DCSC

M. Verhaegen (thanks to K. Hinnen, R. Fraanje, N. Doelman (TNO),
F. Stoffelen (TNO), R. Wilson (Durham UK))

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1. Delft Celebrates Systems and Control

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2. Do Crazy Study and Control

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1. Delft Celebrates Systems and Control
2. Do Crazy Study and Control
3. Dealing with Complexity by Exploiting Structure in and Controller design

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1. What challenges does Complexity offers to Control?
2. Case study: Probing the universe
3. Adaptive Optics (AO)
   - State of the Art
   - A Control Engineering Approach to AO

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4. Challenges for future research (at DCSC)

Complexity (L. complexus)

Websters: refers to that which is made up of many elaborately interrelated or interconnected parts, so that much study or knowledge is needed to understand or to operate it.

Founding Principle of Control Engineering

The field of control is built on the tradition of linking applications, theory and computation to develop techniques with rigorous mathematics.

Panel on Future Directions in CDS, 2002

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Probing the Universe

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Astronomical telescopes are essential tools to access the widest and most comprehensive laboratory of all, the universe we live in.

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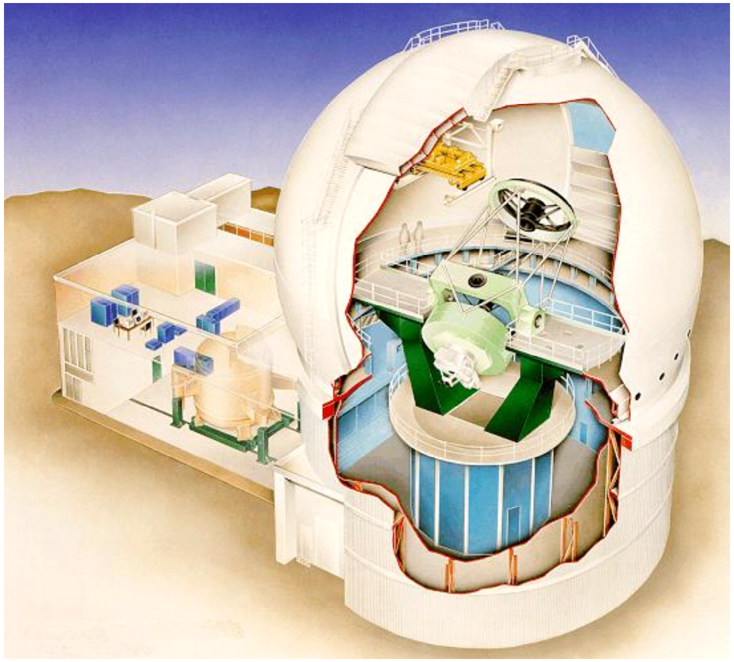

The William-Herschel Telescope

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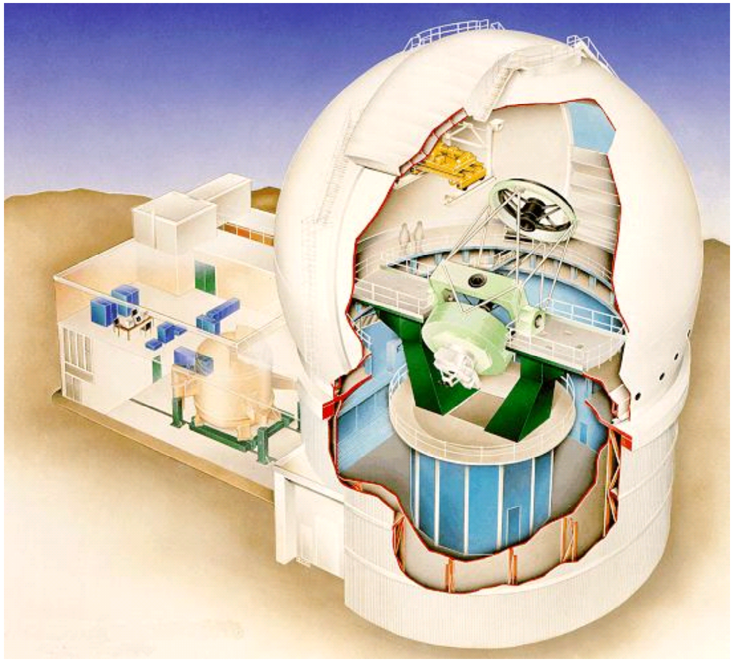
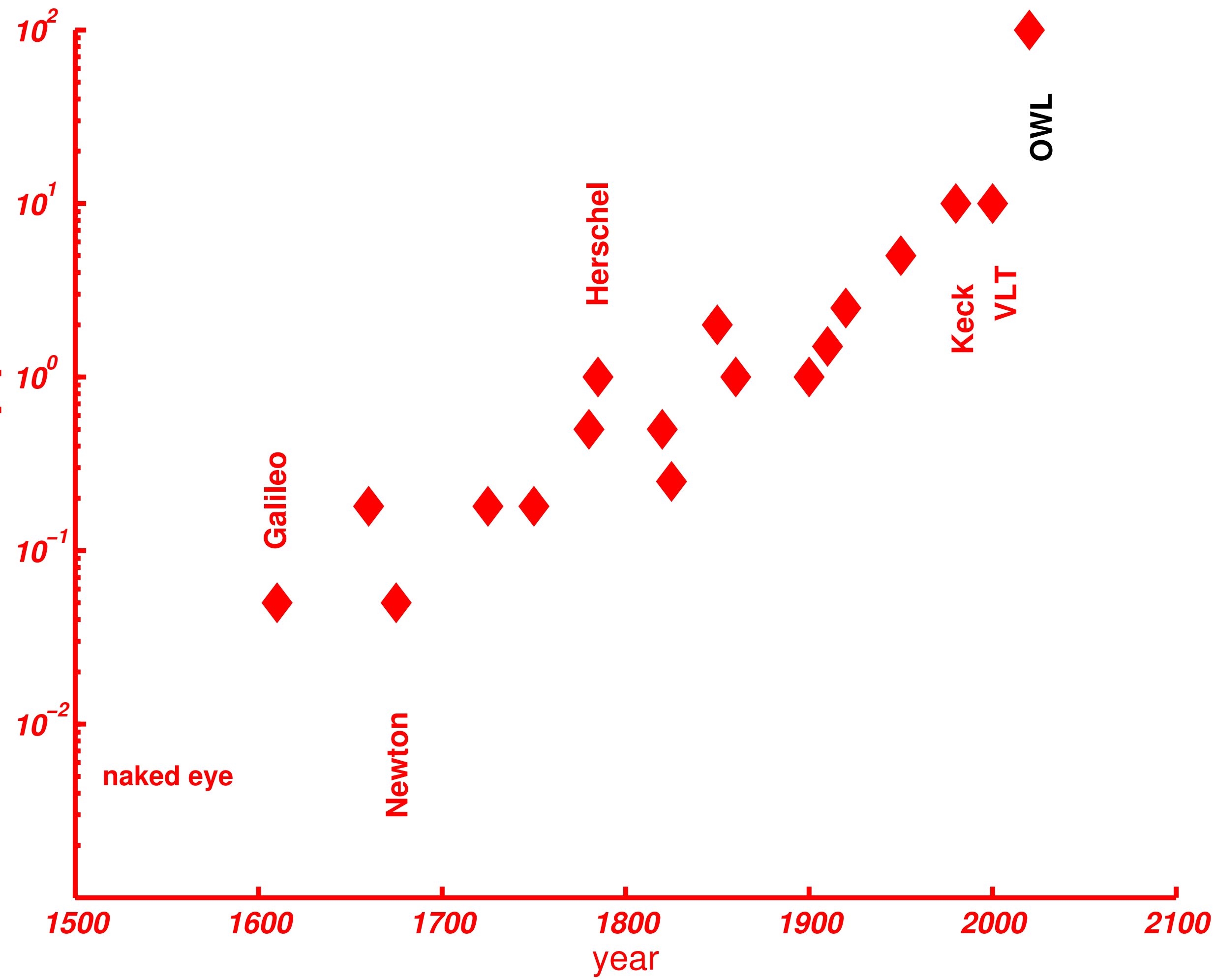


