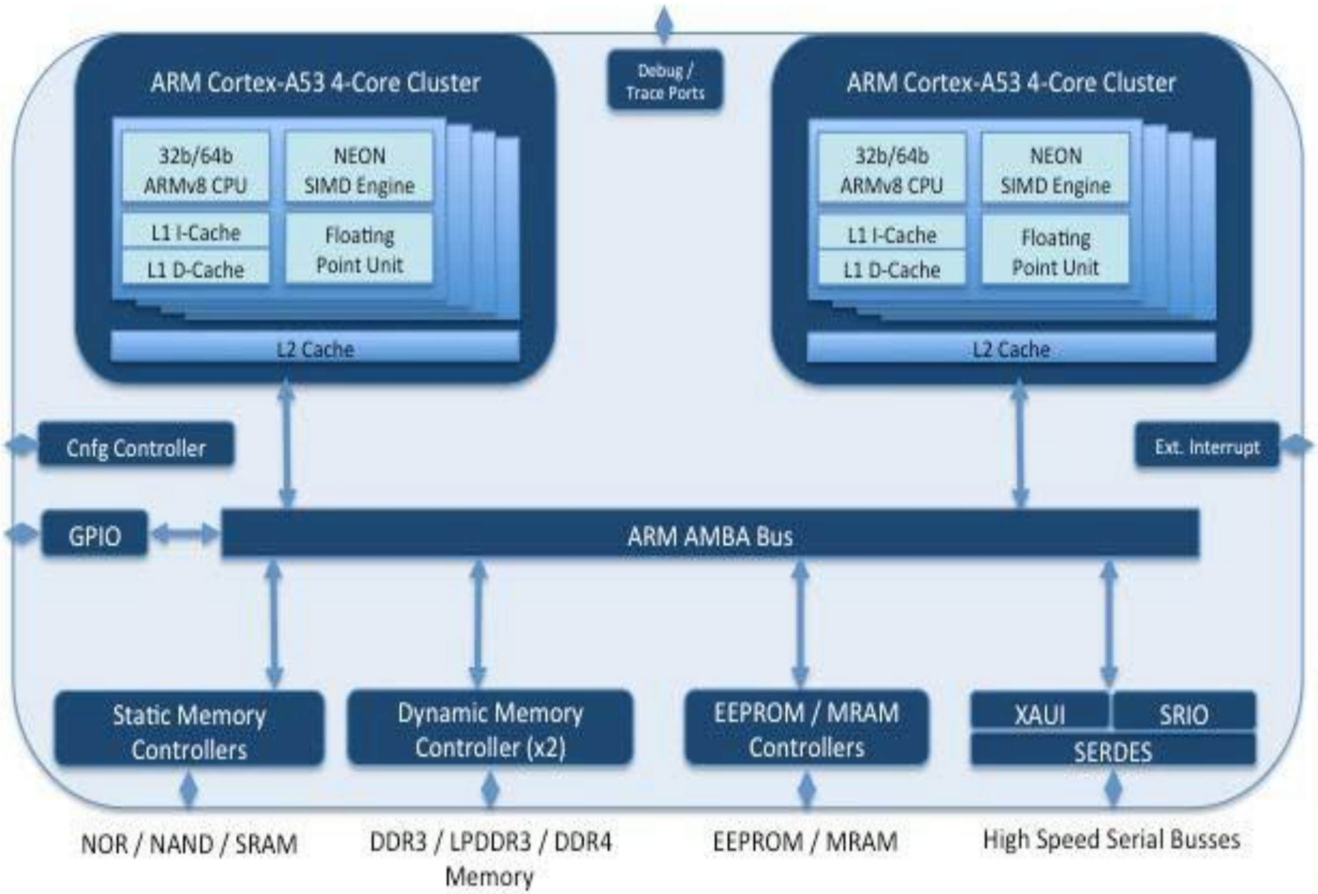
Cubesat grade

Achieved 10 Gbps thru

Full mission grade

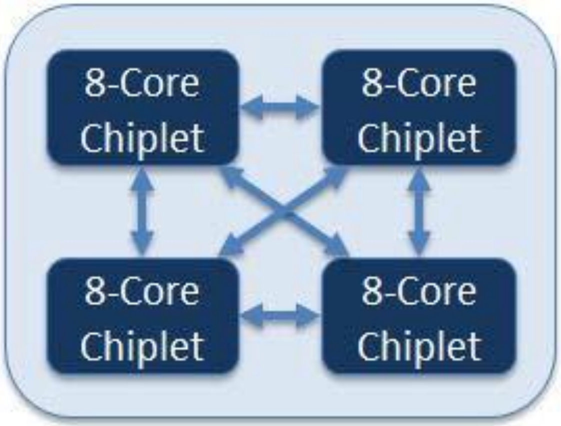
Note: 2018- Delivering double Virtex 5 flight boards to Robotic Refueling Mission 3

NASA Multicenter Effort for High Performance Space Computing (HPSC)



HPSC "Chiplet" Reference Design

- **ARM 64-bit processor cores (8)** and on- chip interconnects scalable **and** extensible in MCM (Multi-Chip Module) or on PCB (Printed Circuit Board) via XAUI and SRIO (Serial RapidIO) and/or increased fault tolerance (e.g. each Chiplet as separate fault containment regions, NMR)
- Target delivery of first chips, 2021



