Dynamic Covariance Scaling for Robust Robot Mapping

Workshop on Robust and Multimodal Inference in Factor Graphs

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Cyrill Stachniss and Wolfram Burgard

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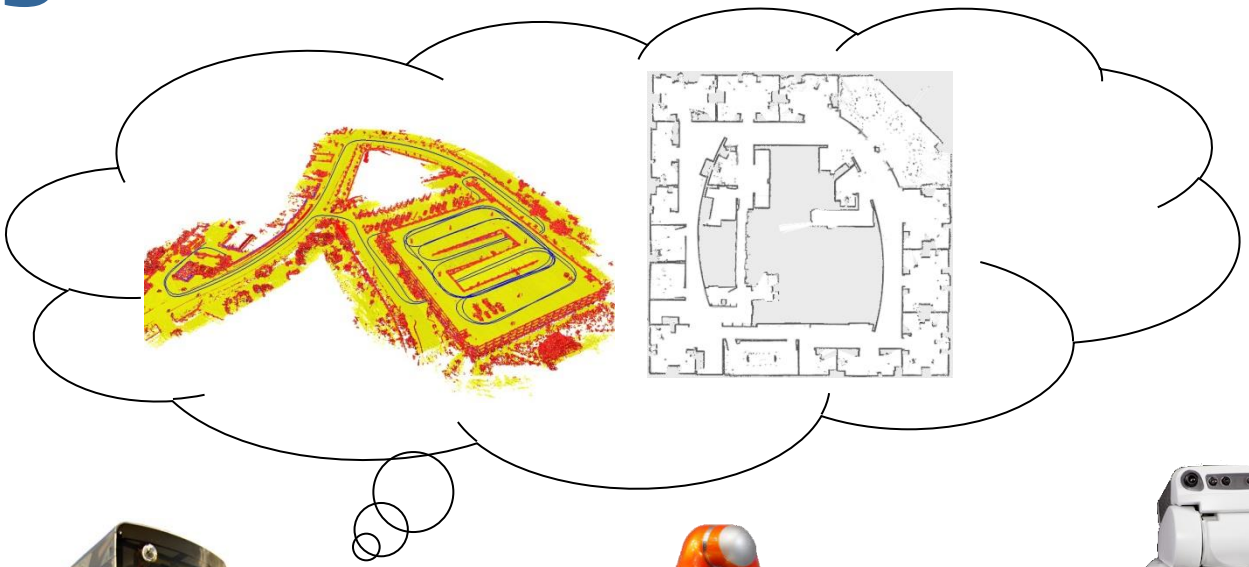
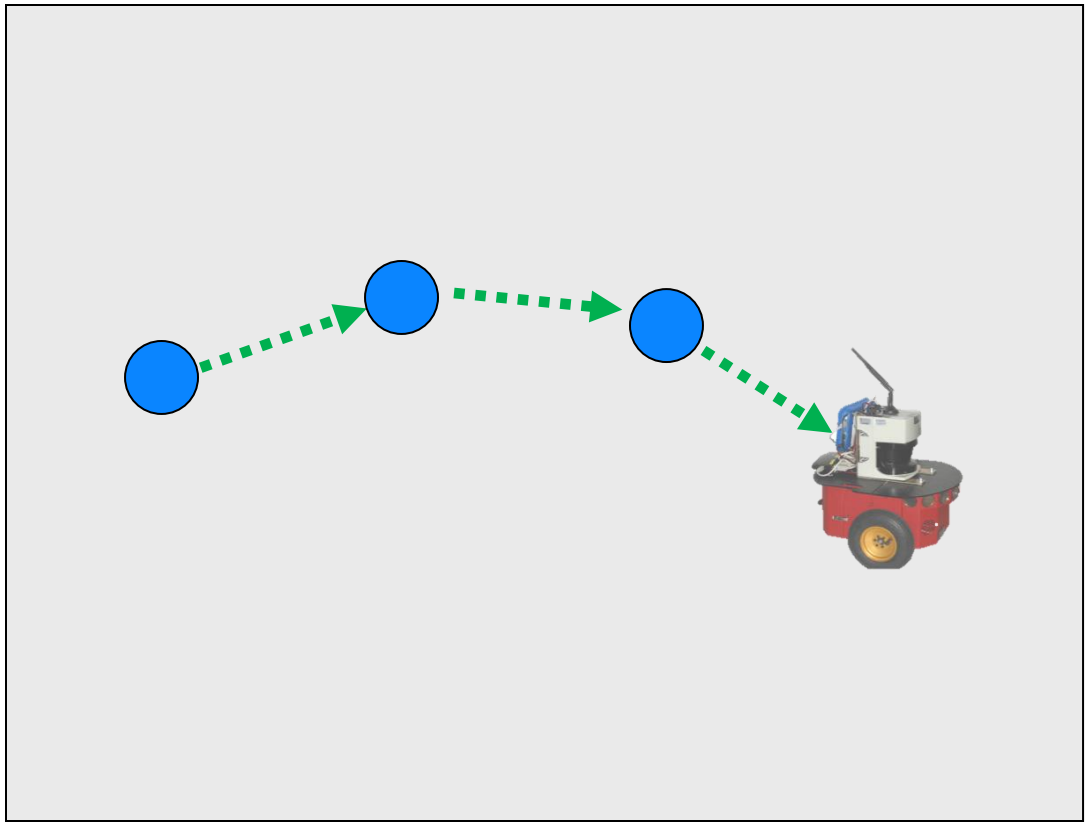
Maps are Essential for Effective Navigation



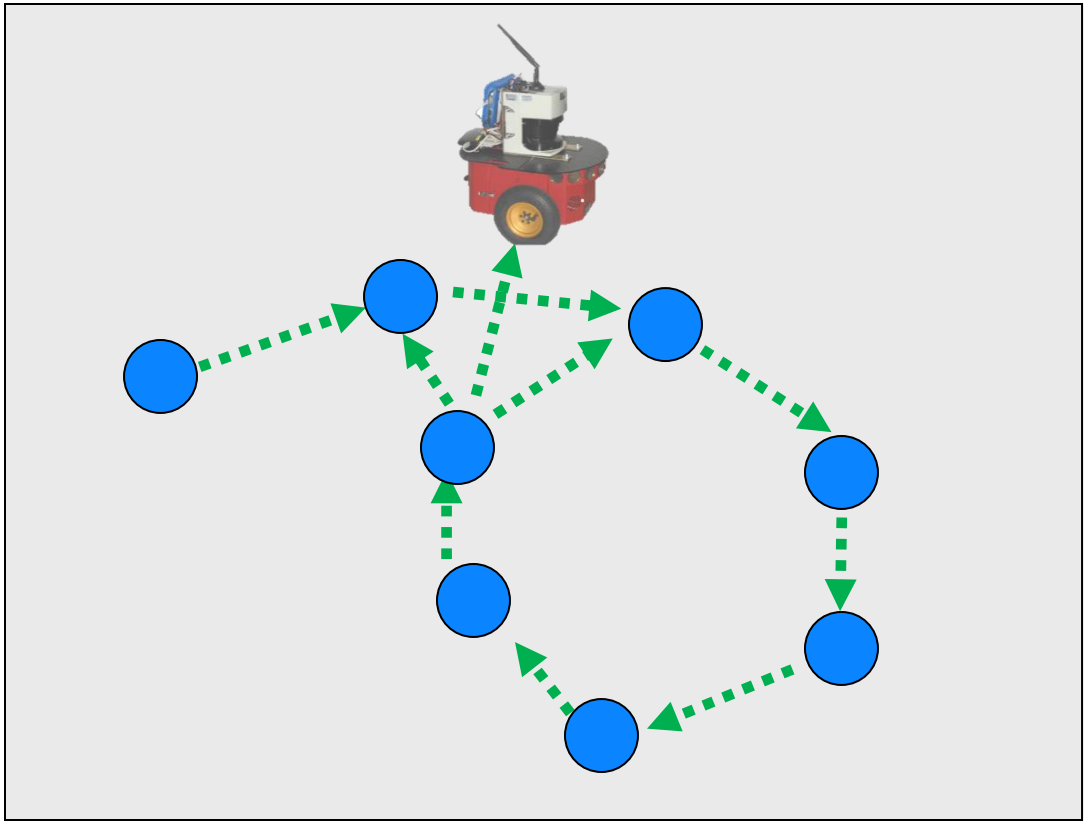
Graph-based SLAM



Robot pose

Constraint

Graph-based SLAM



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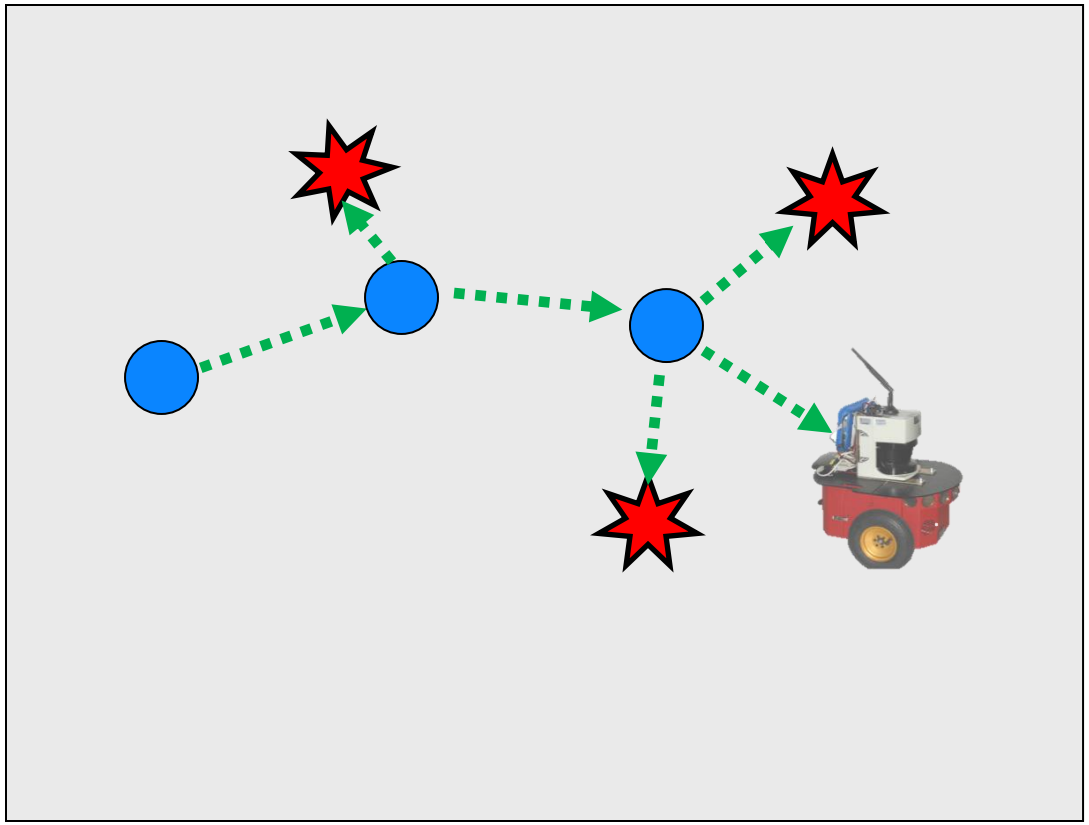
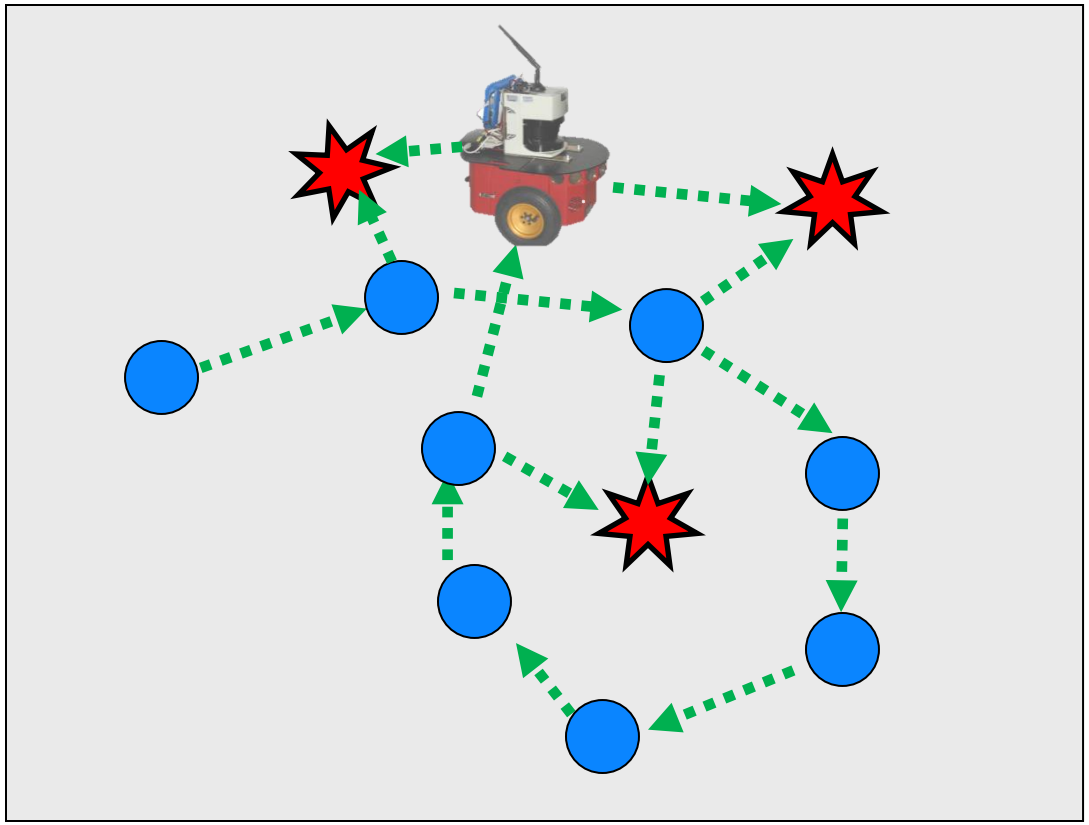


