Ultrahigh Resolution Hyperspectral Compressive Imaging Systems with 3D Photonic Integrated Circuits and their applications in Green House Gas Concentration Estimation

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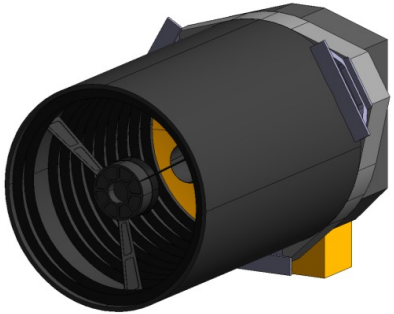
Future Planar Imaging Systems

Orders of Magnitude SWaP and Cost Reduction Achievable for Comparable or much Higher Resolution

Example: MRO HIRISE
0.5 m aperture
0.7m x 1.4m
64.2 kg

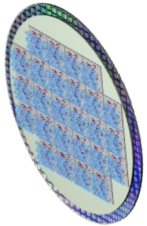


Conventional Telescope and focal plane

Estimate
0.75m x 0.1 m
~ 6kg

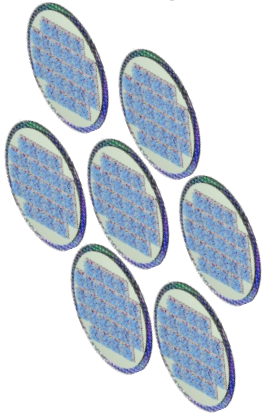
SPIDER Radial Blade
Design: Full sensor replaces conventional telescope

Estimate
0.25m x 0.01 m
~ 0.6kg



SPIDER-VENOM
Design: 3D wafer-scale imager.
SPIDER-BITE is a 22 mm x 22mm Tile of the Wafer

Estimate
4 m x 0.01 m
~ 5 kg



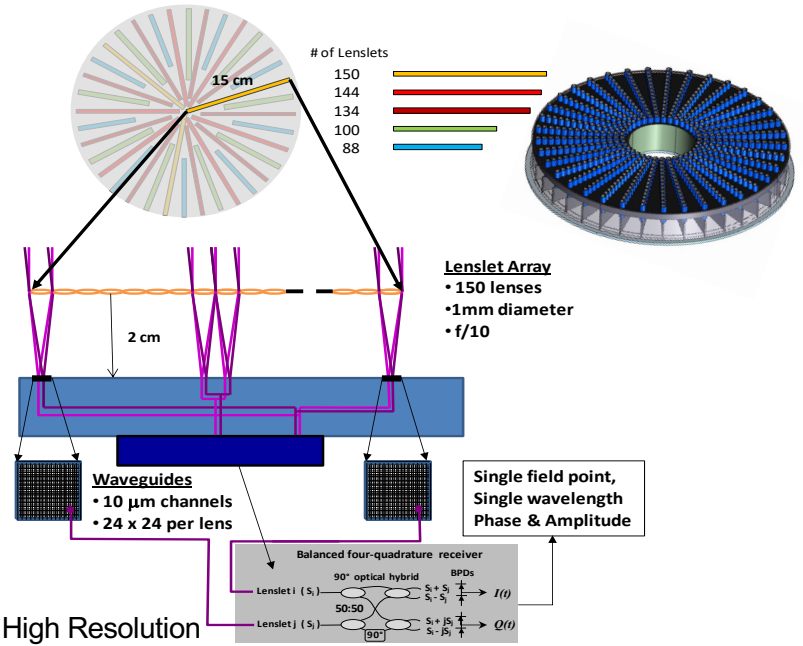
SPIDER-WEB
Design: Multi-Wafer System on a single optical platform or distributed platform

LOCKHEED MARTIN

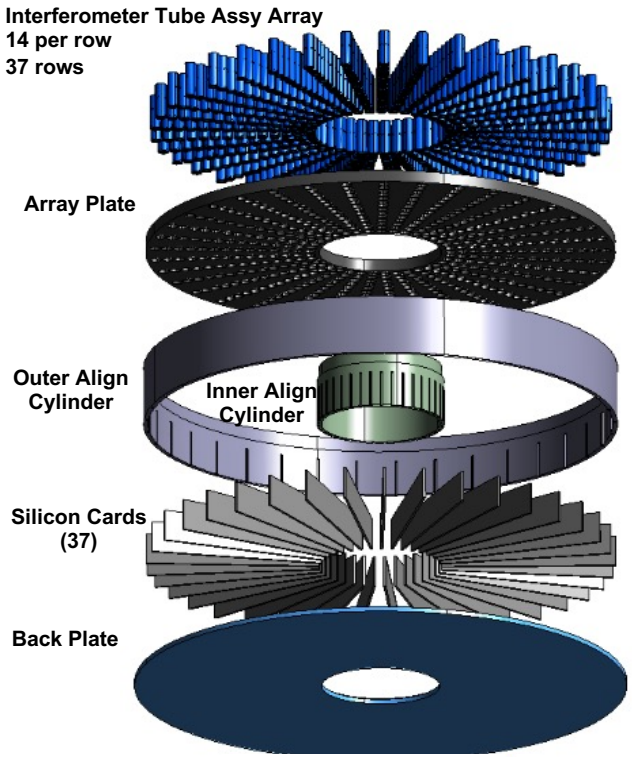
SPIDER: segmented planar imaging detector for electro-optical reconnaissance

ESTO Earth Science Technology Office

Segmented Planar Imaging Detector for Electro-optical Reconnaissance (SPIDER) System Design