Multi-Chiplet Configuration

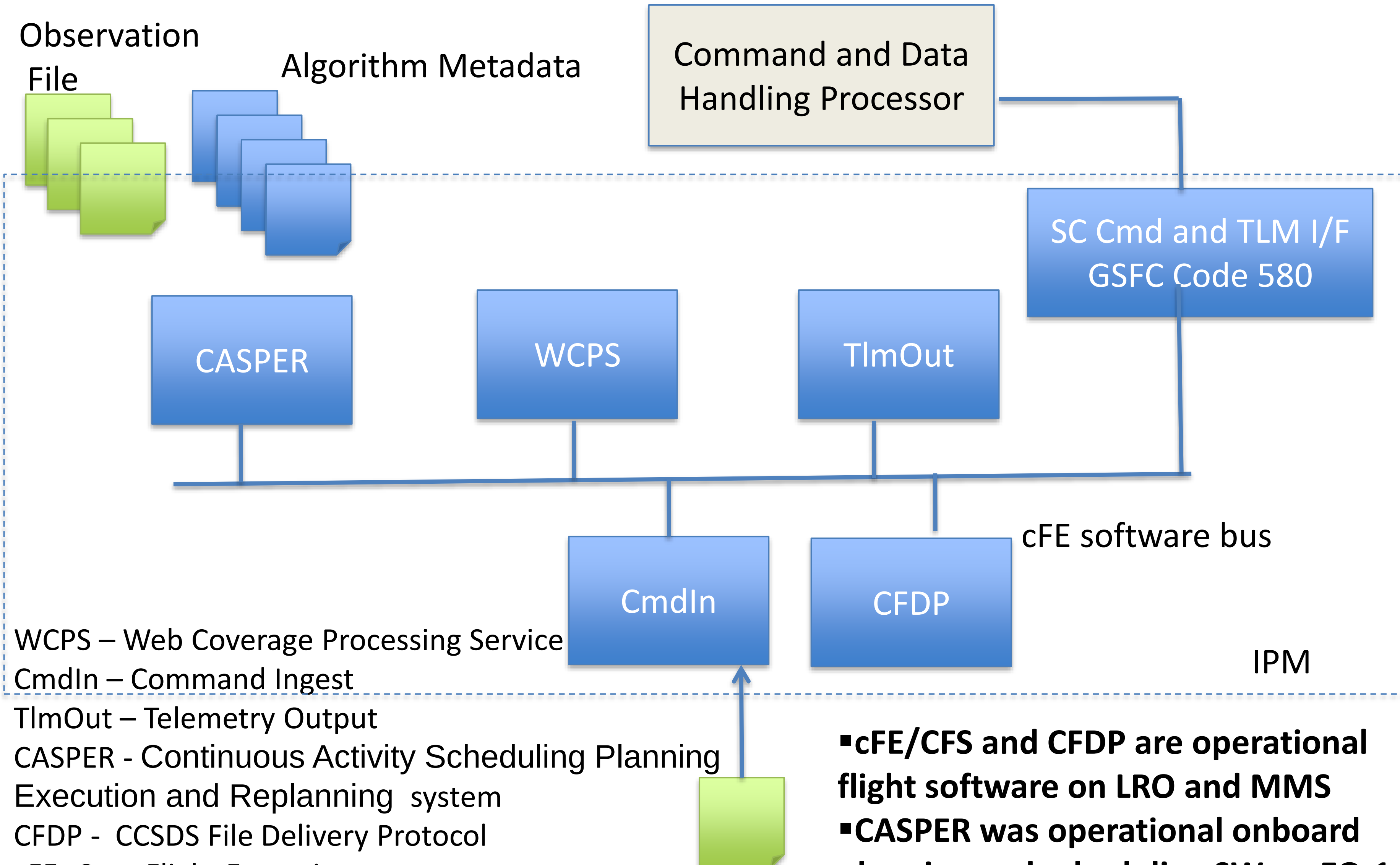
Another Candidate Architecture: Data Compression and Support Electronics (DCSE)

- Data Compression and Support Electronics (DCSE) developed as a high performance data acquisition and data compression SW/FW/HW targeting Xilinx Virtex 7 FPGA board for airborne deployment and System-on-Chip (SoC) boards based on modified COTS for space deployment.
- Integrated single core FLEX data compression targeting Virtex5 FPGA to the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission (launch 2018) and adapted DCSE SoC data acquisition system for 1280 by 480 frames at 240 frame/sec future HSI instrument. We will use DCSE SoC for the Earth Surface Mineral Dust Source Investigation on Space Station (EMIT) mission (launch 2020).
- Future technology developments will explore Multiple Processor System-on-the-Chip (MPSoC) and space qualified XQR Kintex UltraScale FPGA (XQRKU060) embedded with CHROMA-D which will able to provide hardware resource needed for real-time radiance, reflectance and data analysis.

