# Low-Mass Planar Photonic Imaging Sensor

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NEXT GENERATION NETWORKING SYSTEMS LABORATORY

# *Key to Affordability – Low SWaP*

**Orders of Magnitude SWaP Reduction Achievable**

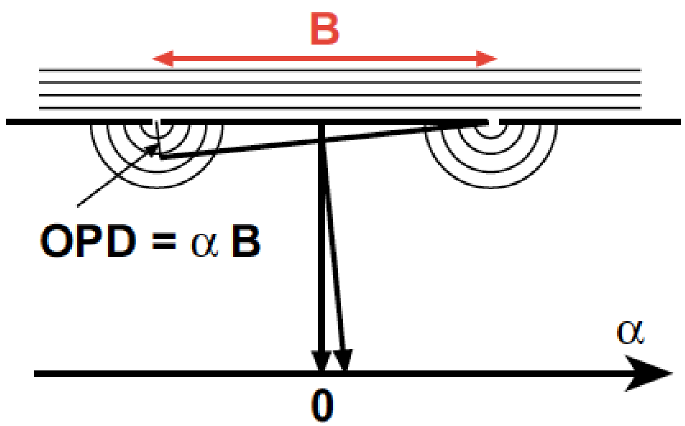
**Conventional Telescope and focal plane**

**SPIDER: Radial Blade Design Option B: outer ring**

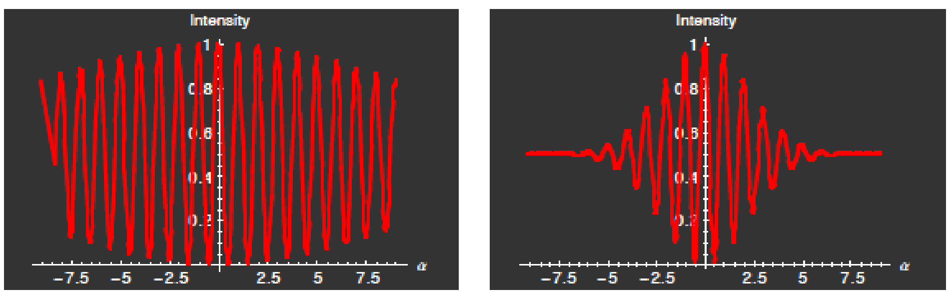
**SPIDER: Radial Blade Design Option A: full sensor**

**SPIDER: Single Chip Design**

# *Basic Idea--Young's Two-Slit Experiment*




**1st Min: OPD = $\lambda/2 \Rightarrow \alpha_{min} = \lambda/(2B)$**



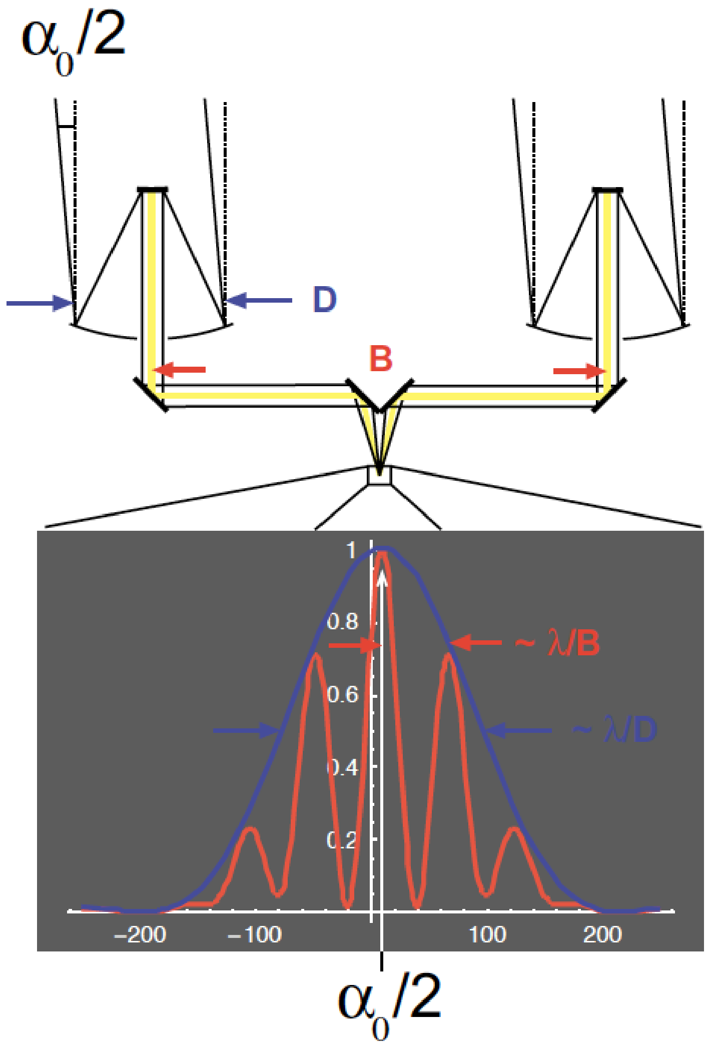

(First and last picture of a movie)

- Light source at infinity at $\alpha = 0$
- Intensity pattern ~ 1+cos as a function of $\alpha$, period length: $\lambda/B$
- OPD > coherence length $\Rightarrow$ fringes disappear

Light source at angle $\alpha_0$
$\Rightarrow$ fringe pattern shifts accordingly

Figure Courtesy of Andreas Glindemann

# *Basic Idea--Michelson Stellar Interferometer*



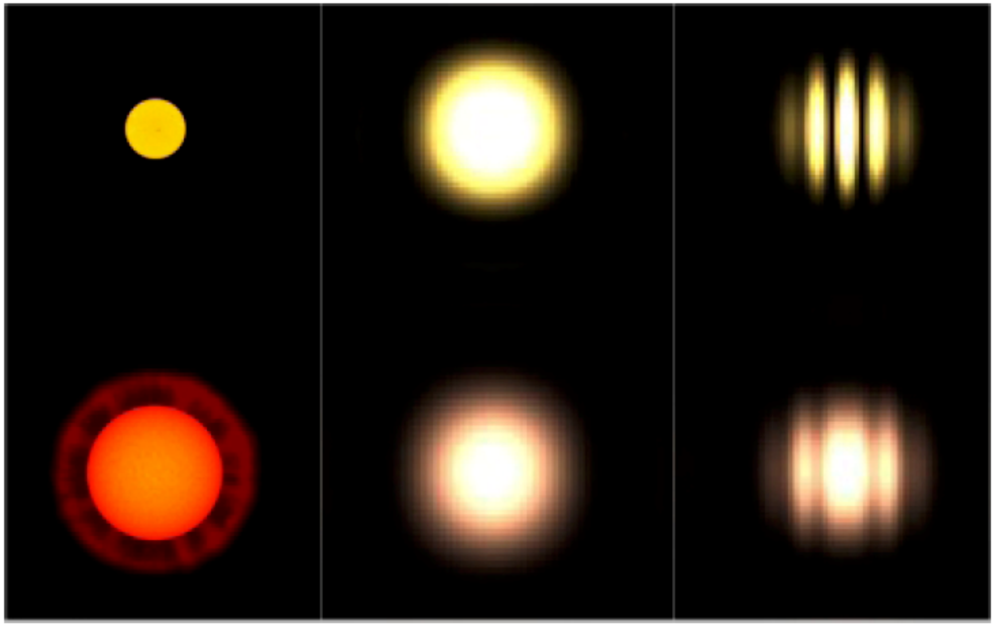

- Stellar source with angular size $\alpha_0$
- Add fringe patterns (i.e. intensities) between $\pm\alpha_0/2$

Figure Courtesy of Andreas Glindemann

# *Advantages of Interferometric Imaging*

Small star

Big star



Objects | Single Telescope | Interf. Fringes

$I_{im}(\alpha) \sim \mathcal{F}(\ D\ )$ | $I_{im}(\alpha) \sim \mathcal{F}(\ B\ )$

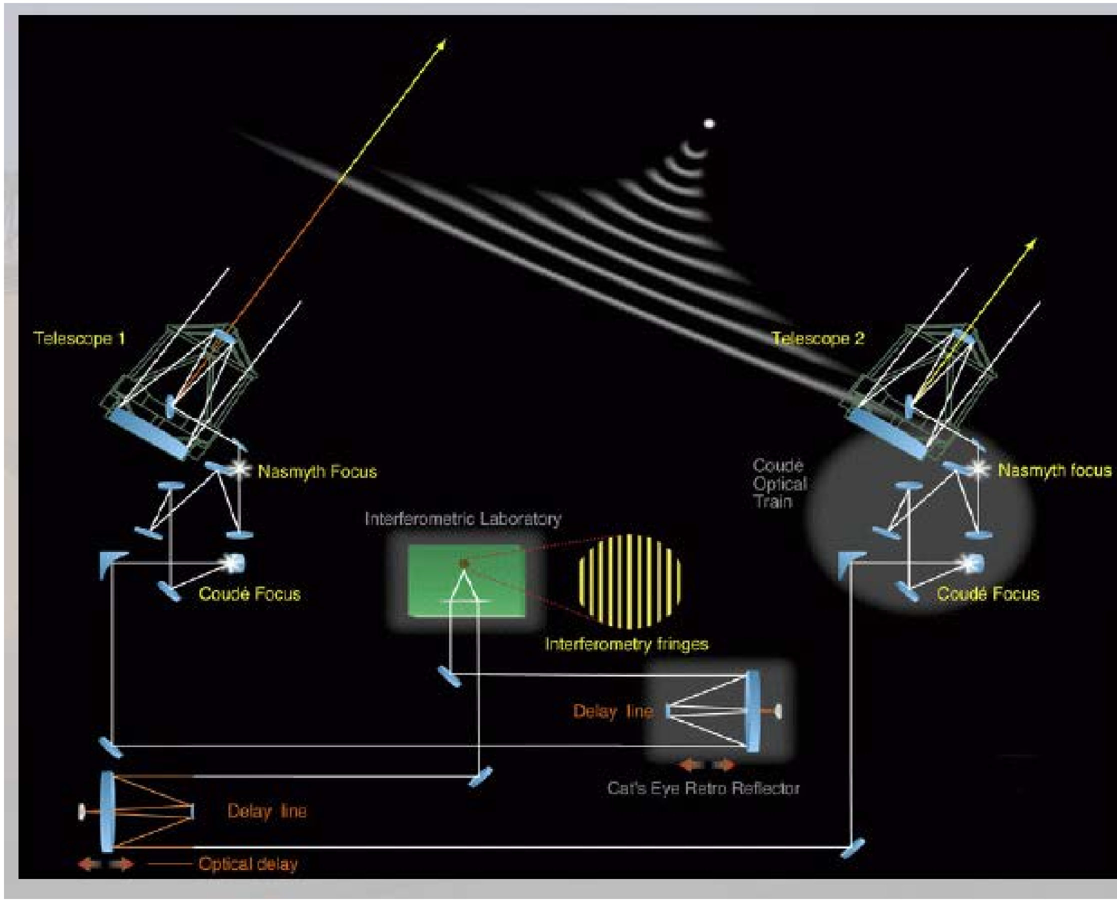
Angular Resolution: $\sim \lambda/D$ | $\sim \lambda/B$

Figure Courtesy of Andreas Glindemann

# *Radio VLA*

# *Basic Algorithm*

- Sample the fields at $r_1$ and $r_2$.
- Optical train delivers the radiation to a lab.
- Delay lines assure that we measure when $t_1=t_2$.
- The instruments mix the beams and detect the fringes.
- Measure the fringes
- Interpret the Fourier spectrum of the target




Courtesy of C. Haniff

# The Output of a Two-element Interferometer

- A combination of E fields from the two collectors can be described as:

$$\Psi_1 = A\exp\left[ik\left(\hat{s}.B + d_1\right)\right]\exp\left(i\omega t\right) \text{ and } \Psi_2 = A\exp\left[ik\left(d_2\right)\right]\exp\left(i\omega t\right)$$

- Summing these at the detector yields:

$$\Psi = \Psi_1 + \Psi_2 = A\left[\exp\left(ik\left[\hat{s}.B + d_1\right] + \exp\left[ik\left(d_2\right)\right]\right)\right]\exp\left(i\omega t\right)$$

- Thus, the time averaged intensity, $\left\langle \Psi\Psi^* \right\rangle$, is given by:

$$\left\langle \Psi\Psi^* \right\rangle \propto \left\langle \left[\exp\left(ik\left[\hat{s}.B + d_1\right]\right) + \exp\left(ik\left[d_2\right]\right)\right] \times \left[\exp\left(-ik\left[\hat{s}.B + d_1\right]\right) + \exp\left(-ik\left[d_2\right]\right)\right] \right\rangle$$

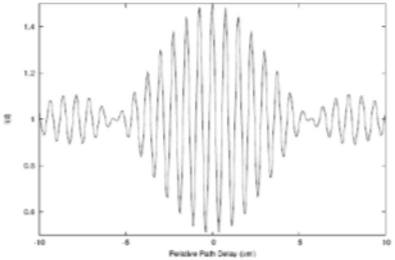
$$\propto 2 + 2\cos\left(k\left[\hat{s}.B + d_1 - d_1\right]\right)$$

$$\propto 2 + 2\cos\left(kD\right)$$

- Here, $D$ is a function of the path lengths, $d_1$ and $d_2$, the pointing direction (i.e., where the source is), and the baseline.

- Measure the fringe visibility at $D = 0$ and the fringe phase (with respect to a ref):

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

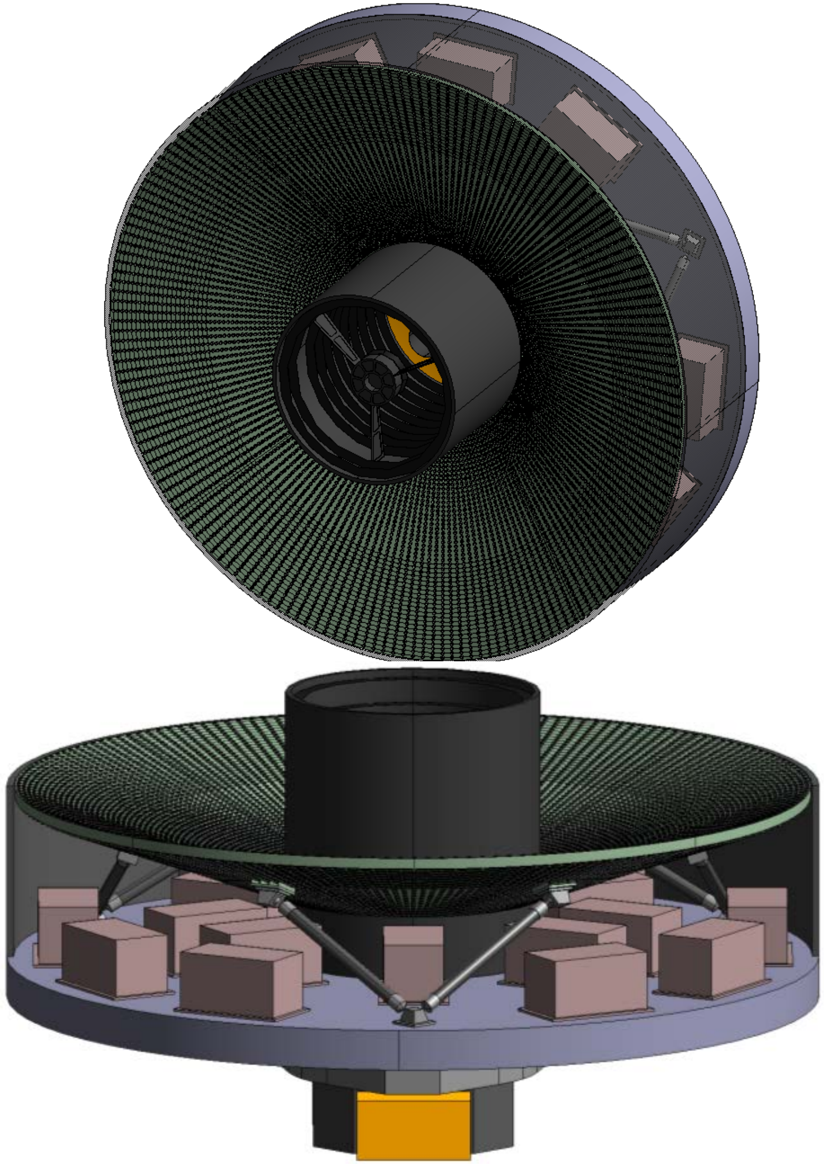


**The fringe amplitude and phase measure the amplitude and phase of the Fourier transform of the source at one spatial frequency.**

Adapted from C. Haniff – The theory of interferometry

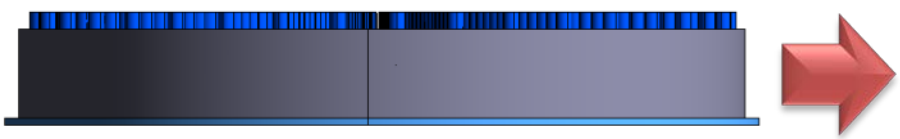
# *SPIDER Provides Low Cost Option to Enhance Resolution of a Conventional Telescope*

