Exoplanets and their Direct Imaging

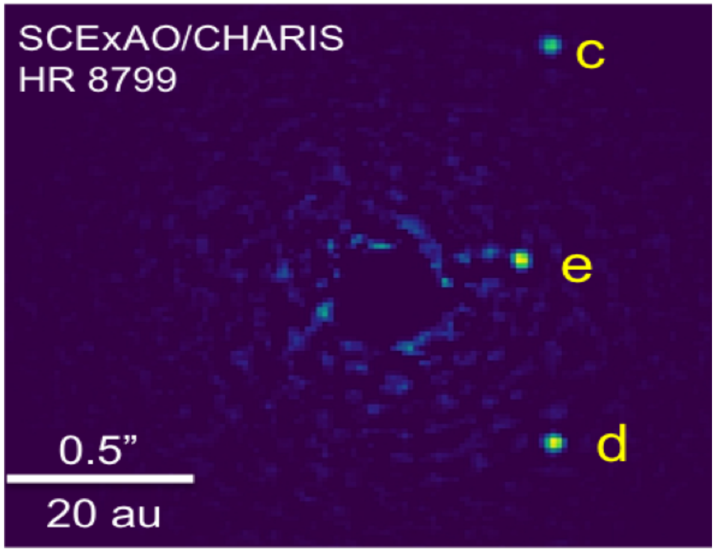
Direct Imaging allows to measure:

1. Position → Constrain the orbits such as eccentricity, time period, mass

2. Flux →
- Temperature, Geometric albedo, constrain the habitability
- Study planet rotation
- Detect clouds/ surface features
- Spectra;

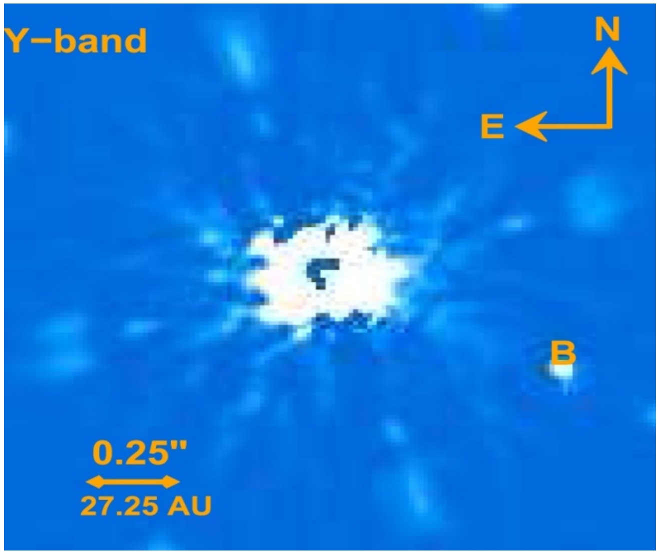
Study the chemical composition of exoplanet atmosphere

Post Coronagraphic Images



HR8799 behind coronagraph
With its planets. (Currie et al. 2019)

How do we measure the flux and position of the companion precisely?



HD1160 behind coronagraph
With its young brown dwarf companion.
(Garcia et al. 2017)

Satellite Spots

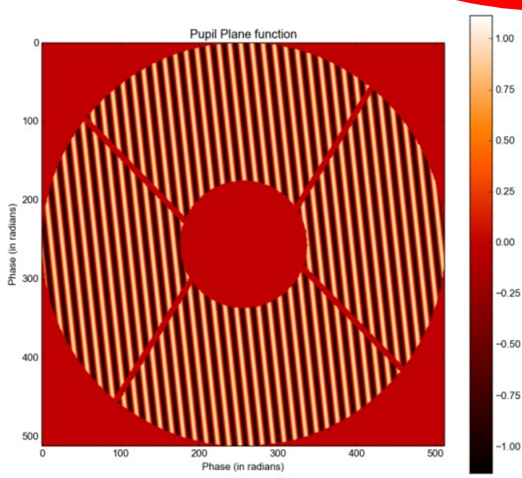
Pupil Plane Phase Modulation

I_{phase} :Focal plane Intensity
FT :Fourier Transform
A :Amplitude Function
Φ :Pupil Plane Phase
Φ_{mask} :Phase Grid
R :Real part
I :Imaginary part
E :Electric field at Pupil

