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Time-resolved pyramid wavefront sensing using Photon-to-Digital Converters

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<https://doi.org/10.4224/40003077>

Wavefront Sensing in the VLT/ELT ERA VII - In Person Workshop, 2022-10-21

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

Oct 21, 2022

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NRC, Herzberg Astronomy & Astrophysics, Victoria, BC

Simon Carrier, Serge Charlebois, Jean-François Pratte

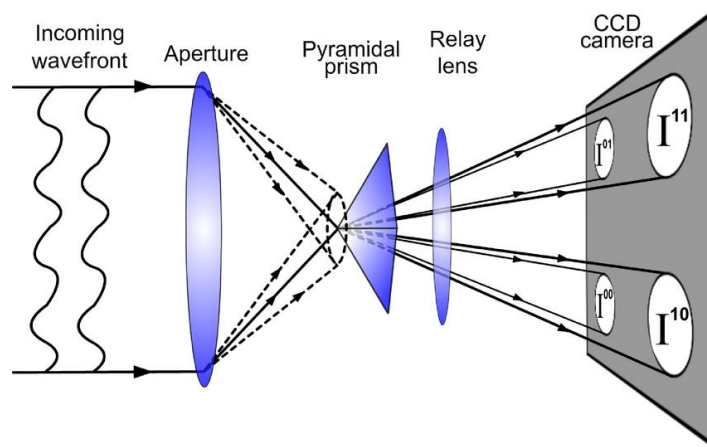
University of Sherbrooke

Presentation to the AO WFS Workshop in Porto (Oct 19-21, 2022)

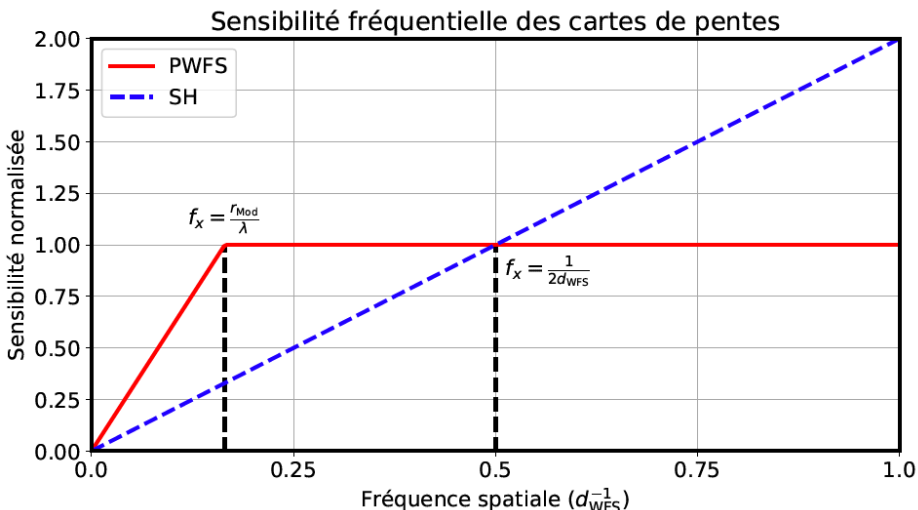
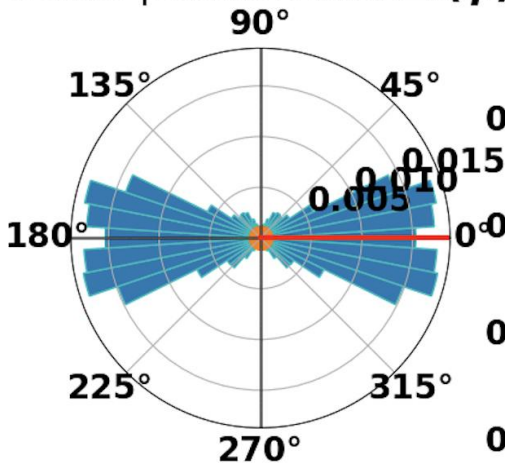


