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# Time-Resolved Pyramid Wavefront Sensing using Photon-to-Digital Converters

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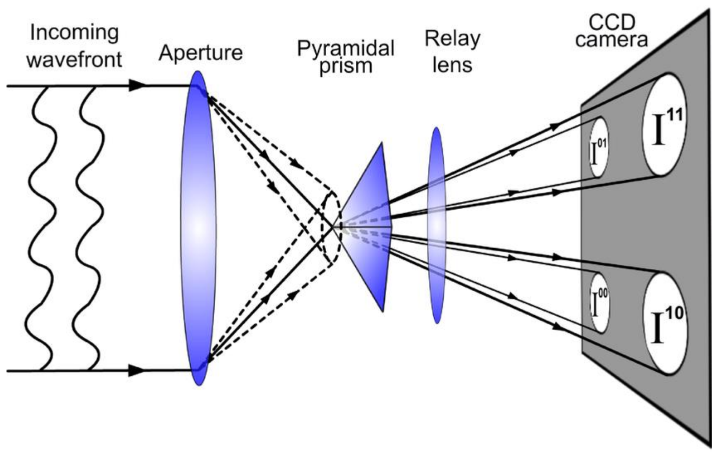
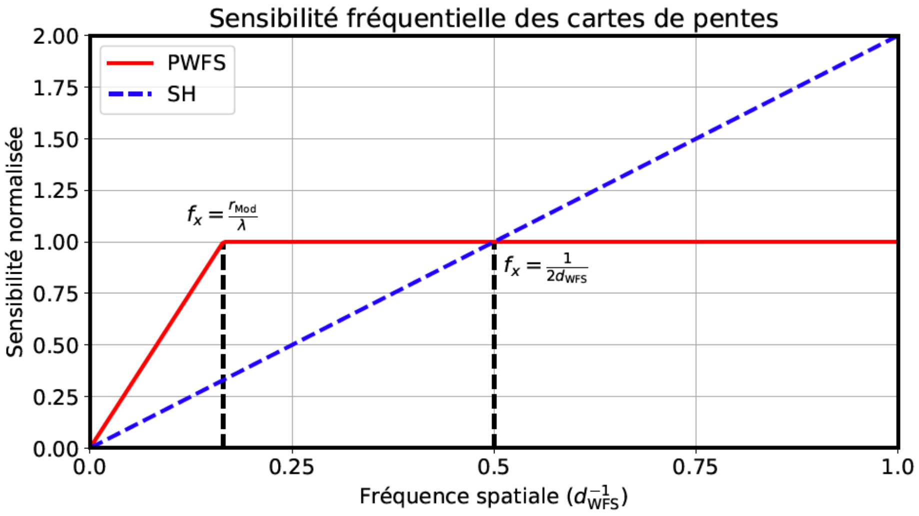
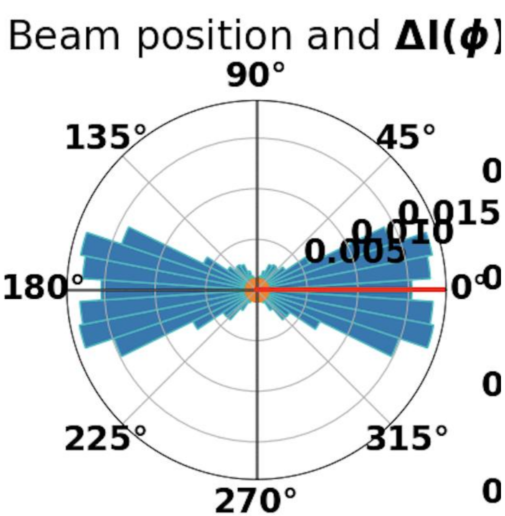
# Sensitivity of PWFS

- For a modulated PWFS, low spatial frequencies have reduced sensitivity
- Some positions in the modulation cycle provide useful information
- Some positions in the modulation cycle provide useless information
- If the modulation cycle can be temporally resolved, then we could reject the photons providing useless information