The William-Herschel Telescope

Telescopes enabled new discoveries, like

Quansars, masers, black holes, gravitational arcs, extra-solar planets, gamma-ray bursts, dark matter, dark energy

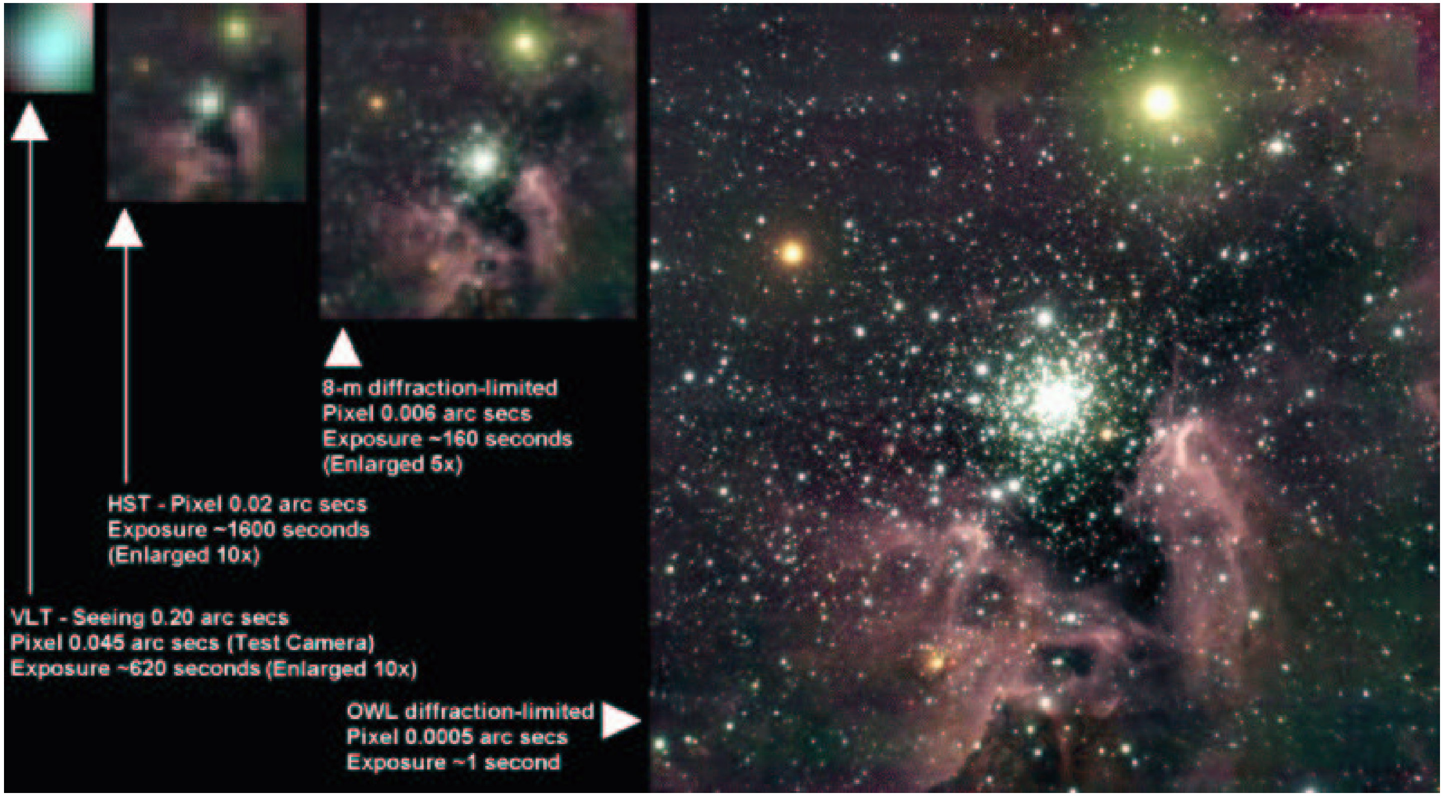
A Quantum Leap in Telescope Development



Evolution of telescope diameter over time

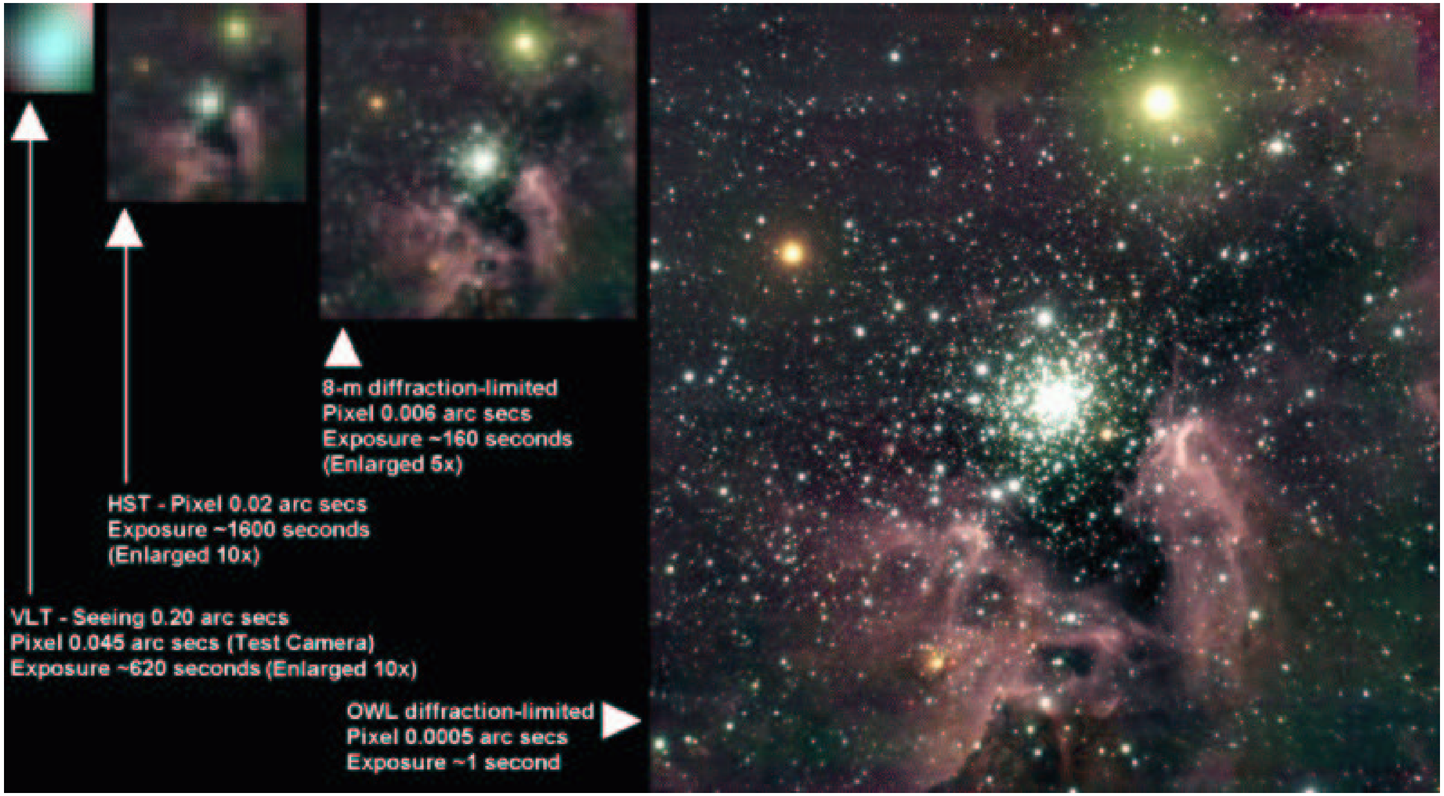
Each new generation of telescopes is designed to answer the questions raised by the previous ones.

Potential of OWL



Simulated images of the increase of resolution and efficiency with telescope size

Potential of OWL



Simulated images of the increase of resolution and efficiency with telescope size

OWL will make us witness the development of galaxies

Complexity Issues in Future Telescope Designs

Future Telescope Dimensions will be possible by the collaboration of distributed sensores and actuators
Example: A 32 meter telescope may consist of 9000 Deformable Mirror (DM) actuators and 16000 Wavefront Sensors (WFS) subapertures.

[B.L. Ellerbroek, et. al, Applied Optics, 2003]

