Thanks for coming to Kira Shanks' Defense!

Begins at 11 AM PST/2 PM EST

There may be a brief closed discussion with the committee on the hour, the presentation should start no later than 11:10

Once the presentation begins, please keep yourself ***muted*** and your ***video off***. Audience questions are encouraged at the conclusion of the presentation!

SCAN ME

While you wait, scan for a "*Guide to Kira's Defense*", information about the Polarization Lab, and the Wyant College of Optical Science

Infrared Polarimetry for Remote Sensing

Kira Ann Shanks

April 22, 2022 | Tucson, AZ

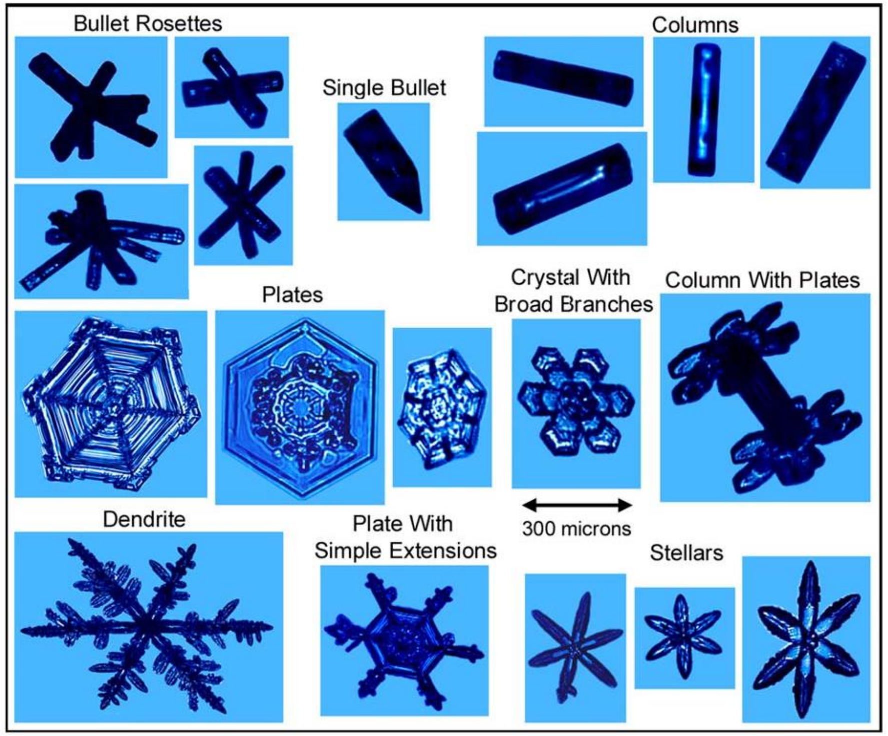
Land Acknowledgement

The work contained in this dissertation was conducted on the land and territories of Indigenous peoples. Today, Arizona is home to 22 federally recognized tribes, and an unknown number of tribes which remain federally unrecognized. Tucson and the University of Arizona exist on the land of the Tohono O'odham and the Pascua Yaqui. In addition, field work in New Mexico took place on the land of the Comanche, Kiowa, and Mescalero Apache.

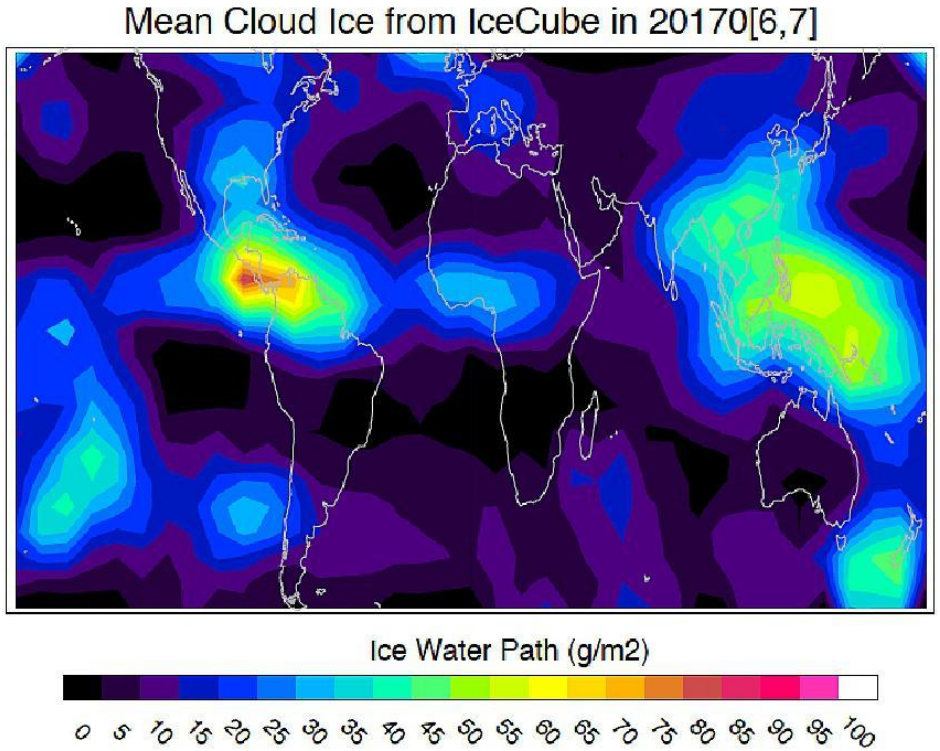
As a person whose work has benefited both from the University of Arizona, a Land-Grant Institution, and field work in the Southwest, I recognize that these efforts were done on land which was stolen from Indigenous peoples who have cared for and inhabited these spaces in perpetuity. It is my hope and must be our sincere and collective mission to prioritize reflection and action on this history of displacement and wrongdoing, and the enduring legacy of Indigenous peoples – ***past, present, and future.***

Credits: NASA/JPL-Caltech

Clouds remain a major source of uncertainty in short- and long-term climate models



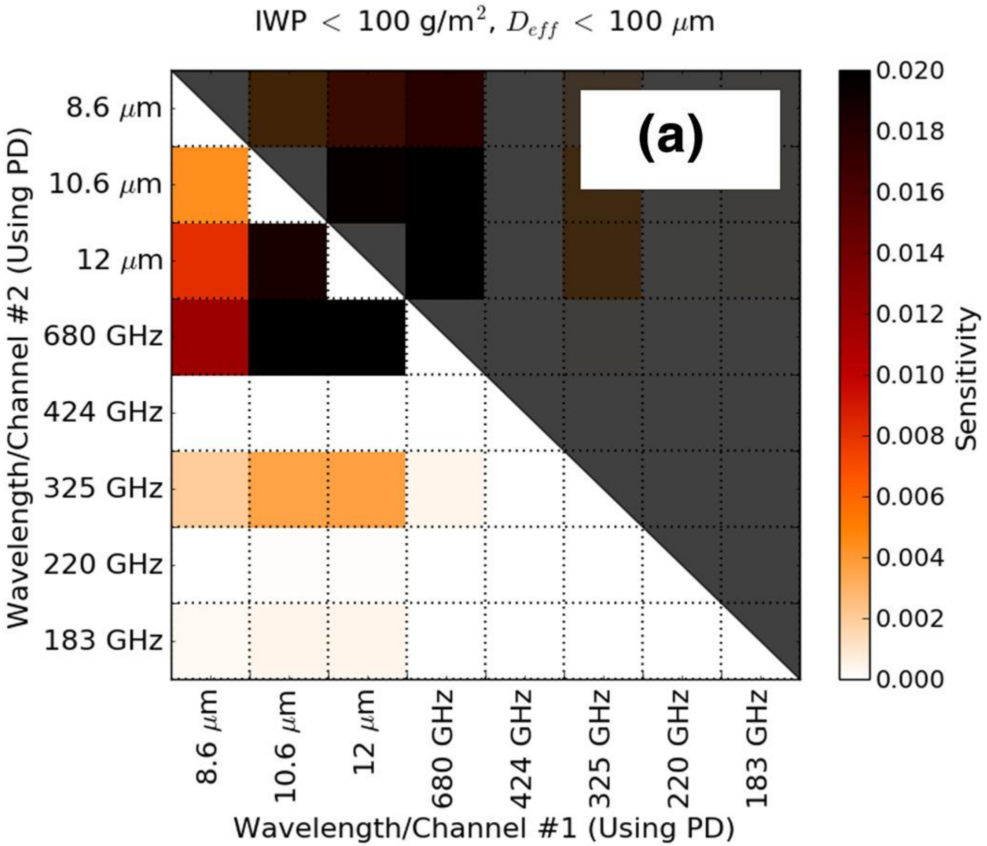
Cloud Ice imaged by NASA's Cloud Particle Imager (CPI)



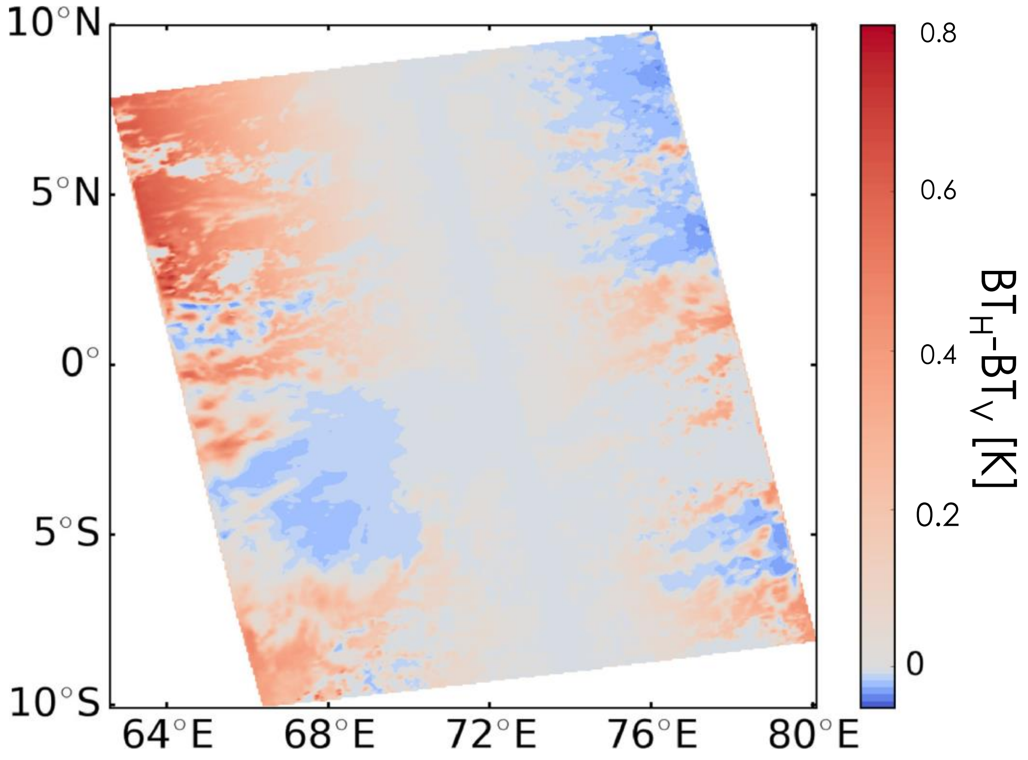
IceCube Cloud Ice Map (883 GHz)

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

LWIR Sensitivity



Simulated Polarization



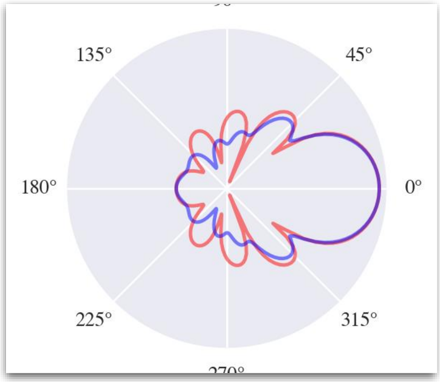
For MODIS Band 31 Image (10.78~11.28 μm)

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): e2019JD031422.

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.

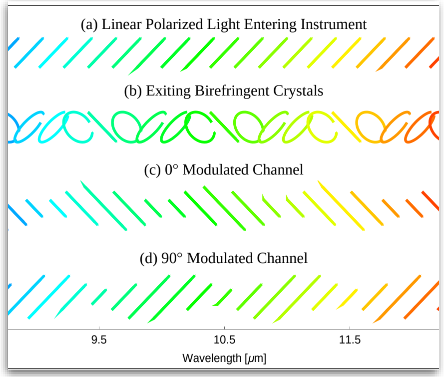
Outline

Phenomenology



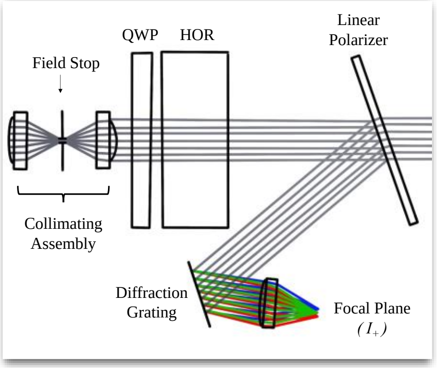
Thermal Radiation
Polarization
Scattering
Performance Metrics

Channeled Polarimetry



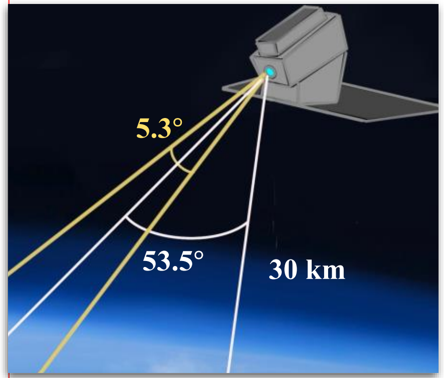
Instrument Concept
Sampling Theory
Optimization

Optical Design



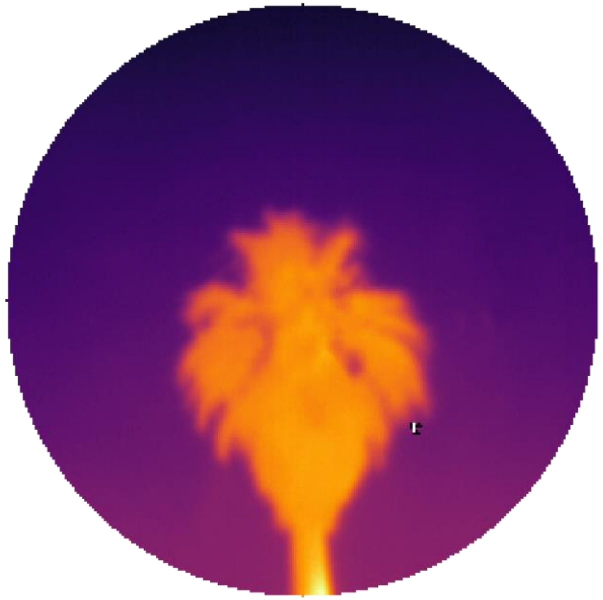
Engineering
Assembly
Characterization

Field Measurements



High Altitude Balloon
Cloud top polarization

Theory **Design and Assembly** **Demonstration**



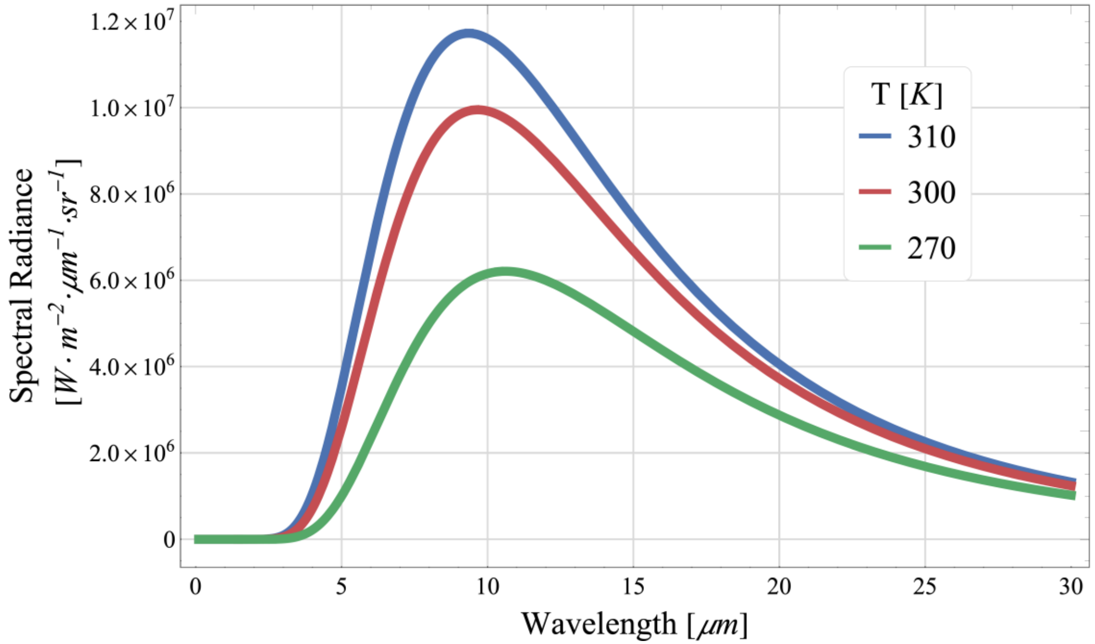
Infrared Polarimetry & Phenomenology

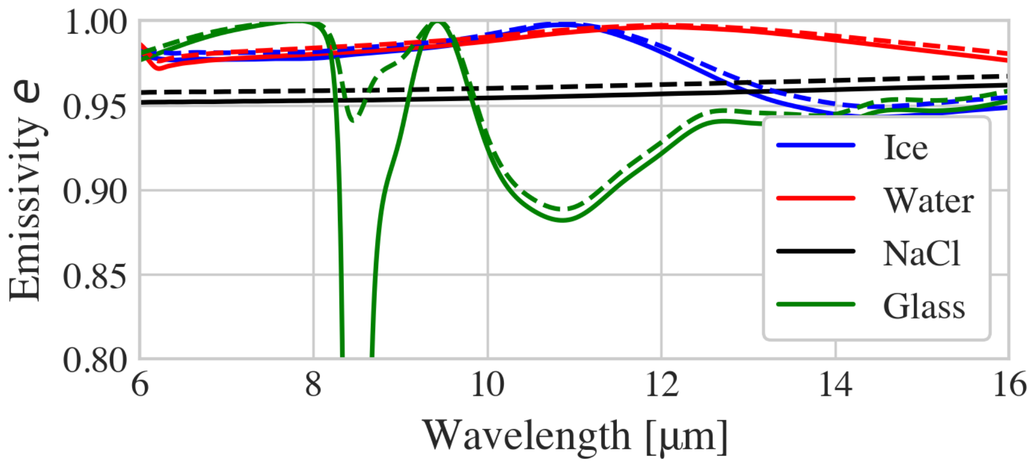
Thermal Radiation

Planck's Radiation Function [W m^{-2} str^{-1}]

$$L(T) = \int_{\lambda_1}^{\lambda_2} L_\lambda(\lambda, T) d\lambda = \int_{\lambda_1}^{\lambda_2} \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda k_b T) - 1} d\lambda$$

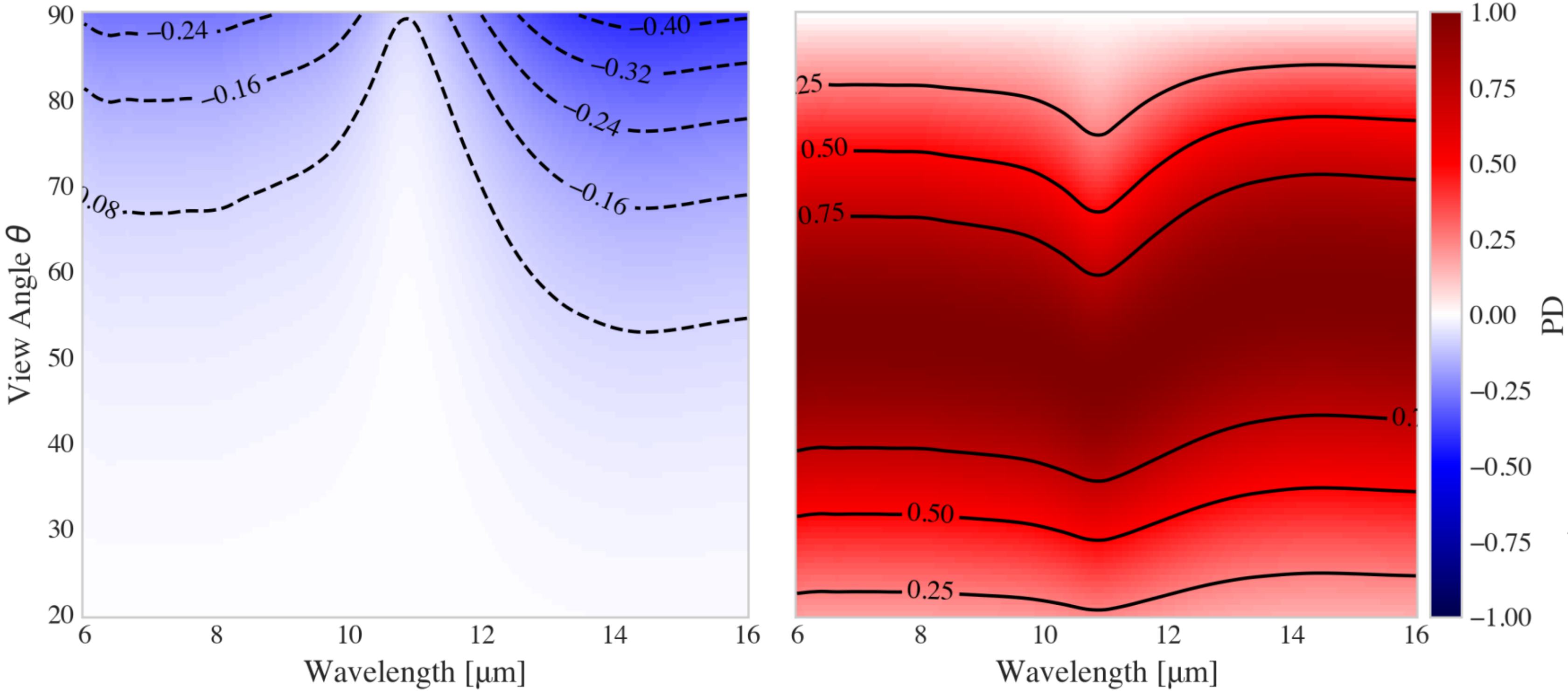
- Physical objects are "graybody" radiators with emissivity e < 1
- Conservation of energy at thermal equilibrium
  - absorptivity (a) = emissivity (e)
  - Reflectivity (R) + emissivity (e) = 1



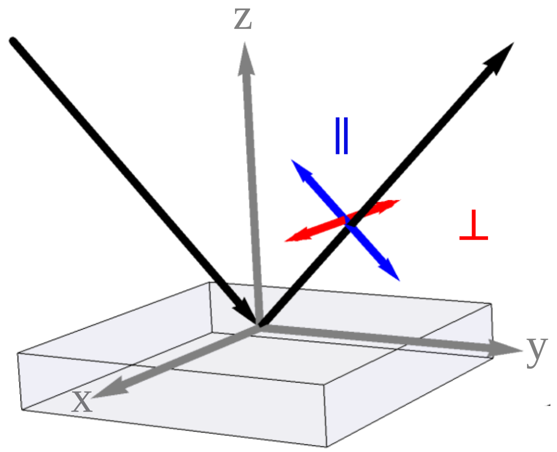


Polarization from Emission and Reflection

Optically Thick Ice Sheet



Emission **Reflection**

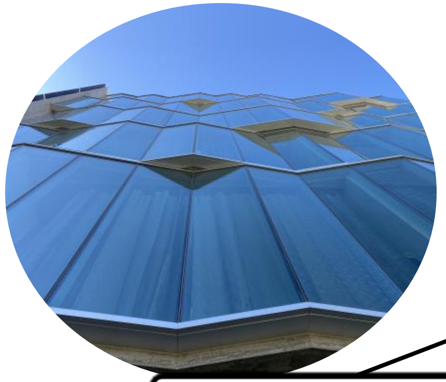


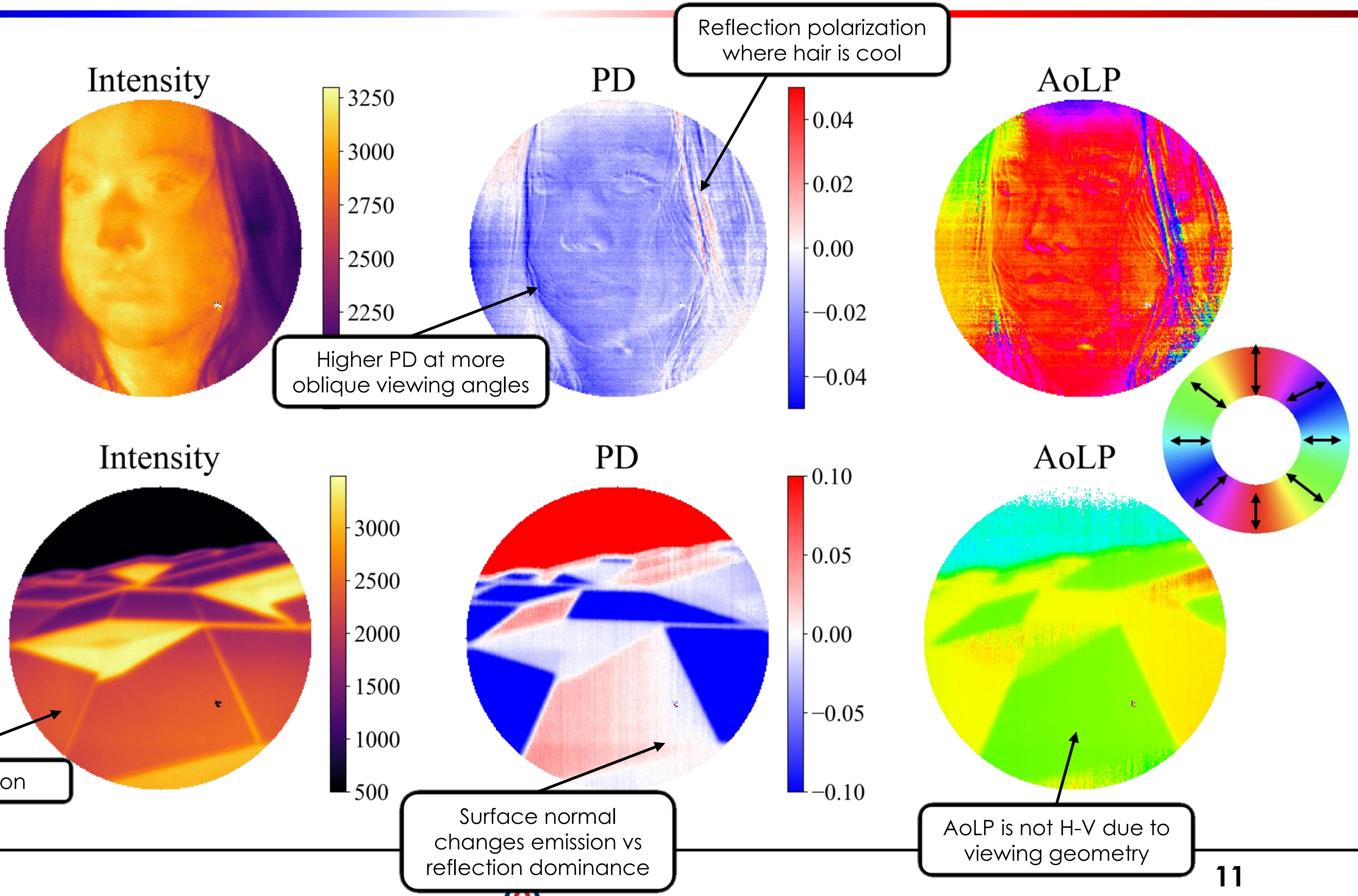
$$PD(\theta,\lambda) = \frac{|E_{\parallel}(\theta,\lambda)|^2 - |E_{\perp}(\theta,\lambda)|^2}{|E_{\parallel}(\theta,\lambda)|^2 + |E_{\perp}(\theta,\lambda)|^2}$$