Robot pose

Constraint

Landmark

Graph-based SLAM



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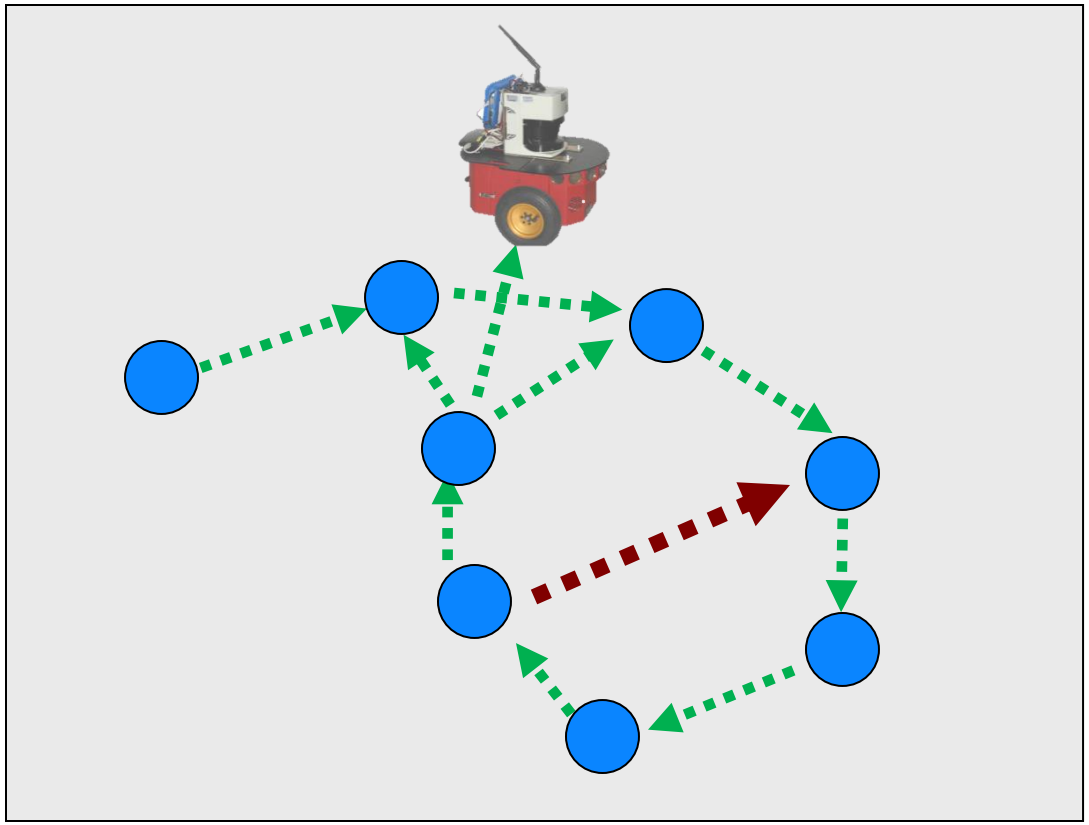
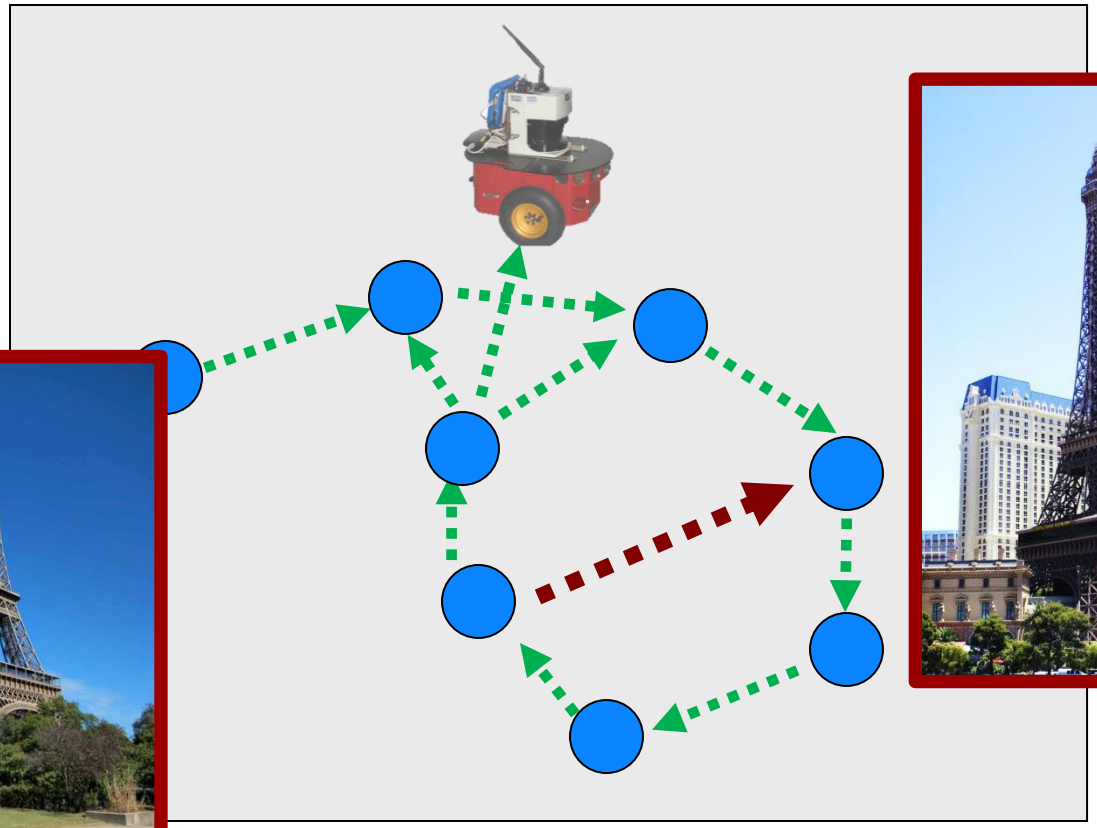


