Status of the Sydney University Stellar Interferometer:

Efficient remote observing and experiments in precision astrometry

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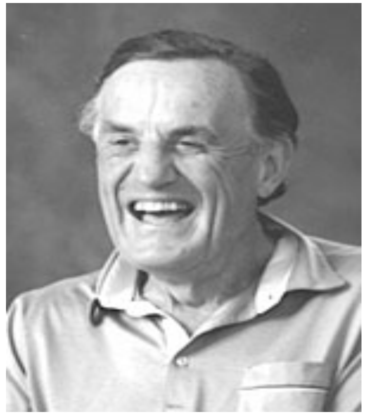
Outline

- SUSI brief history and overview.
- OPLC Upgrade.
- MUSCA – astrometry at SUSI.
- The future…

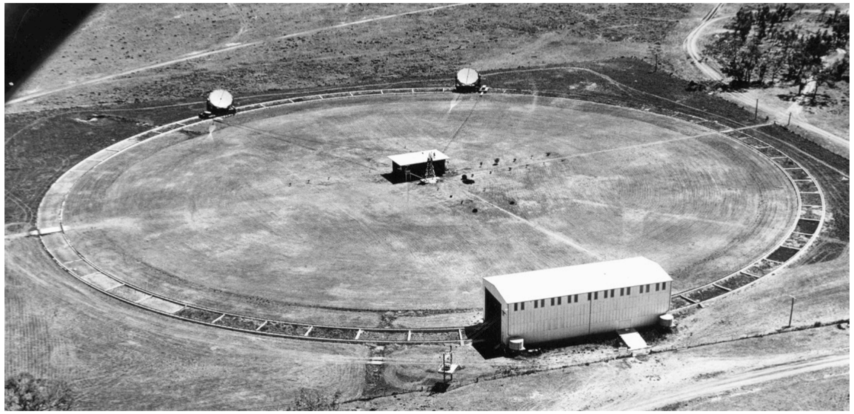
(plus ask me about remote observing)

Happy 50th Birthday Optical Interferometry!

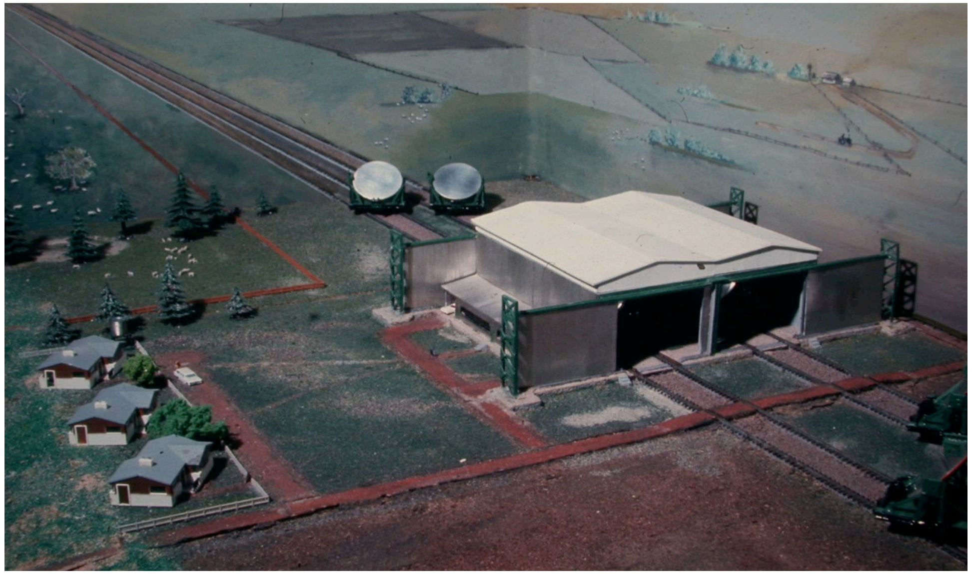
- Critical experiment in both optics and astronomy
  - Established field of statistical optics, coherence
- Restarted stellar interferometry (dead for decades)
  - Established temperature scale for Hot stars
    - Also with Richard Twiss (1920-2005)
- Roy Glauber 2005 Nobel Prize for Quantum Optics

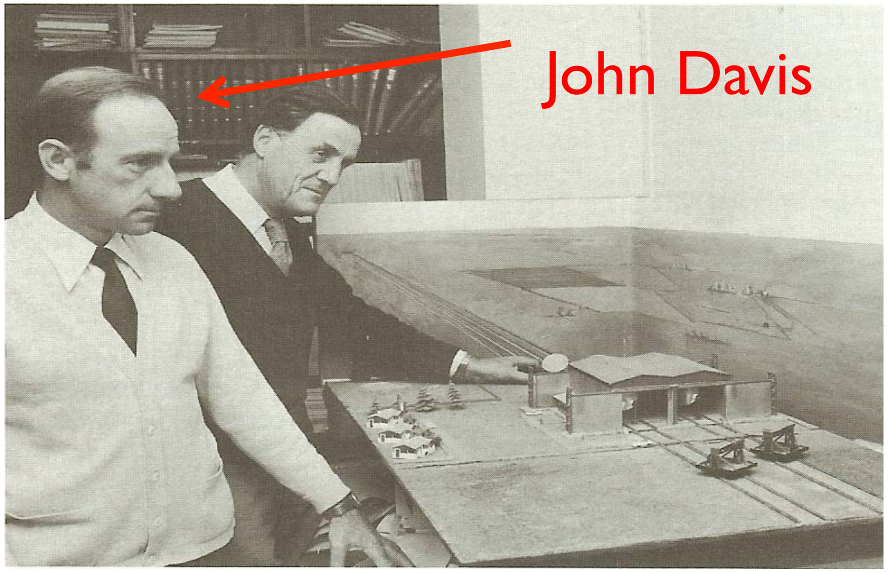


Robert Hanbury Brown
(1916-2002)



A Model of the proposed VLSII





- Two 10 metre diameter siderostats in each arm
- 1 km long railway tracks
- Multi-spectral channel optics at focus of paraboloids

SUSI Staff:

Mike Ireland

Peter Tuthill

Gordon Robertson

William Tango

Postdoc:

Ben Warrington

Xavier Haubois

Student:

Yitping Kok

Aaron Rizzuto

SUSI Staff:

Mike Ireland *AAO & astrophotonics*

Peter Tuthill USyd director/SAM

Gordon Robertson

William Tango

"Retired"

Postdoc:

Ben Warrington

Xavier Haubois

Departed ~2012

Student:

Yitping Kok

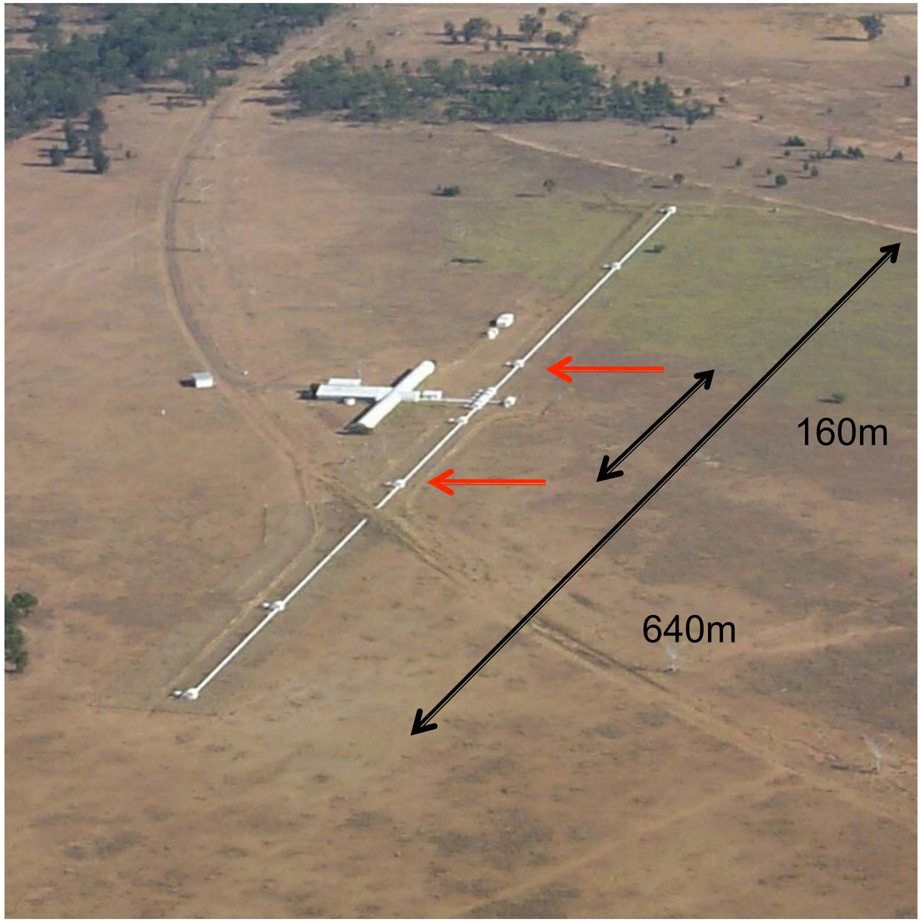
Aaron Rizzuto

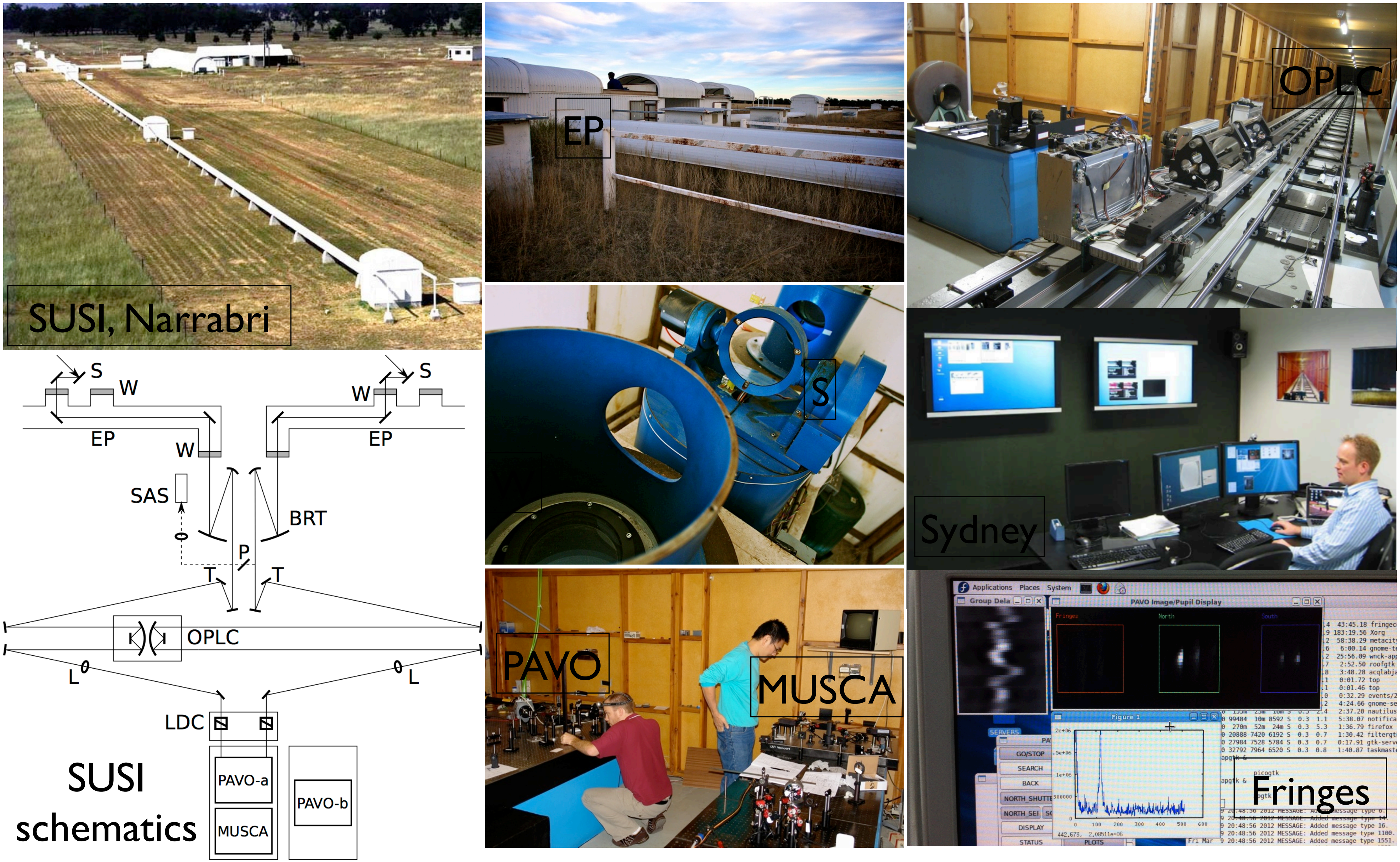
~2013 PhD Completions

Ralph Morgan

Part time

The SUSI Array




SUSI, Narrabri
EP
OPLC
S
Sydney
PAVO
MUSCA
Fringes
S
W
S
W
EP
W
EP
SAS
BRT
P
T
T
OPLC
L
L
LDC
PAVO-a
MUSCA
PAVO-b
SUSI
schematics

