FP7 JRA1:
Adaptive Optics

Norbert Hubin
European Southern Observatory

WP1 Adaptive Optics

seeing beyond atmospheric limits

- Total Budget: 4 011 403 €
- Total Person Months: 259,2 (= 21,60 FTEs)
- EC Contribution: 2 987 800 (= 74,5 %)
- Contract Duration: Jan 2009 - Dec 2012
- ESO (workpackage leader) + 11 Partner Institutes:
  INSU (LAM), INSU (LAOG), INSU (LESIA), INAF, KIS, NOVA, ONERA, MPE, MPIA, UDUR, STFC
- Internal management of JRA1:
  - 8 Tasks and 20 Subtasks
  - 34 Deliverables, incl. 3 Annual Reports
  - 8 Milestones

Objectives of the WP1

- Design and develop Laser Guide Star Adaptive Optics systems for the existing large telescopes (Large Binocular Telescope, Very Large Telescope, William Herschel Telescope), to upgrade extent Adaptive Optics systems for Solar telescope (GREGOR solar telescope) and to upgrade the Very Large Telescope Planet Finder instrument (SPHERE) to maintain its competitiveness in the period 2010-2012.

- Develop Adaptive Optics key technologies required by the existing European Adaptive Optics Facilities: Sodium laser sources at 589 nm for high signal to noise wavefront sensing, real time computer platforms (hardware and Software) for both high order and flexible low order AO systems, optimum control algorithms for new Adaptive Optics concepts (multi-Object AO), calibration of large deformable mirrors and operation strategies for adaptive telescopes.

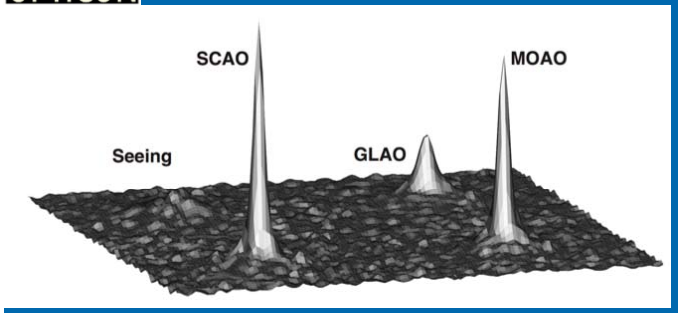
WP1 Work Packages

- WP 1.1: Coordination, reporting: (N. Hubin)
- WP 1.2: Laser Guide Star Multi-Object Adaptive Optics system on William Herschel Telescope (R. Myers)
- WP 1.3: Very Large Telescope Planet Finder Upgrade (J.L. Beuzit)
- WP 1.4: Laser Ground Layer Adaptive Optics System for the Large Binocular Telescope (W. Gaessler)
- WP 1.5: Solar Adaptive Optics (D. Soltau)
- WP 1.6: Sodium Laser prototype for Adaptive Optics (P. Y Madec)
- WP1.7: European Real time platform for Adaptive Optics (E. Fedrigo)
- WP1.8: Optimal Control algorithms for wide field adaptive optics (J.M. Conan)
- WP 1.9: Calibration, control and operation of an adaptive telescope with LGS (J. Kolb)

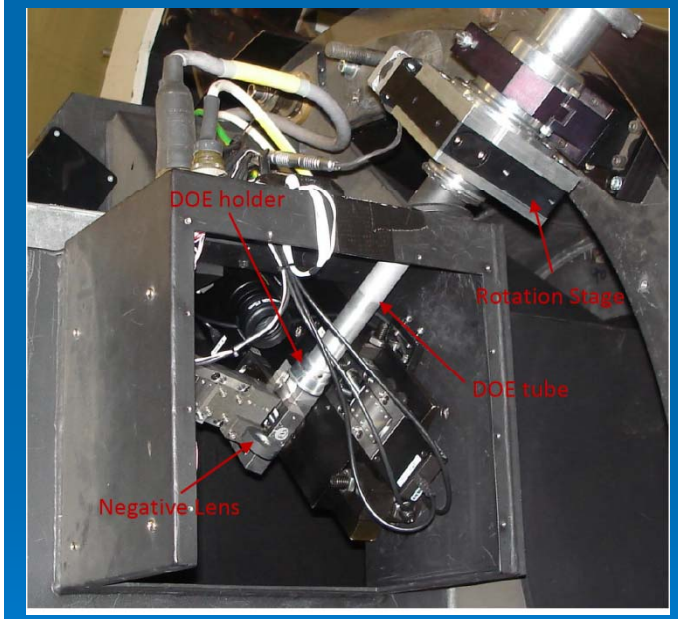
WP 1.2: Laser Guide Star Multi-Object Adaptive Optics system on William Herschel Telescope (R. Myers)

- 2 goals:
  - Upgrade the CANARY instrument on the 4.2m WHT to Laser Guide Star operation on-sky
    - LESIA – Durham – UKATC - ONERA
  - Develop woofer-tweeter technology for CANARY and demonstrate in the Laboratory
    - LAM
- Principal role of CANARY is to provide on-sky demonstration and investigation of a new mode of adaptive optics: Multi-Object Adaptive Optics (MOAO).
- Laser Guide Star upgrade includes lasers, laser guide star wavefront sensors, laser simulator, software
  - Related to WP1.7 and WP1.8

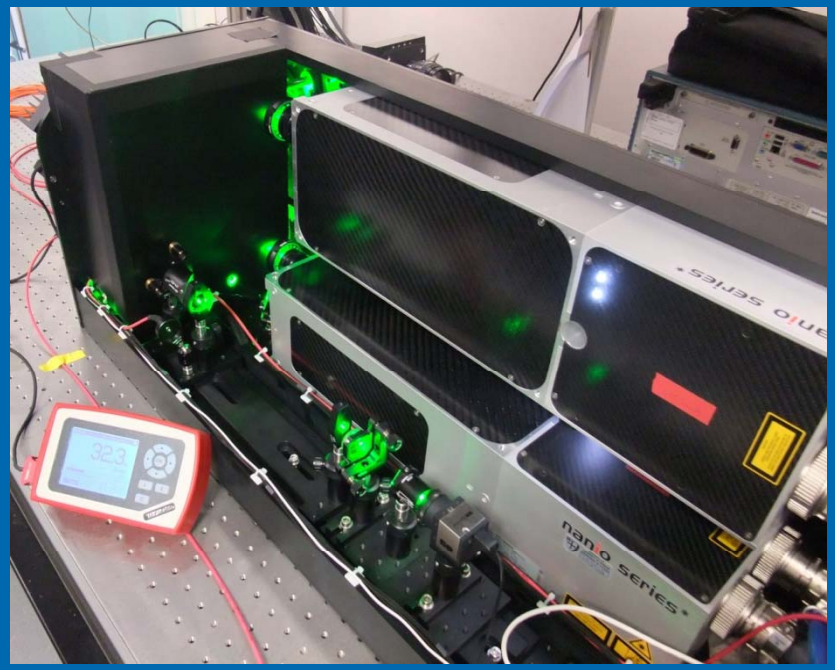
CANARY Upgrade Progress



1st light NGS results Sept. 2010. 1.53 microns



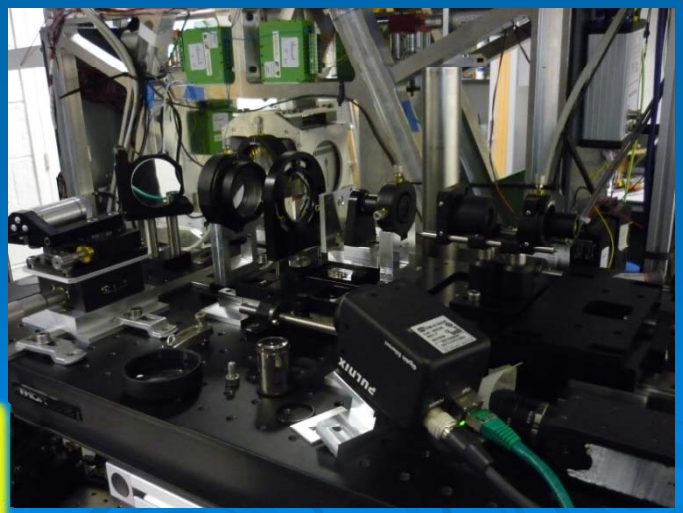
Laser Asterism Rotator and Launch Feed



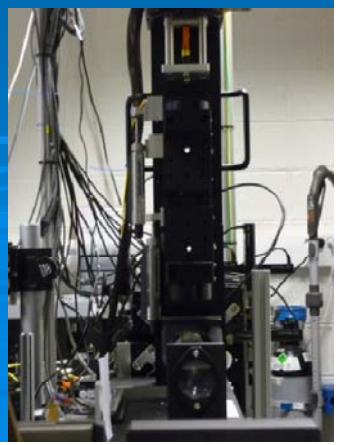
Lasers and beam combination system.

(power meter shows the output exceeding specification at 32W)

and ON –SKY…



LGS WFS Bench



Telescope Simulator with LGS sources

LATEST MOAO results
With LGS + LQG(WP1.8)
H-band: 41% SR

WP 1.3: Very Large Telescope Planet Finder Upgrade

Two main tasks :

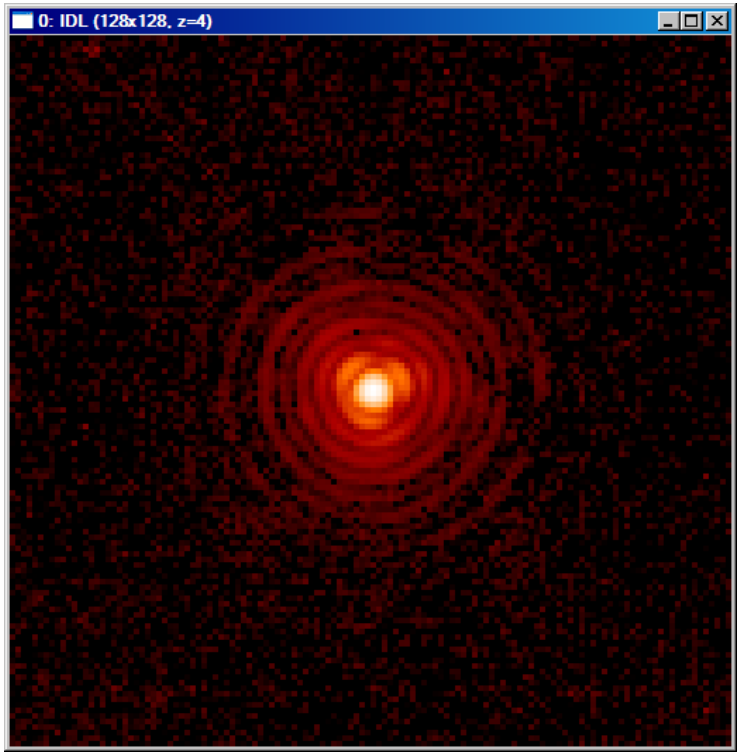
1. Post focal WFS
   - Optimization of classical phase diversity for SPHERE
   - Coronagraphic phase diversity
     - ⇨ Development of a new phase diversity concept working on coronagraphic images

2. New control laws
   - Extension of LQG method
   - New approaches to reduce complexity of calibration process

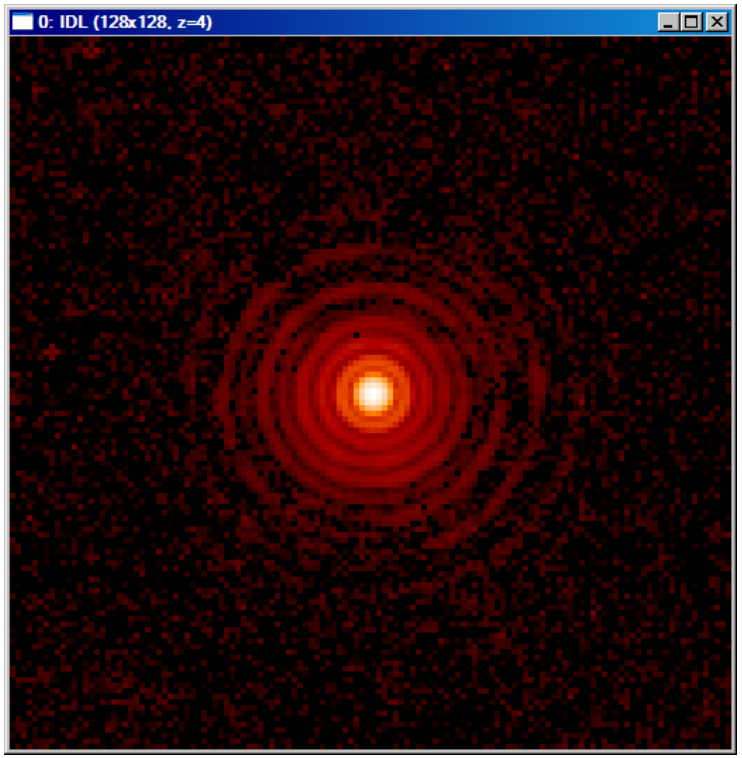
WP1.3: Classical Phase Diversity

Fighting against quasi-static instrumental speckle down to few nm rms level

- ✓ Measuring and compensating for Non Common-Path Aberrations (NCPA)
- ✓ Fully implemented in SPHERE instrument for operations in Paranal



