Parallelization of an LQG TT controller for GeMS RTC

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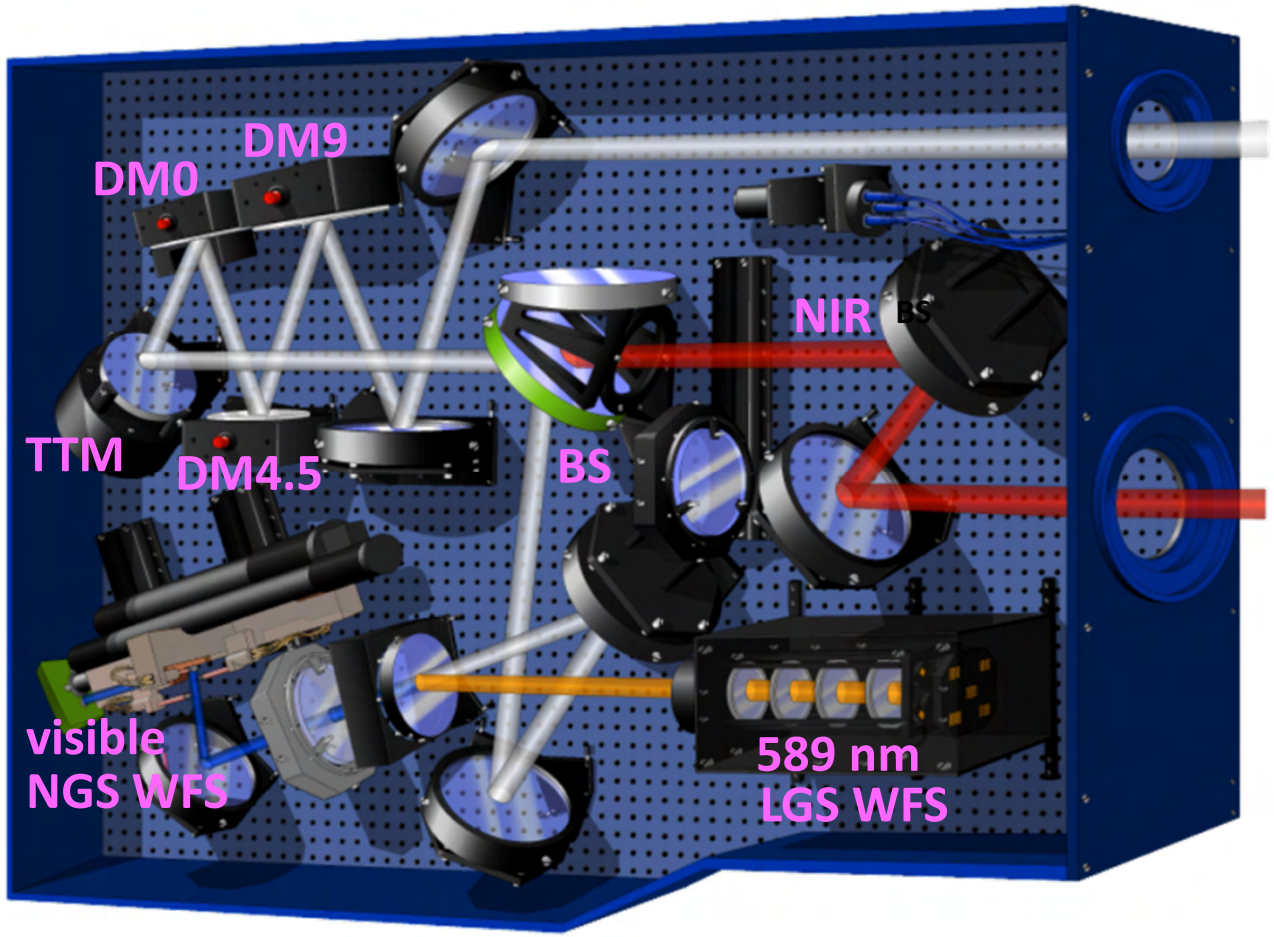
GEMINI OBSERVATORY

Canopus Optical Bench



Beam input

Beam output

DM0: conjugated with ground layer
DM9: conjugated at 9 km
DM4.5: Flat mirror
TTM: Flat TT mirror

2 beam splitters
5 LGS WFSs for high order correction
3 NGS WFSs for Tip-Tilt correction

