Airborne Astronomy and Stellar Occultations

Case for a significant upgrade to the FPI+ Camera

Michael J Person

Research Scientist, MIT Planetary Astronomy Lab

Director, MIT Wallace Astrophysical Observatory

Karsten Schindler

Instrument Scientist, Deutsches SOFIA Institute

Universitaet Stuttgart

SOFIA Instrument RoadMap Workshop – 27-29 July 2020

Utilizing SOFIA’s Overlooked Potential

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- Advantages of an airborne observatory
  - Altitude over weather

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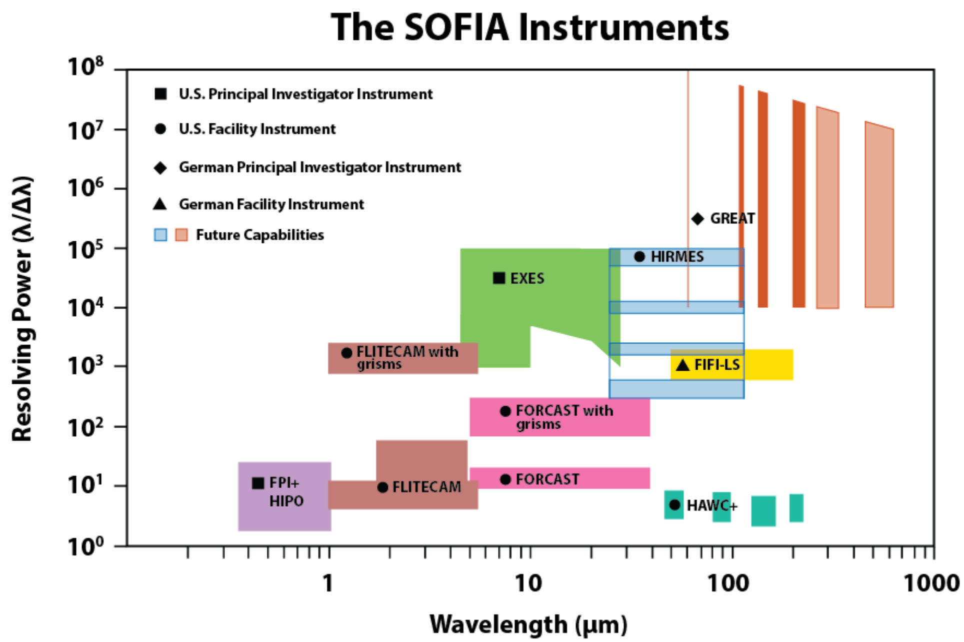
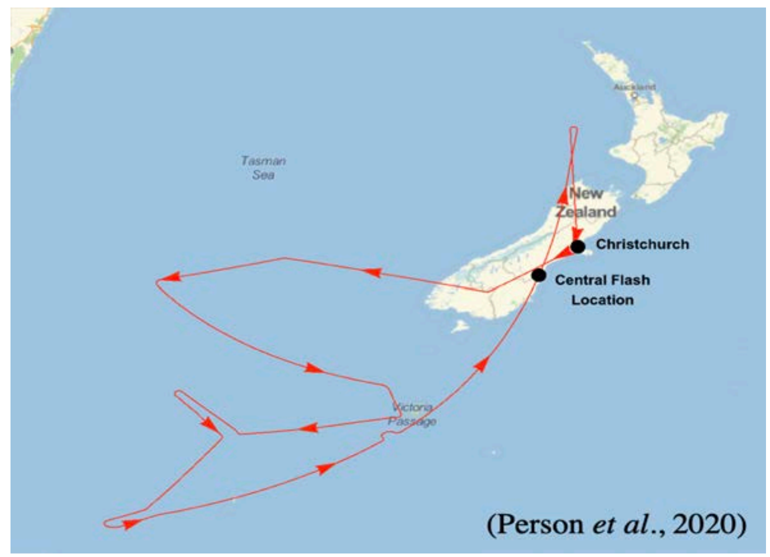


