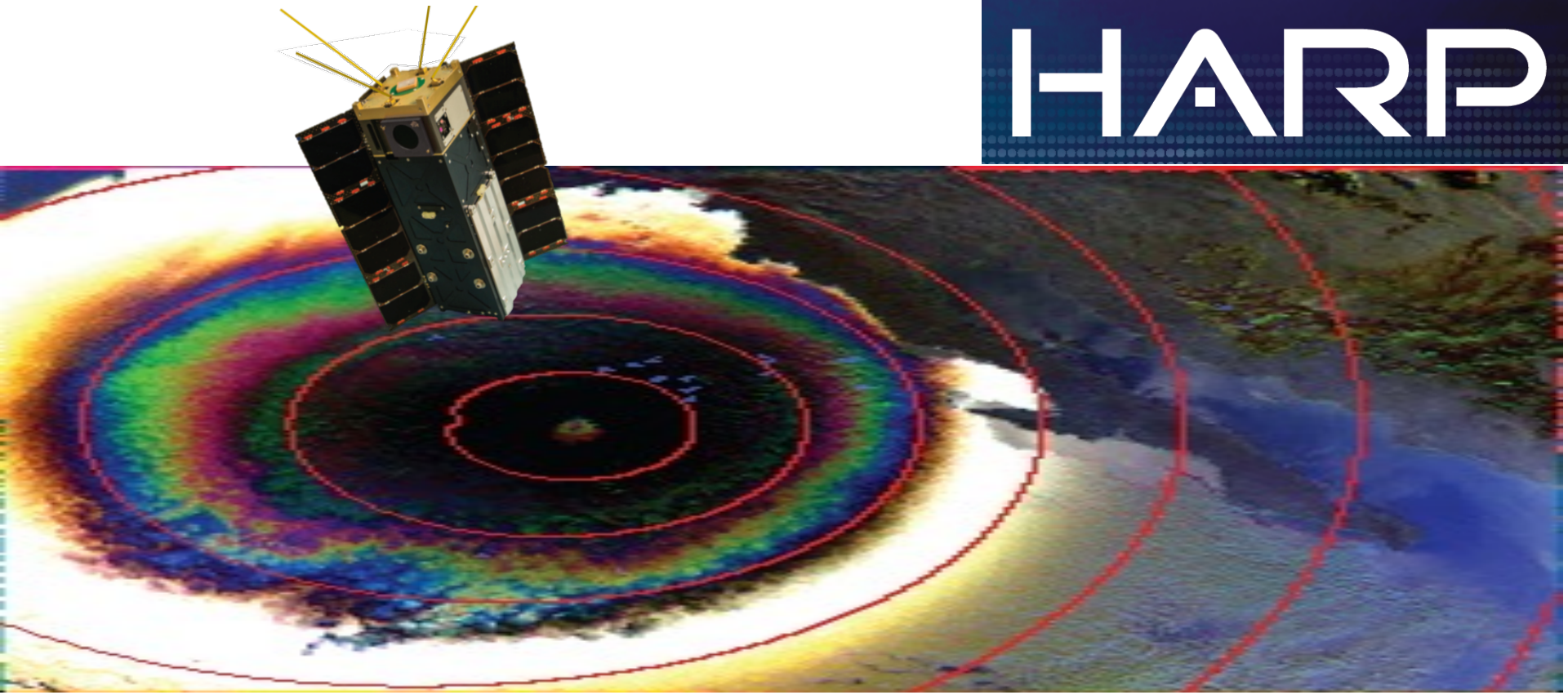


HARP: Hyper-Angular Rainbow Polarimeter CubeSat
(NASA ESTO – InVEST)

J. Vanderlei Martins (UMBC)

June 14th 2016 – ESTO Science and Technology Forum

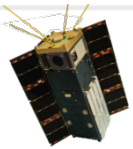
NASA
STC SCIENCE & TECHNOLOGY CORP.
UMBC
UMBC JCET NASA-GSFC
Space Dynamics LABORATORY
Utah State University Research Foundation

HARP Objectives

- Validate the in-flight capabilities of a highly accurate and precise wide field of view hyperangular polarimeter for characterizing aerosol and cloud properties.
- Prove that CubeSat technology can provide science-quality multi angle imaging data paving the way for lower cost aerosol-cloud instrument developments.
- Provide opportunities for student research and engineering training in implementing a space mission.

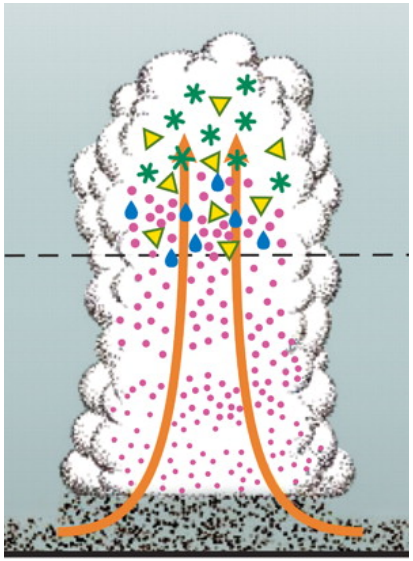
HARP Science Goal

- Demonstrate the ability to characterize the micro physical properties of aerosols and clouds at the scale of individual moderate-sized clouds for the ultimate purpose of narrowing uncertainties in climate change.



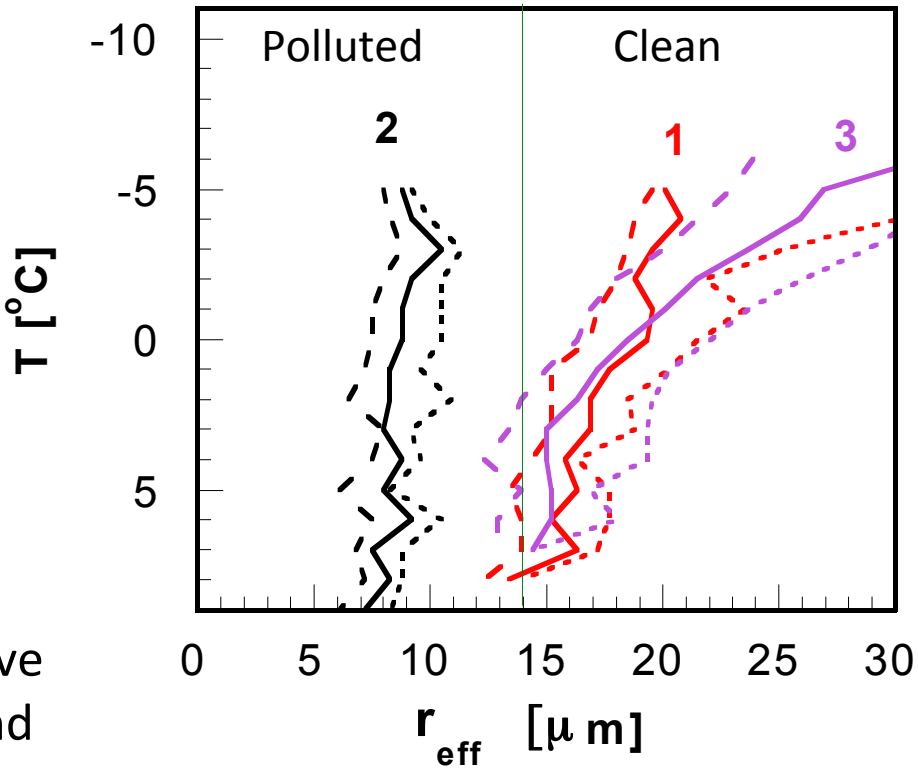
HARP

HARP Science – Clouds and Aerosols

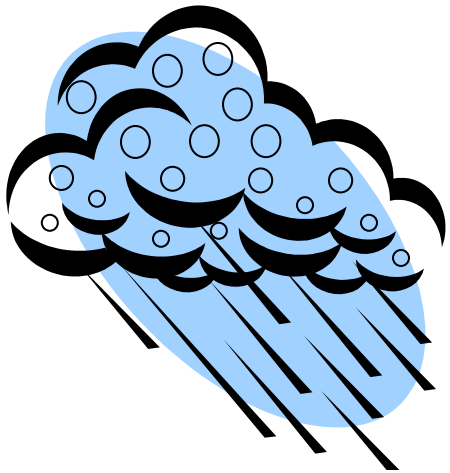


Polluted Clouds have smaller droplets and grow deeper without precipitating

Clouds



Clean Clouds have larger droplets and start earlier precipitation



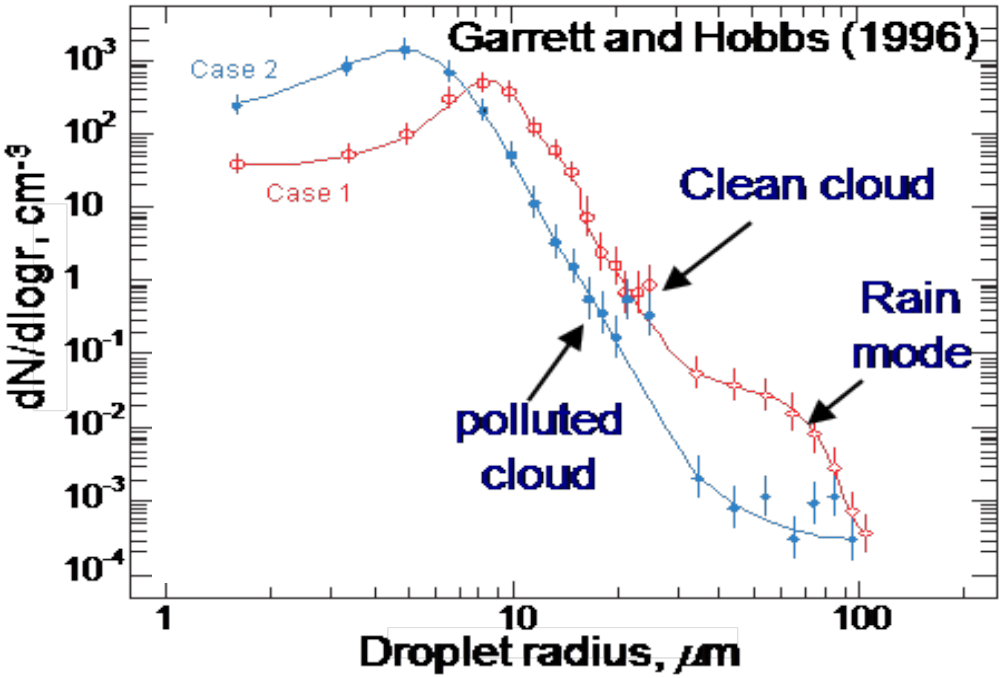
HARP Science

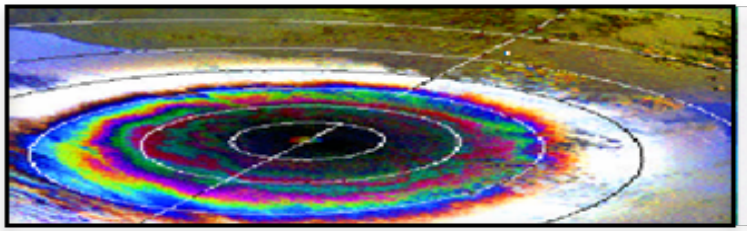
- *Pollution aerosols narrow cloud droplet distributions and postpones rain*

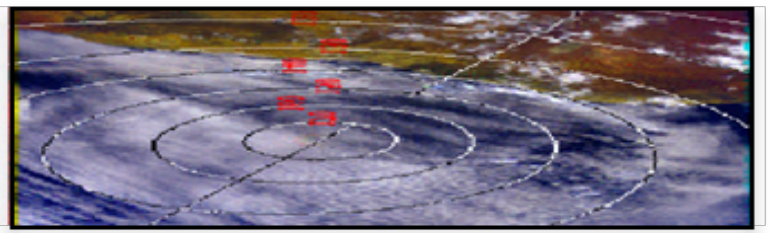
- *Smaller droplets increase cloud albedo and affect Earth's energy balance*

- *Polarized rainbow*

signal provides droplet effective radius and variance measurements



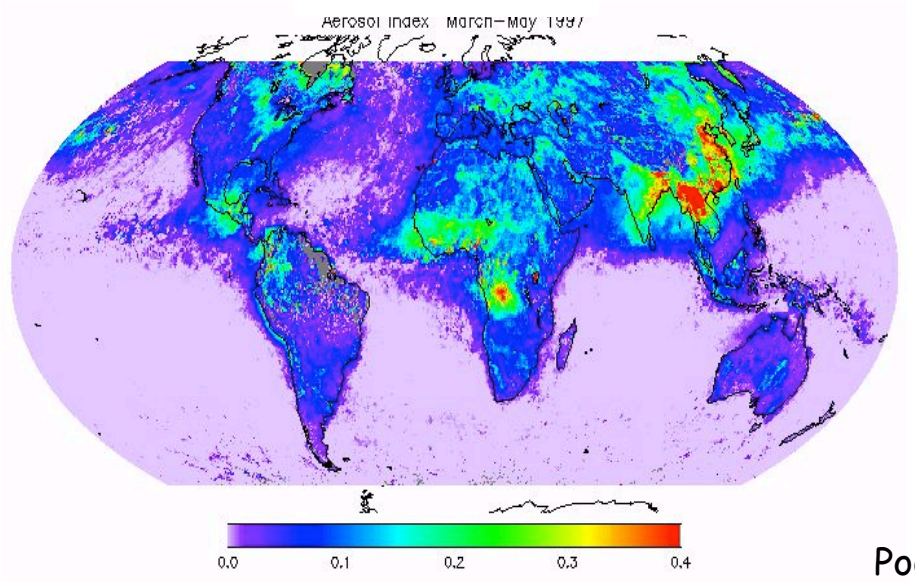




Why Polarization Measurements

Polarization provides new information on aerosol and cloud properties and their interaction. HARP design is an advance over POLDER's filter wheel system.

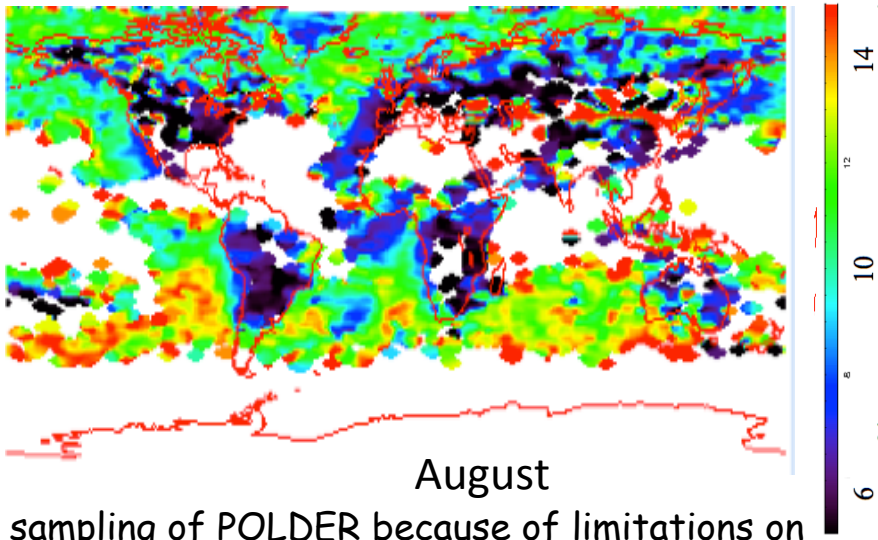
Aerosol load



Bréon FM et al, Science, 2002

Aerosol retrievals are possible with wavelengths proposed in HARP's Goal Mission

Cloud droplet size from POLDER

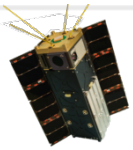


August

Poor sampling of POLDER because of limitations on viewing geometry and filter wheel design is resolved in the HARP concept.