Reference: Presentation at 2017 HyspIRI Science and Applications Workshop in Pasadena on October 17th-19th, 2017

High Performance Space Data Acquisition and Compression based on System-on-Chip Instrument Avionics for Space- based Imaging Spectrometers - Didier Keymeulen/JPL

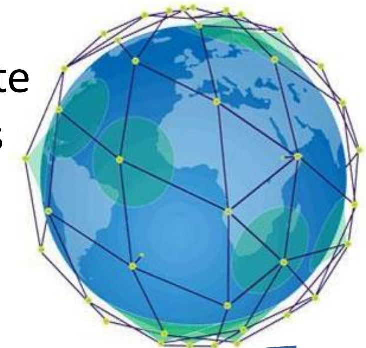
Preliminary Flight Architecture – TRL 7 - 9



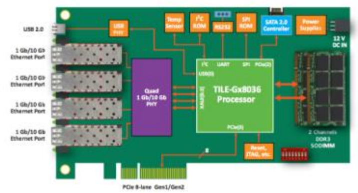
WCPS – Web Coverage Processing Service
CmdIn – Command Ingest
TlmOut – Telemetry Output
CASPER - Continuous Activity Scheduling Planning Execution and Replanning system
CFDP - CCSDS File Delivery Protocol
cFE- Core Flight Executive
CFS – Core Flight Software

- **cFE/CFS and CFDP are operational flight software on LRO and MMS**
- **CASPER was operational onboard planning and scheduling SW on EO-1**
- **WCPS is presently TRL 6**

Generalized Quick Look Concept of Operations



Globalstar or Iridium satellite constellation – continuous phone/modem service



Onboard multicore processor or single Linux processor

FPGA Onboard Accelerator

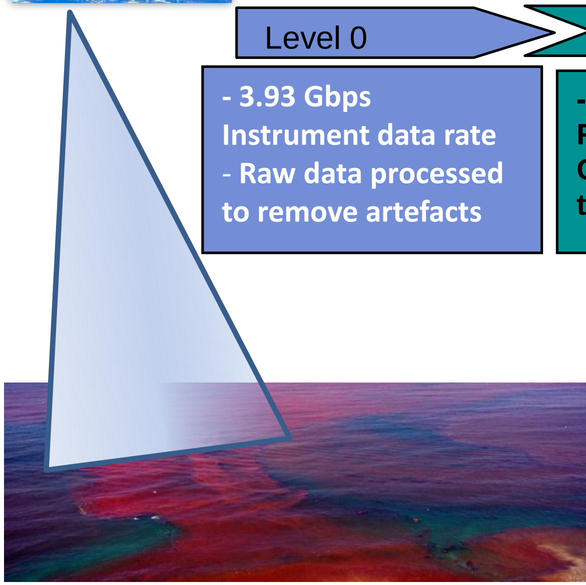
Level 0
- **3.93 Gbps Instrument data rate**
- **Raw data processed to remove artefacts**

Level 1R
- **Apply Radiometric Correction to each pixel**

Atmospheric Correction
- **Convert radiance to reflectance**

Geometric Correction
- **Tag each pixel with correct location information**

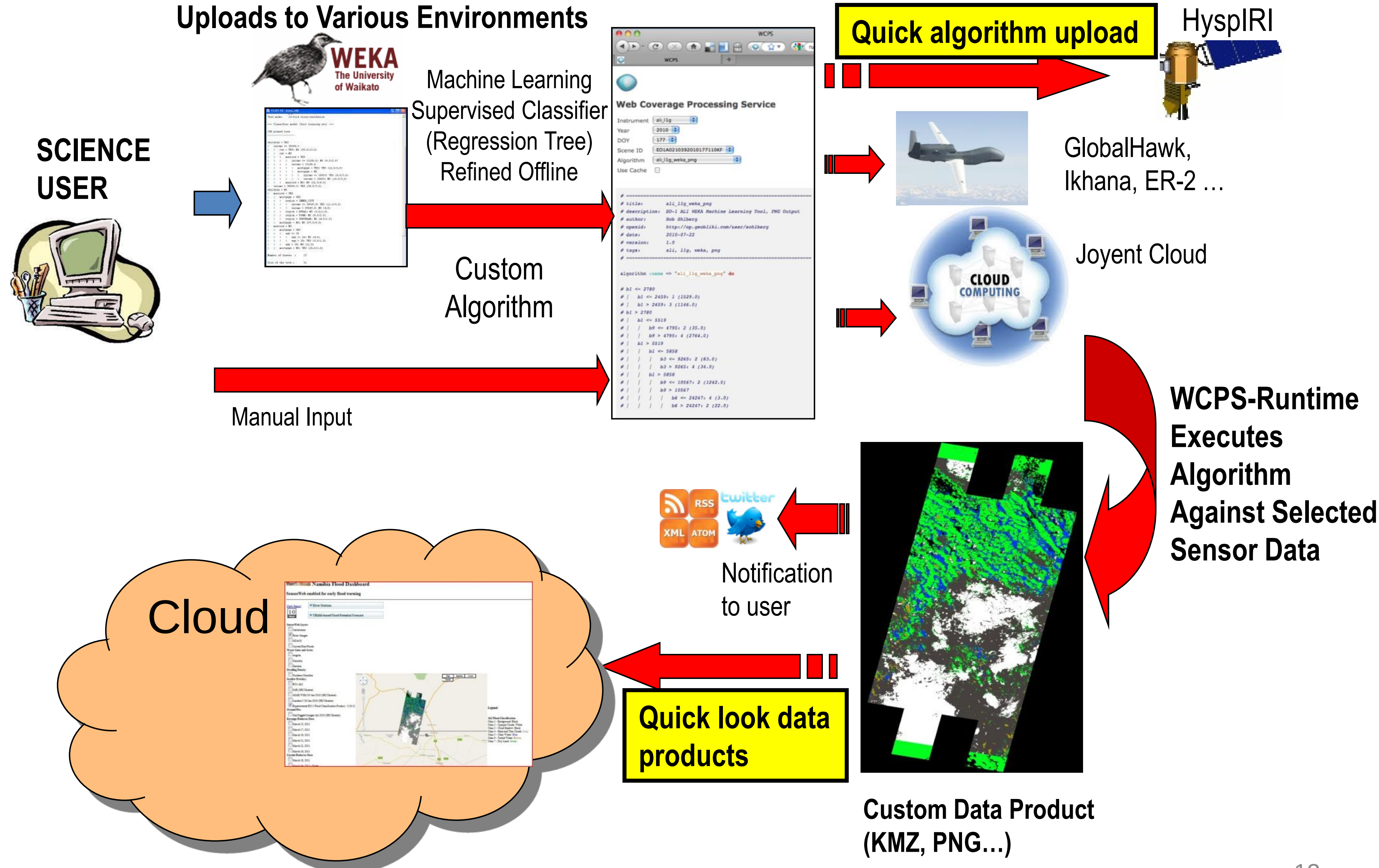
Level3 Classification
- Run Web Coverage Processing Service to run algorithm against data (e.g. spectral angle mapper, vectorizer)



