Impact of Latency and Jitter on the Performance of Adaptive Optics Systems for ELTs

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ESO

Motivation (1/2)

- Challenging performance requirements for AO systems in new generation ELTs
  - Higher number of degrees of freedom → higher complexity
  - Deliver high Strehl images → high-order corrections → faster
  - In challenging ***environmental*** conditions (e.g. worse maximum seeing, telescope induced perturbations,…..)
  - In challenging ***economical*** conditions

↓

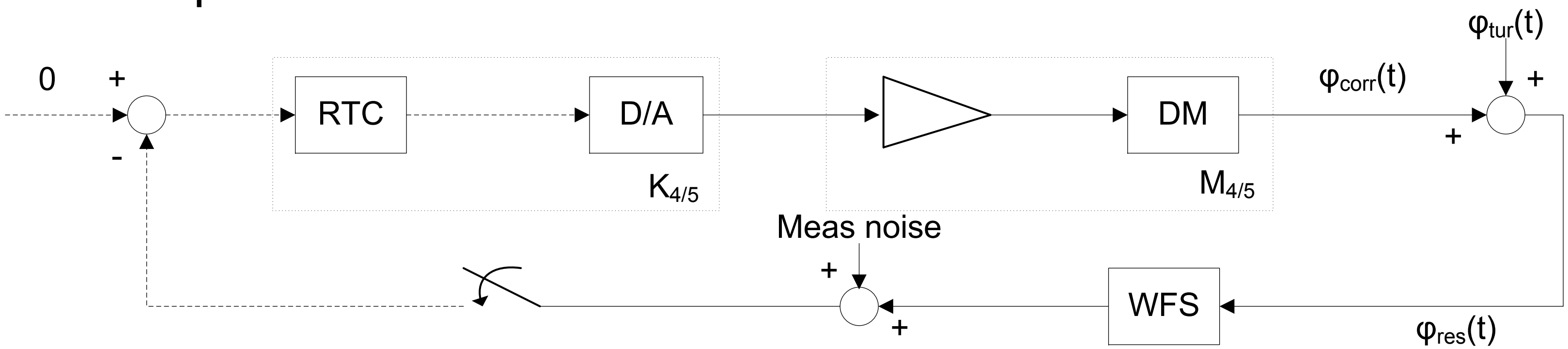
- Challenging requirements on the RTC
  - Amount of computations required per cycle
  - Time required to perform the abovementioned computations
  - At lowest possible cost → selection of RTC technology needs involved trade-off analysis

Motivation (2/2)

- Impact of RTC latency on the performance of AO loop well studied and understood (Fried 1990, Madec 1999, …..)
- Classical results apply to a fairly standard AO loop → can be used to get an idea of the required RTC performance
- More accurate analysis needed for trade-off analysis
  - Assumptions matching the ELT's expected operational conditions
  - More accurate representation of the control cycle timing sequence
- Validation of the analysis tools needed to cross-check the validity of the results
  - Multi-disciplinary approach (e.g. analysis involving multiple tools: control model + high fidelity E2E simulators)

Problem set up (1/3)