SR = 85.5% (no NCPA)



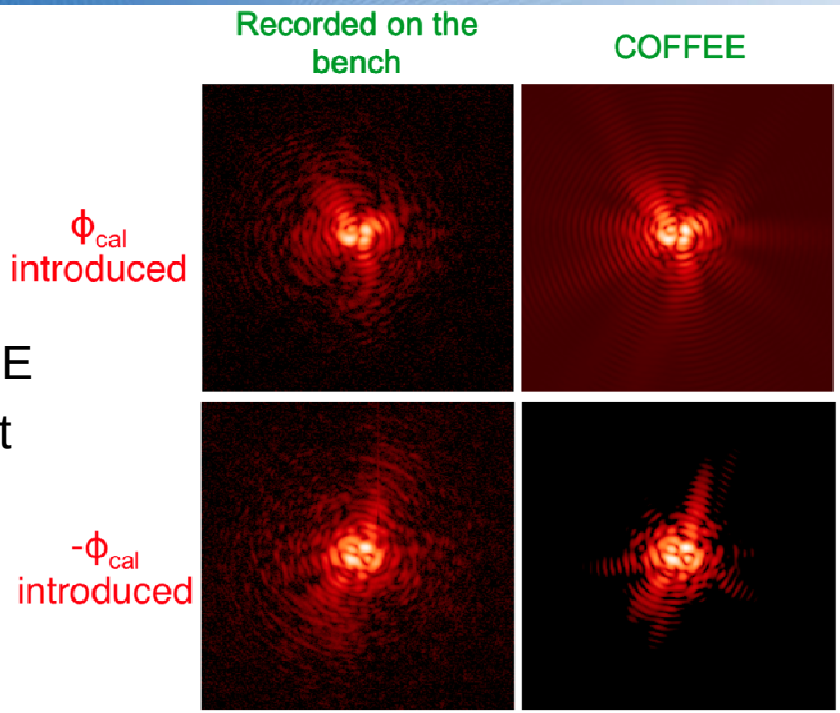
SR ~ 99.0% (with NCPA)

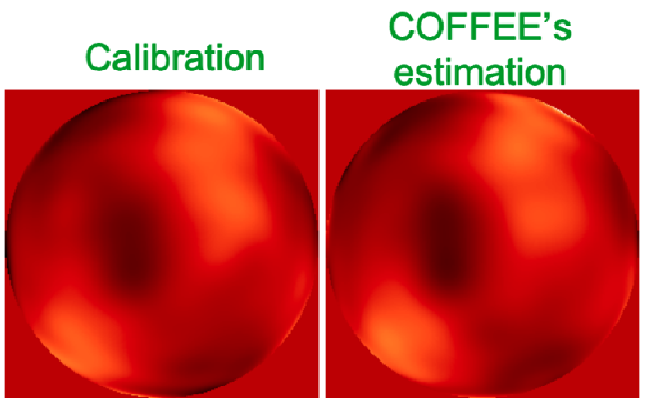
H2 filter, no coronagraph, no spatial filter, AO gain = 0.3

WP1.3: Coronagraphic Phase Diversity

Extension of Phase Diversity to coronagraphic imaging

- ✓ Development of analytical model
- ✓ Full validation by simulations
- ✓ Experimental validation on BOA and SPHERE
- ✓ Demonstration of nm accuracy measurement
- ✓ More tests to come on SPHERE at IPAG (November 2012)
- ✓ Potential upgrade of SPHERE NCPA compensation process
- ✓ Tests on sky only possible starting mid-2013 and could be part of FP7 Opticon-2, WP1.4.6





WP1.3: Optimization of real time algorithms for the SPHERE AO

Two main axis of research

I) Slope Oriented Hadamard:

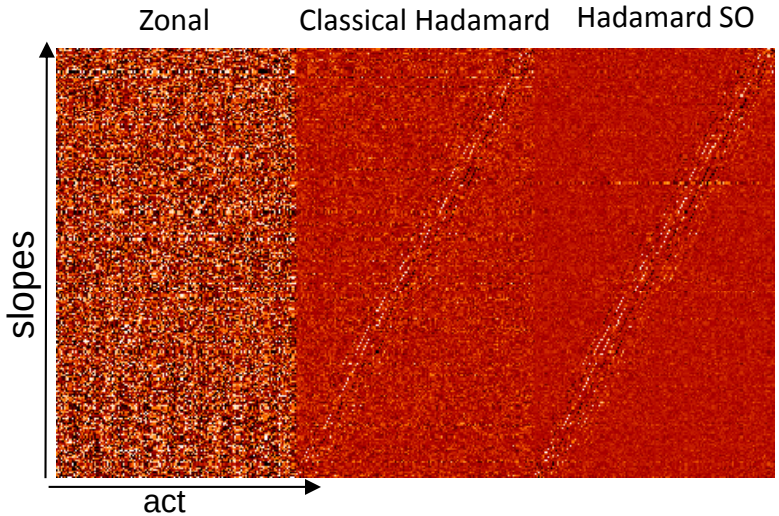
New method for IM matrix computation

(derived from "classical Hadamar")

⇨ **Numerical and experimental tests on SPHERE**

Acquisition time of IM divided by 10 for similar quality compared to standard Hadamard (/1000 compared to zonal)

Meimon et al. AO4ELT 2



II) Optimal control (LQG) on all corrected modes:

LQG signal rejection adapted to turbulent signal temporal signature

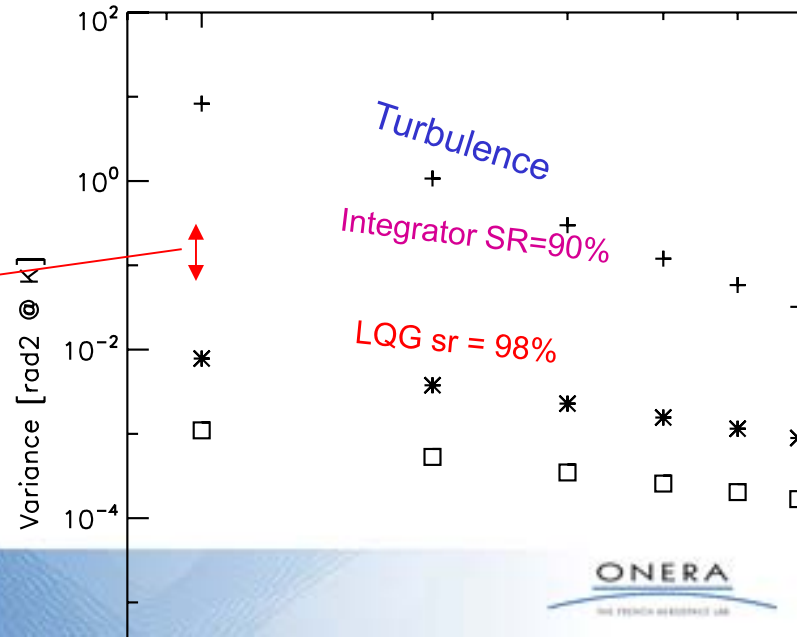
LQG rejection of noise and signal naturally shaped to minimize variance

