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Geodetic Network Design for Low-Cost GNSS

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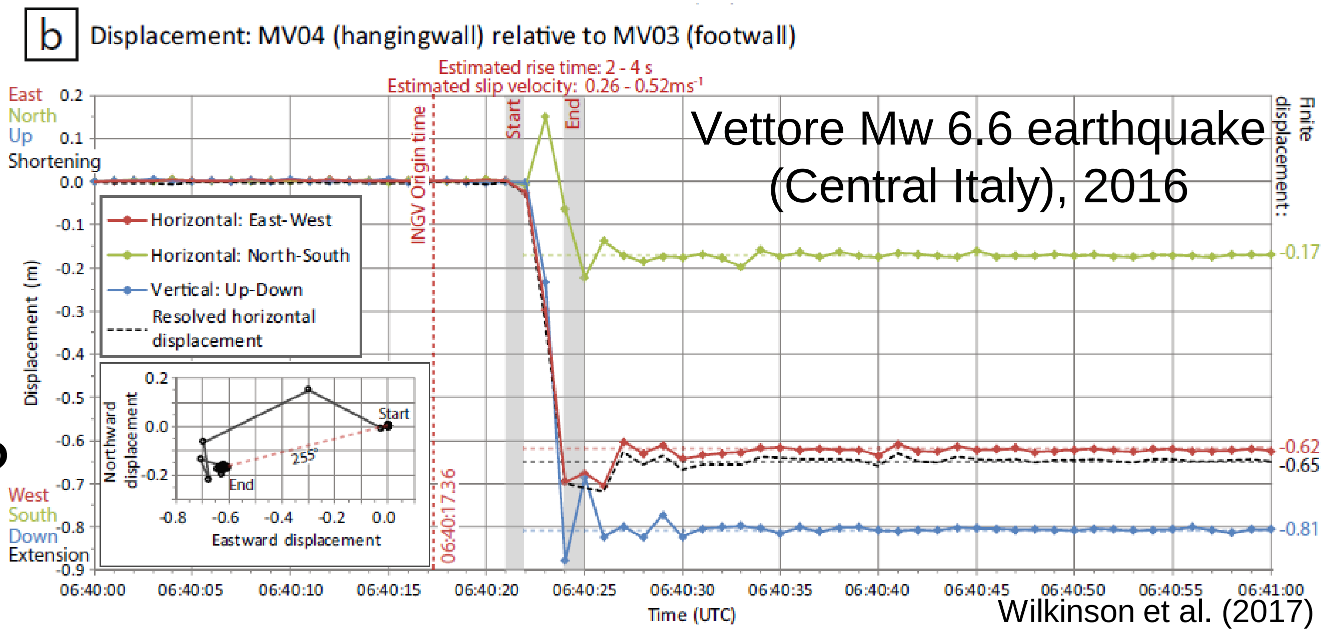
Background

- GNSS stations can be used to estimate distribution of slip on faults in various parts of the earthquake cycle
- Conventional stations are too expensive to deploy **dense** networks around faults
- Low-cost single-frequency receivers offer an alternative (Chen et al., 2001; Cina & Piras, 2015; Lee et al., 2015)

- Previously used for coseismic displacement on faults (Wilkinson et al., 2017)
- What about post- / aseismic ..?



Wilkinson et al. (2017)

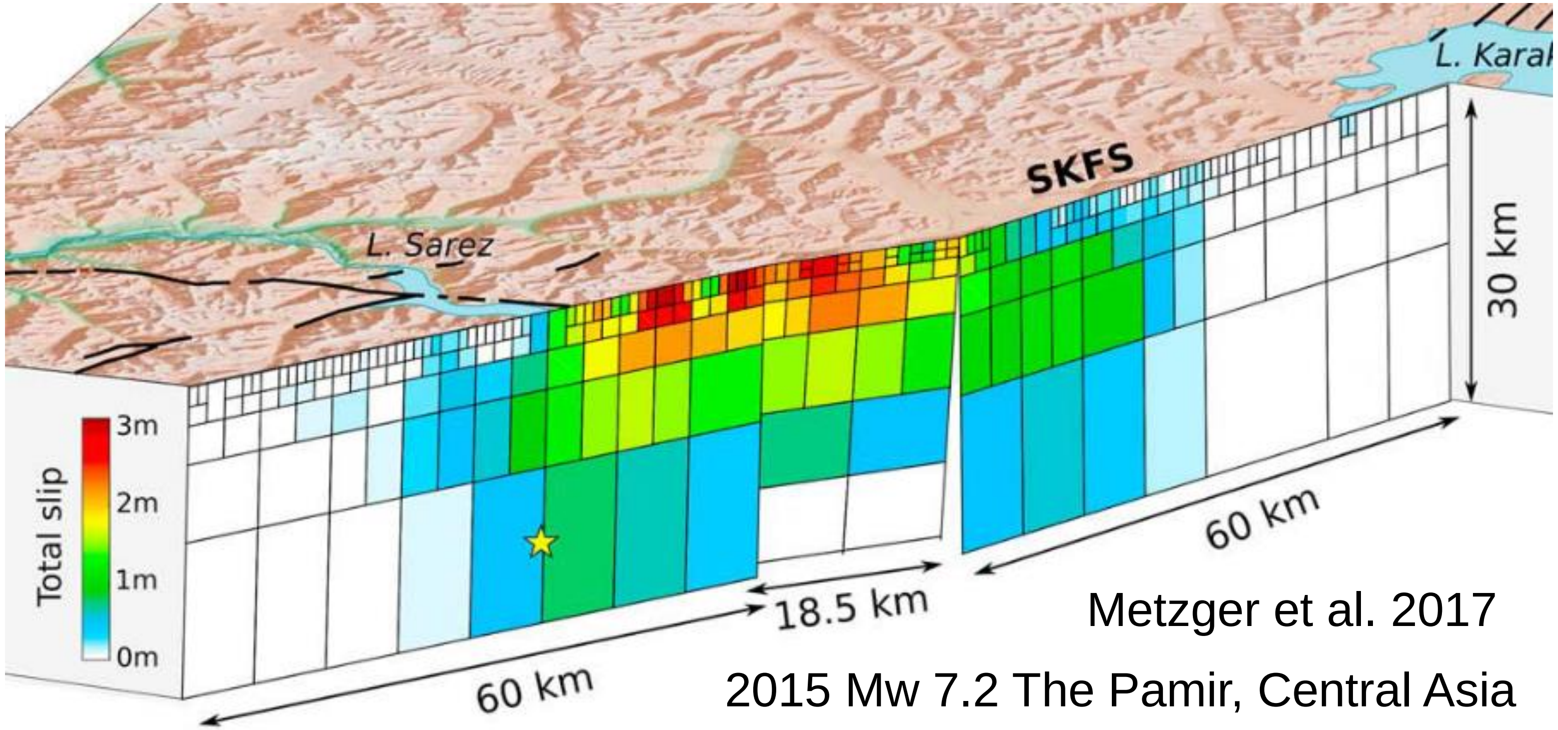
Project Aims

For a continental fault demonstrating aseismic transient deformation, where do we place ‘n’ stations to retrieve the most information?