Sensitivity of PWFS

- 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

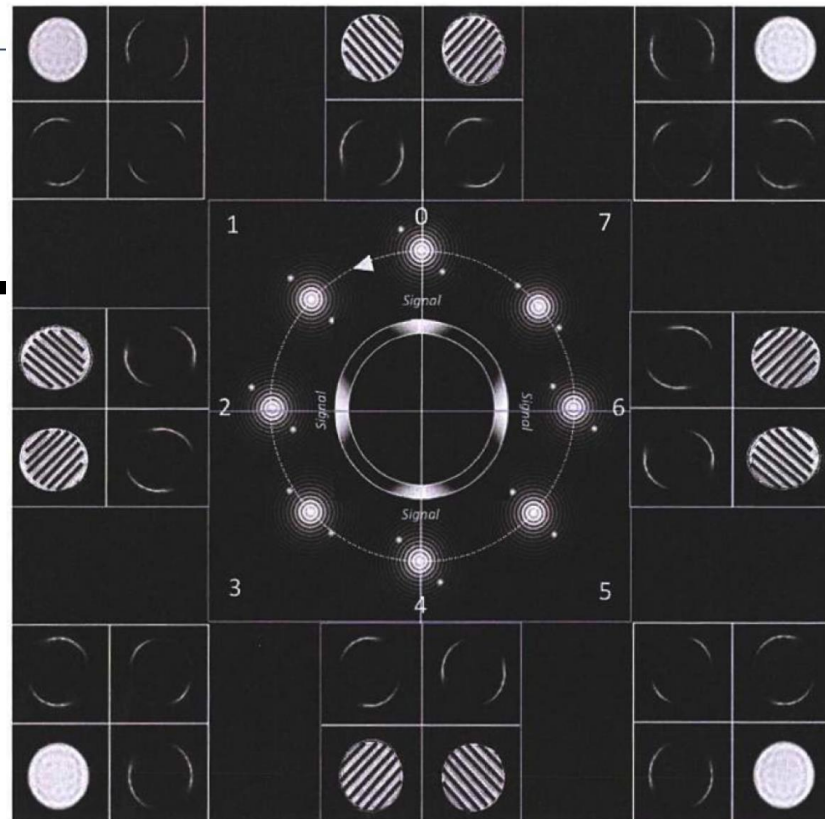


Beam position and $\Delta I(\phi)$

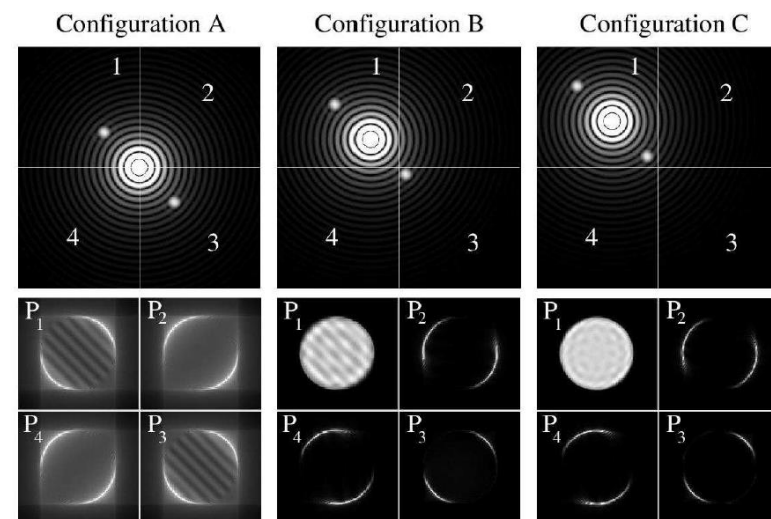


PWFS signal

- 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 $f > r_{\text{mod}}/\lambda$ but when $f < r_{\text{mod}}/\lambda$ 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 λ/D (FWHM) where D is the telescope diameter
- Typical modulation radius is $r_{\text{mod}} = 3-5\lambda/D$
- A larger modulation radius provide more dynamic range but reduces sensitivity.