⇨**Gain of a factor 10 in flux if photon limited**

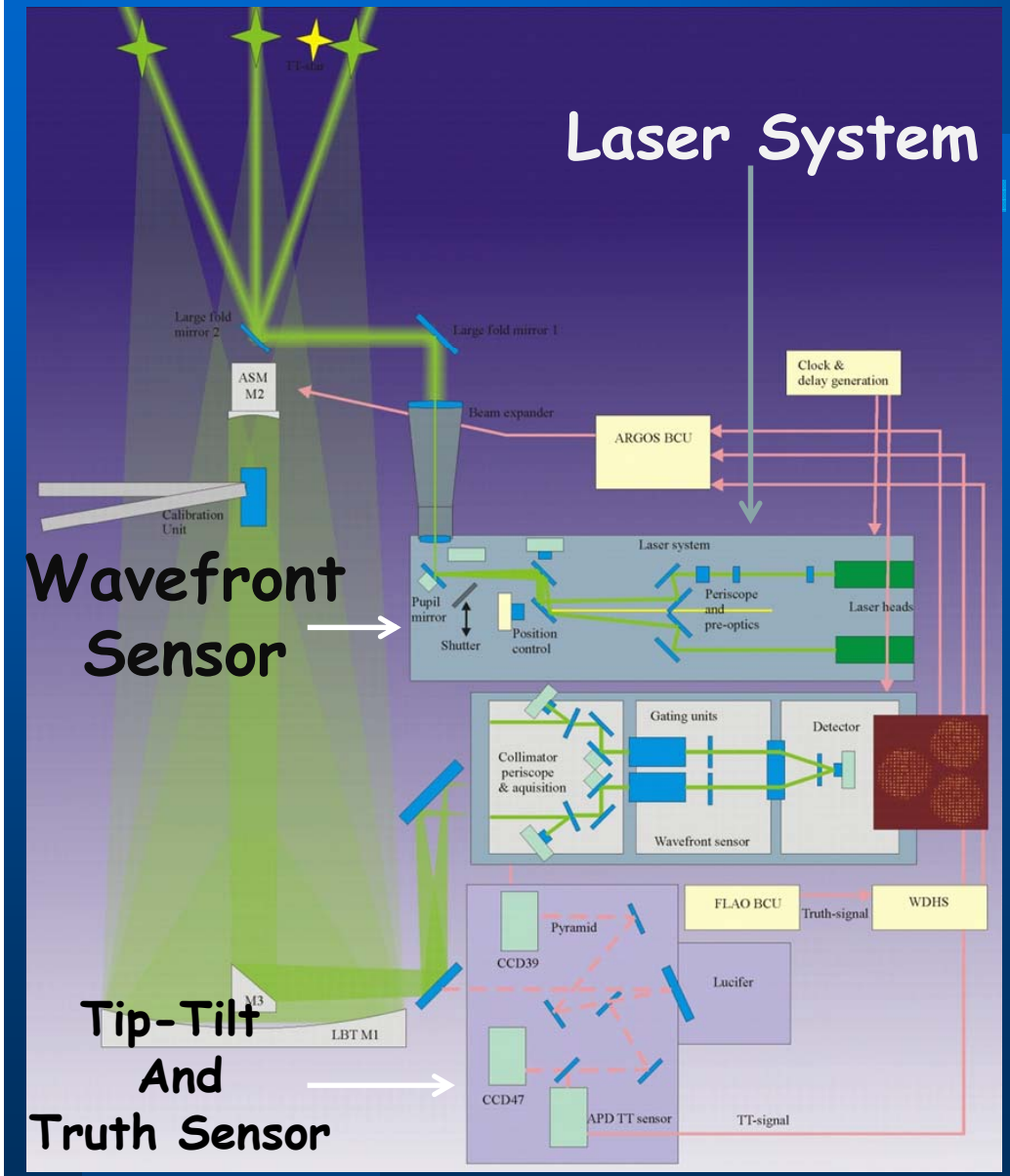
⇨**Smaller sampling frequencies (/3)**

=> Relaxed detector & flux constraints

Conan et al. AO4ELT 2

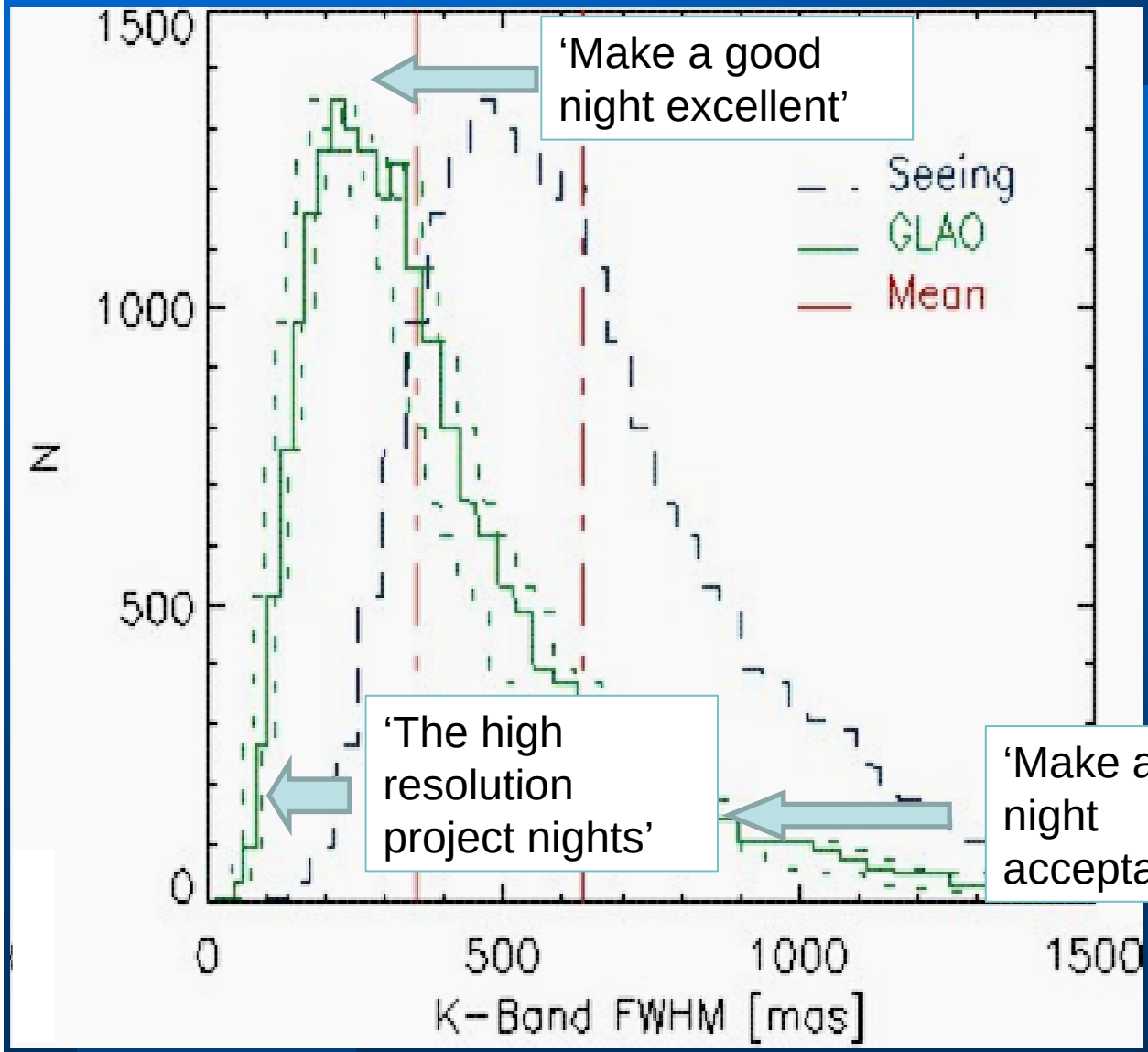


WP1.4: Design Advanced Rayleigh Ground Layer AO for LBT



- 2x3x20W **Rayleigh laser** beacon @12km, 2' radius
- **Ground layer** AO system
- Pockelscell gated **Shack-Hartmann** wavefront sensors
- Calibration unit for day time optimization
- **4' wide field correction** of LUCI (IR-Imaging-spectrograph)