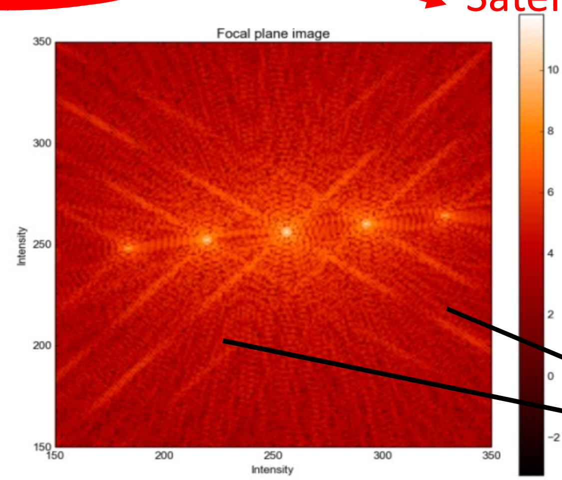
$$I_{phase} = \left|FT\left[Ae^{i(\phi+\phi_{mask})}\right]\right|^2$$
$$= I_0 + -2I\left[E'\left(E * FT(\phi_{mask})\right)\right] - R\left[E * FT(\phi_{mask}) * FT(\phi_{mask})\right]$$
$$+ \left|E * FT(\phi_{mask})\right|^2$$