Hints at smaller droplets over continents, and in particular polluted areas.

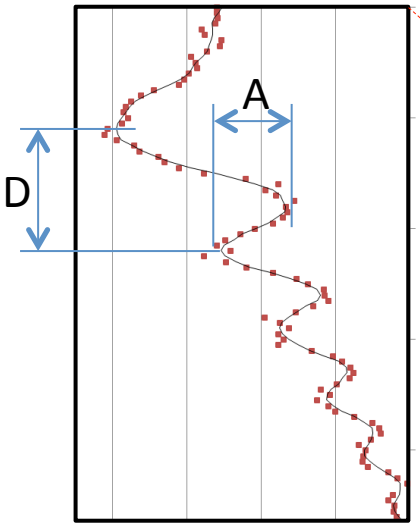
HARP will be the first US imaging polarimeter in Space



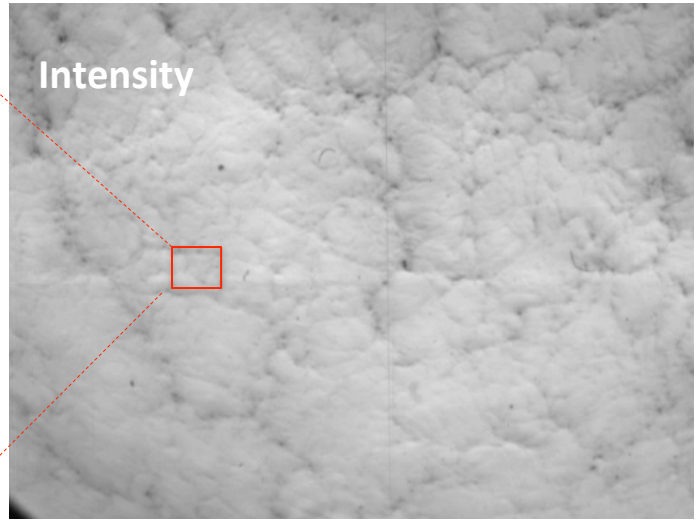
HARP

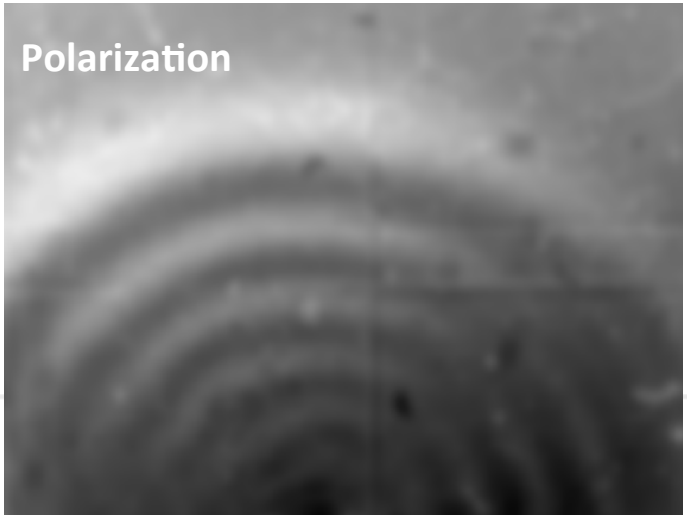
HARP CubeSat Polarimeter

HARP Pioneering Hyper-Angular Capability will Provide Full Cloudbow Retrievals from Small Area (< 4x4km from space)

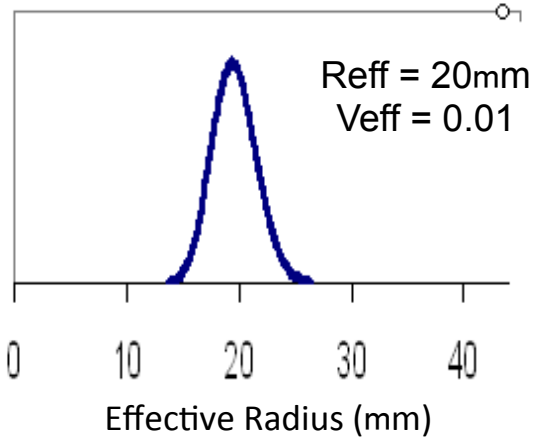


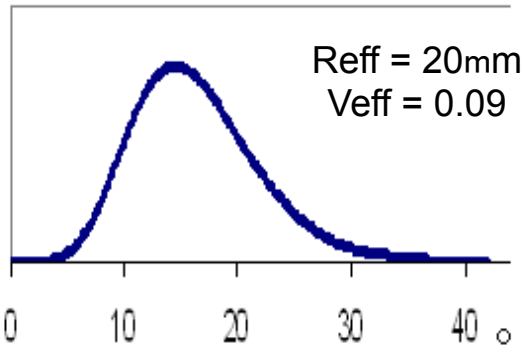
D and A parameters allow for measurements of cloud droplet effective radius and variance





Water Droplet Distribution

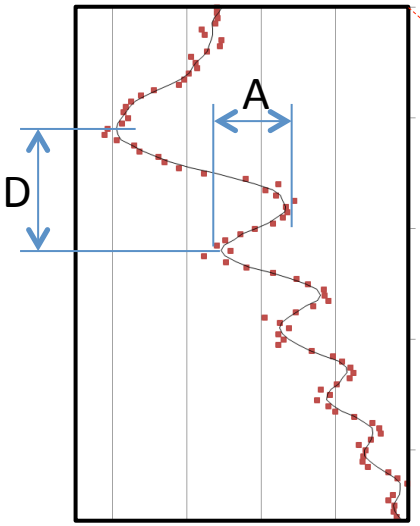


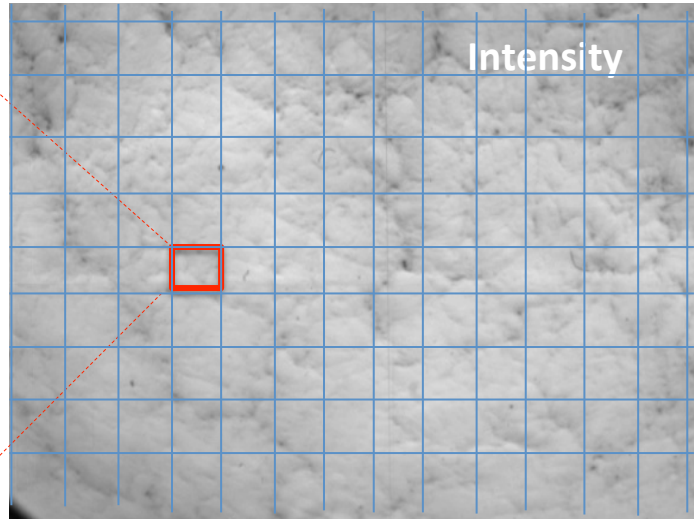


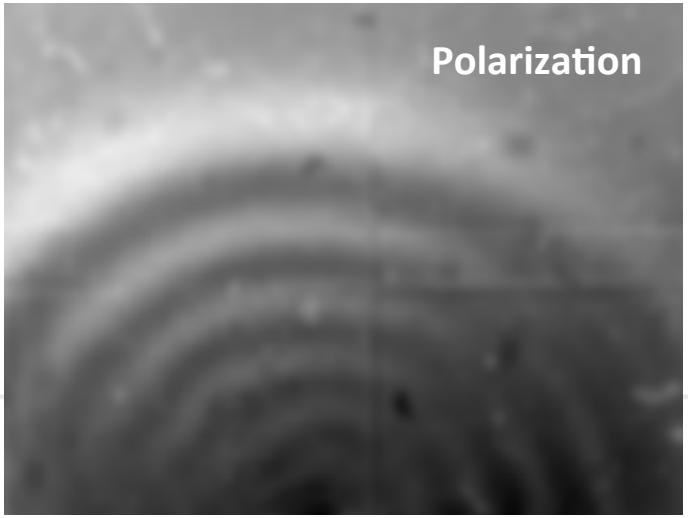
These two cases are undistinguishable from Intensity measurements only (MODIS/VIIRS)

HARP CubeSat Polarimeter

HARP Pioneering Hyper-Angular Capability will Provide Full Cloudbow Retrievals from Small Area (< 4x4km from space)

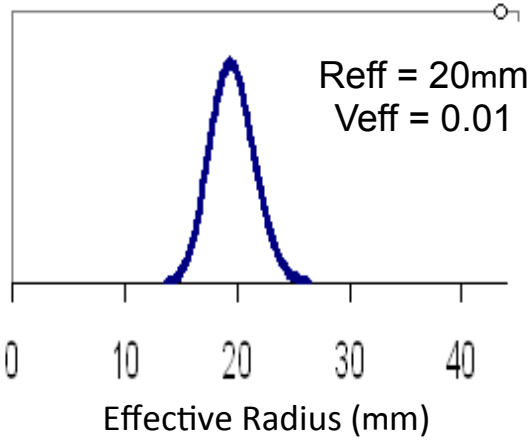


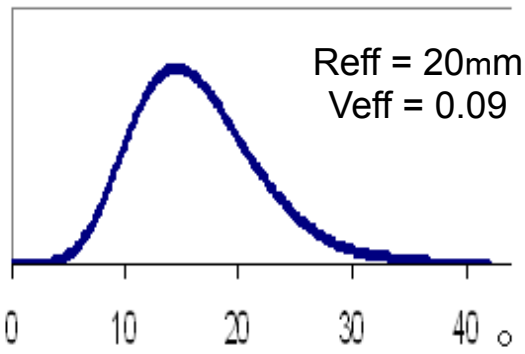




Same retrieval capability for all individual pixels with < 4x4km resolution

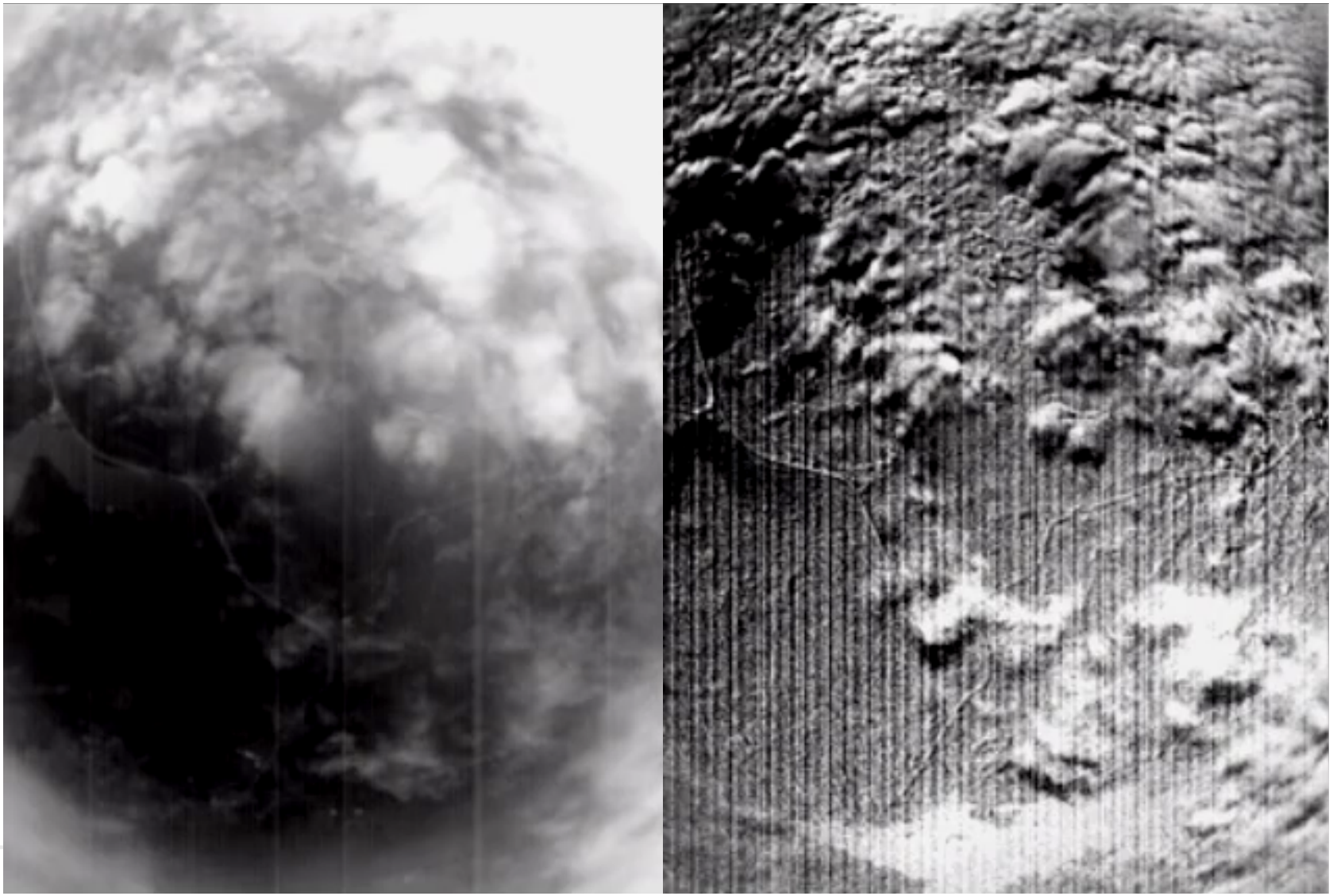
Water Droplet Distribution





These two cases are undistinguishable from Intensity measurements only (MODIS/VIIRS)

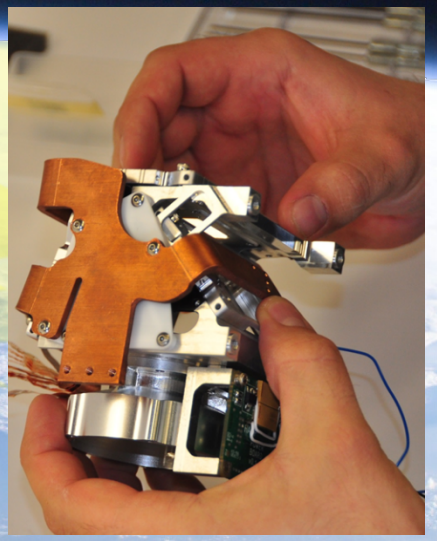
RPI Early Polarimeter Prototype
23 Aug 2013



HARP CubeSat Satellite to launch in Dec. 2016

HARP Polarimeter Specs

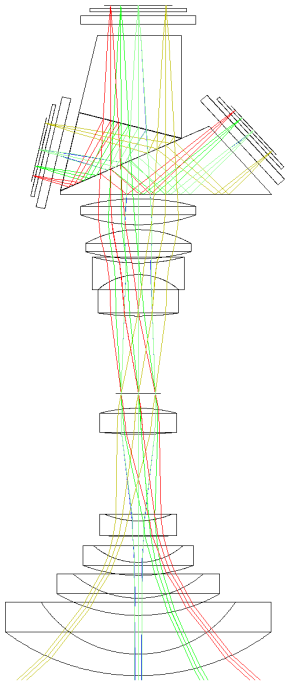
- ISS orbit
- 60 angles for cloudbows
- 20 angles for aerosols
- 440, 550, 670, 870nm
- Nadir pixel resolution 600m
- Super pixel 2.5x2.5km
- 94 deg FOV X-track
- 117 deg FOV along track