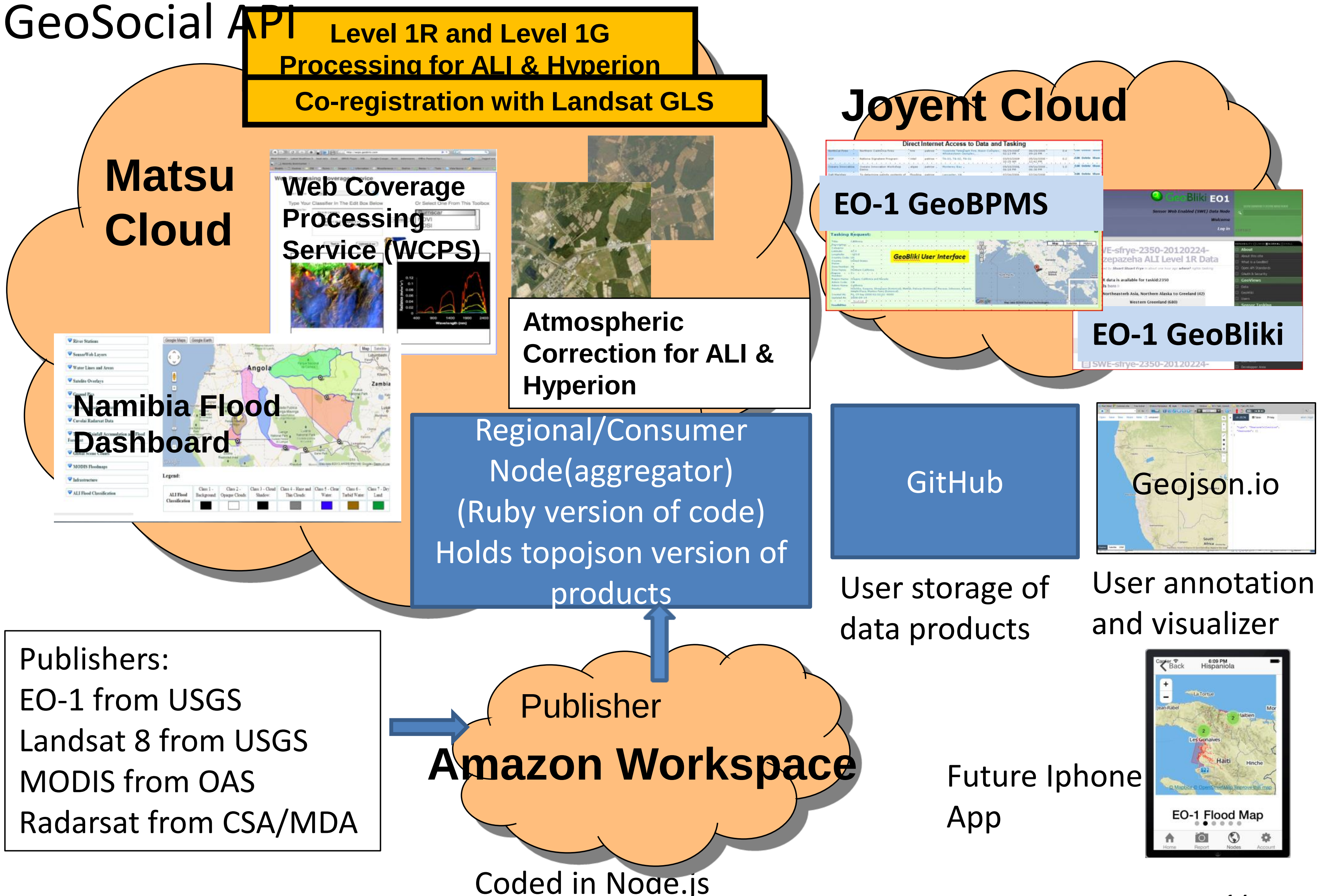
Downlink RT Algal Bloom Maps to Users on Bay 256kbps- 2 Mbps via phone modem

