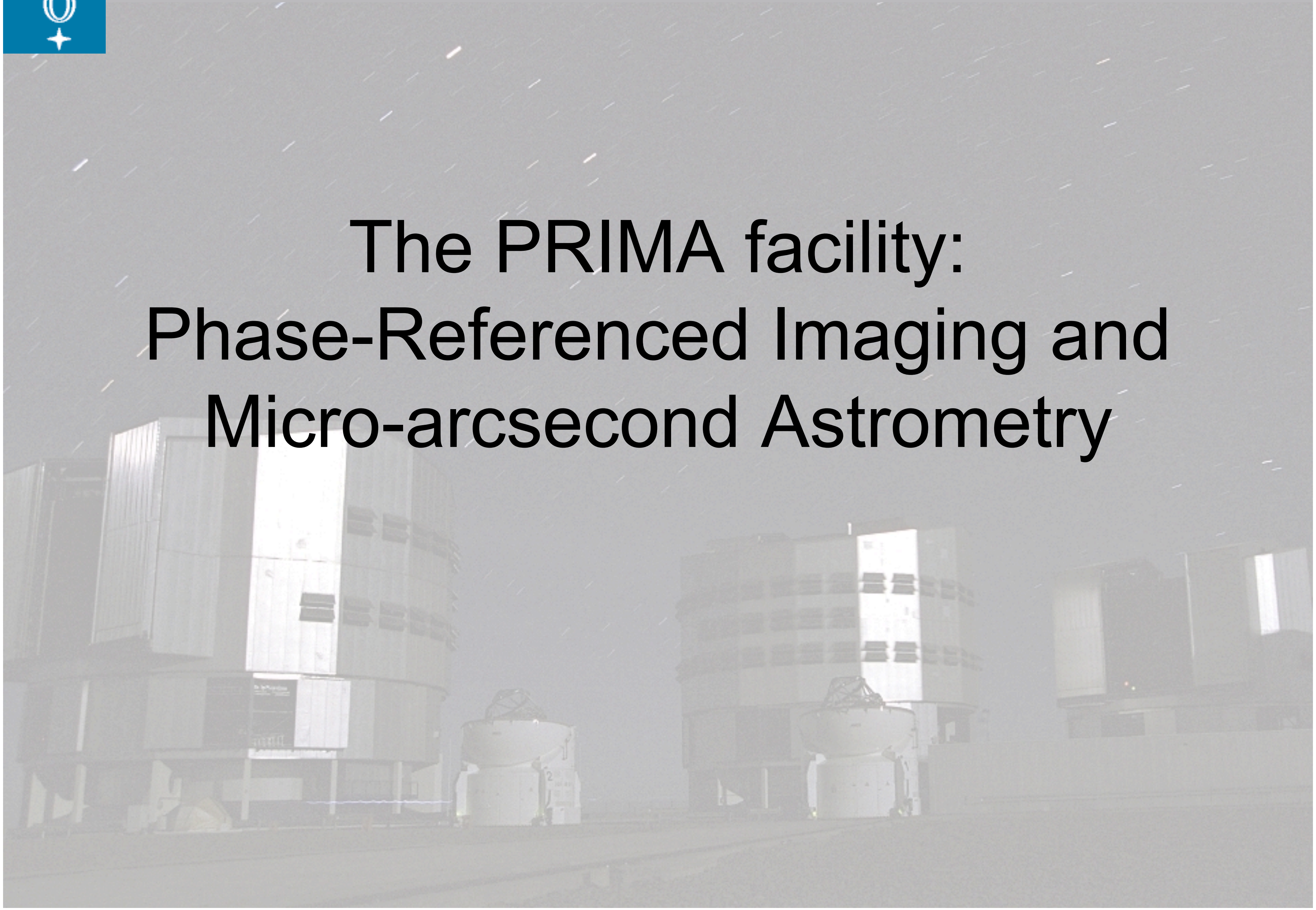
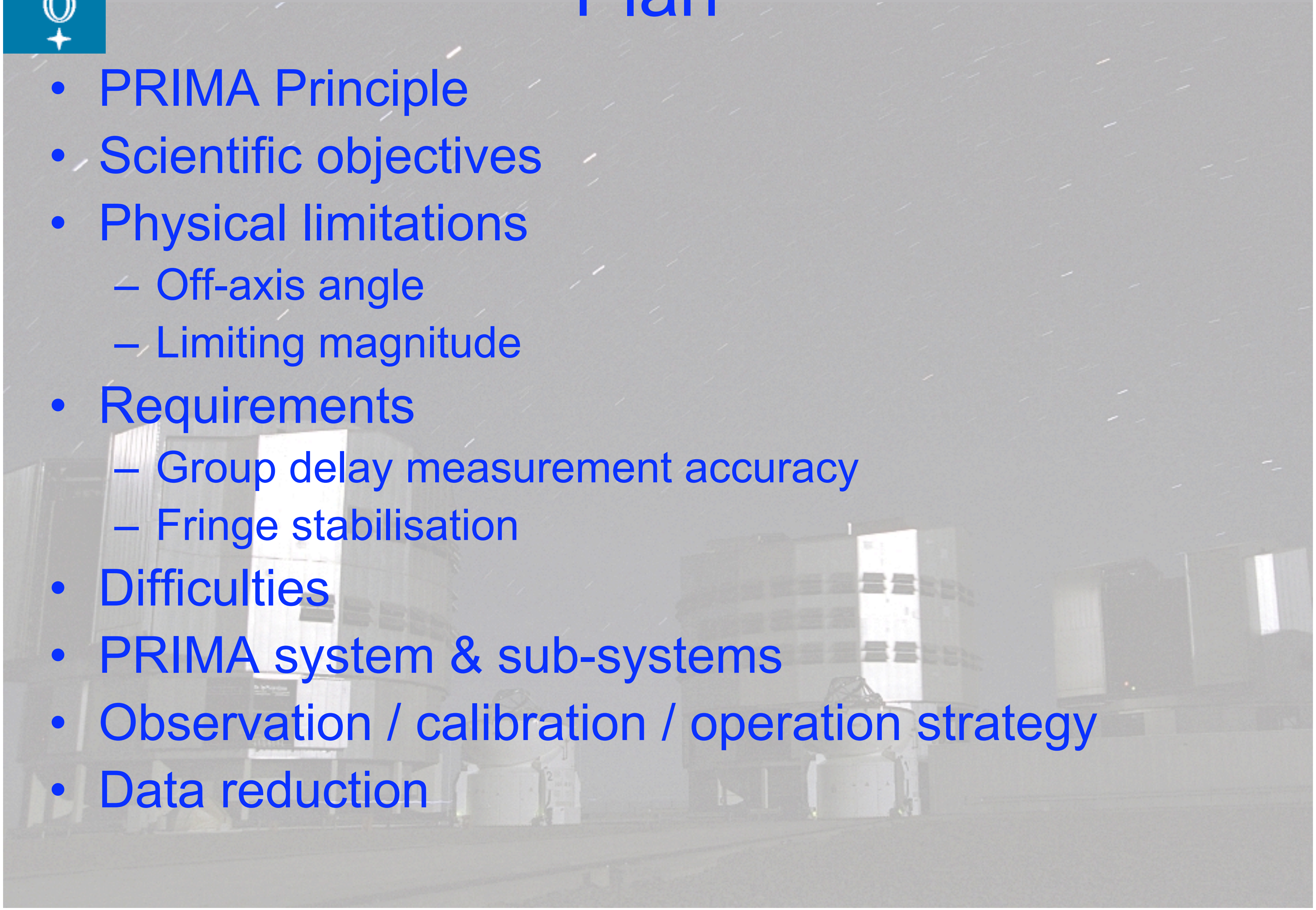
The PRIMA facility:
Phase-Referenced Imaging and Micro-arcsecond Astrometry





Plan

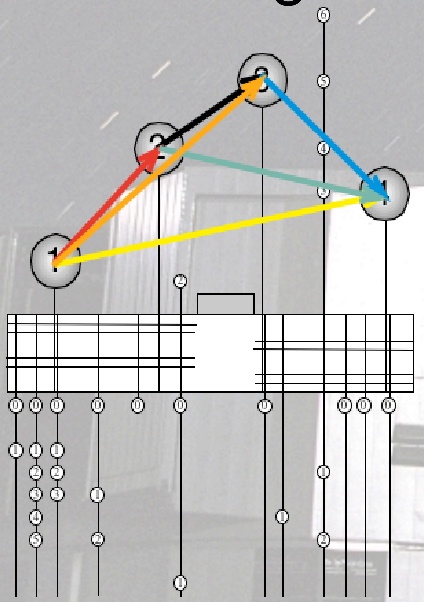
- PRIMA Principle
- Scientific objectives
- Physical limitations
  - Off-axis angle
  - Limiting magnitude
- Requirements
  - Group delay measurement accuracy
  - Fringe stabilisation
- Difficulties
- PRIMA system & sub-systems
- Observation / calibration / operation strategy
- Data reduction

PRIMA motivation

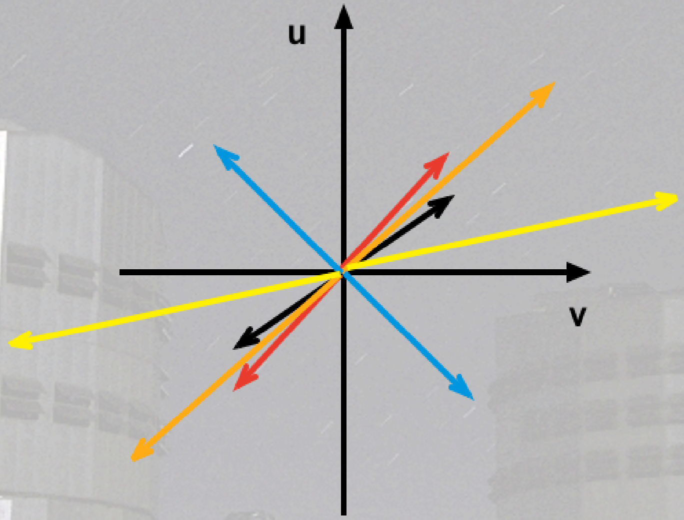
- Main limitation of ground interferometers = atmospheric turbulence =>
  - Fast scrambling of the fringes => snapshots
    => short integration time (~ 50 ms in K)
    => low limiting magnitude (VINCI => K~8 on UT)
  - Impossibility to measure the absolute position / phase of the fringes accurately
    - Fringe position (introduced OPD) <=> astrometry
    - Fringe phase <=> imaging
- Solutions:
  - "Adaptive optics for the piston term" => increase the limiting magnitude
  - Find a phase reference (as quasars in radio astronomy) => phase-referenced imaging and differential astrometry

u-v plane and reconstructed PSF

- Image intensity: $I_{im}(\alpha)$ = IFT ($\Gamma(u_1 - u_2)$) (inverse the Fourier transform)
  with $u_1 - u_2$ = baseline vector and Γ = complex visibility
- Good "synthetic aperture reconstruction" if good u-v coverage

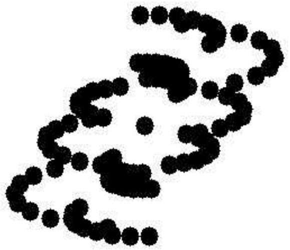


This is NOT the u-v plane

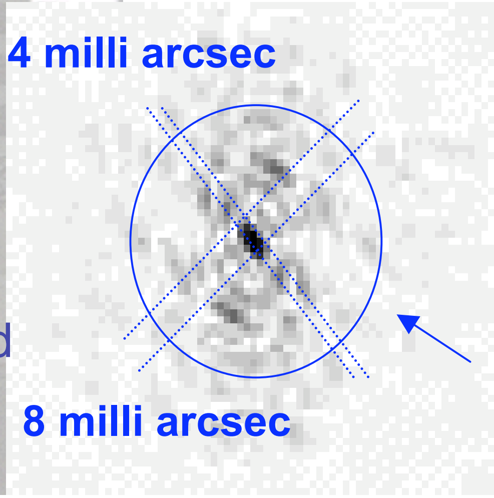


This IS the u-v plane

u-v coverage
(UT 8 hours δ=-15º)

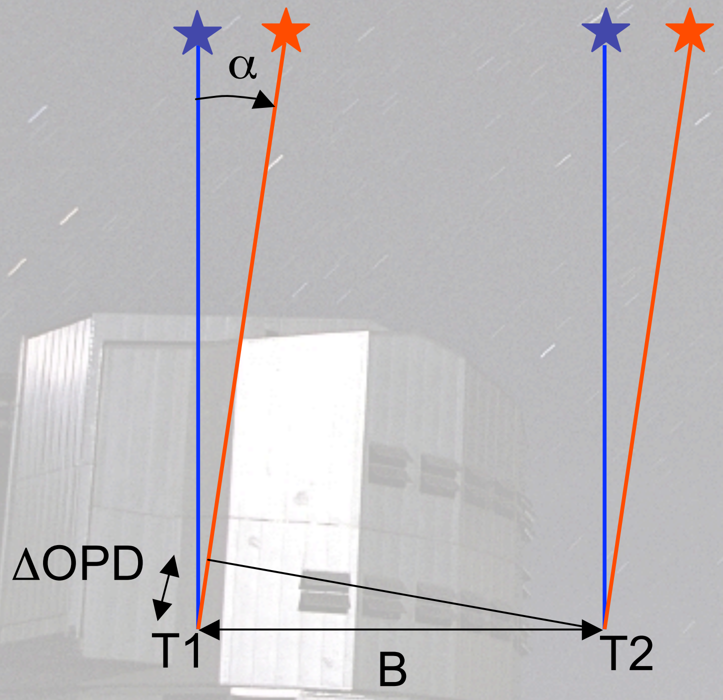


Reconstructed
PSF
K-band



Airy disk
UT

Narrow-angle differential astrometry

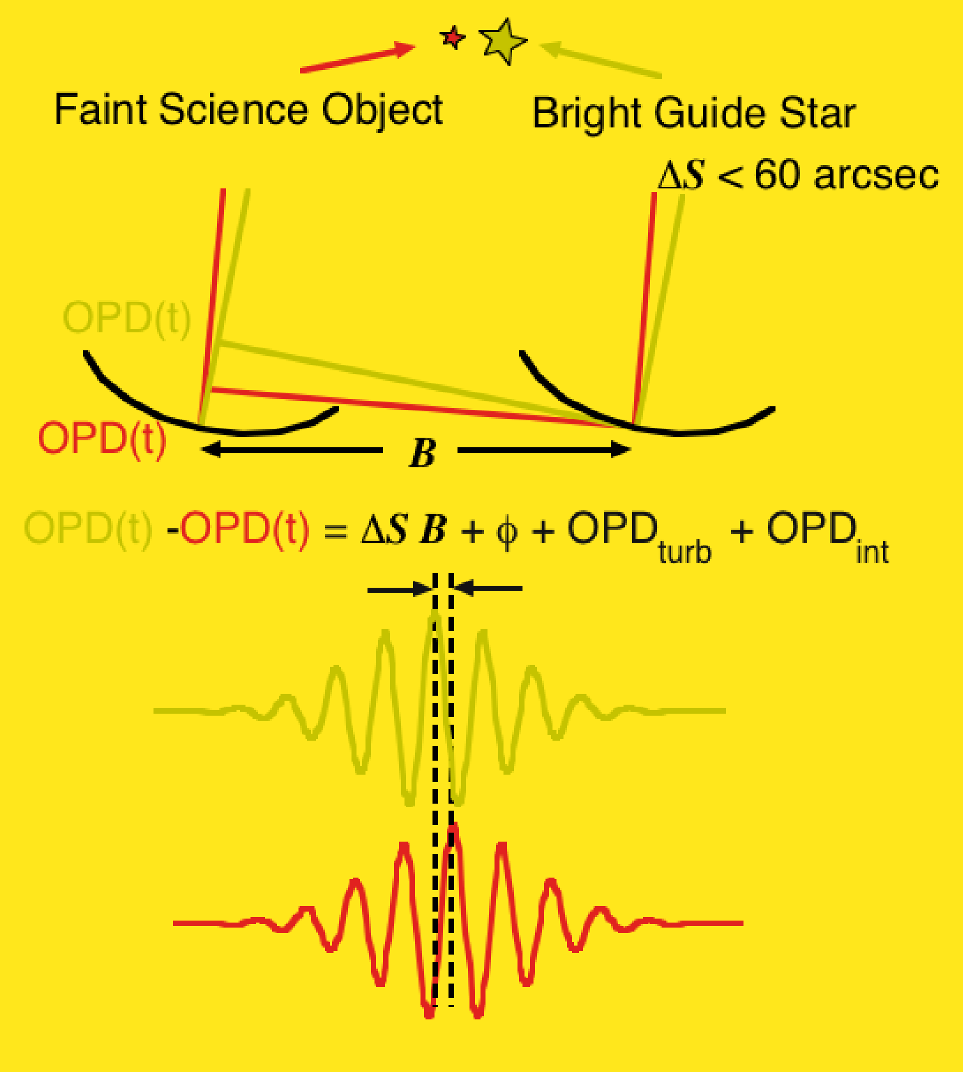


- Observe two stars simultaneously
- Slightly different pointing directions => ΔOPD to be introduced in the interferometer, between the two beams to get the fringes

$$\Delta OPD = B\ .\ \sin \alpha$$

- Moreover, the differential astrometric piston introduced by the atmosphere is several order of magnitude lower than the full piston => these perturbation (of the measured angle) average to zero rapidly
  - ~ 30 min for 10” separation and 200 m baseline