Utilizing SOFIA's Overlooked Potential

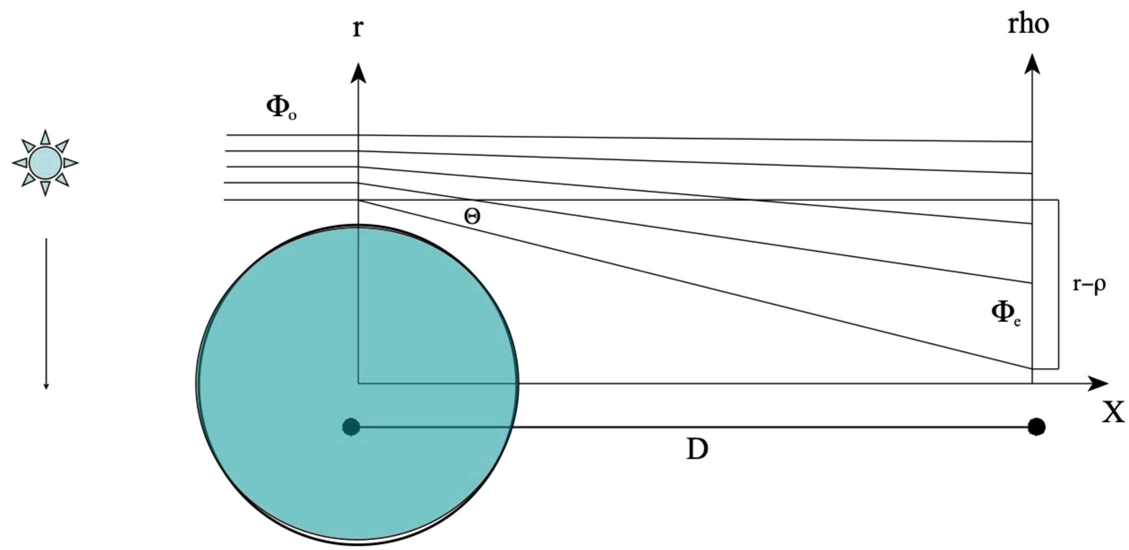
- Advantages of an airborne observatory
  - Altitude over weather
  - Atmospheric absorption allows greater wavelength coverage especially in the large IR bands
  - Science Potential from MOBILITY!
    - Space telescopes DO NOT replace!



(Person *et al.*, 2020)

Occultation Science

- High spatial resolution (a few km in the outer solar system)
  - Limited by factors other than diffraction at the telescope!
    - Measure the sizes of objects that can't be imaged
    - Measure the depth of atmospheres at km resolutions



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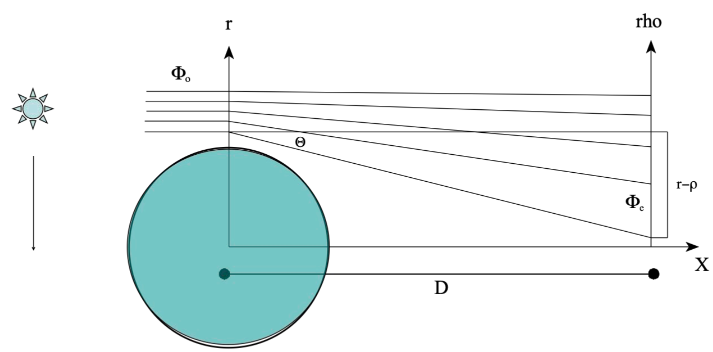
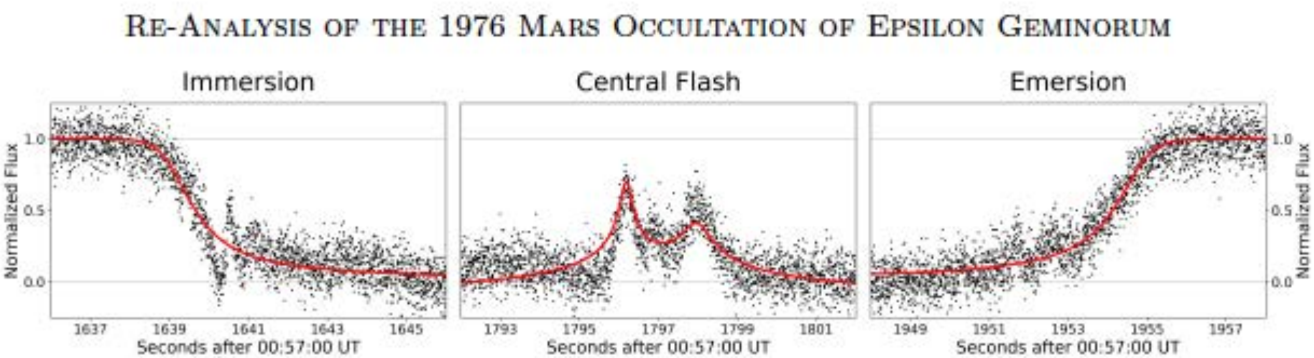
- Direct measurements of atmospheres
  - Temperature, Pressure, Number Density profiles
  - Haze/Extinction profiles (atmospheres and rings)
    - Particle sizes (multi-colors)



