Selection for the NASA Instrument Incubator Program: CHanneled Infrared Polarimeter (CHIRP)

Meredith $\widehat{K}u\hat{p}in\hat{s}ki$

Associate Professor

PI, CHIRP

Wyant College of Optical Sciences

University of Arizona

Industrial Affiliates, Fall 2024

Polarization Laboratory

Jeremy Parkinson
Optical Engineer

Clarissa DeLeon
5th Year PhD

Jaclyn John
4th Year PhD

Masafumi Seigo
4th Year PhD

Micah Mann
3rd Year PhD

Lily McKenna
2nd Year PhD

Uday Talwar
2nd Year PhD

Ellie Spitzer
1st Year PhD

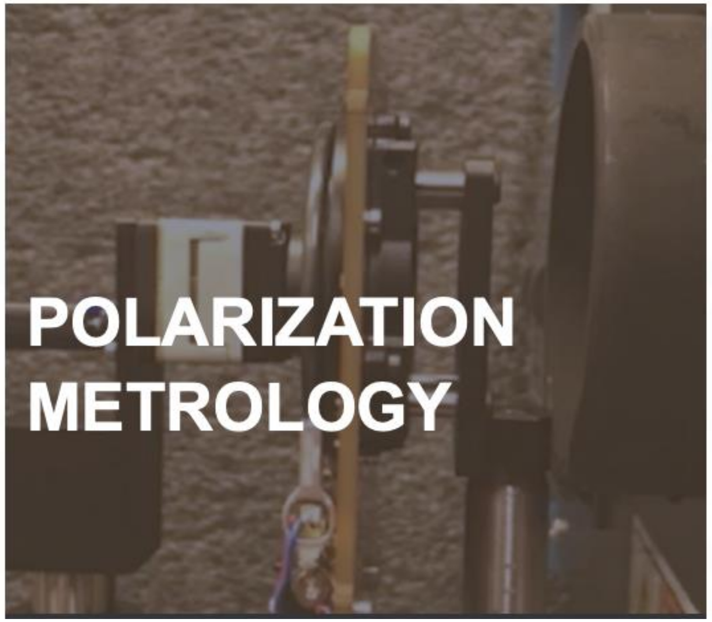
Charlie Tribble
1st Year PhD

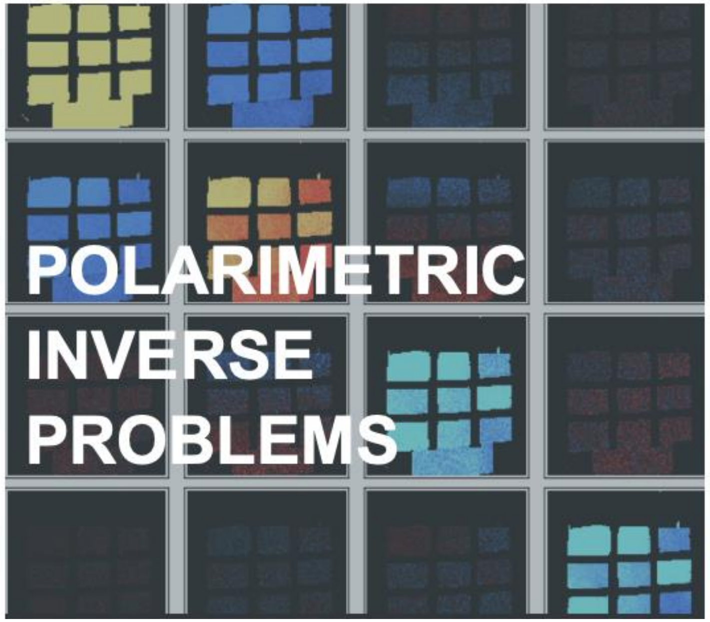
Adeline Tai
Senior

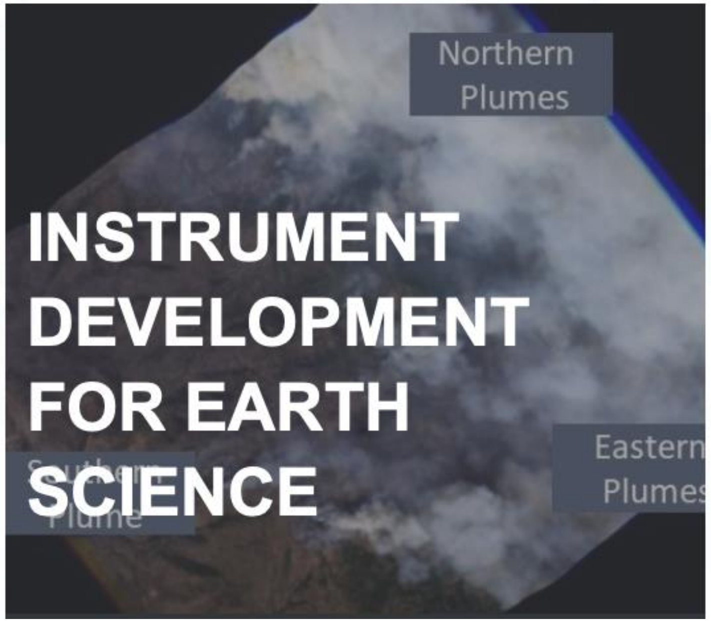
Cole Tsingine
Sophomore

Jenna Little
Sophomore

RESEARCH


POLARIZATION
METROLOGY


POLARIMETRIC
INVERSE
PROBLEMS


Northern
Plumes
INSTRUMENT
DEVELOPMENT
FOR EARTH
SCIENCE
Eastern
Plumes

Instrument Incubator Program

Instrument Development and Demonstration: The Instrument Development and Demonstration program encompasses projects that are more fully realized and span the entire instrument development process, including design, prototypes, models, laboratory and potential airborne demonstrations.

The instruments are inspired by NASA's Earth Science Focus Areas, which include:

- Atmospheric composition
- Weather and atmospheric dynamics
- Climate variability and change
- Water and energy cycle
- Carbon cycle and ecosystems
- Earth surface and interior

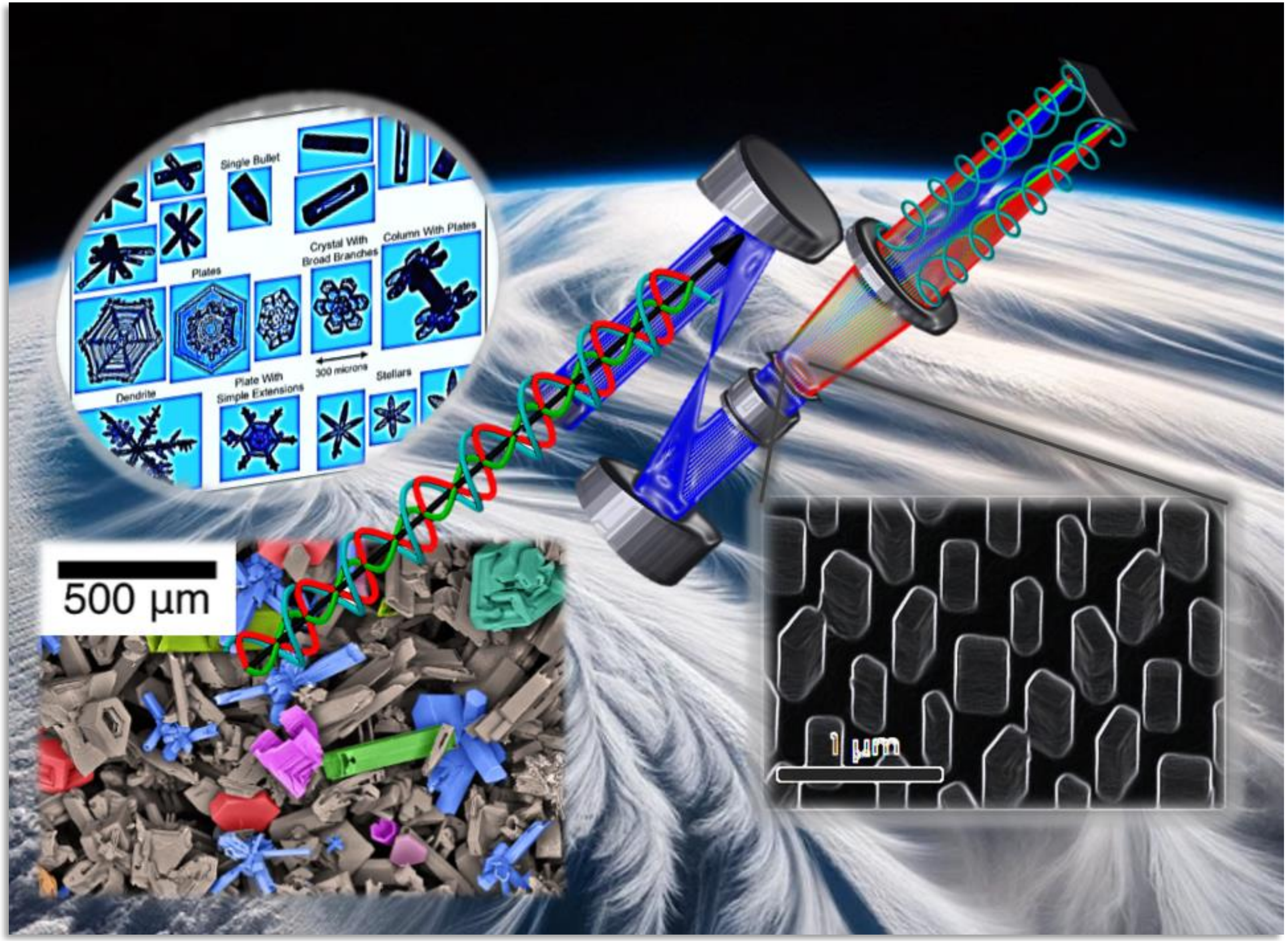
https://esto.nasa.gov/iip/

CHanneled IR Polarimeter (CHIRP)

Science Questions

1. What cause cloudy-sky LWIR polarized radiance?

2. What can LWIR polarimetry tell us about ice particles?



Instrument Specifications

Detections of 1K polarized radiance for 200K targets within a 1-µm spectral window from 8.0 – 11.5 µm

Enabling Technologies

1. Polarization grating
2. HOT-BIRD detector

https://esto.nasa.gov/project-selections-for-iip-23/

Technology Readiness Level (TRL)

All subsystems working together as they would in the final system

IR Channel Spectral Polarimeter (IRCSP) : 2021

CHIRP, 2027 : TRL 4

CHIRP, 2024 : TRL 2

TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
- System prototype demonstration in a space environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported

HOT-BIRD : in

Thermal Vacuum chamber

High Altitude Balloon
ER-2 Aircraft

Environmental Chamber

Metasurface : TRL 2

SP-20205003605 TRA BP Guide Final (nasa.gov)

CHIRP co-PIs

COLLEGE OF ENGINEERING
Chemical & Environmental Engineering

SCIENCE

Sylvia Sullivan
Assistant Professor
CHIRP Science PI

Noah Rubin
Assistant Professor
CHIRP Institutional PI

UC San Diego

INSTRUMENT

JPL
Jet Propulsion Laboratory
California Institute of Technology

NASA
Goddard Space Flight Center

Dong Wu
GSFC Project Scientist

David Ting
Deputy Director,
Center for Infrared Photodetectors

Tobias Wenger
Microdevices Engineer

CHIRP Team

Edguardo Sepúlveda
PhD student

Jeremy Parkinson
Optical Engineer

UC San Diego

Lisa Li
Postdoctoral Scholar

Ellie Spitzer
PhD student

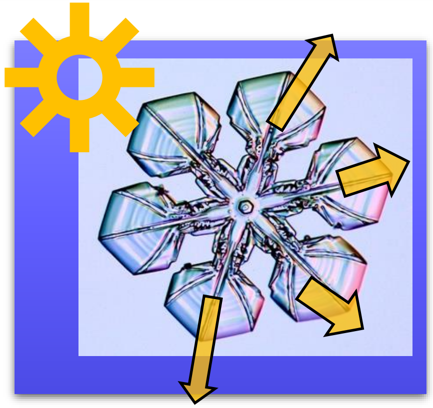
Ramya Anche
Postdoctoral Scholar

JPL
Jet Propulsion Laboratory
California Institute of Technology

Sarath Gunapala
Director, Center for Infrared Photodetectors
Engineering Fellow

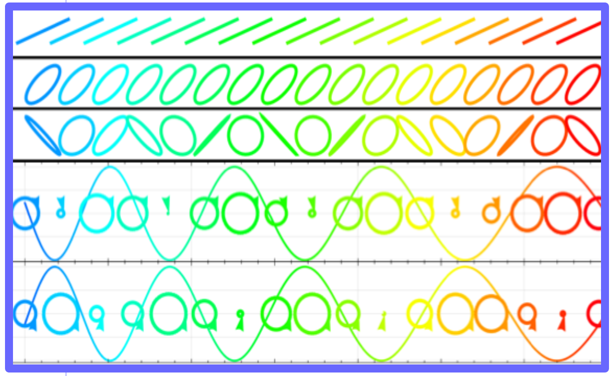
Outline

Science Rationale



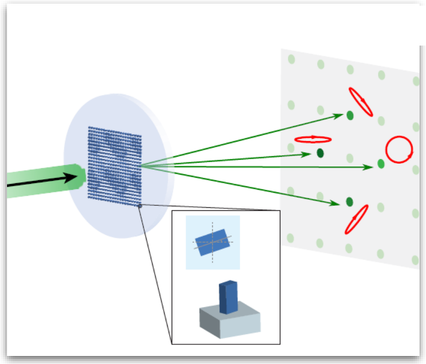
Thermal Radiation
In Earth's Atmosphere

Channeled Polarimetry



IRCSP Observations prototype, IIP-16
Instrument Concept

Polarization Grating



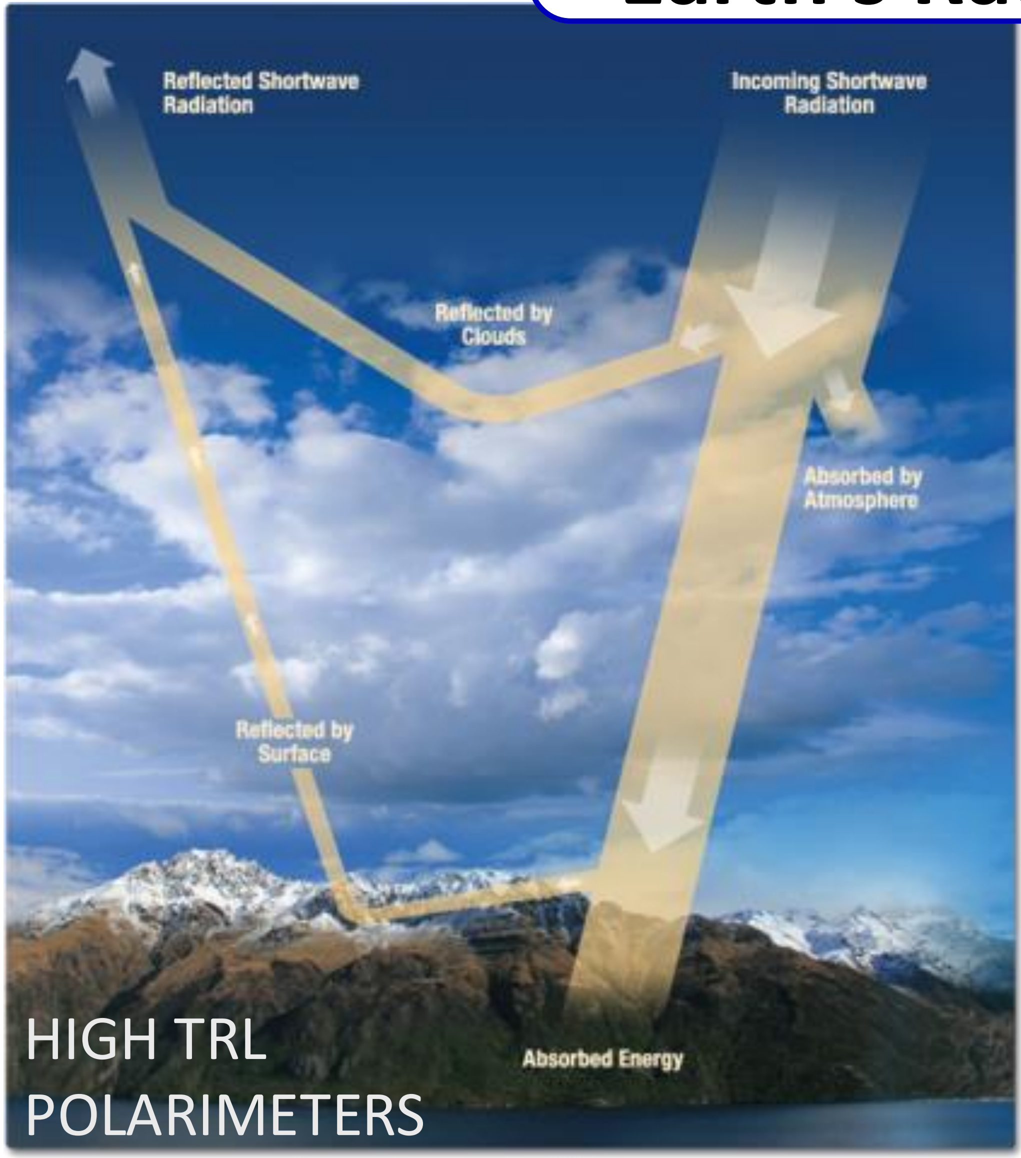
Expected Performance Benefits

HOT BIRD Detector

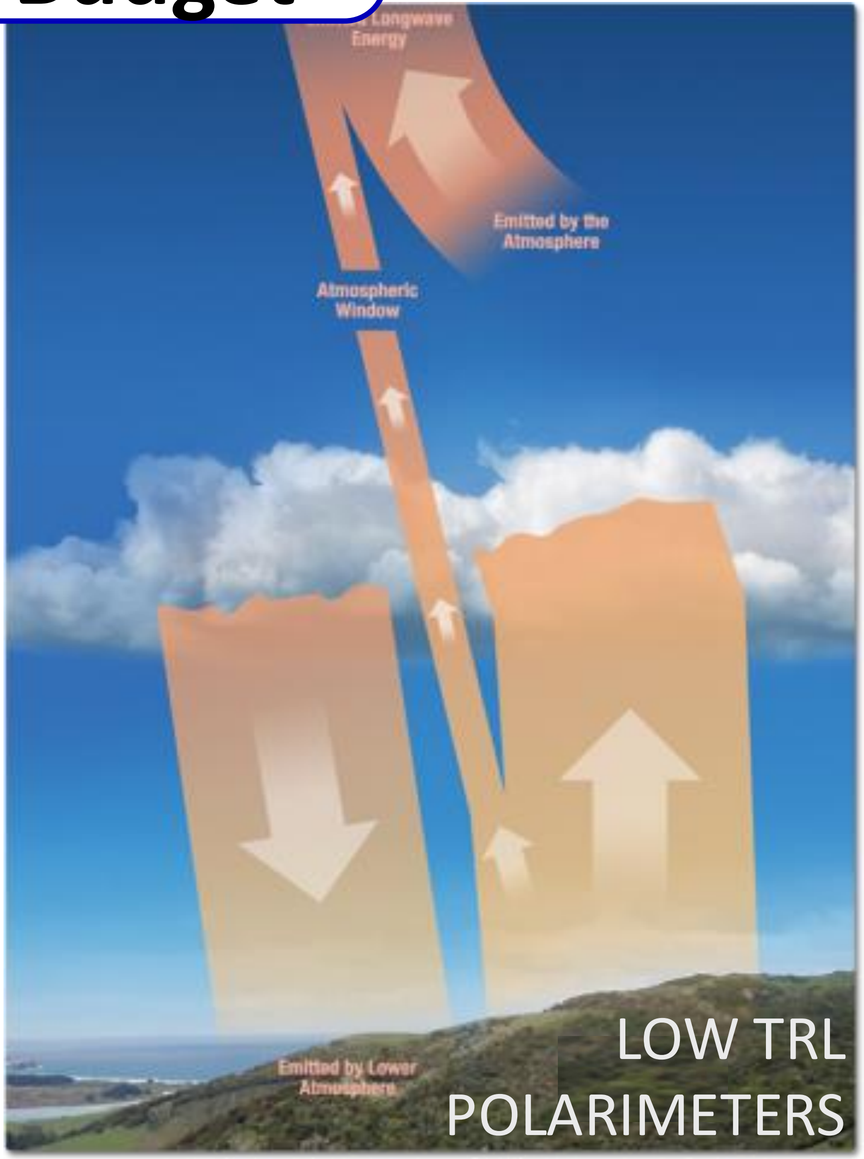
Advances in IR Detector Technology

Sensitivity Studies **System Requirements** **Integration & Testing**

Earth’s Radiation Budget



Shortwave Optical Radiation



Longwave Optical Radiation

Atmospheric ice crystals are highly non-spherical and have a large variety of shapes, sizes, and orientations