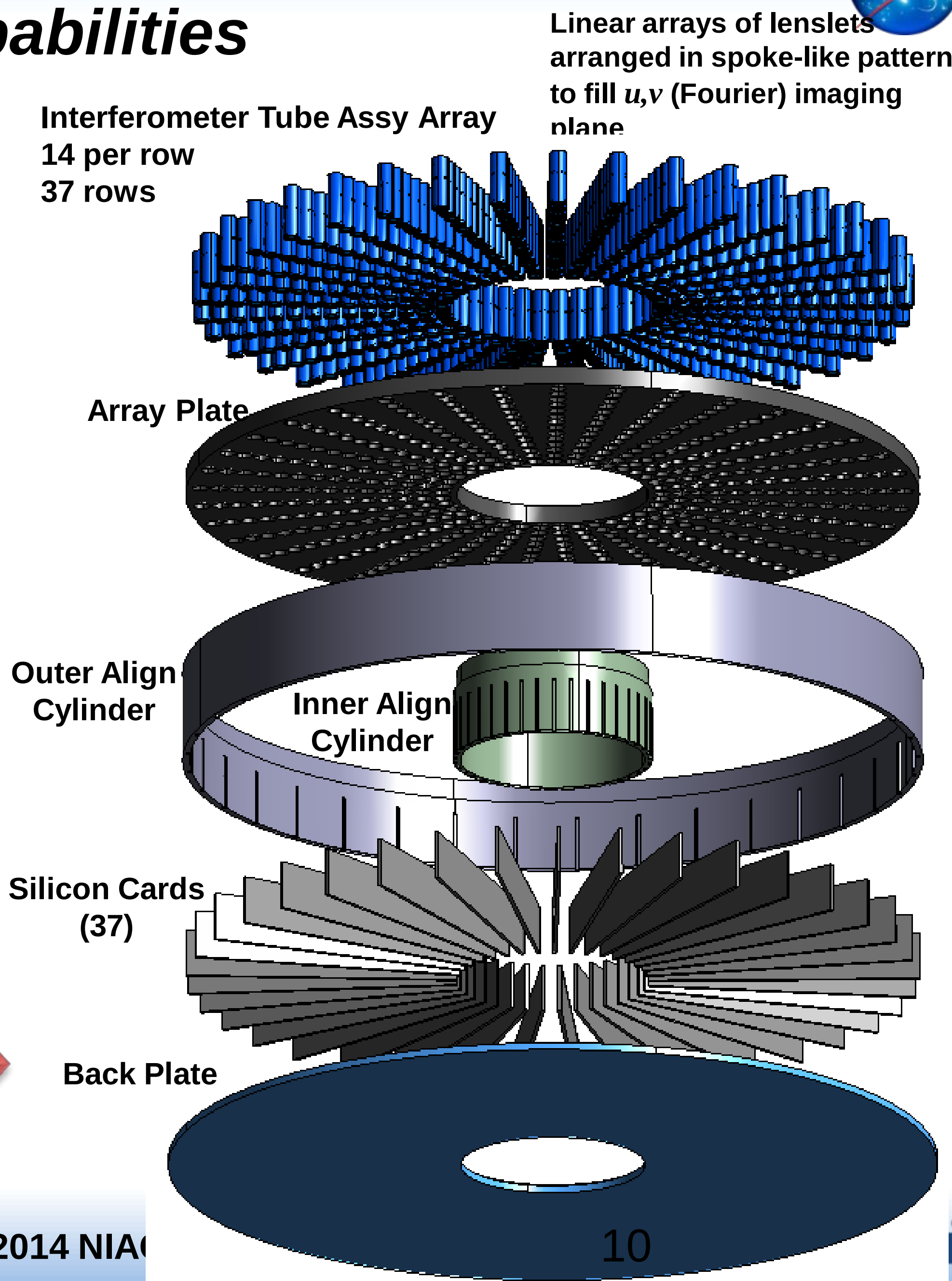
- **Objectives**
  - **Enhanced quality imagery using sparse high resolution image sampling and hyperspectral data**
  - **Increase effective aperture diameter by 2X - 3X (9X mass reduction)**
- **Concept Description**
  - **Moderate aperture diameter conventional imaging telescope with staring focal plane**
  - **White light waveguide coupled interferometers with integrated combiner / phase shifters / detectors**
- **Performance Characteristics**
  - **Moderate resolution full field of view panchromatic image**
  - **Selectable subfield regions enhanced with high resolution and hyper-spectral content**



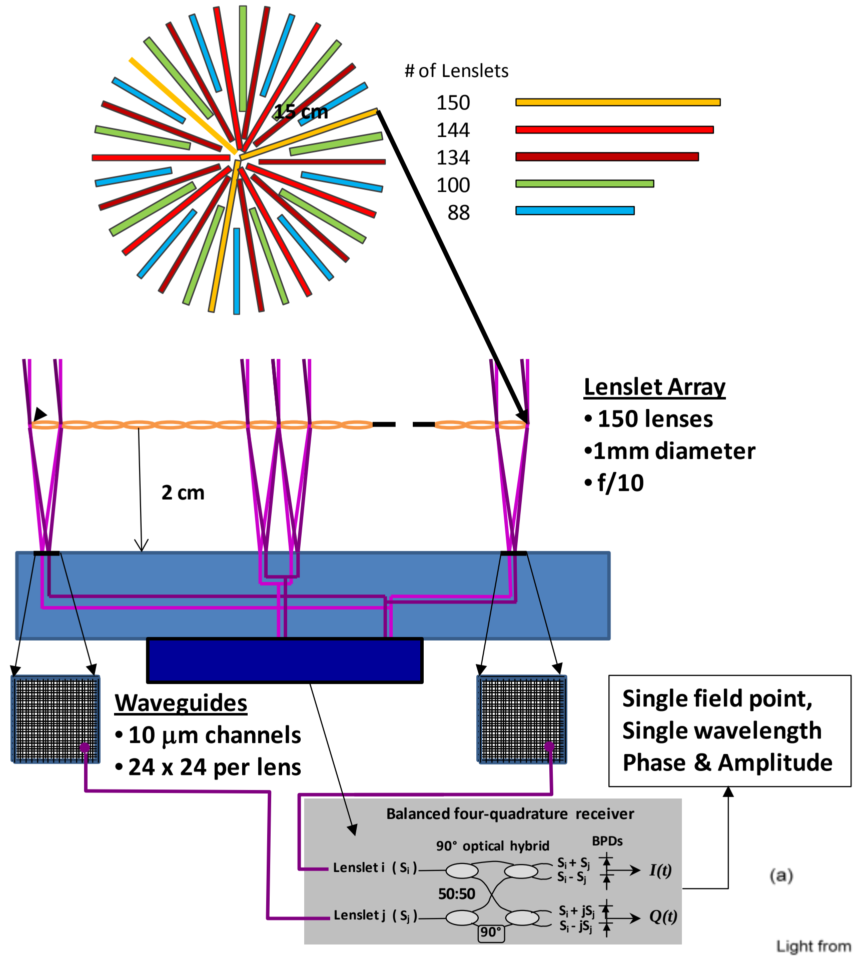
# *SPIDER* Concept Enables Next Generation Imaging Capabilities*

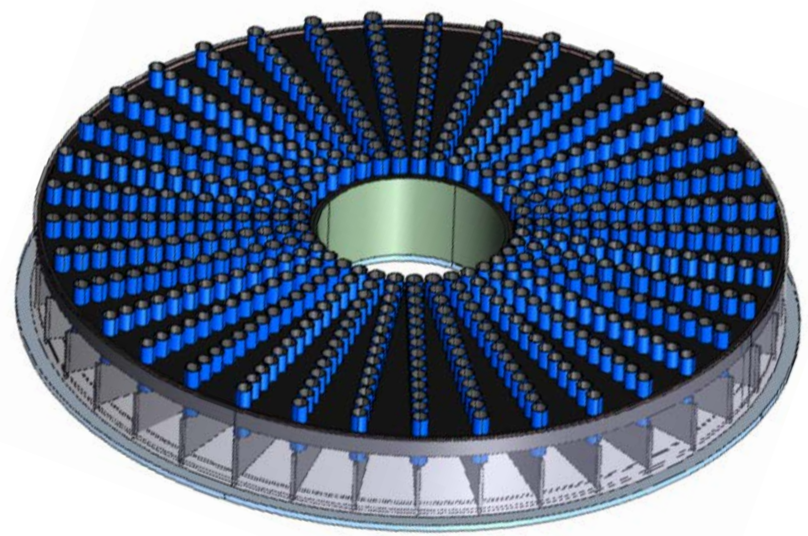
- **Objectives**
  - **Planar "flat panel" telescope with <u>NO</u> large optics**
  - **Large field of view with <u>NO</u> precision gimbals for line of sight steering**
- **Concept Description**
  - **Light input by large area lenslet array "wired" into interferometer channels using nanophotonics (leverages commercial high density optical interconnect 3D computer chip technology)**
  - **Scalable to larger apertures using fiber coupling of multiple interferometer chips**

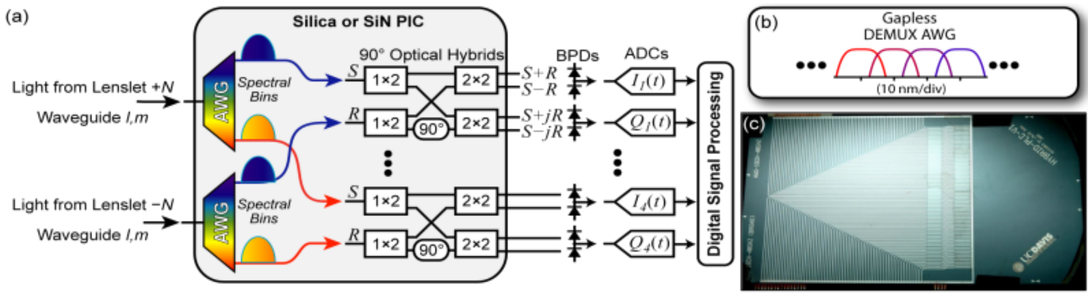




# UC Davis – Lockheed Martin's NIAC Approach

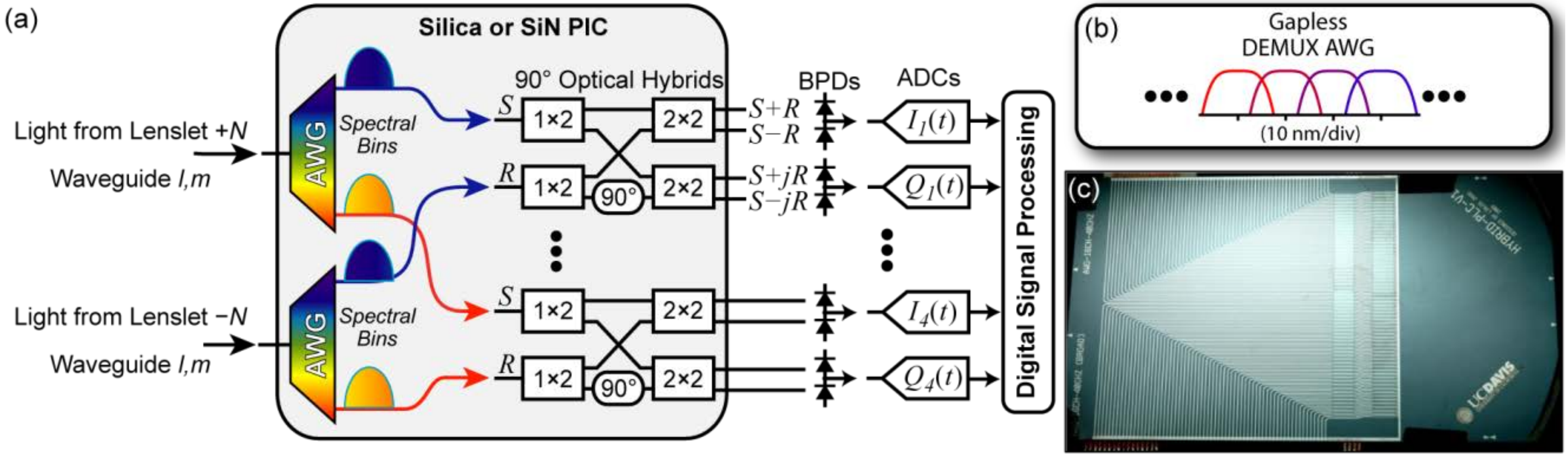




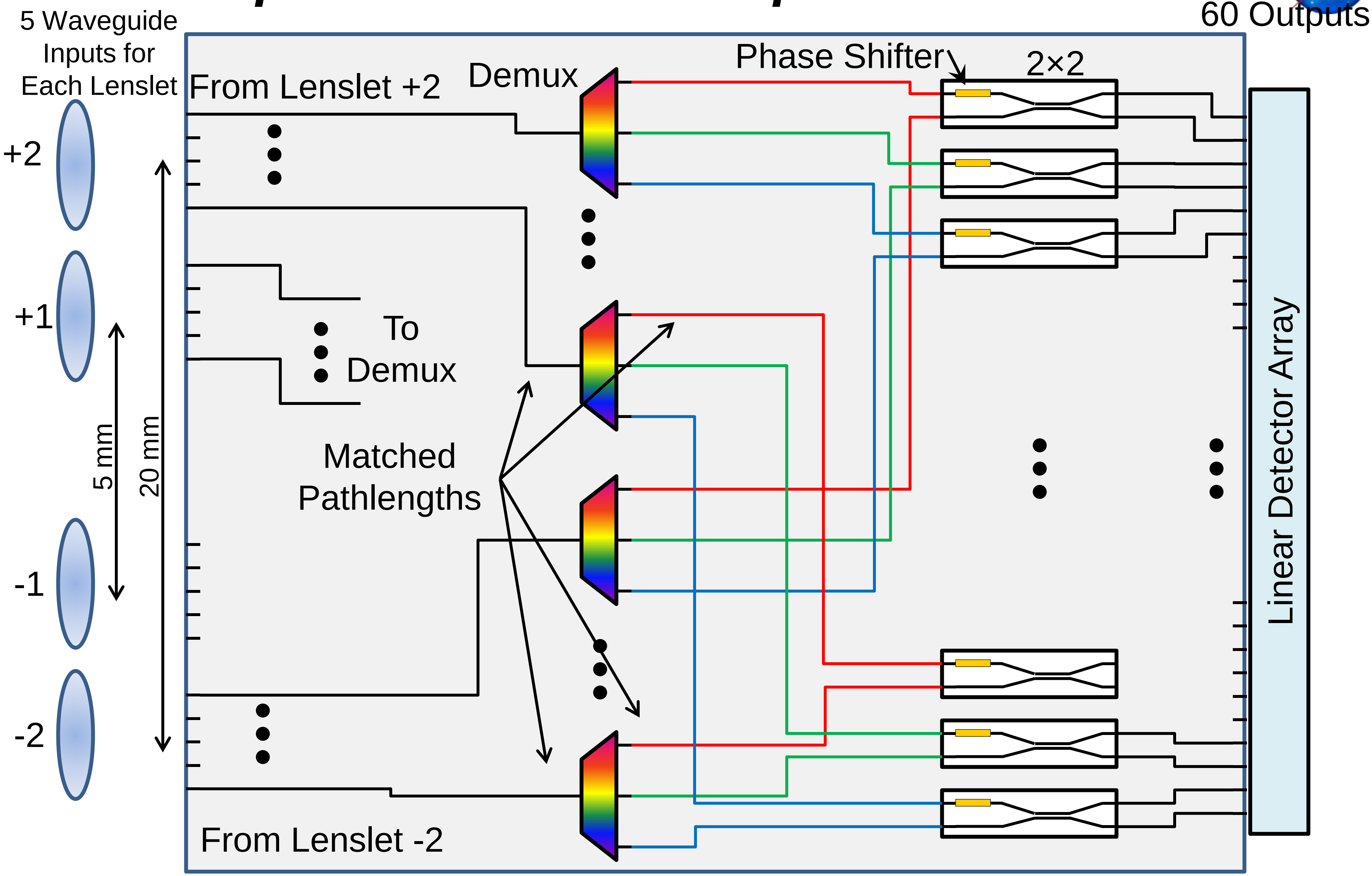

Spectrally Resolved High Resolution Interferometric Telescope

# *Photonic Integrated Circuit (PIC) Design*



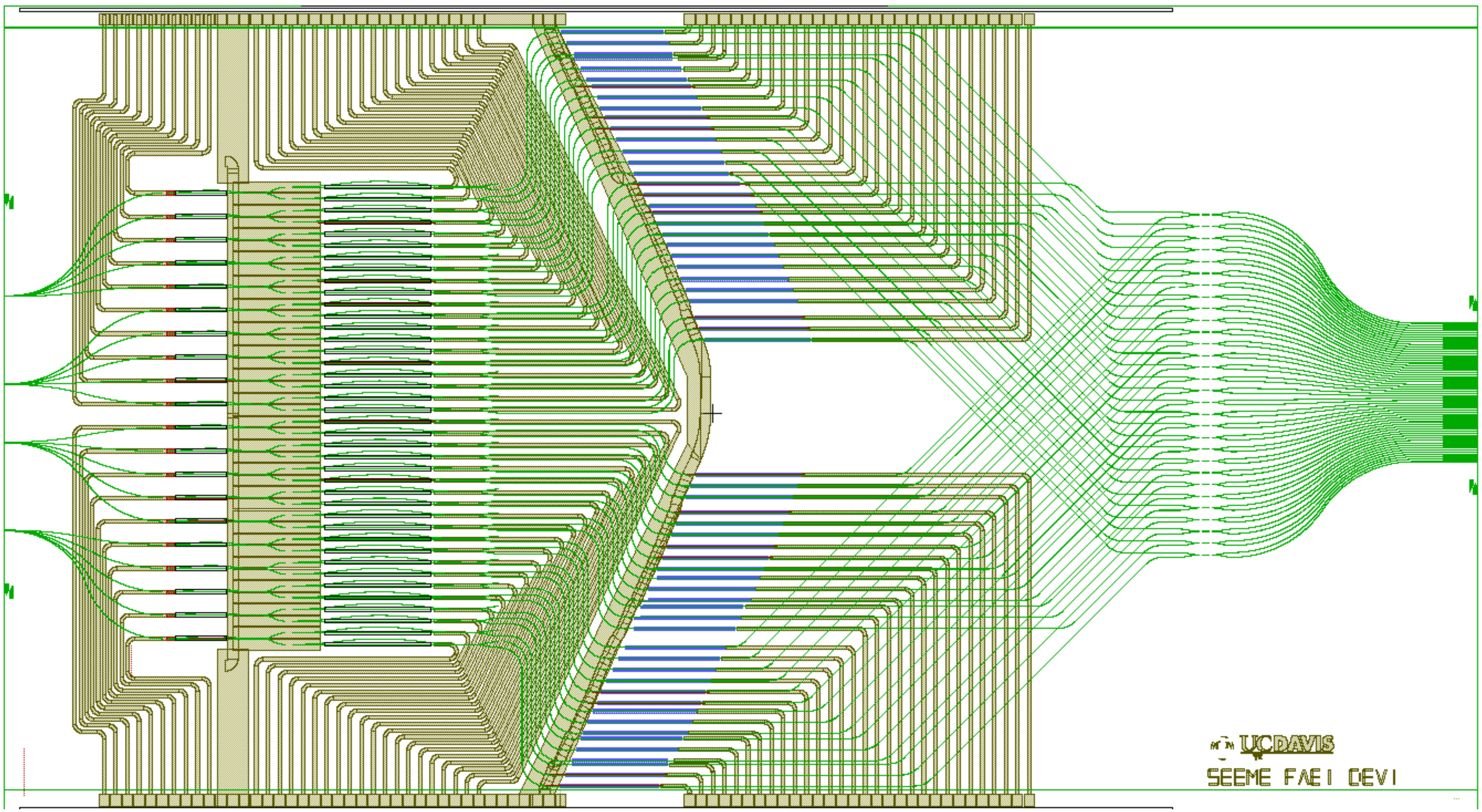

- **Specify spectral bin widths, bin spacing, interferometer phase shift requirements, desired optical mode size, etc.**
- **Simulations of individual photonic components (spectral demultiplexer, splitters, etc.)**
- **Packaging design**
- **Layout of waveguide and metal mask layers including test structures**
- **Design review**

