# The Multi-angle Polarimeter

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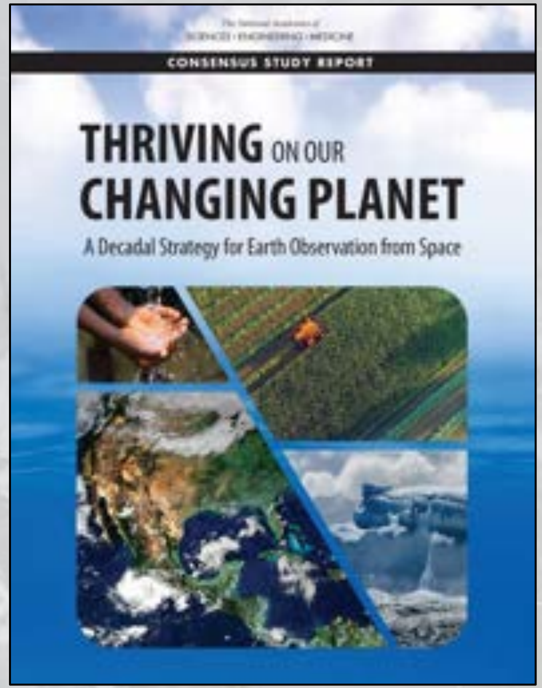
**May 2023**

# Decadal Survey Recommendations

| Targeted Observable | Science/Applications Summary | Candidate Measurement Approach |
|---|---|---|
| Aerosols | *Aerosol properties, aerosol vertical profiles, and cloud properties* to understand their effects on climate and air quality | Backscatter lidar and multichannel/multiangle/ polarization imaging radiometer flown together on the same platform |
| Clouds, Convection, and Precipitation | *Coupled cloud-precipitation state and dynamics* for monitoring global hydrological cycle and understanding contributing processes including cloud feedback | Dual-frequency radar, with multifrequency passive microwave and sub-mm radiometer |

Mentioned together

| Targeted Observable | *Added* Measurement Considerations | *Notes* |
|---|---|---|
| Aerosols | Ocean Ecosystem capability | HSRL desirable but possibly beyond cost cap |
| Clouds, Convection and Precipitation | Diurnal cycle characterization assisted by Program of Record (PoR) | Minimum capability of single frequency radar with dynamics (Doppler or proxy) |




National Academies of Sciences, Engineering, and Medicine 2018

*Pre-Decisional – AOS is in Phase A and NASA makes no commitments on the final design of the mission or instruments*

# Multi-angle Polarimeter Concept

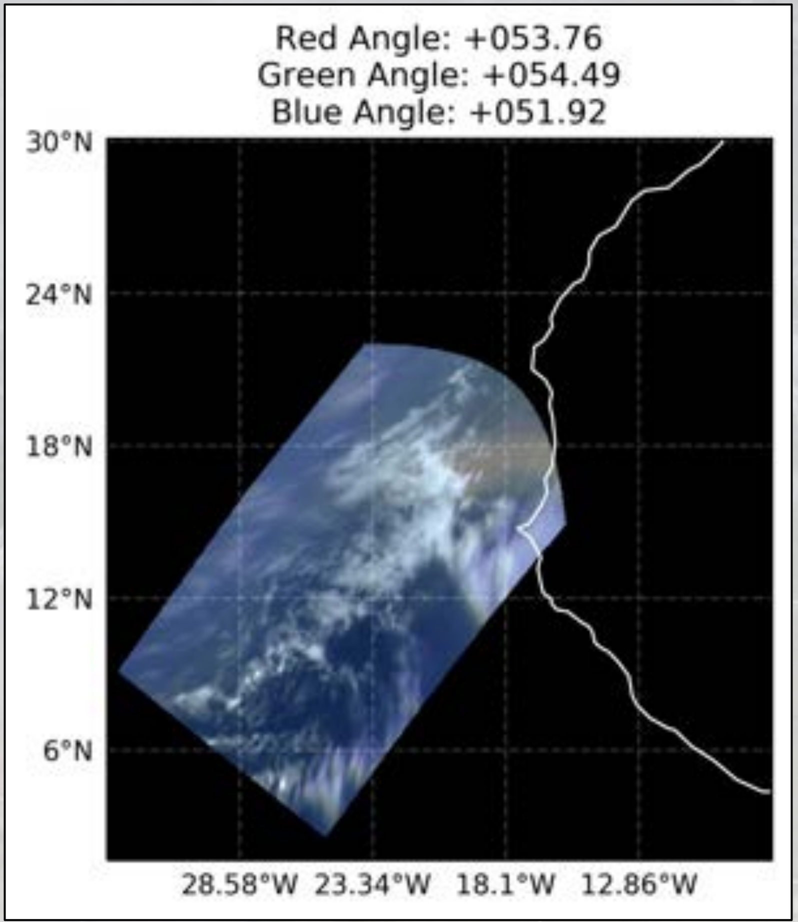
**Decadal survey + ACCP studies recommended:**

Passive radiometer with measurement characteristics

- multi-spectral (UV-VIS-NIR-SWIR)
- multi-angle / hyper-angle (10-60 views per pixel)
- accurate polarization sensitivity

Animation through multi-angle views →

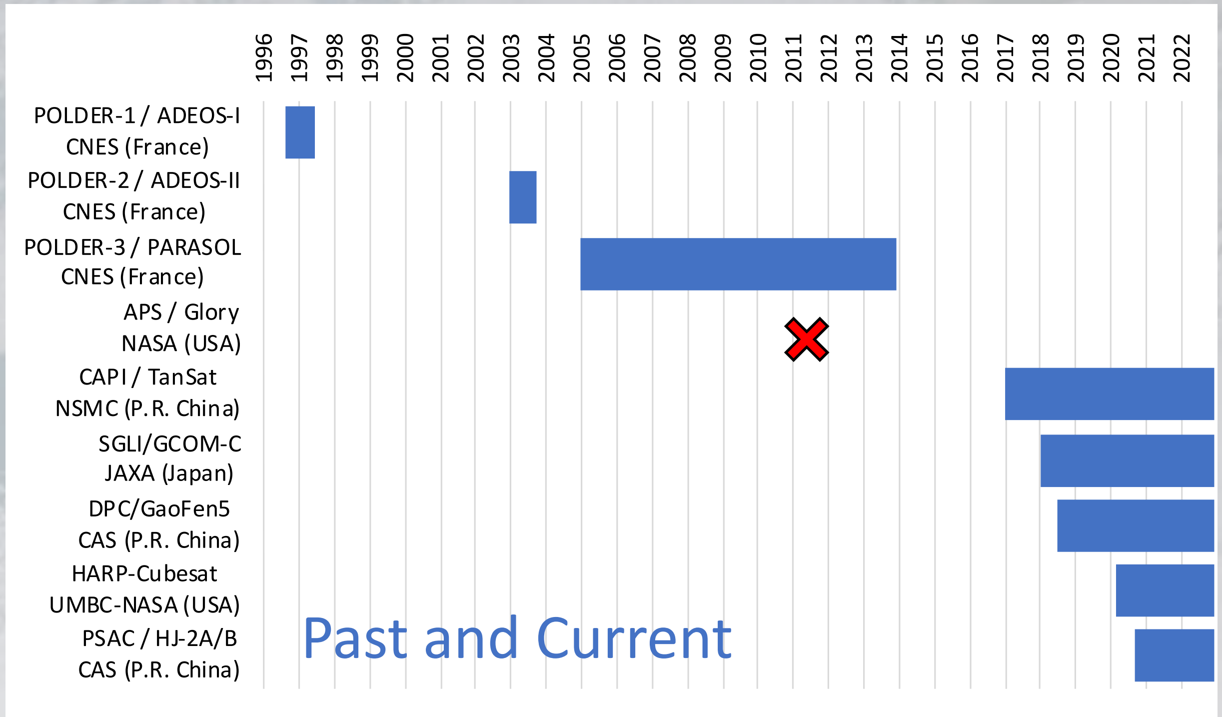
**HARP Cubesat RGB imagery, West Africa with Saharan dust, glint, clouds 2020 / 06 / 13**