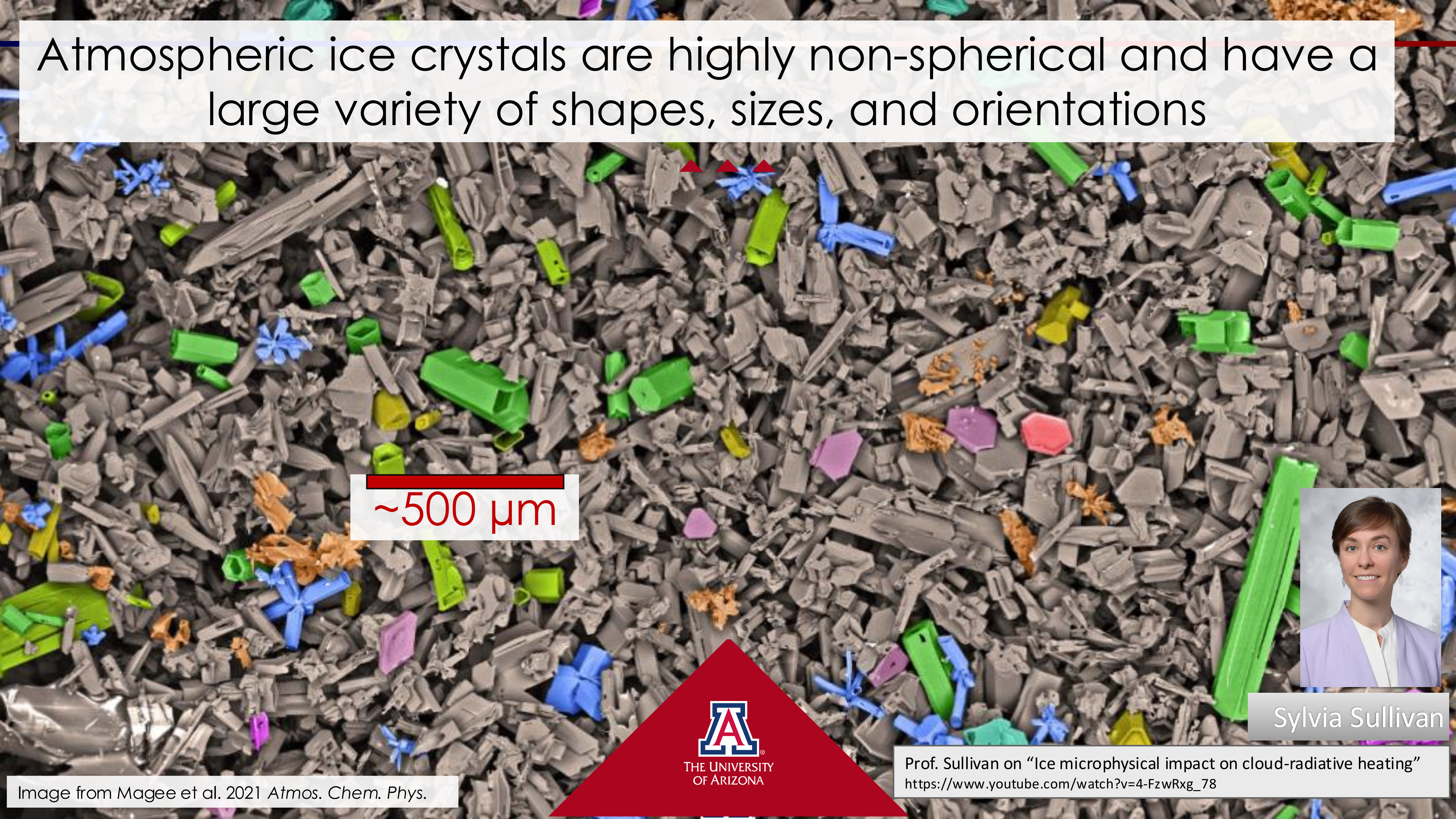


Image from Magee et al. 2021 *Atmos. Chem. Phys.*

Sylvia Sullivan

Prof. Sullivan on “Ice microphysical impact on cloud-radiative heating”
https://www.youtube.com/watch?v=4-FzwRxg_78

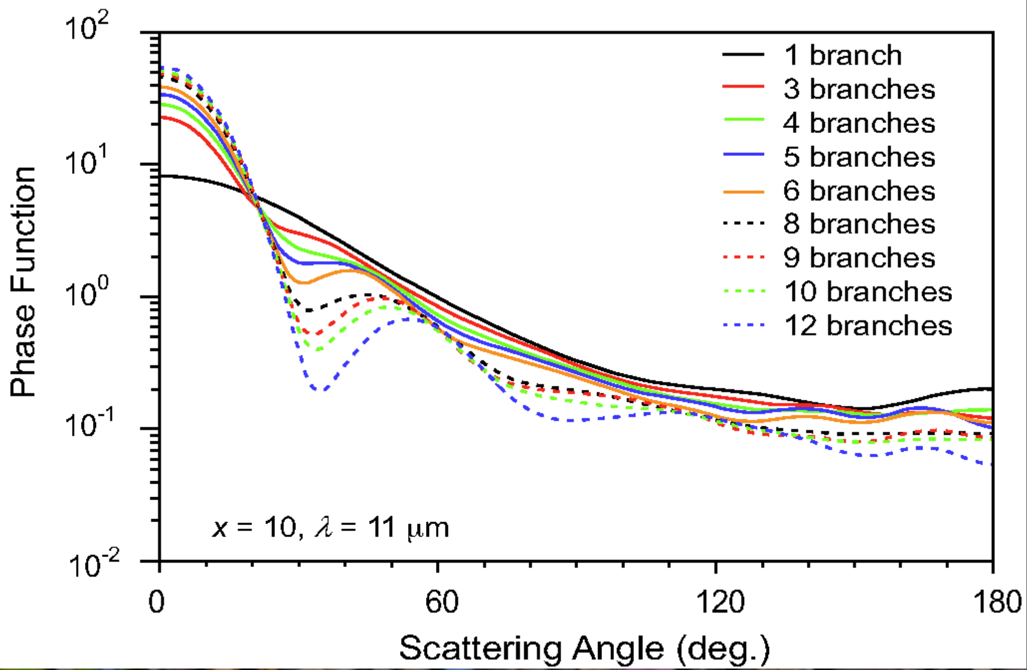
THE UNIVERSITY OF ARIZONA

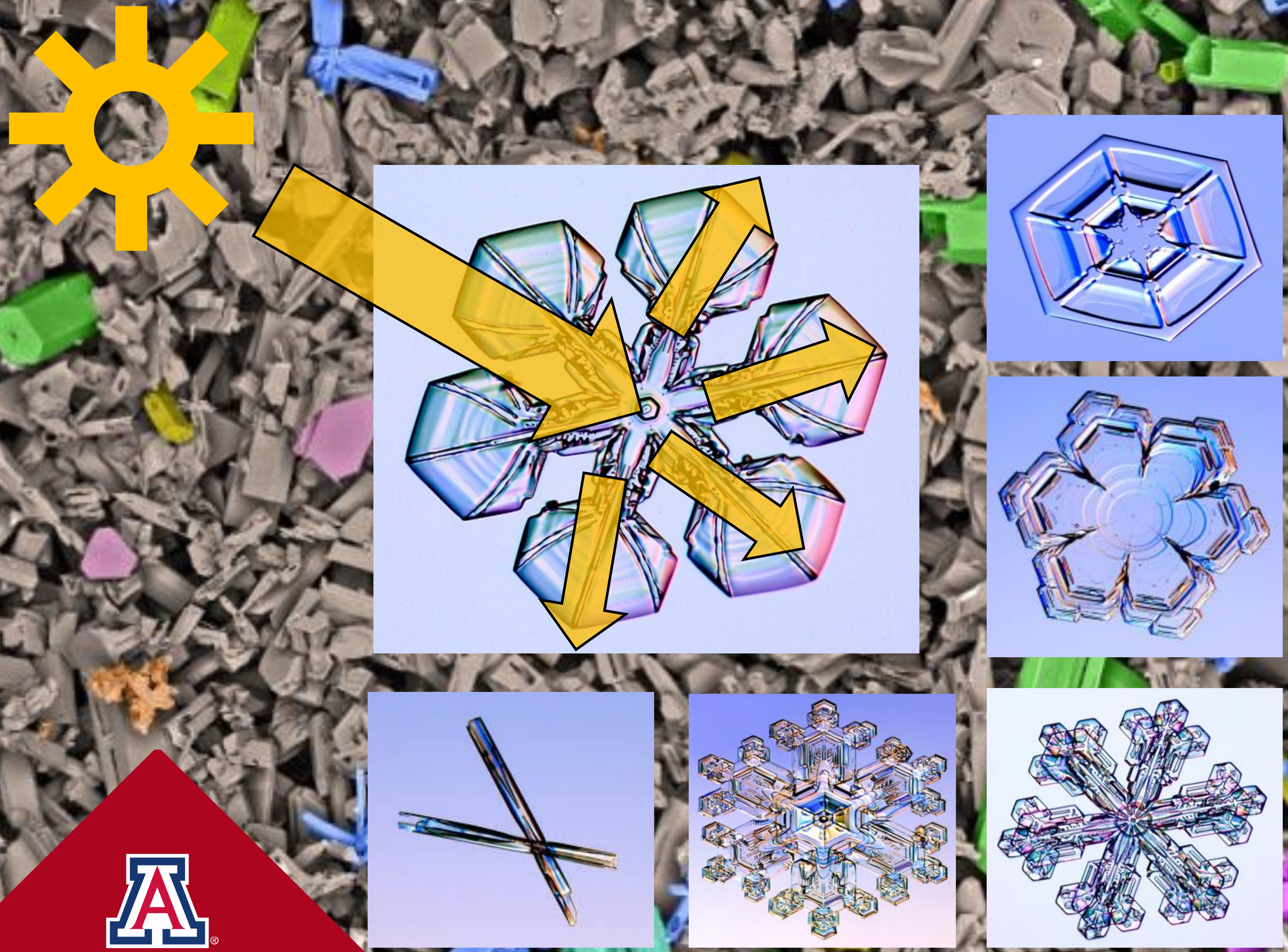
Certain crystal shapes sediment out more slowly, prolonging cloud lifetime

Certain crystal shapes sediment out more quickly, shortening cloud lifetime

The University of Arizona

Crystal size and shape effect ice cloud scattering and remission of solar radiation





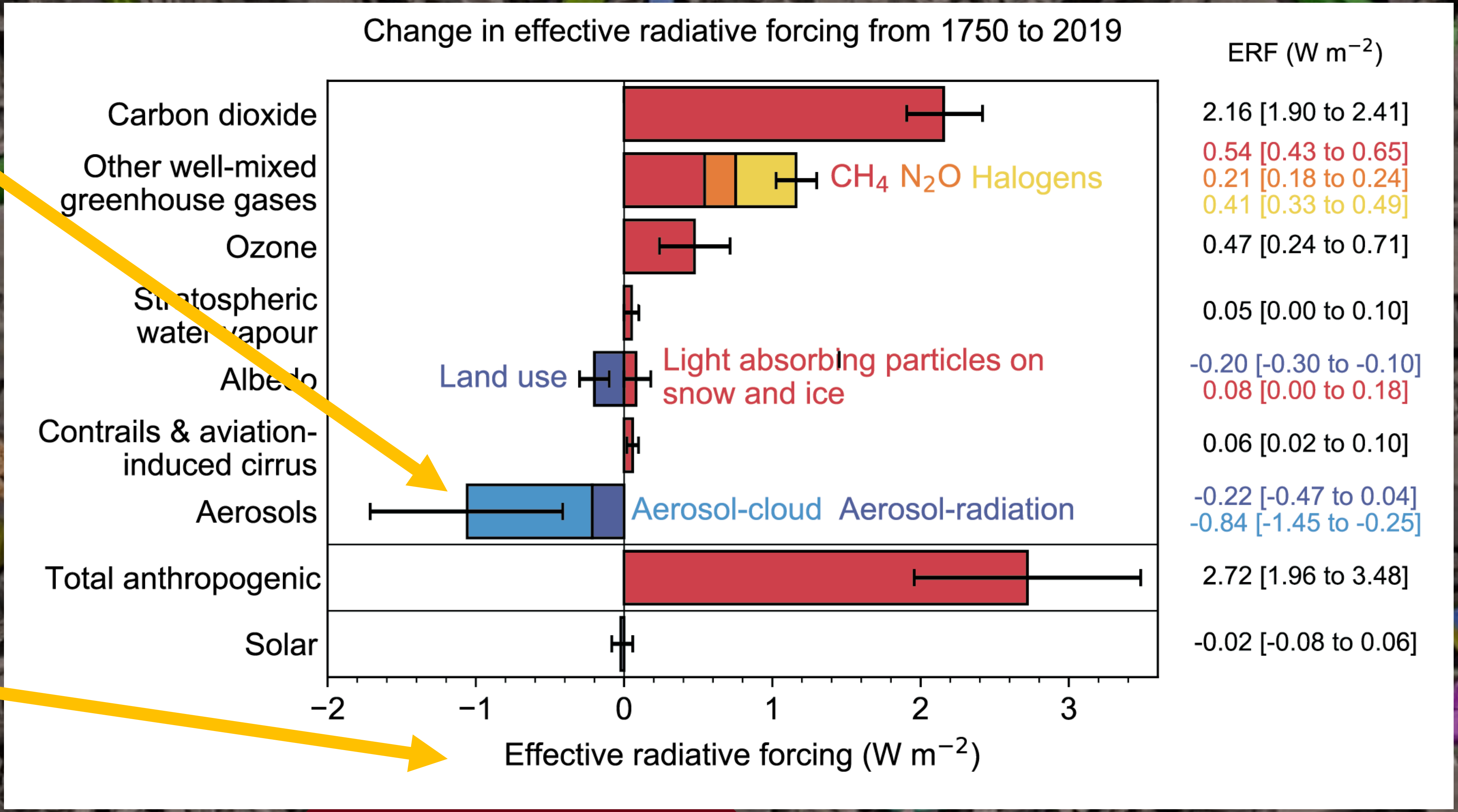
www.Cambridge.org/core/books/light-scattering-by-ice-crystals

THE UNIVERSITY OF ARIZONA

Polarimetry that indicates the shape and orientation of ice crystals could constrain uncertainty in surface warming

How much change in the energy balance is due to clouds?

How much does Earth's energy balance change?

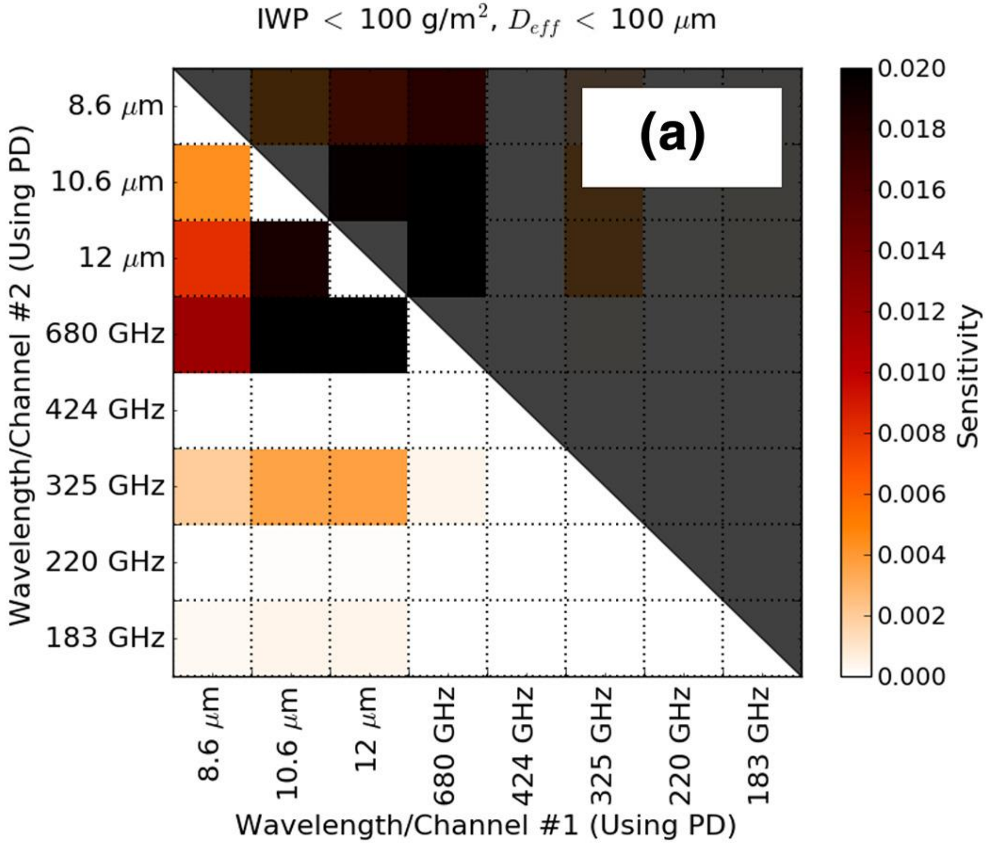


IPCC AR6 WG1 2021 Chapter 7

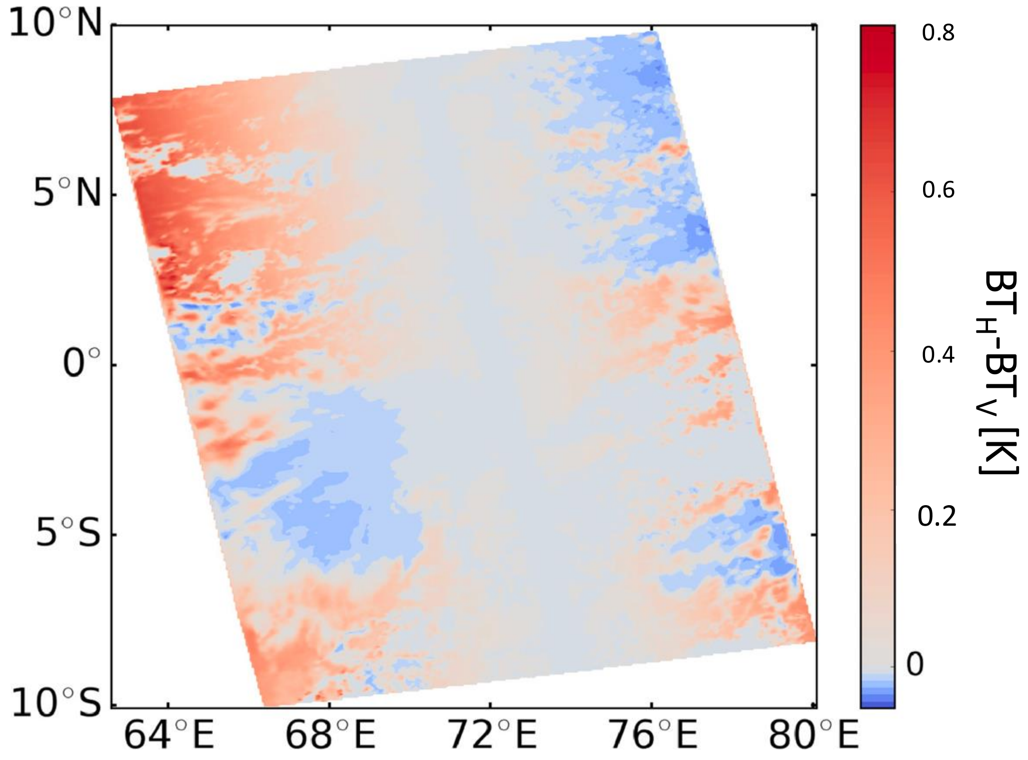
Sensitivity Studies

HYPOTHESIS: *There is measurable cloud-top LWIR polarization which is observable using uncooled detector technology and channeled polarimetry*

LWIR Sensitivity



Simulated Polarization

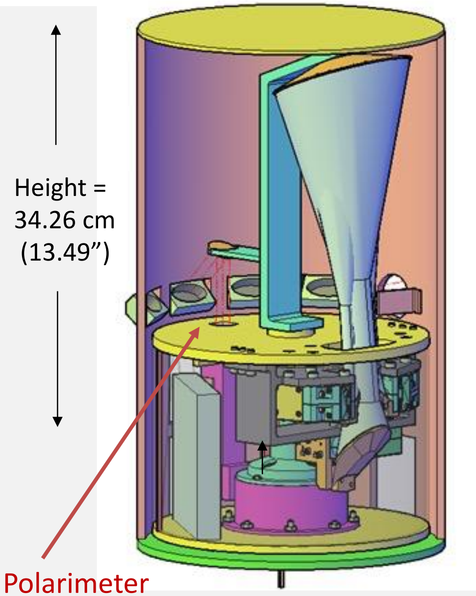


For MODIS Band 31 Image (10.78~11.28 μm)

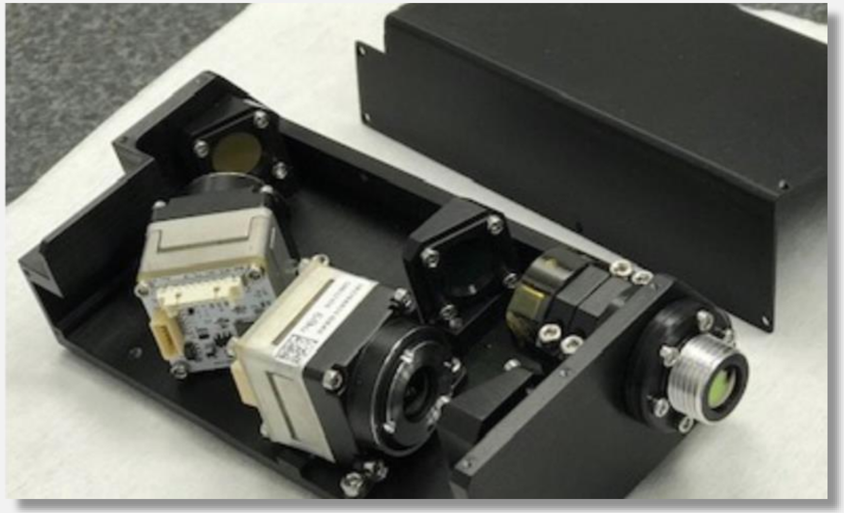
Coy, James J., et al. **"Sensitivity analyses for the retrievals of ice cloud properties from radiometric and polarimetric measurements in sub-mm/mm and infrared bands."** *Journal of Geophysical Research: Atmospheres* 125.13 (2020)

Ding, Jiachen, et al. "**A fast vector radiative transfer model for the atmosphere-ocean coupled system**." *Journal of Quantitative Spectroscopy and Radiative Transfer* 239 (2019): 106667.