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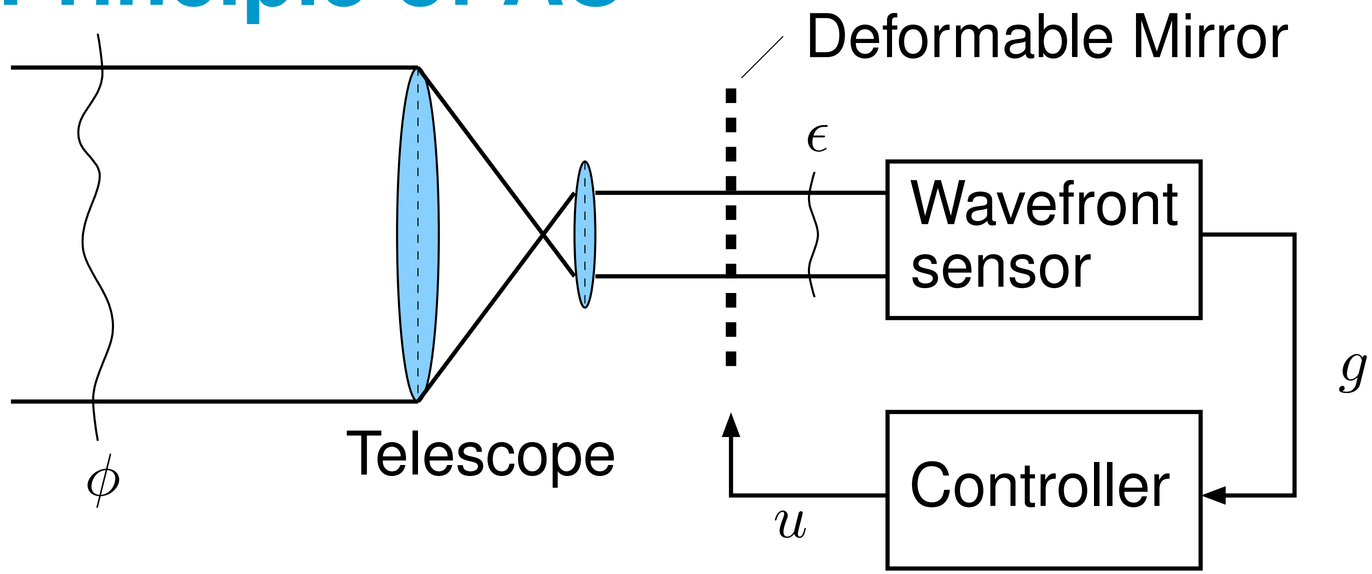
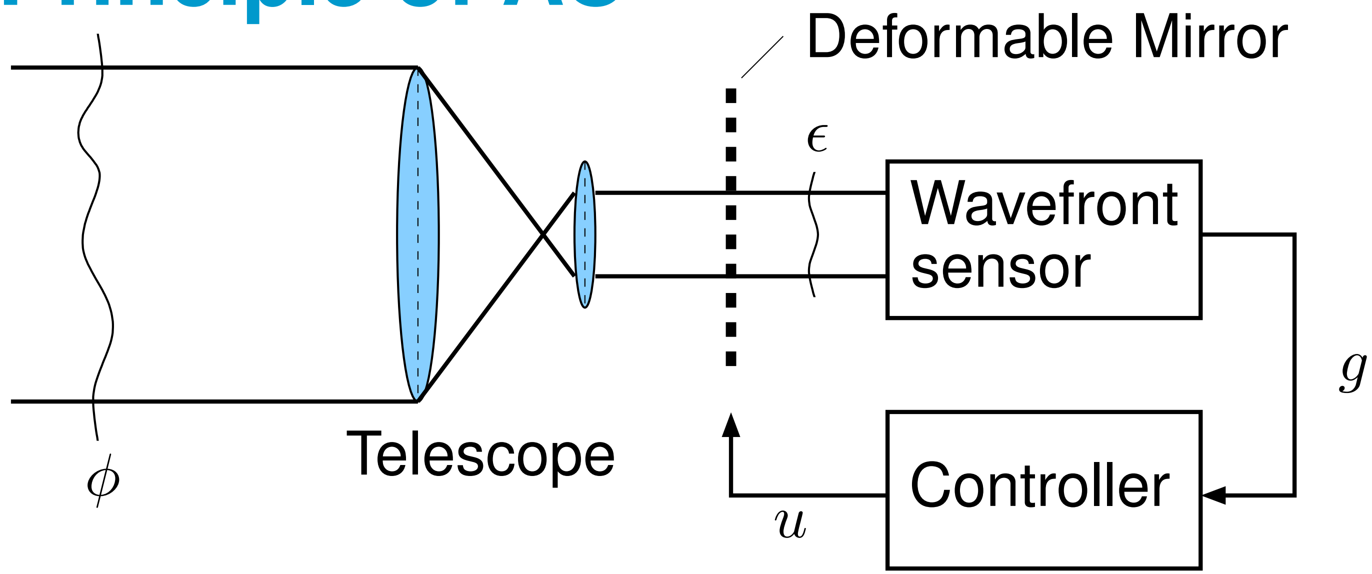
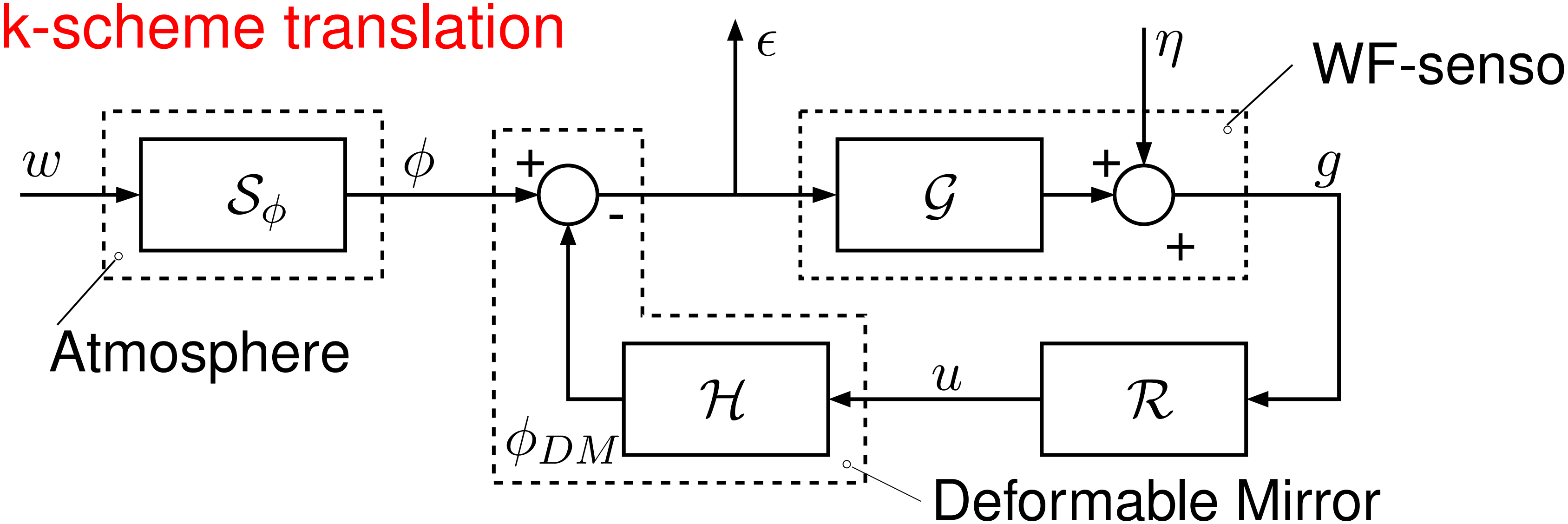
Principle of AO



Principle of AO



Block-scheme translation



State of the Art in AO

The standard formulation to minimize the mean-square residual phase error, i.e. $\|\epsilon\|_2^2$, is based on the simplifying assumptions:

1. Only spatial dependency ($\mathcal{G}$, etc. are large structured matrices).

2. The WFS measurement vector s is a linear function of the phase distortion ϕ, whereas ϕ follows the non-rational Kolmogorov power spectum:

$$\Phi(\kappa) = \frac{0.023}{r_0^{5/3}\kappa^{11/3}},$$

(κ spatial frequency, r_0 Fried coherence length)

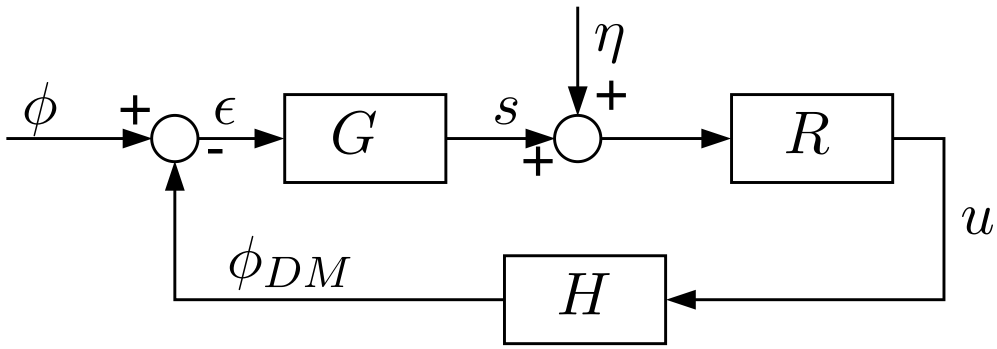
3. The WFS measurement vector s is an open-loop measurement that is obtained prior to correcting the phase errors