- AO Loop



$$WFS(s) = \frac{(1-\exp(-sT))}{sT}$$

$$RTC(s) = \frac{k\exp(-s\tau)}{1-\exp(-sT)}$$

$$DAC(s) = \frac{1-\exp(-sT)}{sT}$$

$$HVA(s) = 1 \quad DM(s) = \frac{\sum a_i s^{n-i}}{\sum b_i s^{m-l}}$$

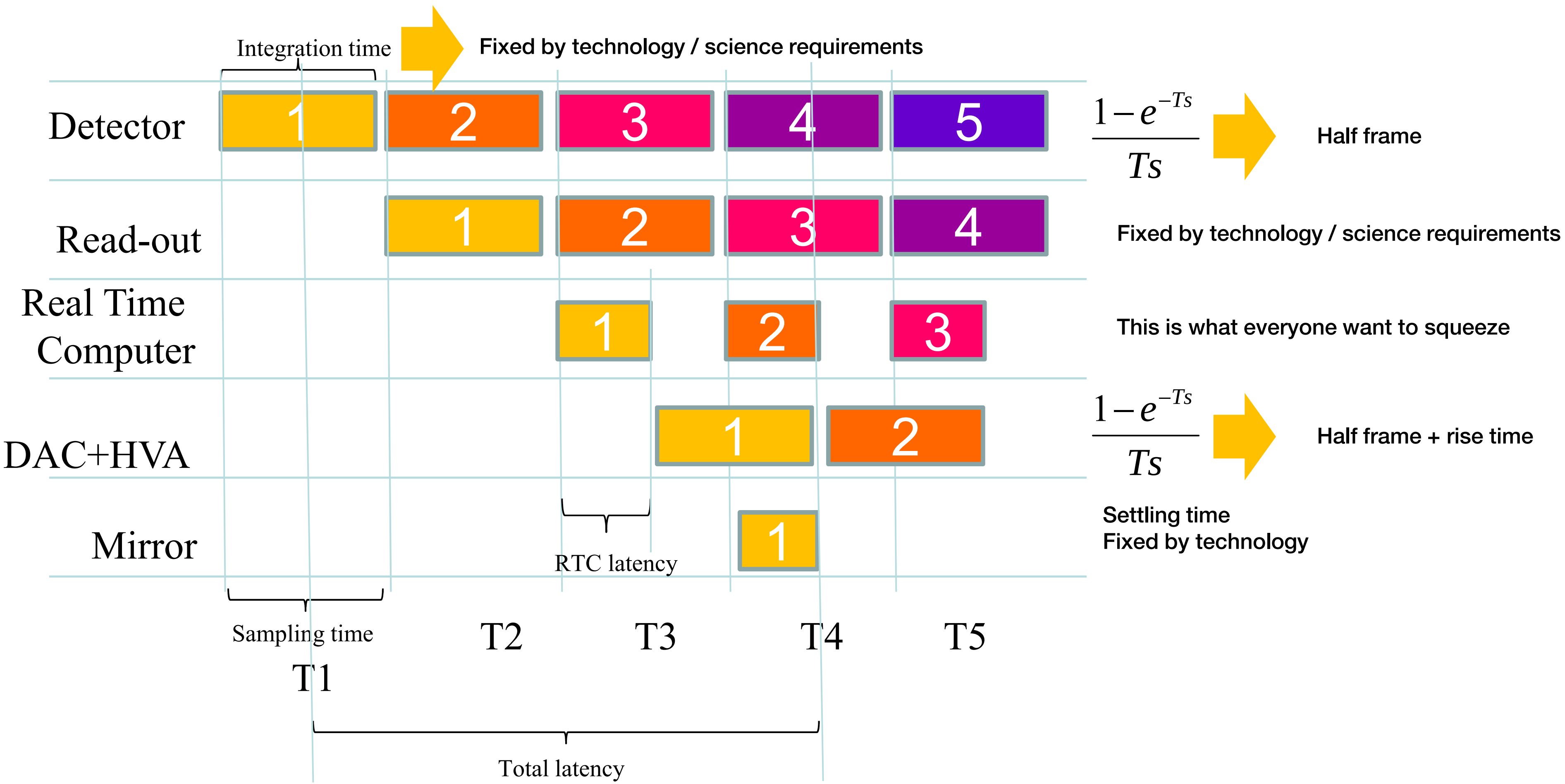
$$L(s) = WFS(s) \cdot RTC(s) \cdot DAC(s) \cdot HVA(s) \cdot DM(s)$$

$$S(s) = \frac{1}{1+L(s)}$$

- RTC Latency: nominal delay associated to RTC computation (deterministic variable)
- RTC Jitter: difference between nominal and actual time delay associated to RTC computation (random variable)

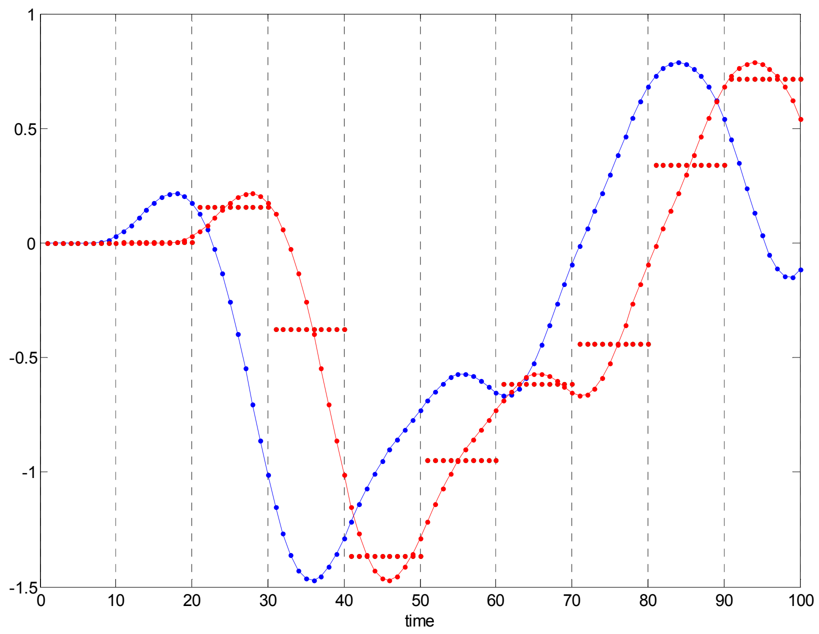
Problem set up (2/4)