Occultations and Airborne Astronomy

- Much of the history of occultation science is a history of airborne astronomy.
  - Atmosphere of Mars



Saunders *et al.*, 2020

NASA Stock Photos

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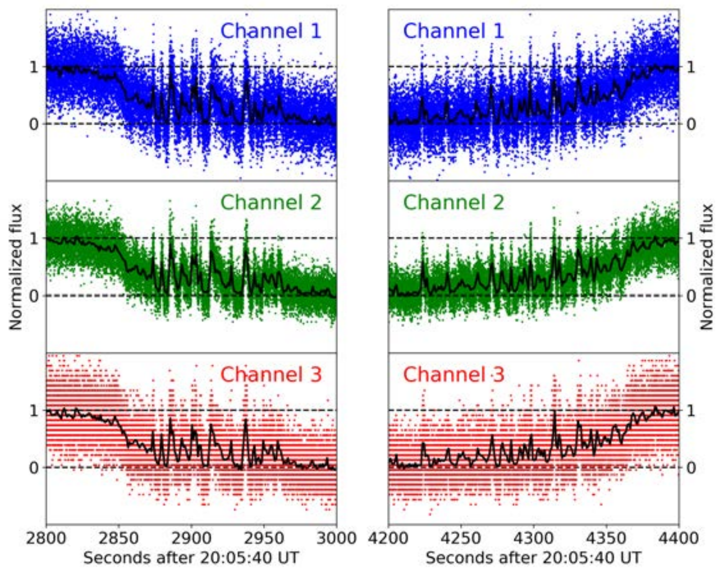

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NASA Voyager 2 Archive

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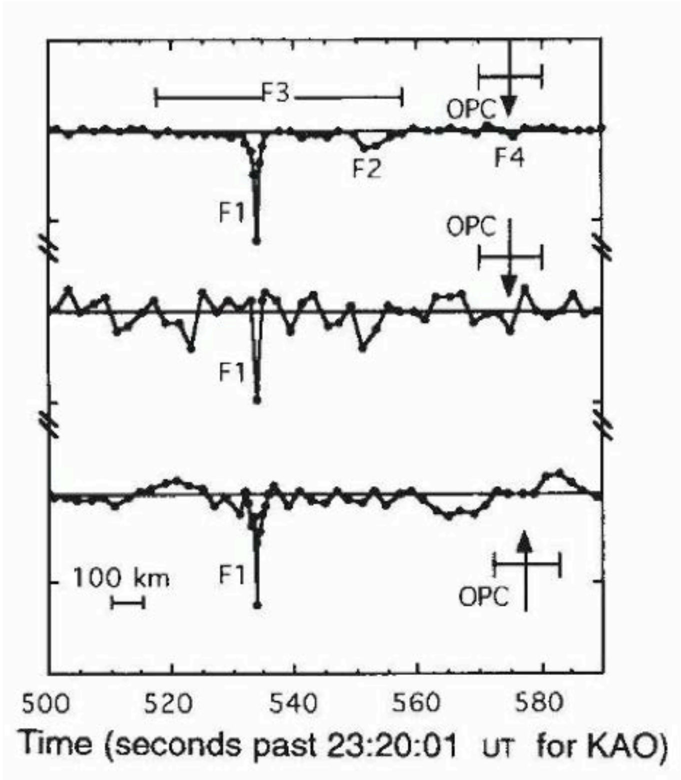

Elliot *et al.*, 1995

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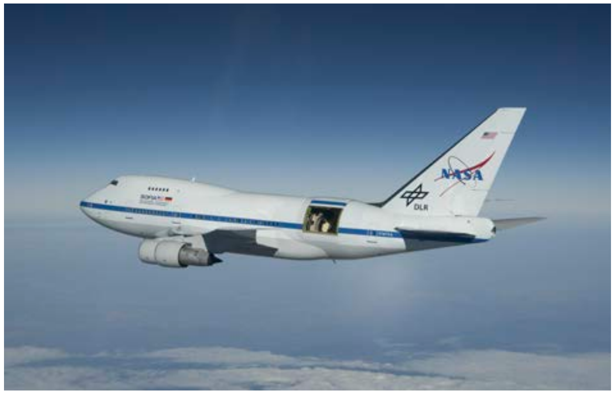