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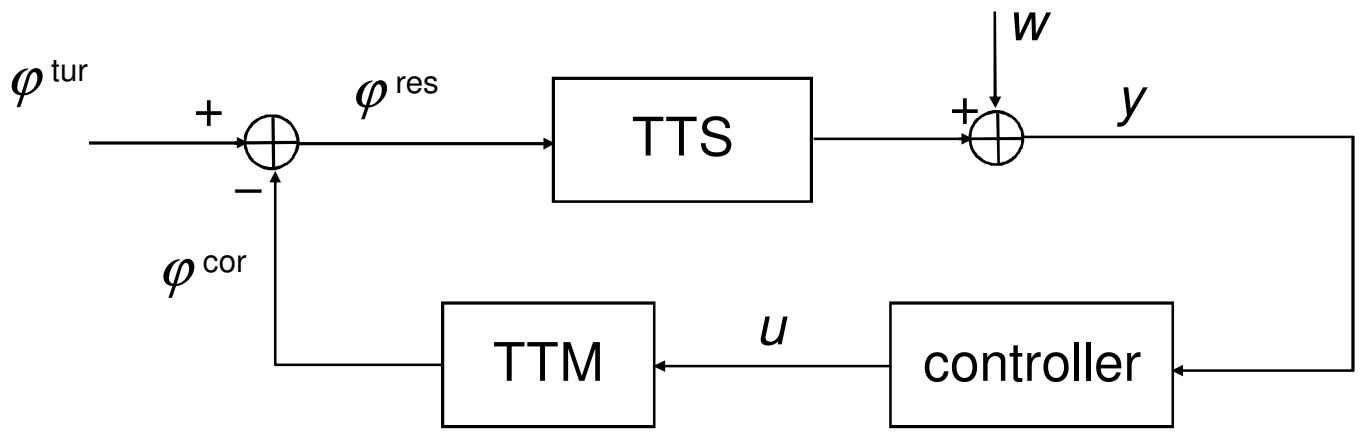
Control feedback loop