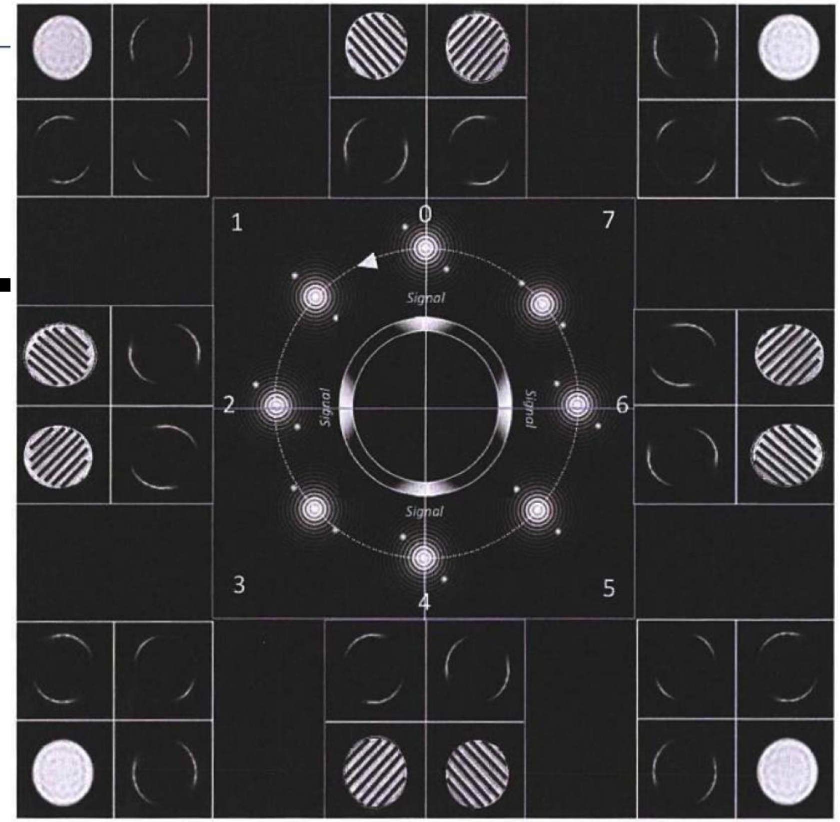


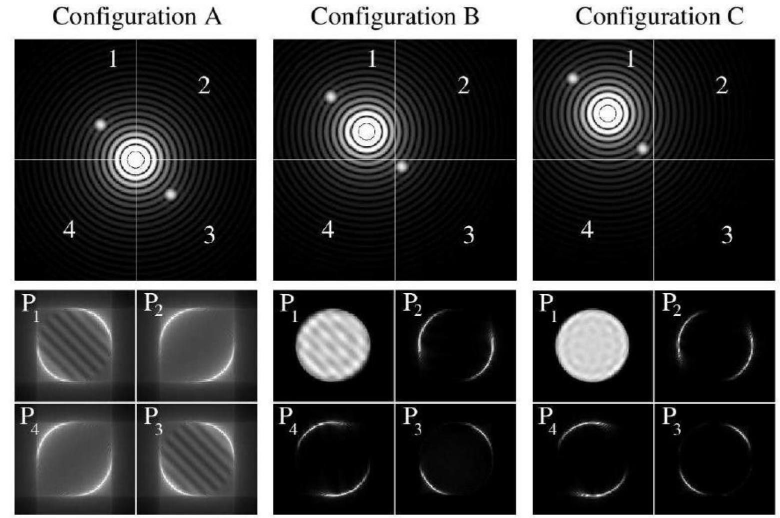



# PWFS signal

- A useful signal (fringes) is recorded only when the two speckles are on a different face of the pyramid
- This is always the case when $f > r_{mod}/\lambda$ but when $f < r_{mod}/\lambda$ there is some time during the modulation cycle when photons are recorded (thus contributing to noise) but no useful signal ("desert crossing"). These photons should be ignored if possible to maximize the measurement SNR.
- The size of the core of the Airy pattern and of the speckles is $\lambda$/D (FWHM) where D is the telescope diameter
- Typical modulation radius is $r_{mod}$=3-5$\lambda$/D
- A larger modulation radius provide more dynamic range but reduces sensitivity.