1. What is the greatest amount of information we can get with an ideal “best possible” network?
   - Non-uniform fault discretisation
2. Design networks to maximise slip information relative to the best possible case
   - Where to place ‘n’ stations

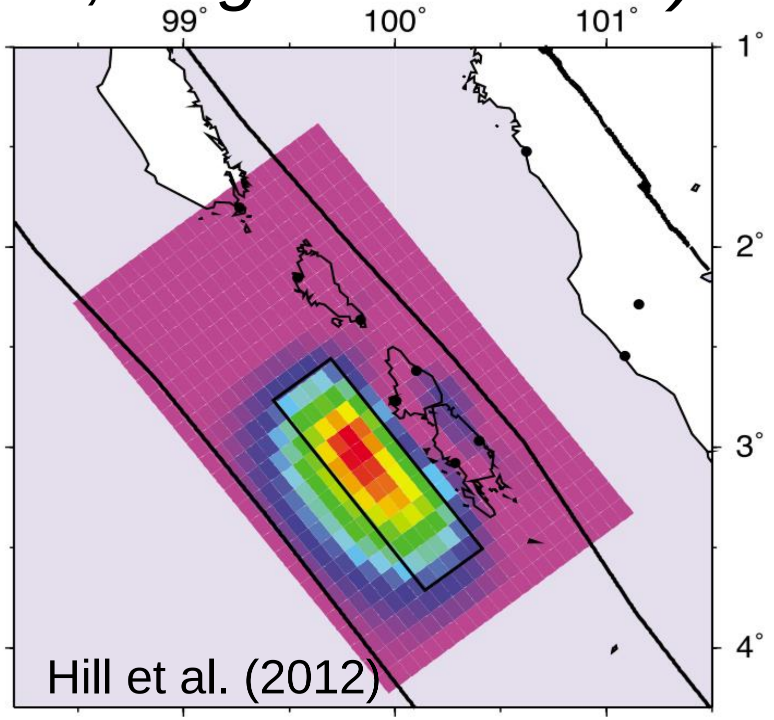
Fault Discretisation

- **Uniform discretisations** - *(Hill et al. 2012; Funning et al. 2005; Sathiakumar et al. 2017; Scognamiglio et al. 2018; Wright et al. 2003)*
- **Non-uniform discretisations** – *(Atzori and Antonioli 2011; Barnhart and Lohman 2010; Metzger et al. 2017; Page et al. 2009)*



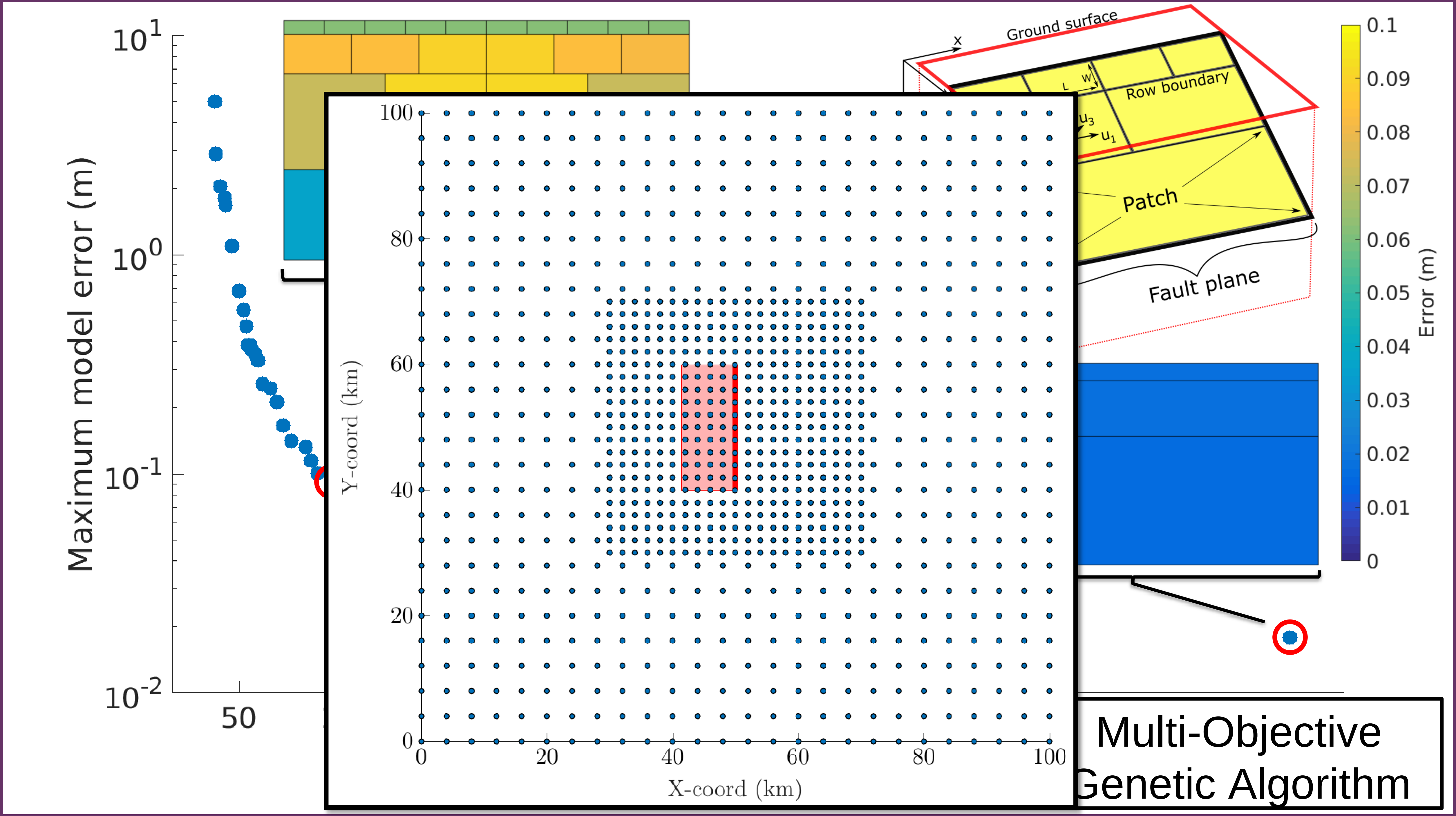
Metzger et al. 2017

2015 Mw 7.2 The Pamir, Central Asia



Hill et al. (2012)

2010 Mw 7.8 Mentawai, Indonesia



Maximum model error (m)
10^1
10^0
10^{-1}
10^{-2}
50
Y-coord (km)
X-coord (km)
0
20
40
60
80
100
Ground surface
x
L
W
Row boundary
u_3
u_1
Patch
Fault plane
Error (m)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Multi-Objective
Genetic Algorithm

Network Design

- Minimise model variance / covariance relative to idealised values

$$Q_m = (G^T Q_d^{-1} G)^{-1}$$

Model VCM

Green's functions, Okada (1985)

Data VCM

Model VCM for network

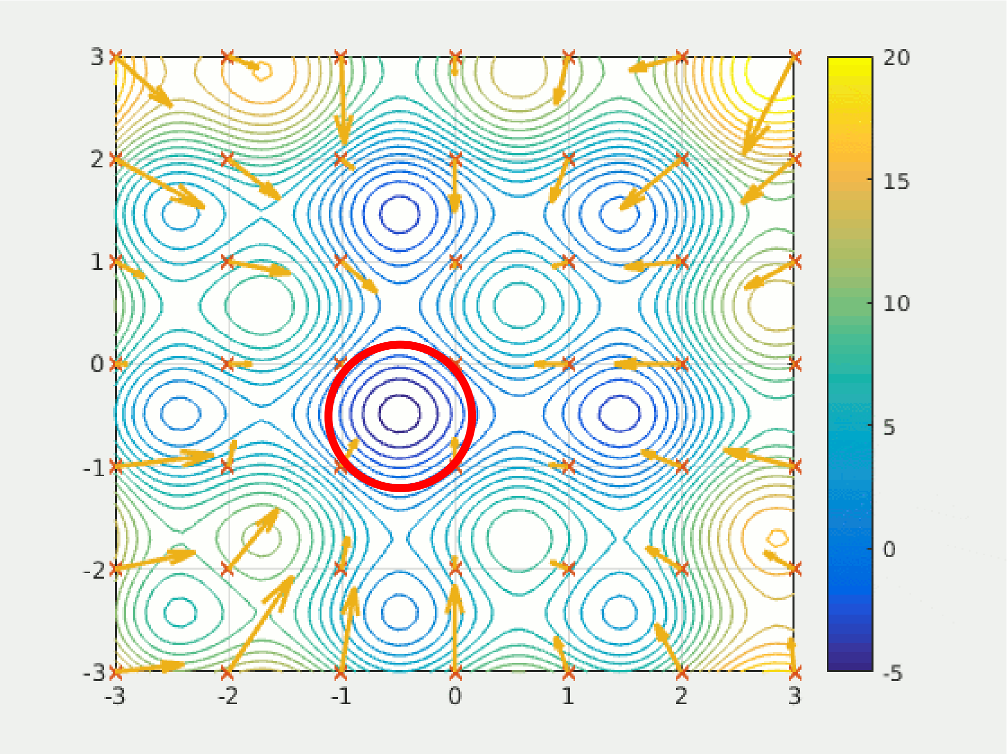
Ideal 'best possible' model VCM

$$d(\boldsymbol{Q}_{m,des}, \boldsymbol{Q}_{m,id}) = \sqrt{\sum_{i=1}^{n} ln^2 \lambda_i(\boldsymbol{Q}_{m,des}, \boldsymbol{Q}_{m,id})}$$

