EuPRAXIA Doctoral Network

Optimization of high-power laser wavefront in the focal region through fast Shack-Hartmann pattern analysis

David Gregocki

ILIL, CNR-INO

University of Pisa

UK Research and Innovation

EuPRAXIA Doctoral Network

Table of contents

01 - Intense Laser Irradiation Laboratory Overview

General background and purpose
Target area with AO setup
Motivation for wavefront sensing improvements at ILIL

02 – Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

General idea of new approach
Synthetic reference grid from aberrated centroids
Exploring a few merit functions on artificial Hartmanngrams

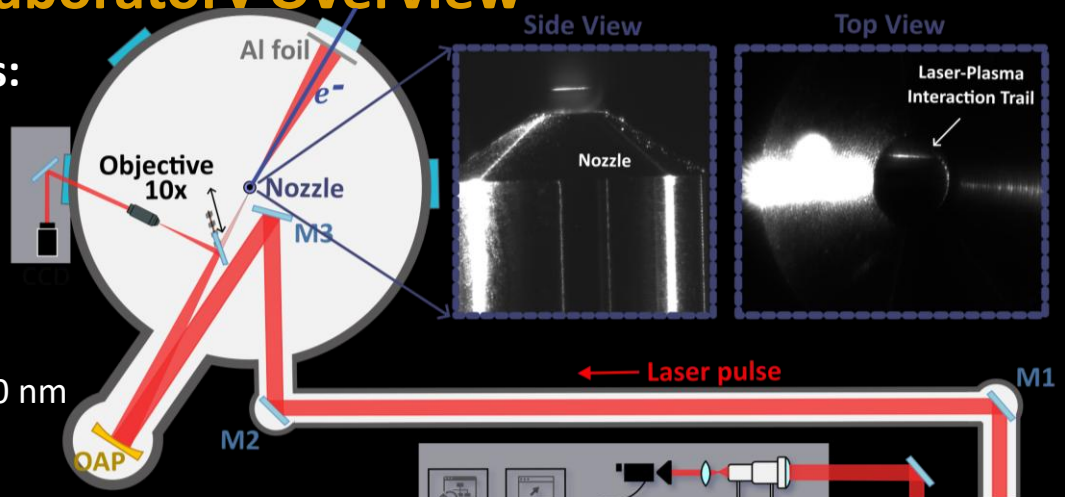
03 - Towards the wavefront correction in real application

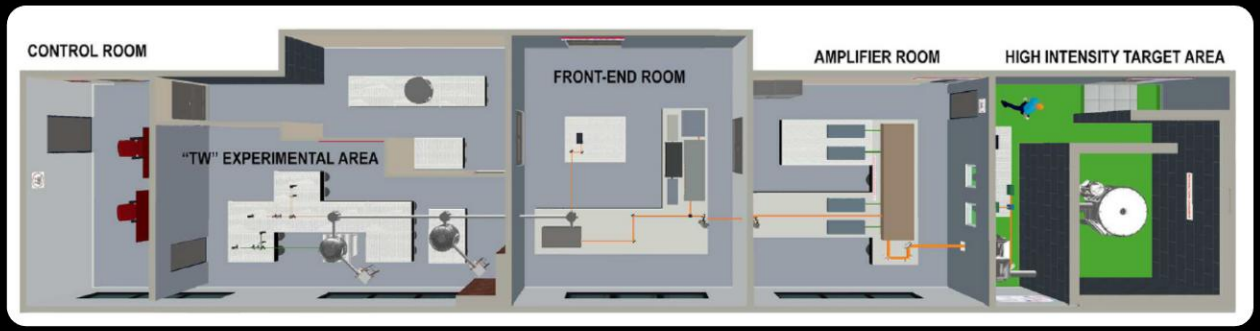
Demonstration of Simple Sequential Wavefront Optimization

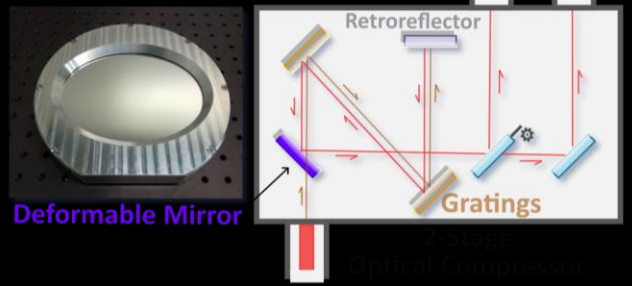
01 - Intense Laser Irradiation Laboratory Overview

Research focus using high-power lasers:

- Electron acceleration
- Proton acceleration
- X-ray sources
- Inertial confinement fusion
- Plasma instabilities
- ~240 TW laser system
- **Laser features**: 10 cm in diameter, 6.0 J, 1Hz, 800 nm and >24 fs duration
- Multi-purpose interaction area for laser-plasma interaction with radiation shielding