Robot pose

Constraint

a single outlier …

Graph-based SLAM

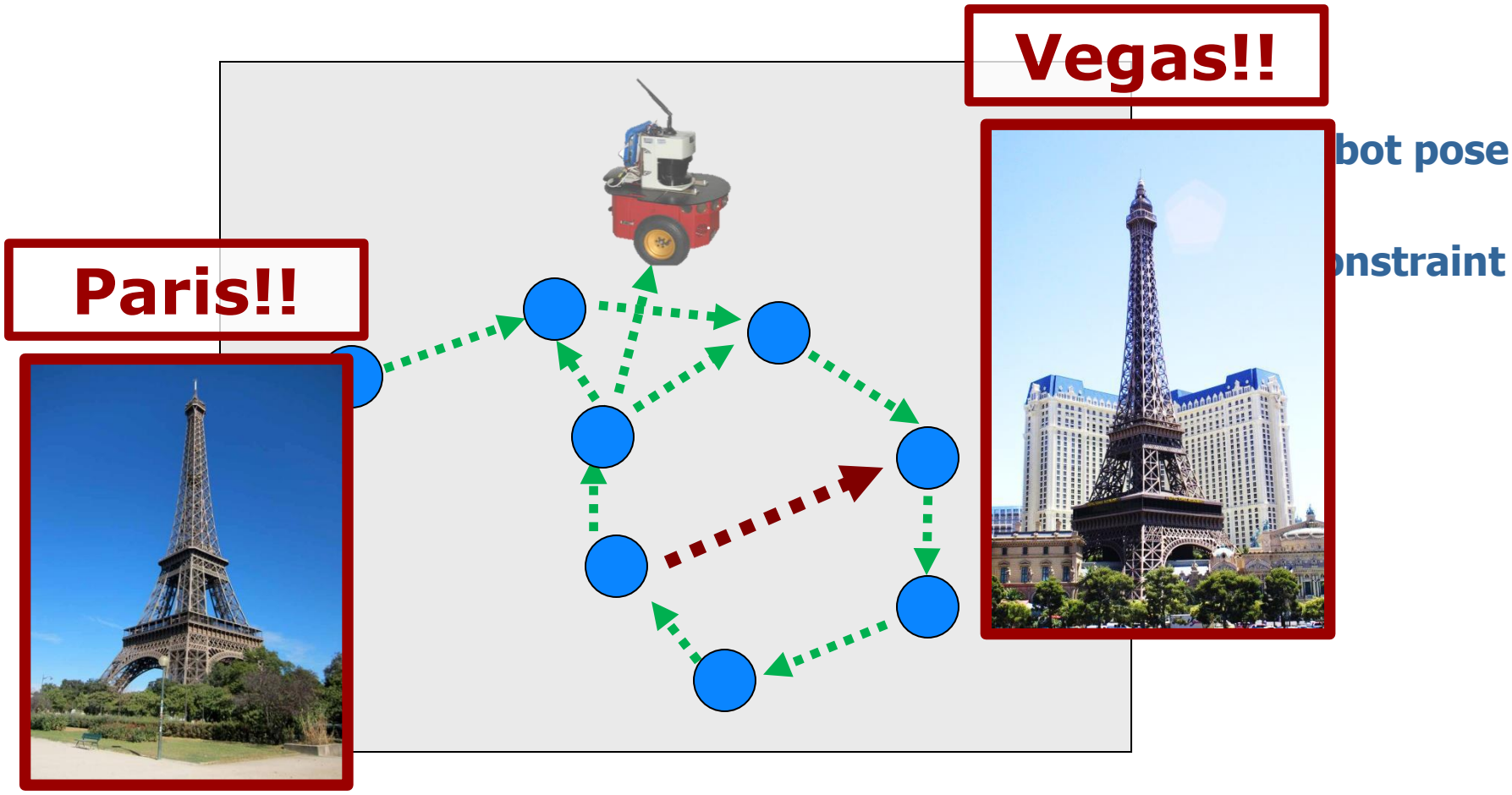


bot pose

onstraint

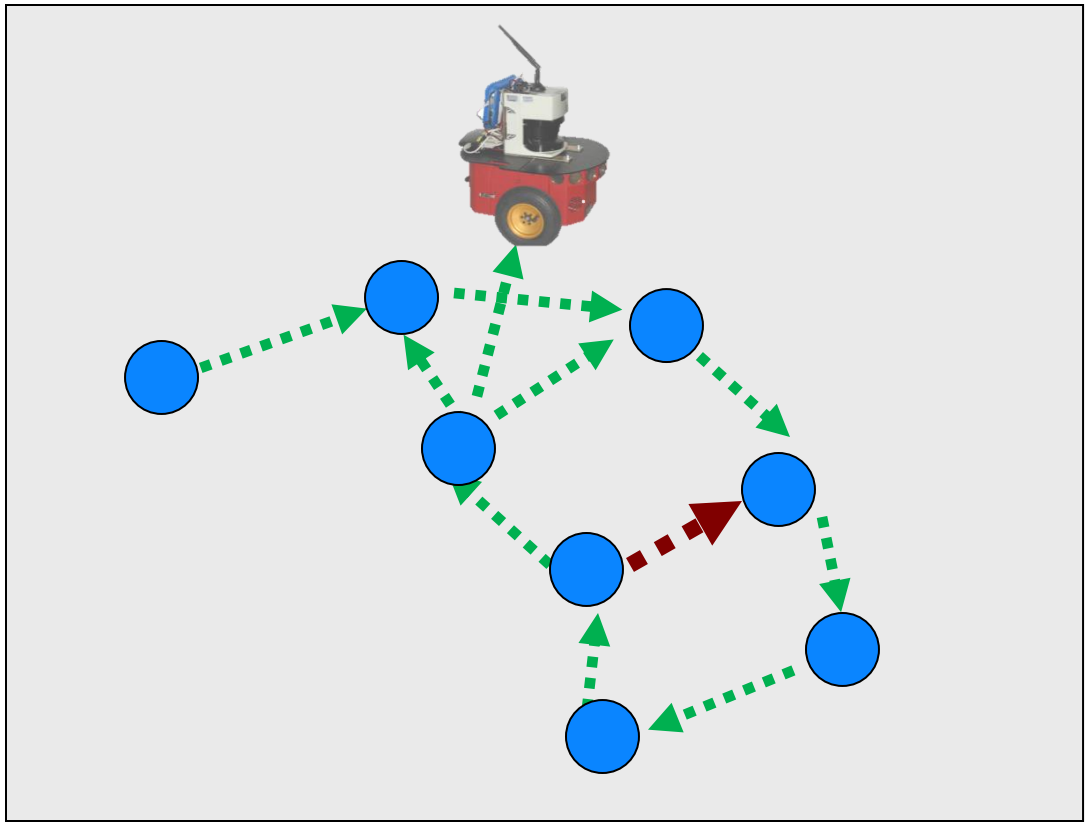
a single outlier …

Graph-based SLAM



a single outlier …

Graph-based SLAM



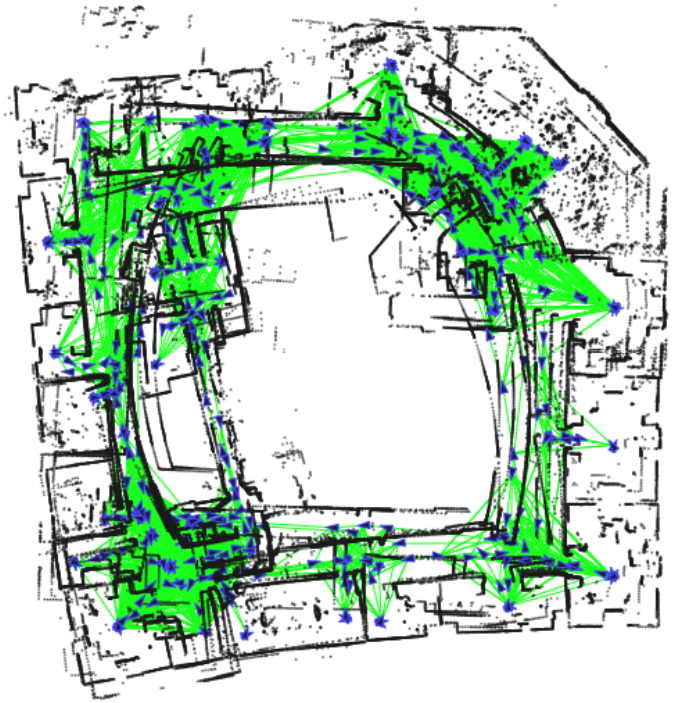
Robot pose

Constraint

a single outlier … ruins the map

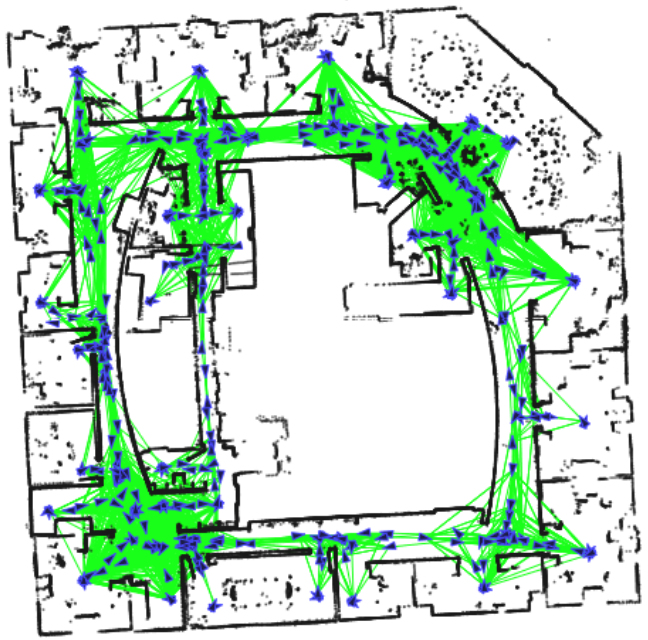
Graph-SLAM Pipeline

Front end → Validation → Back end



Assumption:

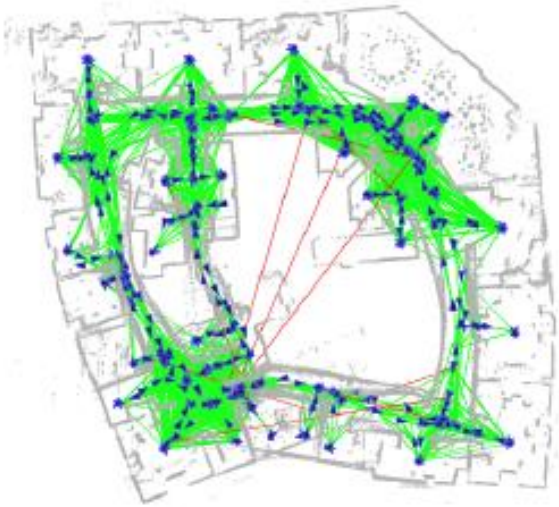
No Outliers



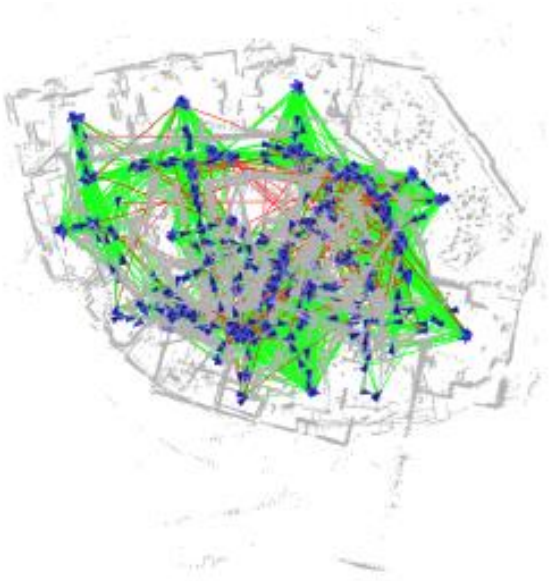
Impossible to have perfect validation

SLAM Back End Fails in the Presence of Outliers

1 Outlier

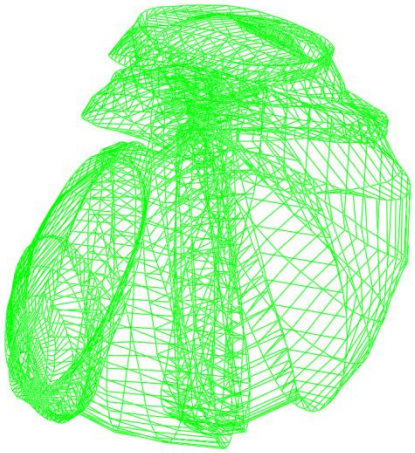


10 Outliers

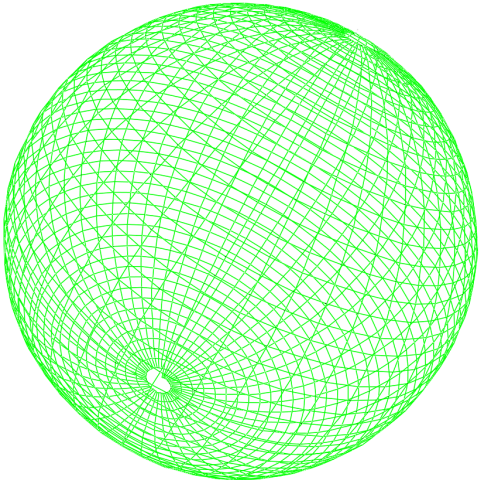


100 Outliers

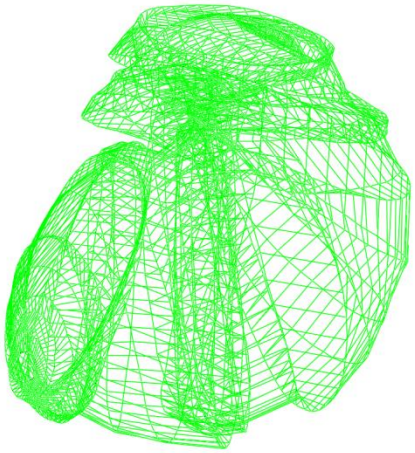
SLAM Back End Depends on the Initial Guess



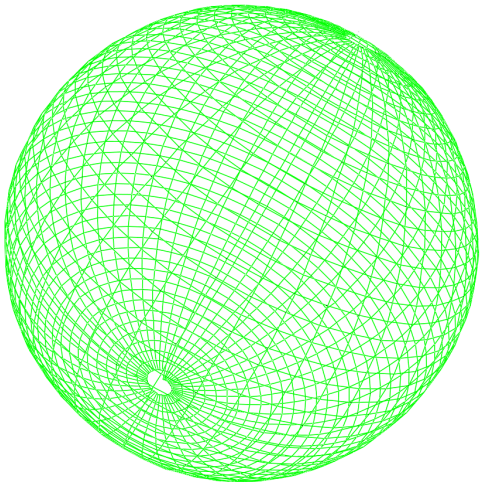
Good Initial Guess

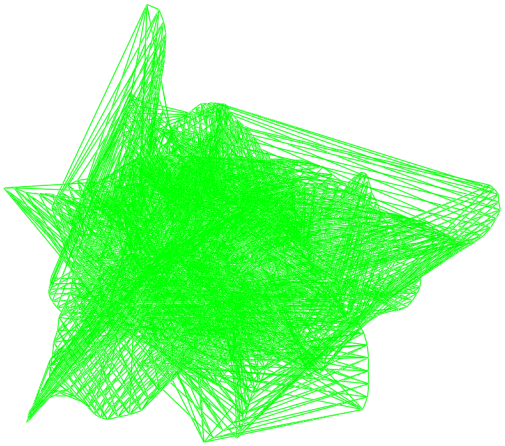


SLAM Back End Depends on the Initial Guess

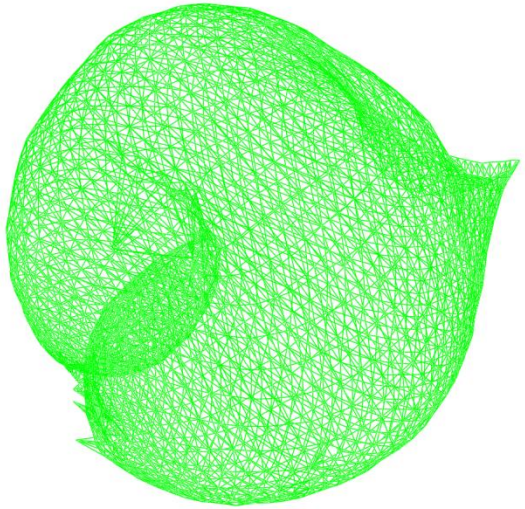


Good Initial Guess





Bad Initial Guess



Typical Assumptions

- **Gaussian assumption is violated**
  - Perceptual aliasing
  - Measurement error
  - Multipath GPS measurements

Typical Assumptions

- **Gaussian assumption is violated**
  - Perceptual aliasing
  - Measurement error
  - Multipath GPS measurements
- **Linear approximation is invalid**
  - Linearization is only valid if close to optimum

Typical Assumptions in Graph-SLAM

- **No outliers**
- **Good initial guess**
- Current methods both **independently**
- Our method approaches **both problems**

Typical Assumptions in Graph-SLAM

- **No outliers**
- **Good initial guess**
- Current methods solve both **independently**
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Our Approach

- **Dynamic Covariance Scaling**

Our Approach:
Dynamic Covariance Scaling

- Successfully **rejects** outliers
- More robust to **bad initial guess**
- Does not increase state space
- Is a robust M-estimator

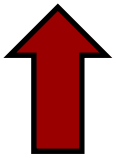
Standard Gaussian Least Squares

$$X^* = \underset{X}{\operatorname{argmin}} \sum_{ij} \underbrace{\mathbf{e}_{ij}(X)^T \Omega_{ij} \mathbf{e}_{ij}(X)}_{\chi^2_{ij}}$$

Dynamic Covariance Scaling

$$X^* = \underset{X}{\operatorname{argmin}} \sum_{ij} \underbrace{\mathbf{e}_{ij}(X)^T \Omega_{ij} \mathbf{e}_{ij}(X)}_{\chi^2_{ij}}$$

$$X^* = \underset{X}{\operatorname{argmin}} \sum_{ij} \mathbf{e}_{ij}(X)^T \left(s^2_{ij} \Omega_{ij}\right) \mathbf{e}_{ij}(X)$$



How to Determine s?

$$X^* = \underset{X}{\operatorname{argmin}} \sum_{ij} \mathbf{e}_{ij}(X)^T \left(s_{ij}^2 \Omega_{ij}\right) \mathbf{e}_{ij}(X)$$

