Optimised Turbulence & Wind Speed Profiling using AO Telemetry

DOUGLAS J. LAIDLAW

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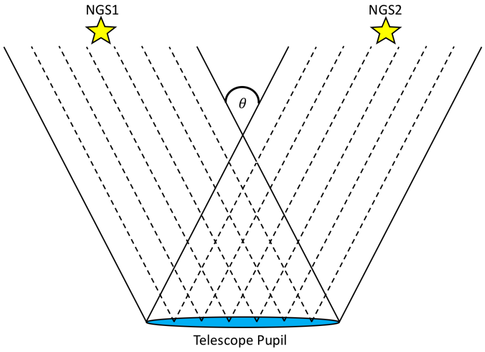
Why the ELT needs a Turbulence Profile

- Performance verification.
- Optimising wide-field AO tomography.
- PSF reconstruction.
- Site monitoring.
- Instrument design.

Demonstrating the Turbulence Profile



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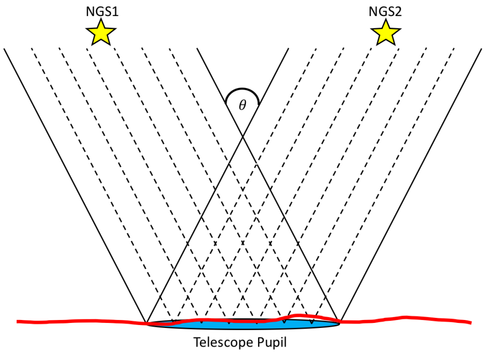
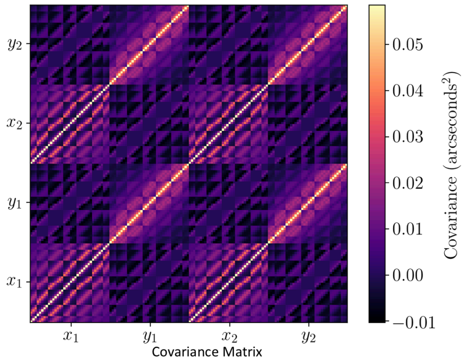
Demonstrating the Turbulence Profile





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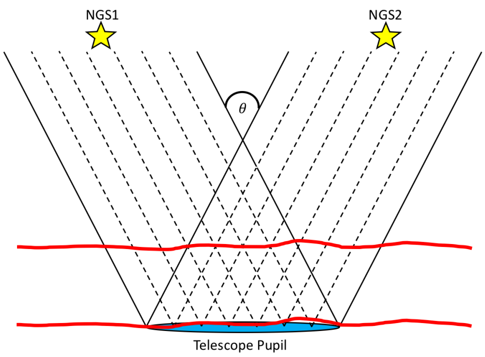

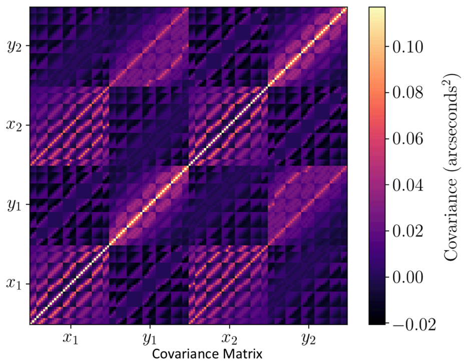

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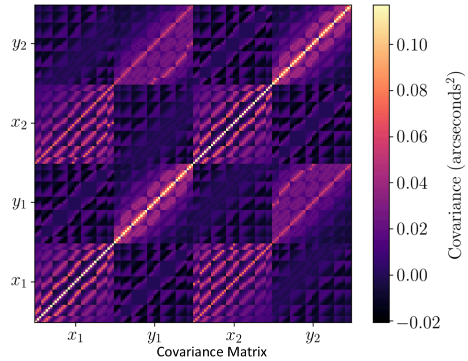
Tomographic Reconstructor

It is necessary to analytically generate tomographic reconstructors as slopes are:

- Noisy.
- Suffer from temporal convergence.