Spectrally Resolved High Resolution Interferometric Telescope



System Parameters

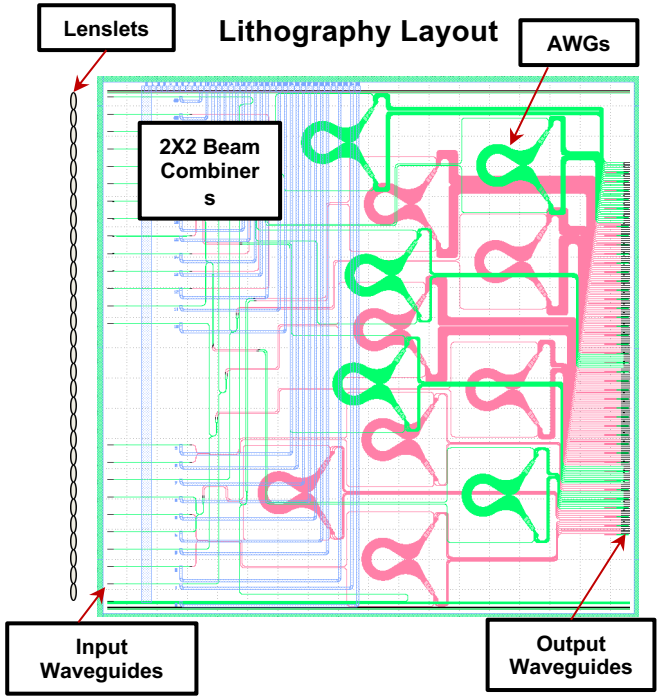
1) $FOV \sim 2.44\,{}^{\lambda}/_{d} \times z$ 2) $D_{eff} = B_{max}$

3) $u_{max} = B_{max}/\lambda_{min}$ 4) $\Delta u = 1/FOV$

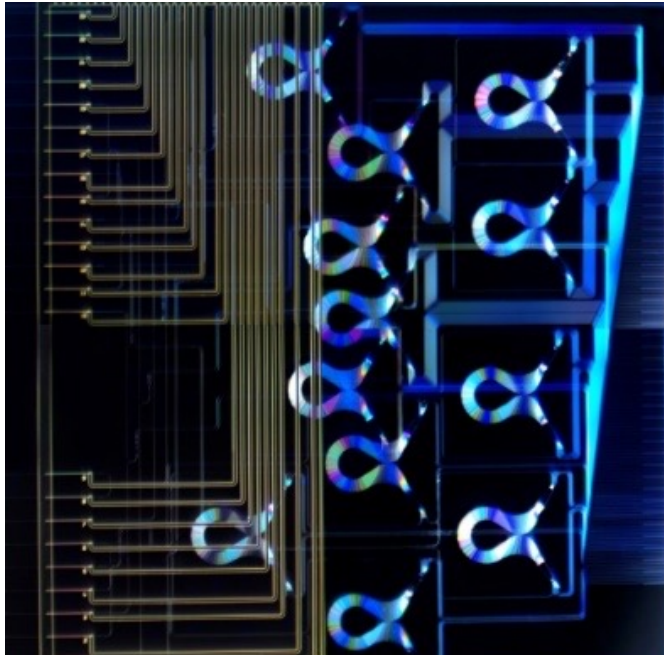
5) $K = {}^{\pi\, u_{max}}/_{\Delta u}$ Intentionally to reduce

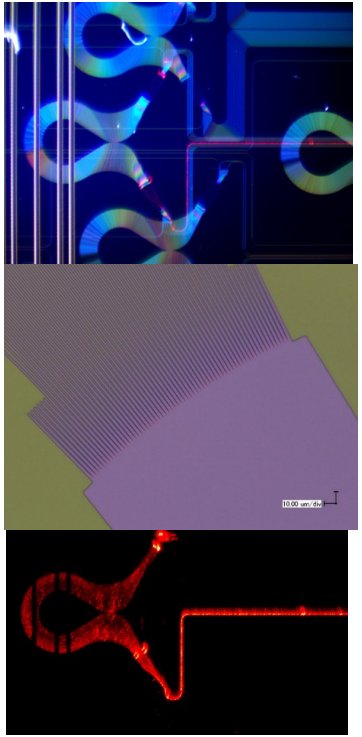
2nd Gen SPIDER PIC (12 baseline, 18 spectral bin) fabricated w/ CMOS Compatible Process @ UC Davis