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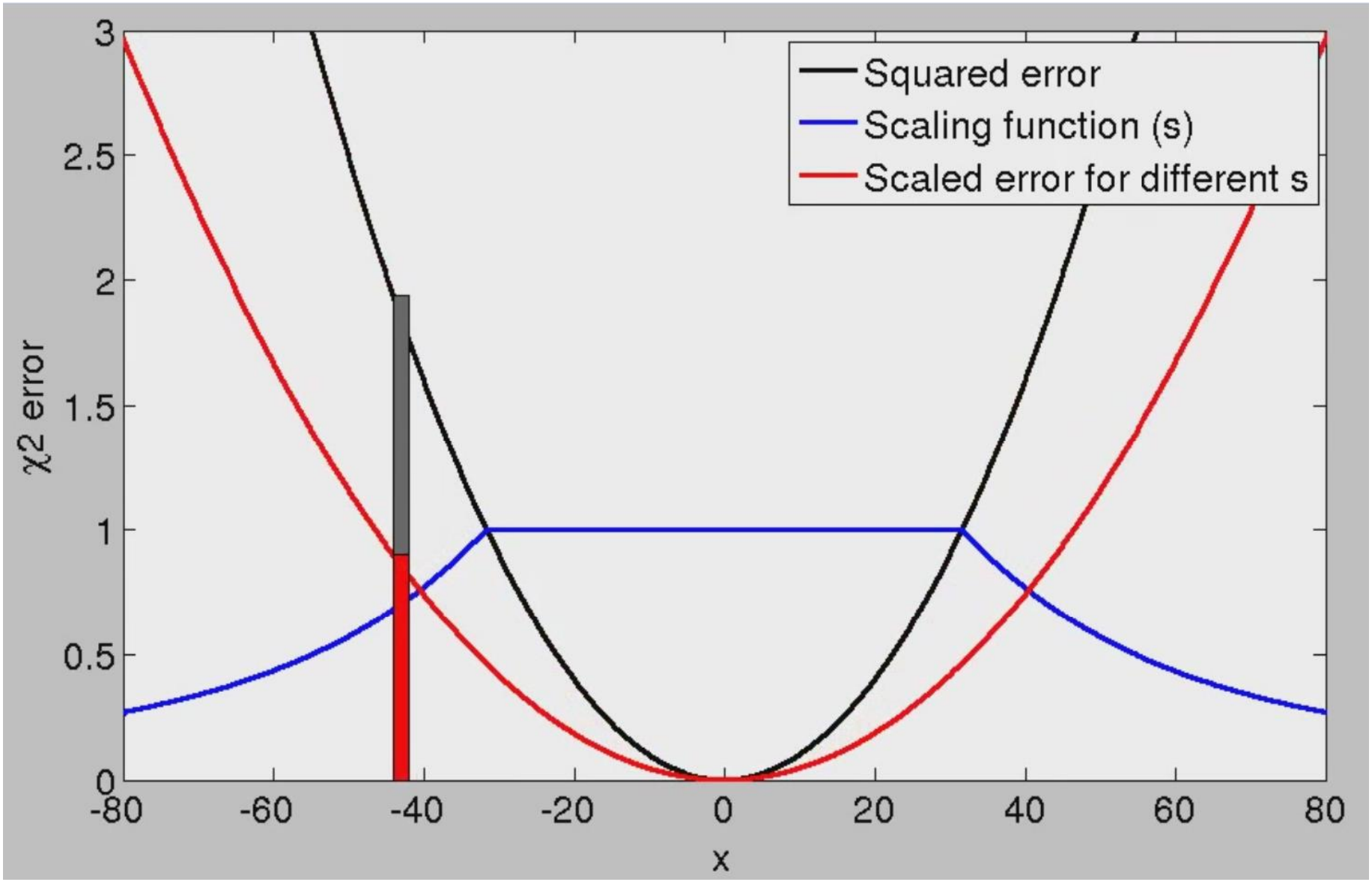
$$\Rightarrow s_{ij} = \min\left(1, \frac{2\Phi}{\Phi + \chi_{ij}^2}\right)$$

Closed form approximation of Switchable Constraints with a M-estimator

Dynamic Covariance Scaling



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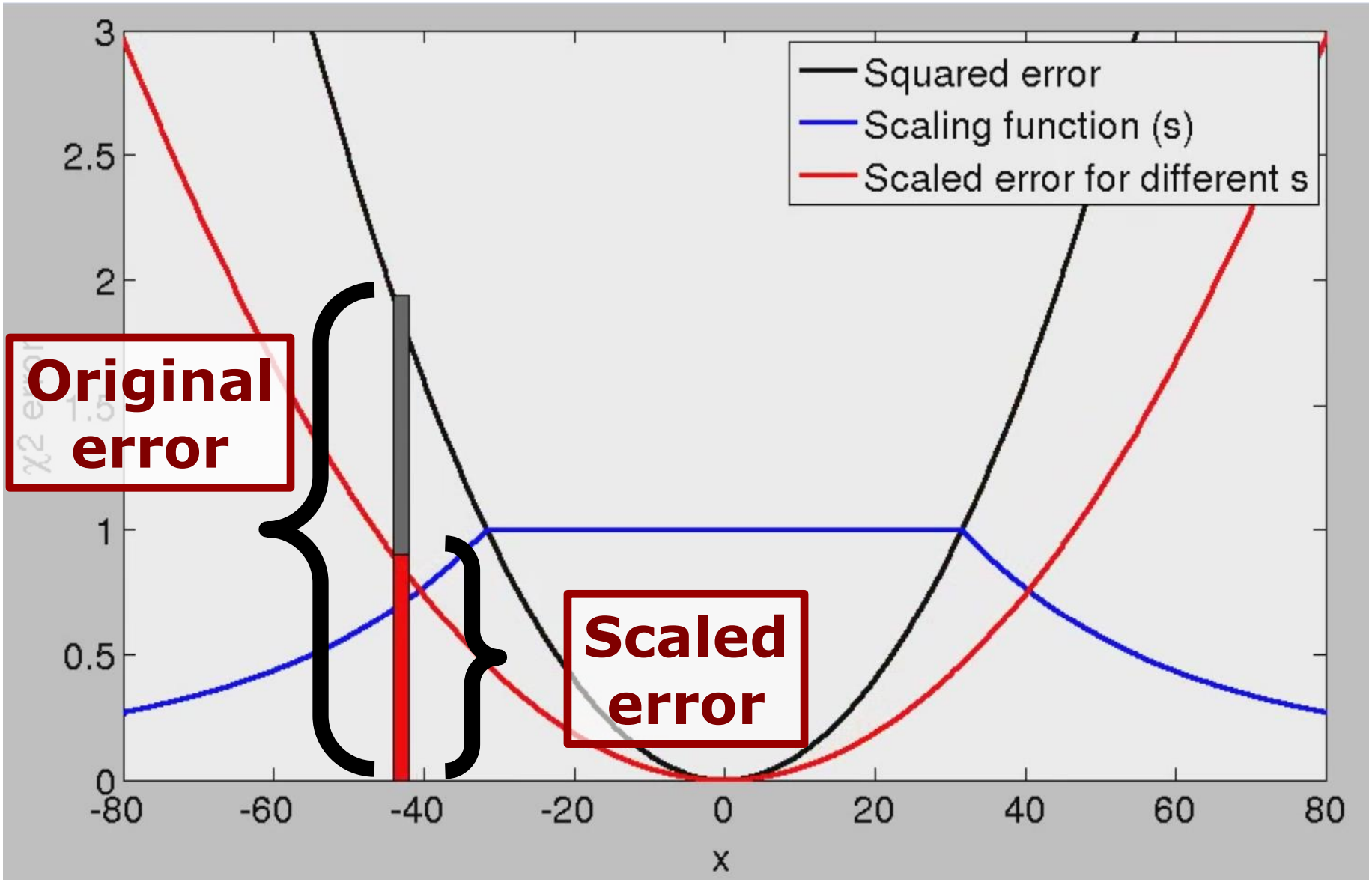
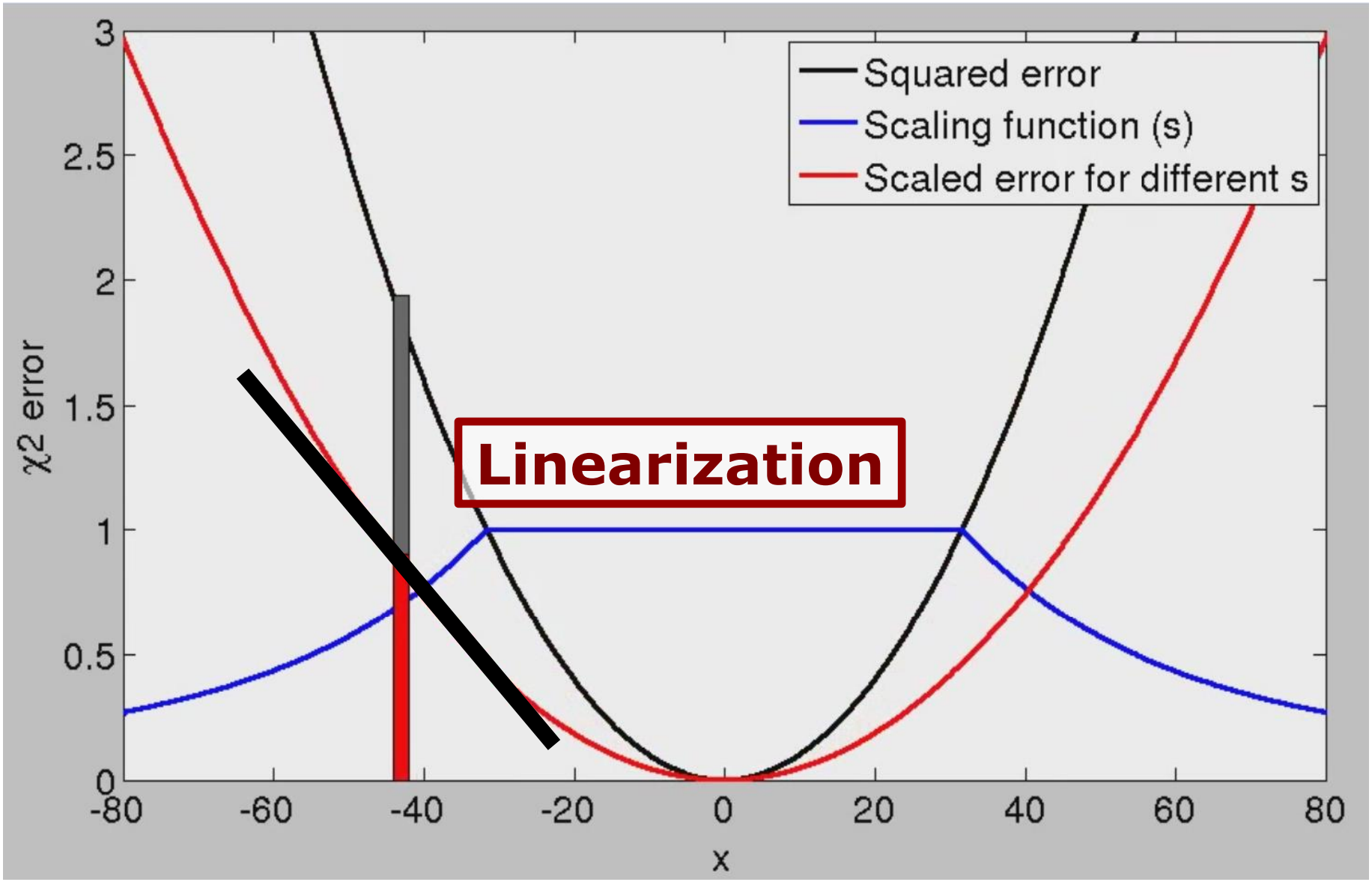
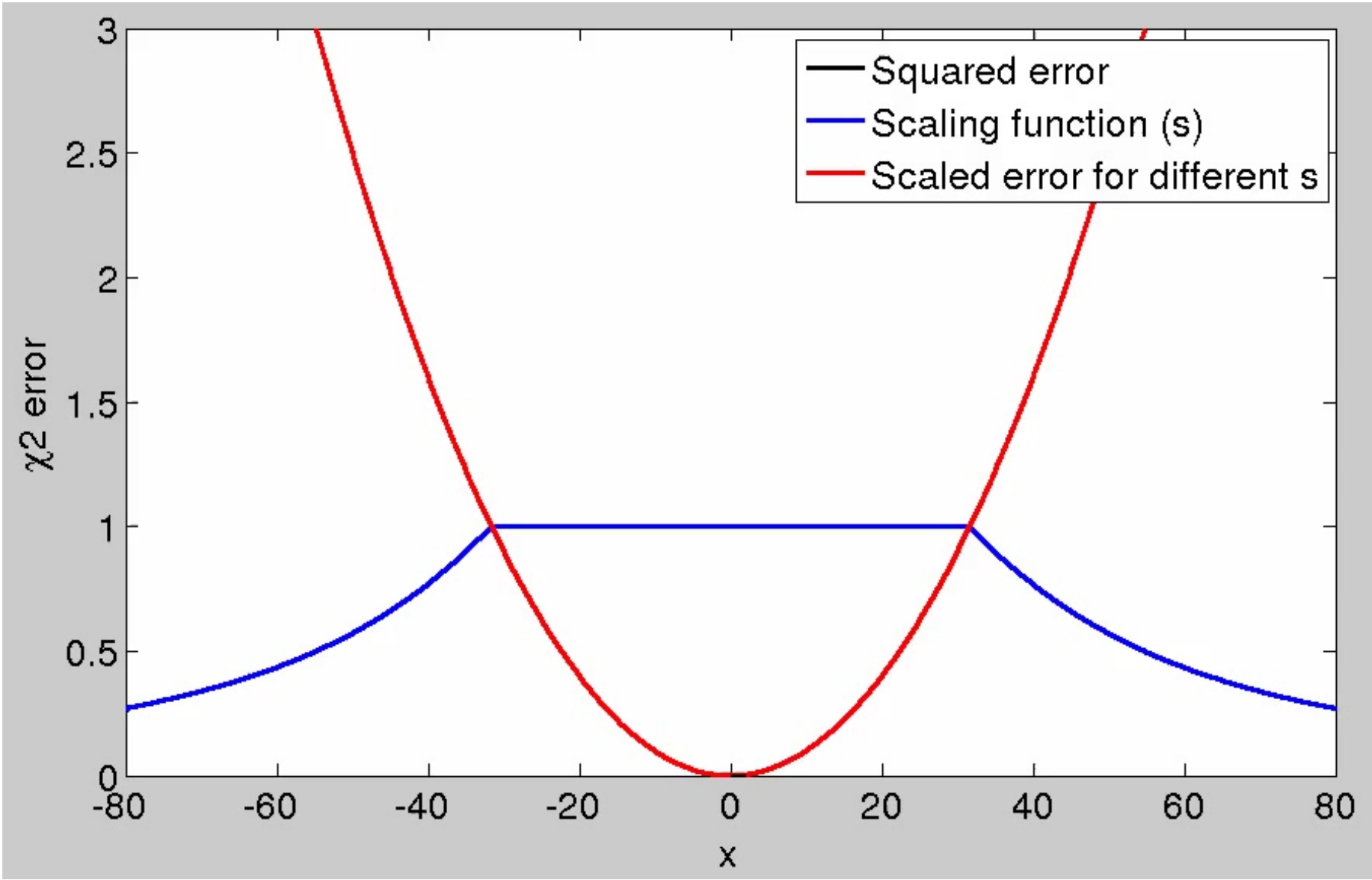