IRCSP Flow-down Requirements



Size	11.89 x 4.8 x 3.5 cm
Mass	0.5 kg
Power	1 W
Spectral Response	8 – 12 micron
Polarimetric Precision	1 K
NEDT	1 K



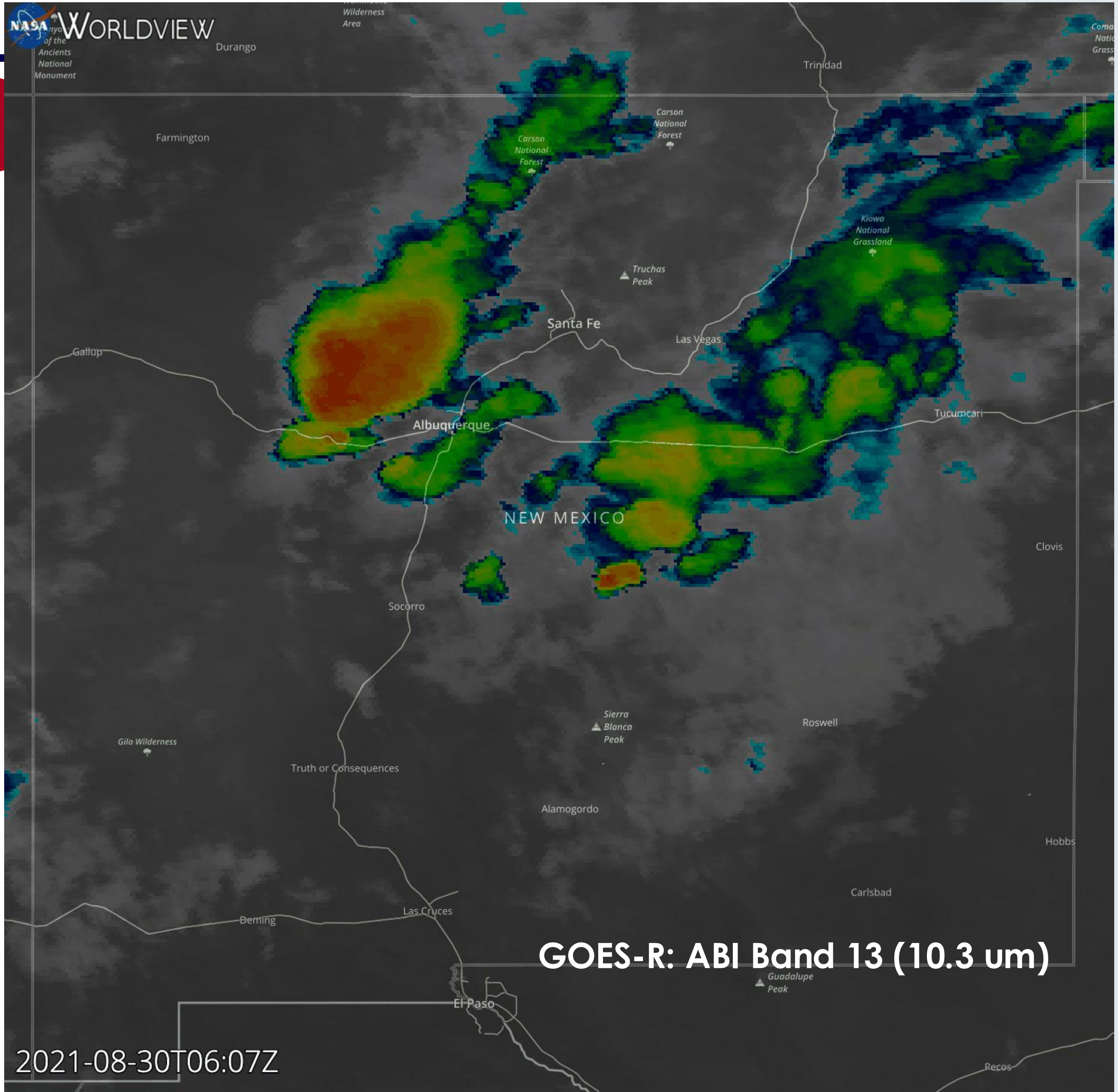
D. Wu *et al*., "Swirp (Submm-Wave and Long Wave Infrared Polarimeter); A New Tool for Investigations of Ice Distribution and Size in Cirrus Clouds," *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium*, 2019, pp. 8436-8439, doi: 10.1109/IGARSS.2019.8898230.

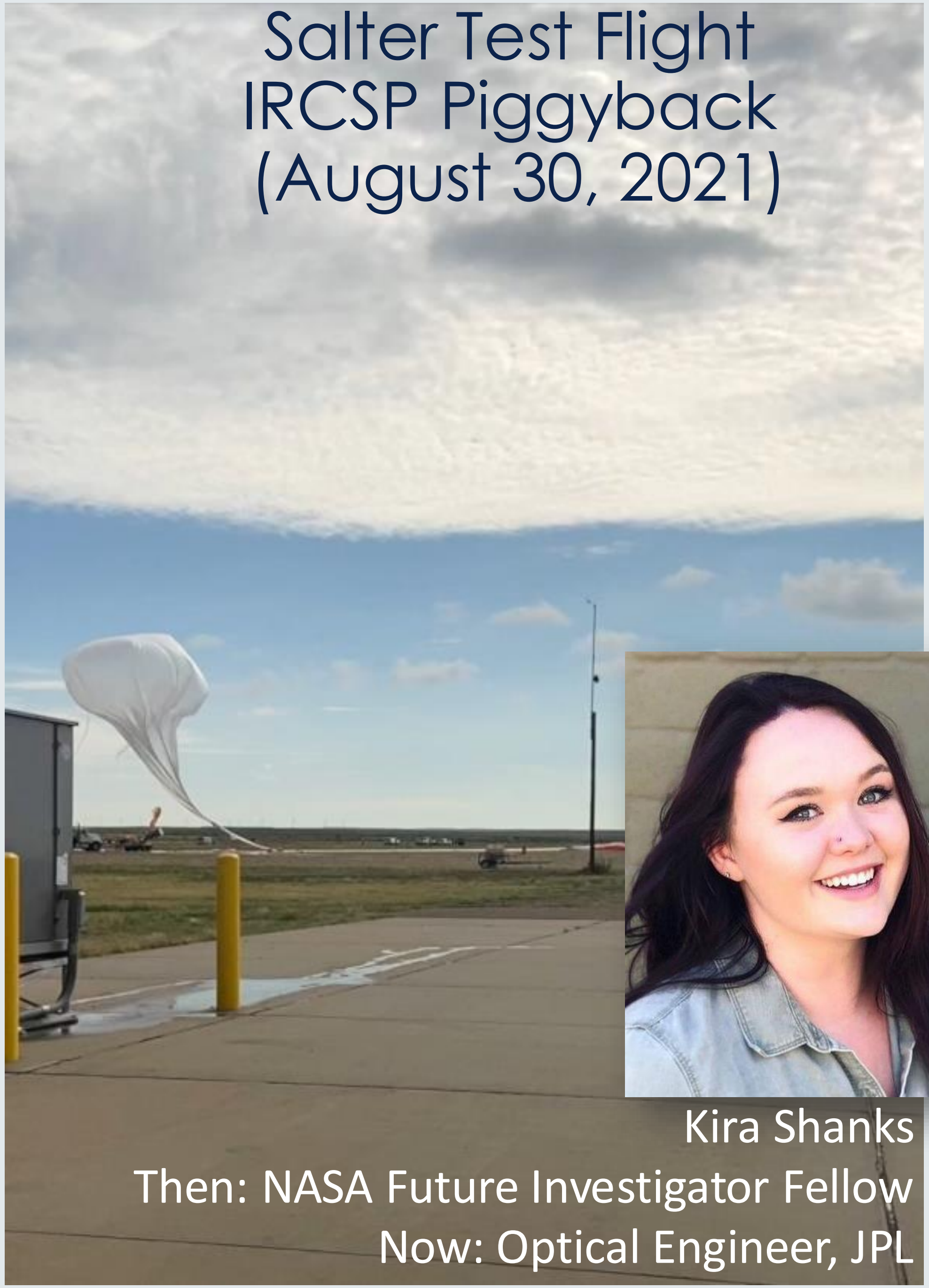
INFRA-RED CHANNELED SPECTRO-POLARIMETER

- Part of the Submm-Wave and IR Polarimeters (SWIRP) CubeSat project out of NASA Goddard Spaceflight Center, PI: Dong Wu
- Linear Stokes measurement with 1-μm polarimetric resolution from 8 – 12 μm
- Less than 10 cm in length, cooling not required, no moving parts

Dong Wu
GSFC Project Scientist

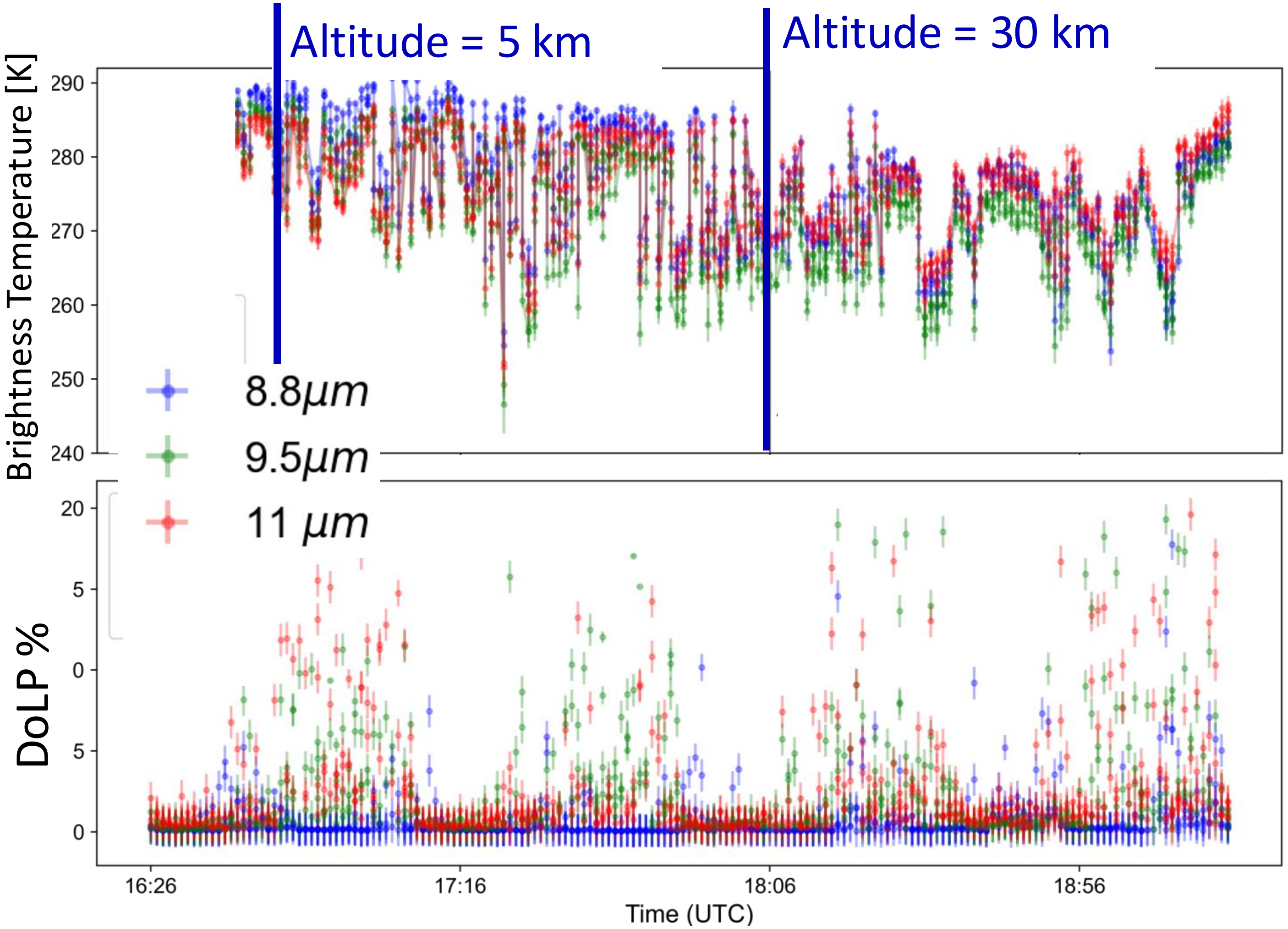
Salter Test Flight
IRCSP Piggyback
(August 30, 2021)





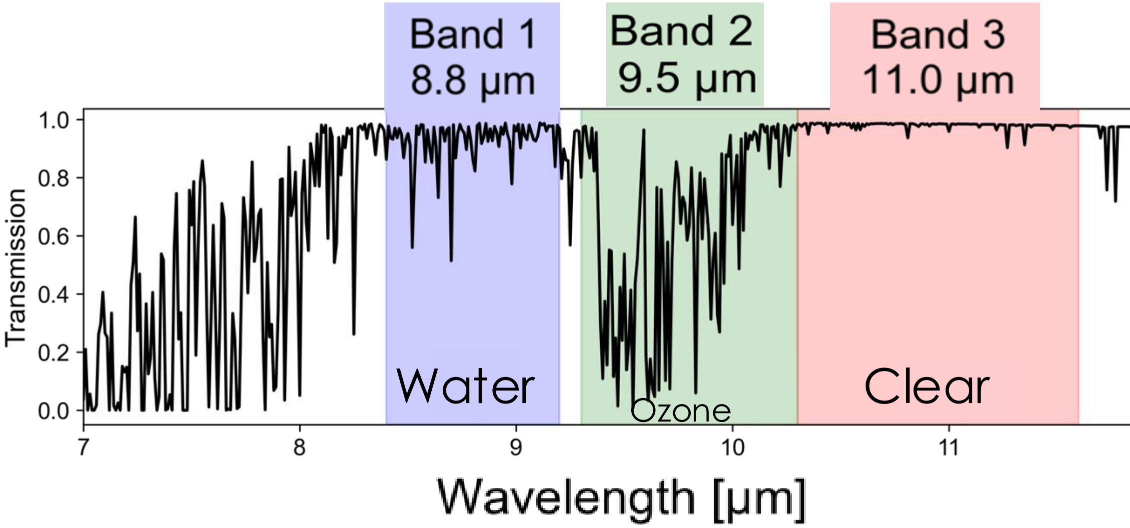
Kira Shanks
Then: NASA Future Investigator Fellow
Now: Optical Engineer, JPL

Degree of Polarization Measurements



OBSERVATION:
Brightness temperature lowest in ozone band at higher altitudes

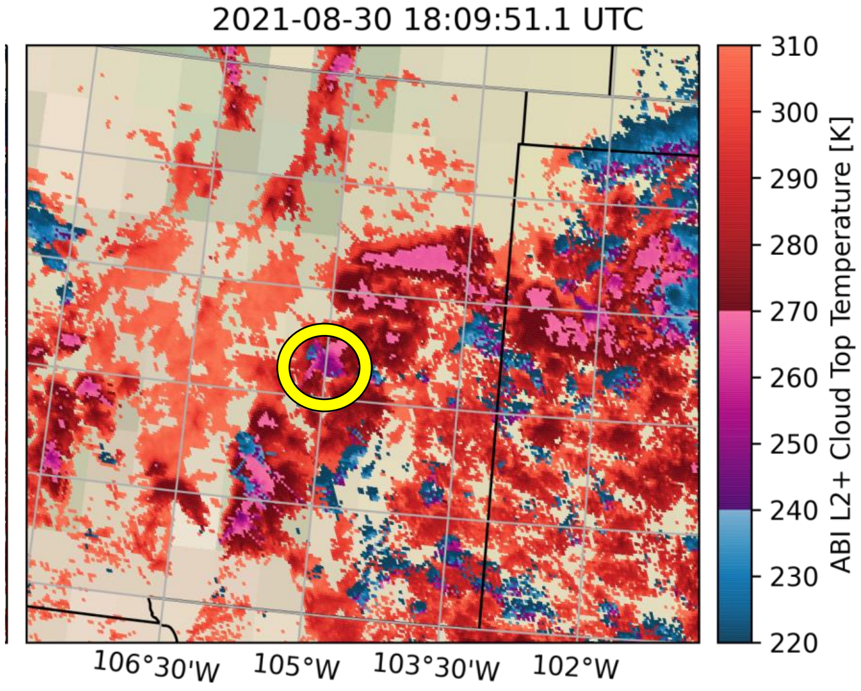
Atmospheric Transmission



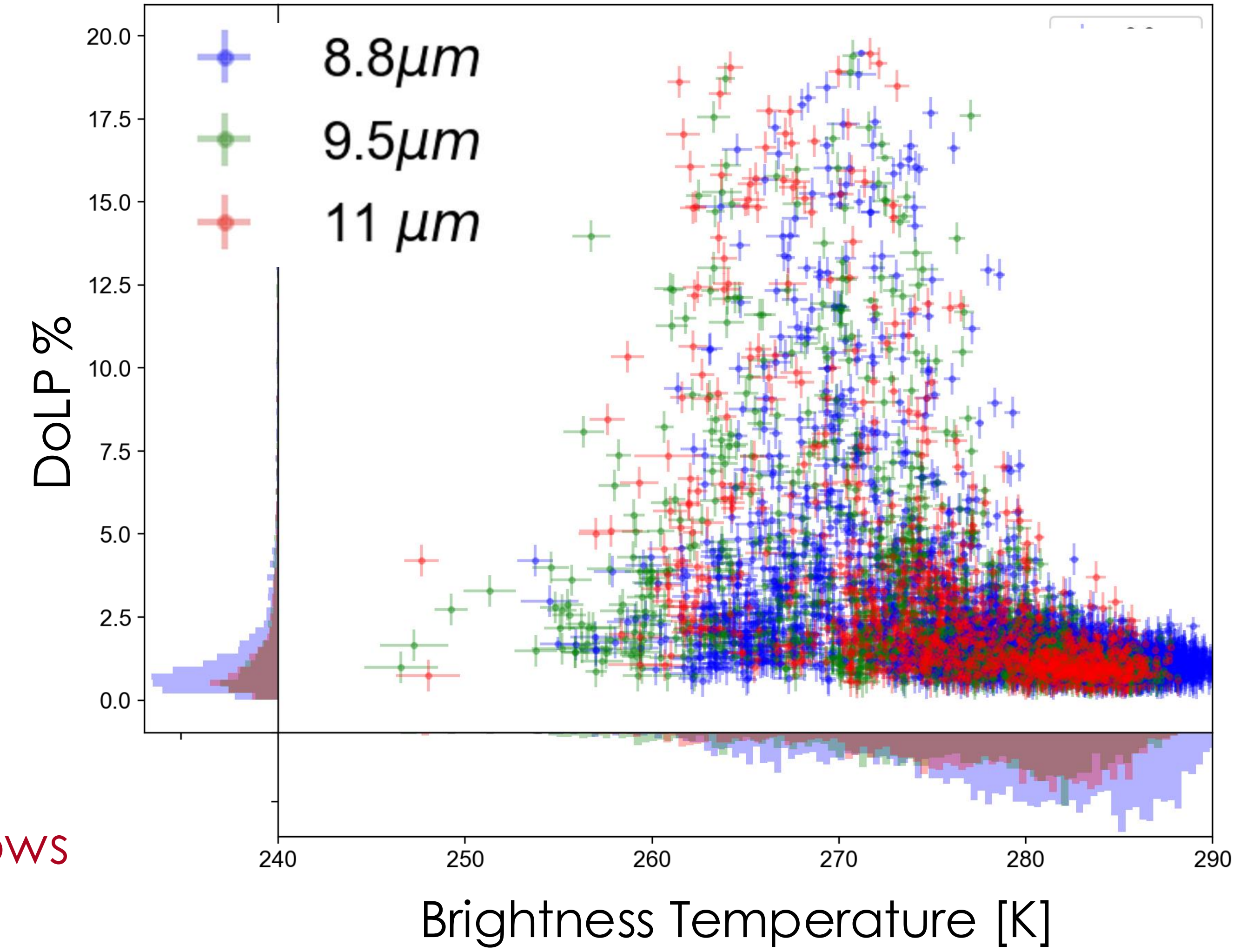
Shanks, K. A., John, J. A., Parkinson, J. C., Wu, D. L., & Kupinski, M. K. (2024). High-altitude demonstration of LWIR polarimetry using uncooled microbolometers. Journal of Quantitative Spectroscopy and Radiative Transfer, 315, 108872.

Degree of Polarization Measurements

Cloud Top Temperatures from NOAA's GOES-16 Advanced Baseline Imager



DoLP versus Brightness Temperature

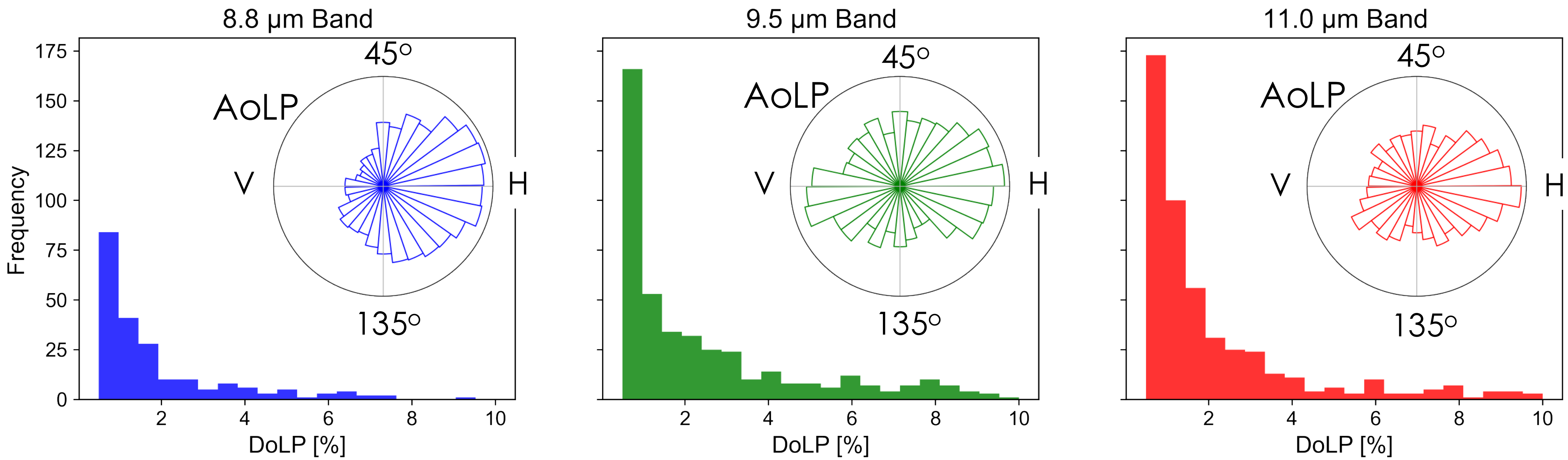


OBSERVATION:
DoLP peaks ~270 K in all three windows

Shanks, K. A., John, J. A., Parkinson, J. C., Wu, D. L., & Kupinski, M. K. (2024). High-altitude demonstration of LWIR polarimetry using uncooled microbolometers. Journal of Quantitative Spectroscopy and Radiative Transfer, 315, 108872.

Degree and Angle of Polarization Measurements

Angle of Linear Polarization (AoLP) Trends



Spectrally resolved AoLP trends support hypothesized split-window sensitivity to cloud microphysical properties

Shanks, K. A., John, J. A., Parkinson, J. C., Wu, D. L., & Kupinski, M. K. (2024). High-altitude demonstration of LWIR polarimetry using uncooled microbolometers. Journal of Quantitative Spectroscopy and Radiative Transfer, 315, 108872.