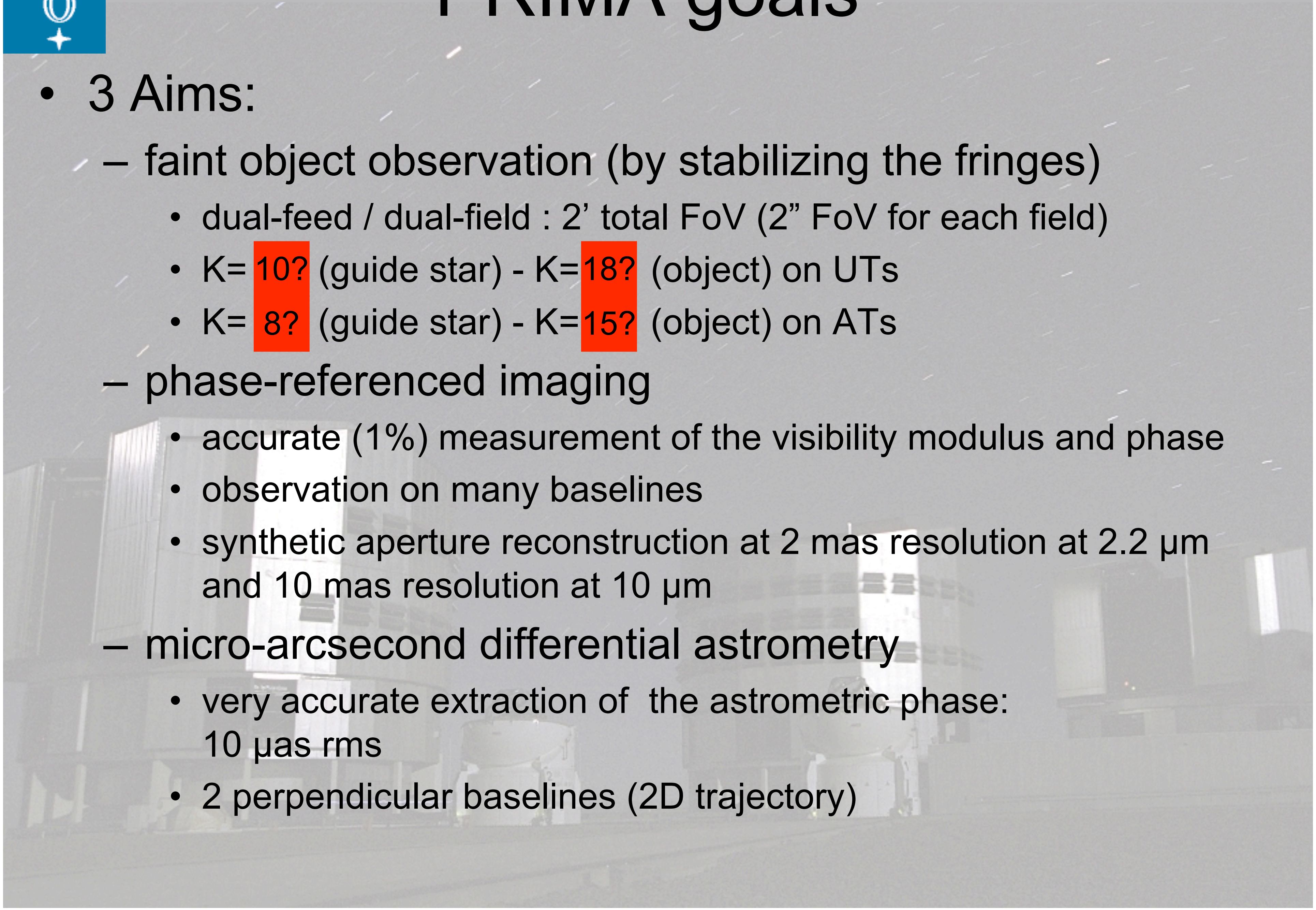
Phase-referencing + astrometry



- Pick up 2 stars in a 2 arcmin field
  - bright star for fringe tracking
  - faint object / star
- $\Delta\mathrm{OPD} = \mathbf{\Delta S.B} + \phi + \mathrm{OPD}_{turb} + \mathrm{OPD}_{int}$
  - OPD_{int} measured by laser metrology
  - OPD_{turb} mean tends to 0
  - $\Delta\mathrm{OPD}$ measured by VINCI / AMBER / MIDI / FSU
  - **ΔS** => object position => astrometry
  - ϕ => object phase => imaging
- complex method but very powerfull
  - many baselines => many nights
- synthetic aperture imaging @ 2mas resolution
- astrometry @ 10 μas precision

The scientific objectives

- General
- Stellar environments
  - young stars
  - evolved stars
  - binaries
- AGNs
- Planets =>
  - differential astrometry
  - gravitational microlensing



PRIMA goals

- 3 Aims:
  - faint object observation (by stabilizing the fringes)
    - dual-feed / dual-field : 2’ total FoV (2” FoV for each field)
    - K= 10? (guide star) - K=18? (object) on UTs
    - K= 8? (guide star) - K=15? (object) on ATs
  - phase-referenced imaging
    - accurate (1%) measurement of the visibility modulus and phase
    - observation on many baselines
    - synthetic aperture reconstruction at 2 mas resolution at 2.2 µm and 10 mas resolution at 10 µm
  - micro-arcsecond differential astrometry
    - very accurate extraction of the astrometric phase: 10 µas rms
    - 2 perpendicular baselines (2D trajectory)

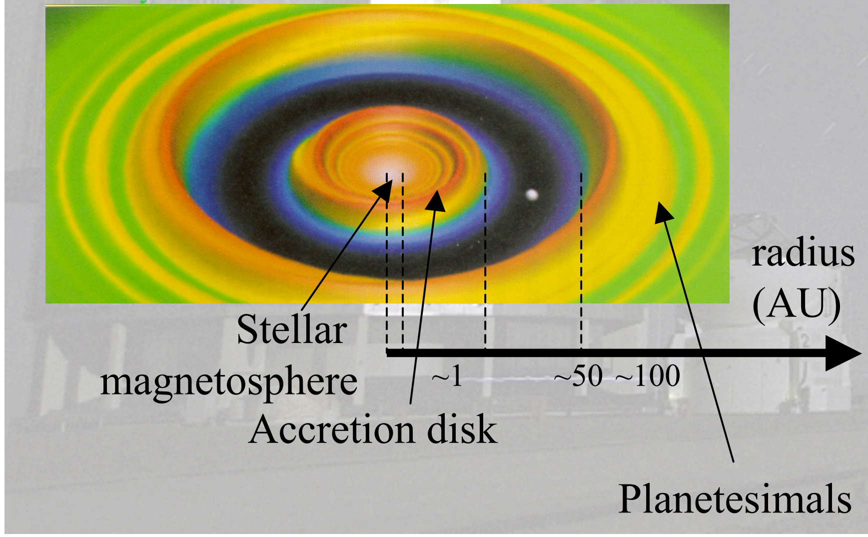
Scientific objectives - imaging

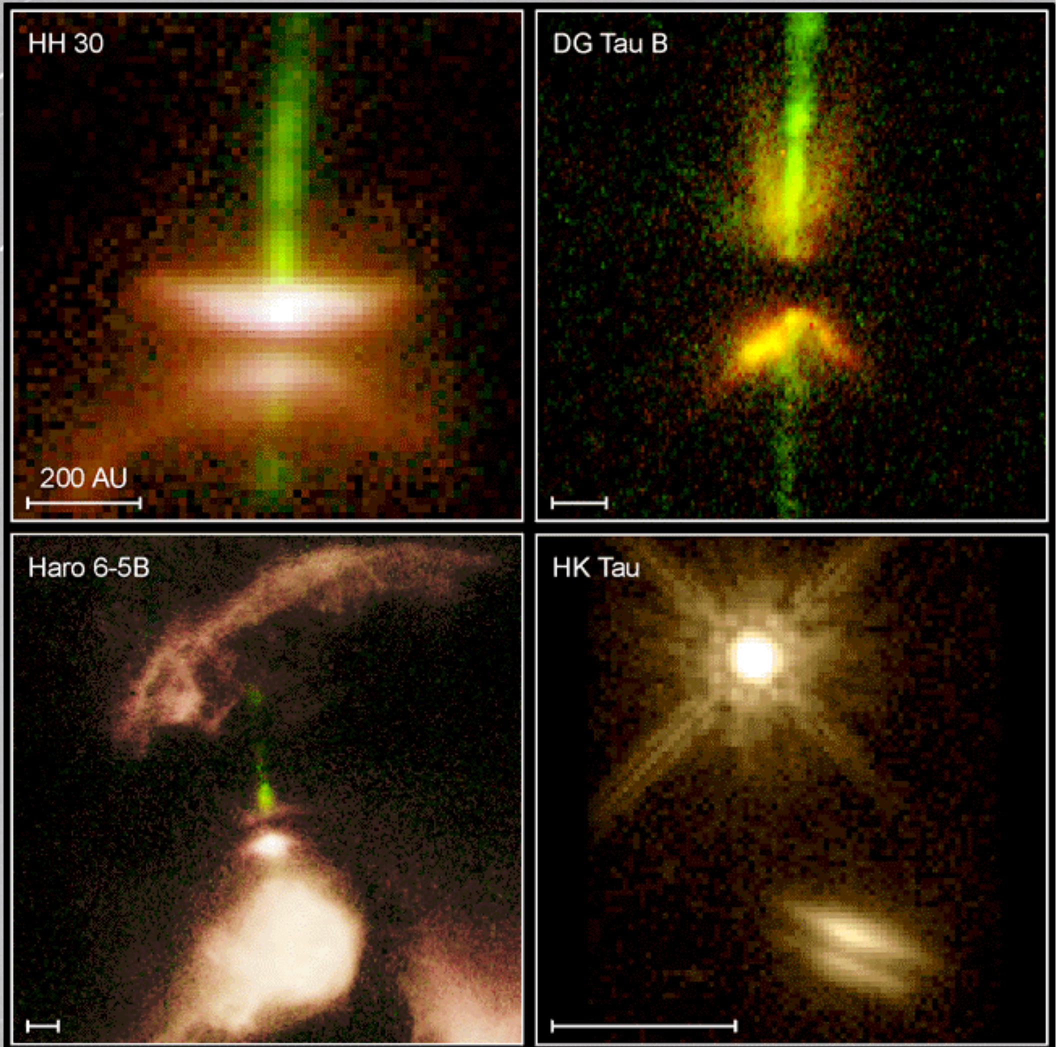
Accretion disks / debris disks

Structures of 1AU scale can be observed:
- up to 1kpc at 2.2 µm and
- up to 100 pc at 10 µm

See O. Chesneau's & F. Malbet's talks

Lynne Allen and Javier Alonso





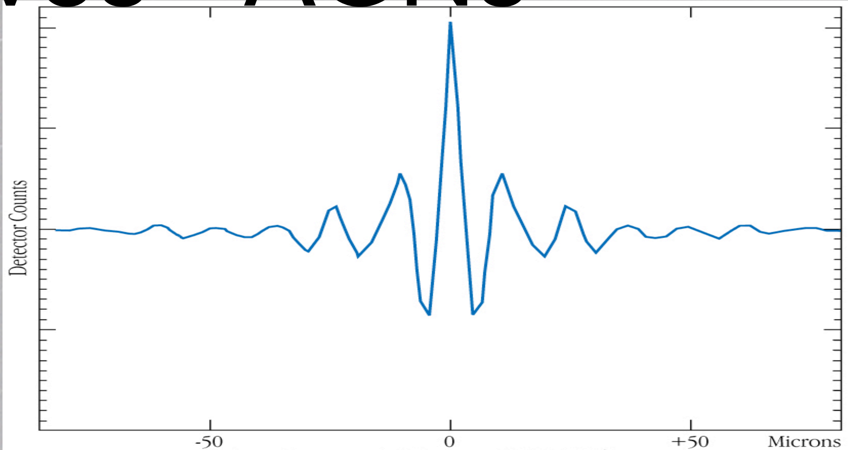
Disks around Young Stars **HST • WFPC2**

PRC99-05b • STScI OPO

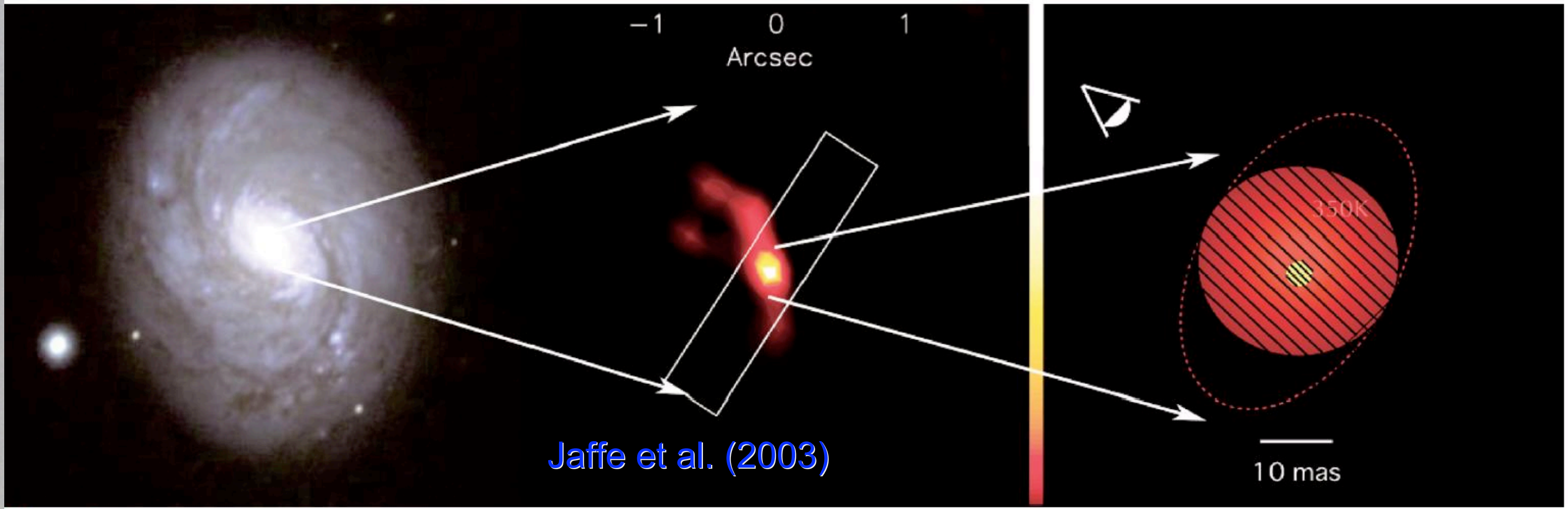
C. Burrows and J. Krist (STScI), K. Stapelfeldt (JPL) and NASA

Scientific objectives - AGNs

- Observation of central core elongation, jets, dust torus...
- Currently ~7 objects observable with MIDI (e.g. NGC 1068), 0-1 with AMBER
- With PRIMA: hopefully >~50 with each => better sample, better spectral coverage
- See W. Jaffe's talk



Interferometric Fringes of NGC 1068



Jaffe et al. (2003)

Figure 9: *Left: 3.4 × 3.4 arcmin optical image of NGC 1068, (NOAO/AURA/NSF). Centre: non-interferometric acquisition image of NGC 1068 taken by MIDI with a 8.7 micron filter, showing the structures on arcsec scales. Also shown are the position of the spectroscopic slit used in the interferometric observations and the directions of North (toward top left) and East (toward bottom left) on the sky. The projected baseline was essentially North/South and the fringe spacing in this direction was 26.3 mas at 10 micron wavelength. Right: sketch of the dust structure in the nucleus of NGC 1068, as derived from modeling the MIDI observations. It contains a central hot component (T > 800 K, yellow) which is significantly smaller than the interferometric beam, and a much-larger well-resolved warm component (T=330 K, red) of diameter 33±5 mas, corresponding to 2.8 pc at the distance of NGC 1068. From Jaffe et al (2003).*

Scientific objectives: Sgr A*

- IR imaging of the matter around the black hole (see J-U. Pott’s poster)
- 10 µas astrometry of the stars in the central cusp
- See J-U. Pott’s and H. Bartlo’s talks

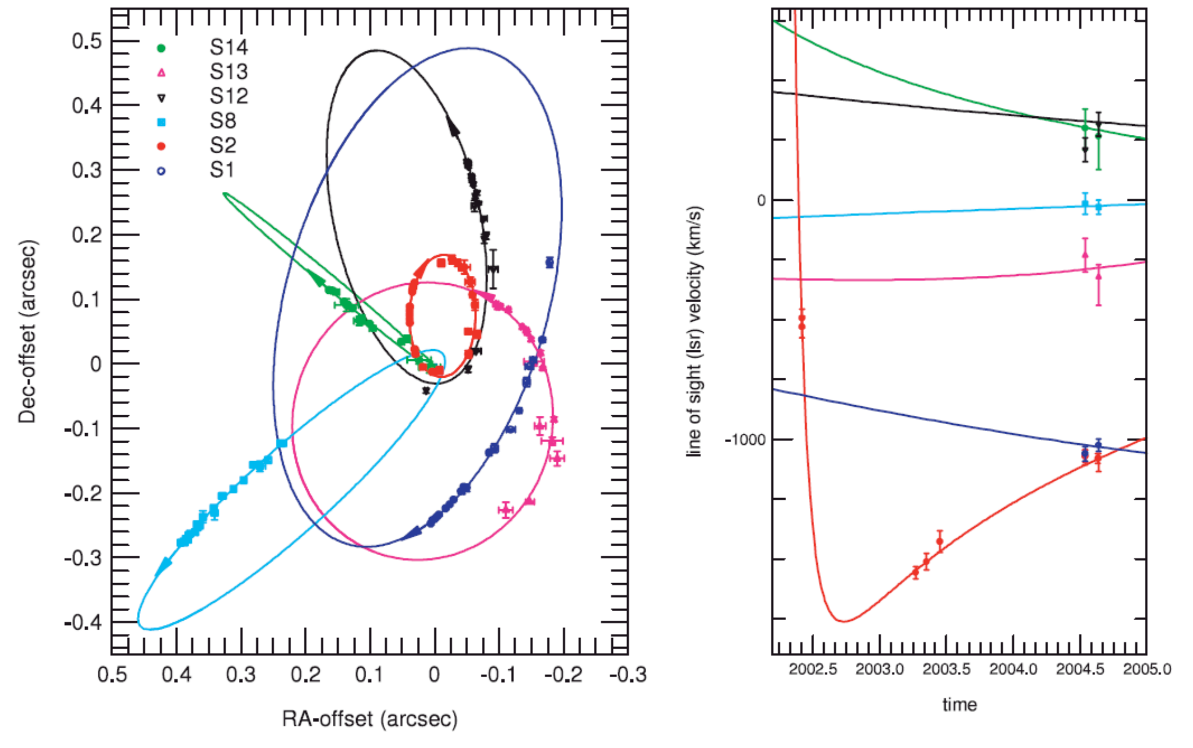
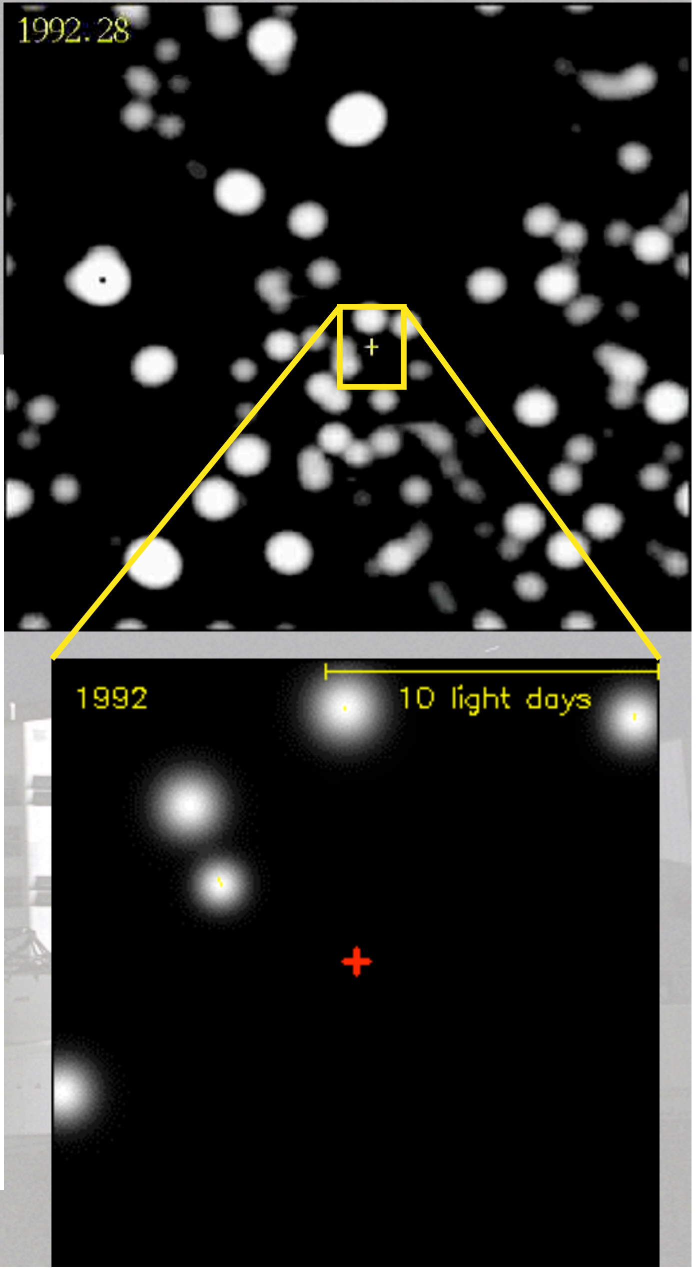