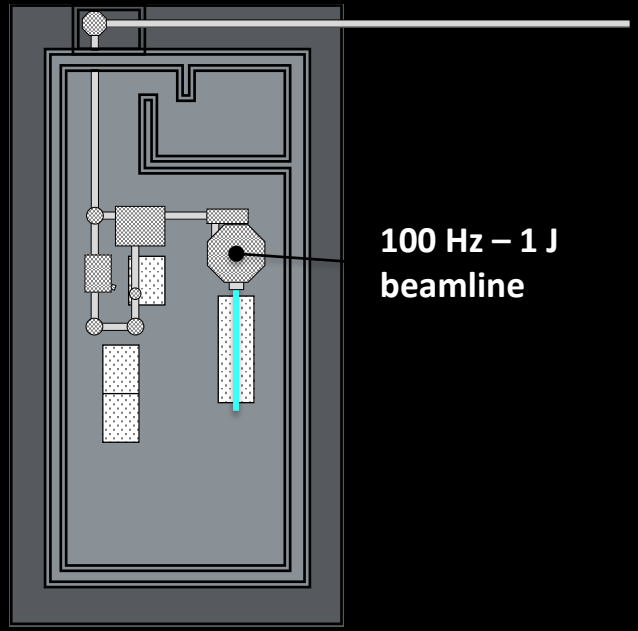


01 - Intense Laser Irradiation Laboratory Overview

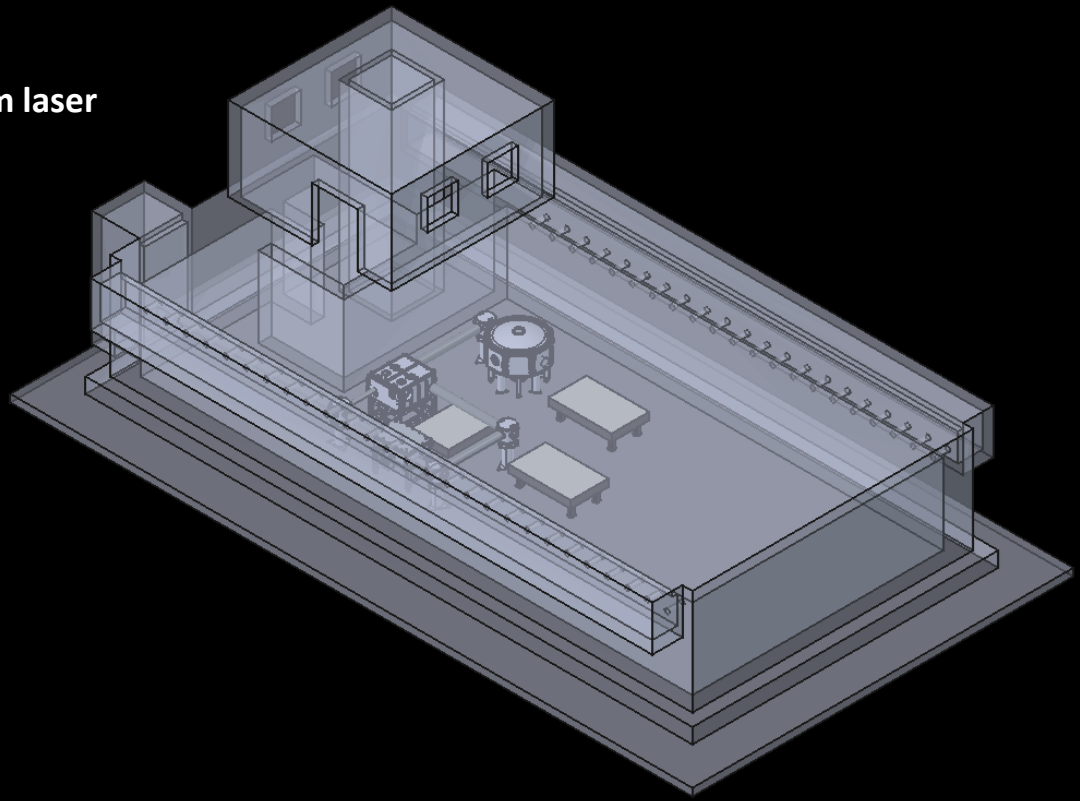
New bunker area:

Underground interaction bunker

Underground vacuum laser pipeline



100 Hz – 1 J beamline



01 - Intense Laser Irradiation Laboratory Overview

Motivation for wavefront sensing improvements at ILIL

General Limitation:

- Very often in many laser facilities, AO misses aberrations from the final focusing optics.

Limitation:

- Post-focus sensing requires recollimation optics.

Drawback:

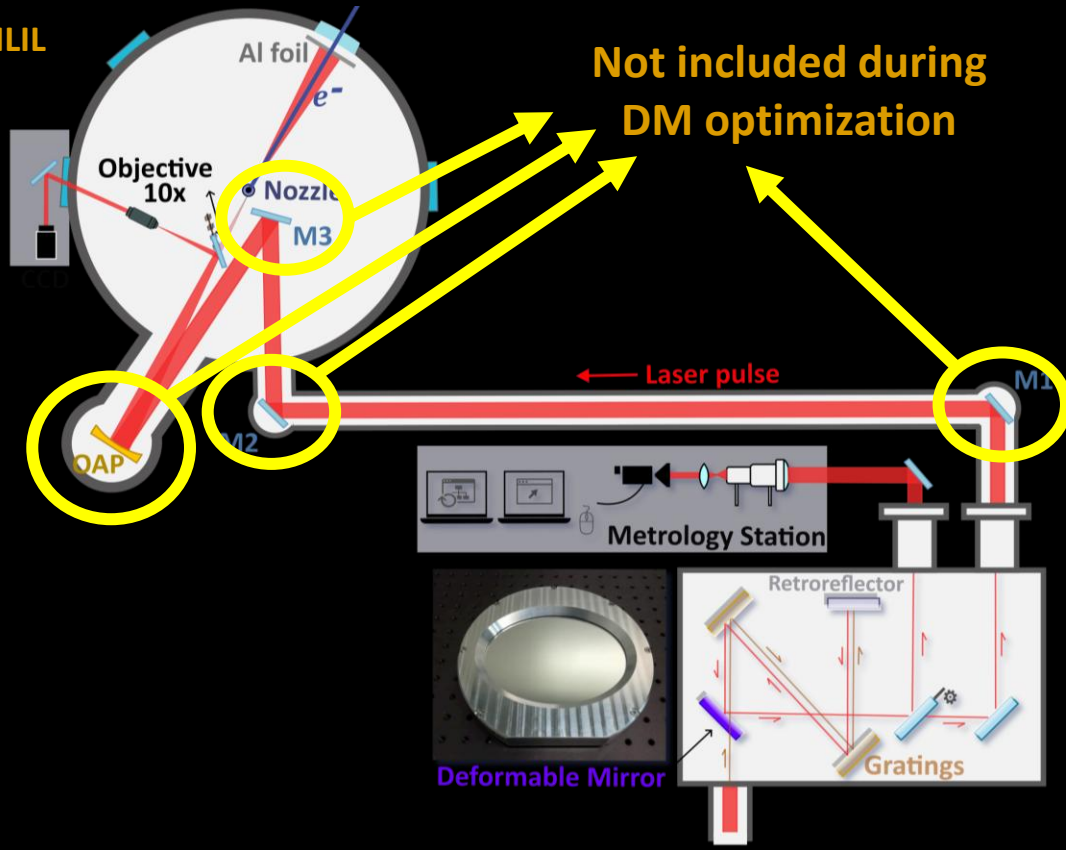
- Recollimation can introduce additional, non-common path aberrations.

Question:

- Can wavefront quality be assessed directly near the focus?
- Additionally, can it be done at 100 Hz?

