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IRA A. FULTON SCHOOLS OF engineering
ARIZONA STATE UNIVERSITY

Yao Group: Nanoscale Optoelectronics Lab

Toward Autonomous Field Inspection of CSP Collectors with a Polarimetric Imaging Drone

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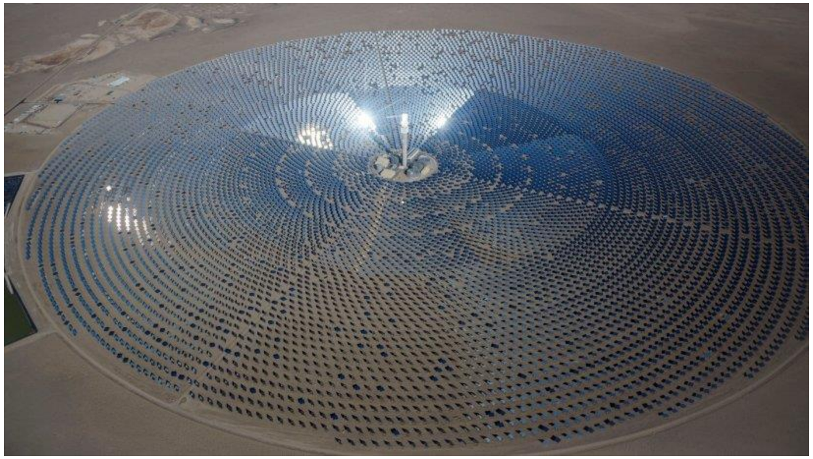
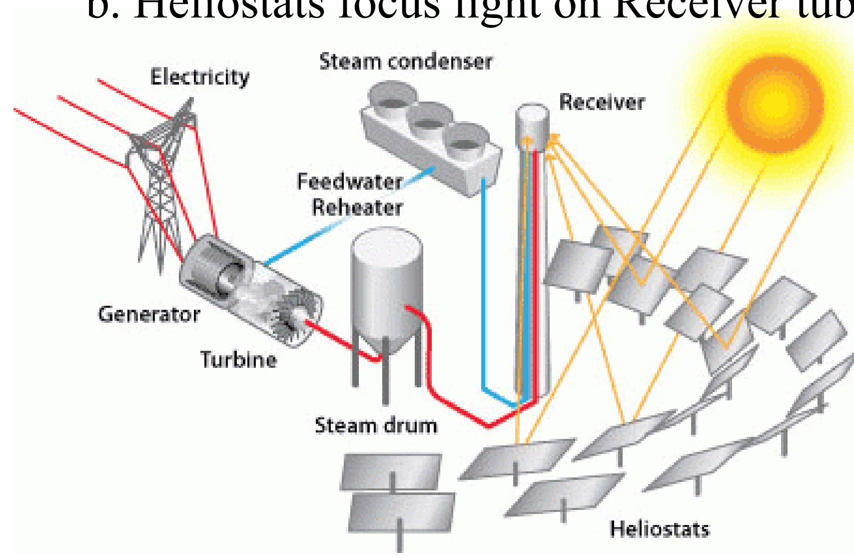
Background

a. Concentrated Solar Power (CSP) plant



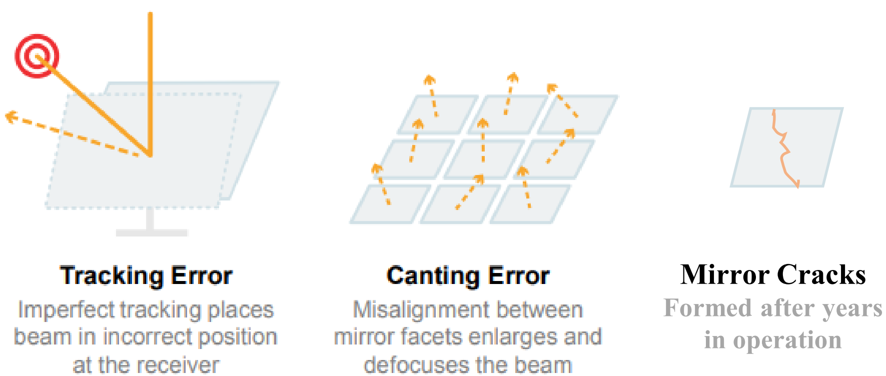
https://www.energy.gov/

b. Heliostats focus light on Receiver tubes



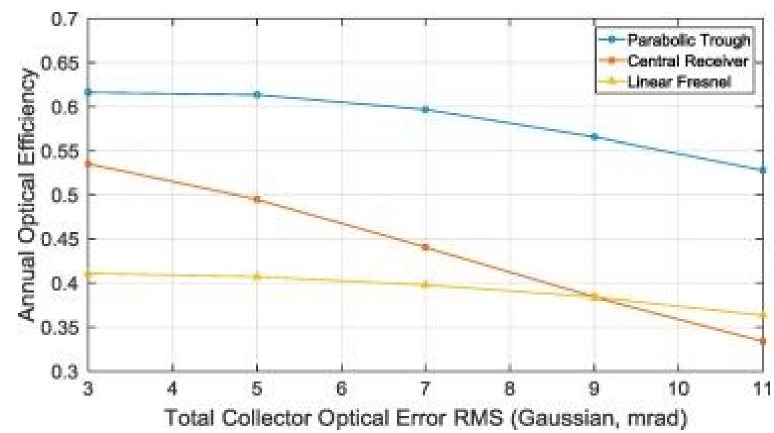
https://www.energy.gov/

c. Optical Error and Mirror Cracks



Steve Schell, Heliogen, https://www.energy.gov/

d. Optical efficiency influenced by optical errors



N. Kincaid, G. Mungas, N. Kramer, M. Wagner, G. Zhu, Applied Energy (2018)

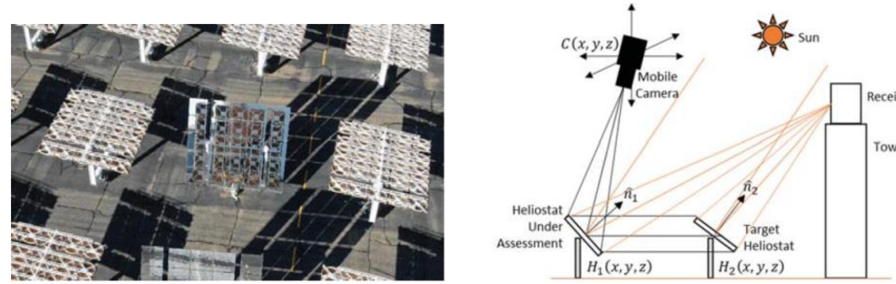
Motivation

www.cspservices.de/performance-testing/

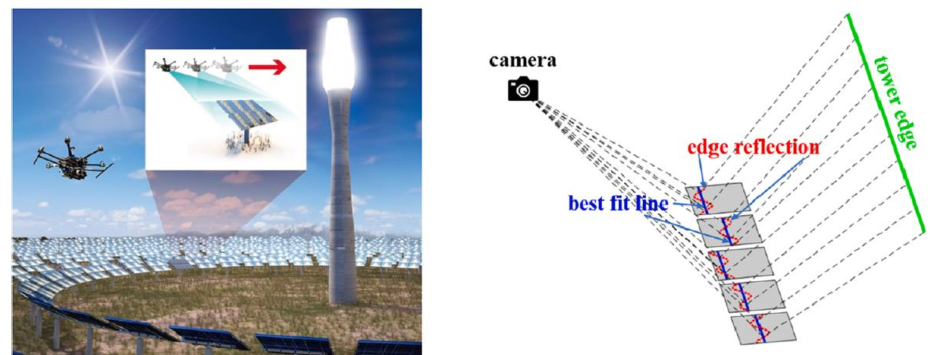
Manual inspection: High cost, slow, intrusive to field operation