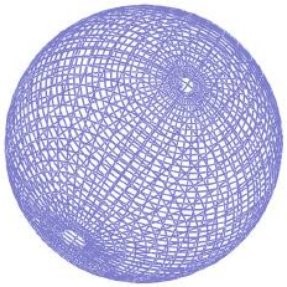
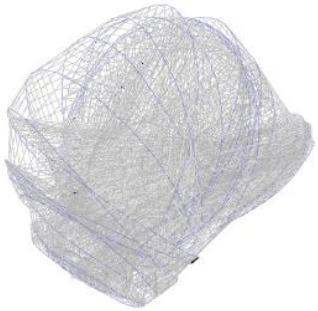
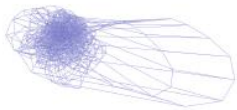
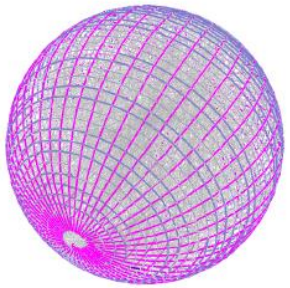
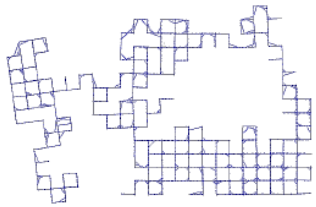
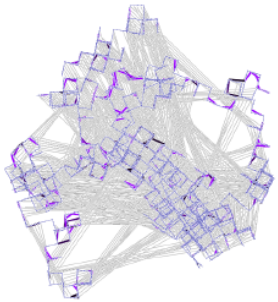
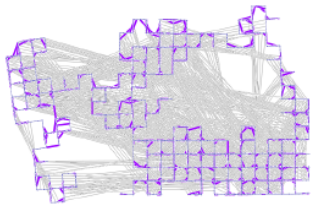
Dynamic Covariance Scaling



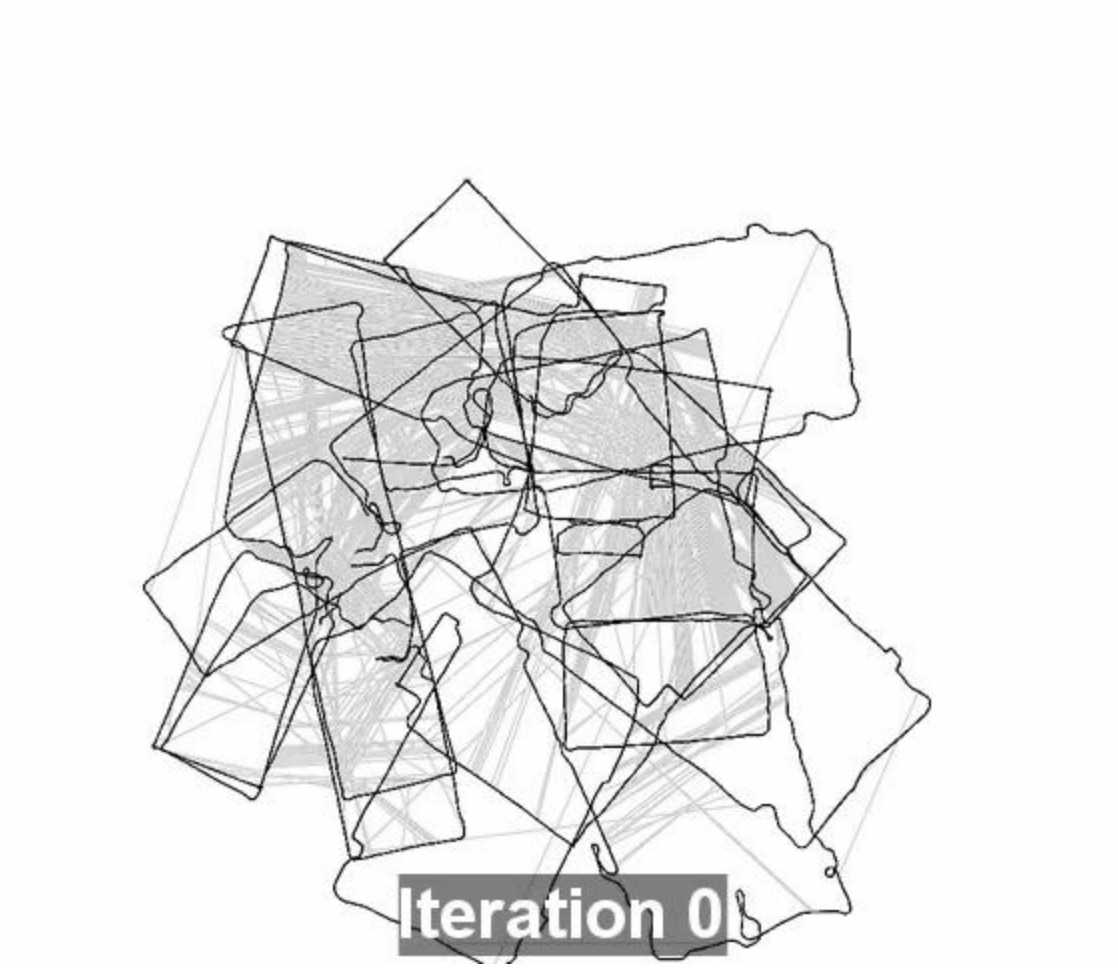
Dynamic Covariance Scaling

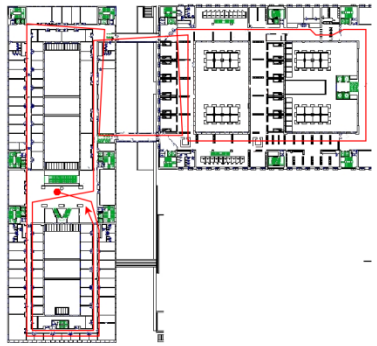


Robust SLAM with Our Method

	Ground Truth	Initialization	Gauss Newton	**Our Method**
Sphere2500 (1000 Outiers)				
Manhattan3500 (1000 Outiers)				

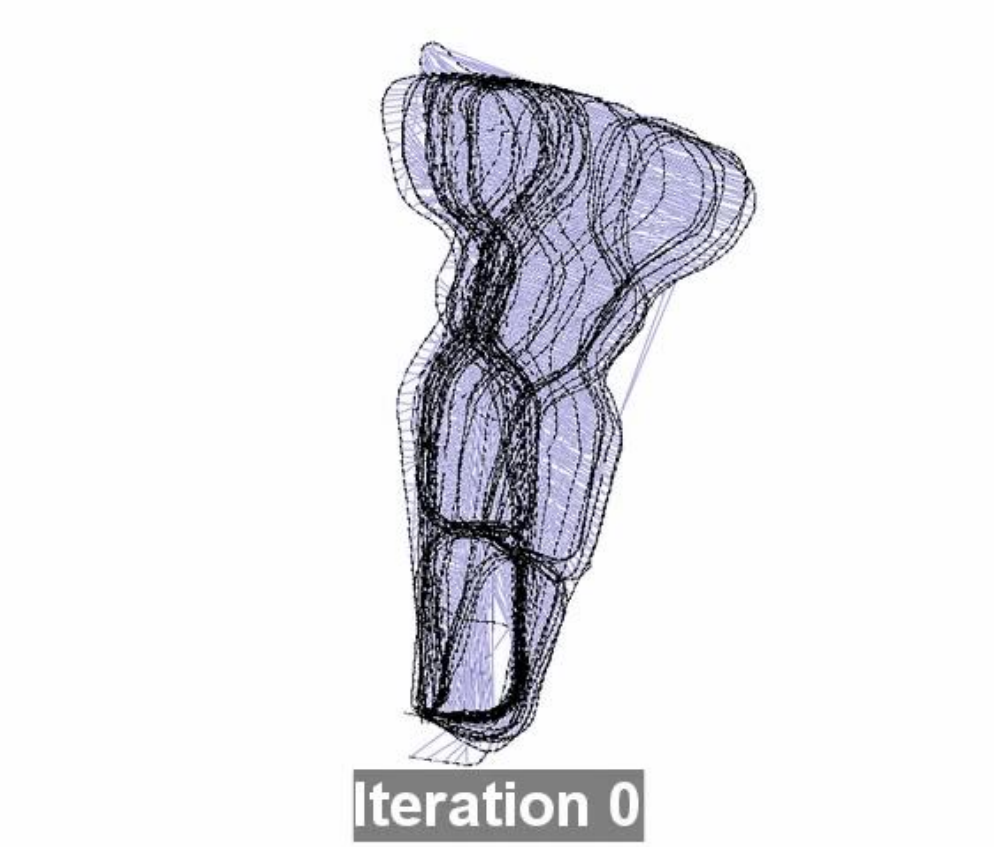
Dynamic Covariance Scaling with Front-end Outliers





Bicocca multisession dataset

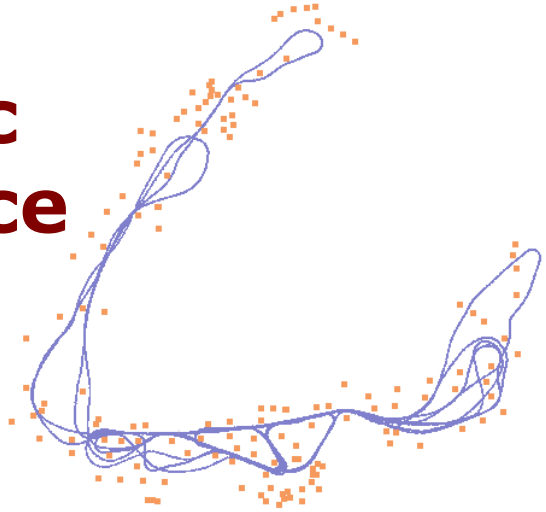
Dynamic Covariance Scaling with Front-end Outliers