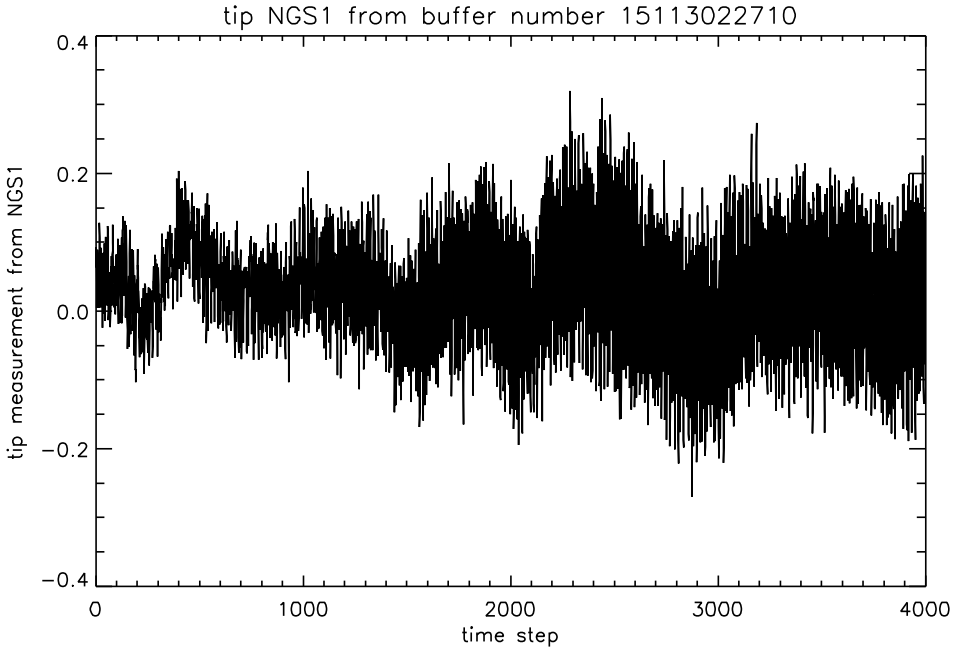


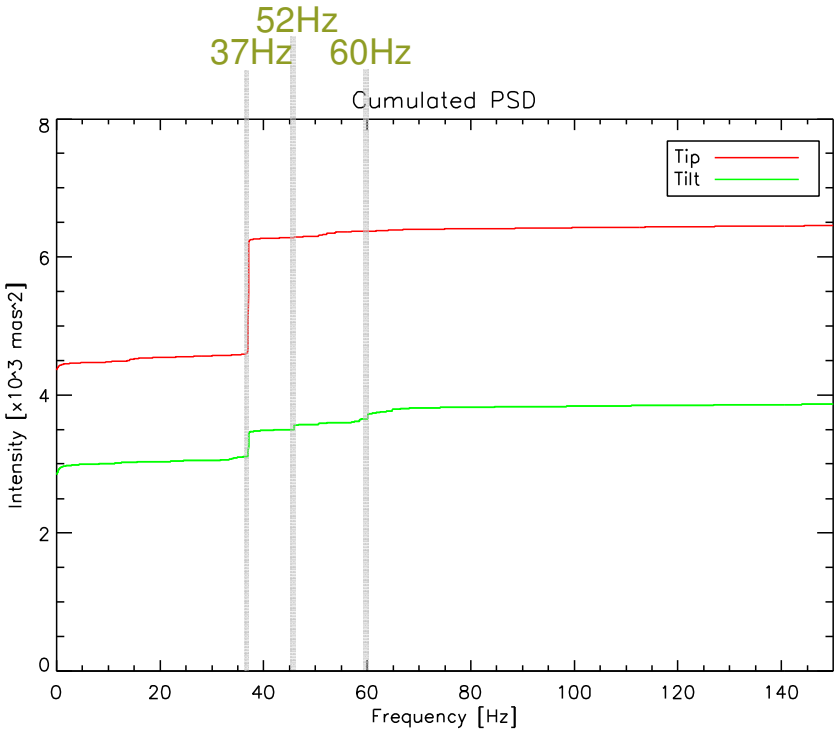
- Linear system with delays
- Tip/tilt sensor (TTS): 4-quadrant diode
- Flat TT mirror (TTM)
- Controller: u constant over time interval ΔT (ZOH)

- Integrator controller: $u_k = u_{k-1} - g\, y_k$

Vibrations affect GeMS TT control loop

- Tip and tilt cumulated spectra





- Solutions?
  - Model-based control
  - Perturbation identification

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Minimum variance control

Linear Quadratic Gaussian (LQG) control

- Optimality criterion

$$J(u) = \mathrm{Var}(\varphi_{k+1}^{\mathrm{res}})^2 = \mathrm{Var}(\varphi_{k+1} - \alpha_u u_k)$$

- Optimal solution

$$\Rightarrow u_k = \frac{1}{\alpha_u} \mathrm{E}\left(\varphi_{k+1} | y_k, \ldots, y_0 \right)$$

$$u_k = \frac{1}{\alpha_u} \hat{\varphi}_{k+1|k}$$

- Practical computation

State-space model

$$\begin{cases} x_{k+1} = Ax_k + v_k \\ \varphi_k = C_\varphi x_k \\ y_k = Cx_k - \alpha_y u_{k-2} + w_k \end{cases}$$

+

Kalman filter

$$\begin{cases} \hat{x}_{k+1|k} = A\hat{x}_{k|k-1} + L_\infty (y_k - \hat{y}_{k|k-1}) \\ \hat{\varphi}_{k+1|k} = C_\varphi \hat{x}_{k+1|k} \end{cases}$$

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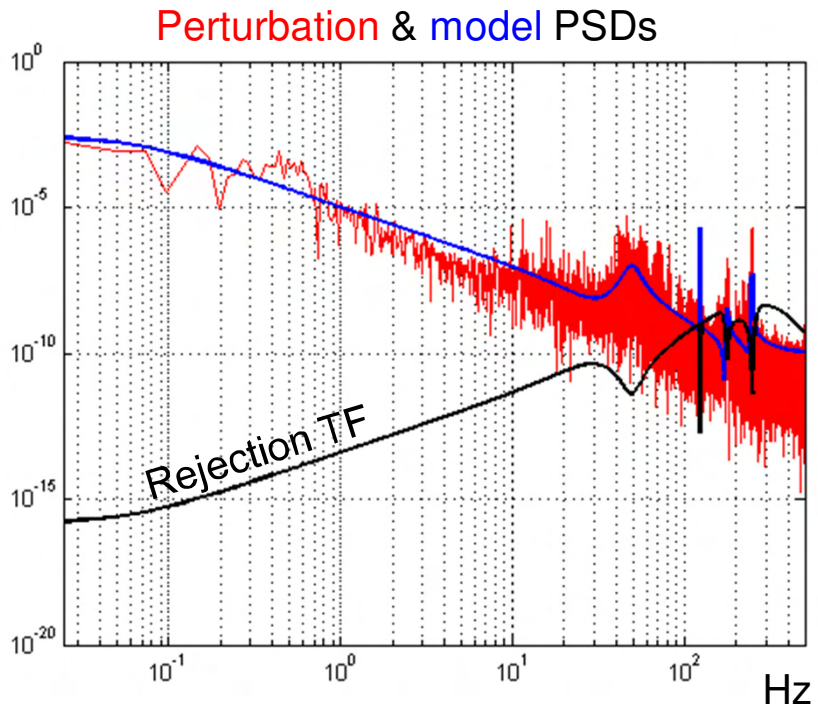
Prediction Error Minimization