Credit: DLR (CC-BY-NC-ND 3.0)

UAV based inspection: Less cost, more efficient, non-intrusive



J. Yellowhair, P. A. Apostolopoulos, D. E. Small, D. Novick, and M. Mann , "Development of an aerial imaging system for heliostat canting assessments", AIP Conference Proceedings 2445, 120024 (2022)



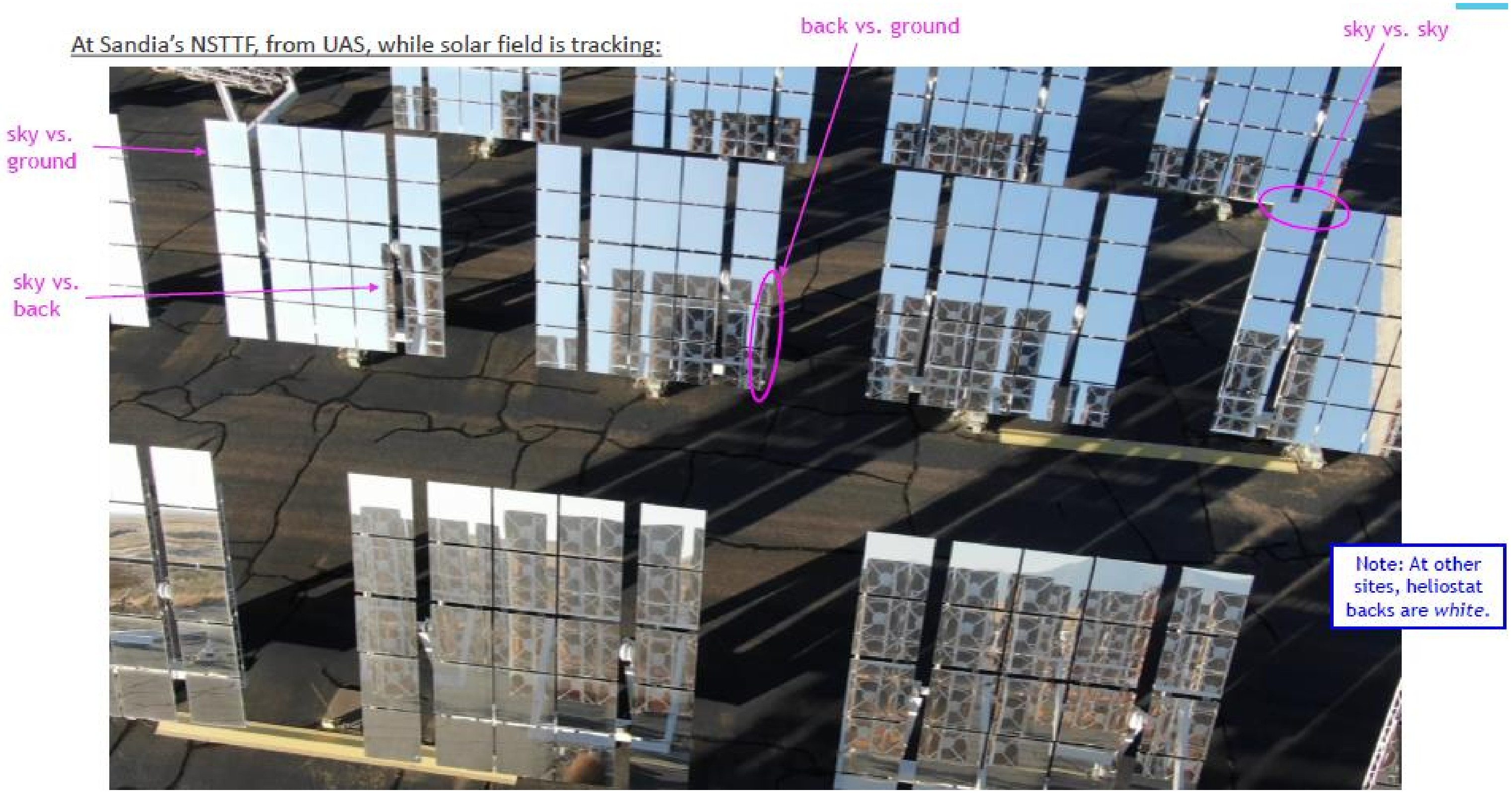
(a) (b)

R. A. Mitchell, G. Zhu, "A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Methodology and in-situ validation"Solar Energy (2020)

- Both rely on visible camera
- Need to detect the mirror edges

Motivation

- UAV-based survey of the field relies on visible camera; need to detect the edges
- Challenges in differentiate the mirrors from the background with visible camera
- Polarimetric imaging is a useful aid to help find the edges in these cases
- Future work can be image fusion with polarization camera and visible camera



Randy Brost, Sandia

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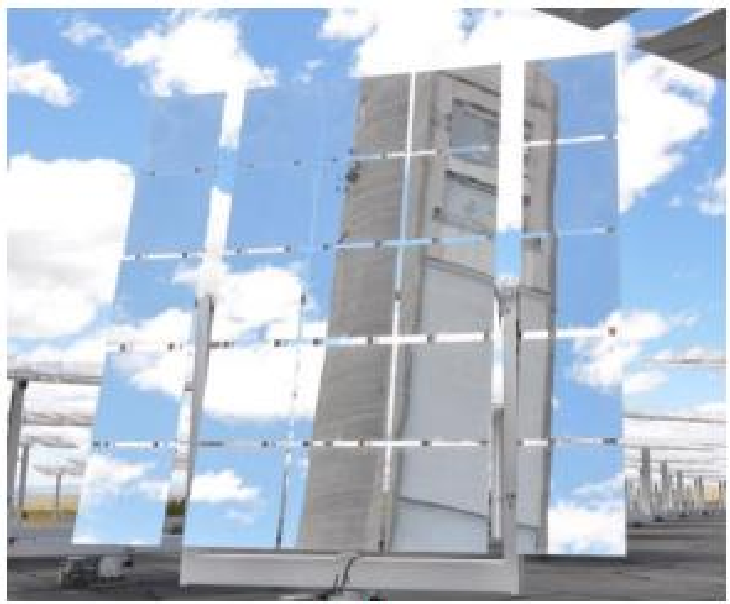

