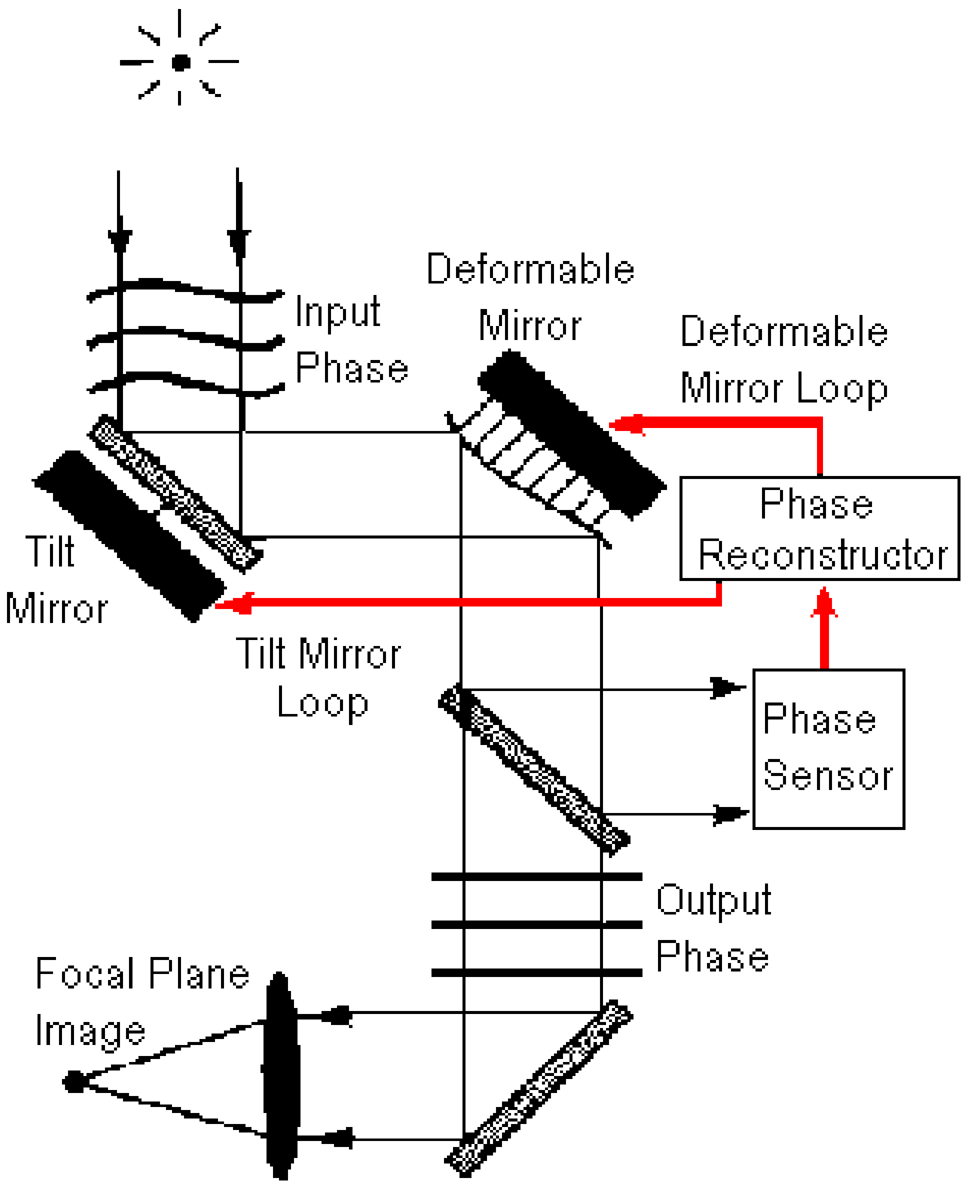
Adaptive Optics

Atmospheric turbulence and its effect on image quality

Image quality metrics
Atmospheric turbulence
Wavefront phase
Measuring important turbulence parameters
Wavefront phase error budget

What is Adaptive Optics ?



Main components of an AO system:

Guide star(s): provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

Deformable mirror(s) (+ tip-tilt mirror): corrects aberrations

Wavefront sensor(s): measures aberrations

Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

Strength of Turbulence : C_N^2

Variations in refractive index due to temperature fluctuations

Refractive index spatial structure function (3D):

$D_N(\rho) = <|n(r)-n(r+\rho)|^2> = C_N^2 \rho^{2/3}$ (equ 1)

Equation is valid between inner scale (~mm) and outer scale (few m)

Taylor approximation: turbulence is a frozen wavefront pushed by the wind (frozen flow)

Between inner and outer scale, turbulence is well described by this power law.