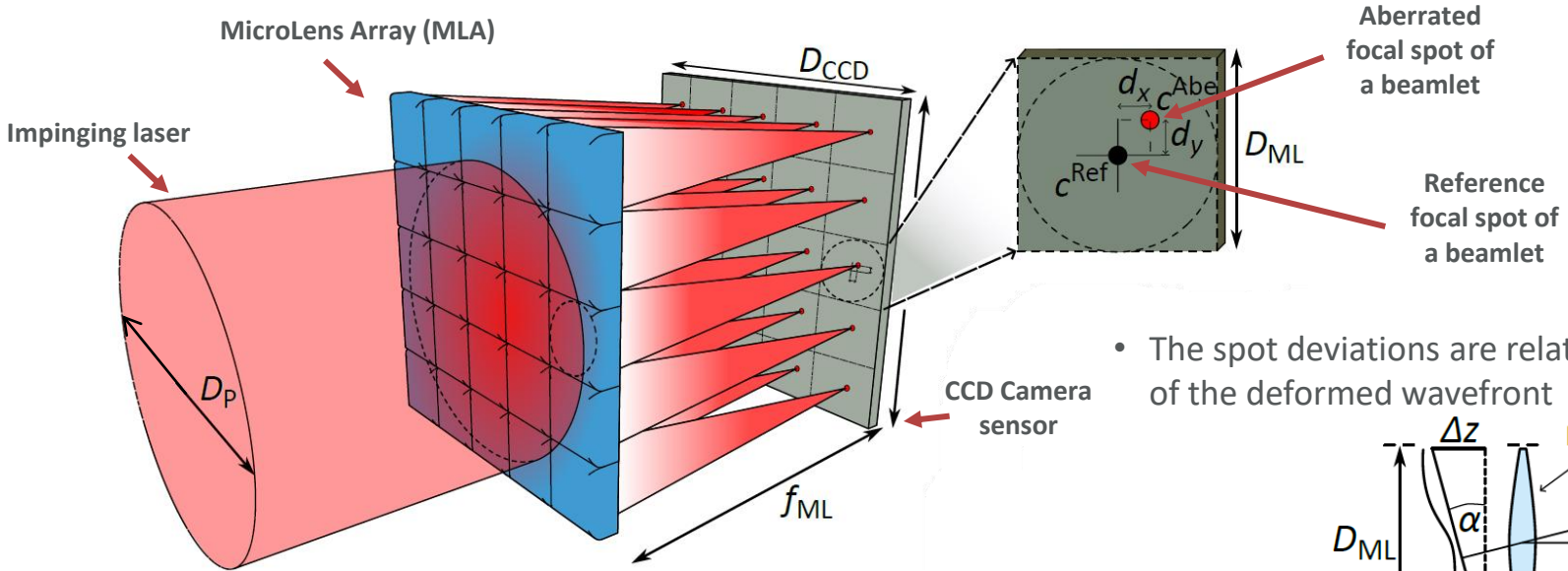
Possible solution:

- Hartmanngram-based metrics after the OAP without any recollimation optics

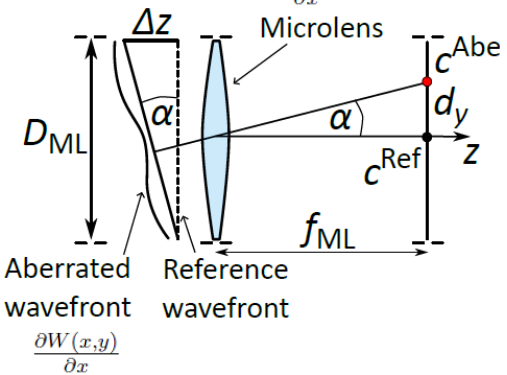


02 Fundamental working principle of SHWS

- Shack-Hartmann Wavefront Sensor (SHWS) measures displacements (with respect to a nonaberrated beam) of the spot of different beamlets focused by an array of lenses



- The spot deviations are related to the slope of the deformed wavefront $\frac{\partial W(x,y)}{\partial x}$



α is proportional to the local wavefront gradient $\alpha_y \approx \frac{\partial W(x,y)}{\partial y}$ and $\alpha_x \approx \frac{\partial W(x,y)}{\partial x}$, assuming paraxial approximation. Hence

$$\tan\alpha = \frac{\Delta z}{D_{ML}} = \frac{d_y}{f_{ML}} \approx \frac{\partial W(x,y)}{\partial y}$$

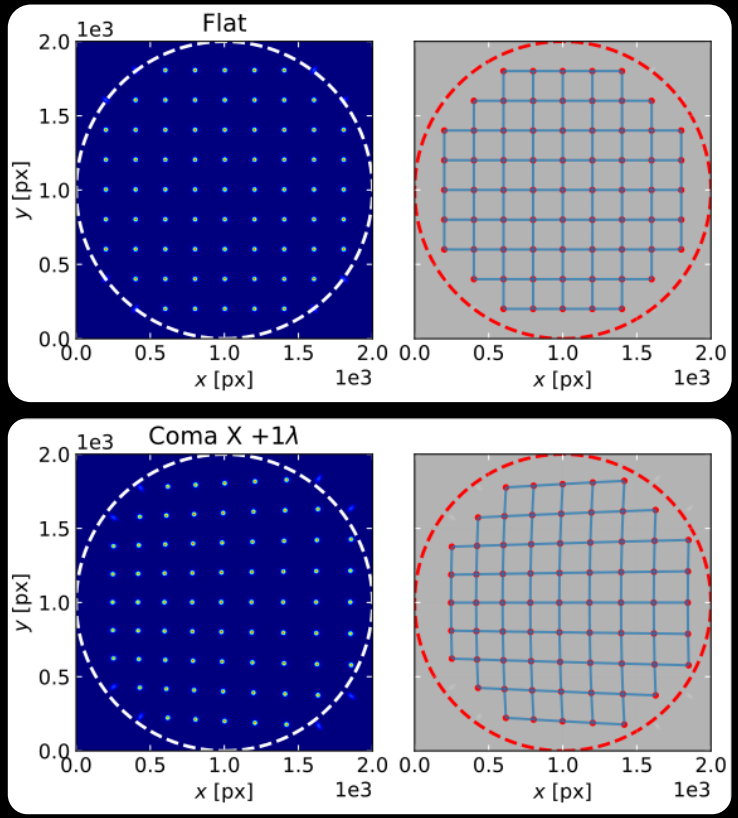
02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

Possible solution

- Hartmanngram-based metrics after the OAP without any recollimation optics

General Idea

- Flat wavefront → regular SHWS spot grid.
- Aberrations → geometric distortions of the spot pattern.
- Distortions can be quantified through:
  - Neighboring centroid separations.
  - Centroid displacements from a reference grid.
- Geometry-based metrics provide a direct measure of wavefront quality.
- Convex, symmetric, and local-minimum-free metrics are ideal for wavefront optimization.



