3 months on AO PSF reconstruction (PSF-R) with Altair/Gemini and Keck-AO

lessons learned so far

Laurent Jolissaint — aquilAOptics, Switzerland
Julian Christou — Gemini Observatory
Peter Wizinowich — W. M. Keck Observatory
Eline Tolstoy — Kapteyn Inst. Netherlands

SPIE astronomical instrumentation 2010

with the help of

Jean-Pierre Véran, HIA/NRC

Al Conrad, W. M. Keck Observatory

Chris Neyman, W. M. Keck Observatory

and

Ralf Flicker

outline

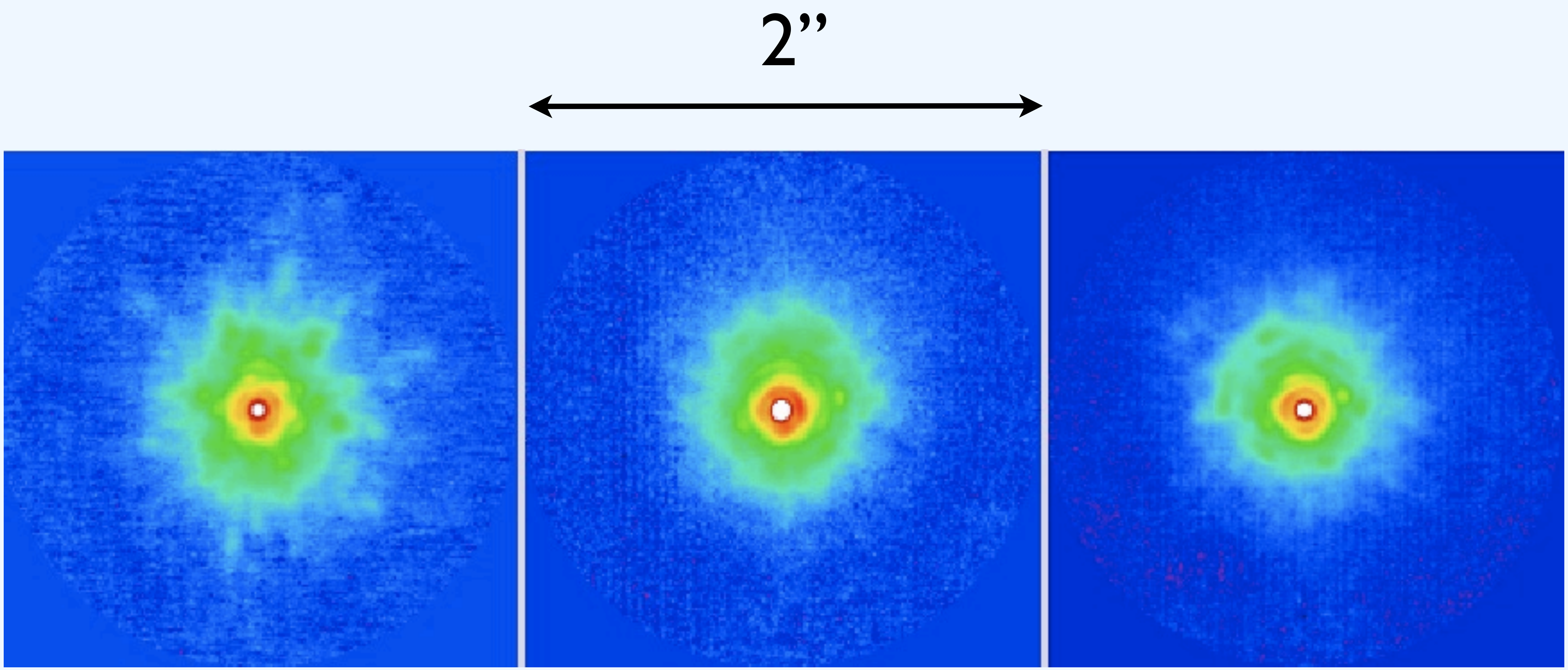
- why we need PSF reconstruction
- recall Jean-Pierre Véran method
- project OPERA goal
- first results on ALTAIR/GEMINI
- the future of PSF-R on multi (L)GS/DM systems

needs for PSF-R in AO

applications

- AO astronomical data reduction
- AO system performance diagnostic

needs for PSF-R in AO



NIRC2 @ Keck NGS AO
K’ band - crowded young star clusters - 30 minutes exposures
courtesy Jessica Lu (Caltech)

Jean-Pierre Véran (JPV) method

- J.-P. Véran et al. JOSA A, 14, 1997
- the JPV method concept:
    - WFS measures the residual wavefront error
    - keep these WFS measurements and reconstruct the long exposure PSF
- developed for single, bright NGS, on-axis
- successfully tested on PUEO/CFHT in 1997
- JPV method can be - in principle - adapted to any AO mode (to be confirmed/discussed)

Jean-Pierre Véran (JPV) method

$$\mathrm{PSF}_{\mathrm{system}}(\vec{\alpha}) = \mathcal{F}\left\{\mathrm{OTF}_{\mathrm{system}}(\vec{\nu})\right\}$$

$$\mathrm{OTF}_{\mathrm{system}}(\vec{\nu}) \approx \mathrm{OTF}_{\mathrm{telescope}}(\vec{\nu}) \times \mathrm{OTF}_{\mathrm{AO}}(\vec{\nu})$$

Jean-Pierre Véran (JPV) method

$$\mathrm{OTF}_{\mathrm{AO}}(\vec{\nu}) = \exp[-(1/2)D_\varphi(\lambda\vec{\nu})]$$

phase structure function $$D_\varphi(\vec{\rho}) = \sum_{i,j=1}^{N} \langle\epsilon_i\epsilon_j\rangle U_{i,j}(\vec{\rho}) + D_\varphi(\vec{\rho})_{[\text{high order}]}$$

$$U_{i,j}(\vec{\rho}) \sim \text{spatial covariance DM modes } M_i \ \& \ M_j$$

residual modes coefficients covariance $$\langle\epsilon_i\epsilon_j\rangle = R\langle\omega_i\omega_j\rangle R^t + \langle\alpha_i\alpha_j\rangle$$ WFS aliasing covariance matrix

WFS measurements

changes with AO run

System model (modes, WFS)

static

Turbulence (r_0, L_0) and modes)

Jean-Pierre Véran (JPV) method

recent improvements

- diagonalize the modes covariance matrix (E. Gendron)
- direct computation of overall OTF is possible (R. Flicker)
- $M_i\, M_j = \sum_k a_k M_k$ with exp(-D/2)=1-D/2+(D/2)^2...

  this minimize the non-stationarity issue (L. Jolissaint) WIP

previous PSF-R projects, reasons for failures

- JPV implemented successfully on PUEO/CFHT (1997)
- since then, several (~6) projects, no real success, why ?

1. PSF-R tools never finalized as reliable service to observer
2. lack of human resources (HR for AO dev, PSF-R low priority)
3. not enough access to telescope time
4. impossible to modify AO control code to implement telemetry
5. accessible telemetry only partial (variances instead of covariance matrices)...

- this makes no sense: we build complex & costly AO system but AO data reduction is limited by uncertainties in PSF knowledge

OPERA project goals (2011)

- OPERA is a PSF-R code for Altair (Jolissaint+Veran 2003)
- Project GOAL: implement PSF-R for good, simplest case
  - ★ on-axis, bright NGS
  - ★ SH-WFS system
- finalize the tool as a service to the observer
- NO new theoretical developments: finish the job first !
- THEN, we can move on to
  - ★ dim guide stars
  - ★ off-axis NGS (Britton, PASP 118, 2006)
  - ★ laser systems, multiple GS
  - ★ tomography, multiple DMs

OPERA project for ALTAIR/Gemini-N

ALTAIR NGS mode

- telemetry data is operational and COMPLETE
- OPERA tested successfully only ONCE on ALTAIR / lab
- ALTAIR does not perform as expected - a risk for PSF-R
- Julian Christou at Gemini now testing ALTAIR (see paper at this conference: ALTAIR performance and updates at Gemini North)
  - ★ lots of bright NGS data available
  - ★ easy access to telescope time
- apply OPERA on sky data, test the code, debug, finalize

OPERA project for Keck AO

Keck AO PSF-R project - CfAO funded

- critical to have another AO system + telescope
- people in charge of project not here anymore
- implement/continue the work of Ralf Flicker
- zonal control, JPV model so far is modal (requires dev)
- telemetry data acquisition functional and COMPLETE
- finalizing PSF-R for NGS mode, with user-oriented tool

OPERA-ALTAIR laboratory results - 2003

• we actually had the chance to test OPERA on Altair without all the troubles of a real telescope (lab, 2003)