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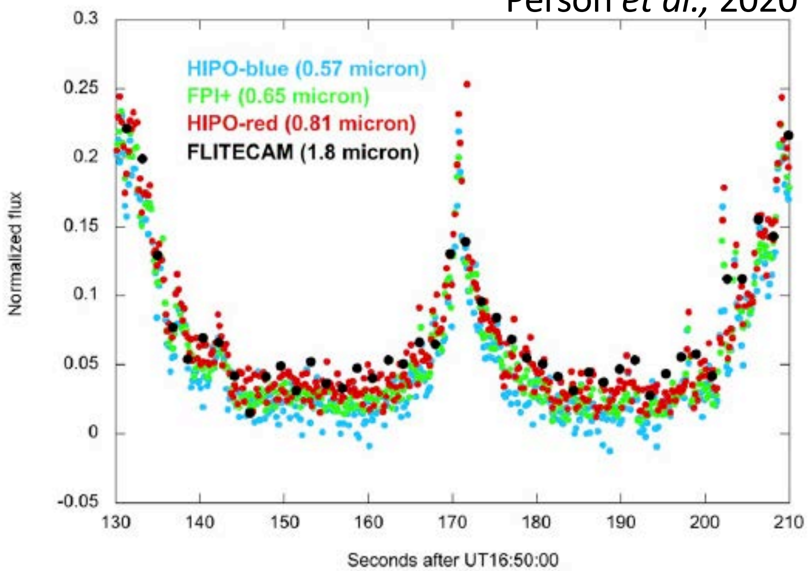
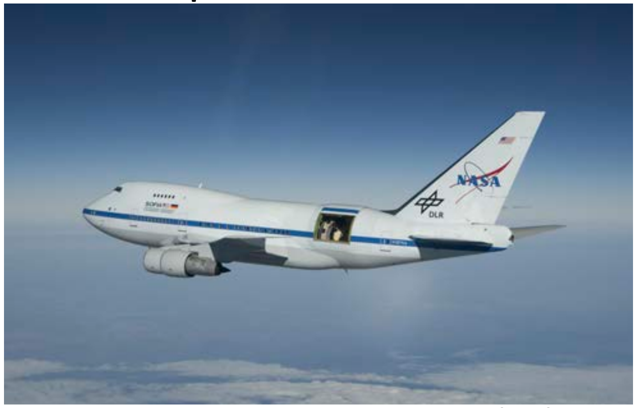
Person *et al.*, 2020





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  - Triton atmosphere collapse