Deo 2019, after Clergeon

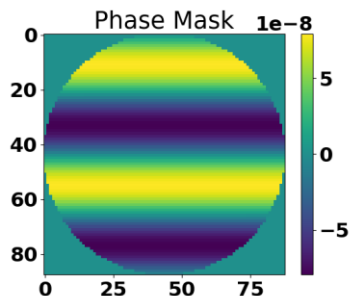


Guyon, 2005

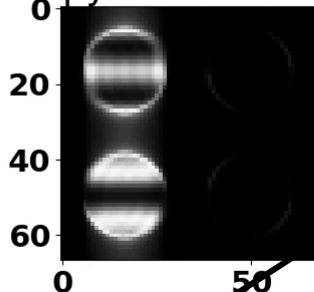
PWFS measurement

Low spatial frequency

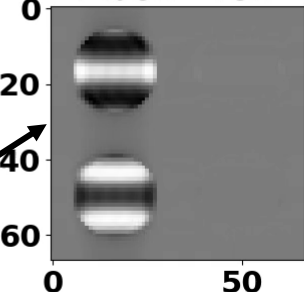
Mode:



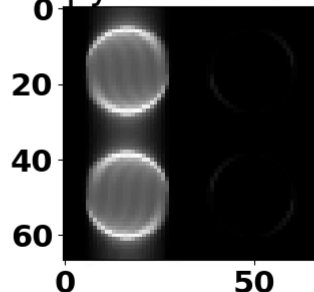
Aberrated pyramid view



Difference Aber. - ref.



Reference pyramid view



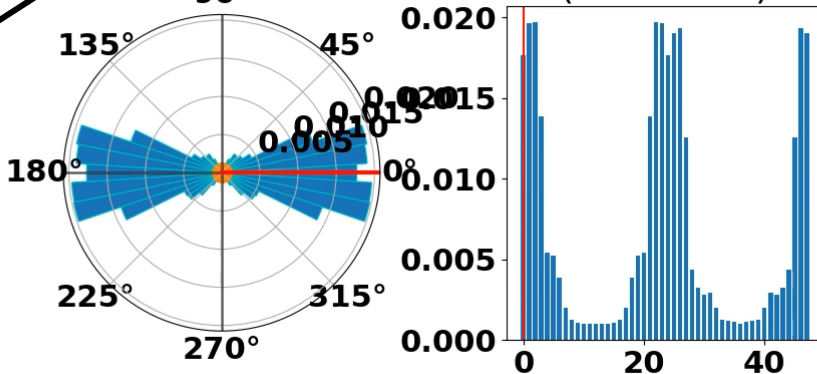
Modulation: $5\lambda/D$

Measurement:

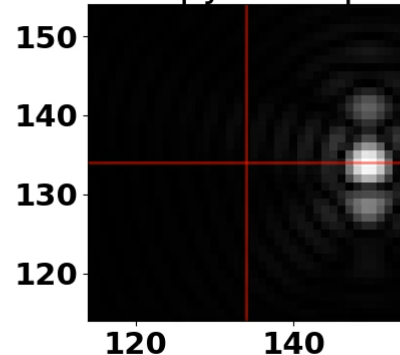
$$\Delta I(\phi) = \frac{I/N - I_{ref}/N_{ref}}{I_{ref}/N_{ref}}$$

Only a few time slices are useful

Beam position and $\Delta I(\phi)$ of the frame number (max = 48)



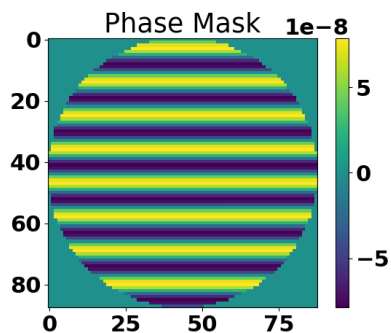
PSF position relative to the pyramid peak



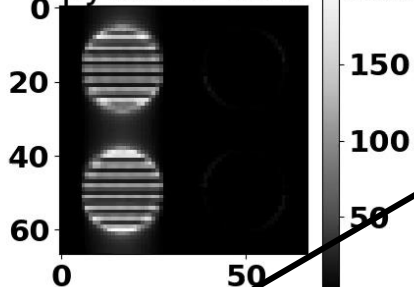
PWFS measurement

High spatial frequency

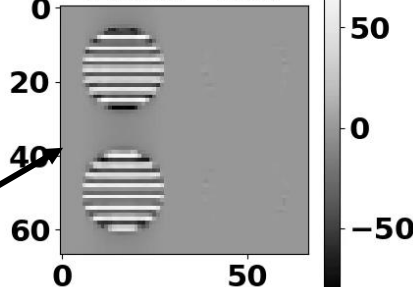
Mode:



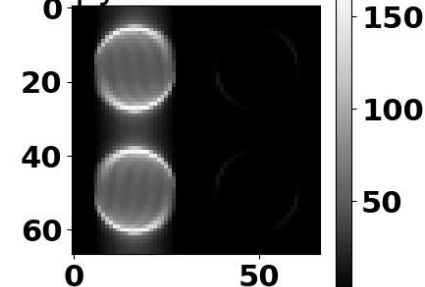
Aberrated pyramid view



Difference Aber. - ref.



Reference pyramid view



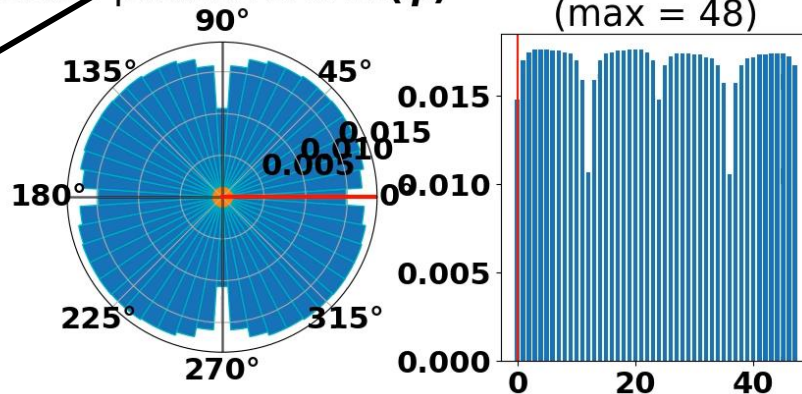
Modulation: $5\lambda/D$

Measurement:

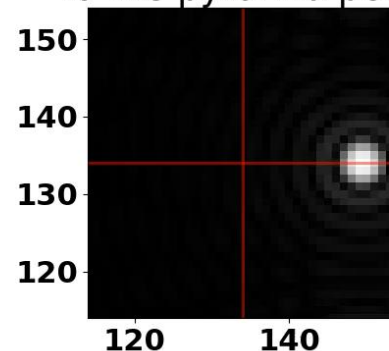
$$\Delta I(\phi) = |I/N - I_{ref}/N_{ref}|$$

All time slices are useful

Beam position and $\Delta I(\phi)$ as a function of the frame number (max = 48)