• optical turbulence generator

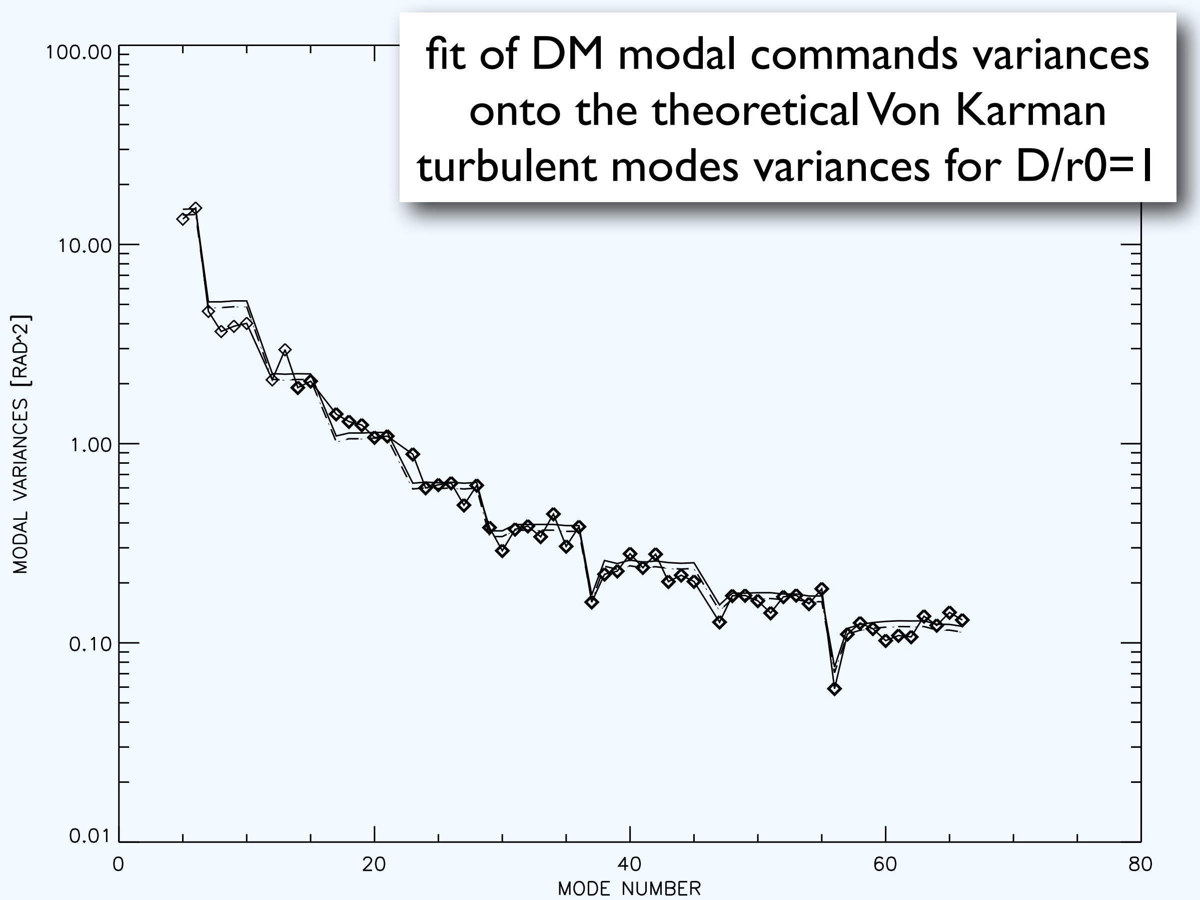
• experience showed that algorithm was

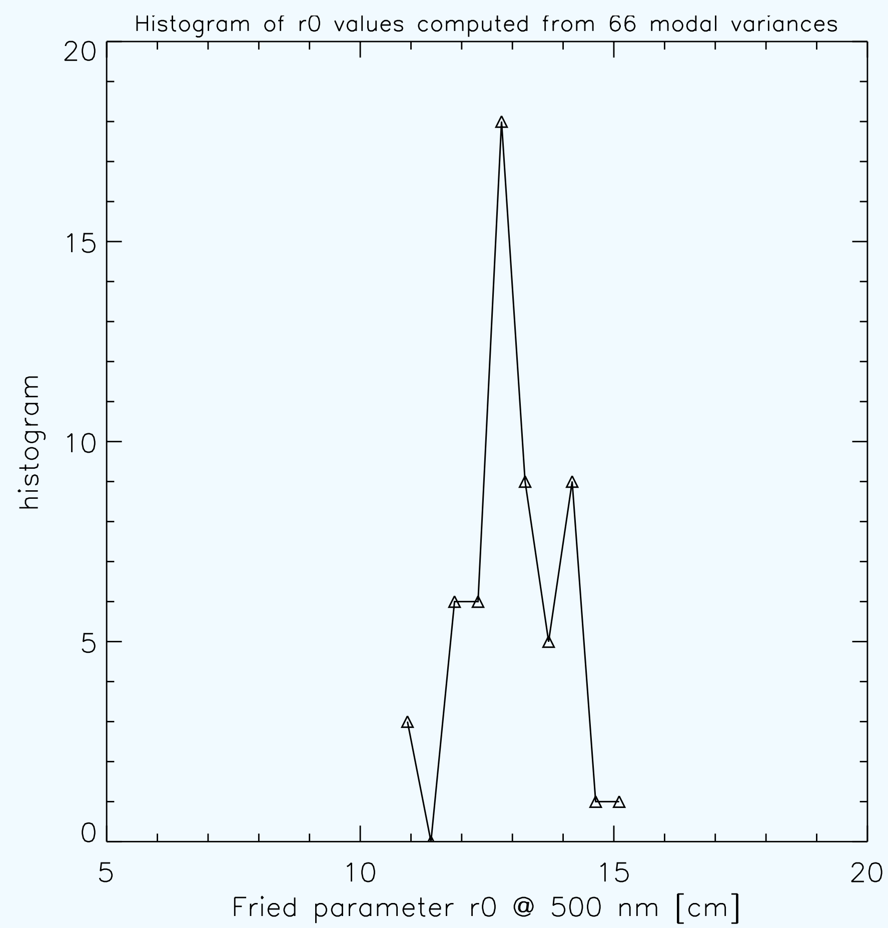
(1) working smoothly

(2) reproduce *reasonably* well the actual PSF

OPERA-ALTAIR laboratory results - 2003

first step: estimate Fried parameter r_0



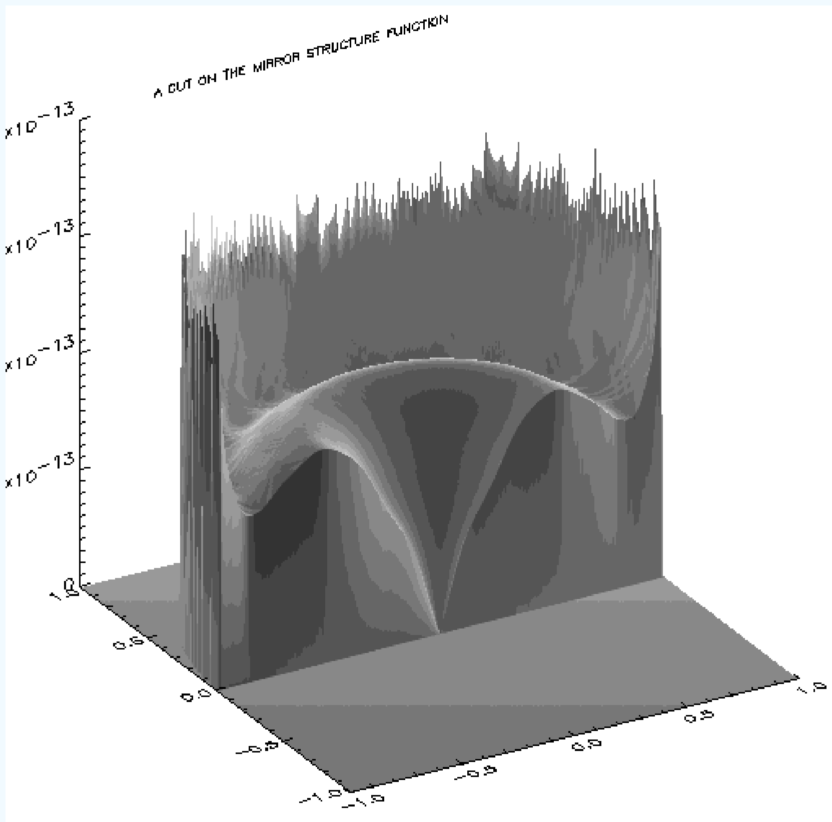


$<r_0>$=12.7 cm, expected in range 10-15 cm

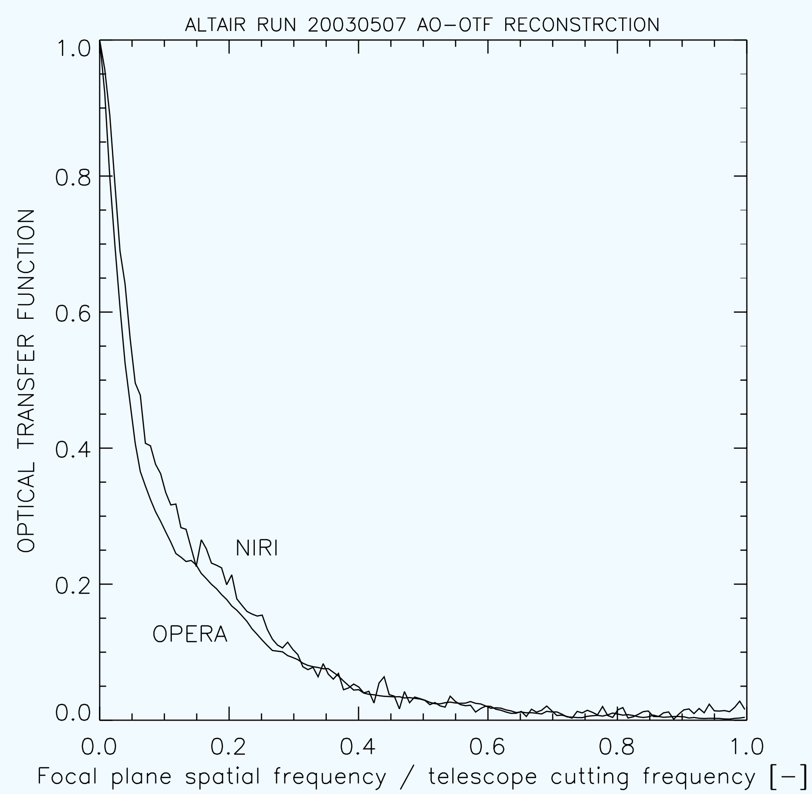
seeing estimate worked well in lab

OPERA-ALTAIR laboratory results - 2003

second step: structure functions & OTF

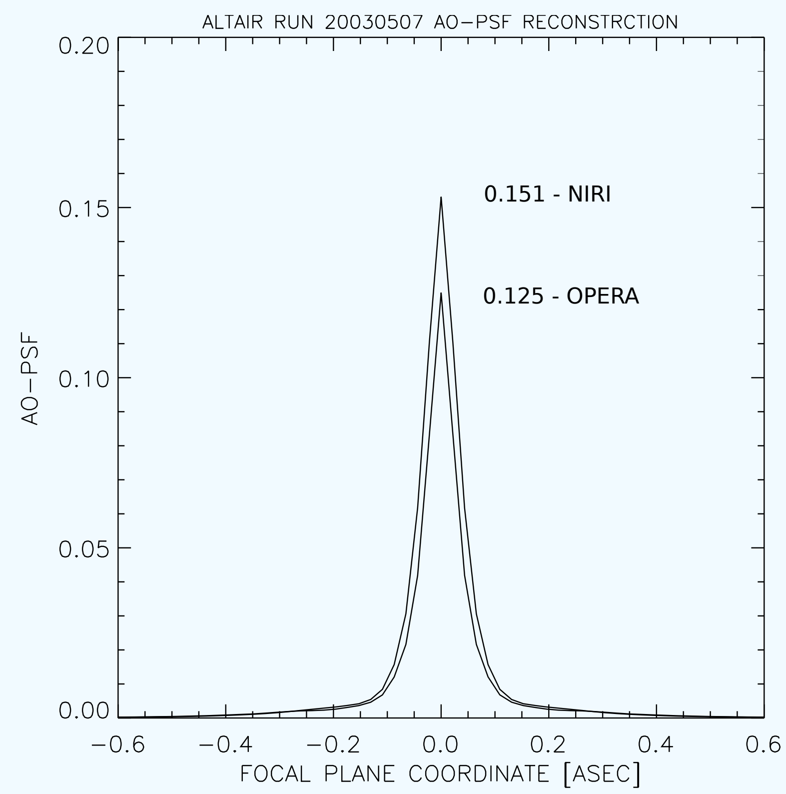


SF



OTF

$\lambda = 1.55\ \mu m$



PSF

- H-band Strehl: 12.5% instead of 15% (about 350 nm WFE)
- known that JPV method pessimistic for low Strehl conditions
- 20% error - not great but OK for 1st run
  - NIRI Strehl estimate was uncertain, "telescope" OTF not really known...