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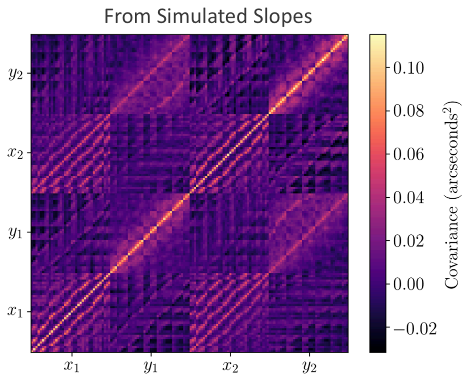

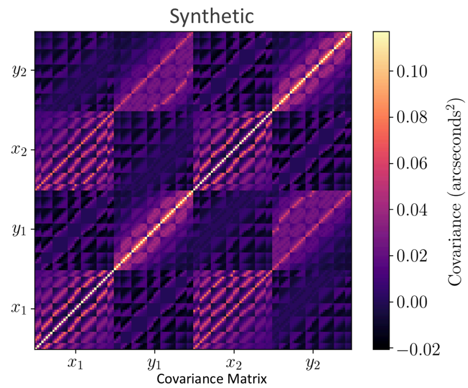

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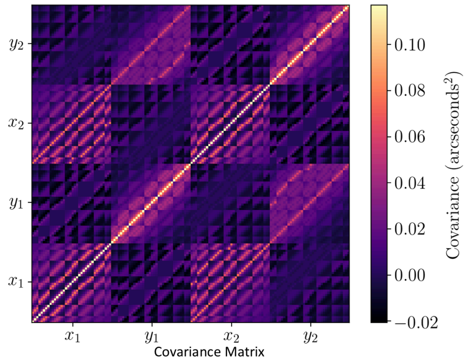
Tomographic Reconstructor

To build a synthetic covariance matrix (and therefore the tomographic reconstructor) the following parameters are iteratively fitted (over 100s of iterations!!) to on-sky covariance:

- WFS optical mis-alignments e.g:
  - Shift.
  - Rotation.
  - Magnification.
- Turbulence Profile.



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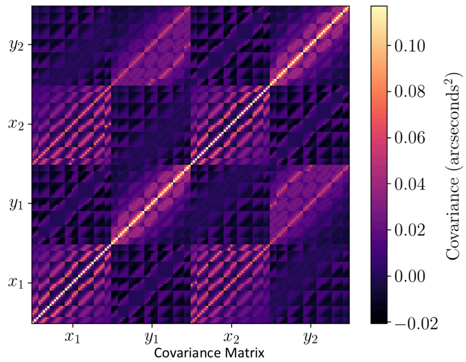
- Turbulence Profile.