θ = *Angle of Emission or Reflection*

Human Face (indoors)

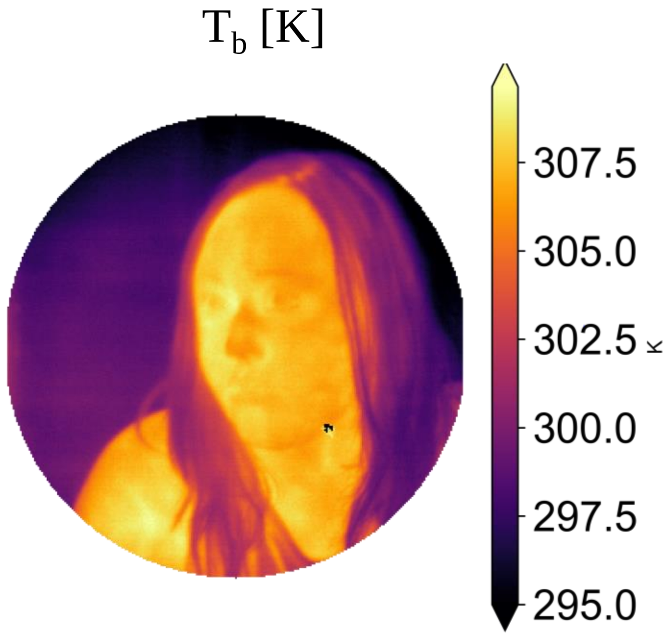
Looking up at the Meinel Optical Science Building

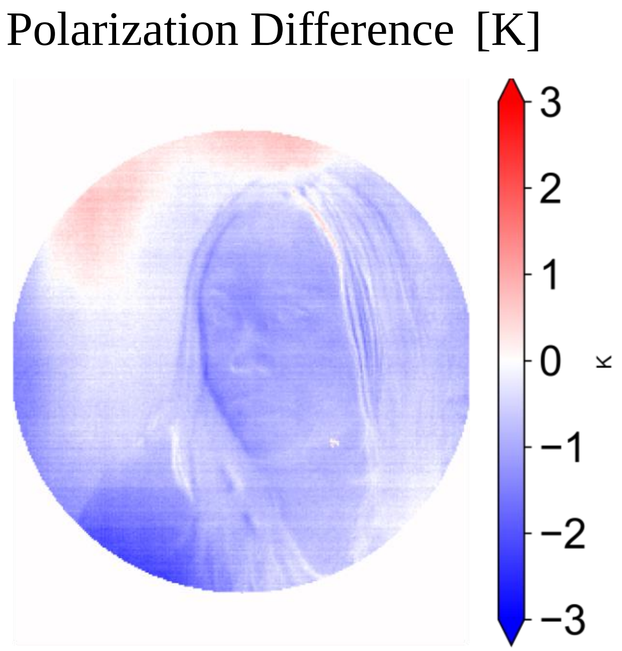




Performance Metrics

Radiance and brightness temperature have a non-linear relationship in the LWIR





Need a performance metric that is dependent on DoLP and scene temperature

Noise Equivalent Differential Temperature (NEDT)

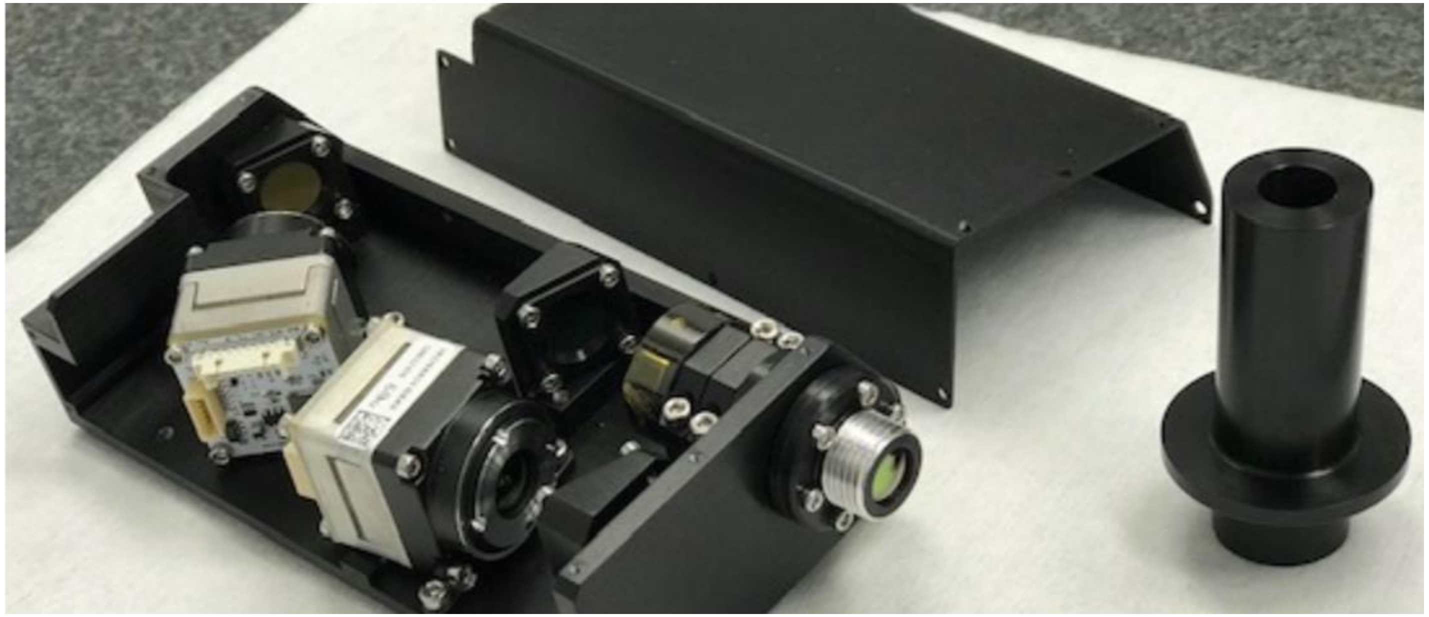
$$\mathrm{NEDT}(T_b) = \frac{\sigma_R(T_b)\cdot\epsilon}{\overline{R}(T_b+\epsilon)-\overline{R}(T_b-\epsilon)}$$

Stokes Resolvable Differential Temperature (SRDT)

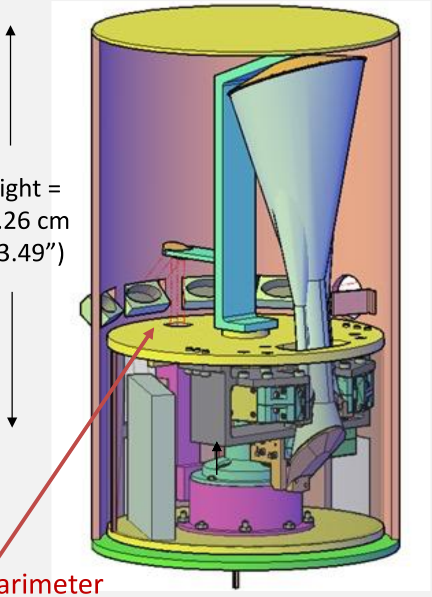
New!

$$\mathrm{SRDT}_{[Q_{\phi=0^\circ}]}(\rho, T_b) = \frac{\sigma_Q(\rho, T_b)\cdot\epsilon}{\overline{Q}(\rho, T_b+\epsilon)-\overline{Q}(\rho, T_b-\epsilon)}$$

Shanks, Kira A. Hart, et al. "Stokes resolved differential temperature: an important metric of polarimetric precision in the long-wave infrared." *Polarization Science and Remote Sensing X*. Vol. 11833. International Society for Optics and Photonics, 2021.



Optical Design of an Infrared Channeled Spectro Polarimeter



IRCSP Flow Down Requirements

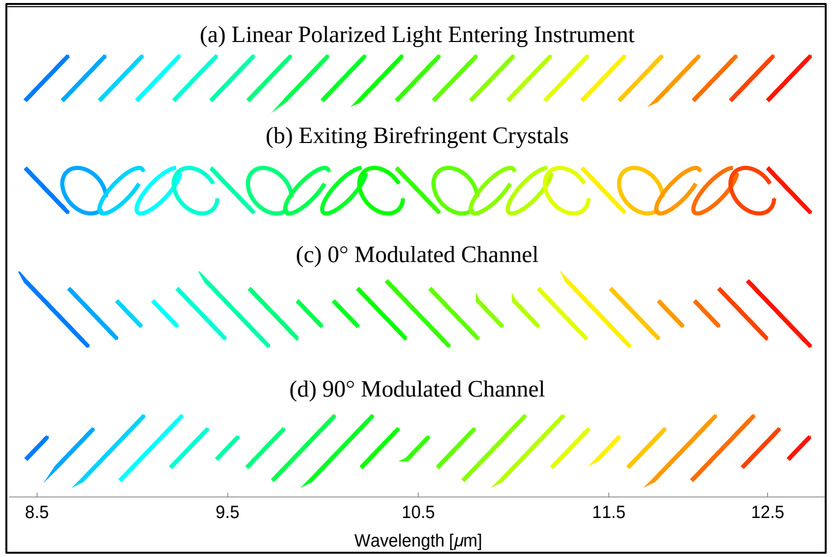
Size	11.89 x 4.8 x 3.5 cm
Mass	0.5 kg
Power	1 W
Spectral Response	8 – 12 micron
Polarimetric Precision	1 K
NEDT	1 K

D. Wu *et al*., "Swirp (Submm-Wave and Long Wave Infrared Polarimeter); A New Tool for Investigations of Ice Distribution and Size in Cyrrus 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-POLARIMETR

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

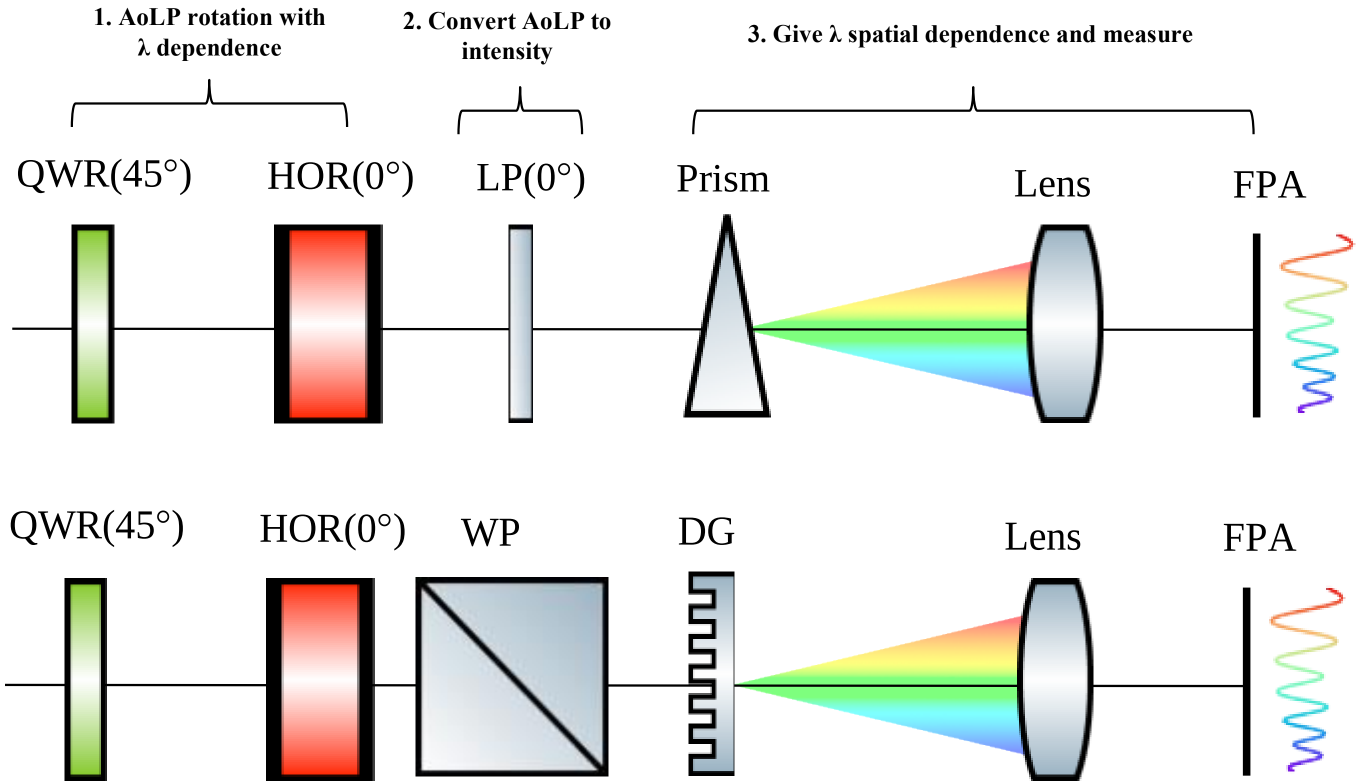
Channeled Spectro-Polarimetry



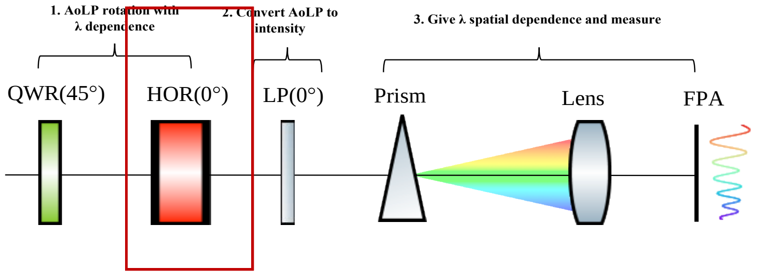
DoLP

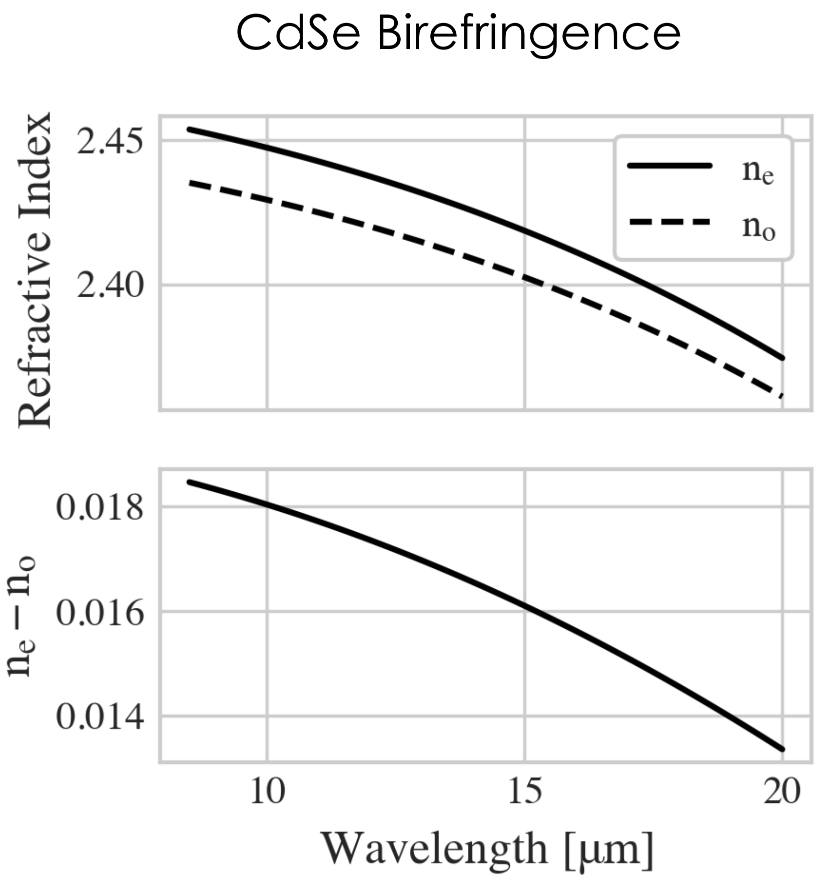
$$I_{\pm}(\lambda,\rho,\phi) = I(\lambda)\left[1 \pm \frac{\rho}{2}\left(\sin(\delta(\lambda) - 2\phi)\right)\right]$$

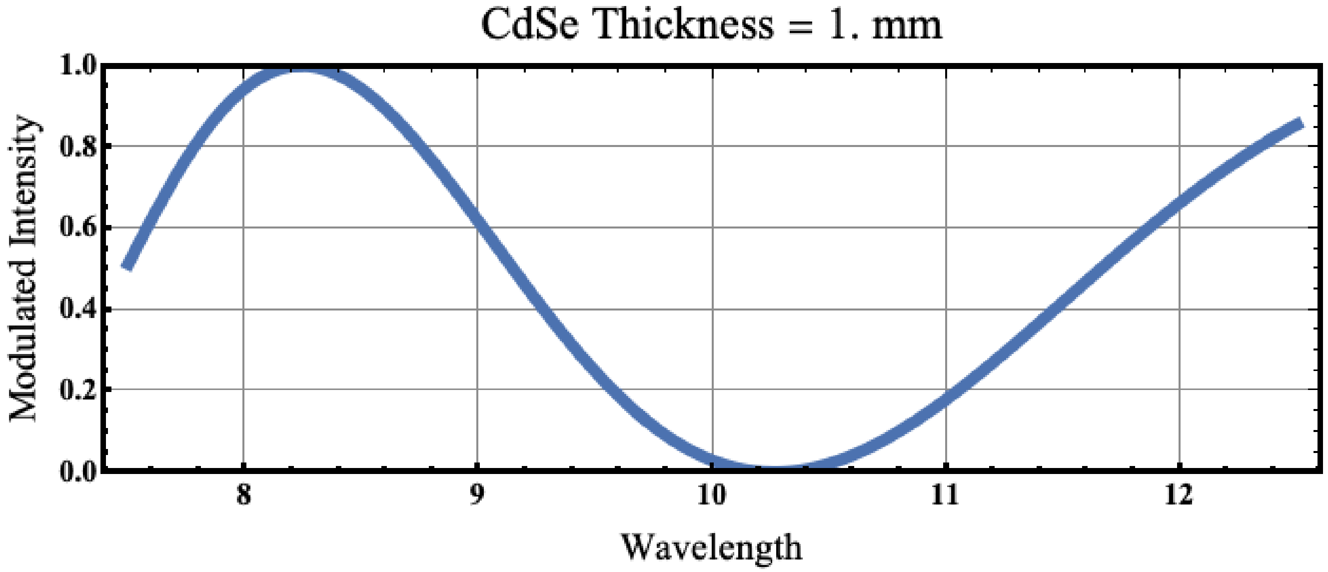
Carrier Frequency AoLP



High Order Retarder





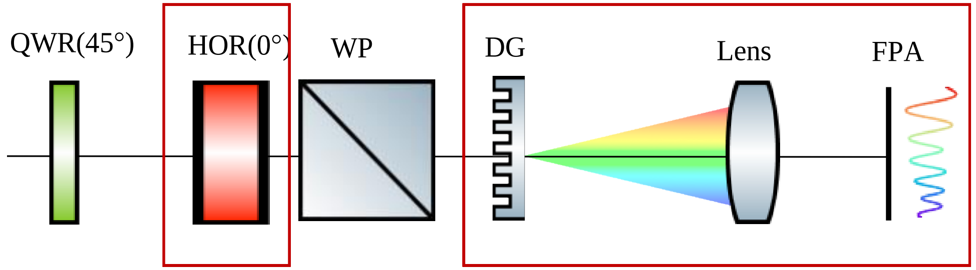


Frequency of modulation increases with crystal thickness

$$\delta(\lambda) = 2\pi \frac{(n_o(\lambda) - n_e(\lambda)) \cdot t_{HOR}}{\lambda}$$

Hart, Kira A., Russell A. Chipman, and Dong L. Wu. "Compact LWIR polarimeter for cirrus ice properties." *Polarization: Measurement, Analysis, and Remote Sensing XIII*. Vol. 10655. International Society for Optics and Photonics, 2018.