# 10-Spatial-Channel × 3 Spectral Band PIC



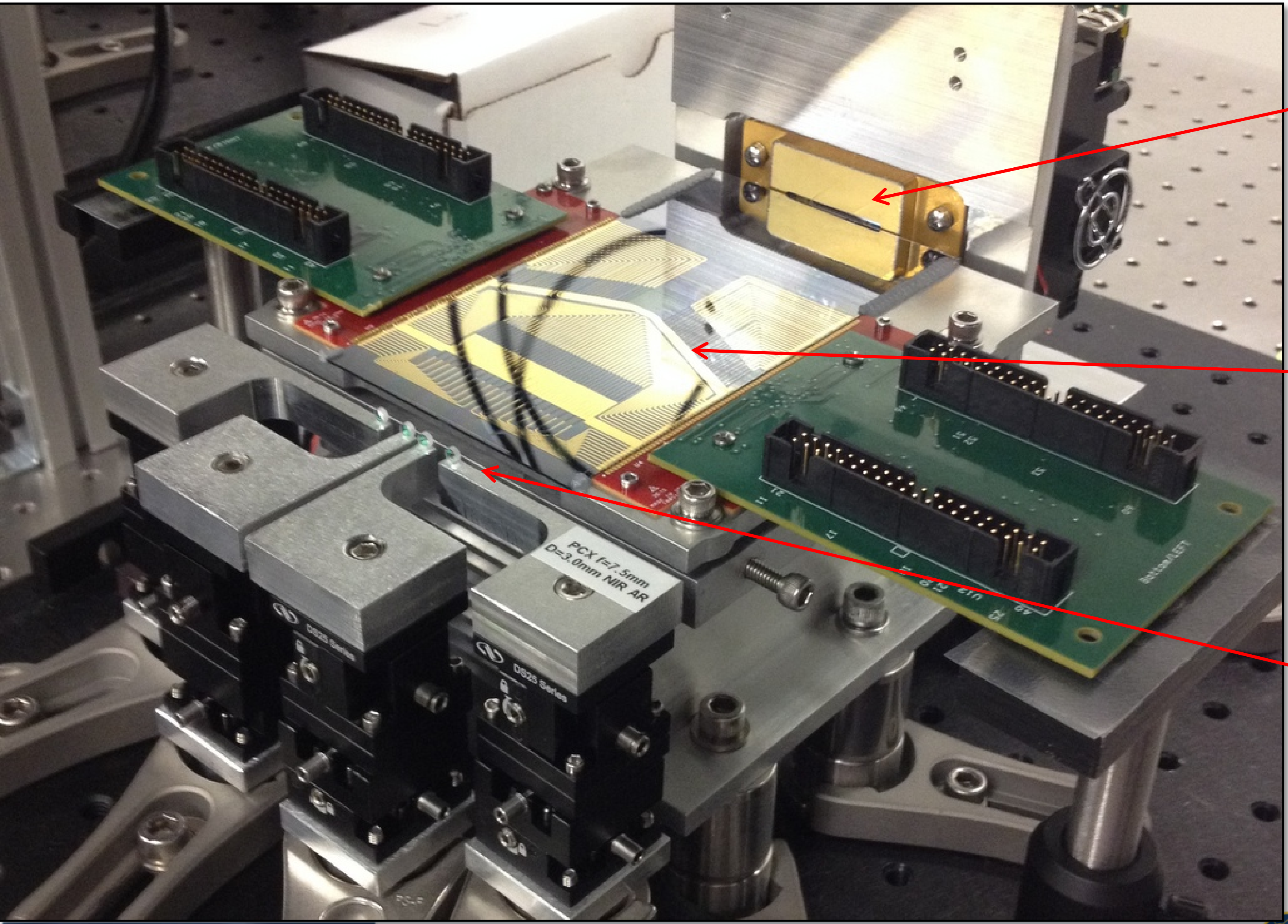
# 10-Spatial-Ch ×3 Spectral Band Main Device Layout

- Layer#1: waveguide
- Layer#2: heater
- Layer#3: electrode
- Layer#4: trench
- Layer#11: waveguide keep out




DARPA funded work

# *Packaged PIC*



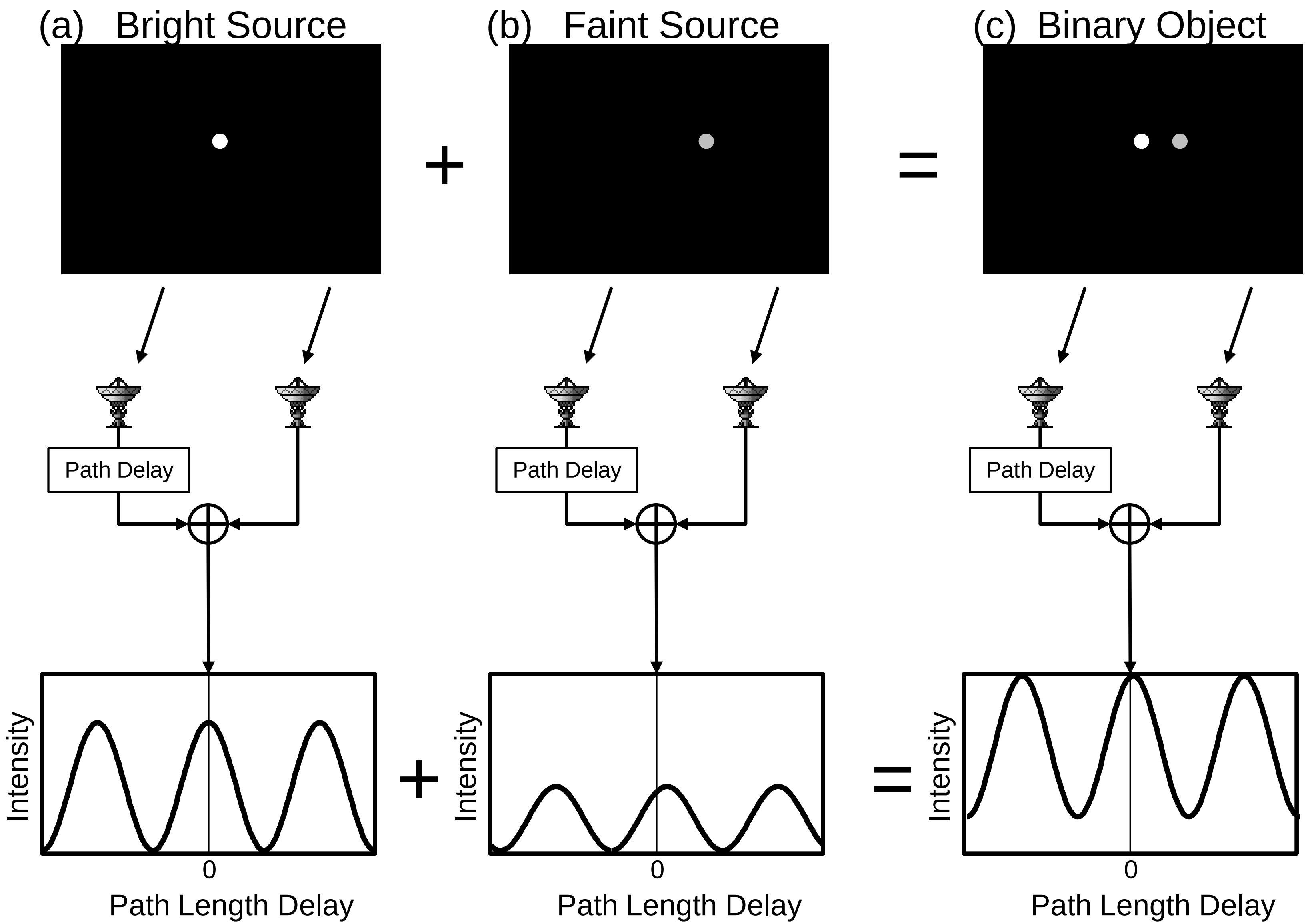

Linear Detector Array

PIC

Lenslets

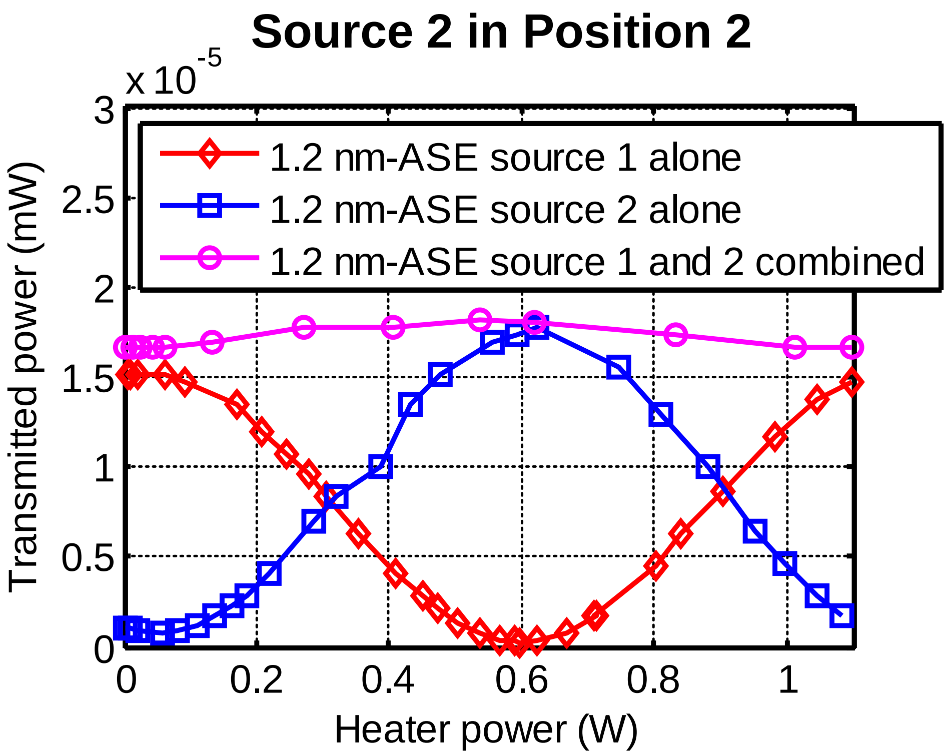
DARPA funded work

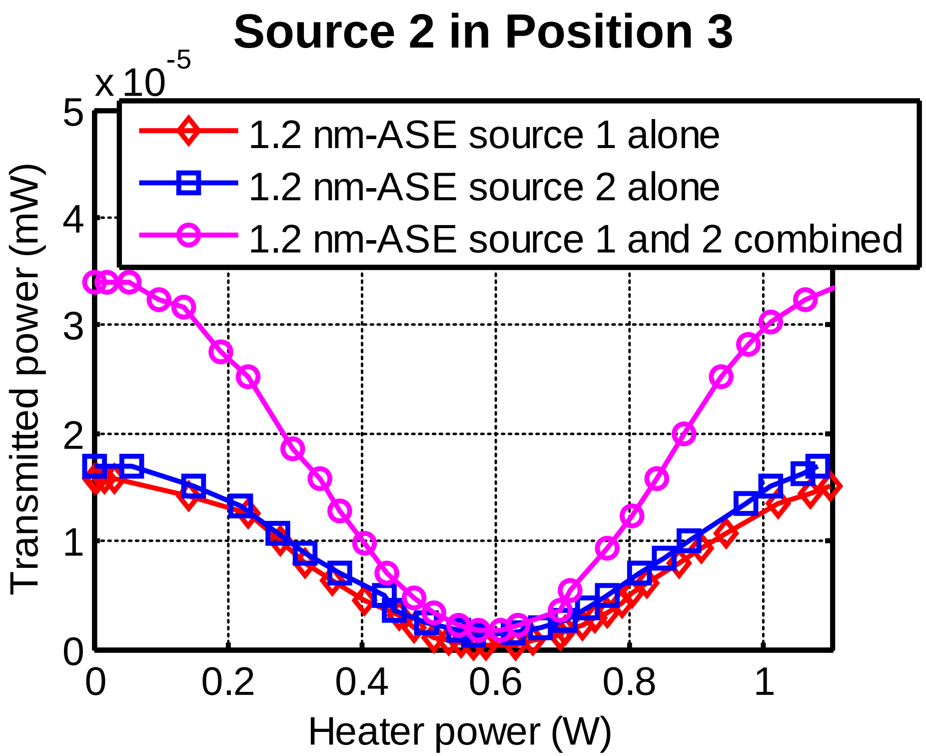
# *Measuring Fringes from One and Two Sources*



# Fringe Measurements of Point Sources

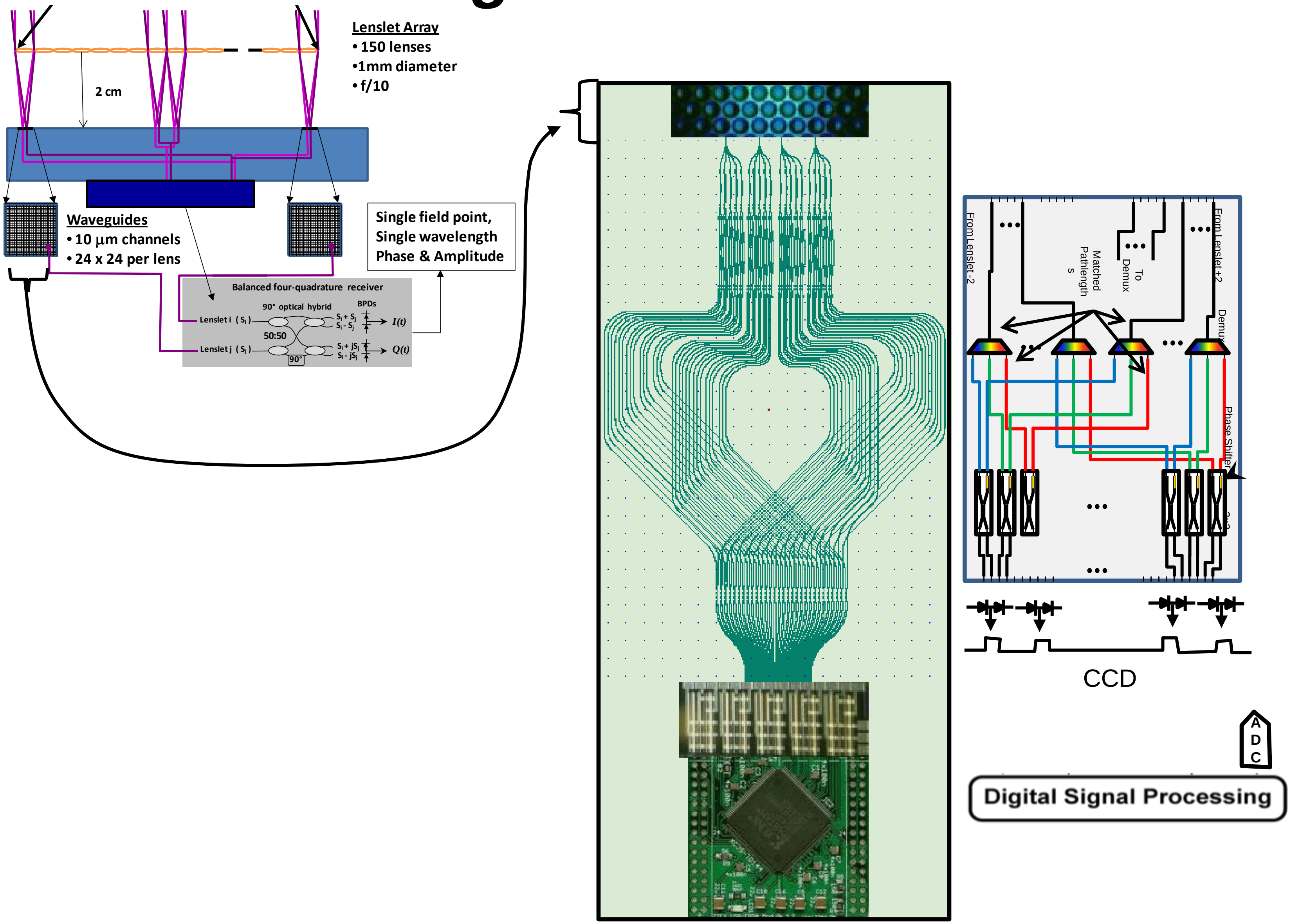
- Fringe extinction >10 dB
- The ASE sources are incoherent with respect to each other