Slow-changing



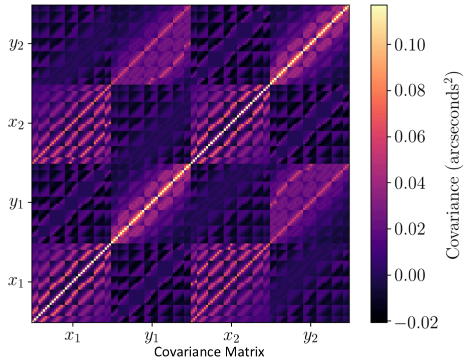
Tomographic Reconstructor

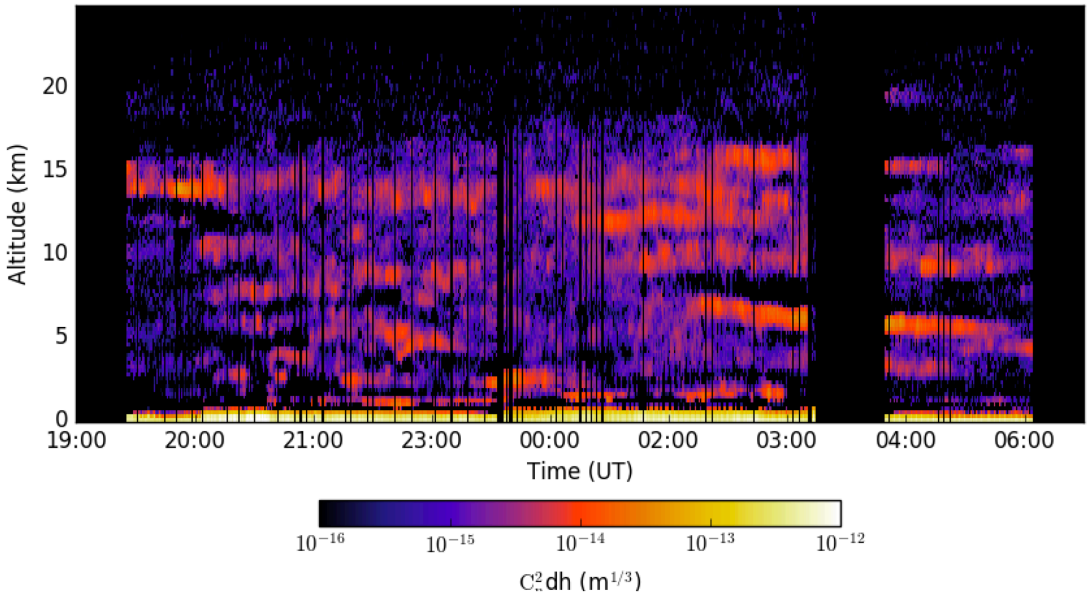
To build a synthetic covariance matrix (and therefore the tomographic reconstructor) the following parameters are iteratively fitted (over 100s of iterations!!) to on-sky covariance:

- WFS optical mis-alignments e.g:
  - Shift.
  - Rotation.
  - Magnification.

Slow-changing

- Turbulence Profile.
  - Variable.
  - Needs to be updated regularly.



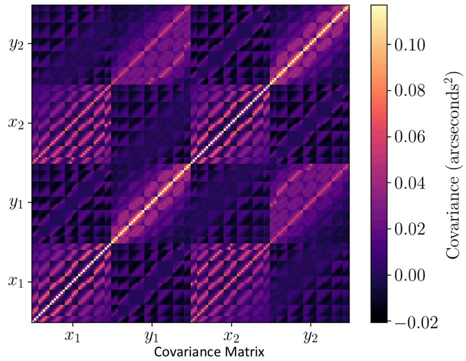


Recovering the Turbulence Profile

Learn and Apply algorithm (Vidal et al. 2010) used to fit on-sky slope covariance by analytically generated response functions. Technique employed known as Learn 3 Step (L3S; Martin et al. 2016).

User inputs:

- On-sky slope covariance.
- Response function altitudes.
- GS Asterism.
- L_0 (fixed at altitude).



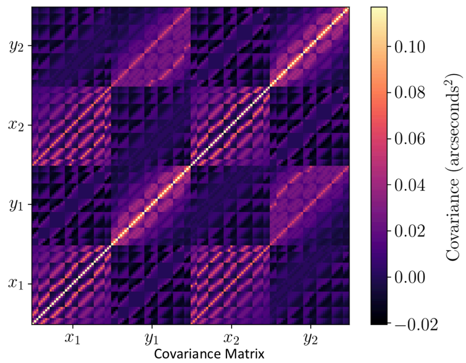
Recovering the Turbulence Profile

The ELT issue…

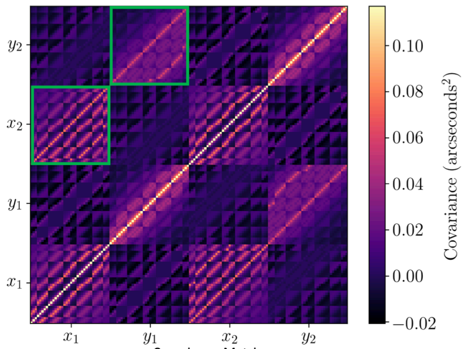
- 74 x 74 WFSs (4028 sub-apertures)
- 64-bit precision.
- 6 WFSs.

⇒ An ELT covariance matrix has $(48336)^2$ data points (~20GB of memory!!).

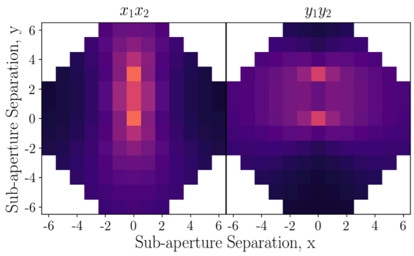
⇒ Measuring the turbulence profile at ELT scales via the covariance matrix fitting process is slow and computationally demanding.



