

The baseline WFC strategy for the ESO ELT

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Task of telescope Wavefront control

- Keep the telescope diffraction limitable

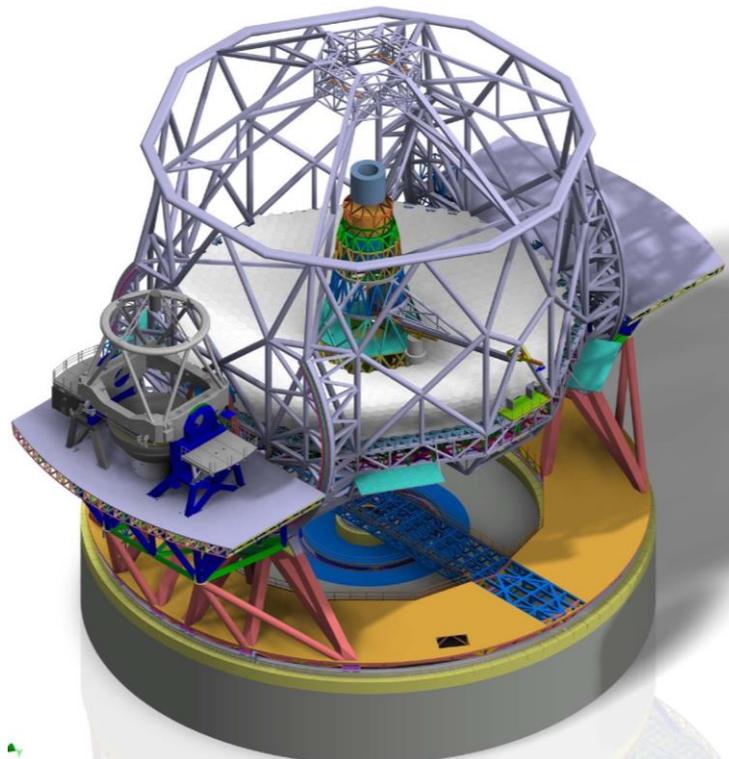
- Continuity of the wavefront
- Stroke management

- Science mode:

- Telescope preset
- Handover to instrument
- Stroke management

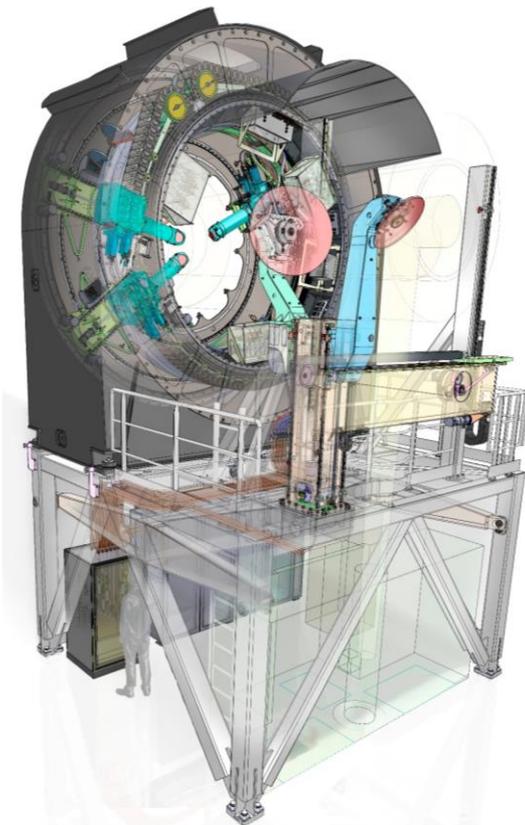
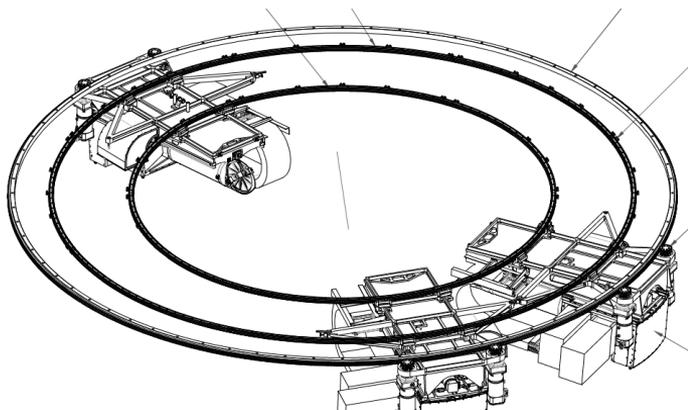
- Engineering mode:

- Phasing
- Demonstrate WF performance



Telescope sky metrologies in science mode

- Location = adapter in the prefocal station [PFS]
- Equipment: 3 guide probes (GP)
 - Patrolling the telescope technical field (2.5' to 5' field radius)
 - WFS:
 - Visible imager (20" field diameter [FoV])
 - 22x22 visible SH (4" FoV)
 - Option for an H-band GP in evaluation phase



■ Location: Phasing & Diagnostic Station [PDS]

- Injection by M6C:
 - intercepts the science field

➤ Sensors:

*On-axis
Guide Probe*

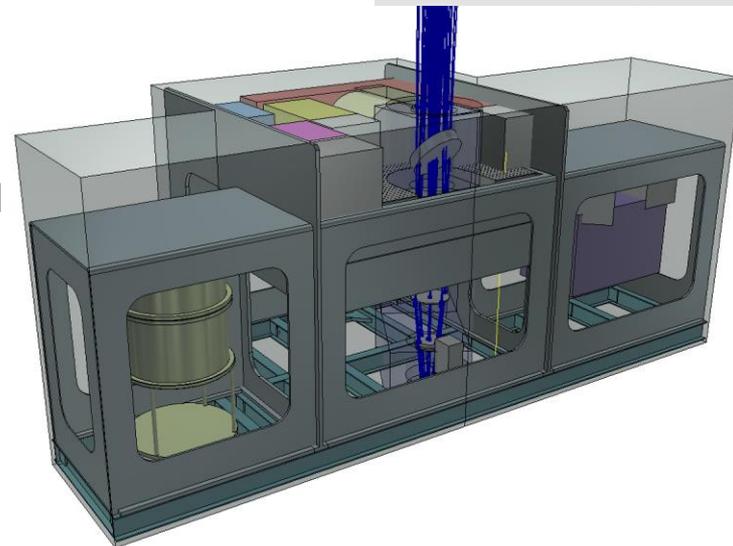
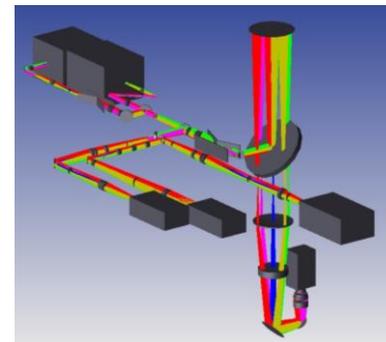
- Visible imager (1 arcmin FoV)
- SHAO: Visible 20x20 SH, 4" FoV

M1 Phasing

- SHAPS: modified visible SH
- ZEUS/ODIN: Zernike phase sensor, H band

*WF performance
measurement*

- K band pyramid
- K band imager



This talk

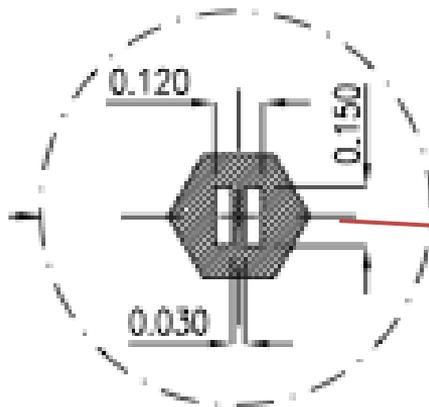
- Context of this afternoon's session: measuring phase discontinuities
- Two aspects involved at ELT:
 - Keep the 6 pupil sectors together (M4 petalling, LWE, M1 sectoring, ...)
 - Addressed in other talks this afternoon:
 - Shearing interferometry (Lorenzo Busoni)
 - PYR + spatial filtering (Nicolas Levraud)
 - Make M1 a continuous surface
 - This talk