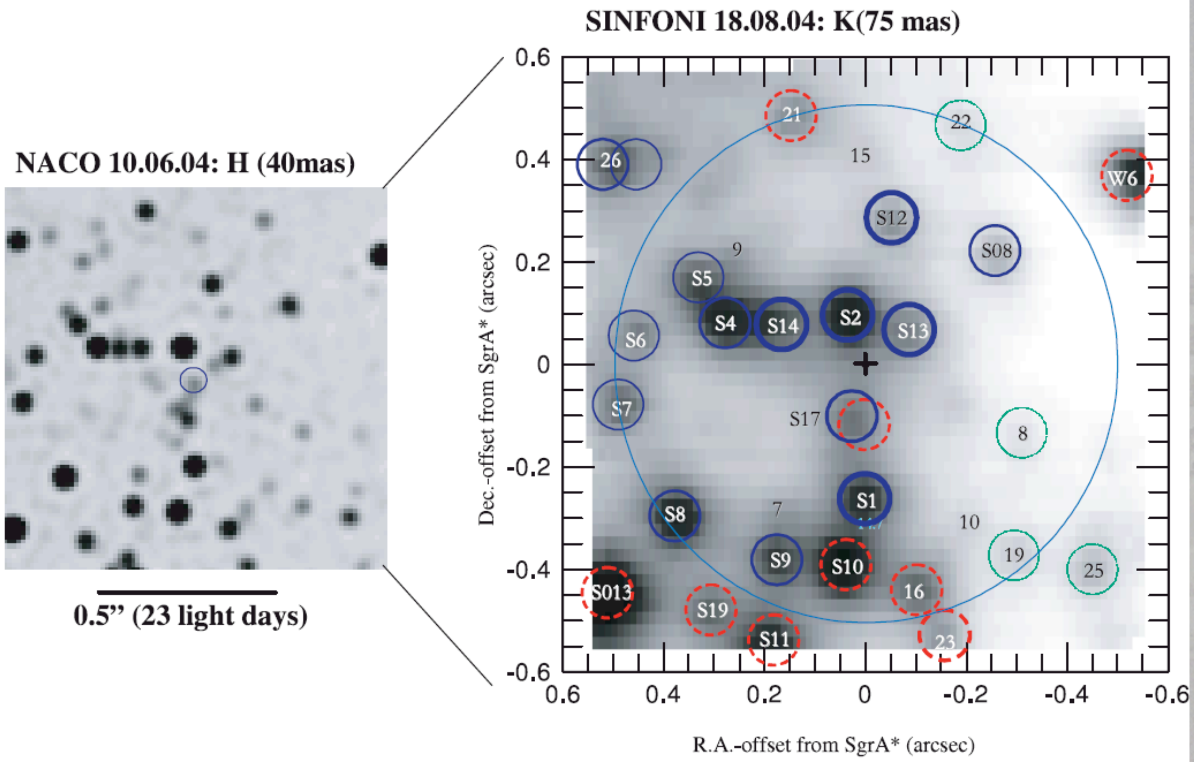
FIG. 7.—Projection on the sky (*left*) and in time/radial velocity (*right*) of the six S stars included in the fitting (see also Schödel et al. 2003). The measured radial velocity of S2 for epoch 2002 is taken from Ghez et al. (2003). The various color curves are the result of the best global fit to the spatial and radial velocity data of S1, S2, S8, S12, S13, and S14. The orbital parameters are listed in Table 2.



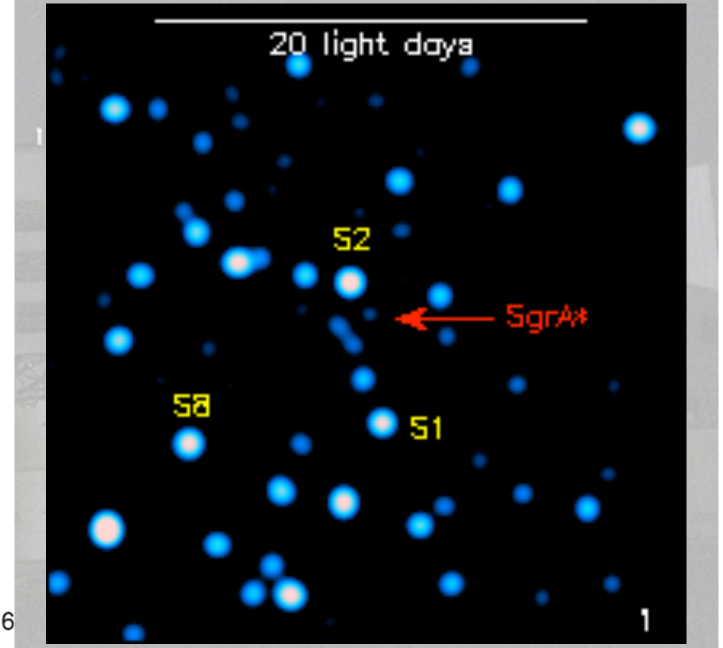
Distance R_0 = 7.62 +/- 0.32 kpc

Scientific objectives: GC flares

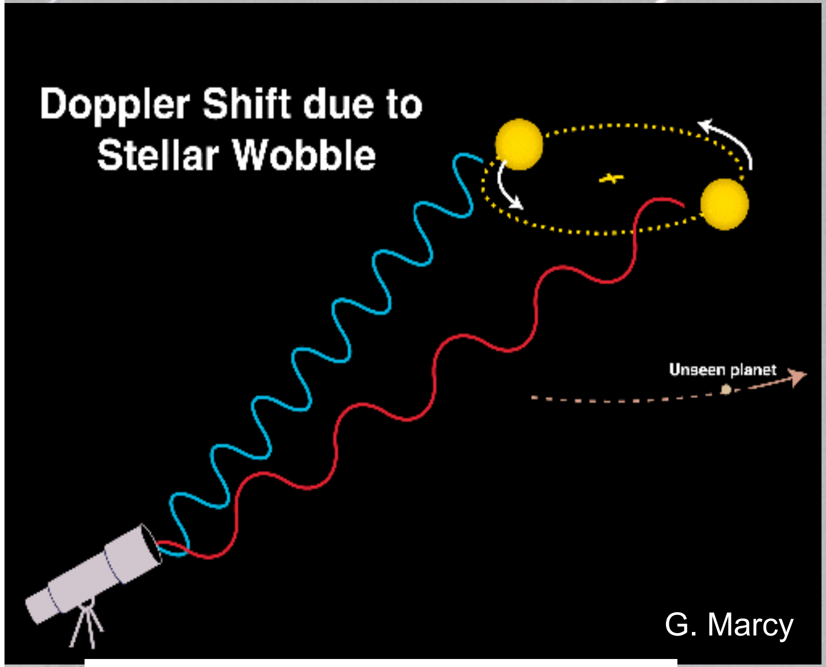
- 10 µas astrometry of the galactic center flares
  - PRIMA can only give partial information on them (1D measurements <=> 1 baseline)
  - if PRIMA can reach the appropriate limiting magnitude (UTs needed, also because of confusion) and accuracy in 30 min (time scale of flare)
  - a better instrument for it would be Gravity



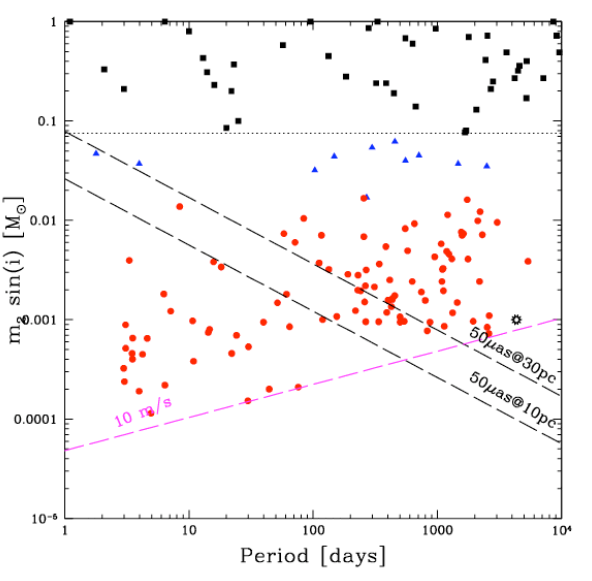
courtesy: F. Eisenhauer (MPE)



Scientific objectives: planets



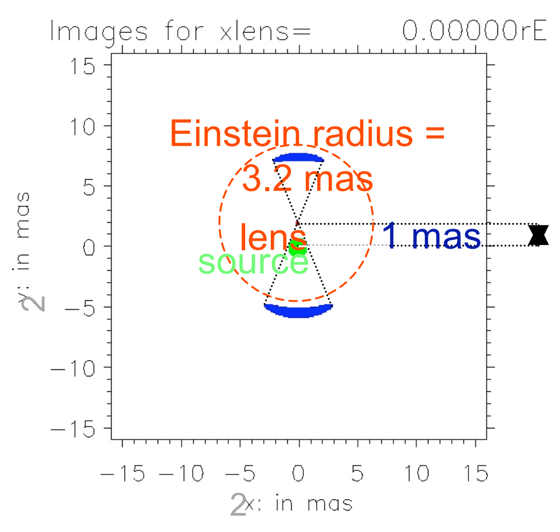
G. Marcy

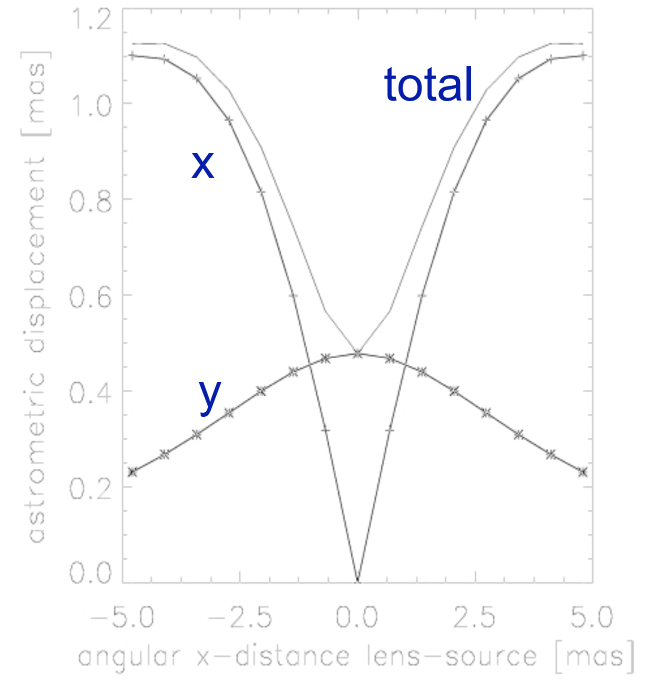


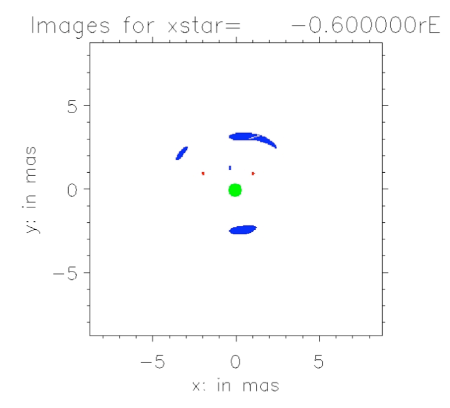
- Reflex motion of the star due to planet presence
- Wobble amplitude proportional to:
  - planet Mass
  - (star mass)$^{-2/3}$
  - (planet period)$^{2/3}$
  - 1 / distance to the star
  - amplitude does **not** depend on orbit inclination
- Complementarity with radial velocities:
  - better for large planets at large distances
  - not sensitive to sin(i)
  - applicable to (almost) all star types
- Need of long-duration survey programmes to characterise planets far from the star
- Need to maintain the accuracy on such long periods !
- See R. Launhardt's talk

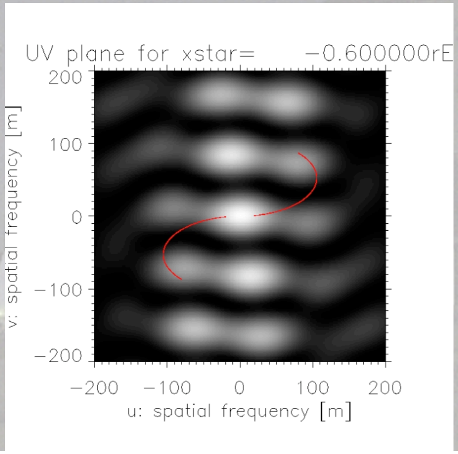
Scientific objectives: micro-lensing

- Difference in amplification on both images =>
  - displacement of total photocenter
- Example: M = 10 M_{sun}, impact parameter = 1mas, r_E = 3.2 mas
  - maximum photocenter displacement = 1.2 mas
  - NOT maximum at closest approach
- In case of planet around the lens:
  - secondary photometric peak and
  - more complex shape (3 to 5 images) => imaging and astrometry
- But has to work on alerts & needs high limiting magnitude (K~15-16 on secondary object)





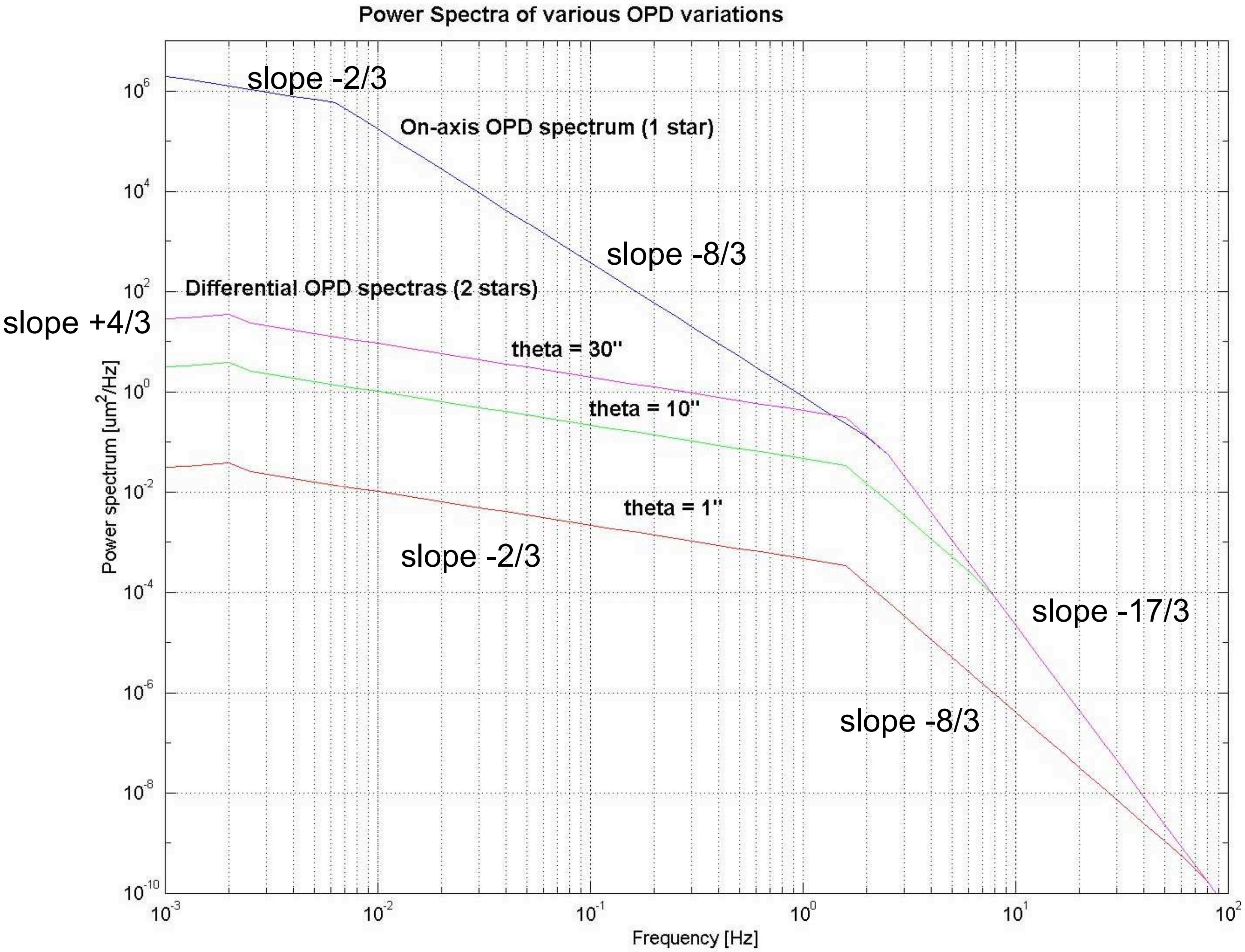




The physical limitations and The scientific requirements

- Physical limitations (more in M. Colavita’s talk)
  - Atmospheric anisoplanatism
  - Sky coverage
- Scientific requirements
  - OPD accuracy for imaging / astrometry
  - OPD stabilization for fringe tracking

Atmospheric anisoplanatism 1



Kolmogorov spectrum

Balloon measurements at Paranal

Seeing = 0.66” at 0.5 µm

τ_0 = 10 ms at 0.6 µm

Atmospheric anisoplanatism 2

- Off-axis fringe tracking <=> anisoplanatic differential OPD

$$\sigma_{OPDmeasurement} \cong 370.B^{-2/3}.\frac{\theta}{\sqrt{T_{obs}}}$$

for narrow angles (θ < 180” UT or 40” AT) and long total observation time T_{obs} >> ~100s