Reducing the Scale of the Problem

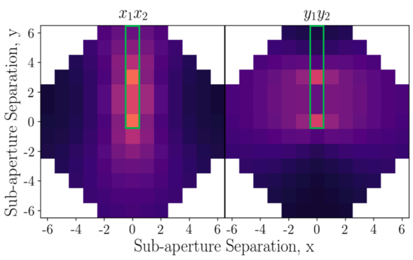


Covariance Matrix



Covariance Map
(SLODAR; Wilson 2002)

Reducing the Scale of the Problem



Covariance Map
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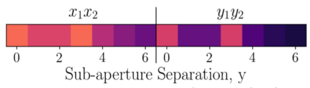
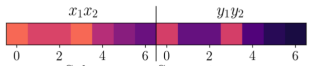


Covariance Map Region of Interest (ROI)

Reducing the Scale of the Problem

	Fraction of Covariance Matrix (2 x WFSs)
Covariance Map ROI	CANARY (7x7 WFSs)
Memory Required	~ 1 / 1.4×10^3



Covariance Map Region of Interest (ROI)

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Reducing the Scale of the Problem

By knowing the separation vector between stars it is possible to move directly from slope-space to the covariance map ROI.

	Fraction of Covariance Matrix (2 x WFSs)
Covariance Map ROI	CANARY (7x7 WFSs)
Memory Required	~ 1 / 1.4×10^3
Number of Cross-covariance Calculations	~ 1 / 40

Covariance Map Region of Interest (ROI)

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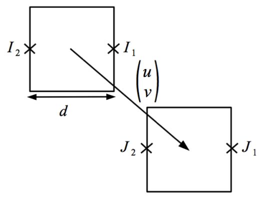
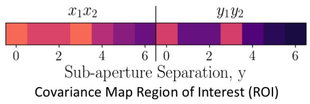
Reducing the Scale of the Problem

Response Functions:

By approximating that slopes are the difference in phase from two middle points on opposite sides of the sub-aperture, a relation is made to the spatial covariance between sub-apertures.



(Martin et al. 2012)



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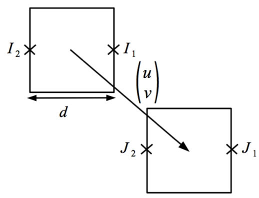

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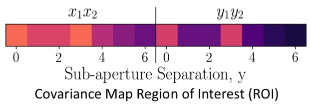

$\Rightarrow$ Covariance map ROI response functions can be generated directly!

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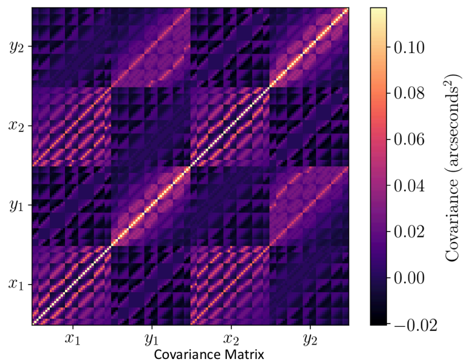
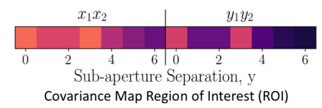
Reducing the Scale of the Problem





	Fraction of Covariance Matrix (2 x WFSs)
Covariance Map ROI	CANARY (7x7 WFSs)
Memory Required	~ 1 / 1.4×10^3
Number of Cross-covariance Calculations	~ 1 / 40
Number of Response Function Calculations	~ 1 / 70

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Reducing the Scale of the Problem

	Fraction of Covariance Matrix (2 x WFSs)		
Covariance Map ROI	CANARY (7x7 WFSs)	AOF (40x40 WFSs)	ELT (74x74 WFSs)
Memory Required	~ 1 / 1.4×10^3	~ 1 / 3.1×10^5	~ 1 / 1.7×10^6
Number of Cross-covariance Calculations	~ 1/40	~ 1 / 280	~ 1 / 540
Number of Response Function Calculations	~ 1/70	~ 1 / 490	~ 1 / 920