- Timing definitions

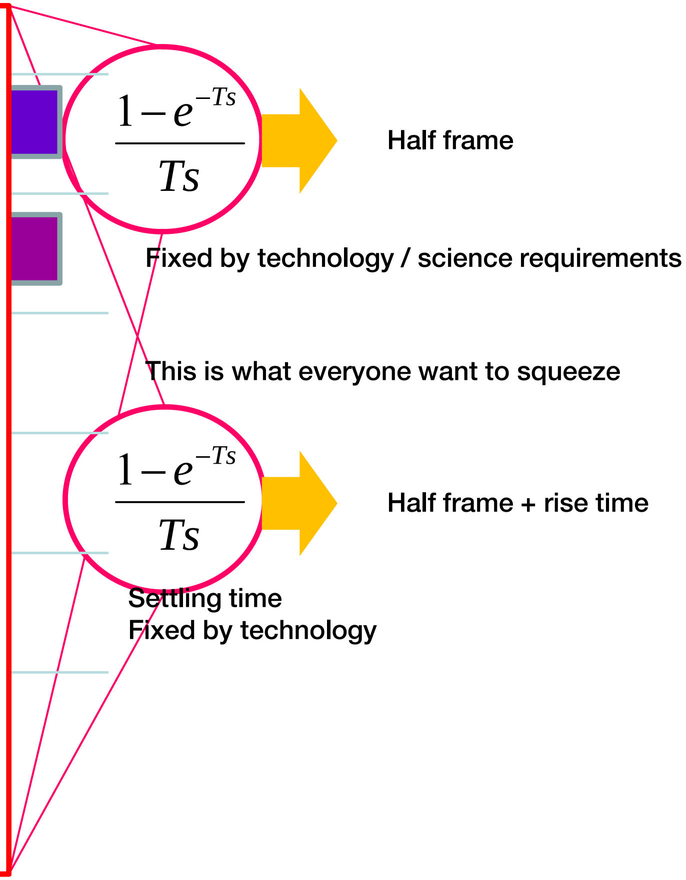


Problem set up (2/4)

- Timing definitions



Sample-and-hold followed by Zero-Order Hold



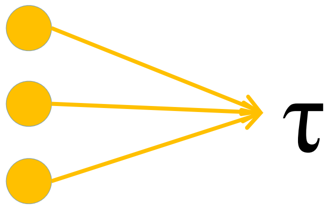
$$\frac{1-e^{-Ts}}{Ts}$$

$$\frac{1-e^{-Ts}}{Ts}$$

Total latency

Problem set up (3/4)

- Timing definitions: Total latency:
  - T/2: statistical delay introduced by the integration of the wavefront sensor
  - T: readout and digitization of the pixels
  - Transmission times between all components
  - Computational time (in every component)
  - T/2: statistical delay introduced by the DAC
  - Rise time of the amplifier + settling time of the mirror



- Minimum latency: Inherent latency: 1 frame delay
  - T/2: statistical delay introduced by the integration of the wavefront sensor
  - Instantaneous readout
  - No communication delay
  - Perfect infinitely powerful real time computer
  - T/2: statistical delay introduced by the DAC
  - Perfect amplifier without rise time and perfect mirror without settling time

Problem set up (4/4)