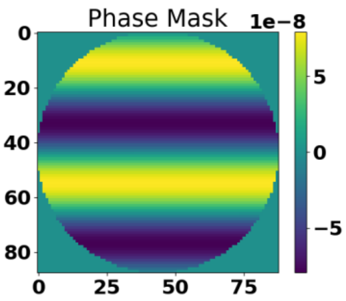
Deo 2019, after Clergeon



Guyon, 2005

# PWFS measurement
# Low spatial frequency

Mode:

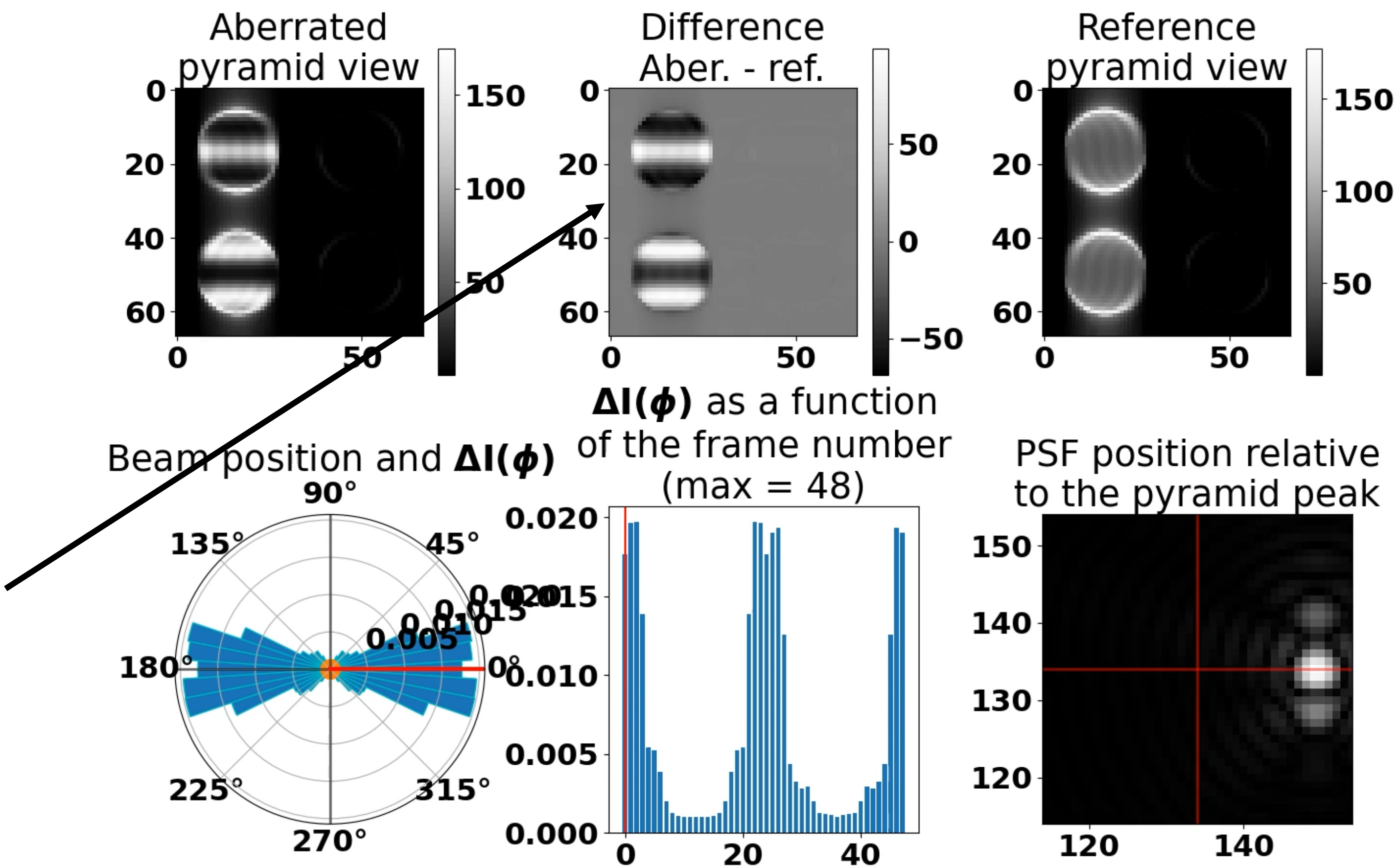



Modulation: 5$\lambda$/D

Measurement:

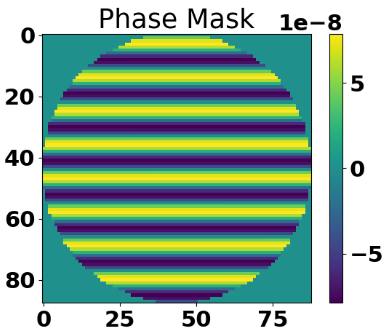
$\Delta I(\varphi)=I/N-I_{ref}/N_{ref}$

**Only a few time slices are useful**



# PWFS measurement
# High spatial frequency

Mode:

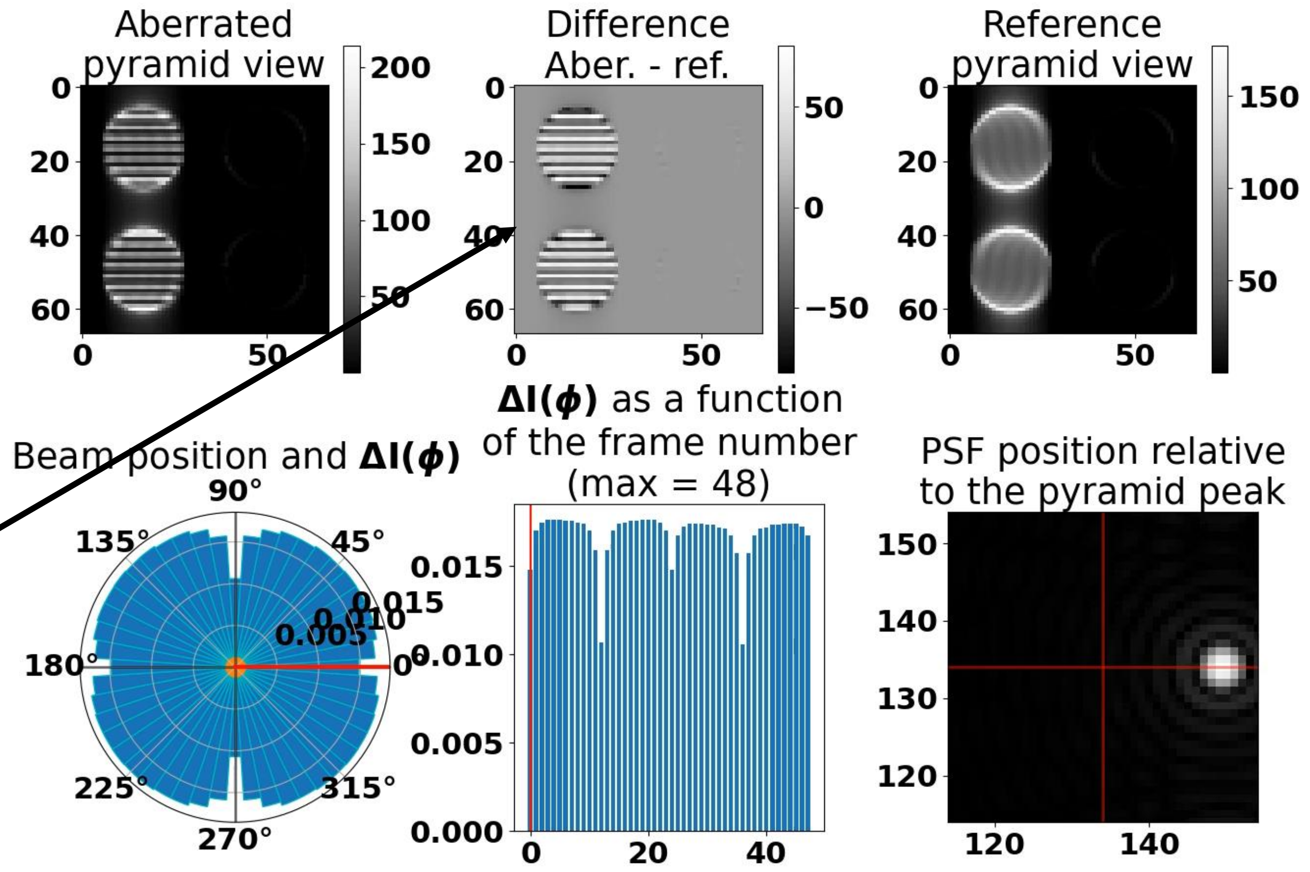



Modulation: 5$\lambda$/D

Measurement:

$\Delta I(\varphi) = I/N - I_{ref}/N_{ref}$

**All time slices are useful**



# Noise propagation

$$\vec{P} = \mathcal{D}\vec{a}$$

Where:
$\vec{P}$ is the pyramid image
$\mathcal{D}$ is the interaction matrix
$\vec{a}$ is the coefficient vector
So $\mathcal{D}$ will have the dimensions pixels of wfs $\times$ number of bases

$\vec{P}$ is the pyramid image, but more specifically, the difference from the detector image from the 'flat' unaberrated detector image.

$$\vec{P} = \frac{\vec{I}}{N_I} - \frac{\vec{I_R}}{N_{I_R}}$$

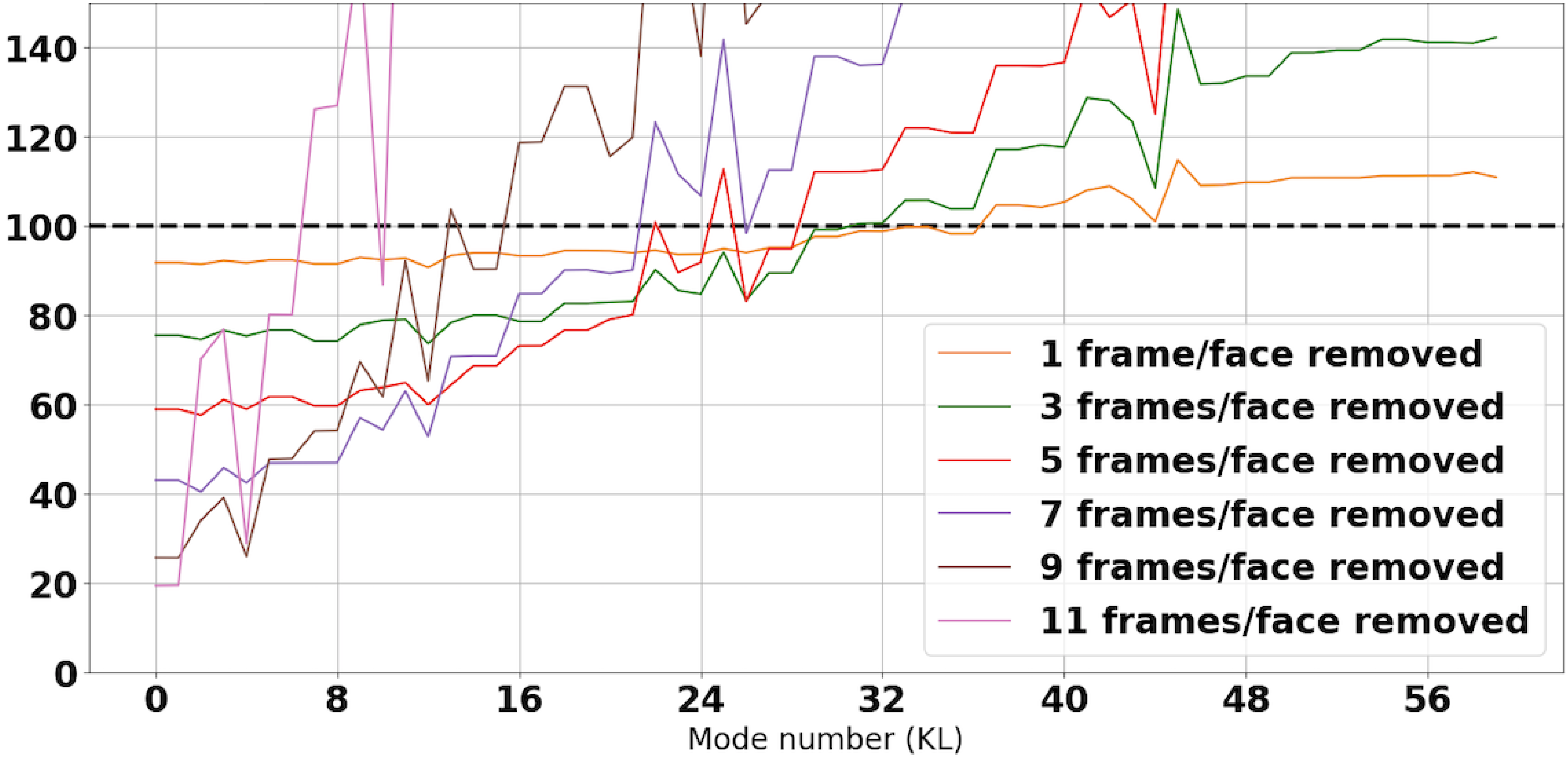
$N$ is the the number of photons
$\vec{I}$ is the detector Image
$\vec{I_R}$ is the flat reference detector image