Science objective



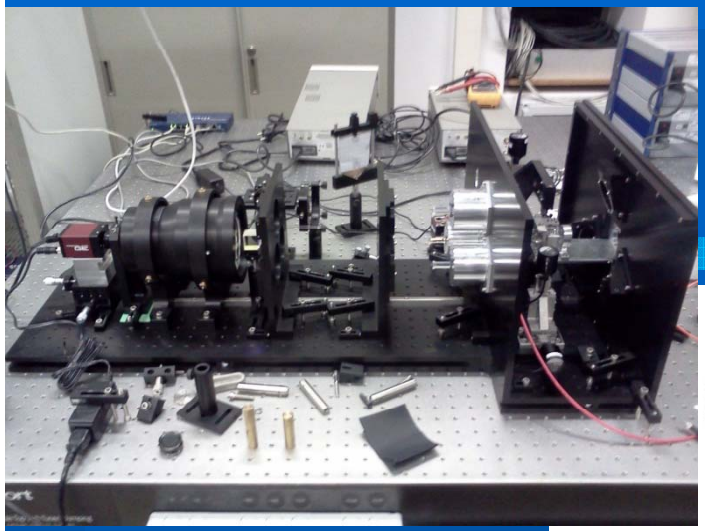
Improve telescope image quality

x2-3 in FWHM

x 4-9 in slit flux

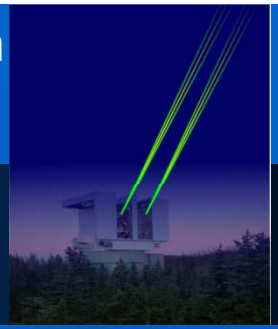
Design completed very early

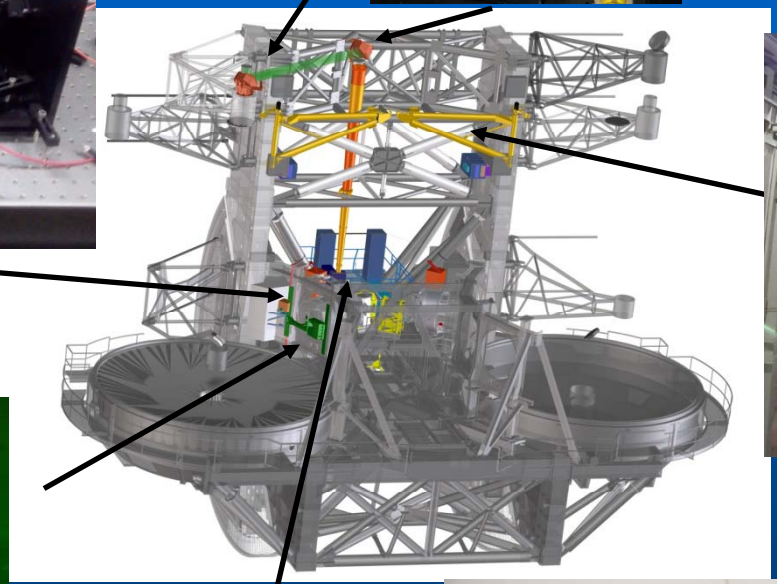
Installation 2012-13



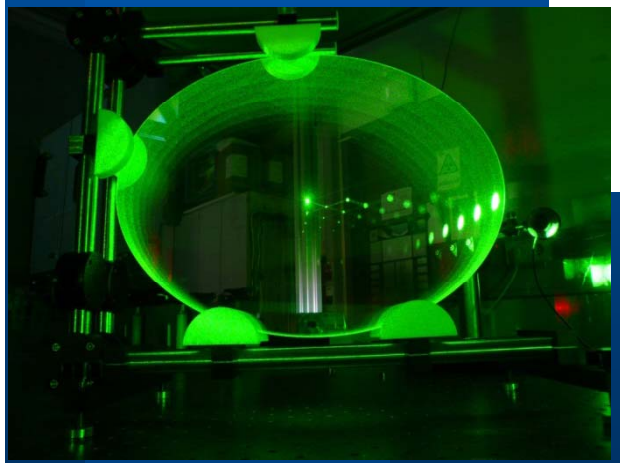
Wavefront Sensor
Summer 2013

Launch system
Fold mirrors
Summer 2012



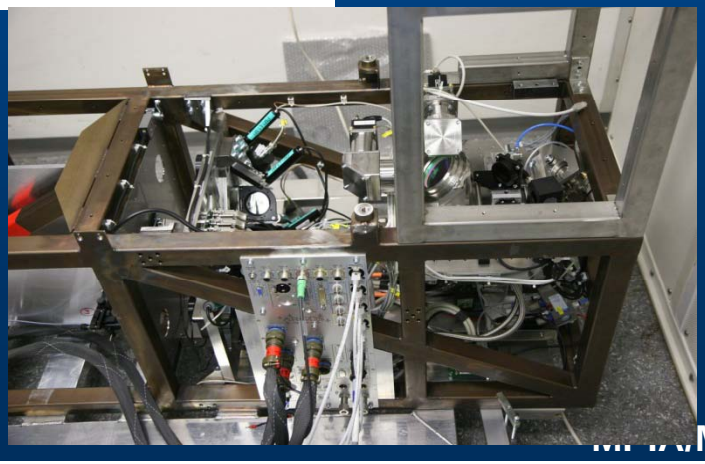


Calibration swingarms
Summer 2011

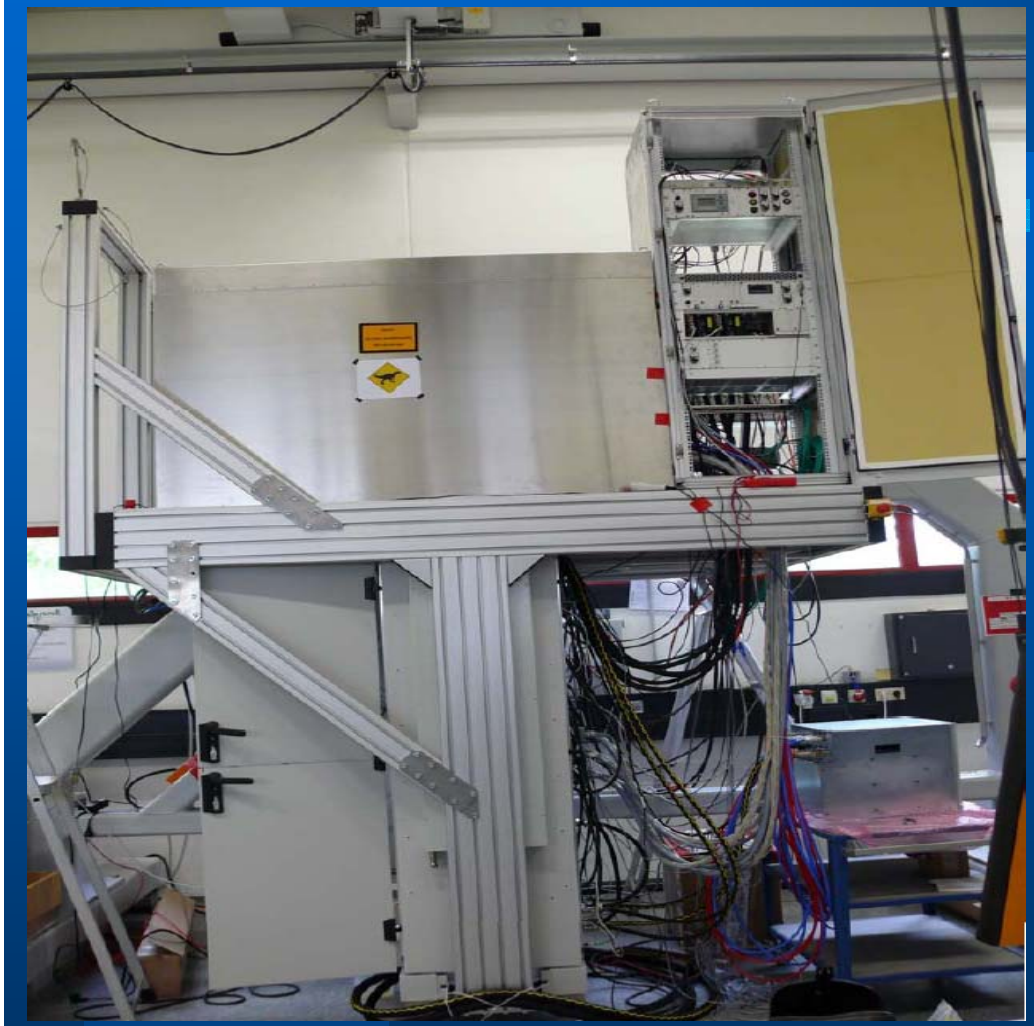


Dichroic
Summer 2013

Lasers
Winter 2012/13



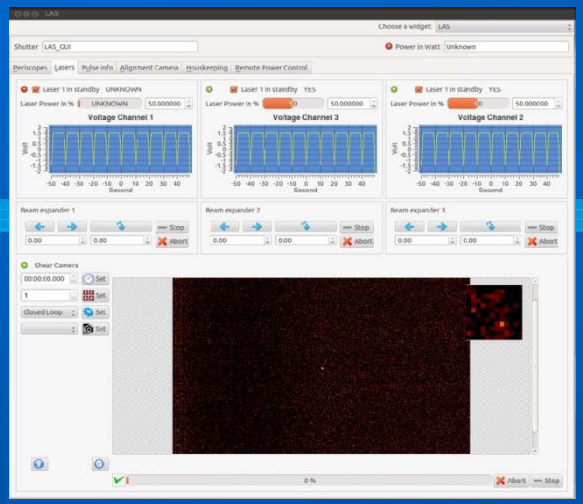
Laser system integration

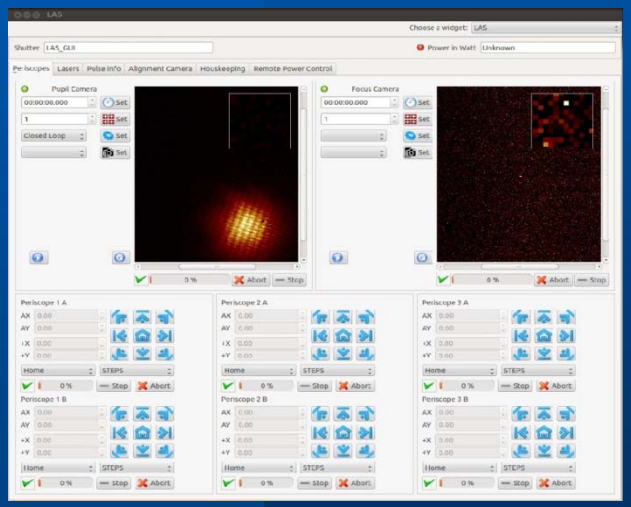


Flexure stand in Garching

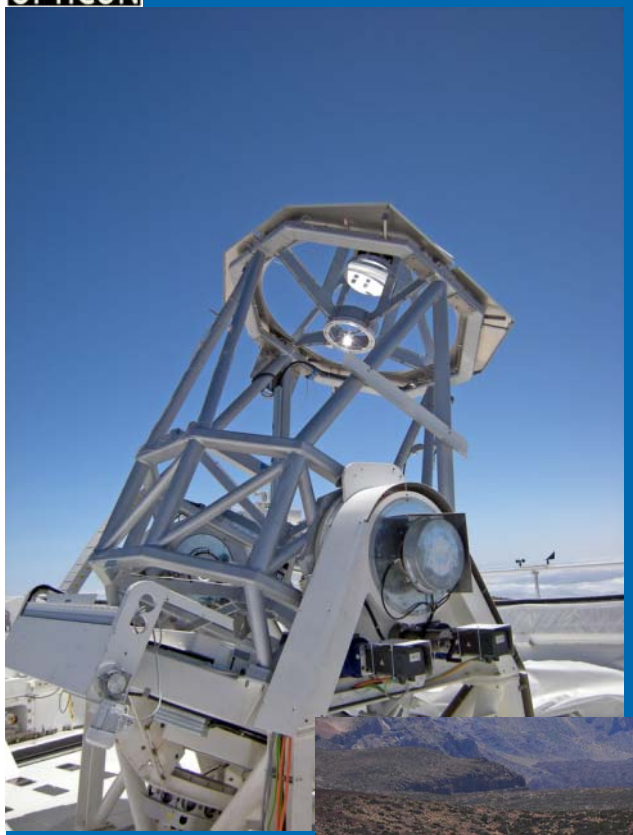
“Sky projection” of lasers

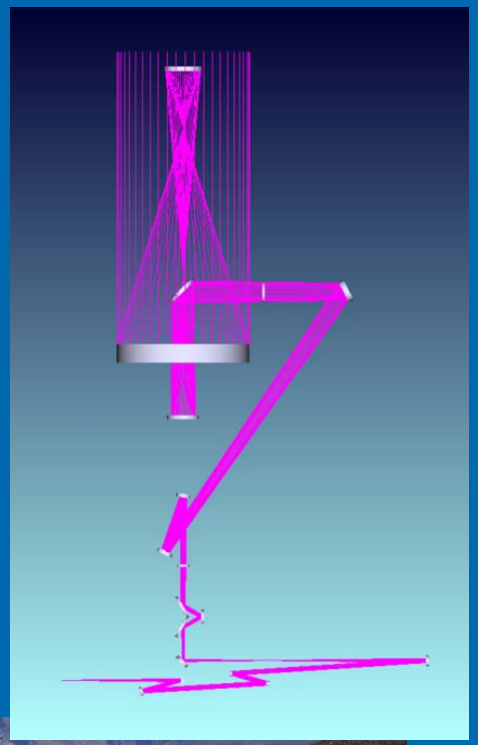
Preliminary Acceptance Europe October 1-5


Voltage Channel 1
Voltage Channel 3
Voltage Channel 2


Pupil Camera
Focus Camera

WP 1.5 Solar High Order AO





New solar telescope on Tenerife:

- Aperture : 1.5 m
- f/38

- WP goal:
  - Procurement, testing, integration of a high order deformable mirror (256 act.)

inauguration
May 21st, 2012

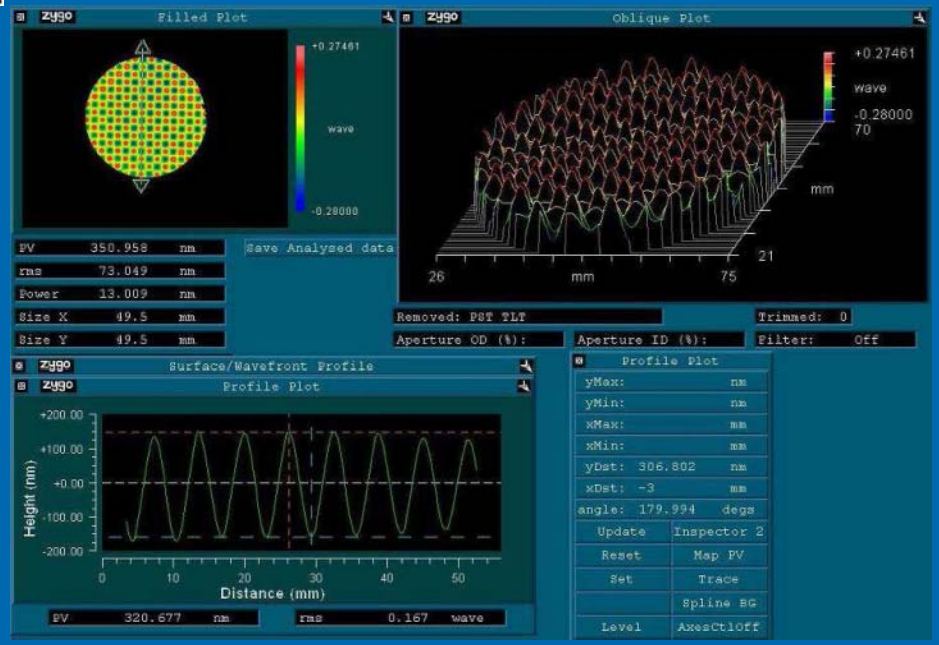
High Order AO for GREGOR

- 8 cm subaperture
- 15 subaps across aperture
- Shack-Hartmann WFS

High Order Solar AO DM Specs

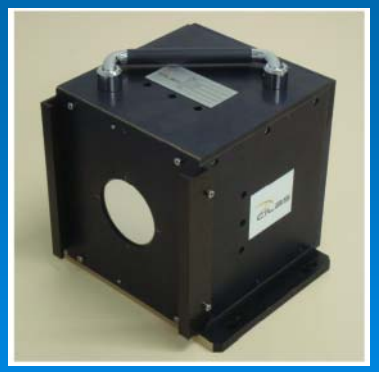
	This mirror will be used at a solar telescope in order to compensate for atmospheric turbulence.
Illuminated diameter	47.35 / 49.02 mm
Angle of incidence	15°
Actuator stroke	> 5 µm ptv
Interactuator stroke	> 1.5 µm at full voltage difference
Coupling	< 30%
Actuator pitch	See Table 1. We encourage the bidder to present a discussion about the tradeoff between pitch, stroke and resonance frequency
Heat load	The mirror will see an absorbed heat load of approx. 3 Watt. Heat conduction to the metallic optical bench shall minimize warming of the mirror (including housing). The bidder shall elaborate on this issue in the tender.
Resonance frequency	> 2 kHz . We encourage the bidder to present a discussion about the tradeoff between pitch, stroke and resonance frequency
Coating	Aluminum
Cable length between mirror and electronic box	> 7 m
Surface Flatness (closed loop)	8 nm (rms) with less than 10% of stroke
Surface flatness with zero voltage	100 nm (ptv)
Microroughness	< 4 nm

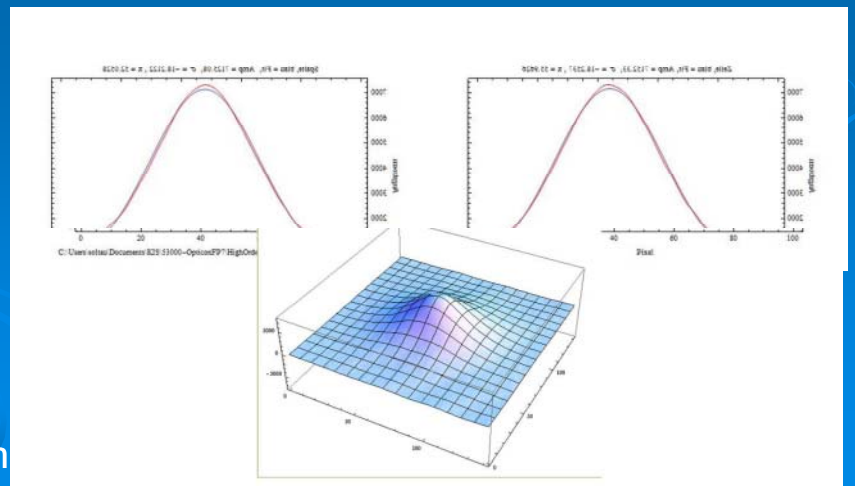
CILAS mirror



factory acceptance test: waffle mode

In house measurements of influence fuctions





Telescope integration

AO GUI

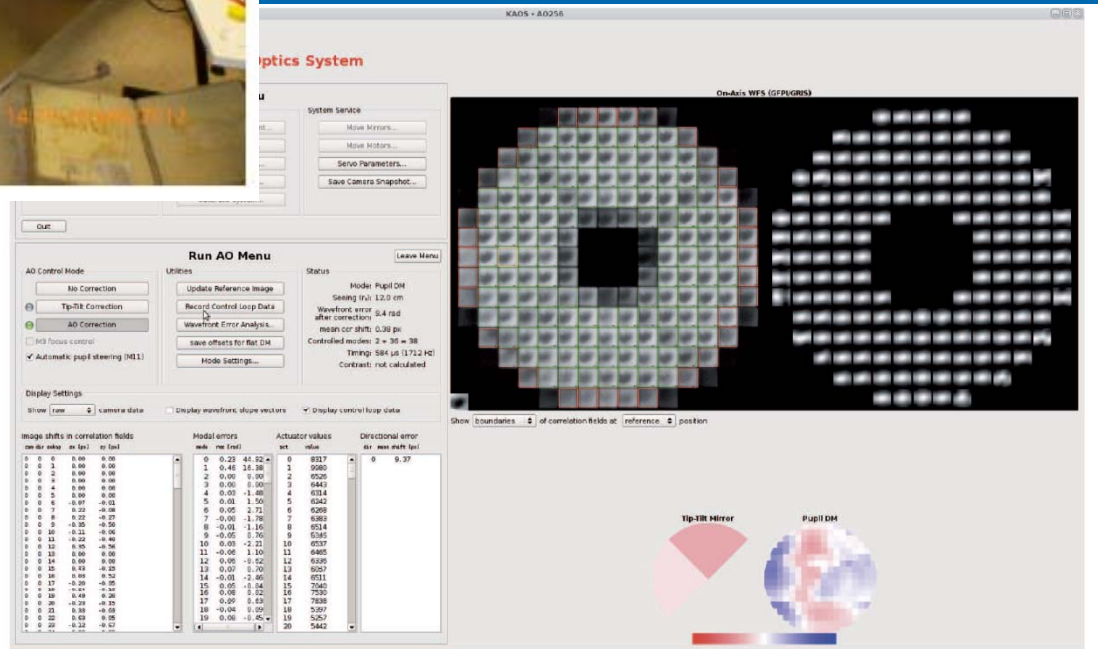
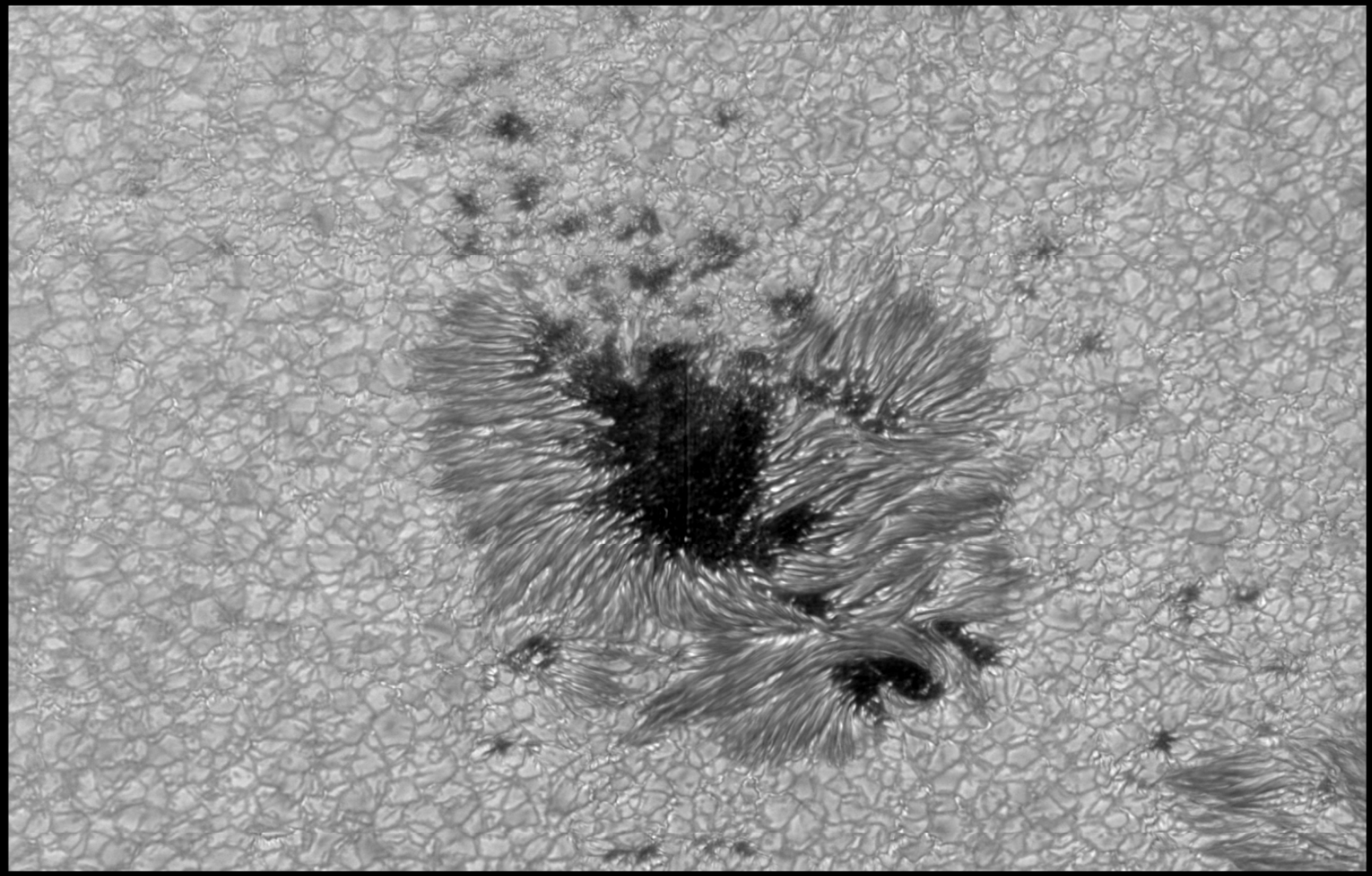