Baseline phasing sensor SHAPS

■ SHAPS = Shack-Hartmann Phasing Sensor

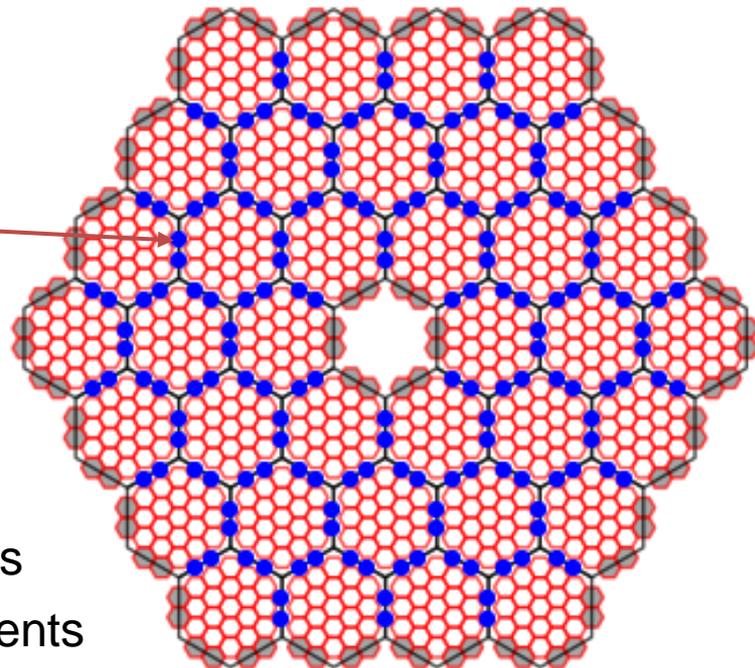
■ Heritage:

- Keck
- GTC
- APE -> MELT



■ Geometry:

- 19 shape sub-apertures / segment
- 2 phasing sub-apertures between segments
- 2 photometric sub-apertures at edge segments



GTC/Keck geometry

Commissioning sequence

■ Sensor characterisation

- Allocate pixels to sub-apertures
- Determine reference pixels

■ Segment capture

- Bring the segments to the SHAPS FOV

■ Stacking

- Align the segments to the reference pixels

■ Shaping

- Correct the segment figure errors

■ Register

- Bring and keep the segment edges to/at the phasing sub-apertures

■ Coherencing

- Bring the relative piston of adjacent segments in the coherence of the optical filter

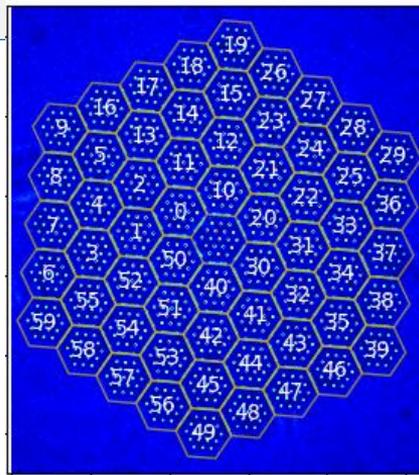
■ Phasing

- Minimize the surface discontinuities
≠ bring M1 to prescription

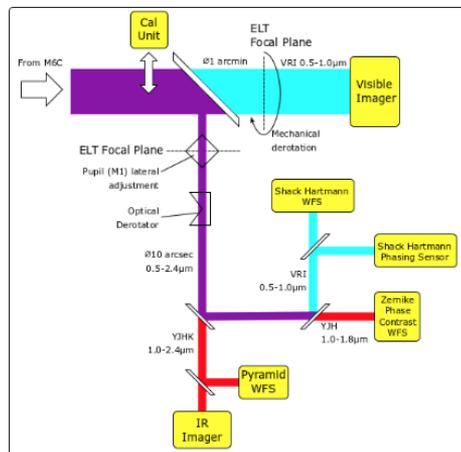
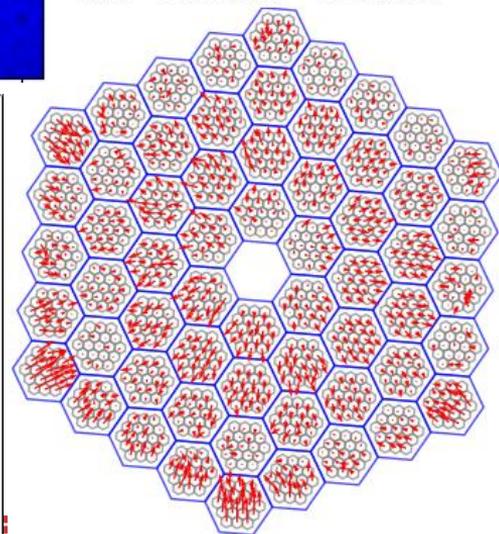
SHAPS characterization

- Reference frame illuminated with fiber at calibration unit
- Detect all spots and fit linear mapping from nominal geometry to observed spot positions
- pointing and focus:
 - Internal SHAPS reference
 - correct the fiber position
- Astigmatism: absorbed in the linear mapping
- Unclear if residual low orders belong to the calibration or the PDS optics. We do not care.

- SHAPS characterisation
- Segment capture
- Stacking
- Shaping
- Register
- Coherencing
- Phasing



rms = 0.21, max = 0.69 pixel

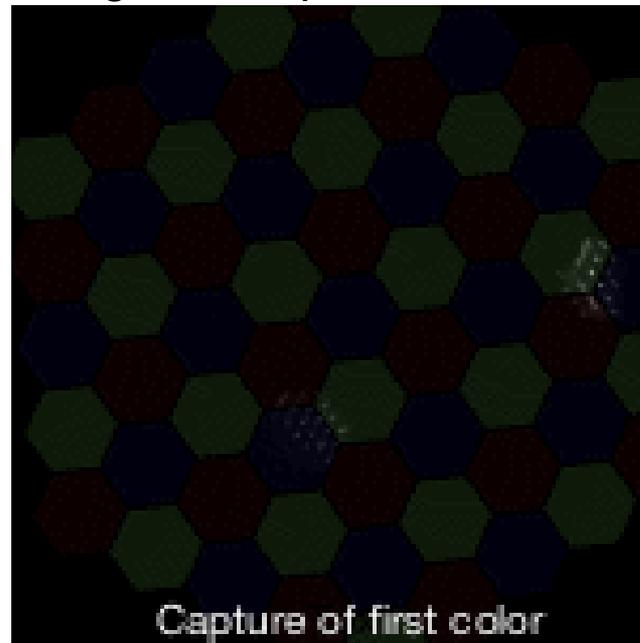


Segment capture & stacking

- SHAPS characterisation
- Segment capture
- Stacking
- Shaping
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- Shack-Hartmann sensors provide simultaneously pupil and field resolution
- When a segment enters the FOV it can immediately be integrated in the stacking/pointing process
- At ELT the segment identification will be done in the PDS imager (FOV = 1 arcmin) with a signature process
- expected initial dispersion = 3 to 5 arcmin
 - Problem of confusion with 800 segments
 - Large differential tilts between segments to be commanded at M1
 - Thankfully, this is done only once

Segment capture on MELT



Segment stacking & shaping

- SHAPS characterisation
- Segment capture
- Stacking
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- Phasing

- 19 shape sub-apertures give visibility on:
 - Tip-tilt (stacking)
 - Commendable modes: focus, astigmatism and trefoil

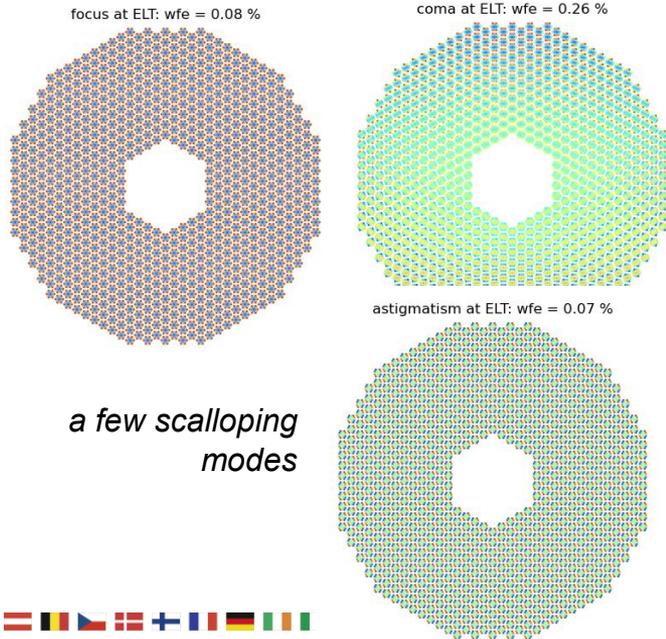
■ Segment shadowed by the spiders are not measurable

- ⚠ the segment figure errors are not the only source of measured aberrations:
 - the transfer of focus and coma between M1 and M2 generate scalloping
 - Figure errors at other mirrors generate additional surface discontinuity at M1 if compensated by stacking