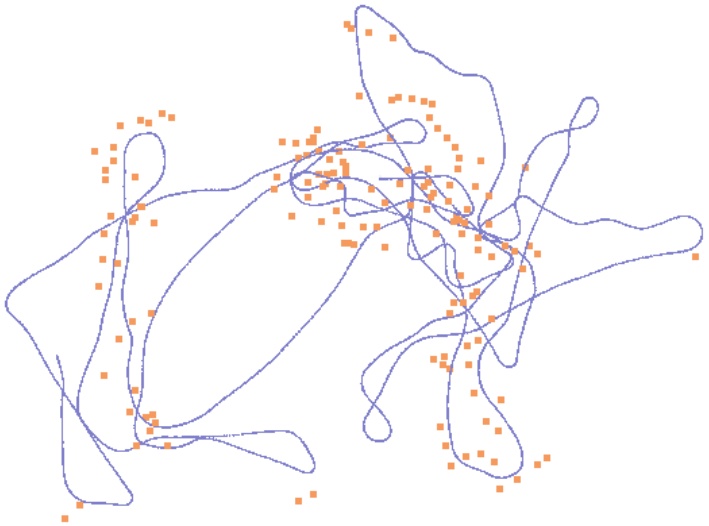


Lincoln-labs multisession dataset

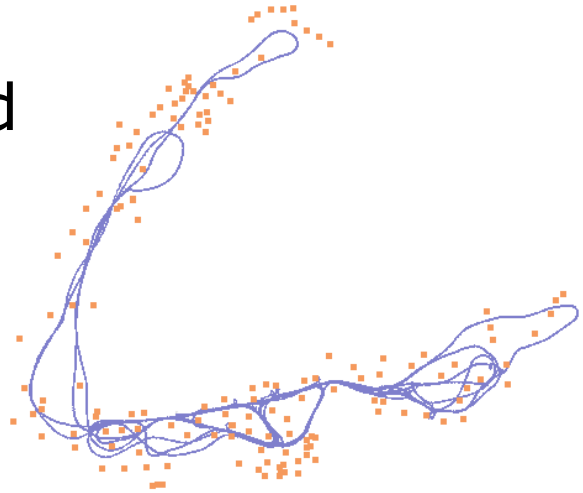
Robust SLAM with Our Method

Dynamic Covariance Scaling





Standard Gauss-Newton

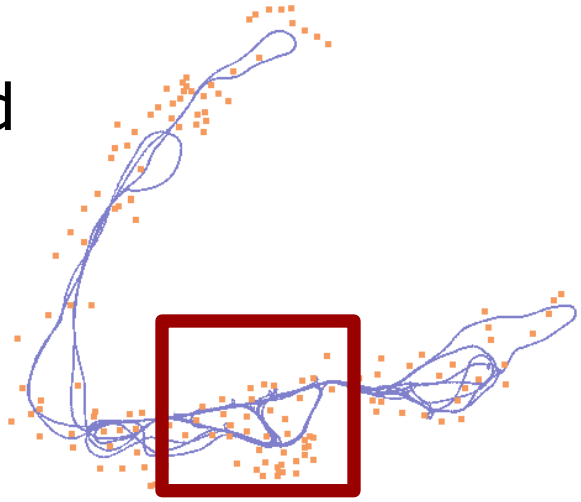


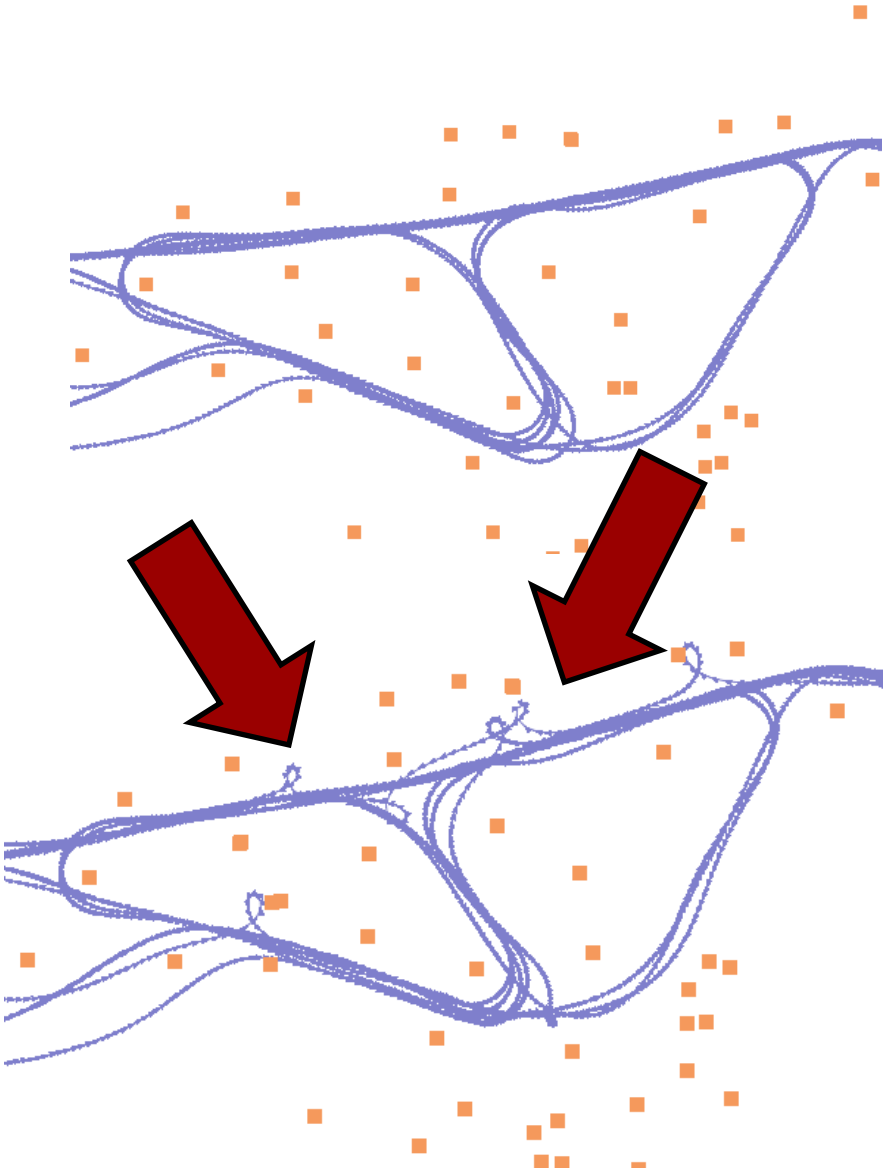
Victoria Park Initialization (Odometry)

Robust SLAM with Our Method

Dynamic Covariance Scaling

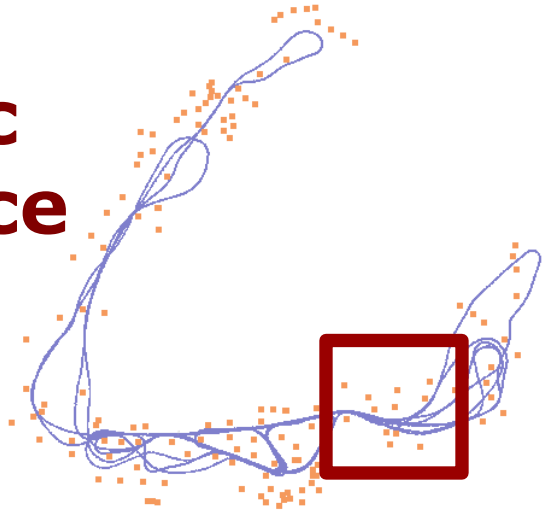
Standard Gauss-Newton

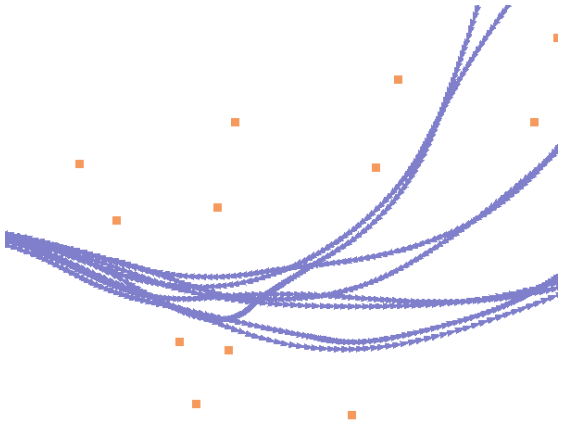




Robust SLAM with Our Method

Dynamic Covariance Scaling





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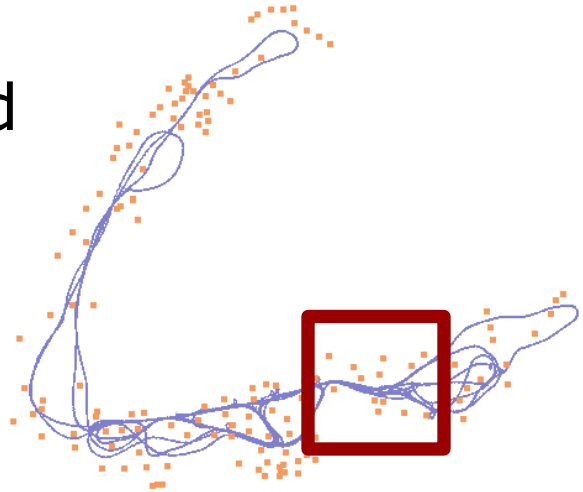
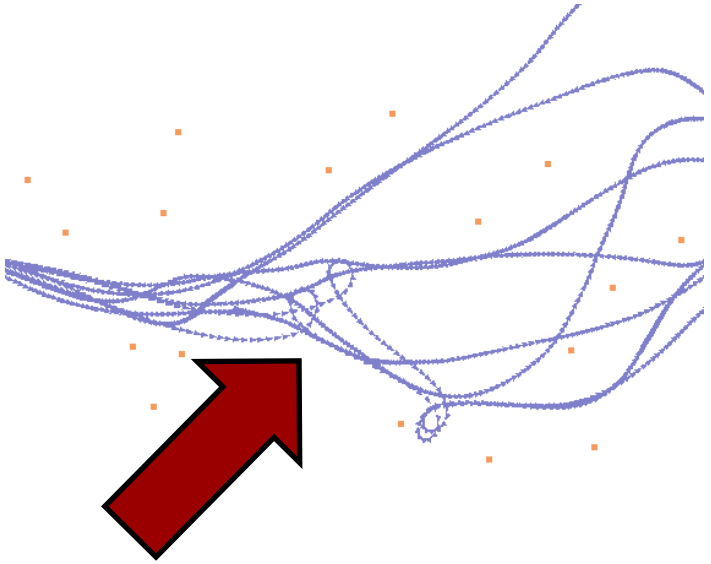
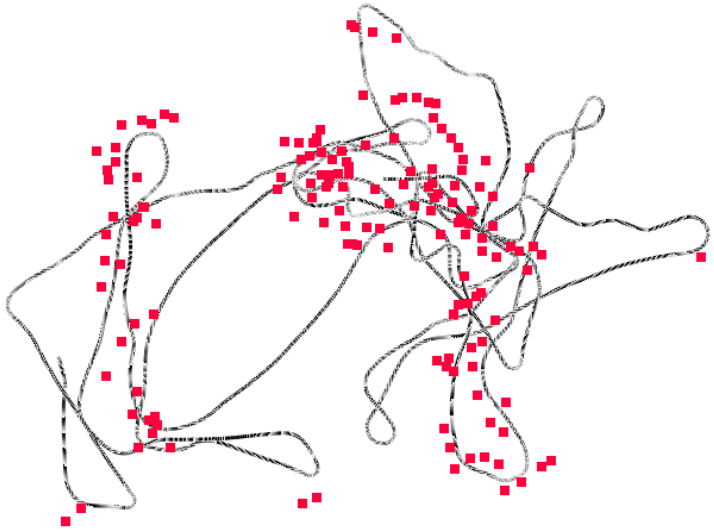
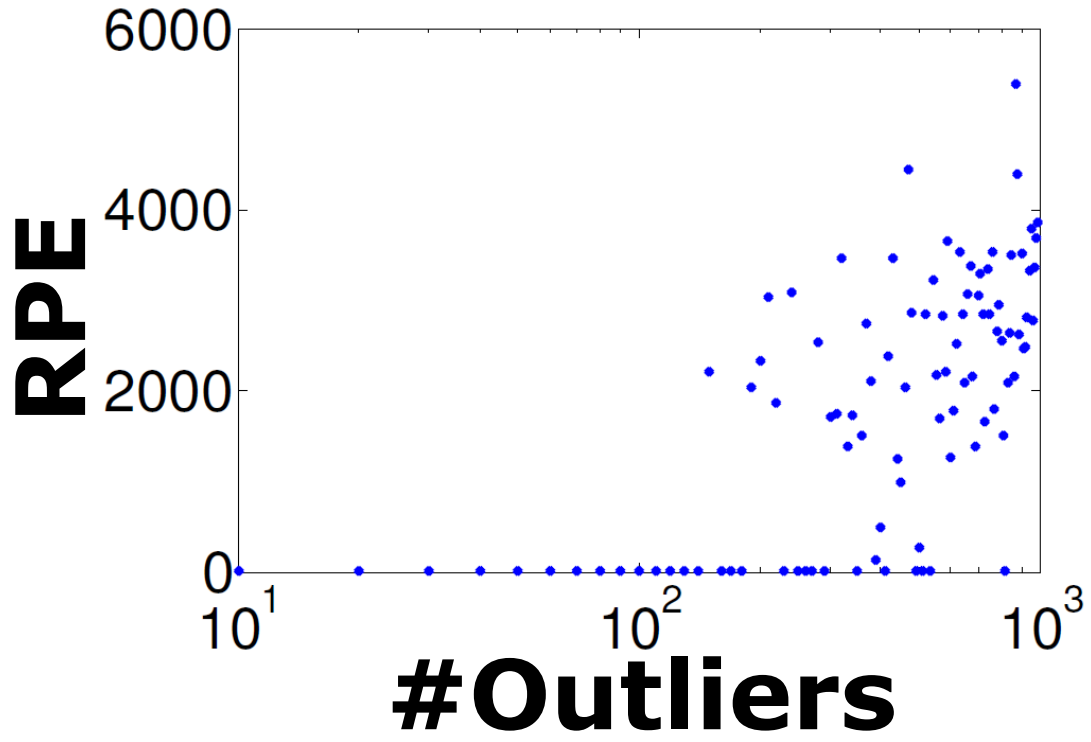