Fig. 8 Snapshot of the GREGOR AO GUI during closed loop. The command buttons are on the upper left, the display of the current shift-, mode- and actuator vectors are situated on the lower left. On the upper right a realtime image of the WFS camera and the resulting correlation functions are displayed. Below the color-coded realtime tip-tilt and DM actuator voltages are shown.

DM at telescope

Successful operation



High resolution (0.1 arcsec) image of a sunspot obtained with GREGOR AO and speckle reconstruction. FOV appr. 100 x 60 arcsec^2

WP1.6 Sodium Laser Development

Context:

- Reliable >20 W Sodium lasers are vital for 8-42m telescopes

Baseline specification

- 20 W laser with D_{2a} & D_{2b} lines in the mesosphere ($\Delta f \approx 1.7$GHz)

Aggressive development strategy

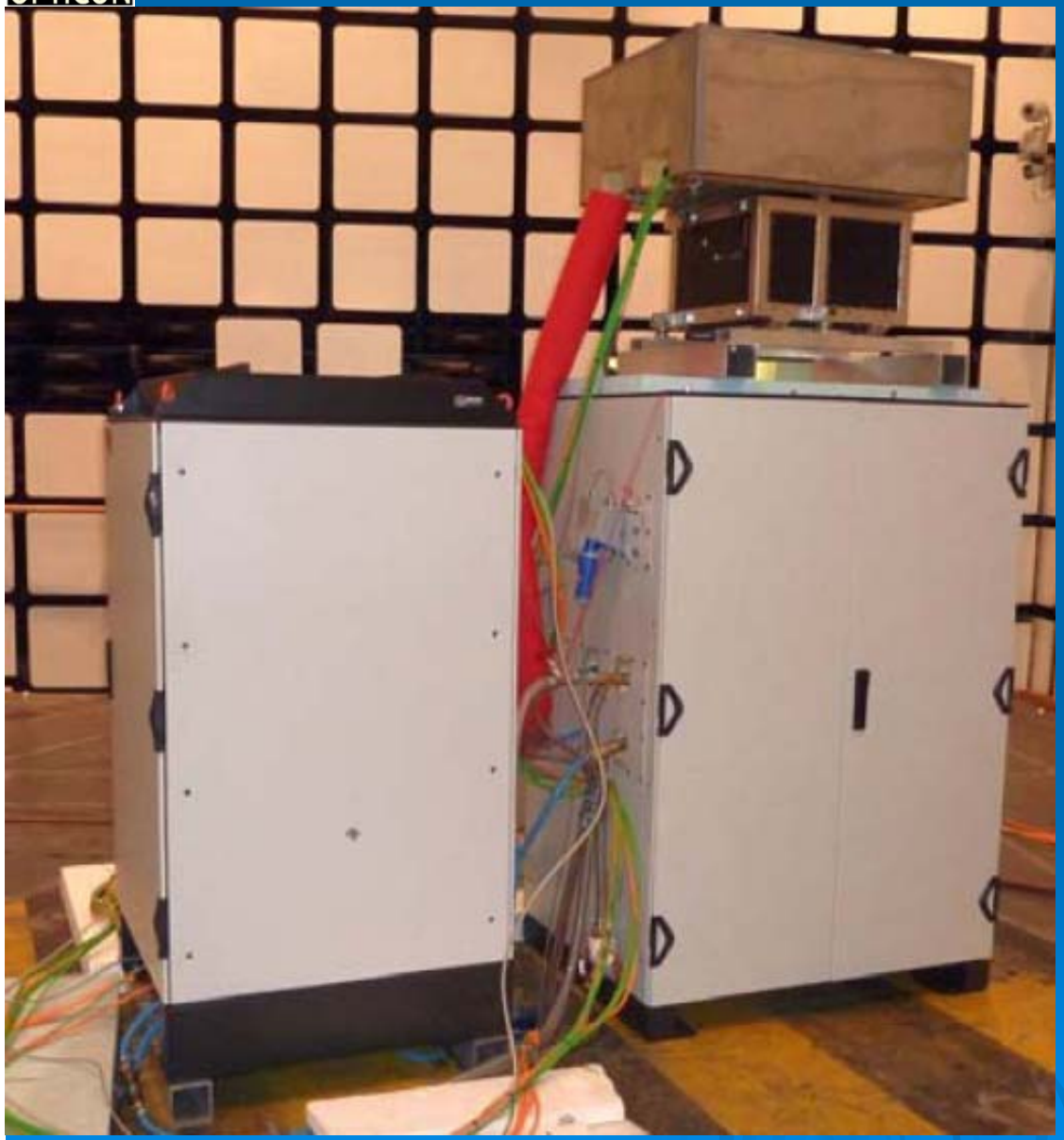
- Worldwide Call for Tender: 28 companies
- First contract: Preliminary design & critical risk reduction technology Demonstrators: duration: 12 months➔ Completed last December
- **Second contract**: Final Design & Pre-Production Unit (funded: OPTICON, ESO, Keck): 27 months COMPLETED in Sept 2012!!!

Major JRA1 achievement so far➔ KECK-TMT-GMT

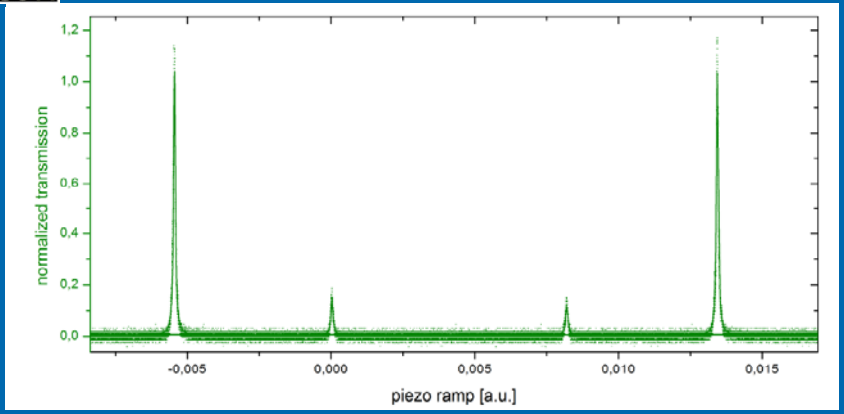
Supporting a European supplier!!!: TOPTICA

- MAIT *and delivery of 4 Laser Units (paid by ESO): 18 months*

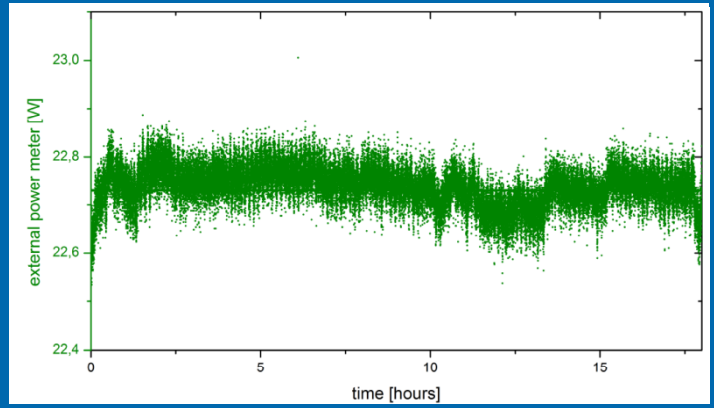
WP1.6 Pre-Production Unit



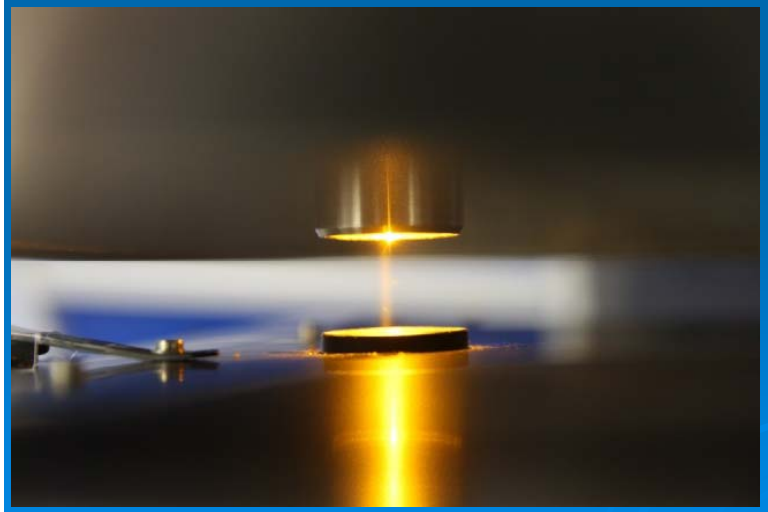
WP1.6 PPU performance

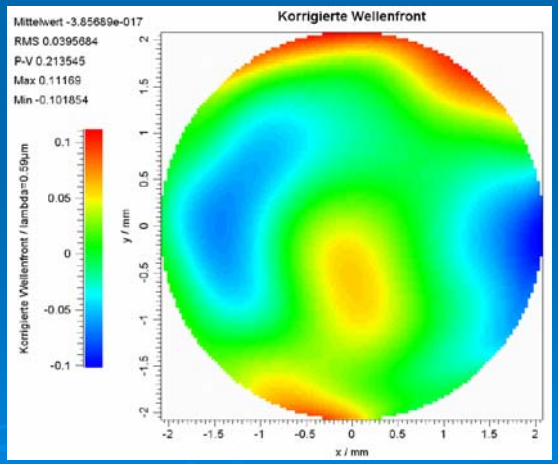


Output optical spectrum
- 18 W in the carrier
- 2.1 W in the ± 1.7 GHz side bands
- 4.4 MHz line width



Long term measurement of the flux
- 18 hours
- 22.7 W ± 0.2% rms (2% PV)