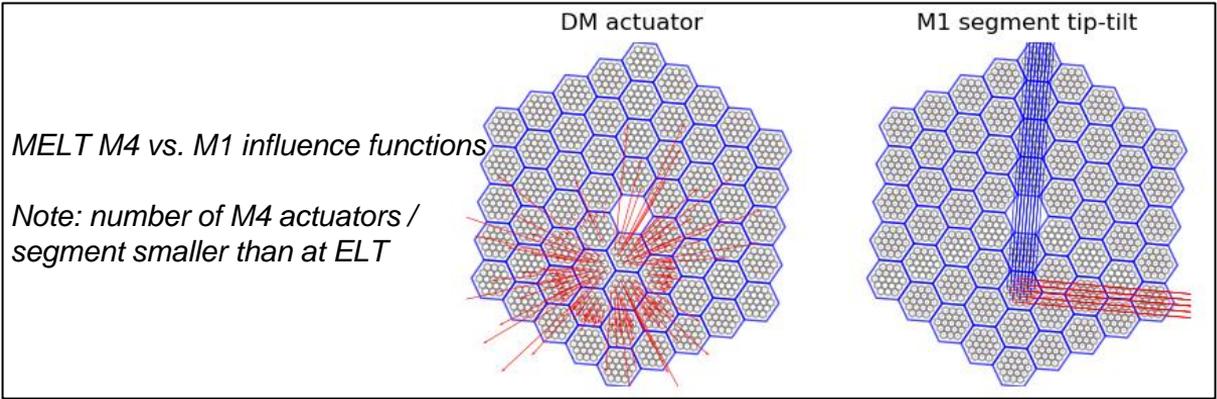
■ We are working on strategies to disentangle continuous and segmented surfaces

$$\text{concave} - \text{convex} = \text{scalloping}$$

the scalloping equation



ex: astigmatism = 50 μm PV -> scalloping ~ 10 nm

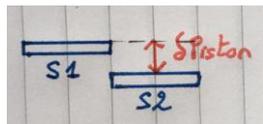




discontinuities in phasing subapertures

■ Phasing subapertures:

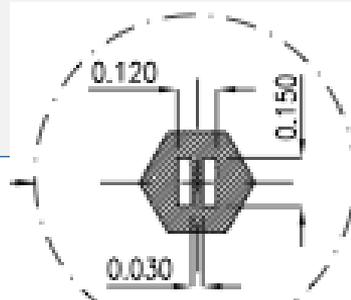
- baseline (75 mm)
- ~ 2 slit width (45 mm)



$$\phi = 2\pi \frac{\delta piston}{\lambda}$$

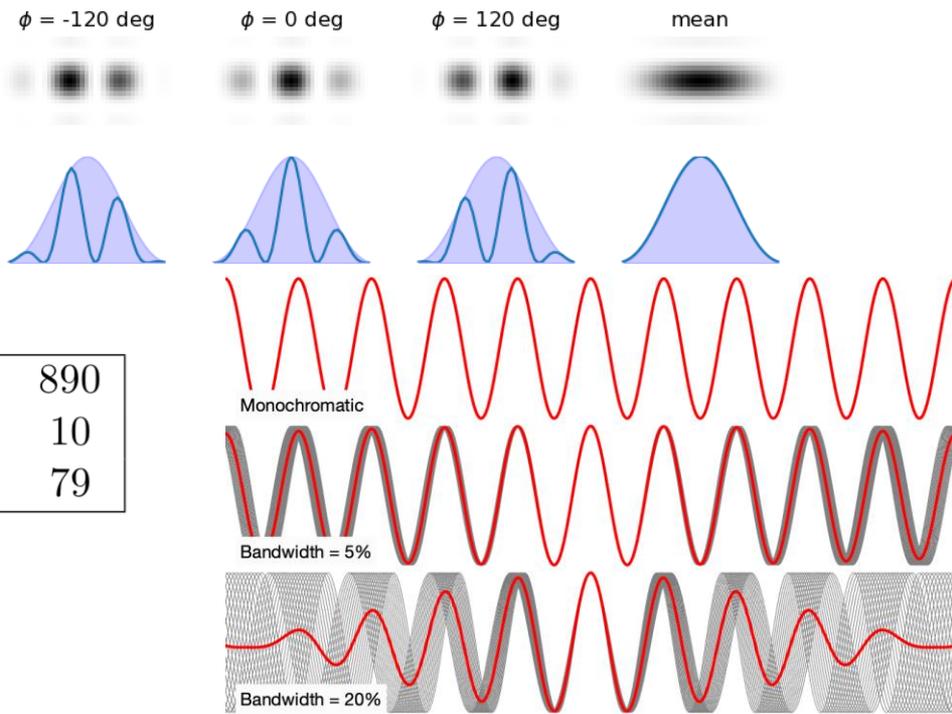
| | | | | | |
|------------------------------------|-----|-----|-----|-----|-----|
| Wavelength [nm] | 870 | 850 | 700 | 650 | 890 |
| Bandwidth [nm] | 100 | 10 | 200 | 10 | 10 |
| Coherence length [μm] | 7.6 | 72 | 2.5 | 42 | 79 |

SHAPS filters



phasing subaperture

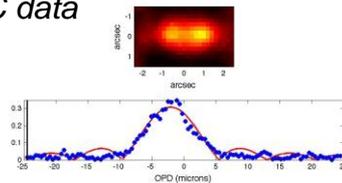
- SHAPS characterisation
- Segment capture
- Stacking
- Shaping
- Register
- Coherencing
- Phasing





coherencing

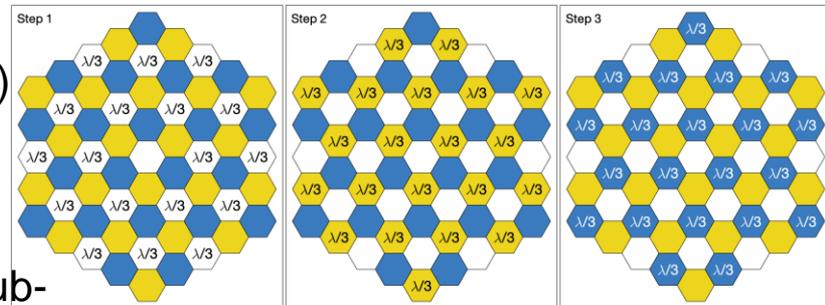
GTC data



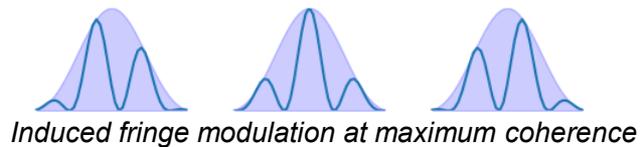
- SHAPS characterisation
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- Register
- **Coherencing**
- Phasing

Strategy:

- Select filter with coherence \sim initial error / 10
- Scan the OPD space with segments
- At each place modulate segments $\pm \lambda/3$ (3 frames)
- Indicator of fringe visibility: $\frac{\text{standard deviation}}{\text{mean}}$ of phasing PSF
- Detect position of maximum coherence for each sub-aperture
- Solve the equation: $\text{max coherence} = \text{IM segment piston}$
- Offset the M1 reference (edge sensors) to the solution
- Iterate with shorter bandpass

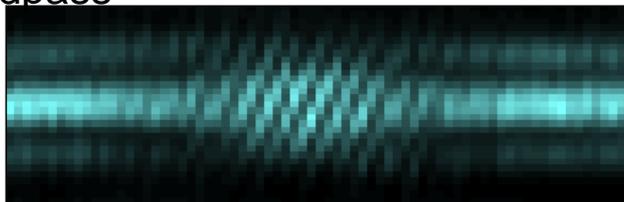


3 steps modulation sequence

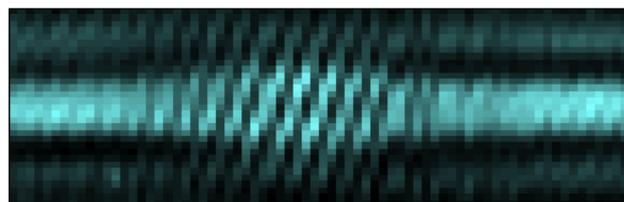


example of GTC coherence data

PSF Profiles



PSF Profiles



- SHAPS characterisation
- Segment capture
- Stacking
- Shaping
- Register
- Coherencing
- **Phasing**

■ Goal: try and reach the surface continuity

■ Two things to do:

- detect the white fringe
- find the position $\phi = 0$

■ 2 techniques experimented at GTC:

- Broad band:
 - Scan the coherence length
 - Measure the coherence and the phase
 - Requires determining the effective wavelength (barycentre of filter x stellar spectrum)
- Measure the phase in two distinct narrow band filters
 - Assume that the sub-aperture is already at the white fringe
 - Inconvenient mitigated by
 - longer synthetic wavelength provided by the two wavelengths
 - Redundancy of measurements => rejection of 2π errors if sparse enough (up to ~2% is ok)

Phase reference

■ Difficult to determine the 0 phase

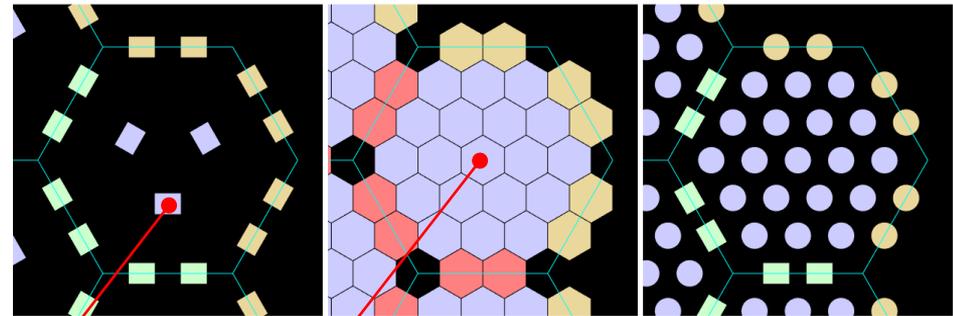
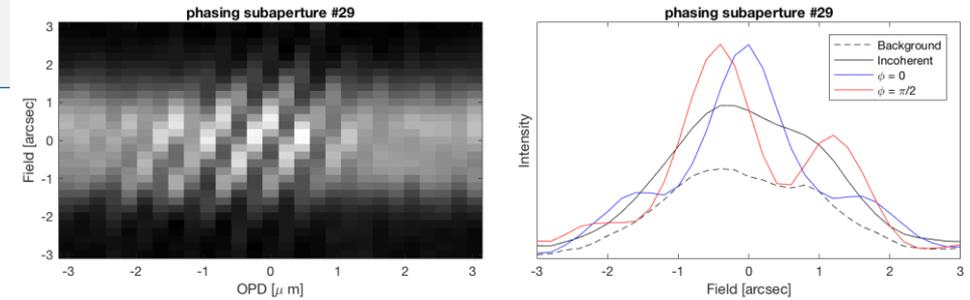
■ Causes:

- The fringe visibility never exceeds 50%
 - GTC learned experience
 - Interferences with nearby shape sub-apertures are suspected to contaminate. (shape sub-apertures at GTC are seeing limited)
- The position of the fringe is not an indicator (coupling to local wavefront tilt)
- Neither the incoherent nor the coherent PSF profiles feature a clear symmetry axis

■ Compromise: determine the point where the asymmetry of the profiles is minimum.

■ Mitigation:

- At ELT the ratio of size between shape and phasing sub-apertures is 60% smaller
- Other LA geometry will be offered



diffraction limited

seeing limited

*Left: less shape sub-apertures
Center: nominal configuration
Right: smaller shape sub-apertures*

Scan strategy:

- Interlace 3 steps sequences with various amplitudes
- Scan length = power of 3 (3, 9, 27, 81, ...).
- At the end of the night all segment pairs went through the same collection of OPD offsets in different orders

Two filters offered:

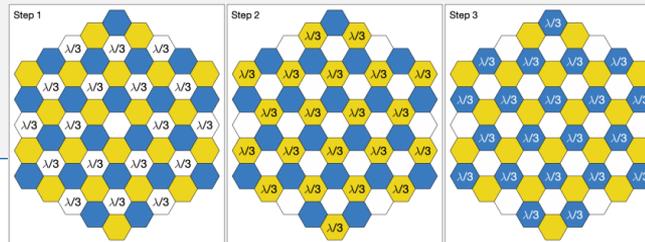
- 700 x 200 nm: coherence = 3.5 waves covered in 9 steps
- 870 x 100 nm: coherence = 9 waves covered in 27 steps.

Favorite filter at GTC: 870 x 100

- Longer coherence
 - Takes more time (27 frames instead of 9)
 - Tolerant to larger initial error
- Better image quality towards the red

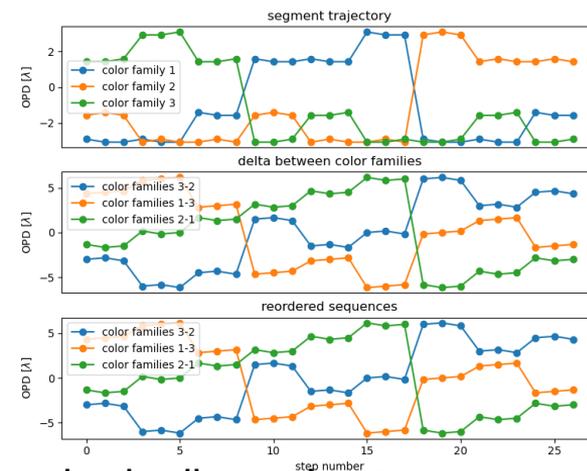
Lesson learned at GTC: need to consider the longitudinal atmospheric dispersion to correctly identify the white fringe for sub-apertures orthogonal to the meridian

(Note: Keck sitting at higher altitude did not have to incorporate this correction)



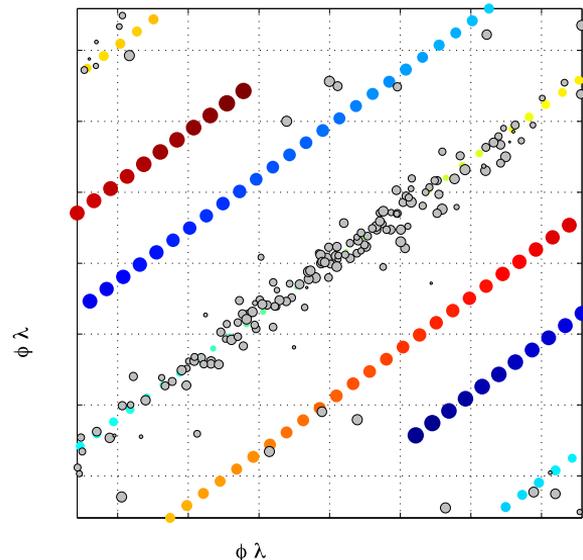
- SHAPS characterisation
- Segment capture
- Stacking
- Shaping
- Register
- Coherencing
- **Phasing**

phasing
27 step sequence



- SHAPS characterisation
- Segment capture
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- **Phasing**

- Filters at 650 and 890 nm (10 nm bandwidth)
- 3 exposures per filter (3 steps sequence amplitude $\lambda/3$)
(Faster than the broad band technique)
- Large separation between two wavelengths
 - Ratio $\sim 4/3^{\text{rd}}$
 - \Rightarrow tolerance to phase noise ~ 30 deg
 - \Rightarrow synthetic wavelength ~ 2.6 μm
- The dispersion of the points $[\phi(\lambda_1), \phi(\lambda_2)]$ around their nominal locus $[\lambda_2 \phi(\lambda_2) = \lambda_1 \phi(\lambda_1)]$ gives an estimation of the measurement noise.



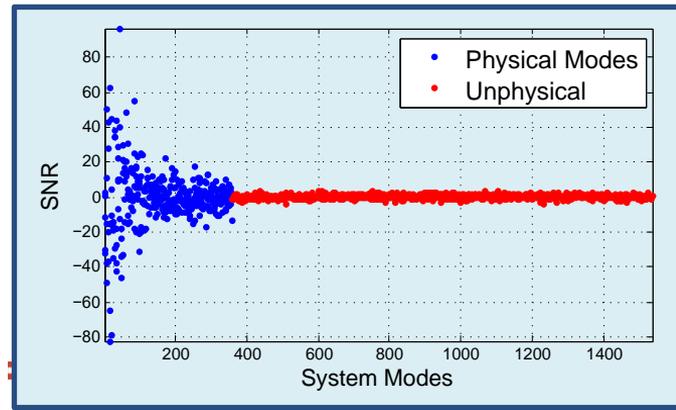
- SHAPS characterisation
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- **Phasing**

■ synthetic interaction matrices:

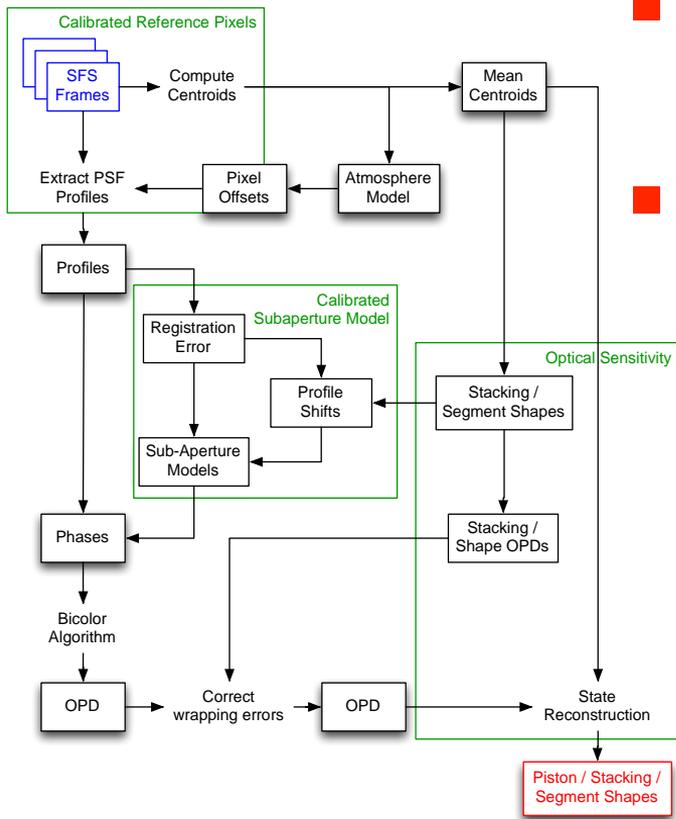
- PTT and figure to OPD
- PTT and figure to shape sub-apertures

■ seconstruction option

- Piston only (assume the stacking is good)
 - Robust inversion but the stacking error stays
- piston and tip-tilt
 - less robust, especially along low order
 - Lowest order (50 modes) rejected from optical phasing at ELT
- piston tip-tilt and shape:
 - complete
 - high degree of redundancy of the data
 - Appropriate for SNR evaluation assuming stochastic errors.



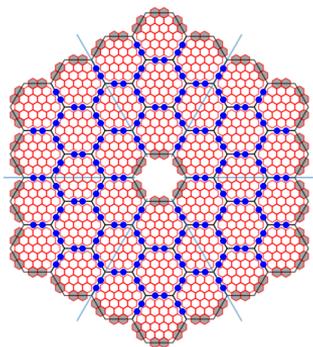
SNR estimation
at GTC



Scaling to ELT

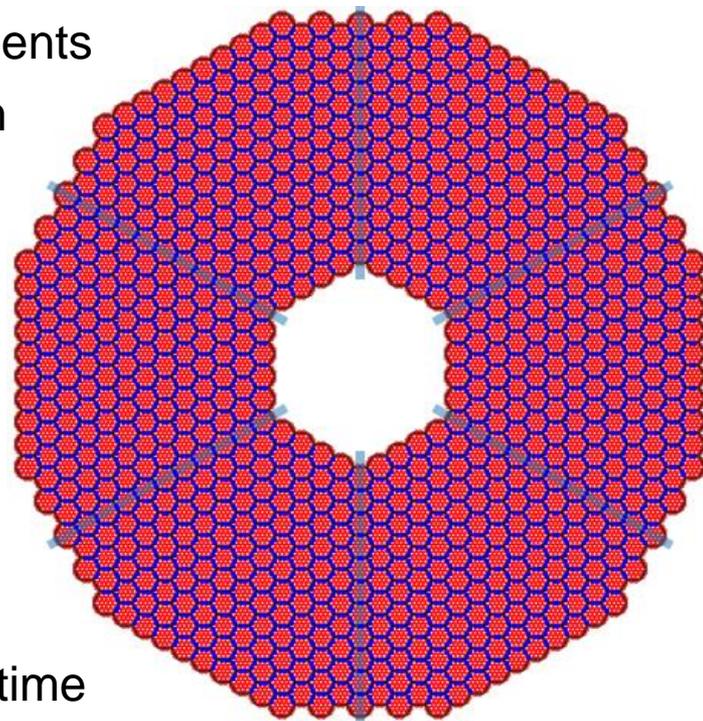
■ GTC:

- 36 1.8 m segments
- Spiders ~50 mm



■ ELT:

- 798 1.42 m segments
- Spiders ~500 mm



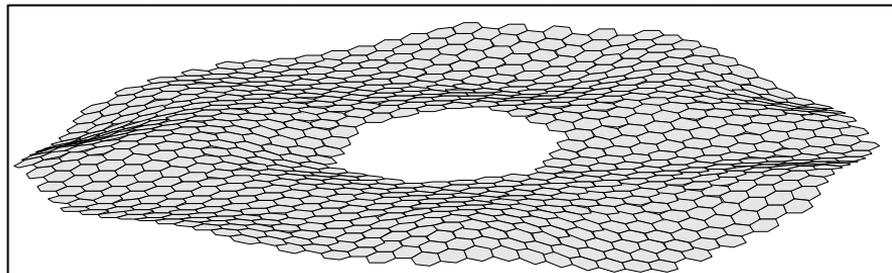
all steps are parallel:
 stacking
 shaping
 coherencing
 phasing

=> same strategy, same execution time

Scaling to ELT: difficulties and risks

■ Difficulties:

- SHAPS confuses a wavefront step with wavefront tilt
 - Solution at GTC:
 - integrate long enough to average out the seeing at the scale of sub-apertures
 - Use the stacking information to offset a posteriori the phasing reference pixels
- At ELT, M1 does not behave along low orders
 - Coupling coefficients Piston / Shear-Gap $\sim 5e-3$ to be measured
 - In-plane deformations (gravity + temperature) ~ 5 mm, up to $200 \mu\text{m}$ between adjacent segments
 - Large noise multiplier along low orders
- ~ 50 modes to be controlled with low order SCAO (SHAO + M4) running at ~ 10 Hz
 - while M1 is incoherent and varying its unphasing state
 - offload M4 to M1 behind the scene
 - Validation status:
 - Simulation
 - MELT



the ELT M1 being super good at producing low order aberrations while keeping its surface nearly continuous

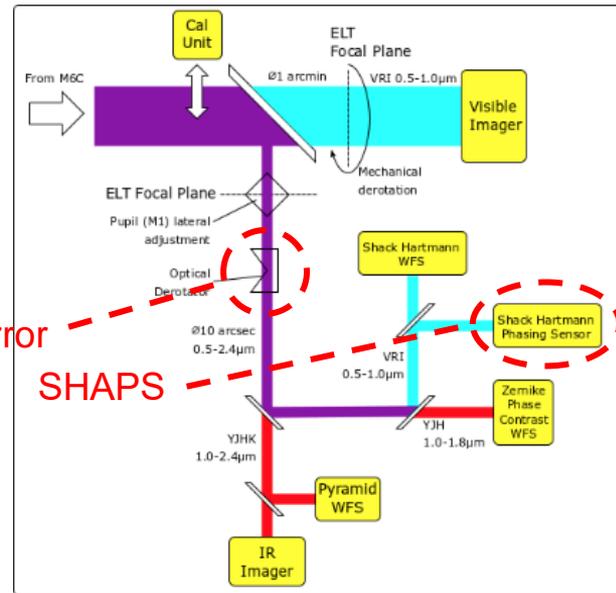
Scaling to ELT: difficulties and risks

■ risk:

- Same absolute tolerance to registration errors as GTC/Keck:
 - ~10 mm
- Telescope 4 times larger and many times floppier structurally
- The registration budget contains many terms:
 - Lateral and clocking error (controlled, see next slide)
 - Magnification error: adjusted with zoom, hopefully not dynamically controlled
 - Anamorphosis: the potential killer (0.05% anamorphosis => 10 mm at edge)
 - Fixed with new lenslet array according to as-built. Conditions:
 - » Static
 - » Caused downstream the K-mirror
 - M1 geometry:
 - AIV errors
 - In plane motions of the segments
 - M1 sag (4 m) ⊗ off-axis condition (telescope alignment error)