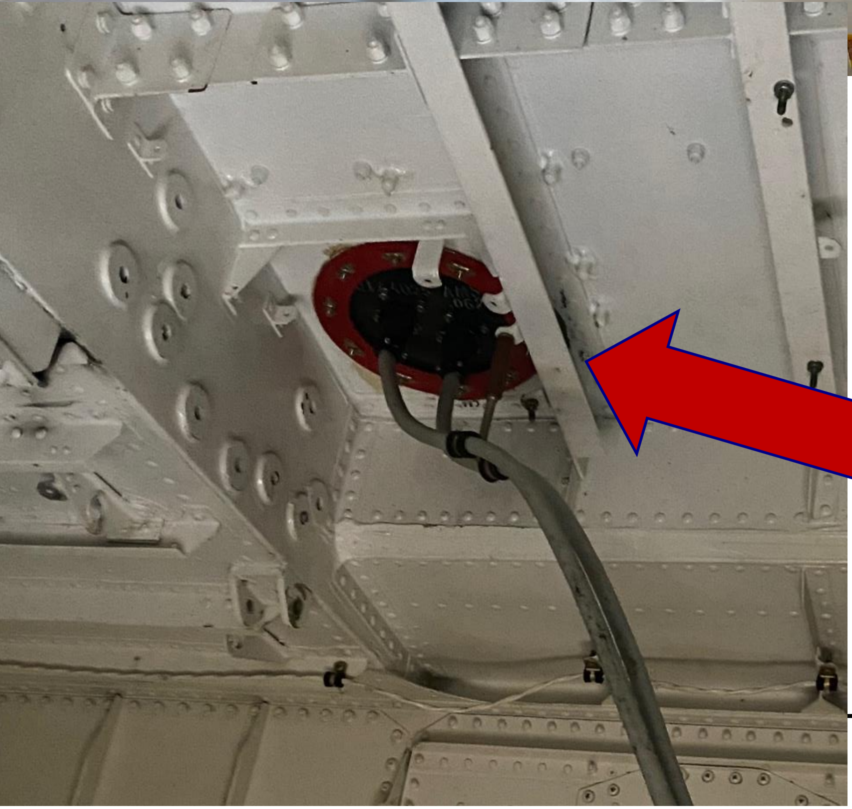
Aircraft Deployment

Minority Serving Institutions
SaSa
NASA Student Airborne Science Activation

- P3 Orion Aircraft out of Wallops Flight Facility in VA, July 2022
- IRCSP was a piggyback instrument
- Flight was part of NASA's Student Airborne Science Activation

Integration

- IRCSP installed in bombay of the plane
- Facing opposite direction of plane's flight path

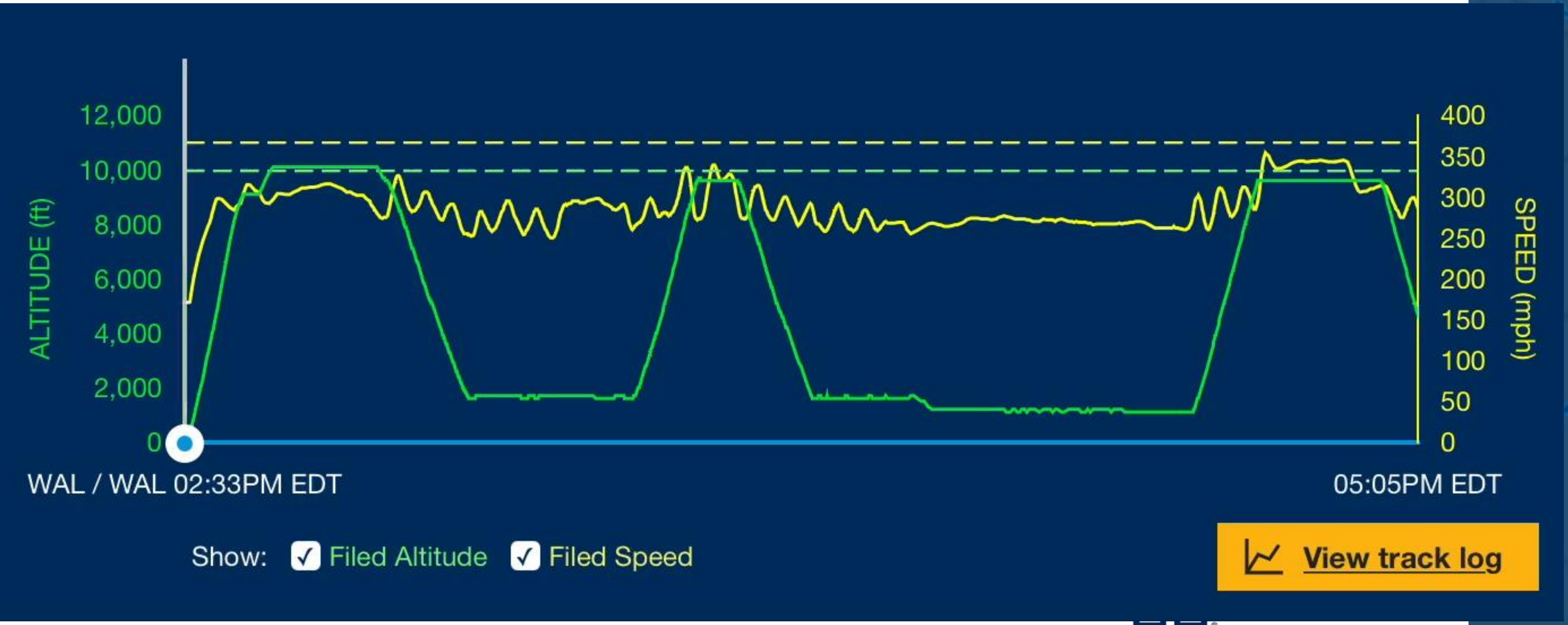


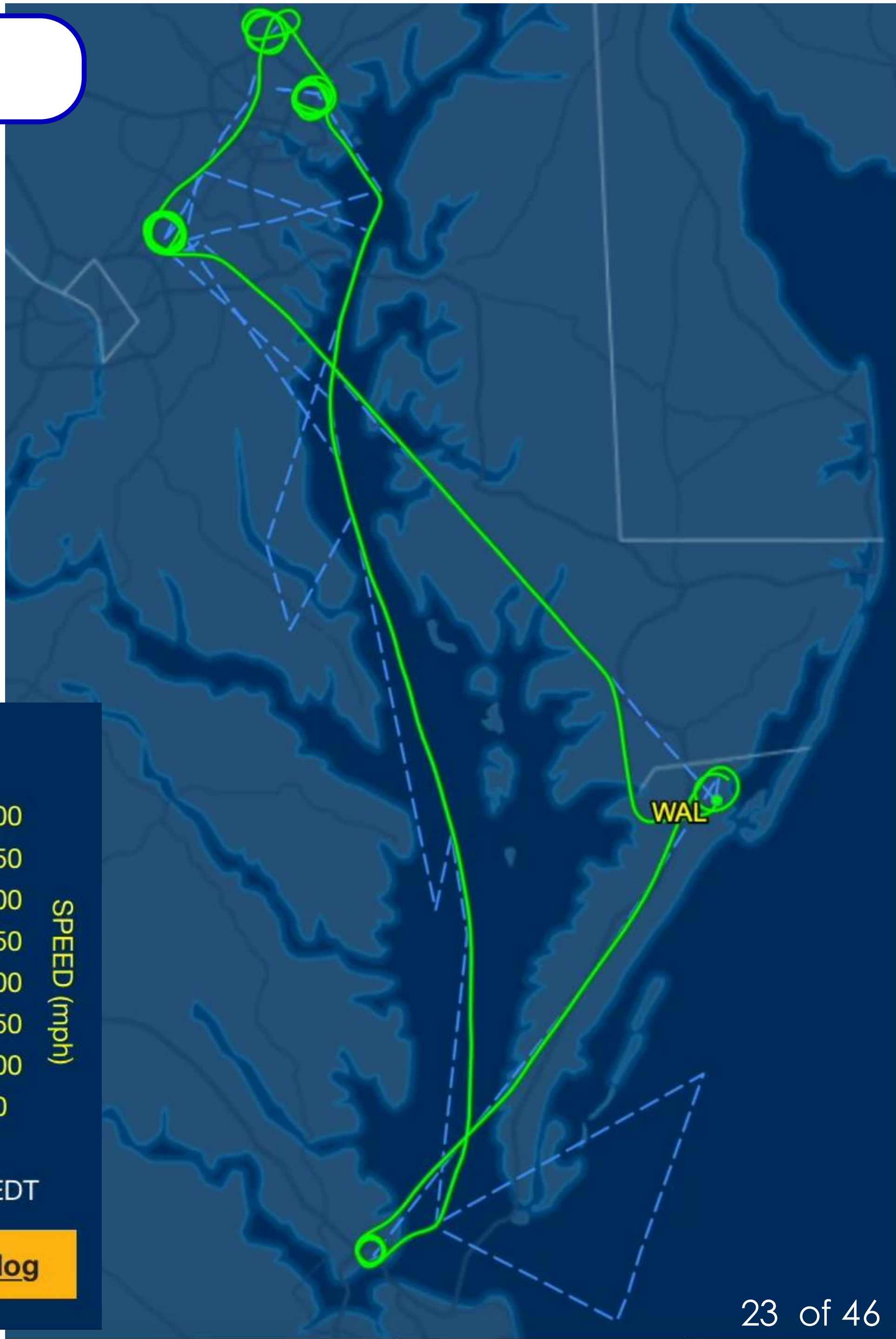
- Interface with aircraft cabin
- Connected to laptop for manual software control

Jeremy Parkinson
Optical Engineer, UA

P3 Flight Path

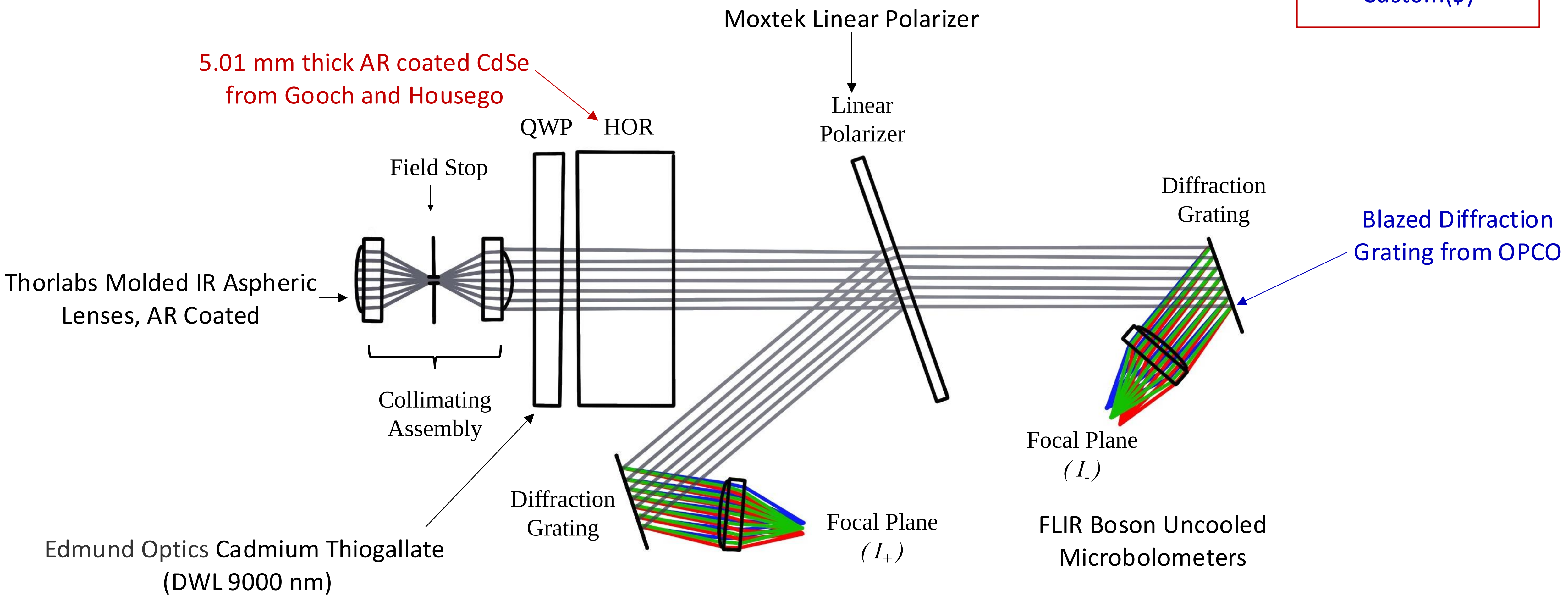
- Three successful science flights
- IRCSP collected ~ 9 hours of measurements
- Max altitude at 10,000 ft
- Lessons learned: constant changes in altitude made it hard for our temperature to stabilize inside the bombay





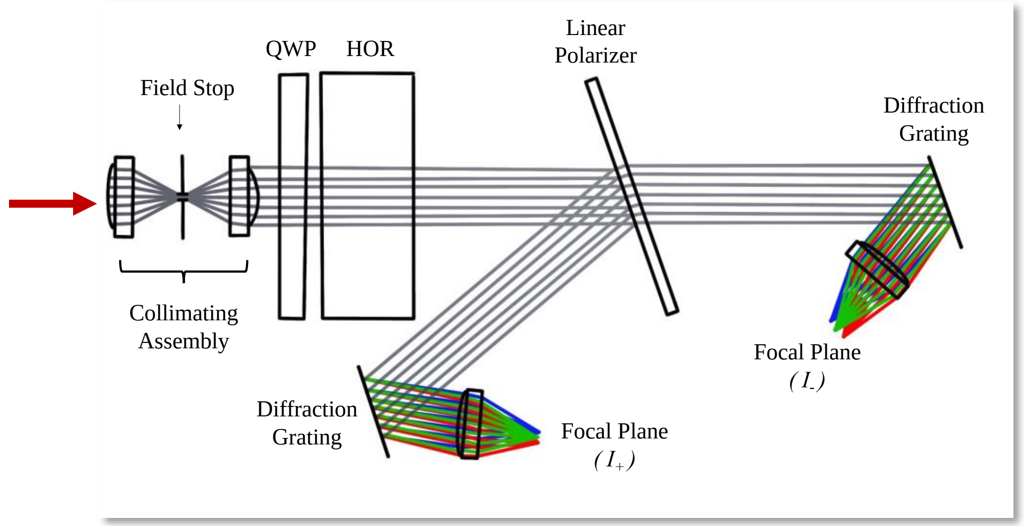
IRCSP Optical Design

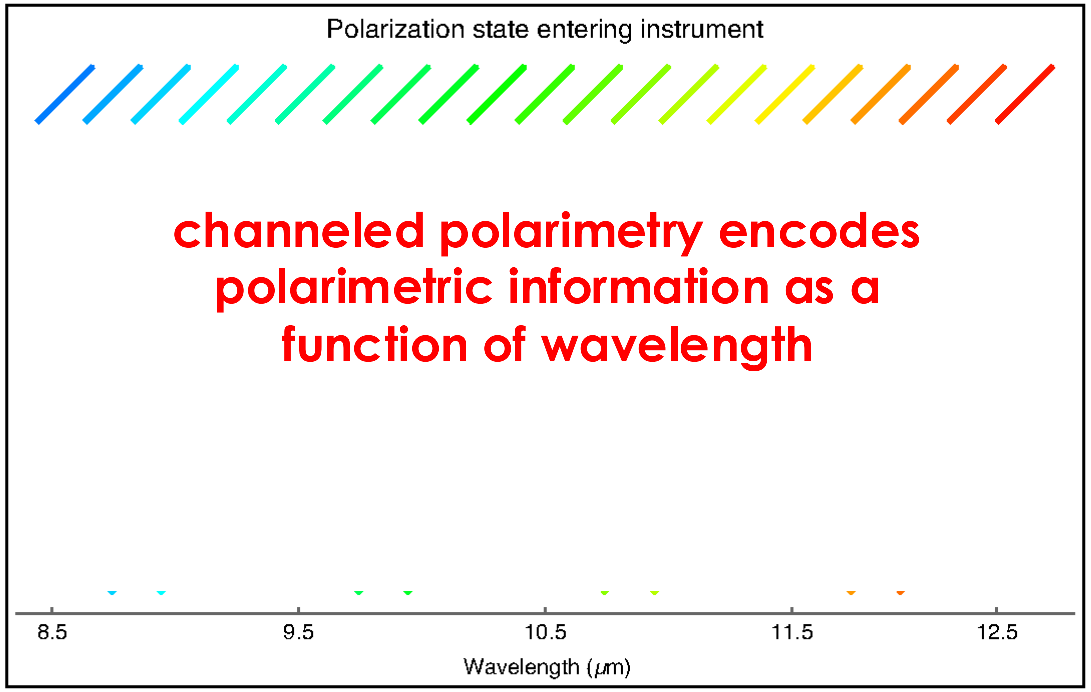
Key:
Off- the shelf
Custom ($$$)
Custom($)



Shanks (née Hart), Kira A., et al. "First results from an uncooled LWIR polarimeter for Cubesat deployment." *Optical Engineering* 59.7 (2020): 075103.

Instrument Concept



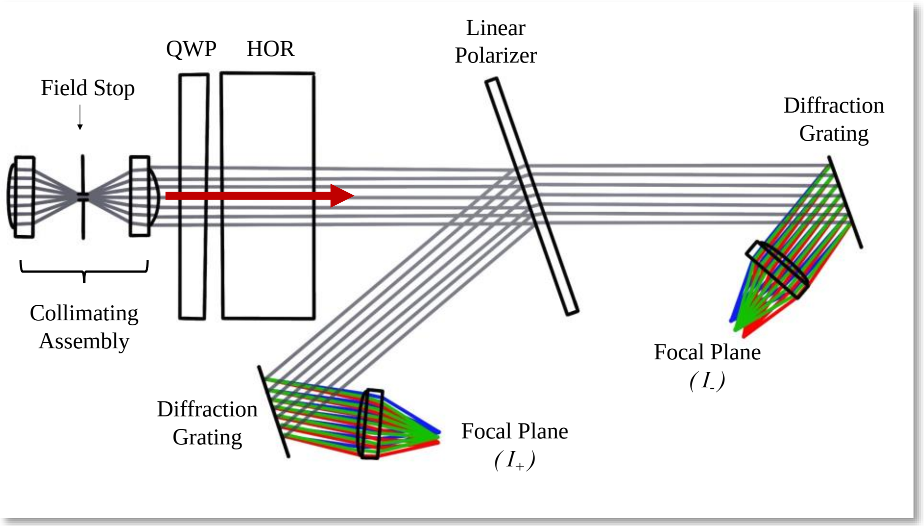


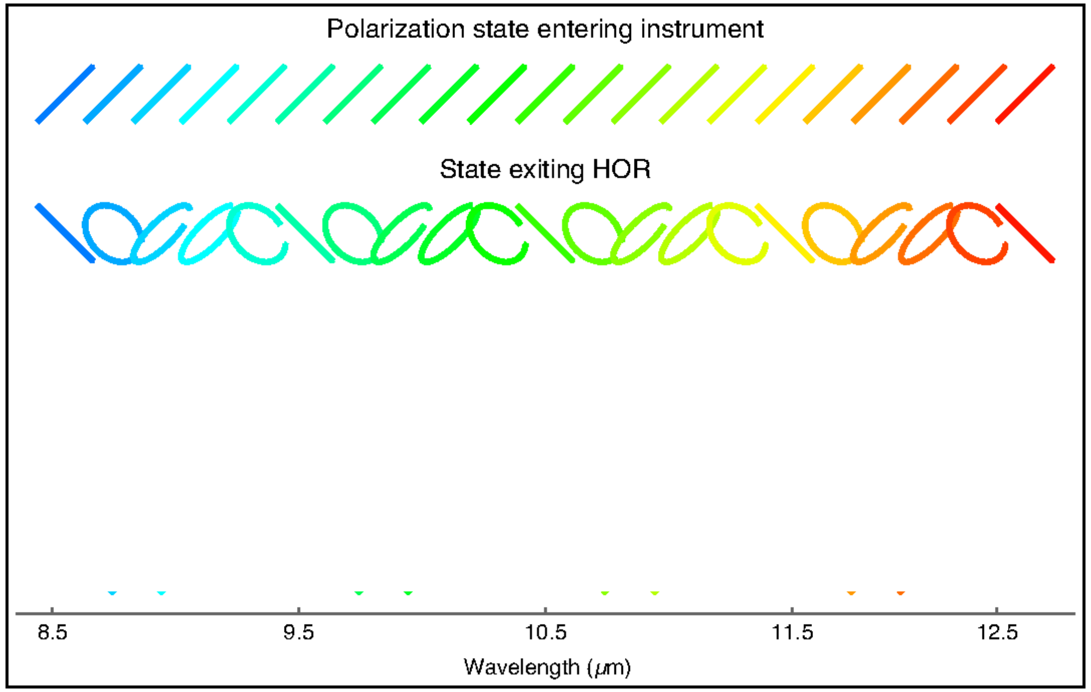
Incoming Linearly Polarized Light

Mueller Matrix Model

$$\frac{1}{2}\begin{bmatrix}1&0&1&0\\0&0&0&0\\1&0&1&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&cos\delta(\lambda)&sin\delta(\lambda)\\0&0&-sin\delta(\lambda)&cos\delta(\lambda)\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&0&0&-1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}1\\Dcos(2\theta)\\Dsin(2\theta)\\0\end{bmatrix}=\frac{1}{2}\begin{bmatrix}1+Dsin(\delta(\lambda)-2\theta)\\0\\1+Dcos(\delta(\lambda)-2\theta)\\0\end{bmatrix}$$

Shanks (née Hart), Kira A., Meredith K. Kupinski, Dong L. Wu, and Russell A. Chipman. "First results from an uncooled LWIR polarimeter for cubesat deployment." *Optical Engineering* 59, no. 7 (2020): 075103.