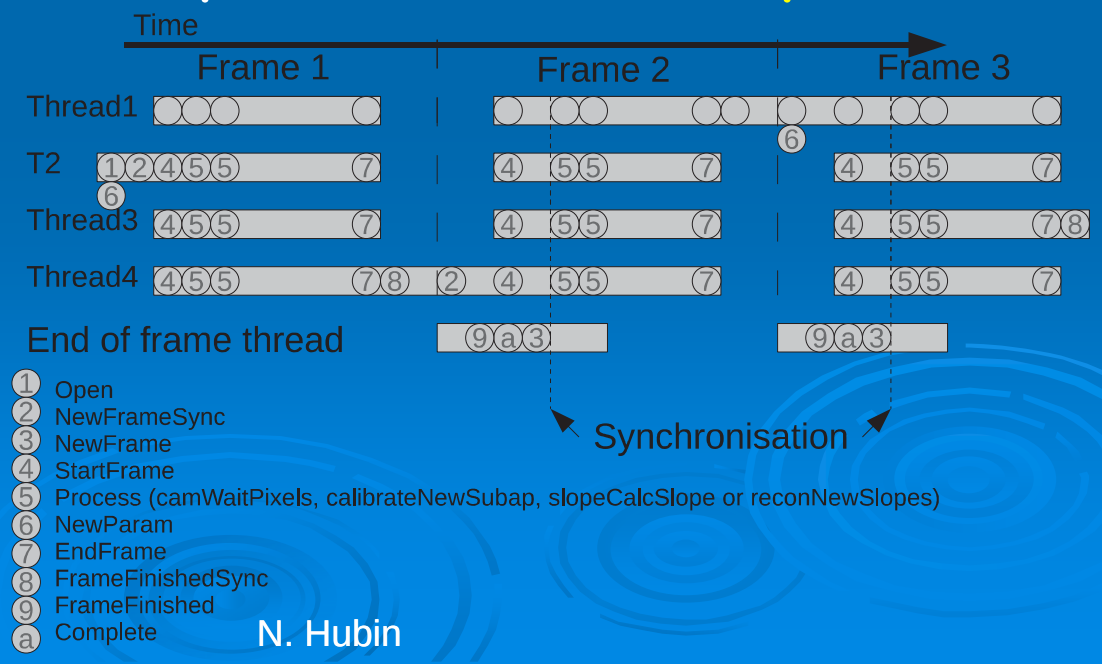




Output beam optical quality
- 23 nm rms @ 22 W

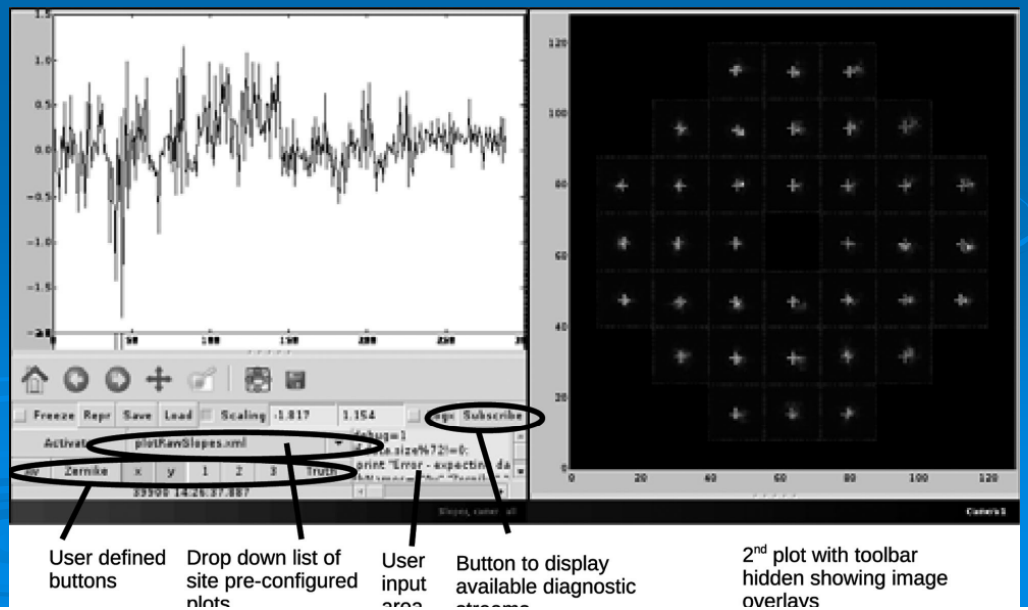
WP1.7: European Real time platform for AO

- DARC:
  The Durham Adaptive optics Real-time Controller
- Developed for the CANARY on-sky MOAO demonstrator for the 4.2m WHT
- Meets or exceeds CANARY's requirements
- Used on-sky since September 2010 & public domain
- Base system runs on COTS multi-core PC with novel threading architecture:



WP 1.7: DARC Advanced Features

- Optional GPU and FPGA acceleration
  - Both used on-sky
- Alternative algorithms implemented:
  - SH WFS Centroiding algorithms: WCOG, moving window, correlation
  - Control: integrator, LQG (ONERA L2TI – WP1.8)
  - Tomography: Learn & Apply (LESIA)
  - MVM, CuRE (Linz)
- Modular design
- Full diagnostics and live displays:
- Full Description published:
- MNRAS **424**, 1483 (2012)



WP1.8: Optimal Control algorithms for wide field adaptive optics

High performance & Flexibility

Spatial & dynamical perturbation model	Turbulence, vibration, windshake
Components characteristics	Mirror dynamics NGS / LGS fusion
Optimal trade-off rejection/noise propagation	Open-loop / Close-loop

Laboratory validations

MCAO & LTAO @ HOMER

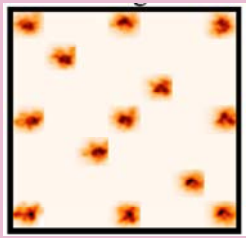
DEMONSTRATION ON CANARY 3 NGS + 1 LGS

Laboratory validation SCAO & MOAO

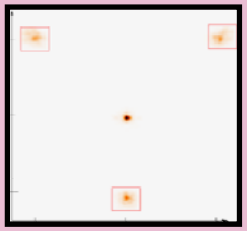
BONUS TRACK
FIRST ON-SKY VALIDATIONS!
with vibration filtering

Optimal LQG Control : From Lab to Sky

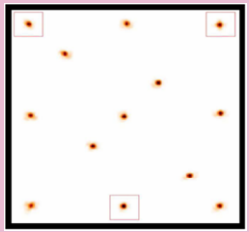
HOMER test bench 2010



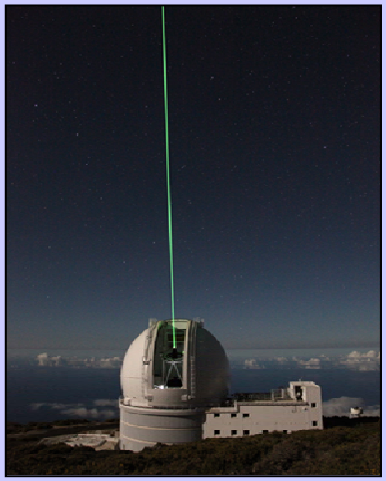
Uncorrected

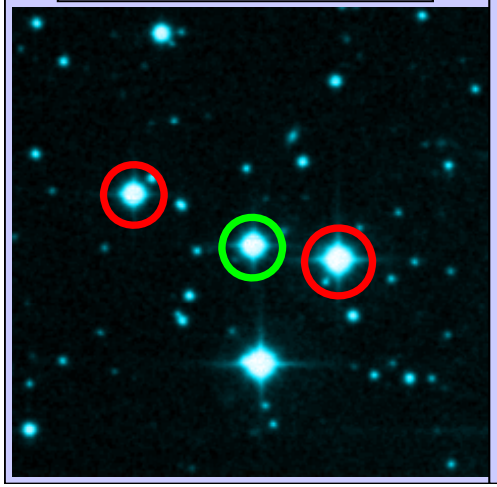


LTAO



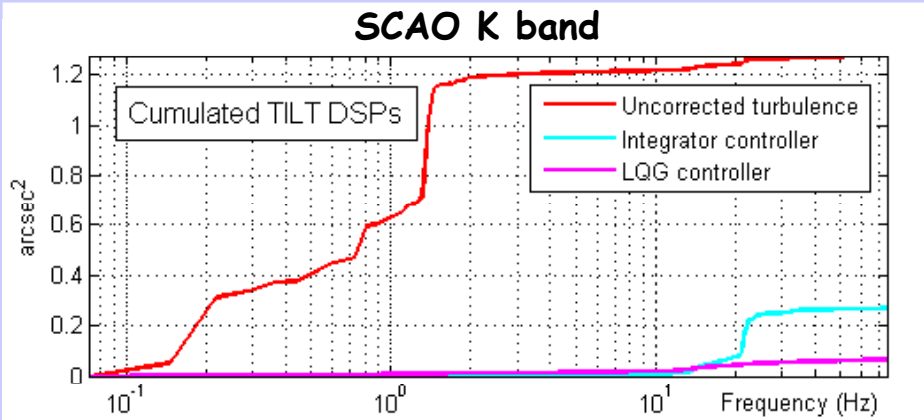
MCAO

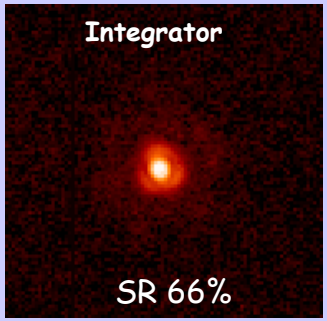


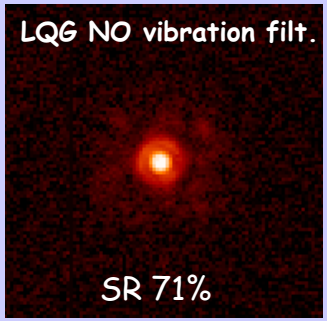


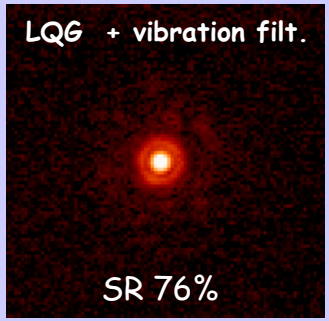
FIRST ON-SKY RESULTS: CANARY summer 2012