Not shown are hyperangle and polarimetric data. The AOS polarimeter would have UV, SWIR and better spatial resolution. From: https://esi.umbc.edu/hyper-angular-rainbow-polarimeter/

| |
|---|
| Addresses climate, weather and air quality objectives with measurements of **cloud** and **aerosol** properties |

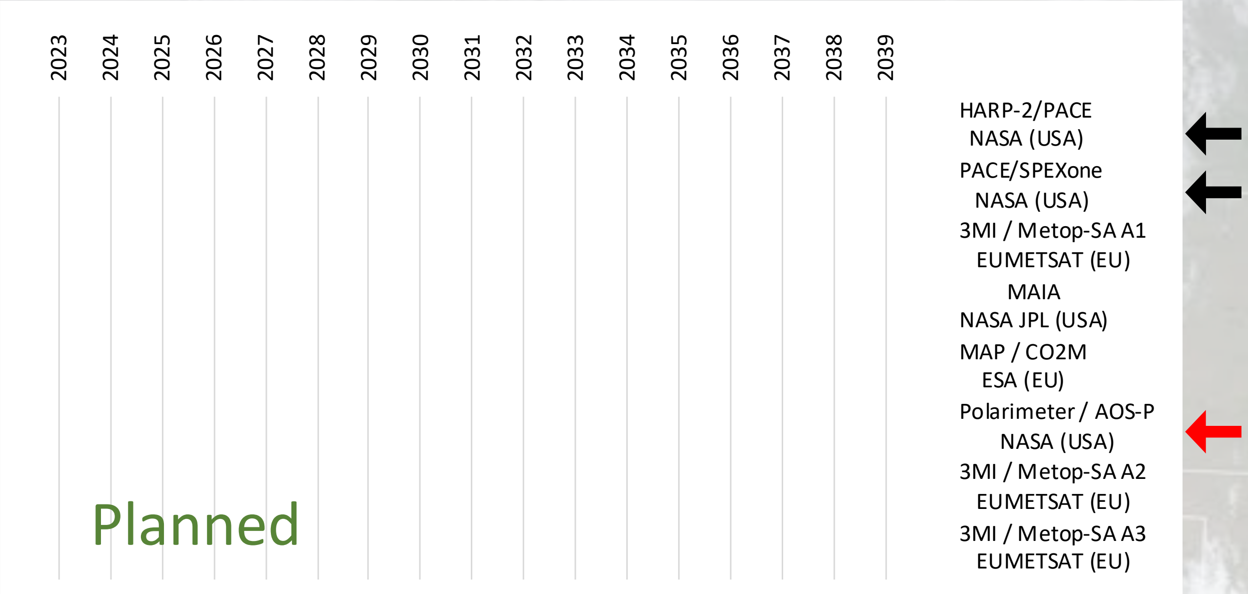
# History of Multi-Angle Polarimeters




## Multi-angle polarimeters in LEO

**POLDER-3** – arguably most successful polarimeter to date.
**APS/Glory** – NASA's attempt at a polarimeter ended in a launch failure
**PACE/HARP2** and **PACE/SPEXone** – 'do no harm' instruments, proof of concept
**HARP-Cubesat** and **MAIA** – US instruments that (did/will) lack global coverage

**AOS** will improve upon POLDER with better cloud measurements (SWIR channels and polarimetric approach), order of magnitude better accuracy and UV for aerosols, and parallax-based feature height detection capability. It will be NASA's contribution to global measurement of aerosols and clouds.




**From:**


Dubovik et al. : Polarimetric remote sensing of atmospheric aerosols: Instruments, methodologies, results, and perspectives, J. Quant. Spectrosc. Ra., 224, 474 - 511 , https://doi.org/10.1016/j.jqsrt.2018.11.024 , 2019.

Advancement of POLarimetric Observations (APOLO-2022) conference presentations: https://pikesmeetings.wixsite.com/apolo-2022