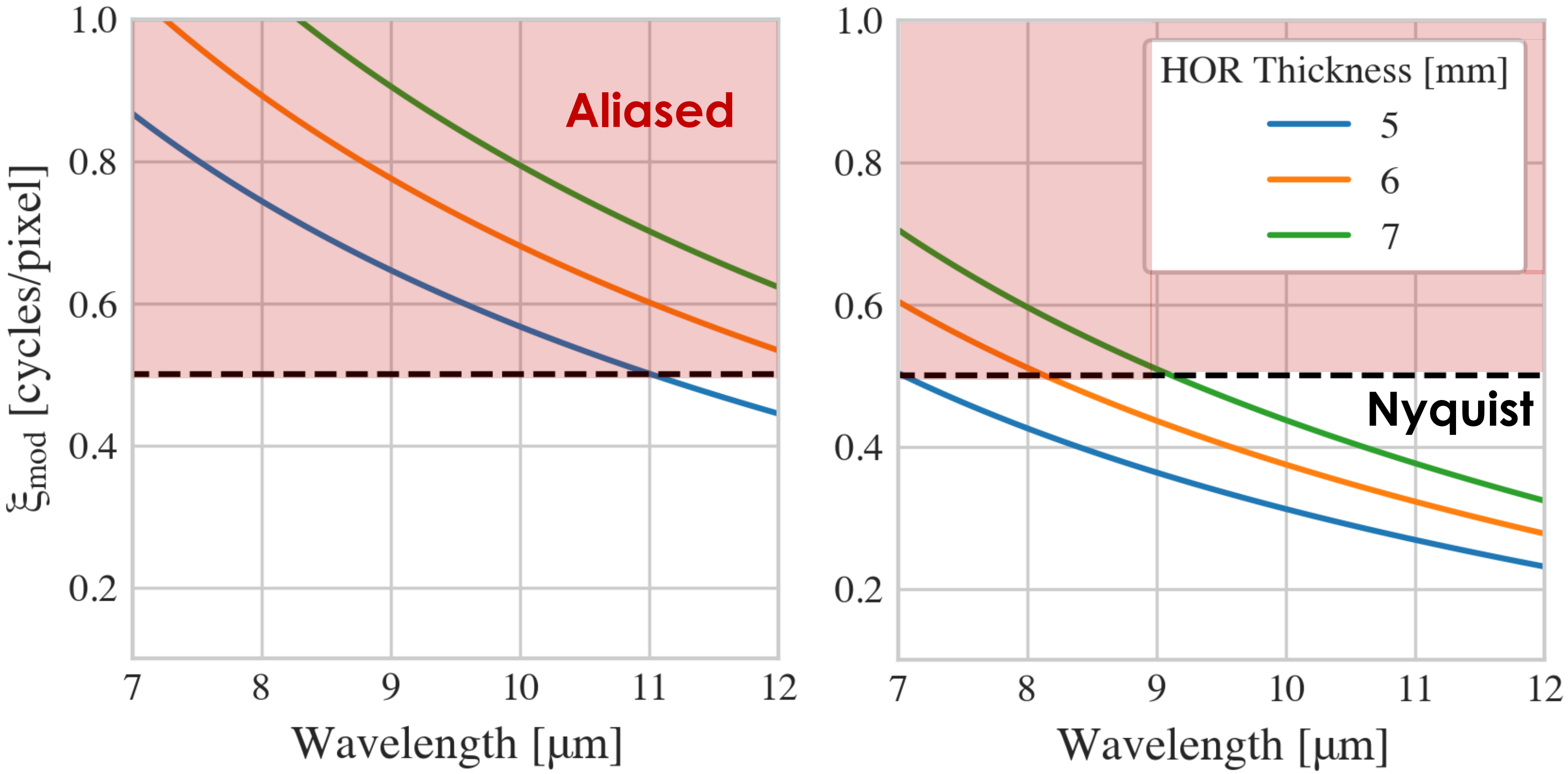
Spatial Frequency at Image Plane



Modulated signal must be sampled with a spatial frequency sufficient to resolve the carrier frequency

Tuning parameters

- HOR thickness
- Spectral dispersion
  - grating density
  - prism wedge angle
- Lens focal length
- Pixel pitch



Grating density = 50 lp/mm = 30 lp/mm

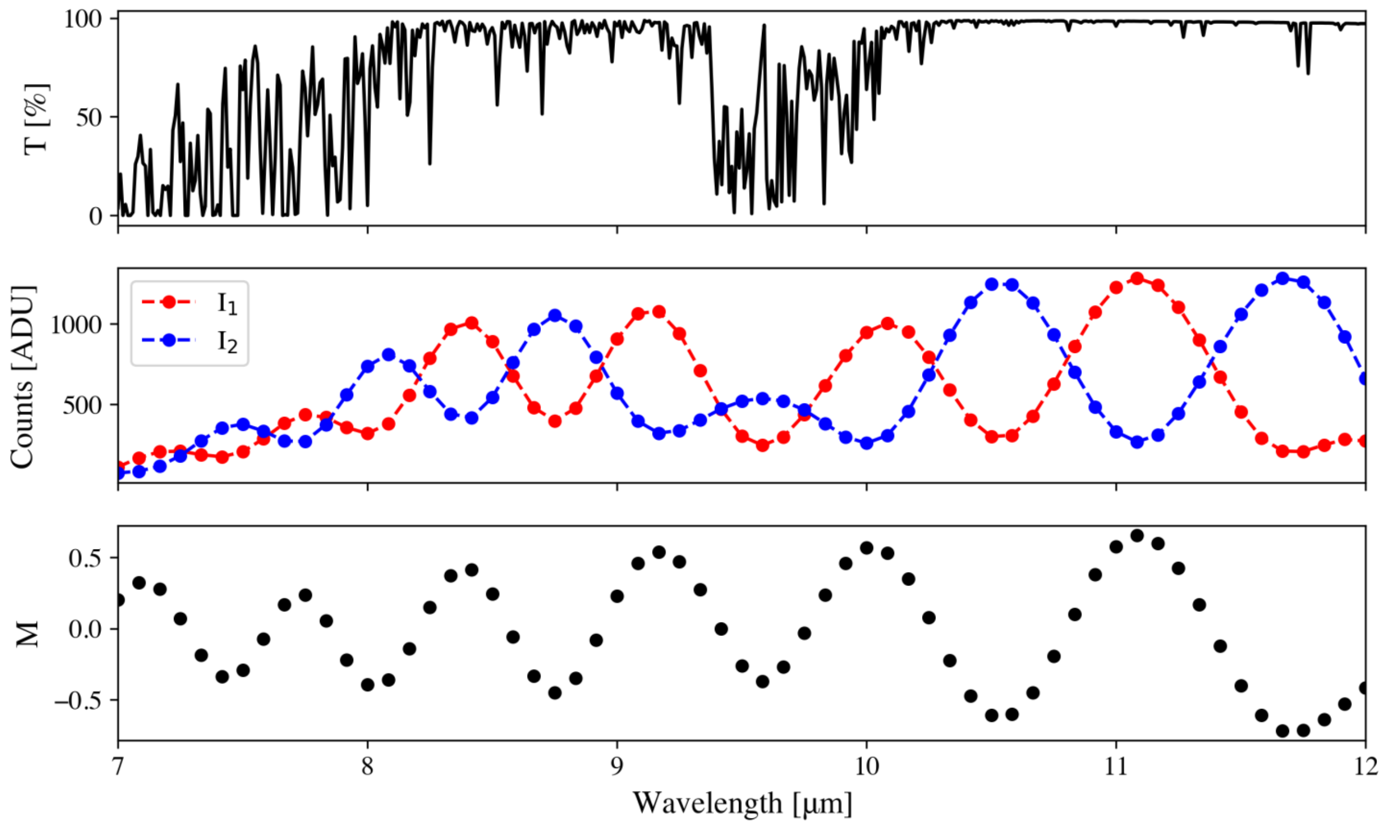
Modulation Function

Need a way to distinguish between polarization and spectral amplitude

$$M(\lambda) = \frac{I_1(\lambda) - I_2(\lambda)}{I_1(\lambda) + I_2(\lambda)} = W(\lambda)\left[\frac{Q}{I}\cos\delta(\lambda) - \frac{U}{I}\sin\delta(\lambda)\right]$$

Polarimetric Efficiency

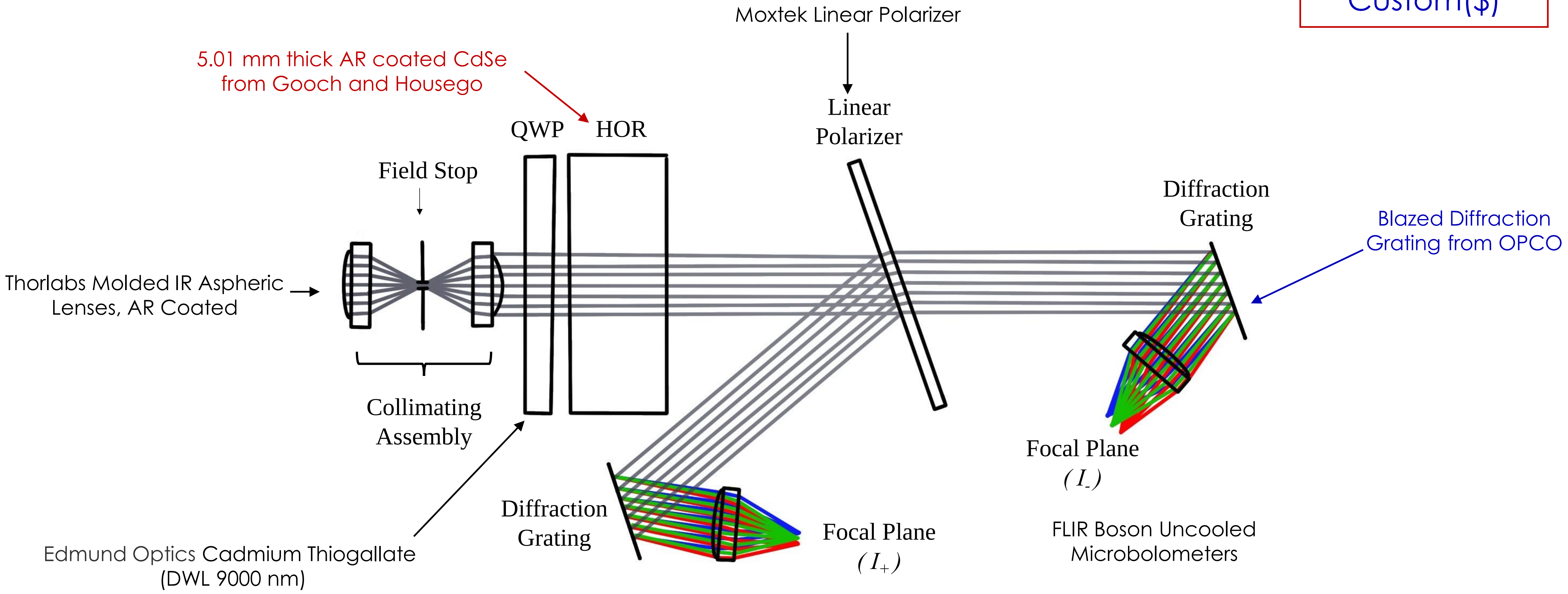
- Analogous to contrast
- Valued between [0,1]
- Result of instrumental polarization, spectral blurring



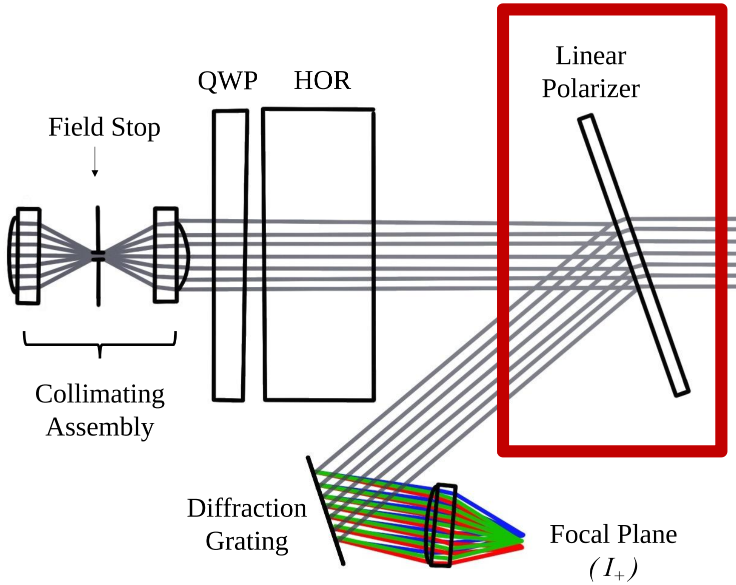
Hart, Kira A., et al. "First results from an uncooled LWIR polarimeter for cubesat deployment." *Optical Engineering* 59.7 (2020): 075103.

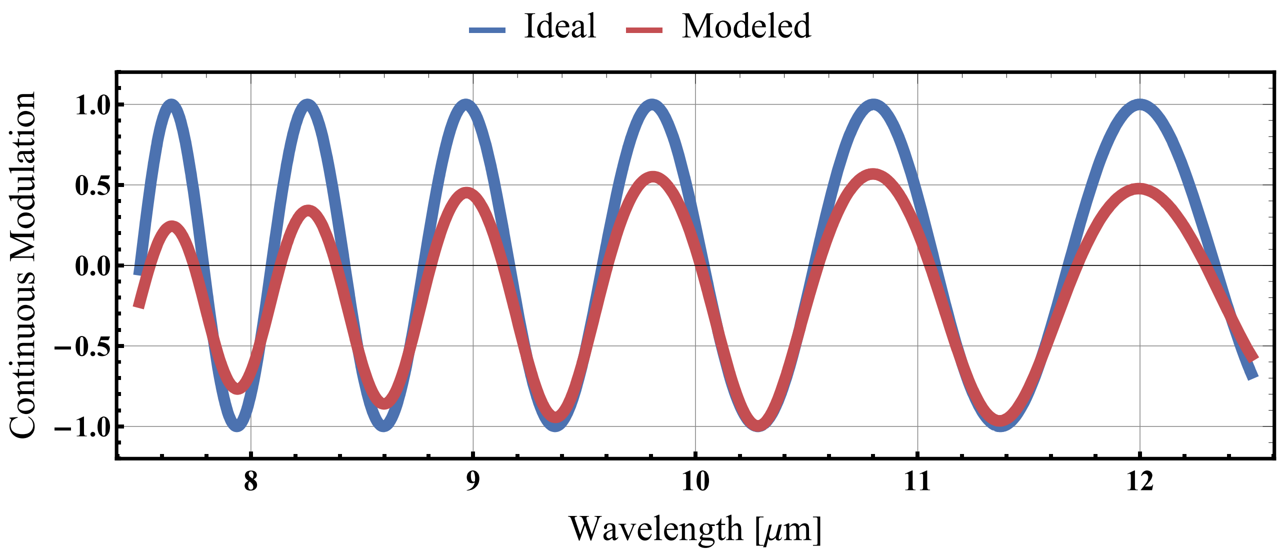
IRCSP Optical Design

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

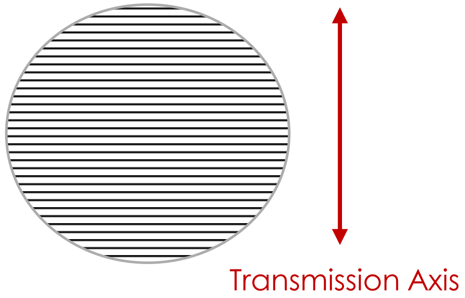


Linear Polarizer Contrast





Contrast from the linear polarizer is higher in transmission than reflection

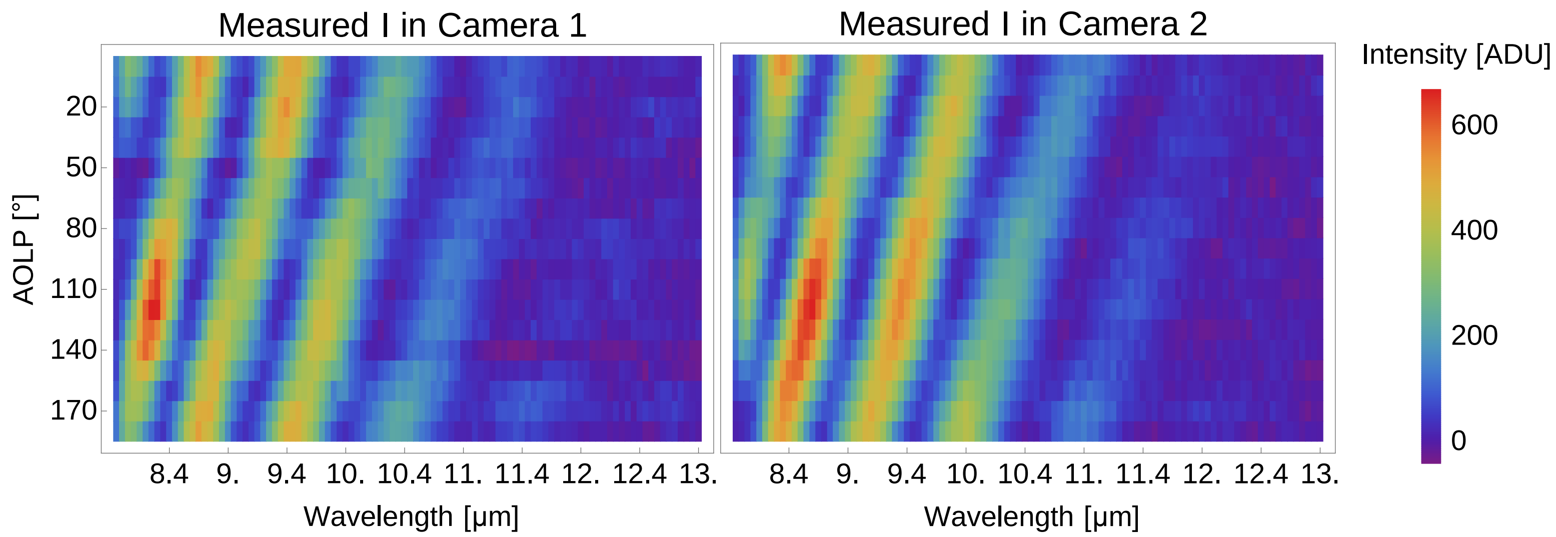


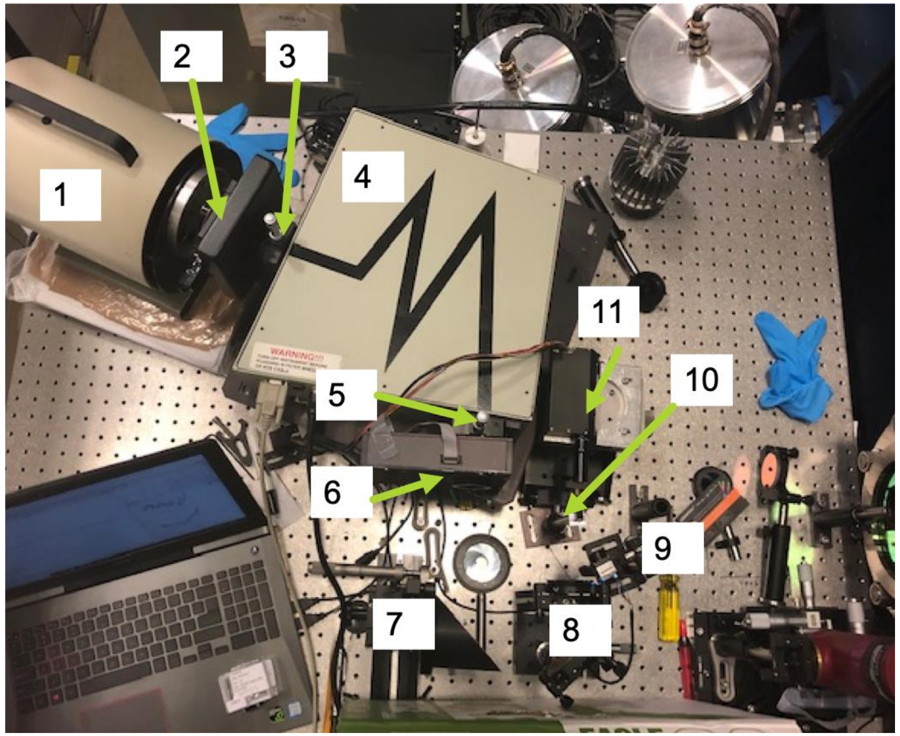
Consequence:

- Reduction in polarimetric efficiency
  Offset in Modulation function

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

Narrowband Polarized Response



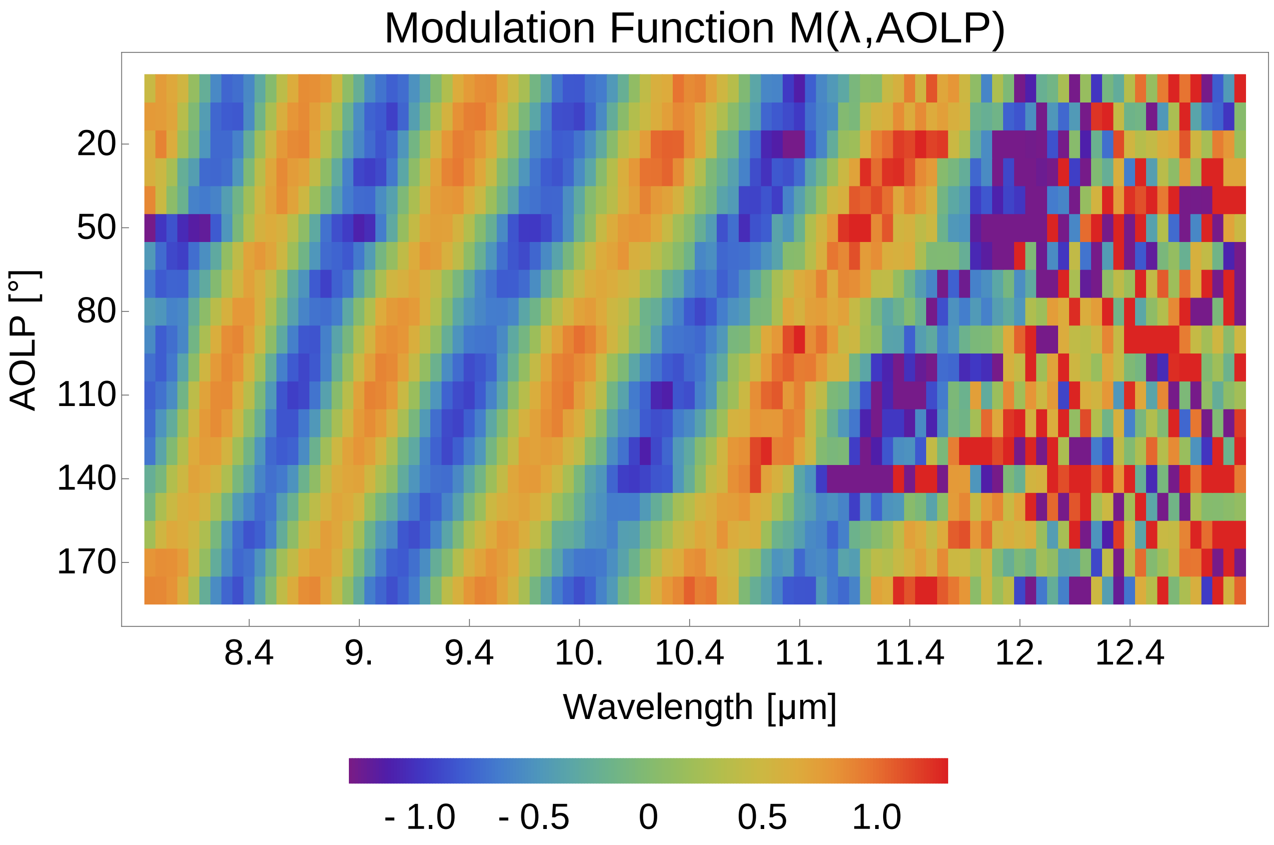


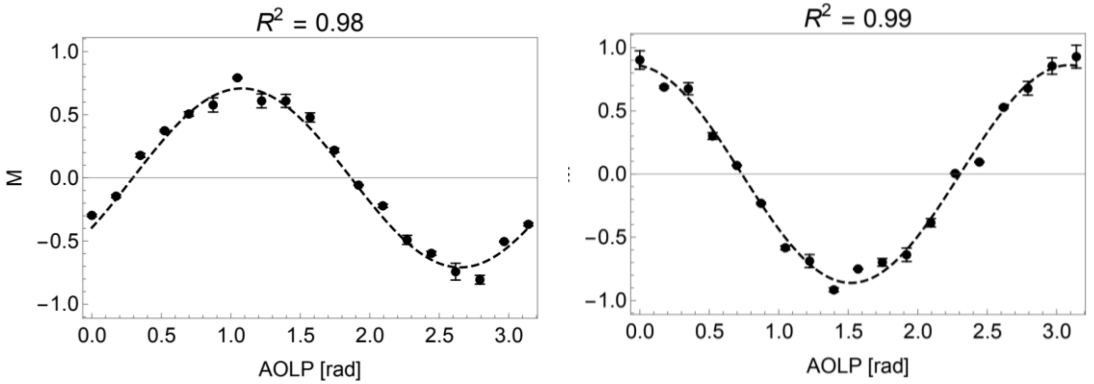
Monochromator has 90 nm spectral resolution; data is collected scanning over wavelength and AoLP

1. Black Body Source, 2. Optical Chopper, 3. Monochromator input slit, 4. Monochromator, 5. Output slit, 6. Spectral filter wheel, 7. Off-axis parabolic mirror, 8. Fold Mirror , 9. Reference detector, 10. Linear polarizer on rotating mount, and 11. IRCSP.