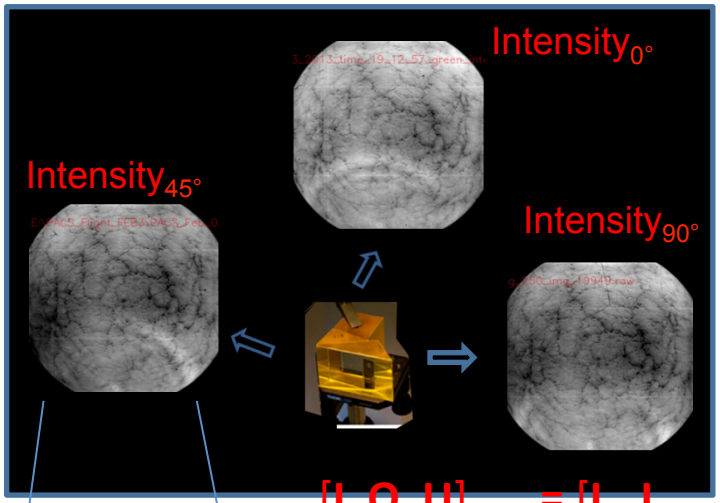
Imaging polarimeter

Repeat for all along track viewing angles

HARP Hyperangular Multi-Wavelength Polarization Images



HARP Prism/Polarization Separation

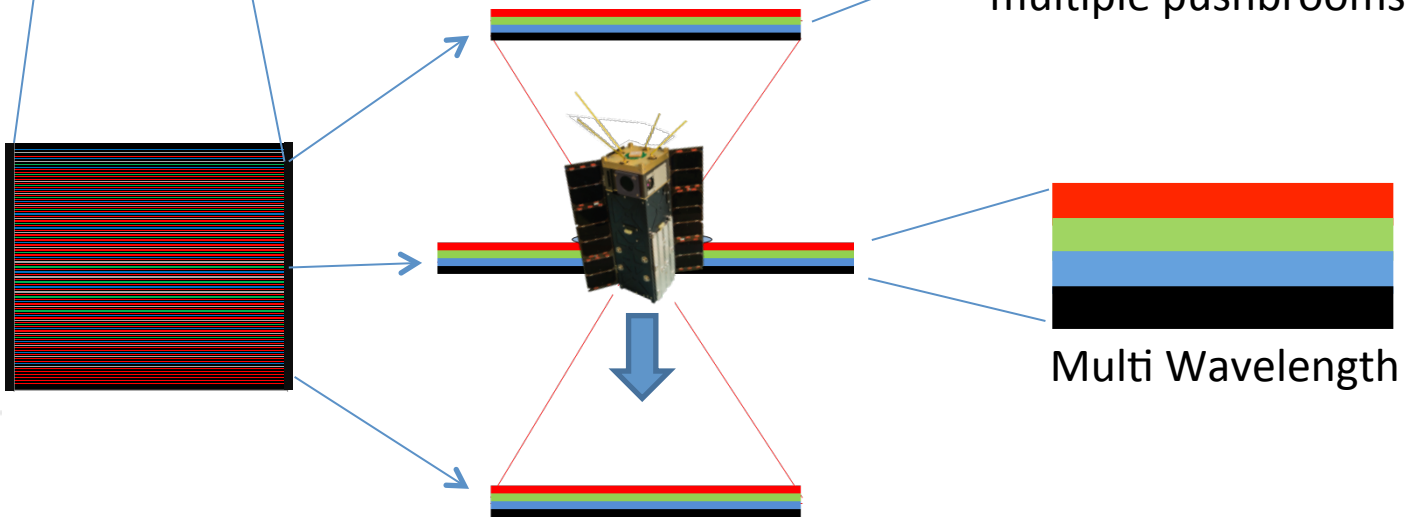


HARP

- Up to 60 viewing angles
- 440, 550, 670, 870nm
- 2.5km resolution
- 94 deg FOV X-track
- 110 deg FOV along track

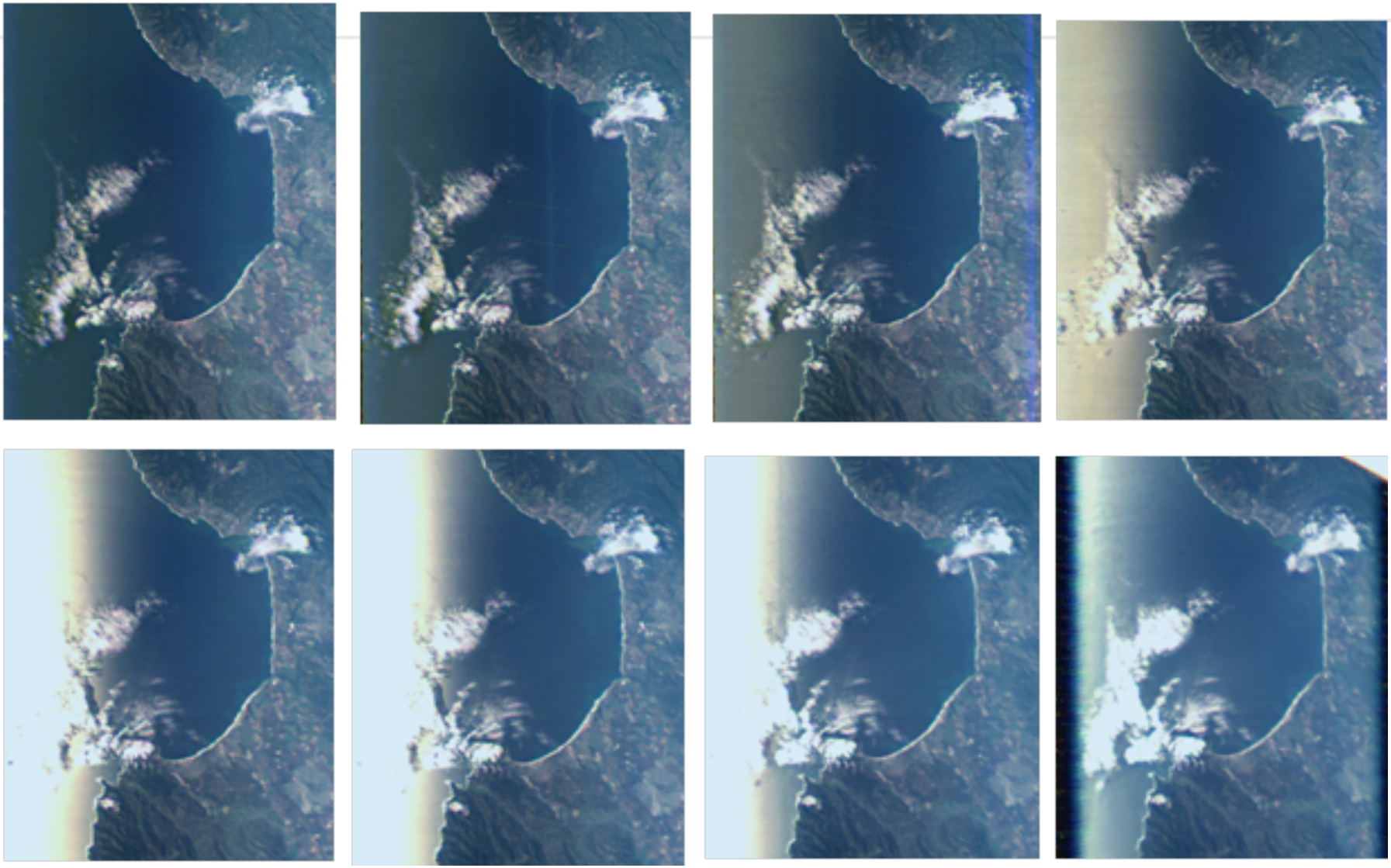
Multi/Hyper Angle with multiple pushbrooms

Stripe Filters: Angular and Wavelength Separation



Multi Wavelength

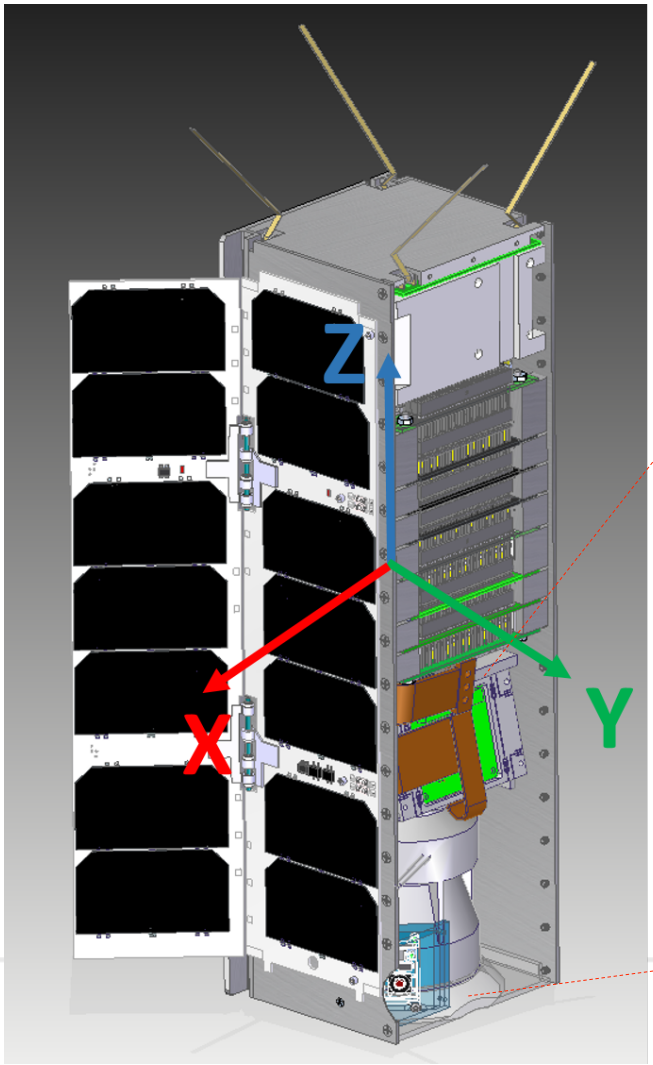
Multiple Viewing Angles (>50 angles by airborne PACS)