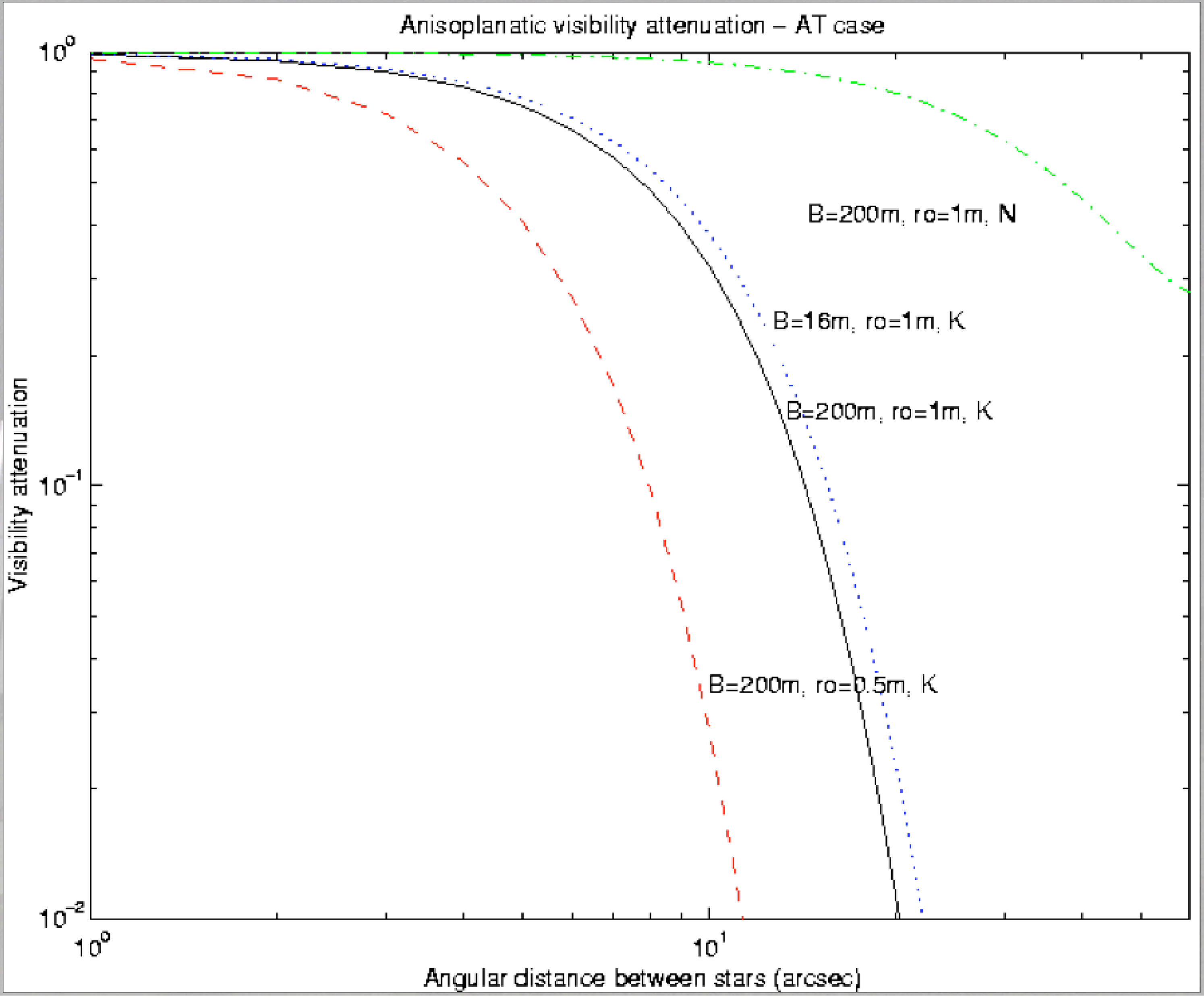
for Paranal seeing = 0.66” at 0.5µm, τ_0 = 10 ms at 0.6µm (L. d’Arcio)

Factor = 300 for Mauna Kea (Shao & Colavita, 1992 A&A 262)

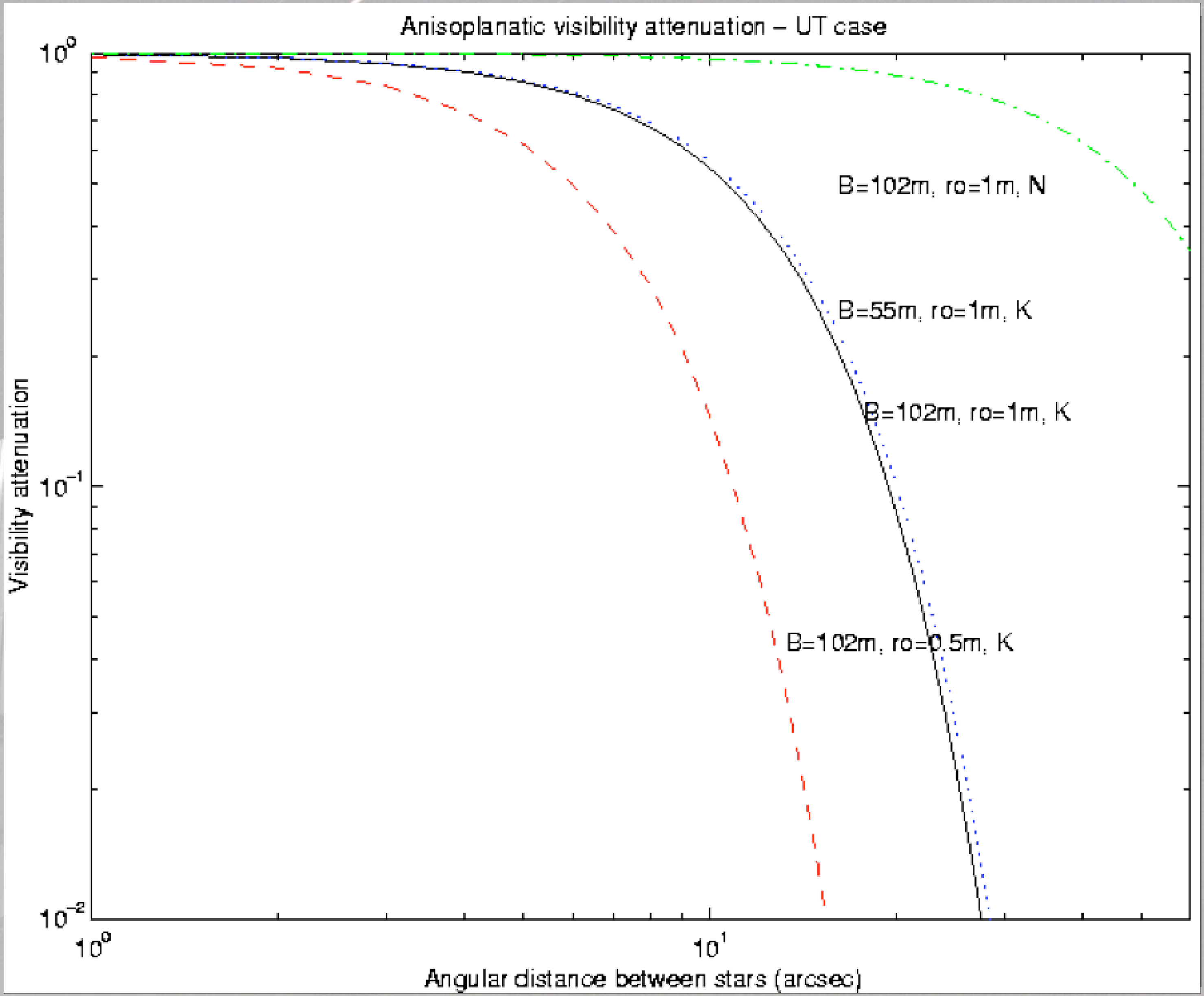
  - Increases with star separation
  - Decreases with telescope aperture (averaging)
  - High impact of seeing quality
- Translates into off-axis maximum angles to limit visibility losses (< 50 to 90%):
  - K-band imaging (2 µm)
    - Bright fringe guiding star within 10-20”
  - N-band imaging (10 µm)
    - Bright fringe guiding star within 2’

$$V = V_0.\exp\left[-2.\left(\frac{\pi}{\lambda}.\sigma_{residual\_OPD}\right)^2\right]$$

Anisoplanatism AT

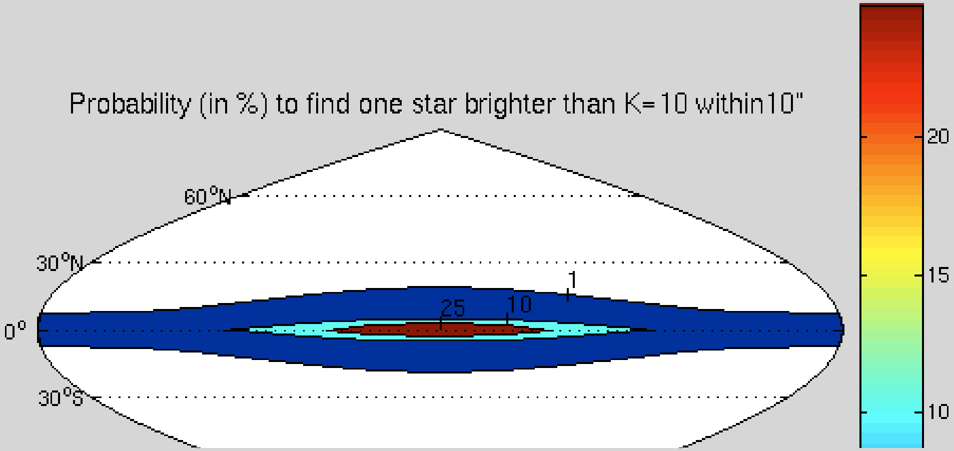


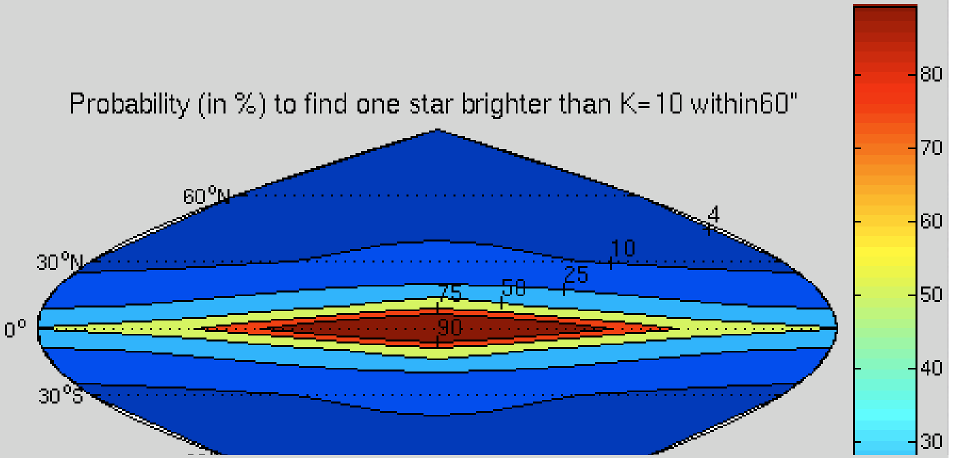
Anisoplanatism UT

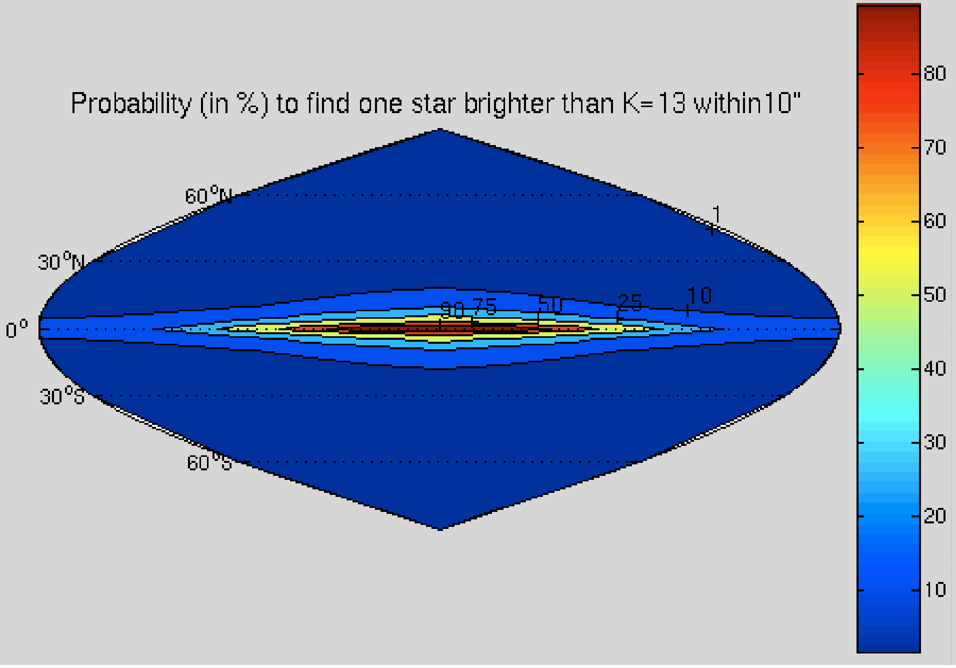


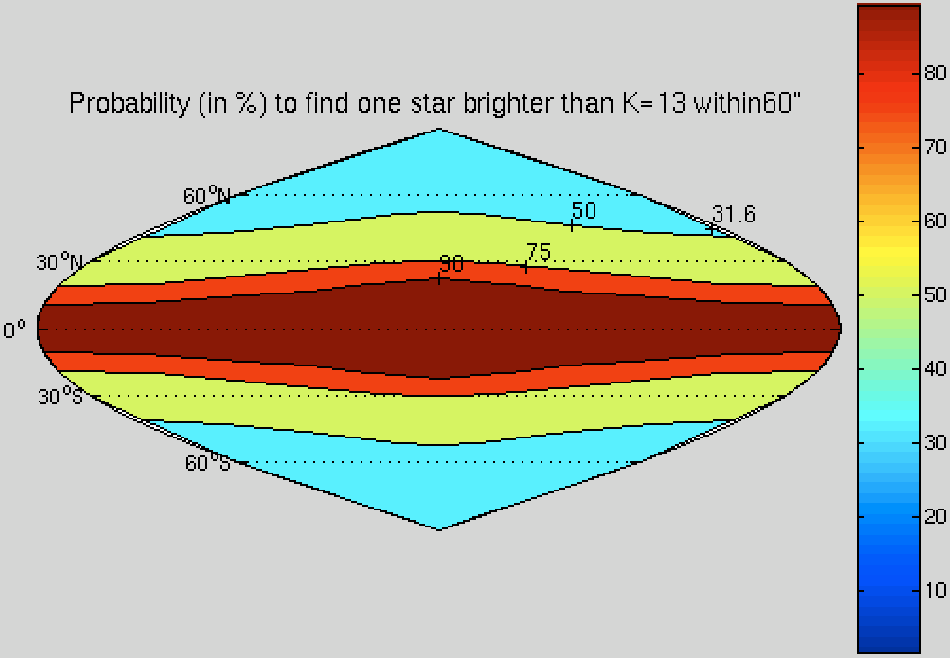
Sky coverage

- Sky coverage <=> limiting magnitude


Probability (in %) to find one star brighter than K=10 within10"


Probability (in %) to find one star brighter than K=10 within60"


Probability (in %) to find one star brighter than K=13 within10"


Probability (in %) to find one star brighter than K=13 within60"

Accuracy requirements

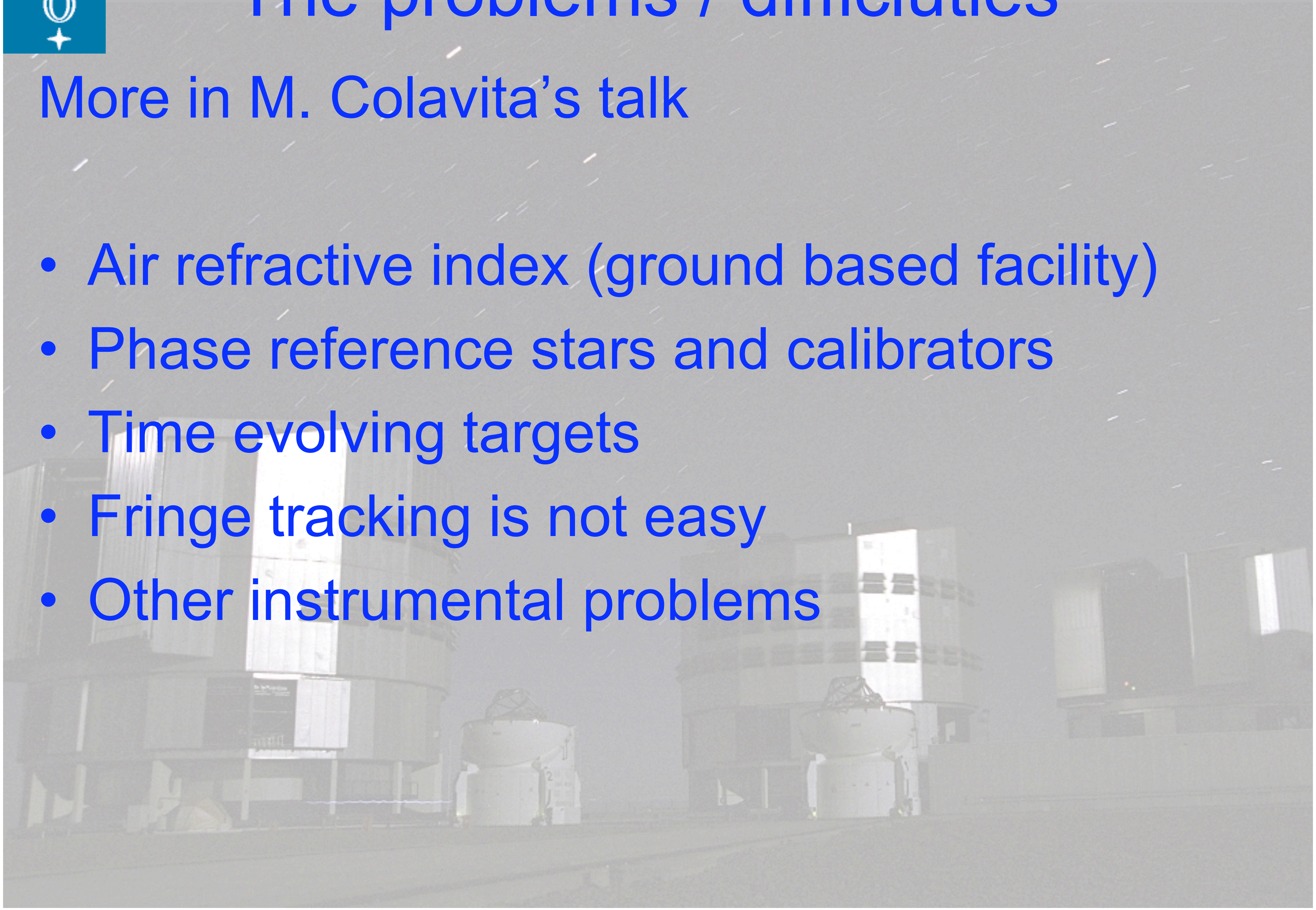
- Phase-referencing measurable: difference of group delay

$$\underset{\text{Fringe sensor}}{\underset{\uparrow}{\Delta OPD}} = \underset{\text{astrometry}}{\underset{\uparrow}{\mathbf{\Delta S.B}}} + \underset{\text{imaging}}{\underset{\uparrow}{\phi}} + \underset{\text{atmosphere}}{\underset{\uparrow}{OPD_{turb}}} + \underset{\text{Internal metrology}}{\underset{\uparrow}{OPD_{int}}}$$