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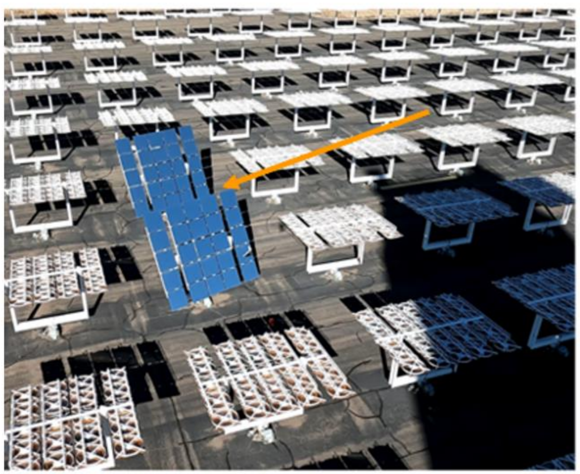
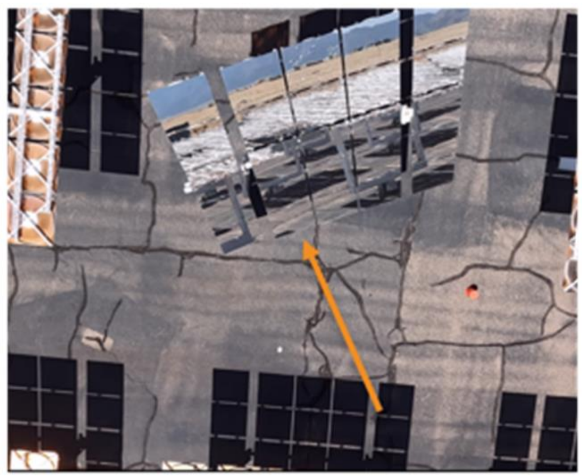
Sky-vs-Sky



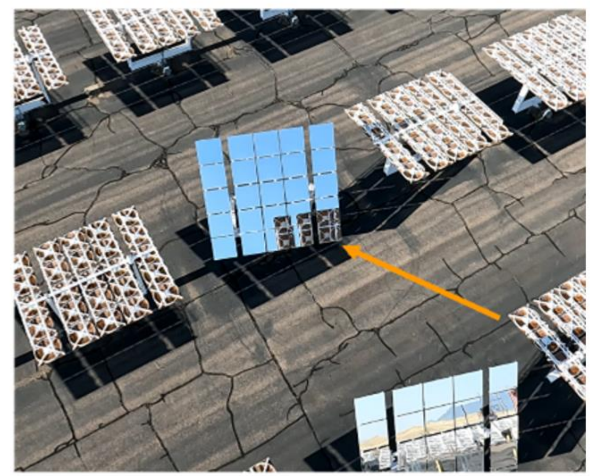
Low contrast between adjacent heliostat mirrors

Ground-vs-Ground



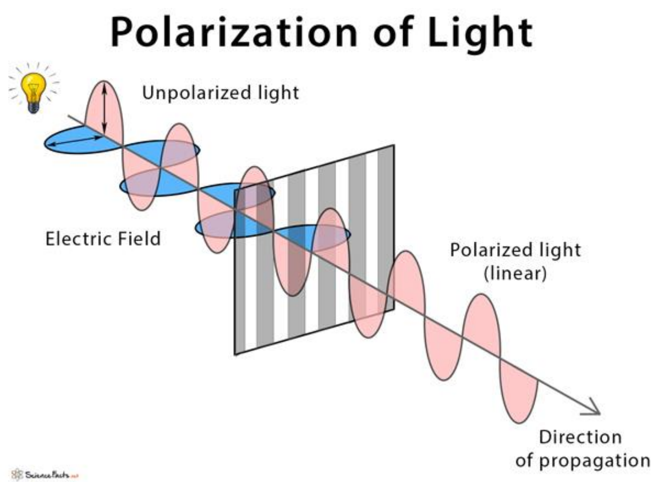
Low contrast between heliostat and adjacent background