Central PSF

Satellite Spot



Simulated Image of Subaru
Pupil Plane



Simulated Image of Subaru
Focal Plane

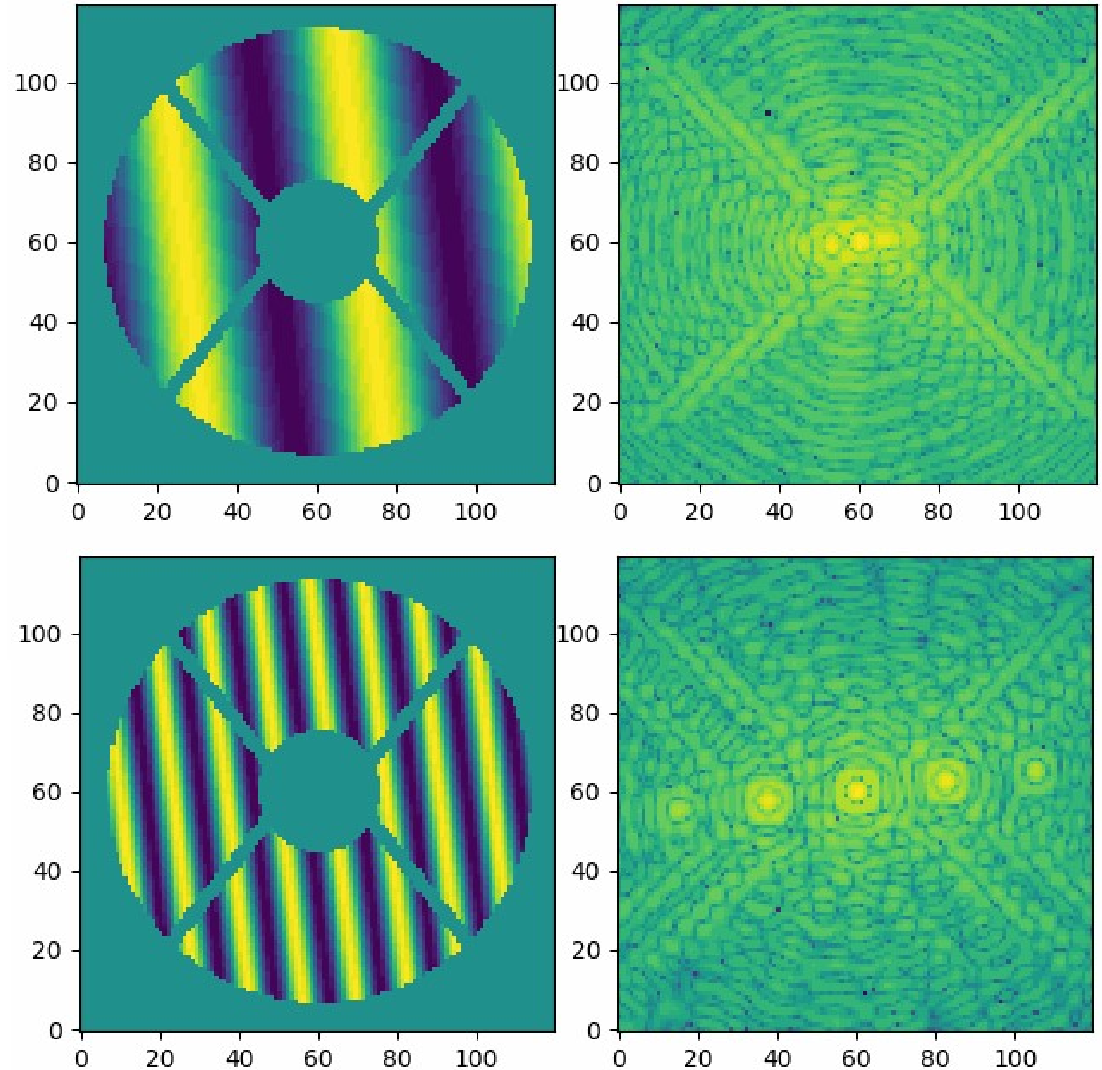
Satellite Spots

Satellite Spots

- Distance between the satellite spots is proportional to the sine wave frequency.

- Intensity of 1st order spot ∝ (Amplitude)^2

- Orientation of the satellite spots is proportional to the orientation of the sine wave.



Simulated image of Subaru **Pupil** Plane

Simulated image of Subaru **Focal** Plane

Making Spots incoherent with background halo

1. The Satellite Spots interfere with the Underlying Background halo

A_h & φ → amplitude & phase of underlying speckle halo

A_s & θ → amplitude & phase of Satellite spot

Total Intensity: $$I_{tot} = \left|A_h e^{i\phi} + A_s e^{i\theta}\right|^2$$

$$= A_s^2 + A_h^2 + 2A_s A_h \cos(\phi - \theta)$$

Satellite Spot (A_s^2)

Background halo (A_h^2)

Coherent mixing term ($2A_s A_h \cos(\phi - \theta)$)

2. Making satellite speckle independent of the background

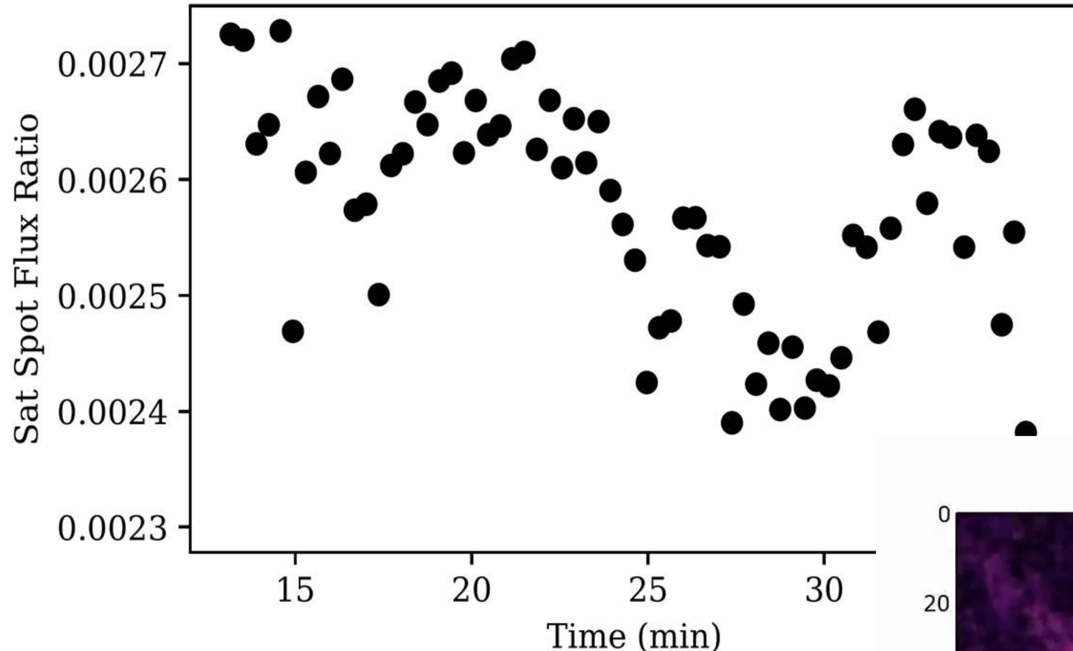
t= 0: $I_{t1} = A_h^{\,2} + A_s^{\,2} + 2A_hA_s\cos(\varphi)$