PAVO

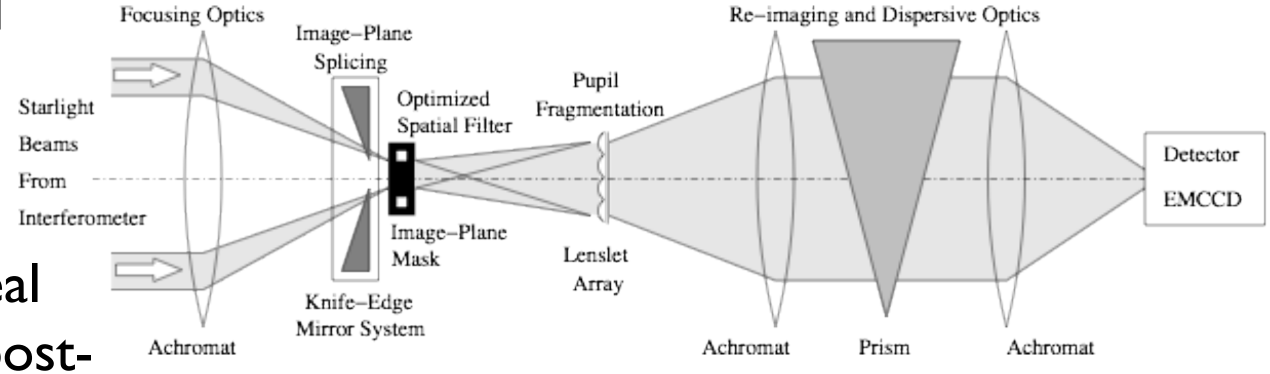
Precision **A**stronomical **V**isible **O**bservation

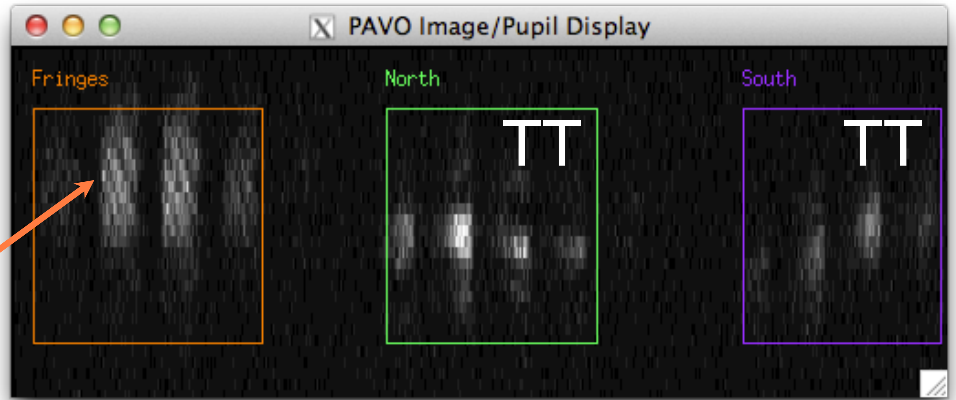
Fizeau-type pupil-plane interferometer

Group-delay tracker (real time), Fringe-tracker (post-processing)

λ =0.52-0.80 μ m, 21 channels

5ms per interferogram





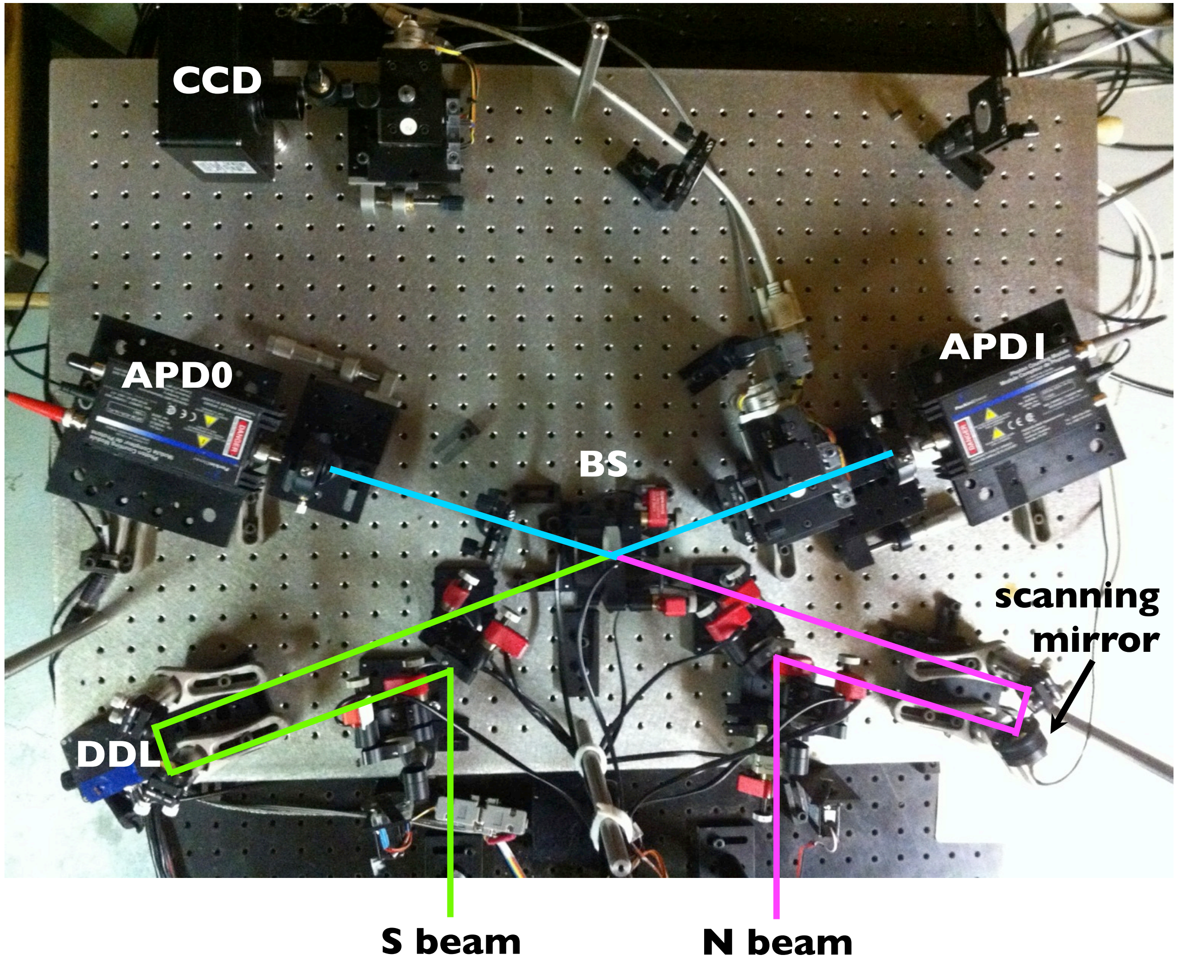
dispersed fringes!

See Rizzuto te al (2013) for major Sco-Cen survey

Ireland et al. , SPIE, 2008

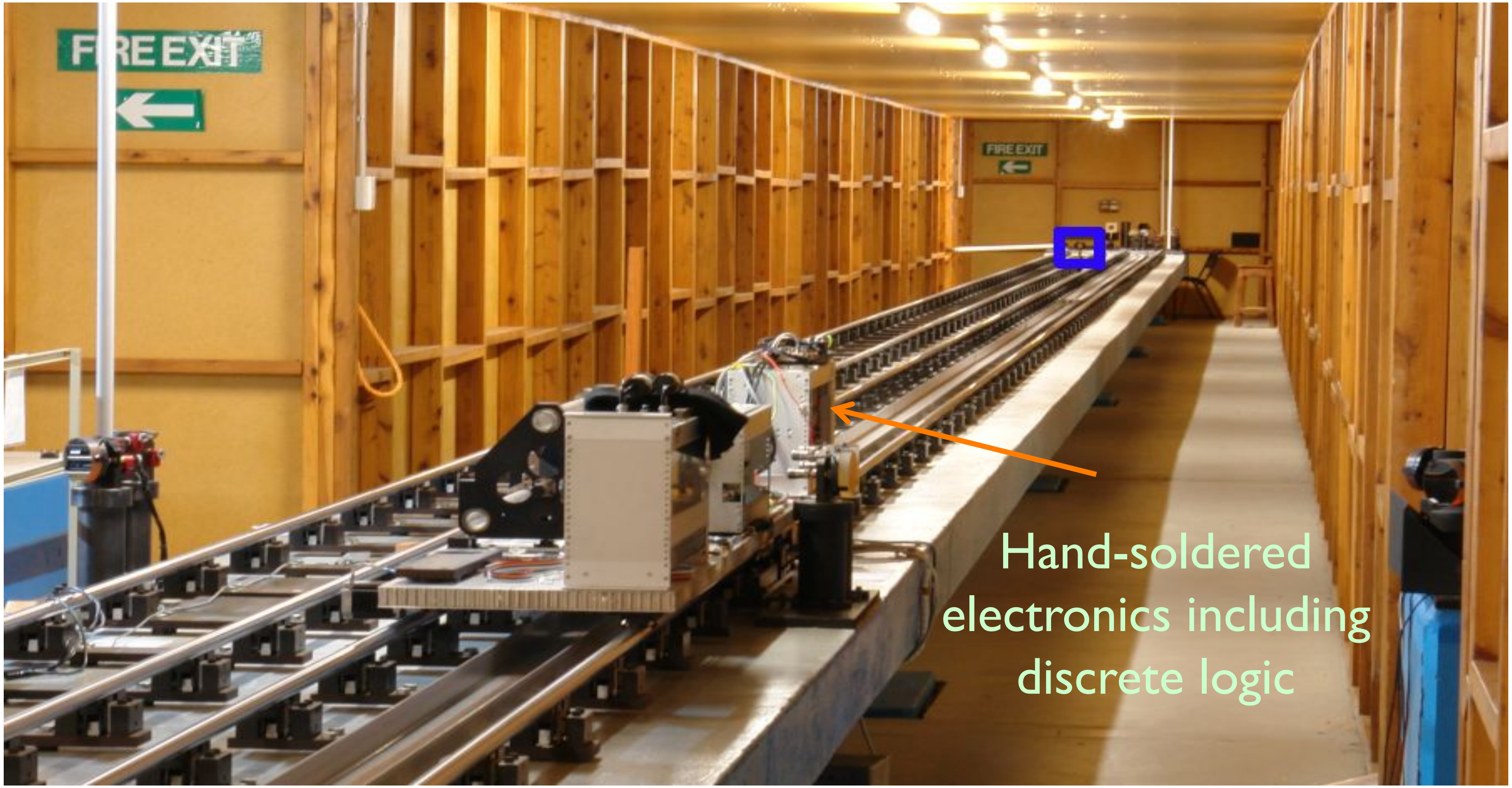
MUSCA

Microarcsecond **U**niversity of **S**ydney **C**ompanion **A**strometry
Michelson interferometer
Astrometric beam combiner
Records fringes (real time), phase-referencing & astrometry (post-processing)
λ =0.833 μ m,
$\Delta \lambda$ =140 μ m