DARPA funded work

# Integrated SPIDER Blade



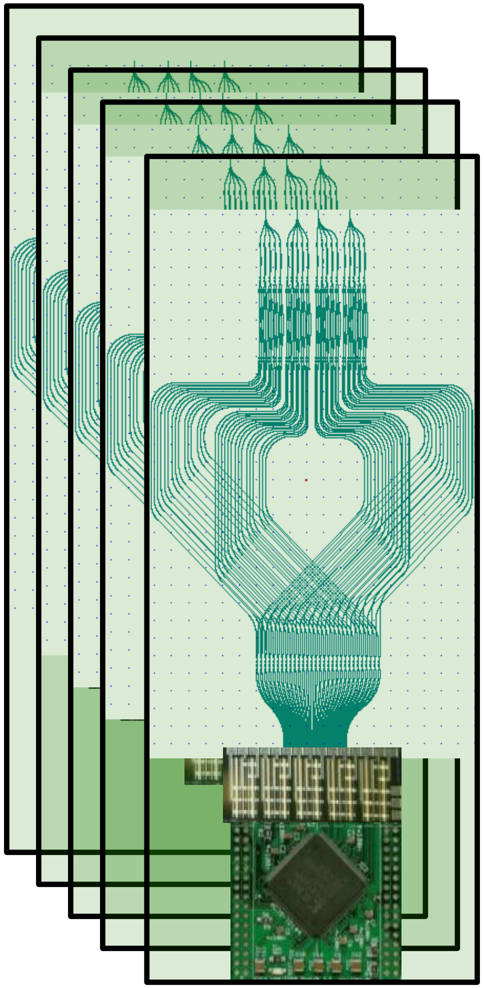

*PIC*

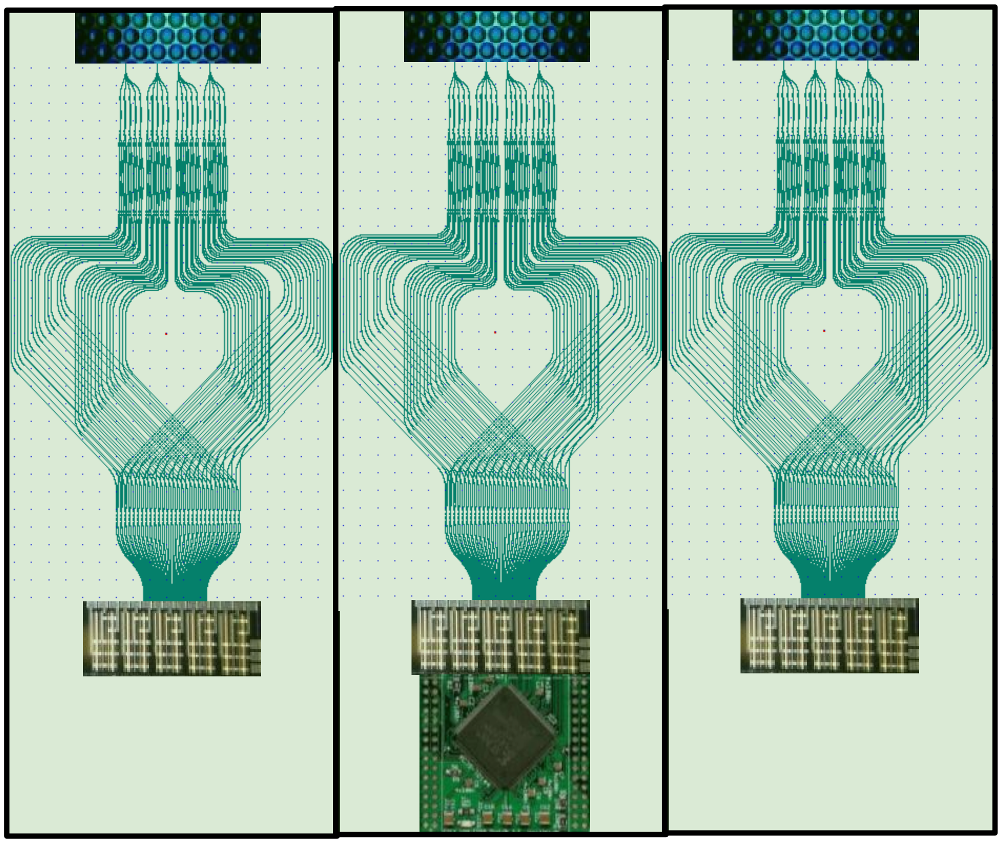
*Self-aligned to*

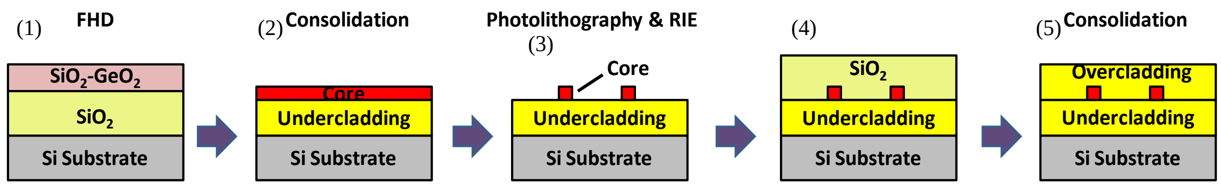
*Silicon Photonics*

*Electronics Board*

# *Integrated SPIDER Blade PIC: two approaches*

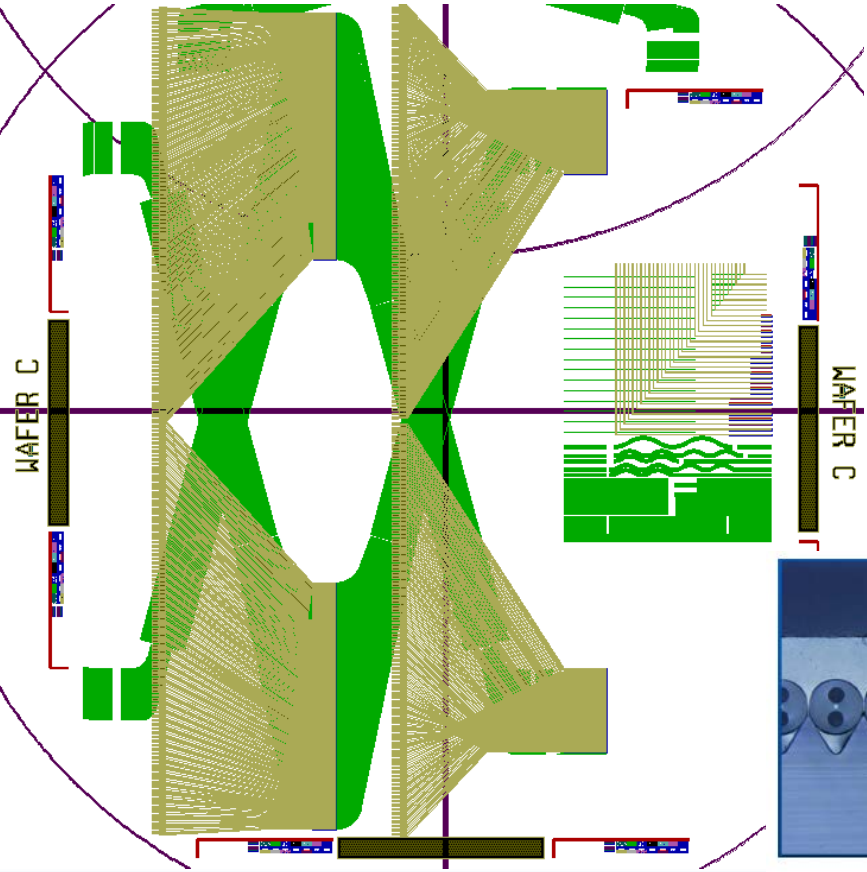




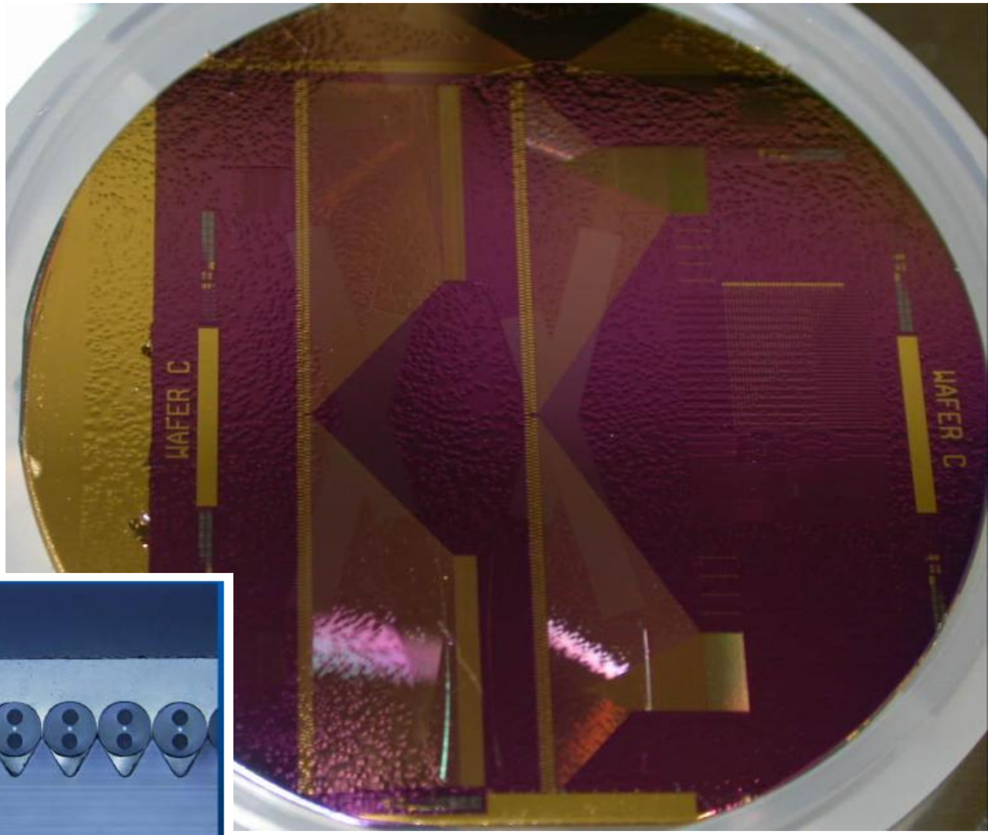


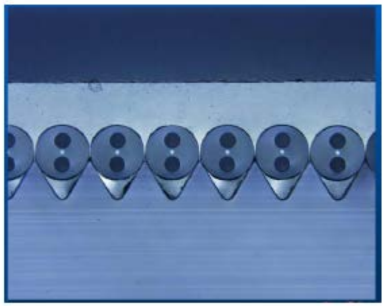
# Our Previous Experience:
# ~8000 waveguides with 1200 independently addressable devices on a chip developed at UC Davis
# 1 THz (100ch x 10 GHz) OAWG Transmitter (DARPA DSO)