Refractive index temporal structure function under Taylor approximation:

$D_N(\tau) = <|n(r,t)-n(r,t+\tau)|^2> = C_N^2 |v\tau|^{2/3}$

Atmospheric Turbulence

Spatial variations in refractive index → poor image quality

Turbulence is energy dissipation effect :

Large motions → breaks down into smaller turbulence cells → friction (heat dissipation) at inner scale

From C_N^2 to wavefront structure function

Wavefront phase spatial structure function (2D):

$$D_{\phi_a}(\rho) = \left\langle \left| \phi_a(\mathbf{r}) - \phi_a(\mathbf{r} + \rho) \right|^2 \right\rangle_{\mathbf{r}}$$

Can be obtained by integrating equ 1 over light path:

$$D_{\phi_a}(\rho) = 6.88 \left(\frac{|\rho|}{r_0} \right)^{5/3}$$ (equ 2)

With r_0 = Fried Parameter [unit = m]

$$r_0 = \left(16.7 \lambda^{-2} (\cos\gamma)^{-1} \int_0^\infty dh C_N^2(h) \right)^{-3/5}$$

Wavelength

Elevation (=0 for Zenith)

From C_N^2 to wavefront error

Wavefront phase error over a circular aperture of diameter d:

$$\sigma^2 = 1.0299 \left(\frac{d}{r_0}\right)^{5/3}$$

r_0 = Fried Parameter [unit = m] = diameter of telescope for which atmospheric wavefront ~ 1 rad^2

In this “collapsed” treatment of turbulence (what is the wavefront in a single direction in the sky), turbulence is fully described by r_0 and wind speed v

If variation of wavefront over small angles is important, the **turbulence profile** becomes important

Atmospheric turbulence, wavefront variance, Image quality

Kolmogorov turbulence

D = telescope diameter

$\sigma^2 = 1.03\ (D/r_0)^{5/3}$

Seeing = λ/r_0

Number of speckles = $(D/r_0)^2$

D = 8 m, r_0 = 0.8 m

(0.2 m in visible = 0.8 m at 1.6 µm)

Wavefront error σ is in radian in all equations.

Wavefront variance σ^2 is additive (no correlation between different sources), and the wavefront error budget is built by adding σ^2 terms.

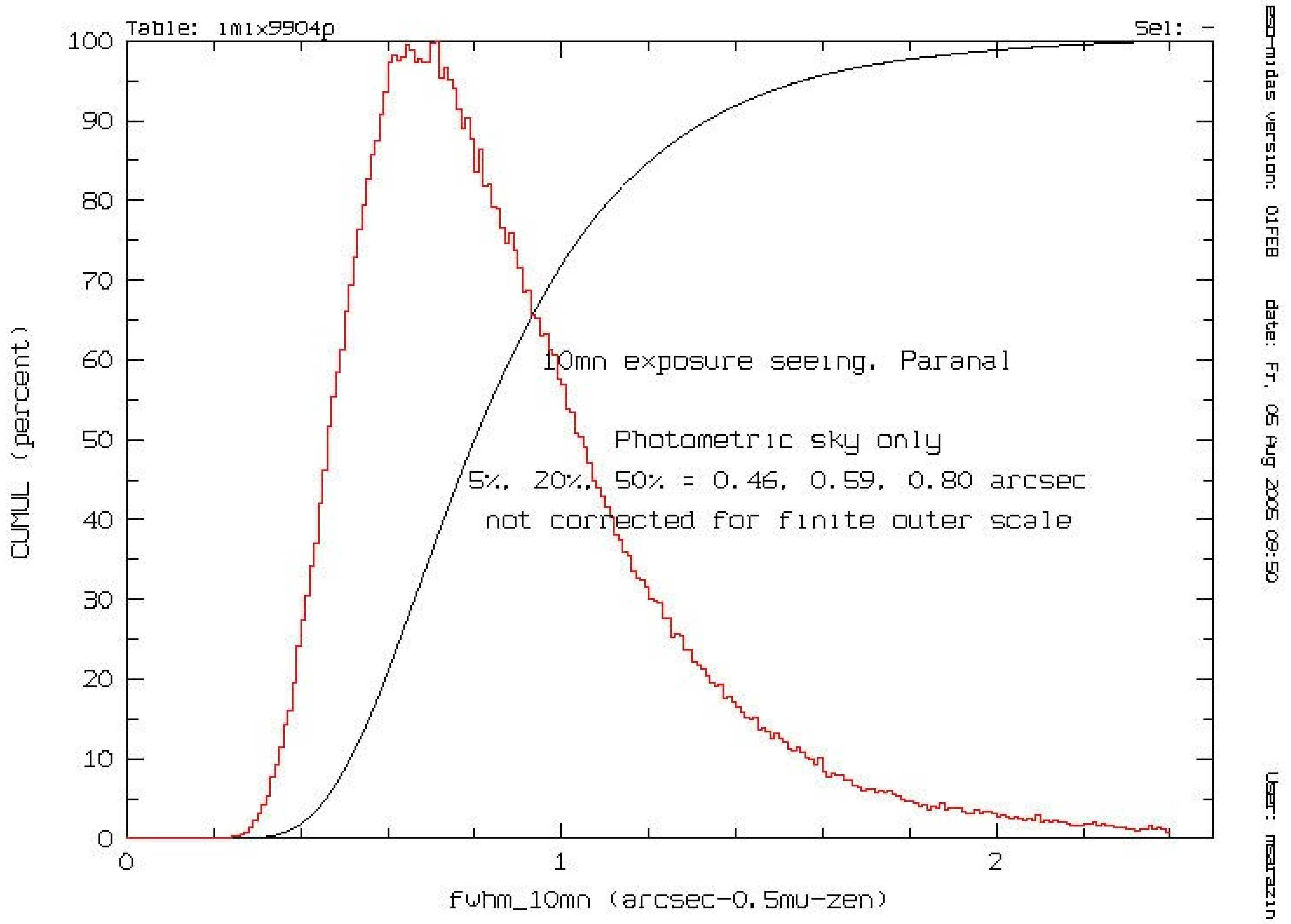
Wavefront error (m) = $\lambda \times \sigma/(2\pi)$