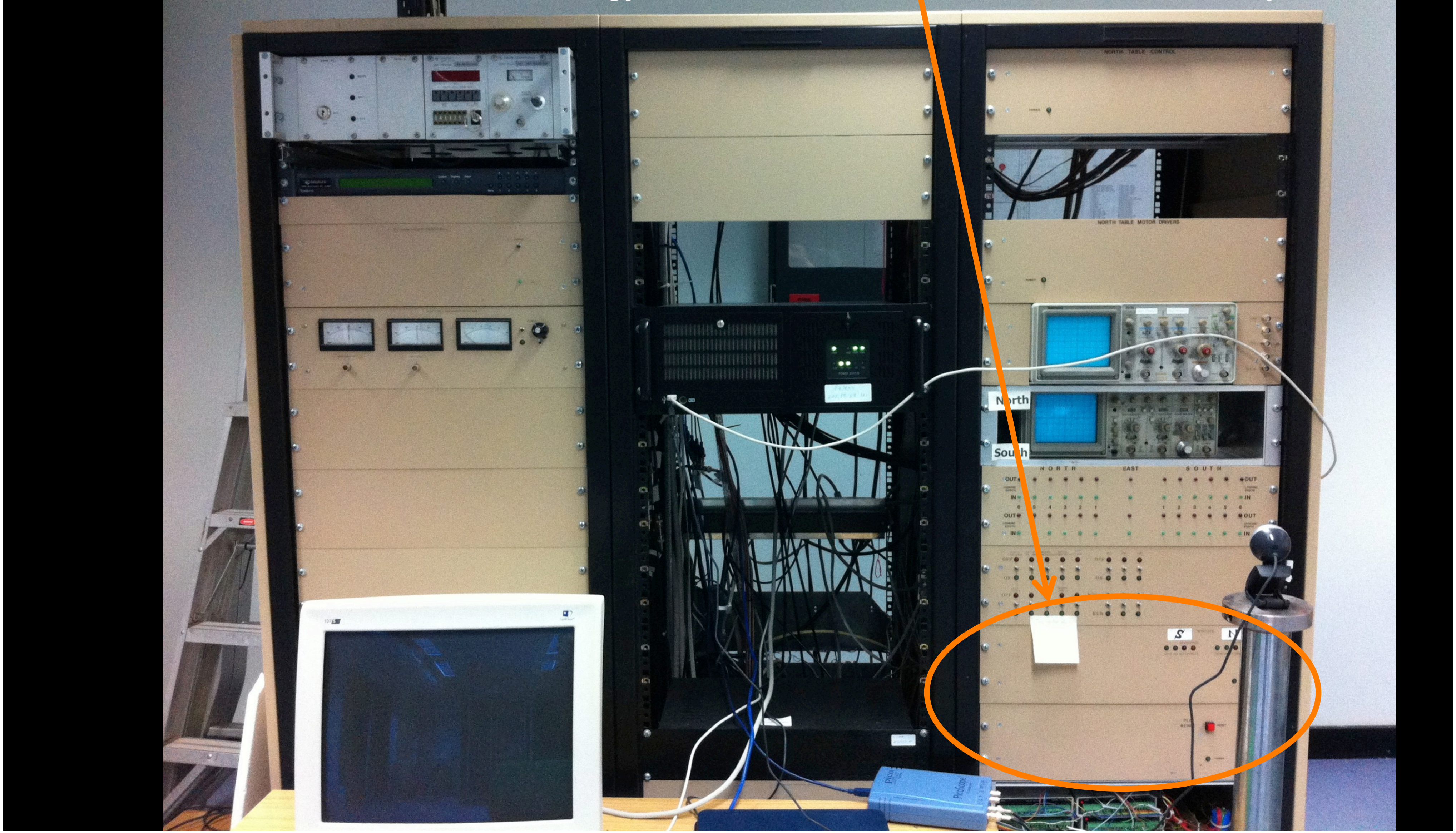
Kok et al., submitted

Optical Pathlength Compensator

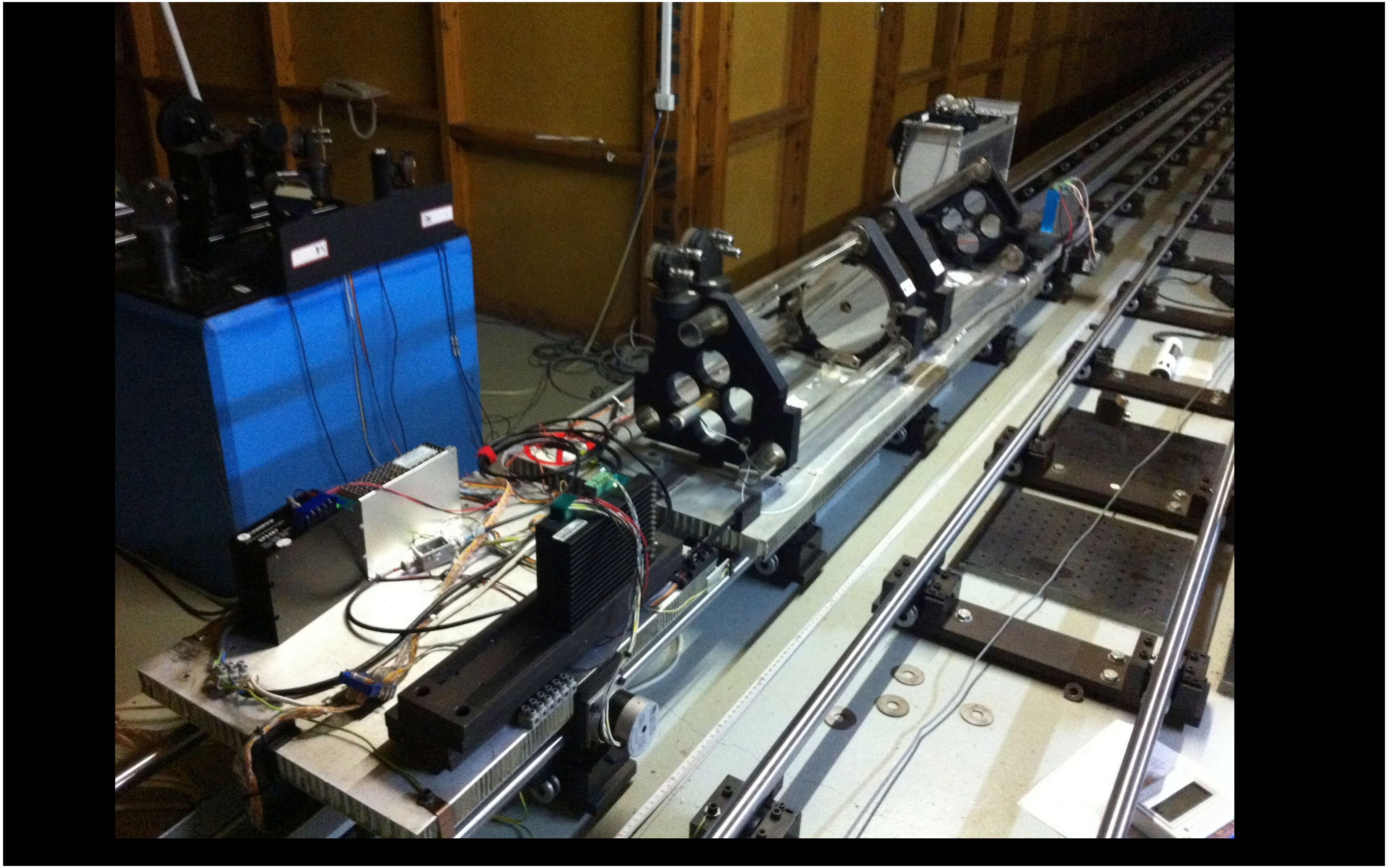


Speed wobbles esp at 2-3mm/s limited baseline. Electronics/software limitation…

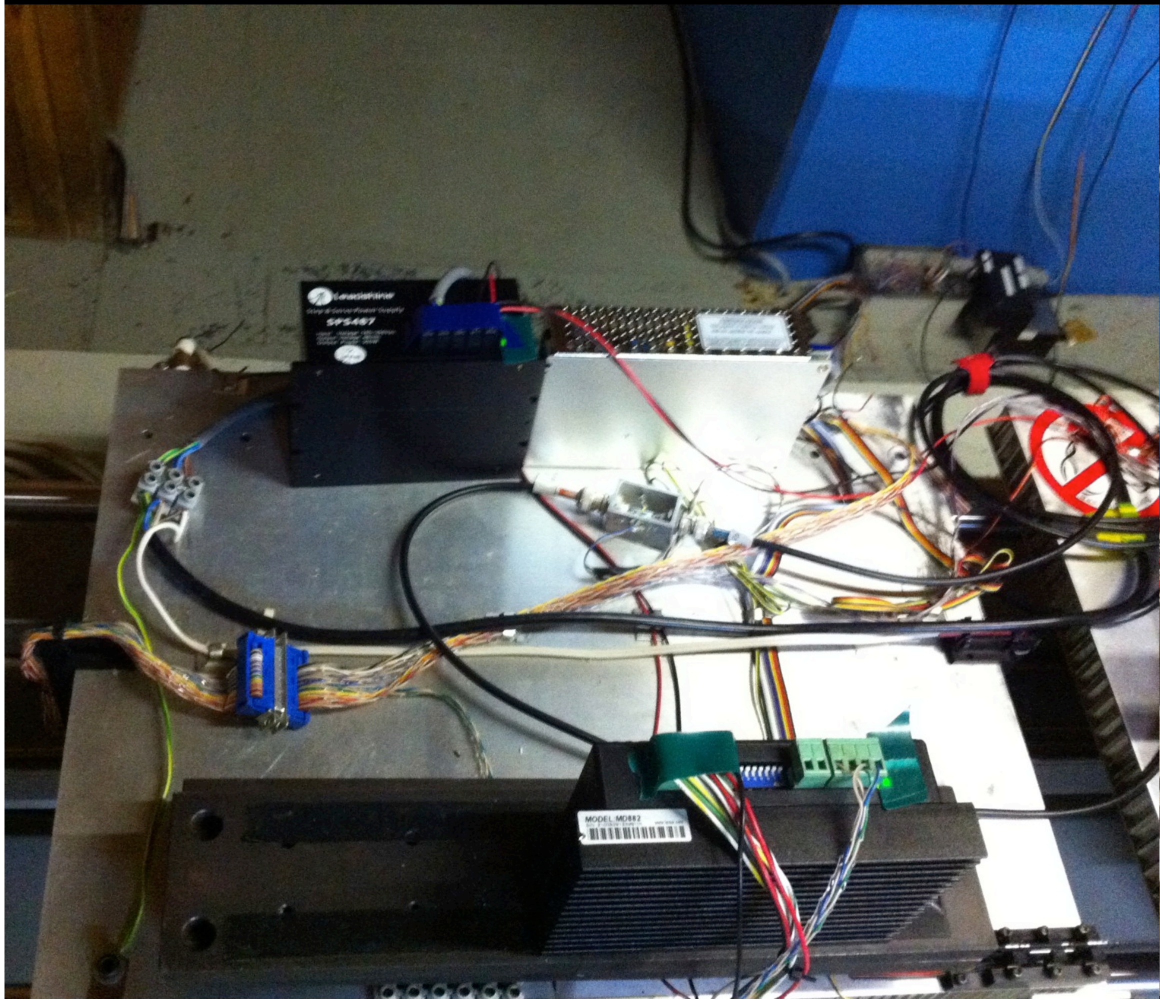
Hand-soldered discrete metrology electronics. Motorola 68000 computer.