Minimize the prediction error forward and backward in time

$$\hat{\theta} = \arg \min_{\theta} \sum_{k=1}^{N_y} (y_k - \hat{y}_{\theta,k|k-1})^2 + \sum_{k=N_y}^{1} (y_{k-1} - \hat{y}_{\theta,k-1|k})^2$$



[Kulcsár & al, SPIE 2012]

- Choice of model order (state dimension)
- Explicit optimization criterion
- Full transition matrix
- Rich behaviour
- State or parameters have no physical interpretation

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Initialization with subspace identification

Identification of state-space model in innovation form

$$\begin{cases} x_{k+1} = Ax_k + K\xi_k \\ y_k = Cx_k + \xi_k \end{cases}$$

$$\underbrace{\begin{bmatrix} y(1) & y(2) & \dots & y(N) \\ y(2) & y(3) & \dots & y(N+1) \\ y(3) & y(4) & \dots & y(N+2) \\ \vdots & \vdots & \ddots & \vdots \\ y(s) & y(s+1) & \dots & y(s+N) \end{bmatrix}}_{Y_{s,N}} = \underbrace{\begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{s-1} \end{bmatrix}}_{\mathcal{O}_s} \begin{bmatrix} x(1) & x(2) & \dots & x(N) \end{bmatrix} +$$

$$\underbrace{\begin{bmatrix} w(1) & w(2) & \dots & w(N) \\ w(2) & w(3) & \dots & w(N+1) \\ w(3) & w(4) & \dots & w(N+2) \\ \vdots & \vdots & \ddots & \vdots \\ w(s) & w(s+1) & \dots & w(s+N) \end{bmatrix}}_{W_{s,N}}$$