Back-vs-Ground

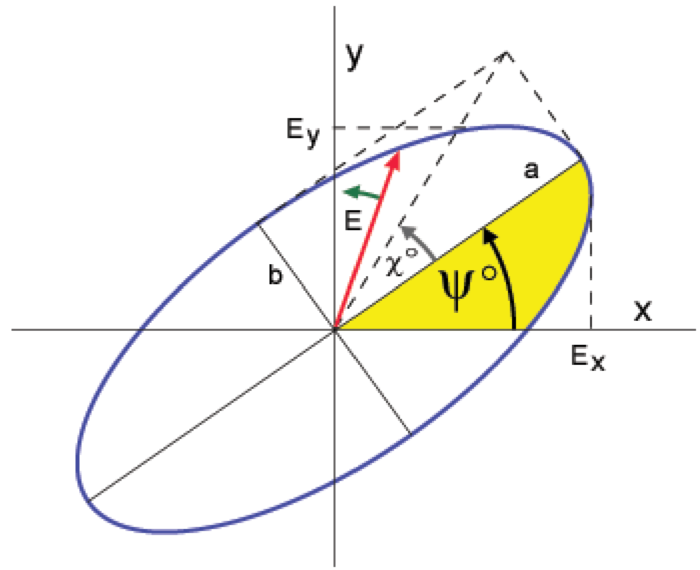


Low contrast between heliostat reflection and adjacent background

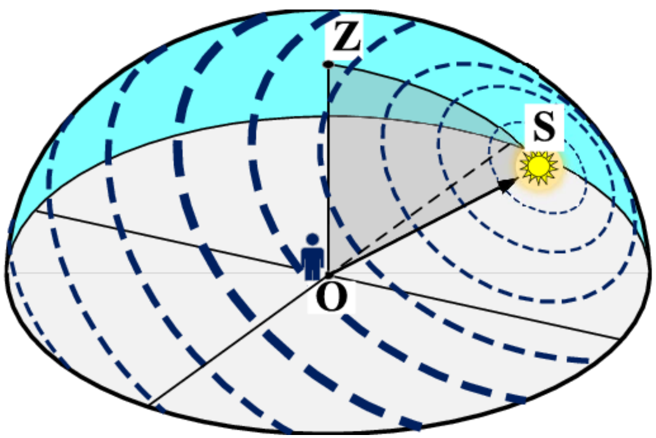
Polarization of the Light



www.sciencefacts.net

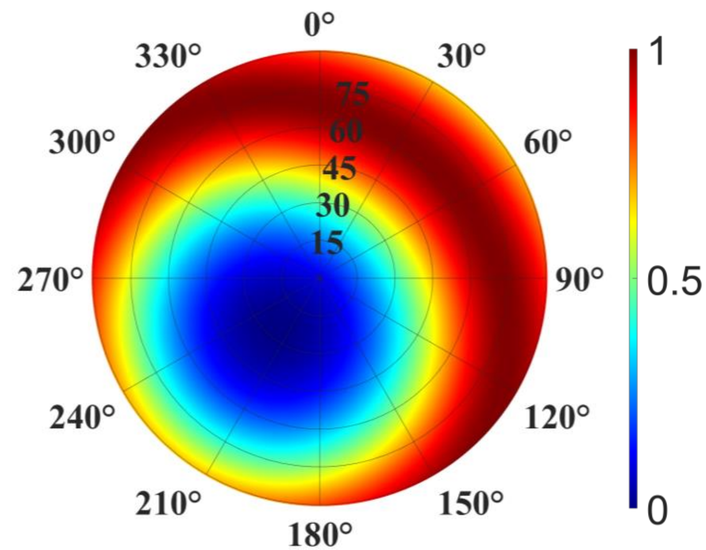


www.nrcan.gc.ca

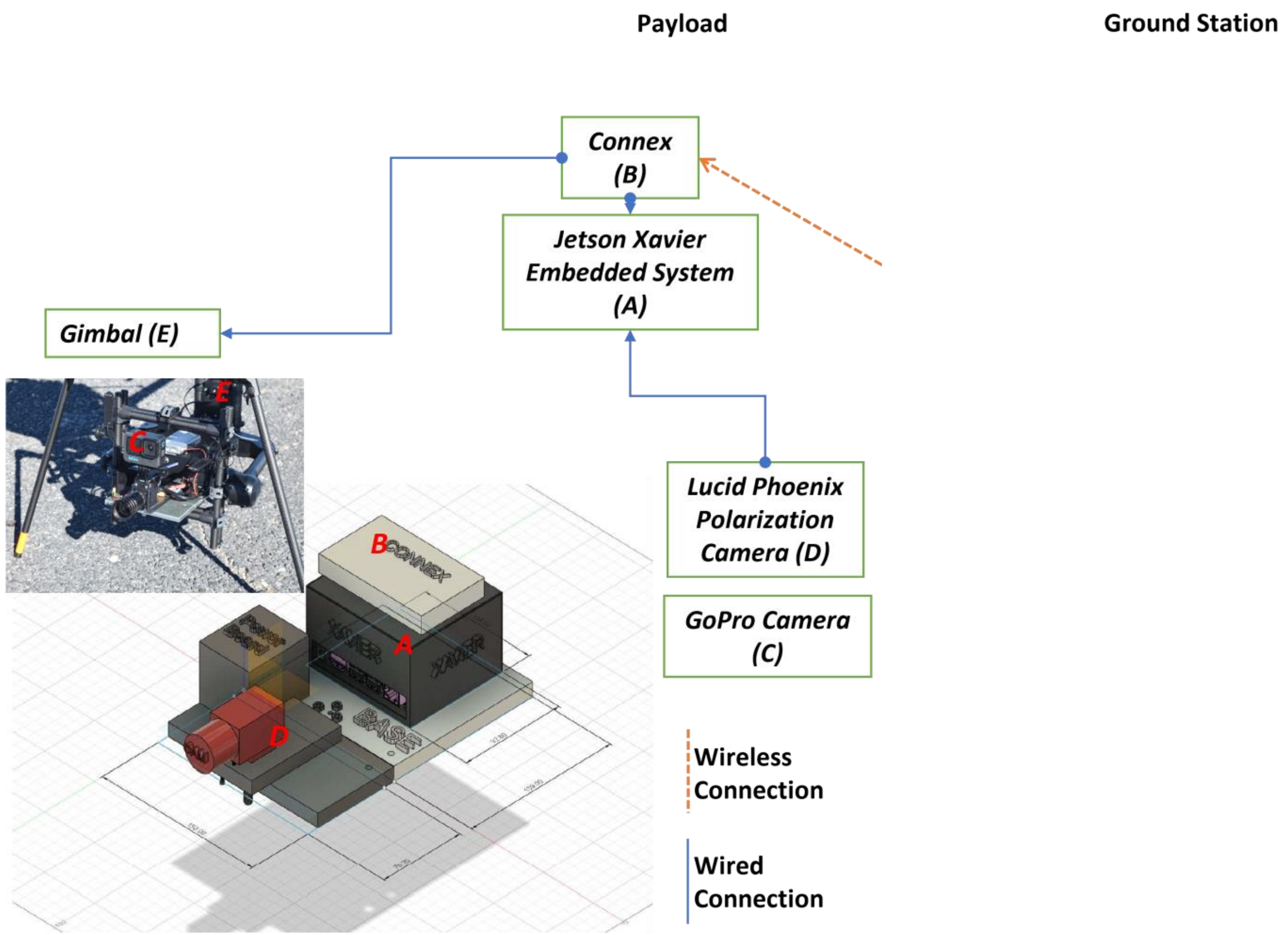


Jing, Zhang & Cao, Yu & Zhang, Xuanzhe & Liu, Zejin. (2015). Sky light polarization detection with linear polarizer triplet in light field camera inspired by insect vision. Applied Optics. 54. 8962.

Degree of Linear Polarization



Unmanned Aircraft System Polarimetric Imaging Setup



- 19 FPS streaming for operator to control
- Adaptive exposure algorithm to avoid over-exposure
- Capture image with remote control