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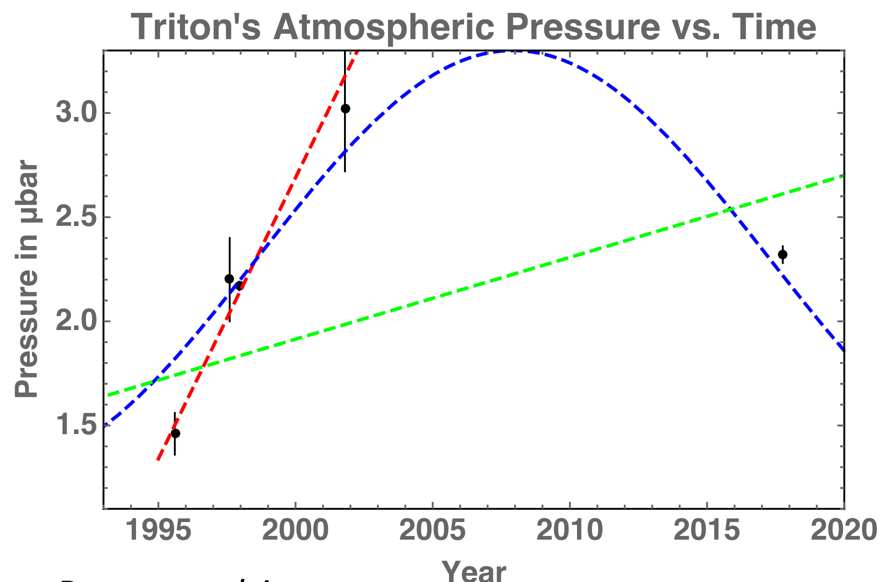
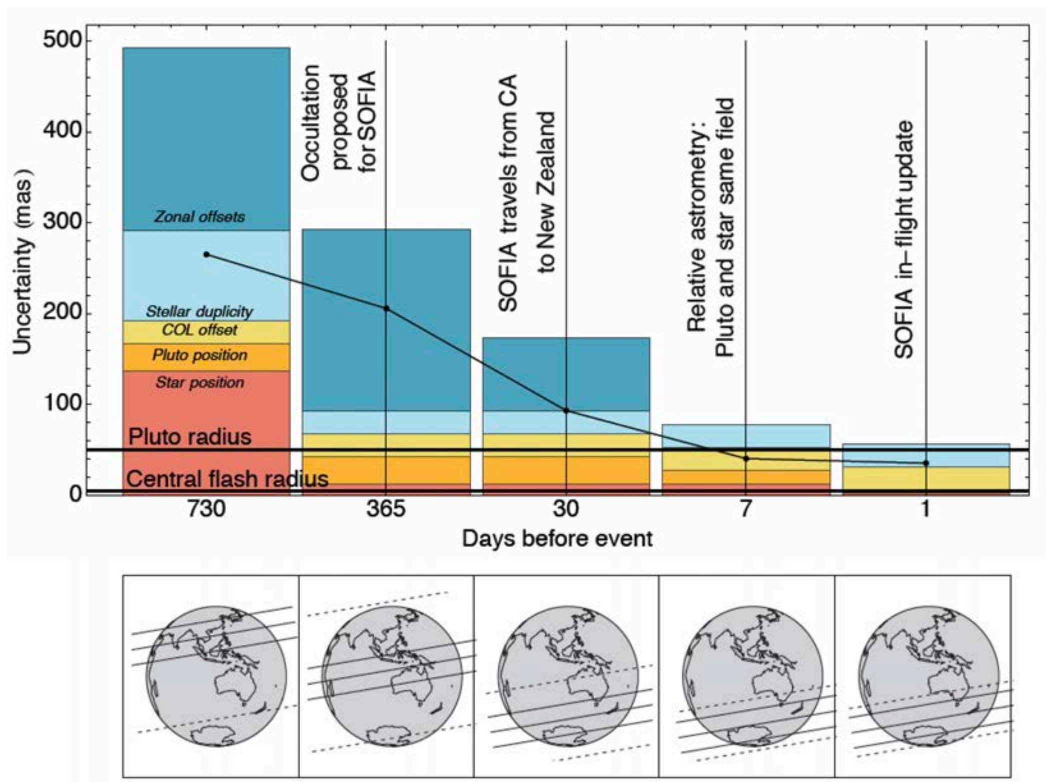


Person *et al.* in prep

Occultations have been challenging!

- Long Campaigns
  - Astrometry
  - Course Planning
- Large Costs
  - Multiple flights
  - Equipment Priorities



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New Age of Occultation Predictions

- GAIA has revolutionized (an in some cases removed) half of the problem

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- The other half of the problem (moving body ephemerides) is on the verge of falling.
    - Rubin Observatory (LSST) and other frequent all-sky surveys.

AURA

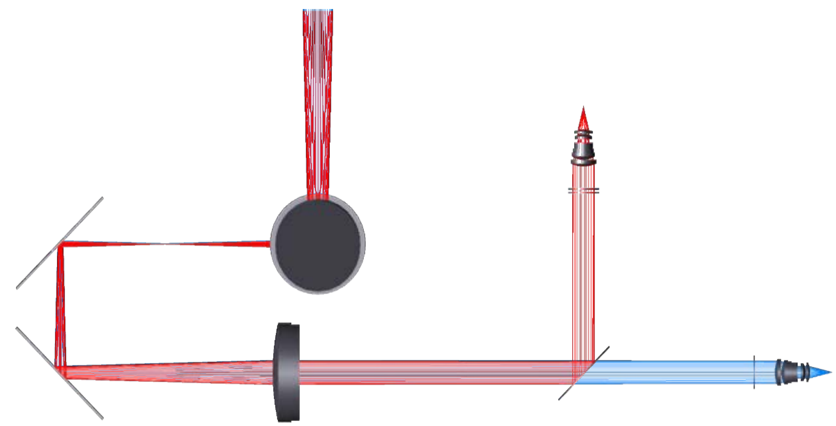
Occultation Science Targets

Science Target Class	Expected SOFIA Available Occultations over 5 years
Small Bodies w/Atmospheres (Pluto, Triton, Titan, etc.)	11
KBO Characterization	50
Centaurs (Chariklo-, Chiron-type objects)	65
Trojan Asteroids (Lucy mission)	150
Comets	2
Giant Planet Atmospheres and Rings	5 (Restricted to the brightest stars)

What do we need?