Mueller Matrix Model

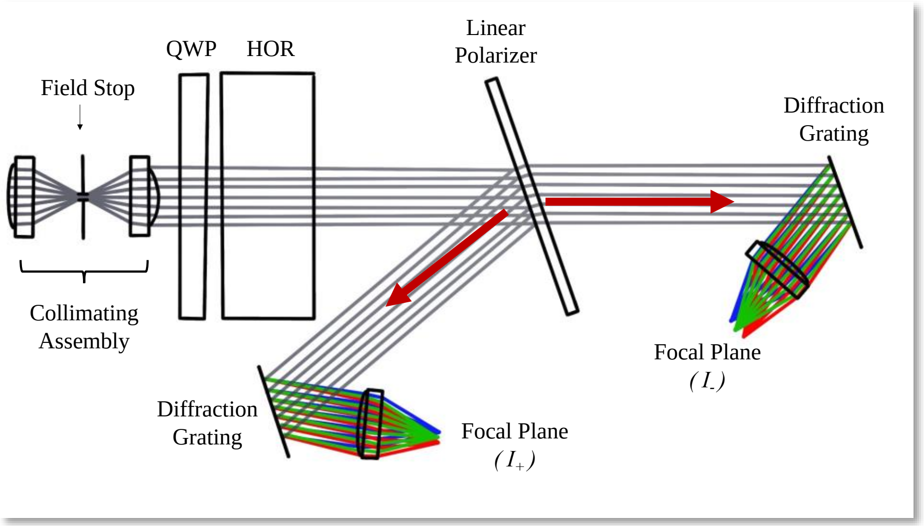
Wavelength dependent circular retardance

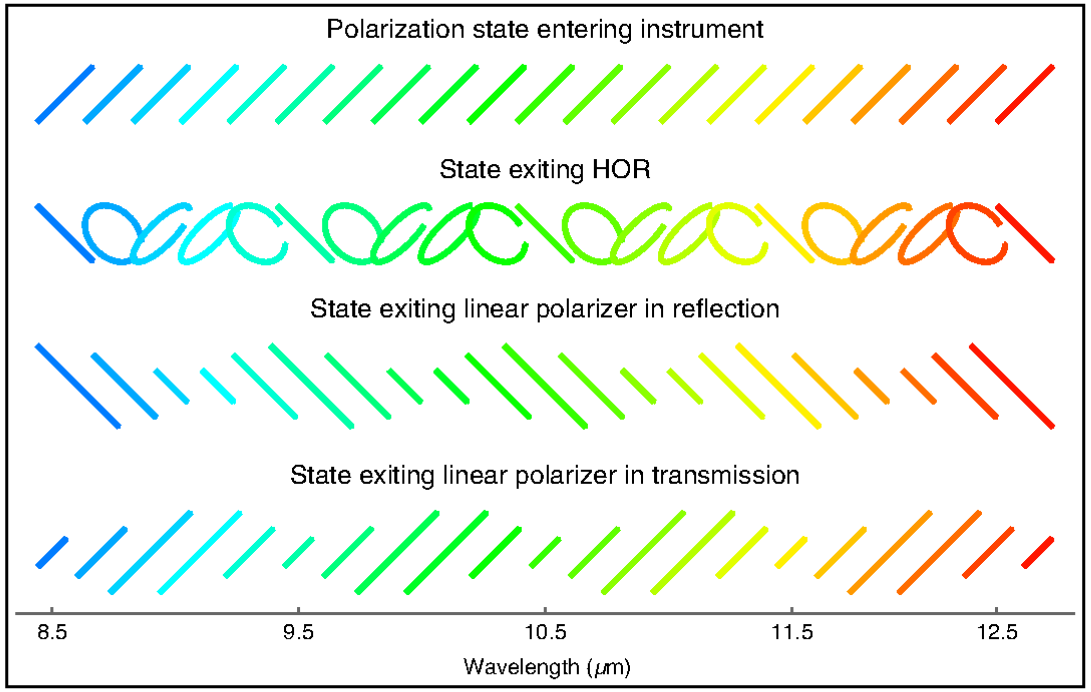
$$\frac{1}{2}\begin{bmatrix}1&0&1&0\\0&0&0&0\\1&0&1&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&cos\delta(\lambda)&sin\delta(\lambda)\\0&0&-sin\delta(\lambda)&cos\delta(\lambda)\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&0&0&-1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}1\\Dcos(2\theta)\\Dsin(2\theta)\\0\end{bmatrix}=\frac{1}{2}\begin{bmatrix}1+Dsin(\delta(\lambda)-2\theta)\\0\\1+Dcos(\delta(\lambda)-2\theta)\\0\end{bmatrix}$$

High Order Retarder

Quarter Waveplate

Instrument Concept



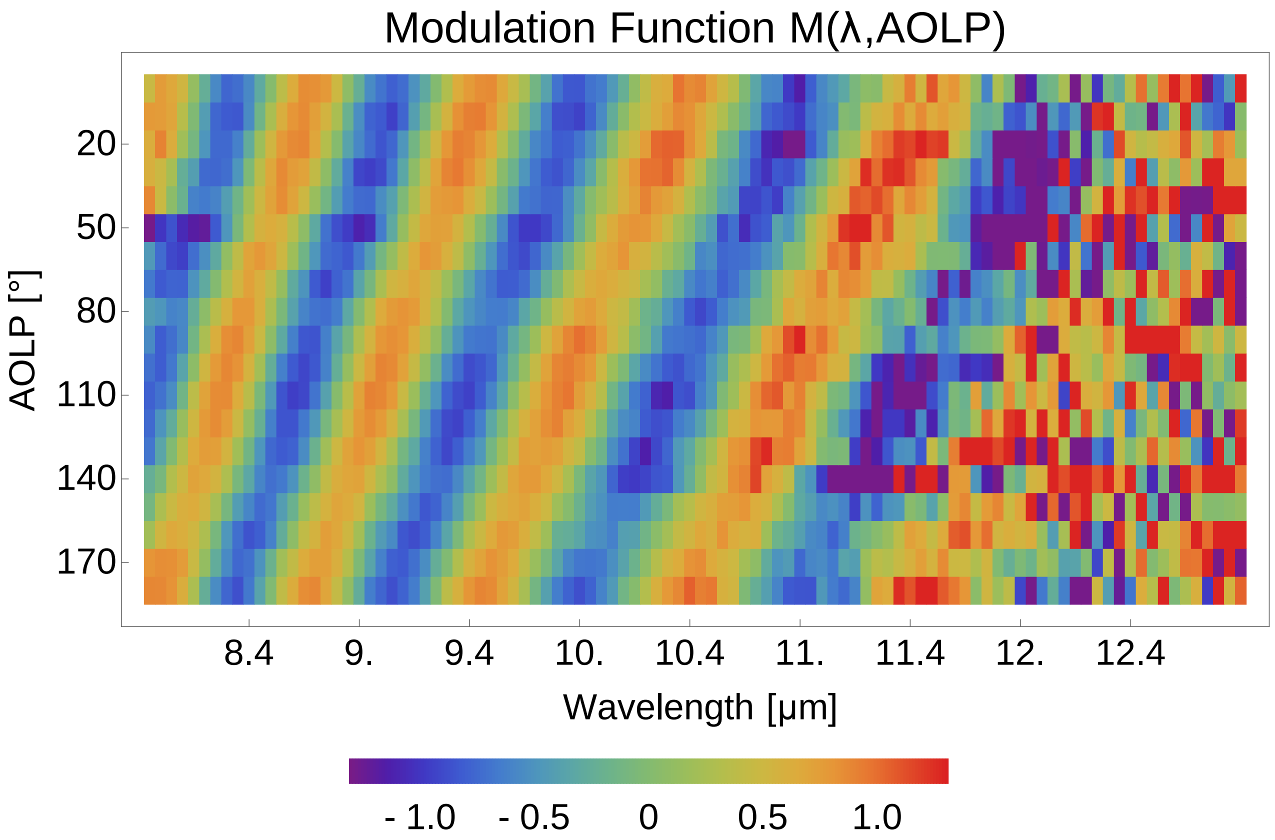


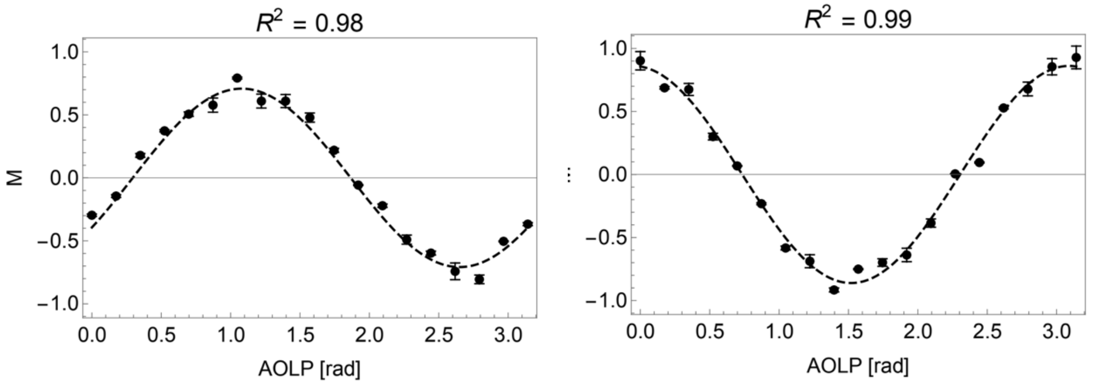
Mueller Matrix Model

$$\frac{1}{2}\begin{bmatrix}1&0&1&0\\0&0&0&0\\1&0&1&0\\0&0&0&0\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&cos\delta(\lambda)&sin\delta(\lambda)\\0&0&-sin\delta(\lambda)&cos\delta(\lambda)\end{bmatrix}\begin{bmatrix}1&0&0&0\\0&0&0&-1\\0&0&1&0\\0&1&0&0\end{bmatrix}\begin{bmatrix}1\\Dcos(2\theta)\\Dsin(2\theta)\\0\end{bmatrix}=\frac{1}{2}\begin{bmatrix}1+Dsin(\delta(\lambda)-2\theta)\\0\\1+Dcos(\delta(\lambda)-2\theta)\\0\end{bmatrix}$$

Linear Polarizer

Narrowband Polarization Efficiency





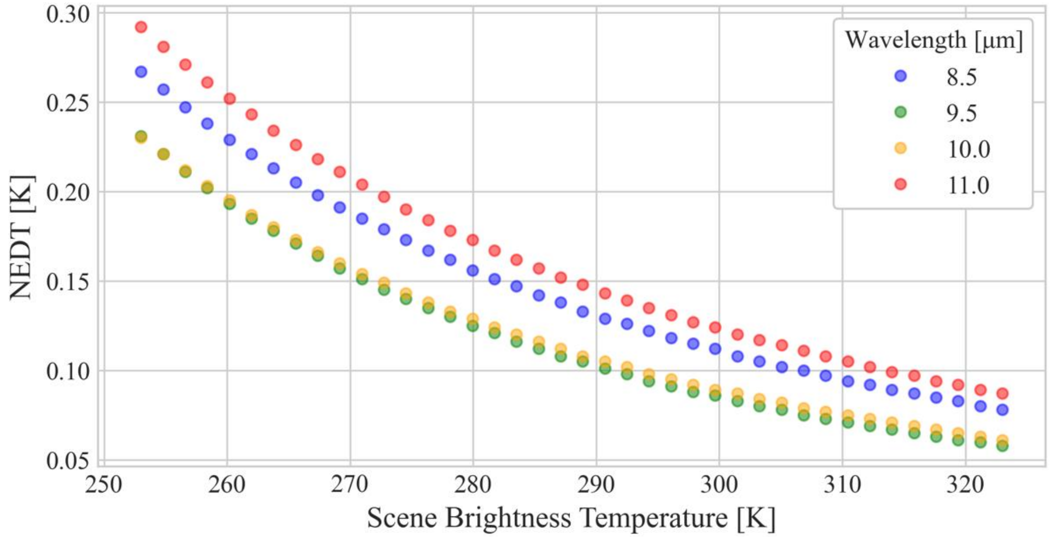
(a) $\lambda = 8.5\mu m$ (c) $\lambda = 10.5\mu m$

Polarimetric Efficiency approaches 100% at longer wavelengths in the absence of spectral blurring

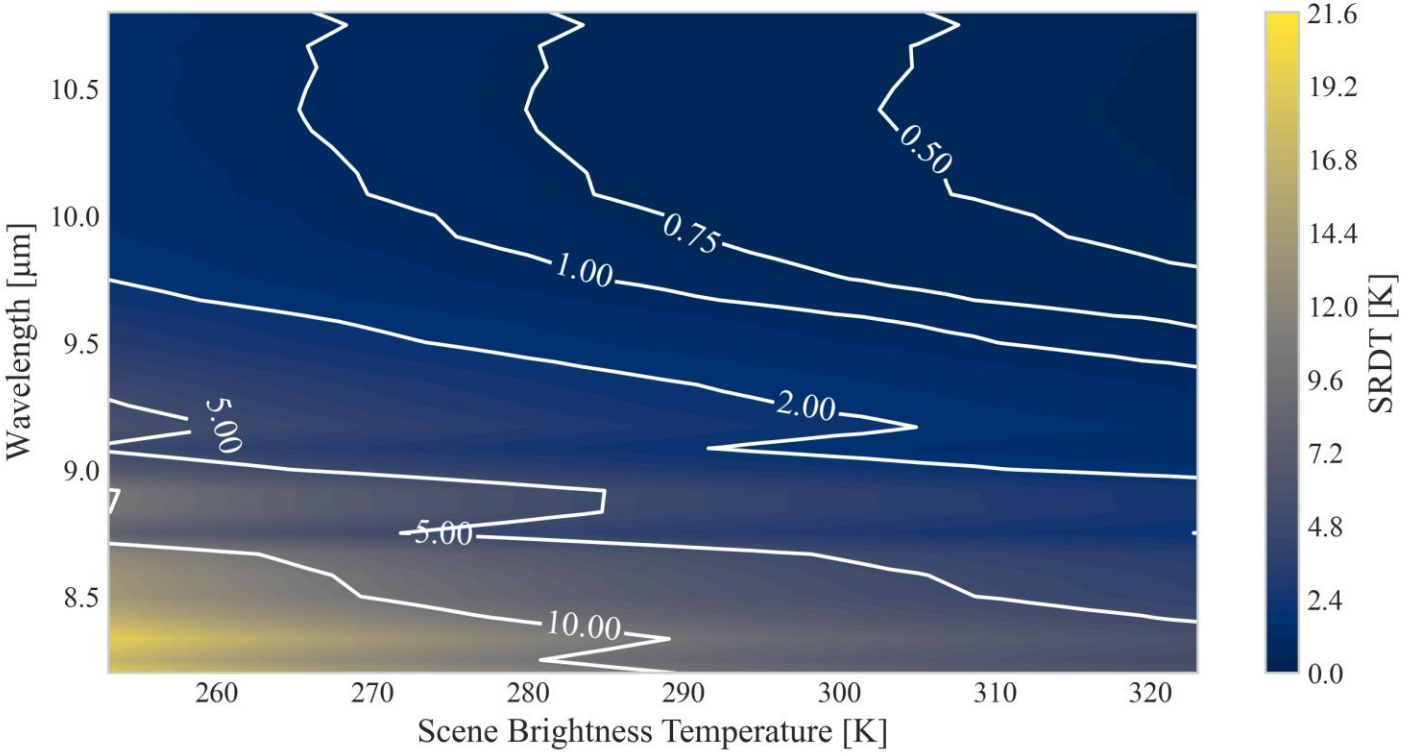
Shanks (née Hart), K A., et al. "First results from an uncooled LWIR polarimeter for CubeSat deployment." *Optical Engineering* 59.7 (2020): 075103.

IRCSP Characterization

Noise Equivalent Differential Temperature



Stokes Resolvable Differential Temperature

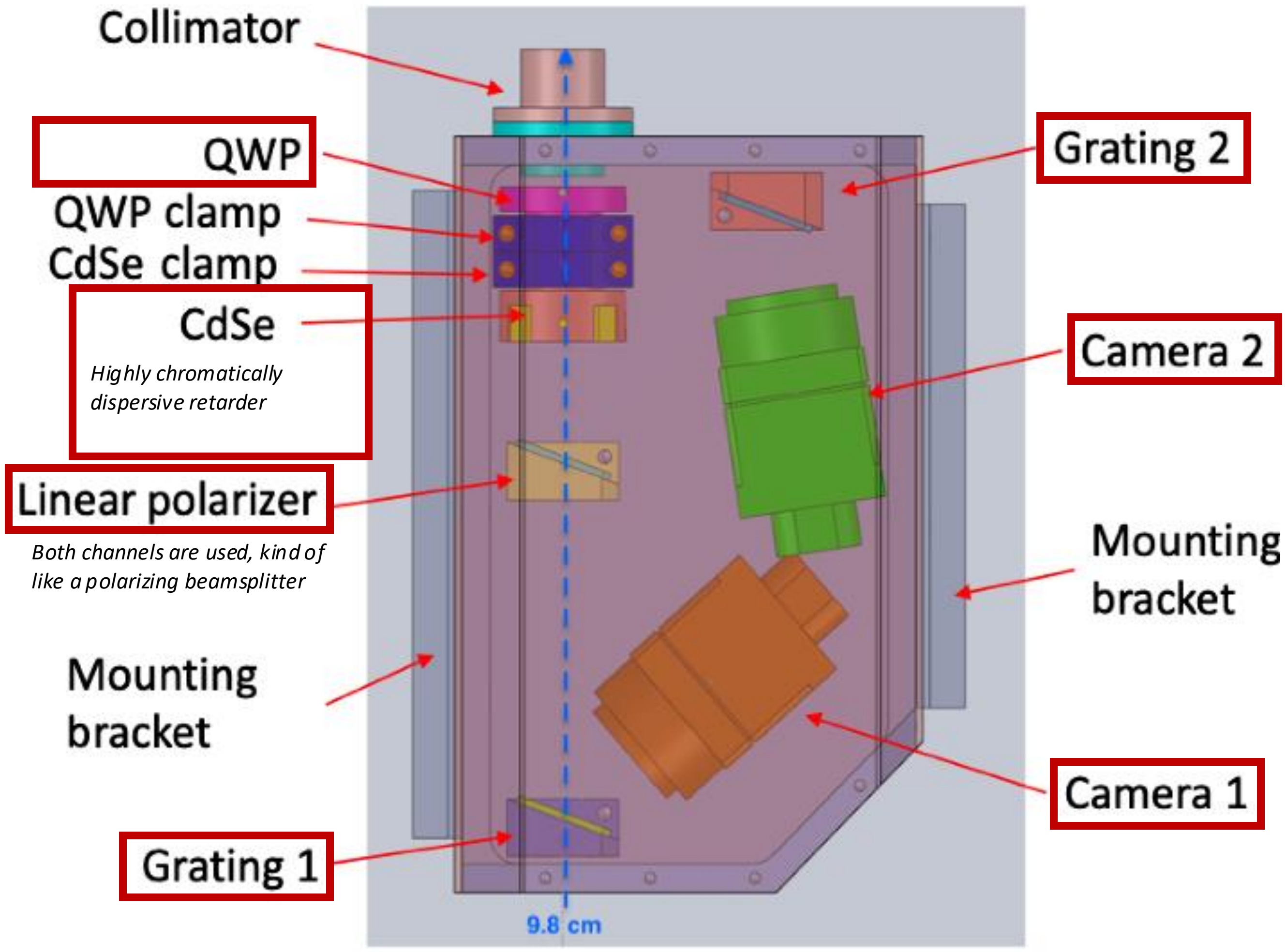


Science Requirements

Size	11.89 x 4.8 x 3.5 cm
Mass	0.5 kg
Power	1 W
Spectral Response	8 – 12 micron
Polarimetric Precision	1 K
NEDT	1 K

Lab measurements at room temperature – reduction in polarimetric efficiency degrades SRDT at shorter wavelengths

Opportunities in LWIR Polarimetry

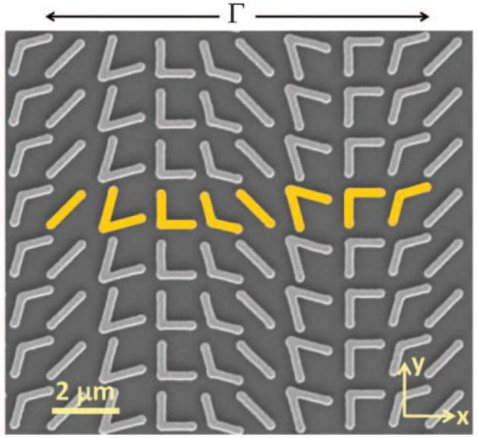


KA Hart et al., *Opt. Eng.* **59** (7), 2019

- Polarization beamsplitters do not exist in the LWIR*.
- IRCSP design relied on commercial wiregrid polarizer as a PBS
  - Mandates use of two sensors and two optical paths
  - Reflected channel has much lower diattenuation, complicating calibration

*One CdSe Wollaston prism exists in literature, *manufacturer refused to make again*.

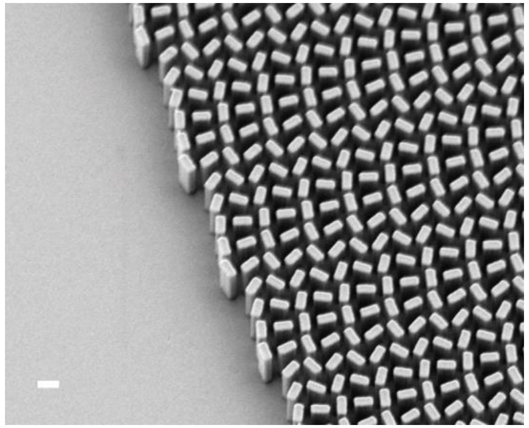
What is a "metasurface"?