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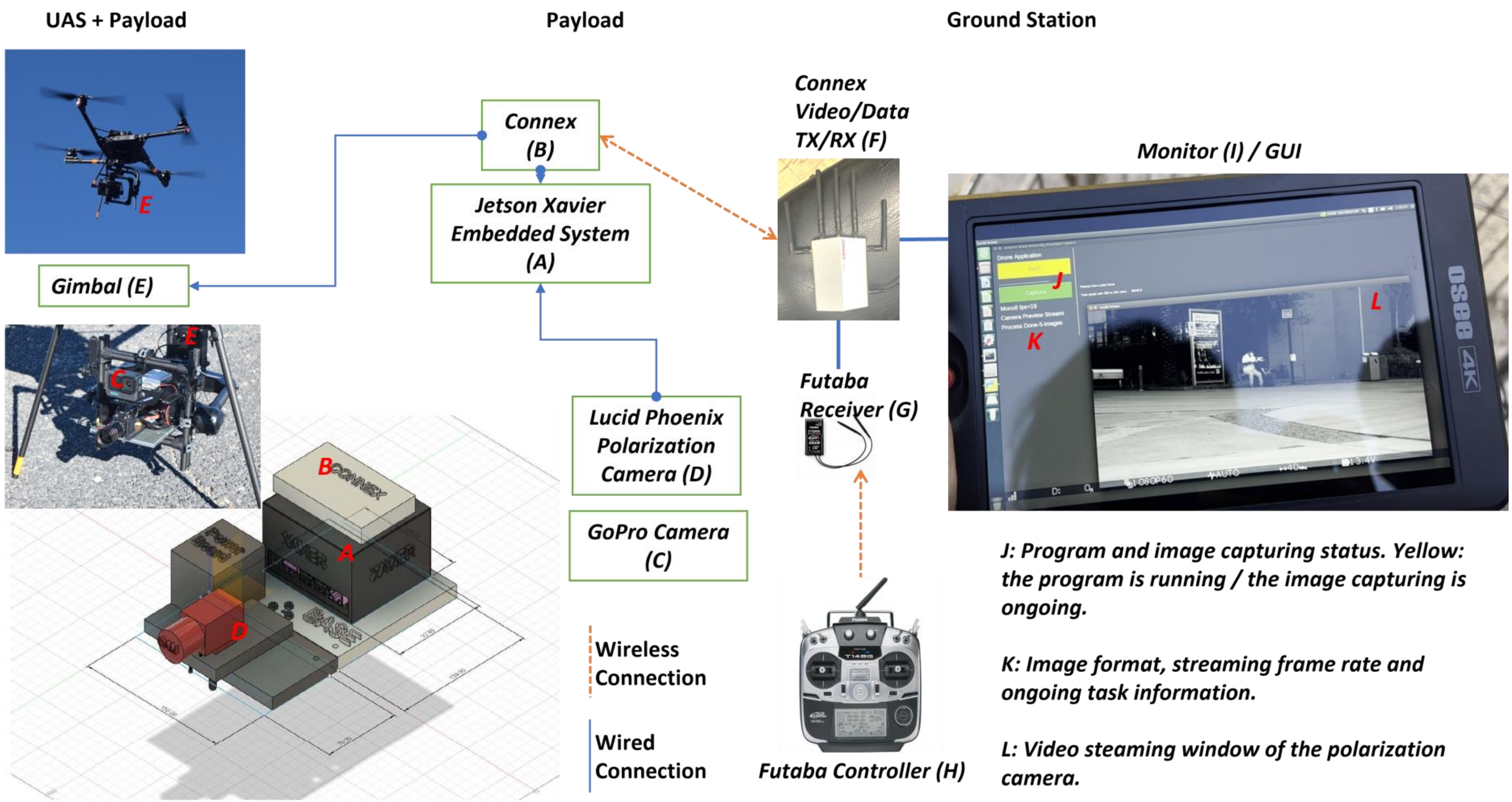
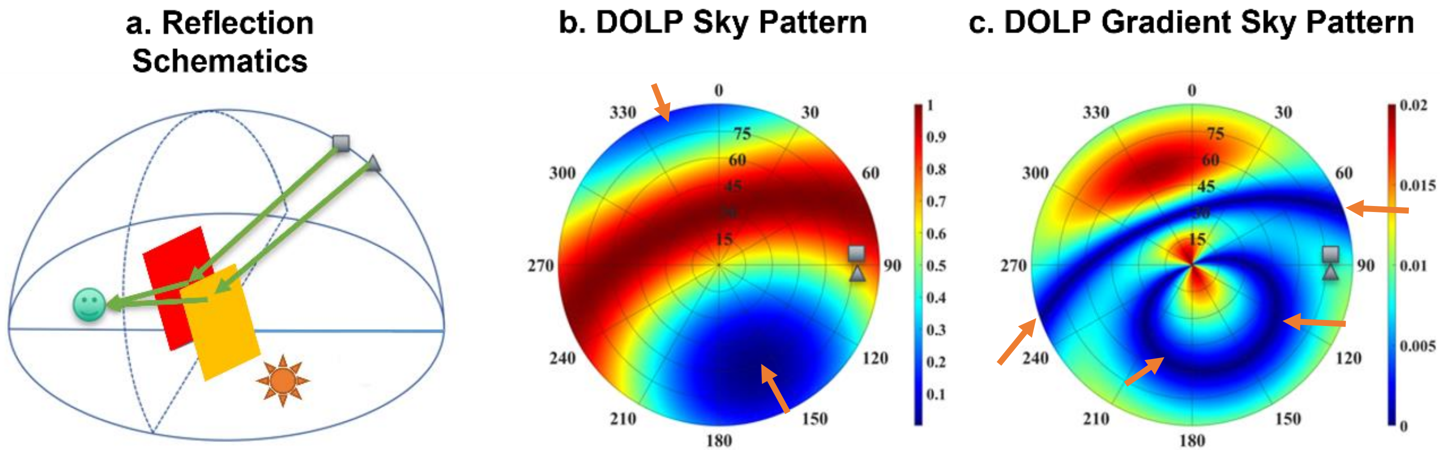


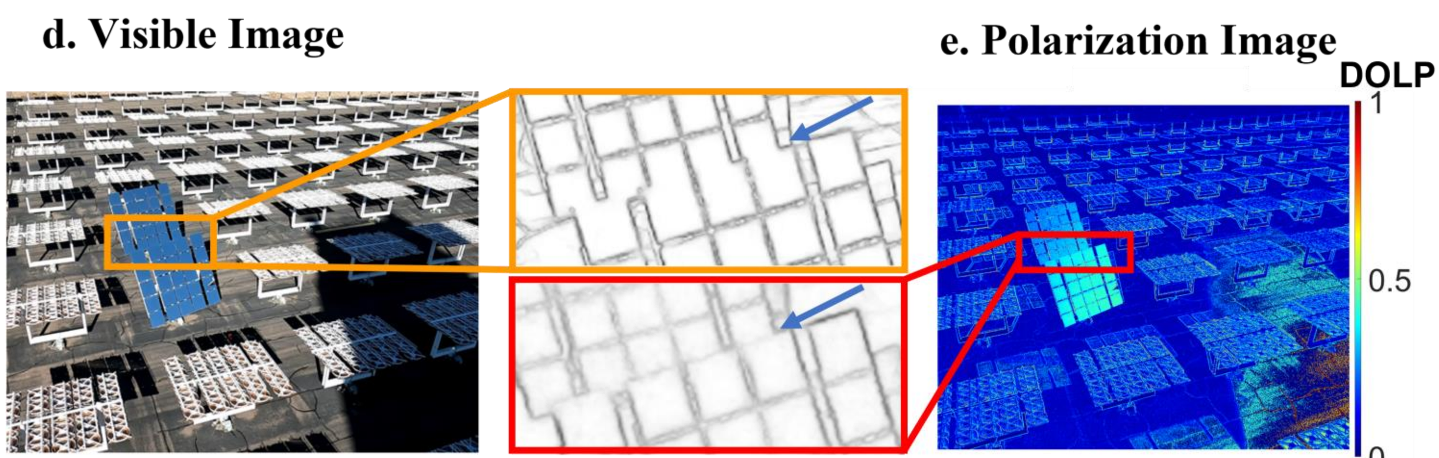
- 19 FPS streaming for operator to control
- Adaptive exposure algorithm to avoid over-exposure
- Capture image with remote control

Results: Sky-vs-sky

With Rayleigh scattering model, we can predict the sky polarization pattern, for Degree of Linear Polarization.