- High Speed Photometry
  - For bright stars, this is the primary limitation on spatial resolution
- Instant Accessibility
  - No more instrument conflicts/changes
  - Single-leg observations without long campaigns
- Multi-wavelength Vis/NIR Sensing
  - Enables far more detailed atmosphere/ring work

(FPI+)+ Upgrade Plan



- Adds Near-IR capability to the FPI+
  - Enables occultation multi-wavelength observations
  - Improves in-flight guiding by providing more NIR guide stars
  - SOFIA is currently blind in NIR wavelengths, adding additional science
- Permanently mounted
  - Low-maintenance cooling with no consumables.
  - Instant access w/o disturbing other instruments on the flange.

Technology Availability and Readiness

- Minimal development time
- Low cost compared to new instrument packages
- Rapid deployment over two years

For Details: I'll turn remaining time over to Karsten Schindler of the DSI FPI+ team.

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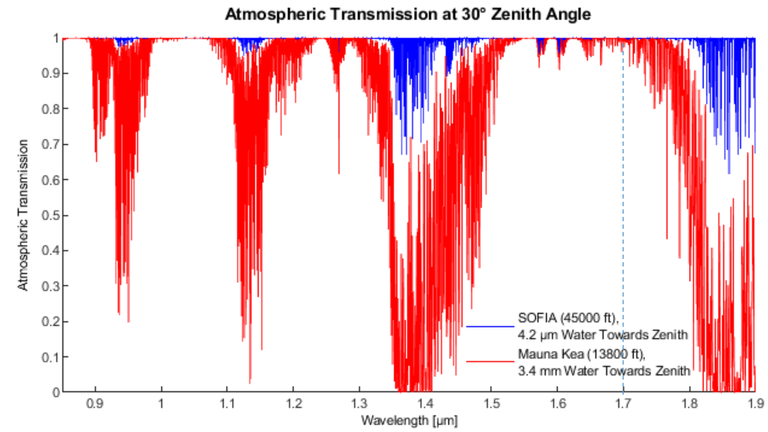
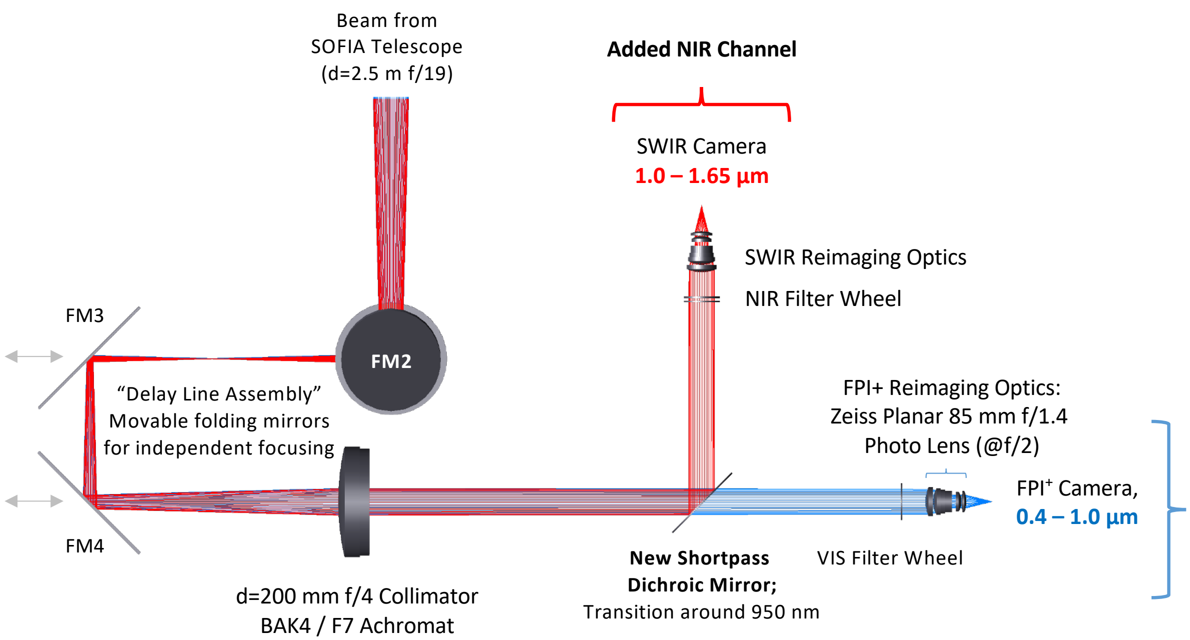
Technological Availability and Readiness