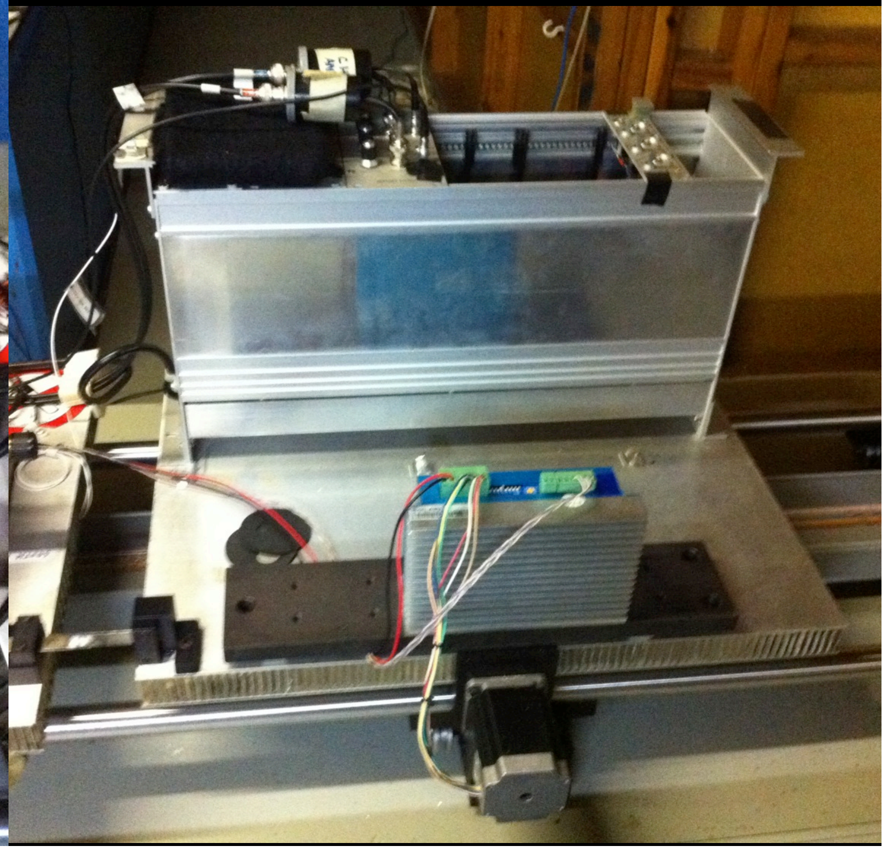


Now only 2 pcs in control room – no custom electronics.



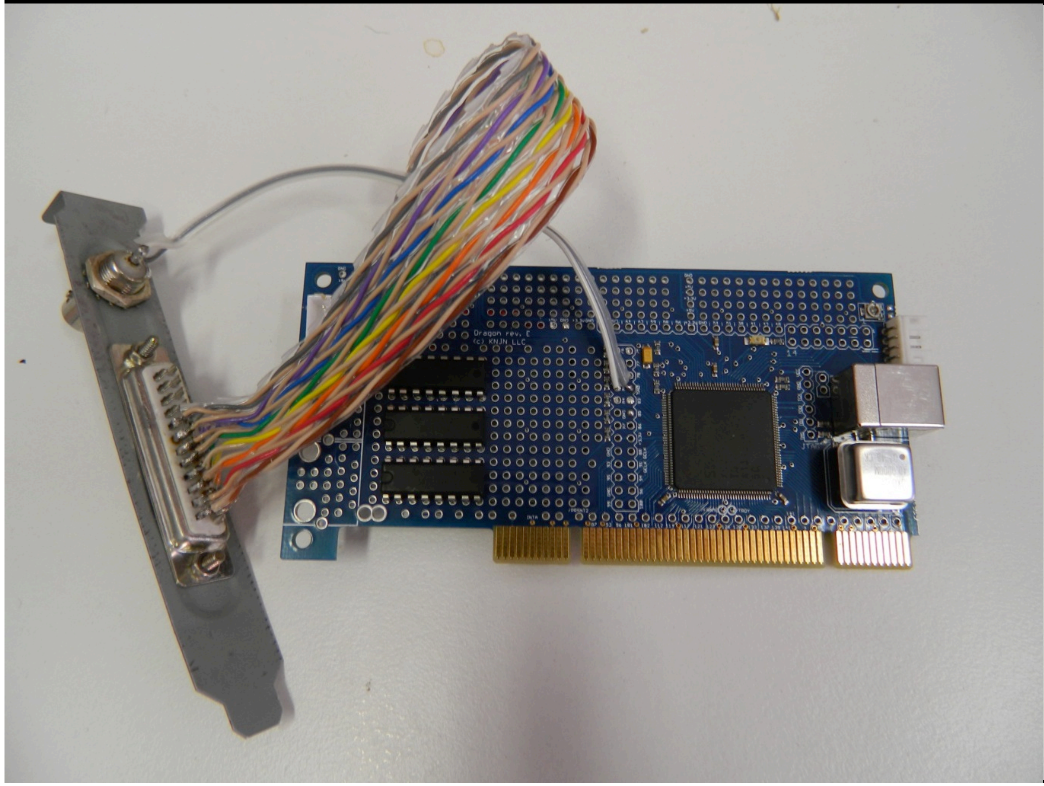
Commercial microsteppers, analog piezo signals

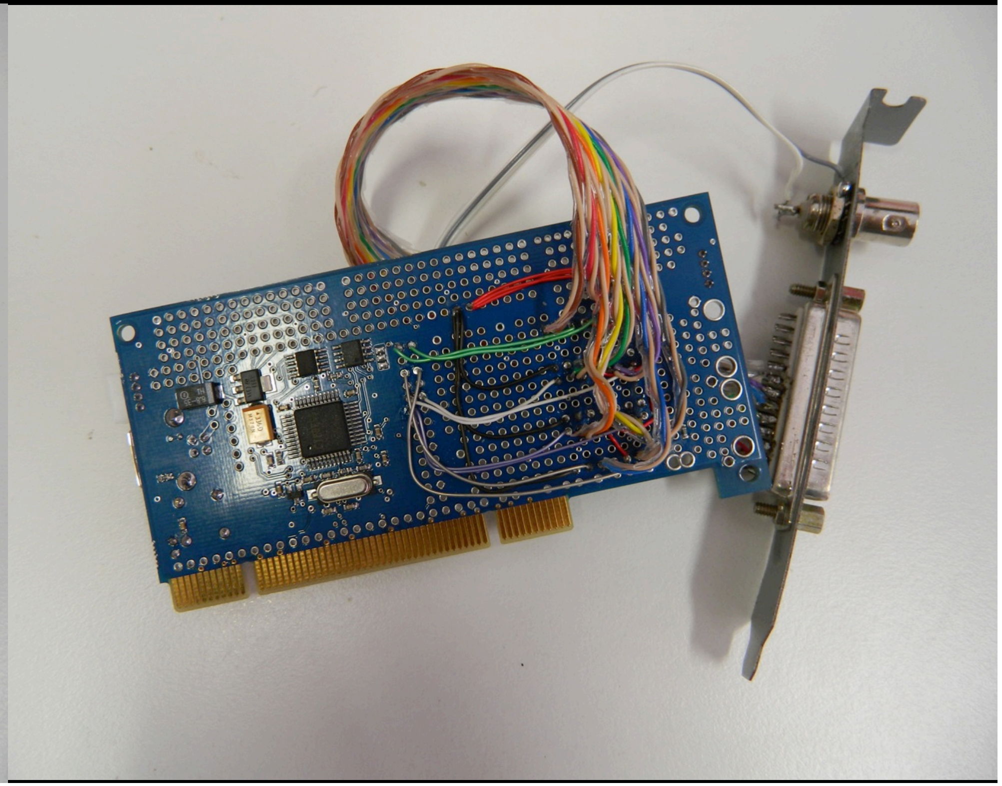




Metrology, motor control Functions on Cheap FPGA PCI card

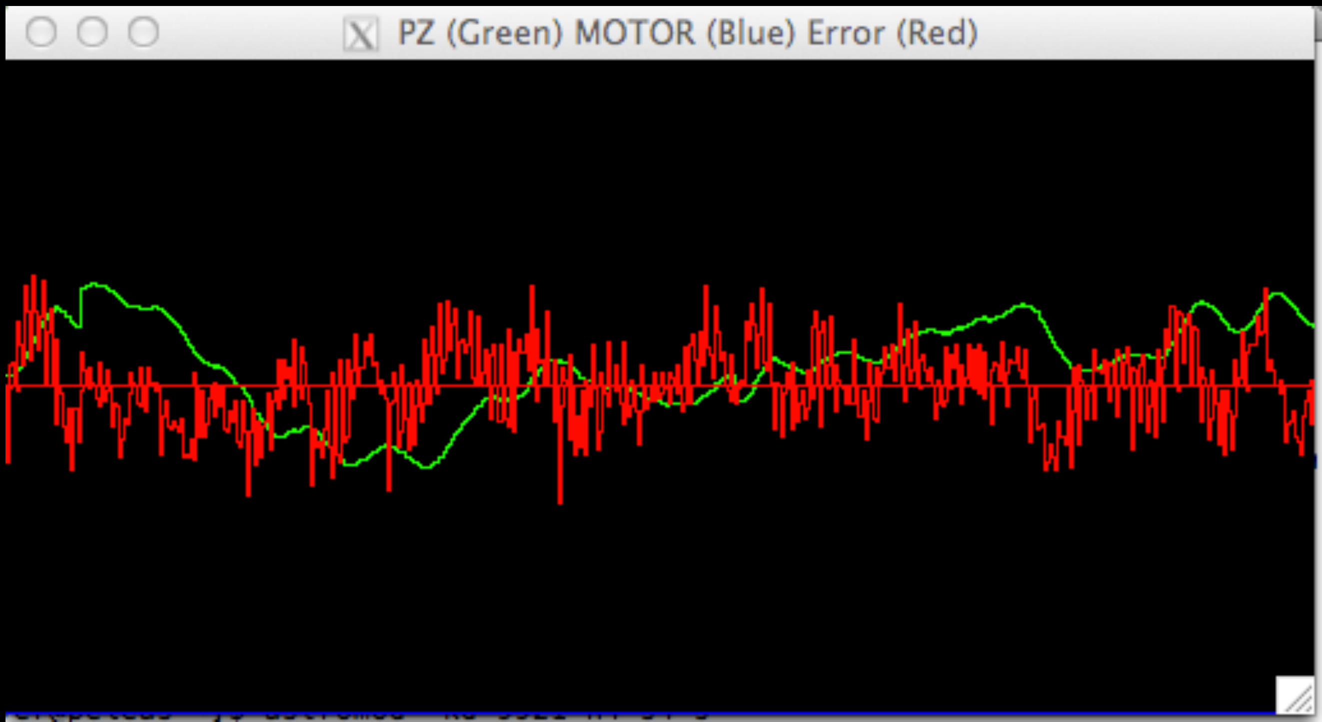
- PCI I/O verilog code came with Dragon PCI
- Metrology is another 35 lines of verilog – double the old resolution and 20 times the IO speed





Results…

- Reliable racking at 4mm/s OPD (used to have problems@2mm/s).
- Spare parts now, and easy expansion to e.g. voice coil.