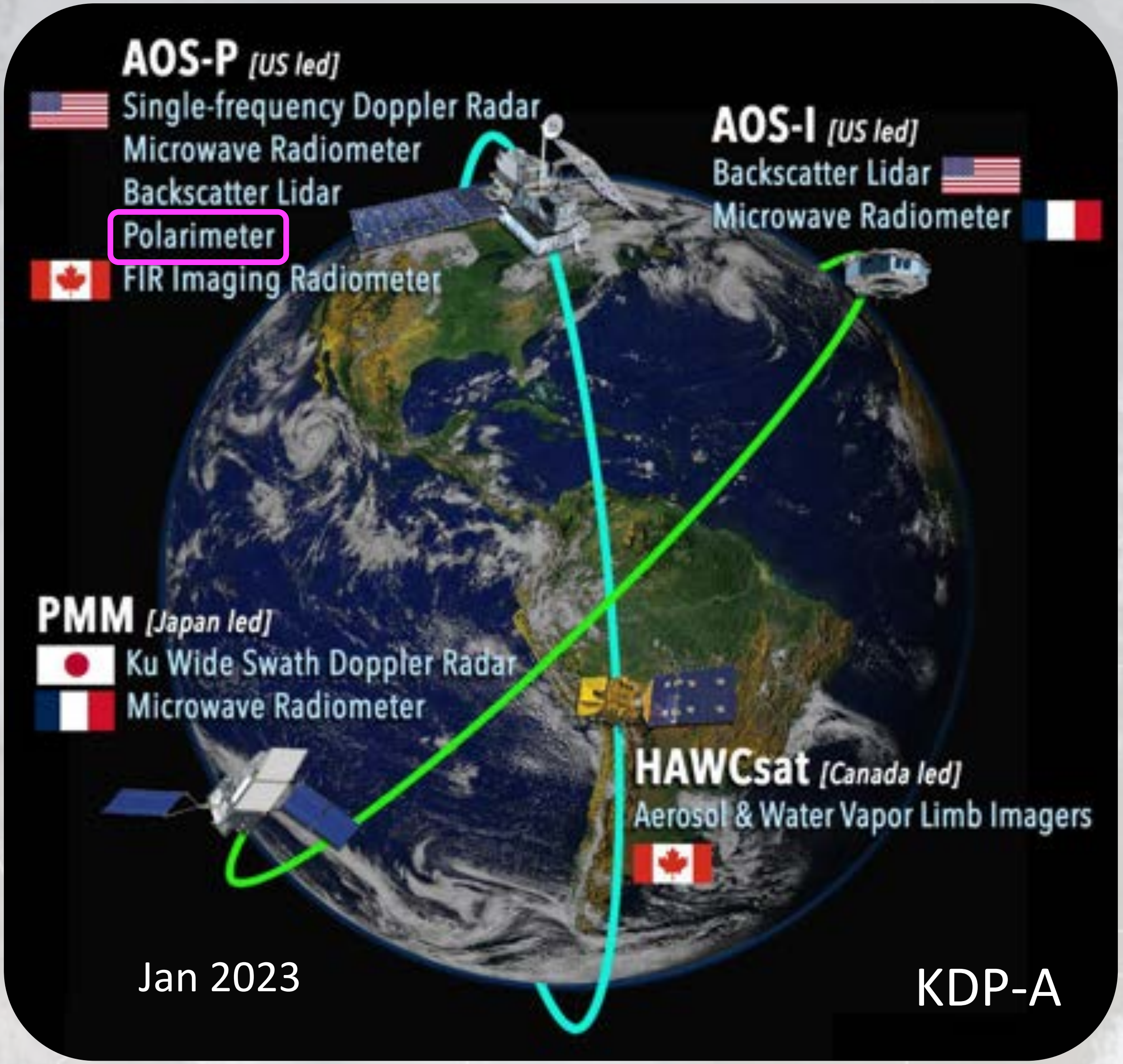
# KDP-A Architecture

The original ACCP Architecture called for a polarimeter in AOS-P and AOS-I

The AOS-I polarimeter was descoped prior to MCR along with other instruments

Some AOS-P polarimeter requirements (SWIR channels) were strengthened to enable a portion of measurements lost with the SW Spectrometer descope

**AOS intends a procurement through open competition**



# (Current) Requirements

## Summary of instrument requirements:

Spatial resolution of 500m at **nadir**, cross track swath of 300km

Total uncertainty: radiometric < 3%, Degree of Linear Polarization (DoLP) < 0.005

| Science driver | Wavelength range | # of bands | # of viewing angles per pixel |
|---|---|---|---|
| Aerosol | UV: 350 – 390 nm | 1 | 10 |
| Aerosol, bi-spectral cloud | VIS-NIR: 410 – 750 nm | 2 | 10 |
| Cloudbow cloud retrieval | Hyperangle: 670 – 870 nm | 1 | 60 |
| Water vapor measurement | NIR: 900 – 960nm | 1 | 10 |
| SWIR cirrus cloud detection | SWIR: 1350 – 1400nm | 1 | 10 |
| Aerosol, bi-spectral cloud | VNIR-SWIR:870 – 1570 nm | 3 | 10 |

**Multi-angle, polarimetric measurements for all channels**

Unique and important capability

## Multiple retrieval categories

**Aerosol:** multiangle, polarimetric UV-VIS-NIR observations to determine **aerosol optical depth** and **aerosol microphysical properties**.

**Bi-spectral Cloud:** pairs of NIR/SWIR channels to determine **cloud optical depth** and **droplet effective radius**

**Cloudbow Cloud:** hyperangle polarimetric VIS/NIR observations to determine **cloud optical depth** and **droplet effective radius and variance**.

**Water vapor** channel to characterize water vapor profile applied to correct water vapor response in other channels

**Cirrus cloud detection** channel in strong water absorption feature to detect thin cirrus clouds that impact other retrievals

# Polarimeter Traceability Matrix: Clouds

Thresholds indicated by [brackets]

| Science Objectives | Geophysical Variable Requirements | |
|---|---|---|
| | Geophysical Variable | Conditions |
| O1. Low Clouds<br><br>O2. High Clouds<br><br>O4. Cold clouds and precipitation<br><br>O6. Aerosol removal, vertical redistribution, and processing<br><br>O8. Aerosol indirect effect | **GV5.** Cloud droplet effective radius<br>**O1, O6, O8** | **Daytime**, low cloud (<5km top)<br>**Uncertainty:** 50% for precipitating clouds, 20% otherwise<br>**Range:** optical depth > 2, effective radius 5-30µm<br>**Resolution:** 500m [1km] nadir<br>**Swath:** 300km [100km] |
| | **GV7.** Cloud optical depth<br>**O1, O2, O4, O6, O8** | **Daytime**<br>**Uncertainty:** max(0.3, 50%)<br>**Range:** 0.3 < optical depth < 50<br>**Resolution:** 1km nadir |

**Daytime measurements of:**

GV5: cloud droplet size

GV7: optical depth

at 500m nadir resolution and 300km swath (baseline) - important for 5 science objectives

The polarimeter has two independent ways to determine these properties; these products have different vertical sensitivity

* Projected performance is for industry study instruments MegaHARP-4 and MegaHARP-2; polarimeter contract will be awarded in Phase B

# Polarimeter Traceability Matrix: Clouds

**Bispectral** (Nakajima-King) heritage algorithms use NIR/SWIR spectral pairs

Lookup table for liquid phase cloud

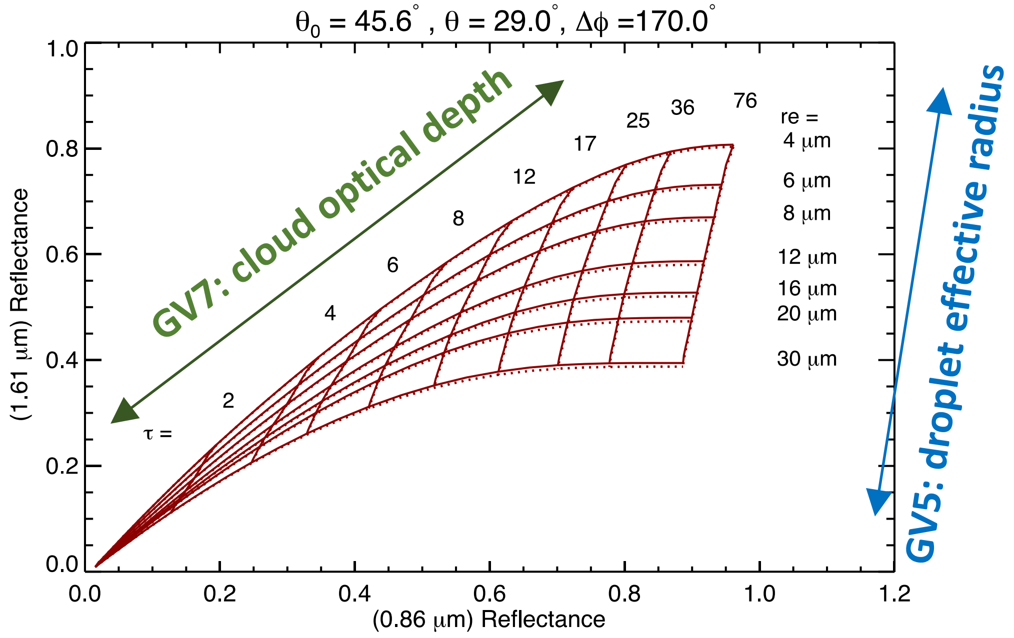



Figure courtesy of Kerry Meyer, NASA GSFC

| SWIR radiance<br>NIR radiance | → | Cloud droplet effective radius (GV5)<br><br>Cloud optical depth (GV7) |
|---|---|---|