- Astrometric requirement
  - For 2 stars separated by 10” - 0.8”seeing - B=200m => Atmosphere averages to 10µas rms accuracy in 30 min
  - <=> 5nm rms measurement accuracy
- Imaging requirement =>
  - dynamic range is important (ratio between typical peak power of a star in the reconstructed image and the reconstruction noise level)
  - DR ~ $\sqrt{M} . \phi / \Delta\phi$ where M = number of independent observations
  - DR > 100 and M=100 <=> $\Delta\phi / \phi < 0.1$ <=> 60nm rms in K

- Ability to do off-axis fringe tracking

The problems / difficluties



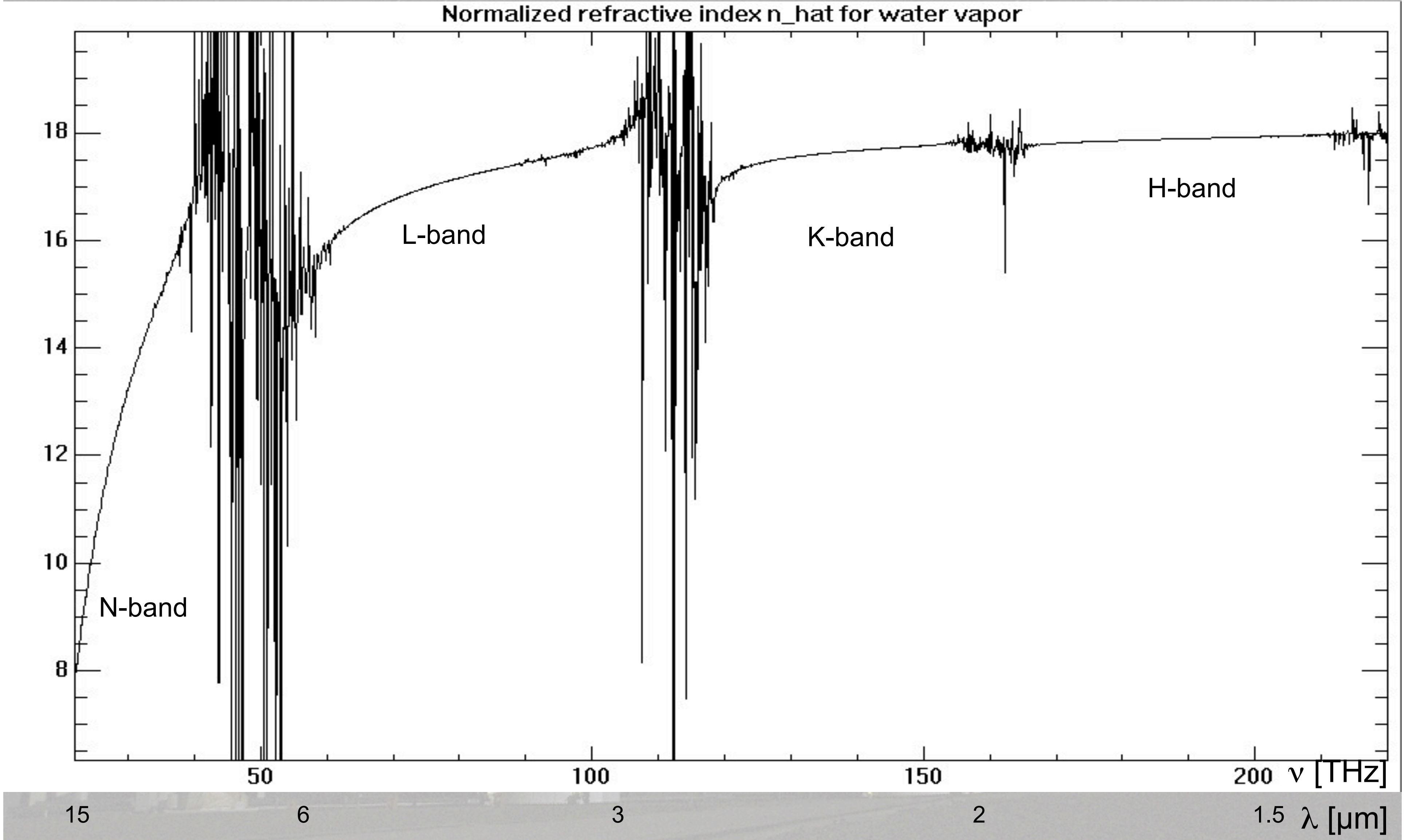
More in M. Colavita’s talk

- Air refractive index (ground based facility)
- Phase reference stars and calibrators
- Time evolving targets
- Fringe tracking is not easy
- Other instrumental problems

Dispersion and H_2O seeing

- Transversal & longitudinal dispersion
- Fringe tracking and observation at different λ
- Air index of refraction depends on wavelength =>
  - phase delay $\neq$ group delay
  - group delay depends on the observation band
  - fringe tracking in K does not maintain the fringes stable in J / H / N bands
- Air index varies as well with air temperature, pressure & humidity
  - overall air index dominated by dry air
  - H_2O density varies somewhat independently
  - H_2O effect is very dispersive in IR (between K and N)
- Remedy: spectral resolution

Refractive index of water vapor (©R. Mathar)



Proper phase references

- We want to do imaging =>
  - usually the scientific target is faint =>
    - Reference star must be bright (K<10 or 13)
    - Bright stars are close and big
  - need of long baselines
- => High probability that your guide star is:
    - resolved => low visibility
    - with resolved structures => non-zero phase
- Phase-referencing cannot disentangle between target phase and reference phase
- Remedies:
  - baseline bootstrapping
  - characterize your reference star (stellar type, spectrum, interferometry) as much as possible prior to observation
  - find a faint star close to the reference one to calibrate it

Time and evolving targets

- Phase-referencing works with 2 telescopes at a time => Measurements of different u-v points are taken at different epochs
- Changing the baseline takes time (one day but not done every day)
- If the object evolves, it is a problem
- Remedies:
  - relocate more often (but overheads increase)
  - if the “evolution” is periodic (Cepheid, planet), plan the observations at the same ephemeris time
  - have more telescopes and switch from one baseline to another within one night
- No snap-shot image like with phase closure but better limiting magnitude

Fringe tracking problems

- See Monday’s talk
- Injection stability:
  - Use of monomode optical fibers as spatial filter => wavefront corrugations and tip-tilt are transformed into photometric fluctuations
  - Strehl ratio is not stable at 10 ms timescales
  - To measure fringes with enough accuracy for fringe tracking, one needs ~ 100 photons at **any** moment
- Telescope vibrations:
  - fast and strong sinusoidal variations of OPD
  - difficult to correct with the normal OPD loop

Solutions:

⇒ fast tip-tilt sensing close to the instrument

⇒ optimize injection before starting

⇒ affects limiting magnitude and efficiency or you accept a not-perfect fringe lock

⇒ “Vibration tracking” (predictive control)

⇒ “Manhattan 2” (accelerometers)

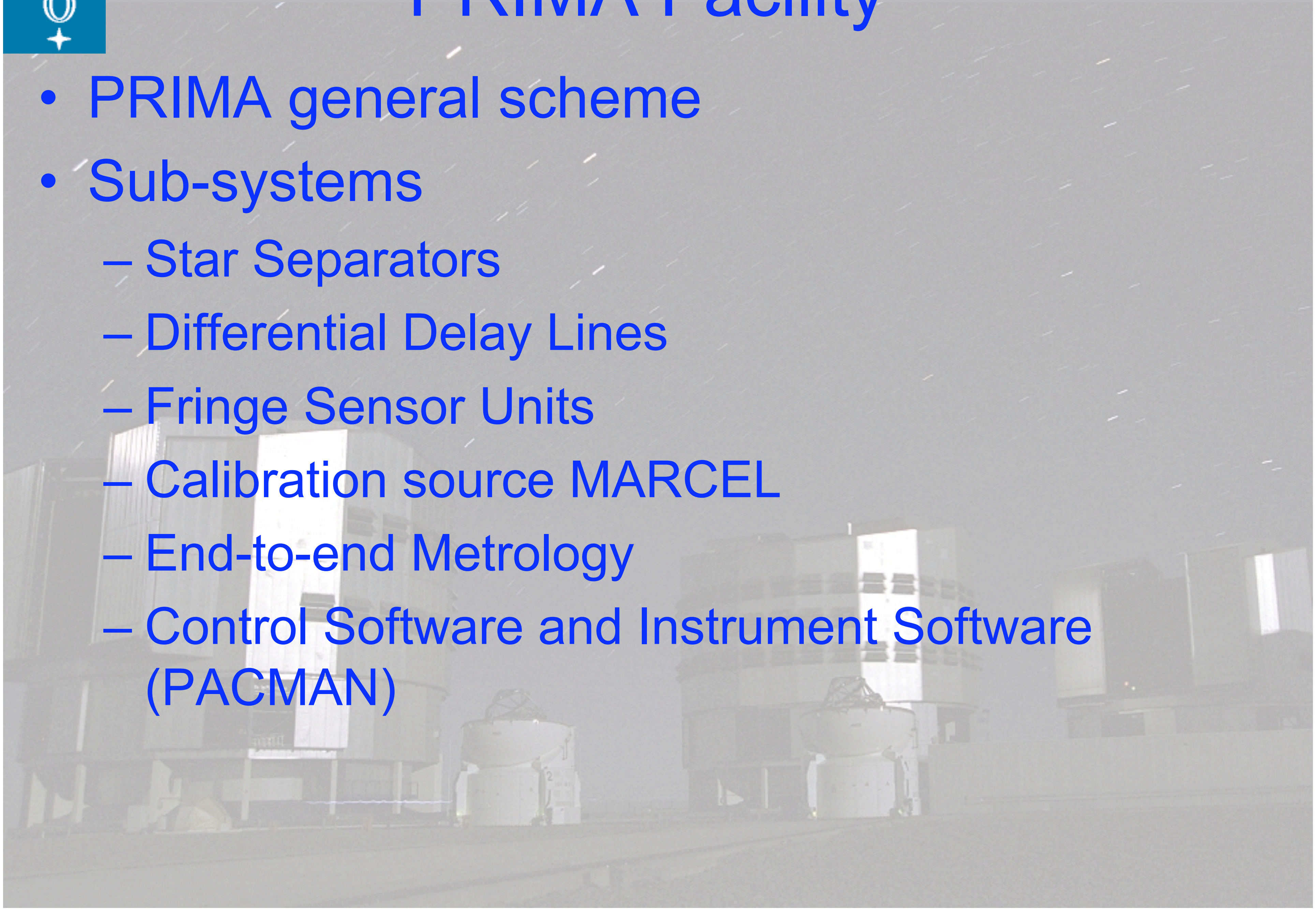
⇒ laser metrology

⇒ active / passive damping

Other instrumental problems

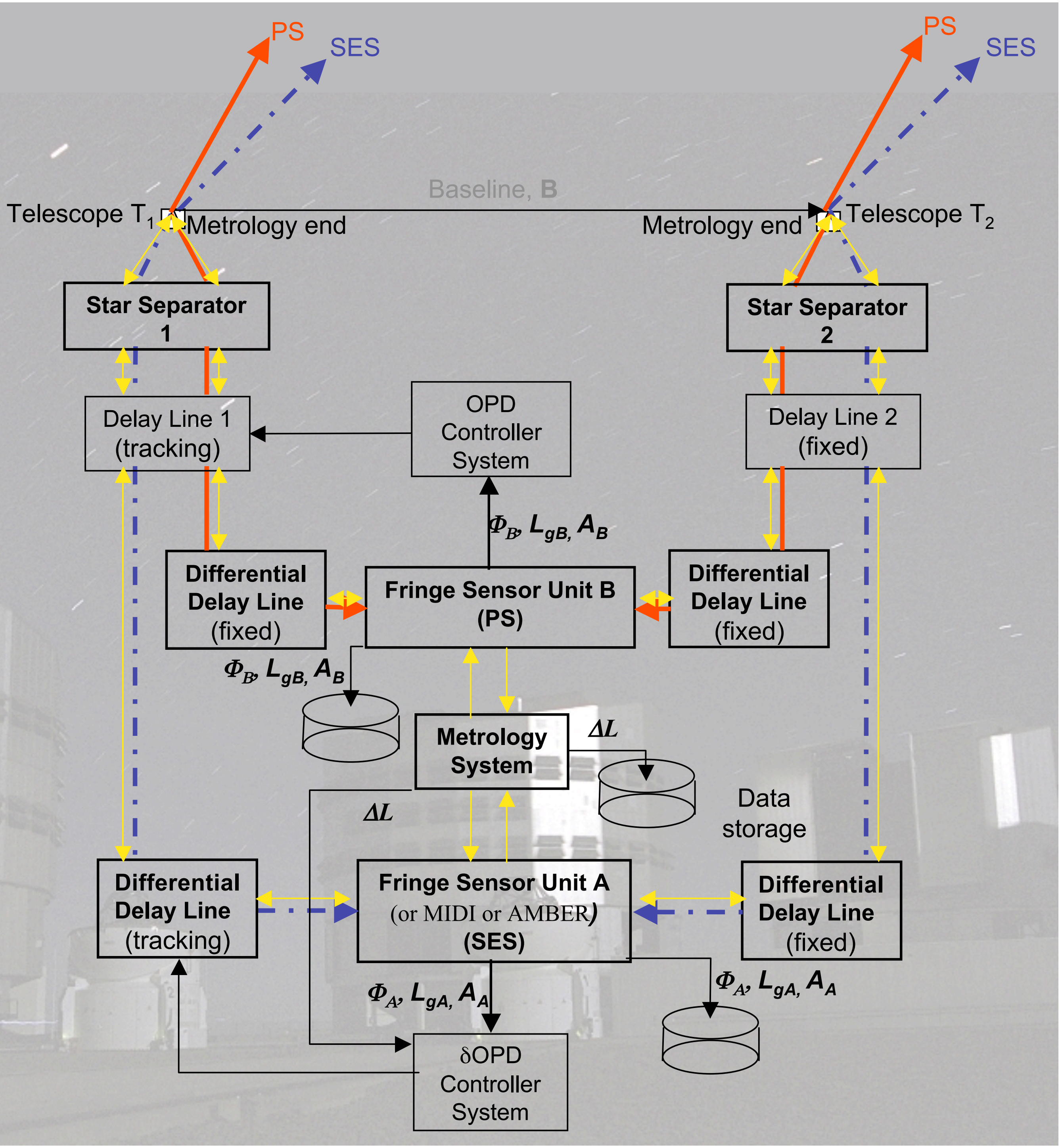
- Baseline calibration:
  - baseline should be known at better than < 50µm
  - experience on ATs:
    - calibration at better than 40µm
    - stability ca be better than 120µm
  - dedicated calibrations are needed
  - stability with time and telescope relocation to be verified
- Telescope differential flexures:
  - not seen by the internal metrology
  - their effect on dOPD must be very limited or modeled
  - differential effect of 2nd order (2 telescopes - 2 stars)
- Mirror irregularities & beam footprints
  - non-common paths (metrology/star) to be minimized
  - bumps on mirrors should be avoided and mapped

PRIMA Facility



- PRIMA general scheme
- Sub-systems
  - Star Separators
  - Differential Delay Lines
  - Fringe Sensor Units
  - Calibration source MARCEL
  - End-to-end Metrology
  - Control Software and Instrument Software (PACMAN)

PRIMA Scheme



PS

SES

PS

SES

Baseline, **B**

Telescope T_1

Metrology end

Metrology end

Telescope T_2

Star Separator 1

Star Separator 2

Delay Line 1 (tracking)

OPD Controller System

Delay Line 2 (fixed)

Φ_B, L_{gB}, A_B

Differential Delay Line (fixed)

Fringe Sensor Unit B (PS)

Differential Delay Line (fixed)

Φ_B, L_{gB}, A_B

Metrology System

ΔL

ΔL

Data storage

Differential Delay Line (tracking)

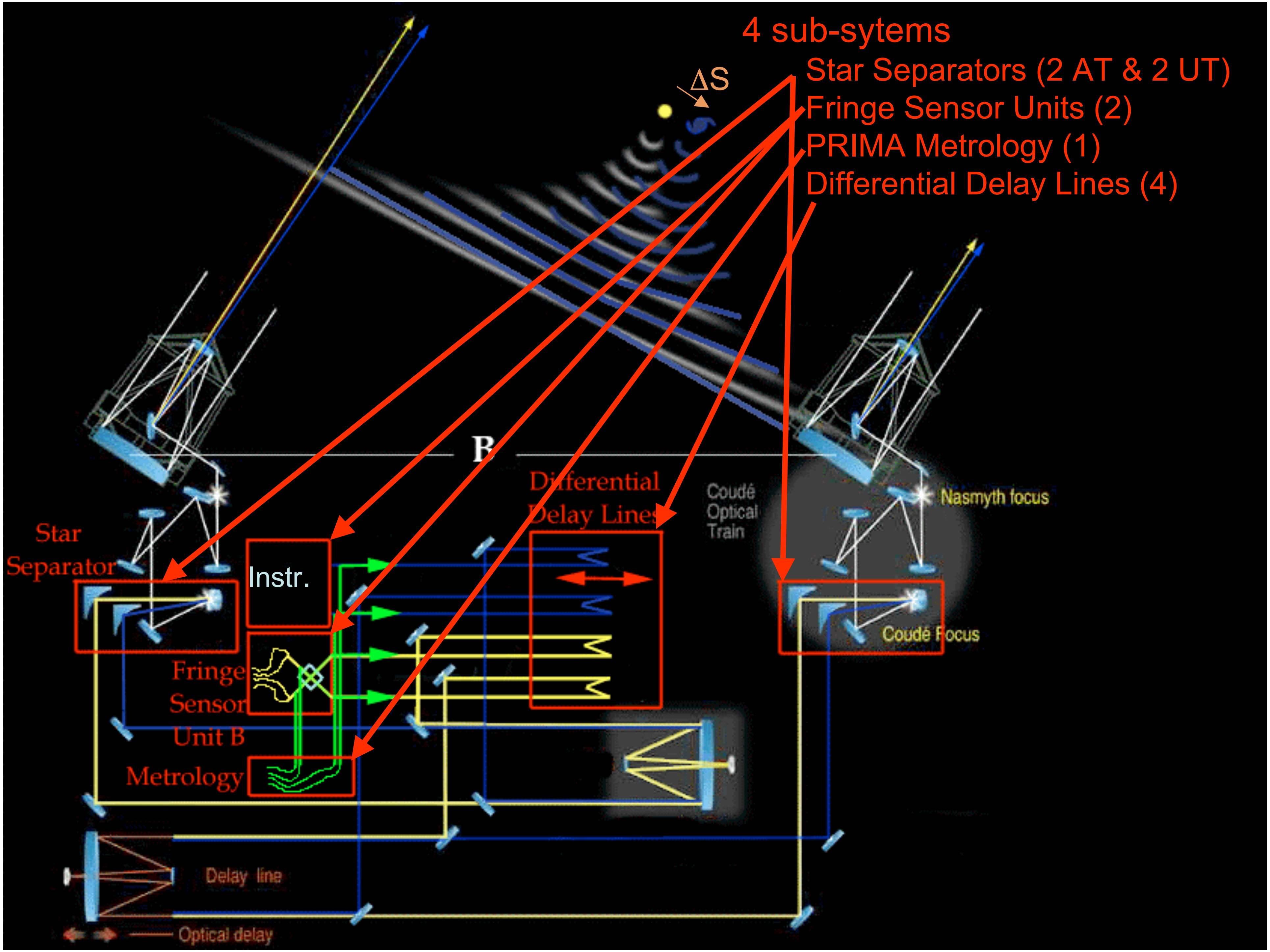
Fringe Sensor Unit A (or MIDI or AMBER) **(SES)**