Dynamic Covariance Scaling with Outliers in Victoria Park

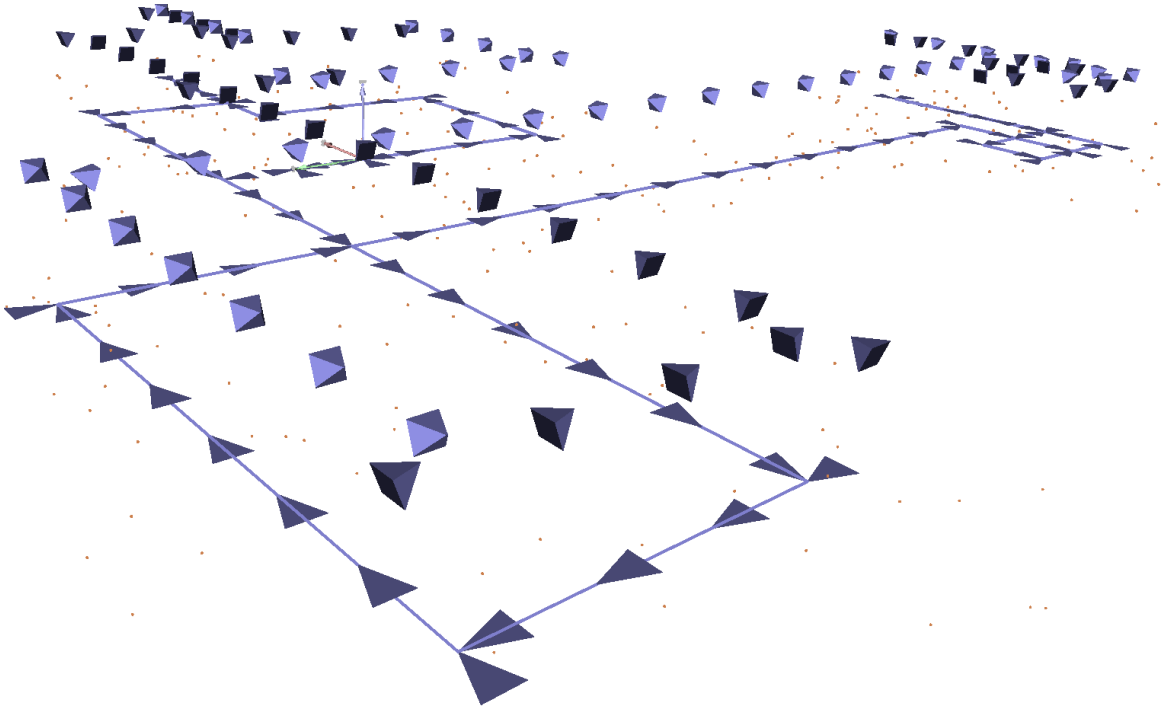




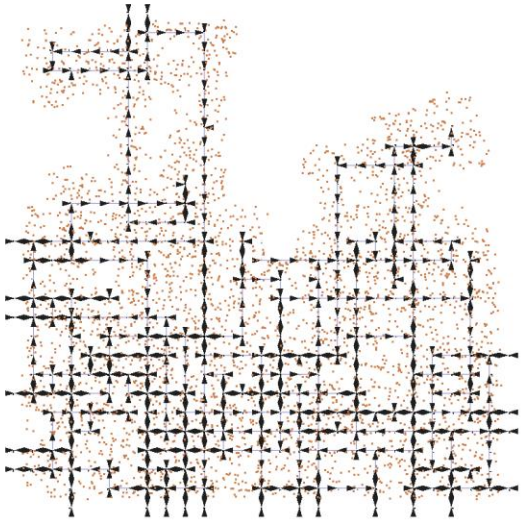
- DCS recovers correct solution
- GN fails to converge to the correct solution even for **outlier-free case**

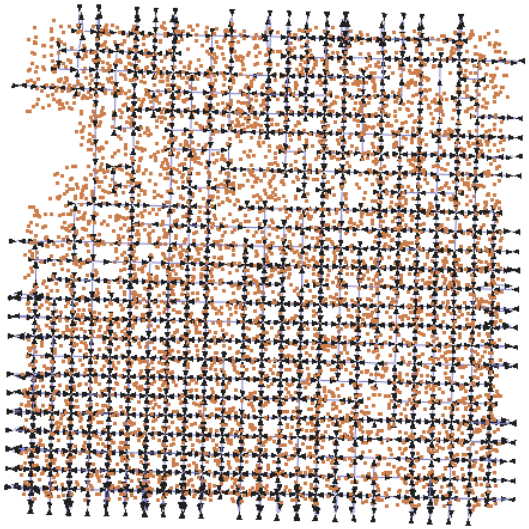
Robust Visual SLAM with Our Method

- 3D grid worlds of different sizes
- Robot perceives point landmarks



Robust Visual SLAM with Our Method





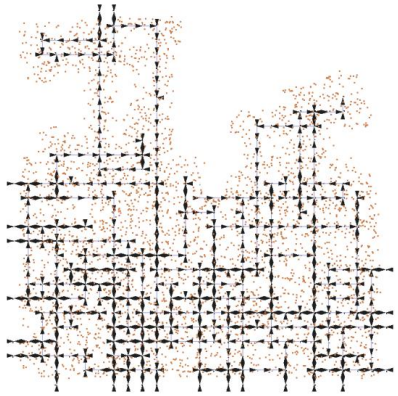
- ~1000 camera poses
- ~4000 features
- ~20K constraints

- ~5000 camera poses
- ~5000 features
- ~100K constraints

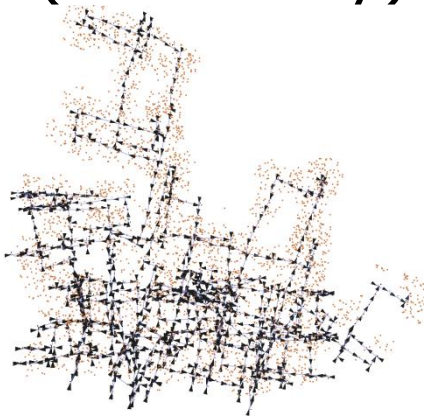
Robust Visual SLAM with DCS

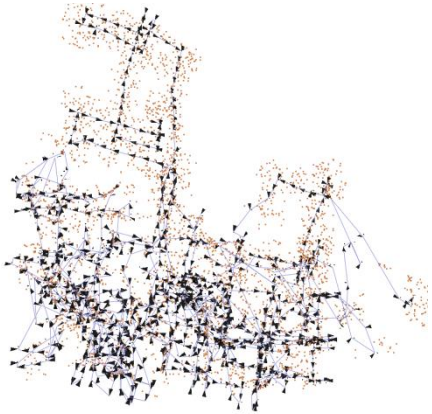
Simulated Stereo
(Bad initial guess)

Ground
Truth



Initialization
(Odometry)





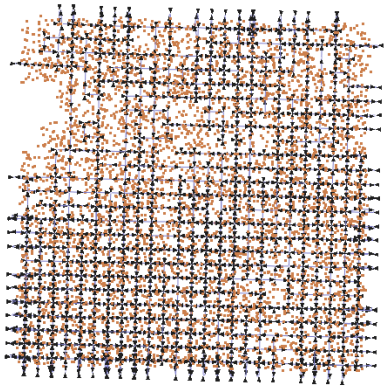
Levenberg-Marquardt
(100 iterations)

Our Method
(15 iterations)

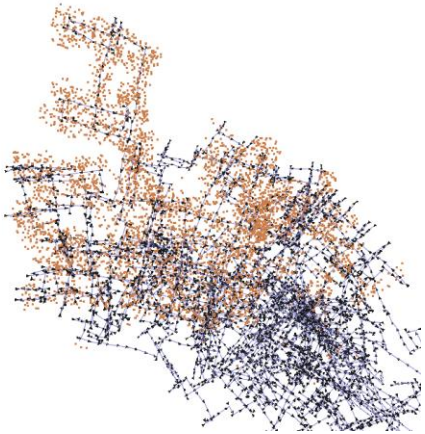
Robust Visual SLAM with DCS

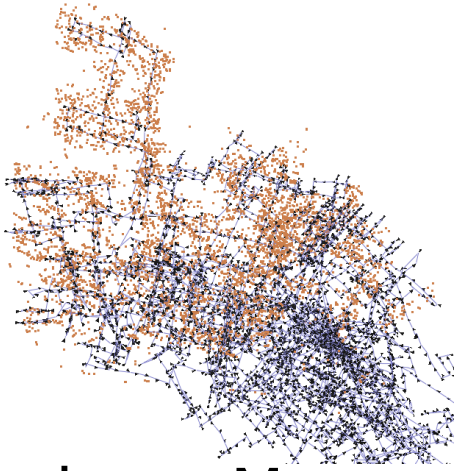
Simulated Stereo
(Bad initial guess)

Ground
Truth

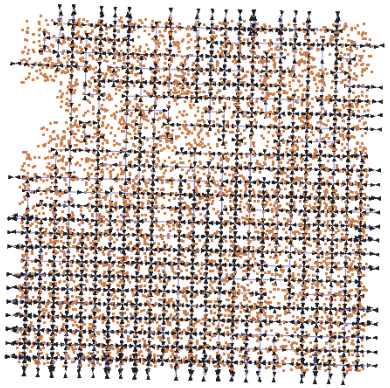


Initialization
(Odometry)



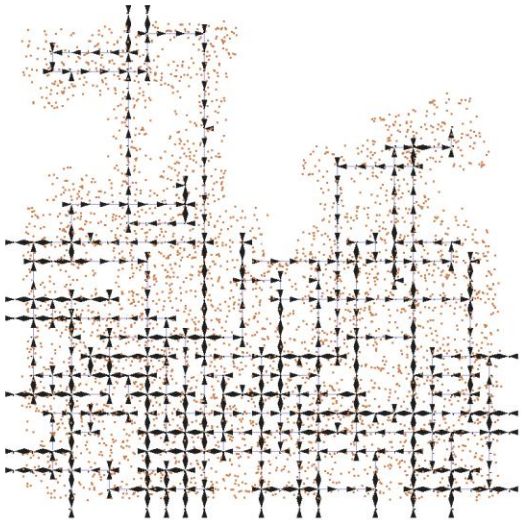


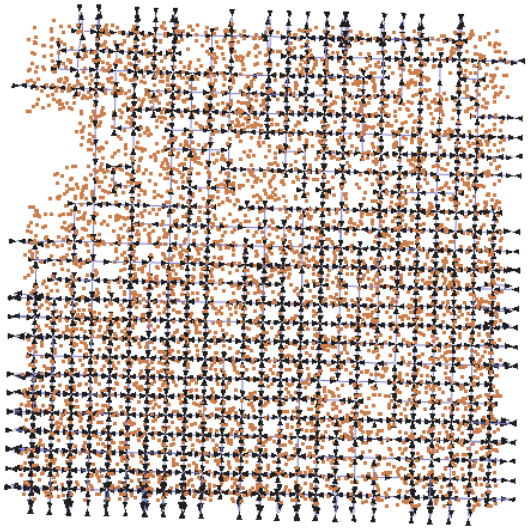
Levenberg-Marquardt
(150 iterations)



Our Method
(15 iterations)

Robust Visual SLAM with DCS





- DCS recovers correct solution in the presence of up to **25% outliers**
- LM fails to converge to the correct solution even for **outlier-free cases**