HARP

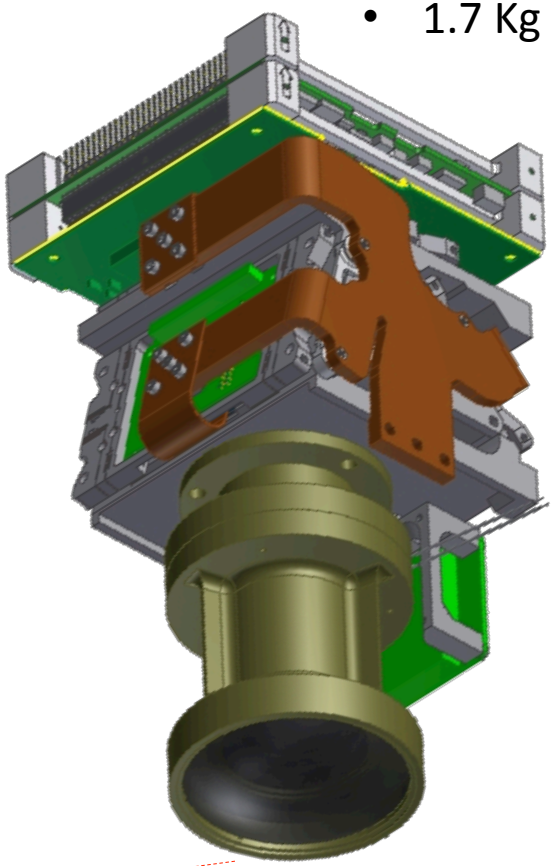
HARP Instrument & Spacecraft

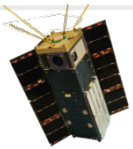
HARP Spacecraft



HARP Imaging Polarimeter

- 6 inches long
- 1.7 Kg

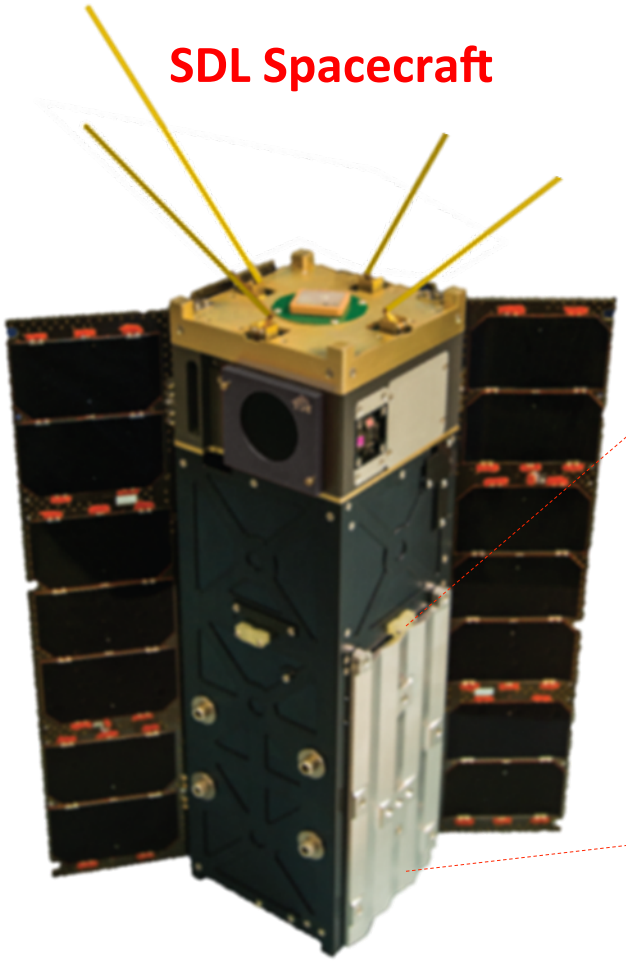




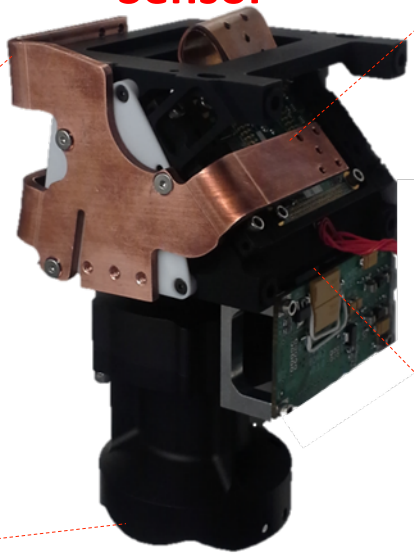
HARP

Photos of Actual Instrument & Spacecraft

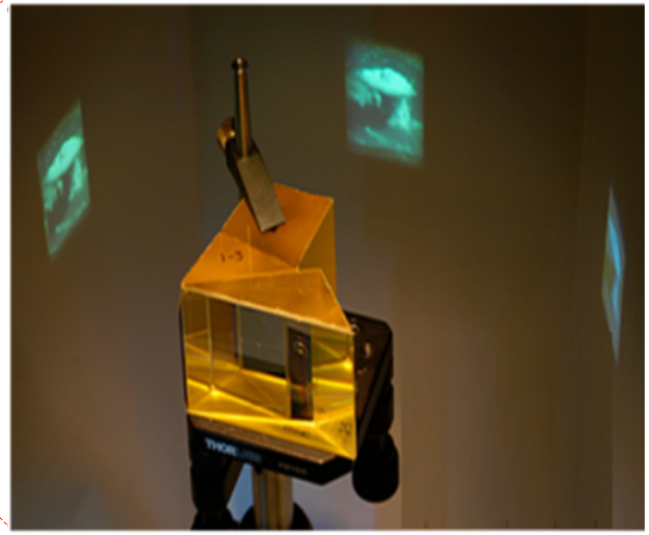
SDL Spacecraft



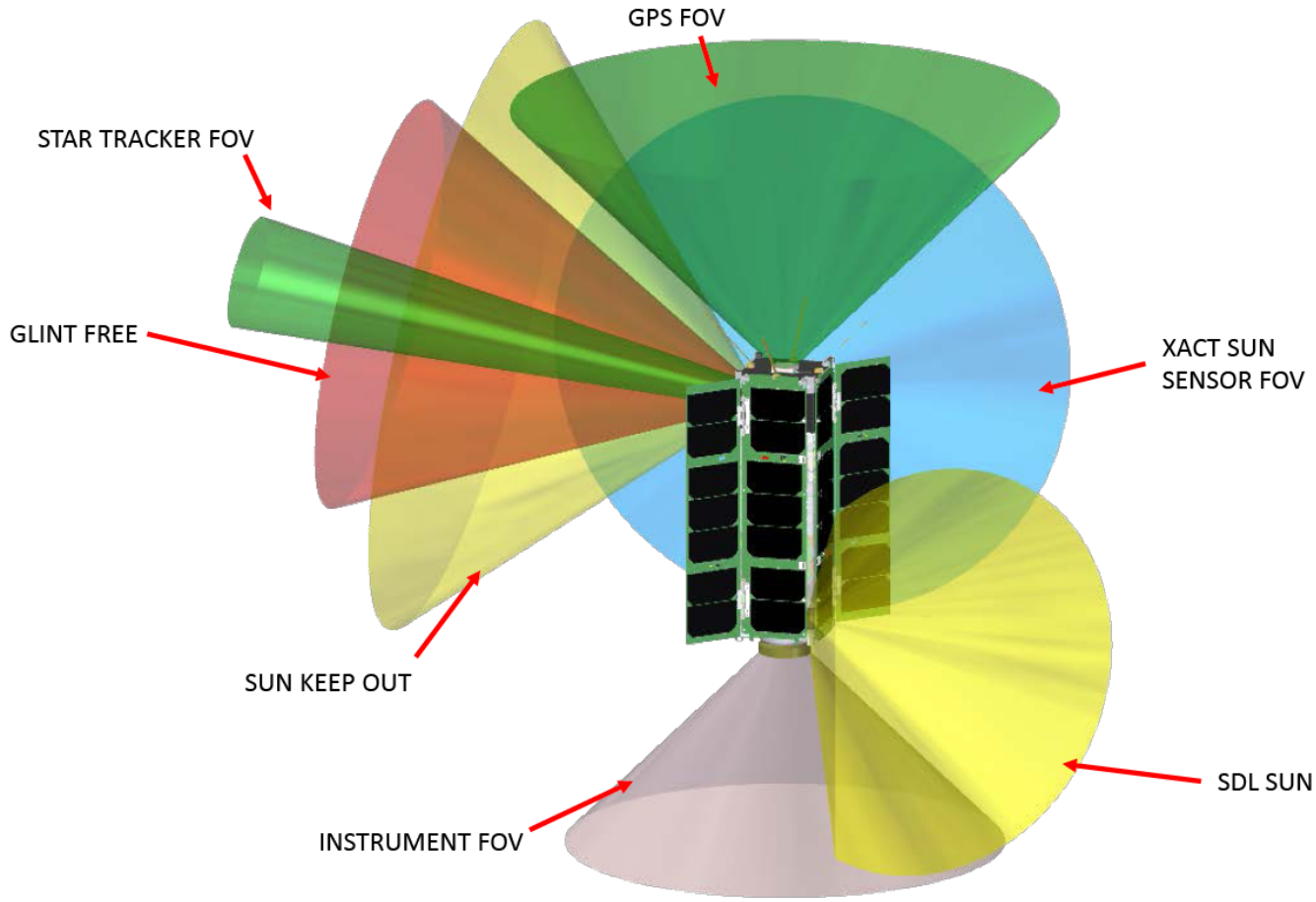
UMBC Sensor



HARP Prism

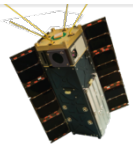


HARP – Full Feature Earth Sciences Satellite

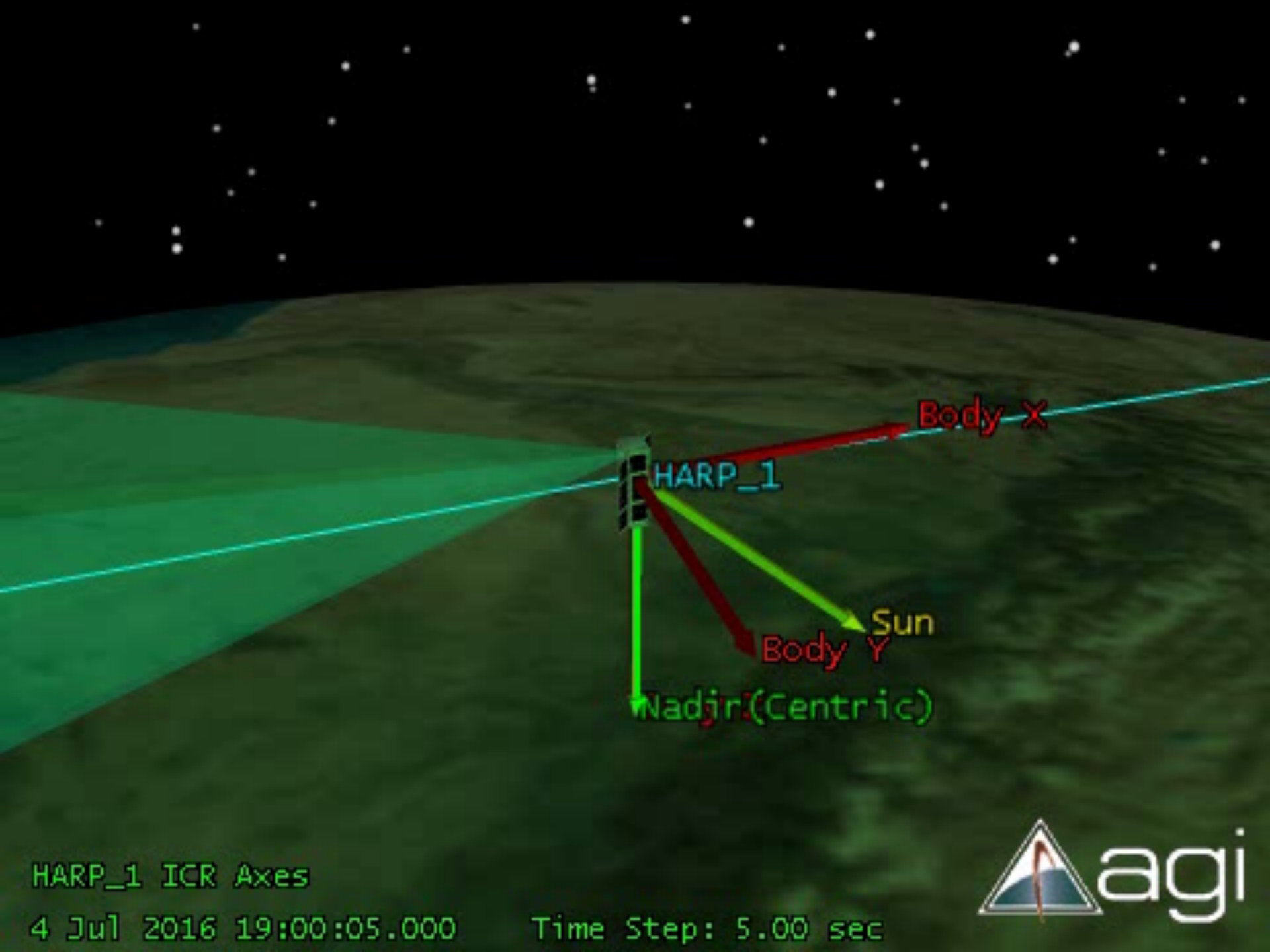


- Accurate ACDS
- Sun Sensor + Star tracker
- < 0.66km pointing knowledge/geolocation
- Wide FOV hyperangular, polarized imaging payload
- 4 wavelengths (0.44, 0.55, 0.67, 0.87um)
- Up to 20 angles in all l
- Up to 60 angles at 0.67um
- UHF radio up to 3Mbits/s
- 2.5km spatial resolution
- 0.66km pixel resolution

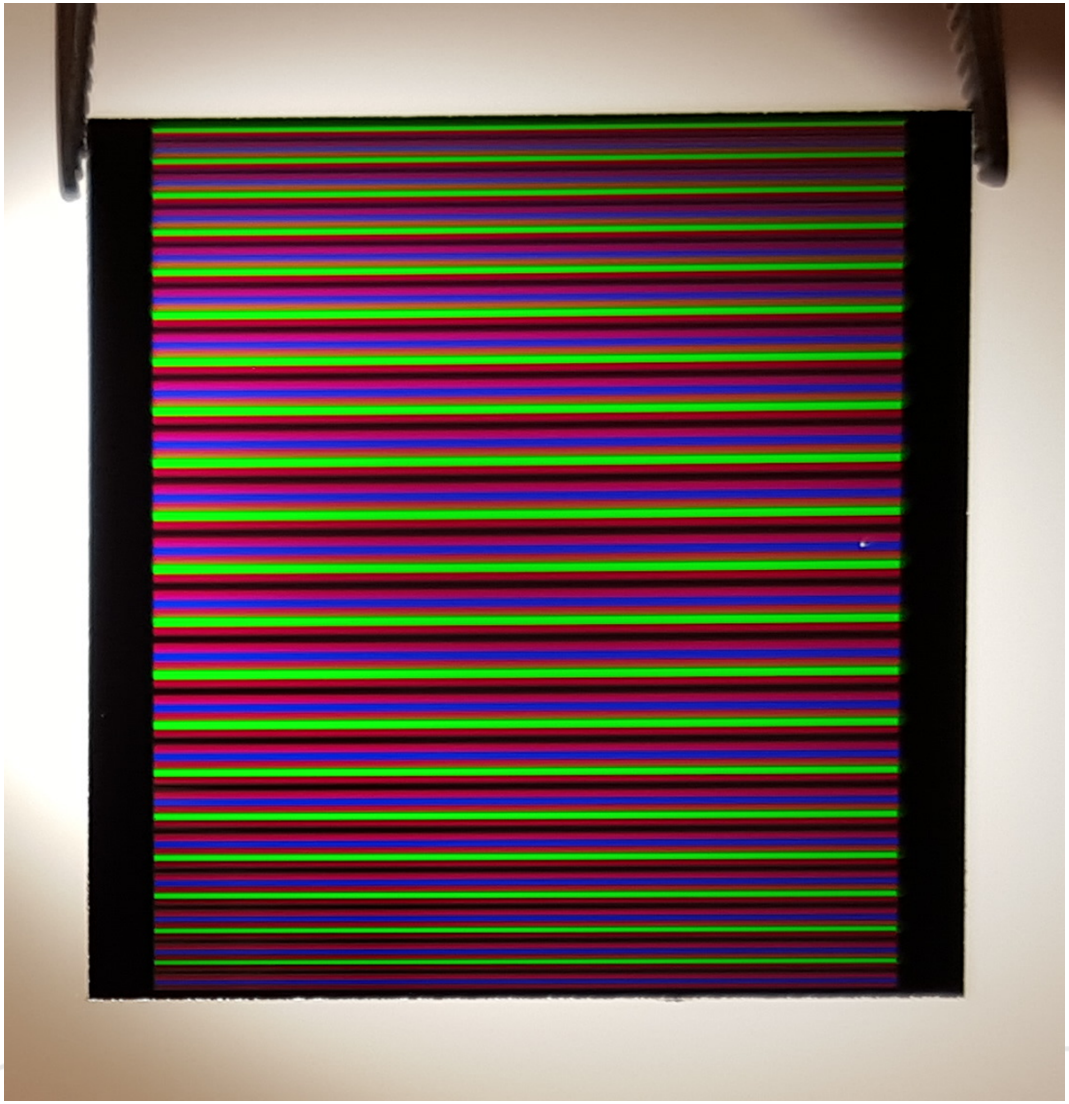
UMBC



HARP


Body X
HARP_1
Sun
Body Y
Nadir (Centric)
HARP_1 ICR Axes
4 Jul 2016 19:00:05.000
Time Step: 5.00 sec
agi

Photograph of actual stripe filter unit



Stripe Filter:

Secret for hyper-angle and multi wavelength sampling

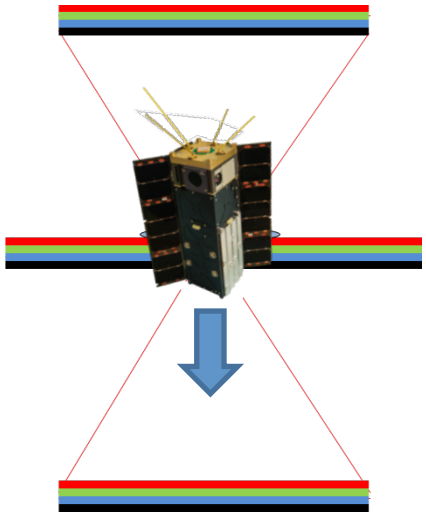
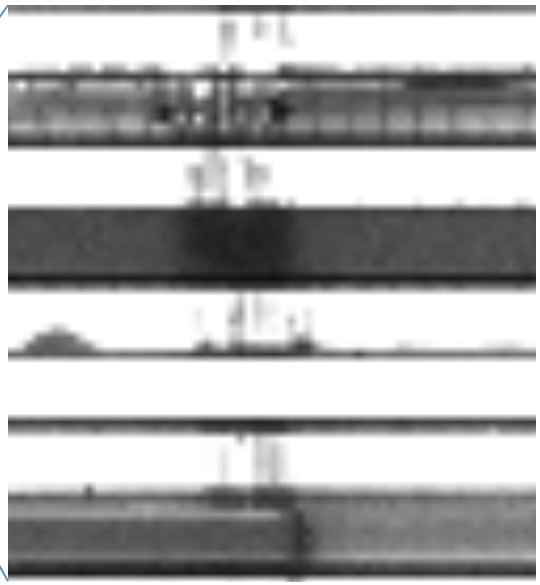
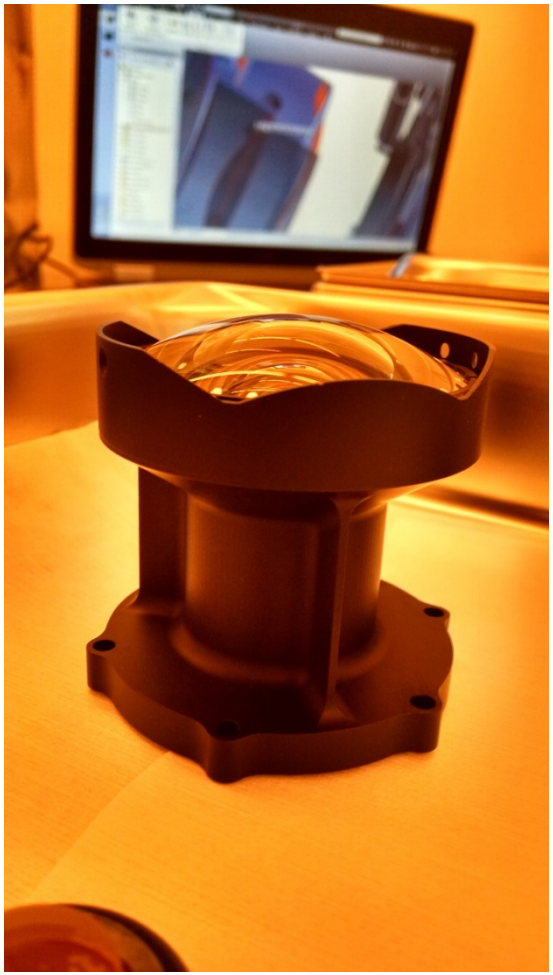
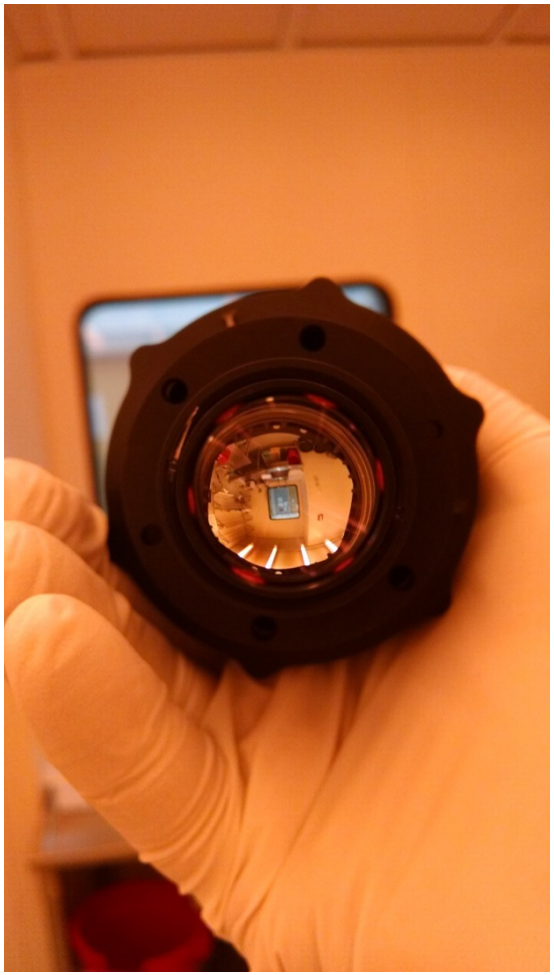