**Details:**

Sensitive to body of cloud , assumes droplet effective variance, no aerosols above clouds

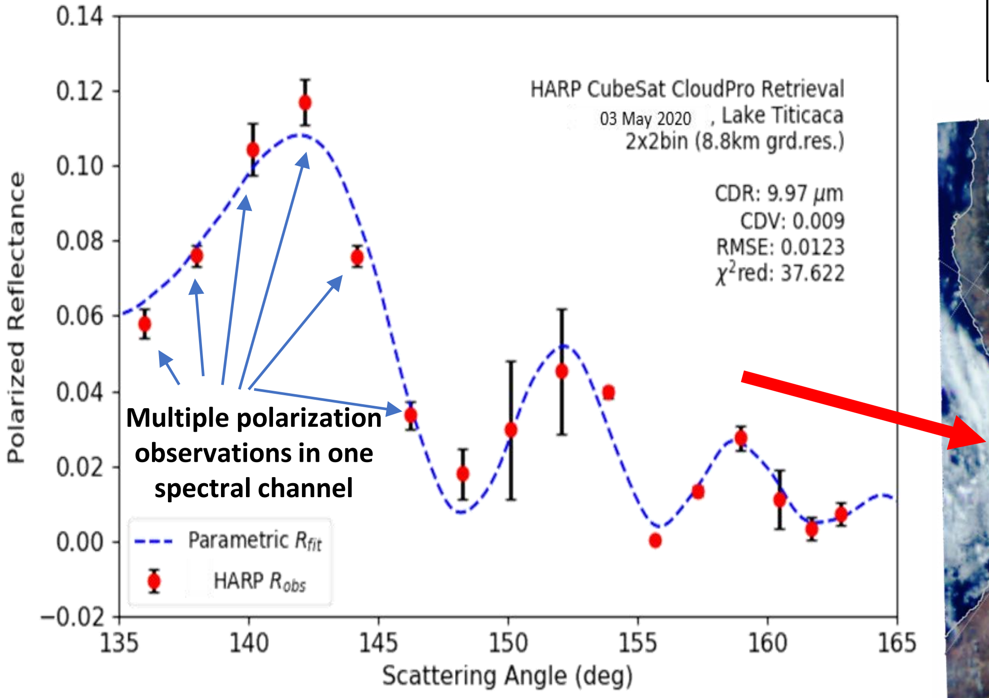
Separate tables for liquid, ice phase clouds

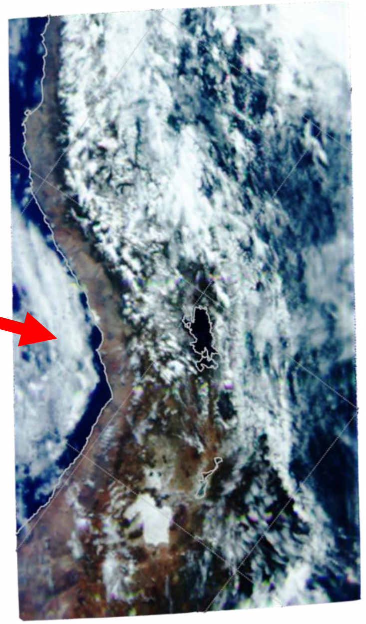
Original concept had a longer wavelength SWIR channel, but study contract indicated this was infeasible

# Polarimeter Traceability Matrix: Clouds

## The **Rainbow** method uses multi-angle VIS polarization

Example from HARP CubeSat



This is also a good way to determine cloud phase

**Hyperangle** (60+), **polarimetric VIS observations** → **Cloud droplet effective radius (GV5)**, **Cloud droplet effective variance**, **Cloud optical depth (GV7)**

**Details:**
Less heritage, but performed with POLDER

Sensitive to top of cloud, less sensitive to 3D impacts, aerosols.

Requires ability to observe at scattering angles > 140˚

Ice clouds: different polarimetric approach which doesn't need hyperangle observations

# Polarimeter Traceability Matrix: Aerosols

Thresholds indicated by [brackets]

| Science Objectives | Geophysical Variable Requirements | |
|---|---|---|
| | Geophysical Variable | Conditions |
| **O3. Convective Processes**<br><br>**O5. Aerosol attribution and air quality**<br><br>**O6. Aerosol removal, vertical redistribution, and processing**<br><br>**O7. Aerosol direct effect and absorption**<br><br>**O8. Aerosol indirect effect** | **GV12.** Aerosol column optical depth (UV, VIS, NIR)<br>**O3, O5, O6, O7, O8** | **Daytime, clear sky, global [ocean]**<br>[UV] VIS-NIR<br>**Uncertainty:** 0.03+0.1*AOD<br>**Resolution:** 0.5 [1] km nadir<br>**Swath:** 300 [100] km |
| | **GV13.** Aerosol column aerosol absorption optical depth (UV, VIS)<br>**O5, O6, O7, O8** | **Daytime, clear sky, global [ocean]**<br>[UV] VIS<br>**Uncertainty:** max(0.003,50%) [ max(0.005, 50%) ]<br>**Resolution:** 0.5 [1] km nadir<br>**Swath:** 300 [100] km |
| | **GV14.** Aerosol column fine-mode effective radius<br>**O5, O6, O7, O8** | **Daytime, clear sky, global [ocean]**<br>**Uncertainty:** max(0.05,0.1*(0.1$^{AOD}$)) µm<br>**Resolution:** 0.5 [1] km nadir<br>**Swath:** 300 [100] km |

**Daytime measurements of**
Aerosol optical depth (GV12)
Aerosol absorption optical depth (GV13)
Aerosol fine mode effective radius (GV14)
+other aerosol microphysical properties

at 500m resolution and 300km swath (baseline)

important for 5 science objectives

* Projected performance is for industry study instruments MegaHARP-4 and MegaHARP-2; polarimeter contract will be awarded in Phase-B