Distance metric

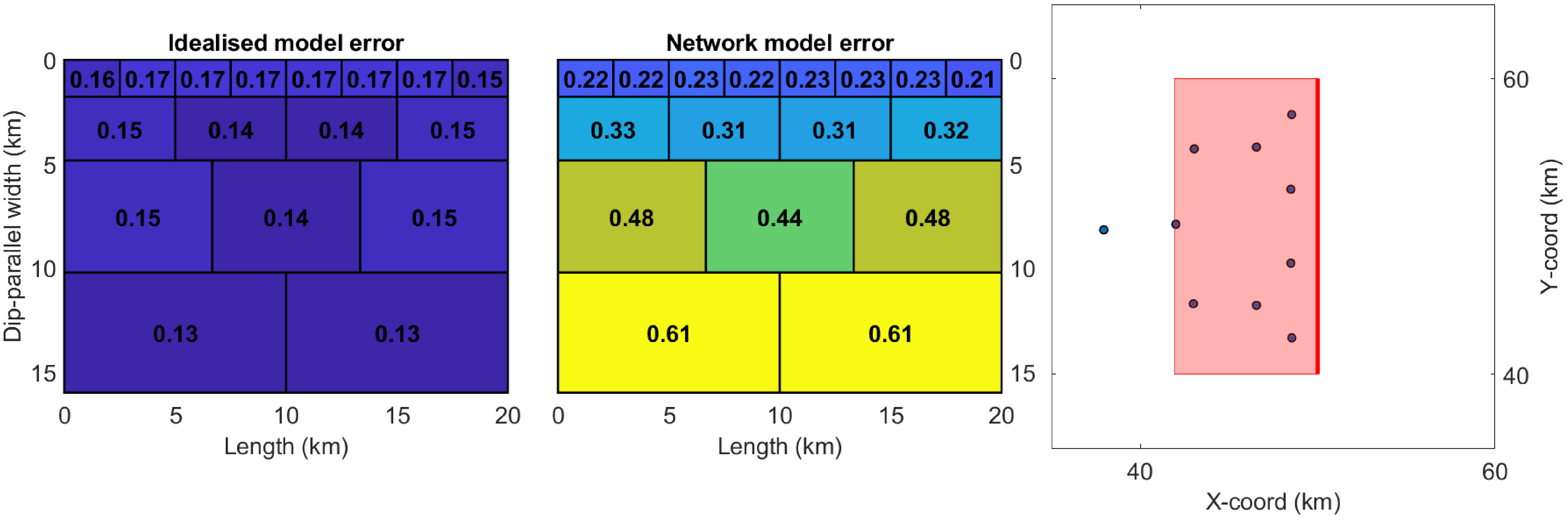
Förstner & Moonen (1999)

Particle Swarm Optimisation



Dual-Frequency Example

- Absolute measurements, no covariance between observations
- Positional errors of 2 cm (North, East) and 4 cm (Up)



Single-Frequency

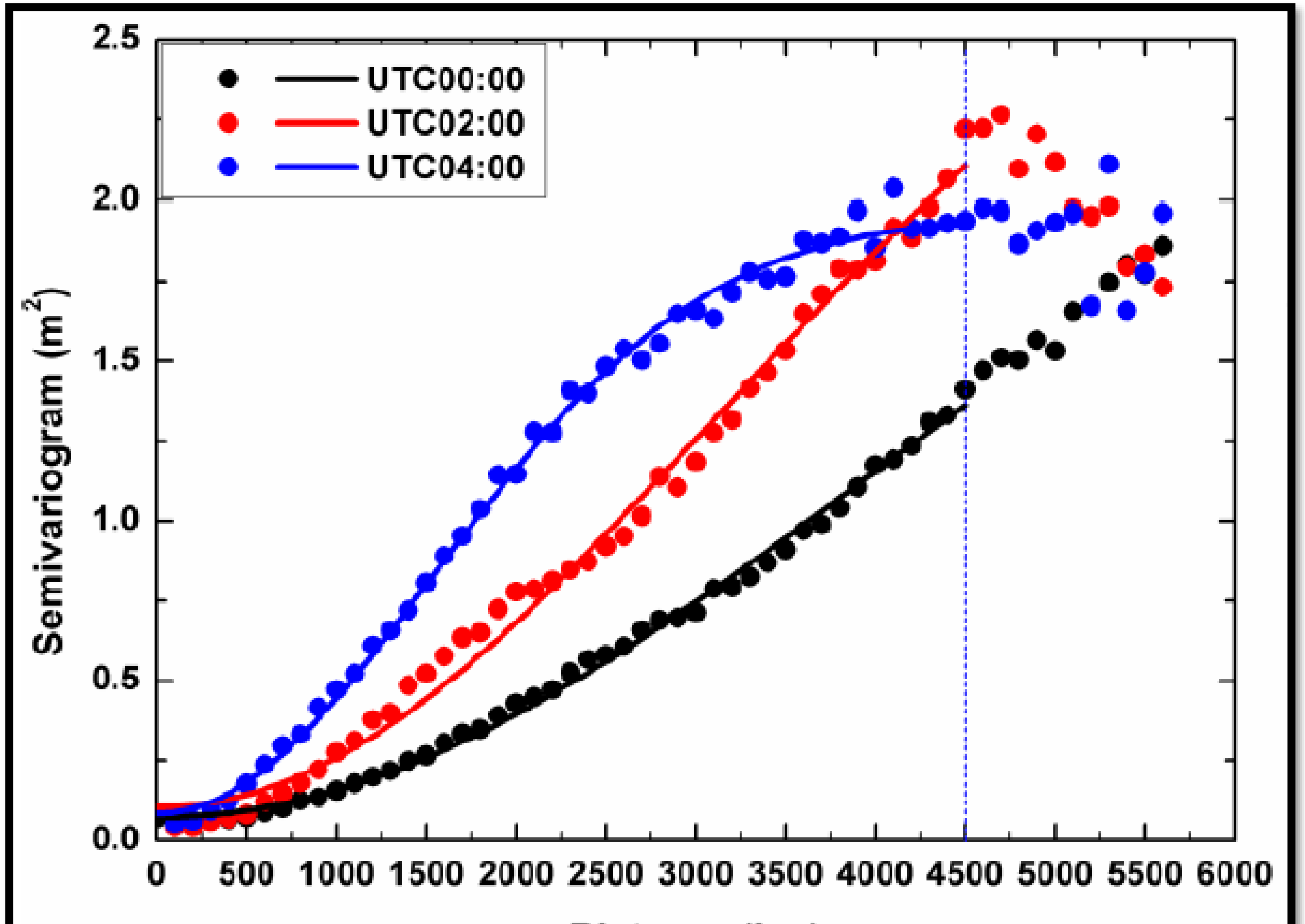
- Single-frequency GNSS stations are unable to mitigate the effects of ionospheric delay "in-station"

Two problems to address :

What is the spatial error structure of the data?