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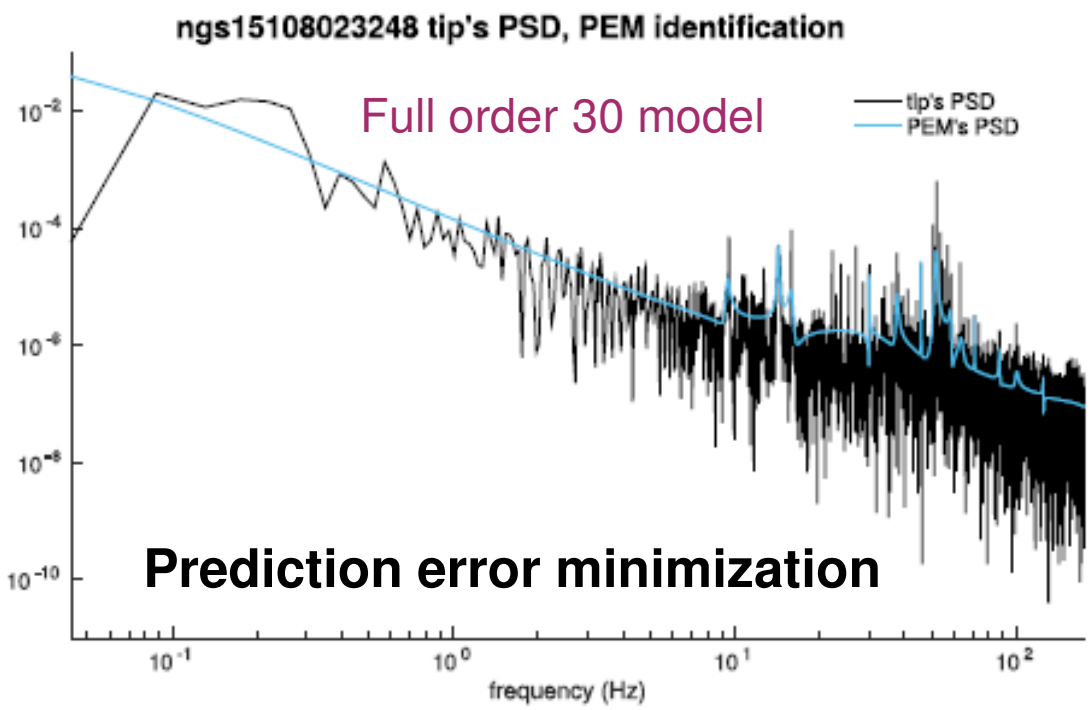
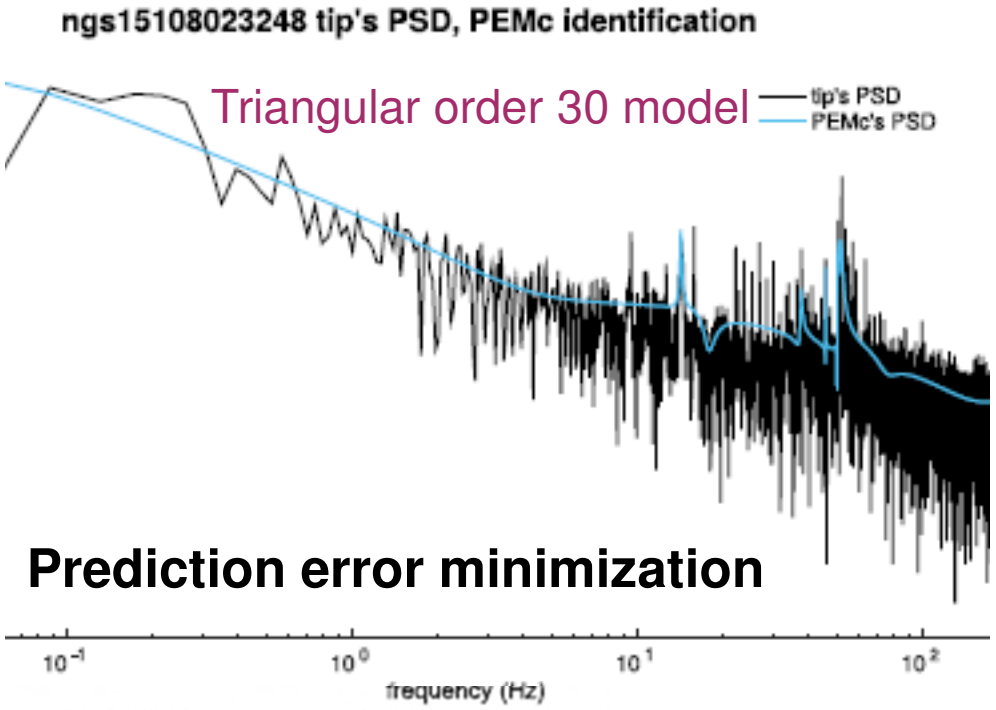
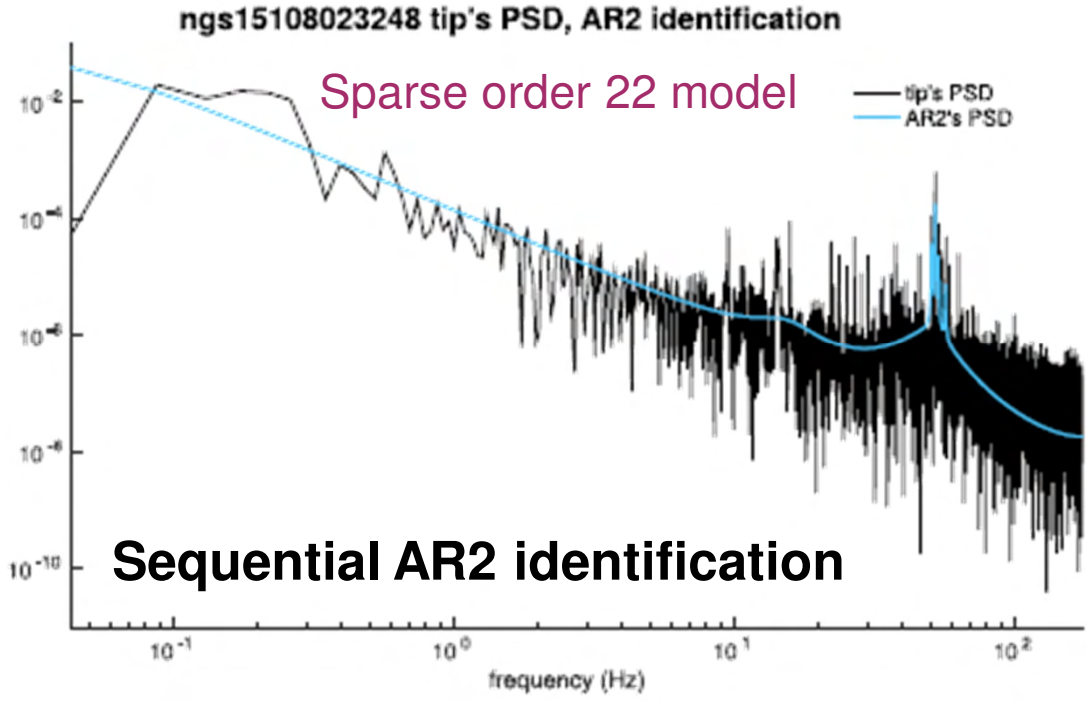
Tip/tilt modelling and identification





TIP power spectral density (PSD) on GeMS



[Juvénal & al, AO4ELT 2015]
[Leboulleux & al, AO4ELT 2015]