t= 0+ δ: $I_{t2} = A_h^{\,2} + A_s^{\,2} + 2A_hA_s\cos(\varphi+\pi)$

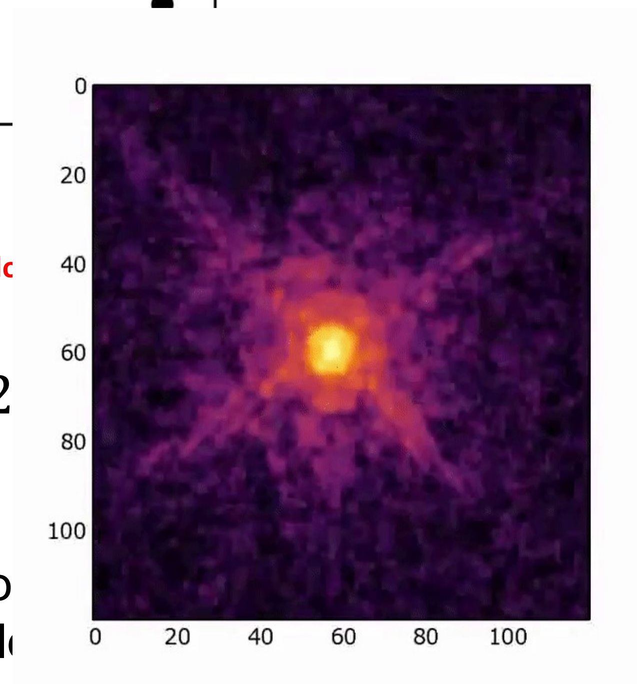
$(I_1+I_2)/2 = A_h^{\,2} + A_s^{\,2}$

At high speed within an exposure

Stability of Incoherent Satellite Spot



Current On-sky stability of Incoherent Satellite Spot (Plc

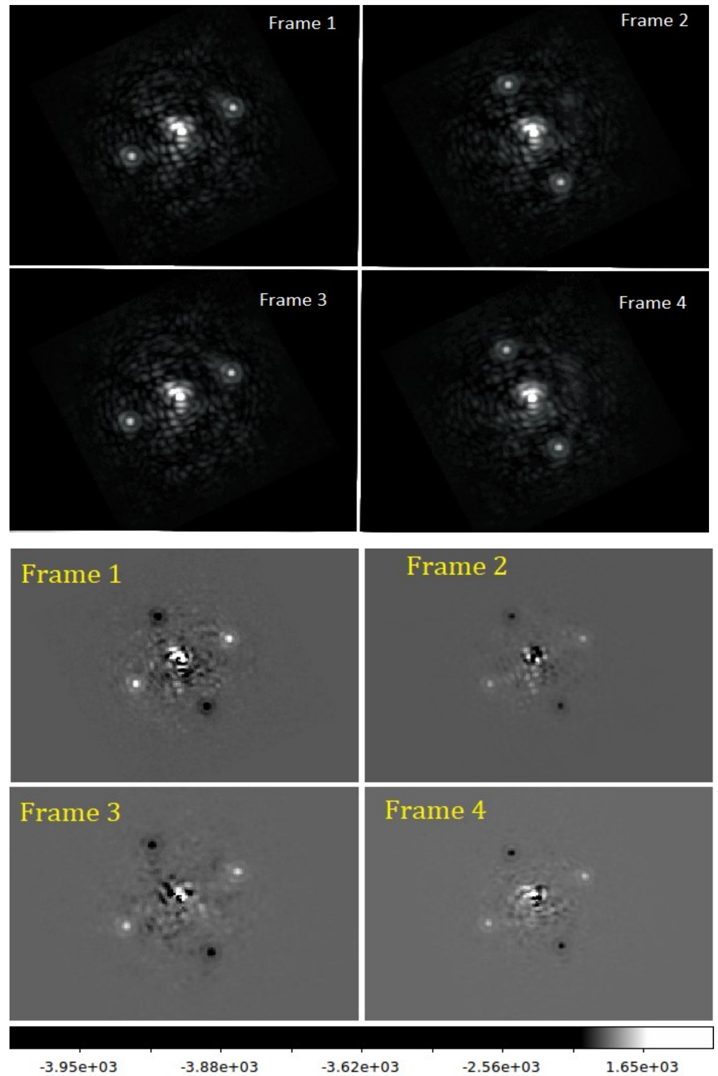


Intensity of Incoherent Satellite Spot → $I_{avg} = A_h^2 + A_s^2$

Backgro speckl

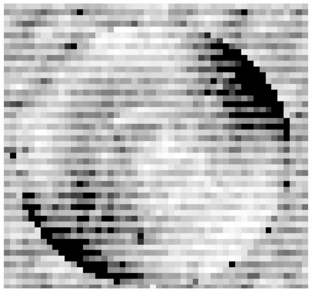
Solution to remove the Underlying Background

- Generate **incoherent satellite speckles**
- **Alternate** the spatial pattern between each exposure
- Dynamically **measure the background lying** beneath the incoherent satellite spots, and subtract them from total flux.