Lithography Layout

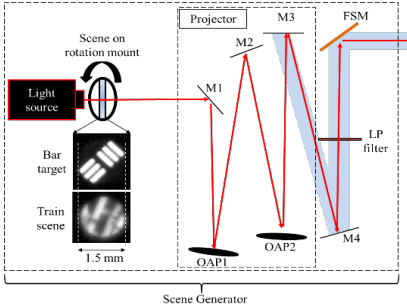


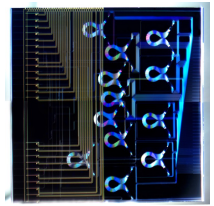
22mm X 22mm die

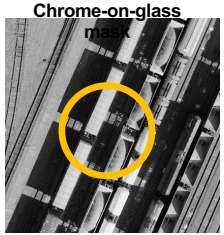


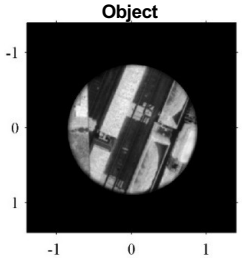


Imaging Reconstruction Experiments – Single Chip Results

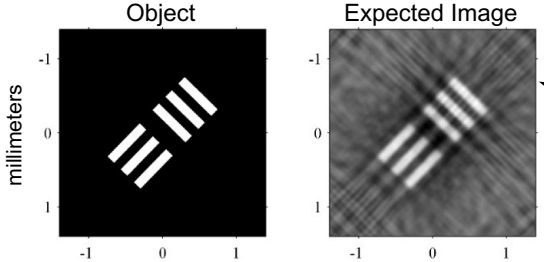




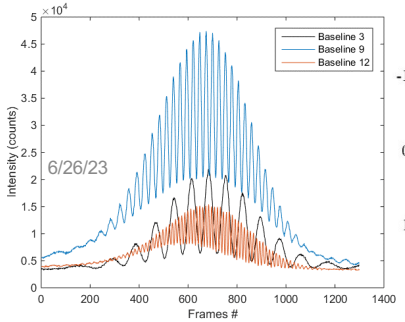


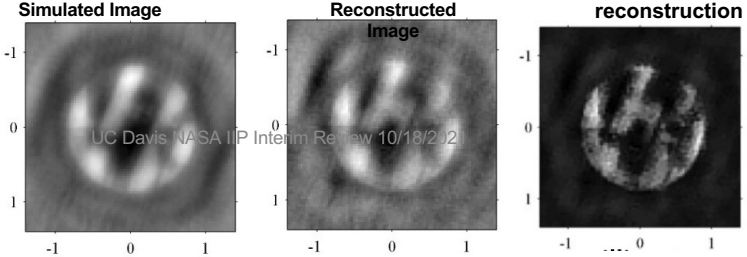


USAF BAR Target



Sparse Fourier sampling artifacts (polar sampling is $\Delta\theta$ = 10 deg)





Provided by Lockheed Martin

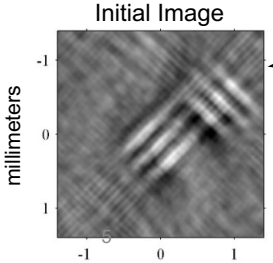
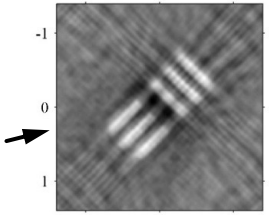


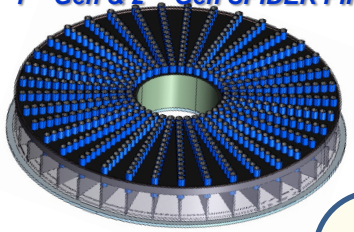
Image is blurred due to wobble in the testbed object rotation stage (this causes phase errors)

Apply linear phase corrections (for each θ) by com paring with simulated data from above

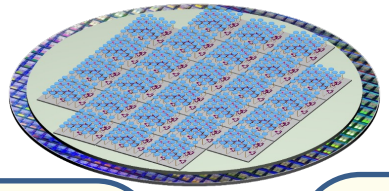


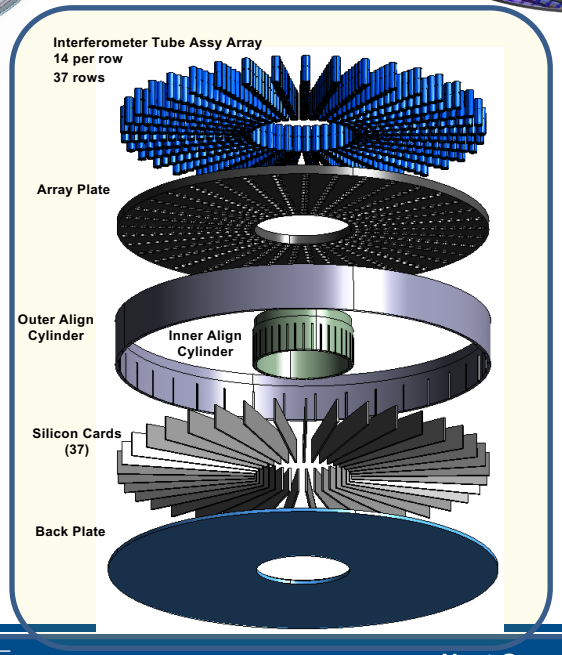
New Directions in SPIDER PIIT

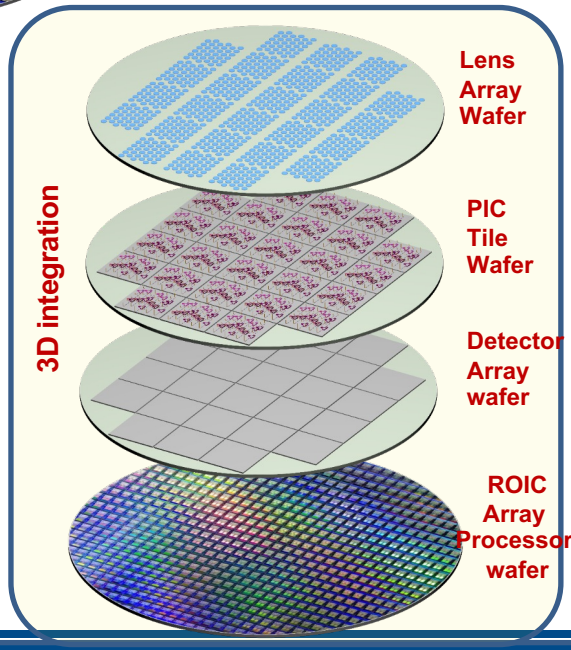
1ST Gen & 2ND Gen SPIDER PIIT



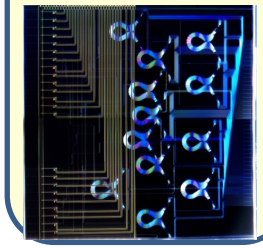
Newly Proposed 3rd Gen SPIDER PIIT







Multi-Layer Si3N4 based interferometric dual-arm AWGs



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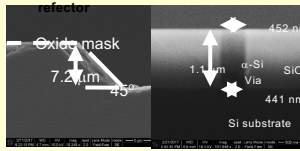
Recently Demonstrated Vertical Light Pipe using 45 degree refector