Red: +/- 1 micron OPD

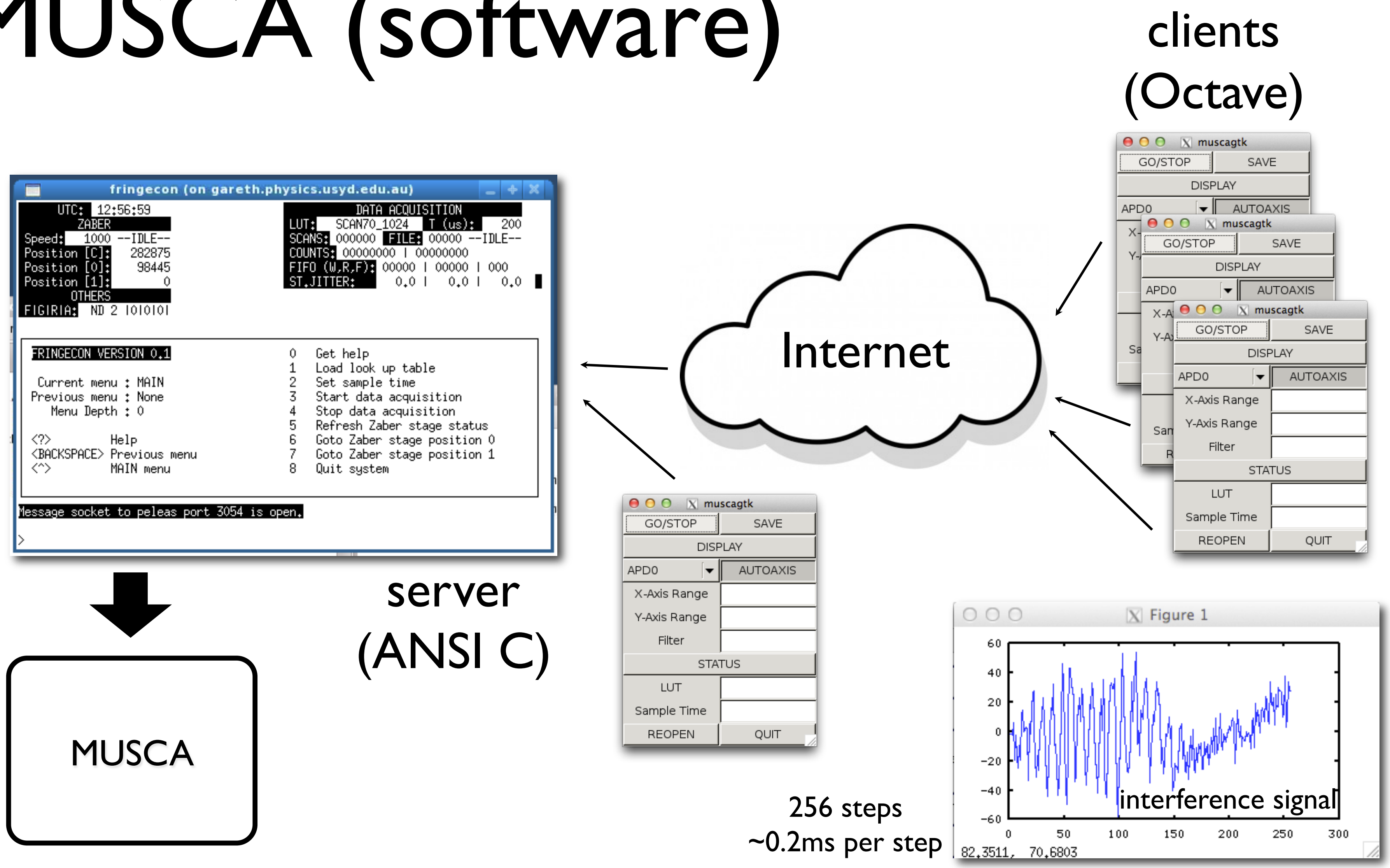
4mm/s OPD

MUSCA* – astrometry with SUSI

*mostly Yitping Kok's work

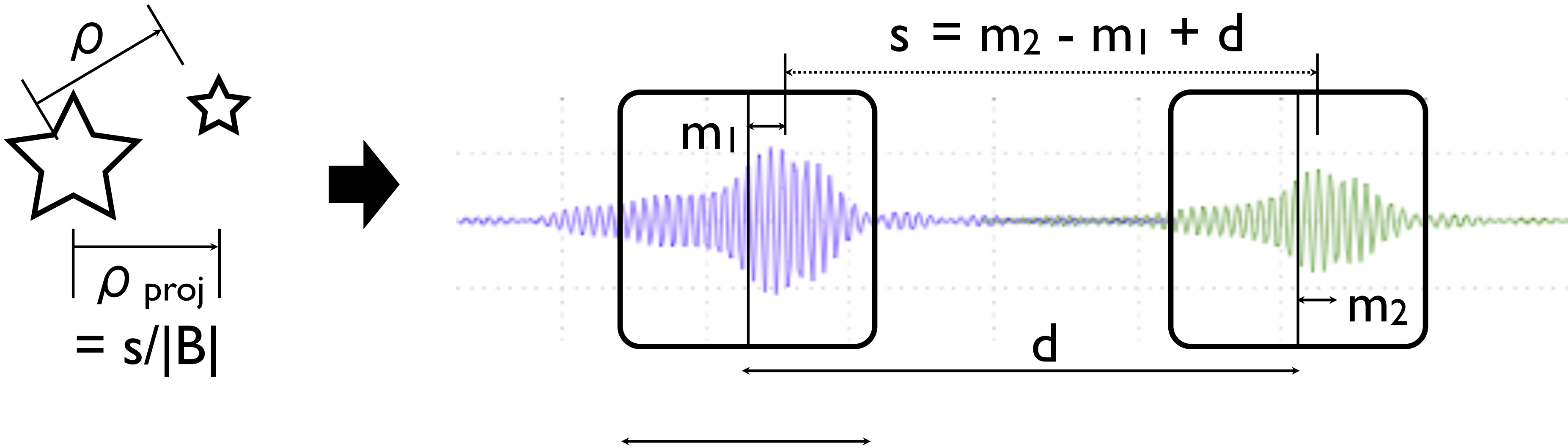
Spec	PHASES	ASTRA	PRIMA	GRAVITY	MUSCA
Key sciences	ExoP	ExoP, GC, AGN, YSO	ExoP, AGN, YSO	GC, AGN, ExoP	ExoP
Fringe-tracking band	K	K	K	K	~R
Science band	K	K	J, H, K, N	K	~0.85μm
Target-ref. stars separation	< 1"	5 - 30"	2 - 120"	< 2"	< 2"
Operational	2002 - 2008	2008 - 2012	2012? -	2014? -	2013? -
References	Lane & Muterspaugh (2004)	Woilez et al. (2010)	Delplancke (2008)	Gillessen et al. (2010)	Kok et al. (2012)

MUSCA (software)



Strategy

main observable = s



B ≡ baseline of interferometer

MUSCA scan range

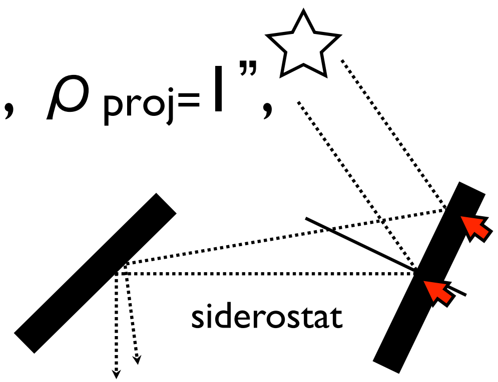
Limitation

Separation of two stars, ρ <2"

Magnitude of reference star, m_V<4

Challenges

- Optical alignment
  - Misalignment <1mm ($\delta\ \rho_{proj}$=10 μas, ρ_{proj}=1", B=100m)
- Optical path length measurement
  - Uncertainty <5nm



$$\frac{\delta \rho_{\mathrm{proj}}}{\rho_{\mathrm{proj}}} \approx \frac{\delta B}{B} + \frac{\delta s}{s}$$

Challenges

- ➡ Optical alignment
  - Misalignment <1mm ($\delta\ \rho_{proj}$=10μas, ρ_{proj}=1”, B=100m)
- Optical path length measurement
  - Uncertainty <5nm

Optical alignment

- LEDs (precisely) installed at siderostats
- Align LED images on the MUSCA camera
- Compute coordinate of centroid to sub-pixel precision
- 1 pixel = $9\mu m \times 9\mu m$
- Tolerance < 4 pixels

Challenges

✓ Optical alignment

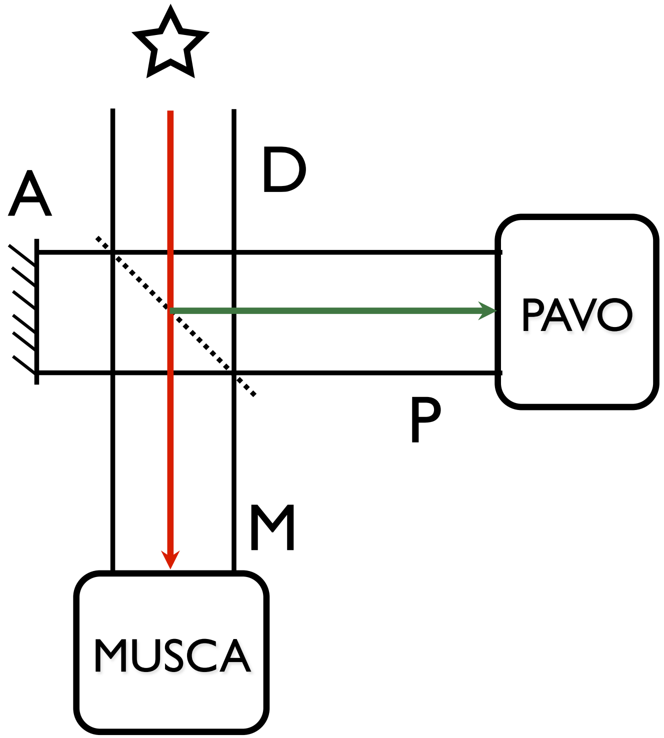
- Misalignment <1mm ($\delta\ \rho_{proj}$=10μas, ρ_{proj}=1”, B=100m)

➡ Optical path length measurement

- Uncertainty <5nm

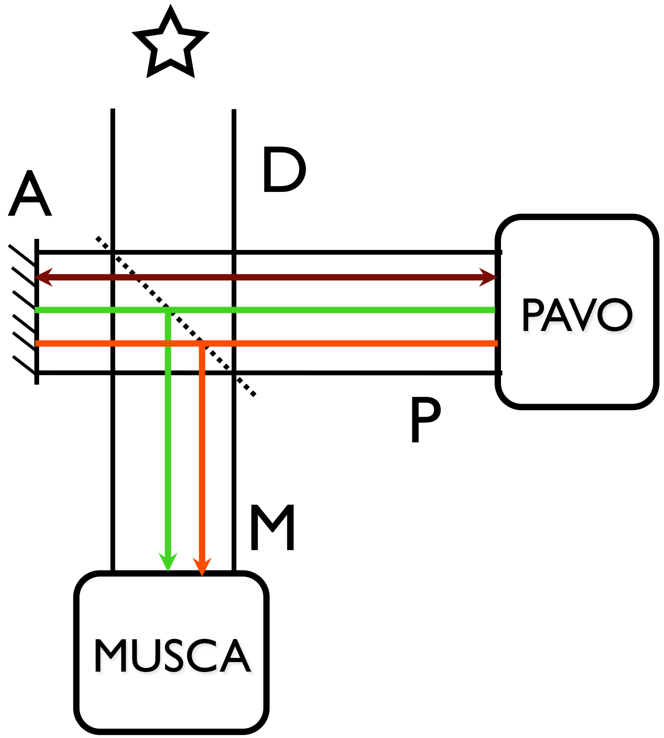
Metrology systems

- Science
  - $m_i = (OPD_D + OPD_{M,0}) + OPD_{\Delta M,i}$
  - $m_i = (x + z - w + d) + OPD_{\Delta M,i}$
- Fringe tracker
  - $z = OPD_D + OPD_P$