Differential Delay Line (fixed)

Φ_A, L_{gA}, A_A

Φ_A, L_{gA}, A_A

δOPD Controller System

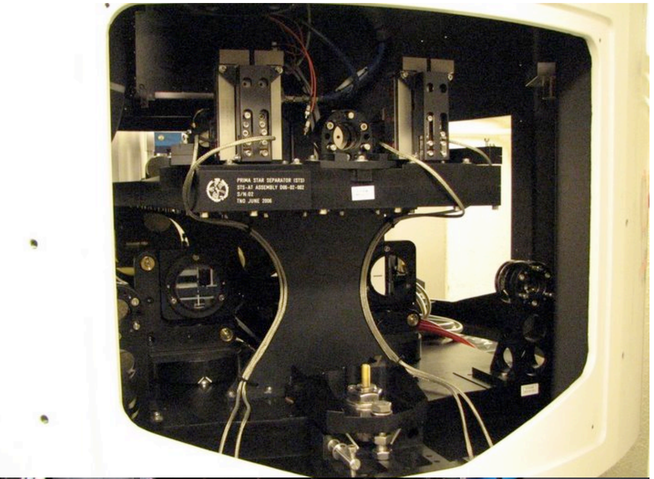


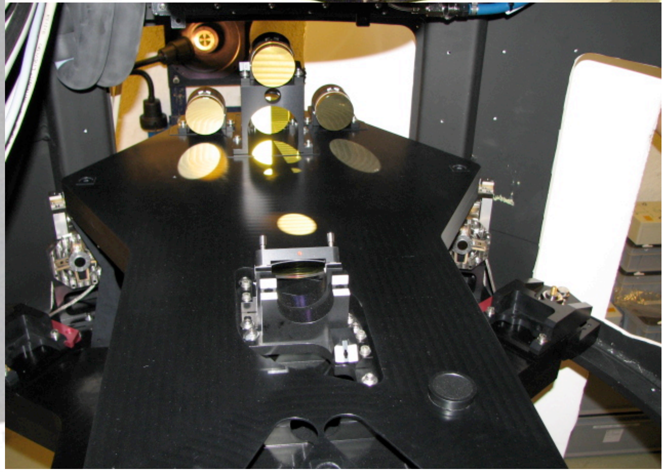
4 sub-sytems

- Star Separators (2 AT & 2 UT)
- Fringe Sensor Units (2)
- PRIMA Metrology (1)
- Differential Delay Lines (4)

Star Separators

- Star separation: from PSF up to 2’
- Each sub-field =
  - 1.5” (UT with DDL - AMBER & PACMAN)
  - 2” (UT without DDL - MIDI)
  - up to 6” (AT)
- Independent tip-tilt & pupil actuators on each beam
- 10Hz actuation frequency (could be pushed to 50 Hz)
- Pupil relay to tunnel center (same as UT)
- Chopping / counter-chopping for MIDI
- Star splitting for calibration step: 40% - 40%
- Star swapping for environment drift calibrations
- Symmetrical design for easing calibrations
- High mechanical & thermal stability
- But: many additional reflections (+8 on AT, +4 on UT)
- Installed on AT#3 and AT#4. Under commissioning.





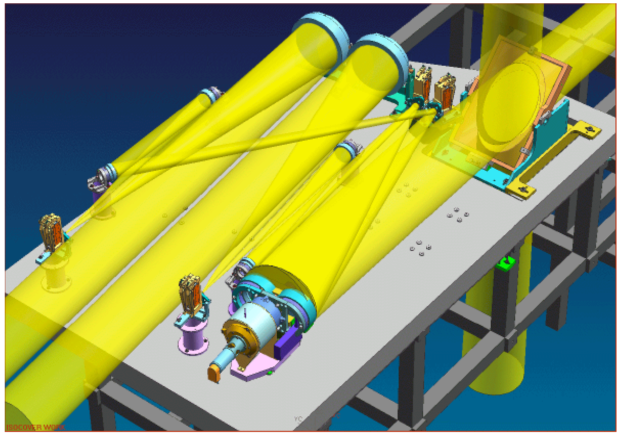


figure 1: Overview of STS-UT system

© TNO

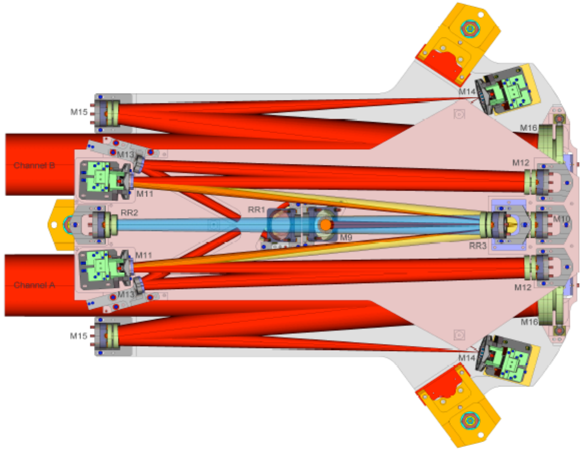
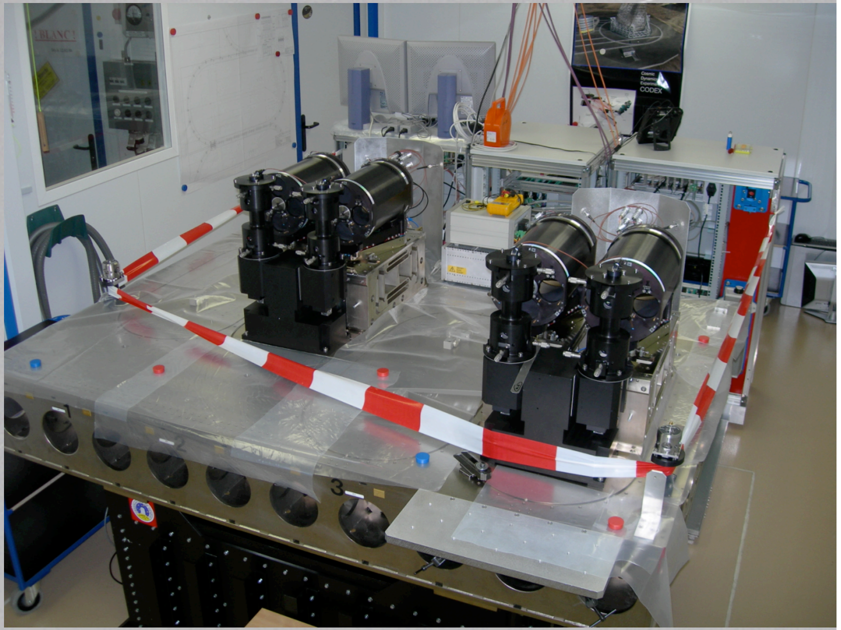


figure 8: Top view on STS

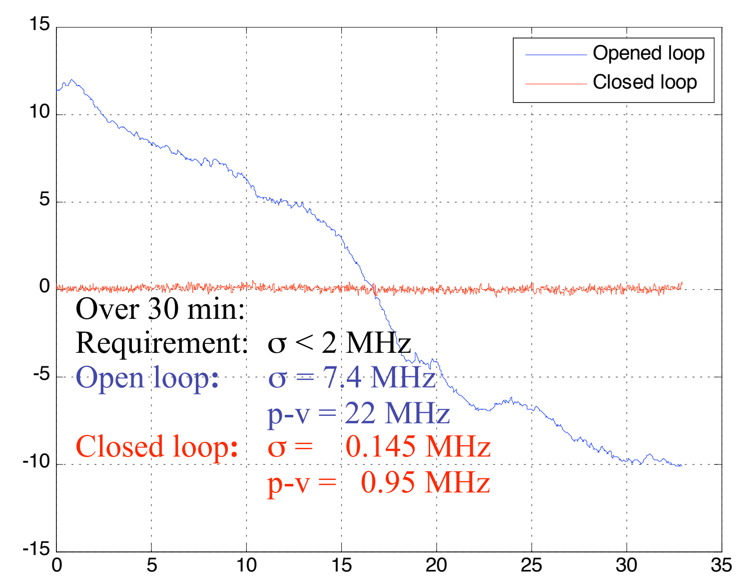
Differential Delay Lines

- To be used with PACMAN and AMBER, not with MIDI
- > 200 Hz bandwidth, < 350 µs pure delay
- Push the lab pupil to FSU (4m further than now)
- Very stringent requirement on pupil lateral motion
- Cat’s eye (3 mirrors, 5 reflections)
- 2 stage actuator (coarse step motor + piezo on M3)
- Internal metrology
- M3 can be actuated also in tip-tilt (pupil correction ?)
- under vacuum
- Preliminary Acceptance Europe: beginning of June

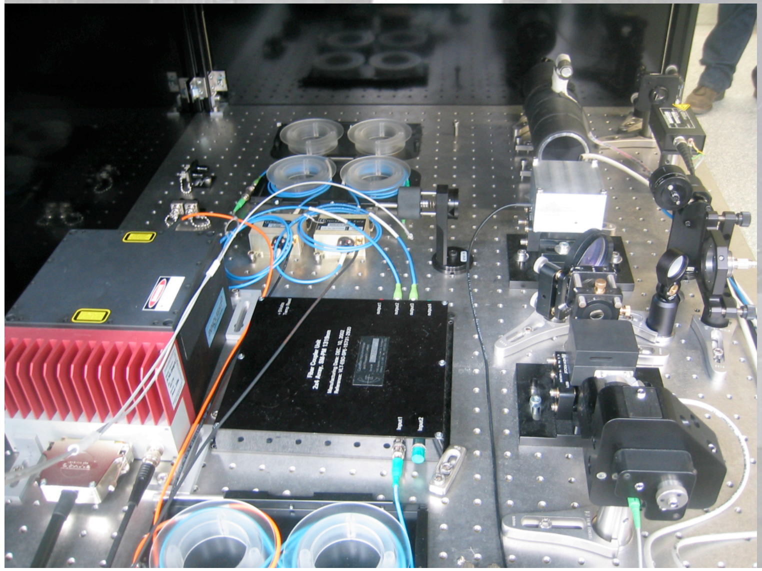


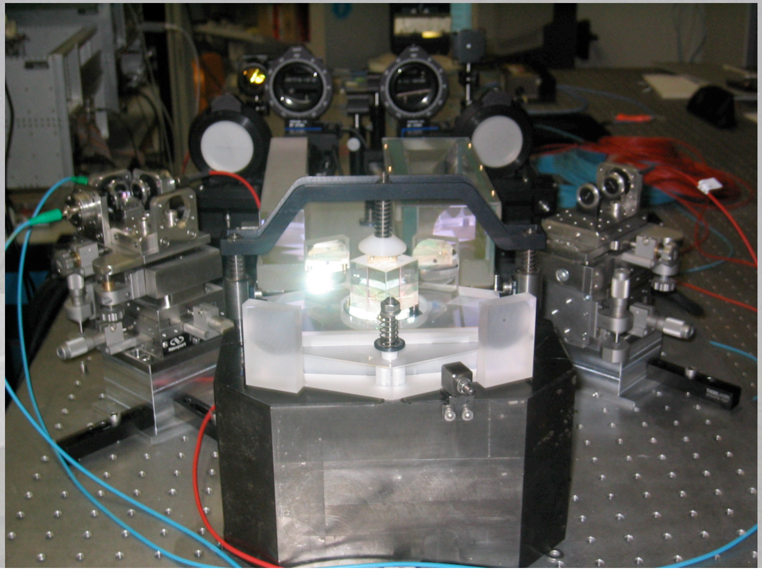
PRIMA Metrology

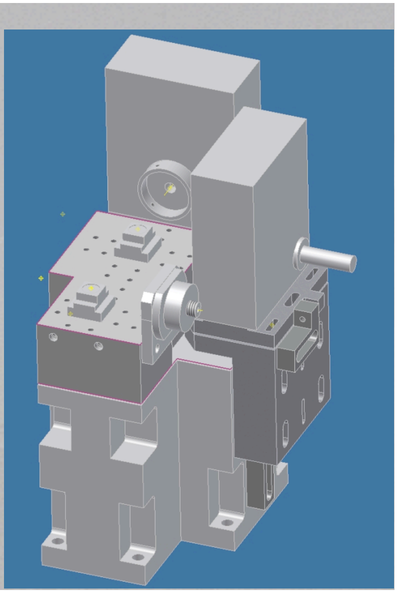
- Super-heterodyne incremental metrology (λ =1.3μm)
- Propagation in the central obstruction, from the instrument to the STS (Retro-reflection behind M9)
- Output measurement (dOPD **and** OPD on one of the stars) written on reflective memory for the OPD/dOPD controller
- Laser frequency stabilization on I_2 at $d\nu/\nu<10^{-8}$ level
- Phase detection: accuracy <1nm rms
- Pupil tracking: Custom low noise 4-quadrant detectors (InGaAs): $\delta d<\pm 100\ \mu m$ Pk
- Working on absolute metrology upgrade



Over 30 min:
Requirement: σ < 2 MHz
Open loop: σ = 7.4 MHz
p-v = 22 MHz
Closed loop: σ = 0.145 MHz
p-v = 0.95 MHz