Image acquired with actual flight lens, detector and filter

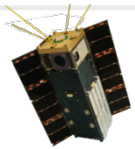


Lens Assembly





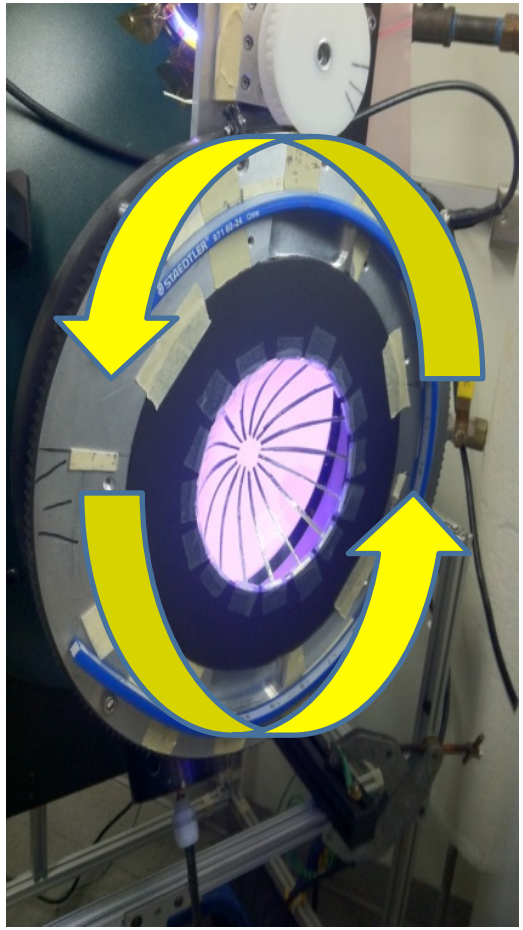
Images acquired through the Actual HARP Flight Lens



HARP

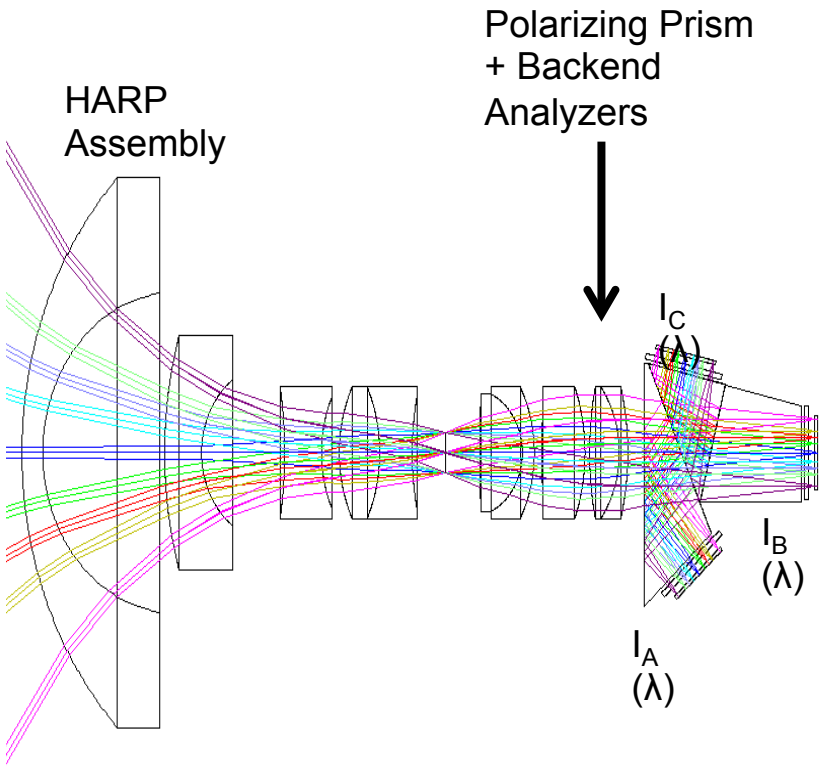
HARP Calibration:

Unpolarized "white" light (integrating sphere)



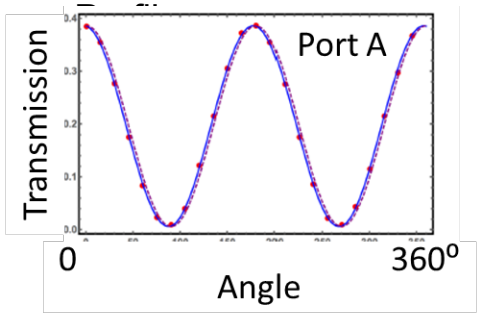
Polarization Dome

$0° \leq \vartheta \leq 320°$

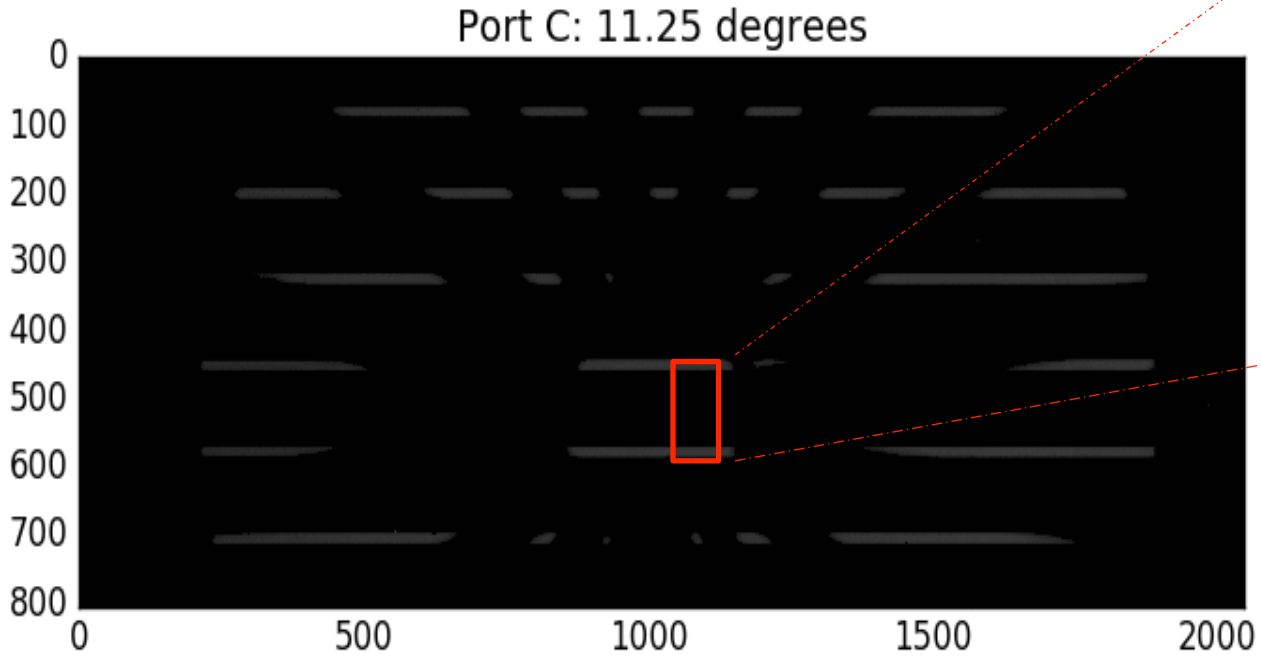


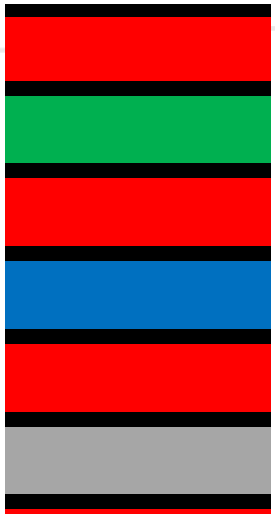
Malus' Intensity

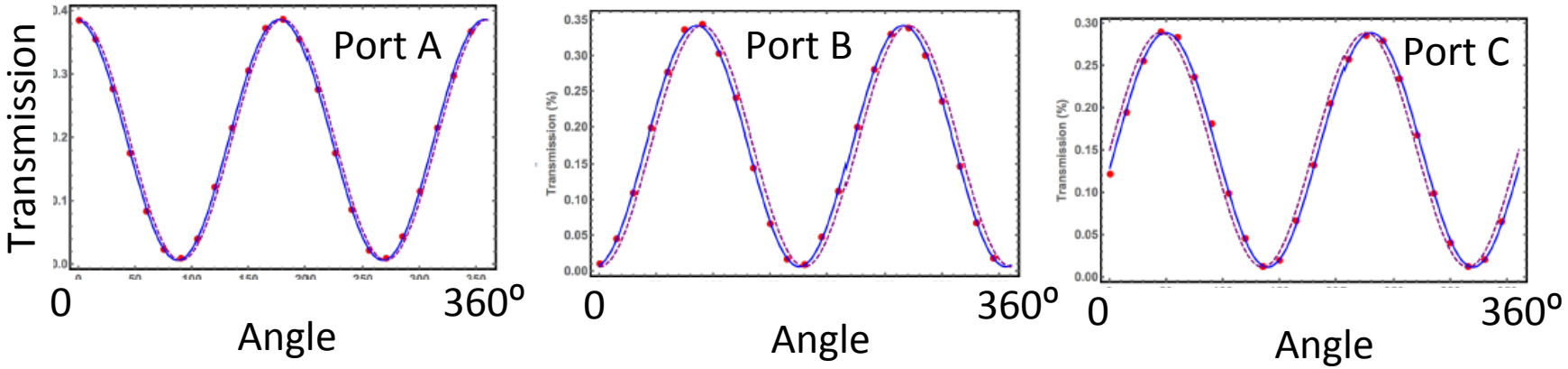
$I \propto \cos^2(\theta)$



Polarization Calibration with Dome



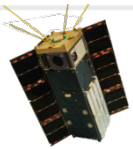




ISS Orbit for HARP:
Synergy with other satellites

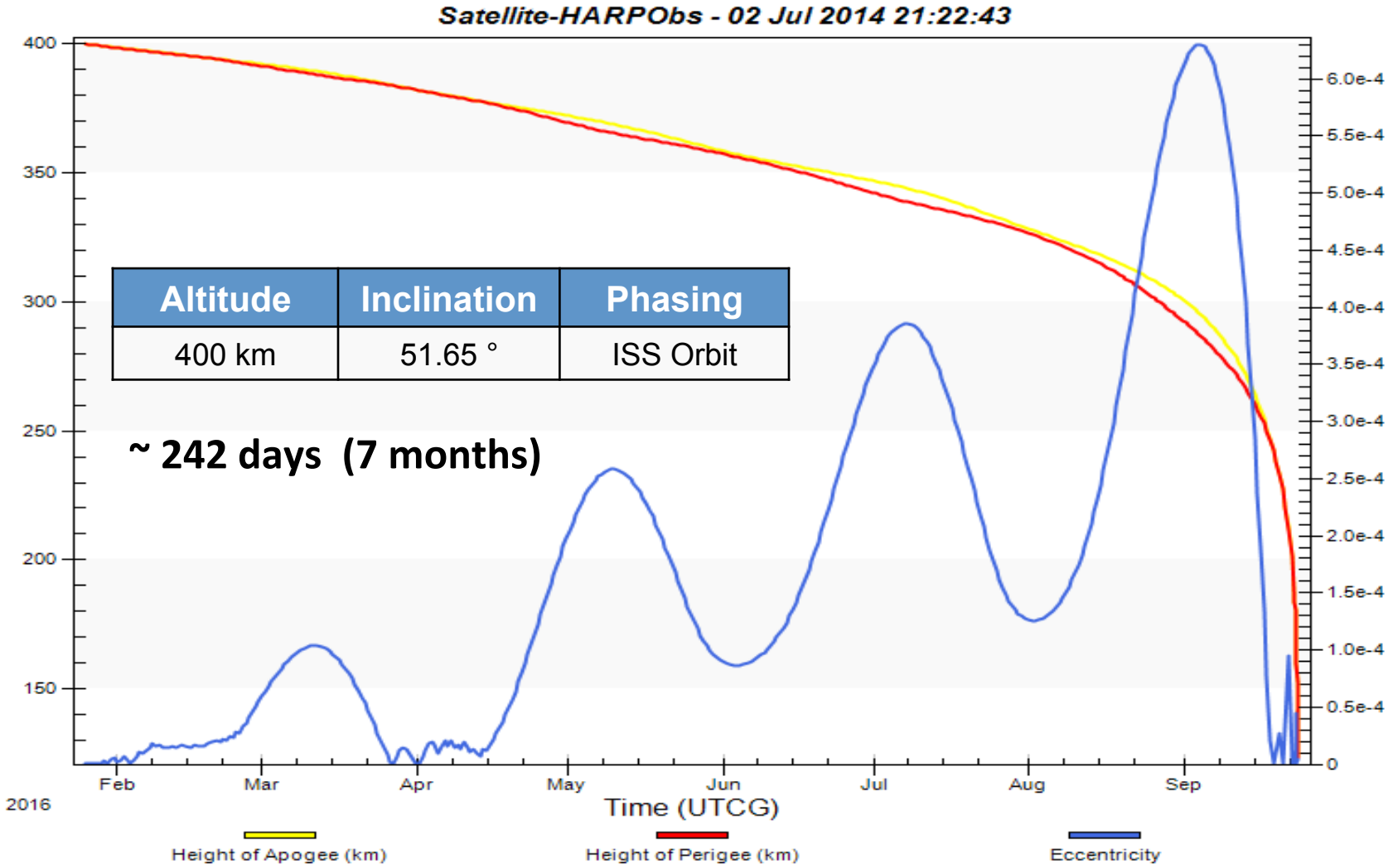
ISS cross within minutes of other satellites several times a day (example):