# Polarimeter Traceability Matrix: Aerosols

## **Simultaneous retrieval** of GV's with radiative transfer model optimization

**multiangle, polarimetric UV-VIS-NIR observations**

↓

**Aerosol optical depth (GV12)**

**Aerosol absorption optical depth (GV13)**

**Aerosol fine mode effective radius (GV14)**

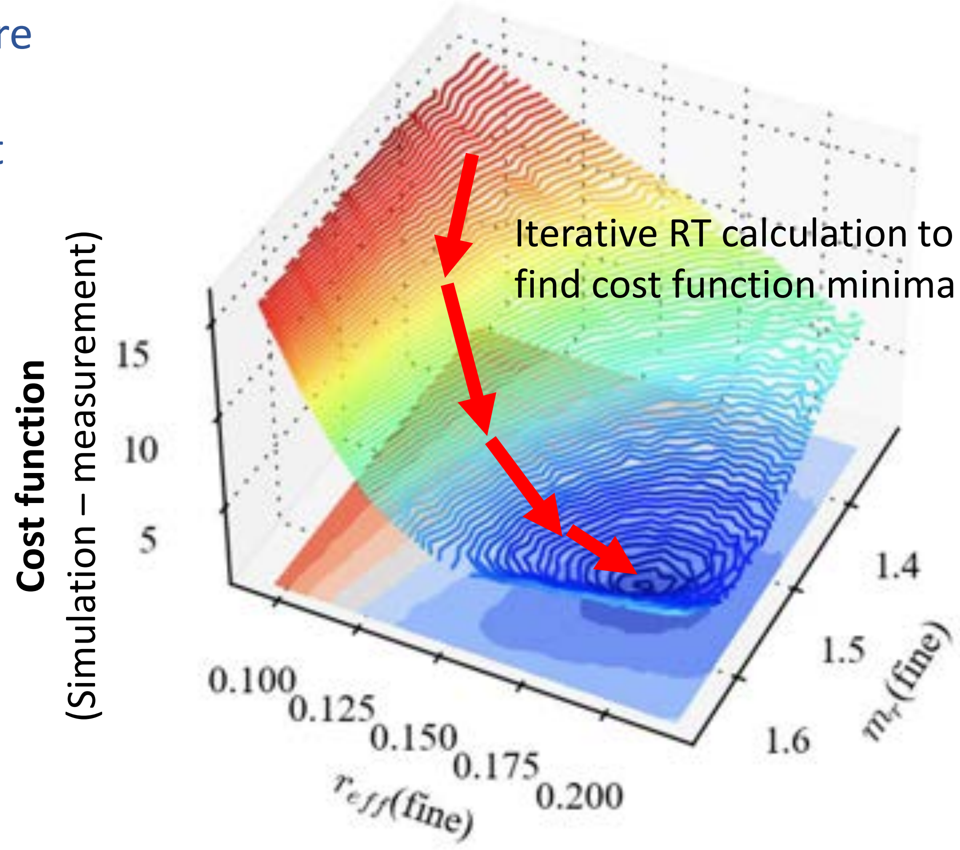
**+other aerosol microphysical properties**

Radiative transfer simulations are iteratively adjusted until the simulation – measurement 'cost function' is minimized

Benefit from PACE algorithm development

Example Algorithms:

GRASP: 10.5194/essd-12-3573-2020
MAPP: 10.1364/AO.57.002394
RemoTAP: 10.5194/amt-2019-287
fastMAPOL: 10.5194/amt-2020-507



# Polarimeter + Lidar Aerosol Synergy

**multiangle, polarimetric UV-VIS-NIR observations**

**Aerosol optical depth (GV12)**

**Aerosol absorption optical depth (GV13)**

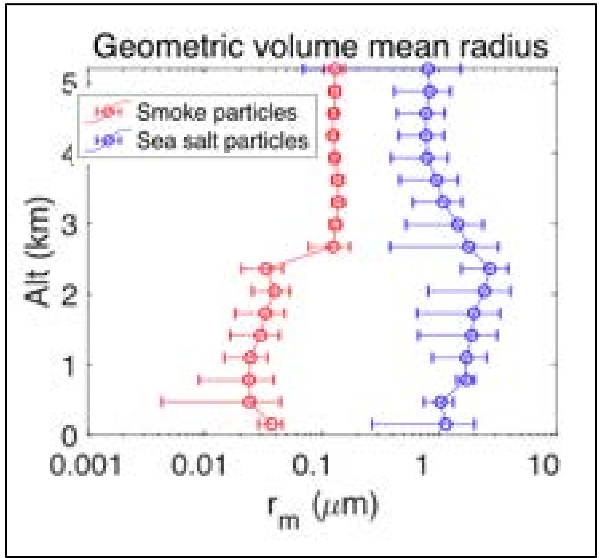
**Aerosol fine mode effective radius (GV14)**

**+other aerosol microphysical properties**

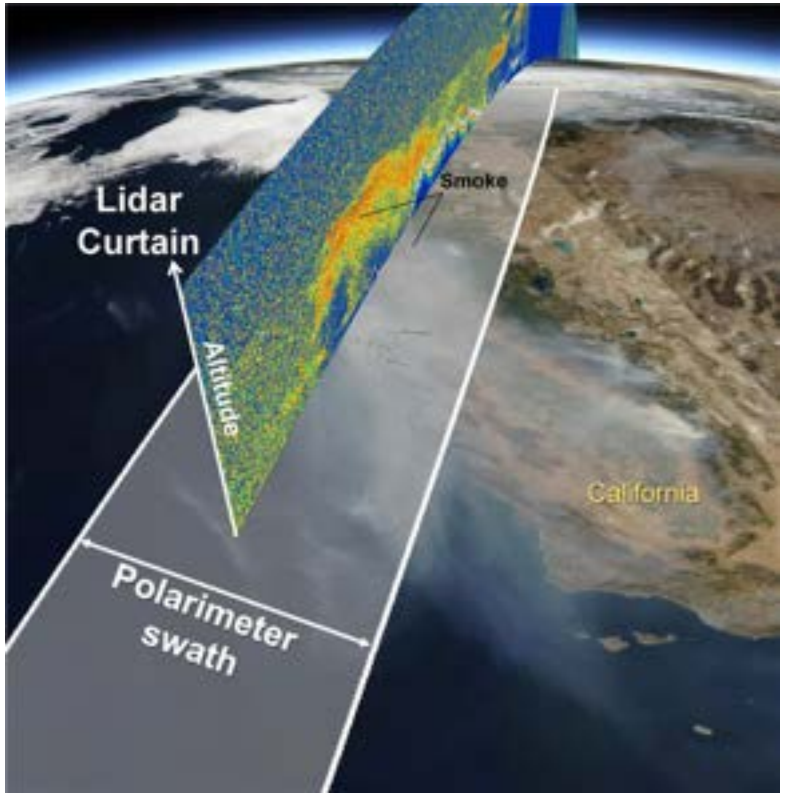
With Lidar synergy

Vertically resolved micro-physical properties

Example of one of several retrieved parameters in F. Xu et al. doi: 10.3389/frsen.2021.620871