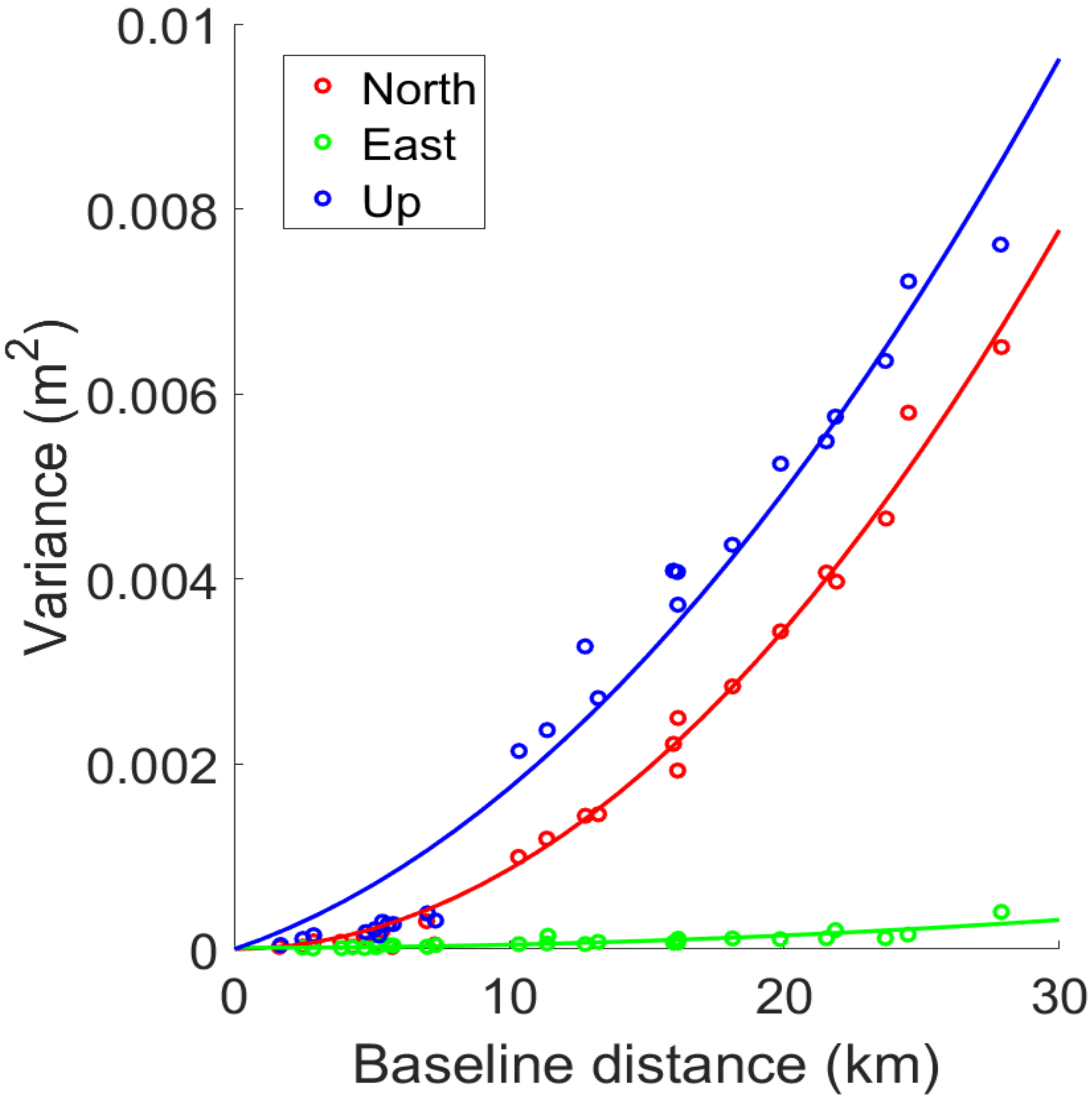
How do we handle a network of paired relative measurements?

Error Structure



From Huang (2017)

From Chen (2015)