02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

Exploring a few merit functions

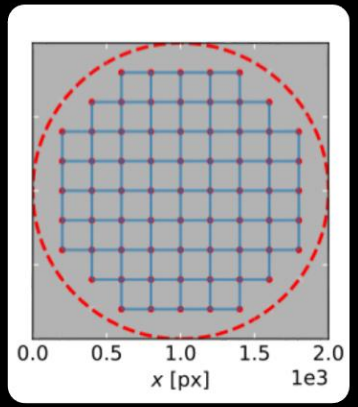
I. Variance of distances between neighboring aberrated centroids

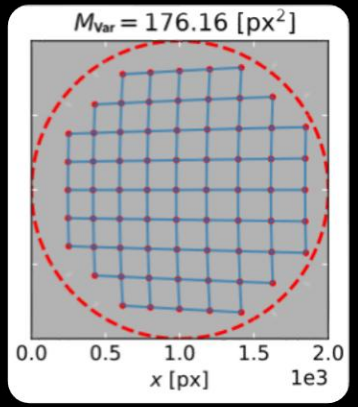
$$M_{\mathrm{Var}} = \frac{1}{|\mathcal{D}|\mu^2}\sum_{\mathrm{d_{ij}}\in\mathcal{D}}\left(\mathrm{d_{ij}} - \mu\right)^2 \quad \wedge \quad \mu = \frac{1}{|\mathcal{D}|}\sum_{\mathrm{d_{ij}}\in\mathcal{D}} \mathrm{d_{ij}}$$

II. Normalized RMS displacement from the reconstructed reference grid

$$M_{\mathrm{NRMS}} = \frac{1}{s}\sqrt{\frac{1}{|P|}\sum_{i=1}^{P}|\boldsymbol{p}_i - \boldsymbol{r}_i|^2}\ ,$$

where $\boldsymbol{r}_{\mathrm{i}}$ are coordinates of reference centroids -> **need for a reference grid s will be defined in the following slides**

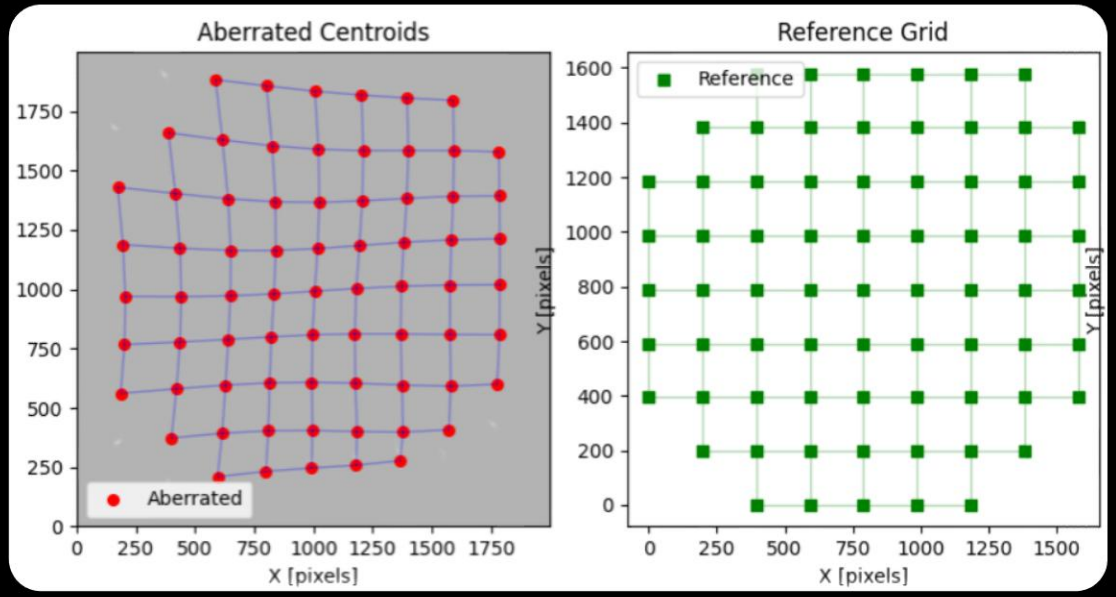




02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

Synthetic reference grid from aberrated centroids

- The initial reference grid $\boldsymbol{r}^0$ is constructed as a perfect square lattice using only the grid indices and spacing defined as average distances between neighboring aberrated centroids



02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

- The entire reference grid is then translated (shifted) to approximately match the centroid pattern
- The translation factor $\boldsymbol{t}$ optimized to minimize the average distance between centroids and reference points.

- Minimizing RMS displacement using:

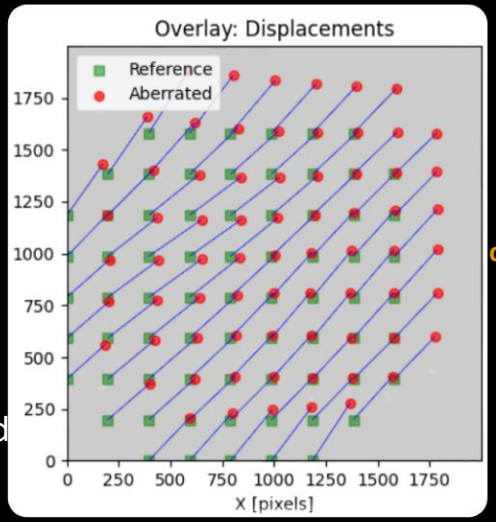
$$\boldsymbol{t}^* = \min_{\boldsymbol{t}} \sqrt{\frac{1}{N}\sum_{i=1}^{N} \left\| \boldsymbol{c}_i - (\boldsymbol{r}_i^0 + \boldsymbol{t}) \right\|^2}$$

- Final aligned grid $\boldsymbol{r}_i = \boldsymbol{r}_i^0 + \boldsymbol{t}^*$, strictly parallel to the horizontal axis of the image.