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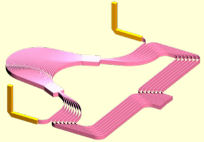
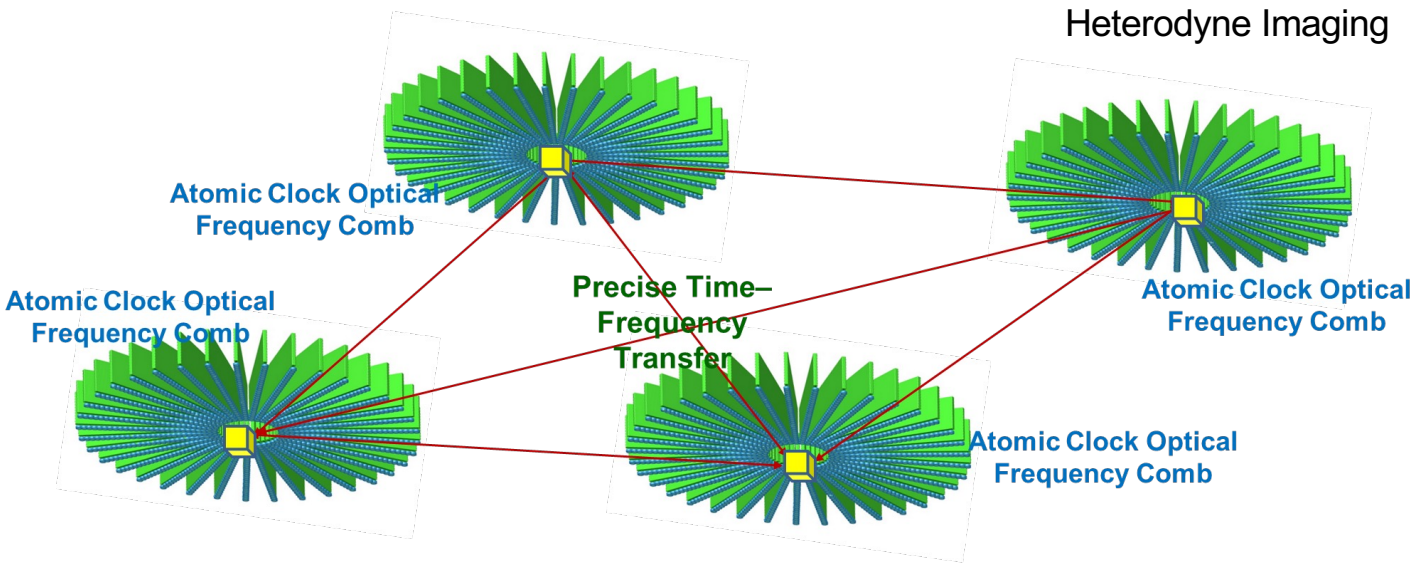
interferometric dual-arm AWGs with Vertical Light Pipes



Synthetic Heterodyne Imaging with Phase-Locked Atomic Clock Optical Frequency Combs

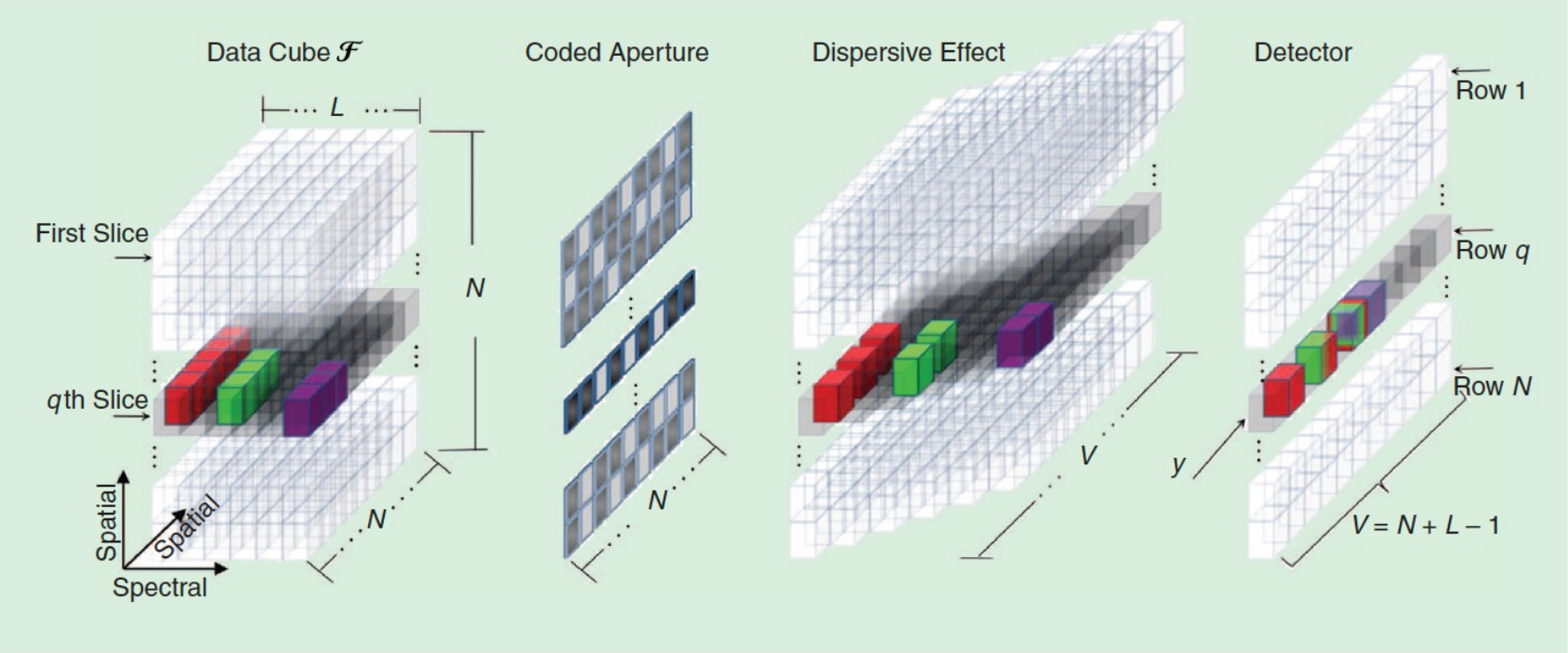


Multiple units of heterodyne interferometric imaging telescopes with phase-locked atomic clock optical frequency combs for synthetic interferometric imaging with extremely high spatial resolution.