N. Yu et al., *Science* **334** (6054), 2011

λ = 8 μm

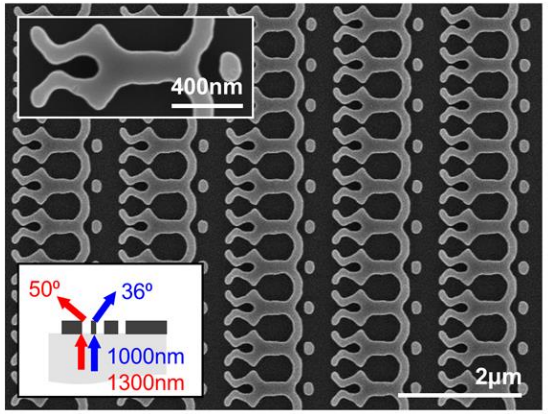
Au on Si



M. Khorasaninejad et al., *Science* **352** (6290), 2016

λ = 530 nm

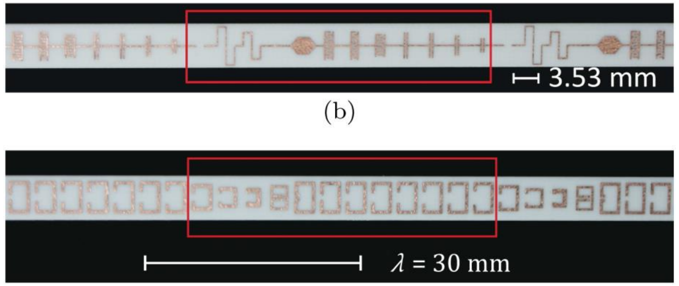
TiO_2 on SiO_2



J. Yang et al., *Nano Lett.* **17** 3742, 2017

λ = 1100 nm

Si on SiO_2



C. Pfeiffer and A. Grbic, *Phys. Rev. Lett.*. **110** (197401), 2013

Cu on RO4003

Microwaves

One definition: A **subwavelength-spaced array of phase-shifting elements intende**d to enact some desired behavior (either in reflection or transmission), generally in free-space. These elements – the "meta-atoms" – can be fabricated with standard semiconductor fabrication techniques in a variety of materials for many different optical (and RF) wavelengths.

Noah Rubin
(UC San Diego ECE)

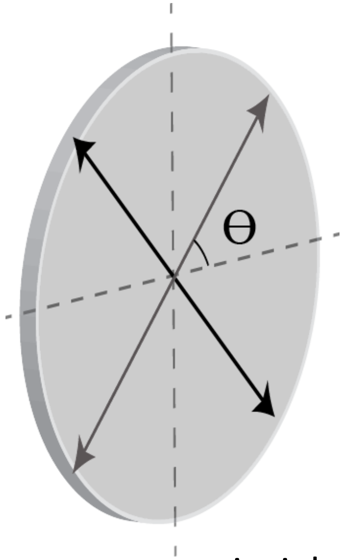
Despite the fancy name, metasurfaces are an advanced type of diffractive/holographic optics.

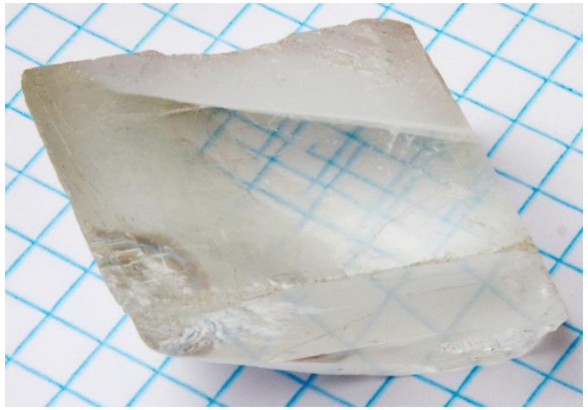
Prof. Rubin seminar: An Introduction to Metasurfaces
https://www.youtube.com/watch?v=1u6hkGSv384

Birefringence

Differential phase delay applied to orthogonal polarization states

Anisotropic Material:

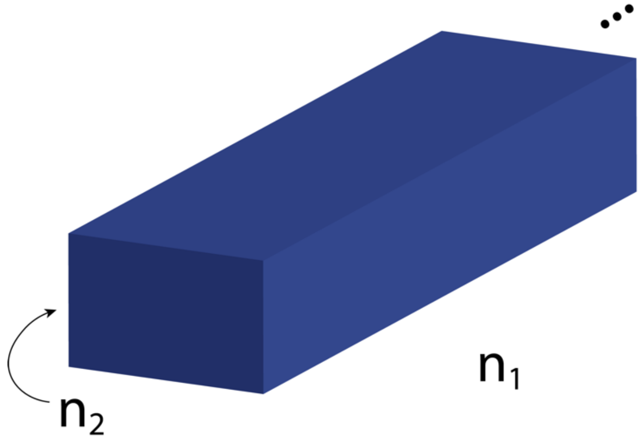




e.g., a uniaxial crystal waveplate

An optical property inherent to a crystal from nature

Form Birefringence:

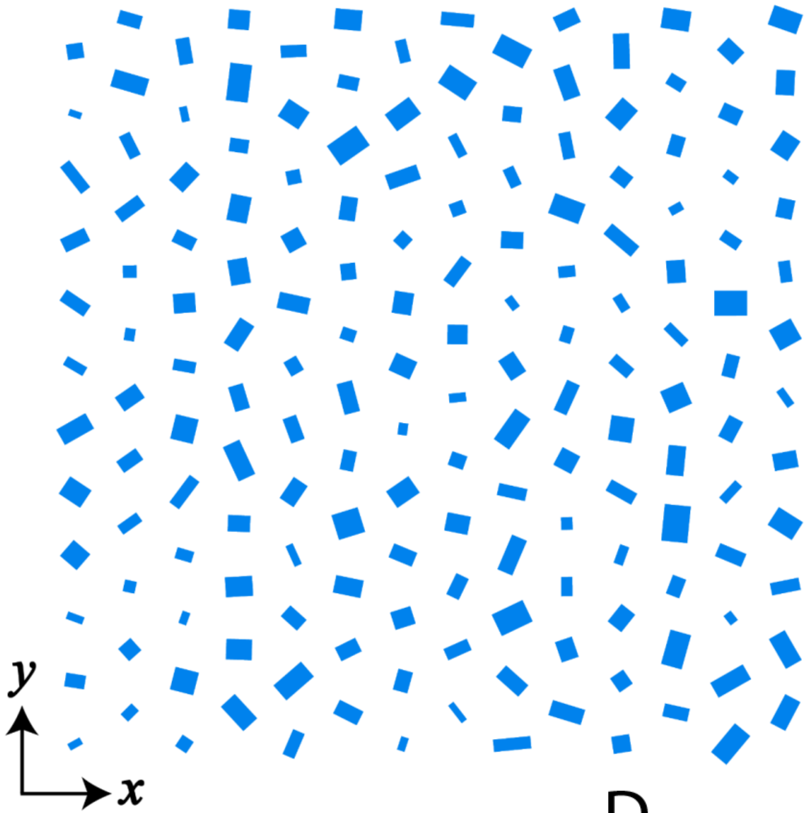


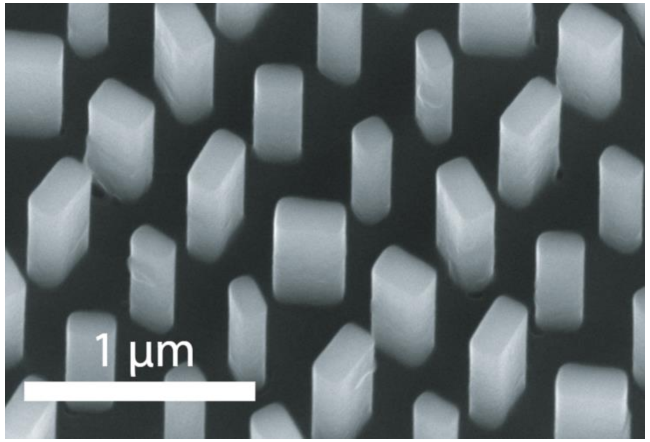
e.g., mode birefringence in a waveguide

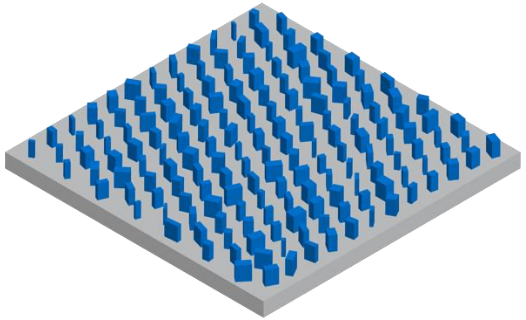
An optical property that can be *designed* by feature shape

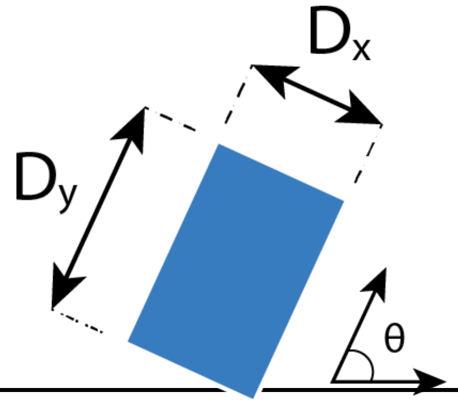
Metasurfaces and Polarization

- Metasurfaces present the capability to control birefringence in a spatially-varying manner.
- Can implement engineered, spatially-varying form birefringence (space-variant Jones matrix).
- **Metasurface-like elements can combine the function of multiple polarization optics into one element**



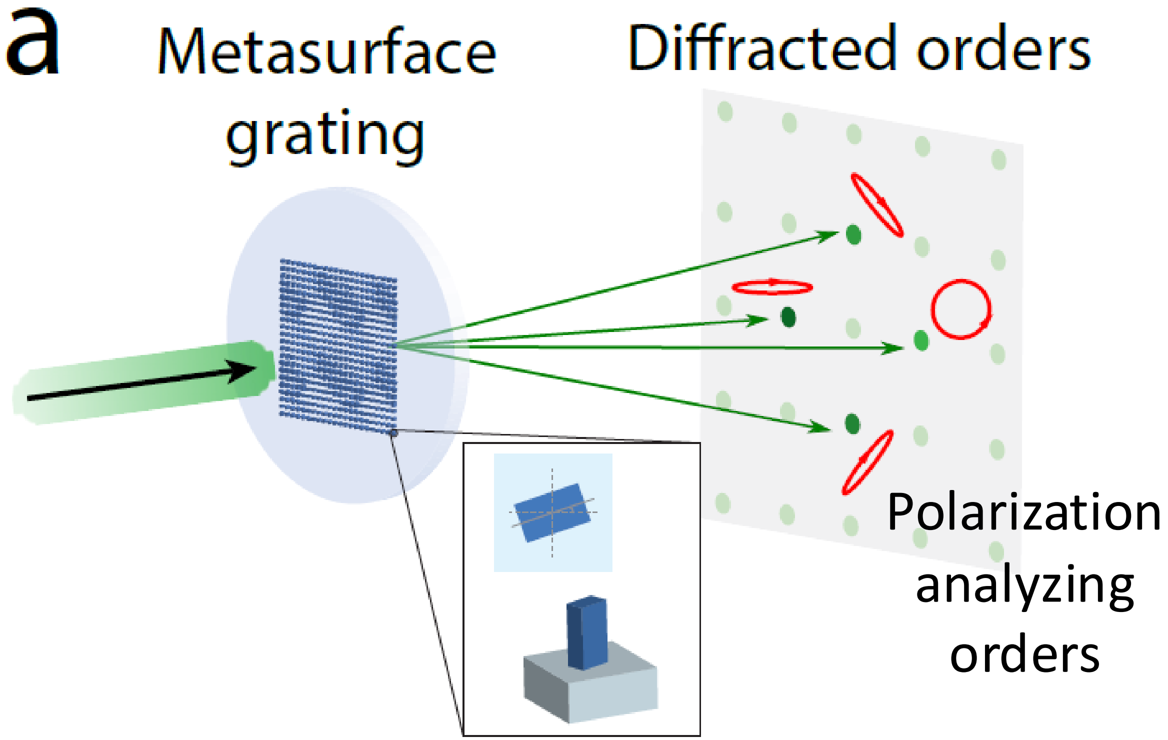






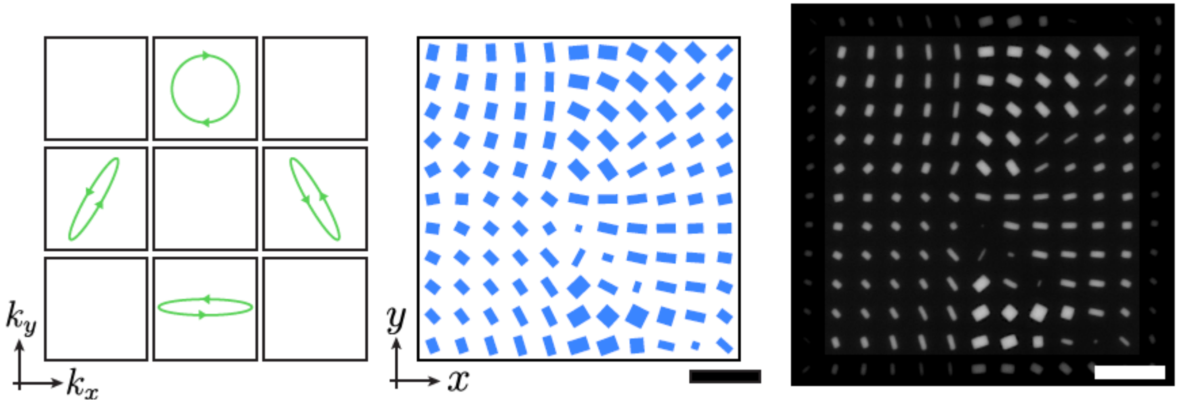
See review article:
NA Rubin, ZS Shi, and F Capasso, *Advances in Optics & Photonics* **13** (4), 2021.

Metasurface Polarization Grating (MPG)



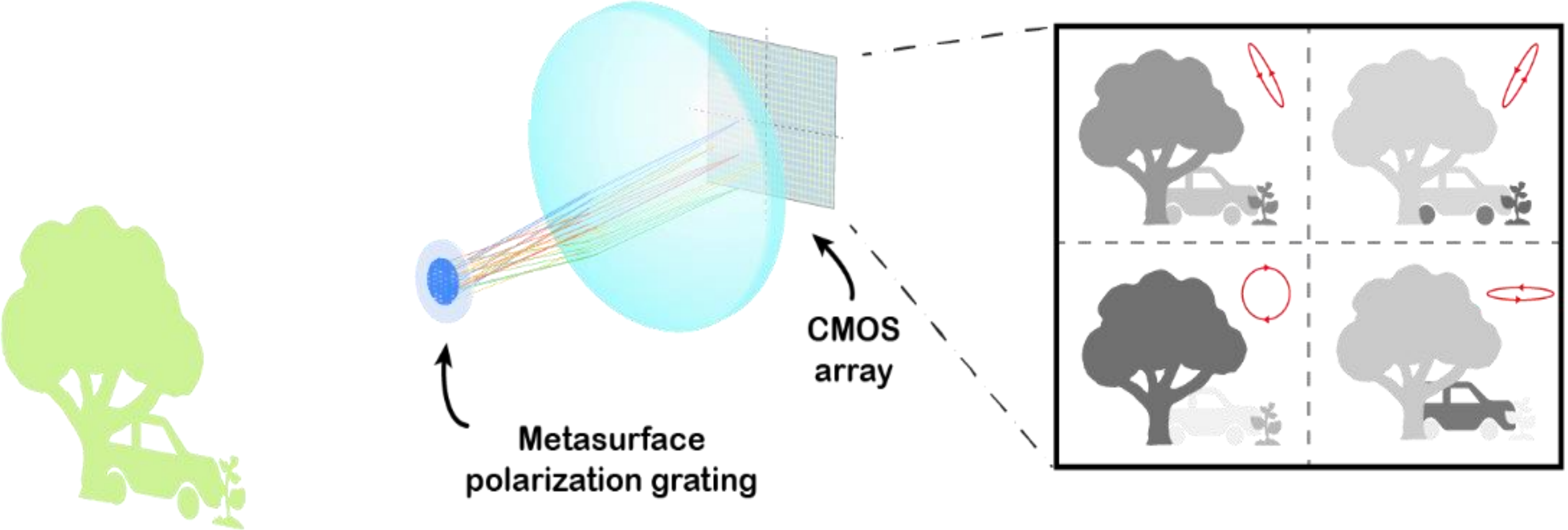
- A metasurface can be designed as a diffraction grating with orders acting as polarizers for an arbitrarily selected set of polarization states.
- These states do not necessarily have to be orthogonal.
- These can provide advantages in in compact polarimetric imaging systems.

Example for visible wavelengths



NA Rubin et al., *Science* **365** (6448), 2019

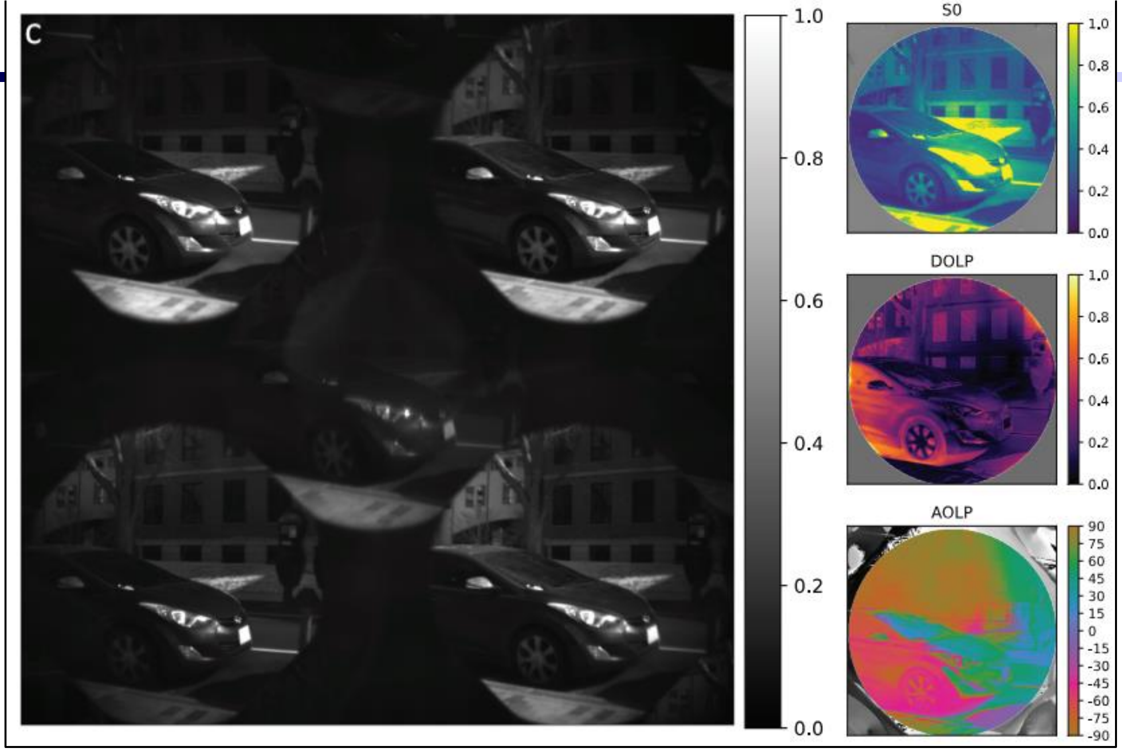
Metasurface Imaging Polarimetry

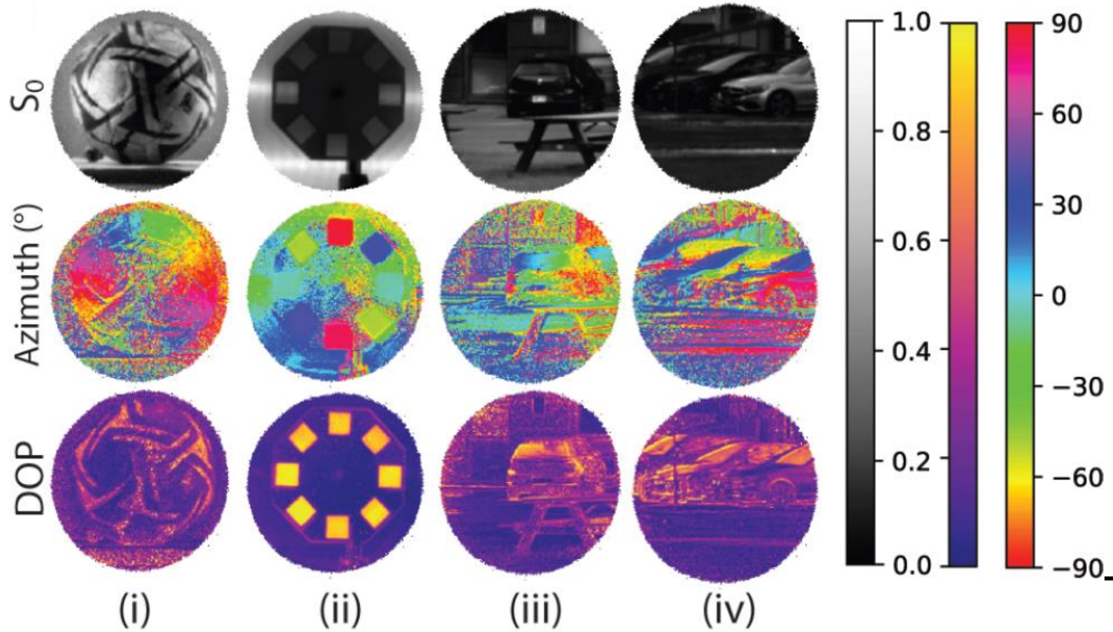


- Compact ✓
- Passive, no moving parts ✓
- “Snapshot” polarization state acquisition ✓
- “Sorting” rather than “filtering” of polarized light ✓