- 13 Apr 2016 07:41:00.489 – Terra/MODIS < 1 min
- 13 Apr 2016 09:21:40.489 – NPP/VIIRS < 1min
- 13 Apr 2016 18:23:30.489 – Aqua/MODIS < 5 min
- 13 Apr 2016 19:57:50.489 – Aqua/MODIS < 5 min
- 13 Apr 2016 22:58:50.489 – NPP/VIIRS < 5 min



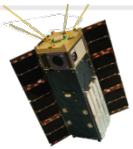
HARP

Mission Lifetime Analysis (worst case)



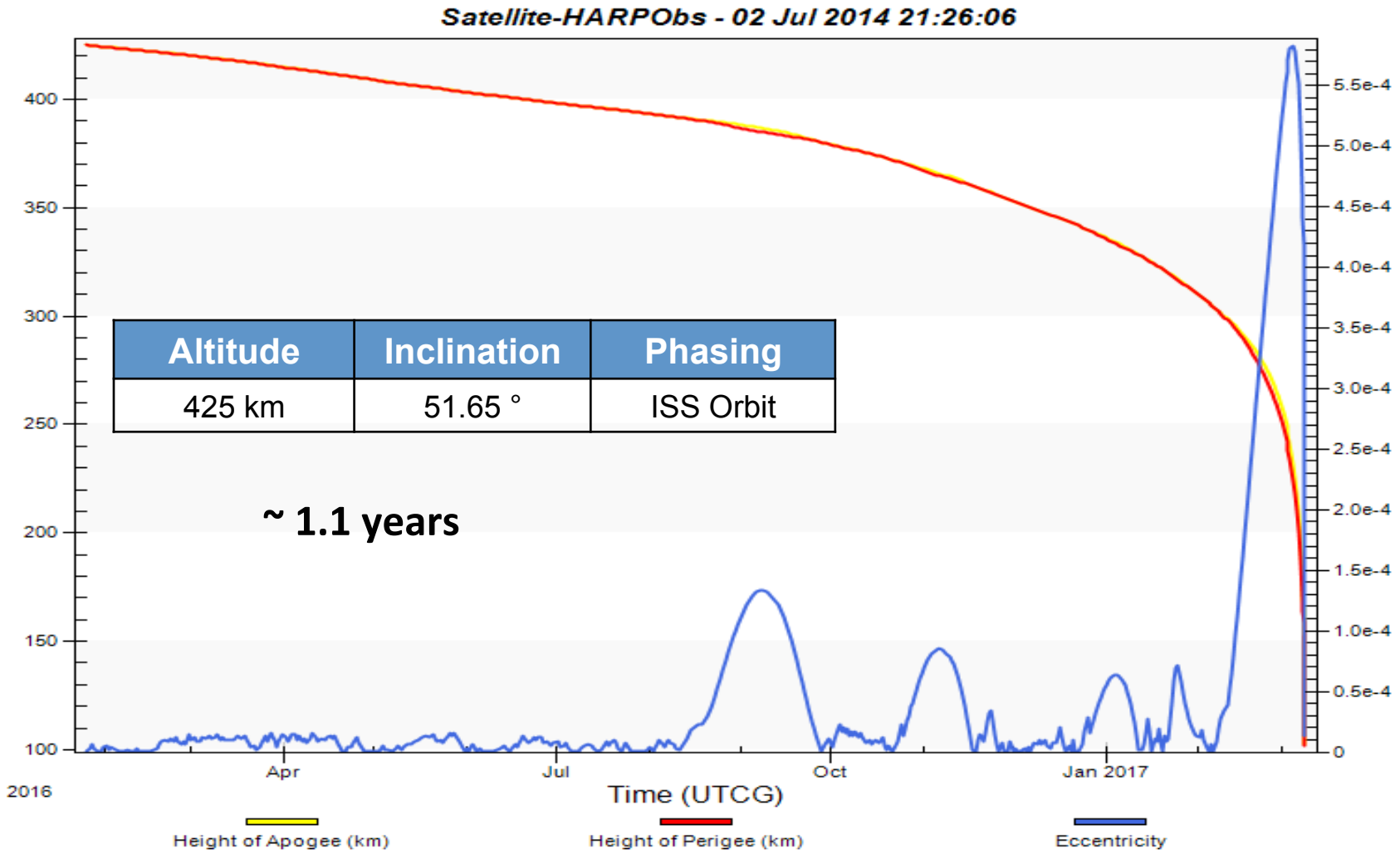
Altitude	Inclination	Phasing
400 km	51.65 °	ISS Orbit

~ 242 days (7 months)



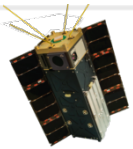
HARP

Mission Lifetime Analysis

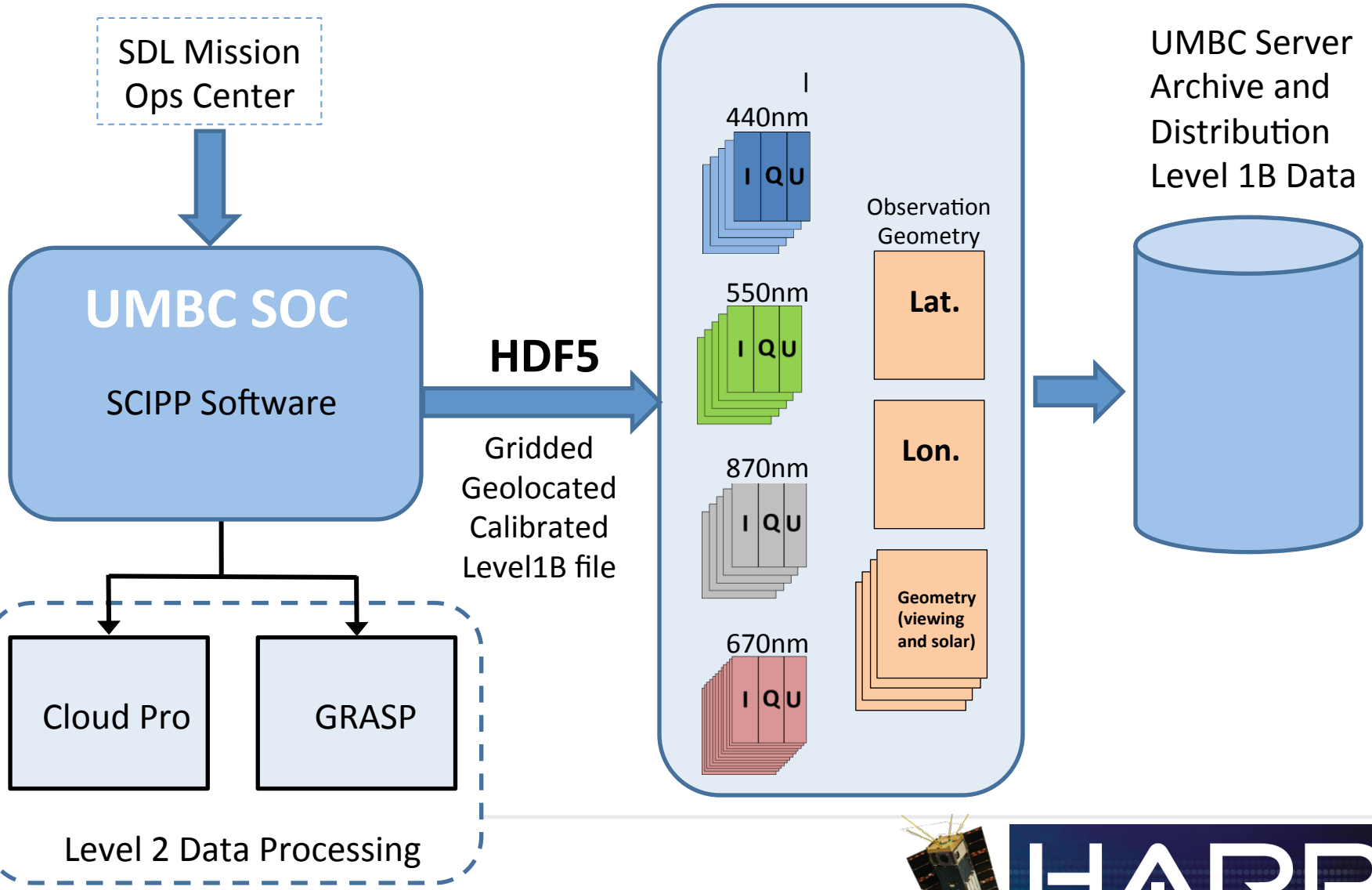


Altitude	Inclination	Phasing
425 km	51.65 °	ISS Orbit

~ 1.1 years



UMBC SOC - HARP level 1B Data Production



UMBC SOC - Level 2 Algorithm

SDL Mission Ops Center

UMBC SOC

SCIPP Software

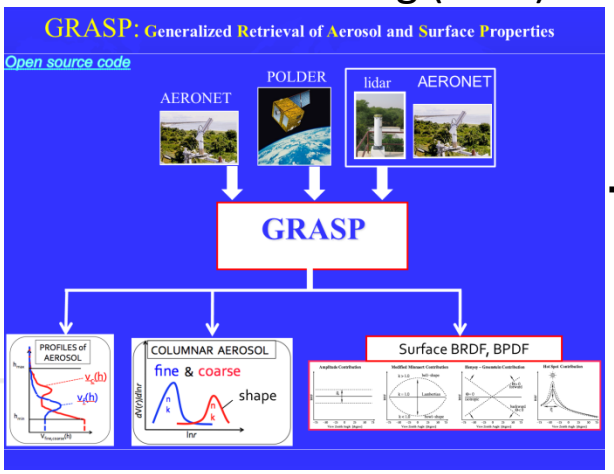
Cloud Processing

CloudPro:

Parametric retrievals:

- Cloud Height
- Droplet Effective radius and variance
- Cloud Phase

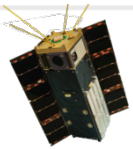
Aerosol Processing (Goal)



UMBC Server Archive and Distribution Level 1B Data

Plans in addition and beyond HARP

- HARP is a potential precursor for the polarimeter in ACE and other future NASA missions
- HARP polarimeter is seeking other flight opportunities:
  - Second copy could go on Space Station or other platforms (PACE?)
  - EVI/EVM proposals
- An Air HARP version is being prepared for ER2 flights
  - Would become a HARP demonstration before launch and a calibration validation effort for HARP CubeSat after launch
- HARP camera, FPGA electronics, and software has many other potential CubeSat applications
- HARP spacecraft concept is been considered for other science proposals
- NESSF proposal funded (Aug 2016) for HARP PhD student.



HARP

ACE would add UV and SWIR Modules

UV module

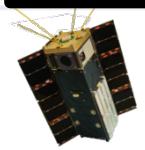
- 360, 380, 412nm
- Up 20 along track viewing angles
- 94 to 110deg cross track
- All bands polarized
- 1.3 km resolution

VNIR module

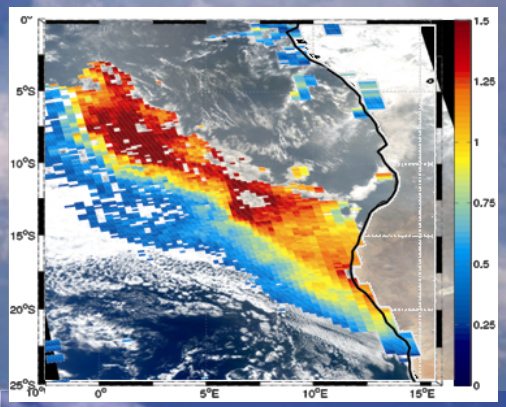
- 440, 550, 670, 765, 870, 910nm
- Up to 20 along track viewing angles
- Up to 60 along track viewing angles
- 94 to 110deg cross track
- All bands polarized
- 1.3 km resolution

SWIR module

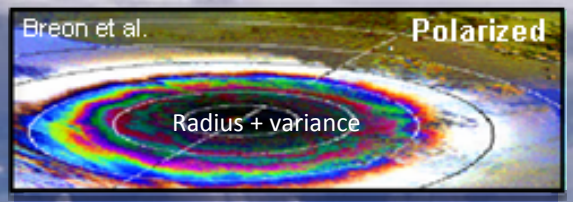
- 1660, 2.130, 2.250nm
- Up to 20 along track viewing angles
- 94 to 110deg cross track
- All bands polarized
- 1.3 km resolution



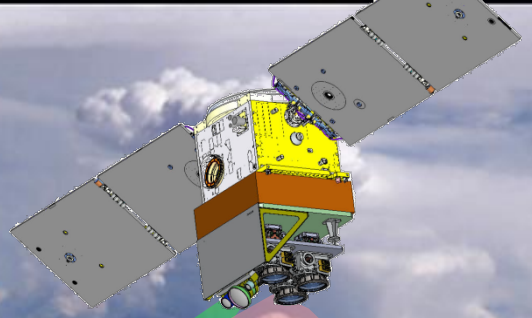
HARP



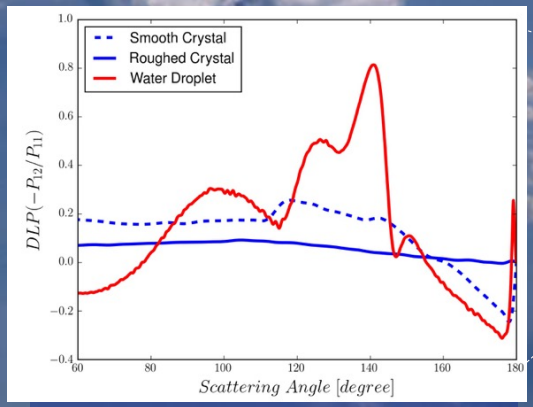
Aerosol above Clouds and Aerosol Absorption (UV and Polarization)



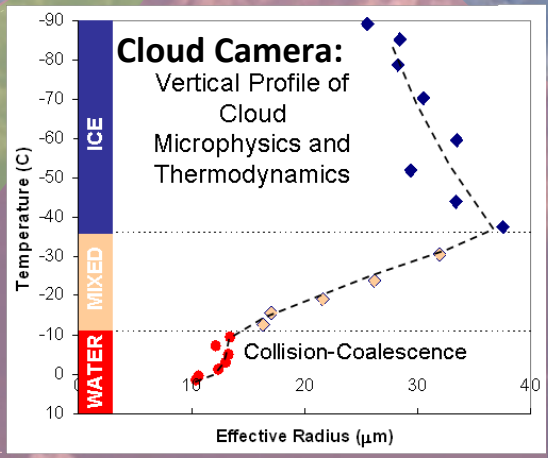
Cloudbow – Water Clouds



Volcanic Ash,
Twilight Aerosols, etc.
(Polarim. + Cloud Radiometer)



Ice/water particle's scattering



CLAIM-3D

PI: J. Vanderlei Martins (UMBC – JCET / 613)

- ***The interaction between aerosol and clouds carry the largest uncertainty in climate forcing***
- ***CLAIM-3D will determine how cloud evolution, droplet sizes, lifetime, vertical structure, thermodynamic phase, and ice particle structure vary as a function of aerosol type and amount***

Project Scientist: A. Marshak (GSFC 613)

- ***CLAIM-3D has unprecedented combination of mature instruments and algorithms to address the interaction between aerosols and clouds***
- ***CLAIM-3D is designed to provide a full court press characterization of the interactions between aerosol and clouds***

HARP

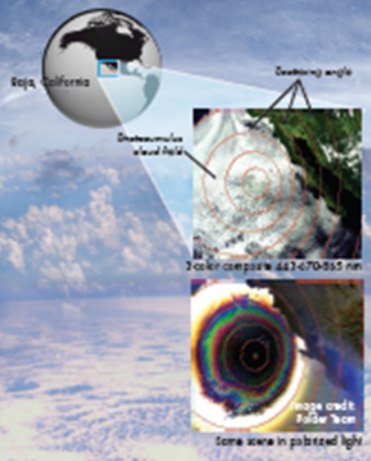
Hyper-Angular Rainbow Polarimeter

In-Space Validation of Earth Science Technologies (InVEST)

The HARP instrument is a wide field-of-view imager that splits three spatially identical images into three independent polarizers and detector arrays. This technique achieves simultaneous imagery of the same ground target in three polarization states and is the key innovation to achieve high polarimetric accuracy with no moving parts. The spacecraft consists of a 3U CubeSat with 3-axis stabilization designed to keep the image optics pointing nadir during data collection but maximizing solar panel sun pointing otherwise. The hyper-angular capability is achieved by acquiring overlapping images at very fast speeds.