Narrowband Polarization Efficiency

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



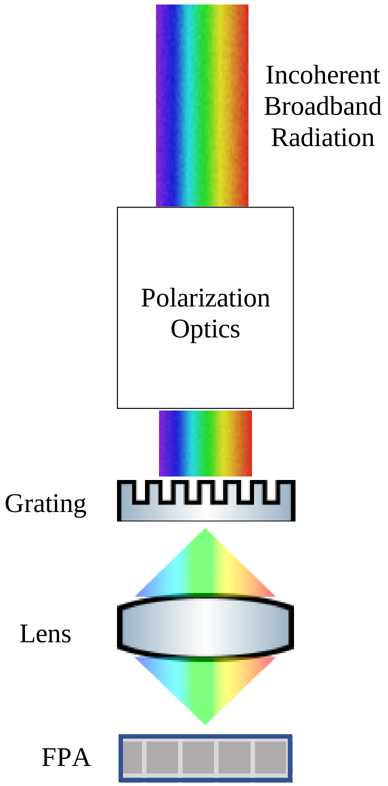


(a) $\lambda = 8.5\mu m$

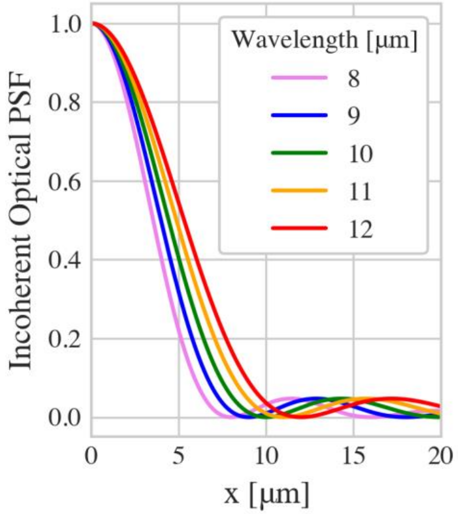
(c) $\lambda = 10.5\mu m$

In the monochromatic limit, instrument performance is well described using a Mueller Matrix Model

Spectral Blurring



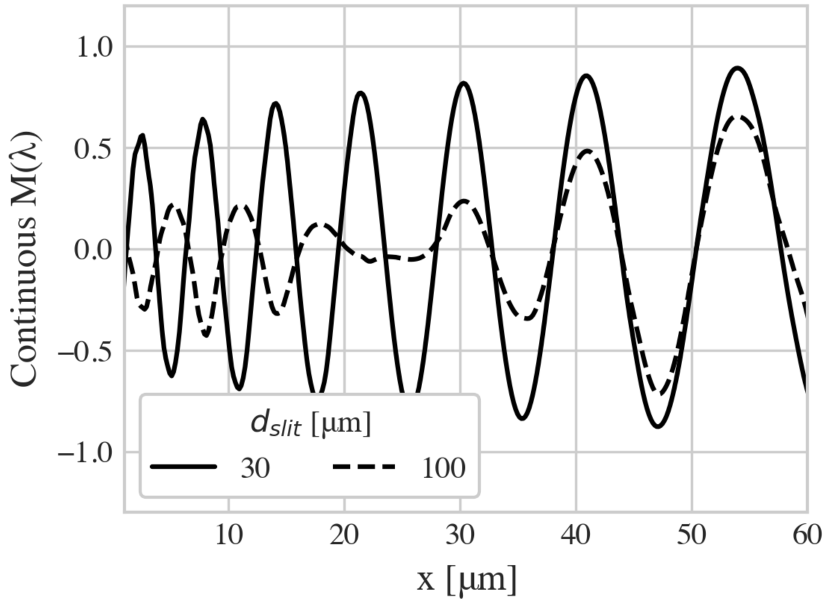
$\int_\lambda I(\lambda,\rho,\phi)\ \times$

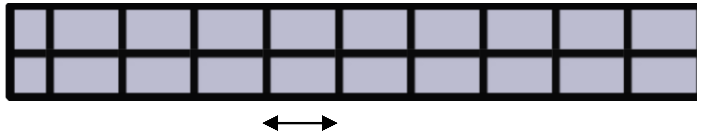


$*$

$d\lambda$ ➡

Without a sufficient continuous – discrete model, polarimetric efficiency is over estimated

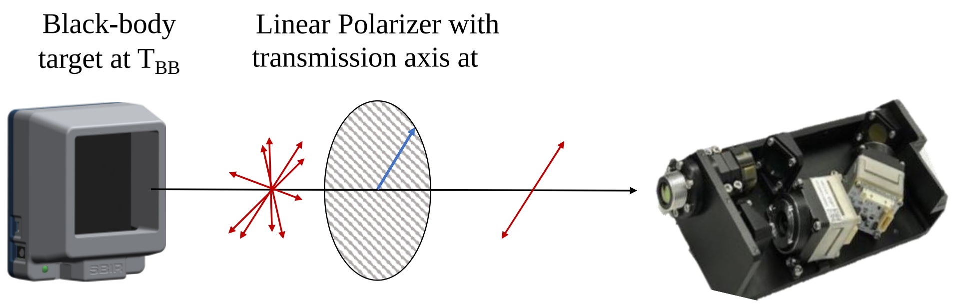


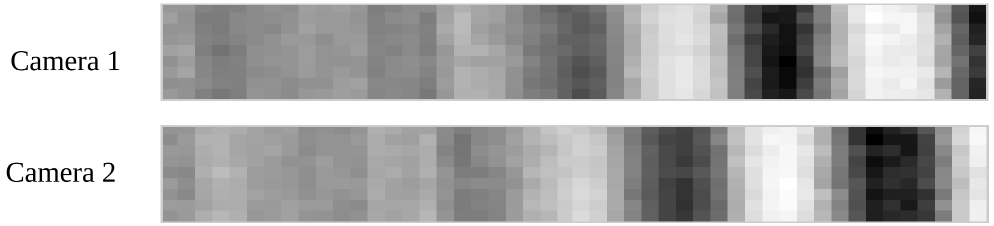


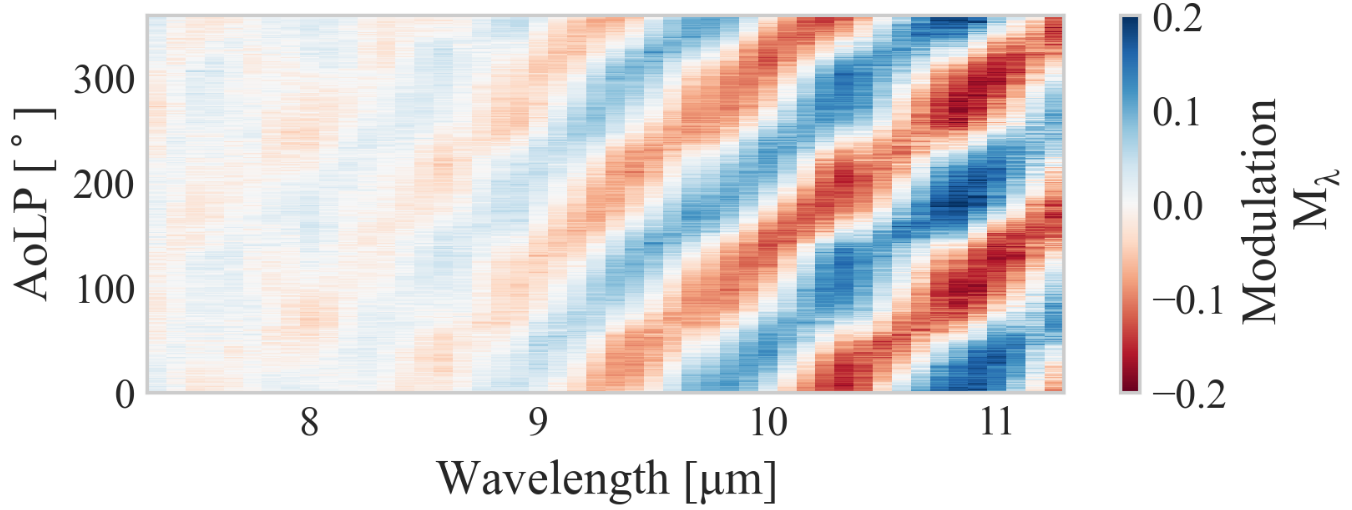
Pixel Pitch = 12 micron

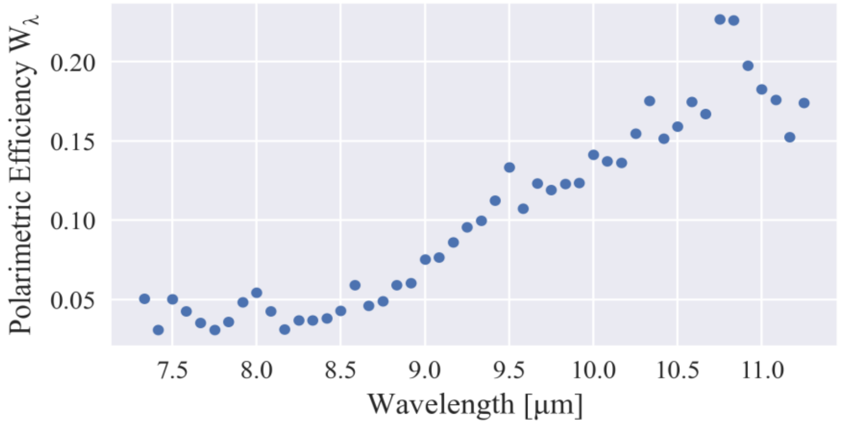
Diffracted image of field stop is sampled at the focal plane

Measured Spectral Blurring







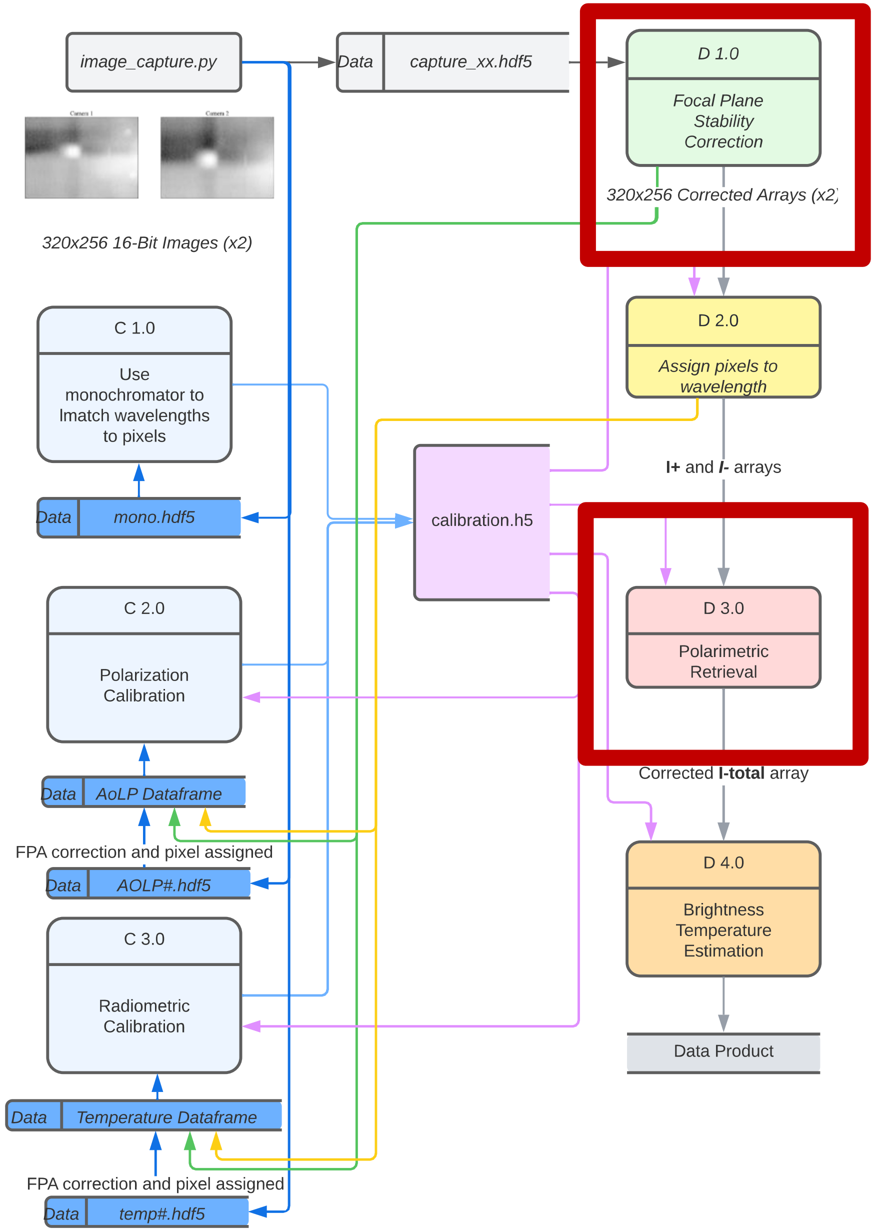


Polarimetric efficiency is reduced due to spectral blurring

Calibration and Data Reduction

- Precision calibration is required to retrieve AoLP, DoLP, and brightness temperature
- Image acquisition are both automated and controlled using Python
- Data are stored in HDF5 files and catalogued in an SQL database

https://github.com/Polarization-Lab/IRCSP/

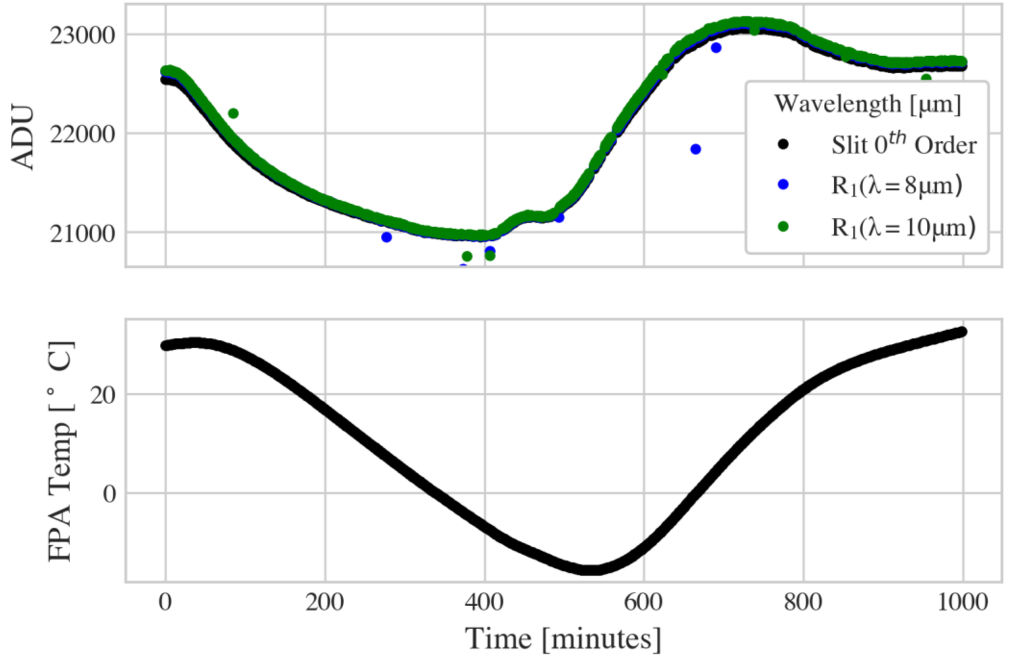


Stabilization of Uncooled Microbolometers

21 x 21 x 11 mm

Grade	NEDT	No-Lens	6.5 mm
Consumer	< 60 mK	$1,280	$1,680
Professional	< 30 mK	$1,600	$2,100
Industrial	< 40 mK	$1,920	$2,520

Model in IRCSP

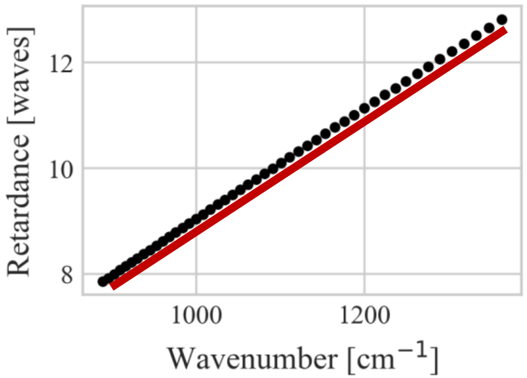


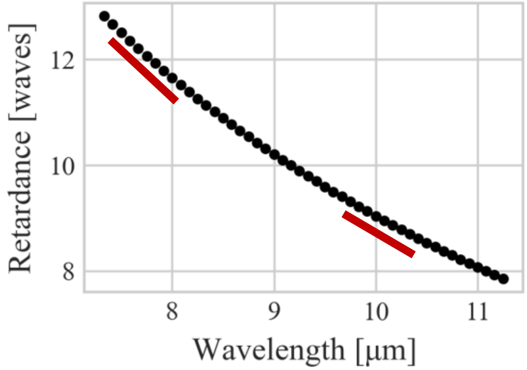
Responsivity of UMBs is highly dependent on focal plane temperature

Demodulation

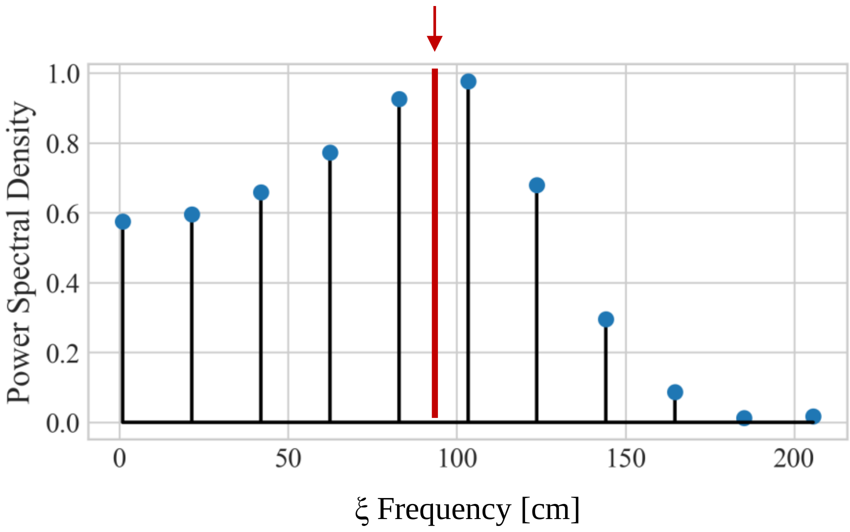
Lomb-Scargle Periodogram : Statistical test for frequency content in non uniformly sampled data

Retardance is linear with wavenumber

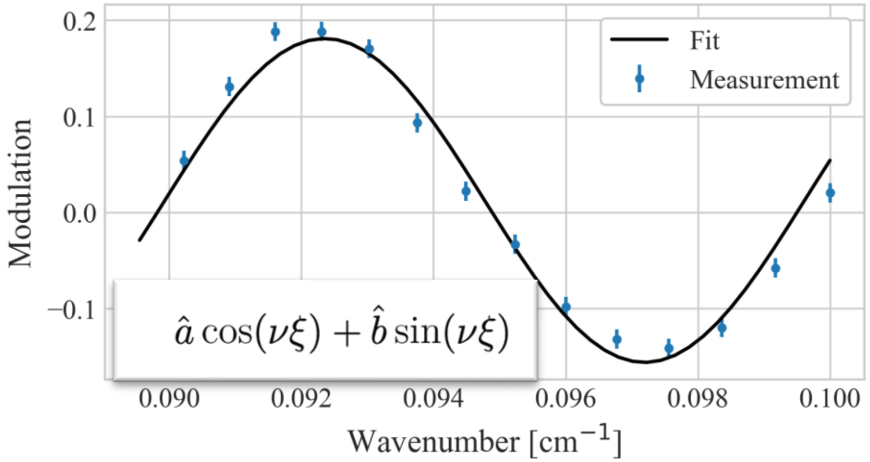




ξ carrier frequency calculated in calibration



(a) Power Spectrum

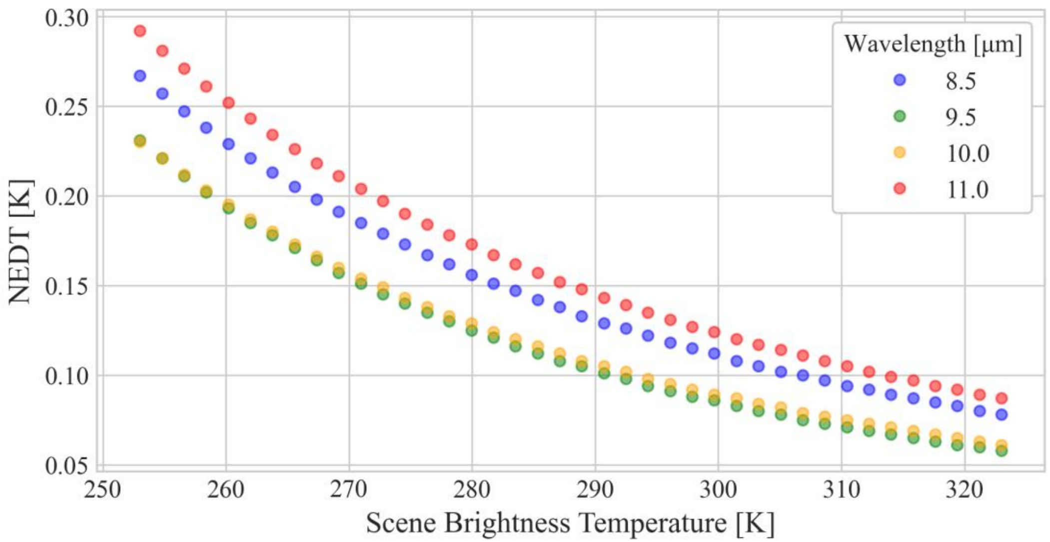


(b) Fit

LS algorithm tests null hypothesis : there is modulation at ξ

Sensitivity of IRCSP

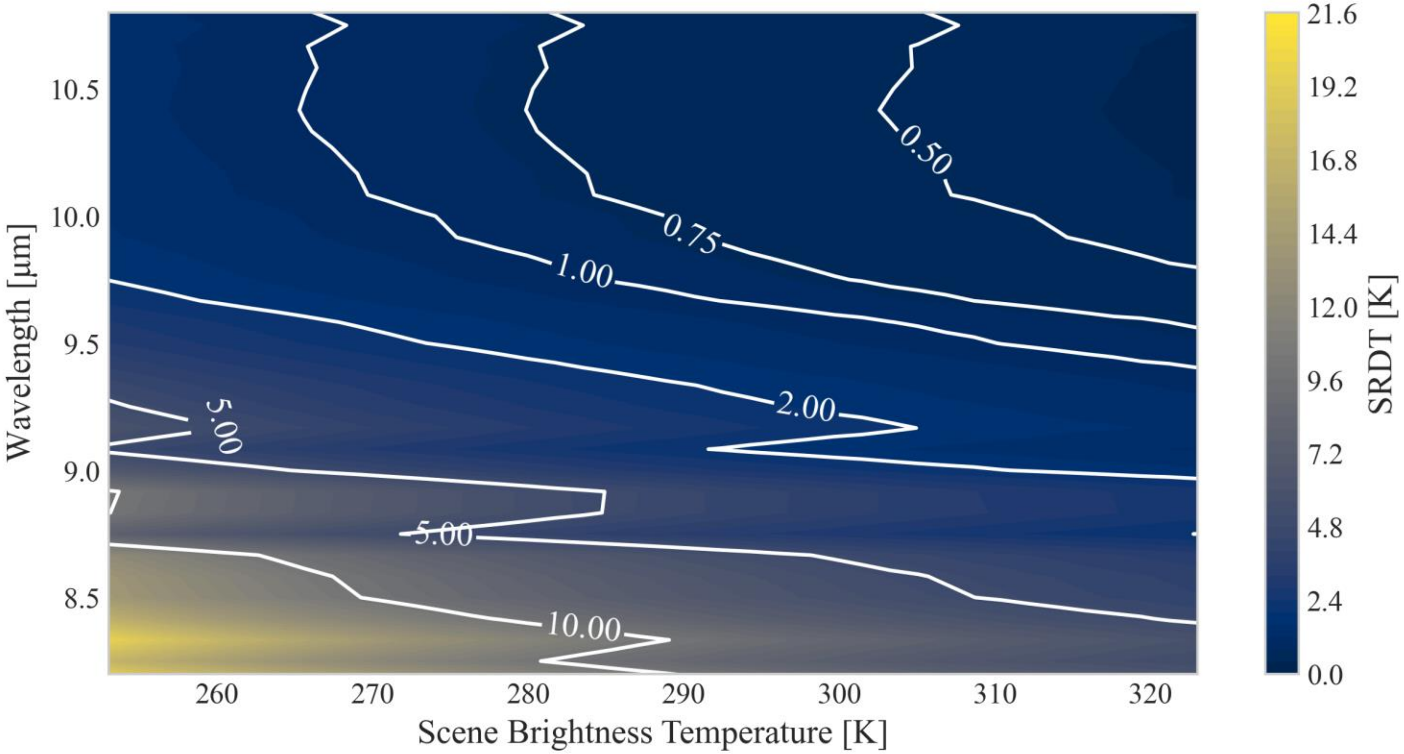
Noise Equivalent Differential Temperature



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

Science Requirements

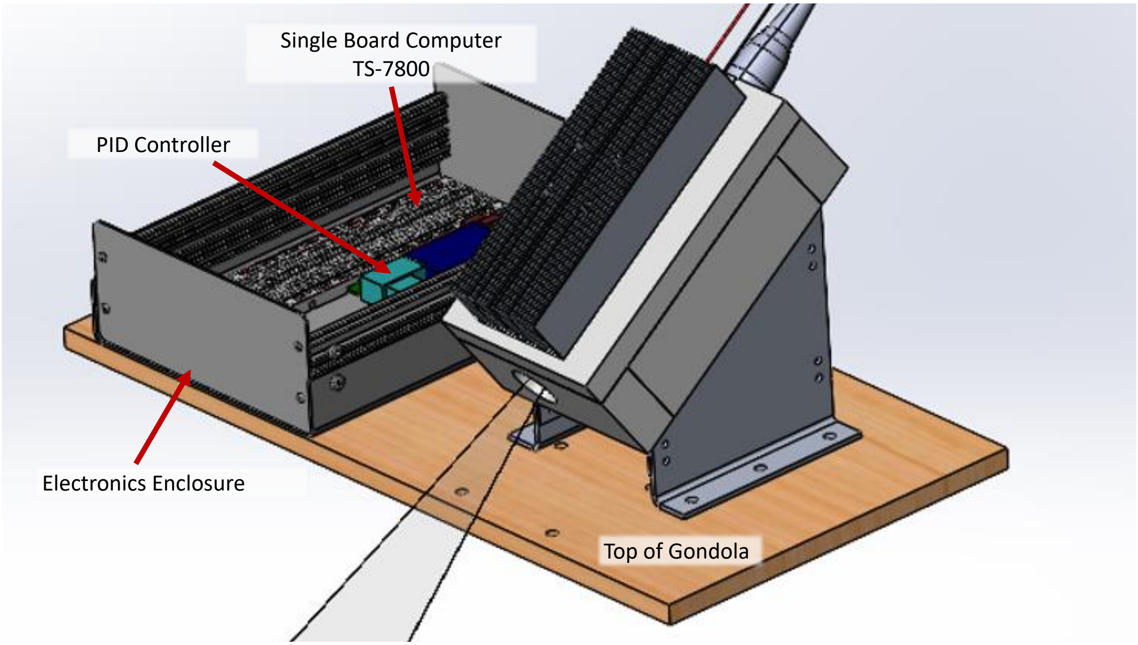
Stokes Resolvable Differential Temperature

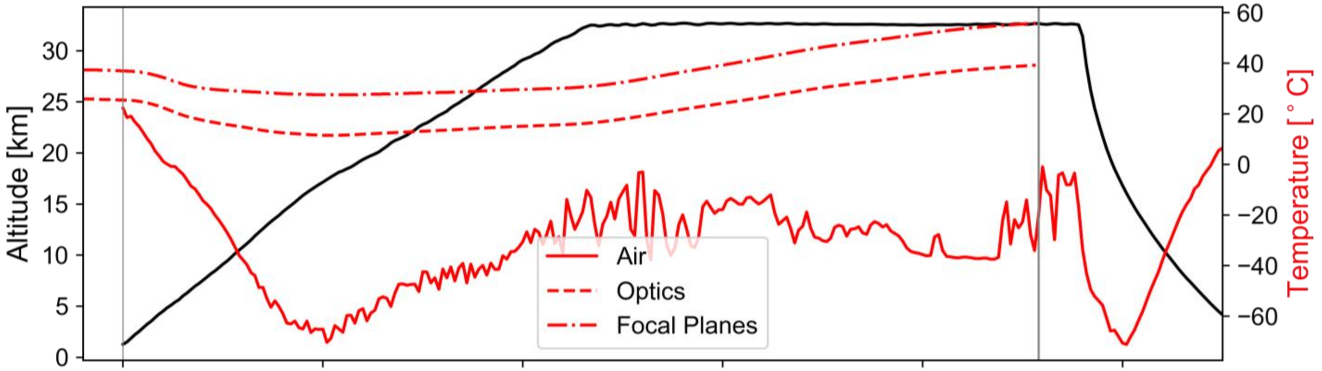


Lab measurements at room temperature – reduction in polarimetric efficiency degrades SRDT at shorter wavelengths