OPERA-ALTAIR sky results - 2010

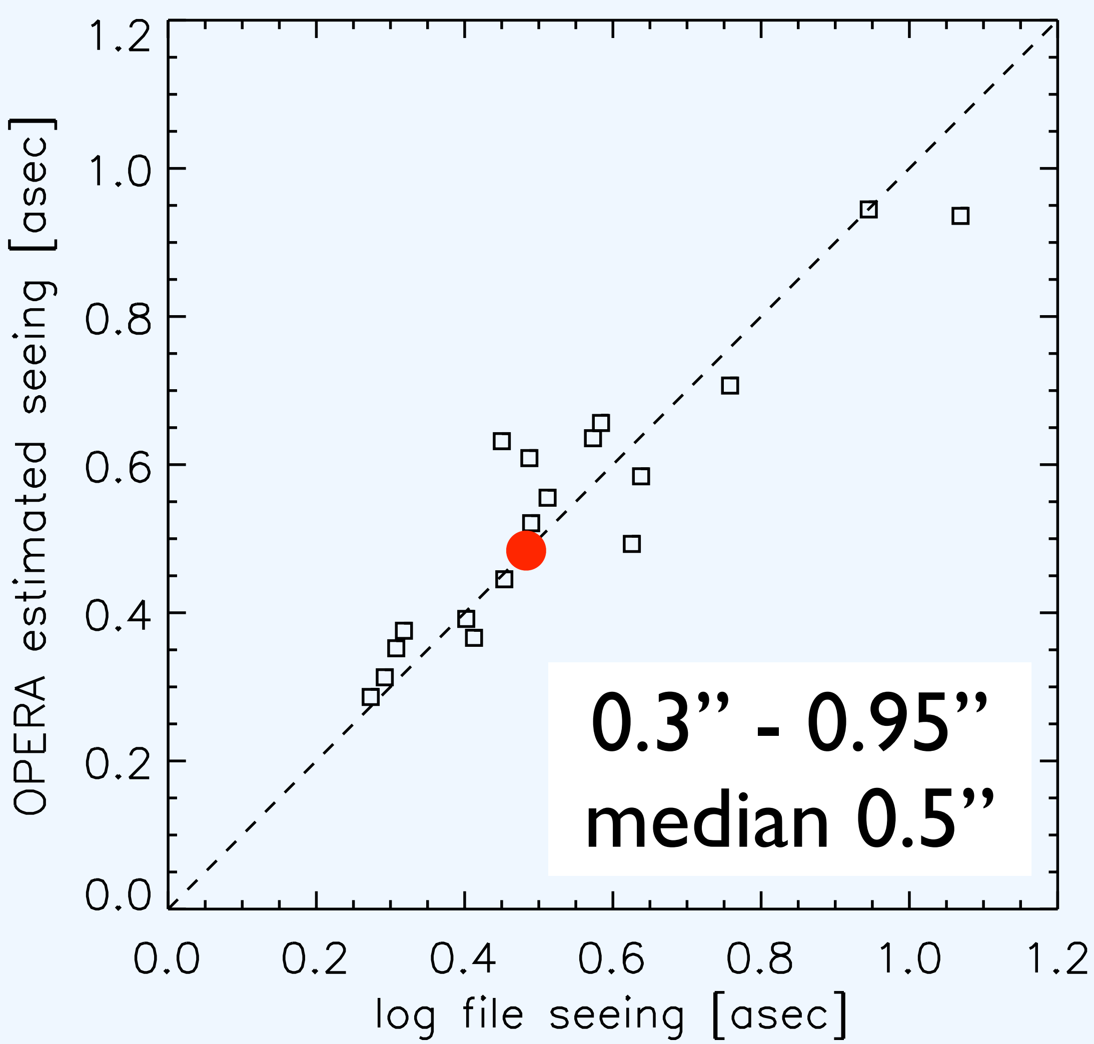
the data

- 20 nights December 2009
- bright NGS (mV<8)
- 60 seconds exposure
- loop full speed at 1 kHz

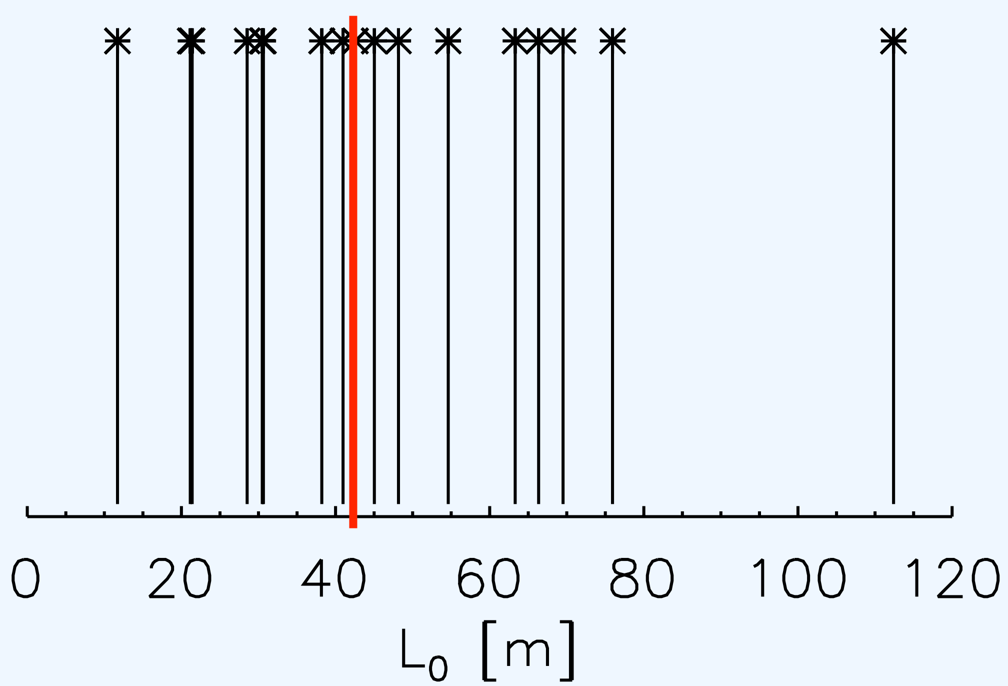
OPERA-ALTAIR sky results - 2010

seeing and outer scale estimate

fit DM modes variances to von Karman model (r0, L0)



0.3" - 0.95"
median 0.5"