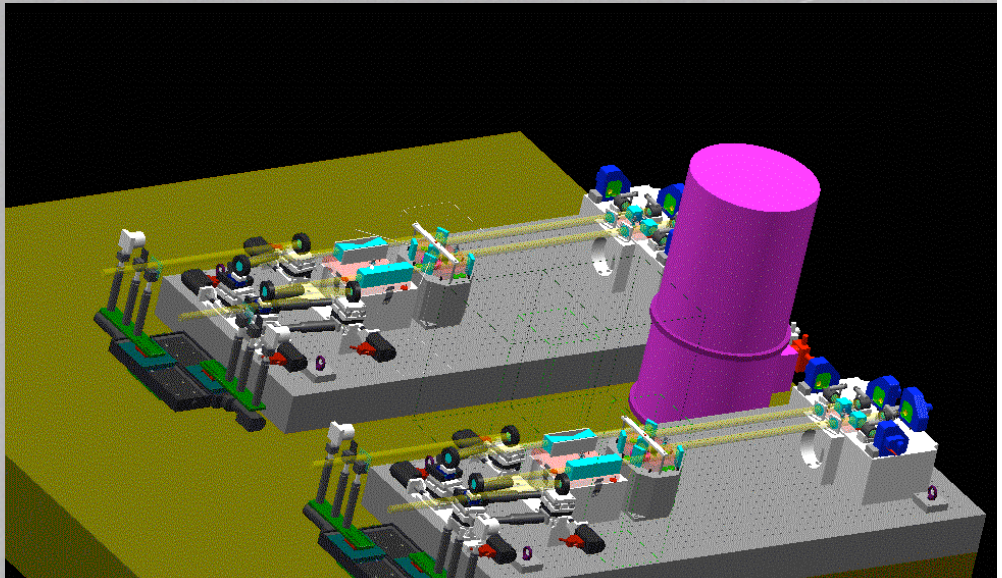


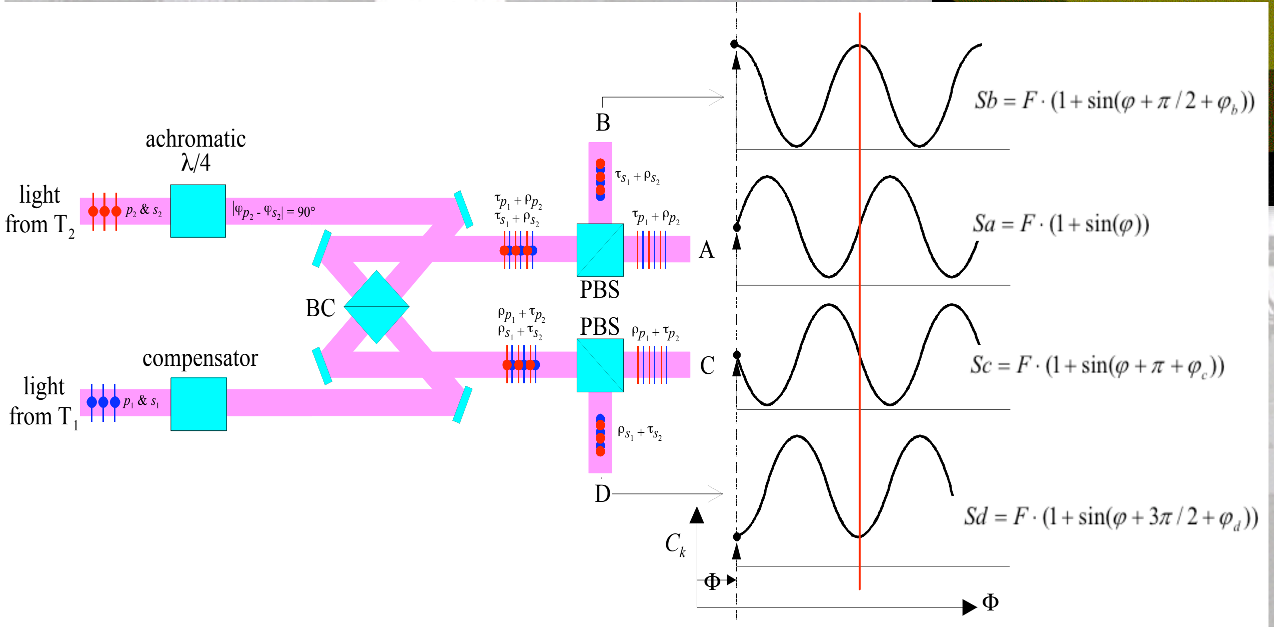




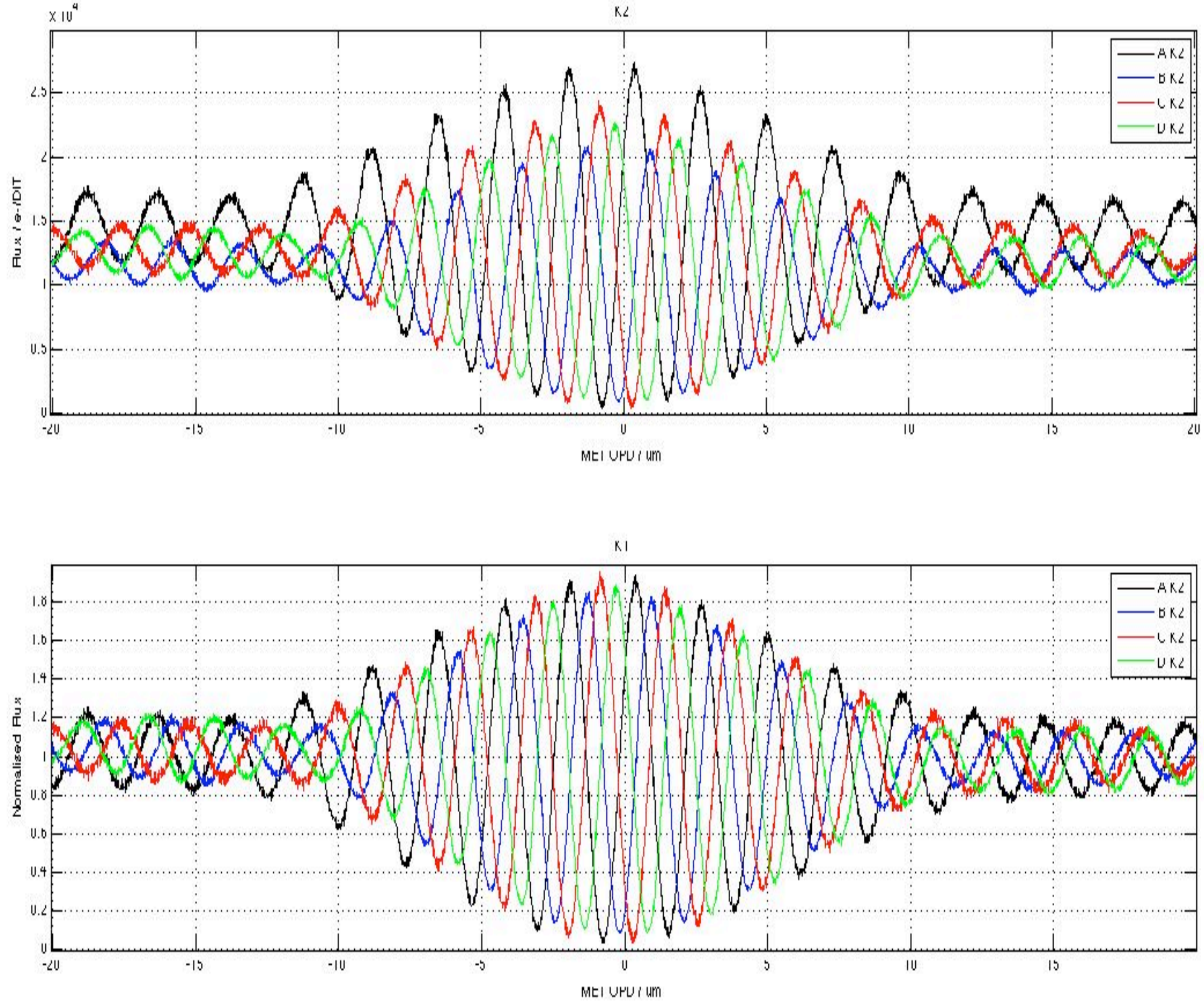
Fringe Sensor Units

- ABCD with no OPD scanning (based on polarization)
- in K band
- OPD and group delay accuracy: < 5nm bias
- up to 8kHz measurement frequency
- single mode fibers after beam combination
- no separate photometric channels
- spectral dispersion for group delay
- fibers up to cryostat to limit background
- fast active injection mirrors for injection
- integrated with PRIMET
- FSUA and FSUB = twins for astrometry





FSU calibration

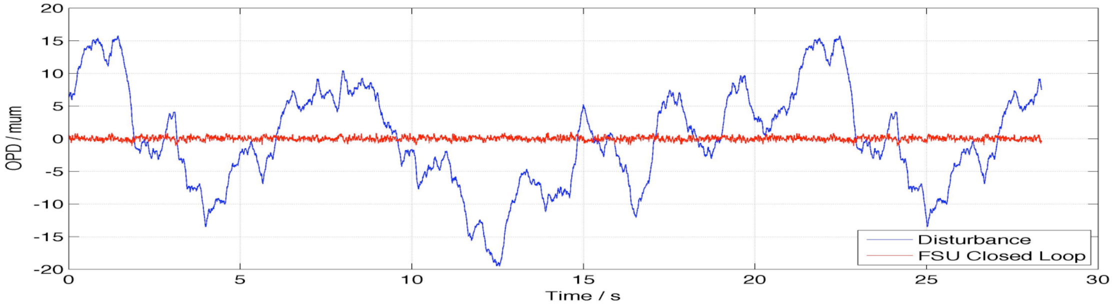


Fringe tracking (phase)

f_{FSU} = 1kHz

f_{OPDC} = 2kHz

no tip-tilt



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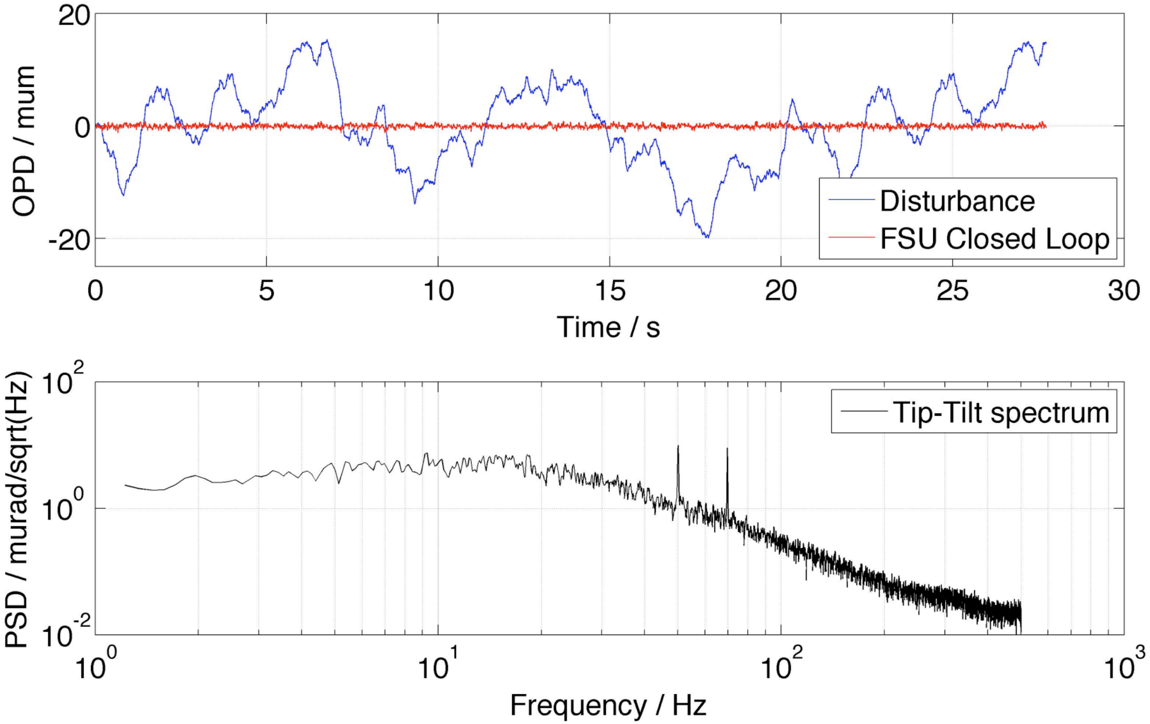
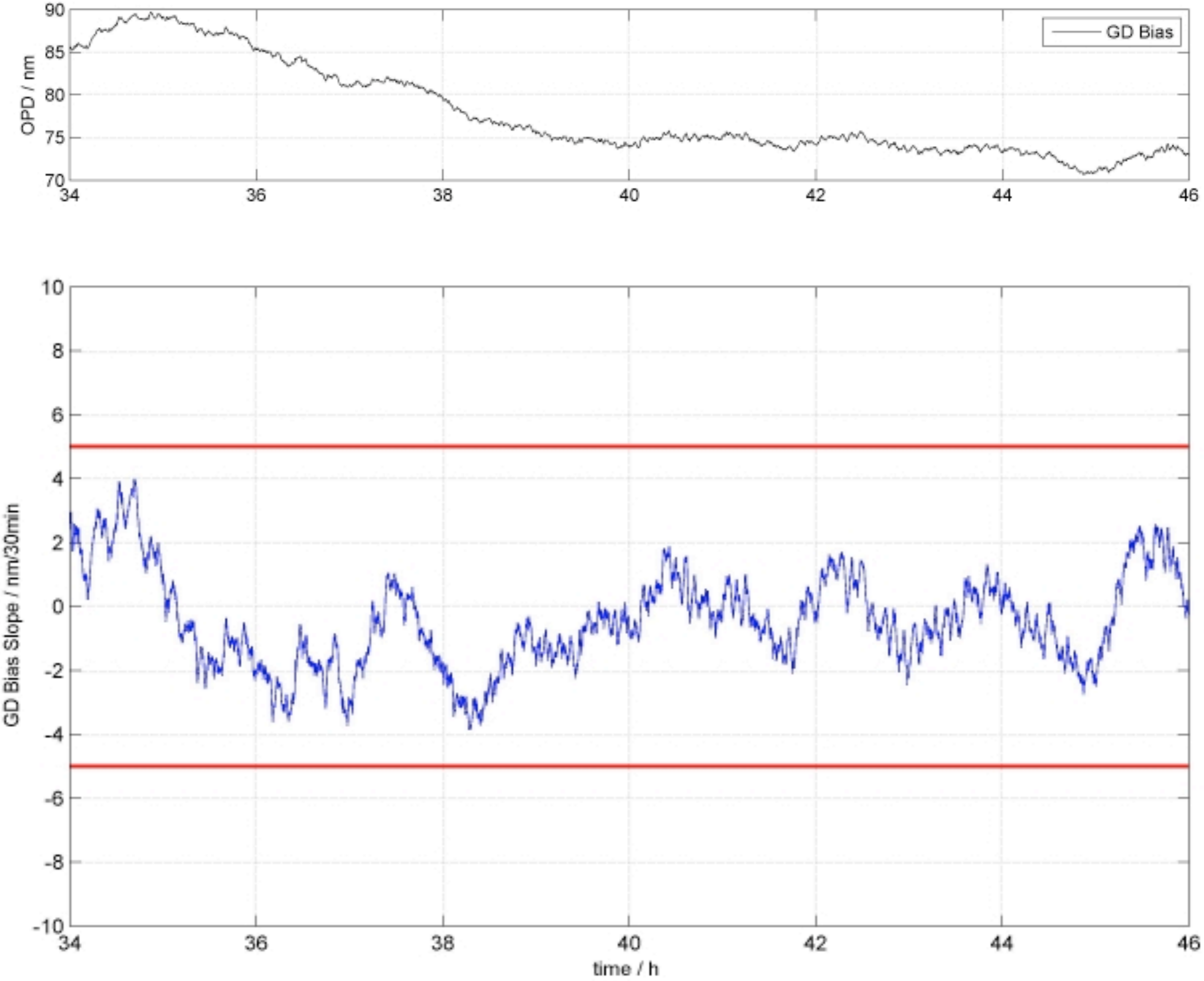
N. di Lieto

f_{FSU} = 1kHz

f_{OPDC} = 2kHz

tip-tilt after IFG ~36 mas rms (AT)



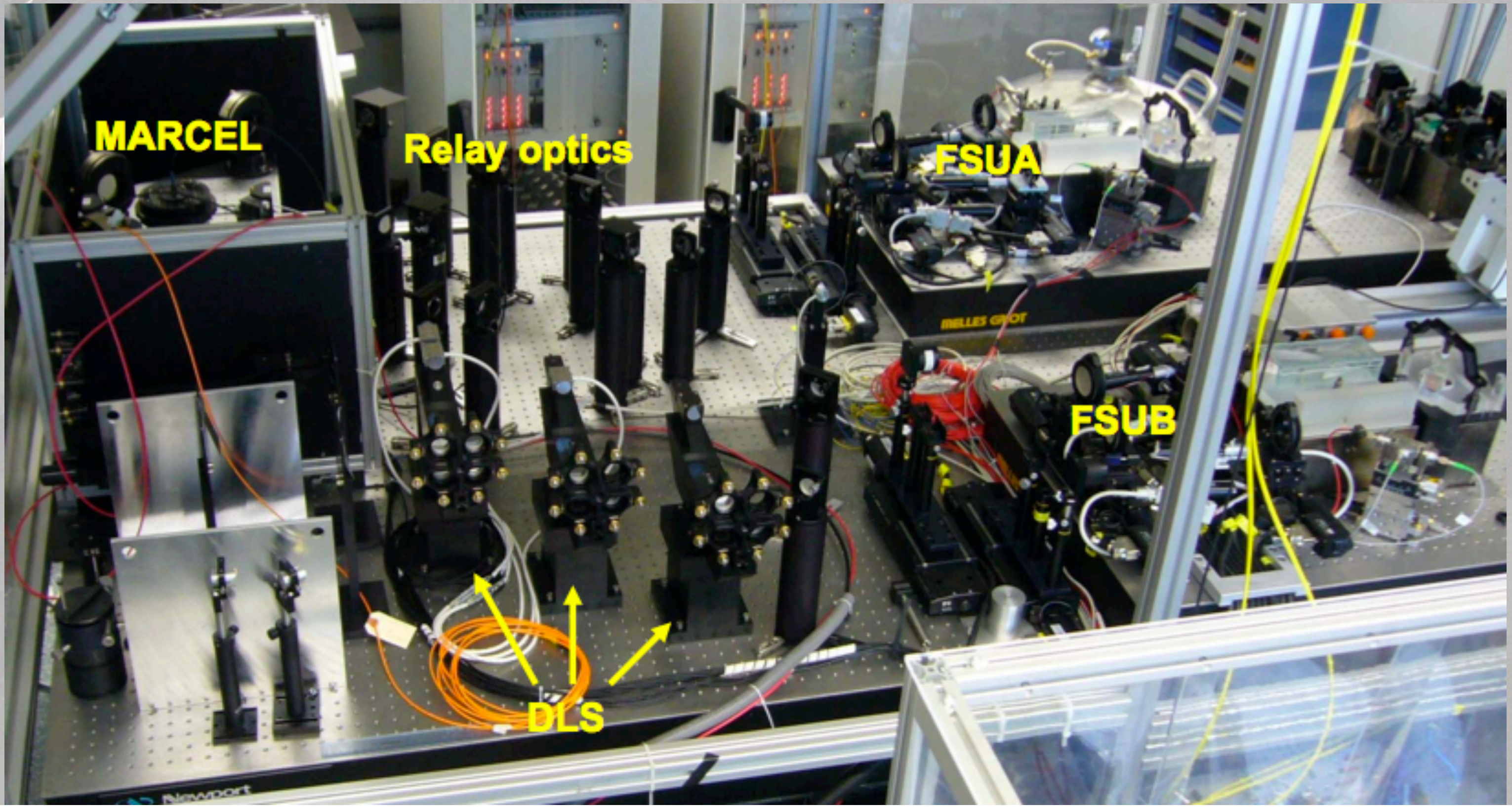


90
85
80
75
70
OPD / nm
GD Bias
34
36
38
40
42
44
46
10
8
6
4
2
0
-2
-4
-6
-8
-10
GD Bias Slope / nm/30min
34
36
38
40
42
44
46
time / h

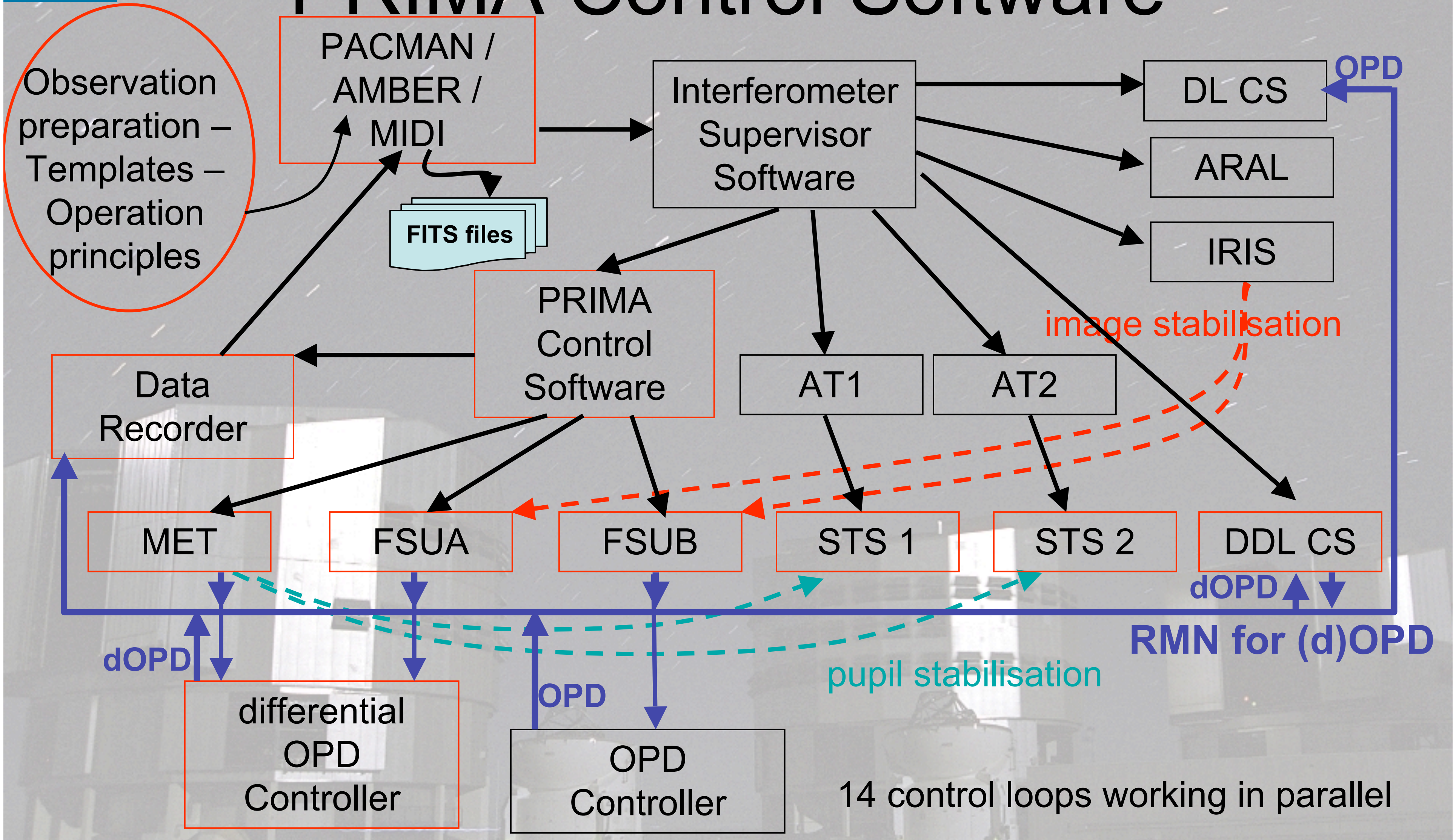
PRIMA testbed

- Testbed needed for:
  - acceptance tests of FSU (almost finished)
  - extensive system tests FSU + PRIMET + VLTI environment
- Includes:
  - MACAO high order residuals
  - tip-tilt perturbations
  - vibrations & other OPD perturbations
  - (D)DL simulators

- System tests:
  - FSU stability
  - IFG, BTK, VTK tuning
  - sensitivity (lim. mag.)
  - detector read-out optimization
  - # of spectral channels (3 / 5)
  - fringe tracking reliability
  - PACMAN & template tests
  - calibration optimization