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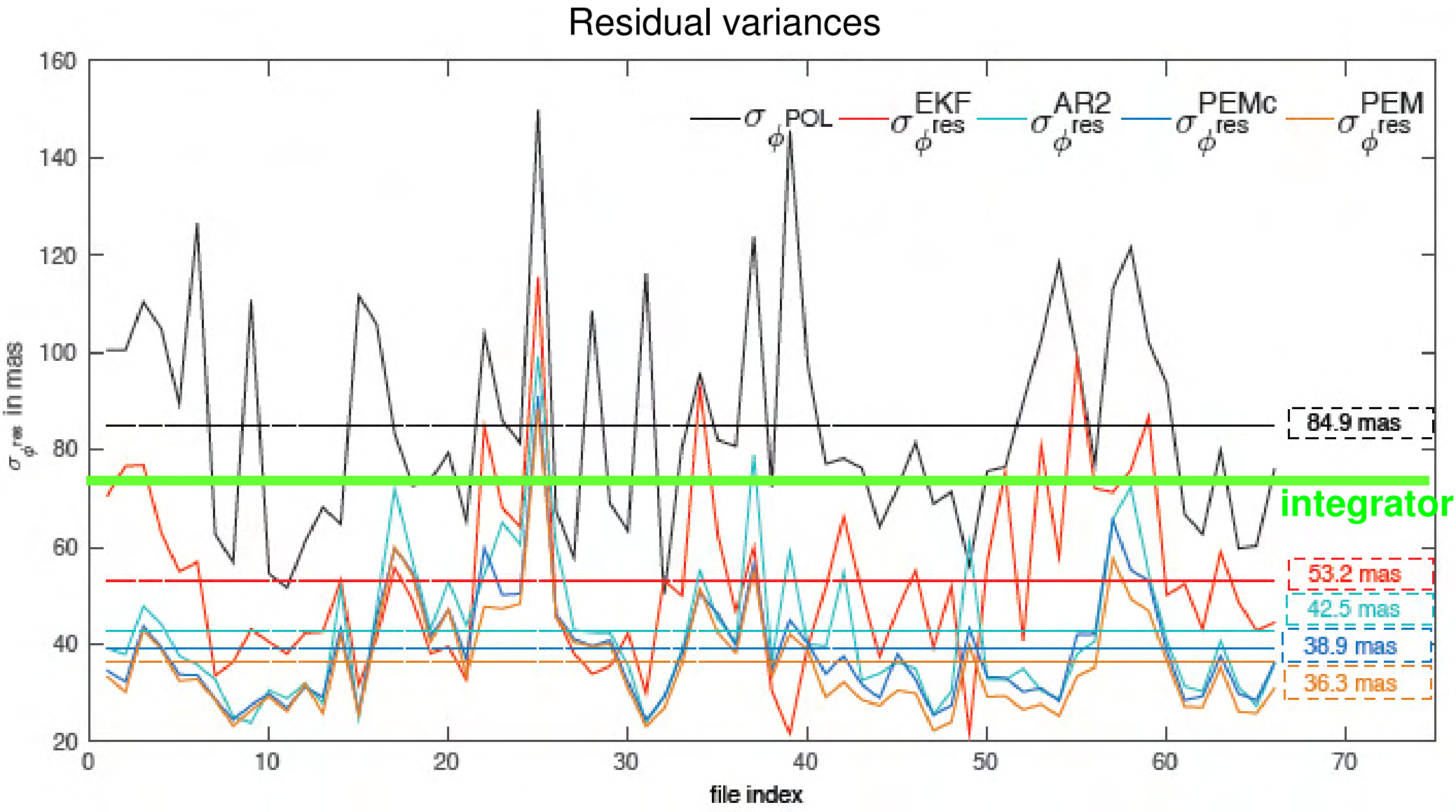
Tip/tilt control performance



[Juvénal & al, AO4ELT 2015]