SCAO K band

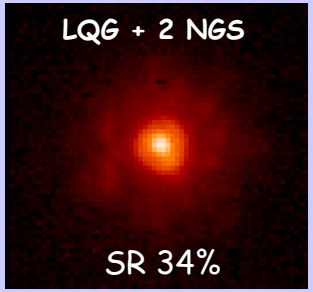


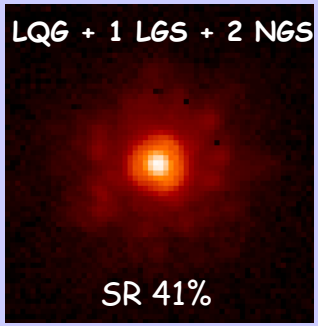






MOAO H band



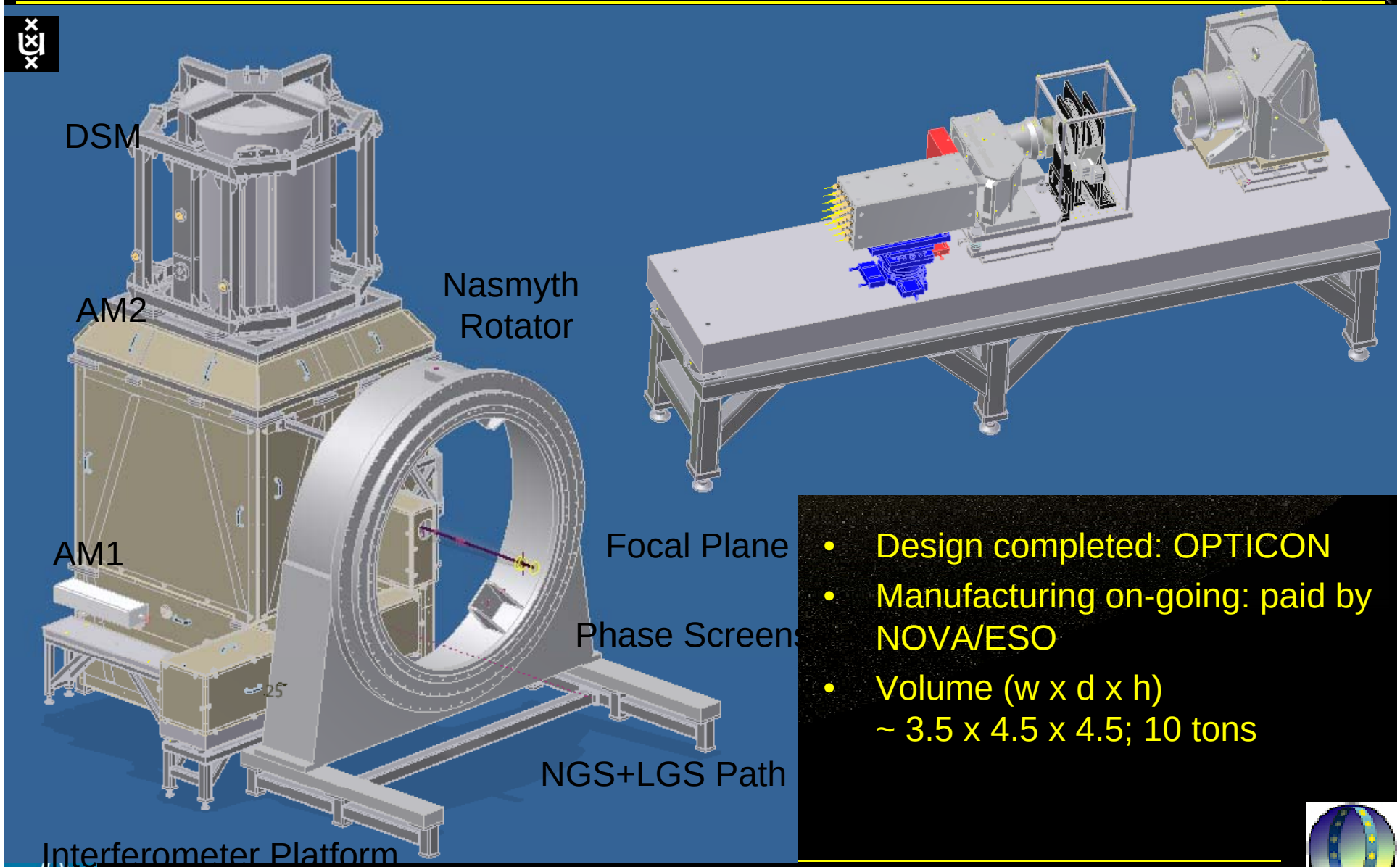


Publications

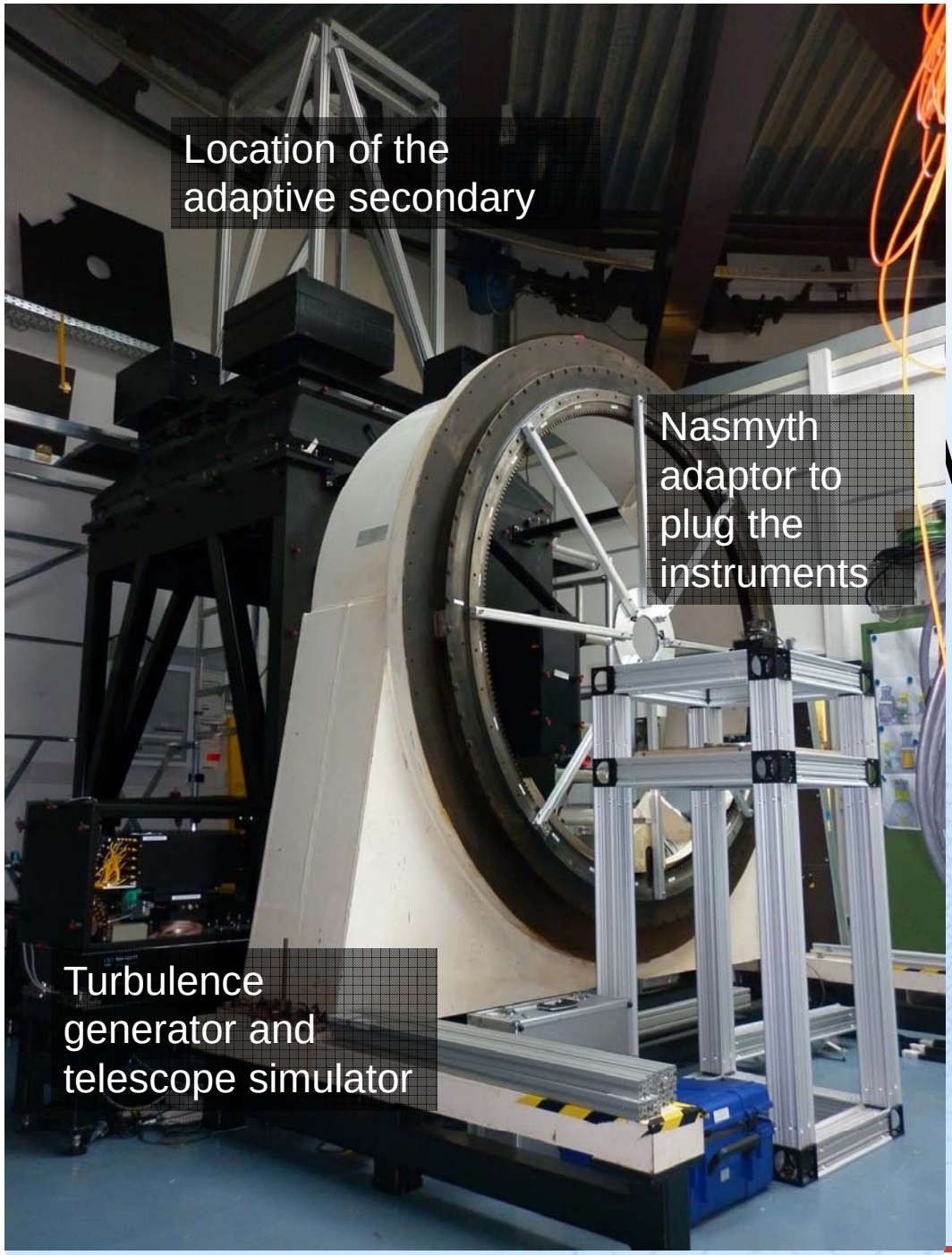
- Correia et al. JOSA A 2010 "*Min.-variance control for woofer–tweeter systems in AO*"
- Sivo et al. Durham RTC Workshop 2011 "*MOAO LQG control structure for CANARY*"
- Sivo et al. AO4ELT2 2011 "*MOAO Real-Time LQG implementation on CANARY*"
- Conan et al. AO4ELT2 2011 "*Are integral controllers adapted to the new era of ELT AO?*"
- Sivo et al. SPIE 2012 "*First laboratory validation of LQG control with the CANARY MOAO pathfinder*"
- Kulcsár et al. SPIE 2012 "*Vibrations in AO control: a short analysis of on-sky data around the world*"

WP1.9 Adaptive telescope calibrations

ASSIST design



- Design completed: OPTICON
- Manufacturing on-going: paid by NOVA/ESO
- Volume (w x d x h)
  ~ 3.5 x 4.5 x 4.5; 10 tons



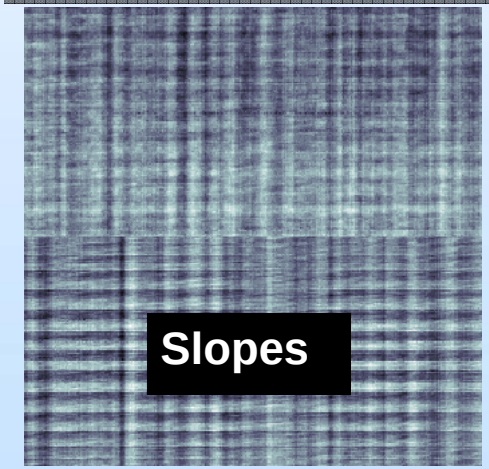
WP 1.9: Full alignment of the ASSIST bench to test the AOF instruments

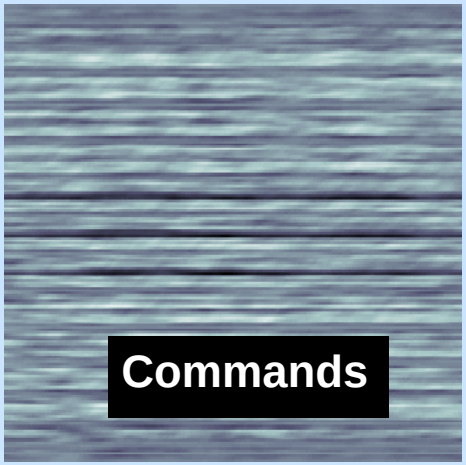
Ready for system testing of the AOF in 2013.

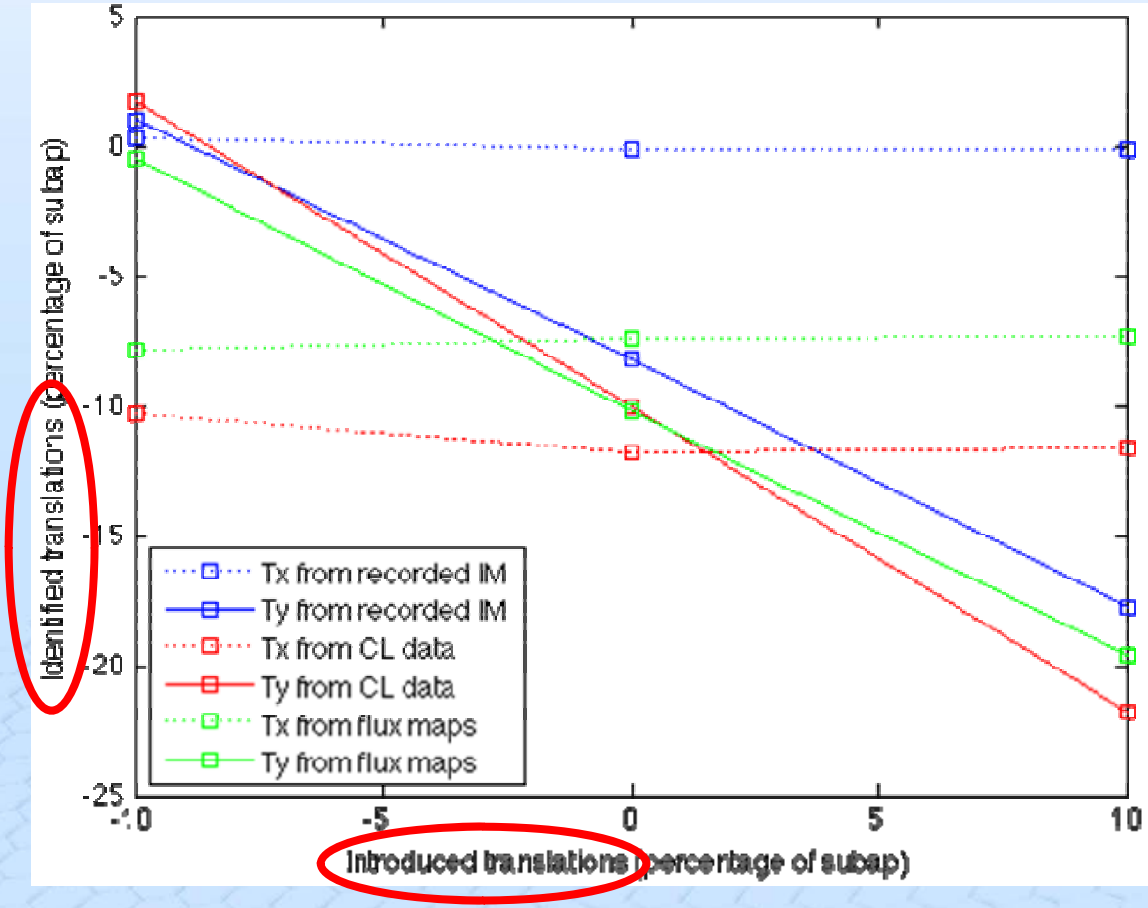
WP 1.9: Large DM online identification

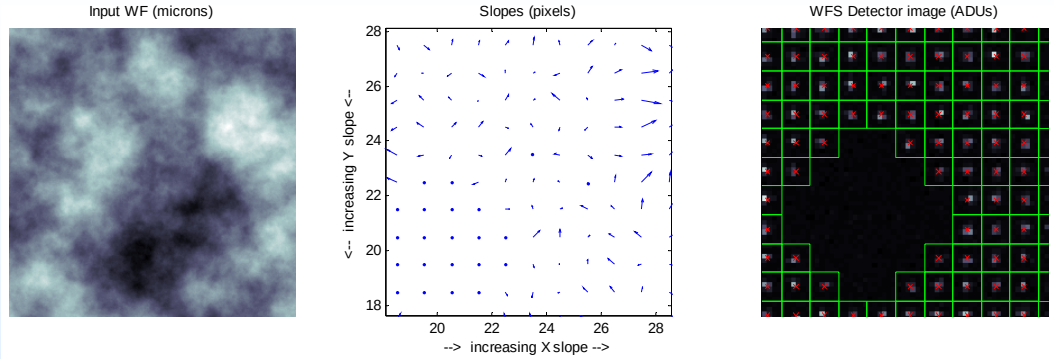
Inputs measured in AO Closed Loop during scientific observations without disturbing them

Outputs: parameters of mis-alignment of the system, in real-time.
Concept validated on the PEACE test bench.