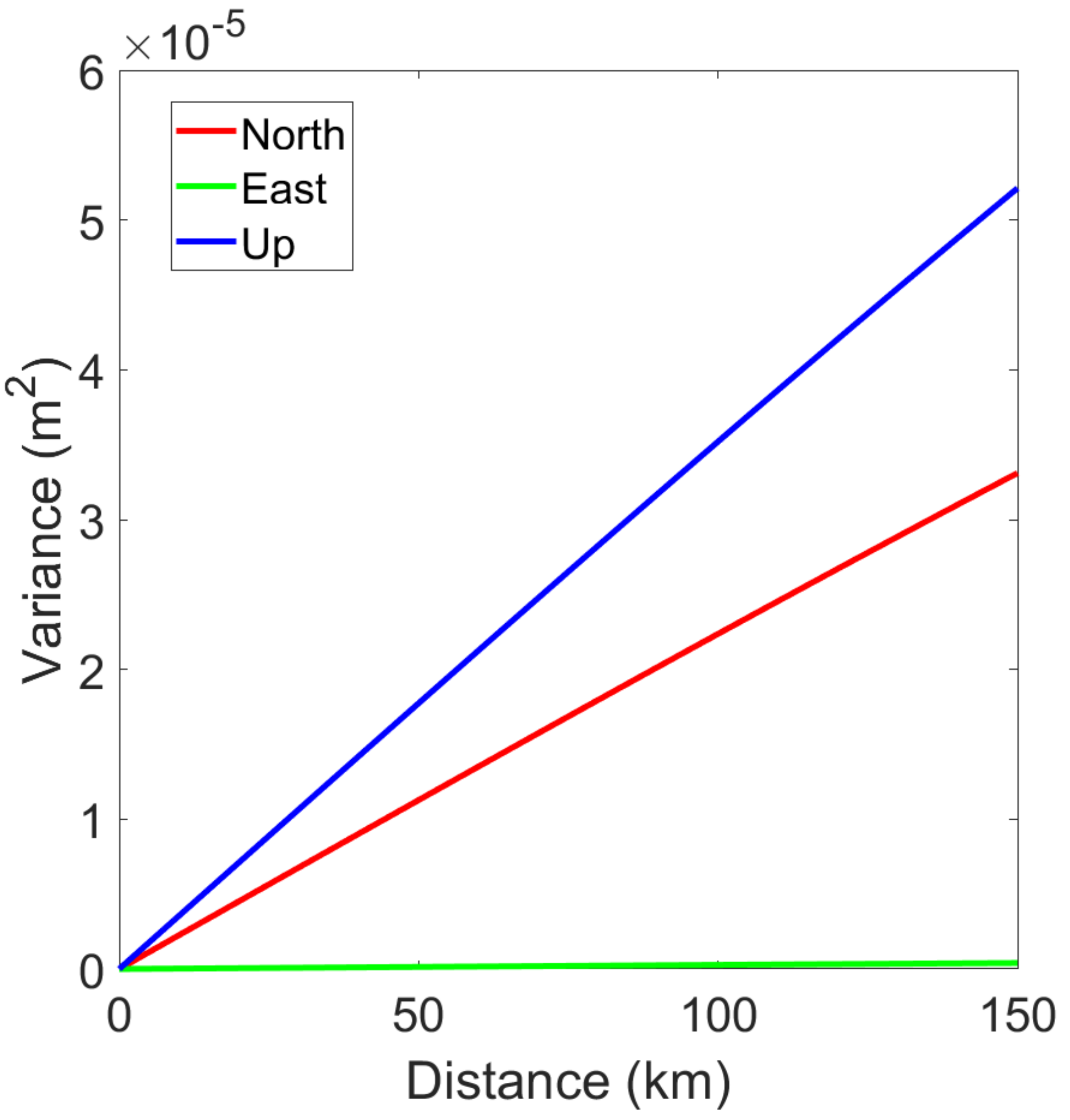


Removal of Planar Trend

Generate random spatial fields from variograms

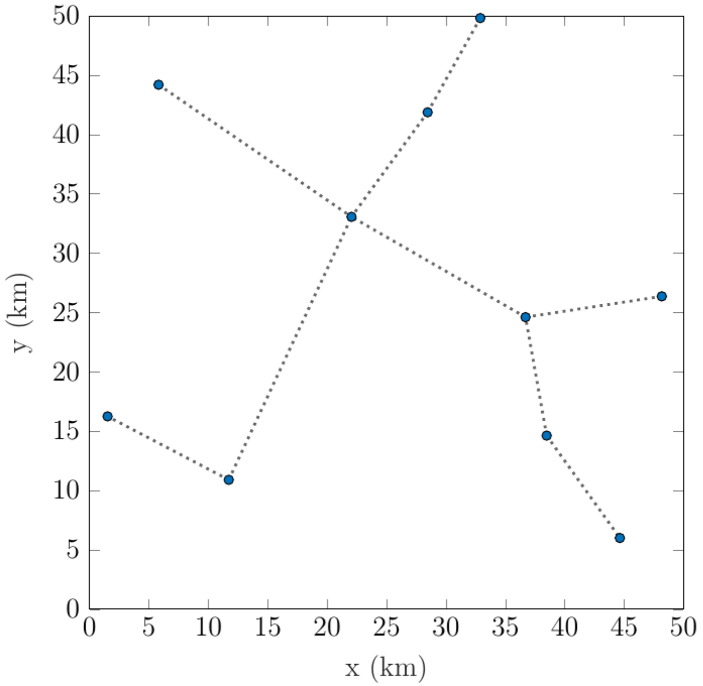
Remove a planar trend

Fit a new model to the detrended data



Relative Measurements

- Paired stations gives “n-1” observations
- Generate a minimum spanning tree with Kruskal’s algorithm (Kruskal 1956)



$\boldsymbol{Q}_{m,id}$ - Fault discretisation ✓

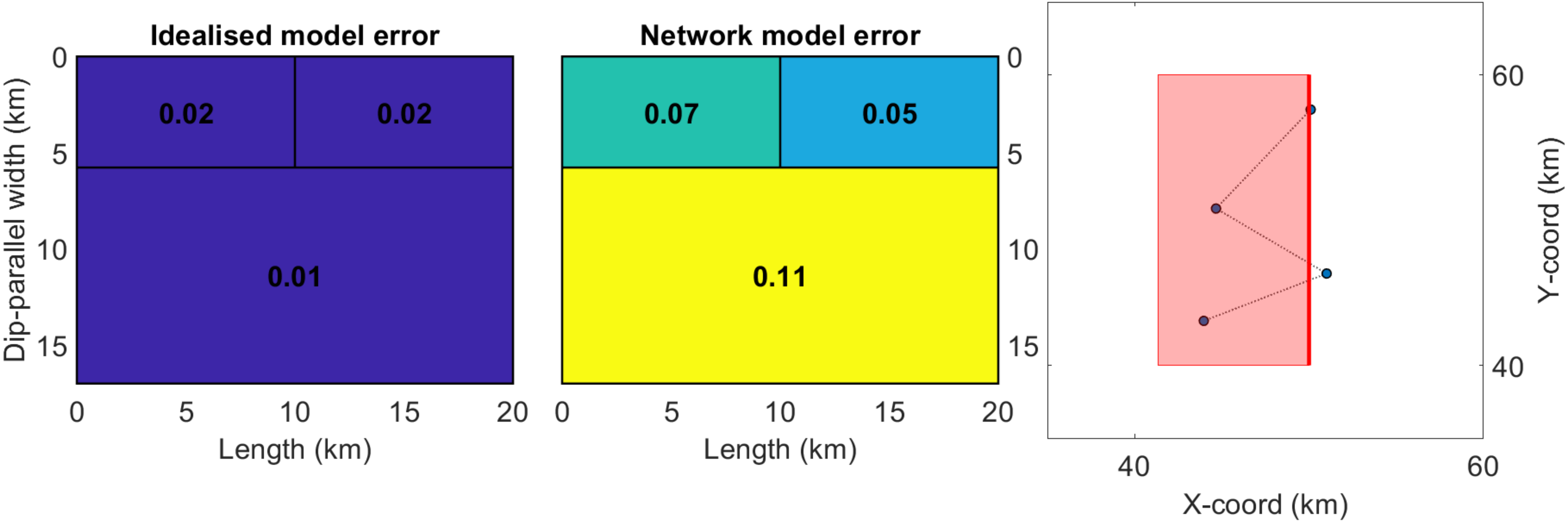
$\boldsymbol{Q}_{d}$ - Single-frequency variograms ✓

$\boldsymbol{Q}_{m,des}$ - Generate from $\mathbf{Q}_\mathrm{d}$ ✓

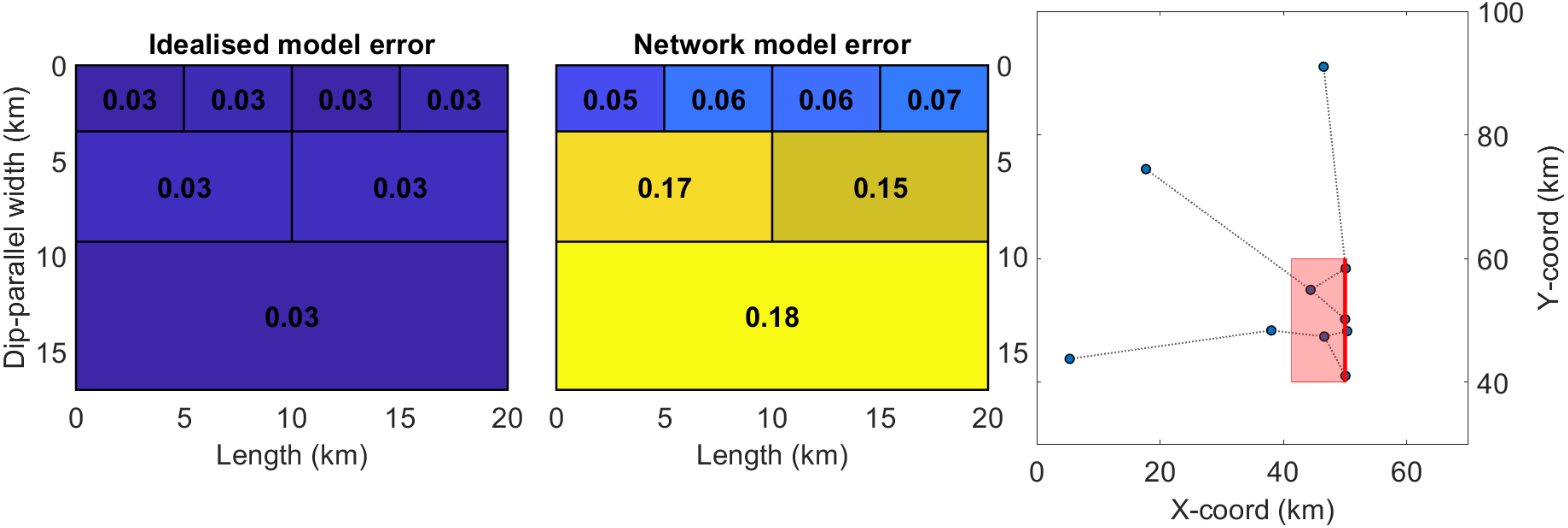
$$\sqrt{\sum_{i=1}^{n} ln^2 \lambda_i(\boldsymbol{Q}_{m,des}, \boldsymbol{Q}_{m,id})}$$