FPI++ NIR Tracking and Science Camera

Karsten Schindler, DSI

- Detector geometry needs to match existing optics
- No consumables
- High frame rate, minimal readout time
- Short lead time, low technical risk





Existing VIS Channel,
8.0 arcmin unvignetted FOV

Requirements

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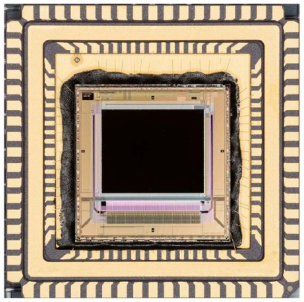

Leonardo SAPHIRA e-APD HgCdTe Array - 320 x 256 pixel, 24 µm pitch

- Conceived for NIR WFS and fringe tracking
- Development initiated by ESO (Finger),
  later supported by University of Hawaii IfA (Hall)
- Current ROIC: ME1001 (fixed a glow source due to mask error on the ME1000)
  - 32 outputs, up to 10 MPixel/s parallel readout -> 3900 Hz full frame
  - Supports various reset modes (global, rolling shutter) and readout strategies (multiple non-destructive reads, CDS)
- No persistence when overilluminated

Detector

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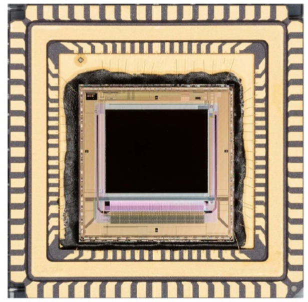
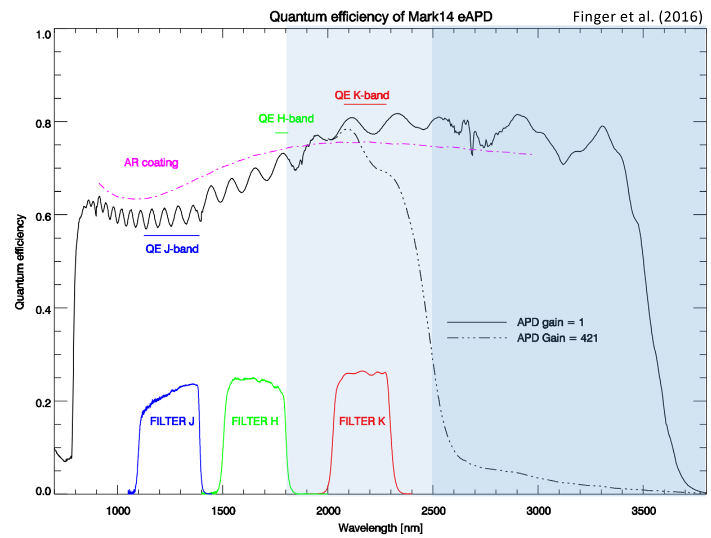


Finger et al. (2016)

Leonardo SAPHIRA e-APD HgCdTe Array - 320 x 256 pixel, 24 µm pitch

- HgCdTe absorption layer sensitive to 0.8 … 2.5 µm, but multiplication layer underneath up to 3.5 µm!
  - Cold short pass filters to block 2.5 … 3.5 µm by default
  - Adjust filter cut-on to suppress ambient thermal background of warm FPI+ foreoptics
- What about the excess noise factor (F) vs gain (G)?
  - For a photometer, F should be unity – always fulfilled at G=1
  - ESO / Finger et al.: Practically unity at gains that are of interest for the FPI+



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First Light Imaging "C-RED One" Camera (introduced 2016)

- Avoids lengthy development of cryogenic instrument and read out electronics
- SAPHIRA 24 µm pixel pitch = sweet spot for optimal sampling with existing FPI+ optics and SOFIA's shear layer seeing
- Pulse tube cooled to 80 K = no consumables
- 25 kg total weight