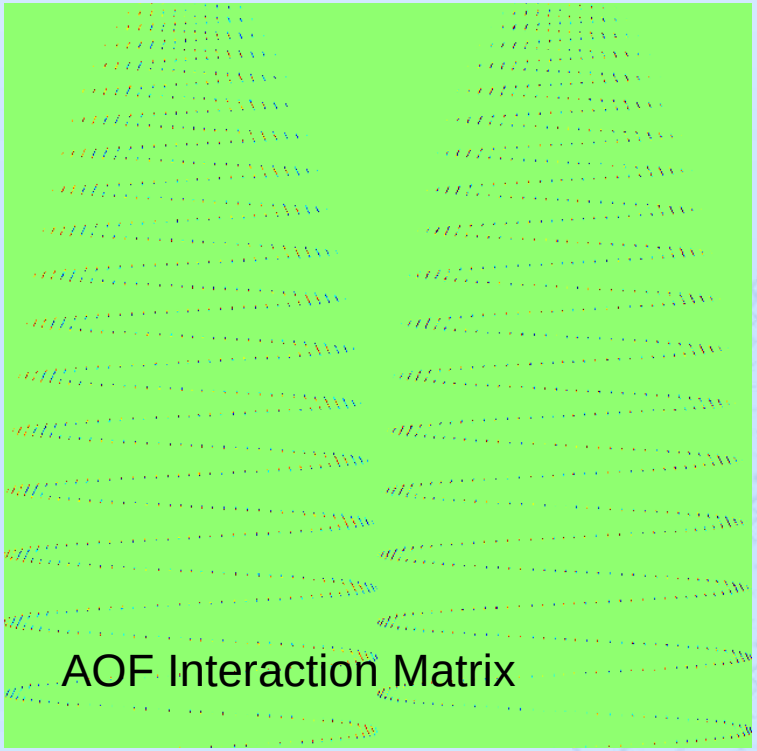




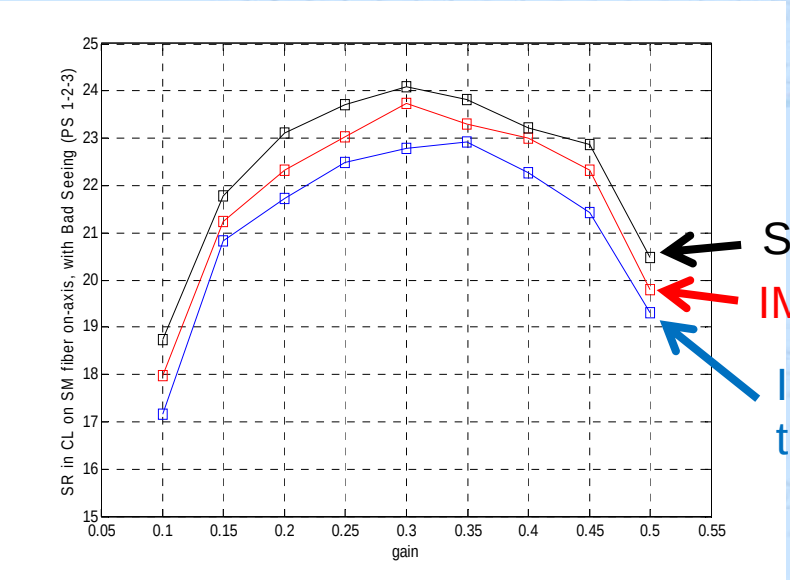


Pseudo-synthetic interaction matrix modeling (WP 1.9.2) & Calibration of a large DM IM on simulated turbulence (WP 1.9.3)

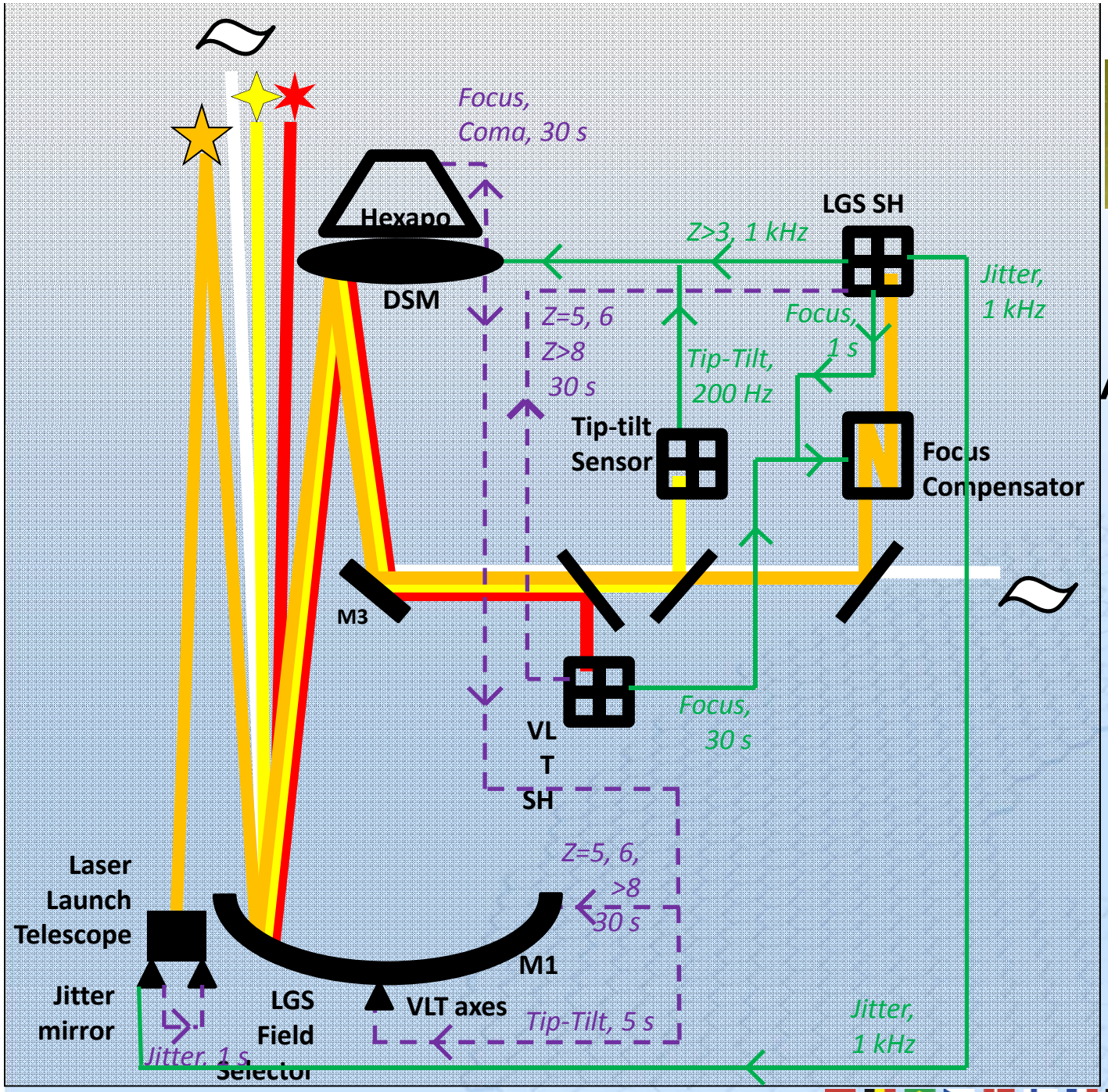
- Matlab code written to simulate the Interaction Matrix of the AOF.
- Accuracy of the code validated in the MAD test bench.
- Performance compared with the one of IM measured on turbulence



MAD Strehl Ratio vs. loop gain



WP 1.9.4: AOF Control loops



- Science light
- LGS light
- TT NGS light
- VLT GS light
- Commands
- Offloads
- WFS

JRA1 Deliverables (I)

Del no.	Deliverable name	WP no.	Lead beneficiary	Estimated indicative person-months	Dissemination level	Delivery date
1.1.1	Annual report year 1	1.1	ESO	4	PP	12
1.1.2	Annual report year 2.5	1.1	ESO	4	PP	30
1.1.3	Annual report year 4	1.1	ESO	4	PP	48
1.2.1	CANARY upgrade Preliminary Design Review	1.2	UoD	16	PP	28
1.2.2	CANARY upgrade Final Design Review	1.2	UoD	28	PP	32
1.2.3	CANARY on-sky test report	1.2	UoD	24	PP	Nov 2012
1.3.1	Optimized phase diversity algorithms report	1.3	ONERA	2	V	24
1.3.2	Post Focal plane wavefront sensor design report	1.3	CNRS-INSU-LAOG	6	PP	Nov 2012
1.3.3	Optimized real time algorithms (SPHERE) design report	1.3	ONERA	3	PP	Sept 2012
1.3.4	Coronagraphic phase diversity algorithms laboratory test report	1.3	ONERA	2	PP	Nov 2012
1.3.5	Post Focal plane wavefront sensor laboratory test report	1.3	CNRS-INSU-LAOG	9	PP	Nov 2012
1.3.6	Optimized real time algorithms (SPHERE) laboratory test report (on BOA, conditional to success 1.3.3)	1.3	ONERA	6	PP	Included in 1.3.3
1.3.7	Coronagraphic phase diversity algorithms (SPHERE) test report	1.3	ONERA	2	PP	Nov 2012
1.3.8	Post Focal plane wavefront sensor (SPHERE) test report	1.3	CNRS-INSU-LAOG	6	PP	Nov 2012
1.4.1	LBT Laser Guide Star Ground Layer AO Kick-off report	1.4	MPE	1	PP	6
1.4.2	LBT Laser Guide Star Ground Layer AO preliminary design report	1.4	MPE	30	PP	24
1.4.3	LBT Laser Guide Star Ground Layer AO Final Design report	1.4	MPE	37.4	PP	18

JRA1 Deliverables (II)

1.5.1	Solar telescope deformable mirrors (one) deliveries	1.5	KIS	1.6	PP	24
1.5.2	1.5 meter GREGOR High order AO test report	1.5	KIS	2	PP	36
1.6.1	Laser Technical Specifications & statement of Work	1.6	ESO	2	CO	6
1.6.2	Laser pre-production unit delivery & test report	1.6	ESO	1.2	CO	48
1.7.1	ORCA Interfaces Specifications	1.7	ESO	6	PP	6
1.7.2	Specifications for modules development	1.7	ONERA	6	PP	6
1.7.3	*ORCA* modules prototype and test report.	1.7	ONERA	23	PP	36
1.8.1	Natural Guide Star Adaptive Optics control specifications for CANARY Real Time Computer	1.8	ONERA	1	PP	18
1.8.2	Monitoring and Adaptive Control Strategy study report	1.8	ONERA	1	PP	Oct 2012
1.8.3	Natural Guide Star Adaptive Optics Control Laborary Test Report	1.8	ONERA	1	PP	Oct 2012
1.8.4	Laser Guide Star Adaptive Optics control specifications for CANARY Real Time Computer	1.8	ONERA	1	PP	26
1.9.1	Large deformable mirror online identification and control matrix study report	1.9	ESO	6	PP	18
1.9.2	Test bench (ASSIST) alignment (NOVA-Leiden). Pseudo interaction matrix modelling report	1.9	ESO	6	PP	24
1.9.3	Calibration of a large Deformable mirror interaction matrix on simulated turbulence study report	1.9	ESO	6	PP	48
1.9.4	Optimal strategy for the operation and control of an adaptive telescope applied to the Very Large Telescope Adaptive Optics Facility	1.9	ESO	6	PP	36

JRA1 Milestones

Milestone number	Milestone name	Workpackage(s) involved	Expected date	Means of verification
1.2.1	Design Review of the Real time Computer for CANARY	1.2	24	Review documentation
1.2.2	CANARY on-Sky readiness review	1.2	42	Review documentation
1.2.3	CANARY on-sky first light	1.2	48	D3
1.5.1	1.5 meter GREGOR High order AO Design review	1.5	16	Review documentation
1.6.1	Laser preliminary design phase technical specifications & contract signature	1.6	6	Contract Signature
1.6.2	Laser pre-production unit preliminary design review	1.6	18	Review documentation
1.6.3	Laser pre-production unit contract signature	1.6	24	Contract Signature
1.6.4	Laser pre-production unit readiness review	1.6	42	Review documentation

Actual contractual deliverables

Deliverables

1.2.1: CANARY on-sky test report (48)
1.3.1: Coronagraphic phase diversity final test report (36)
1.3.2: Post focal plane wavefront sensor final test report (30)
1.3.3: Optimized real time algorithms for (SPHERE) final test report (30)
1.4.1: LBT Laser Guide Star Ground Layer AO Final Design report (42)
1.6.1: Laser pre-production unit delivery and test report (48)

JRA1 status conclusions

- ALL JRA1 key activities in excellent shapes:
  - Sodium laser development: highlight of this JRA1
  - Rayleigh Laser Ground Layer AO for LBT
  - ASSIST- AO Calibration of Adaptive Telescope for VLT
  - CANARY Multi-Object AO demonstrator for WHT
  - Deformable mirror for the GREGOR solar telescope
  - European RTC platform→ CANARY WHT

http://www.eso.org/sci/facilities/develop/ao/fp7/doc/index.html

username: OpticOnjraI

passwd:adaptiveoptics