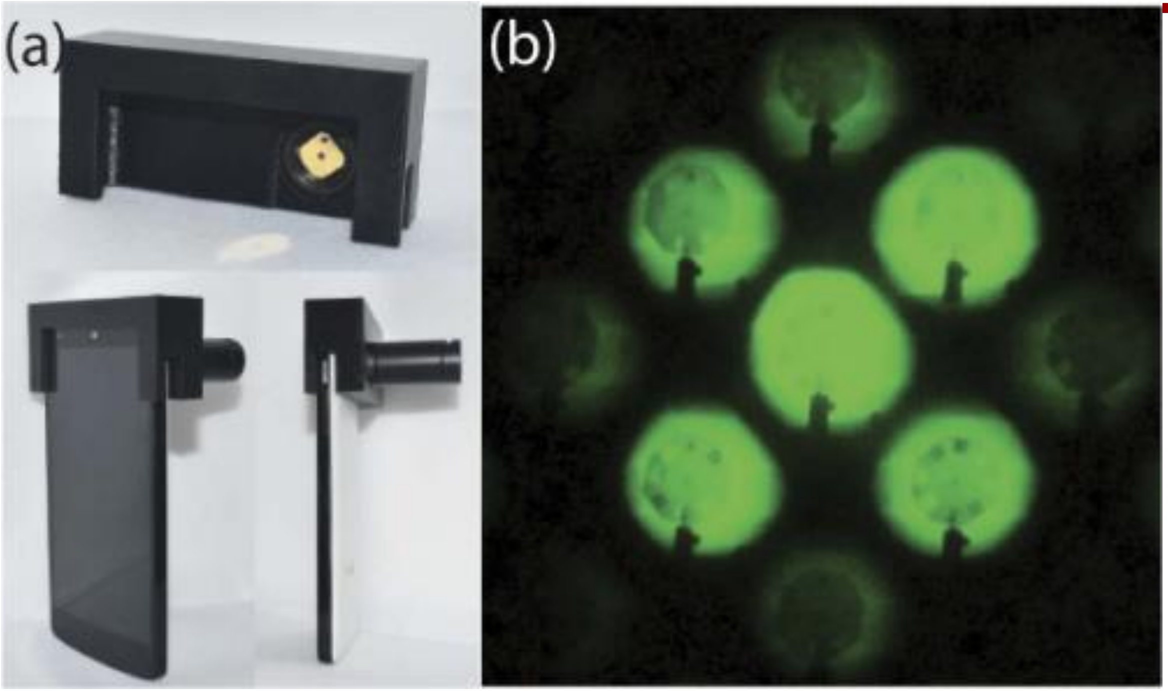
$$\vec{S}(x,y) = \begin{pmatrix} S_0(x,y) \\ S_1(x,y) \\ S_2(x,y) \\ S_3(x,y) \end{pmatrix}$$

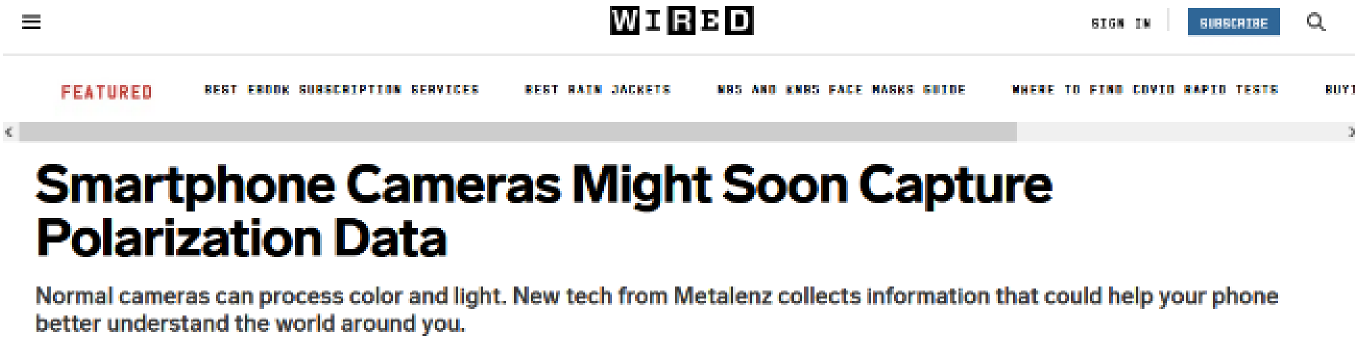
NA Rubin et al., *Science* **365** (6448), 2019





NA Rubin et al., *Optics Express* **30** (6), 2022




WIRED

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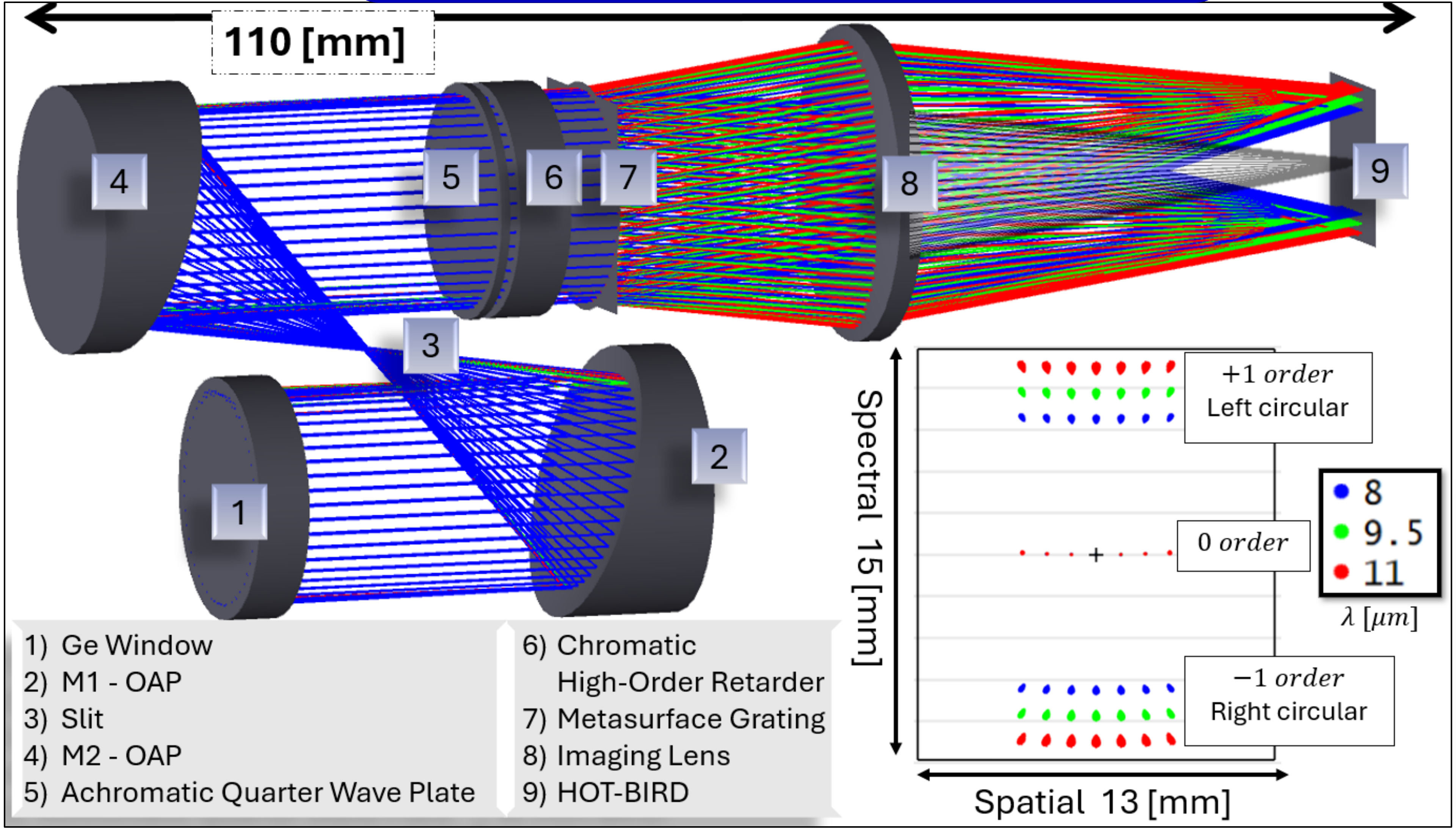
FEATURED | BEST EBOOK SUBSCRIPTION SERVICES | BEST RAIN JACKETS | N95 AND KN95 FACE MASKS GUIDE | WHERE TO FIND COVID RAPID TESTS

Smartphone Cameras Might Soon Capture Polarization Data

Normal cameras can process color and light. New tech from Metalenz collects information that could help your phone better understand the world around you.

Maybe even in your phone (!)

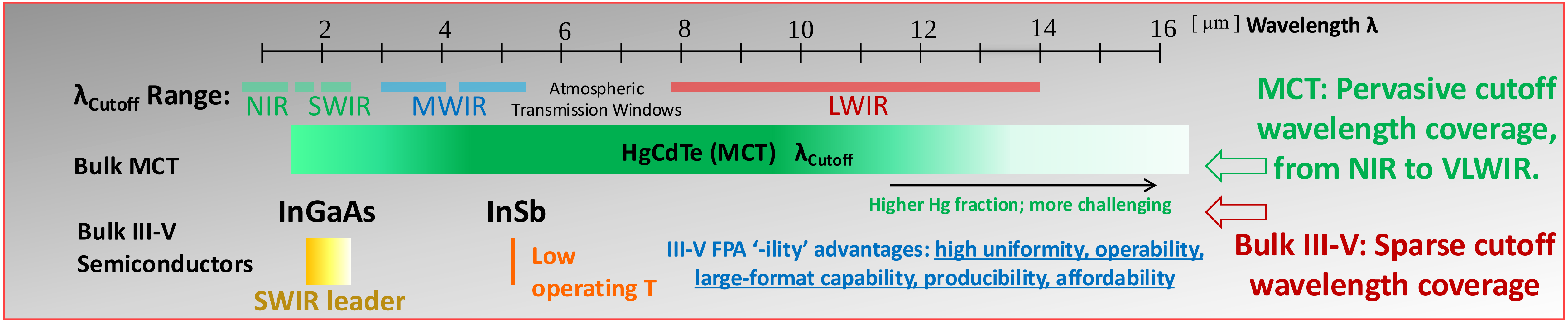
CHIRP Optical Layout



- MPG implements a PBS and spectrometer grating in a single component
- Equal polarimetric performance both orders imaged on a single detector

Jeremy Parkinson
Optical Engineer

Limitations of Conventional III-V IR Photodetectors

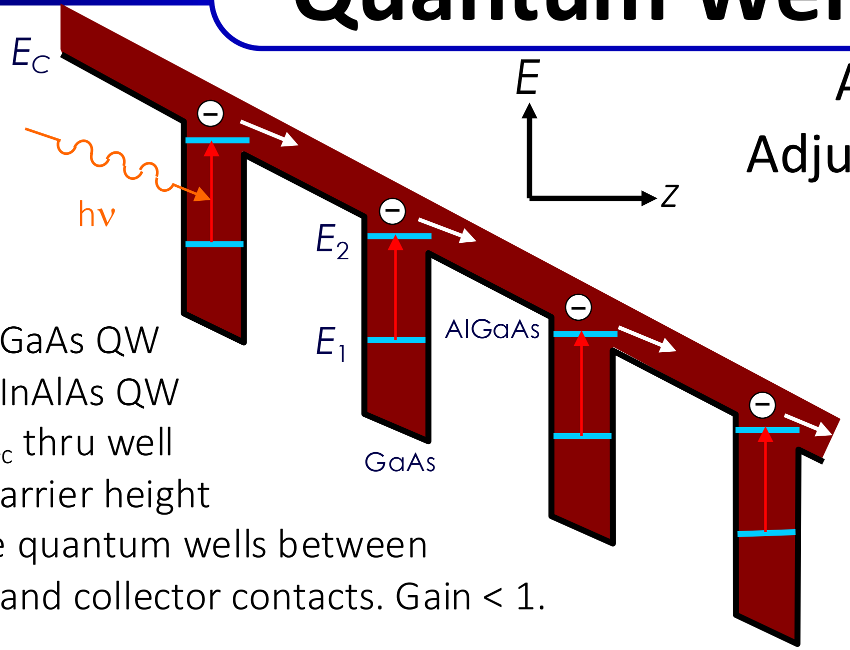


- $Hg_xCd_{1-x}Te$ alloy (**MCT**) is the most successful high-performance infrared detector material to date
  - Varying alloy composition provides continuously adjustable cutoff wavelength coverage, ranging from NIR to VLWIR
  - Soft and brittle II-VI semiconductor. Requires expert handling in growth, fabrication, storage. Costly.
  - Producing high-quality, large-format CdZnTe (CZT) substrates is challenging/costly (Commercial supplier: Nikko, Japan)
- FPAs based on (near) lattice-matched bulk **III-V** photodiodes are successful, if suitable substrates are available
  - SWIR **InGaAs** performs at near theoretical limit. Single color, limited cutoff wavelength adjustability.
  - **InSb** dominated MWIR market, despite lower operating temperature than MCT. Fixed cutoff wavelength.
  - **Lacking the continuous cutoff wavelength adjustability of MCT**

David Ting
Deputy Director,
Center for Infrared Photodetectors

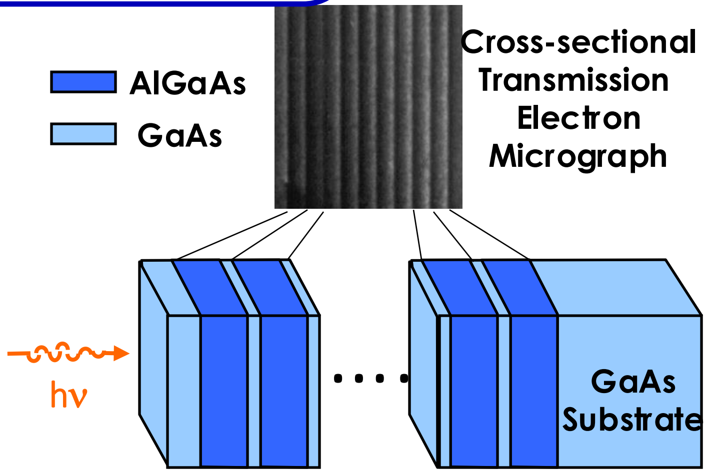
IR Detector Group Goal: Develop high-performance IR photodetectors based on robust III-V materials, with wide-range cutoff wavelength adjustability

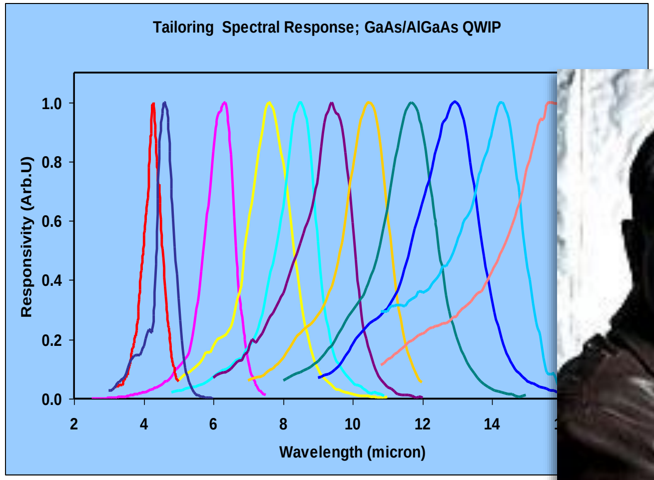
Quantum Well IR Photodetector (QWIP)



- GaAs/AlGaAs QW
- InGaAs/InAlAs QW
- Adjust λ_c thru well width/barrier height
- Multiple quantum wells between emitter and collector contacts. Gain < 1.

Artificial Structures for Adjustable Detector Response





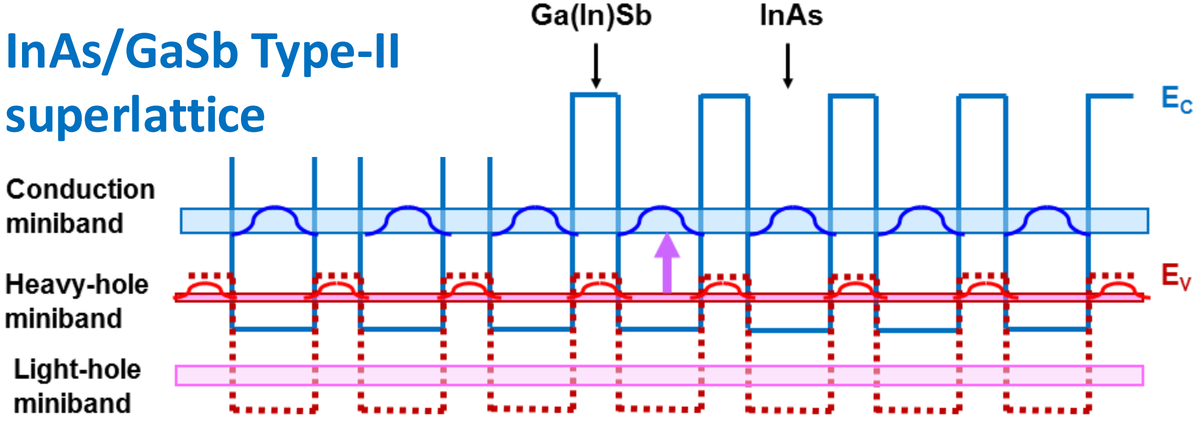
Sarath Gunapala
Director, Center for Infrared Photodetectors
Engineering Fellow

- III-V semiconductor FPA "-ility" advantages
  - High operability, **uniformity**, large-format capability, producibility, affordability.
  - **Temporal stability** (low 1/f noise). No need for frequent system recalibration.
- QWIP FPAs successfully deployed in NASA LandSat-8, HyTES
- QWIP Challenges
  - Requires more cooling to control thermal dark current. Higher generation-recombination (G-R) rate from fast LO phonon scattering.
  - Low external QE. Needs light coupling grating structure for normal-incidence absorption.
  - Relatively narrow band response

Recent Advances in III-V IR Photodetectors

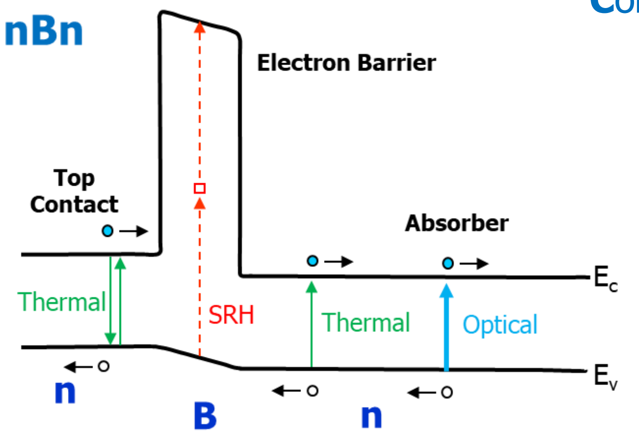
Antimonide IR absorbers

InAs/GaSb Type-II superlattice

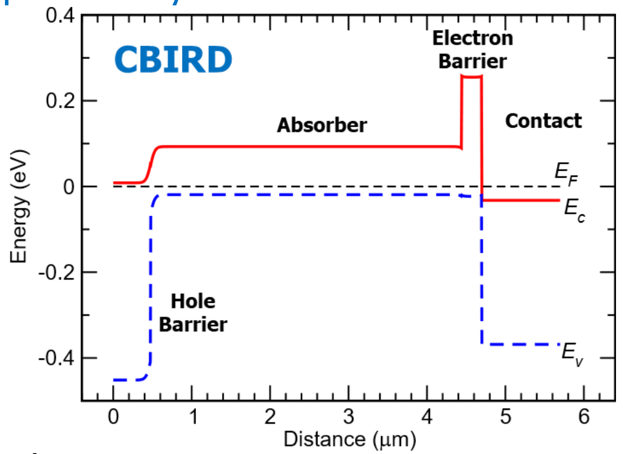


- InGaAsSb alloy: 2-4 μm cutoff wavelength
- Type-II superlattices (T2SLs)
  - Artificial material with continuously adjustable bandgap provides cutoff wavelength coverage from 2 μm to >15 μm
  - Tunneling and Auger dark current suppression
- All can be grown on GaSb substrates
  - 2”, 3”, 4”, 5”, 6” diameter formats now available

Unipolar barrier detector architecture



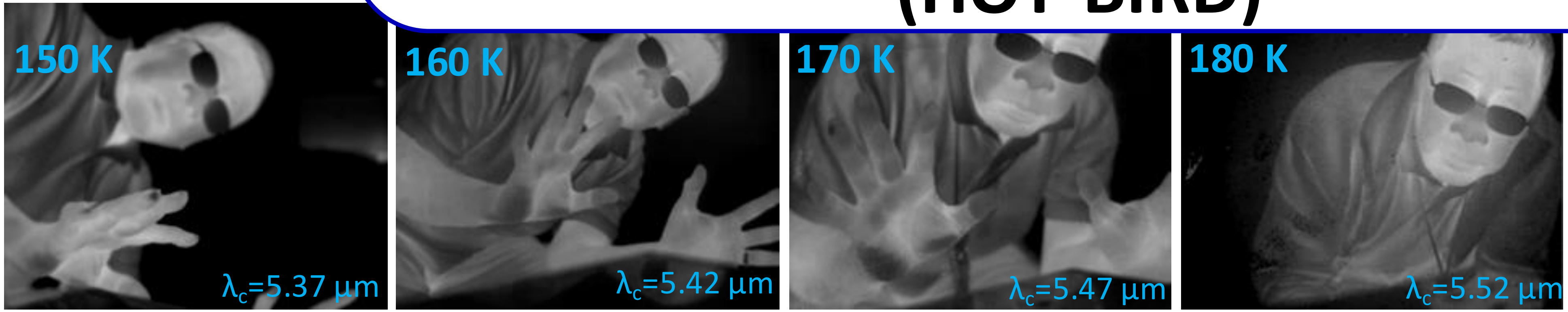
Complementary **B**arrier **I**nfra**R**ed **D**etector



- Unipolar barrier detector architecture
  - Unipolar Barrier blocks electrons not holes (or vice versa)
  - Examples: **nBn** (Maimon & Wicks, *Appl. Phys. Lett.* 2006), XBn, XBp, CBIRD
- Can suppress generation-recombination (G-R) and surface leakage dark current, w/o impeding photocurrent
- Higher operating temperature / sensitivity

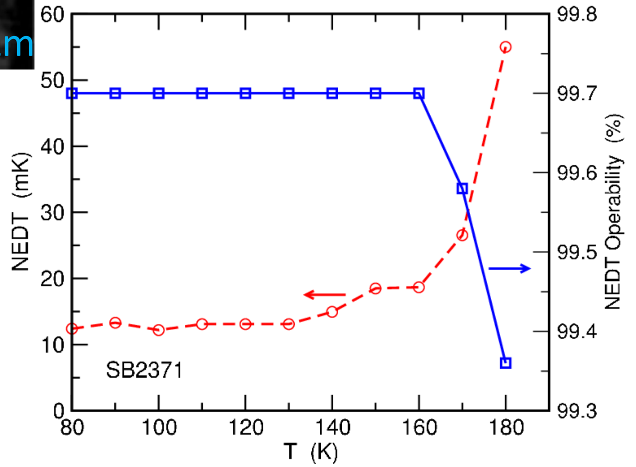
Confluence of these two developments led to a new generation of versatile, cost-effective, high-performance IR detectors and FPAs based on robust III-V semiconductors, with wide-range cutoffs.