We can now generate optimal single-frequency networks

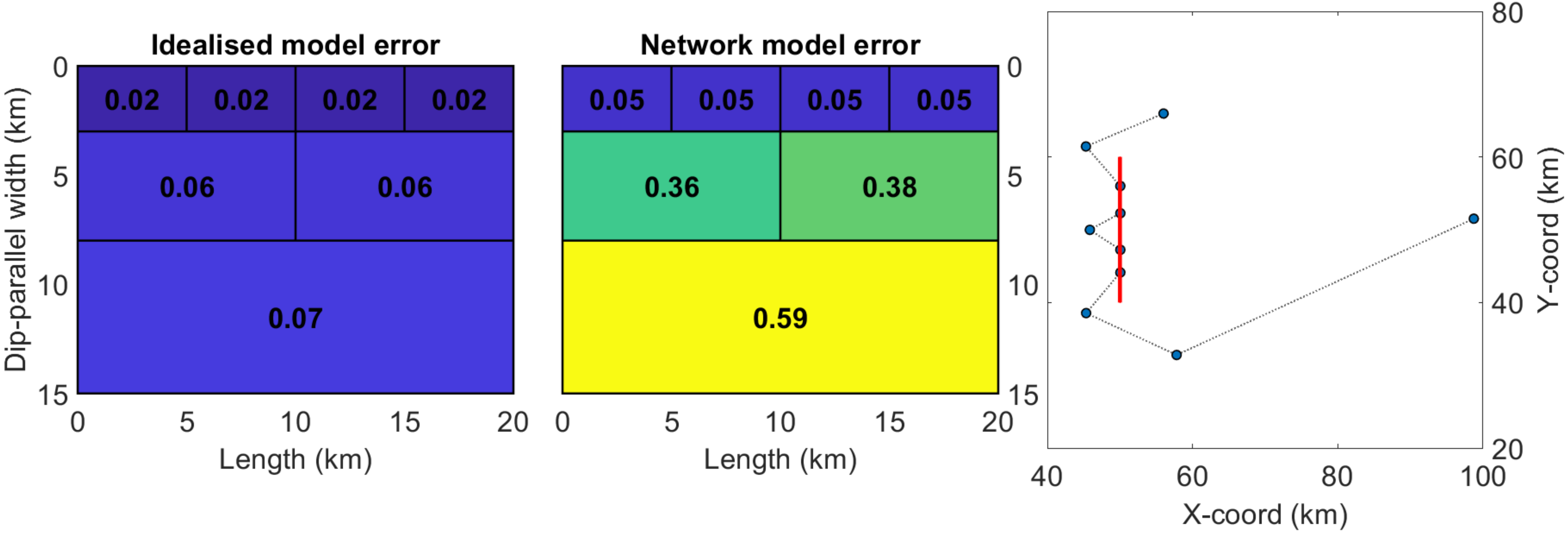
Four Stations



10 Stations


Idealised model error
Network model error
0.03
0.03
0.03
0.03
0.03
0.03
0.03
0.05
0.06
0.06
0.07
0.17
0.15
0.18
Dip-parallel width (km)
Length (km)
Length (km)
X-coord (km)
Y-coord (km)

Strike-Slip Fault



Conclusions

- Relative displacements between multiple single-frequency station pairs have highly correlated errors - planar trend must be removed *a priori* or solved for
- Developed network design approach to investigate single-frequency GNSS deployment for measurement of ‘slow’ tectonic slip
- Single-frequency GNSS may be suitable for studying aseismic slip on continental faults

Future Work

- Explore mixed single- and dual-frequency networks
- Integrate other geodetic datasets (e.g. InSAR)
- Create a set of “general rules” for network layouts

References

- Chen, HY et al. (2015). ‘Reducing distance dependent bias in low-cost single frequency GPS network to complement dual frequency GPS stations in order to derive detailed surface deformation field’. In: *Survey Review* 47.340, pp. 7–17.
- Huang, Ling et al. (2017). ‘Kriging with unknown variance components for regional ionospheric reconstruction’. In: *Sensors* 17.3, p. 468.

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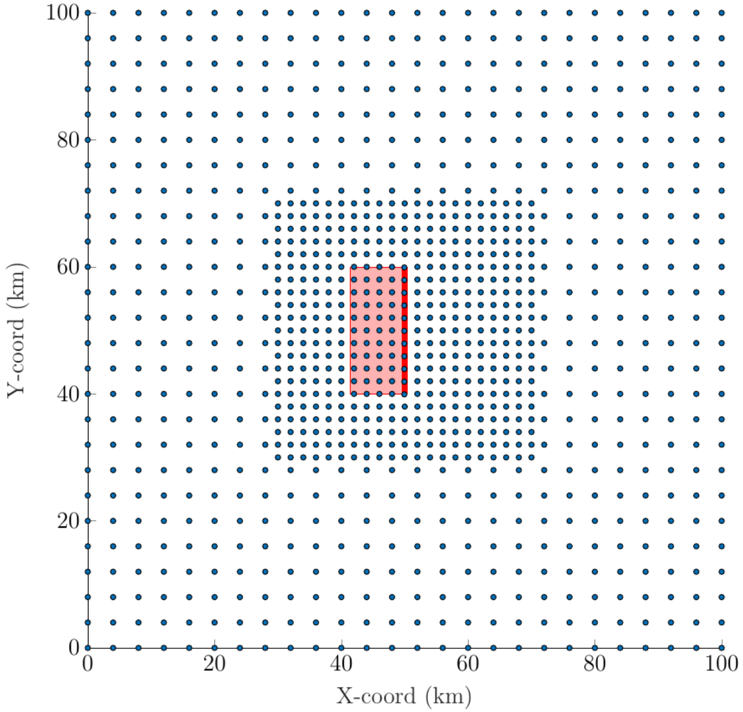

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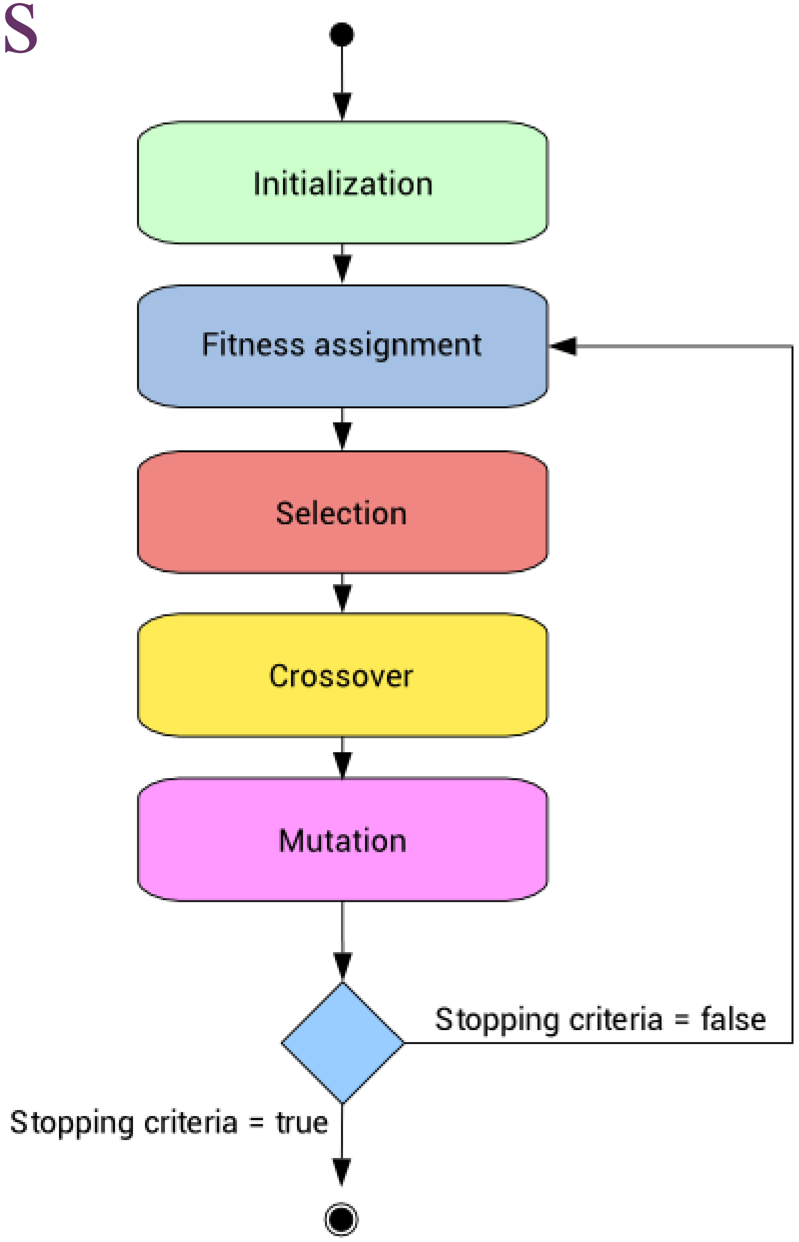
Genetic Algorithms