OBJECTIVES:

- Validate new technology as required by the NASA Decadal Survey Aerosol-Cloud-Ecosystem (ACE) mission
- Demonstrate the on-flight capabilities of a highly accurate wide field-of-view hyper-angle imaging polarimeter for characterizing aerosol and cloud properties
- Demonstrate that CubeSat form-factors can provide high-quality Earth Sciences data



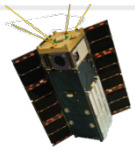
UMBC NASA STC NOAA

Space Dynamics Laboratory

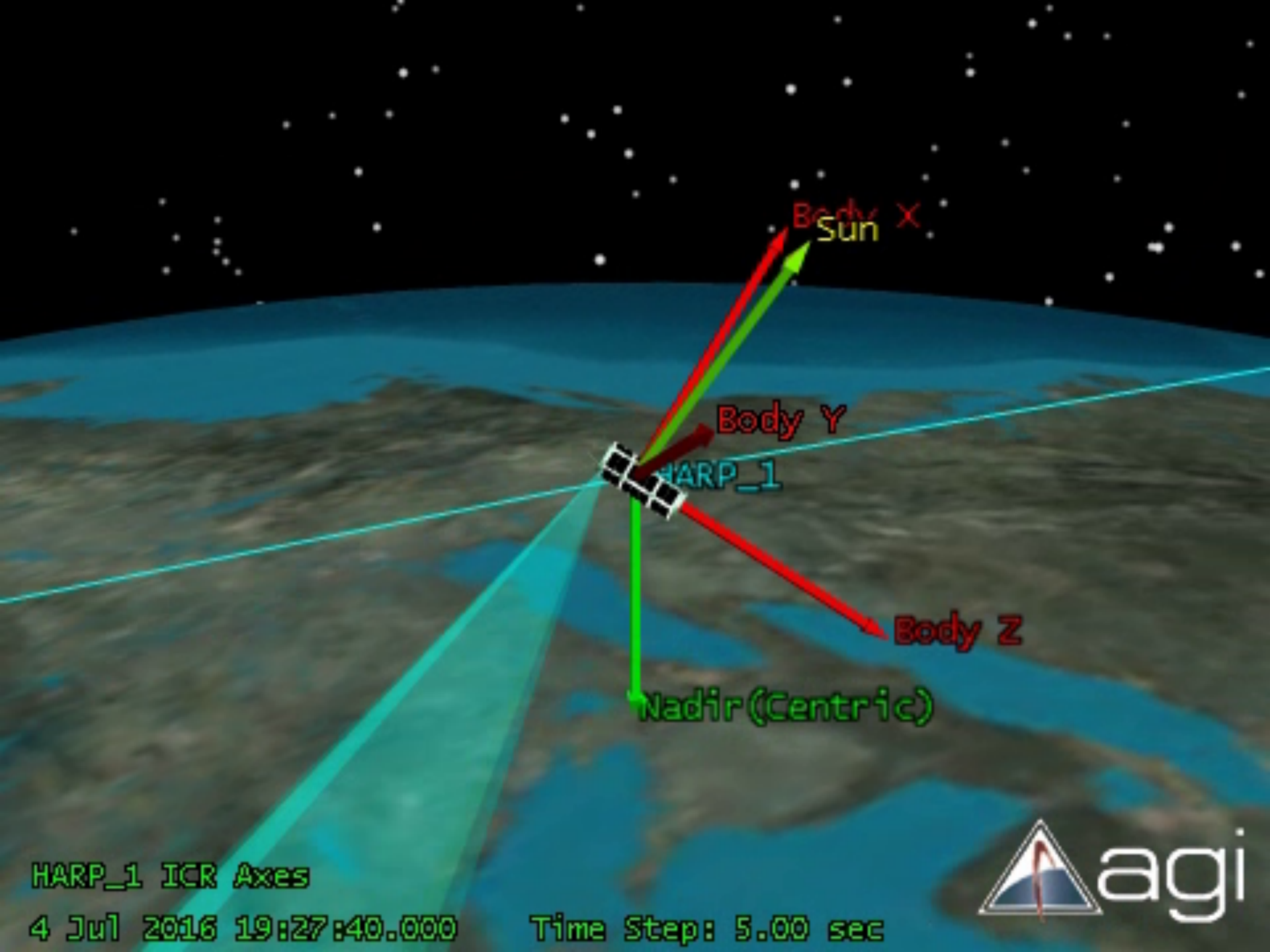
1695 North Research Park Way • North Logan, Utah 84341 • Phone 435.713.3400 • www.sdl.usu.edu

Thank you!!!

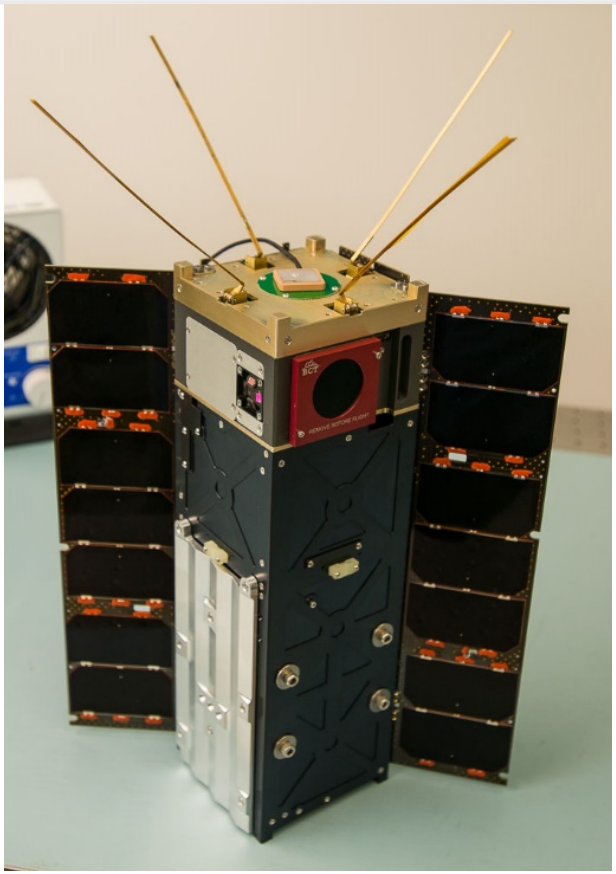
Backup slides:



HARP

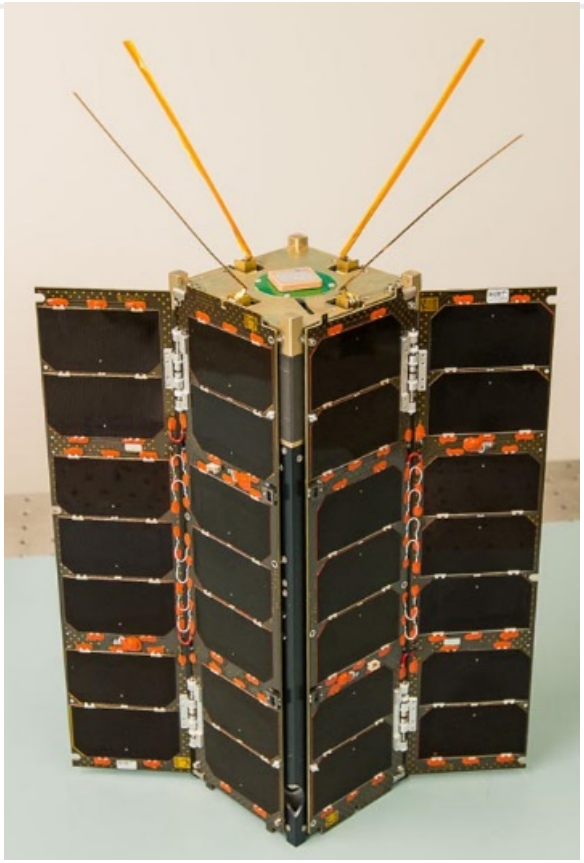

Body X
Sun
Body Y
HARP_1
Body Z
Nadir(Centric)
HARP_1 ICR Axes
4 Jul 2016 19:27:40.000
Time Step: 5.00 sec
agi

Spacecraft Views



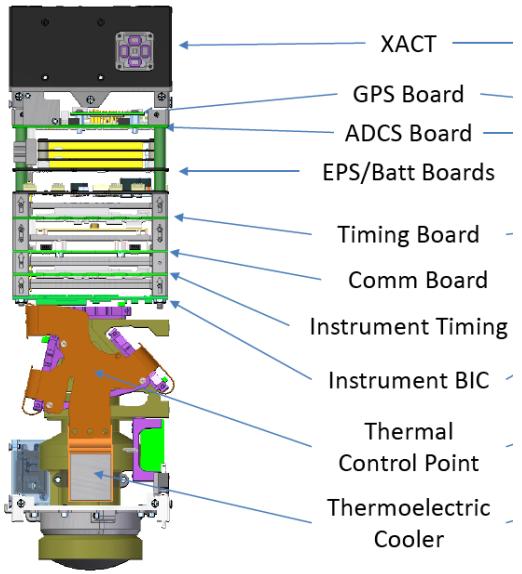
Back view

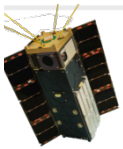
- Thermal Radiators
- Star Camera aperture
- Sun Sensor
- GPS Patch Antenna



Front view

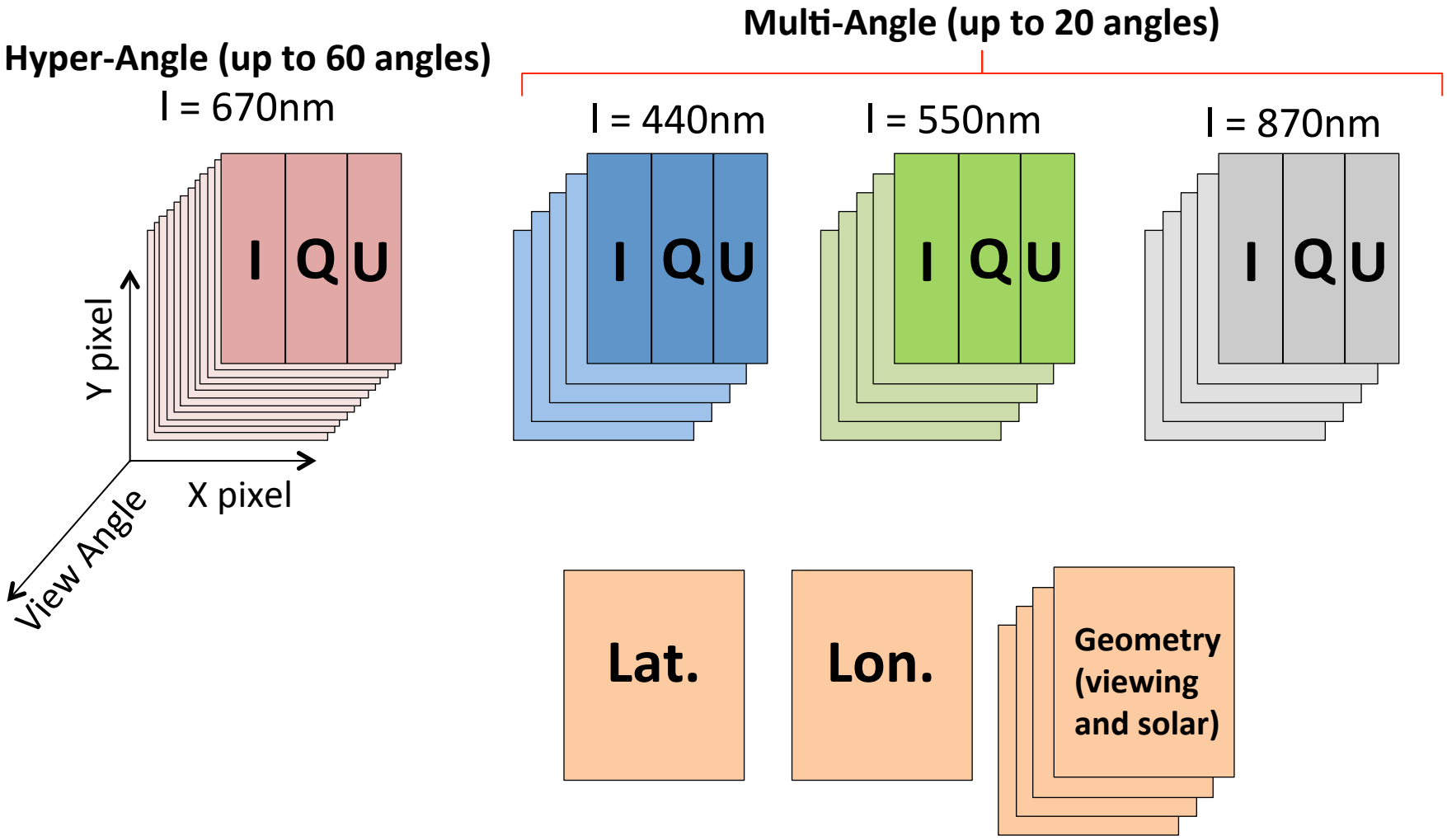
- Deployed Solar Arrays and Antenna
- ADCS Sensors
- Instrument aperture at the bottom





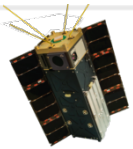
HARP

HARP Data Structure



Goals X Minimum Mission

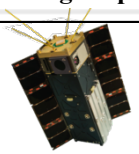
- **Minimum mission** (satisfy our success criteria)
  - Can be achieved with the polarized hyperangular measurement at a single wavelength
  - Demonstrated the use of hyperangular polarized imaging on the retrieval of cloud droplet size distribution in moderate resolution (~4km)
  - Minimum mission provides higher quality single wavelength measurements.
- **Intermediate Mission**
  - Similar to goal mission with 3 wavelengths achieved using color RGB CCD and multi-bandpass filter.
  - Less desirable than goal mission, but still provides more information than minimum mission.
- **Goal mission**
  - Measure cloud, aerosol and surface in up to 4 wavelengths (0.44, 0.55, 0.67 and 0.87um)
  - One wavelength (0.67um) with hyperangular capability for clouds, and other with less angles for aerosols and surface
  - Spatial resolution: between 2.5 and 4km