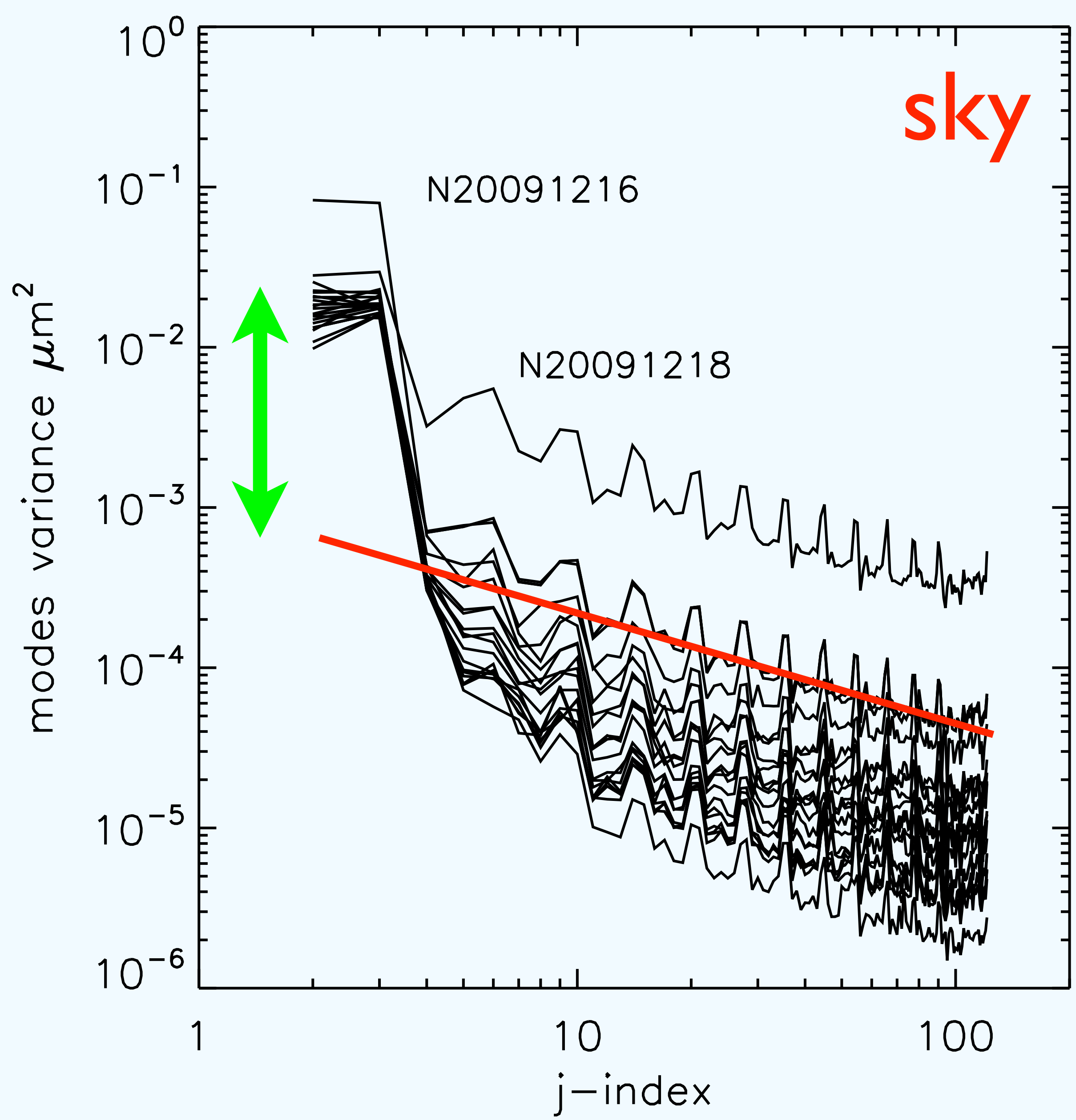


L_0: 12 to 120 m
median 42 m

compatible with median seeing & L0 at Mauna Kea

OPERA-ALTAIR sky results - 2010

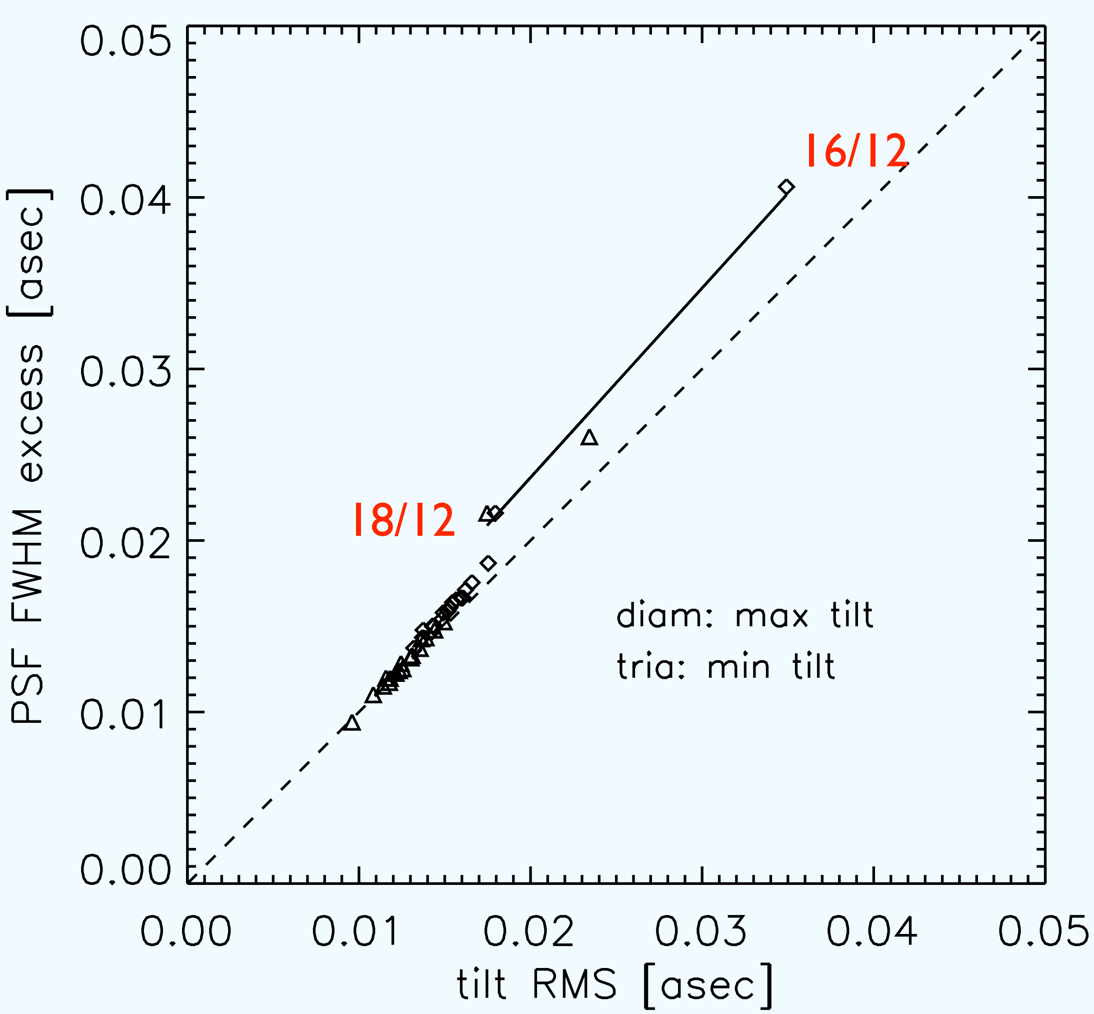
variances of the residual modes (post-AO)



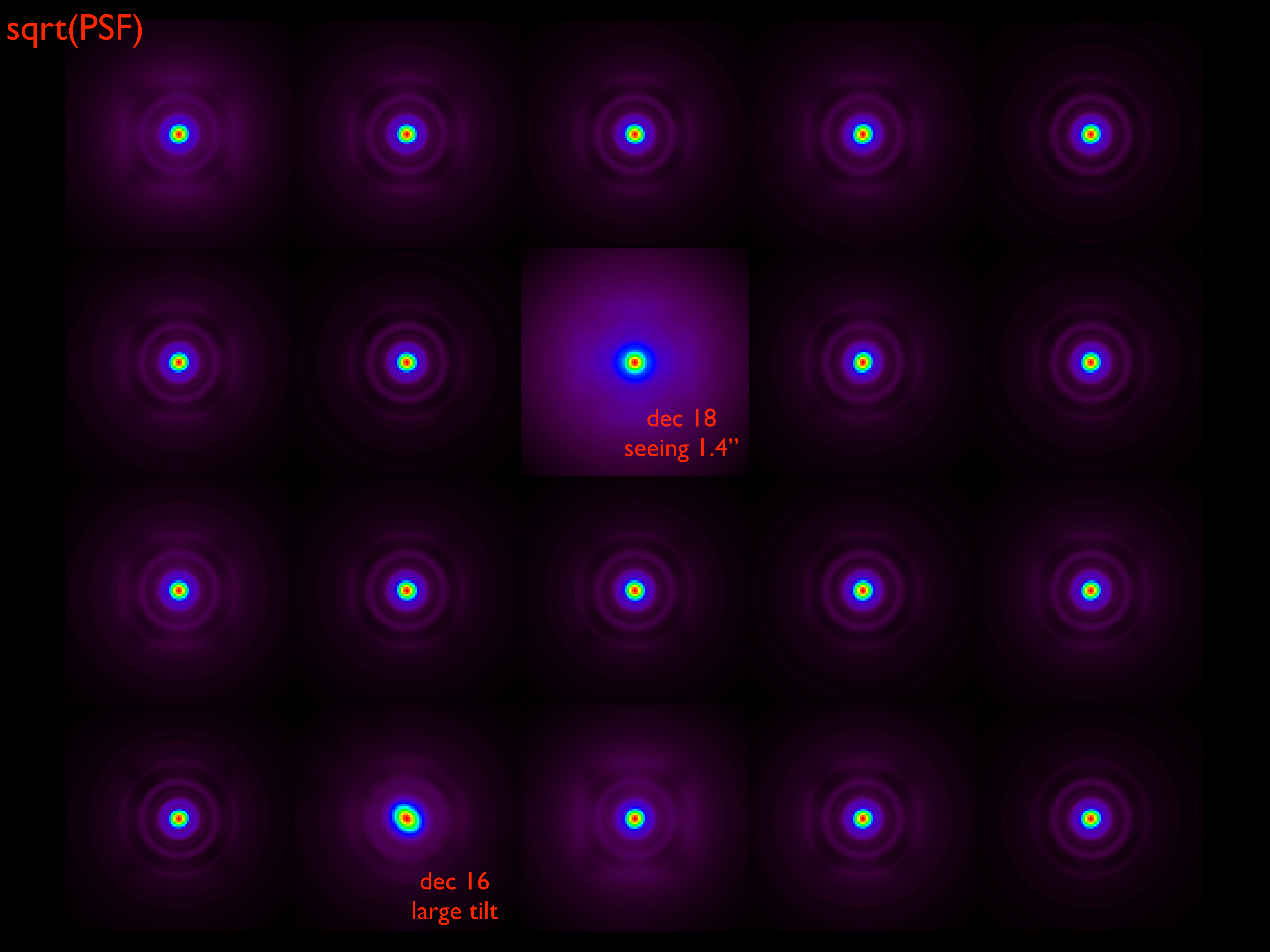
- systematic excess for certain modes
  - the ones in $\rho^m \cos(m\theta)$
- tilt excess ? (extrapolated red line)
- special nights:
  - Dec 16: higher than usual tilt
  - Dec 18: bad seeing (w_0 1.4")
- no problem if not pure Kolmogorov