PSF position relative to the pyramid peak



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

$$\vec{B} = \text{Tr}(\mathcal{D}^+(\mathcal{D}^+)^T)$$

Noise variance

$$1/N_I$$

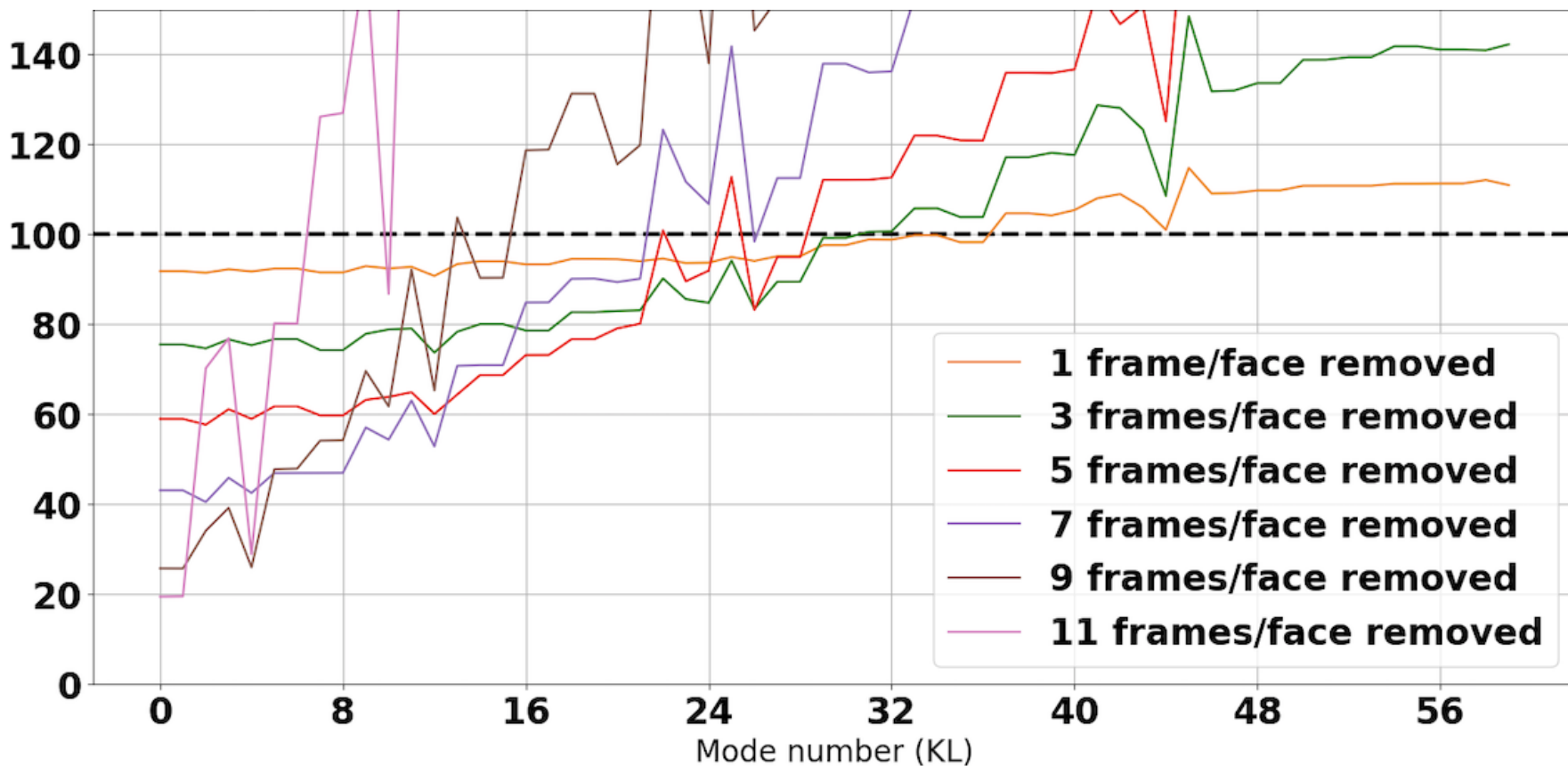
Propagated noise on mode #m

$$B_m/N_{I_m}$$

Hopefully reduces when rejecting frames

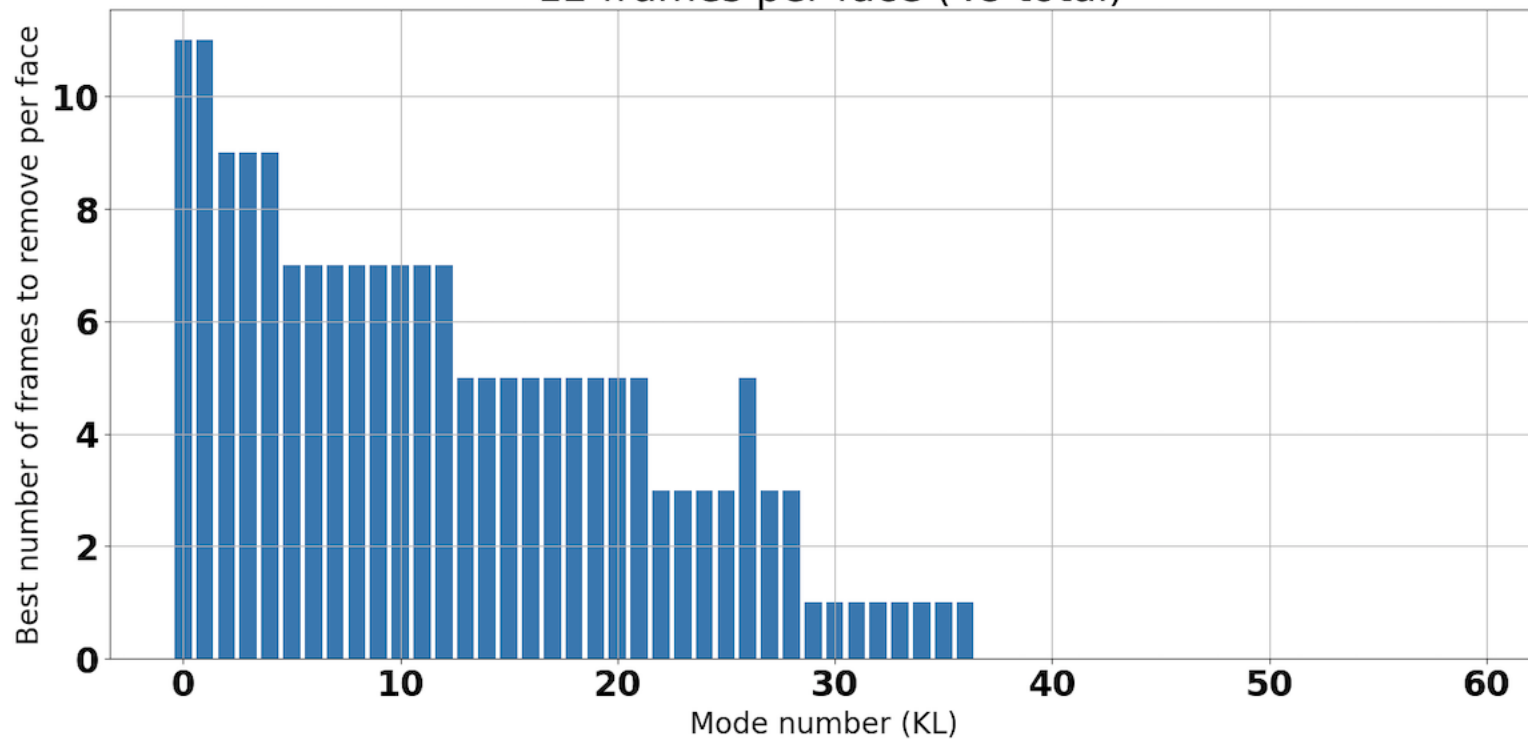
Definitely reduces⁶ when rejecting frames