High Operating Temp Barrier IR Detector (HOT-BIRD)



U. S. Patent No. 8,217,480 (2012); *Appl. Phys. Lett.* **113**, 021101 (2018); *IEEE Photonics Journal* **10**(6), 6804106 (2018).

- InAs/InAsSb T2SL **HOT-BIRD**
  - Customized cutoff wavelength to match InSb. Excellent FPA imaging performance at 160K
- T2SL FPA with ~same cutoff wavelength, but **much higher operating temperature than InSb**
  - Planar InSb (ion implant) ~ 80K. MBE epi InSb ~ 95-100K (can image up to 110-120K)
    - Klipstein et al., Infrared Phys. & Technol. 59 (2013) 172–181
- T2SL FPA demonstrating a clear advantage over a **major incumbent technology (InSb)**
  - In 2018, InSb FPA led market in volume, with >50% market share (units sold).
- Reduces demand on cryocoolers – Enables longer cooler lifetime, or the use of compact coolers.
- Retains the same III-V semiconductor manufacturability & affordability benefits as InSb

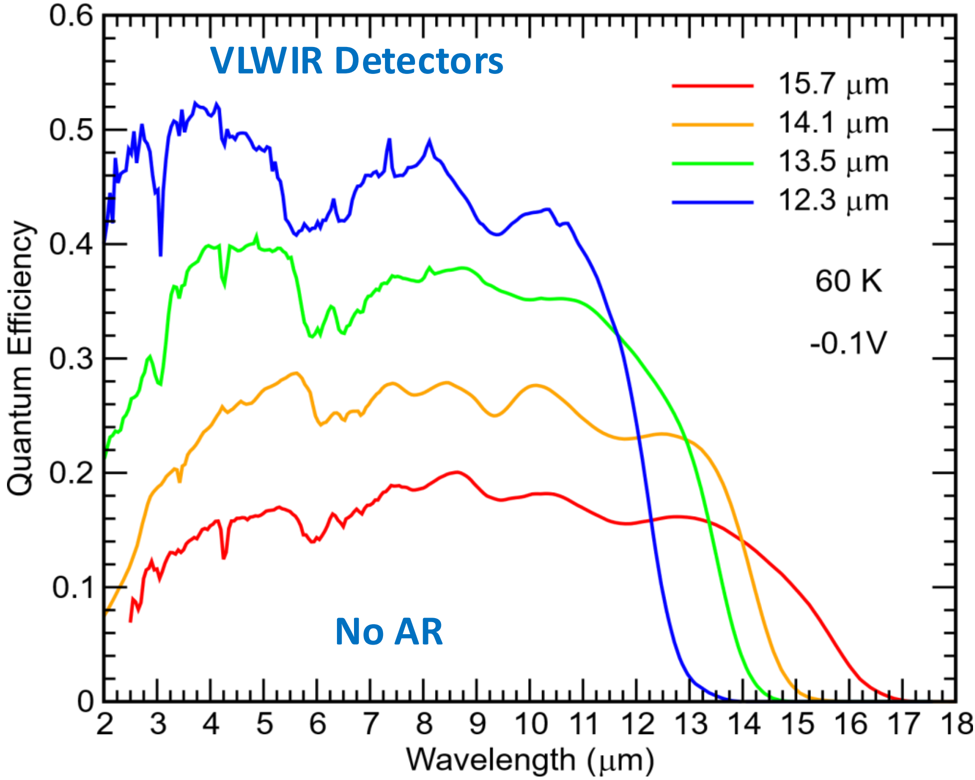


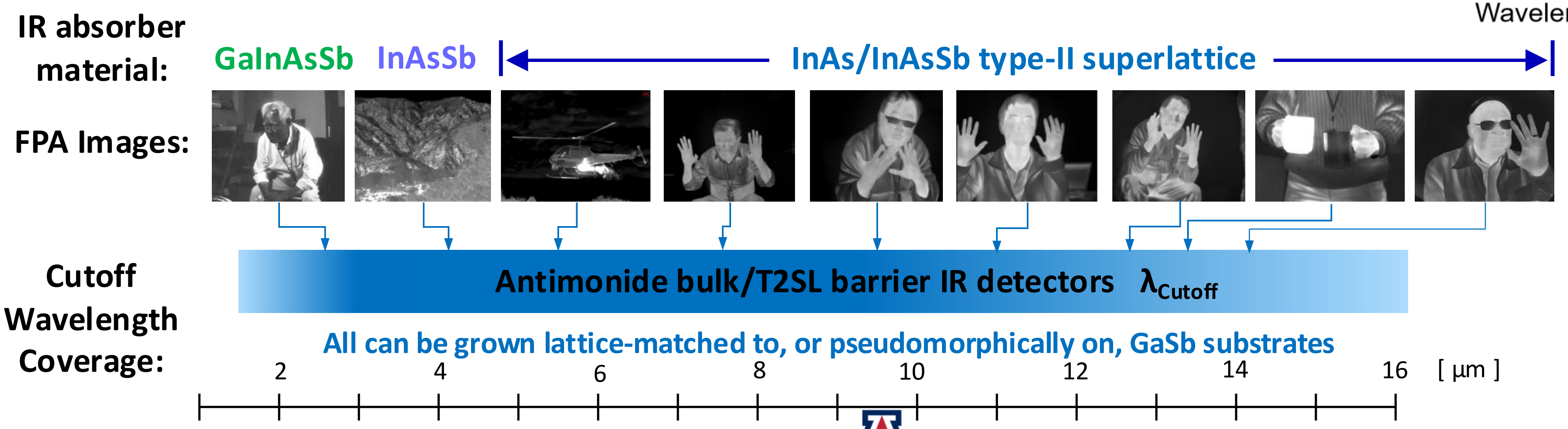
SBF-193 ROIC: 24-µm pitch, 640×512. 300K bkgnd, f/2
160K (170K),
NEDT 18.7 mK (26.6 mK),
Operability 99.7% (99.6%)

Antimonide Unipolar Barrier IR Detector Development at JPL

Demonstrated antimonide alloy and type-II superlattice unipolar barrier IR detectors w/ high uniformity & operability FPAs, with cutoff wavelengths covering SWIR to VLWIR.

- Unipolar barrier infrared detectors
  - IR absorbers: GaInAsSb, InAsSb, InAs/InAsSb T2SL
  - All grown on GaSb substrates
  - Cutoff wavelengths ranging from 2.5 to 15.7 µm demonstrated
- Focal plane arrays
  - Cutoff wavelengths ranging from 2.6 to 14.1 µm demonstrated
  - High uniformity and operability

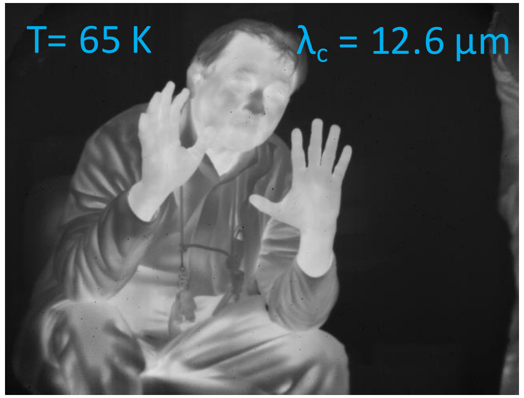




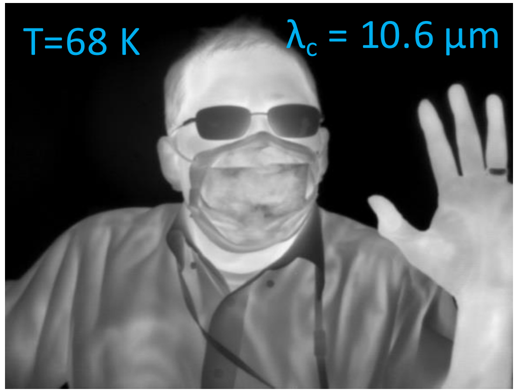
Type-II Superlattice IR Detectors at NASA

- Cost-effective, high manufacturability FPA technology supports NASA interests in constellations of SmallSats / CubeSats

- JPL T2SL barrier IR detector projects for NASA
  - Supported by ESTO SLI-T, ACT, IIP, InVEST; PICASSO
  - LWIR T2SL FPAs for Sustainable Land Imaging – Tech.
  - MWIR T2SL FPA for CubeSat Hyperspectral Imaging
    - CubeSat Infrared Atmospheric Sounder (CIRAS) / Pyro-atmosphere InfraRed Sounder (PIRS)
  - LWIR Hyperspectral Thermal Emission Spectrometer (HyTES)
  - Multiband LWIR imager for studying planetary volcanism
  - Integrated photonics for IR hyperspectral sensing
  - Hyperspectral Thermal Imager (HyTI)
    - 6U SmallSat (2U LWIR instrument). Launched to LEO in 3/2024
  - Compact fire infrared radiance spectral tracker (c-FIRST)
    - 8U SmallSat fire instrument. Prototype scheduled for airborne test soon

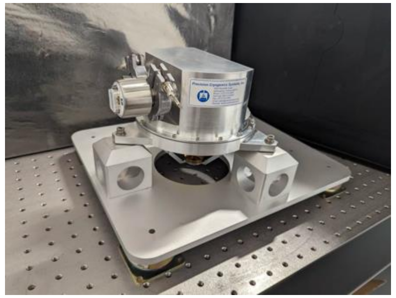


SLI-T

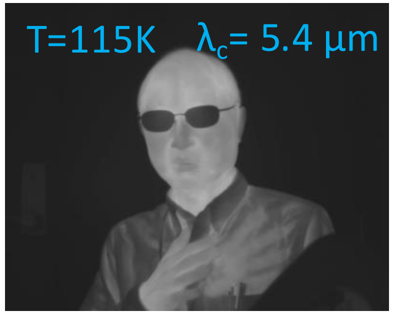


HyTI

6U HyTI SmallSat



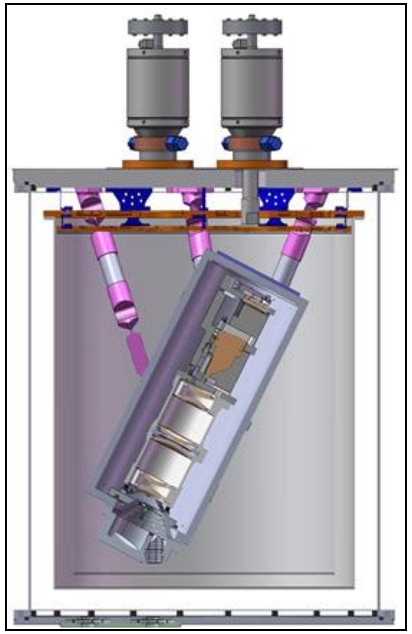
C-FIRST fire instrument



CIRAS/PIRS

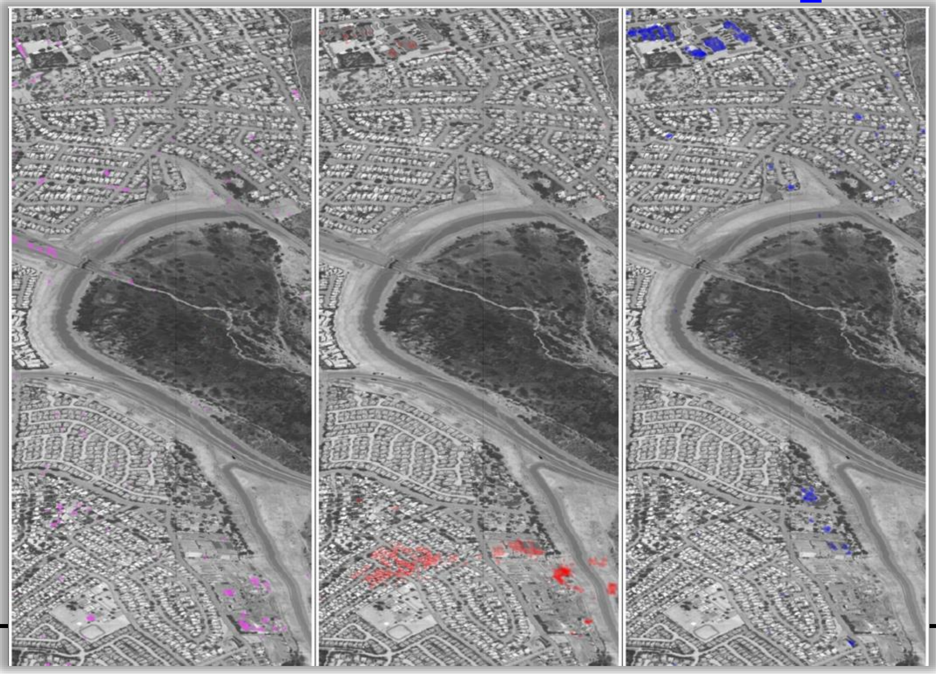
Hyperspectral Thermal Emission Spectrometer (HyTES)

- Airborne hyperspectral imaging spectrometer (NASA Earth Science)
  - 256 spectral channels between 7.5 and 12 µm
  - First flown in 2012, originally with LWIR QWIP FPA
  - Flying with LWIR InAs/InAsSb T2SL FPA upgrade since 2021
  - Both QWIP & T2SL FPAs exhibit **superior temporal stability**;
    no in-flight recalibration over flight duration of several hours



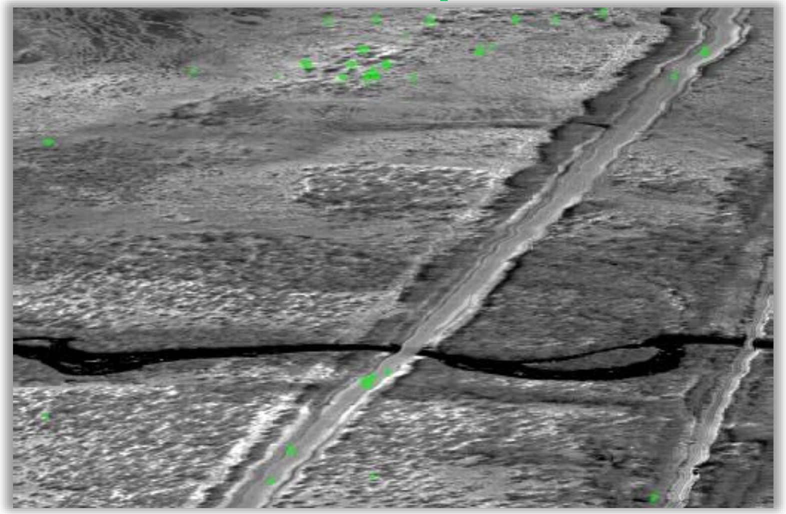
https://hytes.jpl.nasa.gov/

H_2S **NH_3** **SO_2**



2021-05-25, Los Angeles, California

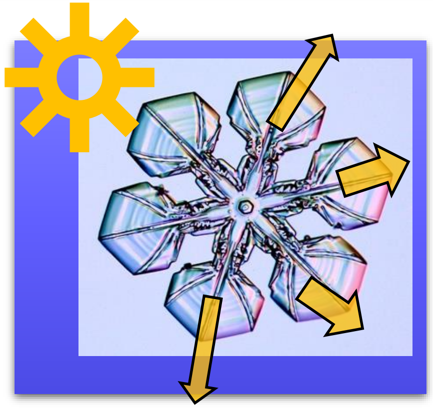
CH_4



2021-08-27, Kiruna, Sweden

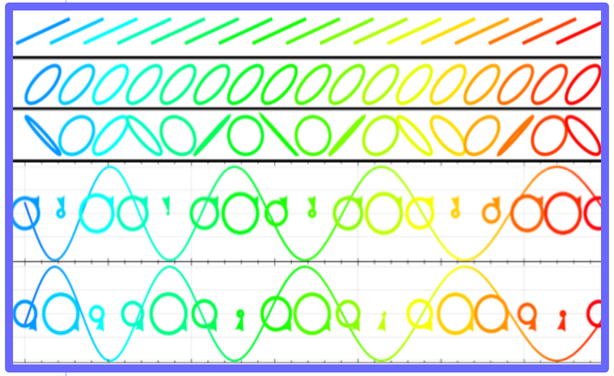
CHIRP Summary

Science Rationale



Thermal Radiation
In Earth's Atmosphere

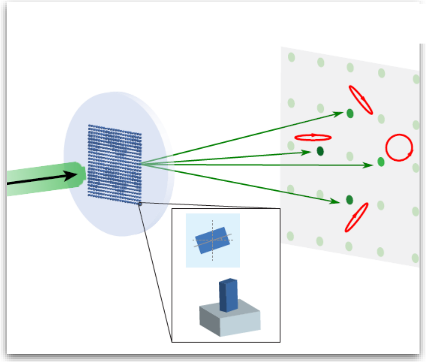
Channeled Polarimetry



IRCSP Observations prototype, IIP-16

Instrument Concept

Polarization Grating



Expected Performance Benefits

HOT BIRD Detector

Advances in
IR Detector
Technology

Sensitivity Studies → **System Requirements** → **Integration & Testing**

Selected IR Detector Publications

- MWIR InAs/InAsSb T2SLS nBn FPA has been highly successful
  - *Appl. Phys. Lett.* **113**, 021101 (2018); *IEEE Photonics Journal* **10**(6), 6804106 (2018)
- (V)LWIR InAs/InAsSb T2SLS detector challenges
  - *J. Electron. Mater*. **49**, 6936–6945 (2020)
- P-type (V)LWIR InAs/InAsSb T2SLS CBIRD detectors / FPAs for QE enhancement
  - *Appl. Phys. Lett.* **118**, 133503 (2021); *J. Electron. Mater*. **51**, 4666–4674 (2022)
- nBn detector with monolithically integrated microlens / metalens
  - *Appl. Phys. Lett.* **112**, 041105 (2018); *Appl. Phys. Lett*. **121**, 181109 (2022)
- Influence of proton radiation on the minority carrier lifetime in MWIR InAs/InAsSb T2SLS
  - *Appl. Phys. Lett.* **108**, 263504 (2016)
- MWIR InAs/InAsSb nBn detector with very low dark current density
  - *Appl. Phys. Lett.* **114**, 161103 (2019)
- Diffusion length & mobility in MWIR InAs/InAsSb T2SLS detector
  - *Appl. Phys. Lett.* **117**, 231103 (2020)
- LWIR T2SLS FPA for NASA Earth Science sustainable land imaging
  - *Infrared Phys. & Technol.* **123**, 104133 (2022)
- Compact fire infrared radiance spectral tracker (c-FIRST)
  - *SPIE Proceedings* **12264**, Sensors, Systems, and Next-Generation Satellites XXVI; 122640E (2022)

Selected Metasurface Publications

- Light propagation with phase discontinuities: generalized laws of reflection and refraction
  - science 334 (6054), 333-337
- Matrix Fourier optics enables a compact full-Stokes polarization camera
  - *Science* 365(6448), eaax1839 (2019)
- Metasurface optics for on-demand polarization transformations along the optical path
  - *Nat. Photonics* 15(4), 287–296 (2021)
- Polarization state generation and measurement with a single metasurface
  - *Opt. Express* 26(17), 21455–21478 (2018)
- Jones matrix holography with metasurfaces
  - *Sci. Adv.* 7(33), eabg7488 (2021)
- Polarization in diffractive optics and metasurfaces
  - *Adv. Opt. Photonics* 13(4), 836–970 (2022)
- Structuring total angular momentum of light along the propagation direction with polarization-controlled meta-optics
  - *Nat. Commun.* 12(1), 6249 (2021)
- Imaging polarimetry through metasurface polarization gratings
  - *Opt. Express* 30(6), 9389–9412 (2022)
- Metasurface-enabled single-shot and complete Mueller matrix imaging
  - *Nat. Photonics* 1–9 (2024)
- Evaluation and characterization of imaging polarimetry through metasurface polarization gratings
  - *Appl. Opt.* 62(7), 1704–1722 (2023)
- Generalized polarization transformations with metasurfaces
  - *Opt. Express* 29(24), 39065–39078 (2021)
- Polarization-controlled holography using dielectric metasurfaces
  - *Proc. SPIE* 11710, 1171006 (2021)

Selected IRCSP Publications

- First results from an uncooled LWIR polarimeter for cubesat deployment
  - *Opt. Eng.* 59(7), 075103 (2020)
- Compact LWIR polarimeter for cirrus ice properties
  - *Proc. SPIE* 10655, Polarization: Measurement, Analysis, and Remote Sensing XIII, 227–232 (2018)
- SWIRP: Compact submm-wave and LWIR polarimeters for cirrus ice properties
  - *Natl. Radio Sci. Meet. (NRSM)* (2019)
- Near space demonstration of a compact LWIR spectro-polarimeter for ice cloud measurements
  - *Proc. SPIE* 12112, Polarization: Measurement, Analysis, and Remote Sensing XV, 143–159
- Linear Stokes measurement of thermal targets using compact LWIR spectropolarimeter
  - *Proc. SPIE* 11412, Polarization: Measurement, Analysis, and Remote Sensing XIV, 91–103 (2020)
- Stokes resolved differential temperature: an important metric of polarimetric precision in the long-wave infrared
  - *Proc. SPIE* 11833, Polarization Science and Remote Sensing X, 98–110 (2021)
- SWIRP (submm-wave and long wave infrared polarimeter); a new tool for investigations of ice distribution and size in cirrus clouds
  - *IGARSS IEEE Int. Geosci. Remote Sens. Symp.* (2019)
- High-altitude demonstration of LWIR polarimetry using uncooled microbolometers
  - *J. Quant. Spectrosc. Radiat. Transf.* 315, 108872 (2024)
- SWIRP (Submm-Wave and Long Wave InfraRed Polarimeter); Development and Characterization of a Sub-Mm Polarimeter for Ice Cloud Investigations
  - *Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment* (2020)
- Demonstration of LWIR channeled spectro-polarimeter
  - *Proc. SPIE* 11132, Polarization Science and Remote Sensing IX, 1113207 (2019)
- LWIR Spectro-Polarimeter for Cloud-Induced Polarization Measurements
  - *99th Am. Meteorol. Soc. Annu. Meet.* (2019)

Selected Atmospheric LWIR Publications

- Infrared polarimetry for remote sensing
  - *The Univ. of Arizona*, PhD Dissertation (2022)
- Spatial distribution of cloud droplet size properties from Airborne Hyper-Angular Rainbow Polarimeter (AirHARP) measurements
  - *Atmos. Meas. Tech.* 13(4), 1777–1796 (2020)
- The HARP hyperangular imaging polarimeter and the need for small satellite payloads with high science payoff for earth science remote sensing
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