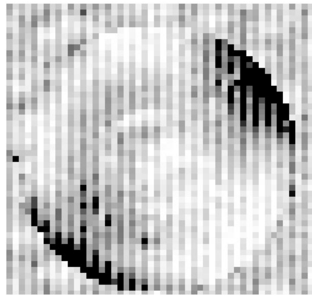


On-sky Images of HR8799 taken with CHARIS

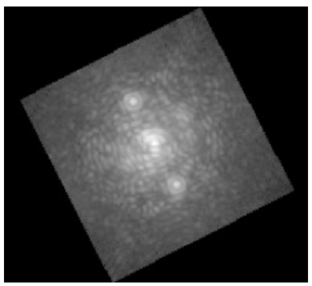
Implementation on SCExAO instrument



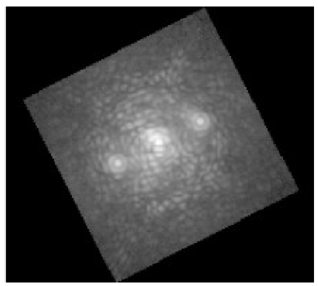
Phase grid on DM, Pattern 1



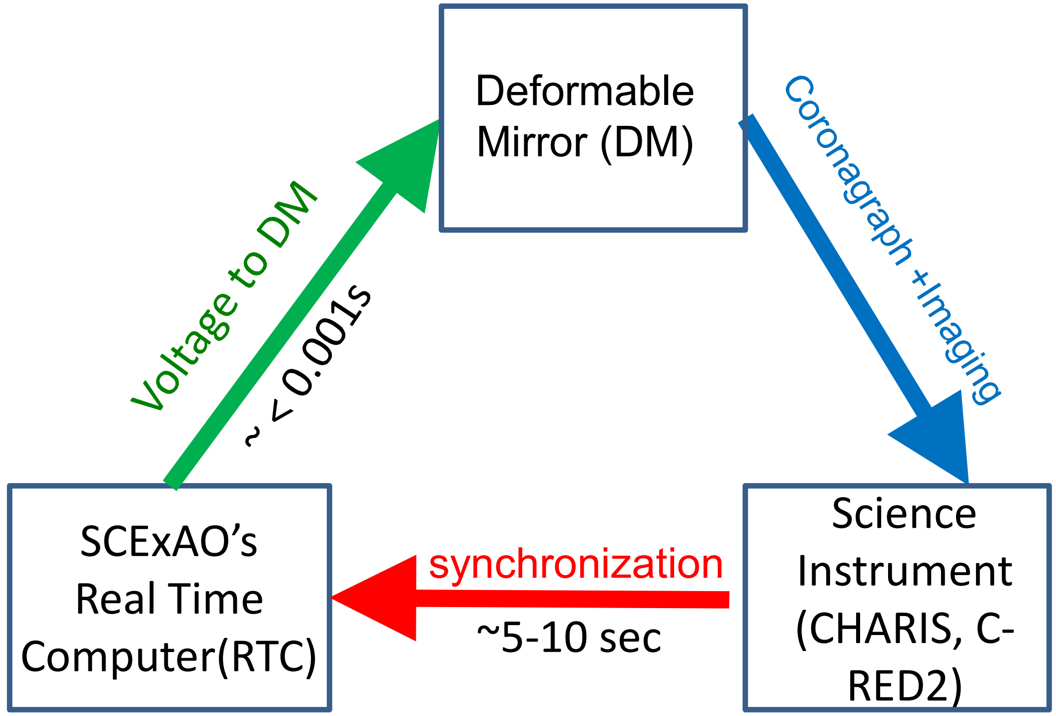
Phase grid on DM, Pattern 2



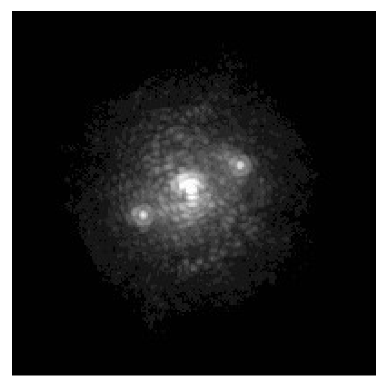
On-sky Image of HR8799 for Pattern 1 with CHARIS