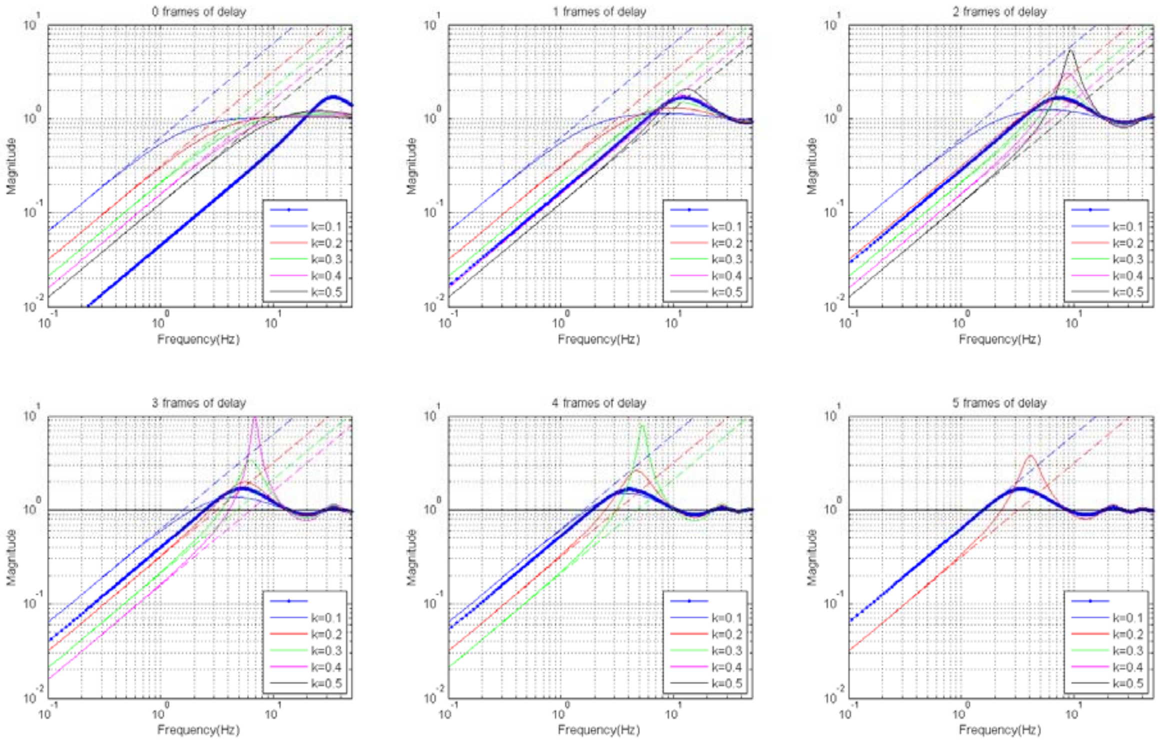
- Tools

	Bench	E2E Simulation	Control model
Minimum latency	2 frames	1 frame	1 frame
Can simulate	• **Latency as multiple frames** • **Jitter** • Custom defined exogenous perturbation signals • Cross coupling between different modes • Mis-registration • Mirror dynamic response	• **Latency as multiple frames** • **Jitter only as frames dropped** • Custom defined exogenous perturbation signals • Cross coupling between different modes • Mis-registration	• **Latency** • **Jitter with different** probability distributions • Mirror dynamic response • Custom defined exogenous perturbation signals
Cannot simulate	• Sub-frame latency • Sub-frame jitter (not yet)	• Mirror dynamic response • Sub-frame jitter • Sub-frame latency	• Cross coupling between different modes • Mis-registration

Impact of the latency

- More delay ➔ smaller gain with same margin ➔ smaller bandwidth

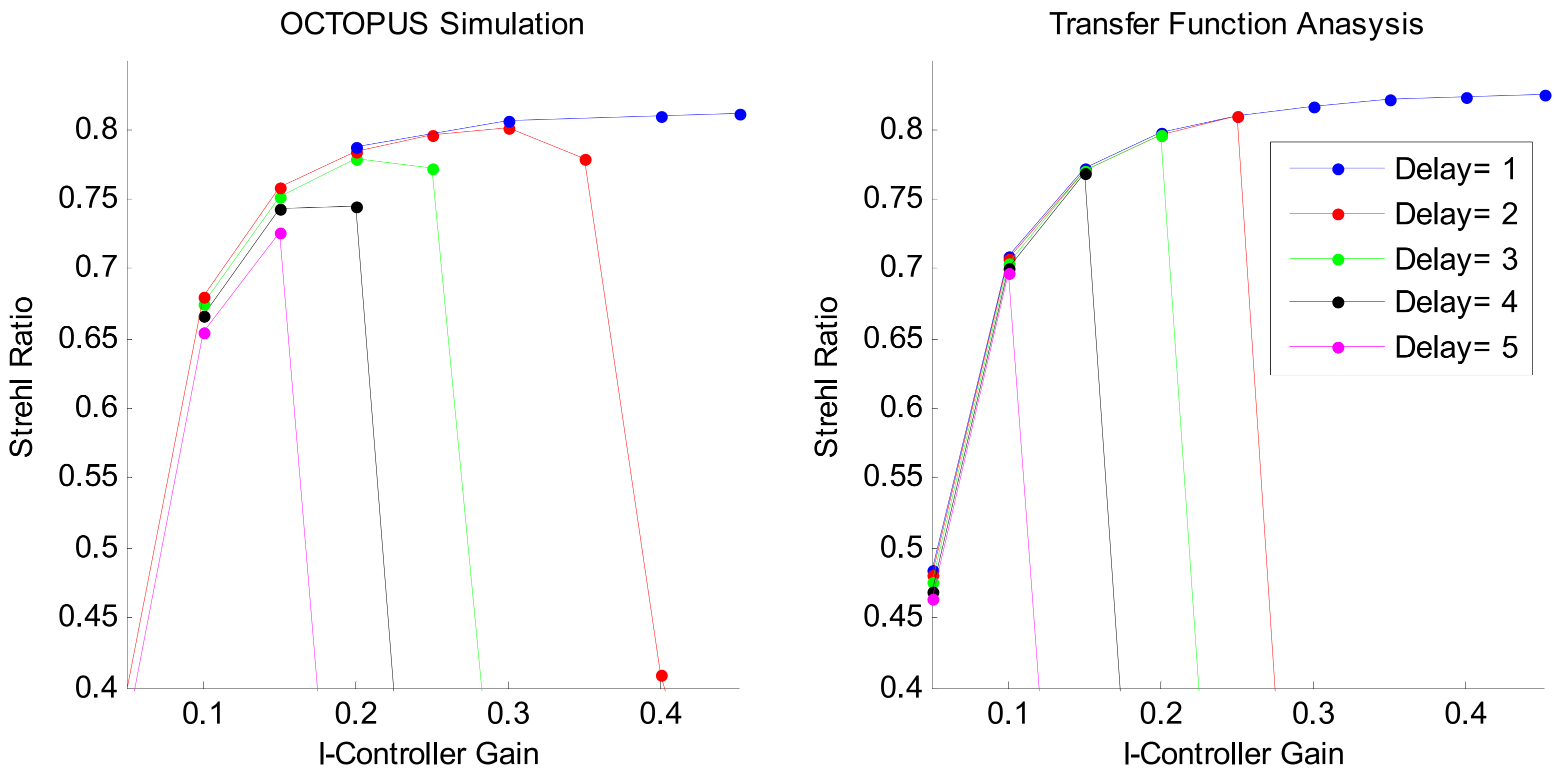
Delay	0	1	2	3	4	5
Gain	1.4	0.38	0.22	0.16	0.12	0.10