+ horizontal context



# Summary of RFI responses

| Instrument | Class | Mass (kg) | Avg. Power (W) *pk | Dimensions (m) | Orbit avg. data rate (Mbps) | Polarized UV channels | Polarized VIS-NIR channels | Polarized SWIR channels | Hyperang. channels | # views | Swath | Resolution (km) | Rad. Unc. | DoLP Unc. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ACCP Study** | | | | | | | | | | | | | | |
| **S-Polar01** | C | 65 (CBE) 80 (MEV) | 48 | 0.7 x 0.9 x 0.5 | depends on # targets | - | 2 | 1 | - | mechanically gimballed | 160 | 0.132 x 0.124 | 4%-6% | 0.50% |
| **S-Polar02 (a)** | C | 122 | 167* | 1.5 x 0.9 x 0.9 | 6.6 | - | 2 | 1 | - | 5 | 160 | 0.132 x 0.124 | 4%-6% | 0.50% |
| **S-Polar02 (b)** | D | 10/camera + 64 | 15/camera * | 6U for cameras + 0.7x0.9x0.5 | 1.5/camera | - | 2 | 1 | - | 5 | 160 | 0.132 x 0.124 | 4%-6% | 0.50% |
| **S-Polar03** | D | 256 | 400 | 0.90 x 0.68 x 0.96 | 20 | 24 | 196 | - | - | 1 | 300 | 0.175 x 0.500 | 5% | 0.50% |
| **S-Polar04 (a)** | D | 6 | 23 | 0.10 x 0.20 x 0.17 | 26.7 | 2 | 4 | 4 | 1 | 10 (60) | 1130 | 1 | 3% | 0.50% |
| **S-Polar04 (b)** | [illegible] | 21 | 23 | 0.49 x 0.24 x 0.49 | 26.7 | 2 | 4 | 4 | 1 | 10 (60) | 1130 | 1 | 3% | 0.50% |
| **S-Polar04 (c)** | D | [illegible] | 39 | 0.79 x 0.66 x 0.39 | 34.6 | 3 | 6 | 6 | 1 | 10 (60) | 1130 | 1 | 3% | 0.50% |
| **S-Polar04 (d)** | D? | 65 | [illegible] | [illegible] | [illegible] | [illegible] | 6 | 6 | 1 | 10 (60) | 1130 | 1 | 3% | 0.50% |
| **S-Polar05** | D? | 11 (CBE) 15 (MEV) | [illegible] | [illegible] | [illegible] | 1 | 30 | - | - | 5 | 100 | 2.3x2.7 | 2% | 0.30% |
| **S-Polar06** | C | 57.2 (MEV) | 73 | 0.62 x 0.57 x 0.49 | 0.126 | - | 6 | 3 | 9 | 255 | 5.6 | 5.6 | 5% | 0.20% |
| **S-Polar07** | D? | 35 | 46 | 0.38 x 0.60 x 0.43 | 55 | 2 | 5 | 4 | 1 | 10 (60) | 550 | 0.5 | 3% | 0.50% |
| **S-Polar08** | D? | 61 | 51 | 0.46 x 0.55 x 0.52 | 60 | 2 | 4 | 6 | 1 | 10 (60) | 550 | 0.5 | 3% | 0.50% |
| **S-Polar09** | D? | 3 | 10 | 0.40 x 0.20 x 0.11 (optical) [illegible] | 0.15 | 1 | 4 | - | - | 3 | 3 x 120km | 1 | 3% | 0.30% |
| **Pre-Phase A** | | | | | | | | | | | | | | |
| **Mega-HARP** | | 35 | 69.2 | 0.58 x 0.40 x 0.44 | 55? | 2 | 4 | 4 | 1 | 10 (60) | 344 | 1? | 3% | 0.50% |
| **HARP2-UVS** | | 21 | 34.6 | 0.24 x 0.49 x 0.48 | 26.7? | 1 | 4 | 4 | 1 | 10 (60) | 861 | 1 | 3% | 0.50% |
| **EHARP** | | | | | | 2 | 6 | 7 | 1 | 10 (60) | | | 3% | 0.50% |
| **EPIC MAP** | | | | | | - | 3 | 2 | | 5 | | 1 | 3% | 0.30% |

Basis for ACCP study

Concepts in UMBC/SDL polarimeter study (as MegaHARP4, MegaHARP2)

**There was a robust response to early RFIs, but many did not meet needs.**

Green: meets baseline requirements

Yellow: Doesn't meet baseline, threshold ok

Orange: Doesn't meet threshold

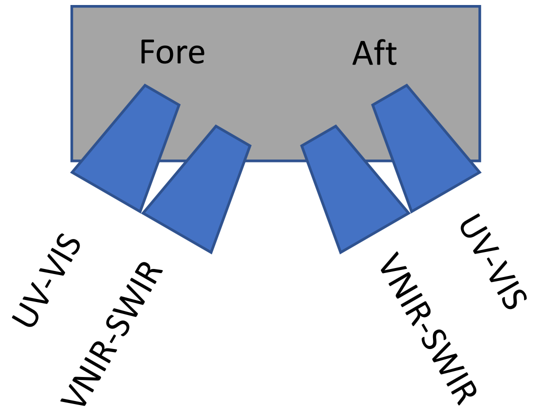
# Instrument Study with Partners UMBC/SDL

Earth System Observatory
AOS
Atmosphere Observing System

NASA

## MegaHARP-4

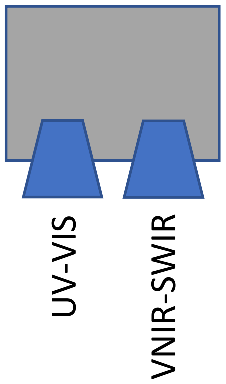
Spatial resolution baseline




**Nadir: <500m resolution**

## MegaHARP-2

Spatial resolution threshold

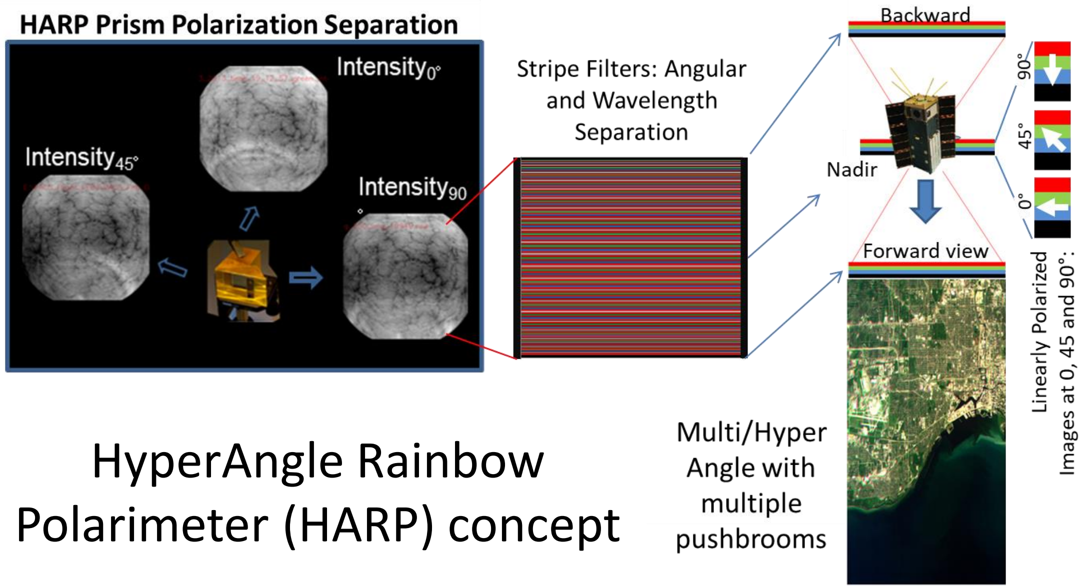



**Nadir: 1km resolution**

Ability to meet requirements is otherwise identical

Geophysical Variable horizontal resolution may vary

MegaHARP uses wide field of view optics, prism based amplitude polarization separation, and linear stripe filters