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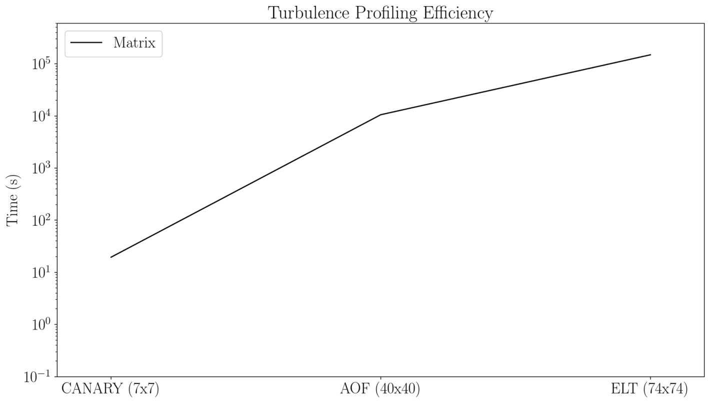
Efficiency Demonstration

To test the speed of the fitting algorithms, matrix and map ROI turbulence profiling procedures were timed on 2015 16GB MacBook Pro.

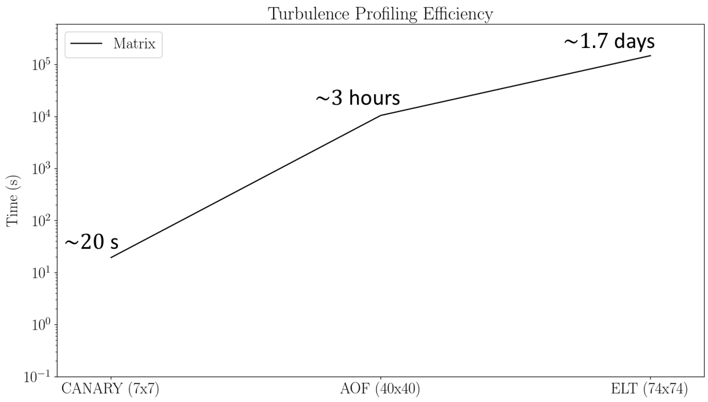
- WFS slopes simulated in SOAPY for CANARY, AOF and ELT.
- 8 response function altitudes fitted.
- 2 NGSs.

Efficiency Demonstration



On my laptop!

Efficiency Demonstration



On my laptop!

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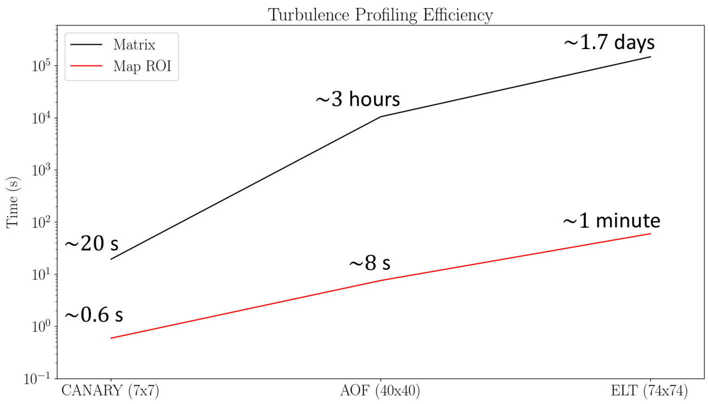

On my laptop!

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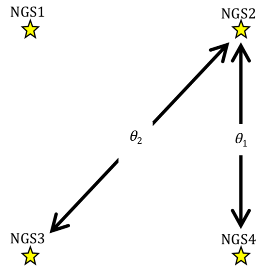
Performance Verification - Simulation

- WFS slopes were simulated for CANARY's configuration in SOAPY for 4 NGSs.
- 35-layer ESO profile.
- Integrated r_0: 0.1m
- L_0 at all layers: 25m
- 10,000 slope iterations at a frame rate of 150Hz.
- Simulation repeated 5 times so that a standard error on the results could be resolved.