Strehl ratio ~ $e^{-\sigma^2}$

(Marechal approximation, valid for Strehl ratio higher than ~0.3)

Seeing (or its equivalent r_0) is the most used metric to quantify atmospheric turbulence

WITHOUT AO (and with long exposures), this is the only relevant quantity to describe atmospheric turbulence



ESO VLT seeing statistics, 1999-2004

With AO, **isoplanatic angle** and **coherence time** become important

How quickly does the wavefront change with location on the sky is quantified by **isoplanatic angle**

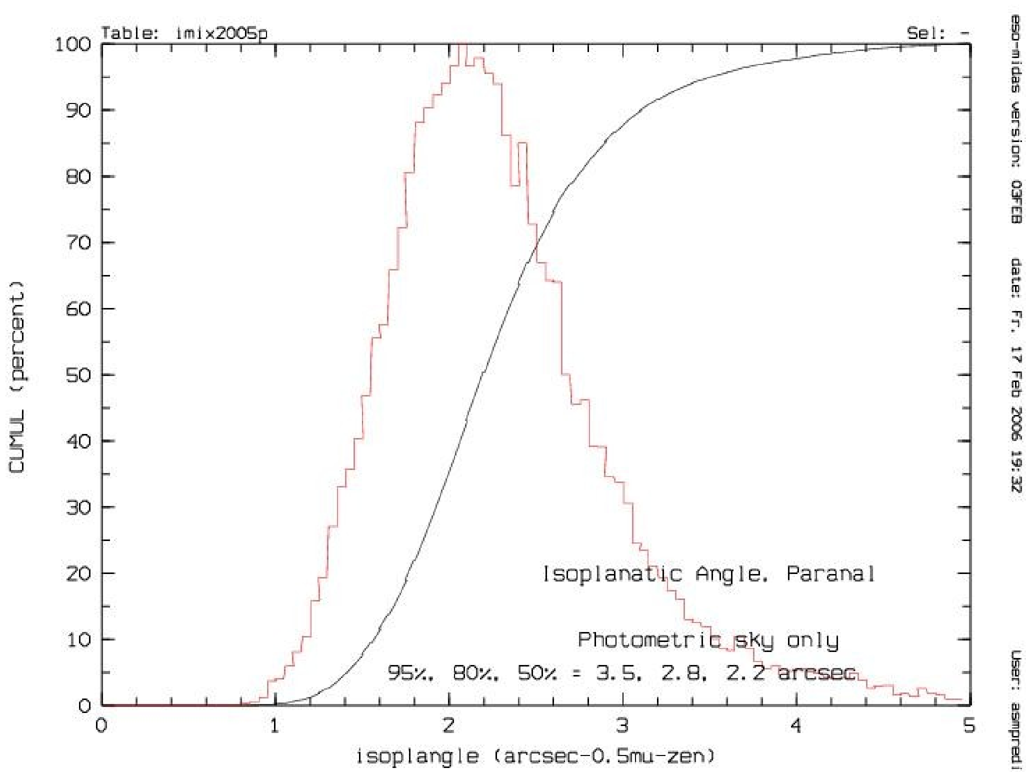
→ field of view of corrected image

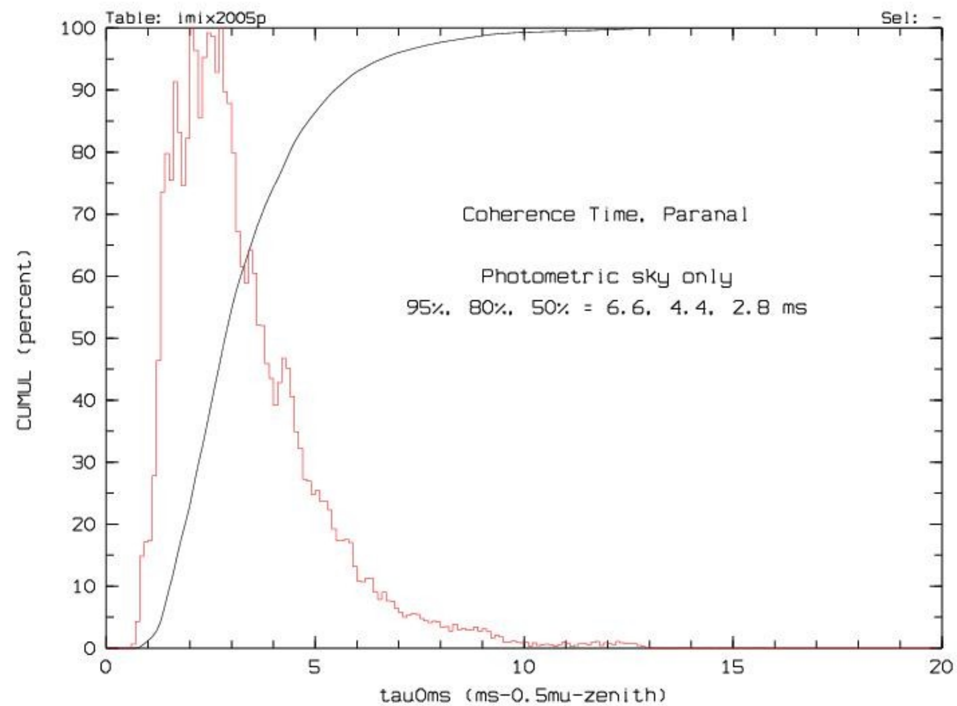
→ how far from science target can the guide star be

Speed at which wavefront changes is quantified by **coherence time**

→ how fast should the AO system run ?

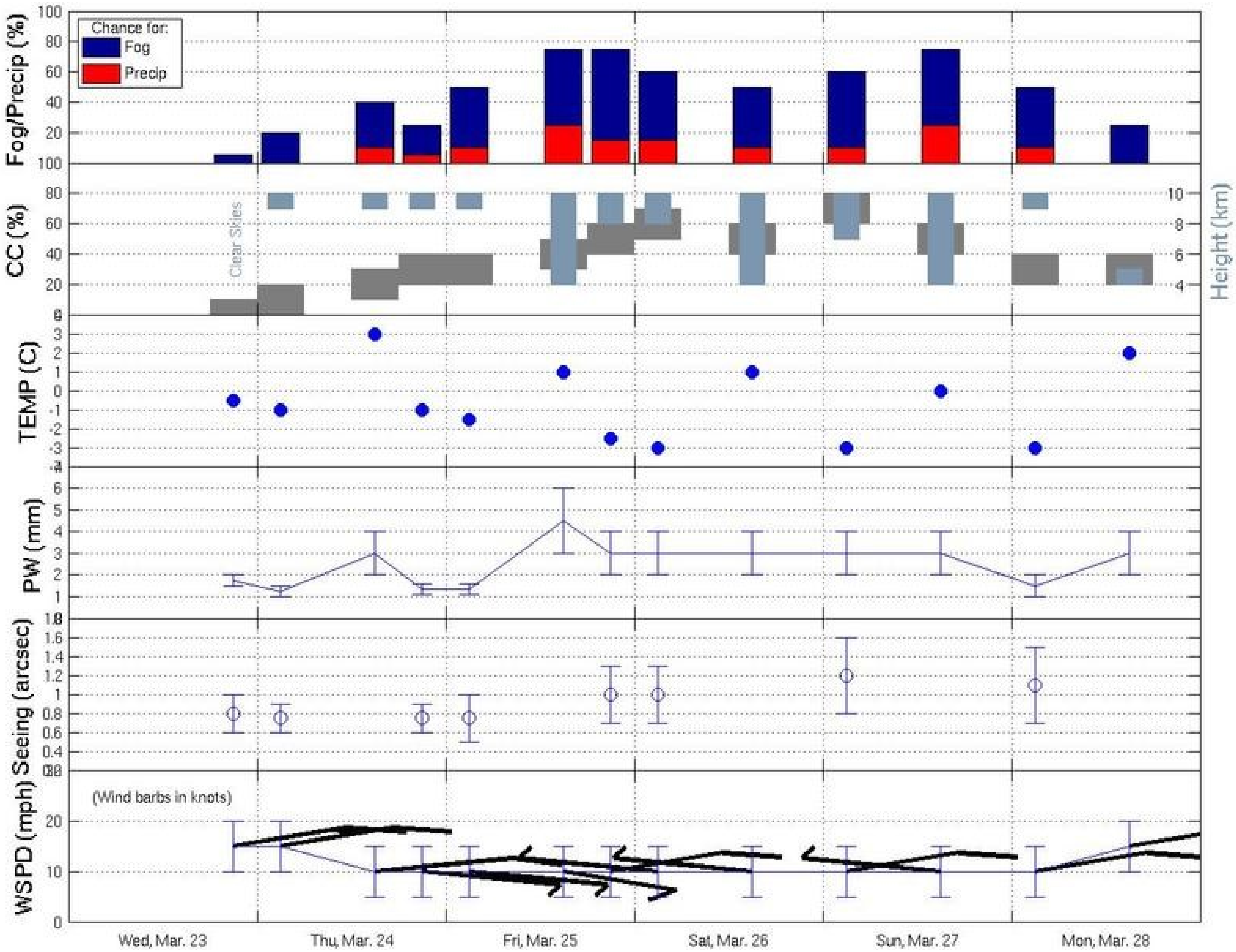
→ how faint a guide star can be used ?