S J B Yoo: US Patent : Achieving ultra-high resolution heterodyne synthetic imaging across multiple platforms using optical frequency comb sources : US9995581B2

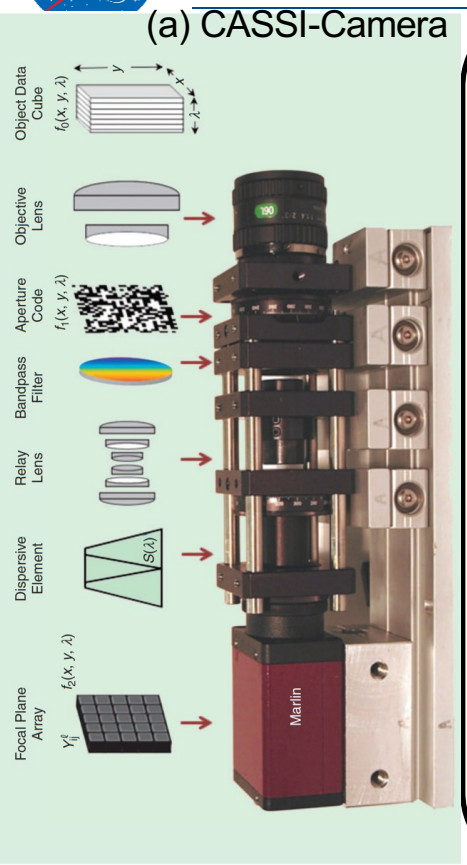
https://patents.google.com/patent/US9995581B2/en

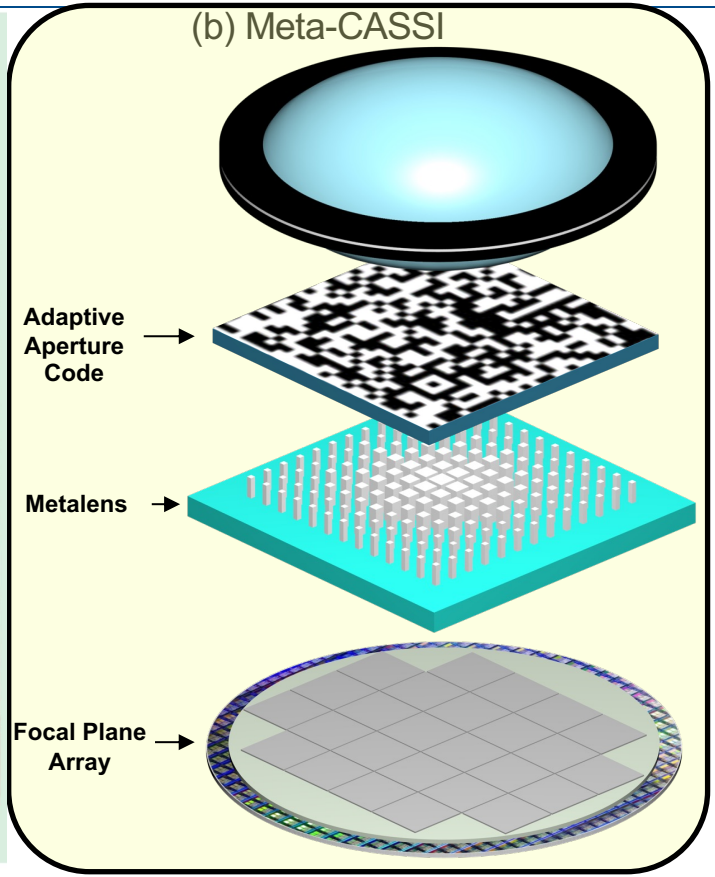
Compressive Imaging

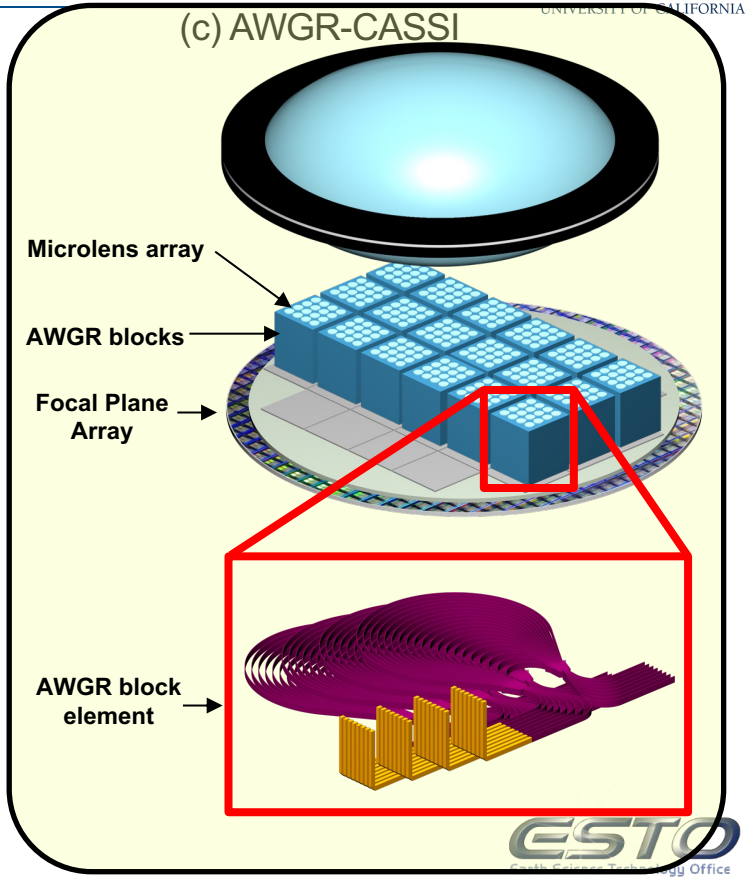


G. R. Arce, D. J. Brady, L. Carin, H. Arguello, and D. S. Kittle, "Compressive coded aperture spectral imaging: An introduction," *IEEE Signal Process. Mag.*, vol. 31, no. 1, pp. 105–115, 2014, doi: 10.1109/MSP.2013.2278763.