On-sky Image of HR8799 for Pattern 2 with CHARIS



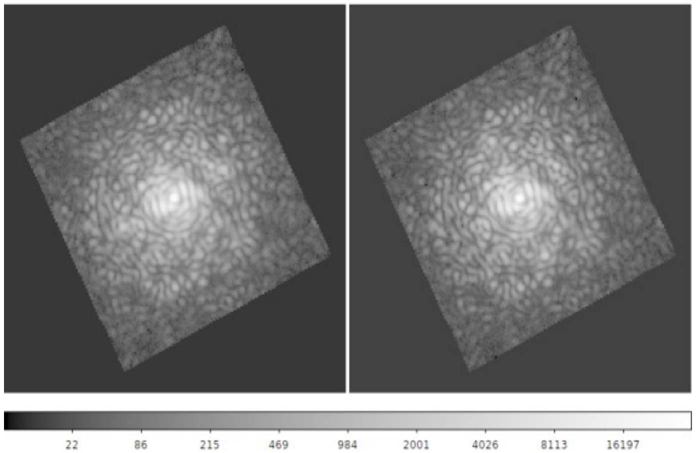
Pattern Switch Command after a frame is collected-
→ 1. Change the spatial pattern (sychronized to science camera's exposure time)
→ 2. Switch the phase of each spot by 0 & π at 2kHz



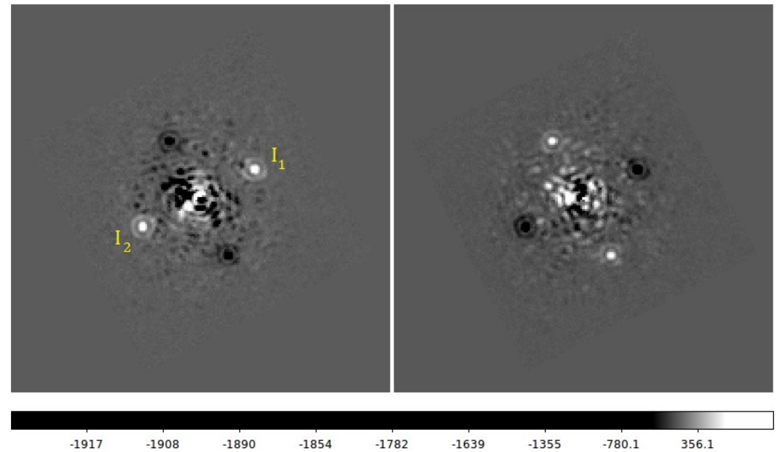
On-sky Images of HR8799 with CHARIS

On-sky Validation

Fainter Grid

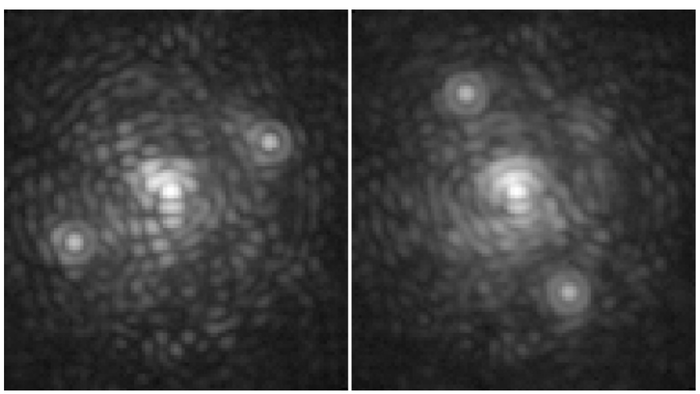


On-sky Image of β Leo with 8.8nm satellite spot CHARIS with two different speckle pattern