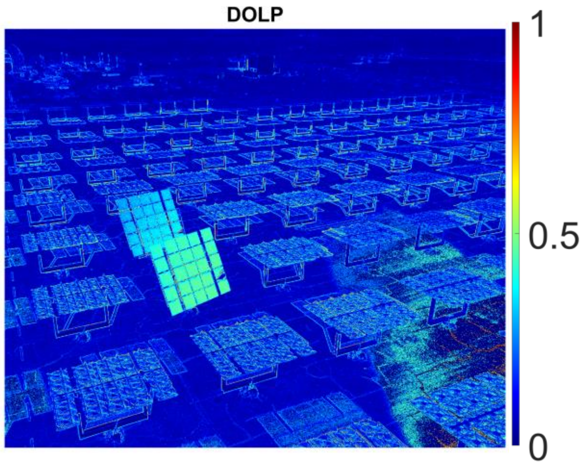
We can plan the flight such that mirror are reflecting region of sky where DoLP changes fast (high DoLP gradient), the small angle difference between adjacent heliostats result in different DoLP values. Arrows indicating the region that will not serve our purposes.

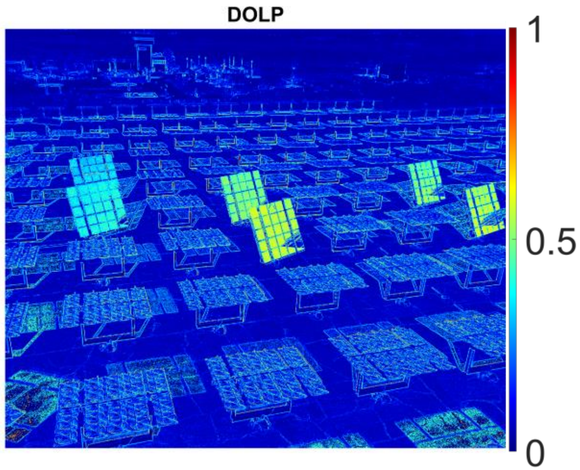


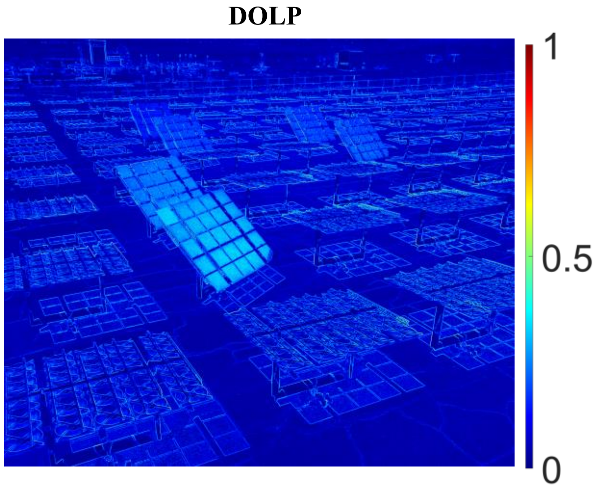
Results: Sky-vs-sky

Test Date	Successful	Unsuccessful	Total Images	Success Rate
Dec 16th, 2021	36 sets	4 sets	40 sets	90%
Apr 28th, 2022	72 sets	6 sets	78 sets	92.31%
All	108 sets	10 sets	118 sets	91.53%

We counted the edges that were manually identified as sky-vs-sky and report the number that were found. If the number agrees with the ground truth of the heliostats, we count this as a successful detection.