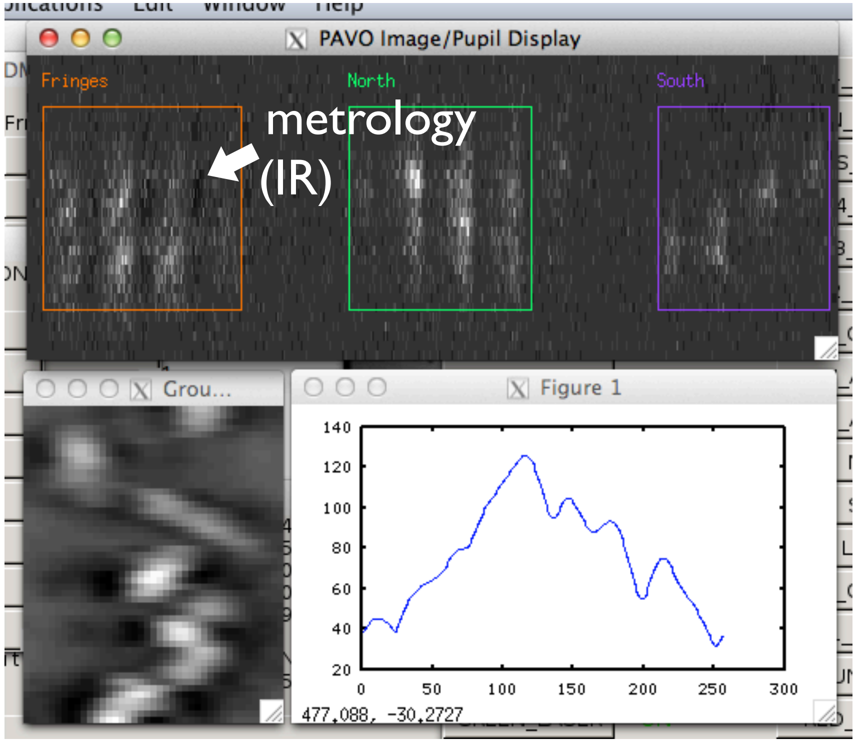


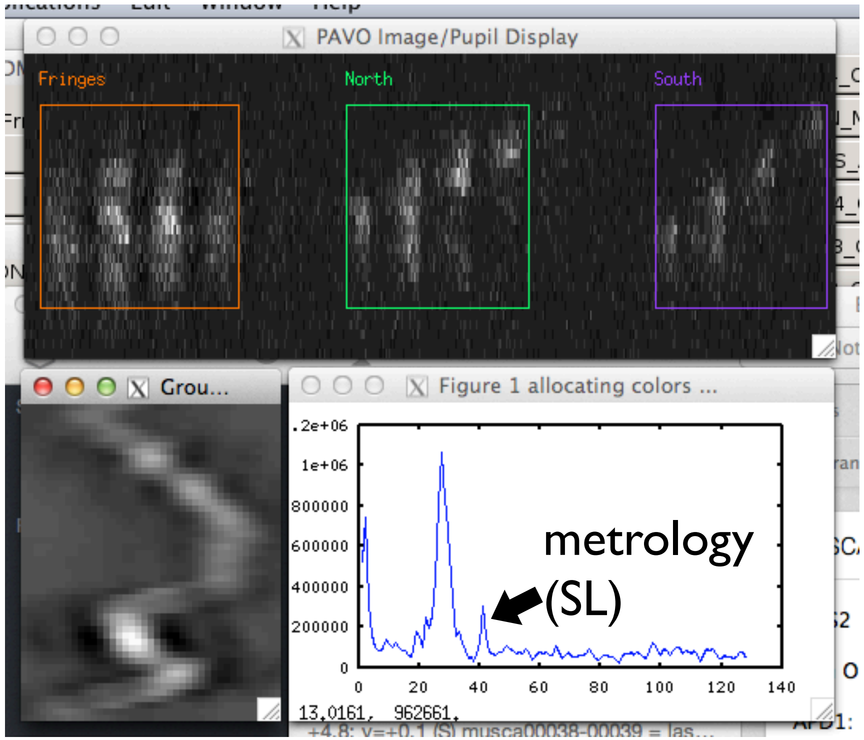
Metrology systems

- IR LED metrology
  - $w = 2OPD_P + 2OPD_A$
- Single laser (SL) metrology
  - $x = OPD_D + 2OPD_A + OPD_{M,0}$
- Dual laser (DL) metrology
  - $d = \Delta OPD_M$

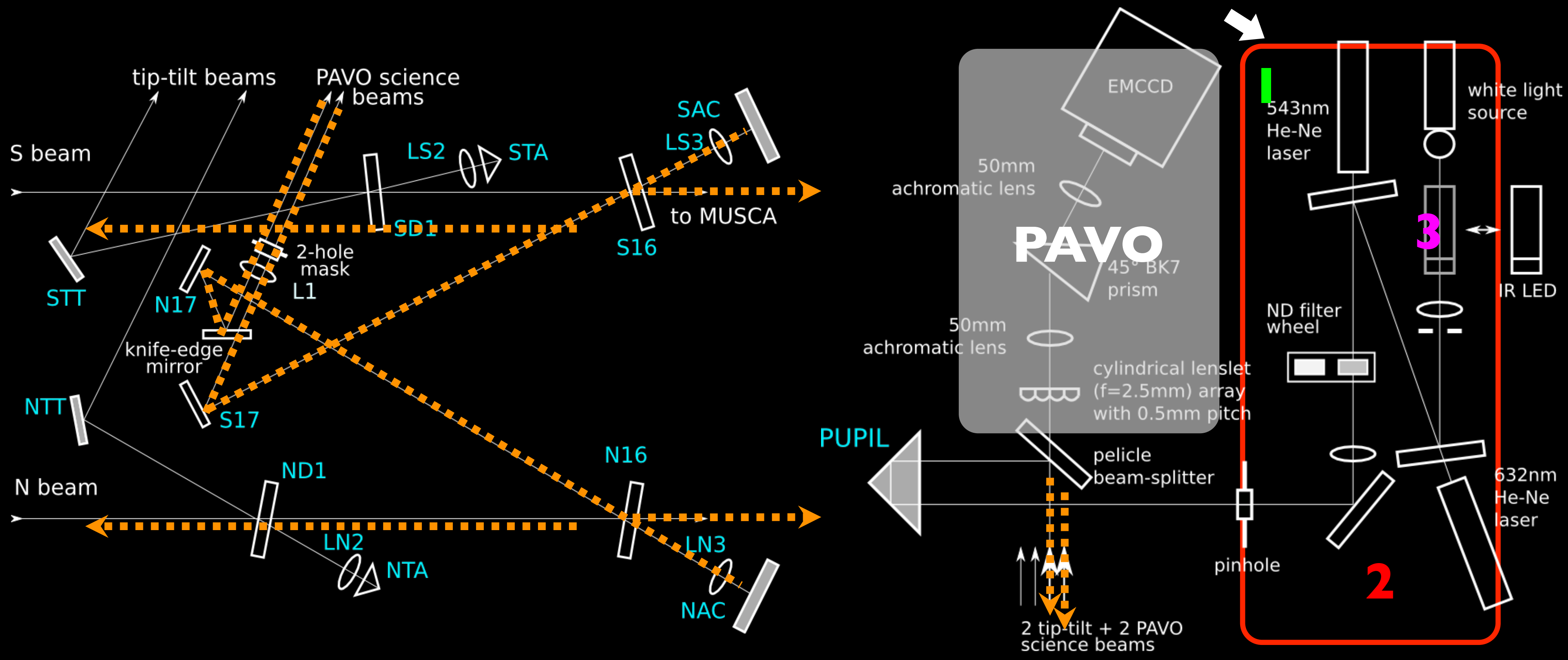


Metrology systems





Metrology systems



Challenges

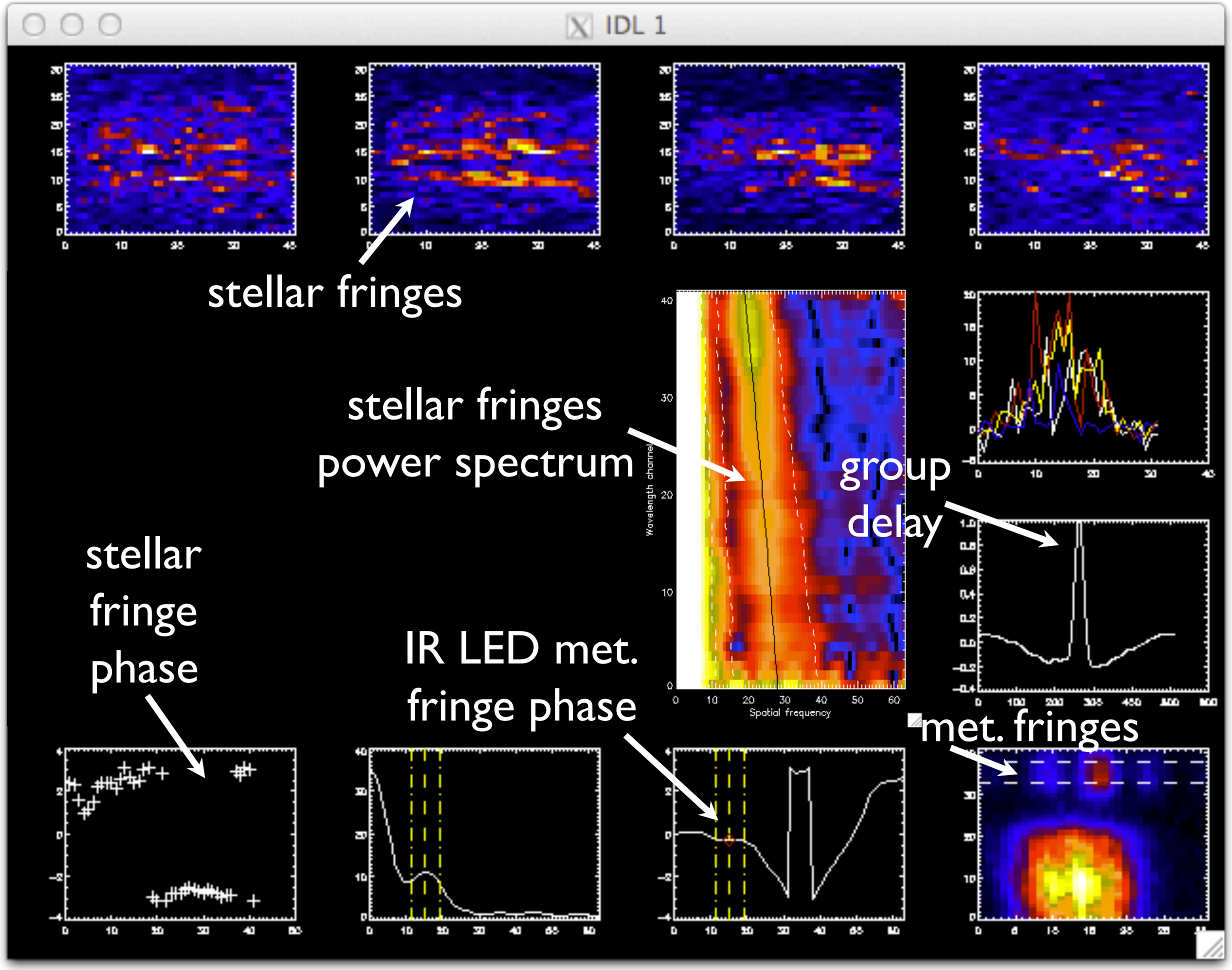
✓ Optical alignment

- Misalignment <1mm ($\delta\rho_{proj}$=10μas, ρ_{proj}=1”, B=100m)