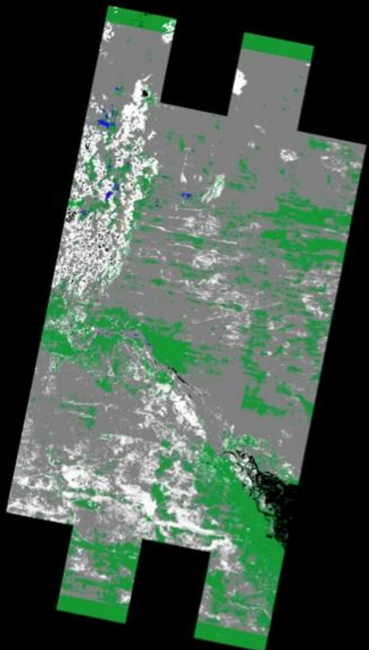
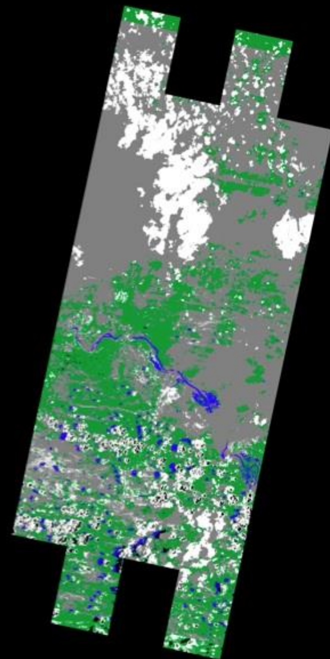
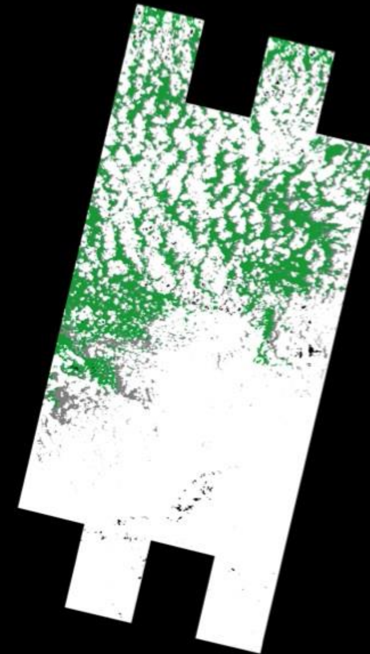
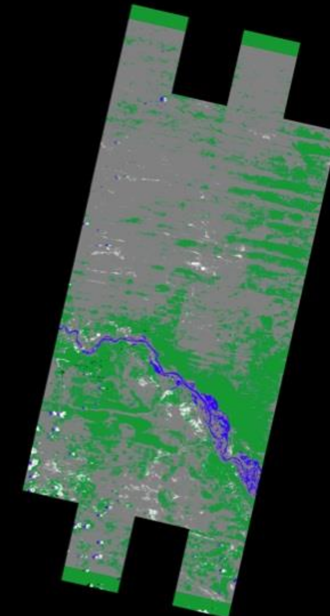
IPM Quick Load/Quick Look Ops Con Via Use of WCPS to Load Onboard Algorithms from Ground

[2012 Work] Web Coverage Processing Service (WCPS)-Client Uploads to Various Environments



EO-1 Cloud Architecture Heritage Software with Experimental GeoSocial API



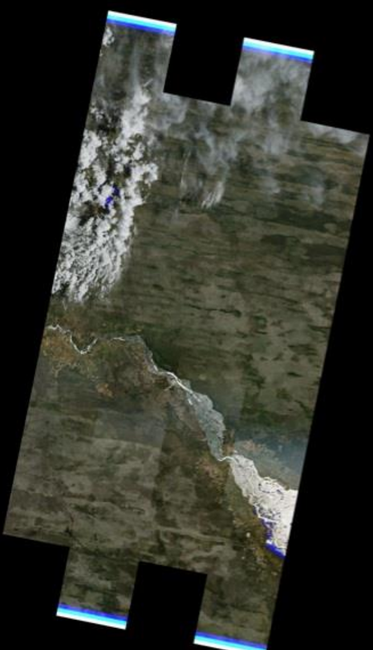
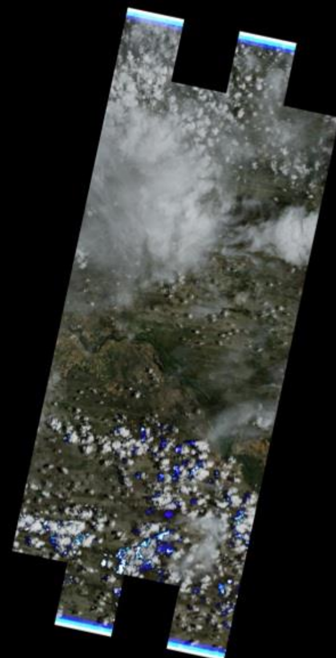
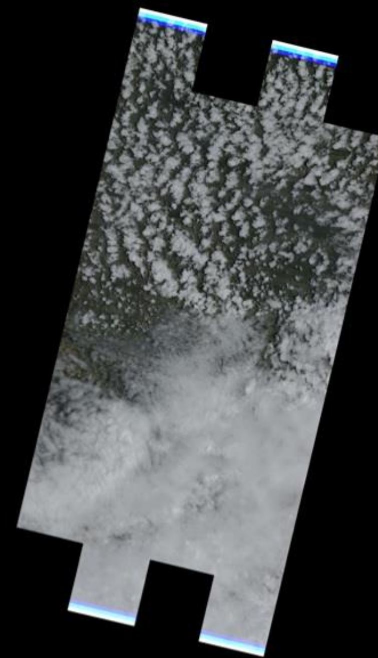





9-JAN-12

14-JAN-12

24-JAN-12

1-FEB-12


IPM Test Flight Bussmann Helicopter

April 13th 2015 / St. Leonard, MD (WCPS Ground Validated, but target onboard)