Noise propagation



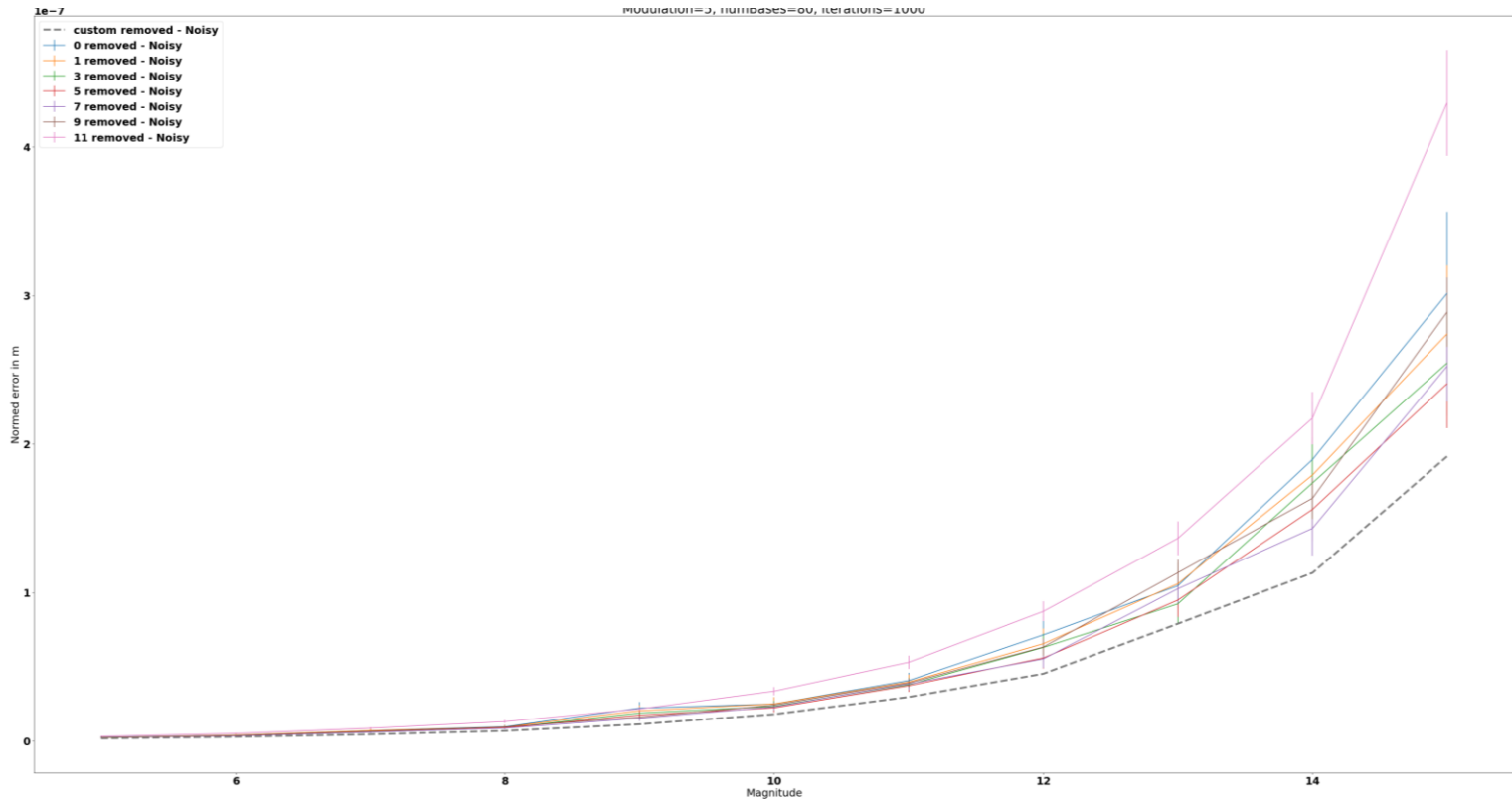
Optimal frame rejection

Optimal number of frames to remove per face for each mode
12 frames per face (48 total)



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 m²) for particle physics
 - Fast neutron imaging (Oak Ridge – NA22)
 - Medical imaging
 - Time-of-Flight Positron Emission Tomography
 - Time-of-Flight Computed Tomography
 - Quantum communications

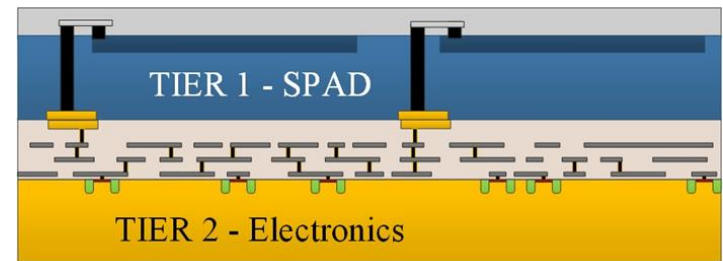


Review

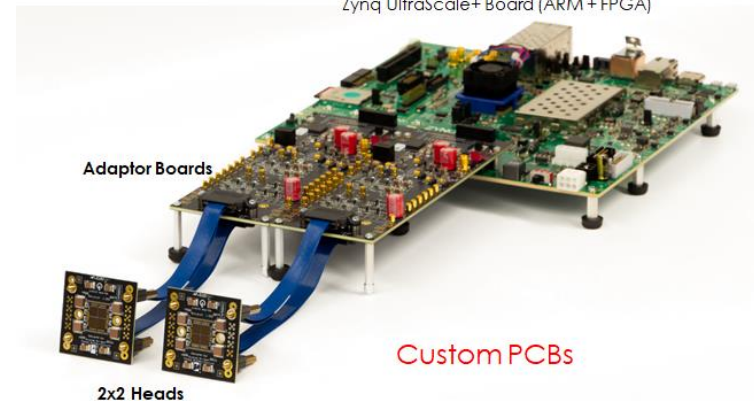
3D Photon-To-Digital Converter for Radiation Instrumentation: Motivation and Future Works

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

DOI: [10.3390/s21020598](https://doi.org/10.3390/s21020598)



Tile Controller: Commercial Xilinx Zynq UltraScale+ Board (ARM + FPGA)



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?