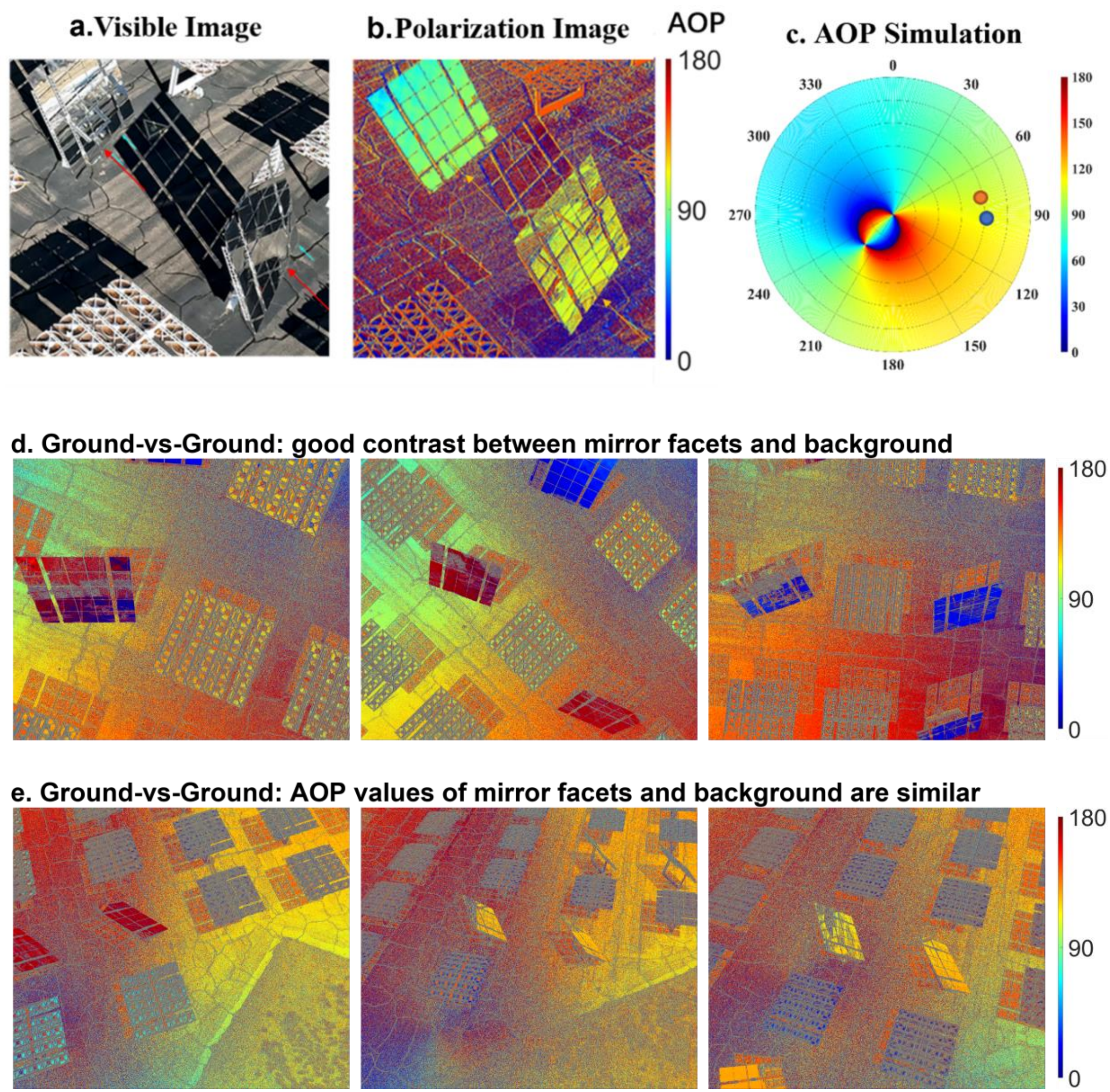


Results: Ground-vs-Ground

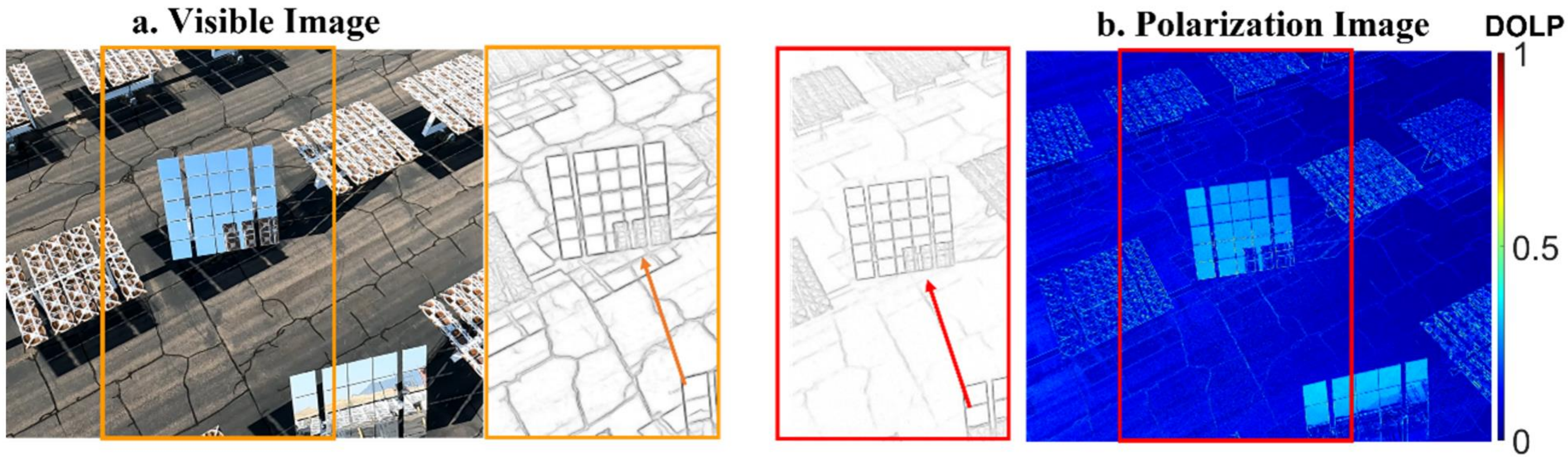
We observed that Angle of Polarization shows good contrast of heliostats vs. background.

The values of the background AoP and the heliostat mirror AoP determine the contrast.

Future Plan: develop scattering model to predict the polarization images of ground. One can position and point the drone in precalculated directions for sufficient contrast (difference in AOP) between mirrors and the background to achieve high accuracy of detection.



Results: Back-vs-Ground



- Visible Image: various features in the background make it difficult to detect the edges
- Polarization Image: easier to single out the mirror facets.

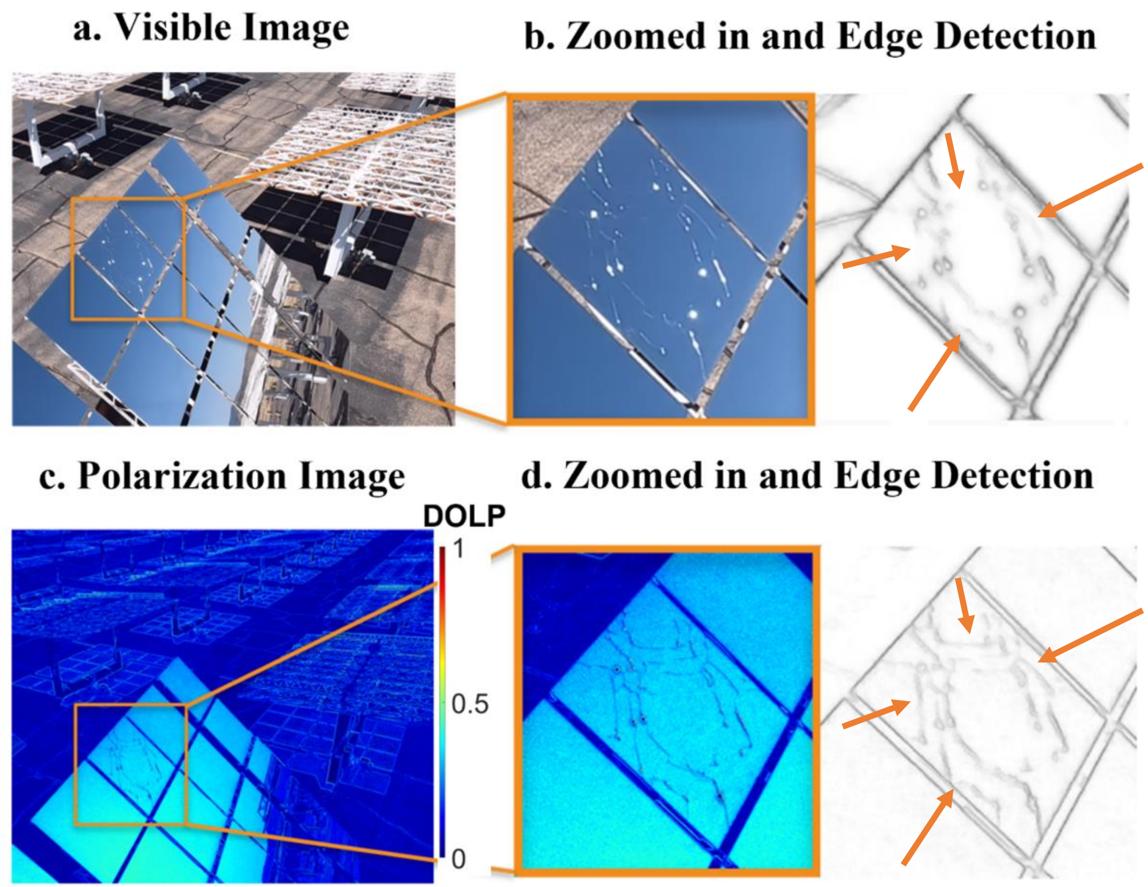
- Some commercial plants have heliostats with white frames. It could be challenging for visible cameras to differentiate their images from the background of the same color.