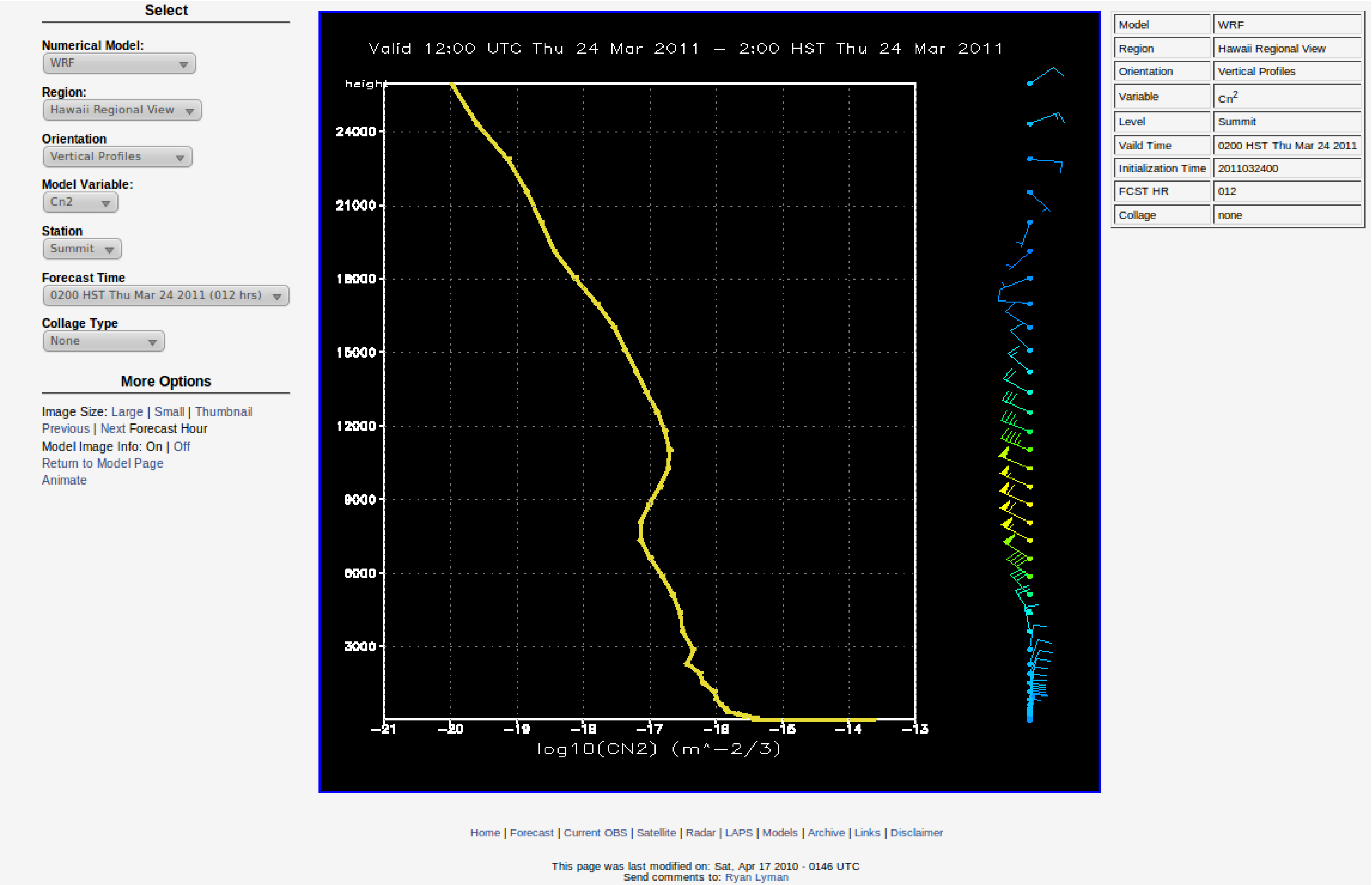


ESO VLT seeing statistics, 2005

Example: Mauna Kea observatory forecast



C_N^2 profile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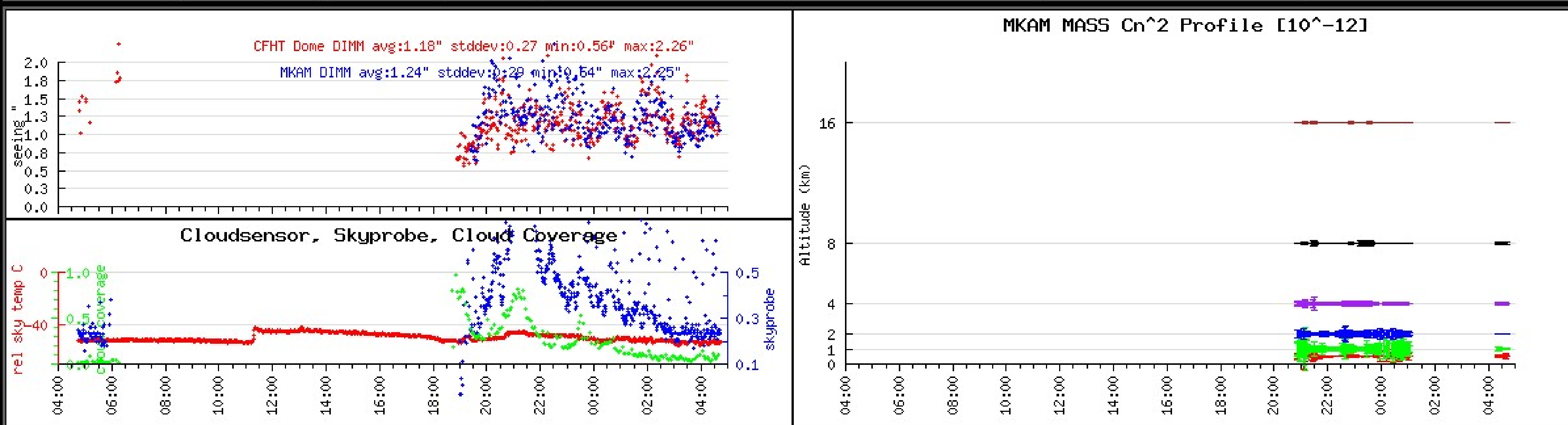
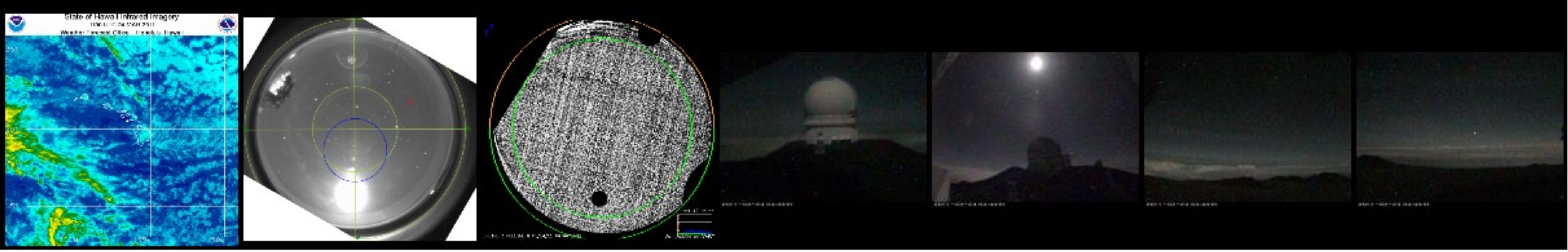
Canada France Hawaii Telescope (CFHT) weather summary page

DIMM: Differential Image Motion Monitor
MASS: Multiaperture Scintillation Sensor

Currently	Ambient	RH %	Wind	Sky Temp	Last Cloud Coverage	Last Skyprobe	Last Dome DIMM seeing	Last Seeing Monitor Seeing
Mar 24 2011 4:43AM	0C	10%	6 @ 79deg	-53.01C	10% @ Mar 24 2011 4:39AM	0.23 @ Mar 24 2011 4:42AM	1.08" @ Mar 24 2011 4:37AM	1.06" @ Mar 24 2011 4:42AM





Differential Image Motion Monitor (DIMM)

Concept: measure differential motion, for a single star, between images formed by different subapertures of a single telescope

RoboDIMM for Isaac Newton group of Telescope (LaPalma, Canary islands, Spain)

Coherence time

Assuming perfect DMs and wavefront knowledge, how does performance decrease as the correction loop slows down ?