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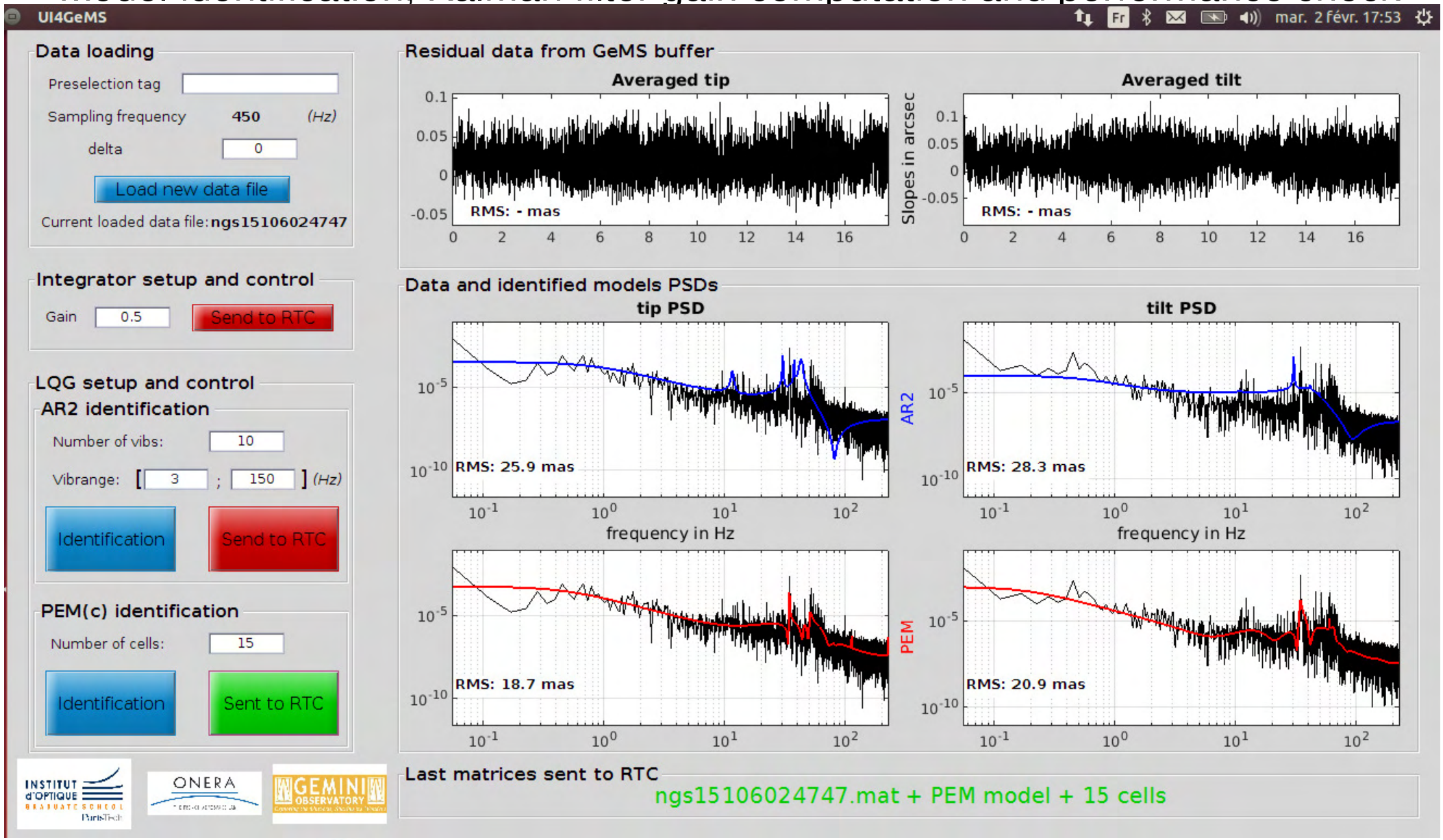
Off-line GUI

Model identification, Kalman filter gain computation and performance check

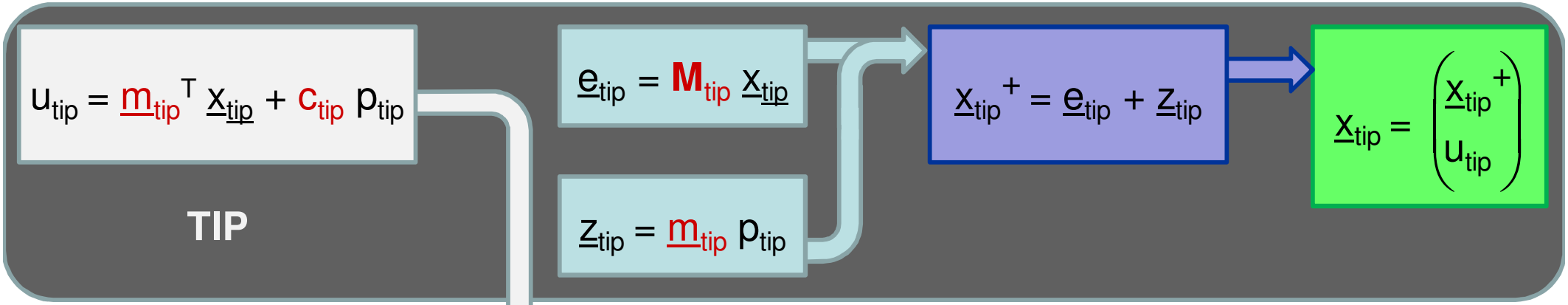


Inside GeMS RTC: TigerSHARC ADSP-TS201

- Dual-Computation blocks
- RTC cycle: 1300µs
- TT specs: < 850µs
- Brute force implementation >1000µs