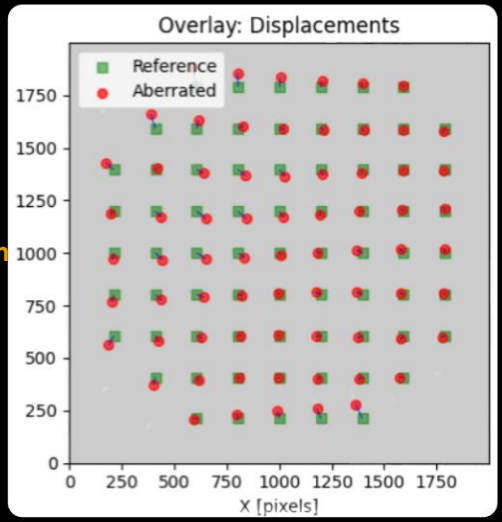
In addition

- Modal wavefront reconstruction can be used

- Wavefront retrieval was tested on artificial and after also on real Hartmanngrams



Translation optimization

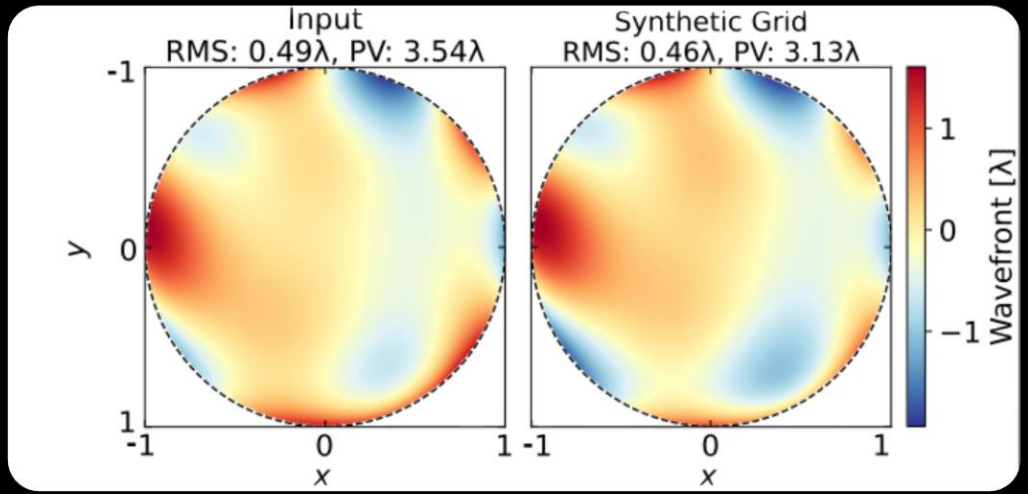


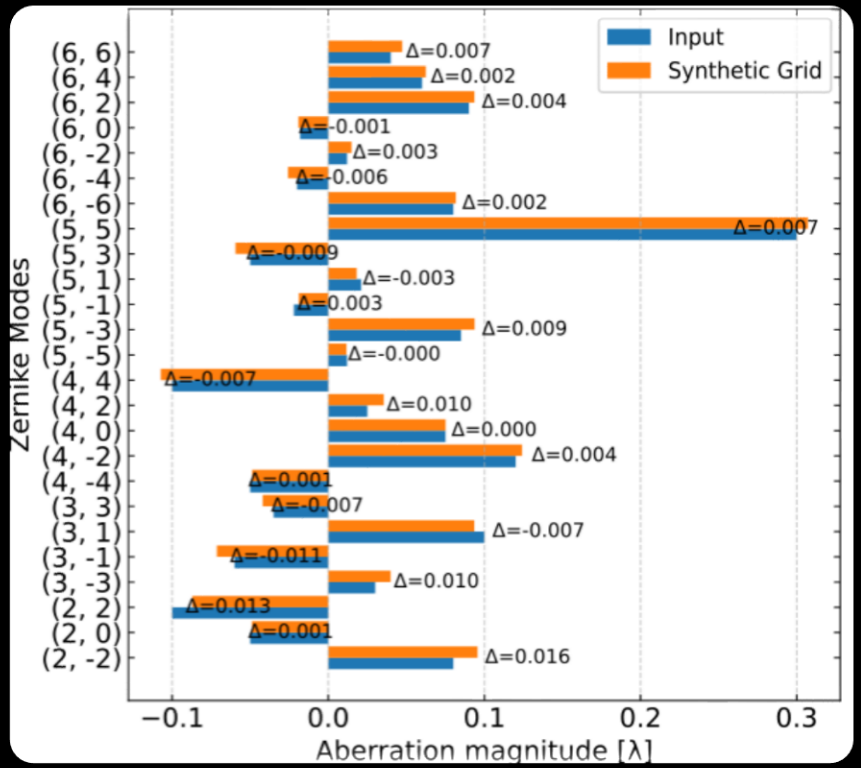
02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

Synthetic reference grid from aberrated centroids

- Tested on artificial and real Hartmanngrams

Artificial:





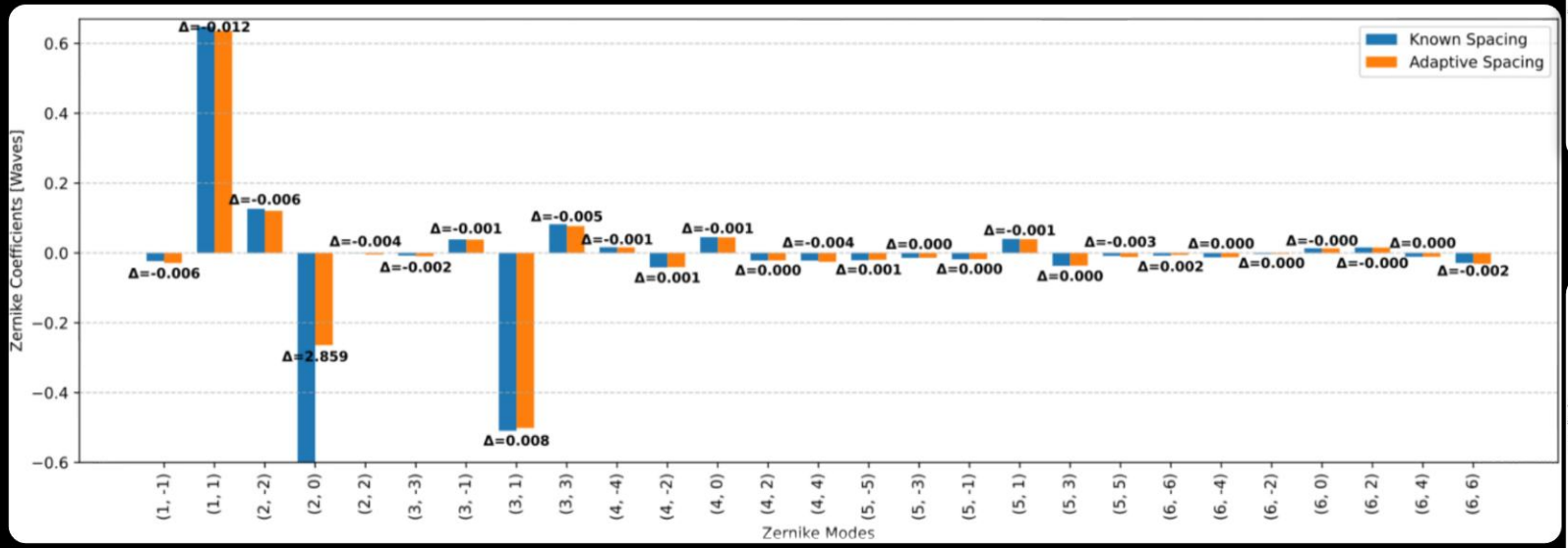
02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

Synthetic reference grid spacing from aberrated centroids using

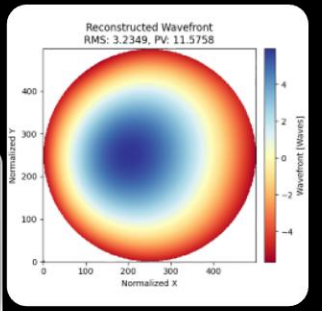
(A) Known lenslet separations

(B) Average distance between neighboring centroids -> $\text{Spacing} = \frac{\overline{d_{\text{Hor}}} + \overline{d_{\text{Ver}}}}{2}$

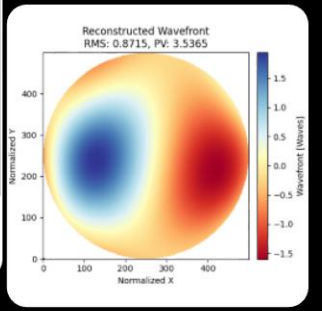
Real: Flat Wavefront (Set after DM calibration)



(A) With known spacing



(B) With adaptive spacing

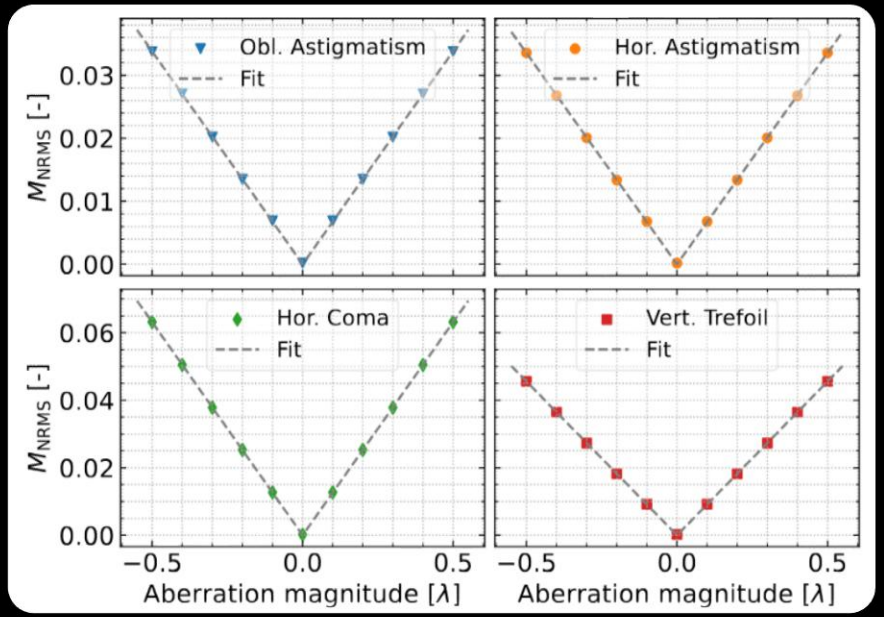


02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

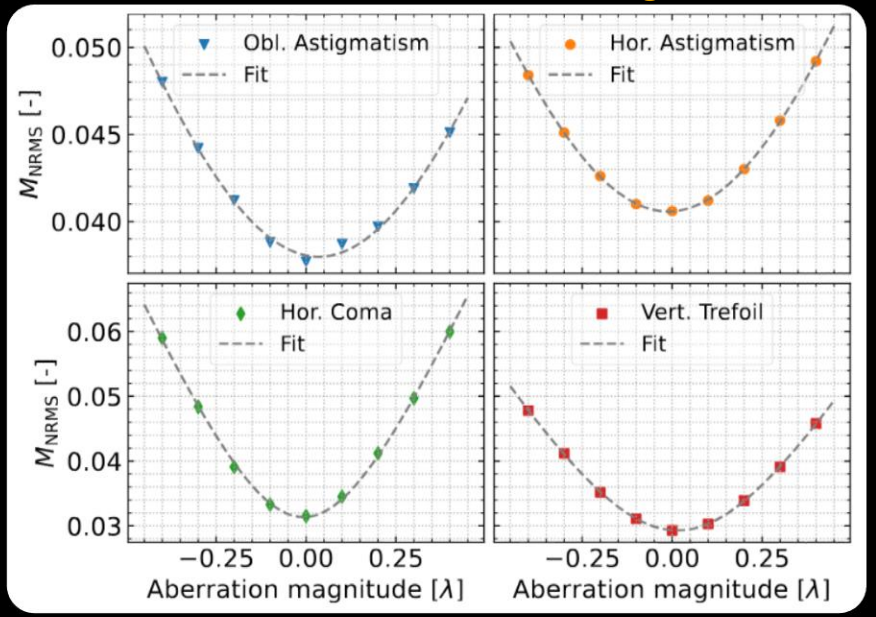
Exploring a few merit functions on artificial Hartmanngrams