CODED APERTURE SNAPSHOT SPECTRAL IMAGERS (CASSI)







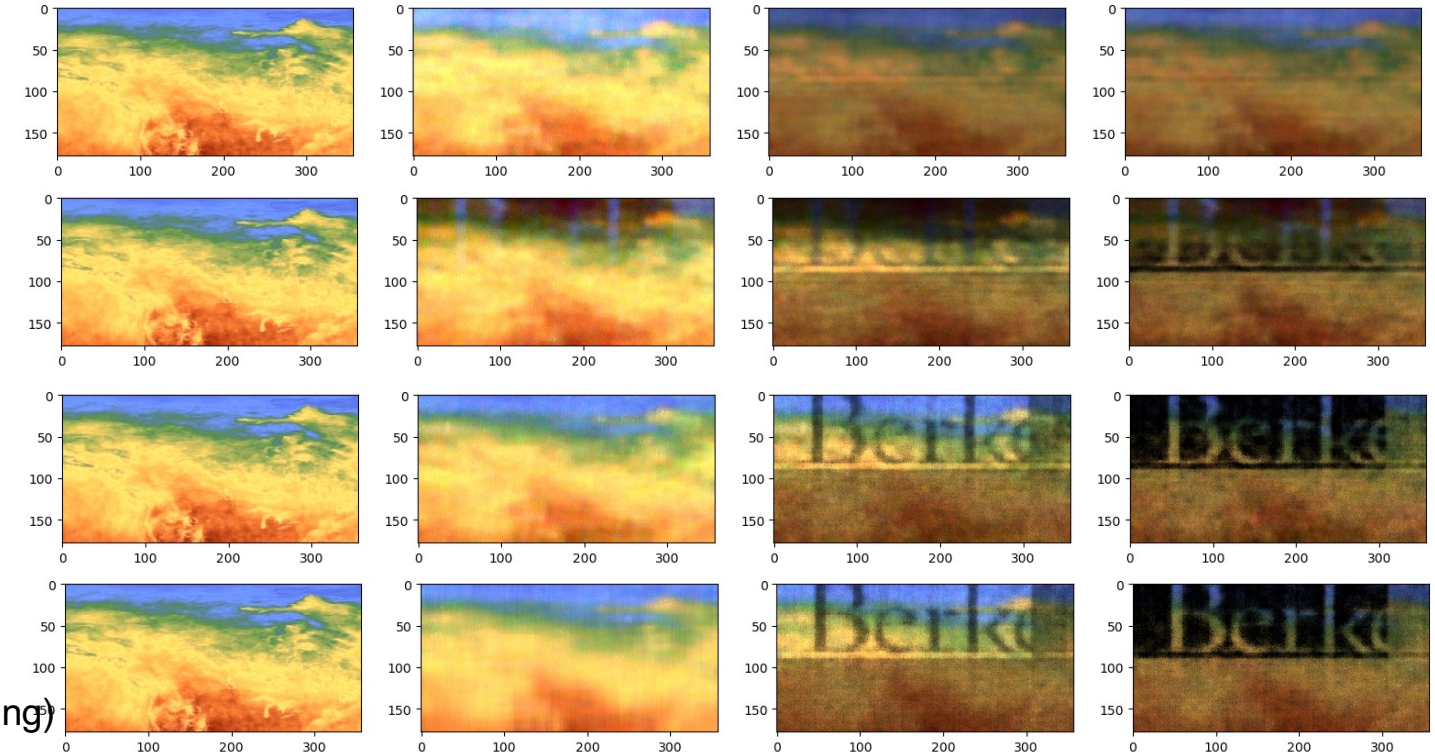
Simulation Experimental Results

1/12 FSR Dispersion

2/12 FSR Dispersion

4/12 FSR Dispersion

12/12 FSR Dispersion (Not compressing)