OPERA-ALTAIR sky results - 2010

measured tilt RMS and reconstructed PSF FWHM excess

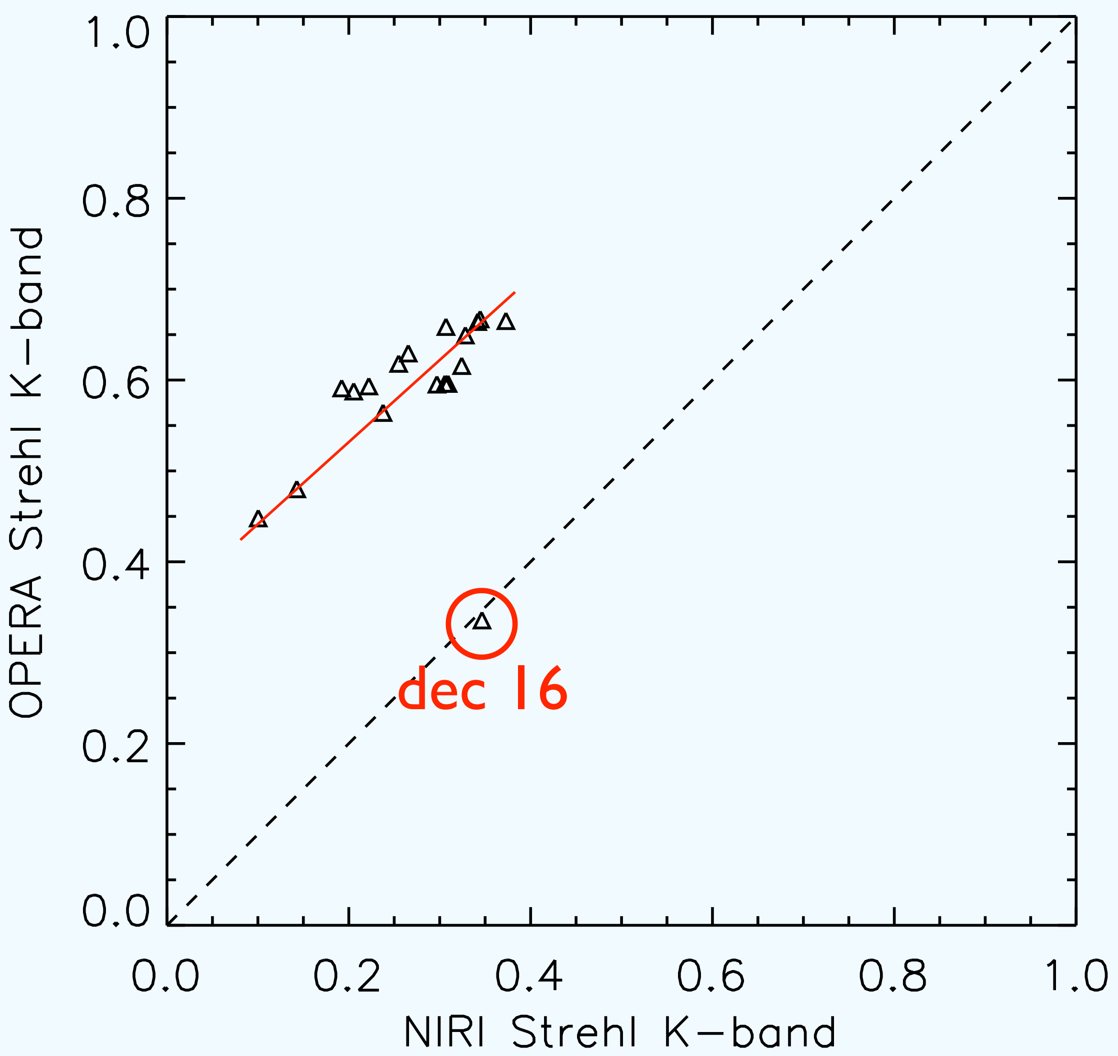


- excellent agreement WFS tilt & PSF fwhm
  - PSF-R works well for tip-tilt (critical)
- tilt RMS 10 to 18 masec (med 14 masec)
  - compatible with Christou's data
- tilt-based Strehl (K-band) is 71%
  - what would be the minimal tilt w/o telescope/instrument vibrations?
- nights dec 16 & dec 18:
  - excess of 1.6 masec due to higher orders

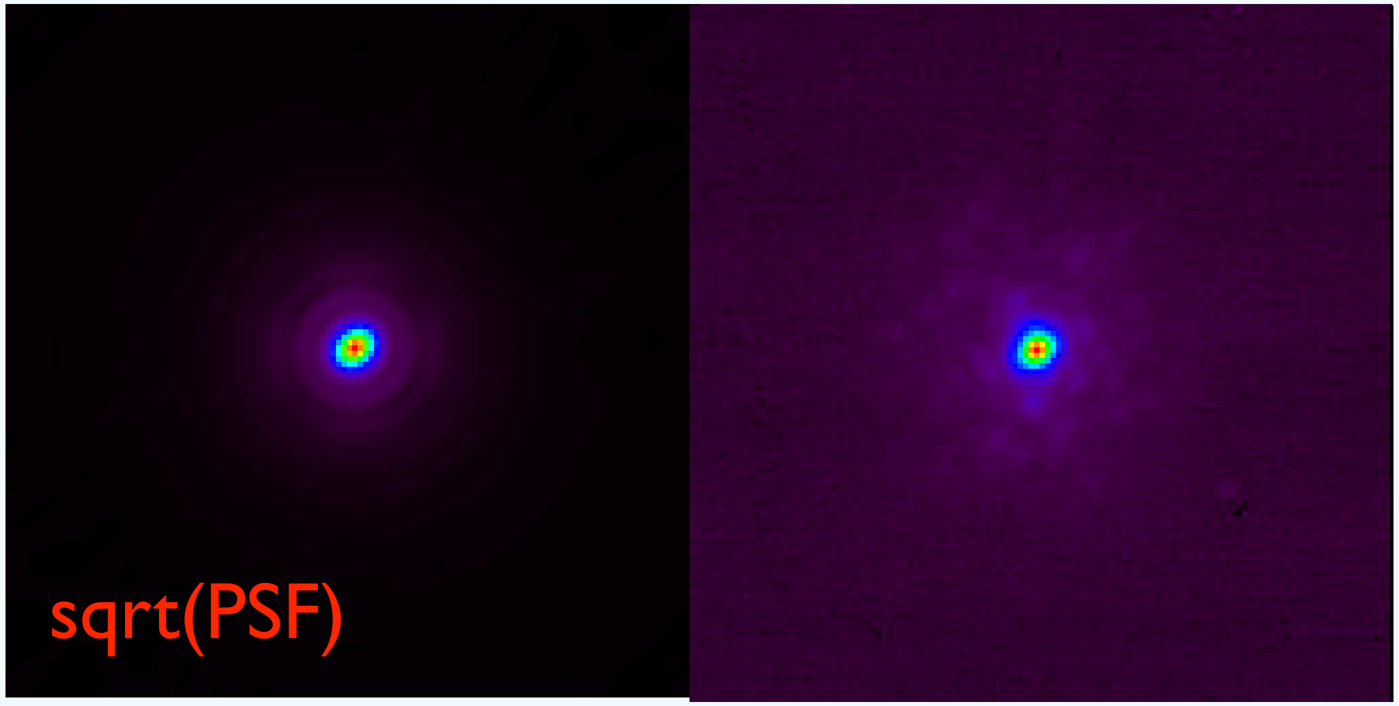

sqrt(PSF)
dec 18
seeing 1.4”
dec 16
large tilt

OPERA-ALTAIR sky results - 2010

reconstructed PSF Strehl

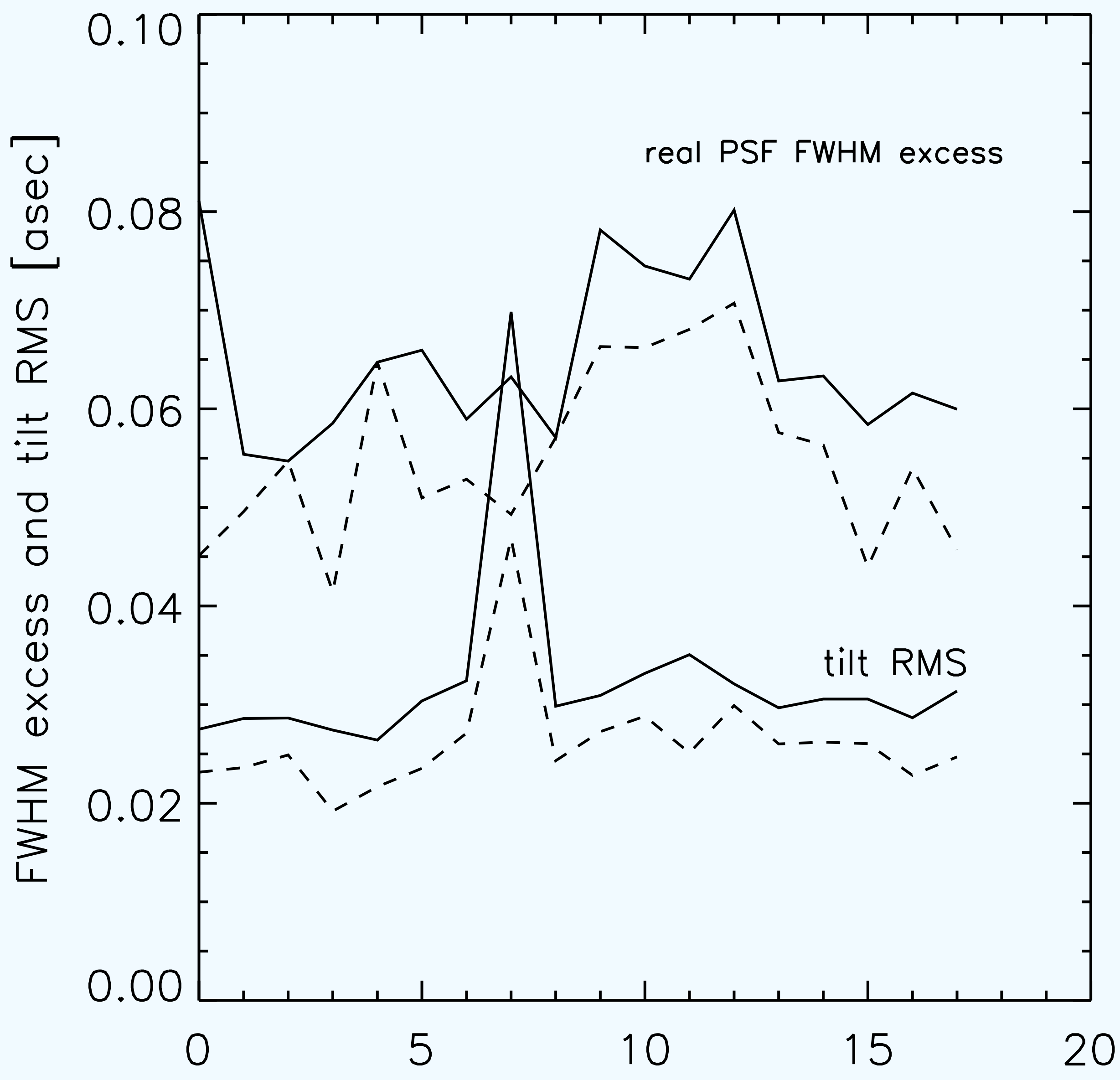


- S(opera) = S(niri) + X (?)
  - I was expecting a product
- at least some correlation
- dec16: tilt dominates other errors: good reconstruction of core