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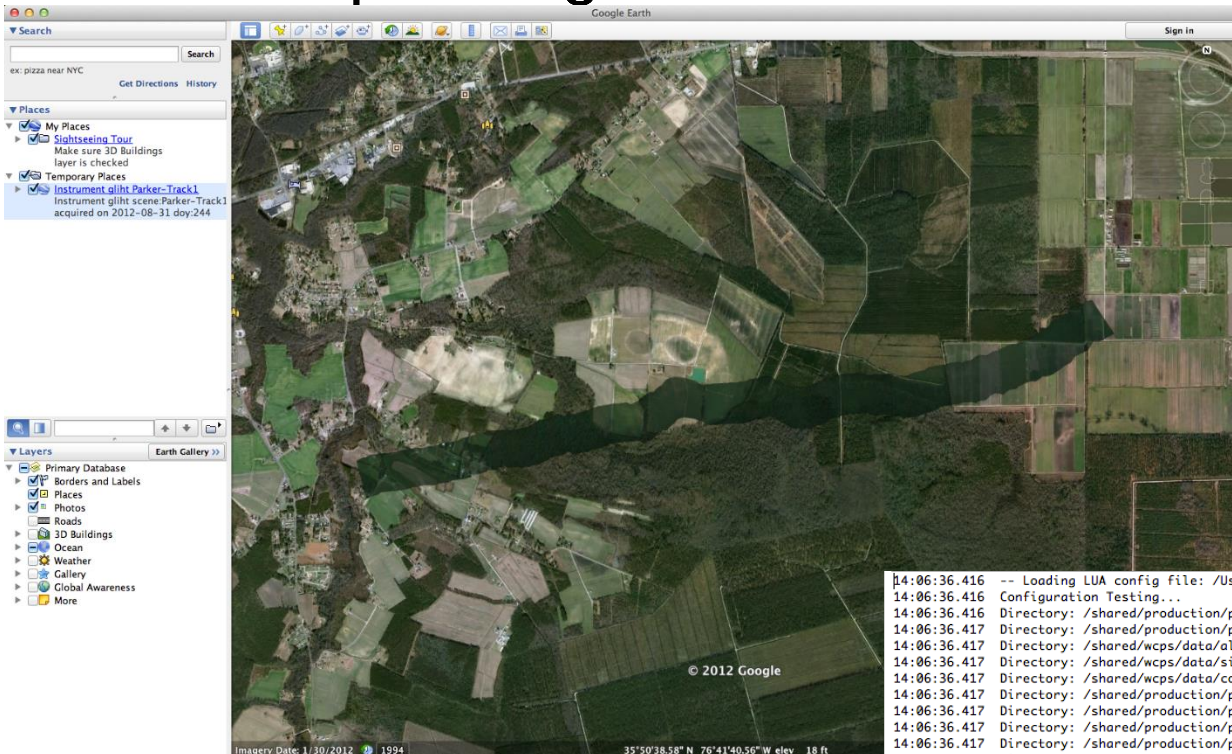
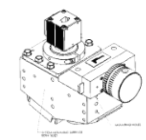
Geo-Correction for Airborne Platforms (GCAP) Operating on G-LiHT Airborne Data