- The performance variation (residuals) depends on the input PSD

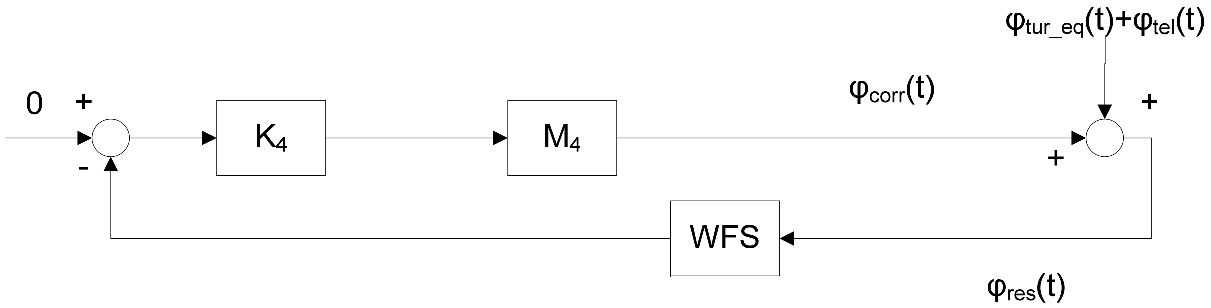
Validation of analysis method

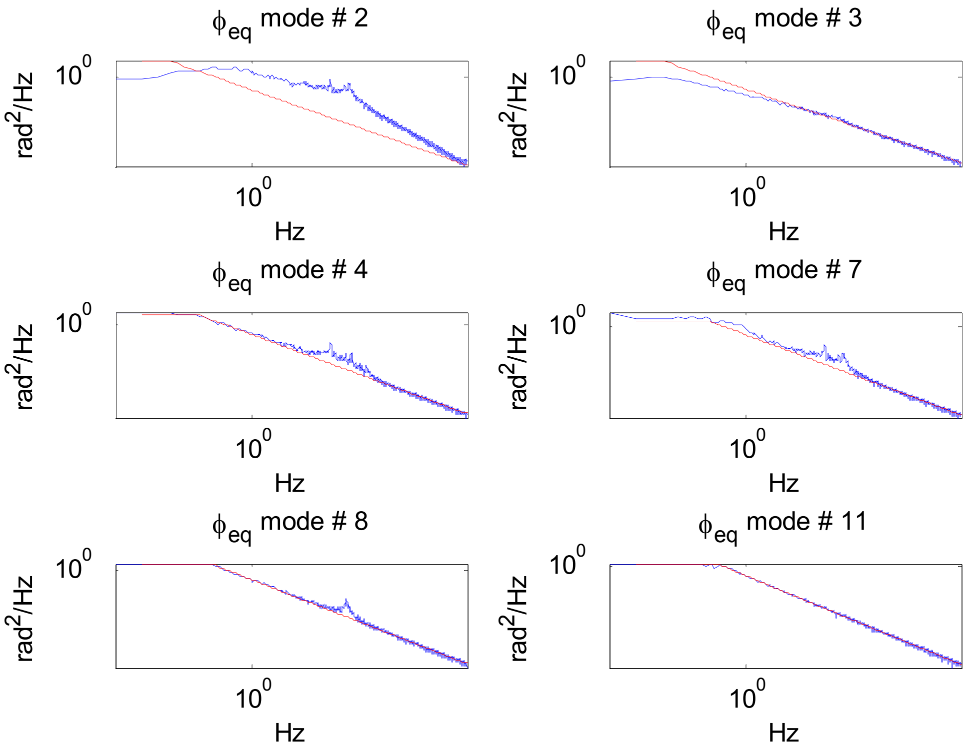
- Comparison with E2E case



- Analysis confirms that the control model captures the most important contributors to system performance