Mask Layout

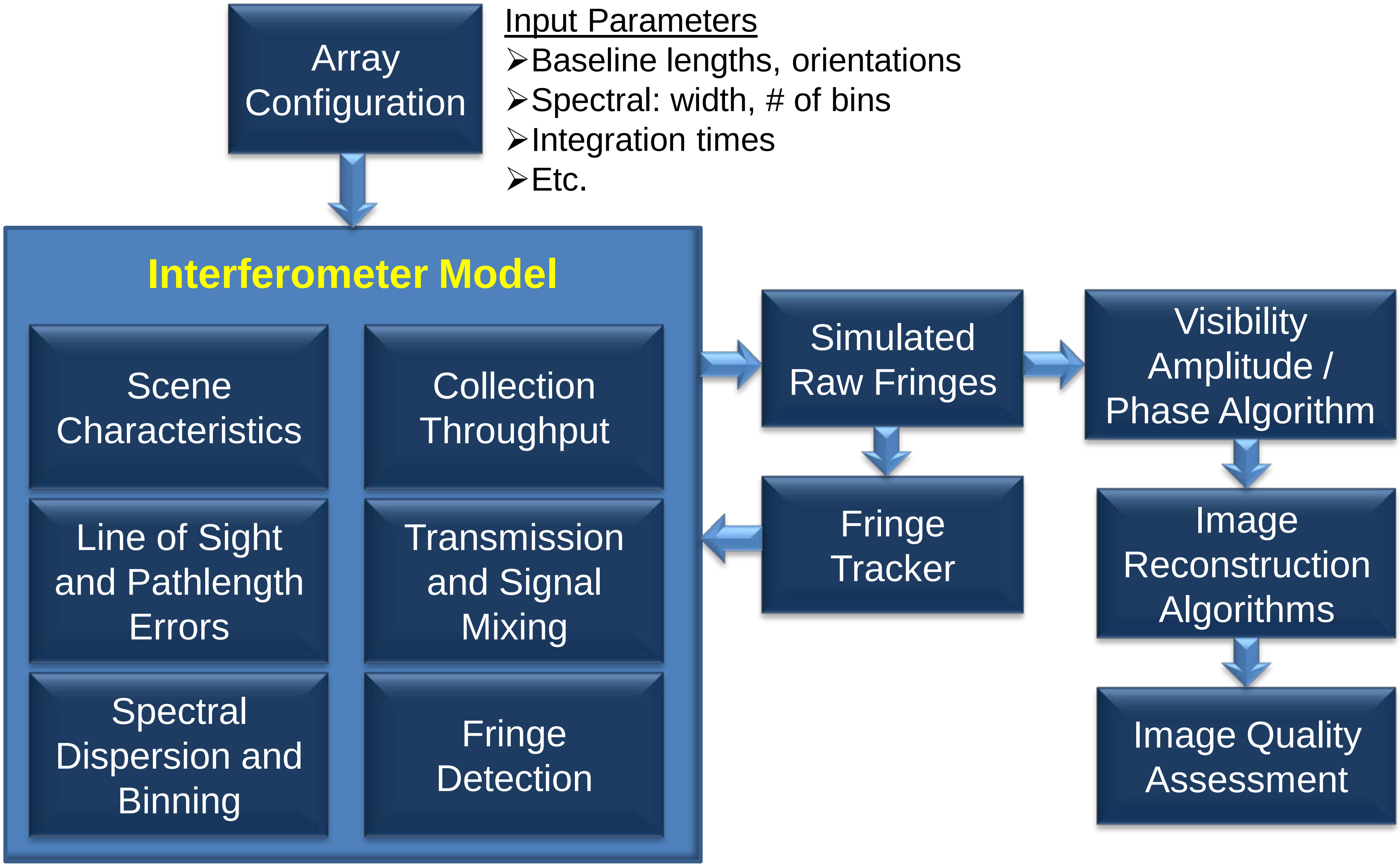



Fabricated Chip

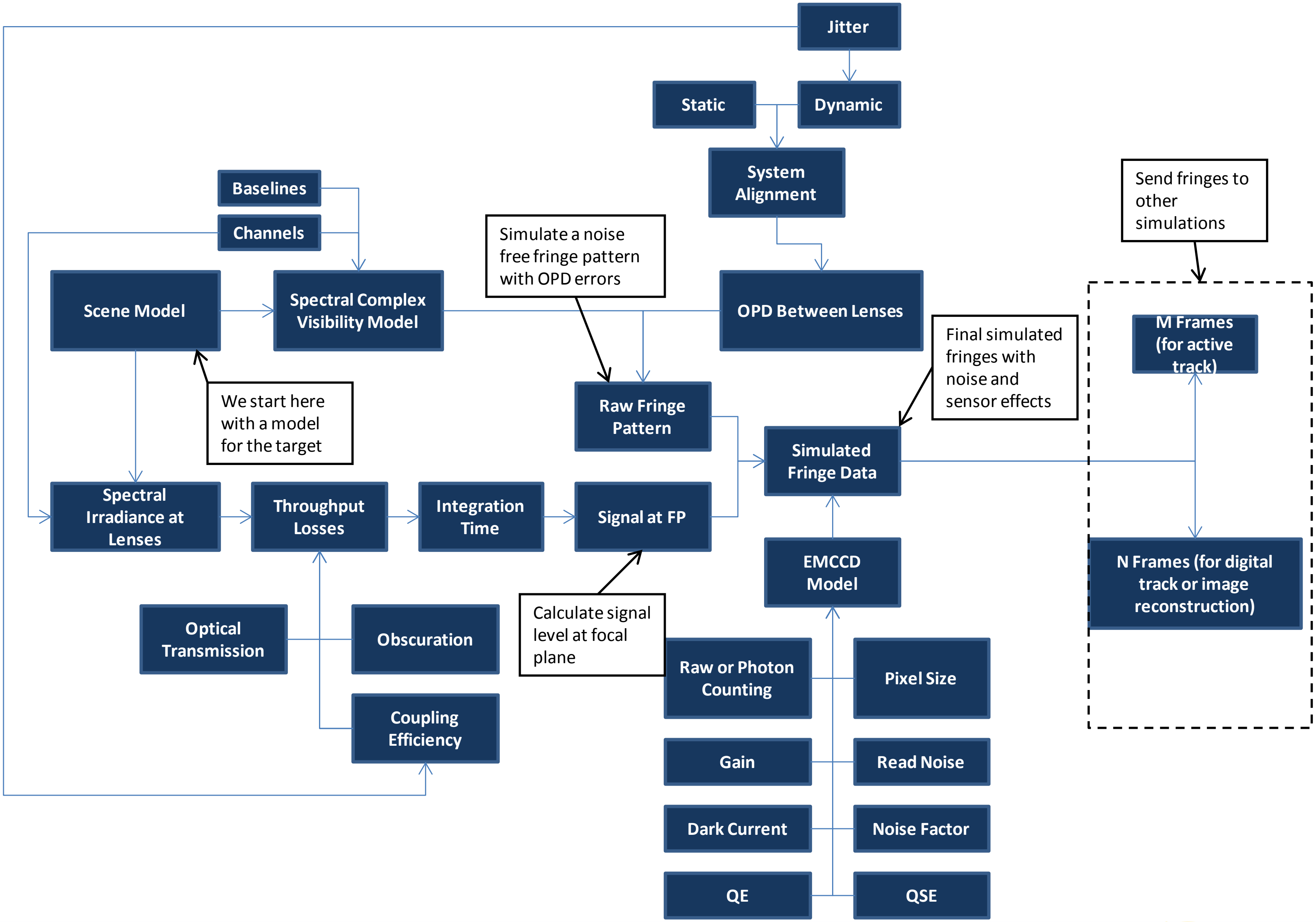


# Modeling / Simulation Flow Chart

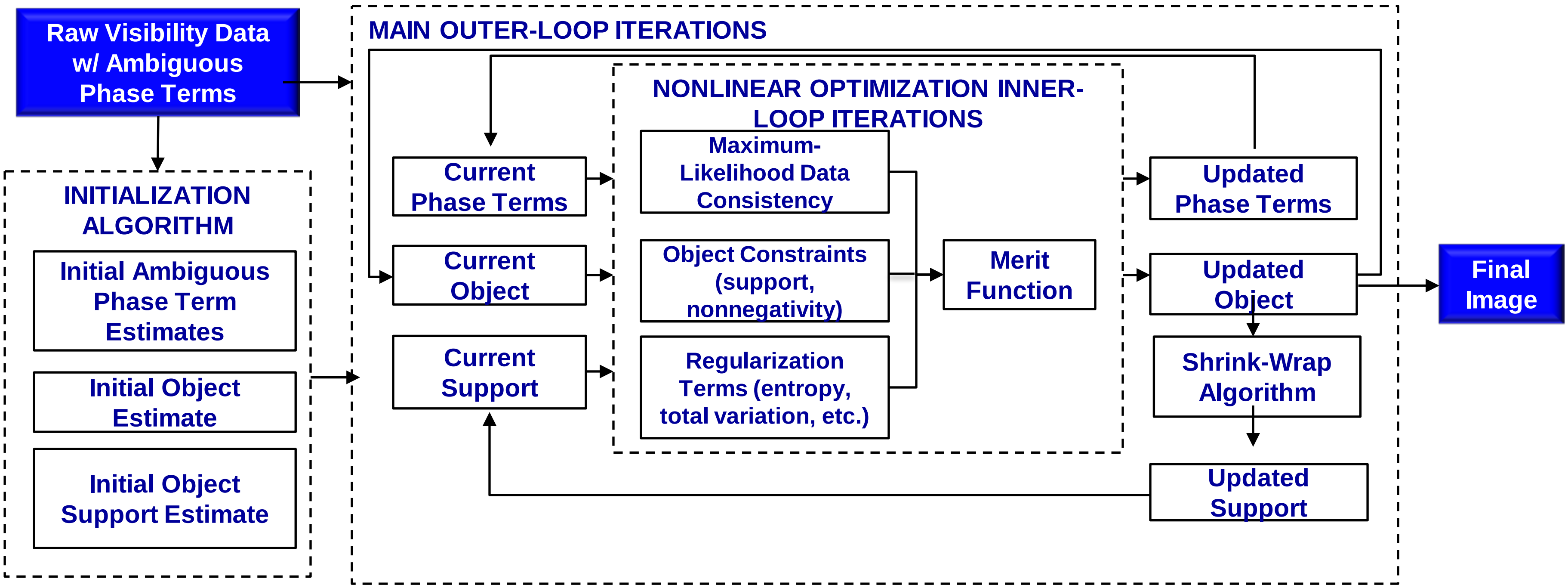


# Interferometer Model (detail)



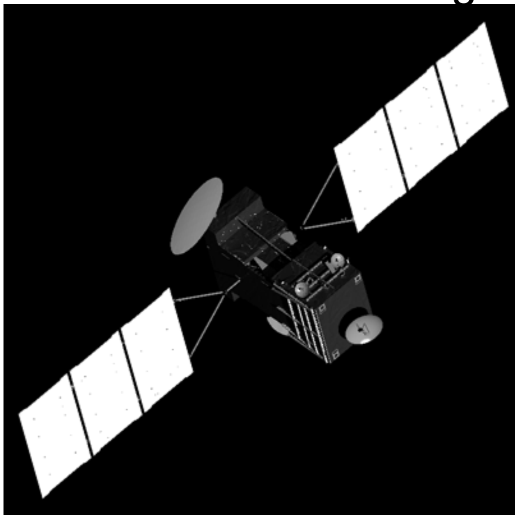
# Image Reconstruction Flow Chart

- Developed by University of Rochester (Dr. Jim Fienup) under Lockheed Martin's IRAD funding
- Image reconstruction details will be tailored to imager conceptual design

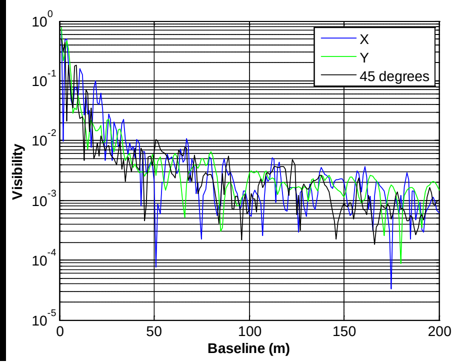


# Image Simulations

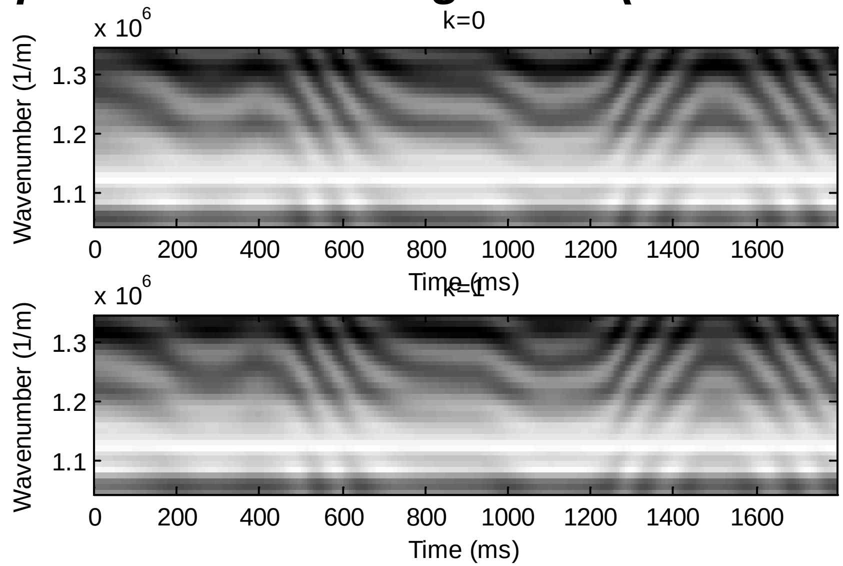
DIRSIG model of target



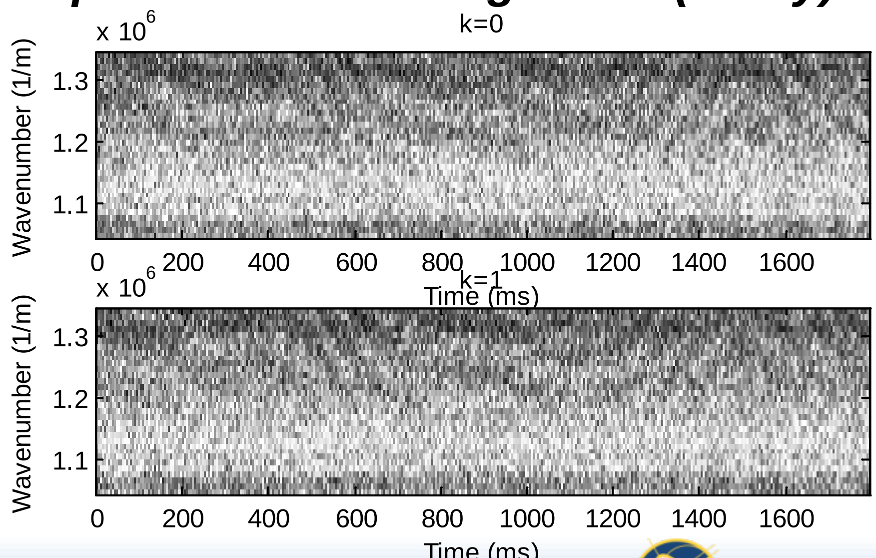
## Visibility




## Example Simulated Fringe Data (Noise Free)



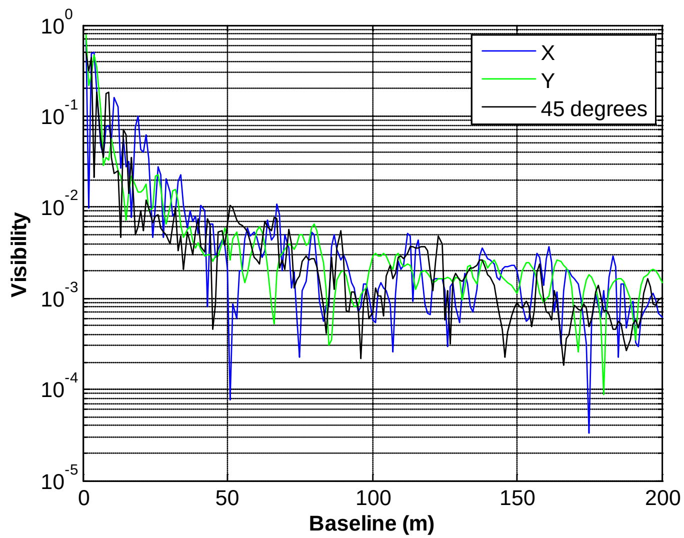

## Example Simulated Fringe Data (Noisy)




- 131 spectral bands uniformly spaced in wavelength between 0.5-1.8 $\mu$m
- Each band uses the units of W/cm$^2$-str-$\mu$m at the top of the atmosphere
- Resolution of image is 1.65 cm
- More details elsewhere

Lockheed Martin IRAD work

# Visibility and Signal Calculation

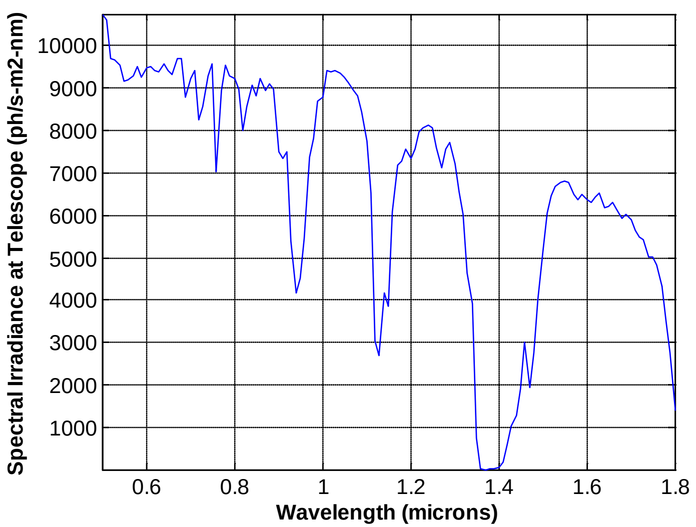



- Complex visibility at a distinct wavelength is the scaled and normalized Fourier Transform of the target

$$V\left(B_x, B_y; \lambda\right) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R\left(x, y; \lambda\right) \exp\left(-i \frac{2\pi}{\lambda z}\left(xB_x + yB_y\right)\right) dxdy}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R\left(x, y; \lambda\right) dxdy}$$

$V$ = Complex Visibility, $B_x, B_y$ = Baseline, $\lambda$ = Wavelength

$R(x, y)$ = Target Radiance, $z$ = slant range to target




- Spectral irradiance calculation (ph/s-m$^2$-nm)
- Visual magnitude of DIRSIG target is ~9.78
  - Spectral irradiance can be scaled by a factor of 0.324 to give $m_v$=11

$$I\left(\lambda\right) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} R\left(x, y; \lambda\right) \times \frac{c\lambda}{h} dxdy}{z^2} \times \frac{10000}{1000} \times \tau_{atm}\left(\lambda\right)$$

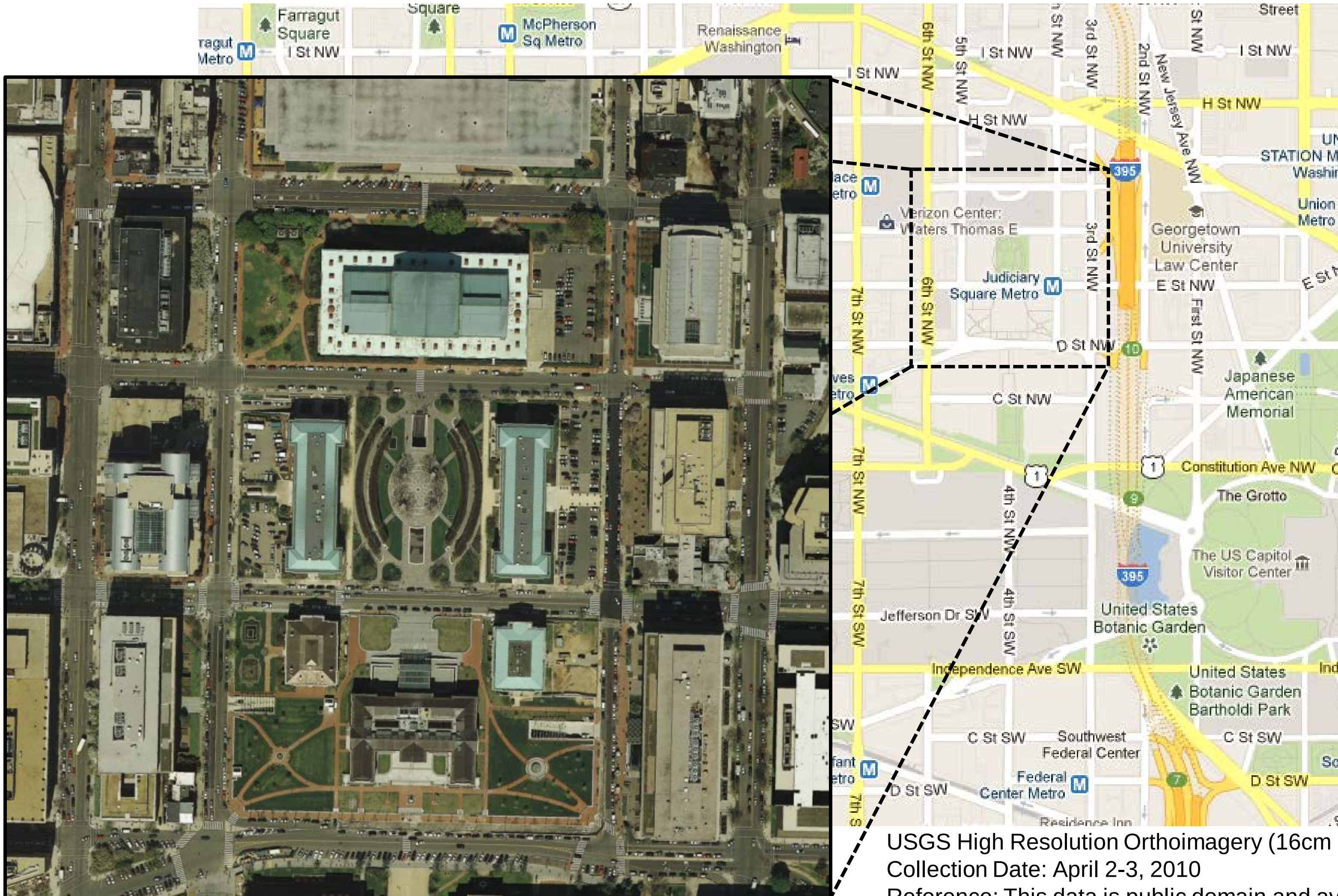
$c$ = Speed of light, $h$ = Planck's constant

$\tau_{atm}(\lambda)$ = Atmospheric Transmission

Lockheed Martin IRAD work

# *Scene Data used for Imager Simulations*

Judiciary Square, Washington, D.C.




USGS High Resolution Orthoimagery (16cm GSD)
Collection Date: April 2-3, 2010
Reference: This data is public domain and available from the United States Geological Survey through http://nationalmap.gov.