■ mitigation

- Active registration control
- Alternative phasing sensor: ZEUS



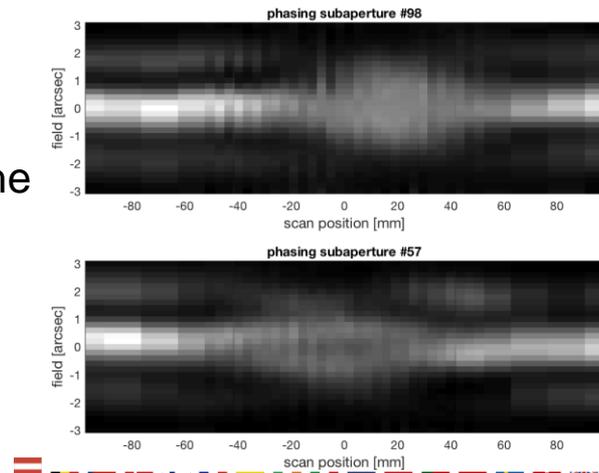
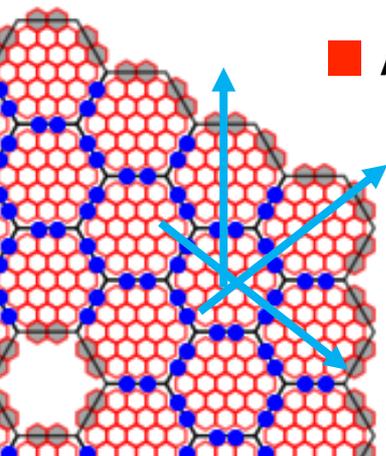
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- Phasing

■ A destructive task:

- Make sure M1 is incoherent (the easiest commissioning task)
- Scan the pupil steering actuator along the 3 gap directions
 - Transition the phasing sub-apertures from one segment to the other
 - The PSF will go coherent – incoherent – coherent.
 - The position where the incoherence was maximum is when the the segment edge is at the sub-aperture.
- Procedure experienced successfully at GTC

■ At ELT:

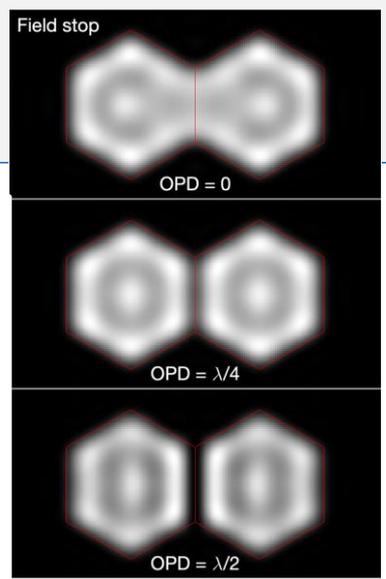
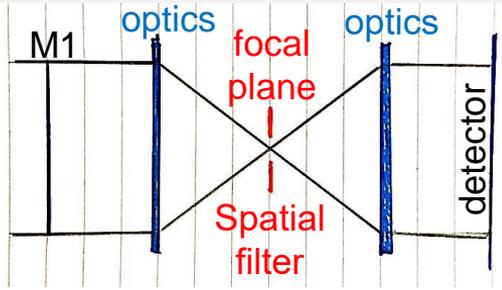
- Additional photometric sub-apertures at the pupil edge
- Set point determined along destructive procedure
- Lateral and clocking errors restored after each frame



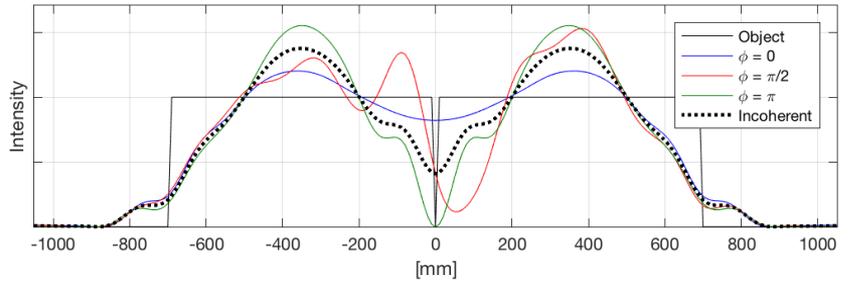
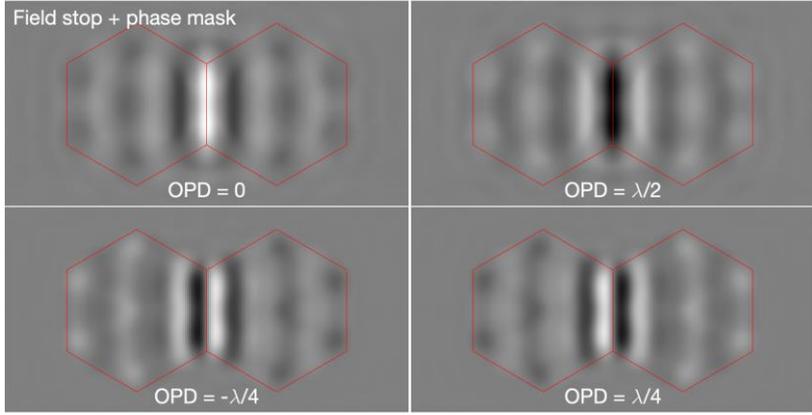
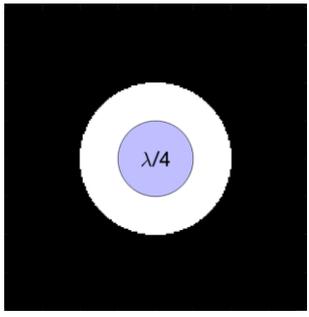
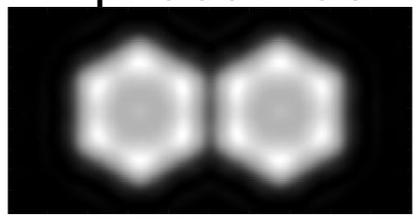
Phasing: plan B

- ZEUS, aka ODIN
 - APE experiment heritage*
- Phasing signal produced by spatial filtering in an intermediate focal plane, detection in the pupil plane
- No lenslet array, no manufacturing tolerance
- A posteriori allocation of pixels to segment edges.

* *Dohlen, Kjetil, "Phase Masks in Astronomy: from the Mach-Zehnder Interferometer to Coronagraphs", Astronomy with High Contrast Imaging II, Editors : C. Aime and R. Soummer EAS Publication Series, 12 (2004) 33-44*

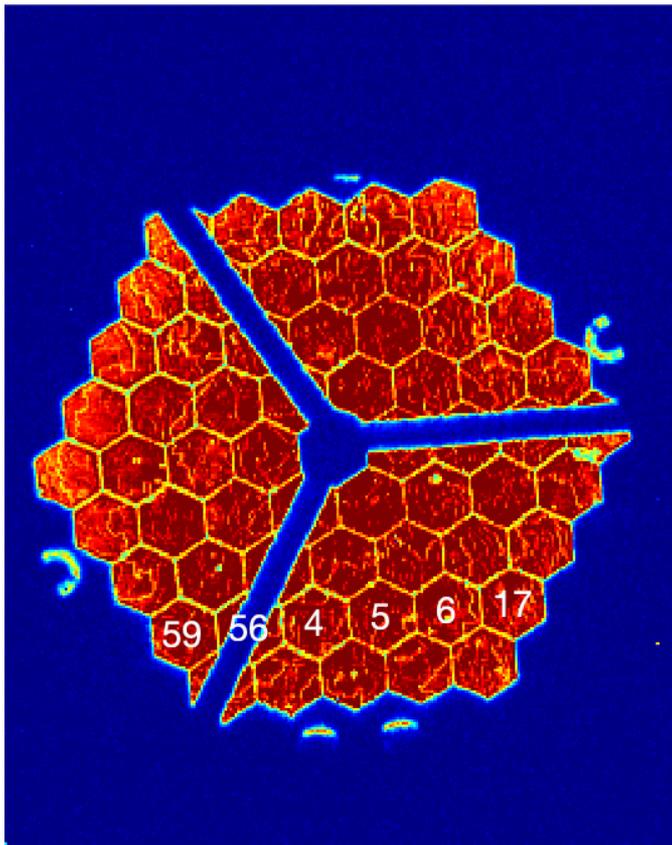


- Direct pupil imaging
- spatial filtering
- phase mask



- Field stop = 1 arcsec
 - Diffraction limited in most conditions
- H band:
 - Pupil resolution ~ 35 cm = half a segment edge
 - Reduces the sensitivity to edge polishing error
- Phase mask diameter ~ 0.5 arcsec
 - Reduces the sensitivity to wavefront steps
 - increases tolerance to pointing error