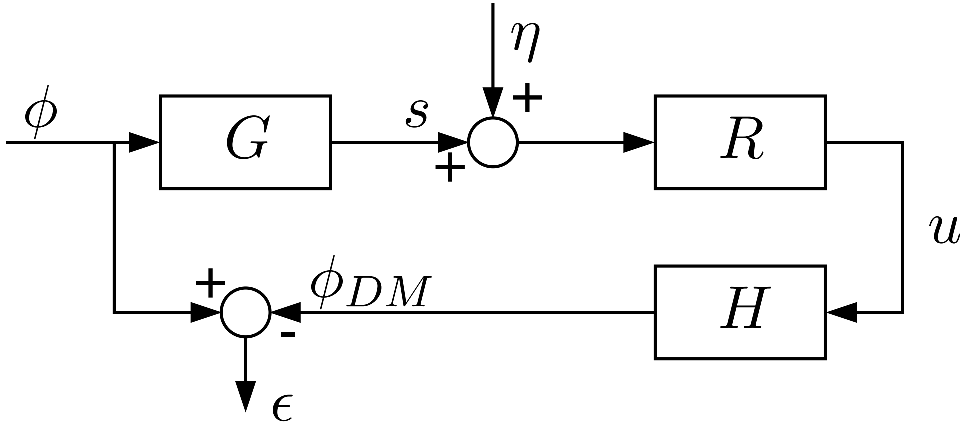
[B.L. Ellerbroek, et. al, Optical Society of Am., 2003]

State of the Art in AO

By the standard assumptions, the feedback control problem is “linearized” into a feedforward reconstruction problem.

feedback $\overset{\text{Assumptions}}{\longrightarrow}$ feedforward





$\min_R \|\epsilon\|_2^2$

?

$\min_R \|\epsilon\|_2^2$

$$\hat{R} = (HH^T)^{-1}H^T C_\phi G^T (GC_\phi G^T + C_n)^{-1}$$

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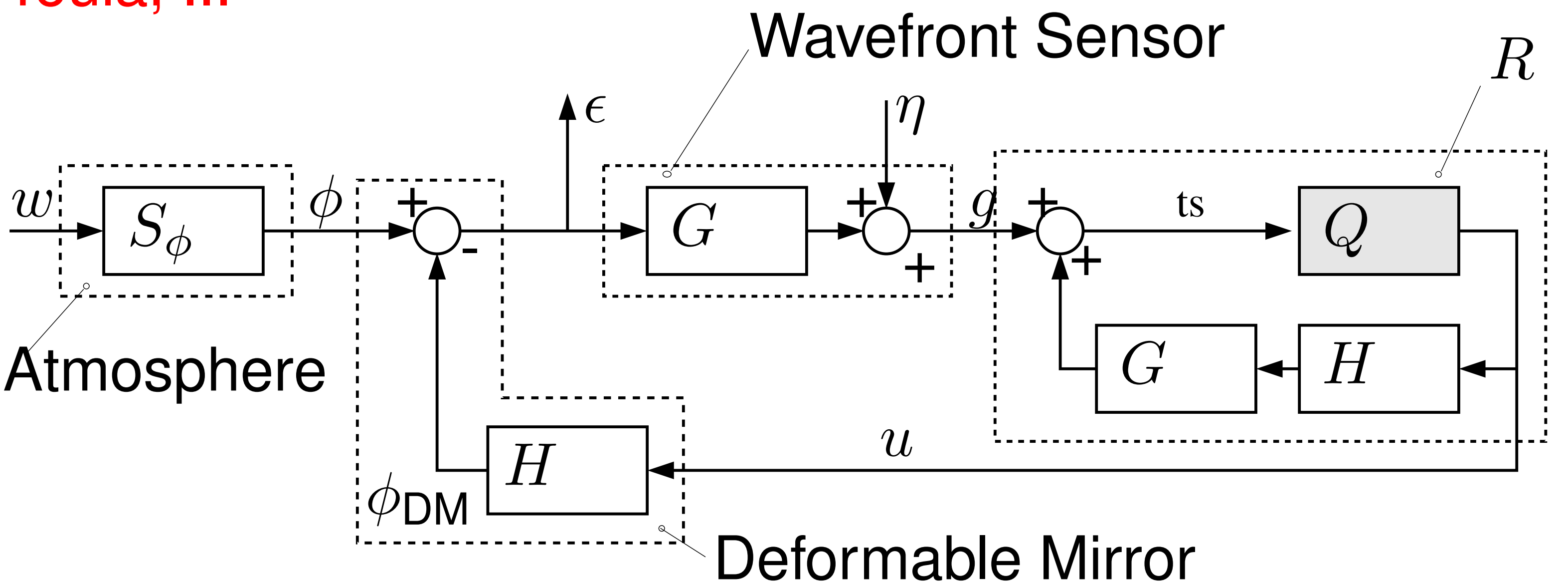
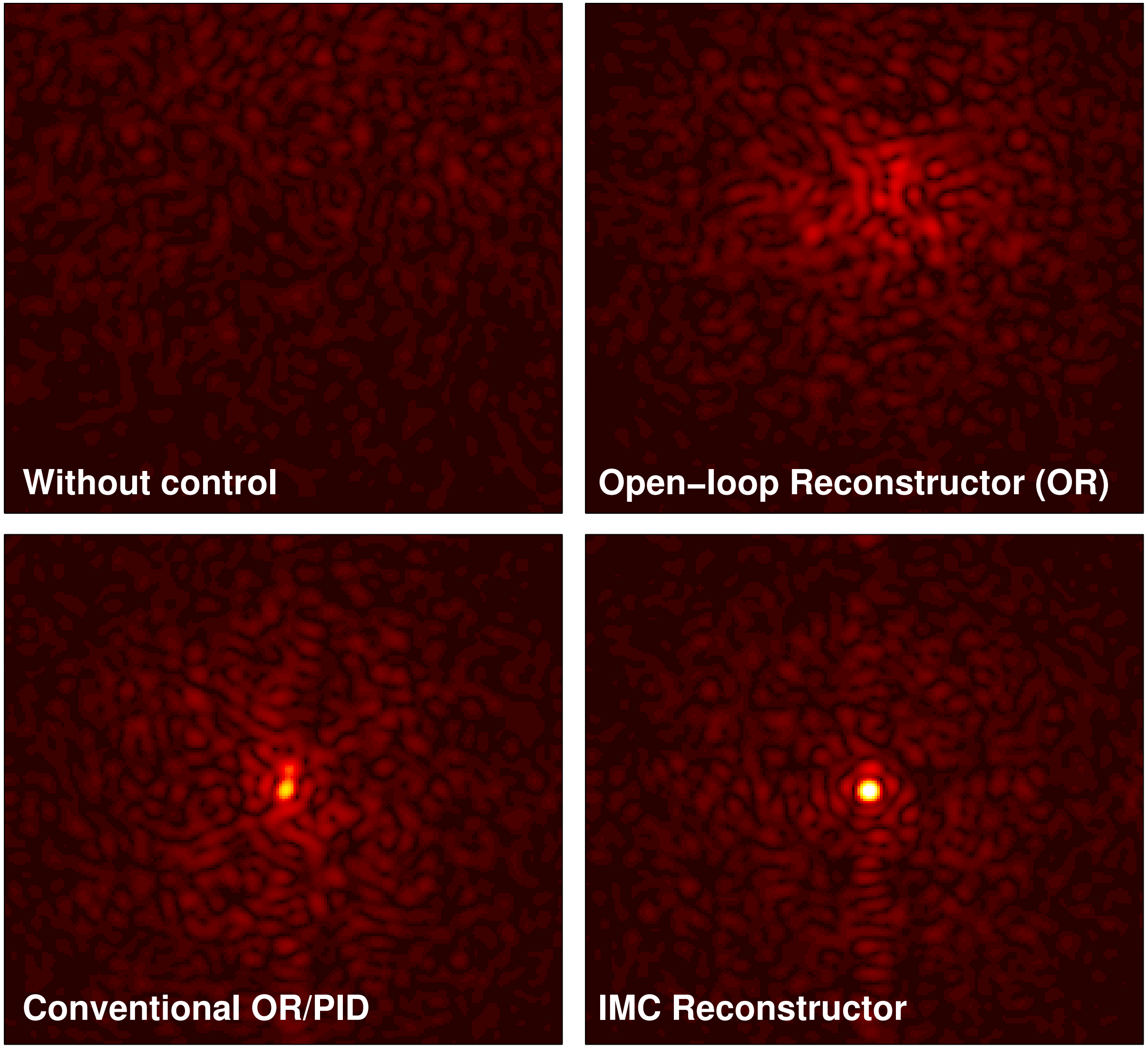
Control Engineering Approach to AO