- Use the Matlab function ‘gamultiobj’ from the optimisation toolbox
- Analogy of evolution
- Assess fitness using model error and number of patches
- Attempts to find solutions along the full pareto front
- ‘fgoalattain’ as a hybrid function



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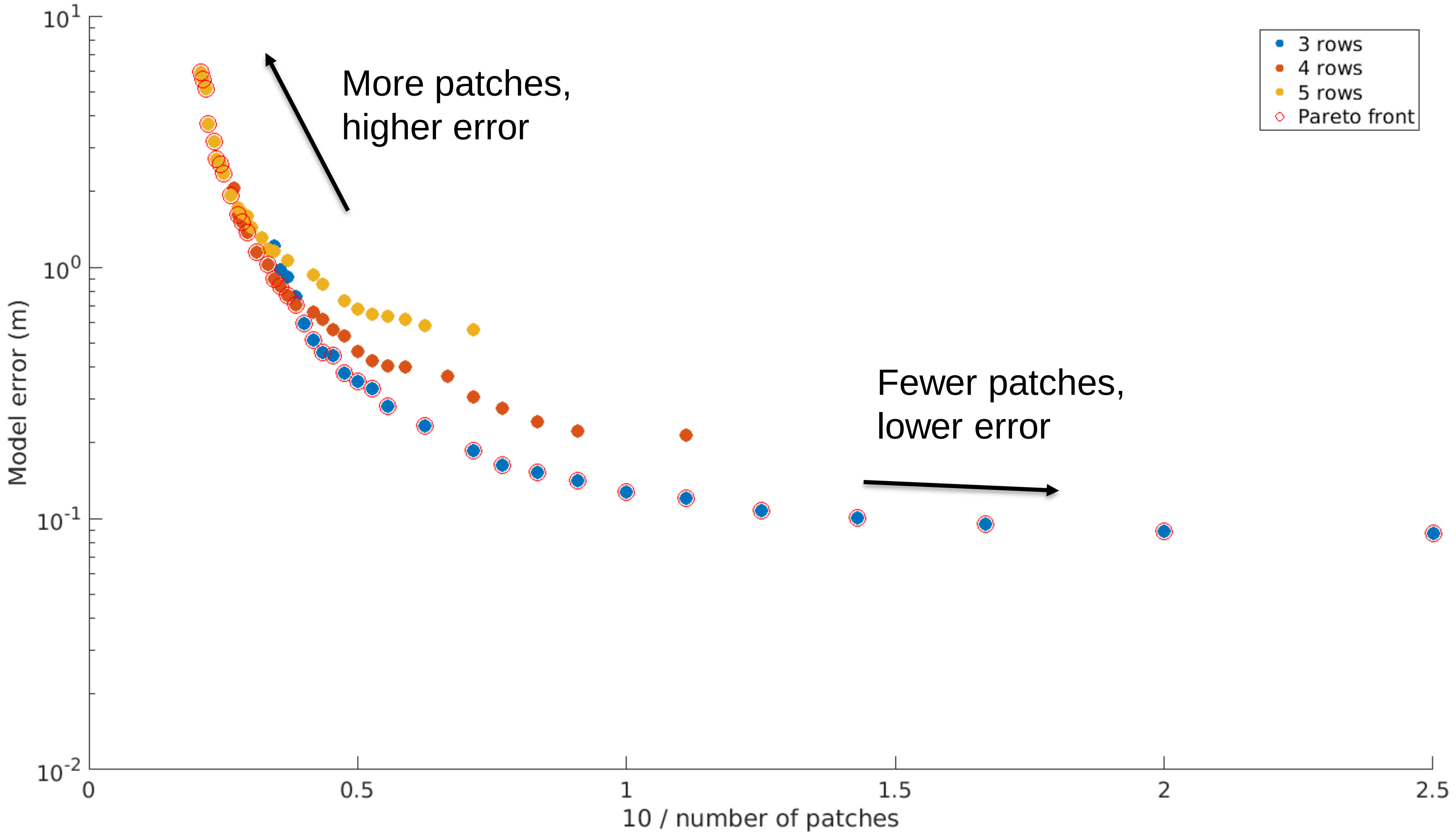
Pareto Front