| Noise propagation coefficient | Noise variance | Propagated noise on mode #m |
|---|---|---|
| $\vec{B} = \mathrm{Tr}(\mathcal{D}^+(\mathcal{D}^+)^T)$ | $1/N_I$ | $B_m/N_{Im}$ |

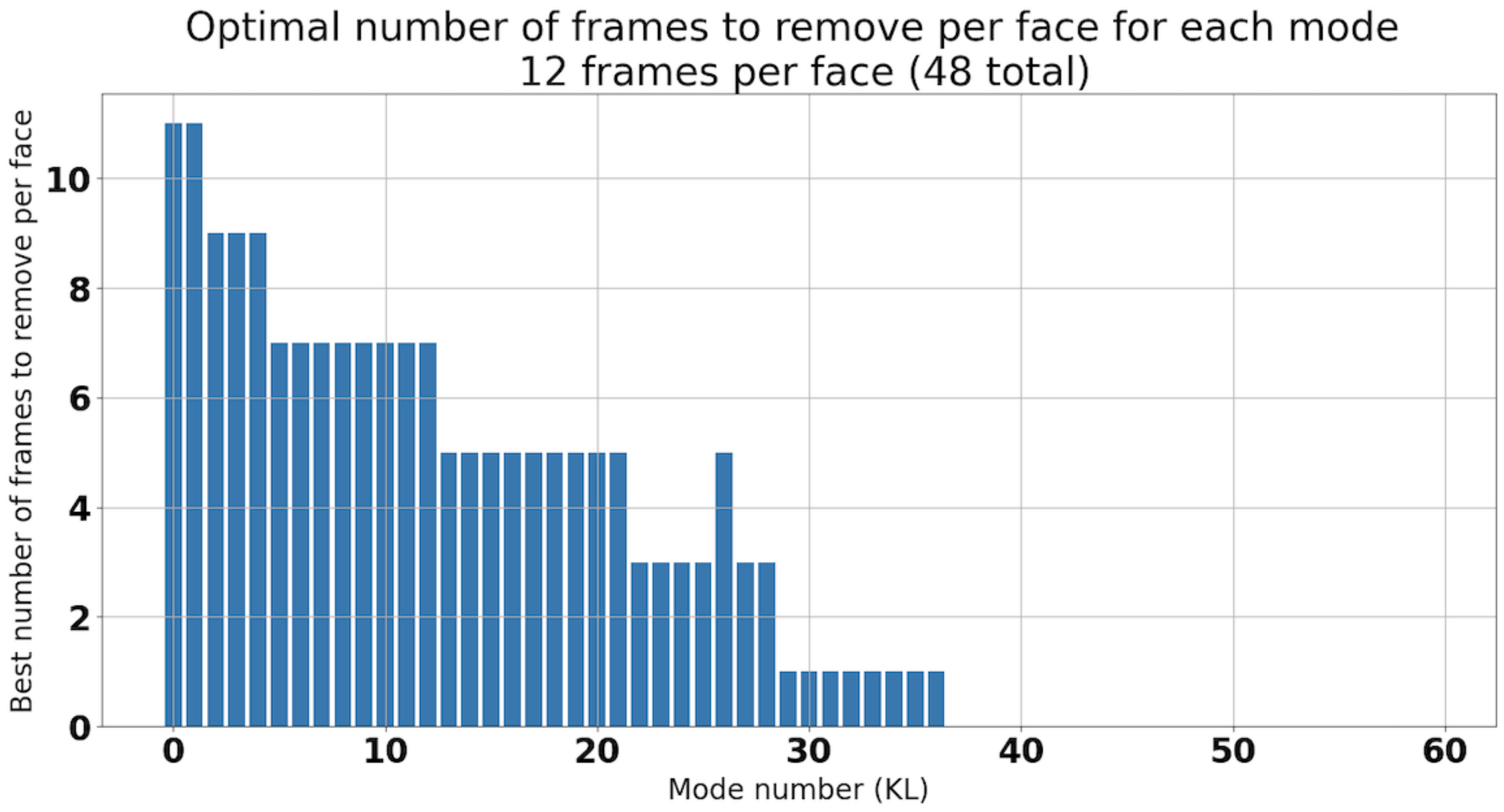
Hopefully reduces when rejecting frames

Definitely reduces when rejecting frames