- System Read Noise:
  - 20 e^- rms for CDS at G=1 (F=1)
  - <1 e^- rms for CDS at G≥20 (F~1)
- Dark current, looking at room temperature black body, 1 MHz:
  - 70 e^-/px/s dark current (G=1)
  - 40 e^-/px/s dark current (G~10, suppresses sensitivity >2.5µm)

- Optimized towards high frame rates (up to 3500 Hz single reads full frame) – more than enough

Commercial Camera Package

Numerous C-RED One cameras commissioned and operational:

- MIRC-X at CHARA, combining the light from all six CHARA telescopes on Mt. Wilson
- SCExAO at Subaru (KERNEL project)

In preparation:

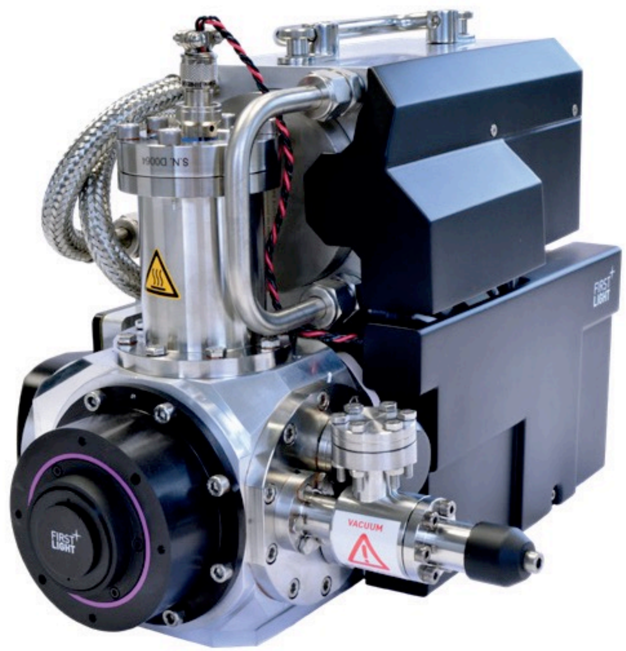
- MAORY, Multi-conjugate Adaptive Optics RelaY for ELT

More SAPHIRA arrays in the community

- WFS and fringe tracker in VLTI GRAVITY
- Lucky Imaging at NAU / Siding Springs
- IfA visitor / test instrument (Hall, Atkinson et al.) at NASA IRTF, ROBO-AO (Mt. Palomar), LASSO at Kitt Peak, KPIC at Keck

- Existing user base
- Published data in the literature
- Established product

First Light Instruments



Action Items:

- Assessment of adding 25 kg+ on the SOFIA TA (likely requires some balancing on TA side, but no show stopper)
- SWIR reimaging optics
  - Commercial lens ⇨ easy, but limited FOV
  - Custom lens to utilize full TA FOV, iterative design with manufacturer to adapt cold stop geometry
- Pulse-tube cooler's hot side utilizes closed cycle water cooler for heat transfer –
  forced air cooling is possible (demonstrated e.g. with Sunpower CryoTel cryocoolers),
  First Light open to make a change to avoid liquid on SOFIA

FWHM at NIR wavelengths ≥ 3.2 arcsec

SWIR Lens	Plate Scale	FOV	Procurement
50 mm f/1.2	**1.60 arcsec/pixel**	**8.5 x 6.8 arcmin²**	**Custom**
75 mm f/1.8	1.07 arcsec/pixel	5.7 x 4.5 arcmin²	COTS

Action Items

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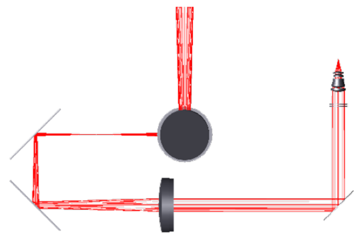
Sensitivity Analysis



Assumptions:

- M2V type star, T=3530 K
- APD Gain = 1 ⇨ No excess noise factor
- Huge 1.6 arcsec pixels
- OH sky emission and atmospheric transmission calculated by ATRAN
    - Sky background totally dominates
    - APD gain makes little difference
- Each optical surface treated as a thermal radiation source

Current M3-1	SNR = 60 (tracking limit)	SNR = 10 (detection limit)
1 s exposure	J=12.9 mag	J=14.9 mag
3 s exposure	J=13.5 mag	J=15.5 mag