(Spatial Dependency only)
Feedback control problem can readily be solved using IMC, Youla, ...



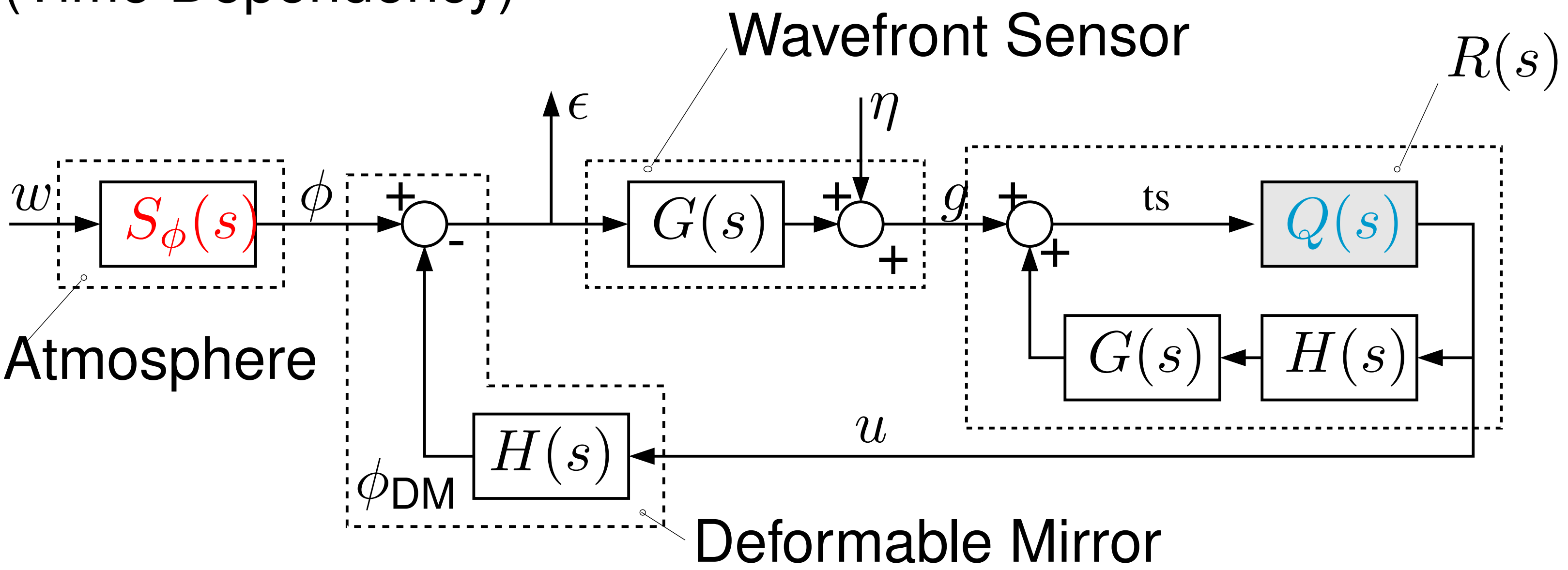
$$\min_{Q} \|\epsilon\|_2^2 \rightarrow \begin{cases} \hat{Q} & = & (HH^T)^{-1}H^T C_\phi G^T (GC_\phi G^T + C_n)^{-1} \\ \hat{R} & = & (I - \hat{Q}GH)^{-1}\hat{Q} \end{cases}$$

Comparison Standard AO solution with IMC



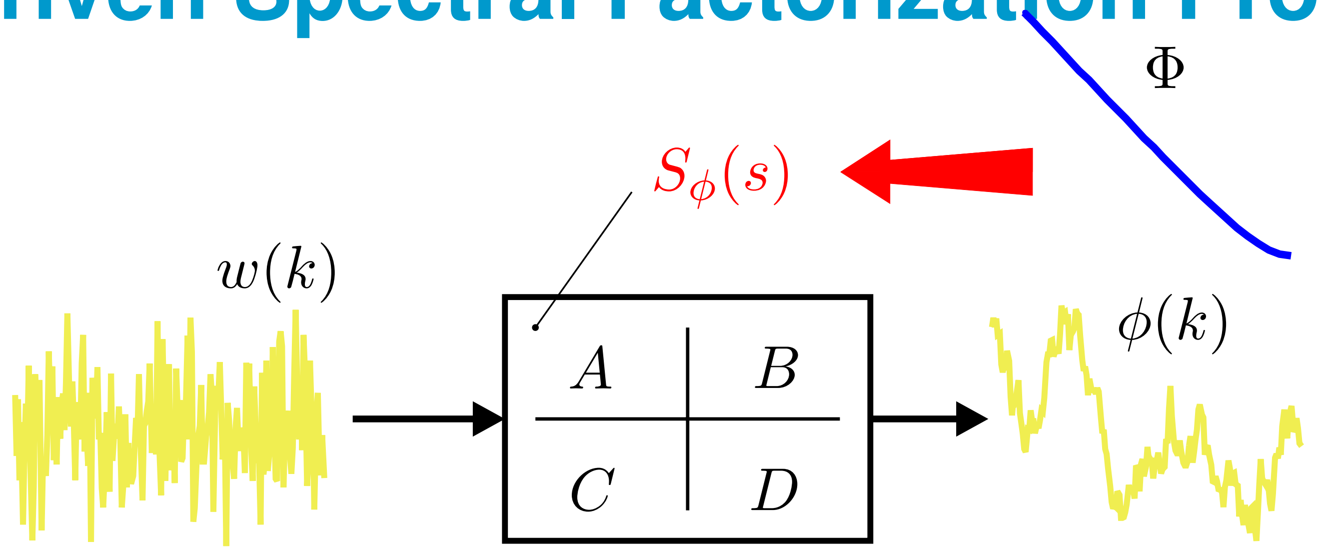
Control Engineering Approach to AO

(Time Dependency)