Assuming pure time delay t

$\sigma^2 = (t/t_0)^{5/3}$

t_0 = coherence time "Greenwood time delay"= 0.314 r_0/v

v = 10 m/s

r_0 = 0.15 m (visible)   0.8 m (K band)

t_0 = 4.71 ms (visible)   25 ms (K band)

Assuming that sampling frequency should be ~ 10x bandwidth

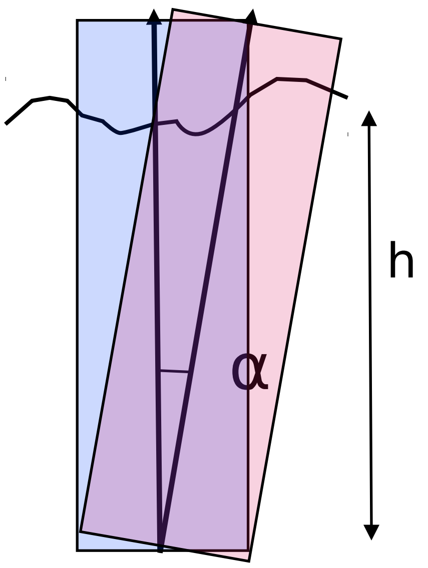
for "diffraction-limited" system (1 rad error in wavefront):
sampling frequency = 400 Hz for K band

for "extreme-AO" system (0.1 rad error):
sampling frequency = 6 kHz for K band

Isoplanatic angle

Atmospheric wavefront not the same for different directions on the sky

Two equivalent views of the problem:
- Wavefront changes across the field of view (MOAO)
- Several layers in the atmosphere need to be corrected (MCAO)



If we assume perfect on-axis correction, and a single turbulent layer at altitude h, the variance (sq. radian) is :

$\sigma^2 = 1.03\ (\alpha/\theta_0)^{5/3}$

Where α is the angle to the optical axis, θ_0 is the isoplanatic angle:

$\theta_0 = 0.31\ (r_0/h)$

D = 8 m, r_0 = 0.8 m, h = 5 km −> θ_0 = 10”

To go beyond the isoplanatic angle: more DMs needed (but no need for more actuators per DM).

Amplitude effects, chromaticity

Atmospheric wavefronts (in optical path) are chromatic, and include amplitude (scintillation)

Several effects:

- Diffraction propagation converts phase into amplitude (scintillation)

- Diffraction propagation is chromatic → scintillation is chromatic

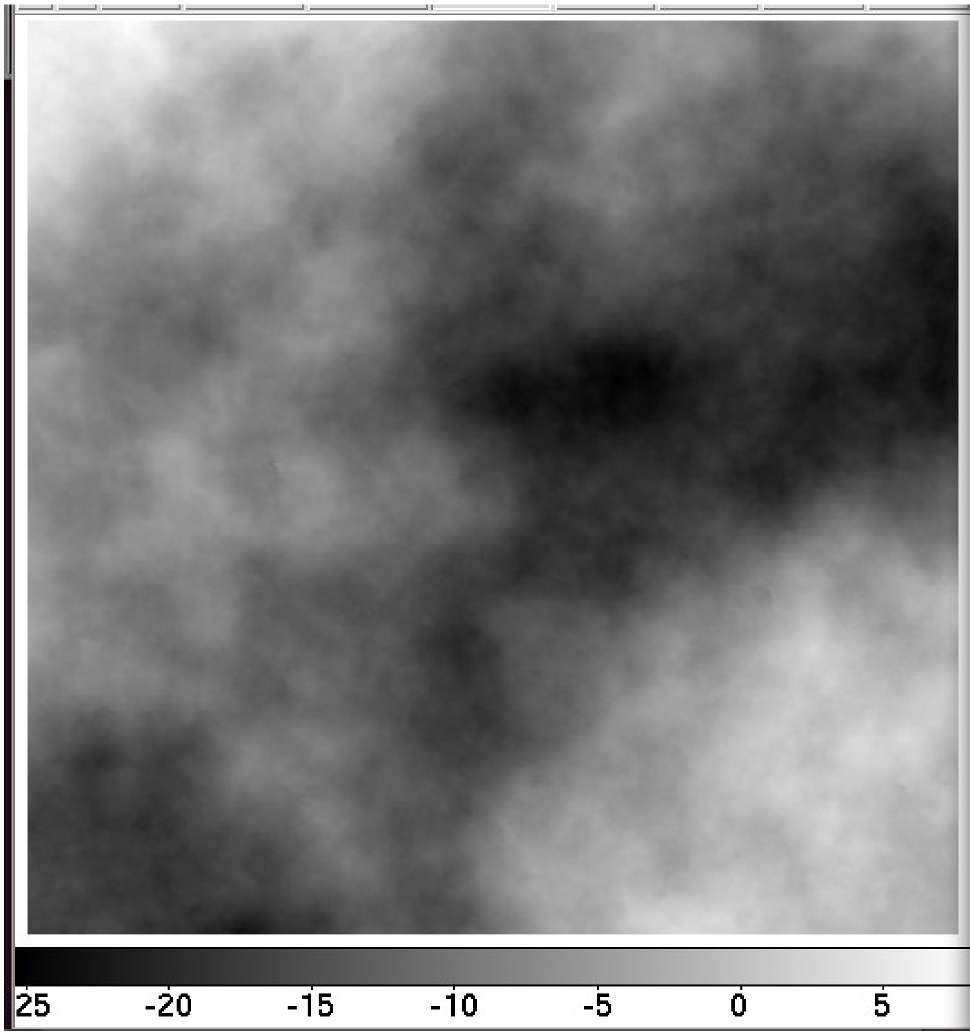
- Refraction index of air is slightly chromatic