Headwall imaging spectrometer

Run WCPS

```
14:06:36.416  -- Loading LUA config file: /Users/imvuong/Documents/code/wcps/data/wcps.frodo.lua
14:06:36.416  Configuration Testing...
14:06:36.416  Directory: /shared/production/proddata exists
14:06:36.417  Directory: /shared/production/proddata/wcps exists
14:06:36.417  Directory: /shared/wcps/data/algos exists
14:06:36.417  Directory: /shared/wcps/data/sigs exists
14:06:36.417  Directory: /shared/wcps/data/colormaps exists
14:06:36.417  Directory: /shared/production/proddata/ams_l1g exists
14:06:36.417  Directory: /shared/production/proddata/ams_l2 exists
14:06:36.417  Directory: /shared/production/proddata/gliht_l1g exists
14:06:36.417  Directory: /shared/production/proddata/gliht_l2 exists
14:06:36.417  Directory: /shared/production/proddata/ali_l1g exists
14:06:36.417  Directory: /shared/production/proddata/ali_l1g_ac exists
14:06:36.417  Directory: /shared/production/proddata/ali_l2 exists
14:06:36.417  Directory: /shared/production/proddata/hyperion_l1r exists
14:06:36.417  Directory: /shared/production/proddata/hyperion_l1r_ac exists
14:06:36.417  Directory: /shared/production/proddata/hyperion_l1g exists
14:06:36.418  Directory: /shared/production/proddata/hyperion_l1g_ac exists
14:06:36.418  Directory: /shared/production/proddata/hyperion_l2 exists
14:06:36.418  wcps init  1
14:06:36.418  WCPS Execute vis_composite gliht_l1g Parker-Track1 0 1 NA  init 1
14:06:36.418  WCPS Execute vis_composite gliht_l1g Parker-Track1 0 1 NA
14:06:36.418  WCPS Execute algo:vis_composite inst:gliht data:l1g scene:Parker-Track1 cache:0 userid:1 sig:NA...
14:06:36.418  Execute file: /shared/wcps/data/algos/gliht_l1g/vis_composite.lua
14:06:36.419  Creating Atom file /shared/production/proddata/gliht_l2/gliht_l1g/Parker-Track1/vis_composite.atom...
14:06:36.419  get band for instrument: gliht data: l1g
14:06:36.420  get band 160 - file /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1-B160.tif
 min:0.000000 mean:30.582403 stdev:76.606514 max:3142.000000  zeroes:8943407 positive:2063923
14:06:36.492  get band for instrument: gliht data: l1g
14:06:36.492  get band 80 - file /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1-B080.tif
 min:0.000000 mean:59.534584 stdev:135.201553 max:4063.000000  zeroes:8943407 positive:2063923
14:06:36.549  get band for instrument: gliht data: l1g
14:06:36.549  get band 40 - file /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1-B040.tif
 min:0.000000 mean:35.607391 stdev:84.499809 max:3577.000000  zeroes:8943407 positive:2063923
14:06:39.119  write_file:/shared/production/proddata/gliht_l2/gliht_l1g/Parker-Track1/vis_composite.png
14:06:39.119  Making kmz
14:06:39.120  Creating doc file: /shared/production/proddata/gliht_l2/gliht_l1g/Parker-Track1/doc.kml
14:06:39.129  Output filesize: 4174419 and tiling is set to 1
14:06:39.307  Making thumnail
14:06:39.660  Making atom entry
14:06:39.661  closed Atom file /shared/production/proddata/gliht_l2/gliht_l1g/Parker-Track1/vis_composite.atom
execute result:0
14:06:39.682  Done.
```

```
<terminated> gcap [C/C++ Application] /Users/imvuong/Documents/code/gcap/src/.libs/gcap (10/15/12 2:05 PM)
config.c:32: INPUT_FILENAME = /Users/imvuong/Documents/code/gcap/data/input/Parker-Track1.bin
config.c:32: IMU_POSITION_FILE = /Users/imvuong/Documents/code/gcap/data/input/110728_132454.pos
config.c:32: INSTR_TIMESTAMP_FILE = /Users/imvuong/Documents/code/gcap/data/input/Parker-Track1.asc
config.c:32: BAND = 40 80 160
config.c:32: OUTPUT_DIR = /shared/production/proddata/gliht_l1g/Parker-Track1/
config.c:57: ROLL_OFFSET = 0.000000
config.c:57: PITCH_OFFSET = 0.000000
config.c:57: ALTITUDE_OFFSET = 0.000000
config.c:57: HEADING_OFFSET = 0.000000
config.c:57: INSTR_TIMESTAMP_OFFSET = -0.460000
config.c:57: INSTR_VIEW_ANGLE = 53.000000
main.c:213: Input image size: 1004x5465x402.
gcap.c:166: UL: 35.851659867857456732,-76.730605800650906190
gcap.c:167: UR: 35.851659867857456732,-76.658554548188419631
gcap.c:168: LL: 35.836418930876448030,-76.730605800650906190
gcap.c:169: LR: 35.836418930876448030,-76.658554548188419631
main.c:218: Output image size: 6494x1695x402.
main.c:234: Writing file: /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1-B040.tif.
main.c:234: Writing file: /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1-B080.tif.
main.c:234: Writing file: /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1-B160.tif.
main.c:143: UL: 35.851659867857456732,-76.730605800650906190
main.c:144: UR: 35.851659867857456732,-76.658554548188419631
main.c:145: LL: 35.836418930876448030,-76.730605800650906190
main.c:146: LR: 35.836418930876448030,-76.658554548188419631
main.c:148: Writing file: /shared/production/proddata/gliht_l1g/Parker-Track1/Parker-Track1.meta.
```

Run GCAP

Heritage Products(Flight Validated)

- Autonomous Sciencecraft Experiment (ASE) formerly on Earth Observing 1
  - Snow, Water, Ice, Land (SWIL) onboard classifier
  - Surface water extent mapping (floods)
  - Thermal analysis (volcano, fires)
  - Onboard cloud classifier using Hyperion (MIT/LL algorithms)
  - Onboard cloud classifier used on AVIRIS and on EO-1 ASE

    Aviris - Thompson DR, Green RO, Keymeulen D, Lundeen SK, Mouradi Y, Nunes DC, Castaño R, Chien SA. Rapid spectral cloud screening onboard aircraft and spacecraft. IEEE Transactions on Geoscience and Remote Sensing. 2014 Nov;52(11):6779-92.

    EO-1 - EO-1 - Wagstaff, K.; Chien, S.; Altinok, A.; Rebbapragada, U.; Thompson, D.; Schaffer, S.; and Tran, D. Cloud Filtering and Novelty Detection using Onboard Machine Learning for the EO-1 Spacecraft. In International Symposium on Artificial Intelligence, Robotics, and Automation for Space (ISAIRAS 2018), Madrid, Spain, July 2018. Also appears at AI in the Oceans and Space Workshop, International Joint Conference on Artificial Intelligence (IJCAI 2017)

    https://ai.jpl.nasa.gov/public/papers/wagstaff_ijcai2017_novelty.pdf

  - Random Decision Forests for clouds, water and other classifications(Rebbapragada, Altinok, Thompson/JPL) [Chien-2016 HyspIRI Wkshop]
  - Visual salience classification technique for high variability pixels (Wagstaff et al, ACM TIST 2012)[Chien – 2016 HyspIRI Workshop]

Heritage Products (ground validated)

- Rapid onboard co-registration of Advance Land Imager bands with Global Land Survey chips