$$\min_{Q(s)} \|\epsilon\|_2^2 = \min_{Q(s)} \|\Big(I - H(s)Q(s)G(s)\Big)S_\phi(s)\|_2 \rightarrow \begin{cases} \text{Sensitivity Min.} \\ \text{Spectral Fact..} \end{cases}$$

Data Driven Spectral Factorization Problem



Given $N+1$ equidistantly distributed samples of a physical meaningful *matrix valued* power-spectrum:

$$\Phi_k = \Phi_y(\mathrm{e}^{j(2\pi k/2N)}), \quad k = 0, \ldots, N, \qquad \Phi_k \in \mathbb{C}^{l \times l},$$

estimate the state-space quadruple $[A, B, C, D]$ of the spectral factor $S_\phi(z)$ as accurately as possible . . .

Performance criterion

More specifically, determine the spectral factor

$$S_\phi : \begin{cases} x_{k+1} = Ax_k + Bw_k \\ \phi_k = Cx_k + Dw_k \end{cases}$$

such that:

- $S_\phi(z)$ is *stable*, i.e. $|\lambda_i(A)| < 1,\ \forall i \in \{1, \dots n\}$
- $S_\phi(z)$ is *minimum phase*, i.e. $|\lambda_i(A - BD^{-1}C)| < 1$
- and the following *cost-function* is minimized:

$$J(A, B, C, D) = \sum_{k=0}^{N} \| \left(\Phi_k - S_\phi(z_k) S_\phi^T(1/z_k)\right) \circ W_k \|_F^2,$$

with W_k a weighting function and $z_k := \mathrm{e}^{j(2\pi k/2N)}$.

Conic linear program

$$\min_{\gamma}, \text{ s.t. } \left\|\text{vec}\left\{\left(\Phi_k - L_{AC}(z_k)\mathcal{Q}_{BD}L_{AC}(1/z_k)\right) \circ W_k\right\}_k\right\|_2 \leq \gamma, \ \mathcal{Q}_{BD} \succcurlyeq 0$$

$$\Updownarrow$$

$$\min_{z}\{b^T z | c - E^T z \succcurlyeq_{\mathcal{K}} 0\}, \ \ \mathcal{K} := \mathcal{K}_l \times \mathcal{K}_s$$

with

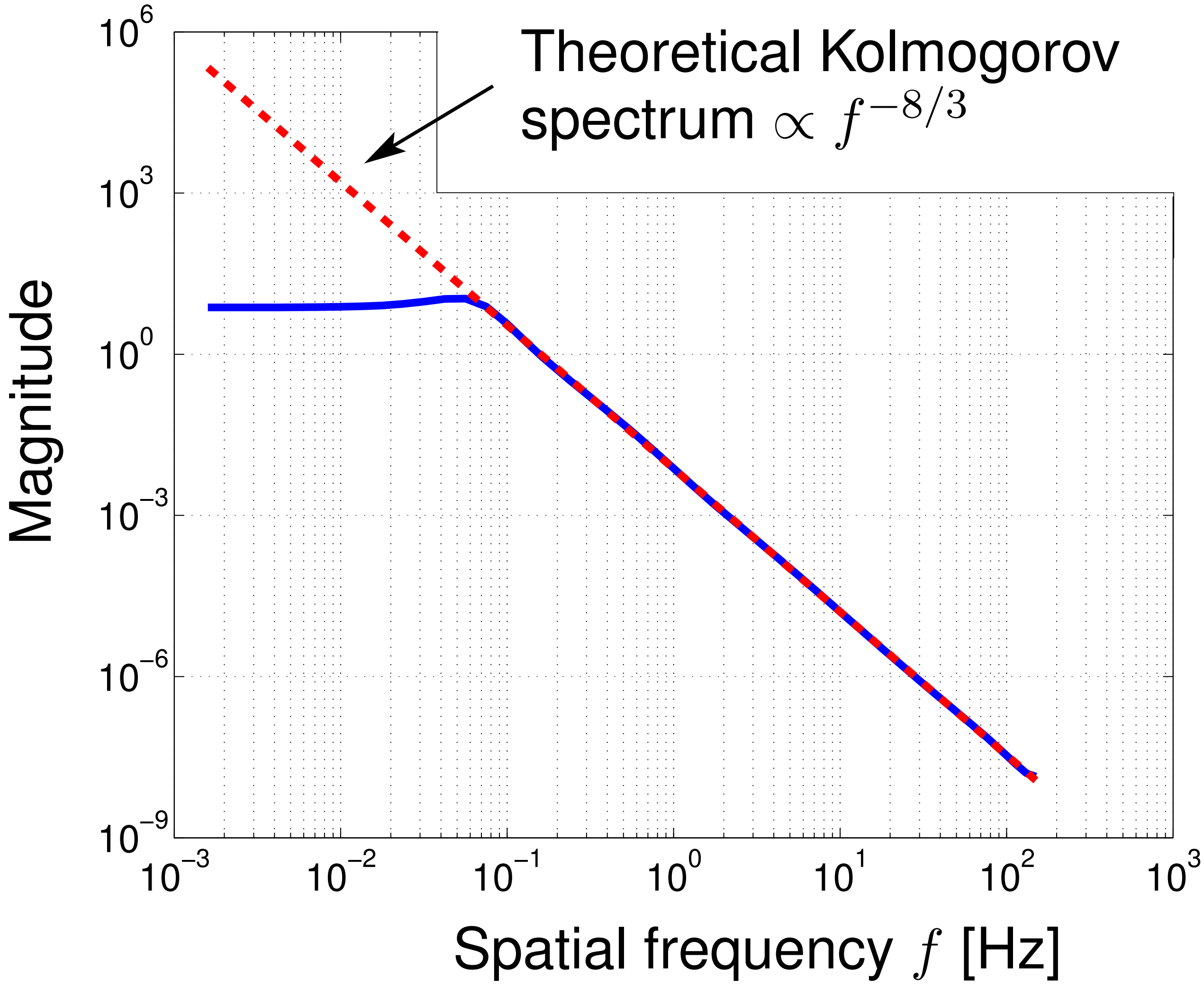
$$z := \left[\frac{\gamma}{\text{vec}(\mathcal{Q}_{BD})}\right], \ \ b^T := \left[1 \,|\, 0_{1\times\,(n+l)^2}\right] \ \Rightarrow \ b^T z = \gamma$$

and c and E^T such that:

$$c - E^T z = \left[\begin{array}{c}\gamma \\ \square \\ \hline \text{vec}(\mathcal{Q}_{\mathcal{BD}})\end{array}\right]$$

The conic linear program is efficiently solved by the Matlab toolbox SeDuMi, developed by J. Sturm.