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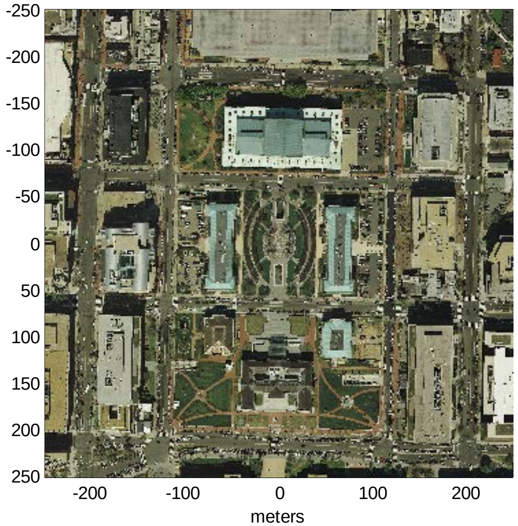
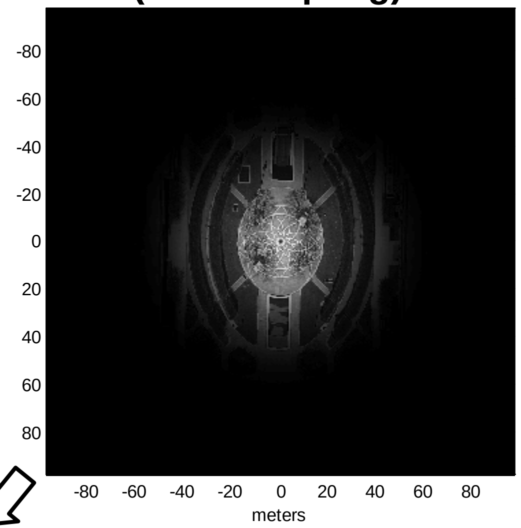
# Simulation for a Single Sub-Image

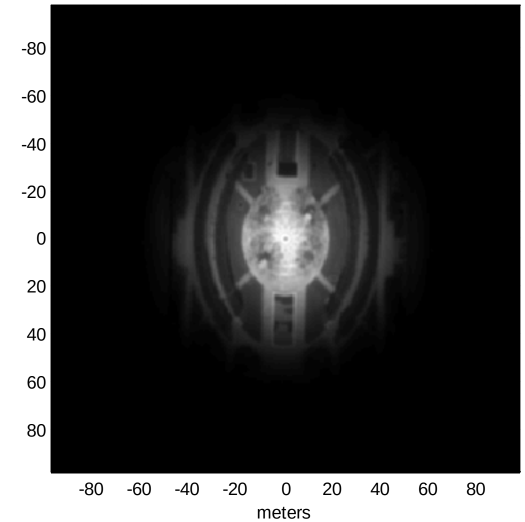
**1. User selects FOV for sub-image**



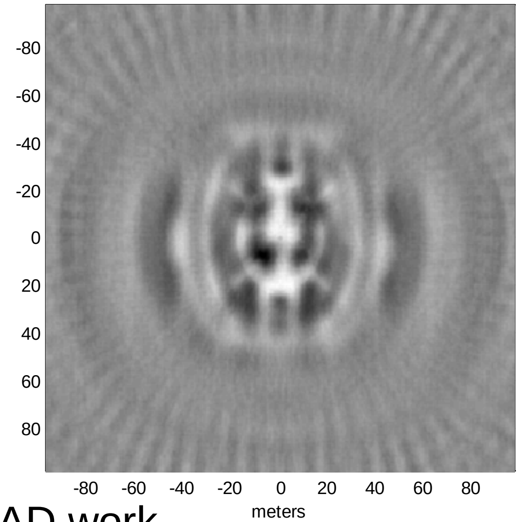

**2. Crop scene and apodize (fiber coupling)**



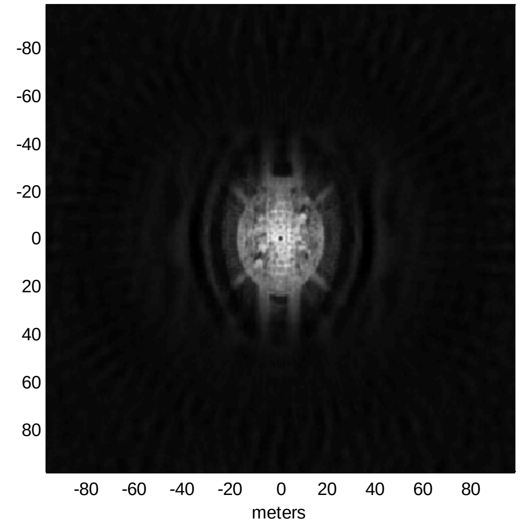

**3. Make a conventional comparison sub-image**




**4. Compute *u-v* data & make "dirty" image**

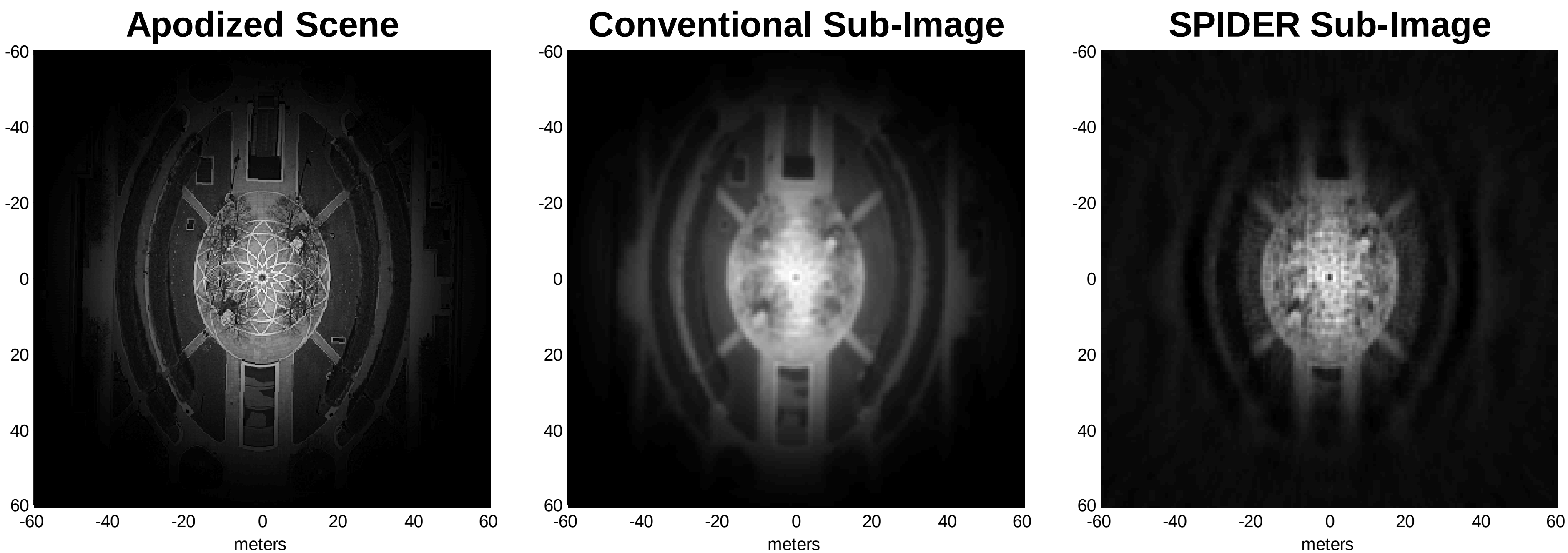



**5. Reconstruct sub-image**




Lockheed IRAD work

# Sub-Image Comparisons



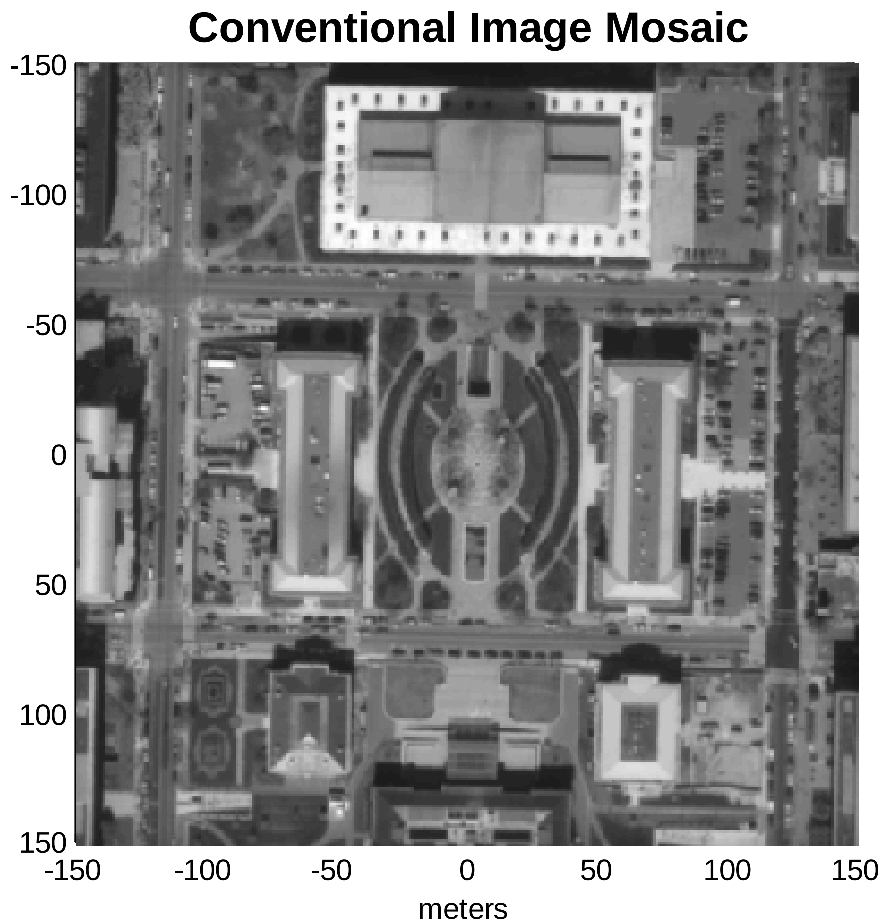

***No Wiener filter applied**

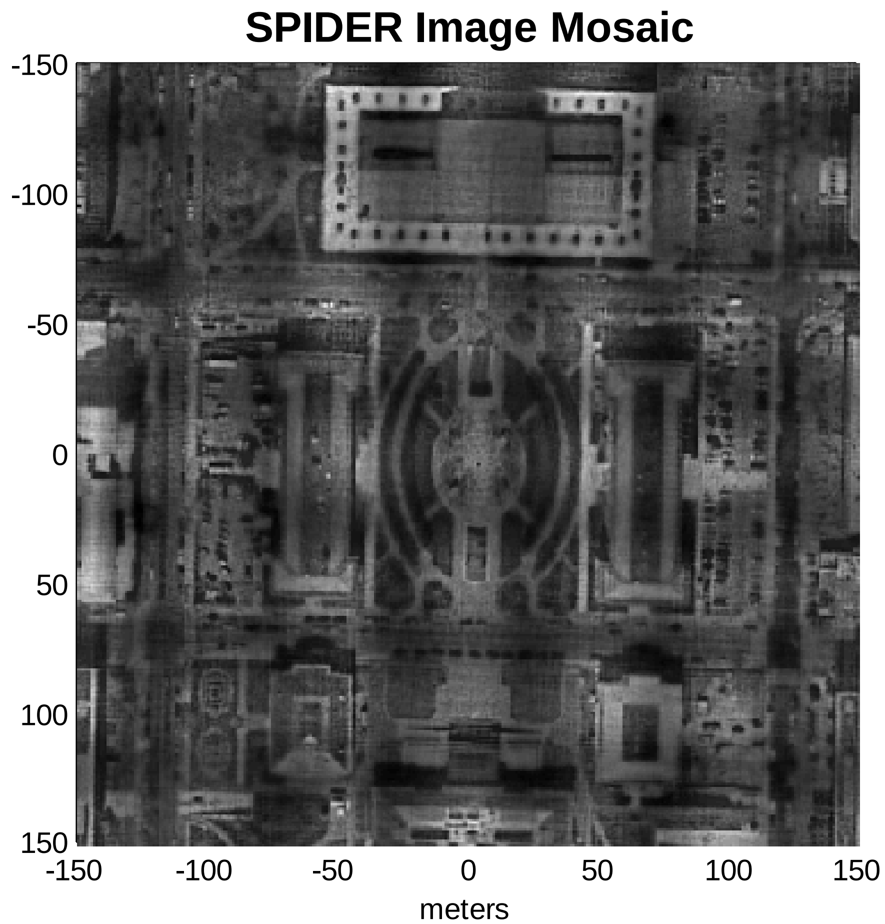
**SPIDER sub-image shows finer detail, but the point-spread function (PSF) sidelobes give a slightly noisy appearance (there was no measurement noise in the simulation)**

*Wiener filter is often used to remove blur in images due to linear motion or unfocussed optics

Lockheed Martin IRAD work

# Image Mosaic Comparison

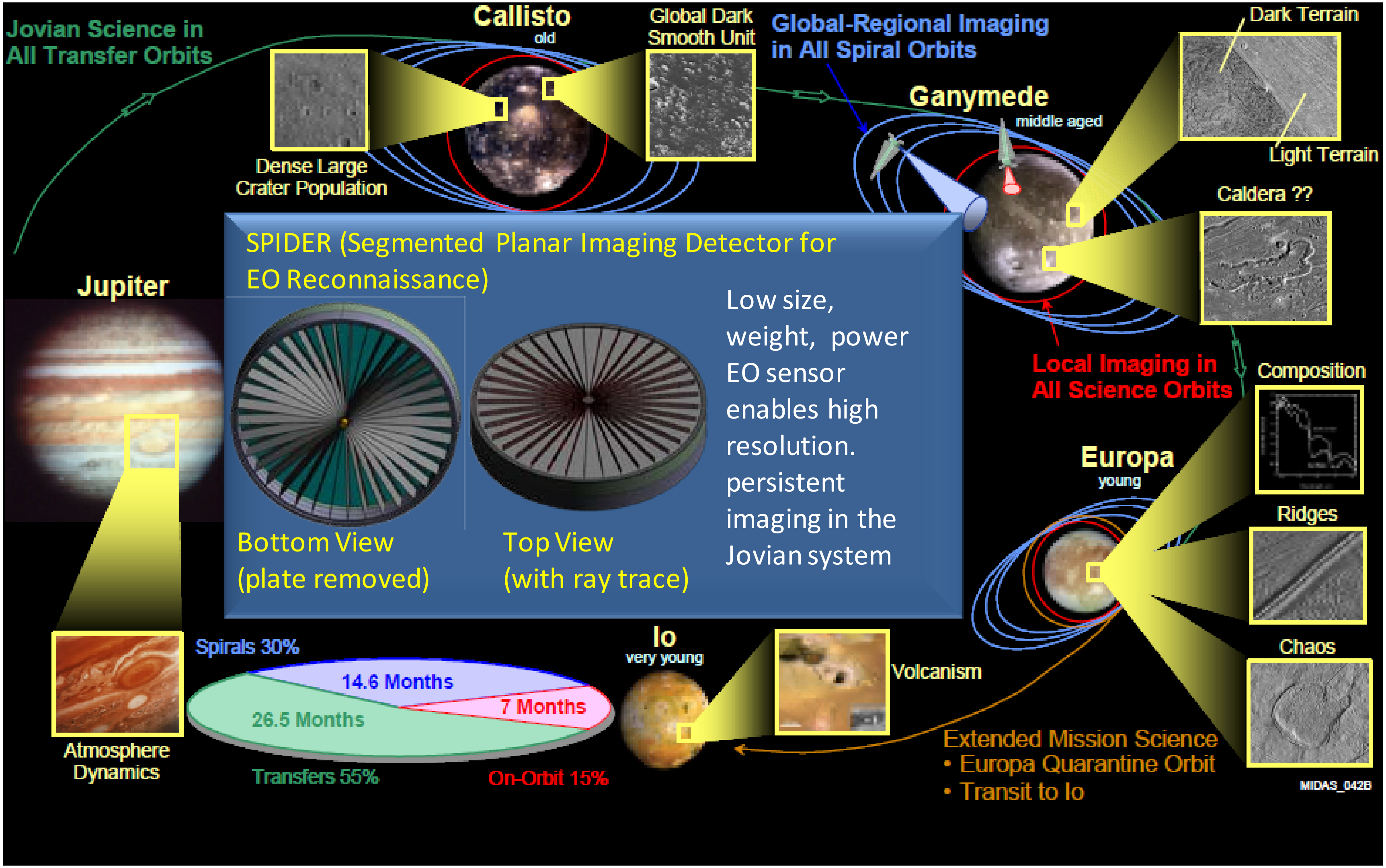



**The "banding" in the SPIDER image is likely due to the lack of low spatial frequency *u-v* samples near DC**

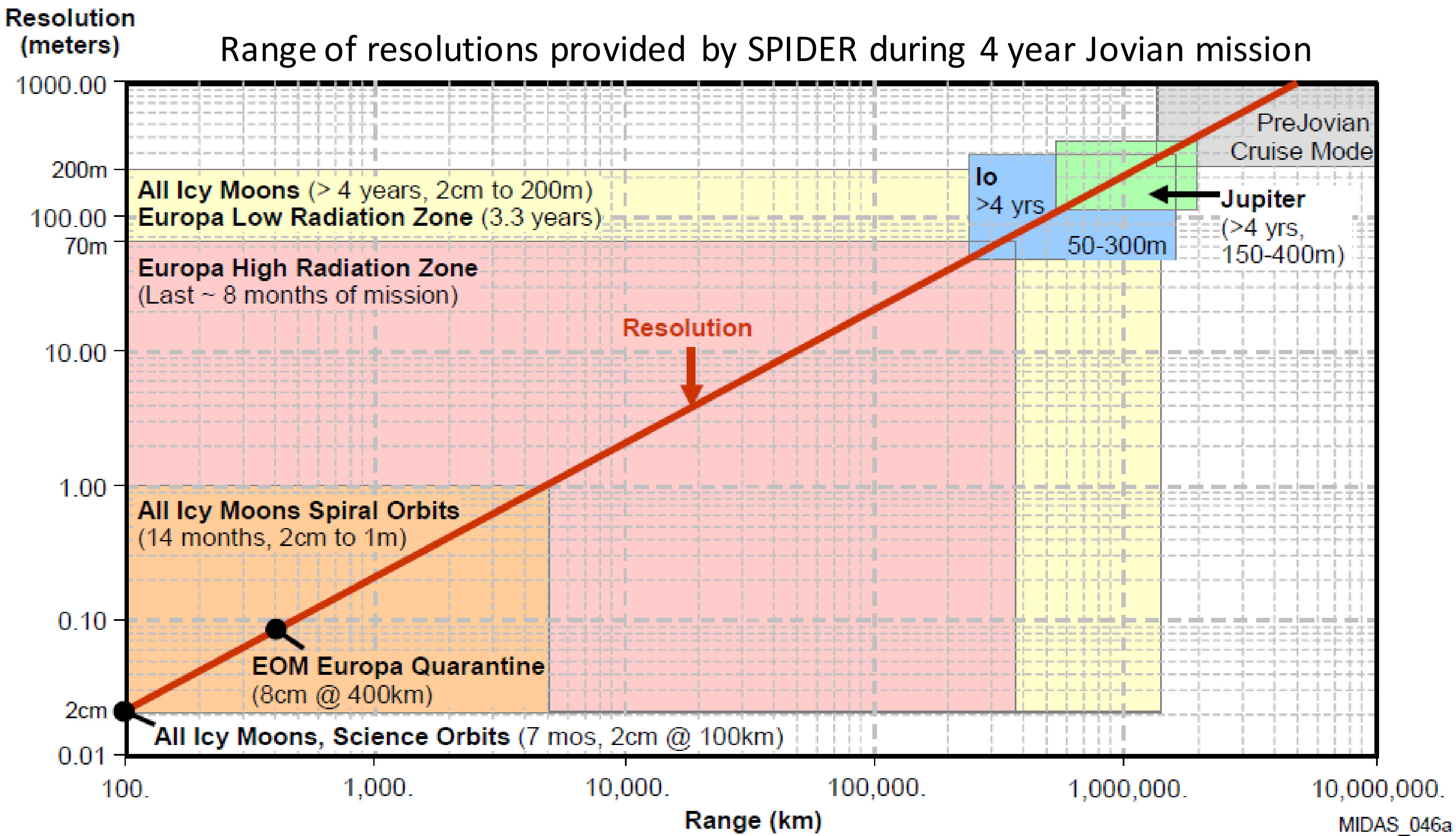
Lockheed Martin IRAD work

# Jupiter Icy Moons Orbiter Reference Mission



# SPIDER Provides High Resolution Capability

1.5 m diameter aperture SPIDER



# Europa Multiple Flyby Notional Topographical Imager (TI)

Europa Study 2012 Report – Europa Multiple Flyby Mission, JPL D-71990 (2012)

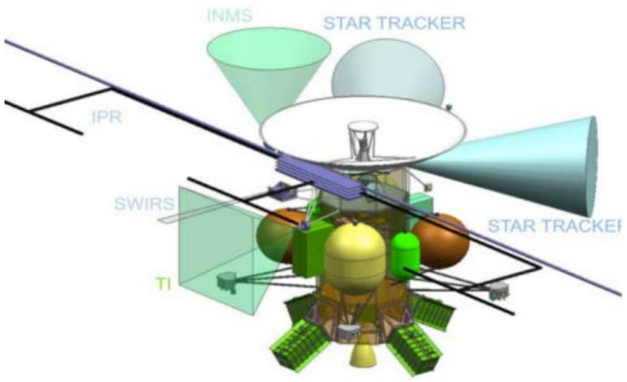
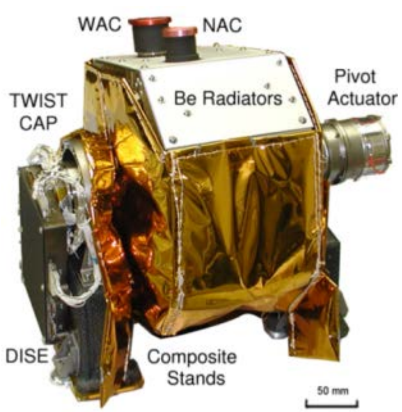


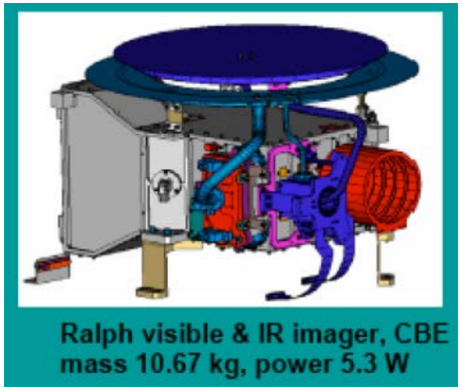
Figure C.2.2-1. Notional model payload accommodation and fields of view.