  Reference: Cappelaere, et al, "Rapid Onboard Co-registration for EO-1 and Landsat "

  at 2015 HyspIRI Symposium

- Synthesis of Landsat 8 bands using Hyperion data
  - Study: "EO-1 Hyperion Multispectral Band Synthesis"
    - Guoqing Sun, Stephen G. Ungar and Elizabeth M. Middleton
  - Prototype Hyperion to OLI band demonstration
    - Chien, Results from ALI and OLI Multispectral Band Synthesis, Machine Learning Classification, and Salience onboard the Earth Observing One Mission at 2017 HyspIRI Science and Applications Workshop in Pasadena on October 17th-19th, 2017
- Compact onboard Orthorectification technique (Cappelaere)
  - Heritage: NGA, IKHONOS, Quickbird, Sentinel, Pleiades
  - Rational polynomial technique
  - Help from Jim Storey
  - Need compact digital elevation model to store onboard
  - Use with FPGA

  Reference: Cappelaere, Storey, Franks "HyspIRI Instrument Payload Module Onboard OrthoRectification"

Intelligent Payload Experiment (IPEX) Cubesat

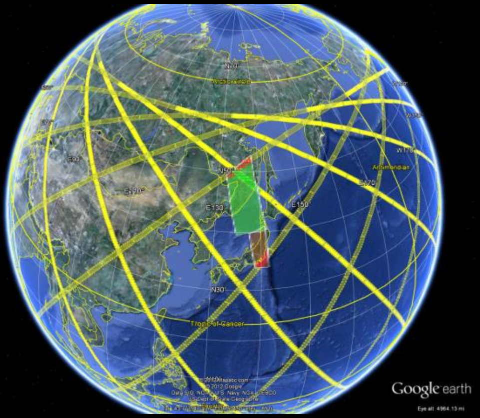
- 1u Cubesat Funded by ESTO
- Launch 6 Dec 2013

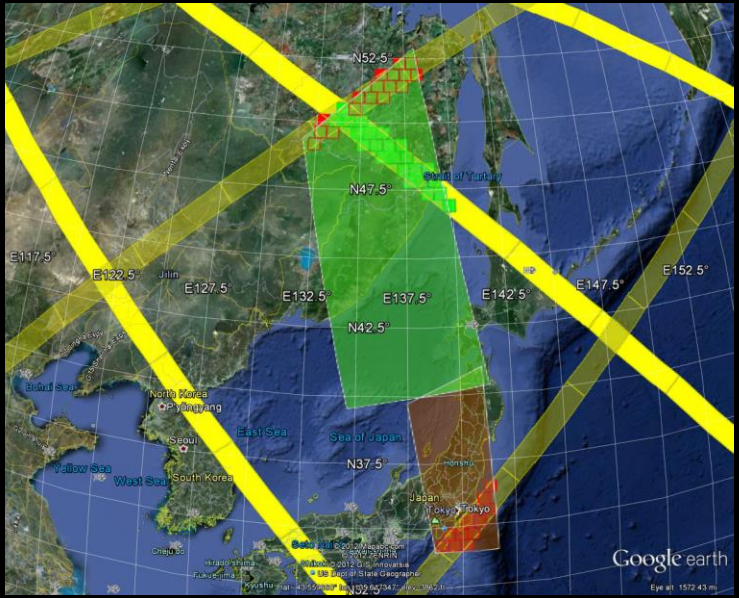
- Level 1 mission success Jan 2014
  - Over 30,000 image products validated onboard

- Extended Operations through 2014

IPEX: Lights Out Payload Operations

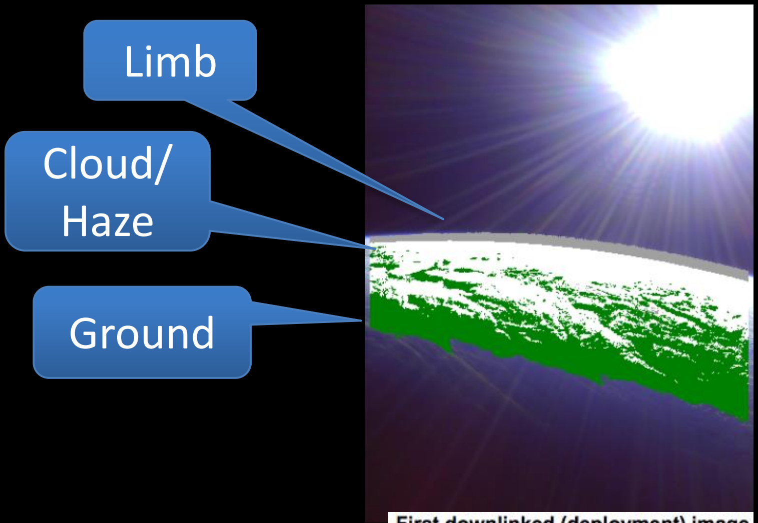
- Uses CLASP [Rabideau et al. 2010] Coverage Scheduler
- Users identify regions of interest, products automatically scheduled based on priority, visibility, and detections
- Use in ECOSTRESS, planned for OCO-3





IPEX: Onboard Processing

- Flew Gumstix™ payload processor
- Validated onboard generation of 30,000+ products onboard
  - Gumstix products compared to Atmel products
  - Band ratios
  - TextureCam
  - Salience



Salience unsupervised learning

Ground reconstructions of onboard products

Conclusion

- 10 years of prototyping various aspects of IPM
- Onboard processor technology has dramatically improved in terms of onboard processing capacity
- Many of computations that were ground based can now be done onboard
- Increasing use on onboard artificial intelligence to increase imaging productivity and saliency