Orig. Image | Recov. Image | Recov. TE Image | Recov. TM Image

Proposed CASSI Green House Gas Estimation System

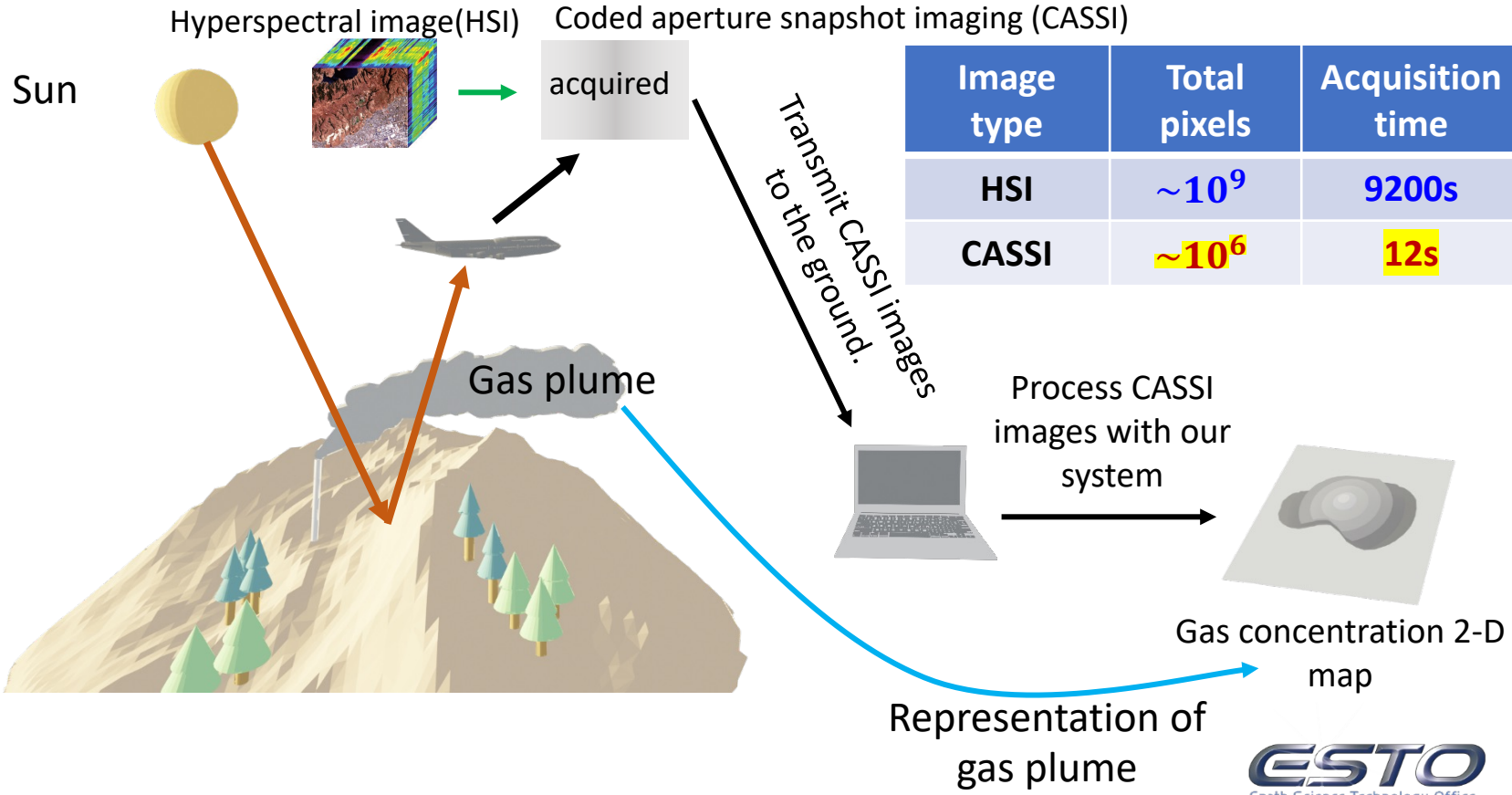
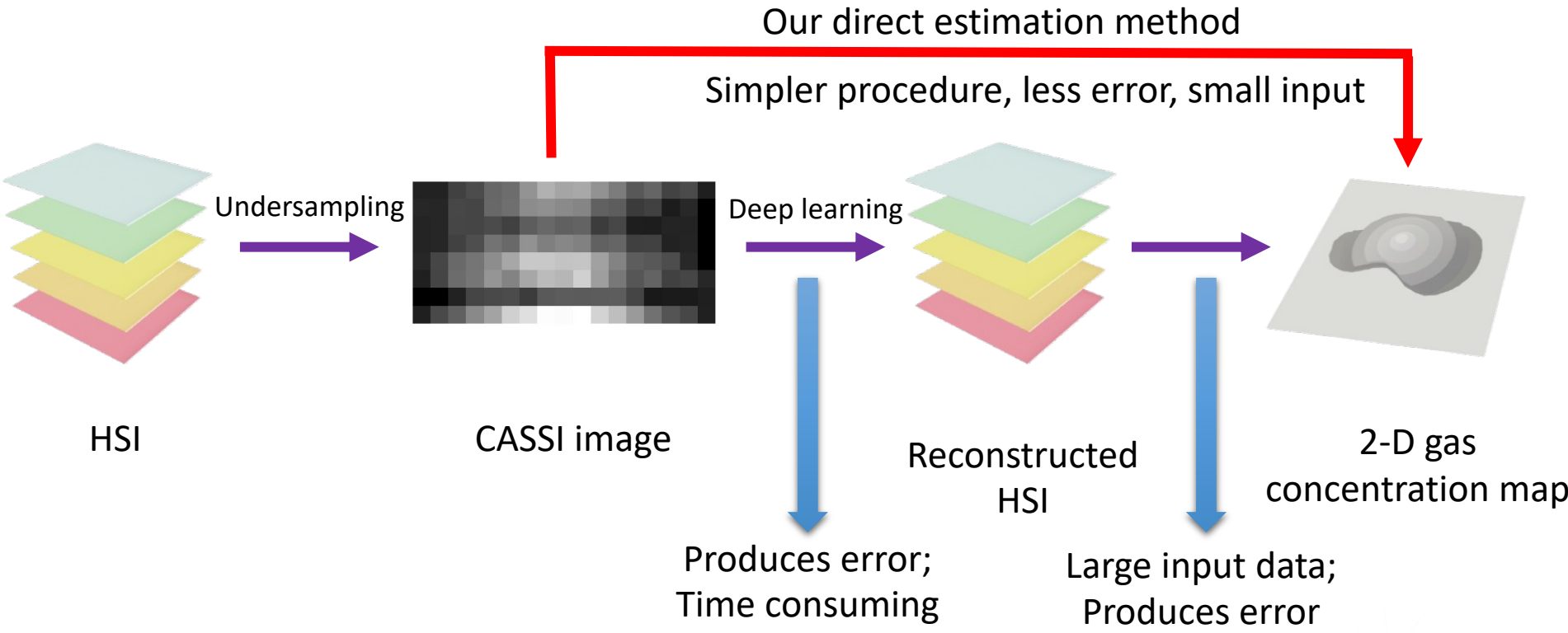