- **Proposed Traditional Imager**
  - **250 μrad IFOV → 25 m Ground-Sampled-Distance (GSD) at 100 km**
  - **4096 detectors, 5.5-ms integration time**
  - **Push-broom mode collection**
  - **5×5×4-cm radiation shielded enclosure**
  - **2.5 kg unshielded mass**

## Similar Imagers

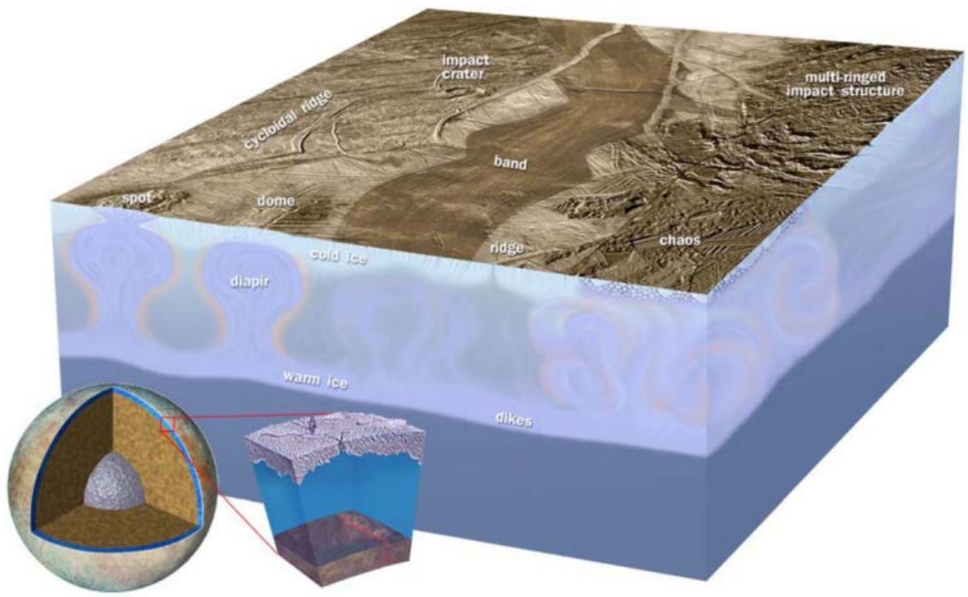


MRO Mars Color Imager (MARCI)



New Horizons Multi-spectral Visible Imaging Camera (MVIC)

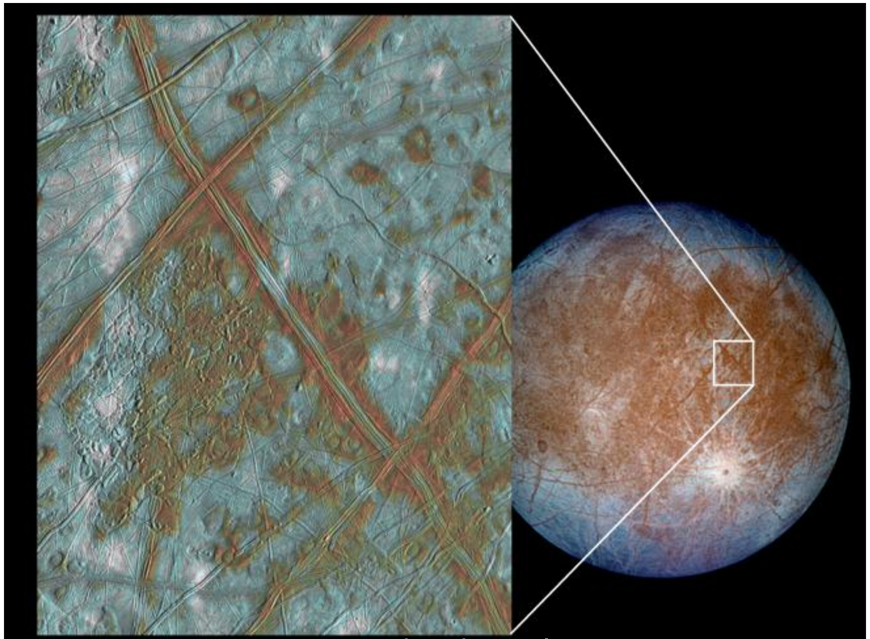
## Diagram of Europa's ice shell



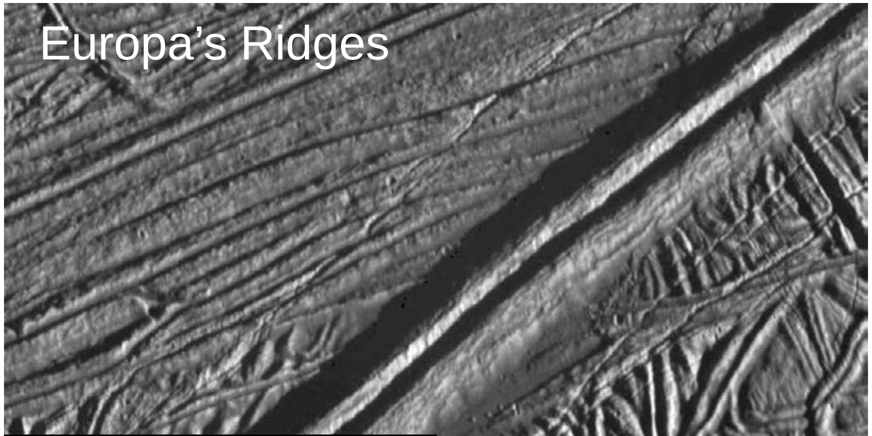
# *SPIDER-based Topographical Imager (TI)*

- **SPIDER Topographical Imager**
  - **4 cm diameter aperture (same enclosure)**
  - **15 µrad IFOV → 1.5 m Ground-Sampled-Distance (GSD) at 100 km**
  - **10 Mpixel area, 150-ms integration time**

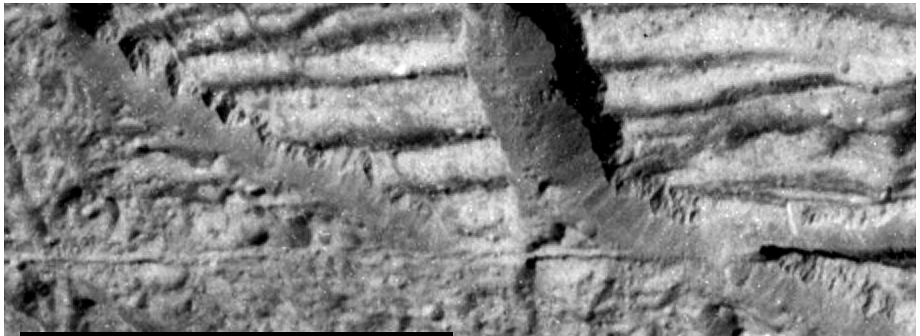
**For the same mass, SPIDER could collect 10× the area on ground with 17× the resolution**



NASA Photojournal PIA03002




NASA Photojournal PIA00589



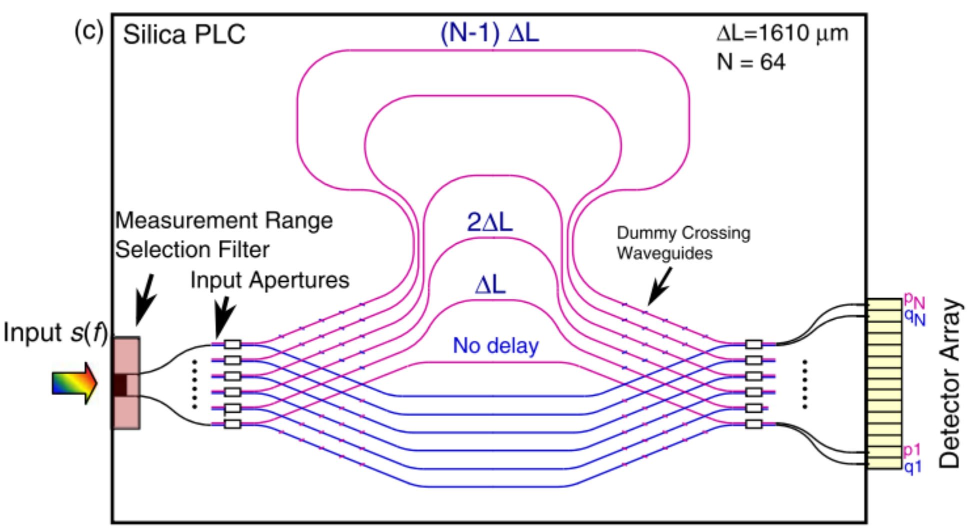
NASA Photojournal PIA01182

# *Ultrahigh Resolution Integrated Spectrometers*

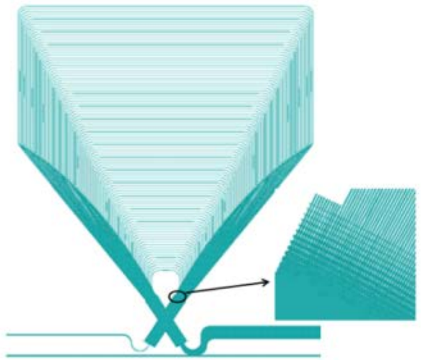
*"Improved spectral observations at significantly higher spectral and spatial resolution than is presently available, together with detailed laboratory analyses under the appropriate temperature and radiation environment, are needed to fully understand Europa's surface chemistry."*

Europa Study 2012 Report – Europa Multiple Flyby Mission, JPL D-71990 (2012)

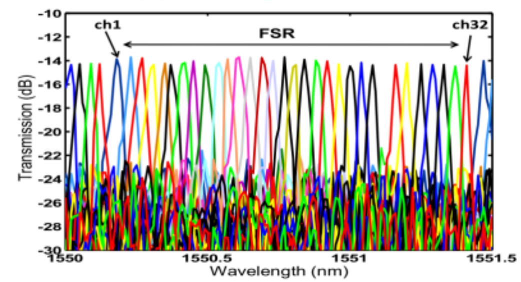
**"Fourier-transform, integrated-optic spatial heterodyne spectrometer on a silica-based planar waveguide with 1 GHz resolution"** by Nicolas K. Fontaine, Katsunari Okamoto, Tiehui Su, and S. J. B. Yoo, in *Optics Letters*, Vol. 36, No. 16, pp. 3124-3126, August, 2011.



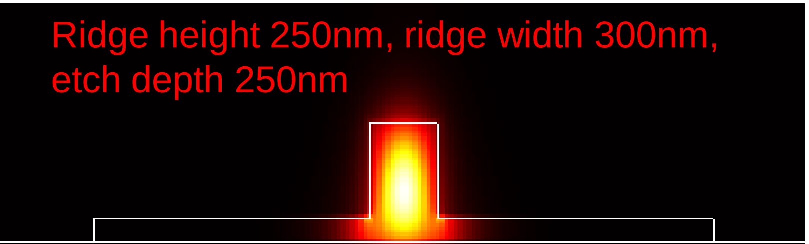

**5 GHz Channel Spacing InP-Based 32-Channel Arrayed-Waveguide Grating"** by W. Jiang, K. Okamoto, F. M. Soares, S. Lourdudoss, and S. J. B. Yoo, in *OFC*, Paper OWO2, 2009.



| | |
|---|---|
| Number of Channels | 32 |
| Number of Arrayed Arms | 104 |
| Channel spacing (GHz) | 5 |
| Free spectral range (GHz) | 160 |
| Grating order | 1095 |
| Path length difference Δ L (μm) | 527.142 |
| Radius of slab region (μm) | 3198.384 |
| Bend radius of arrayed arms (μm) | 500 |
| Chip size (mm×mm) | 21 × 22 |



# Athermal Photonics and Spectrometers

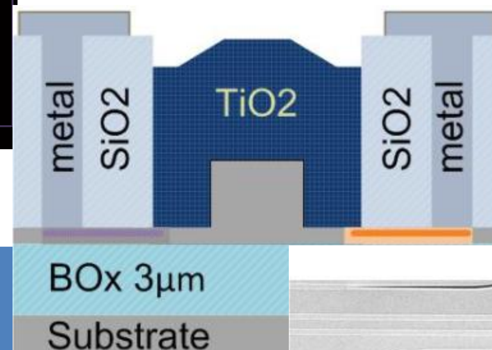



neff = 2.1669, ng = 3.7392,
Aeff = 0.224401, D = -6004.884 ps/nm/km
97% TE (3% minority field)
FWHM horiz.= 92.5nm 1/e horiz.= 141.6nm

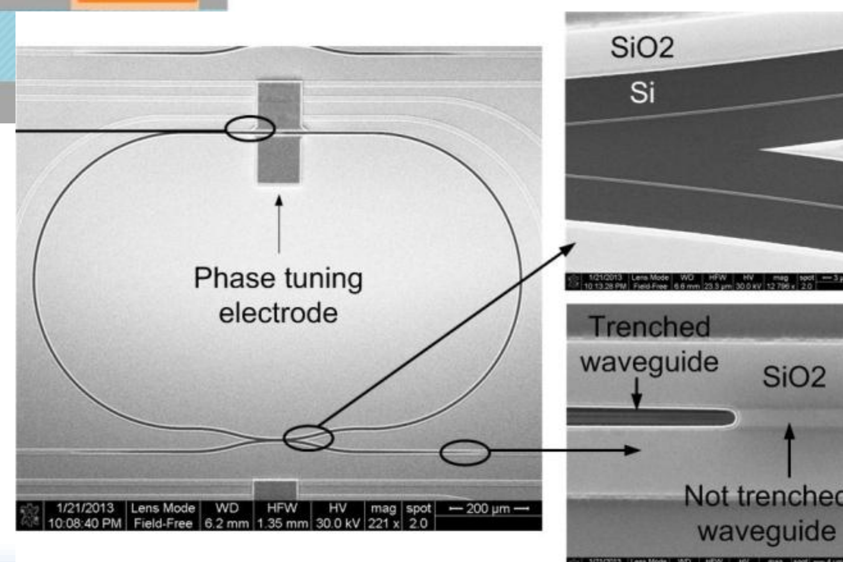
$$n_{eff} = \sum \Gamma_i (n_i + \frac{dn_i}{dT} \Delta T)$$

Athermalization means

$$\frac{dn_{eff}}{dT} = \sum \Gamma_i (\frac{dn_i}{dT}) = 0$$




| | Thermo-Optic Coefficient (k^-1) | Refractive index |
|---|---|---|
| **Silicon** | **$+1.8\times10^{-4}$** | **3.467** |
| **SiO2** | **~ 10-5** | **1.444** |
| **PUA** | **$-4.2\times10^{-4}$** | **~1.45** |
| **TiO2** | **$-3\times10^{-4}$ $-2.3\times10^{-3}$** | **~2.483** |