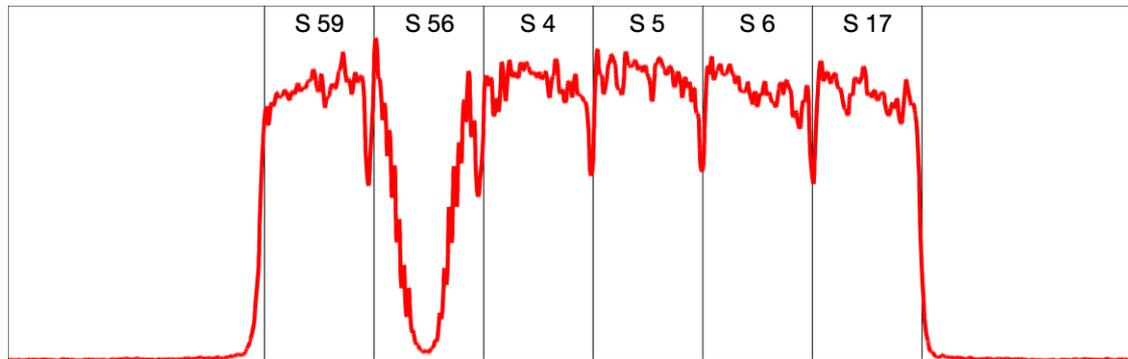
ZEUS on MELT: incoherent frame



Prerequisite:

M1 stacked with SHAPS

Note: registration tolerance much looser for stacking

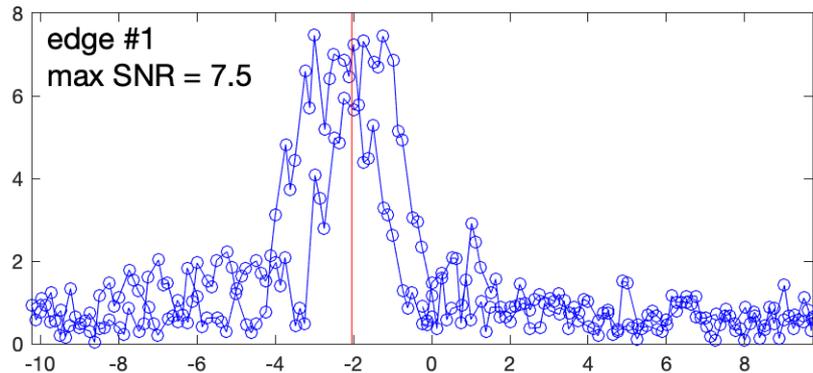
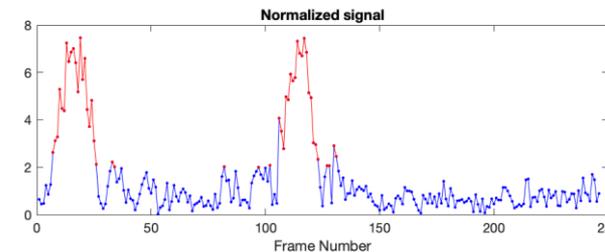
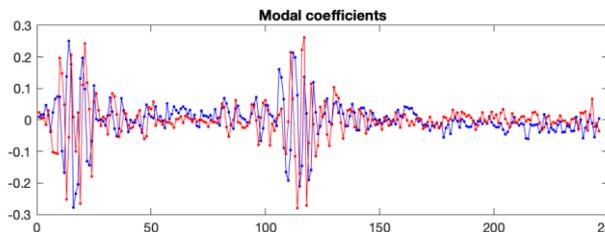
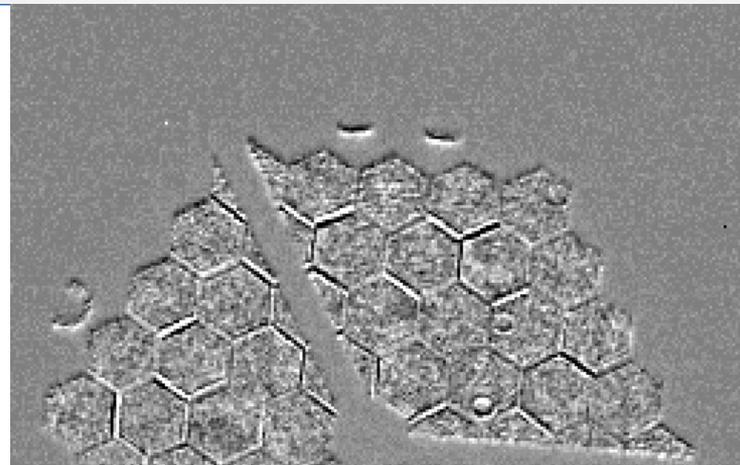


*Note: no phase mask in this exposure,
FOV larger than 1 arcsec*

ZEUS on MELT: coherencing

- Long range scan
- Signal = variance of pixel intensity
- Reconstruction: solve equation

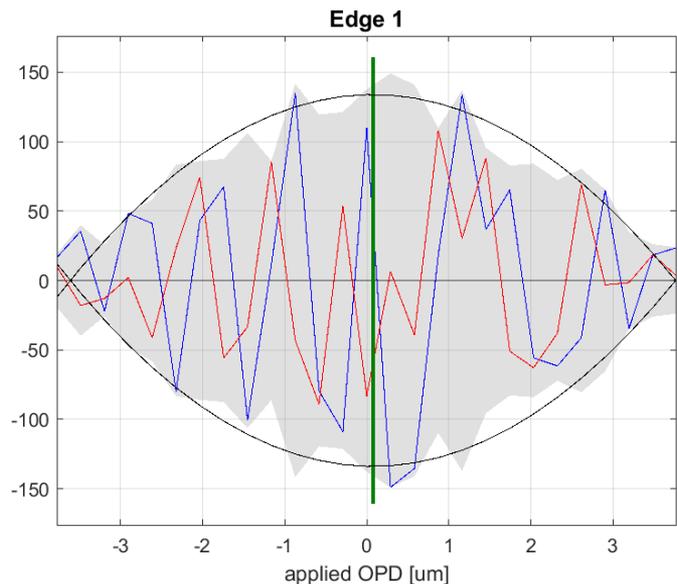
$$OPD = P2OPD * P$$



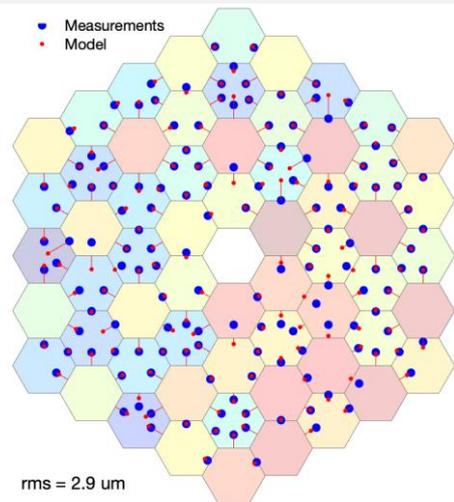
ZEUS on MELT

white fringe determination

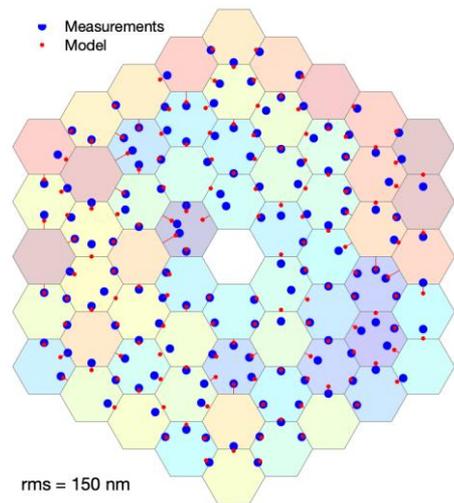
- Same principle as for cohencing
- short scan amplitude (27 steps i.e. 9 fringes)
- fit the coherence envelope
- find the maximum coherence



1st iterat



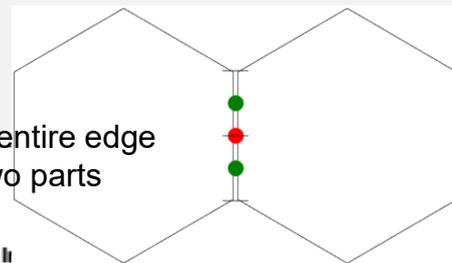
3rd iteration
(scale x 10)



ZEUS on MELT phasing strategy

Two options:

- red integrate signal along entire edge
- green : cut the edges in two parts



■ Modulation: 3 steps

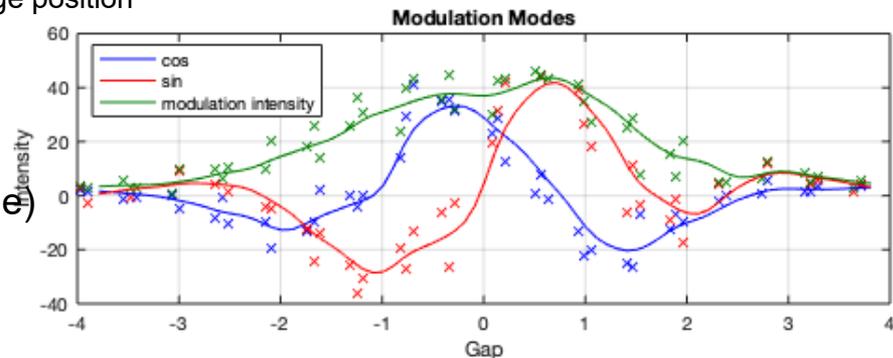
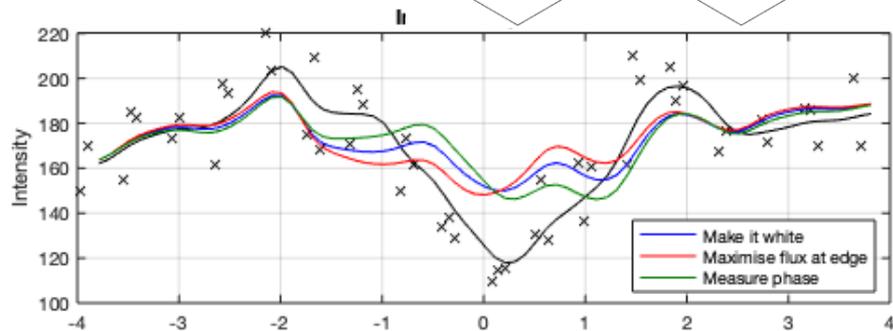
■ Signal extraction

- Fit frames on basis $[1, \cos\delta\phi, \sin\delta\phi]$
- Estimate phase at 2 points per edge
- 3 phase estimation technics
 - Make intensity uniform
 - Maximize flux where intensity modulation is maximum
 - Find $\delta\phi$ such that the signal is asymmetric relative to the edge position

■ Reconstruction: solve equation

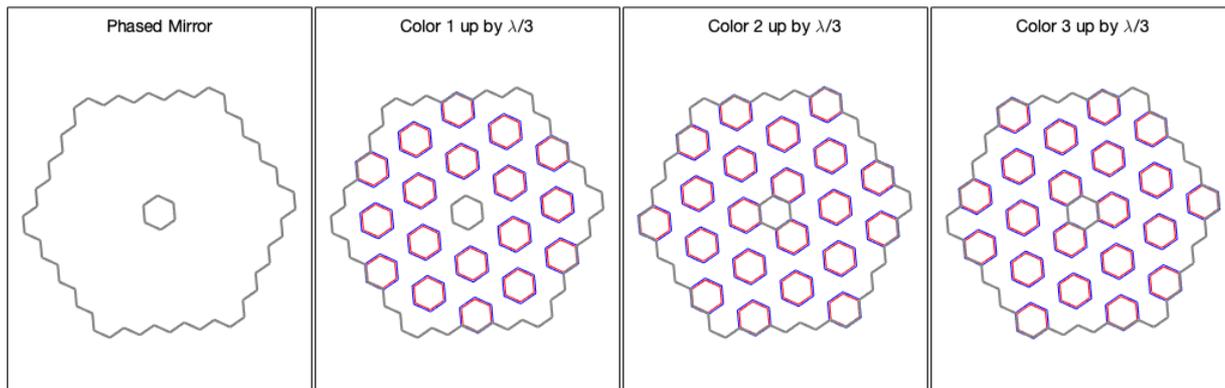
$$\text{OPD} = \text{PTT2OPD} * \text{PTT} \quad (\text{red option, fragile})$$

$$\text{or } \text{OPD} = \text{P2OPD} * \text{P} \quad (\text{green option, less fragile})$$

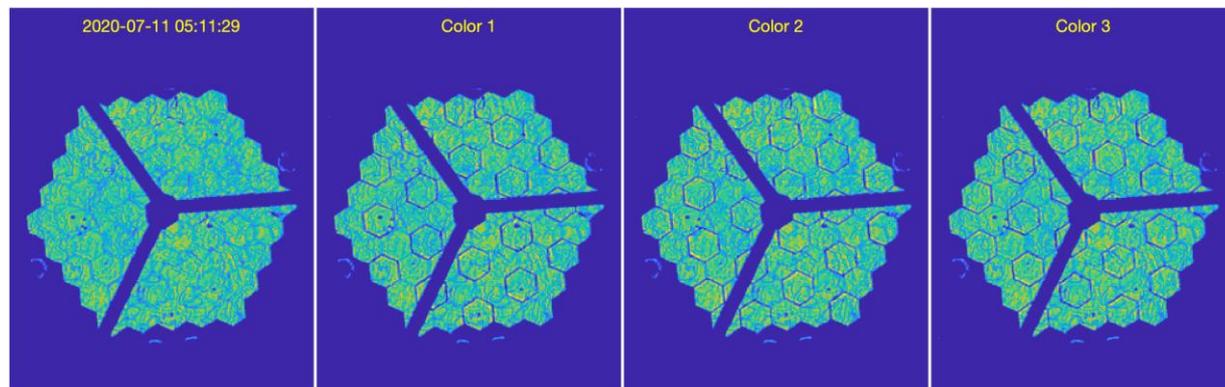


ZEUS on MELT: phasing results

expectation

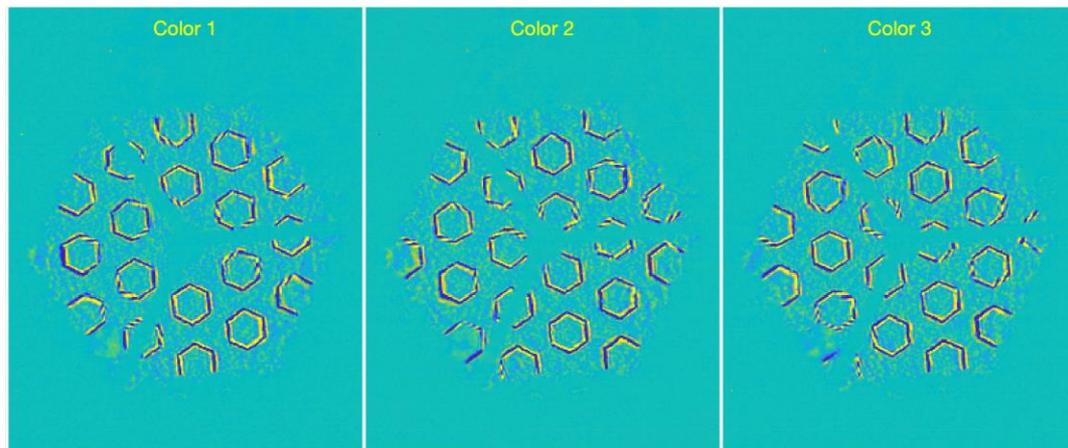
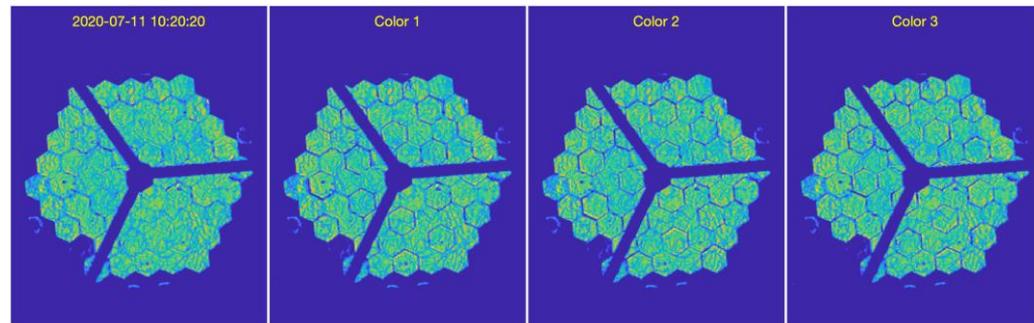


observation



Result to be stabilized

- The phasing usually converges for a few iterations
 - Performance TBD
- The solution depends on the algorithm
 - => there are unknown biases in the measurements
- It diverges when the procedure is iterated too many times
 - > difficulties near the pupil edges
 - > uneasy to keep the stacking
 - the current formulations of the phase extraction algorithms have limited dynamic range against tip-tilt errors
 - the signal is clearly visible to the eyes



conclusion

■ Baseline = SHAPS

- Considered mature
- Procedure and algorithms are defined
- Identified risks are mitigated

■ Plan B = ZEUS

- Concept tested at APE and on the bench with MELT
- Procedure and algorithms in development
- Lack of field experience

■ ZEUS is also seen a complement to SHAPS providing independent validation of the phasing solution.