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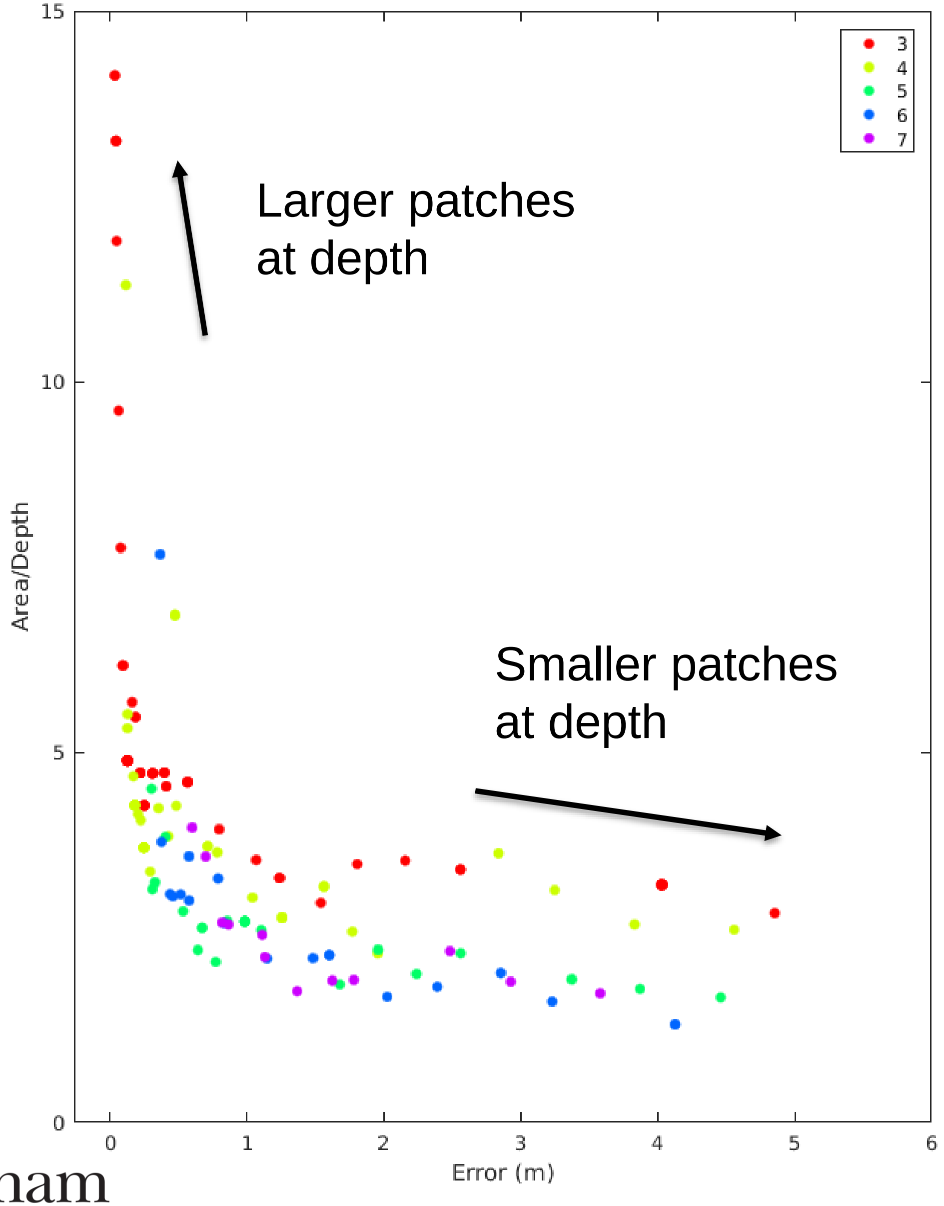
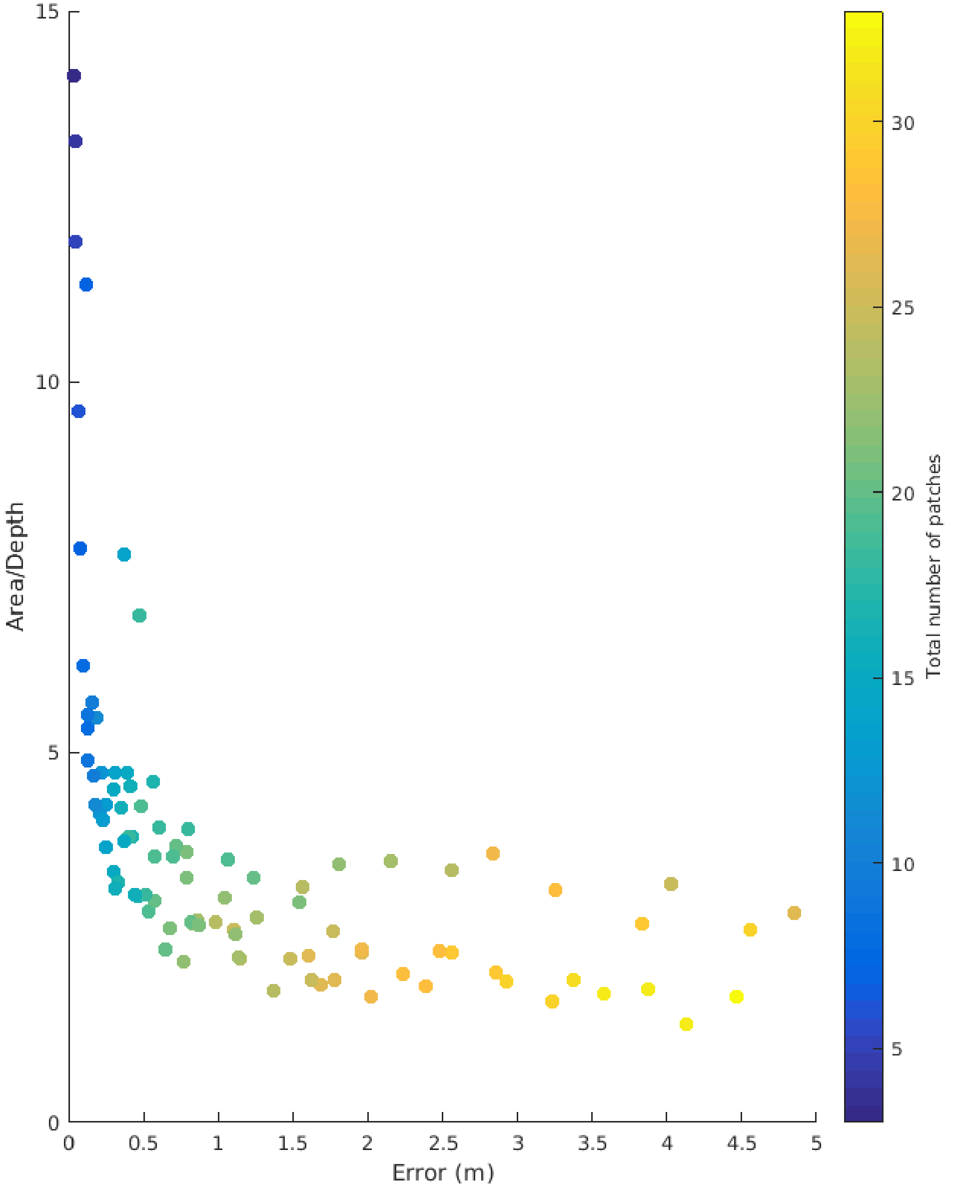
Pareto Front





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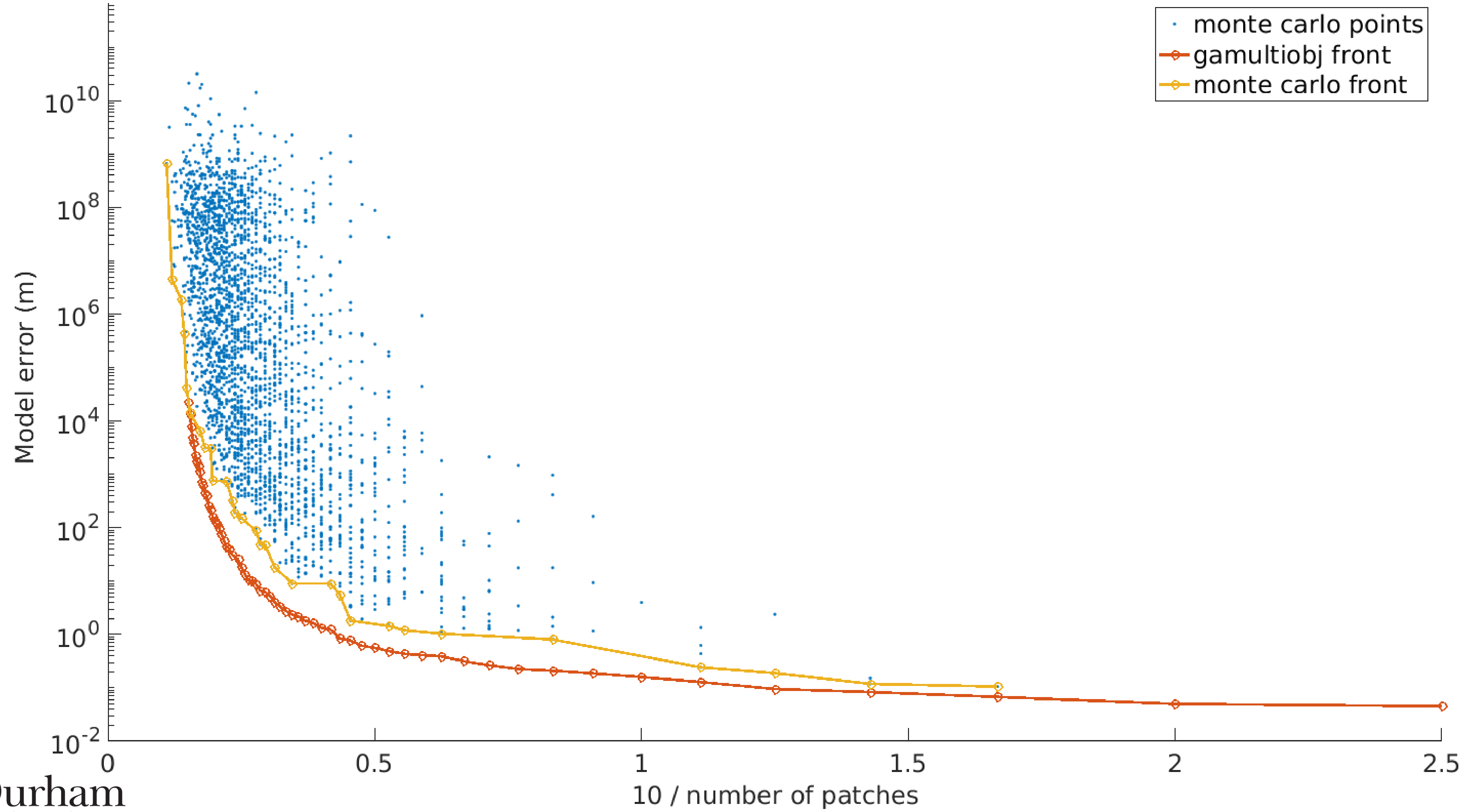
Monte Carlo Comparison



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