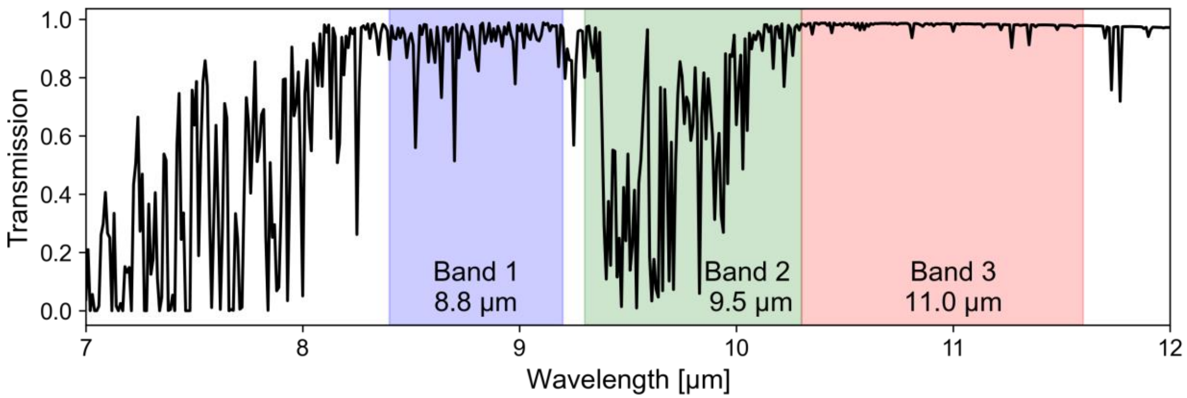
Field Measurements

High Altitude Balloon Adaptation



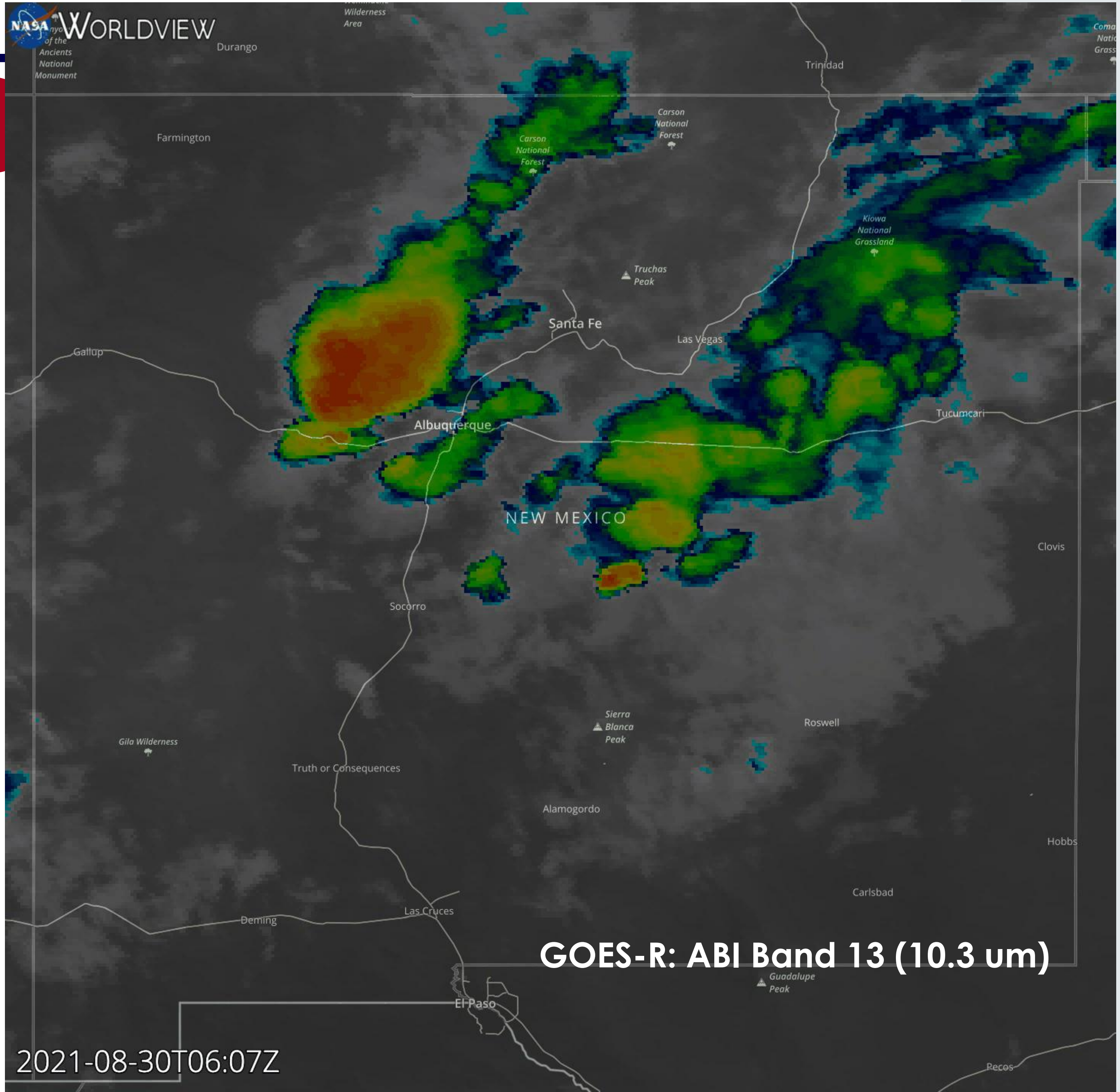


Targeted Spectral Bands

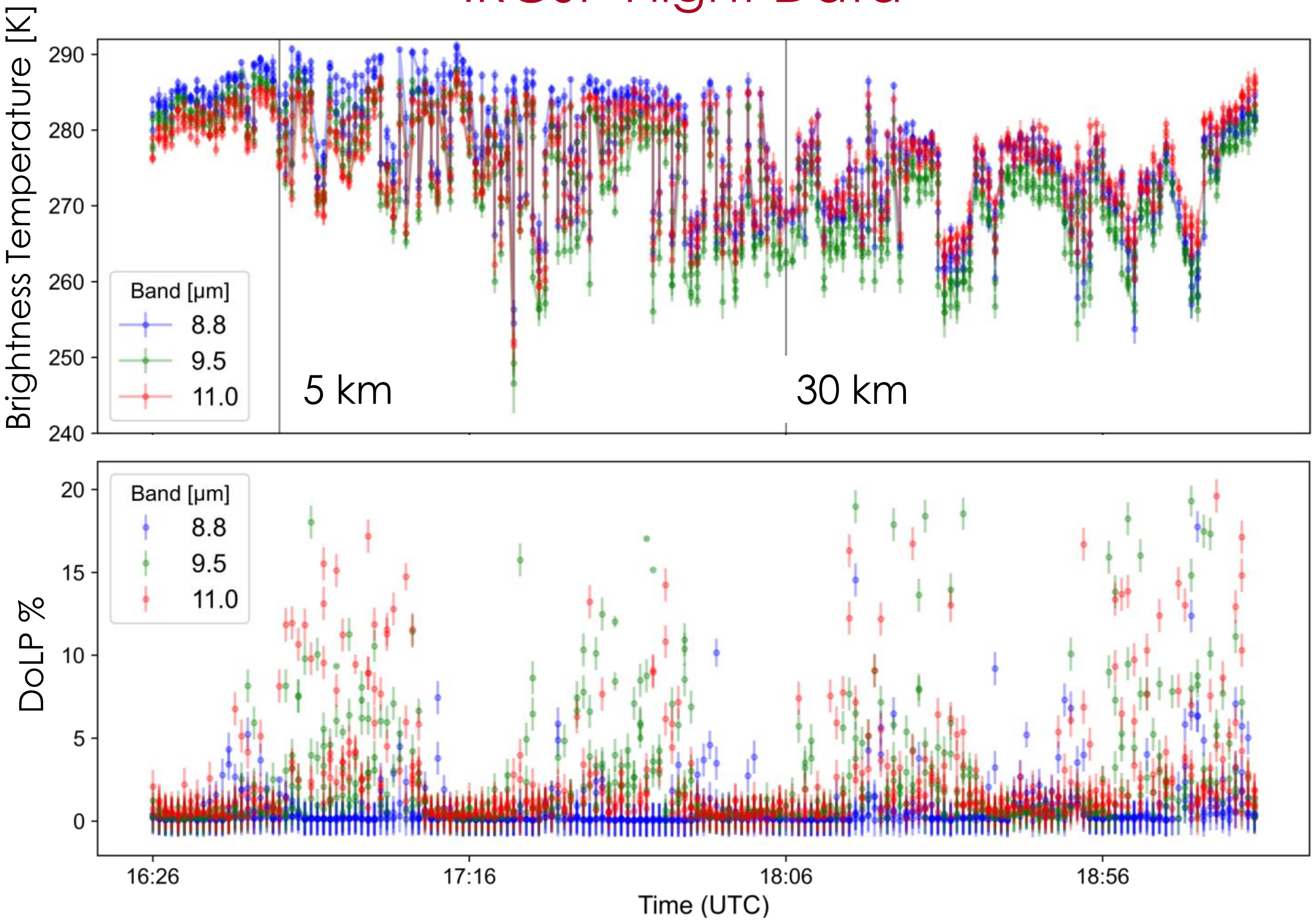


Band	Center Wavelength [µm]	Spectral Resolution [µm]	NEDT (270K)	Name
1	8.8	0.8	1 K	water vapor
2	9.5	1.0	1 K	ozone
3	11.0	1.3	1.5 K	clear

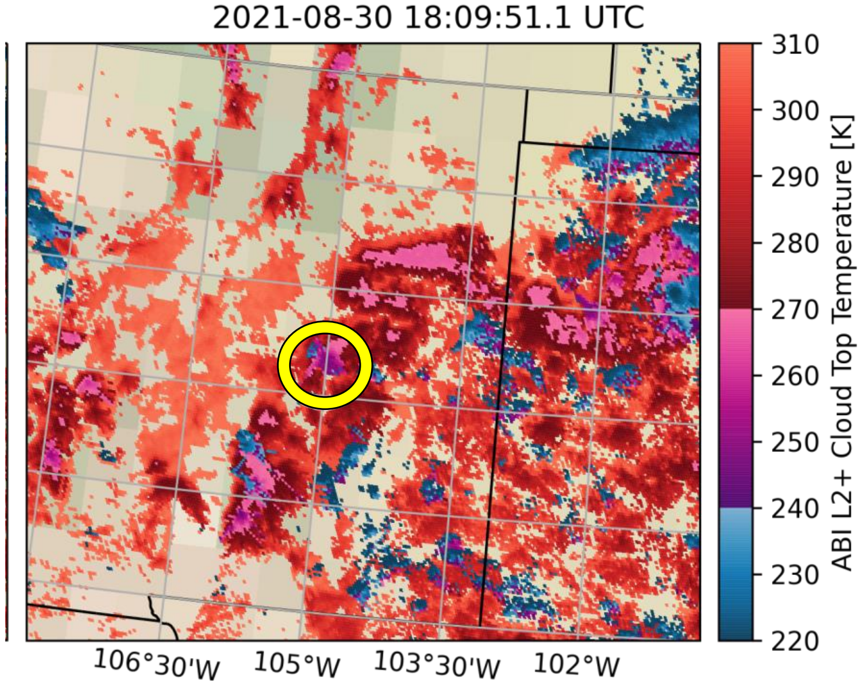
Salter Test Flight (August 30, 2021)



IRCSP Flight Data



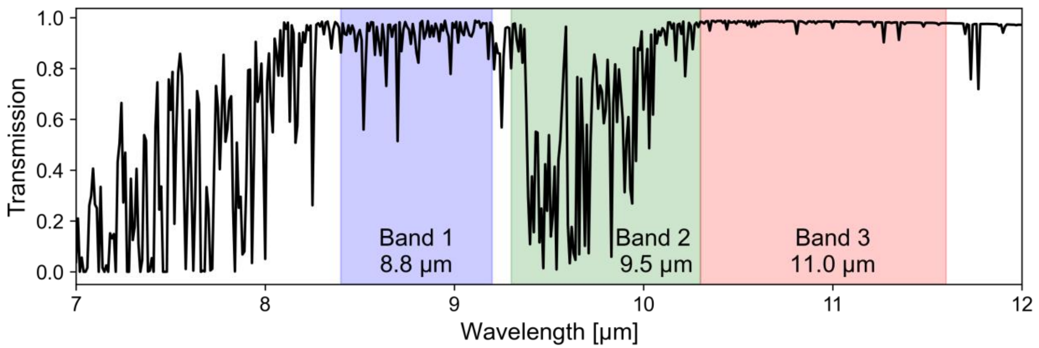
Cloud Top Temperatures from NOAA's GOES-16 Advanced Baseline Imager



ABI Data Sourced From

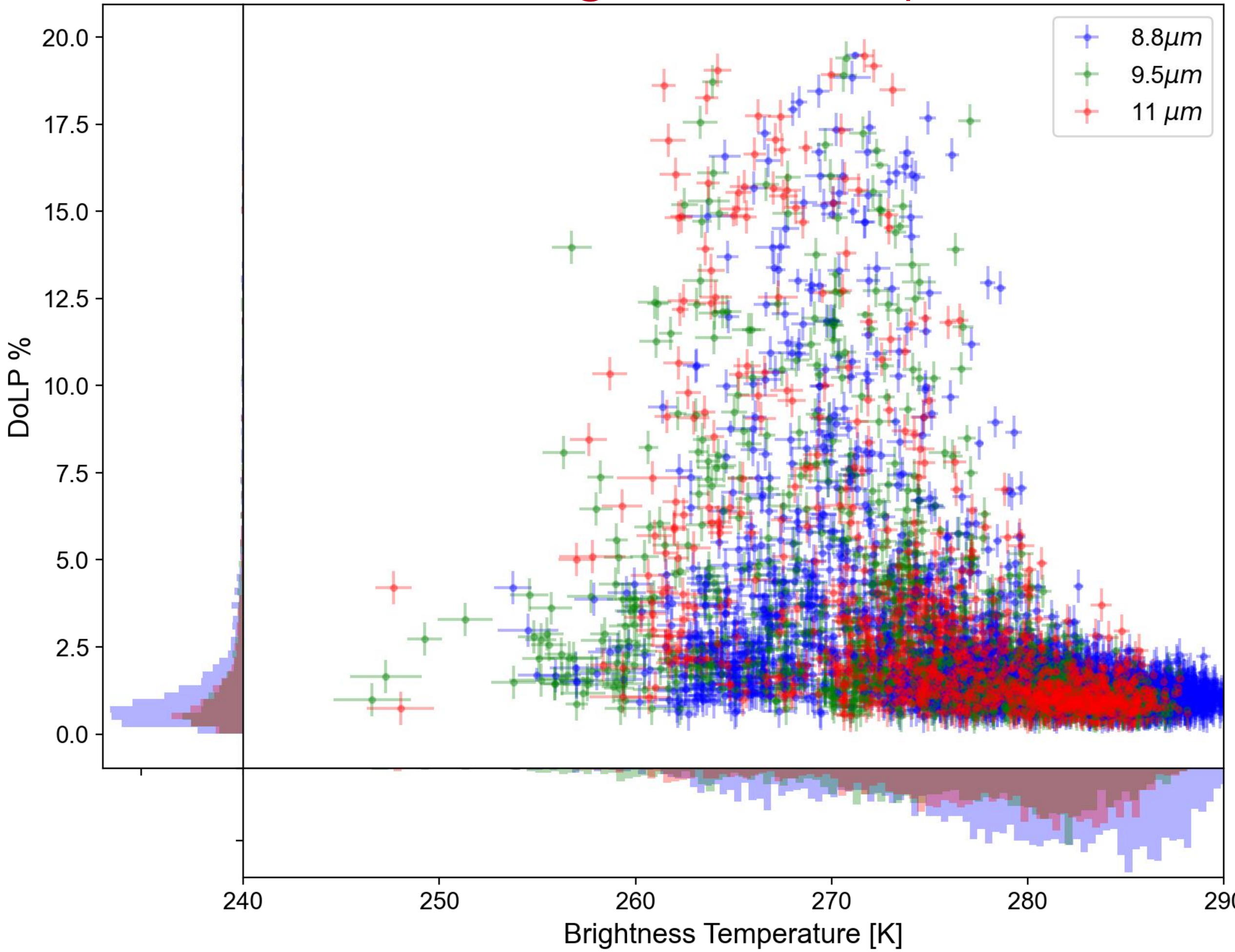
GOES-R Algorithm Working Group, and GOES-R Series Program (2017): NOAA GOES-R Series Advanced Baseline Imager (ABI) Level 2 Cloud and Moisture Imagery Products (CMIP).[ACHTF-M6]. NOAA National Centers for Environmental Information. doi:10.7289/V5736P36.

Measured Polarization Trends

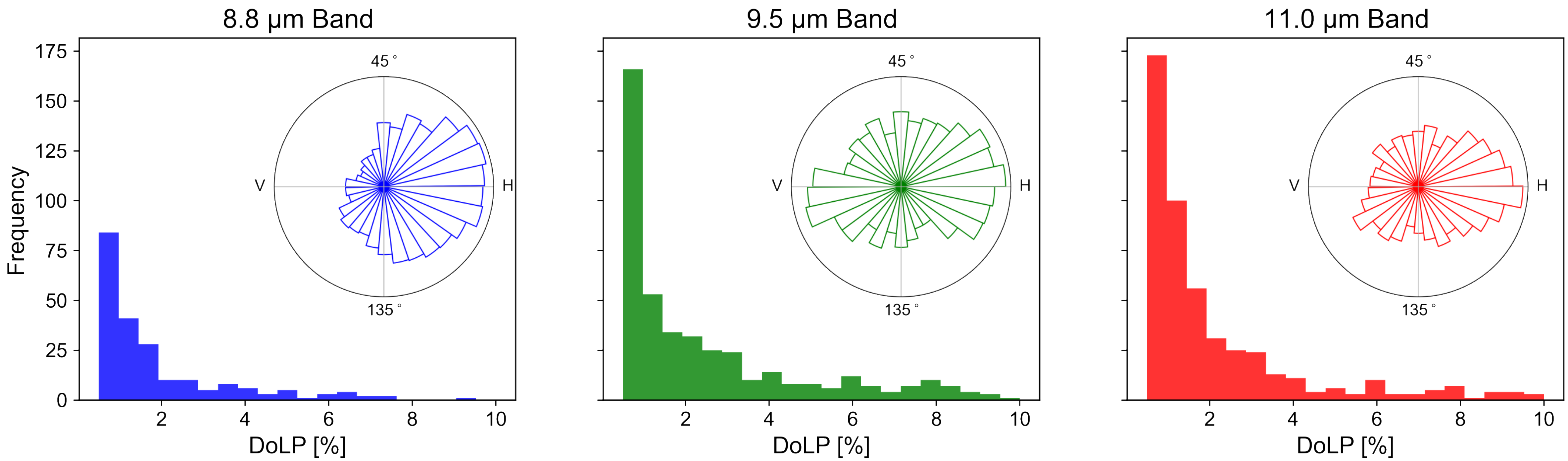


In all 3 windows, there is a peak in measured DoLP centered near brightness temperatures of 270 K

DoLP vs. Brightness Temperature



Measured Polarization Trends

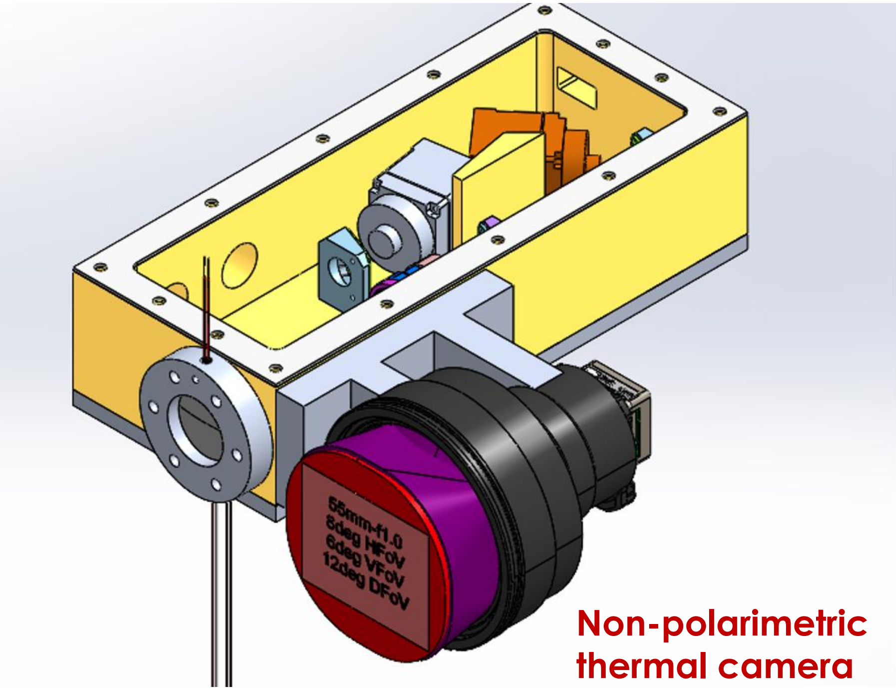


Spectrally resolved trends in AoLP support hypothesized split-window sensitivity to cloud microphysical properties

Impact & Future Directions

- Feasibility of IRCSP technology has been demonstrated
- First observation of high altitude down-viewing LWIR polarization
- Evaluate sensitivity of LWIR polarimetry to microphysical properties
  - Retrieval algorithms
  - Deployments during varying weather conditions
- Future deployments are planned develop the technology further
  - Summer 2022 balloon campaign out of Fort Sumner, NM
  - July 2022 P-3 Orion aircraft out of Wallops Flight Facility

Summer 2022 IRCSP Payload Modifications

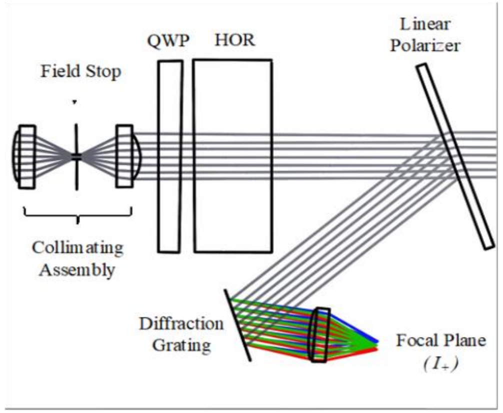


Non-polarimetric thermal camera

Credit: Jeremy Parkinson

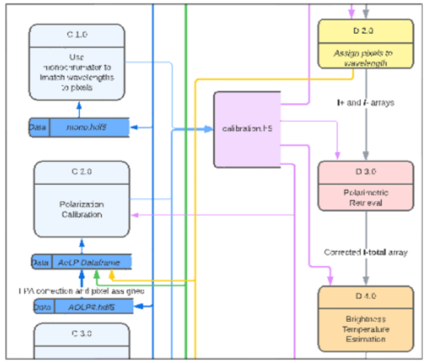
P-3 Orion aircraft out of Wallops Flight Facility 28,000ft

Optical Design of the IRCSP

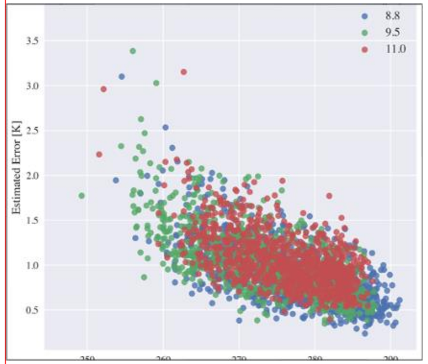


Adaptation of Uncooled Microbolometers

Software



Field Measurements



Major Impacts

Acknowledgements

Committee Members	Meredith Kupinski, Russell Chipman, Lars Furenlid, Dong Wu (*Special Member, NASA Goddard Spaceflight Center*)
Polarization Lab	Lisa Li, Jeff Davis, Brian Daughtry, Adriana Stohn, Kyler Langworthy, Erica Mohr, Quinn Jarecki, Jeremy Parkinson, Jake Heath, Khalid Omer, Cedar Andre, Clarissa DeLeon, Masafumi Seigo, Jaclyn John, Caroline Humphreys
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Capstone Team	Nayleth Ramirez , Jaclyn John, Eddie Contreras , Thor Neill , Wassim Khawam, Jeremy Parkinson
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Thank you to my family, friends, and husband Dan for supporting me on this journey—I couldn't have done it without you!





Thanks for coming to Kira Shanks' Defense!

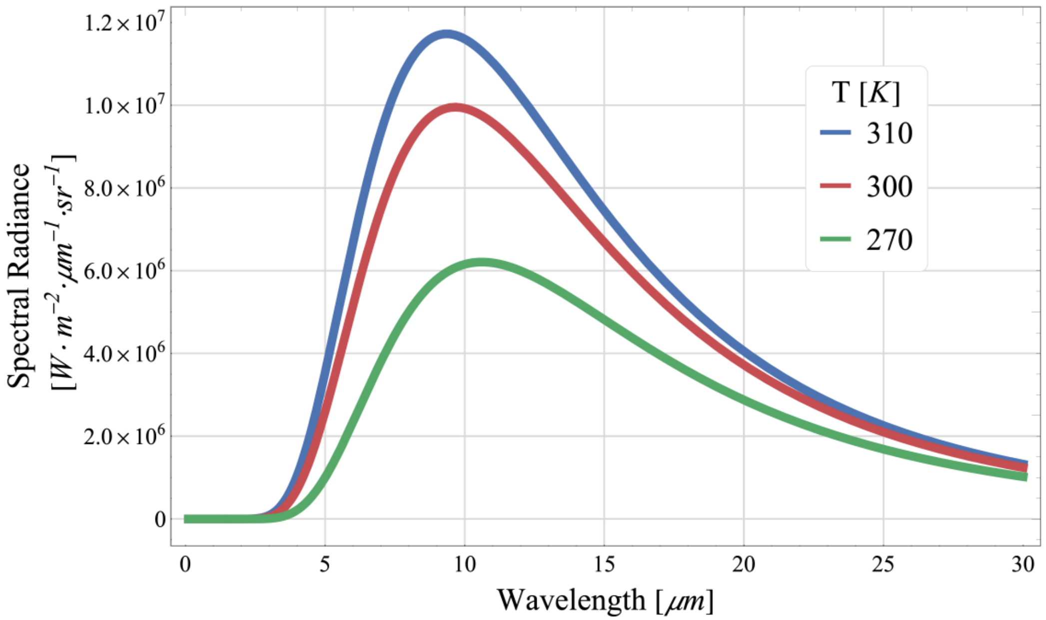
The committee is now in closed session.