OPERA-ALTAIR sky results - 2010

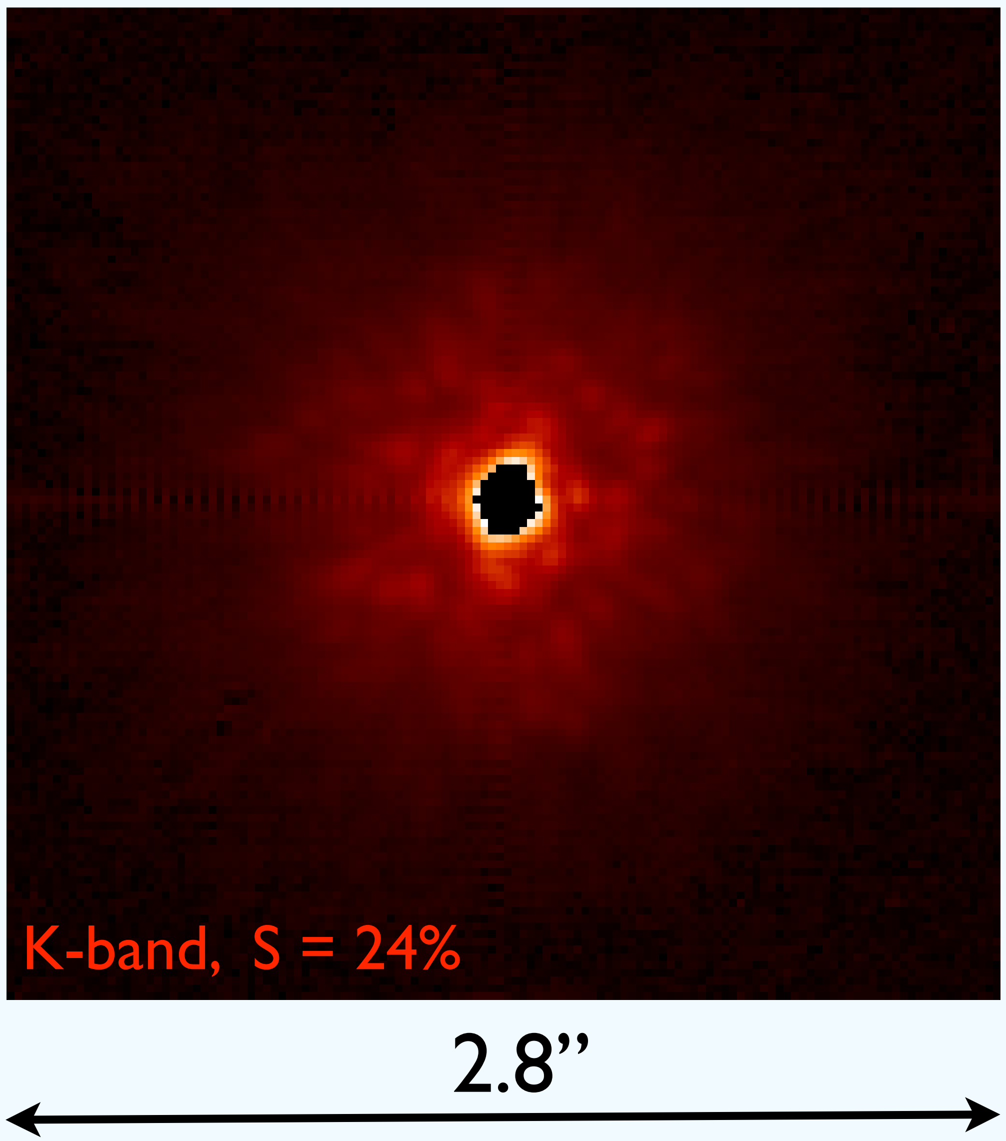
measured tilt RMS and REAL PSF FWHM excess



- FWHM excess on REAL PSF is twice what we expect from WFS measurements
- post-AO vibrations ? NCPA vibrations ?

OPERA-ALTAIR sky results - 2010

a typical NIRI PSF (the wings only)



- nothing to do with the reconstructed PSF ...

- wings populated with residual speckles and/or permanent ones ?

OPERA-ALTAIR sky results - 2010

- I had no clue on telescope+instrument PSF so had to assume perfect ones (no telescope WFE)
- there ARE telescope errors:
  - low orders partially corrected by AO
  - high orders uncorrected
- there ARE instrument errors & NCPA:
  - not corrected at all - or generated by AO
- JPV method as it is now treats only turbulent aberrations

OPERA-ALTAIR sky results - 2010

- we need to add the telescope and NCPA errors into JPV model
- we have a model for the telescope errors based on the same approach as JPV (covariance of modes):
  Analytical modeling of the optical transfer function of a segmented telescope with/without adaptive optics correction of the telescope's dynamical aberrations;
  Jolissaint, Ellerbroek, Angeli SPIE 6271, 2006

good for Keck AO

- telescope errors need to be calibrated/measured
  - ★ can we identify these into the WFS measurements ?
- NCPA: independent measurement, then implement into code.

AO correction of
dynamic & static telescope errors

open the bracket (...

Long Exposure OTF calculation

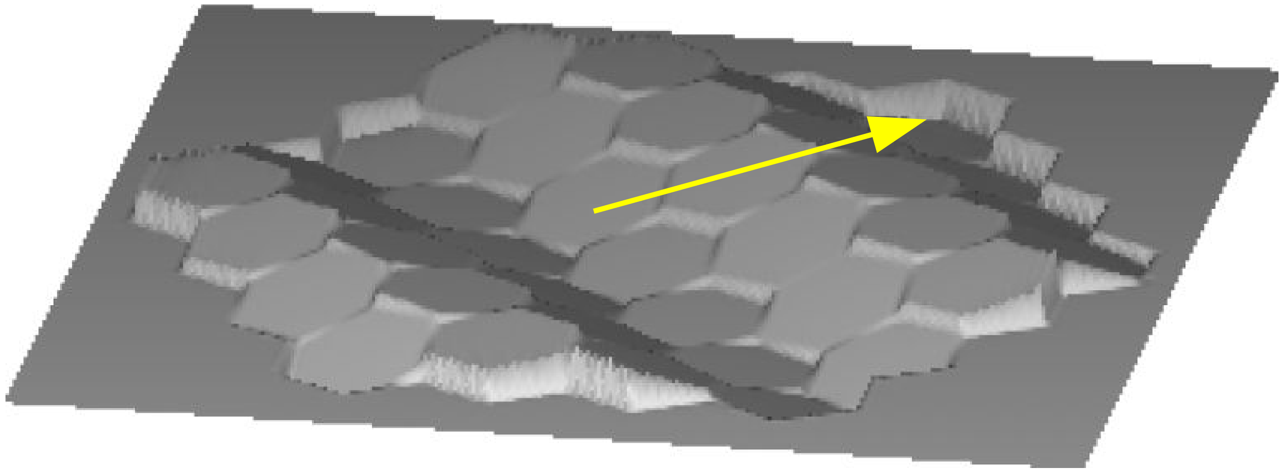
- Inputs are
  - Segment modes FT (pre-computed, cst.)
  - Aberrations covariance segment-to-segment & modes-to-modes
- 1) Apply AO filter on modes Fourier Transforms (AO mode on)
- 2) FT{Structure function} ~ **sum (** covariance * FT{Modes} **)**

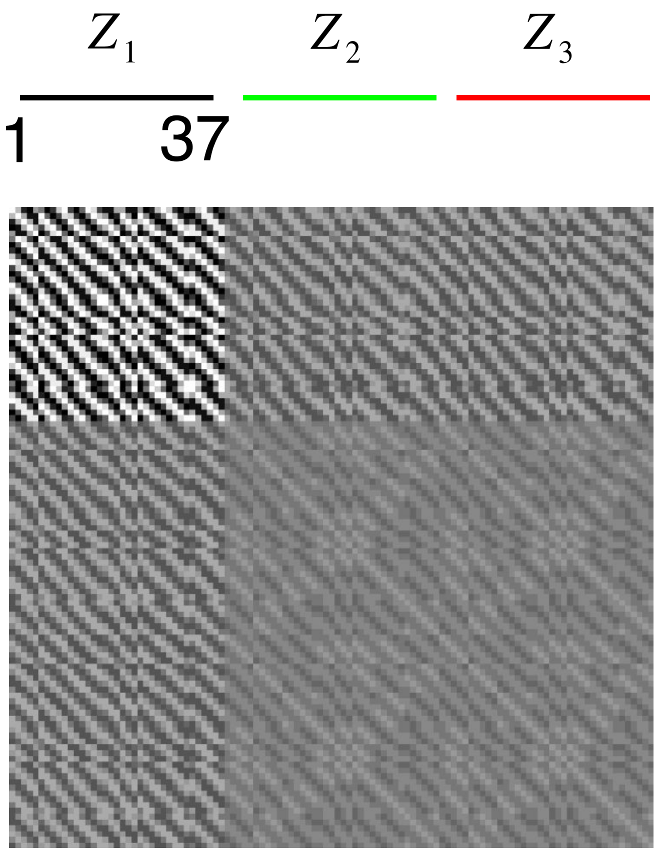
$$FT[numerator\,\overline{D}(\lambda\vec{f})]=$$
$$2\tilde{P}(\vec{v})\sum_{k,l=1}^{Nm} i^{p_{k,l}} \boxed{FT[M_k(\vec{r})M_l(\vec{r})]} \sum_{i=1}^{Ns} \boxed{\gamma_{i,k;i,l}} \cos(2\pi\vec{v}\cdot\vec{r}_i+p_{k,l}\pi/2)$$
$$-2\sum_{i,j}^{Ns}\sum_{k,l}^{Nm} \boxed{\gamma_{i,k;j,l}} \boxed{\tilde{M}_k^*(\vec{v})\tilde{M}_l(\vec{v})} \exp[i2\pi\vec{v}\cdot(\vec{r}_i-\vec{r}_j)]$$

Example of M1 covariance "matrix"

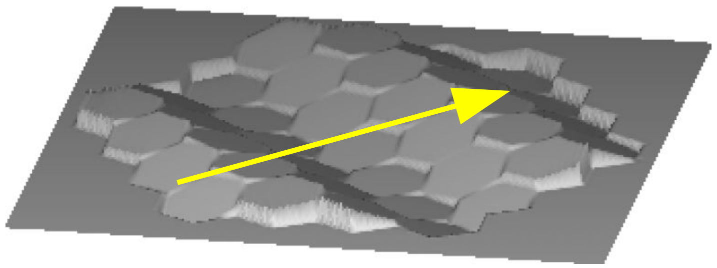
Cosine wave across the mirror (here 37 seg):

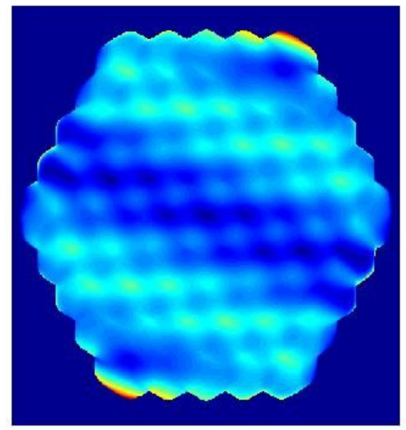
$$W(\vec{r},t) = A\cos(\vec{k}\,\vec{r} - \omega t)$$