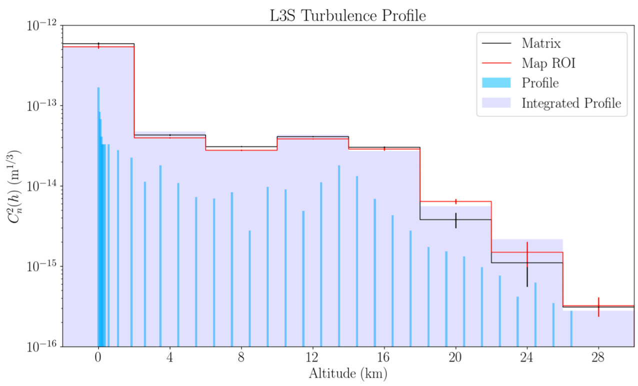


$$h_{\text{max}} = \frac{D}{\theta_1} = 32 \text{ km}$$

Fitting Algorithms:

- L_0 at altitude: 25m
- Response functions fitted at 8 evenly-spaced layers from 0 to 28km

Performance Verification - Simulation



Simulation's Integrated Profile

$$G = \frac{1}{N}\sum_{i=1}^{N}\left|\log\left(C_n^2(h_i)_{\text{Target}} \Big/ C_n^2(h_i)_{\text{Fit}}\right)\right|$$

Target Array	G
Matrix	0.38 ± 0.10
Map ROI	0.29 ± 0.06

Performance Verification – On-sky

- WFS slopes were provided from CANARY, an AO testbed on the 4.2m WHT.
- Each dataset required to have 4 NGSs, 10,000 slope iterations and a frame rate of ~150Hz.
- Corresponding turbulence profiles were observed by stereo-SCIDAR on the 2.5m INT.
- L_0 at all layers: ?
- A total of 20 CANARY datasets were analysed

Fitting Algorithms:

- L_0 at altitude: 25m
- Response functions fitted at 8 evenly-spaced layers from 0 to 28km

CANARY

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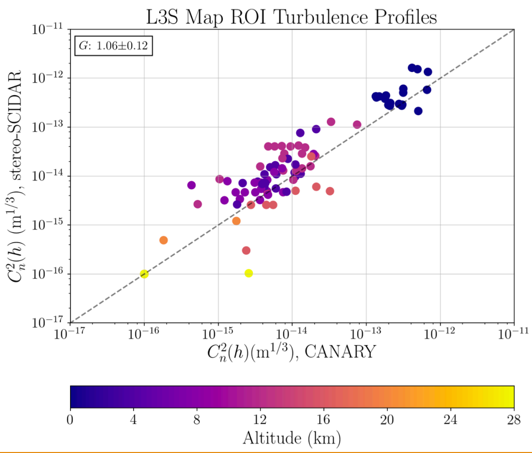
Performance Verification – On-sky



stereo-SCIDAR's Integrated Profile

$$G = \frac{1}{N}\sum_{i=1}^{N}\left|\log\left(\frac{C_n^2(h_i)_{\mathrm{Target}}}{C_n^2(h_i)_{\mathrm{Fit}}}\right)\right|$$

Target Array	G
Matrix	1.23 ± 0.11
Map ROI	1.06 ± 0.12

CANARY

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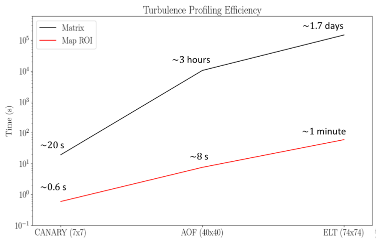

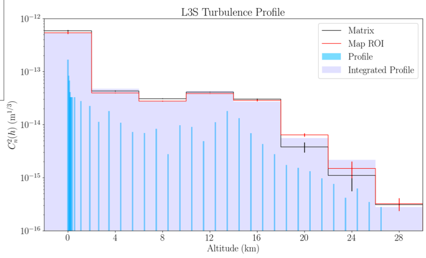

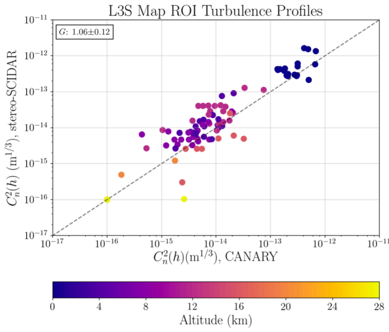

1. Compared to matrices, covariance map ROIs can be calculated and generated much, much faster.
2. For turbulence profiling, fitting to covariance map ROIs is as accurate as fitting to covariance matrices.

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