Image type	Total pixels	Acquisition time
HSI	$\sim 10^9$	9200s
CASSI	$\sim 10^6$	12s

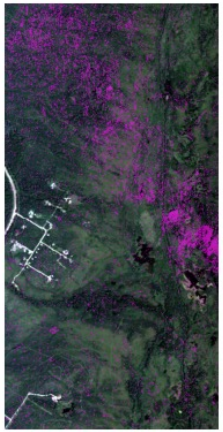
ESTO
Earth Science Technology Office

Proposed CASSI Method vs. Conventional CASSI Method



Challenge Problem: gas (CH_4) absorption estimation

Spectral band range A 1829nm – 2179nm	Spectral band range B 2179nm – 2430nm
No CH_4 absorption	Major CH_4 absorption
Background unaffected by CH_4	Background affected by CH_4

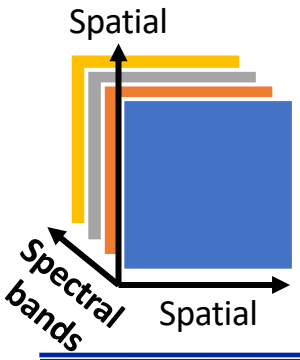


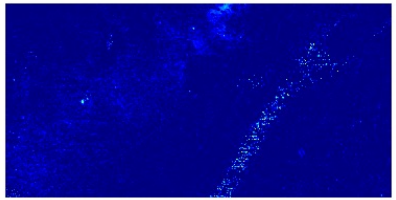
$$CASSI_A = Backgroud_A$$

$$CASSI_B = Background_B + gas\ absorption$$

Spectral band correlation:

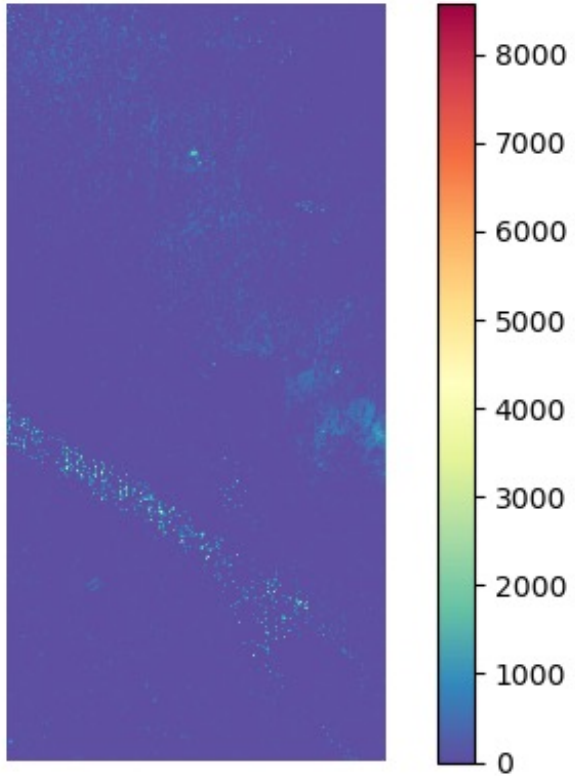
$$Backgroud_A \longrightarrow Backgroud_B$$



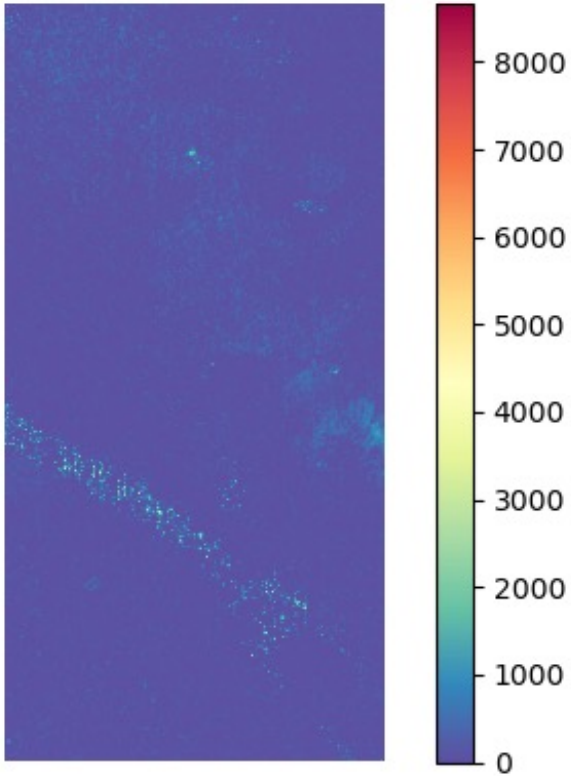


Gas absorption

Simulation results: concentration estimation



Ground truth



Estimated

NMSE	Max error (ppm·m)	PSNR (dB)
0.503	8249	33dB

Summary

- Successful Demonstrations on 1st Gen and 2nd Gen SPIDER PIIT is currently driving 3rd Gen SPIDER PIIT with wafer-scale 3D Electronic-Photonic Integrated Circuits with possibly 1000x reduction in size, weight, and power compared to panchromatic imagers currently supported by NASA IIP.
- 4th Gen SPIDER PIIT with synthetic aperture imaging can be a game changer in scalability in resolution.
- Compressive Hyperspectral Imaging on CASSI currently supported by NASA ACT provides ~ 1000x reduction in measurement resources (detectors, measurement time, data transfer requirements).
- Meta CASSI and AWGR CASSI hardware prototype development in progress.
- CASSI Simulator with new algorithm successfully demonstrates Greenhouse concentration imaging.