✓ Optical path length measurement

- Uncertainty <5nm

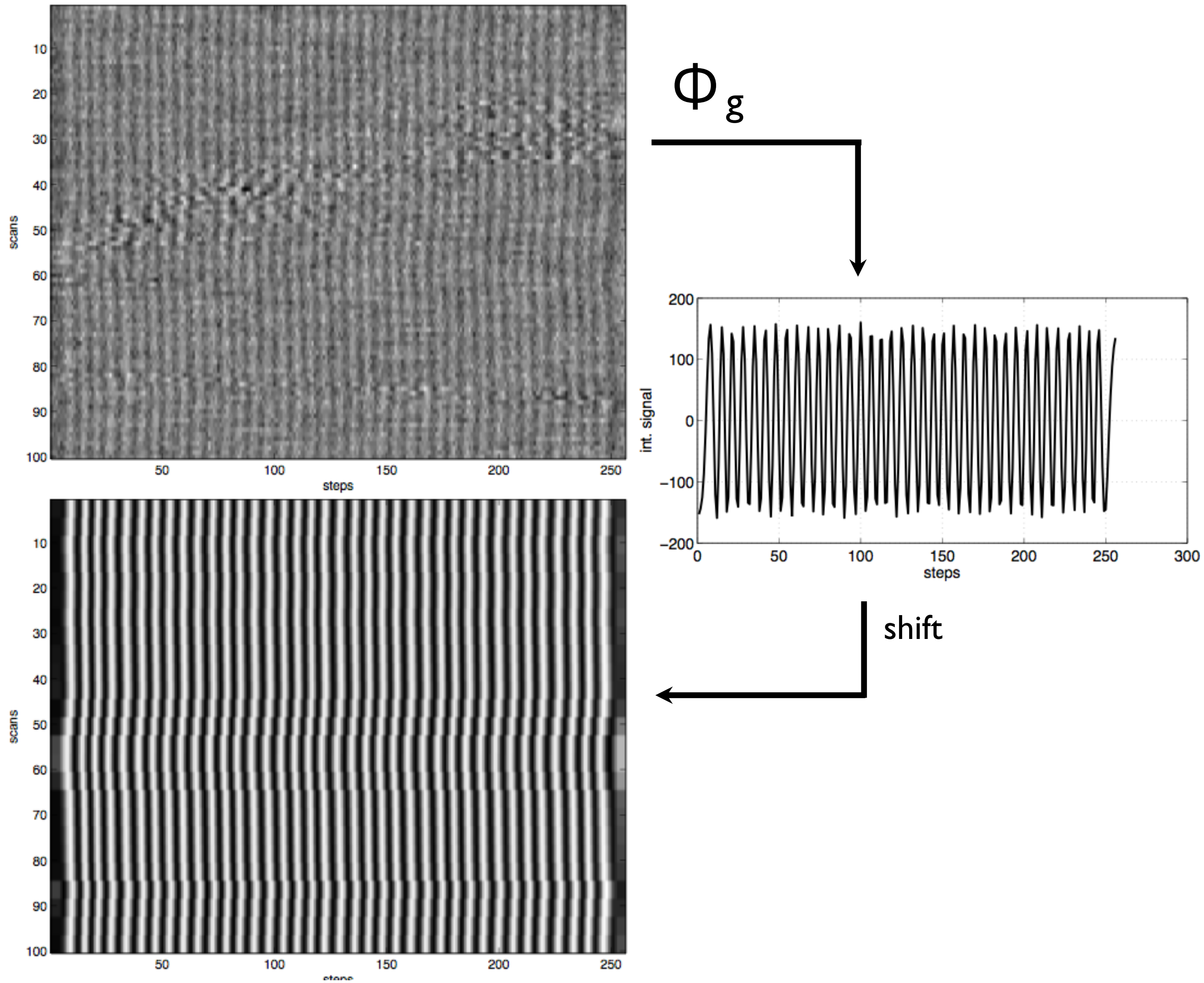
Fringe tracking & IR LED met. (PAVO)



- Estimate stellar fringe phase for PR
- Recover IR LED metrology fringes
- Monitor the n.c. optical path within PAVO

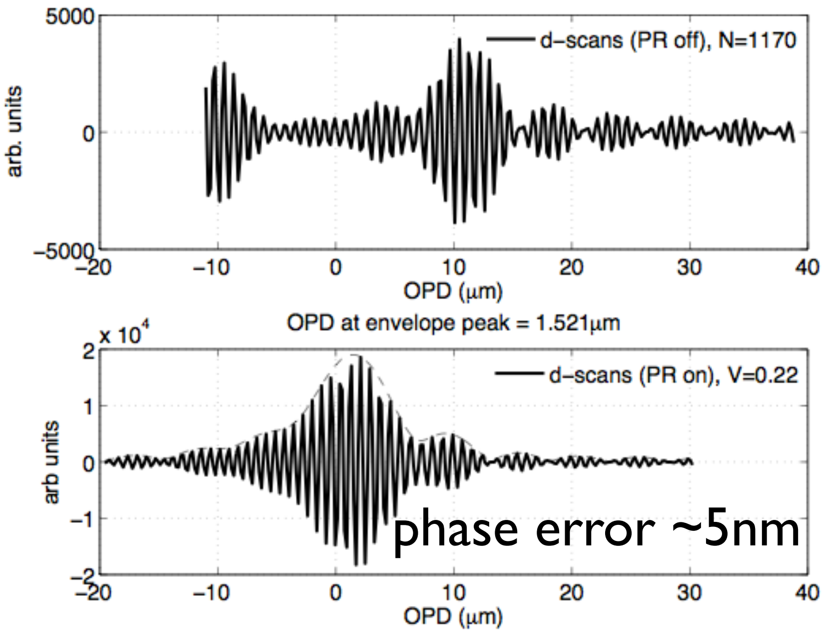
Kok et al., SPIE, 2012
Kok et al., 2013, submitted

single laser (SL) met. (MUSCA)



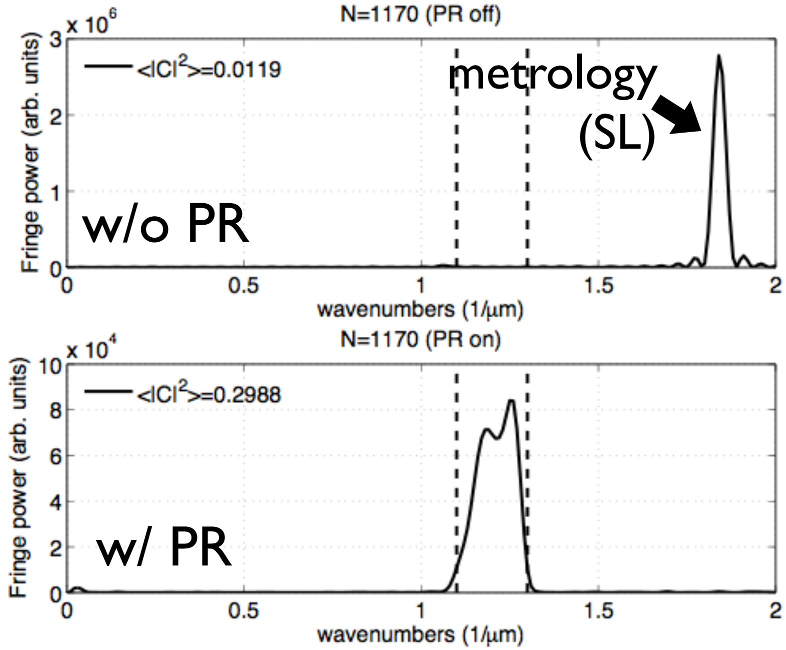
- Recover faint metrology laser fringes
- Monitor the n.c. optical path within MUSCA
- Measure optical delay of scan steps

fringe packet (1)



FT^{-1}

del Ori Aa

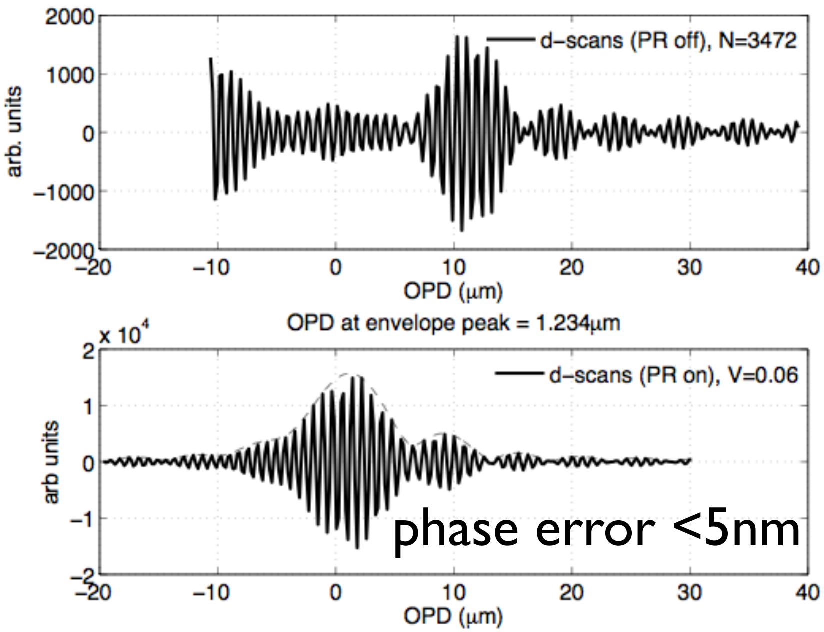


first self phase-referenced fringe packet (FP) at visible wavelengths

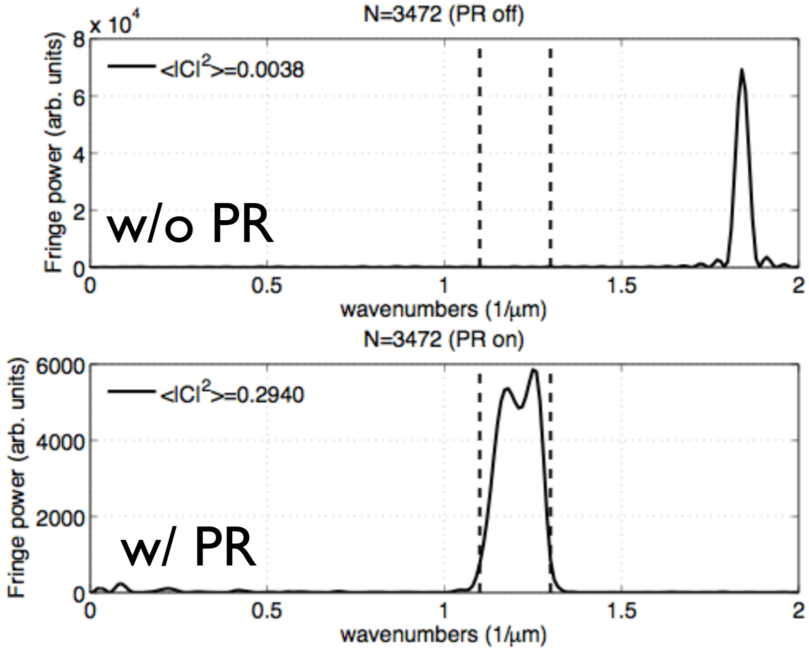
~1.4 mins of *good scans* in ~12 mins of observation

fringe packet (2)

del Ori Ab



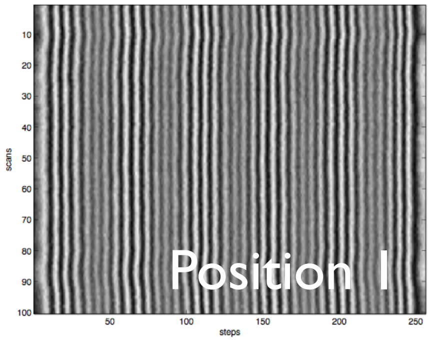
FT^{-1}

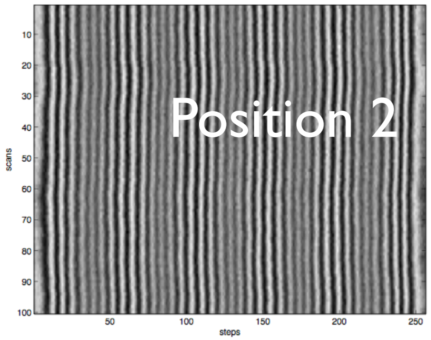


first dual-star phase-referenced
fringe packet at visible wavelengths

~3 mins of *good scans* in
~45 mins of observation

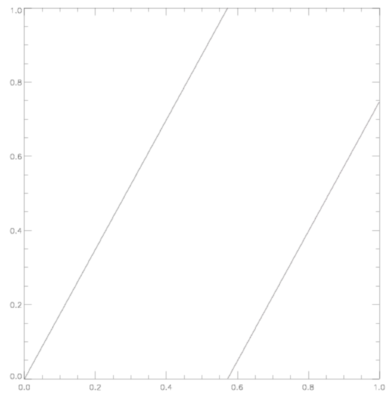
dual laser (DL) met.