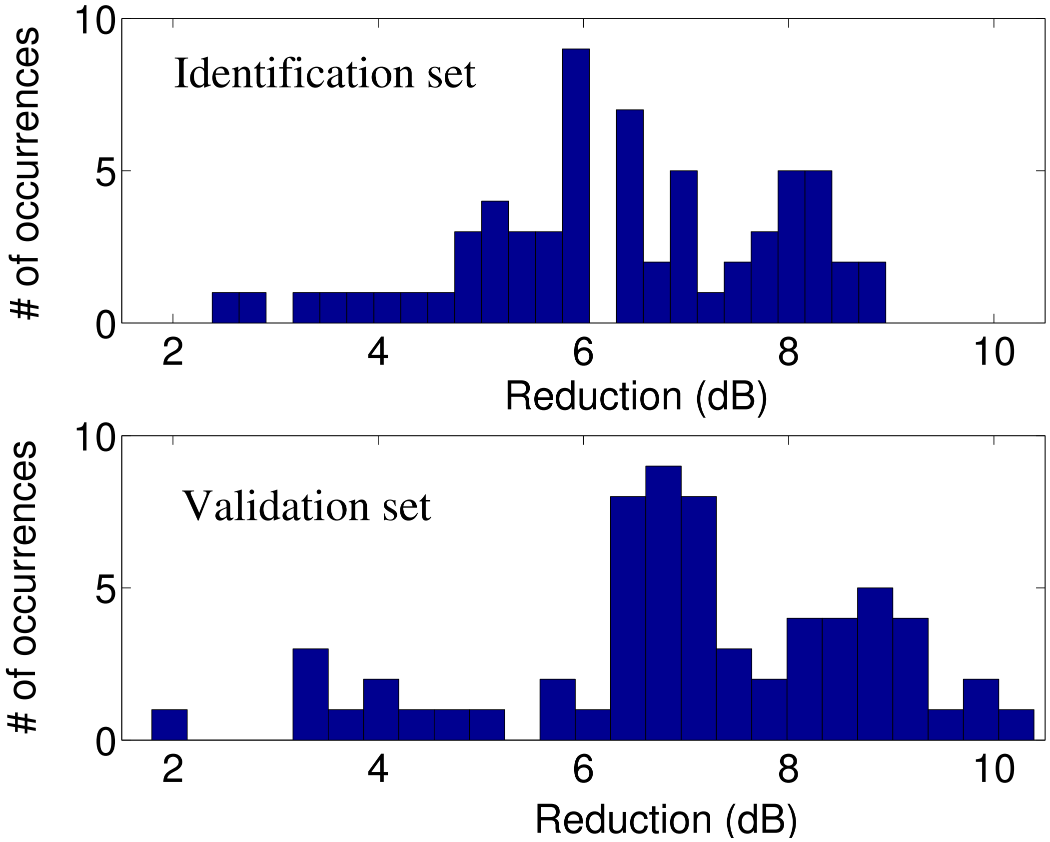
Kolmogorov power spectrum approximation



Performance SSAR(X) algorithm

Using real-life data from William Herschel Telescope (La Palma, Canary Islands), 1997 with an 8×8 Shack-Hartmann WFS. $(\ell = 64, s = 50, n = 41)$

Reduction prediction error w.r.t. random walk approach



Efficiency SSAR(X) algorithm

Main Algorithmic Steps in Calculating $(A, C) \in (\mathbb{R}^n, \mathbb{R}^\ell)$

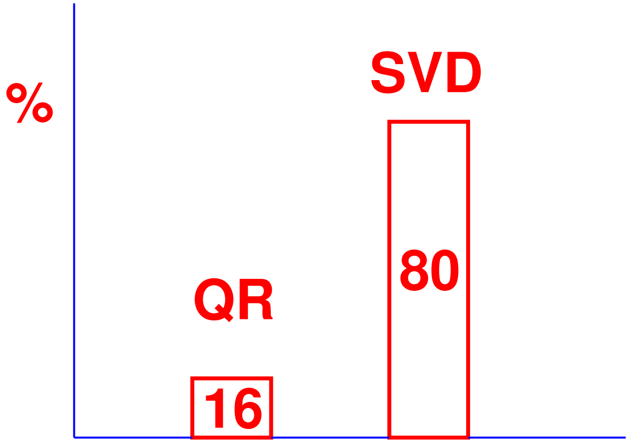
- QR factorization of Block-Hankel matrices $\in \mathbb{R}^{2s\ell \times N}$
- SVD of lower triangular matrix

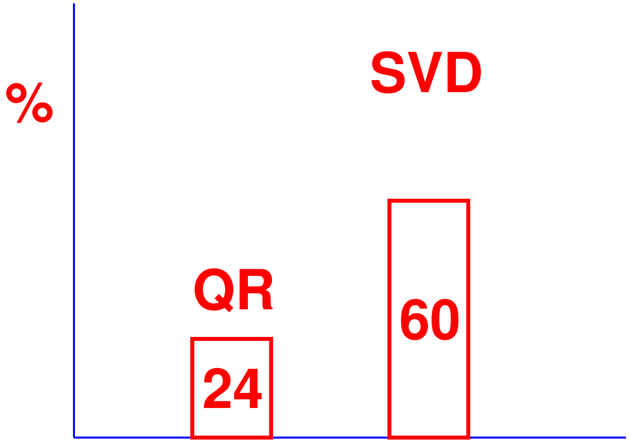
Efficiency SSAR(X) algorithm

Slicot
- **Hankel structure**
- **lower triangular form**

1529 sec

"Standard" Matlab
3392 sec





Concluding Remarks

1. Spatial-Time Dependency need to be considered in AO for ELT

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   DRIVE CAREFUL,

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DRIVE CAREFUL, STAY IN CONTACT