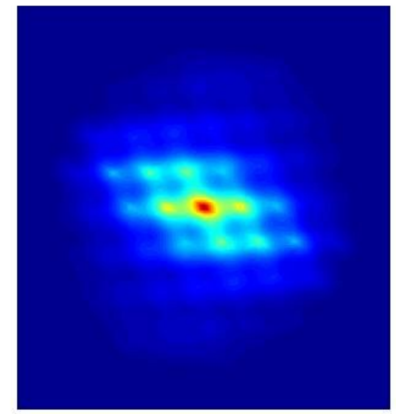


Dynamic aberrations, example

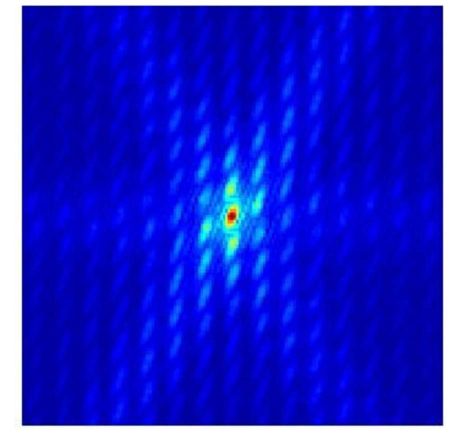




Structure function

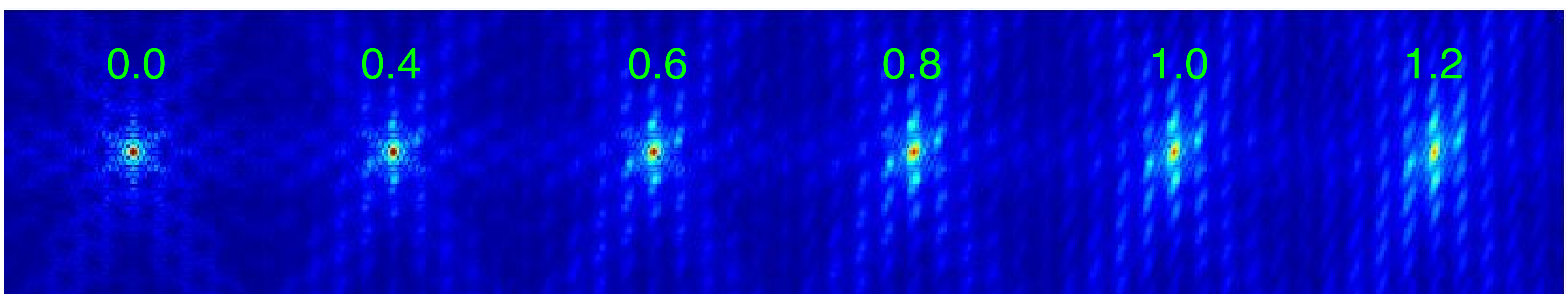


<OTF>



<PSF>

Wave amplitude from 0 to 1.2 lambda



NOT TMT pupil (37 segments, Keck-like example) close the bracket ...)

OPERA-ALTAIR sky results - 2010

- it is important to realize that PSF-R objective is not to debug the AO system but to reproduce what is seen on the focal plane, <u>no matter what</u>

- if unwanted errors cannot be controlled but can at least be modeled, that's already a good point for AO data reduction

OPERA-ALTAIR sky results - 2010

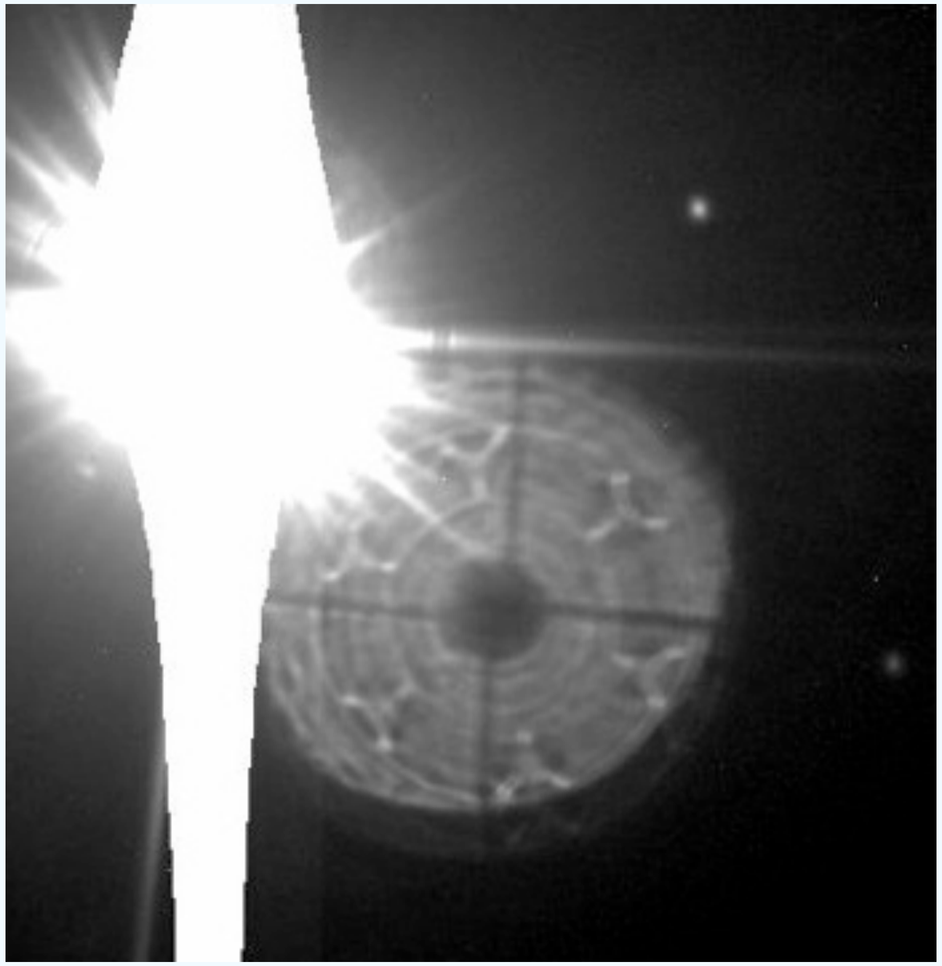
Gemini telescope M2 print-through

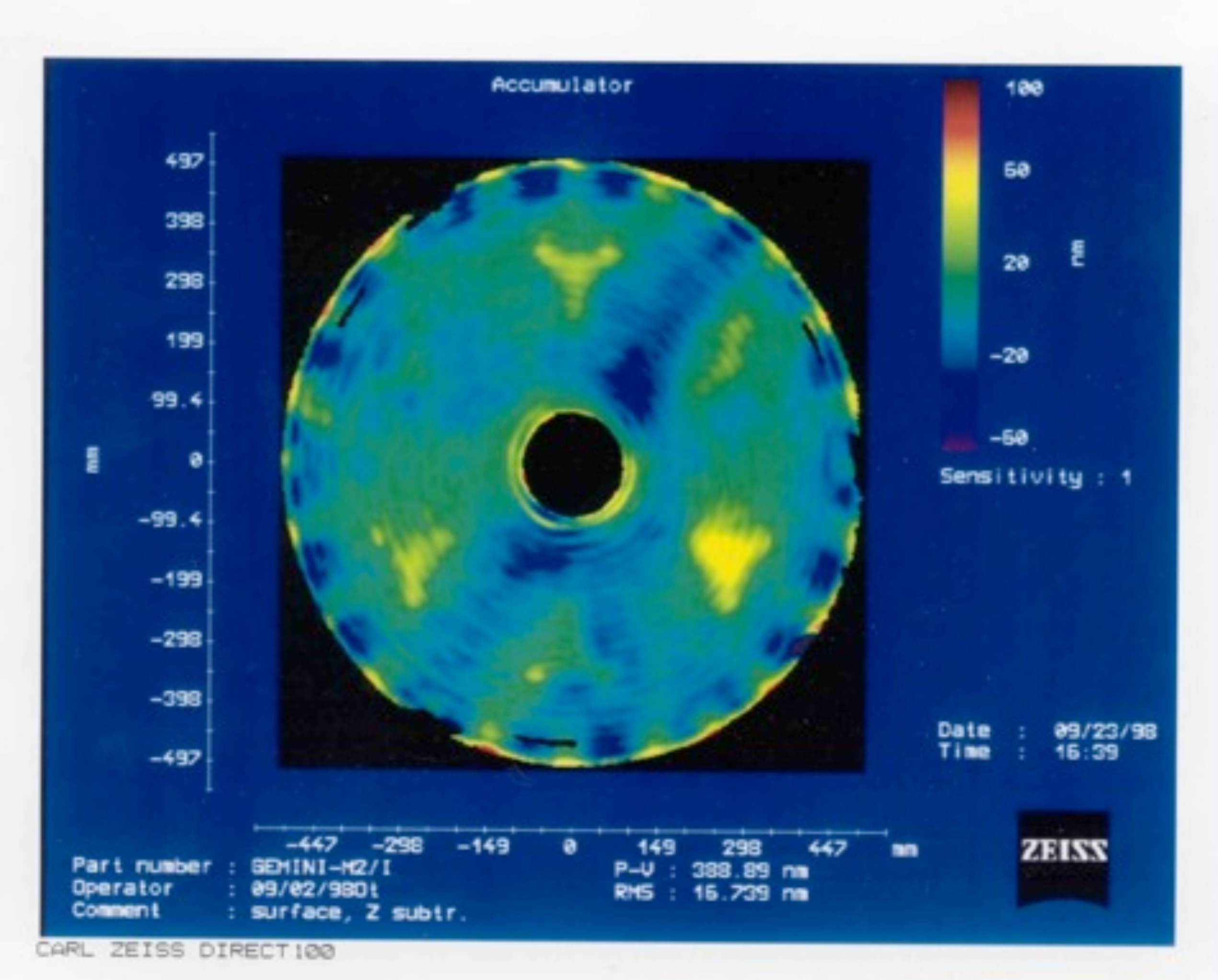
the big offender

a typical (annoying) telescope error

OPERA-ALTAIR sky results - 2010

acquisition camera image of a very bright star, which display a ghost image (heavily defocused) courtesy JP Véran