NAR~400 μm

$\Delta\Phi_g$



$\Delta\Phi_r$

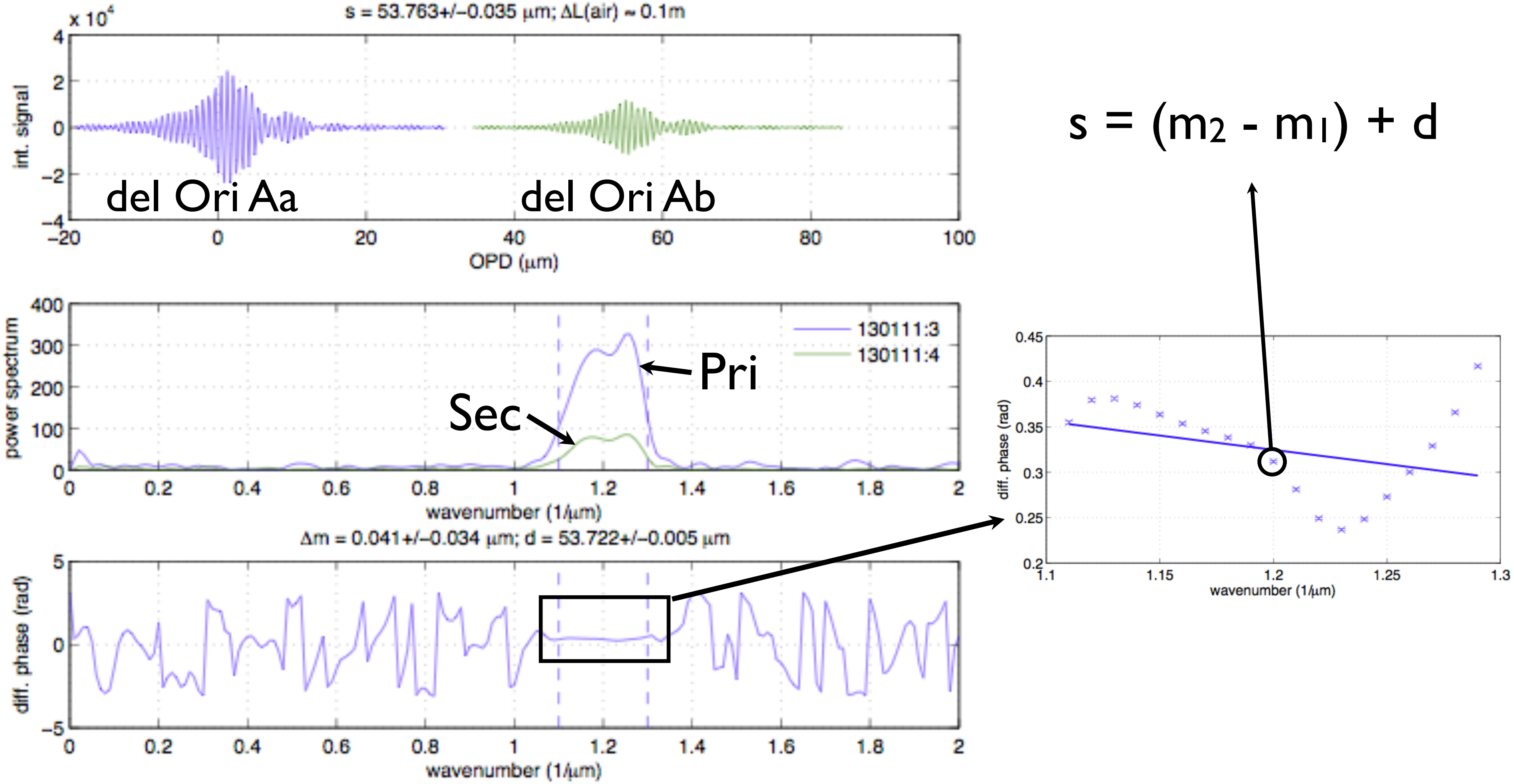
www.zaber.com

$\pm 15\,\mu$m

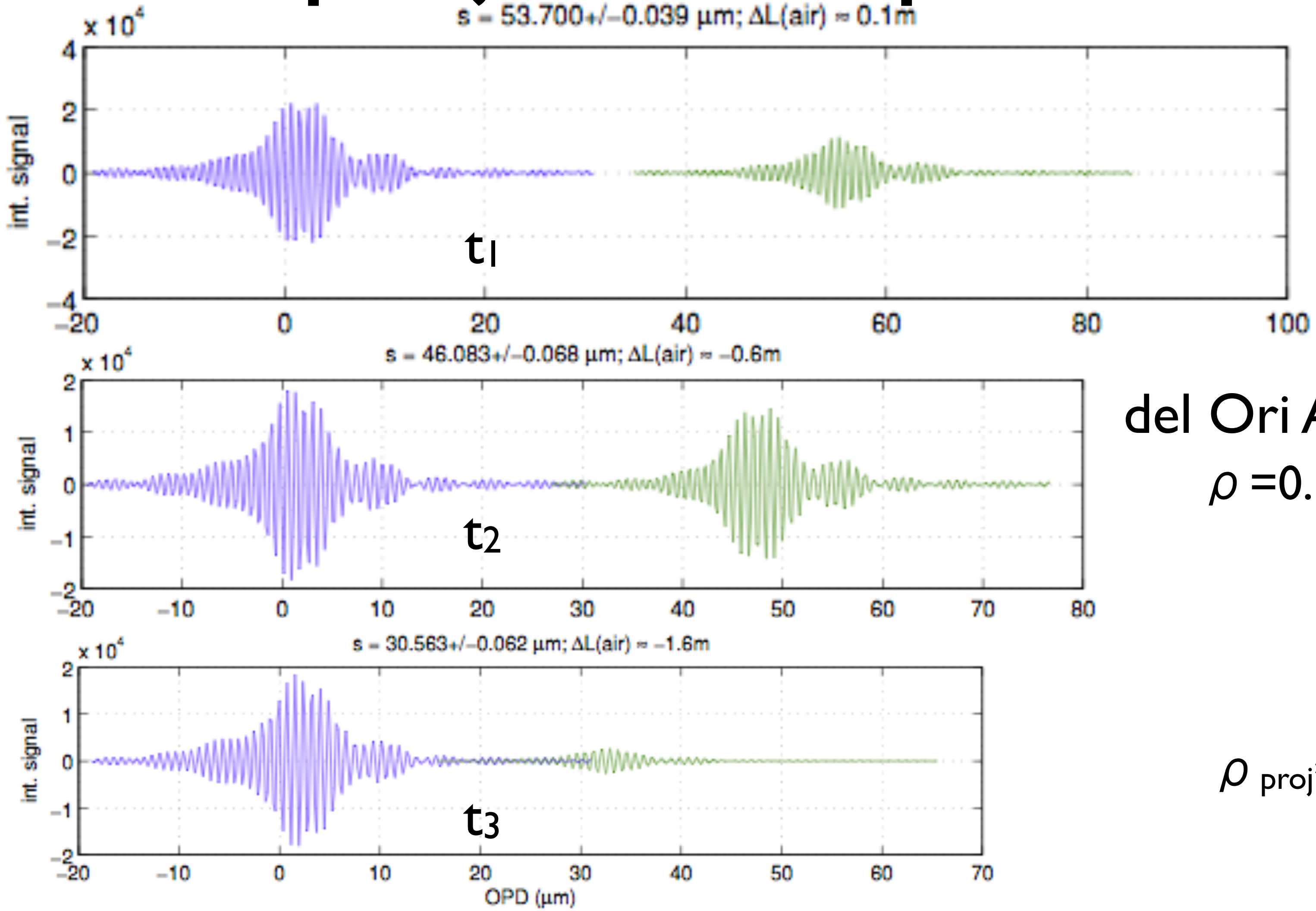
- Measure displacement of DDL in MUSCA
- Homodyne detection → low cost absolute metrology
- Utilizes a built-in open loop position control in the differential delay line
- Uncertainty of measurement <5nm after 500 scans
- Frequency-stabilized lasers not a must if d < 0.5mm

Kok et al., AO, submitted

fringe packets separation



projected separations



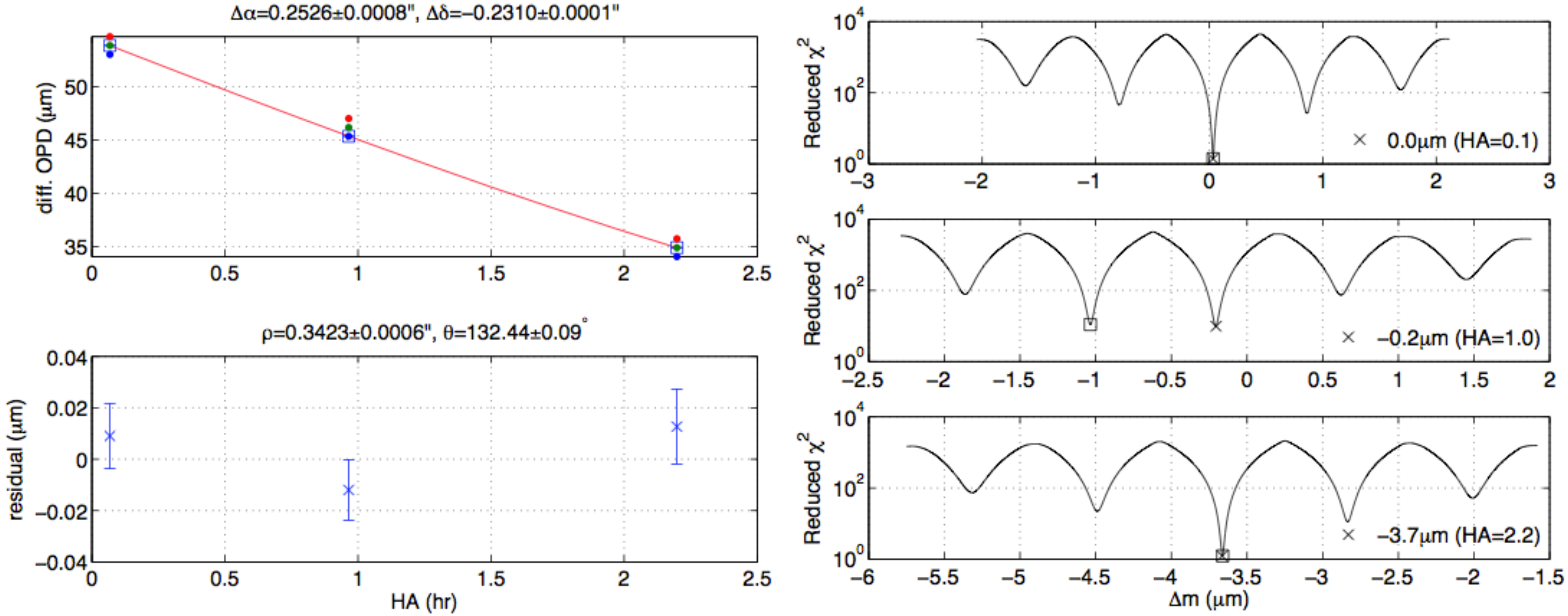
del Ori Aa, del Ori Ab

ρ =0.3”, θ =133°

ρ_{proj}≈0.11-0.18”

Astrometry & Dispersion Issues

Del Ori Aab



Astrometry often has one-wave ambiguity due to variable dispersion + extrapolating from PAVO to MUSCA

Milestones

- ✓ Hardware design and installation
- ✓ On-sky fringes (1st light: 2011)
- ✓ Self phase-referencing
- ✓ Dual star phase-referencing
- ▸ High-precision narrow-angle astrometry
- • Routine observations

MUSCA Conclusions

- MUSCA + metrology systems in test phase
- Minimal cost
- Phase-referencing of MUSCA can achieve $\lesssim$5nm phase precision in <5mins of good scans
- Demonstrated dual star phase-referencing in visible wavelengths for the first time
- Demonstrated narrow-angle astrometry
- Next step, *high-precision* narrow-angle astrometry

BUT… the PAVO phase-referencing magnitude limit has not been in-practice good enough for the science goals.

- A better site (e.g. Antarctica) and larger aperture would help.

What Next?

- SUSI's sensitivity of V=5.5 in excellent conditions is not as good as it could be, but is enough for science with PAVO.
- The SUSI group will find the ~$10,000 per year and occasional on-site visits to keep running for now, but real science explotation requires outside interest.
- Sensitivity partly limited by throughput (e.g. Ireland 2006 PhD thesis).
- Also limited by low V^2 which isn't understood – system V^2 often around 0.25 despite spatial filtering and a 5ms exposure time.
- A ~0.5 mag gain could come from post-processing aberration correction (not fully implemented in software).