Parallel implementation

- 2 computation blocks, each with 3 independent operations



$$u_k = \alpha_u C_\varphi \hat{x}_{k+1|k}$$
$$= \alpha_u C_\varphi (A - L_\infty C)\hat{x}_{k|k-1} + \alpha_u C_\varphi L_\infty y_k$$

$$\hat{x}_{k+1|k} = A\hat{x}_{k|k-1} + L_\infty (y_k - \hat{y}_{k|k-1})$$
$$= (A - L_\infty C)\hat{x}_{k|k-1} + L_\infty y_k$$

$$\hat{y}_{k|k-1} = C\,\hat{x}_{k|k-1}$$

TTM

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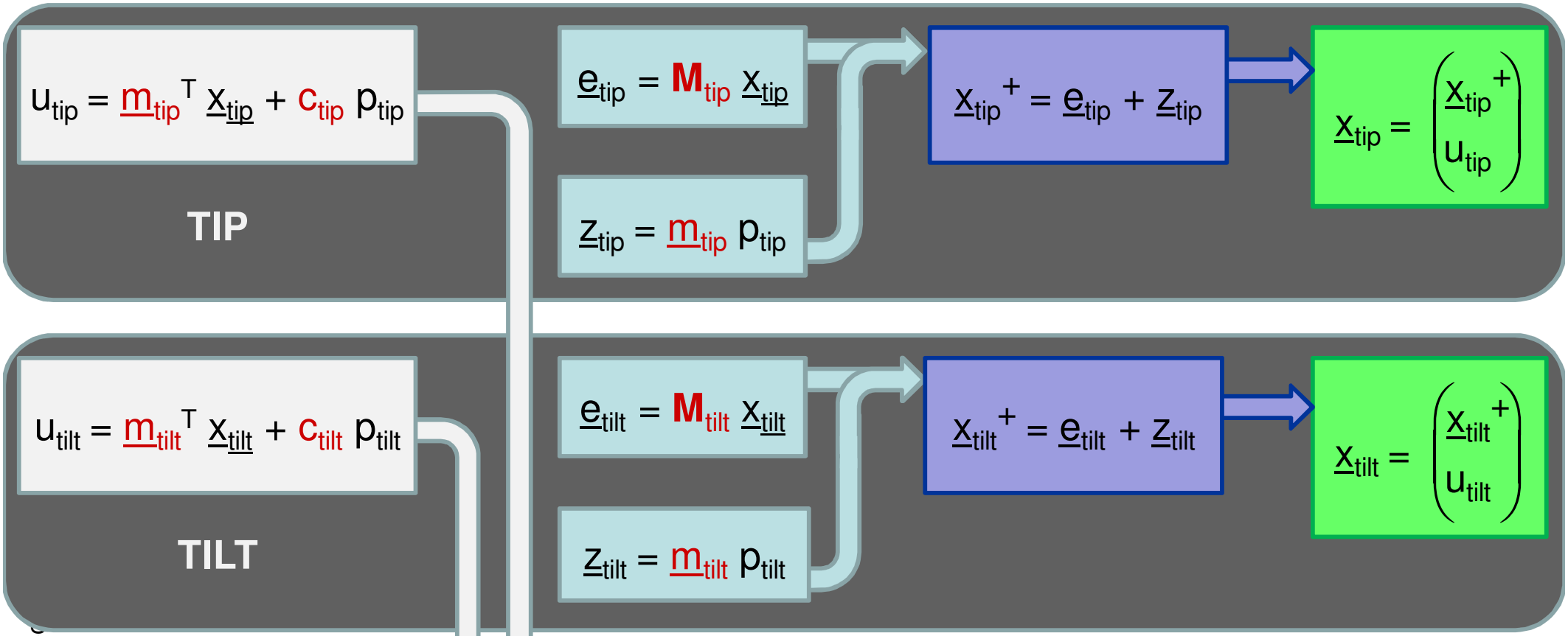
Parallel implementation

- 2 computation blocks, each with 3 independent operations



N = 32

Total TT computation time < 300 µs

Conclusion & perspectives

- Implementation valid for any linear controller
- On-sky tests probably in fall 2017
- High performance control for TT or for a few low-order modes is not an issue
- Generalization to any AO system?
  - Off-line Kalman/observer gain computation (updates)
  - On-line: 4 independent MVM of dimensions
    n_x^2, $n_x\, n_y$, $n_u\, n_x$, $n_u\, n_y$ with $n_x \geq n_u, n_y$
- Exploration of new structures
  - Combine HPC methods with physical descriptions
  - Massive parallelization of off-line and on-line calculations

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Thank you for your attention!