HARP

Requirements Traceability Matrix

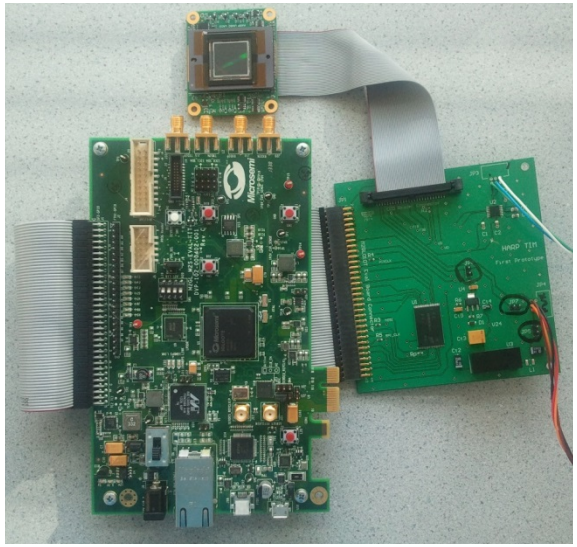
Mission Objectives	Measurement Requirements	Sensor Requirements	Observatory Requirements
1. Space validation of new technology required by the Tier 2 Decadal Survey Aerosol-Cloud-Ecosystem (ACE) mission science definition team 2. Prove the on-flight capabilities of a highly accurate wide FOV hyperangular imaging polarimeter for characterizing aerosol and cloud properties	**Wavelengths:** 1x VIS or NIR in atmospheric window for clouds only 3x VIS or 2x VIS + 0.87 µm for color imagery and to begin characterizing aerosols **Angles:** 1x wavelength with 20x spanning scattering angles ≥ 130 ° and ≤ 170 ° **Polarization:** ≤ 2% accuracy **Spatial resolution:** ≤ 4 km @nadir **Swath:** ≥ 900 km **Statistical sample size:** ≥ 15,000 fully observed 1° squares. This is achieved by a combination of swath, sampling duration, and length of mission. **Targets:** Cloudy regions, aerosol events and AERONET sites of tropical belt (± 40 °) over land and ocean (avoid snow/ice).	**Configuration:** Single telescope Modified Philips prisms to split into 3x identical images onto 3x CCDs, measuring 3x polarization states simultaneously Patterned focal plane filters (stripes or pixel patterns) for multi-wavelength images and aerosol characterization. **FOV:** ≥ 90 ° along track **Time Stamping Resolution:** ≤ 10 ms **Detector Thermal Sink Stability:** 0 – 20 °C offset prior to observation ≤ ±2.5 °C delta during observation	**Mission Duration:** ≥ 90 days **Orbit Altitude:** Circular, 450-650 km (600 km nominal) **Orbit Inclination:** ≥ 30 ° **Data Acquisition:** ≥ 13 min/day during 1x orbit **Pointing Knowledge:** ≤ 0.063 °, 1 σ (660 m geo-location accuracy) **Pointing Accuracy:** ≤ 5 °, 1 σ (50 km geo-location accuracy) **Pointing Stability and Jitter:** ≤ 0.063 °/s, 1 σ ≤ 0.0015 °/ms, 1 σ **Science Telemetry**: ≥ 1.43 Gbits/day (M-F) **Storage Capacity**: ≥ 4.29 Gbits **Calibration Maneuvers:** Monthly sweep of Earth's limb and moon **Instrument Orientation:** See Figure A.1
	Measurement Goals		**Observatory Goals**
	Wavelengths: 4x VNIR **Polarization:** ≤ 0.5% accuracy **Spatial resolution:** ≤ 2.5 km @nadir		**Mission Duration:** ≥ 1 year **Data Acquisition:** ≥ 78 min/day during 6x orbits **Telemetry**: ≥ 8.6 Gbits/day (M-F) **Storage capacity**: ≥ 26 Gbits



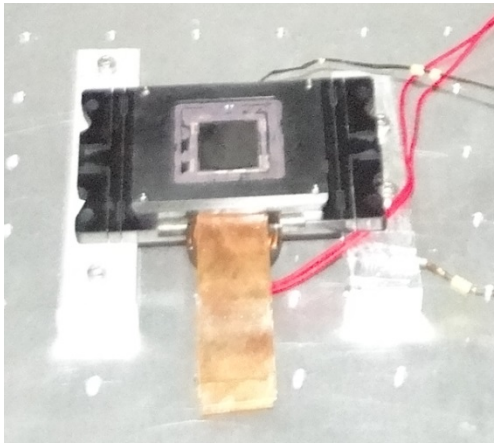
HARP

Hardware Development and testing at UMBC

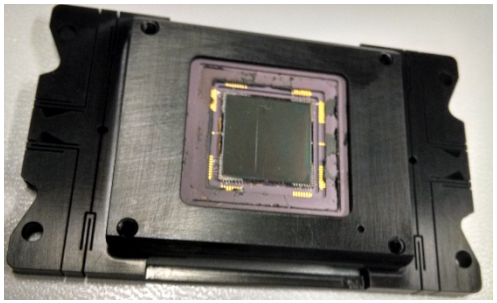
IBIC Software functional test s



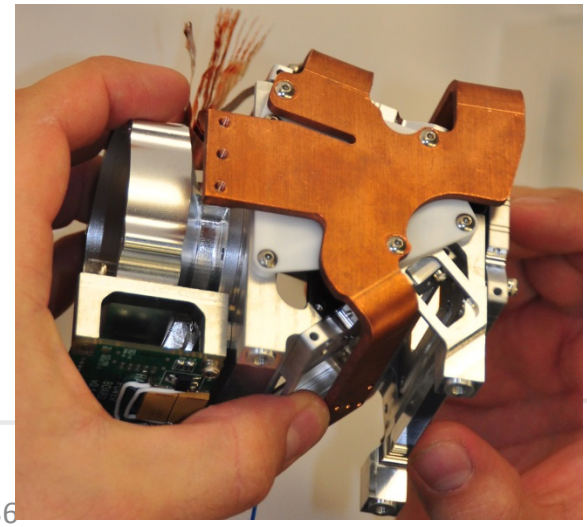
Detector Thermal System Testing

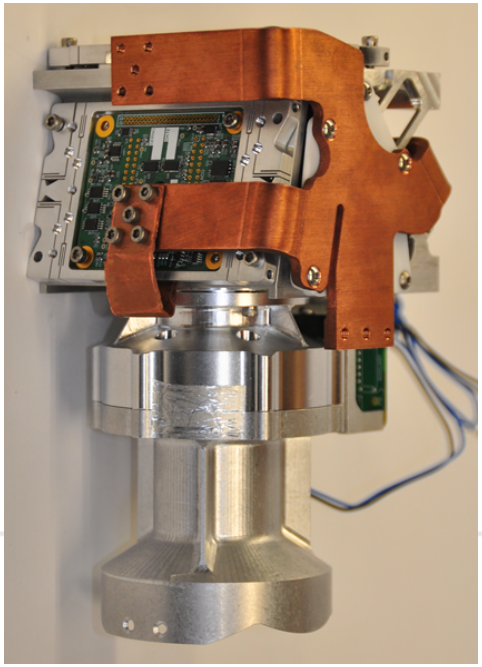


Tests of detector's alignment stage

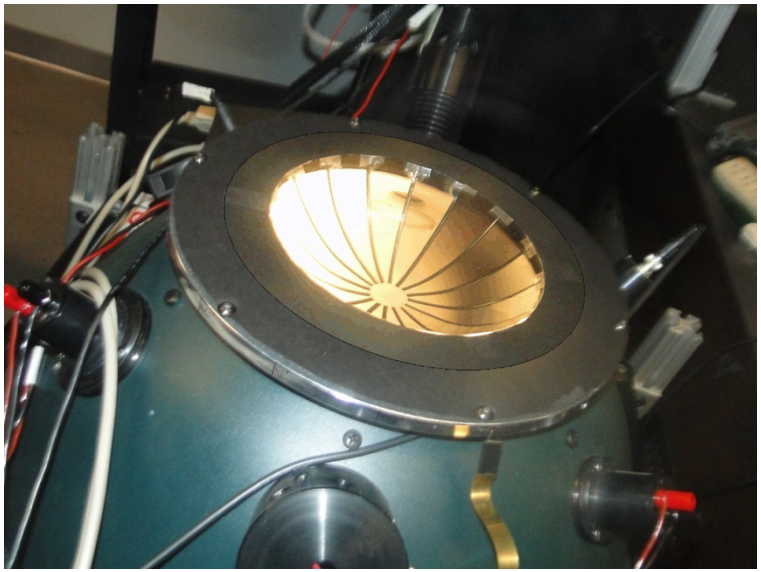


Mechanical Fit Checks

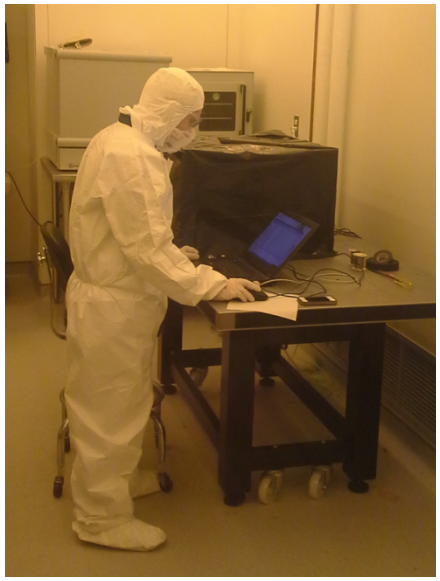




UMBC Calibration/Testing Facilities

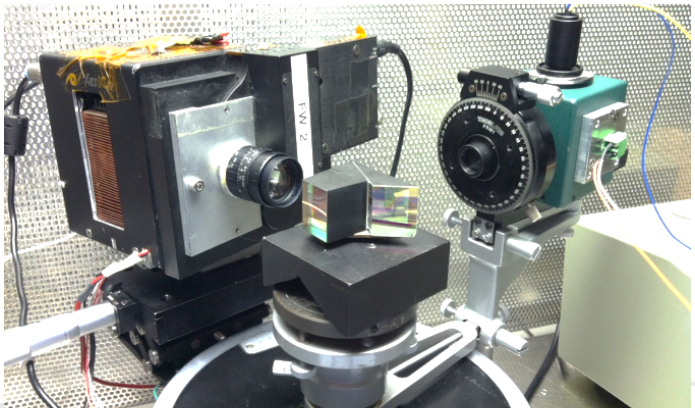


Polarization Calibrator

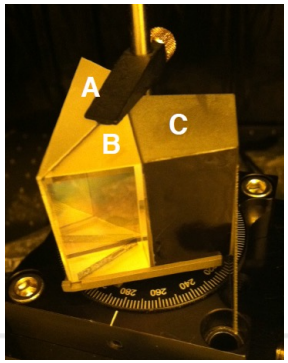


Clean room assembly and testing

Thermo-Vac testing



Prism Polarization Testing

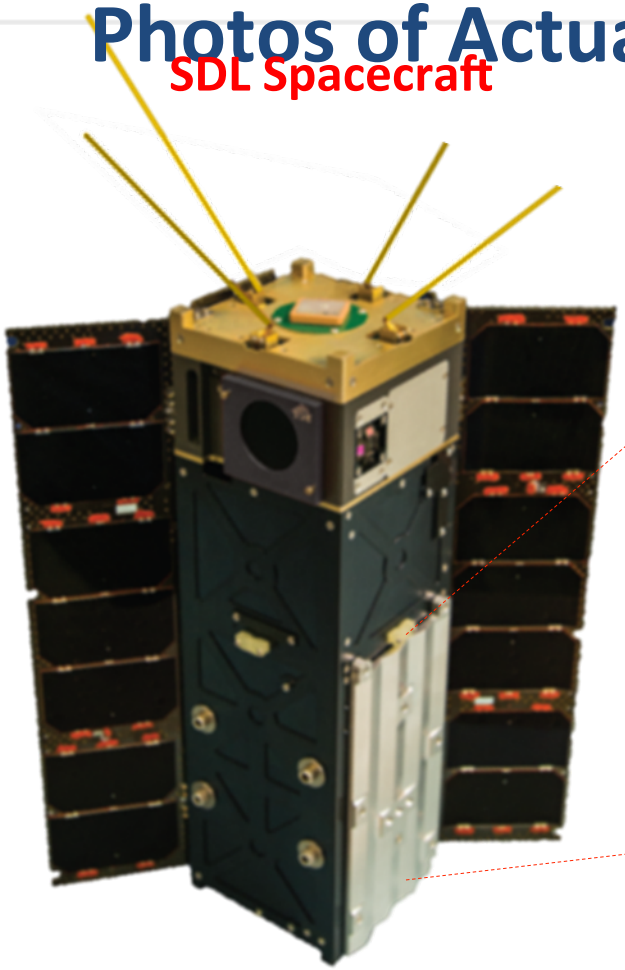


Shutter : successful endurance and thermo-vac

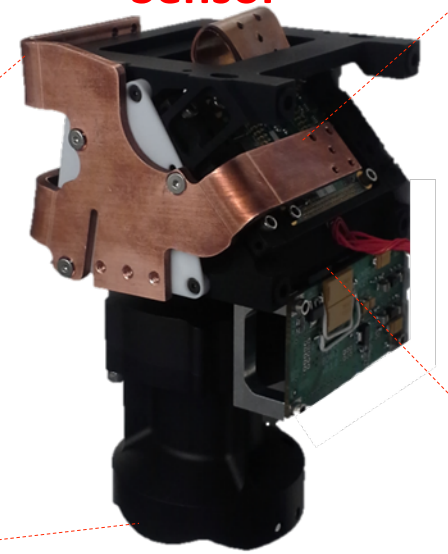
HARP

Photos of Actual Instrument & Spacecraft

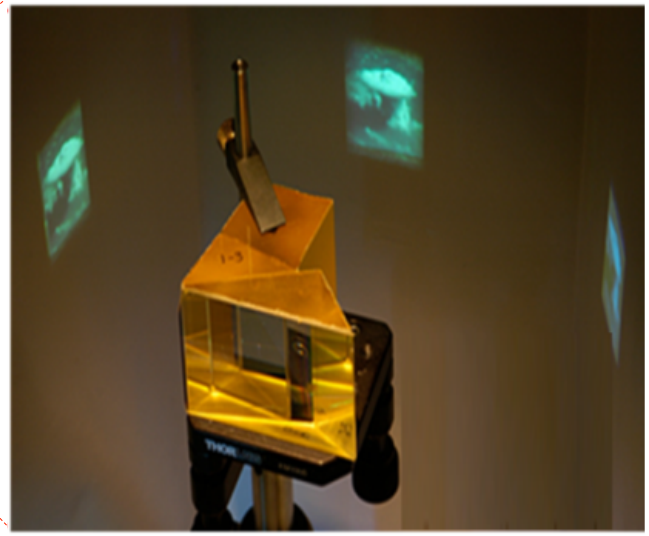
SDL Spacecraft



UMBC Sensor



HARP Prism



HARP Stripe Filter