II. Normalized RMS displacement from the reconstructed reference grid

Zero wavefront background



Non-Zero wavefront background



EuPRAXIA Doctoral Network

02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

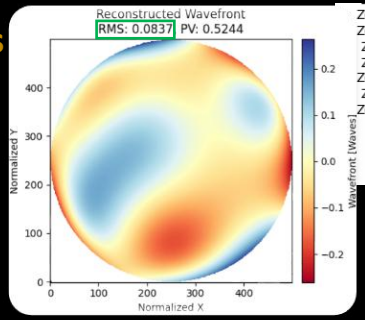
Exploring a few merit functions on artificial Hartmanngrams

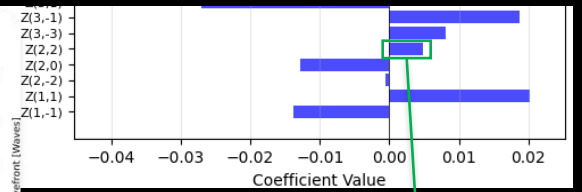
II. Normalized RMS displacement from the reconstructed reference grid

Real Hartmanngrams:

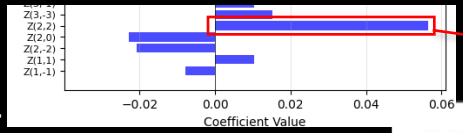
- Measurements repeated over two experimental days.
- Single aberration mode applied on top of the residual DM-corrected wavefront.
- Residual astigmatism shifts the optimum away from zero applied aberration.
- Added astigmatism can compensate the residual error.
- **Single-mode scans reveal clear wavefront correction capability.**

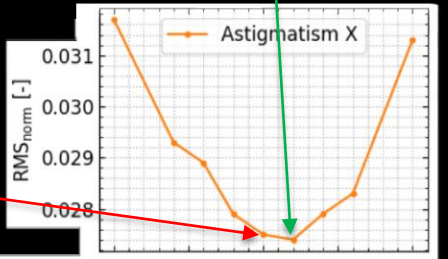
AstigmatismX = 0.1 waves

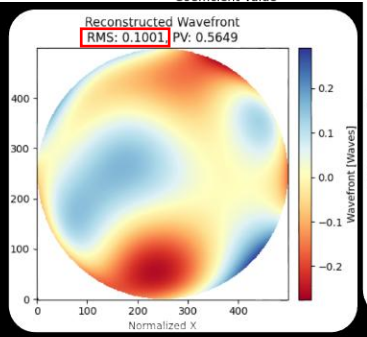


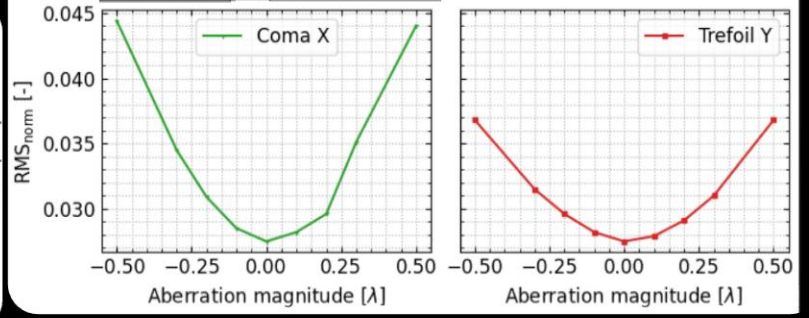


Starting position









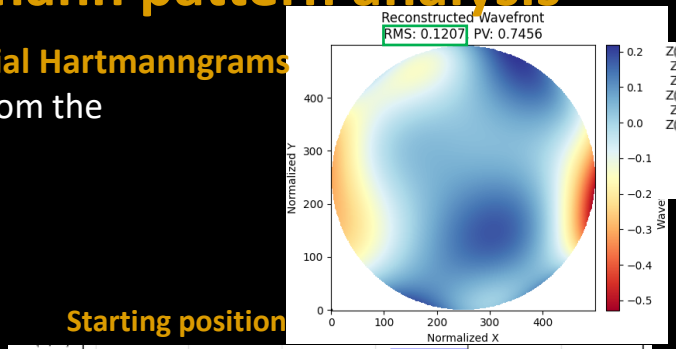
02 - Idea behind wavefront quality quantification in the focal region through fast Shack-Hartmann pattern analysis

Exploring a few merit functions on artificial Hartmanngrams

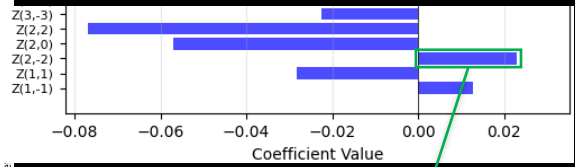
II. Normalized RMS displacement from the reconstructed reference grid

Real Hartmanngrams:

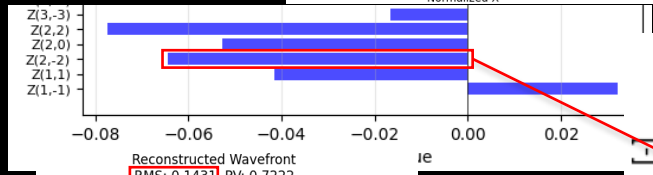
- **Single-mode scans reveal clear wavefront correction capability.**