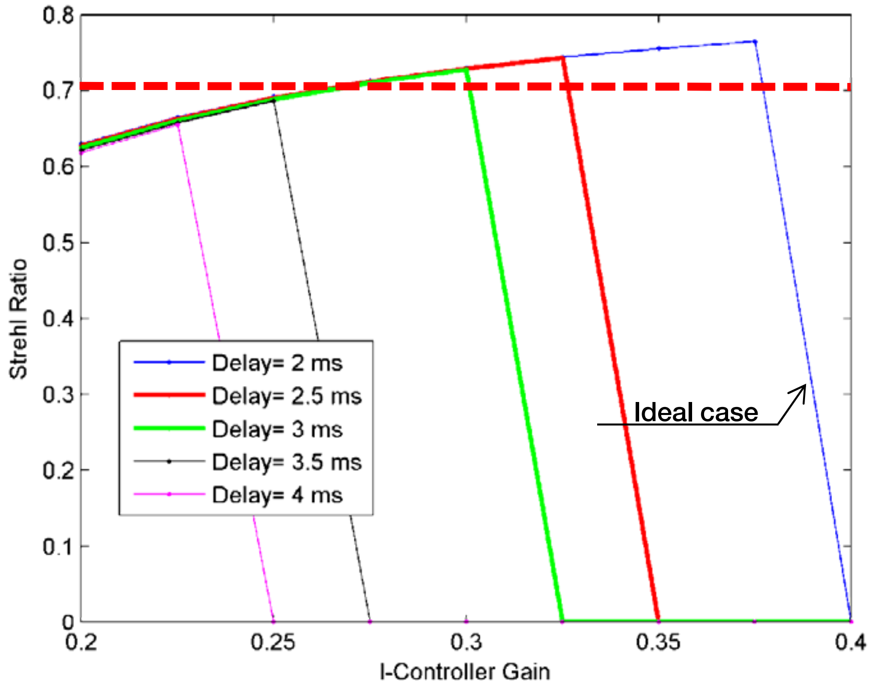
E-ELT AO Loop





- AO loop target: reject atmospheric + telescope-induced perturbations
- M5 removes low frequency large stroke perturbations
- AO loop (driving M4 mirror) to cope with remaining perturbations

Latency Analysis Results

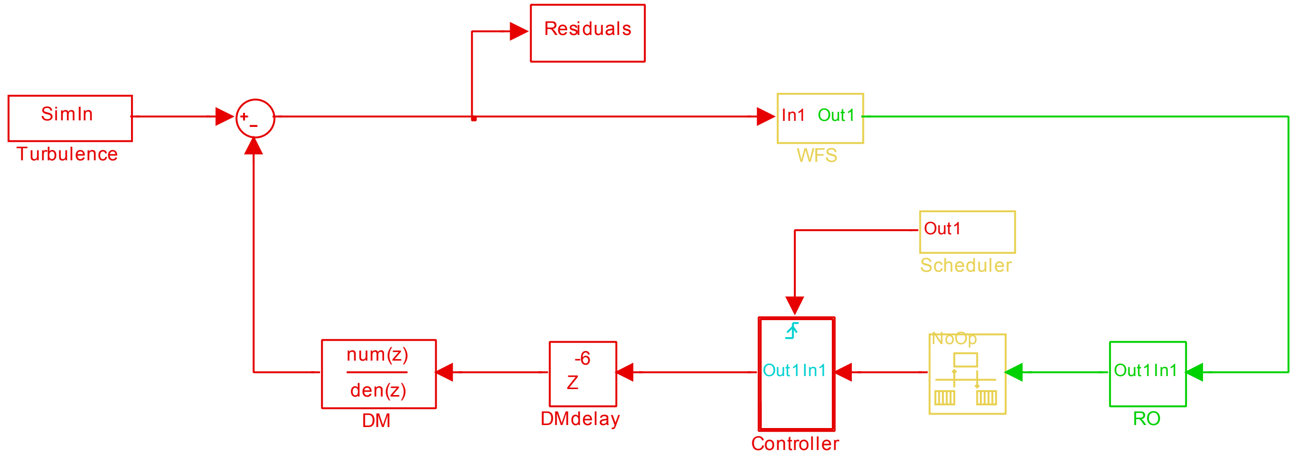


- Median ELT seeing conditions
- High flux
- Specification: 70% Strehl
- Achieved
  - 72% (1ms Latency)
  - 74% (0.5ms Latency)

- T/2 WFS: included in model
- T readout: assumed 2ms
- Transmission times between all components
  - To be considered in given delay
- Computational time (in every component)
  - 150us in Mirror Controller included
  - **Requirement: 1ms for the RTC**
  - **WPU included in RTC**
- T/2 DAC: included in model
- Rise time of the amplifier + settling time of the mirror
  - Ideal amplifier, settling time included in model