# Noise propagation

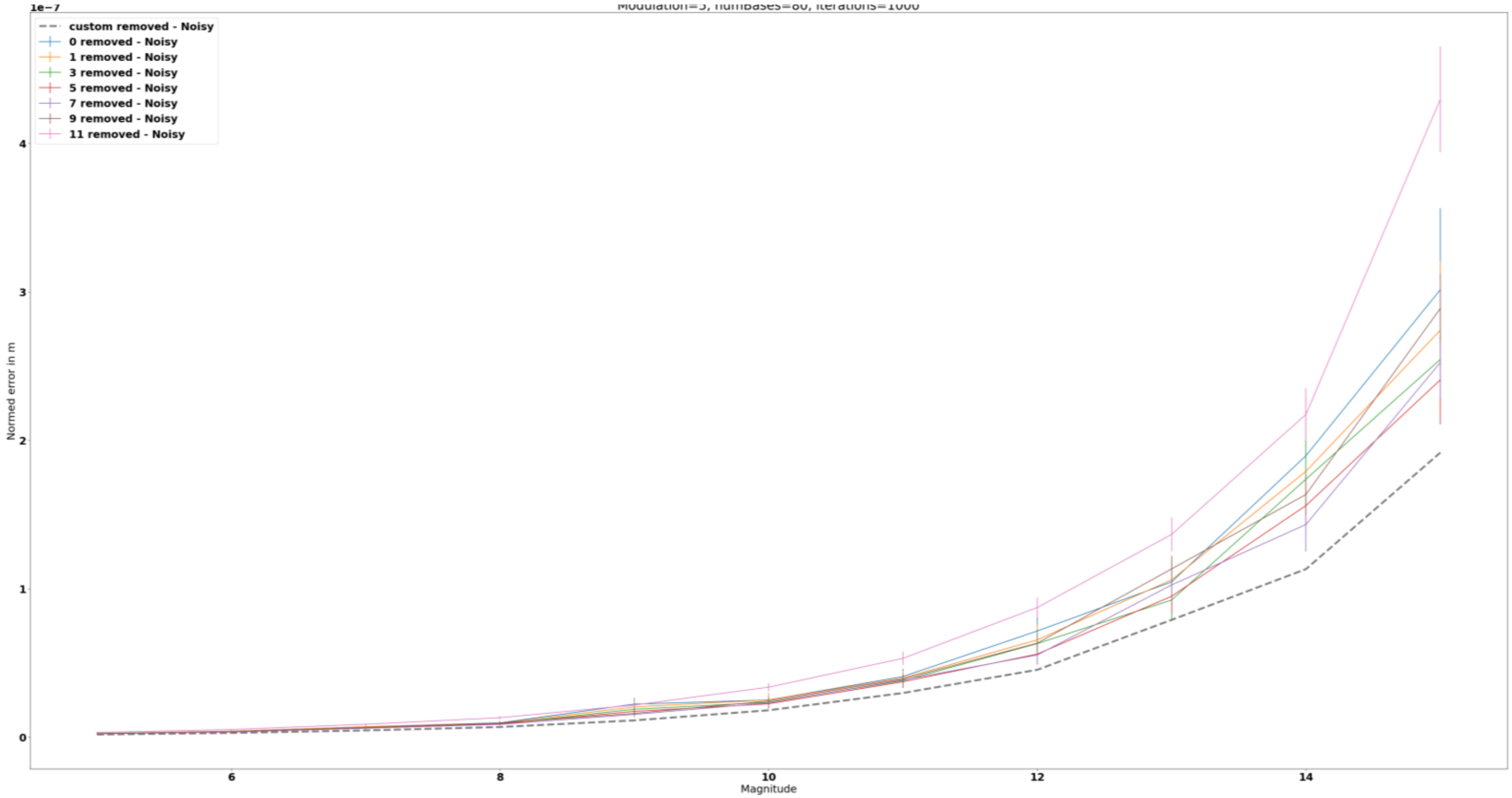


# Optimal frame rejection



# Reconstruction error

- 8-meter telescope, assumes 100% throughput in V band
- Modulation circle decomposed in 48 time slices
- 100nm RMS wavefront maps with $f^{-2}$ power law (residual)