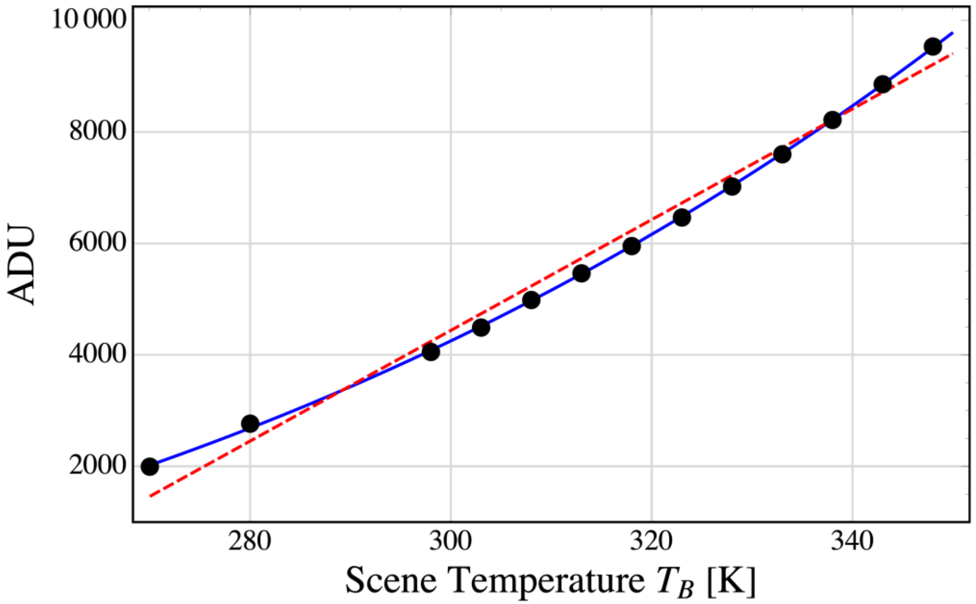
Feel free to stay on the call and talk among yourselves. We'll bring you back into the room when the results are announced

SCAN ME

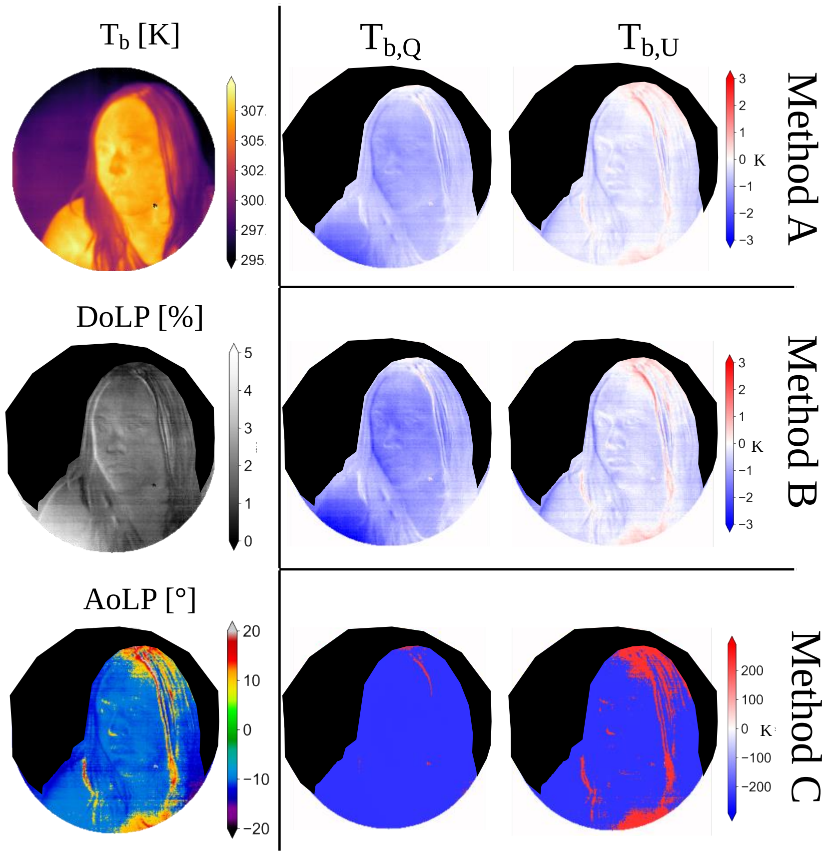
While you wait, scan for a "*Guide to Kira's Defense*", information about the Polarization Lab, and the Wyant College of Optical Science

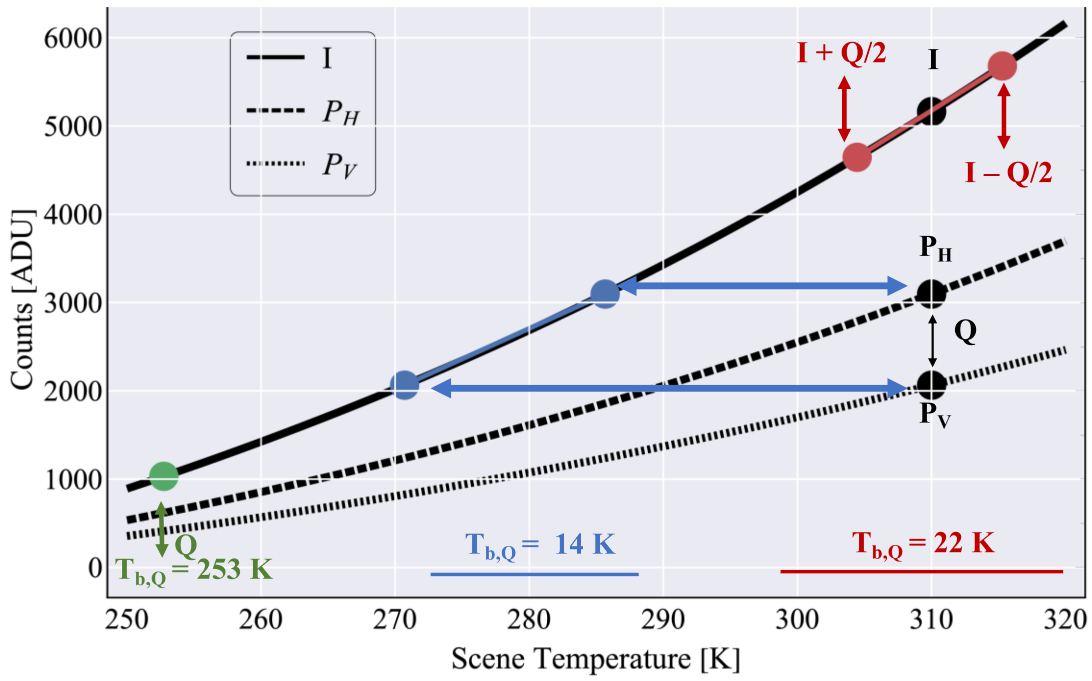
Modified Stokes Parameters



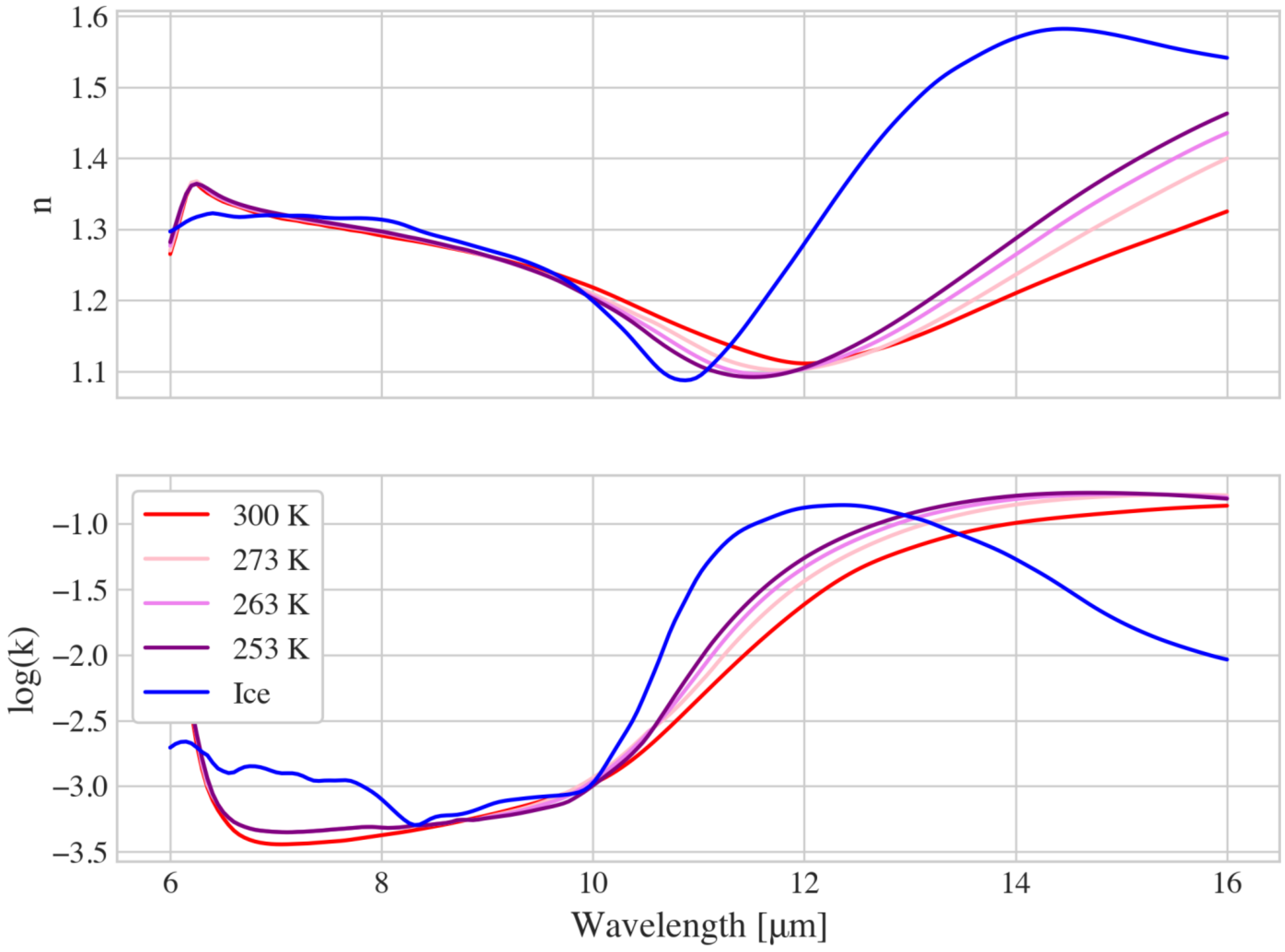


Modified Stokes Parameters





Light Matter Interaction



Polarization dependence described by the Fresnel Equations

$$R_{\parallel} = \left| \frac{n_i \cos\theta_t - n_t \cos\theta_i}{n_i \cos\theta_t + n_t \cos\theta_i} \right|^2$$

$$R_{\perp} = \left| \frac{n_i \cos\theta_t - n_t \cos\theta_t}{n_t \cos\theta_i + n_i \cos\theta_t} \right|^2$$

Conservation of energy and angular momentum:

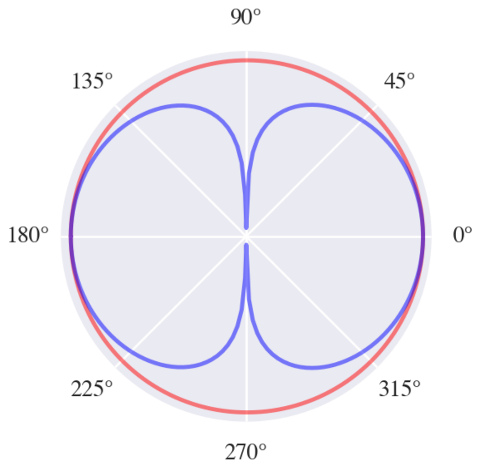
$$e_{\parallel/\perp} = 1 - R_{\parallel/\perp}$$

Polarization dependent emission

Atmospheric Scattering

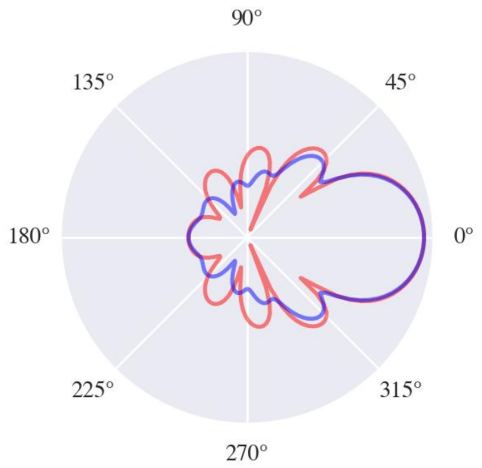
smoke	.1-1 μm
dust aerosols	1-20 μm
cloud water droplets	5 - 50 μm
cloud ice	20 - 100 μm
raindrops	2 mm