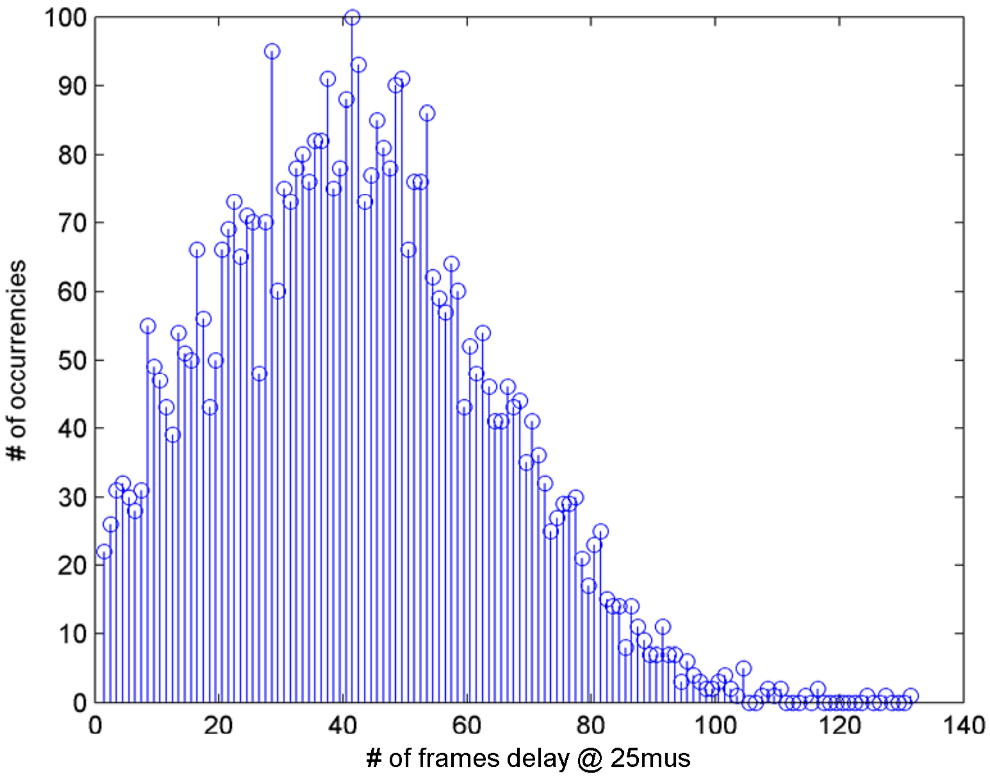
- M4 expected response fitted from VLT/DSM measurements
- Gain achieving maximum specified robustness margin (6dB Modulus margin)

Jitter Simulations (1/2)



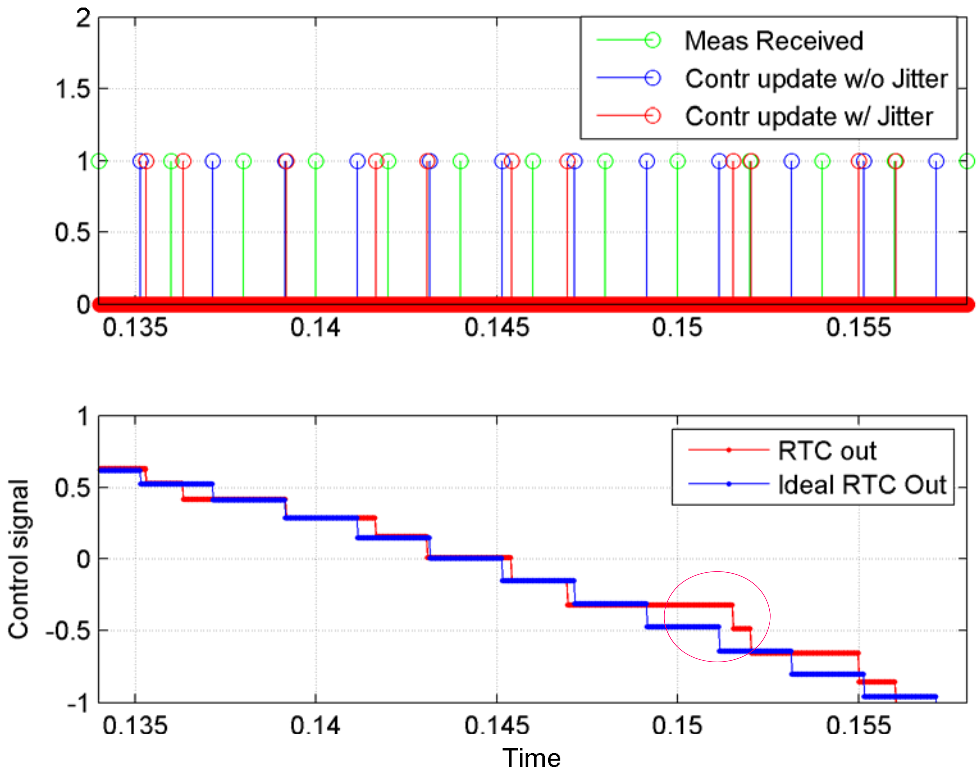
- Controller output update executed at randomly variable time instants
- Can simulate violation of Hard-RT constraints producing dropped measurements
- Can use different jitter probability distributions
- Low impact on simulation time (10 sec ELT simulation performed on a laptop within 15mins)

Jitter Simulations (2/2)