HyperAngle Rainbow Polarimeter (HARP) concept

UMBC Space Dynamics Laboratory Utah State University

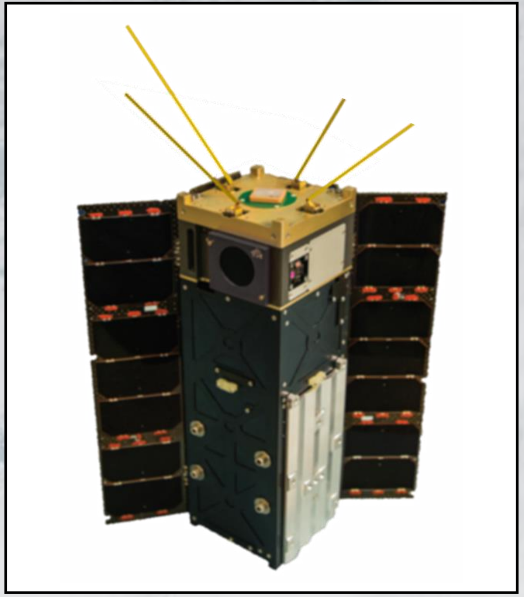
See: Martins, et al. IEEE IGARSS 2018, 6304--6307.

# MegaHARP heritage

**Heritage**: PACE/HARP2 (launch 2024), HARP-Cubesat (recent de-orbit)

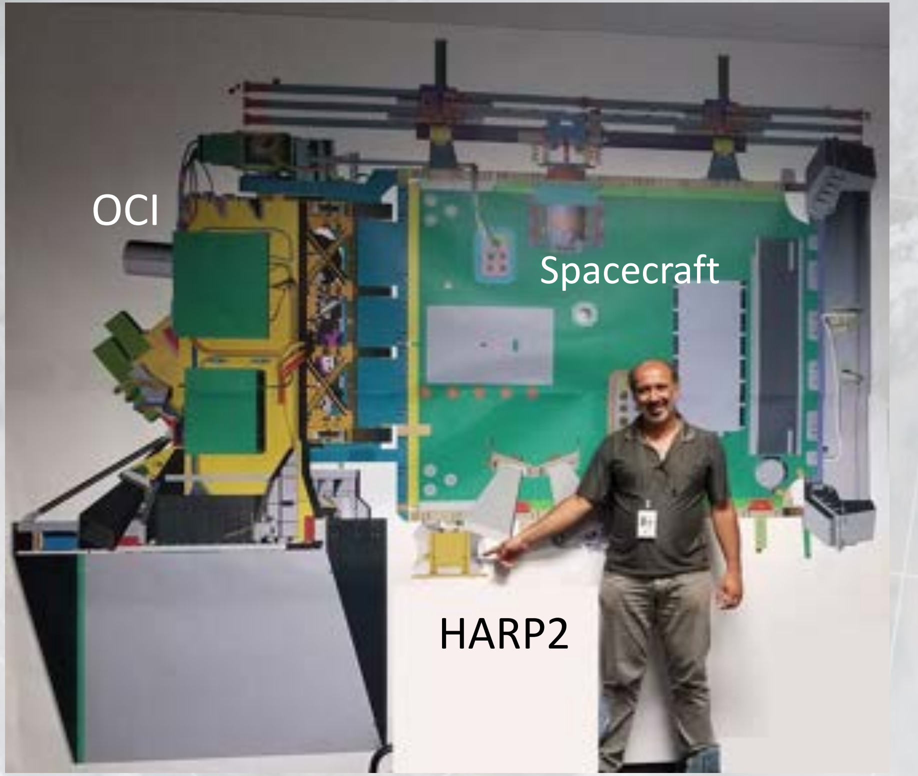
Compared to MegaHARP, these do not have SWIR, have coarser spatial resolution, and less sophisticated calibration mechanisms and less accuracy.

**HARP CubeSat**



January 2020 – April 2022
4km resolution
No onboard calibrator
Limited downlink bandwidth, coverage

**Plankton, Aerosol, Cloud, ocean Ecosystem (PACE)**




pace.gsfc.nasa.gov
Launch in 2024

HARP2 is a contributed 'do no harm' instrument

# Conclusions

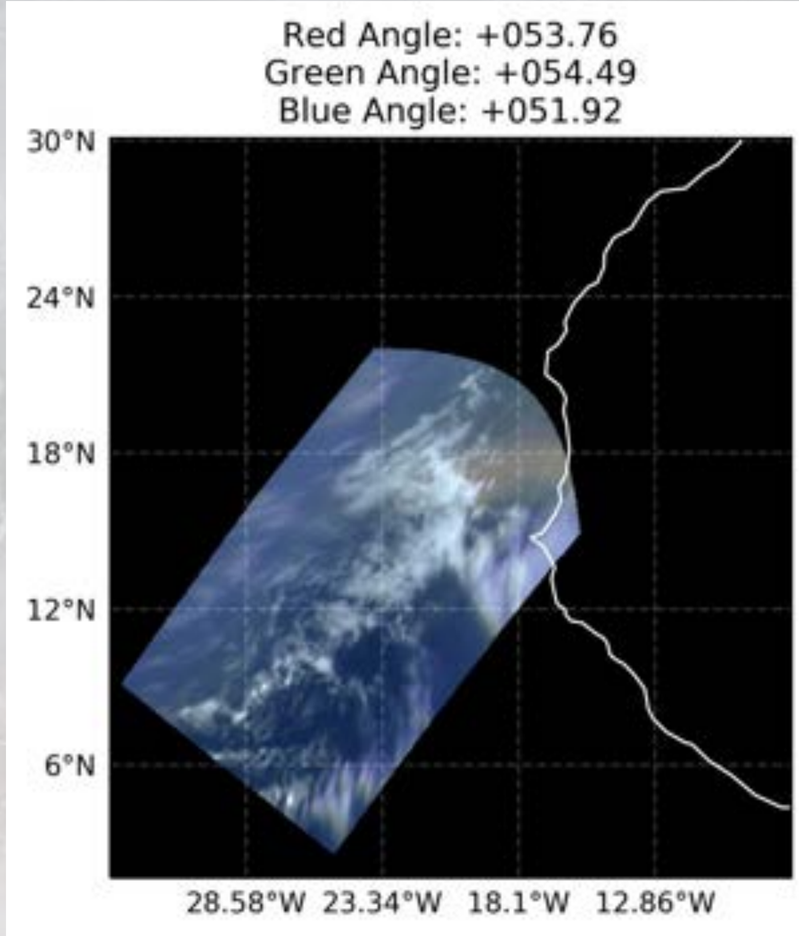
The **AOS-P polarimeter will support all eight science objectives** by making daytime, passive, measurements of cloud and aerosol optical properties in a swath.

RFI material and a pre-phase A study demonstrate the likelihood of **at least one viable RFP response** that can meet requirements. Descope/costing options are included.