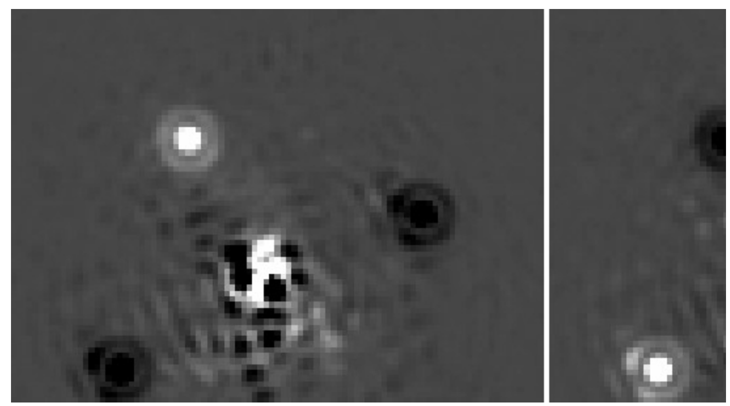


Corresponding PSF subtracted images

Brighter Grid



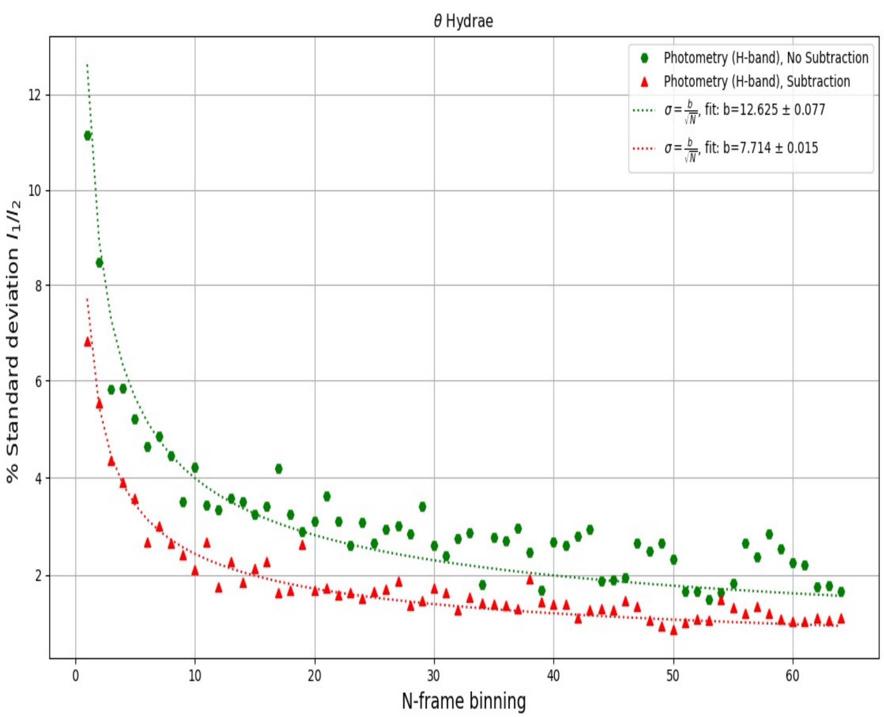
On-sky Image of θ Hydrae with 30nm satellite spot CHARIS with two different speckle pattern



Corresponding PSF subtracted images

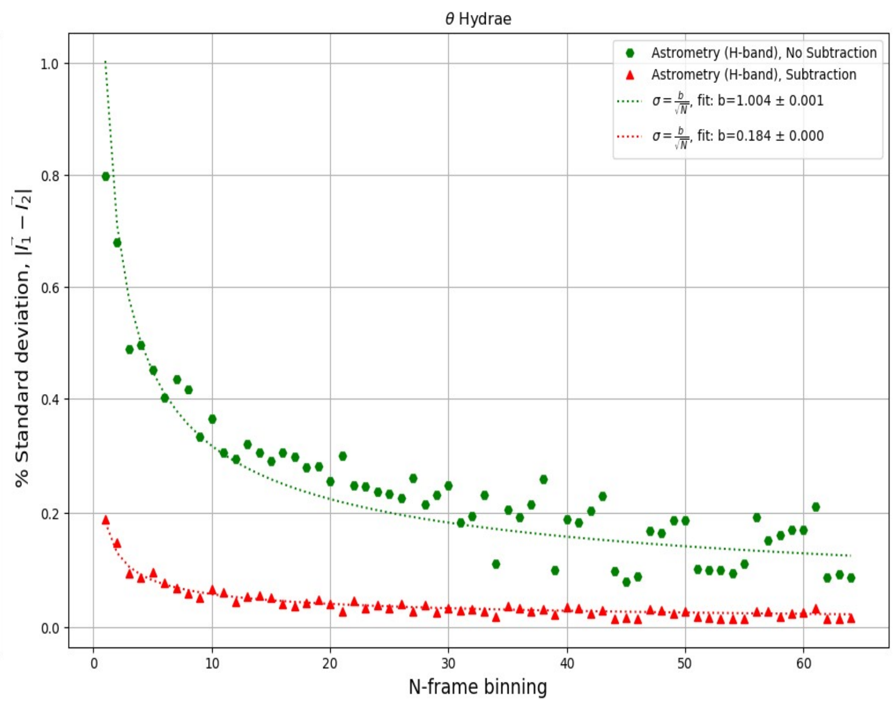
On-sky Results on θ Hya (Long time series)

Co-added the data frames, and calculated the resultant deviation in the measurement.