In this case, we expect polarization image to provide sufficient contrast. (We are seeking potential collaborators to test this case.)

Results: Mirror Cracks

Visible Image: the detection of cracks depends on the camera viewing angle and relative position to the Sun incidence.

Polarization Image: the scattering caused by the crack results in low DoLP. Let mirrors reflect high DoLP region of the sky, the contrast is better.



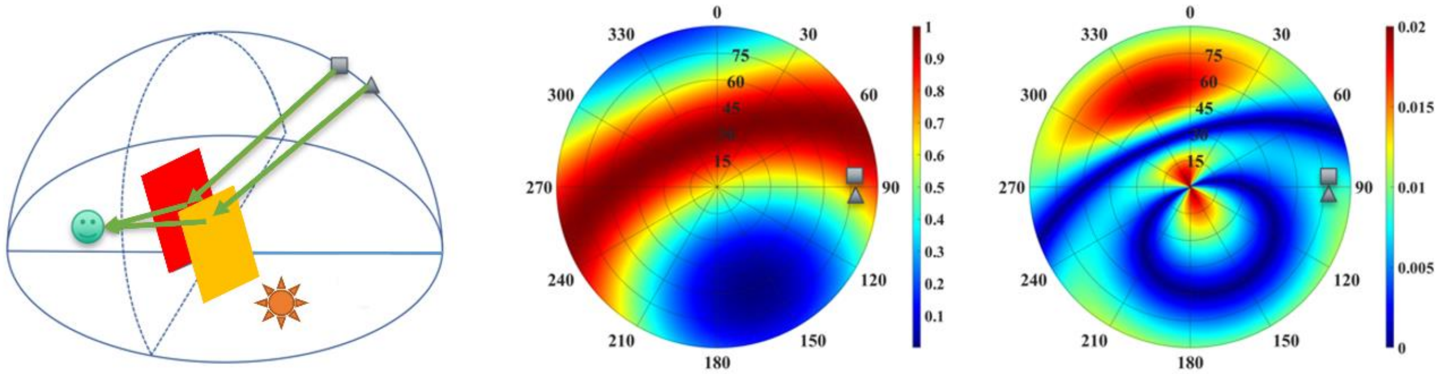
Test Date	Successful	Unsuccessful	Total Images	Success Rate
Dec 16th, 2021	2 sets	N/A	2 sets	100%
Apr 28th, 2022	28 sets	2 sets	30 sets	93.33%
All	31 sets	2 sets	33 sets	93.94%

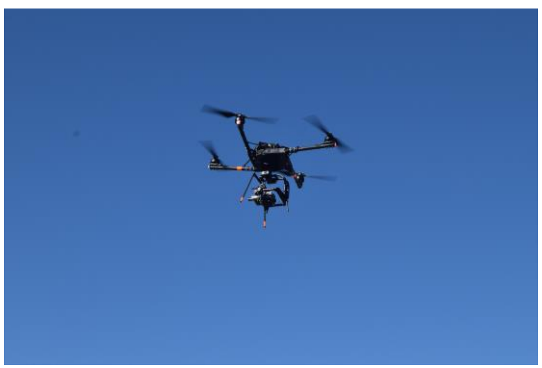
Summary

a. Reflection Schematics

b. DOLP Sky Pattern

c. DOLP Gradient Sky Pattern





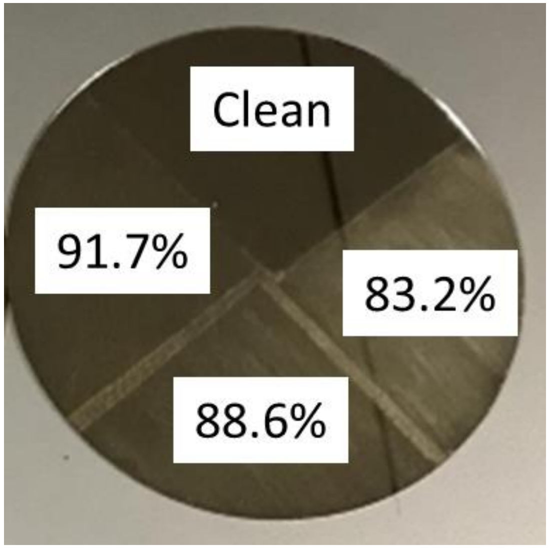
- We integrated a polarimetric imaging system on UAS
- We can plan the flight to collect desired polarization images with good contrast
- In future, we plan to
    - Integrate a visible camera for image fusion, adding color and intensity information to the captured images.
    - Apply the polarimetric imaging system for optical error inspection with method such as UFACET, and for mirror cracks detection for early identification of potential heliostat failure.

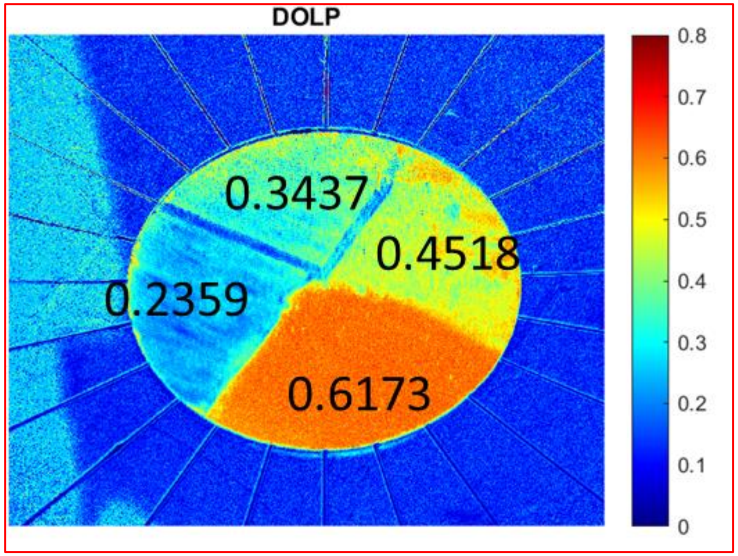
Same system can be used for mirror soiling detection!

Field Deployable Mirror Soiling Detection Based on Polarimetric Imaging

Friday morning 10:30 AM

Emerging and disruptive concepts (*Kiva Auditorium*):





Acknowledgement

We would like to thank Anthony Evans, Kevin Good, Kevin Hoyt, and George Slad for their assistance with data collection during heliostat field and flight operations.