$D_{eff} = 0.1\,\lambda$

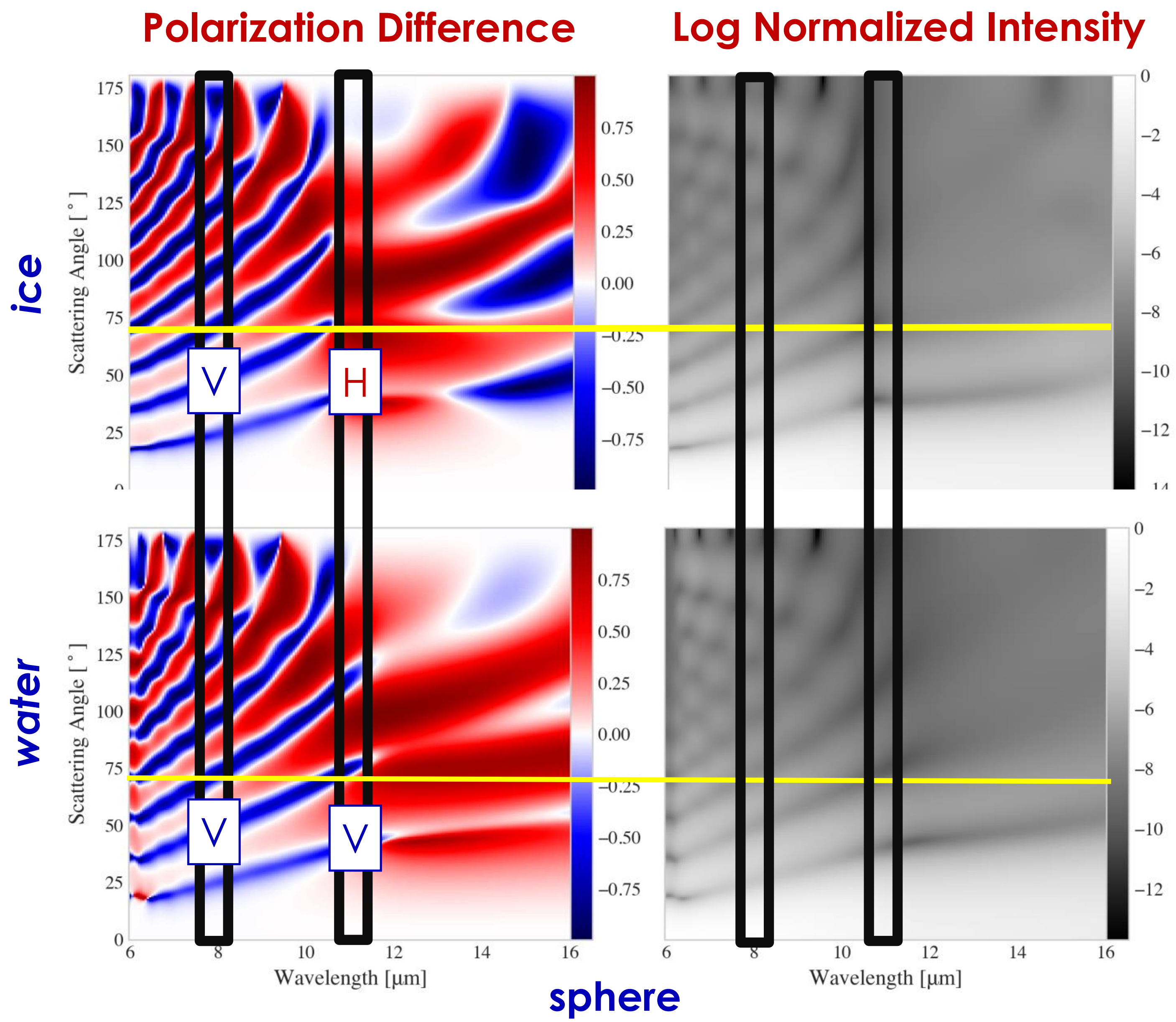


Rayleigh

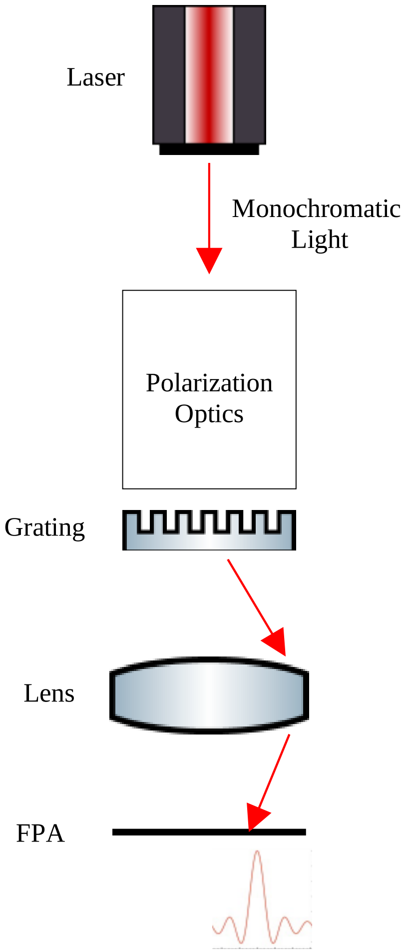
$D_{eff} = 2\,\lambda$

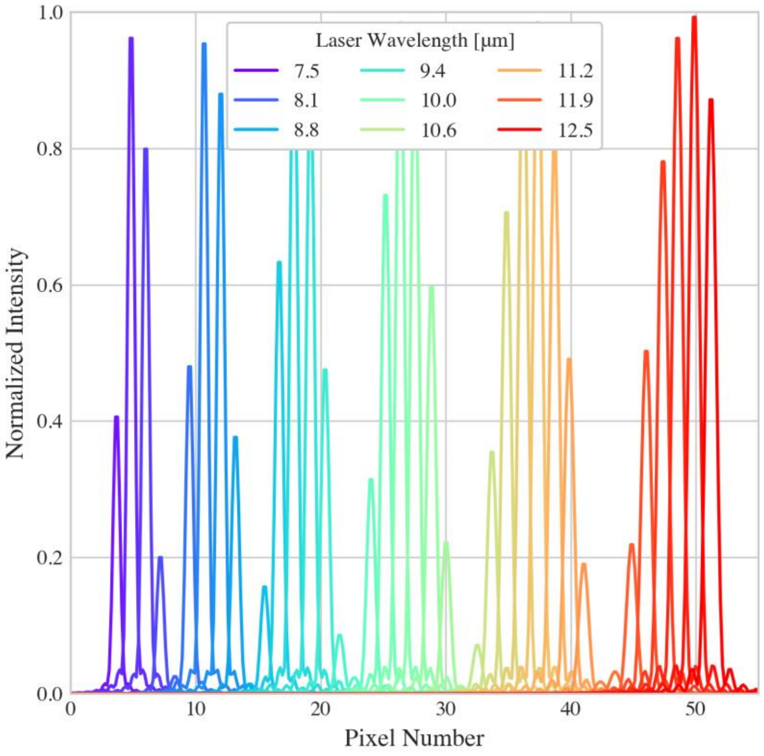


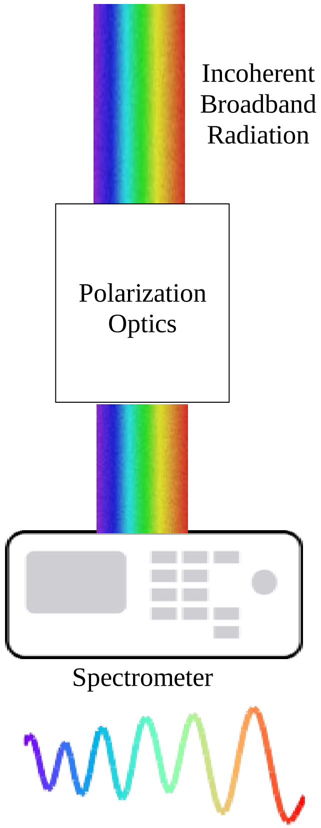
Mie

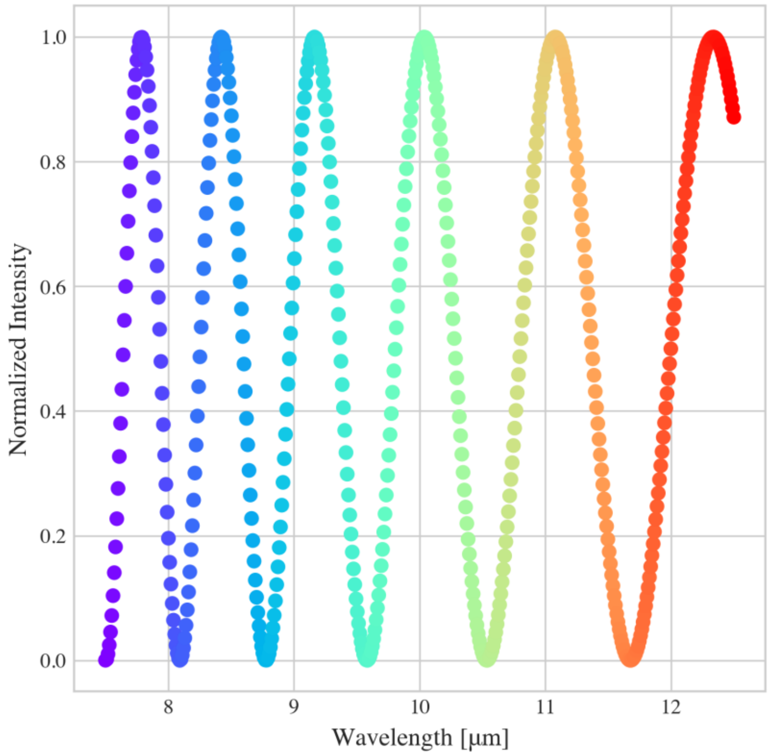


Spectrally Resolved Characterization





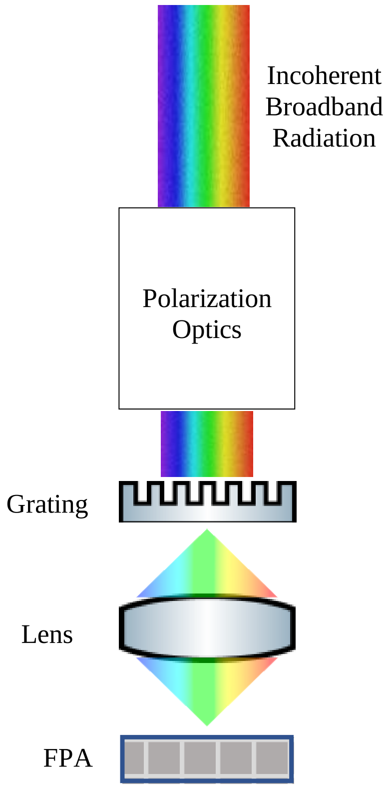


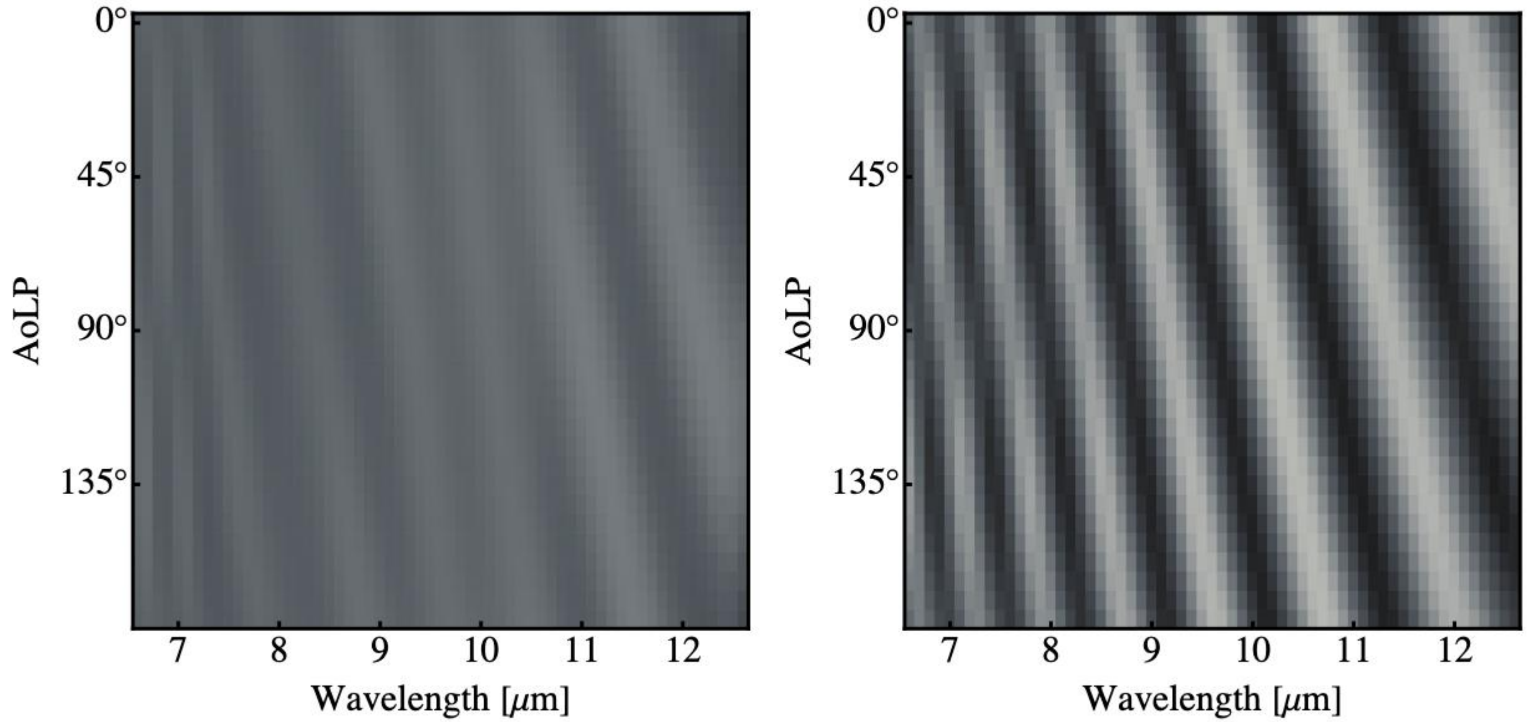


Monochromatic Source -*scan over wavelengths*

Fine Spectral Resolution

Simulated Spectral Blurring

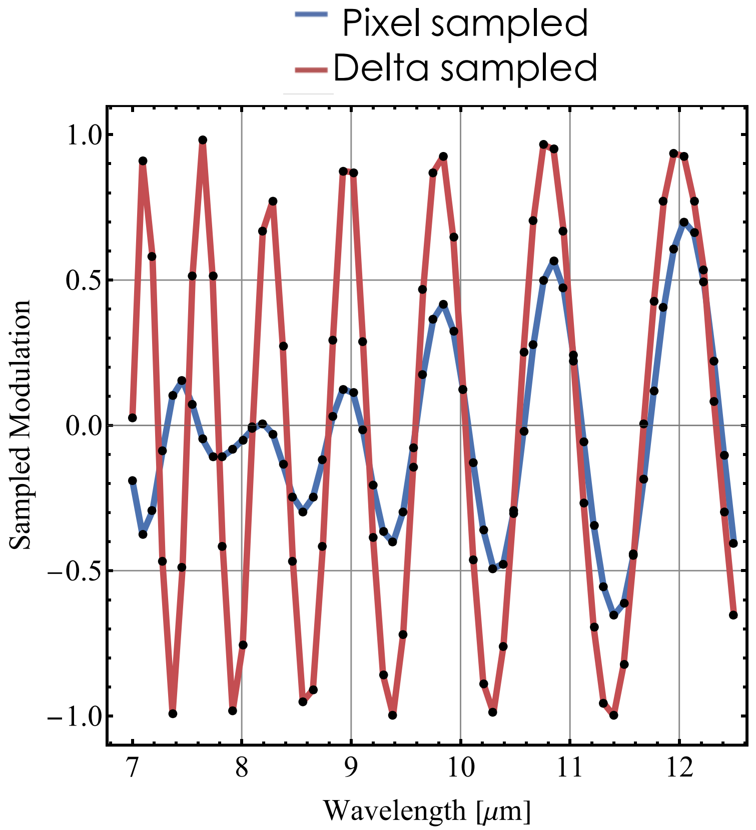




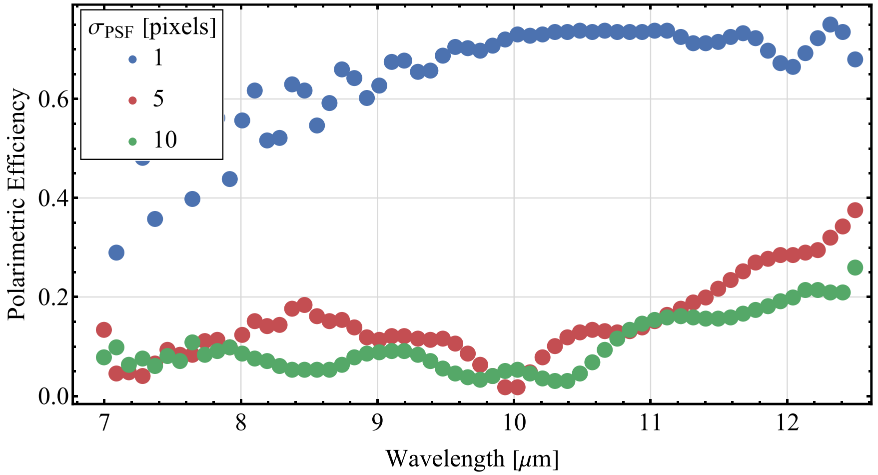
(a) $t_{\mathrm{HOR}} = 5$ mm , $\sigma_{\mathrm{PSF}} = 10$ (b) $t_{\mathrm{HOR}} = 5$ mm , $\sigma_{\mathrm{PSF}} = 1$

Hart, Kira A., et al. "Linear Stokes measurement of thermal targets using compact LWIR spectropolarimeter." *Polarization: Measurement, Analysis, and Remote Sensing XIV*. Vol. 11412. International Society for Optics and Photonics, 2020.

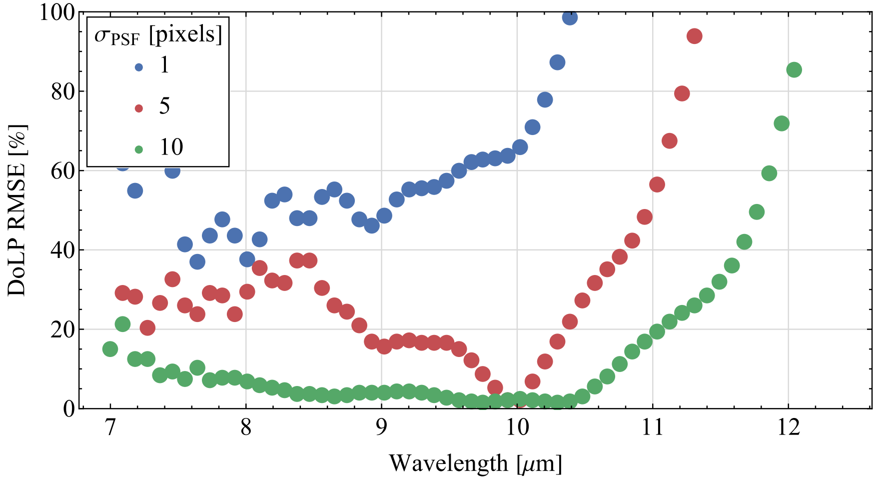
Impact on Performance



Without pixel sampled model, polarimetric efficiency is overestimated

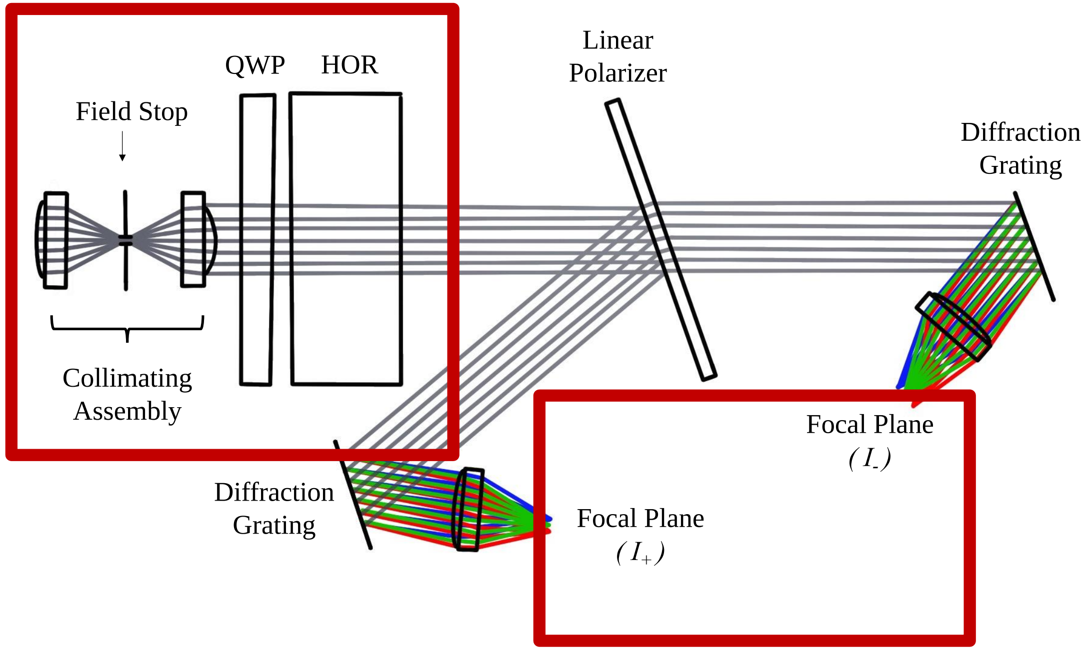


Spectral blurring reduces polarimetric efficiency

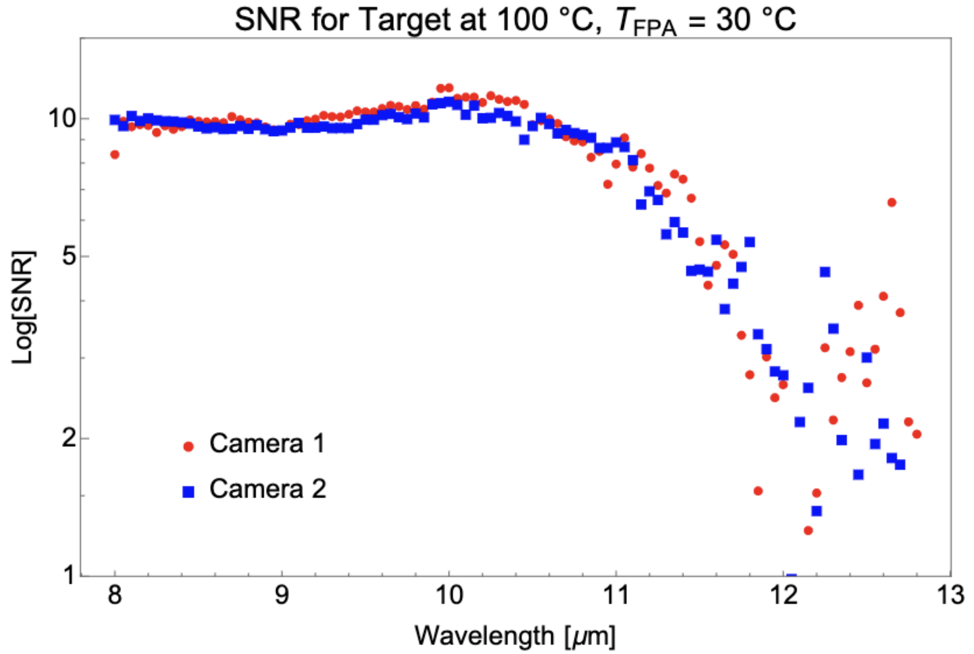


as throughput decreases, accuracy is degraded

Spectrally dependent transmission



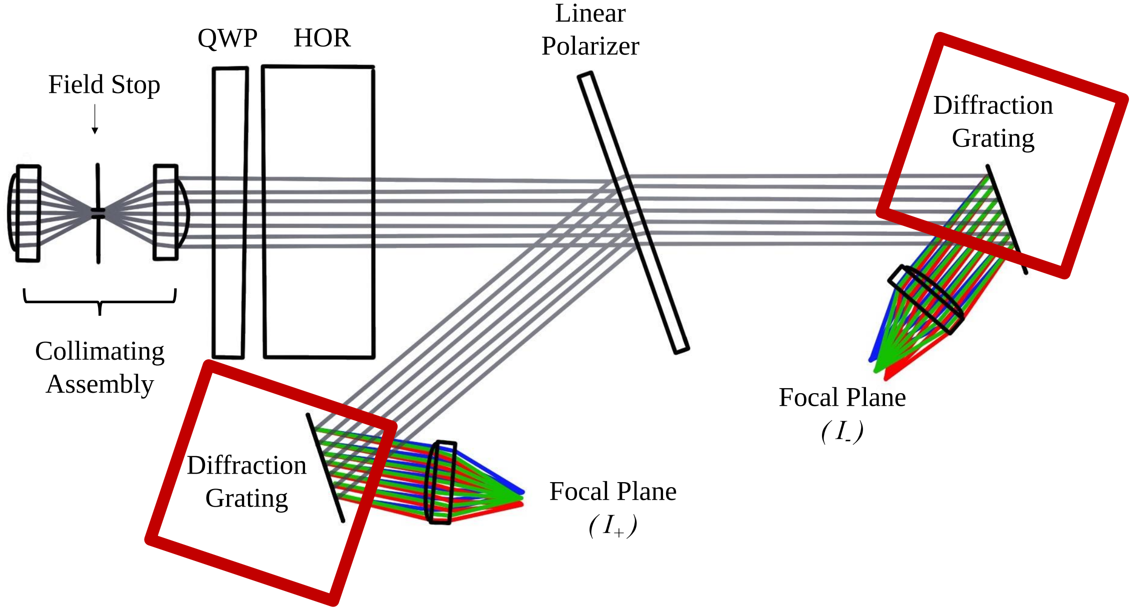
Spectrally dependent transmission and detector efficiency



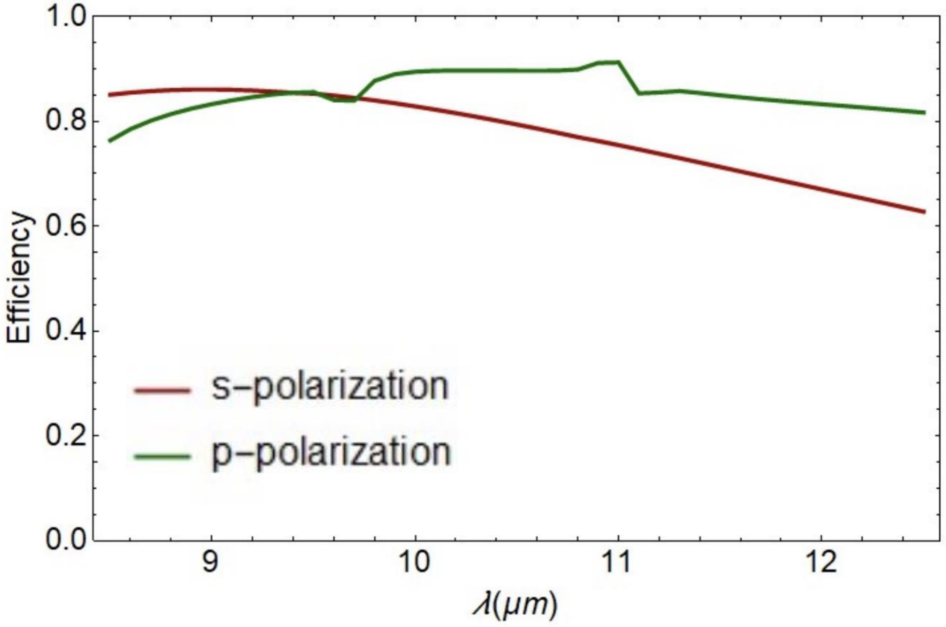
Consequence:

- Reduced sensitivity at longer wavelengths

Grating Efficiency



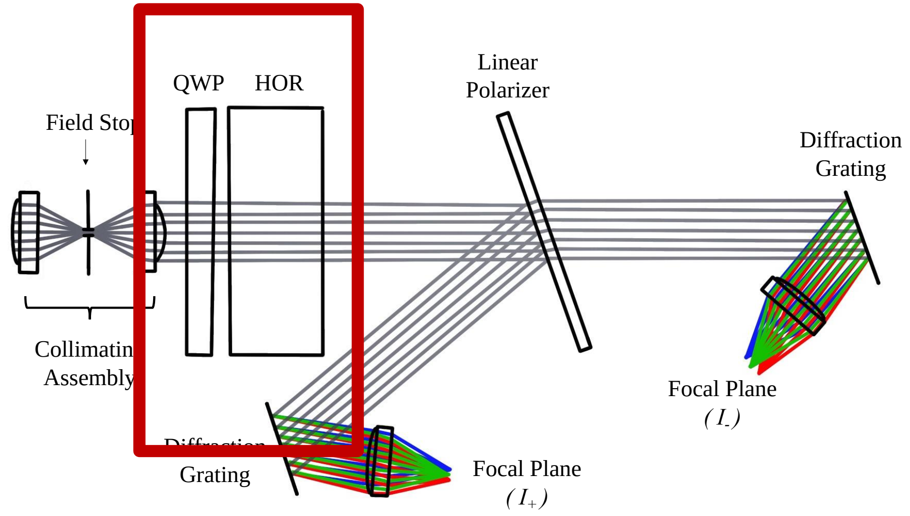
Gratings have polarization dependent efficiency – path dependent, AoLP independent

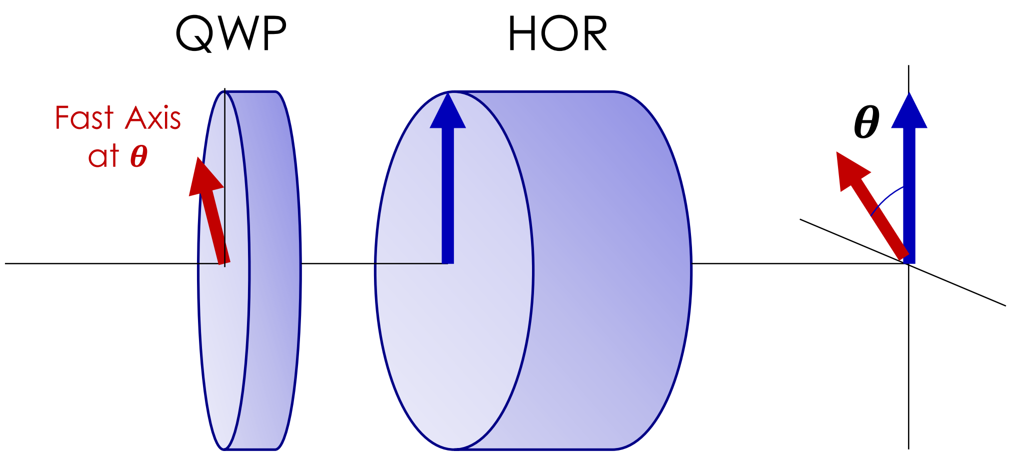


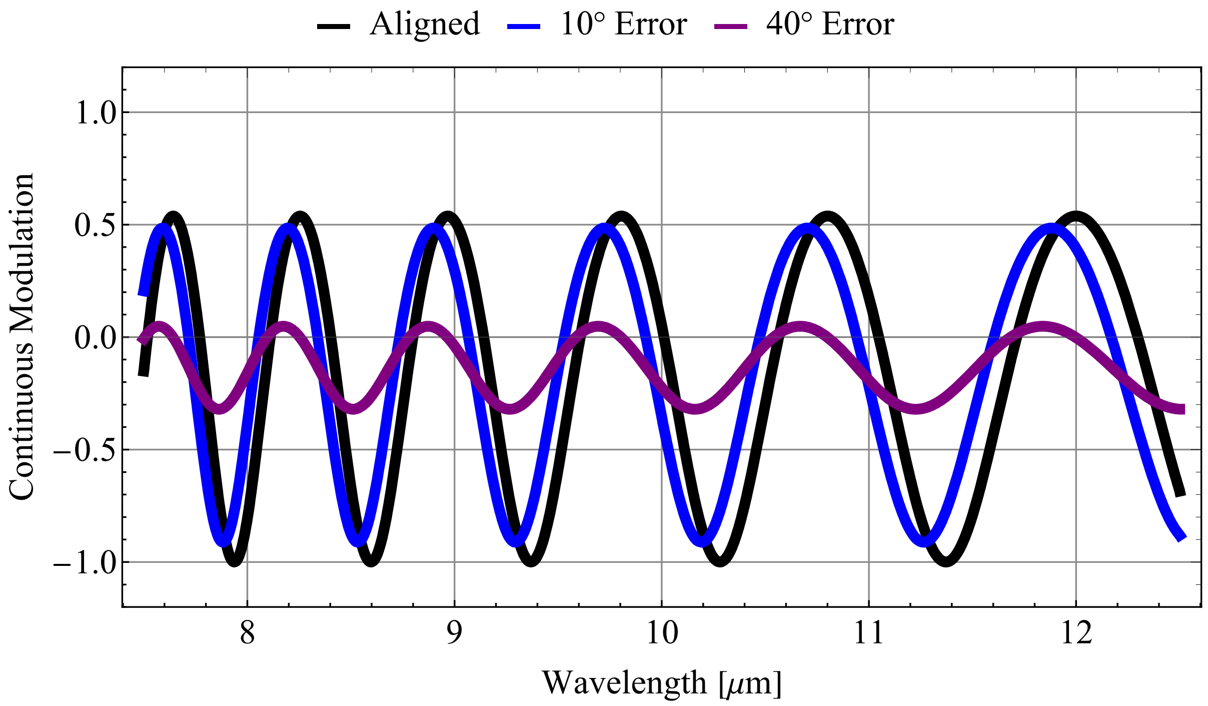
Consequence:

- Offset in Modulation function
- Reduced throughput

Retarder fast axis alignment

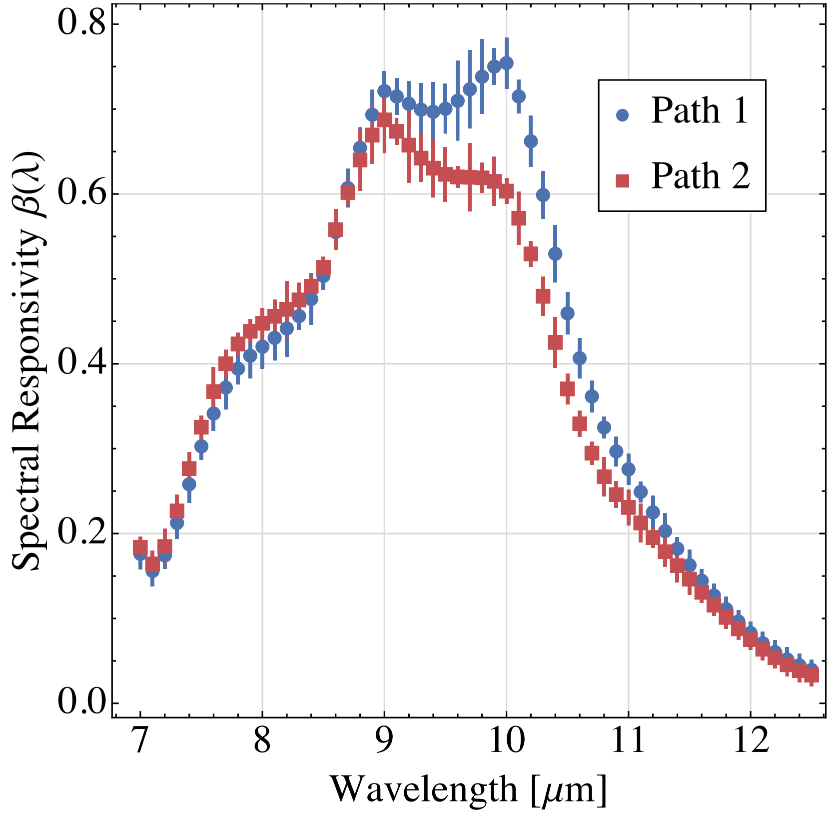


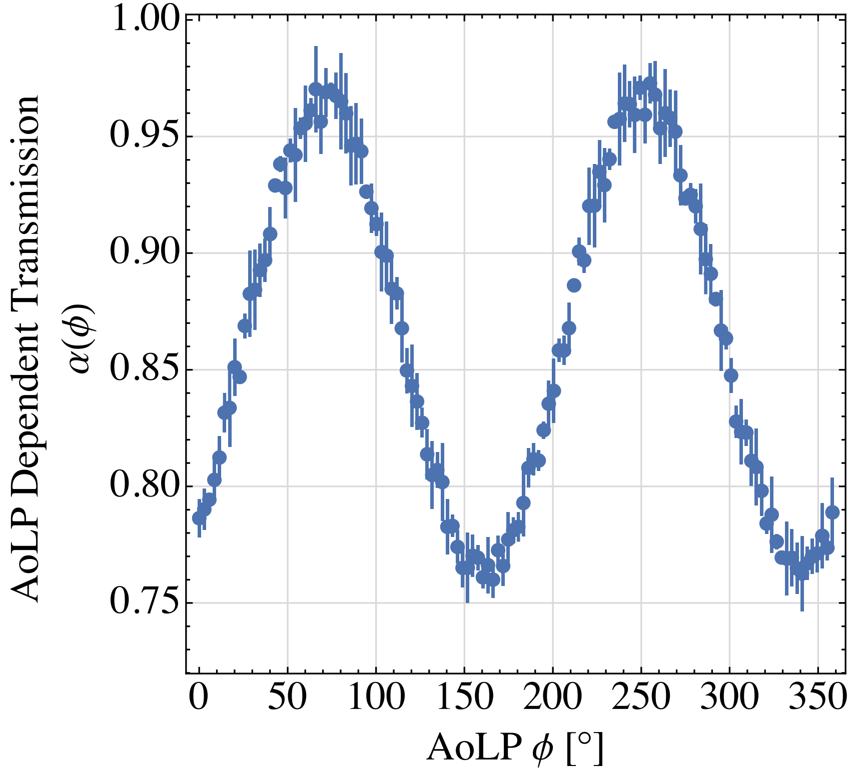




Consequence:

- Reduction in polarimetric efficiency
- Shift in carrier frequency phase



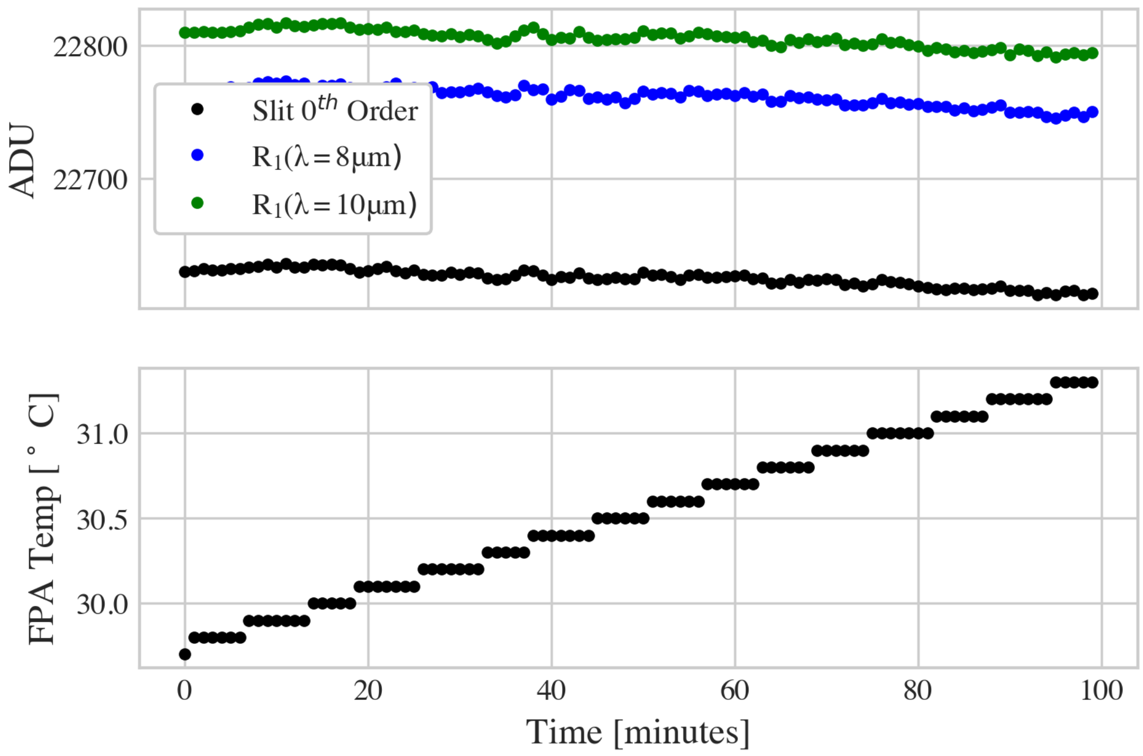


Symbol	Component	Description	Dependencies
T_{Lens}	Collimating Lenses	transmission	λ, ϕ, θ
η	QWP	linear retardance error	λ, θ
T_{QWP}	Quarter Wave Plate	transmission	λ, ϕ
T_{HOR}	High Order Retarder	transmission	λ, ϕ
γ_{FPA}	Detectors	Efficiency	λ
γ_{DG}	Grating	Efficiency	λ

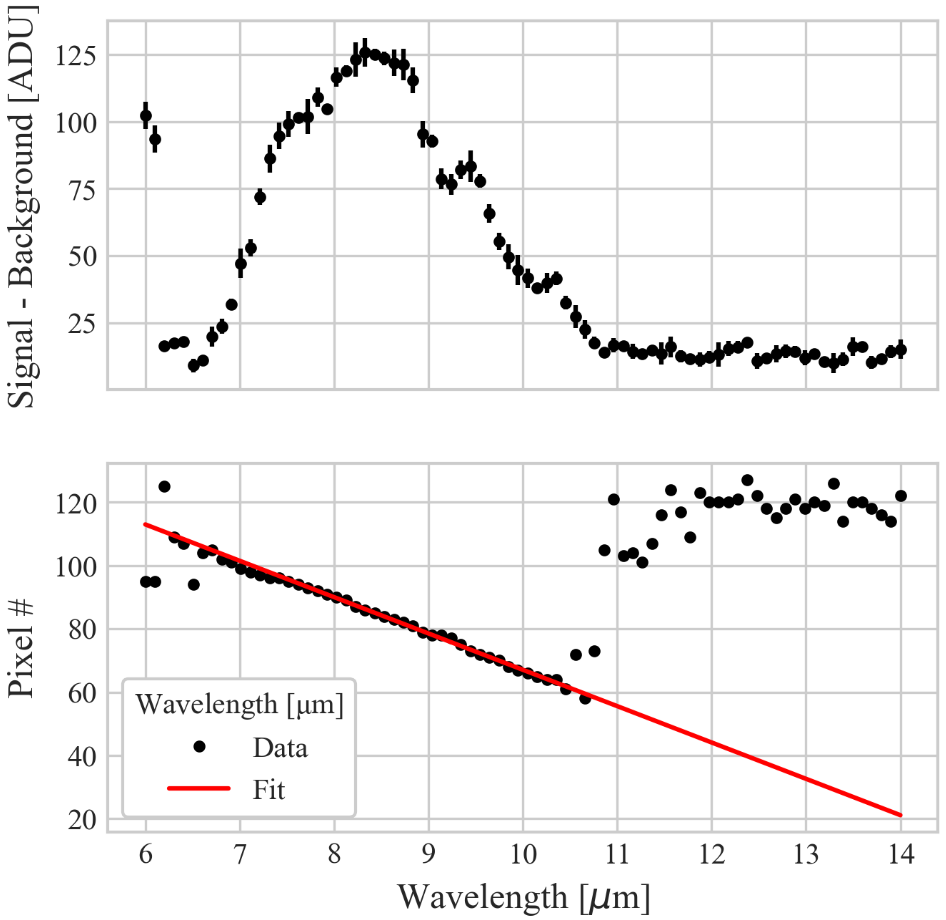
λ	Wavelength
θ	Angle of Incidence
ϕ	Angle of Polarization

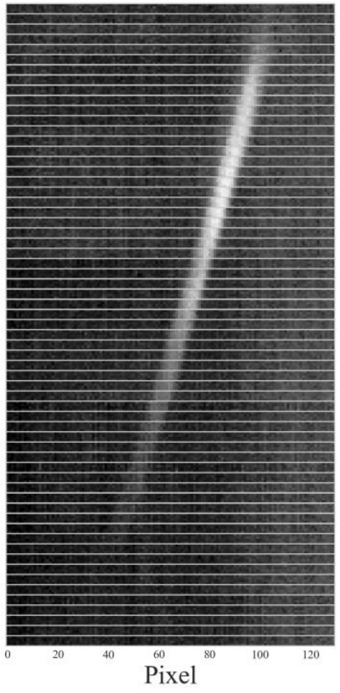
Pre-Processing

Focal Plane Stabilization using Internal Target



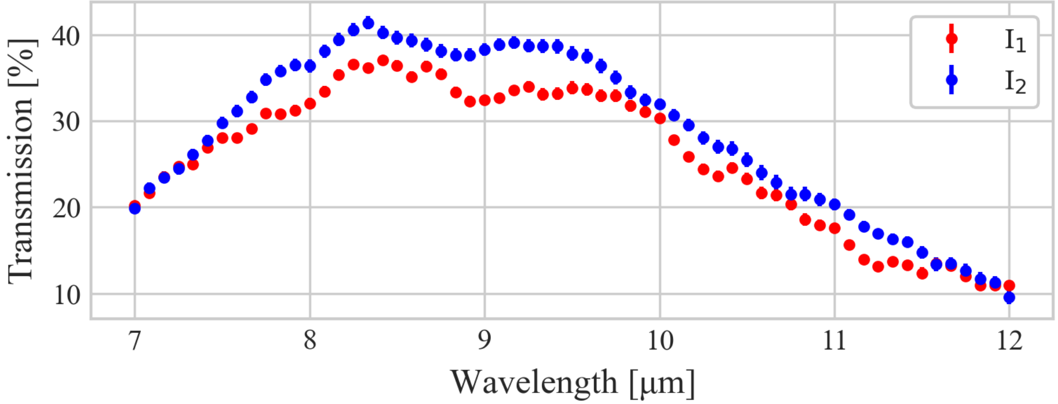
Wavelength Assignment



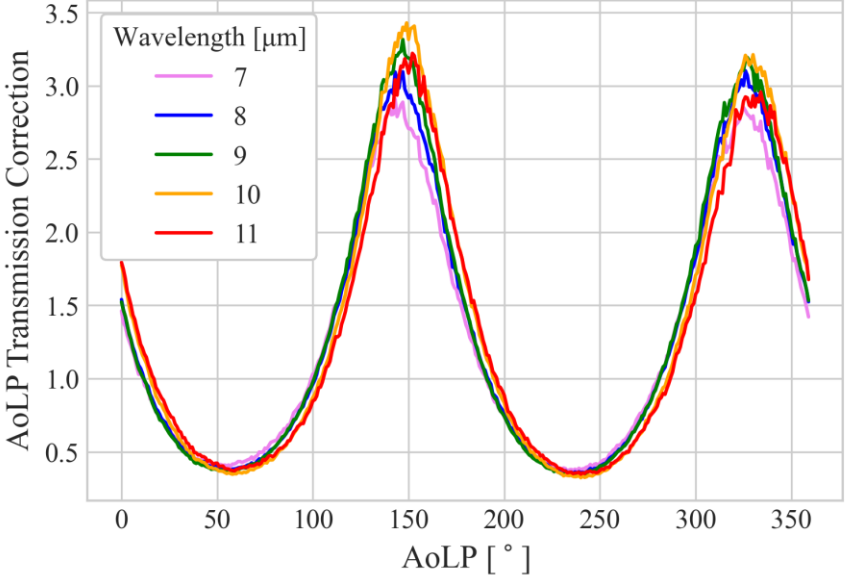


Radiometric Calibratio

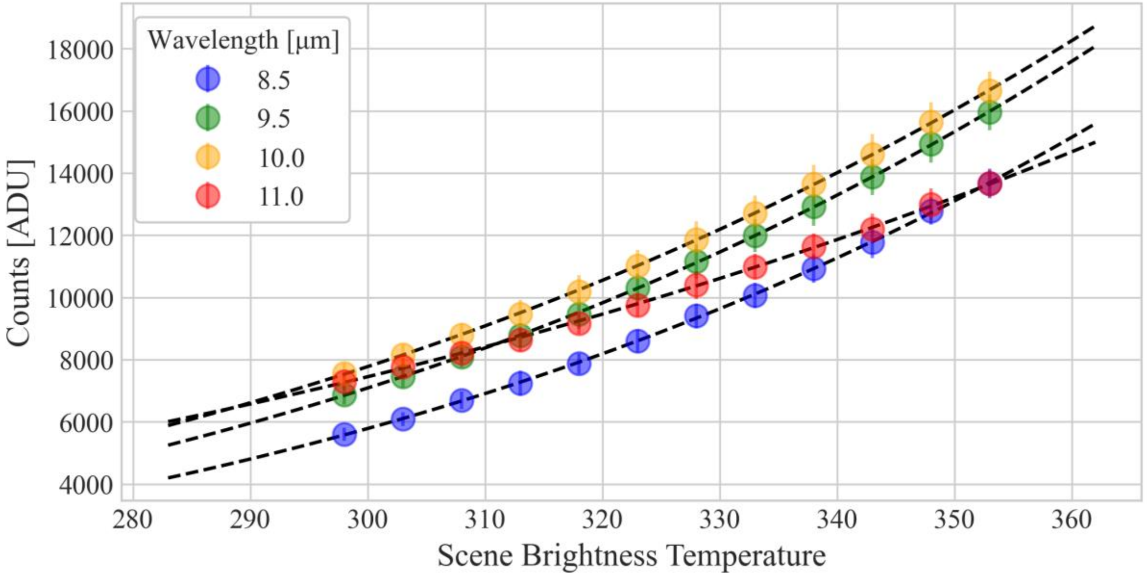
Correct for spectrally dependent transmission



Correct for AoLP dependent transmission

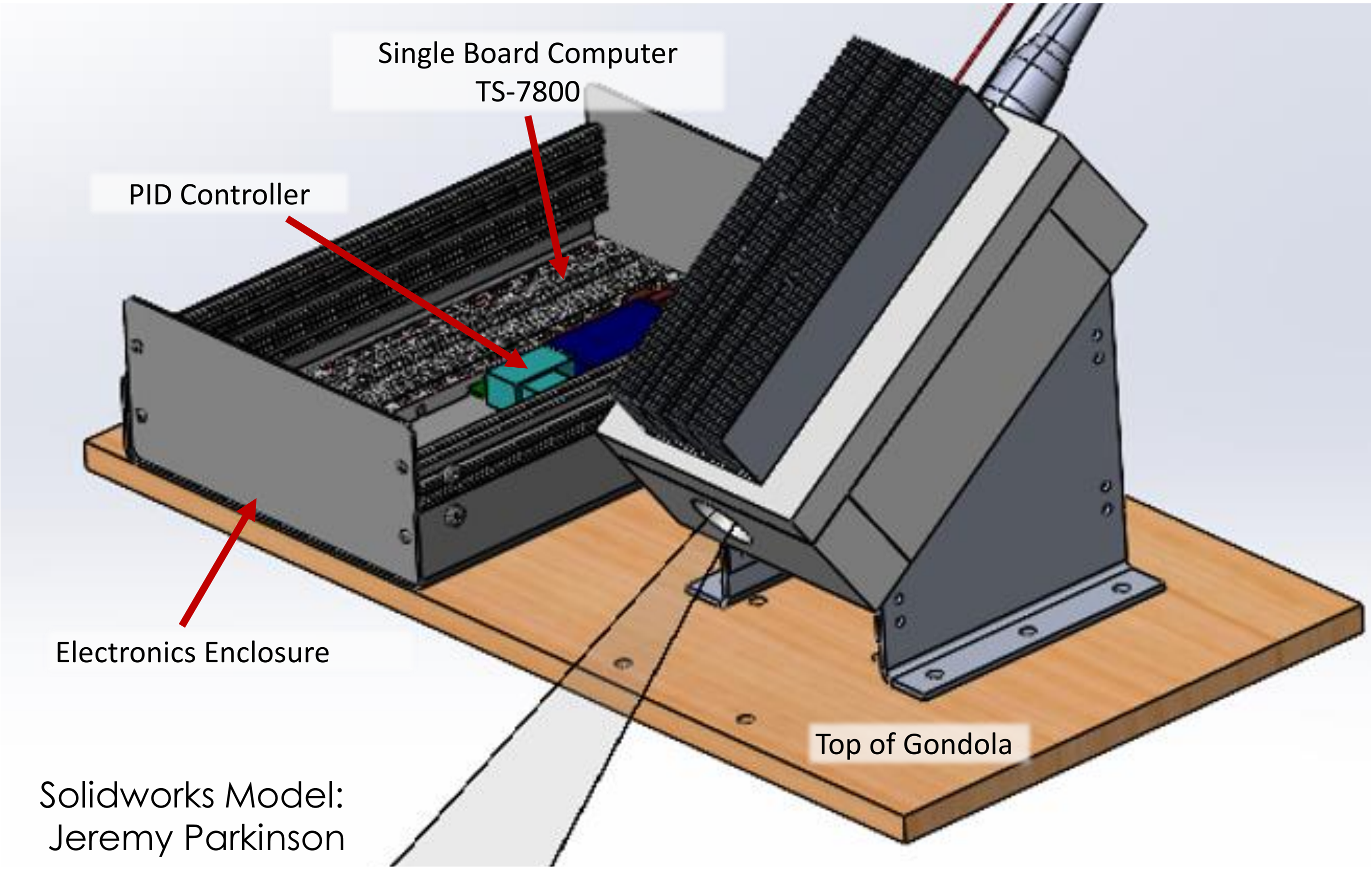


Brightness Temperature Look-Up Table

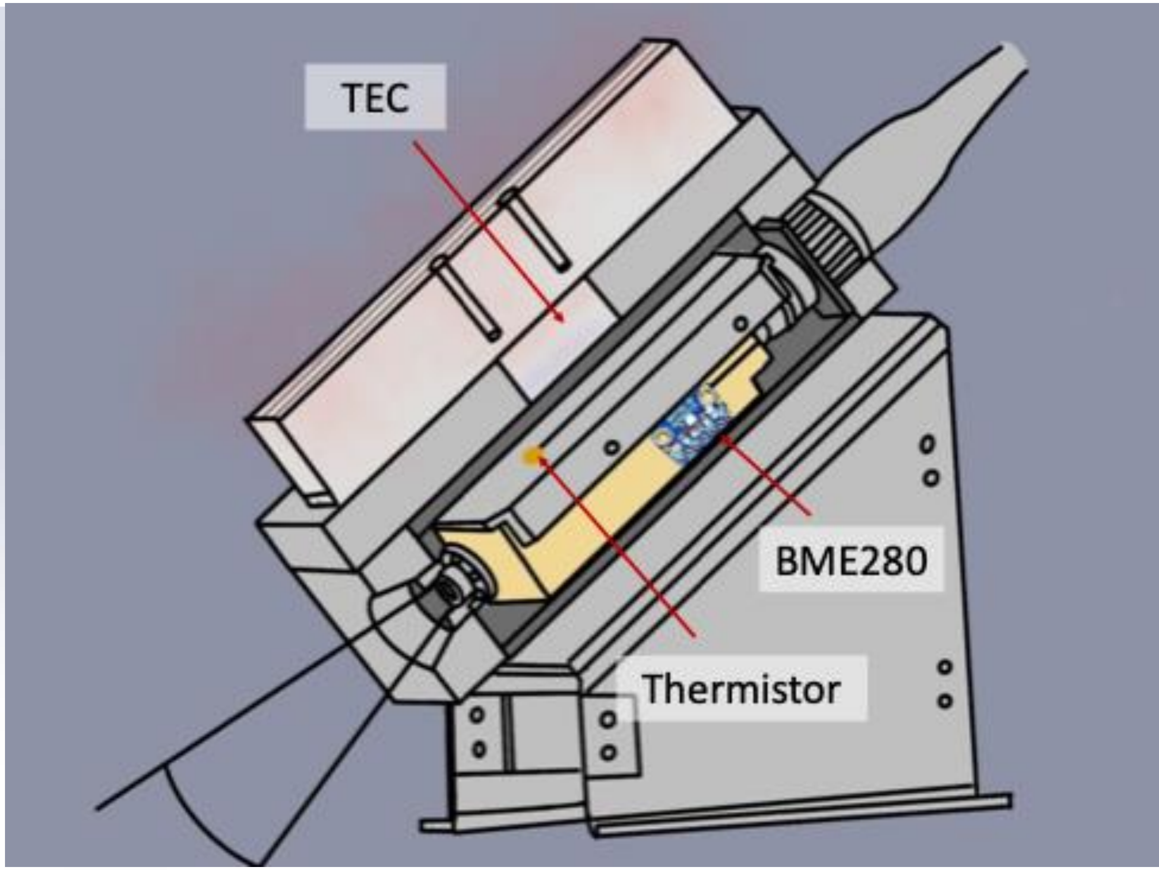


Calculated by sampling an unpolarized blackbody target at many temperatures

Payload Design

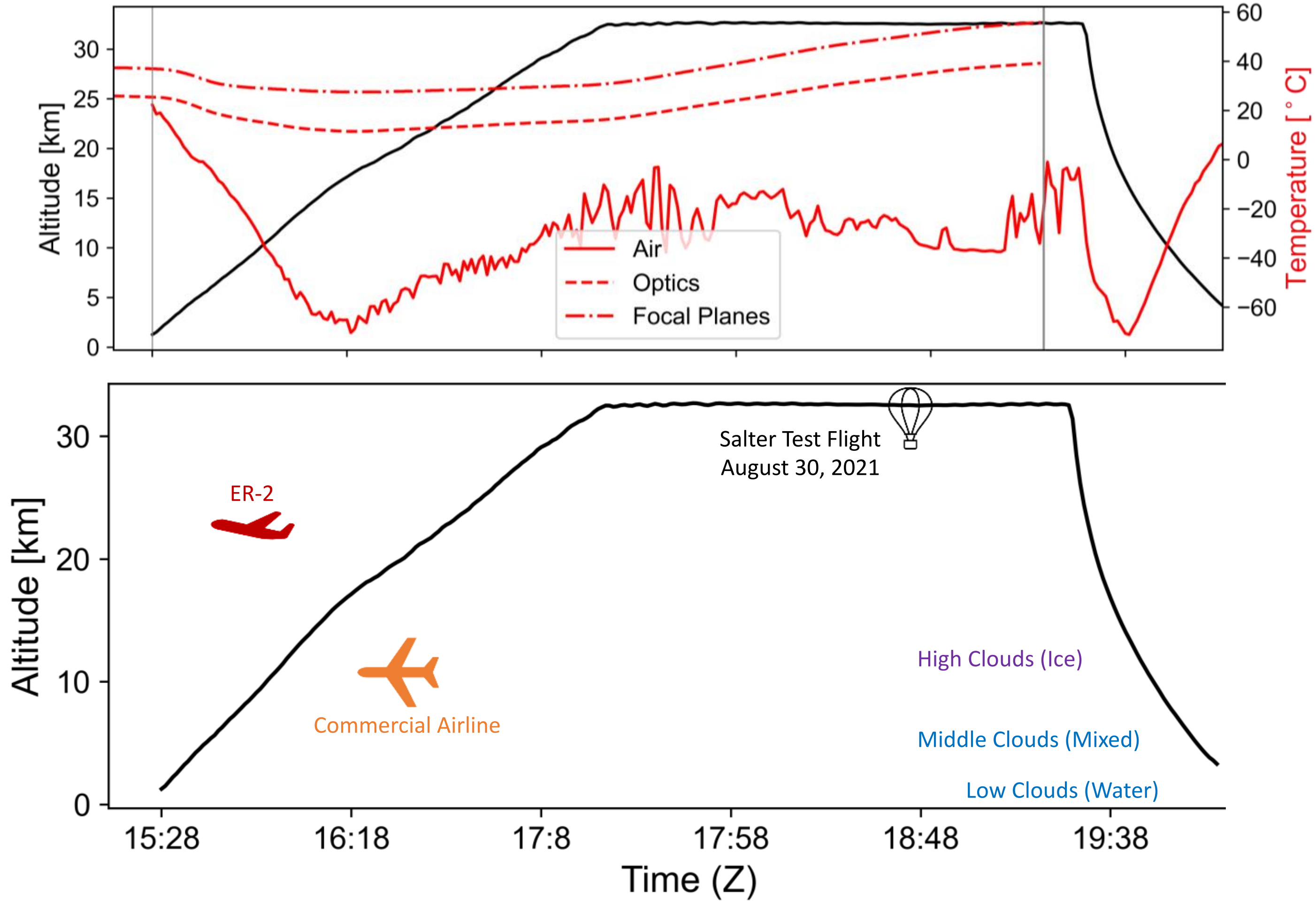


Solidworks Model:
Jeremy Parkinson

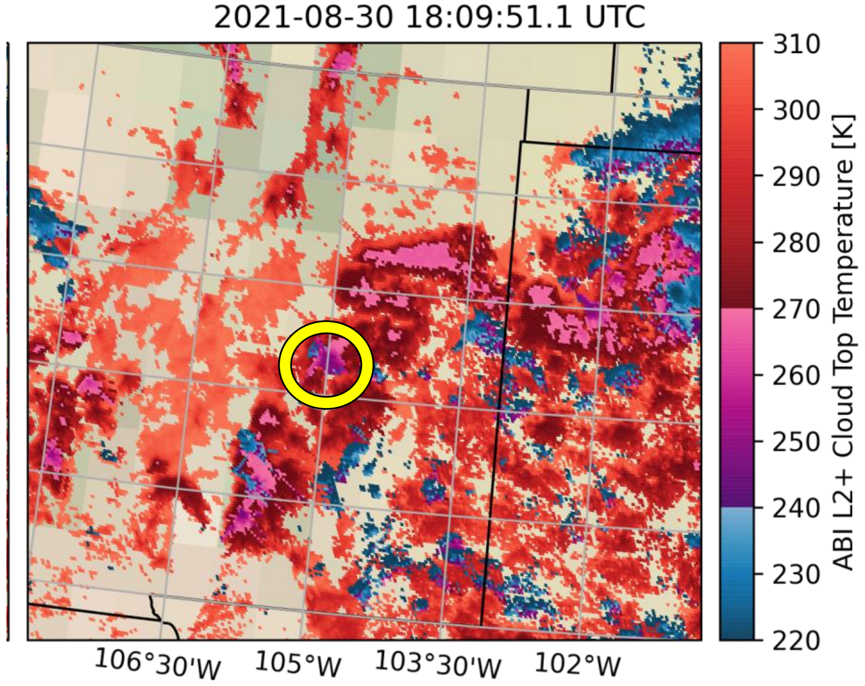


https://github.com/Polarization-Lab/IRCSP-Payload

IRCSP Recorded Telemetry



Cloud Top Temperatures from NOAA's GOES-16 Advanced



ABI Data Sourced From

GOES-R Algorithm Working Group, and GOES-R Series Program (2017): NOAA GOES-R Series Advanced Baseline Imager (ABI) Level 2 Cloud and Moisture Imagery Products (CMIP).[ACHTF-M6]. NOAA National Centers for Environmental Information. doi:10.7289/V5736P36.