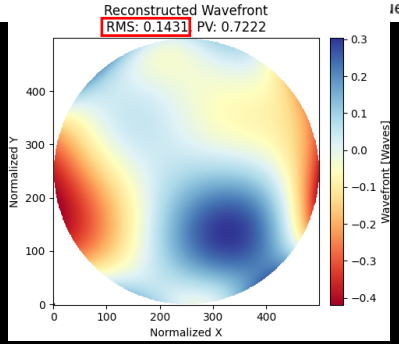


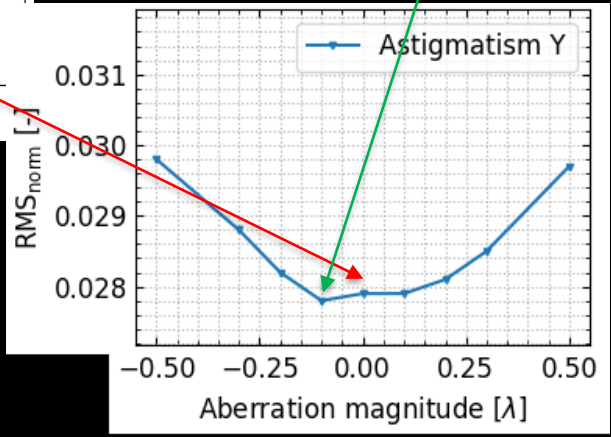
AstigmatismY = 0.1 waves



Starting position







EuPRAXIA Doctoral Network

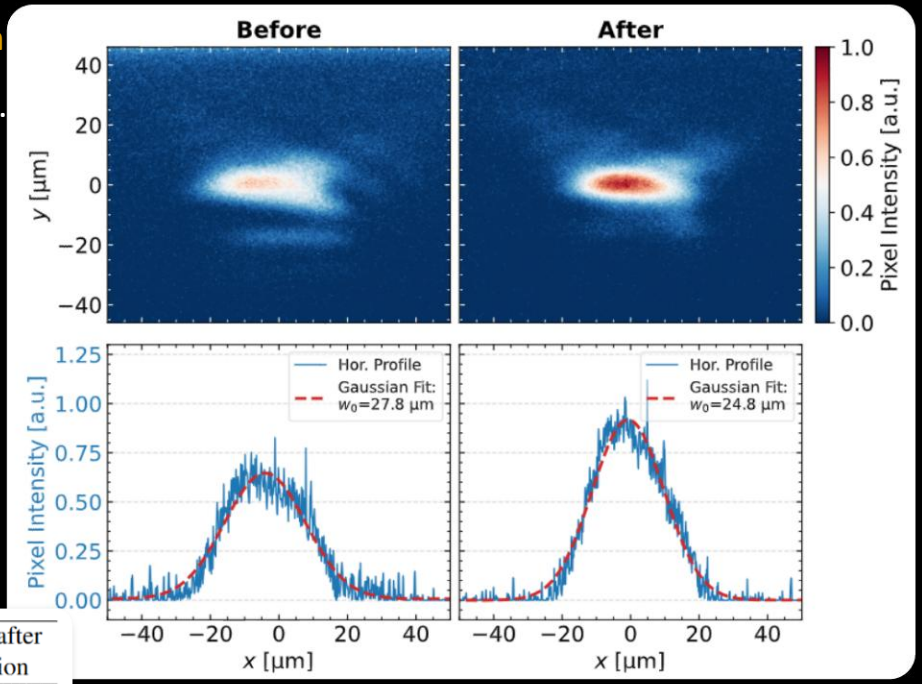
03- Towards the wavefront correction in real application

Demonstration of Simple Sequential Wavefront Optimization

- Simple Python-based optimization using the NRMS metric.
- Mode-by-mode correction of aberrations.
- For each mode:
  - Sweep the mode amplitude.
  - Capture a Hartmanngram and evaluate NRMS.
  - Select the amplitude that minimizes NRMS.
  - Permanently apply the correction to the DM.
- Repeat sequentially for all aberration modes.

Note

- Single optimization pass only.
- No adaptive sweeps, mode prioritization, or convergence acceleration.



Aberration amplitude c	At the DM	At SHWS before optimization	At SHWS after optimization
Obl. Astig.	-0.20λ	0.18λ	0.06λ
Hor. Astig.	0.10λ	-0.43λ	-0.07λ
Hor. Coma	0.20λ	0.24λ	0.07λ
Ver. Trefoil	-0.30λ	-0.35λ	-0.12λ
	Wavefront RMS	0.78λ	0.42λ
	M_{NRMS}	0.043	0.038

Summary

- *Examined a novel wavefront quality metric based on Hartmanngram geometry.*
- *Synthetic reference grid reconstructed directly from aberrated centroid distributions.*

Key Results

- *Two metrics investigated:*
  - *Distance variance between aberrated centroids*
  - *Normalized RMS of centroid displacements between the reference*
- *Both metrics exhibit symmetric, convex responses with well-defined global minima.*
- *NRMS remained sensitive to all tested aberration modes.*

Implications

- *Enables efficient mode-by-mode wavefront optimization.*

Outlook

- *Development of more advanced optimization algorithms.*

EuPRAXIA

Doctoral Network

Thank you!

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement no. 101073480.

UK Research and Innovation

02 – Backup slides

Exploring a few merit functions on artificial Hartmanngrams

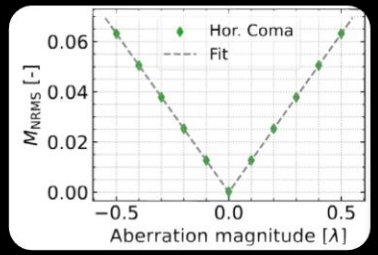
II. Normalized RMS displacement from the reconstructed reference grid

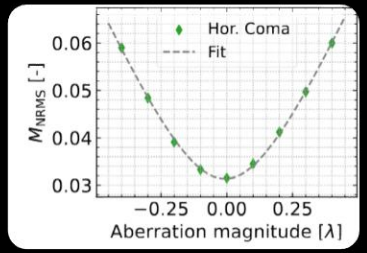
- Centroid displacement $q_i = |\mathbf{p_i} - \mathbf{r_i}|$ measures the deviation from the reference grid.
- It is proportional to the local wavefront gradient.
- The total wavefront is decomposed into a baseline term and an additional aberration mode:

$$W = W_{\text{base}} + cW_{\text{mode}}$$

- By linearity, the resulting centroid displacement is the sum of the individual contributions:

$$q_i = q_{i,\text{base}} + c \cdot q_{i,\text{mode}}$$





- Then the squared RMS over all $|P|$ displacements is

$$\text{RMS}^2 = \frac{1}{|P|} \sum_i^P |q_{i,\text{base}} + c \cdot q_{i,\text{mode}}|^2$$

- Expanding the square norm gives

$$\text{RMS} = \sqrt{\text{RMS}^2_{\text{base}} + 2\text{cov}(W_{\text{base}}, W_{\text{mode}})c + c^2\text{RMS}^2_{\text{mode}}}$$