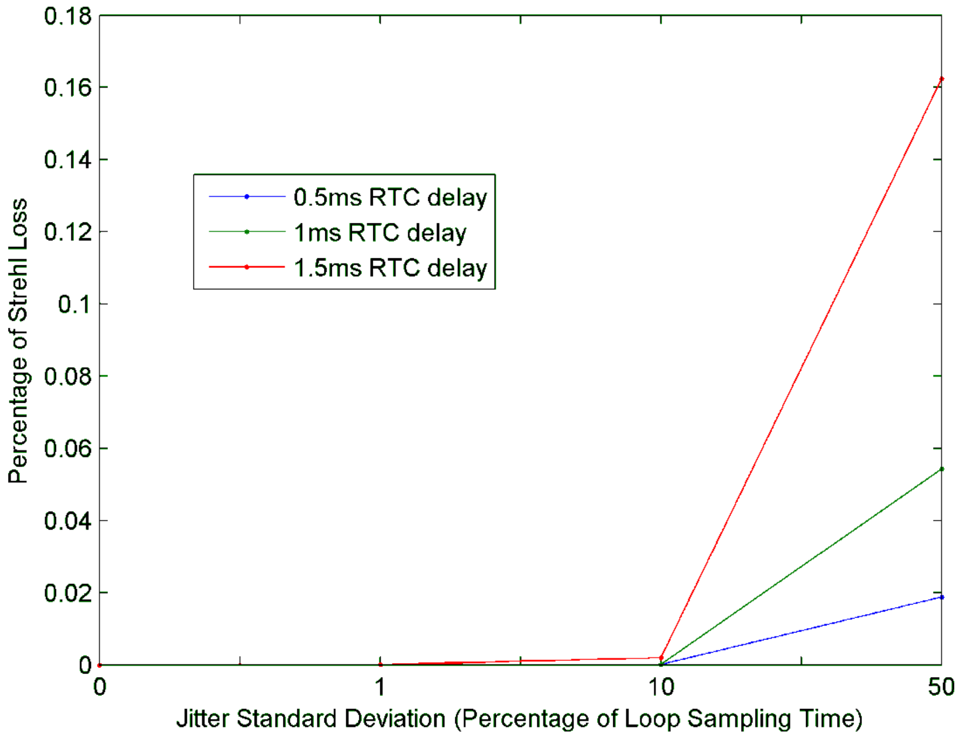
- Example: jitter normally distributed around mean latency
- Tail probability < mean cut to keep causality
- Other distributions can be easily simulated (e.g. uniform)
- Jitter+Latency can be > than integration time

Jitter Simulations (2/2)



- Ideal (no jitter) vs. real-life controller
- Time line:
  1. received measurement event (green)
  2. controller output update (blue w/o jitter, red w/ jitter)
- Missed frames are also simulated

Results of Jitter Simulations

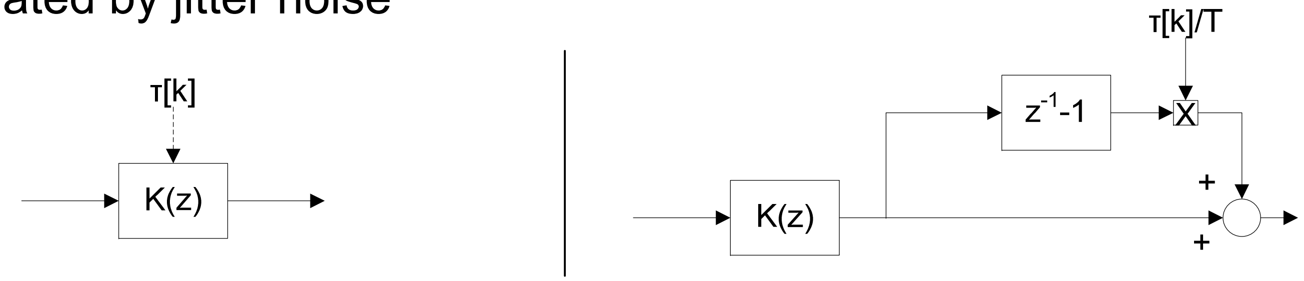


- Latency requirement for prototype ELT WFRTC
  - 20µs (1% sampling time)
- Assumed optimal gain configurations computed for latency study

- Jitter up to 1% → fully negligible
- @10% Jitter some (small) performance degradation observable

More insight into Jitter Results

- Control Jitter:
  - Multiplicative perturbation in output to the controller
  - Weighted by derivative-like action
  - Modulated by jitter noise



- Jitter induced perturbation expected to increase if:
  - Exogenous signals with higher power @ high freqs→ interaction with measurement noise/ higher order systems
  - High controller gain @ high freqs → more sophisticated control algorithms are considered.

Conclusions

- Set up of methodologies to analyze impact of latency and jitter on AO system performance focusing on realistic operational scenarios
- Analysis proposed includes the major contributors to AO system performance in ELTs
- Results of the analysis to be used to identify best cost effective technology for WFRTC

- Future work

- Evaluate realistic models of computer jitter
- Extend the analysis beyond SCAO systems
- Evaluate Jitter trade off considering more involved control strategies
- Validate analysis using laboratory facilities