# Photon-to-Digital Converter

- **Photon to bit conversion** at the photodiode level
  - SPAD integrated on top of electronics in order to increase fill factor (QE 50-60%, up to 80% eventually)
- < 70 ps FWHM single photon timing resolution
- Embedded signal processing
  - <10 ps Time-to-Digital Converters (TDC)
  - Coincidence, dark count filters, etc.
- Made in Canada:
  - Designed at U. de Sherbrooke
  - Photodiodes fabricated at Teledyne DALSA (Bromont, Qc)
- Applications in radiation instrumentation
  - Large scale detection systems (>10 m$^2$) for particle physics
  - Fast neutron imaging (Oak Ridge – NA22)
  - Medical imaging
    - Time-of-Flight Positron Emission Tomography
    - Time-of-Flight Computed Tomography
  - Quantum communications

sensors MDPI

*Review*

**3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works**

Jean-François Pratte *, Frédéric Nolet *, Samuel Parent, Frédéric Vachon, Nicolas Roy, Tommy Rossignol, Keven Deslandes, Henri Dautet, Réjean Fontaine and Serge A. Charlebois

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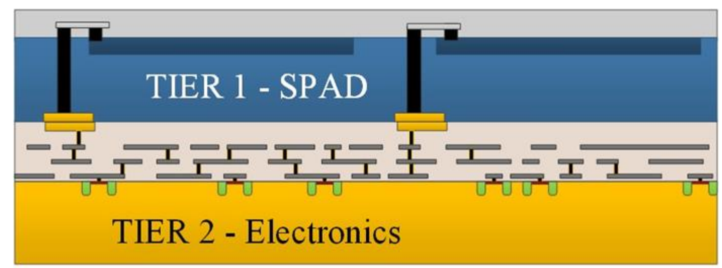
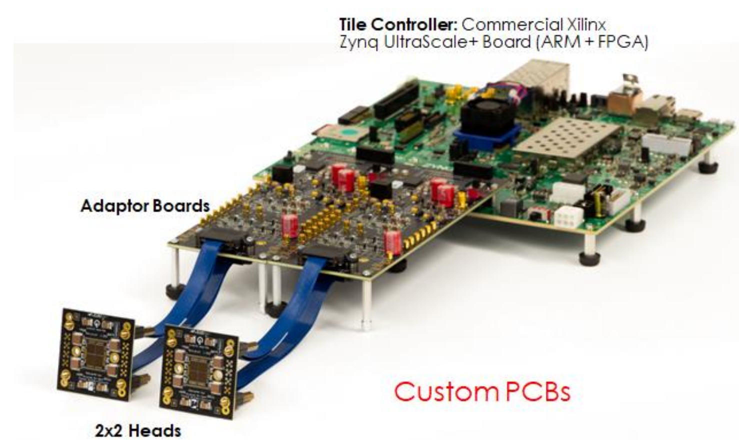
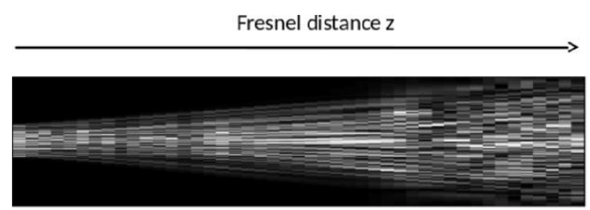


# Conclusion

- Time resolved WFS might improve the sensitivity of PWFS
- Temporal super-resolution might be just as useful as spatial super-resolution for WFSing.
- Photon-to-Digital Converters might enable this technology at a reasonable cost
- Other WFSs might benefit to
  - Curvature sensing?




Non-linear Curvature WFS (Mateen, 2017)