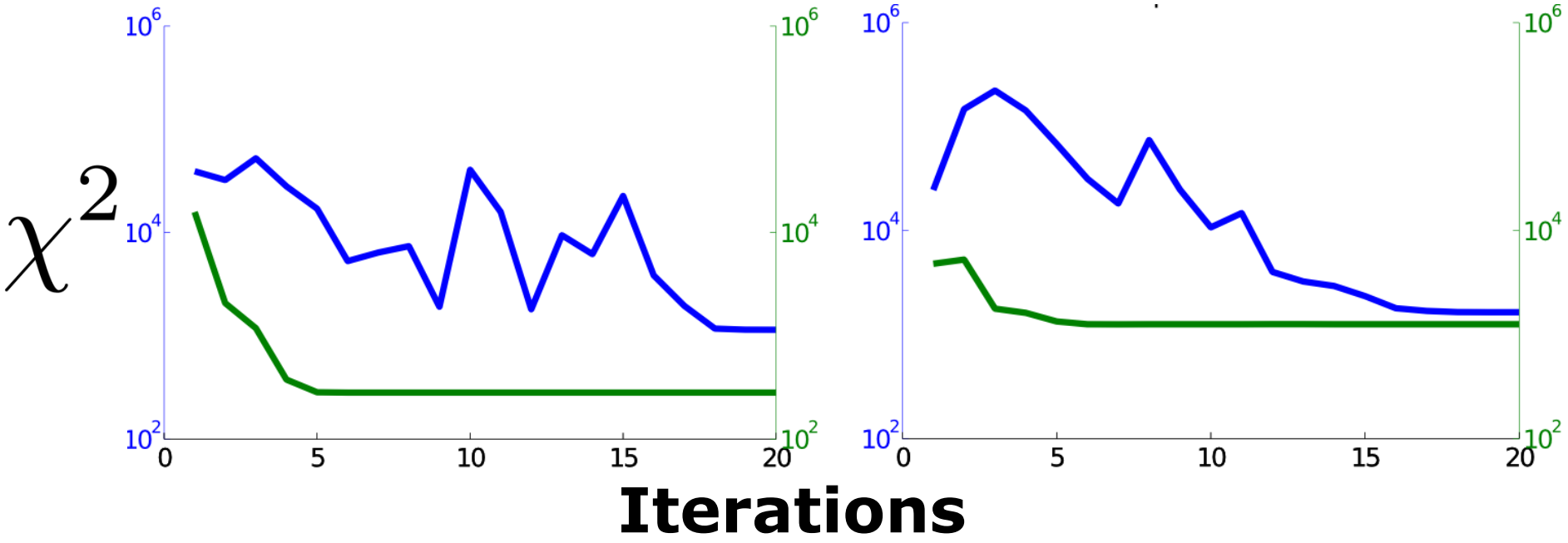
Convergence – 1000 Outliers

Switchable Constraints

Dynamic Covariance Scaling

Manhattan3500

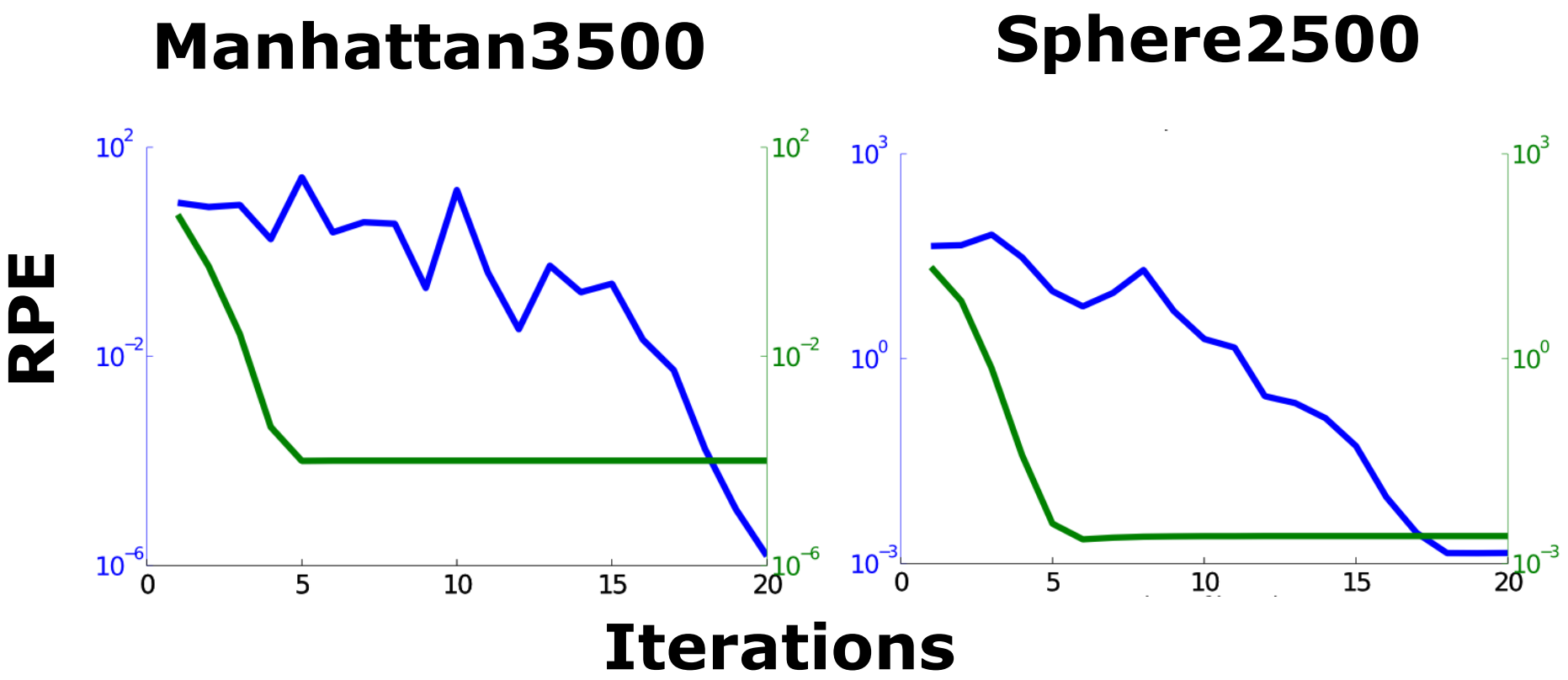
Sphere2500



Convergence – 1000 Outliers

Switchable Constraints

Dynamic Covariance Scaling

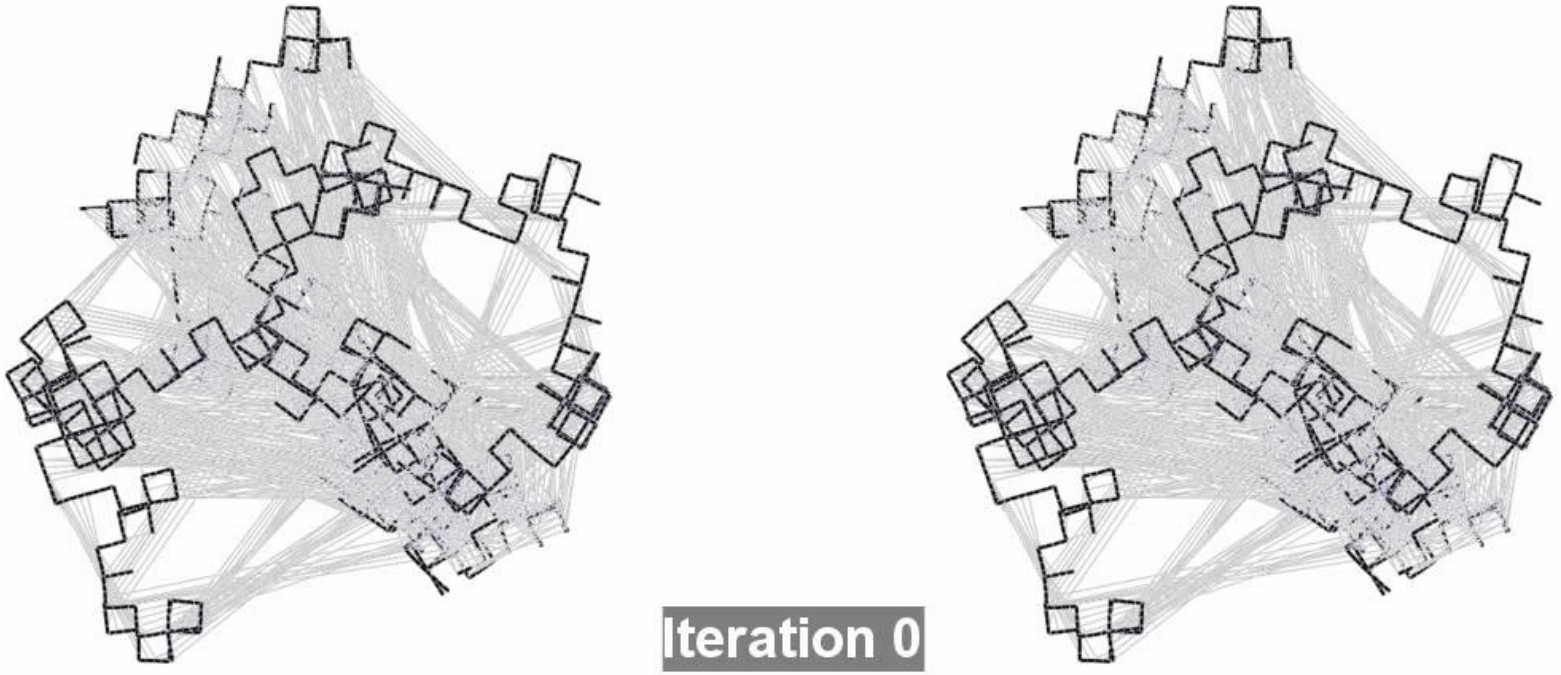


Convergence with Outliers

Switchable Constraints

Dynamic Covariance Scaling

Switchable Constraints (SC) ManhattanOlson Dynamic Covariance Scaling (DCS)



Conclusion

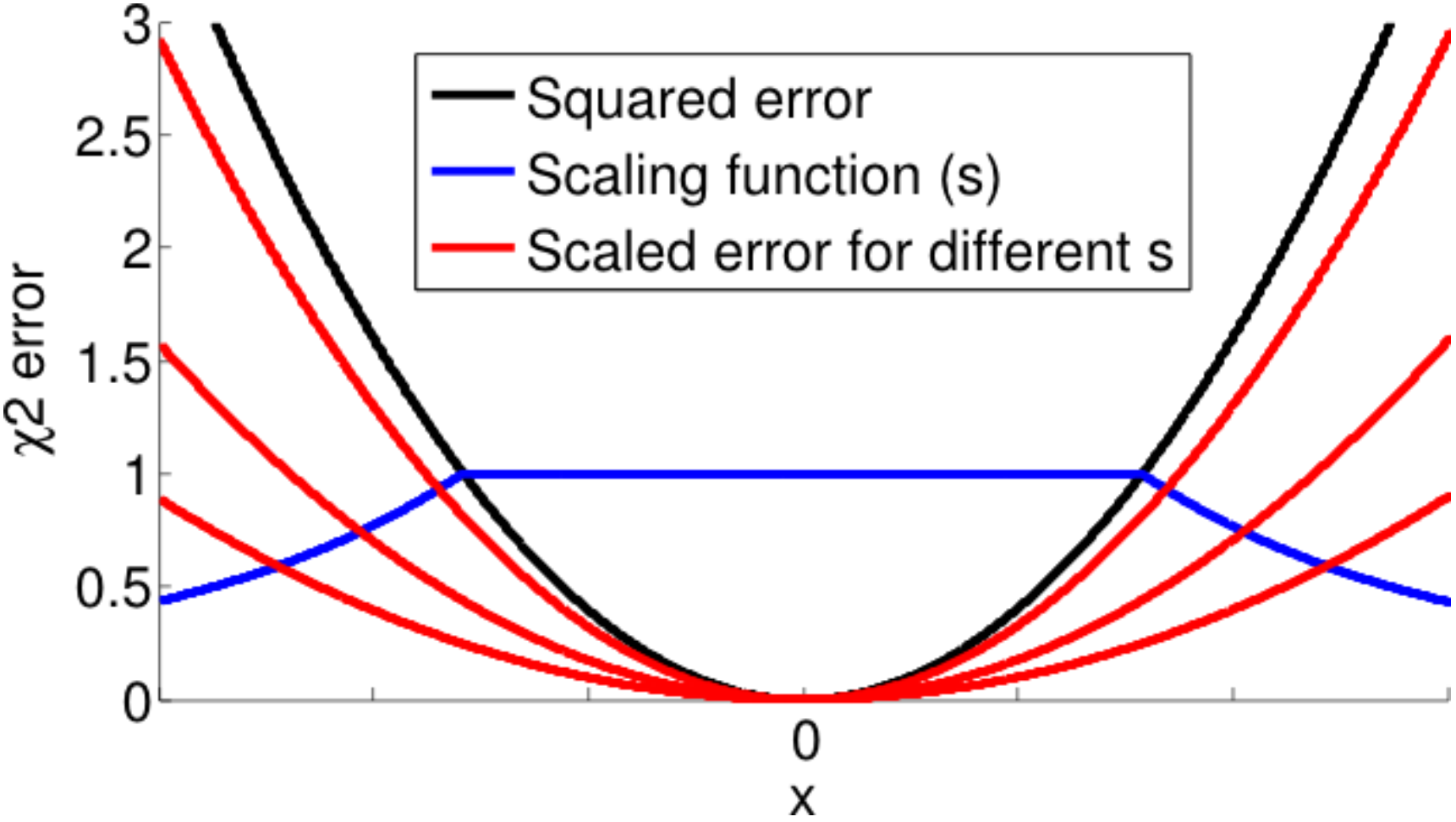
- **Rejects outliers** for 2D & 3D SLAM
- **No increase in computational complexity**
- More robust to **bad initial guess**
- Now **integrated in g2o**

Thank you for your attention!

Open Discussion:

- Best way to compare?
  - Keep outliers/null hypothesis for DCS, SC, MM?
- Standard for outlier datasets
  - Real, simulated
- Online or batch?
- Initialization
  - Odometry
  - Minimum Spanning Tree

Questions?


Squared error
Scaling function (s)
Scaled error for different s
χ2 error
3
2.5
2
1.5
1
0.5
0
0
x