detected at the manufacturer premises

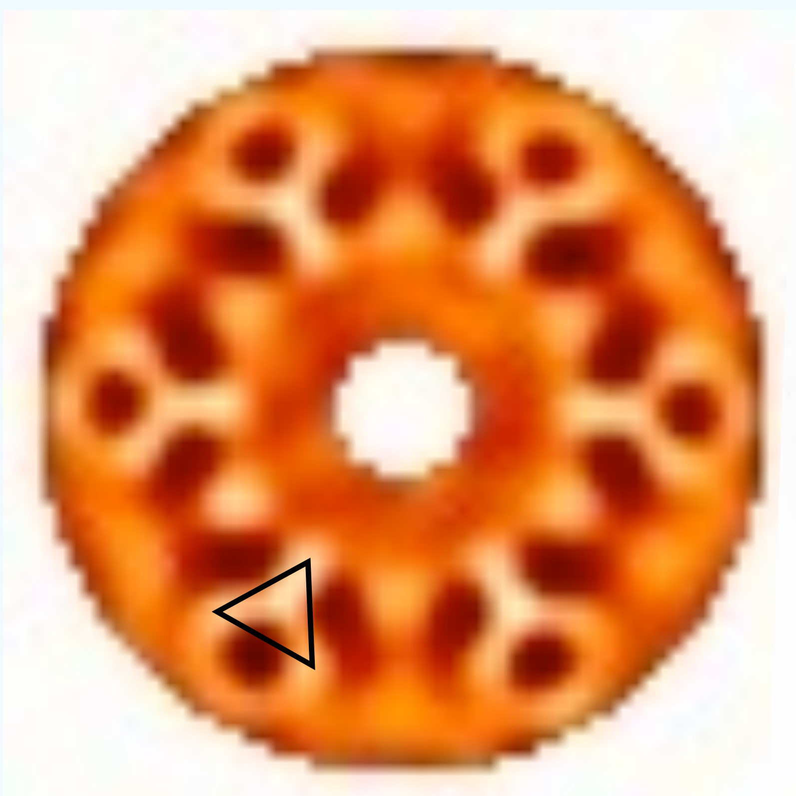
but WFE was within specs

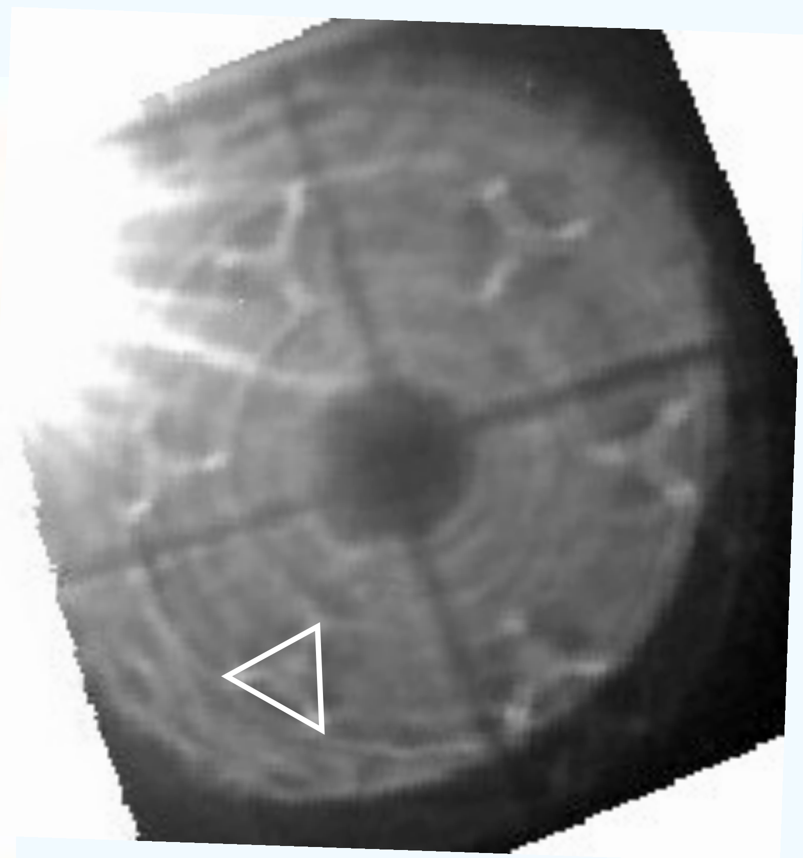
measured: 17 nm RMS, 389 nm P2V

OPERA-ALTAIR sky results - 2010

J-P Véran (2003) analysis
Output ALTAIR static map
RMS 55-80 nm P2V 350-540 nm

This is high spatial frequency stuff,
above ALTAIR WFS capacity (12-by-12 SH)





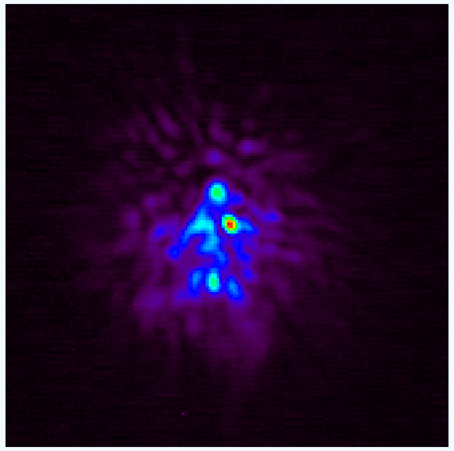
appr. 100 nm RMS of
high order WFE

appr. 30-150 nm RMS
median 80 nm
of low order WFE
from WFS aliasing

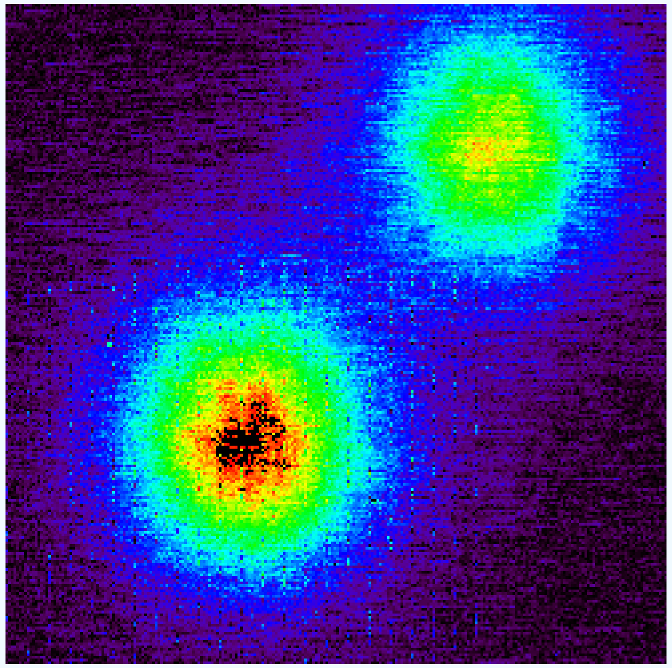
equivalent K-Strehl 70%

not accounted for in our PSF-R model (I will not wait too long...)

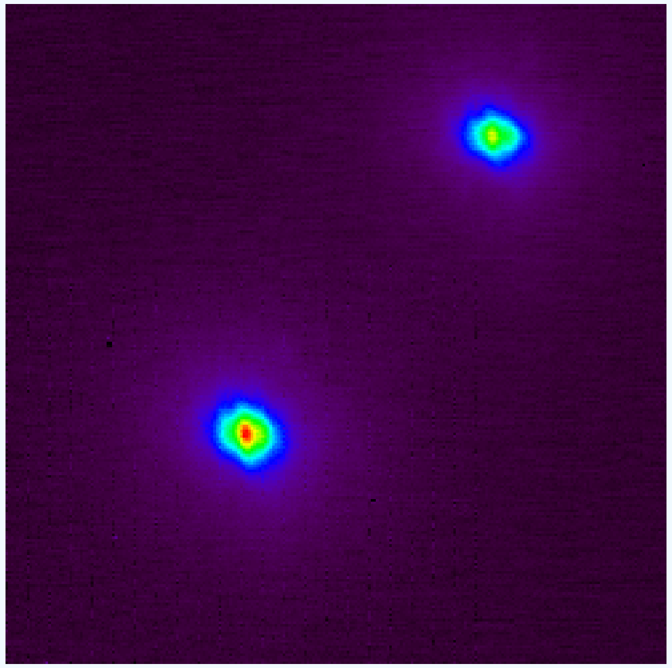
KECK-AO PSF - a diversity of cases...



0.1 seconds
exposure
K' filter



tip-tilt only
30 seconds



TT + DM
30 seconds
dim NGS

- short exposure
- tip-tilt only
- dim NGS star (low bandwidth)

NONE of these cases covered yet...
while these are frequent observing conditions

PSF-R on complex systems: a personal view

the old way

1. build a telescope
2. add an AO system
3. hire a postdoc to do the PSF-R

PSF-R on complex systems: a personal view

- hidden aberrations from telescope + others
- telemetry can be difficult
- cannot modify control software (where is the doc?)
- cannot measure WFE <u>where</u> we need it
- not enough access to telescope time if high pressure

postdoc <u>forced</u> to play WFE detective... no fun

PSF-R on complex systems: a personal view

the current way

1. build a telescope <u>with</u> AO specs
2. hire a postdoc to do the PSF-R

PSF-R on complex systems: a personal view

- might need to improve/implement telemetry (data storage, pre-processing...)
- is calibration really understood/efficient ?
- can we modify the control software ?
- ... can I get telescope time ?

probably better though...

PSF-R on complex systems: a personal view

the best way

1. build a telescope <u>with</u> AO specs <u>and</u> include everything (software, hardware, telescope time) needed to do and finalize the PSF-R
2. hire a postdoc

now that sounds right

in any case: this is mandatory now as astronomers are specifically requesting PSF-R for ELTs

PSF-R on complex systems: a personal view

- but would this ideal case be sufficient ? not sure ...
  - ★ Keck NGS: 7 entries in the WFE budget
  - ★ Keck LGS: ~ 12 entries
  - ★ ATLAS/E-ELT (LTAO): ~ 16 entries
  - ★ NFIRAOS/TMT (MCAO): > 20 entries
- are we going to build a JPV-like model for <u>all these errors</u> ?

not looking good...

PSF-R on complex systems: a personal view

Other alternatives for PSF-R

(1) AO seen as a black box:

a dedicated PSF calibration source at the system input(s)
+ a dedicated PSF detector or WFS at the system output(s)
no model assumption, we take everything

(2) poor man's PSF-R:

PSF modeling using Fourier models, feed by
AO system parameters and measured turbulence
parameters - excellent match in GLAO

to conclude...

- we believe JPV method works well but needs an update with telescope errors and NCPA
- PSF-R at Gemini-N / Altair on its way
- PSF-R at Keck has just started
- importance of including PSF-R at the beginning of AO system planning to ensure success
- we can start developing PSF-R theory for LTAO/ MCAO/MOAO but keep an eye on NGS mode projects on real telescope environment
- exploring back-up solutions - critical, start now