Photometry

Factor of 2x improvement



Astrometry

Improvement from 3.24 mas to 0.2 mas

Sources of Error

Physical Parameters	Photometry (%)	Astrometry (in mas)
1. Speckle Noise -Adaptive Optics -Non-common Path Aberrations	1	0.3
2. Photon Noise -Stellar Source -Background sky emission -stray light -Detector quantum efficiency	0.07	0.02
3. Readout Noise	0.03	0.01
4. Flat fielding (or pixel sensitivity)	0.3	0.1

Total Noise On-Sky: $\approx \sigma_s$

Therefore, move to a regime where I can measure the fast background speckle variation.

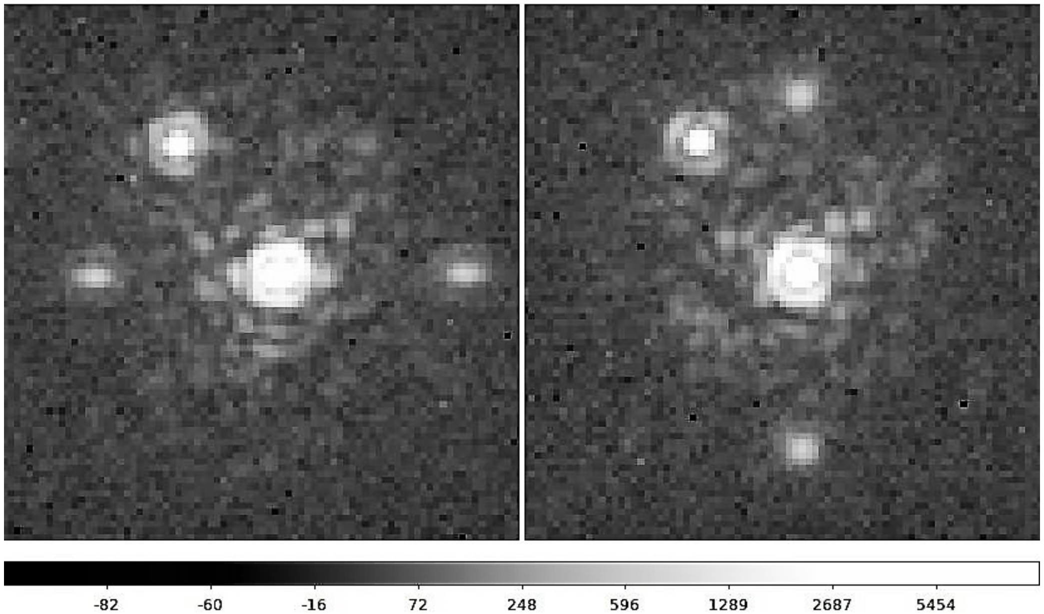
Switch the spatial pattern at high speed.

Fast Synchronization with C-RED2

Testing Stability of Satellite Speckle with fast spatial modulation, fast frame rate camera (C-RED2)

• The spatial pattern was switched every ~2 ms.

• This switching was synchronized with C-RED2 (fast infrared camera, frame rate ~2 kHz) camera exposure.



Pattern1 Pattern 2

HIP 18413, Binary star. H_mag = 4.9, Spectral type = G3V C

Conclusions

• Demonstrated a practical solution to photometric and astrometric calibration challenging in high contrast imaging.

• Quantitatively demonstrated that relative flux measurement between companion and host is insensitive to Strehl and background PSF halo variation.

• We obtained a photometric accuracy of **~1% in 15s exposures** with a 10^{-3} contrast satellite speckle.

• This technique is applicable for orbits, spectra, & time variation measurements from high contrast images

• This technique is now **open to astronomers** as a part of regular science observation.


Thank you!
Wavefront Sensing in the VLT/ELT era V and
AO Workshop Week II