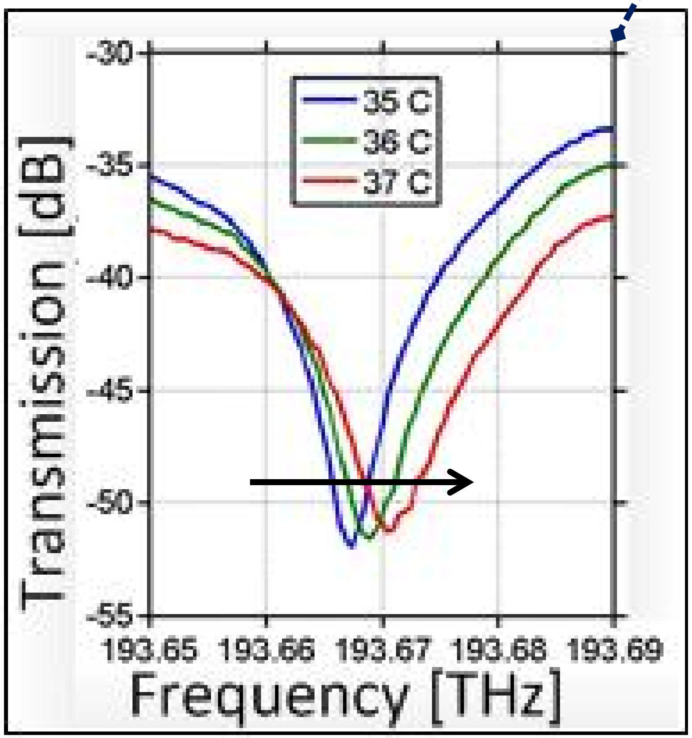


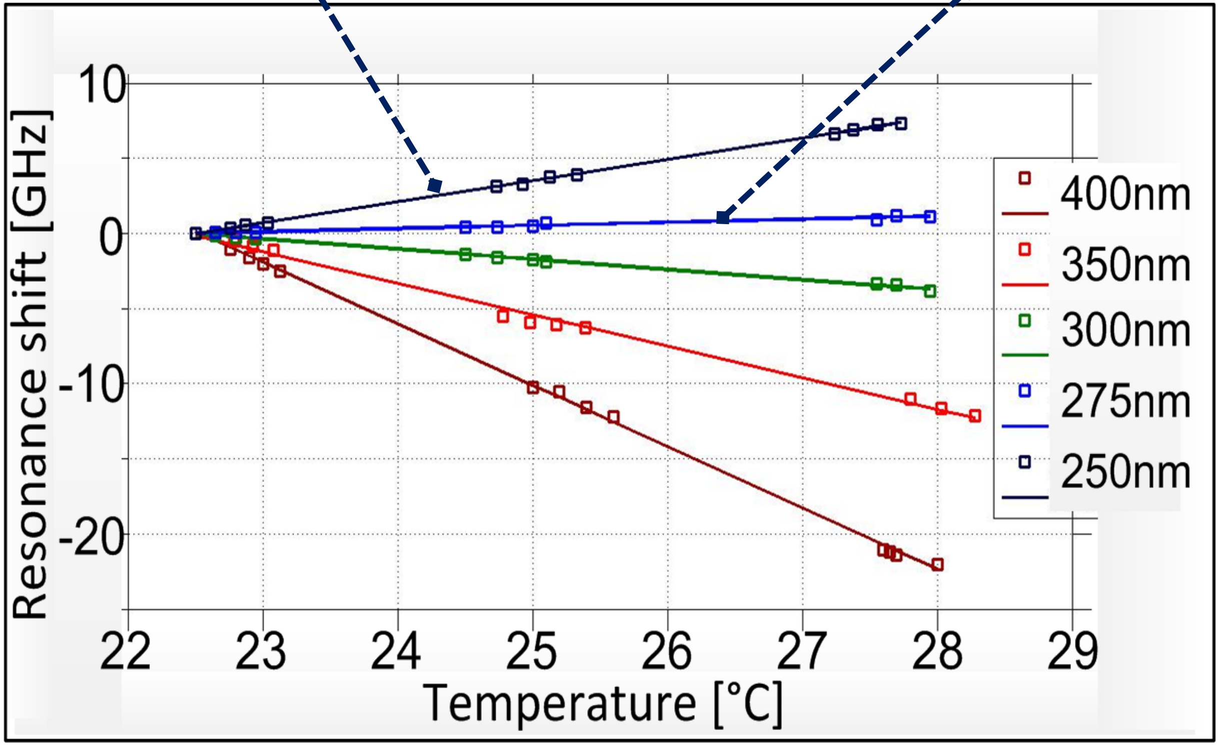
# *Athermal Photonics and Spectrometers*
# *e.g. Silicon Photonic Resonator with $TiO_2$ overcladding*

Ring resonator with
250nm wide waveguide

Blue shift
-11.3 pm/°C
(+1.41 GHz/°C)

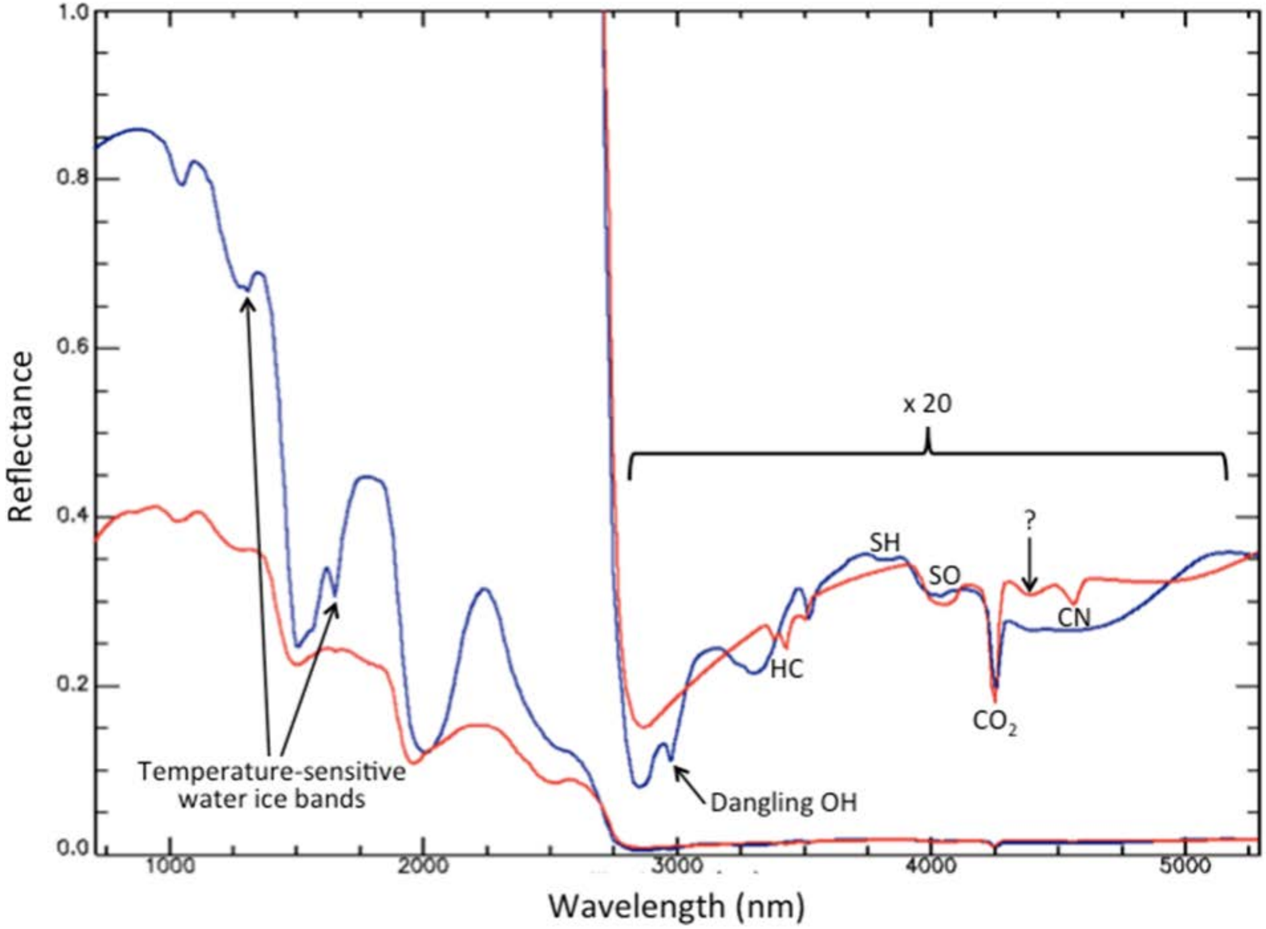
Blue shift
-1.60 pm/°C
(+0.20 GHz/°C)



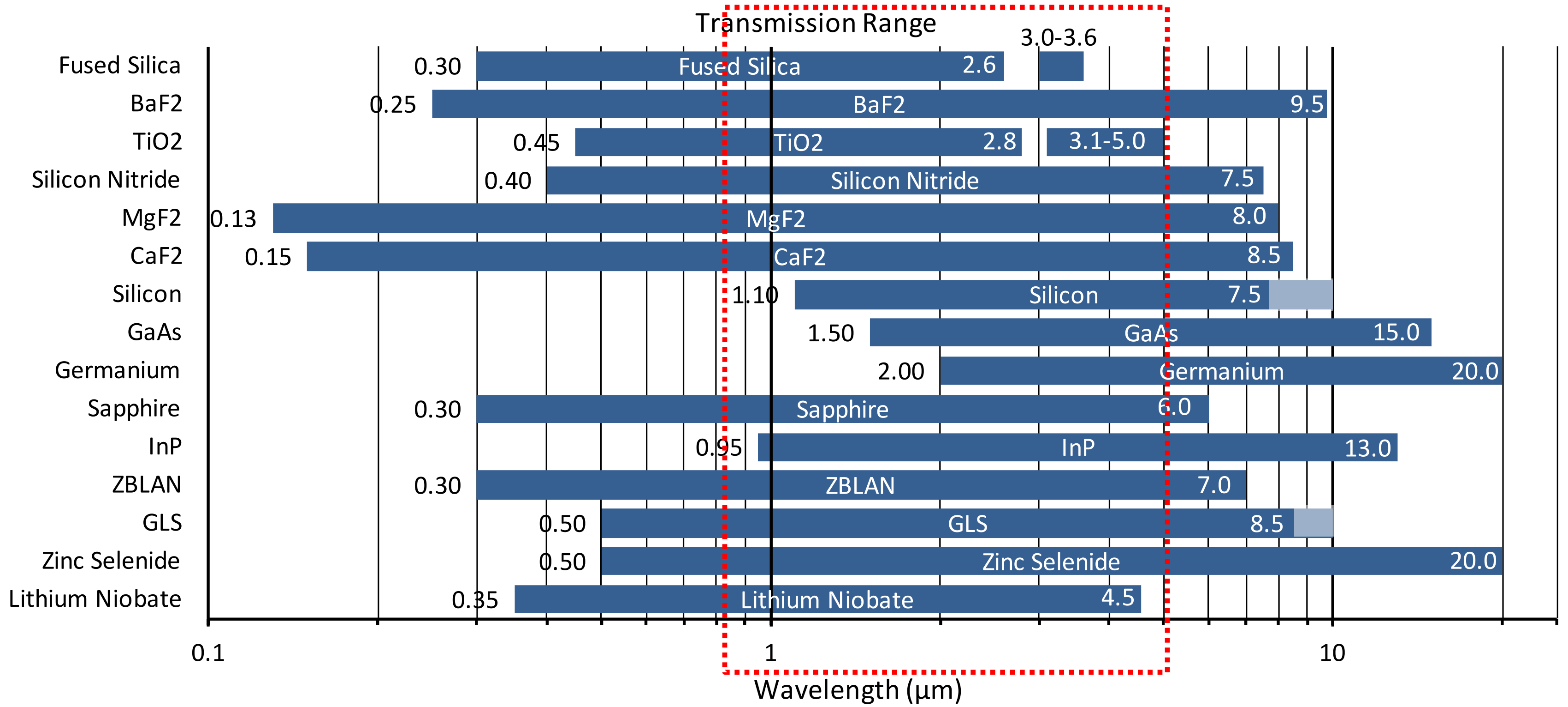
# *Identifying Compounds on Europa*

*"Notional reflectance spectra for ice-rich regions (blue curves) and ice-poor regions (red curves) on Europa … in the 1–5 µm spectral range."*

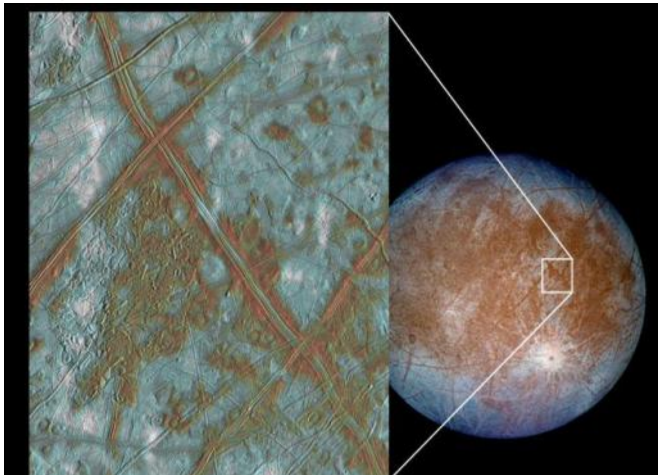


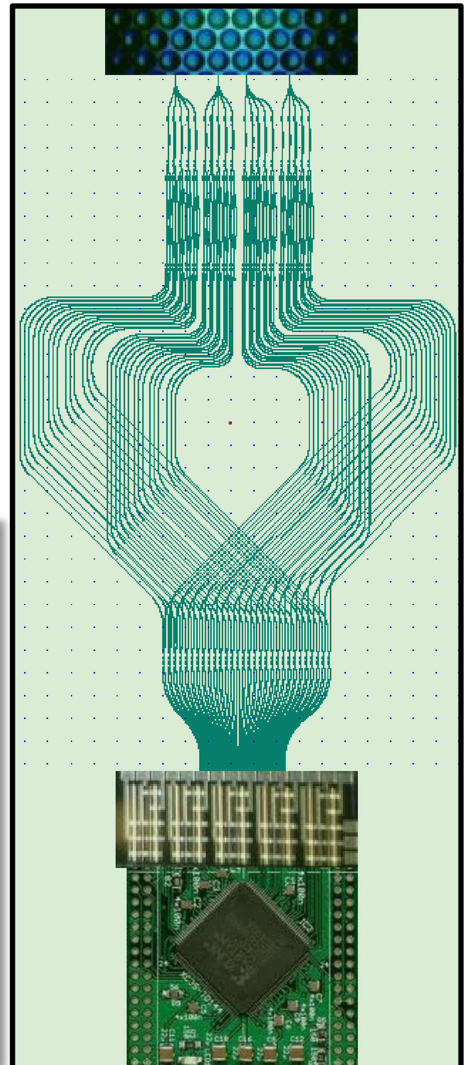

Europa Study 2012 Report – Europa Multiple Flyby Mission, JPL D-71990 (2012)

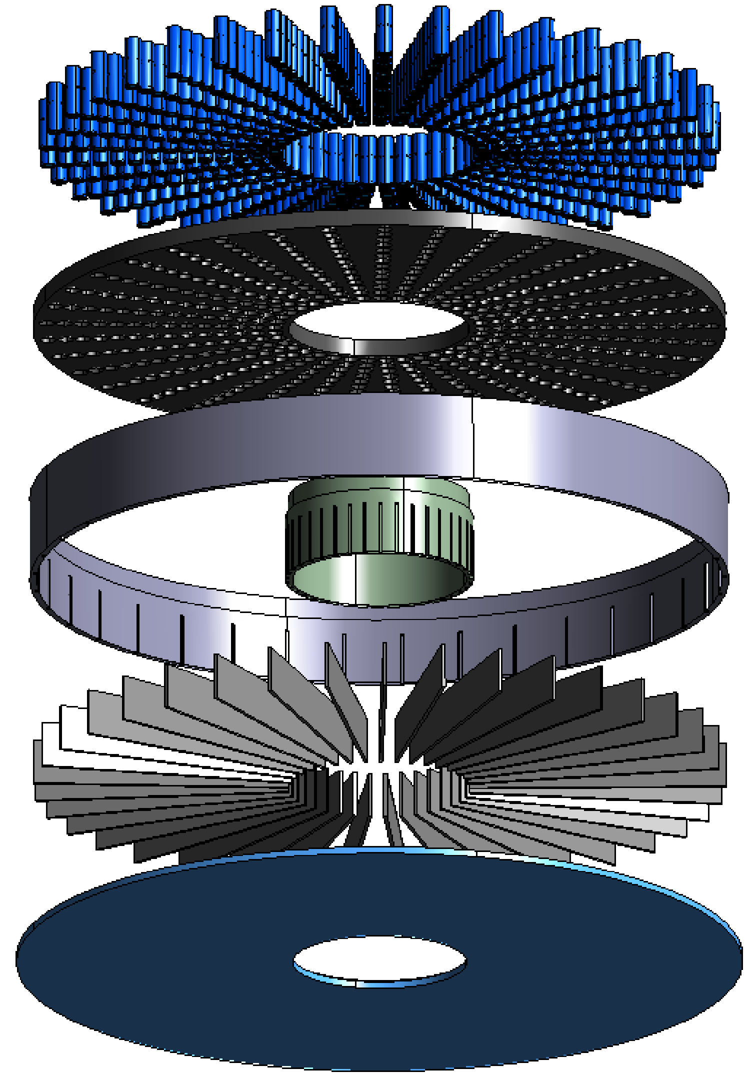
# Transmission Range of Selected Materials



# Thank you for support


NASA Photojournal PIA03002



| ID | Task | Objective | Benefit |
| --- | --- | --- | --- |
| 1 | Develop radiometry model of Europa | Provide input data to address required integration times for a realistic mission scenario (Europa Clipper). | Anchor results to a specific mission of interest (relevant to a broad class of "icy moons" type missions). |
| 2 | Develop SPIDER design | Tailor our design for the Europa Clipper reference mission to show potential and identify key technologies. | Showcase low cost and SWaP. |
| 3 | Evaluate various PIC material platforms and architectures | Provide data on waveguide coupling efficiencies and device losses to improve SPIDER model | Quantifies performance limitations due to current technology constraints. |
| 4 | Develop image reconstruction algorithm | Adapt existing algorithms to optimize performance for Europa reference mission. | Increases fidelity of critical algorithm required to generate science products. |
| 5 | Develop SPIDER model (predict raw signal characteristics including SNR) | Provide realistic data to enable high fidelity predictions of sensor performance. | Addresses performance limitations due to fundamental physics constraints. |
| 6 | Perform image simulations and evaluate predicted performance | Provide quantitative performance predictions to assess feasibility of meeting science goals. | Forms the basis for scaling design and performance to a broad class of imaging missions. |
| 7 | Develop a technology roadmap | Identify technology needs and provide a roadmap to guide further investigation and to show where there is significant leverage of existing technology. | Minimize development cost by leveraging Lockheed Martin IRAD, commercial industry and DARPA investments. |