- Atmospheric dispersion → light path from source to telescope is slightly different for different colors (~cm offset beetween red and blue light at few km altitude)

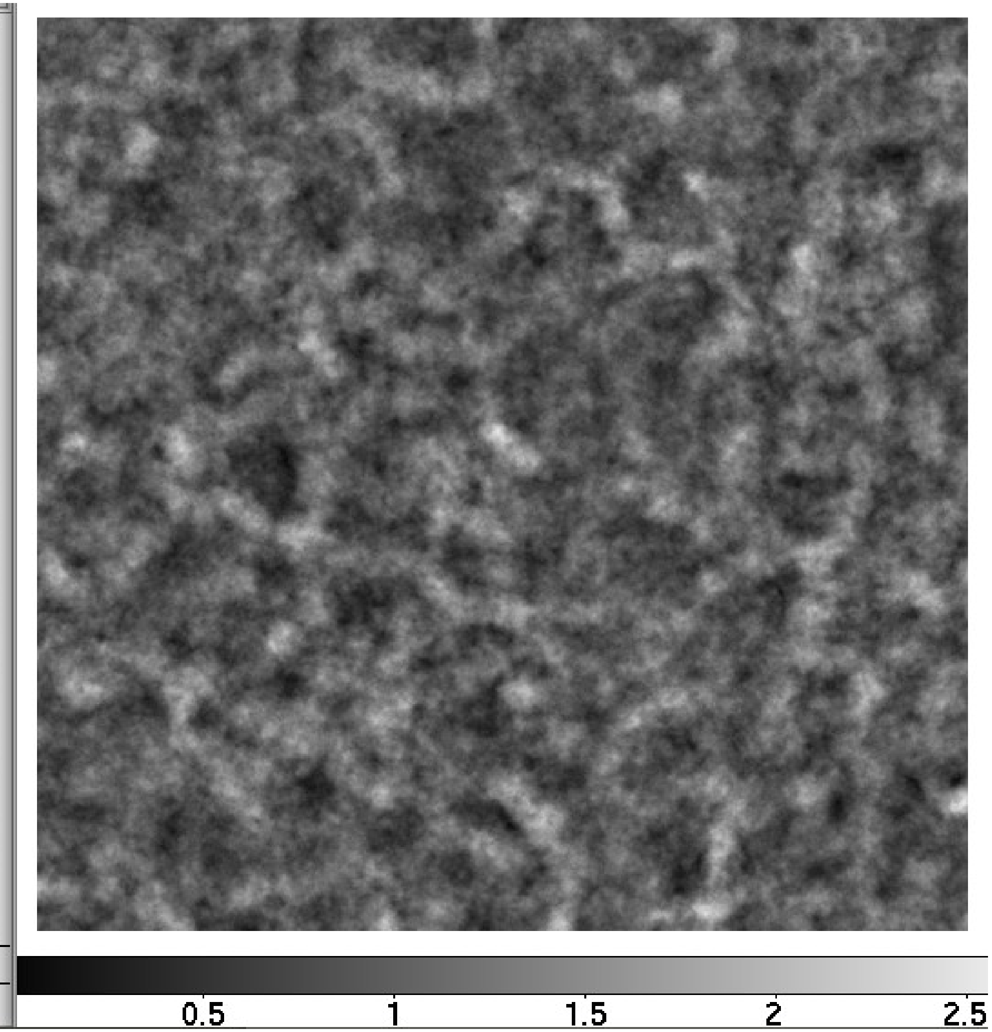
Amplitude and chromaticity effects << phase corrugations
But can be important in Extreme-AO systems aiming at very high quality correction

Example Scintillation

2mm / pixel, 1024x1024 pix (~2m x 2m)
lambda = 500nm,   Zenith angle = 30 deg, 0.8” seeing at zenith
Site: Mauna Loa observatory (3500m altitude)



phase [radian]



amplitude