The polarimeter, with lidar synergy, will **enable first ever observations** of aerosol property profiles, cloud and aerosol processes and more.

Proposed designs improve upon heritage with better accuracy, spatial resolution and spectral range (UV through SWIR). Overall budget and SWaP is relatively small compared to active instruments.

**HARP Cubesat RGB imagery, West Africa with Saharan dust, glint, clouds 2020 / 06 / 13**




*Pre-Decisional – AOS is in Phase A and NASA makes no commitments on the final design of the mission or instruments*

# Extra material

EARTH SYSTEM OBSERVATORY
AOS
ATMOSPHERE OBSERVING SYSTEM

# Polarimeter Traceability Matrix: Clouds

NASA

Thresholds indicated by [brackets]

| Science Objectives | Geophysical Variable Requirements: Geophysical Variable | Geophysical Variable Requirements: Conditions | Observables | | Measurements: Requirements | Measurements: Projected Performance* | Instrument: Requirements | Instrument: Projected Performance* |
|---|---|---|---|---|---|---|---|---|
| **O1. Low Clouds**<br>**O2. High Clouds**<br>**O4. Cold clouds and precipitation**<br>**O6. Aerosol removal, vertical redistribution, and processing**<br>**O8. Aerosol indirect effect** | **GV5.** Cloud droplet effective radius **O1, O6, O8** | **Daytime**, low cloud (<5km top)<br>**Uncertainty:** 50% for precipitating clouds, 20% otherwise<br>**Range:** optical depth > 2, effective radius 5-30µm<br>**Resolution:** 500m [1km] nadir<br>**Swath:** 300km [100km] | Passive bi-spectral (NIR, SWIR) radiance pairs | Bispectral method | **Spectral:** 1 NIR, 1 SWIR at 1600 nm | UV-VIS: 380, 410, 550, 660<br>NIR-SWIR: 870, 940, 1230, 1380, 1570<br>**Exceeds baseline** | **Resolution:** 500m [1km] at nadir | MegaHARP-4: 0.5km<br>**Meets baseline**<br>MegaHARP-2: 1km<br>**Meets threshold** |
| | | | | | **View angles**: 1 (nadir) | 10 view angles within ± 57˚ along track for all channels except 660nm, which has 60<br>**exceeds baseline** | **Swath:** 300km [100km] | MegaHARP-4: 394km<br>**Exceeds baseline**<br>MegaHARP-2: 1008km<br>**Exceeds baseline** |
| | | | | | | | **Uncertainty:** 3% radiometric | 3% radiometric<br>**Meets baseline** |
| | | | **-- OR ---** | | | | | |
| | **GV7.** Cloud optical depth **O1, O2, O4, O6, O8** | **Daytime**<br>**Uncertainty:** max(0.3, 50%)<br>**Range:** 0.3 < optical depth < 50<br>**Resolution:** 1km nadir | Passive hyper-angle VIS polarization in one channel | Rainbow method | **Spectral:** 1 NIR hyper-angle | NIR hyperangle: 660<br>**meets baseline** | **Resolution:** 500m [1km] at nadir | MegaHARP-4: 0.5km<br>**Meets baseline**<br>MegaHARP-2: 1km<br>**Meets threshold** |
| | | | | | **View angles:** 60 within ± 57˚ along track | 60 view angles within ± 57˚ along track for 660nm channel<br>**meets baseline** | **Swath:** 300km [100km] | MegaHARP-4: 394km<br>**Exceeds baseline**<br>MegaHARP-2: 1008km<br>**Exceeds baseline** |
| | | | | | | | **Uncertainty:** 3% radiometric, 0.005 DoLP polarimetric | 3% radiometric, 0.003 DoLP polarimetric<br>**Meets/exceeds baseline** |

* Projected performance is for industry study instruments MegaHARP-4 and MegaHARP-2; polarimeter contract will be awarded in Phase B

# Polarimeter Traceability Matrix: Aerosols

Thresholds indicated by [brackets]

<table>
<tr><th rowspan="2">Science Objectives</th><th colspan="2">Geophysical Variable Requirements</th><th rowspan="2">Observables</th><th colspan="2">Measurements</th><th colspan="2">Instrument</th></tr>
<tr><th>Geophysical Variable</th><th>Conditions</th><th>Requirements</th><th>Projected Performance*</th><th>Requirements</th><th>Projected Performance*</th></tr>
<tr><td rowspan="3">O3. Convective Processes<br><br>O5. Aerosol attribution and air quality<br><br>O6. Aerosol removal, vertical redistribution, and processing<br><br>O7. Aerosol direct effect and absorption<br><br>O8. Aerosol indirect effect</td><td>GV12. Aerosol column optical depth (UV, VIS, NIR)<br>O3, O5, O6, O7, O8</td><td>Daytime, clear sky, global [ocean]<br>[UV] VIS-NIR<br>Uncertainty: 0.03+0.1*AOD<br>Resolution: 0.5 [1] km nadir<br>Swath: 300 [100] km</td><td rowspan="3">Passive, multi-angle, total and polarimetric radiance for [UV] VIS-NIR-SWIR</td><td>Spectral: 1 UV, 3 VIS-NIR, 3[2] SWIR to 2250 [1600] nm</td><td>UV-VIS: 380, 410, 550, 660<br>NIR-SWIR: 870, 940, 1230, 1380, 1570<br>UV meets baseline<br>VIS-NIR exceeds baseline<br>SWIR meets baseline in # of channels, threshold in range</td><td>Resolution:<br>500m [1km] at nadir</td><td>MegaHARP-4: 0.5km<br>Meets baseline<br>MegaHARP-2: 1km<br>Meets threshold</td></tr>
<tr><td>GV13. Aerosol column aerosol absorption optical depth (UV, VIS)<br>O5, O6, O7, O8</td><td>Daytime, clear sky, global [ocean]<br>[UV] VIS<br>Uncertainty: max(0.003,50%) [ max(0.005, 50%) ]<br>Resolution: 0.5 [1] km nadir<br>Swath: 300 [100] km</td><td rowspan="2">View angles:<br>10 [5] within ± 57˚ along track</td><td rowspan="2">10 view angles within ± 57˚ along track for all channels except 670, which has 60<br>Meets/exceeds baseline</td><td>Swath: 300km [100km]</td><td>MegaHARP-4: 394km<br>Exceeds baseline<br>MegaHARP-2: 1008km<br>Exceeds baseline</td></tr>
<tr><td>GV14. Aerosol column fine-mode effective radius<br>O5, O6, O7, O8</td><td>Daytime, clear sky, global [ocean]<br>Uncertainty:<br>max(0.05,0.1*(0.1$^{AOD}$)) µm<br>Resolution: 0.5 [1] km nadir<br>Swath: 300 [100] km</td><td>Uncertainty:<br>3% radiometric, 0.005 DoLP polarimetric</td><td>3% radiometric, 0.003 DoLP polarimetric<br>Meets/exceeds baseline</td></tr>
</table>

* Projected performance is for industry study instruments MegaHARP-4 and MegaHARP-2; polarimeter contract will be awarded in Phase-B