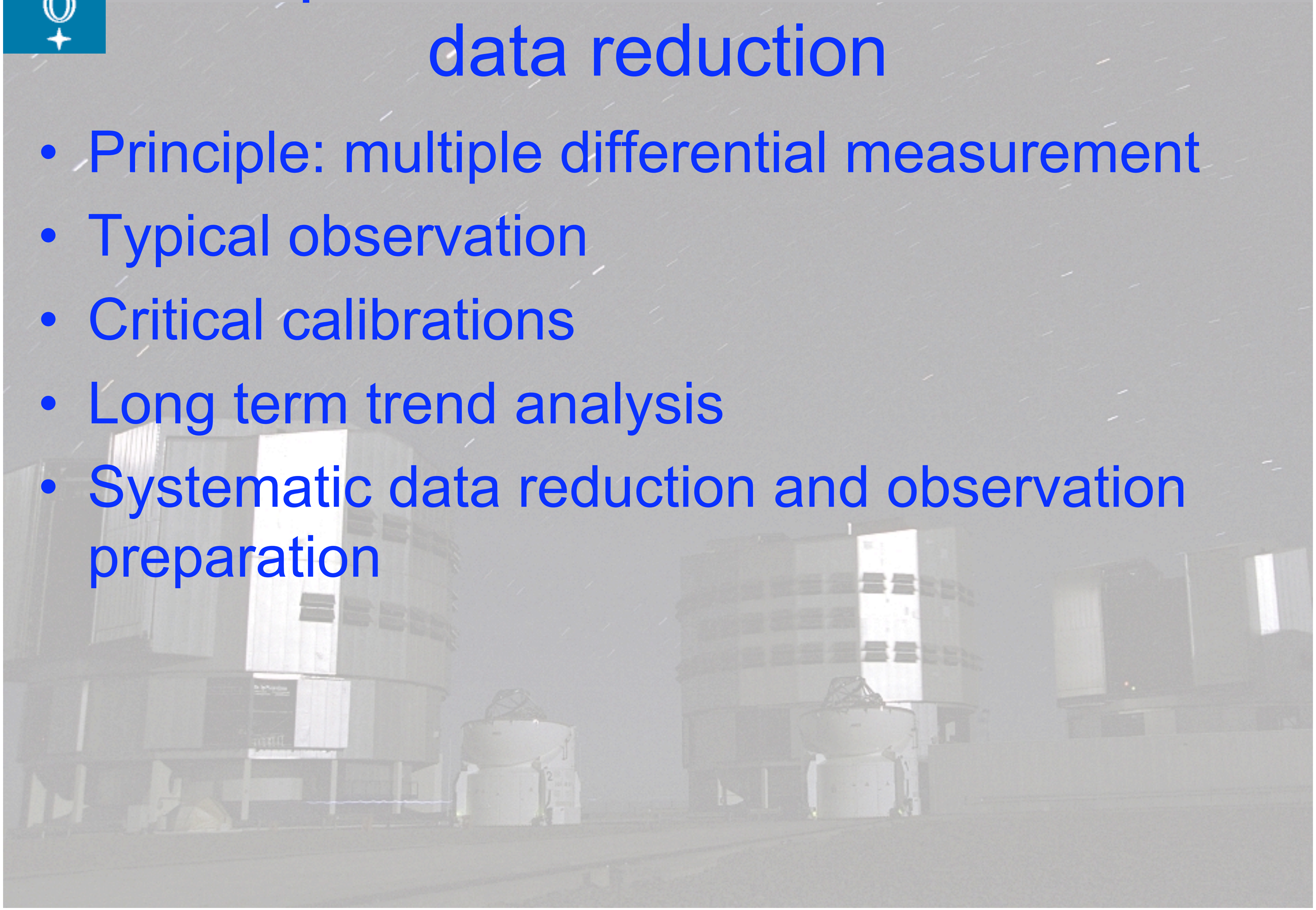


PRIMA Control Software



14 control loops working in parallel

Operation, calibration and data reduction



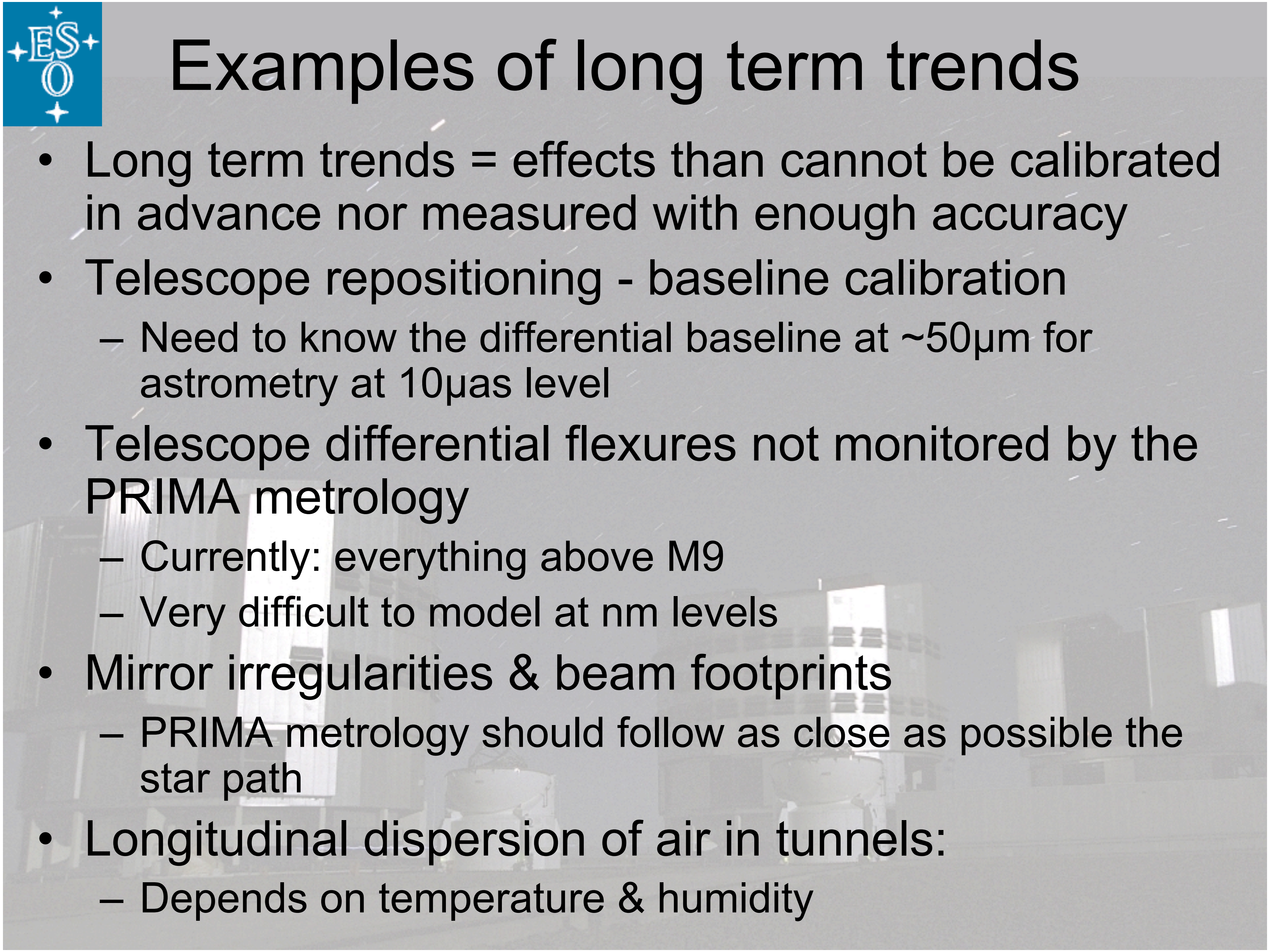
- Principle: multiple differential measurement
- Typical observation
- Critical calibrations
- Long term trend analysis
- Systematic data reduction and observation preparation

Multiple differences

- PRIMA = quintuple difference
  - 2 telescopes, 2 stars, 2 swaps, metrology/star λ, 2 moments in time
- Very differents scales:
  - 500m (metrology path) =>
  - 120m OPD =>
  - ~1cm dOPD =>
  - ~100nm fringe stabilization =>
  - 5nm measurement accuracy => 10^{-11} ratio to propagation length
- PRIMA challenges:
  - very complex system (reliability)
  - differences to be done cleanly
  - 10µas accuracy requires stability & data logging
    - PRIMA can control some things but not the environment
    - need to measure / calibrate what is not controlled
    - need to minimize by operation what cannot be calibrated
    - need of adapted data analysis and reduction software (PAOS = PRIMA Astrometric Observation & Software) for long term trends

Critical PRIMA calibrations

- Swapping beams (astrometry) =>
  - is needed to reject longitudinal differential effects between both beams and to “zero” the incremental metrology
  - no interruption of PRIMA metrology is allowed
- Injected flux and fiber alignment =>
  - no photometric channels is a weakness of the FSU
  - relative stability of the 4 FSU fibers has to be measured
- FSU / VLTI spectral calibration =>
  - fundamental for the group delay bias / stability
- Baseline calibration =>
  - to be known with an accuracy better than 50µm
  - dedicated observations / calibrations are needed
- Polarization calibration of the VLTI =>
  - potential cyclic errors => dedicated observation mode

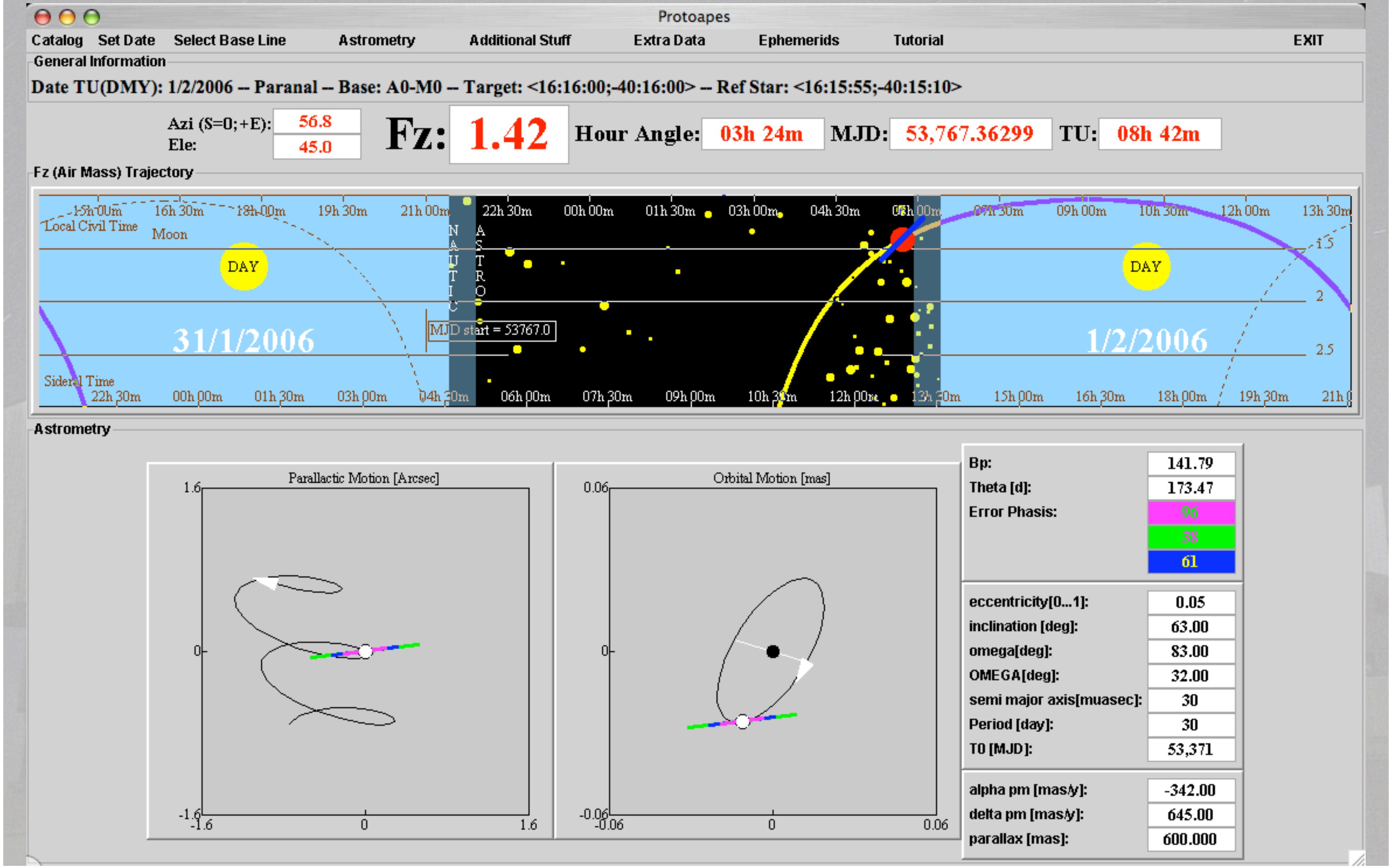


Examples of long term trends

- Long term trends = effects than cannot be calibrated in advance nor measured with enough accuracy
- Telescope repositioning - baseline calibration
  - Need to know the differential baseline at ~50μm for astrometry at 10μas level
- Telescope differential flexures not monitored by the PRIMA metrology
  - Currently: everything above M9
  - Very difficult to model at nm levels
- Mirror irregularities & beam footprints
  - PRIMA metrology should follow as close as possible the star path
- Longitudinal dispersion of air in tunnels:
  - Depends on temperature & humidity

Astrometric PrEparation Software

developed by the DDL-PAOS Consortium



Date TU(DMY): 1/2/2006 -- Paranal -- Base: A0-M0 -- Target: <16:16:00;-40:16:00> -- Ref Star: <16:15:55;-40:15:10>

Azi (S=0;+E): 56.8

Ele: 45.0

Fz: 1.42

Hour Angle: 03h 24m

MJD: 53,767.36299

TU: 08h 42m

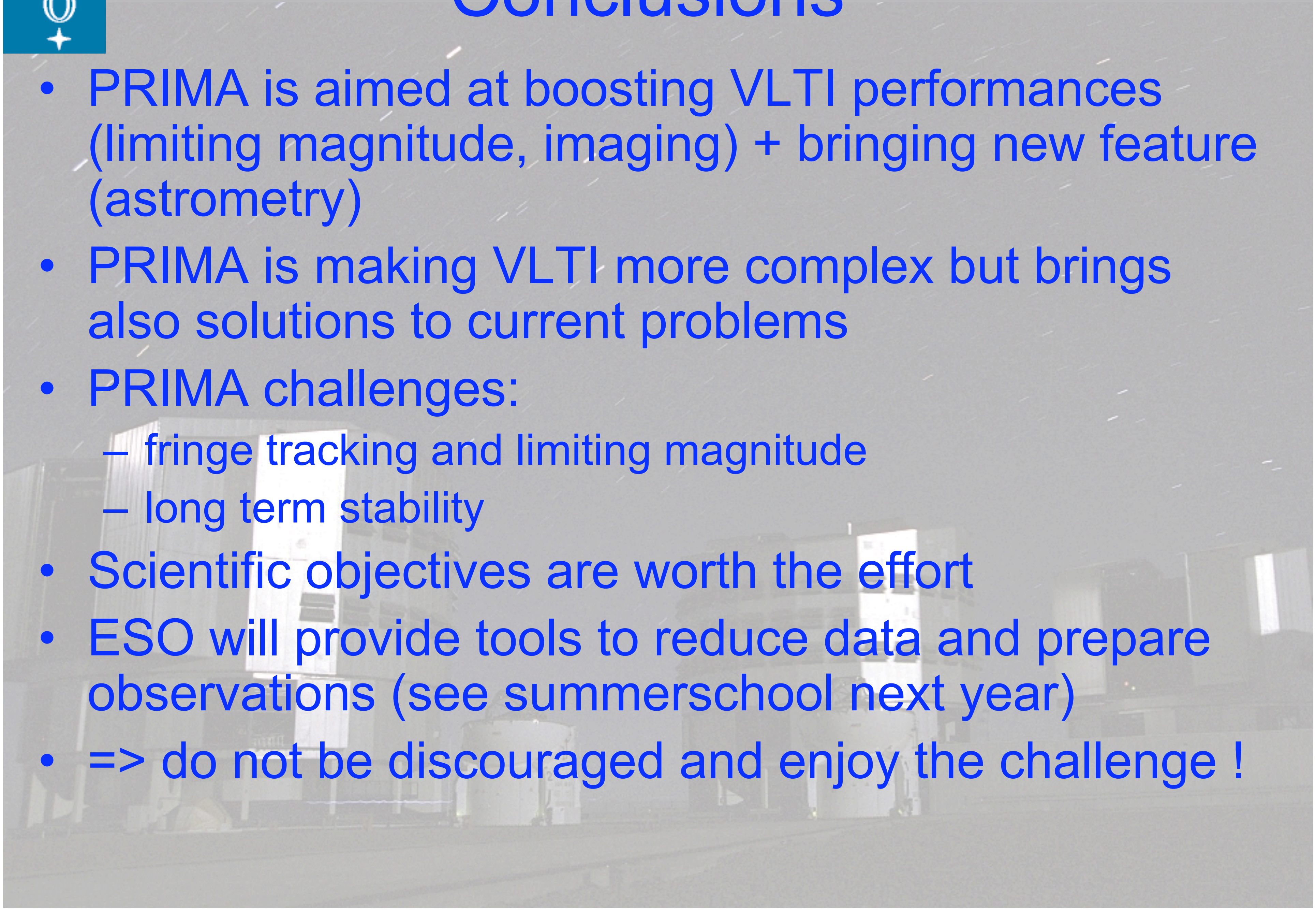
Bp:	141.79
Theta [d]:	173.47
Error Phasis:	96 33 61
eccentricity[0...1]:	0.05
inclination [deg]:	63.00
omega[deg]:	83.00
OMEGA[deg]:	32.00
semi major axis[muasec]:	30
Period [day]:	30
T0 [MJD]:	53,371
alpha pm [mas/y]:	-342.00
delta pm [mas/y]:	645.00
parallax [mas]:	600.000

Data Reduction Software and Analysis Facility

PAOS Consortium

- Pipeline
  - Correction of detector effects + data compression
  - Gives an approximate ΔOPD
- “Morning-after” off-line processing
  - Correction of daily effects (dispersion) using an “old” *calibration matrix*
  - Narrow-baseline calibration
  - Gives a better ΔOPD and angle
- Data Analysis Facility (end of 6-month period)
  - Fitting of long term trends & better fitting of daily trends
  - Computation of an accurate *calibration matrix*
- Off-line processing (end of 6-month period)
  - Idem as morning after but with updated *calibration matrix*

Conclusions



- PRIMA is aimed at boosting VLTI performances (limiting magnitude, imaging) + bringing new feature (astrometry)
- PRIMA is making VLTI more complex but brings also solutions to current problems
- PRIMA challenges:
  - fringe tracking and limiting magnitude
  - long term stability
- Scientific objectives are worth the effort
- ESO will provide tools to reduce data and prepare observations (see summerschool next year)
- => do not be discouraged and enjoy the challenge !