Towards Task-aware Trajectory Optimisation for Satellite Inspection via Differentiable Simulation

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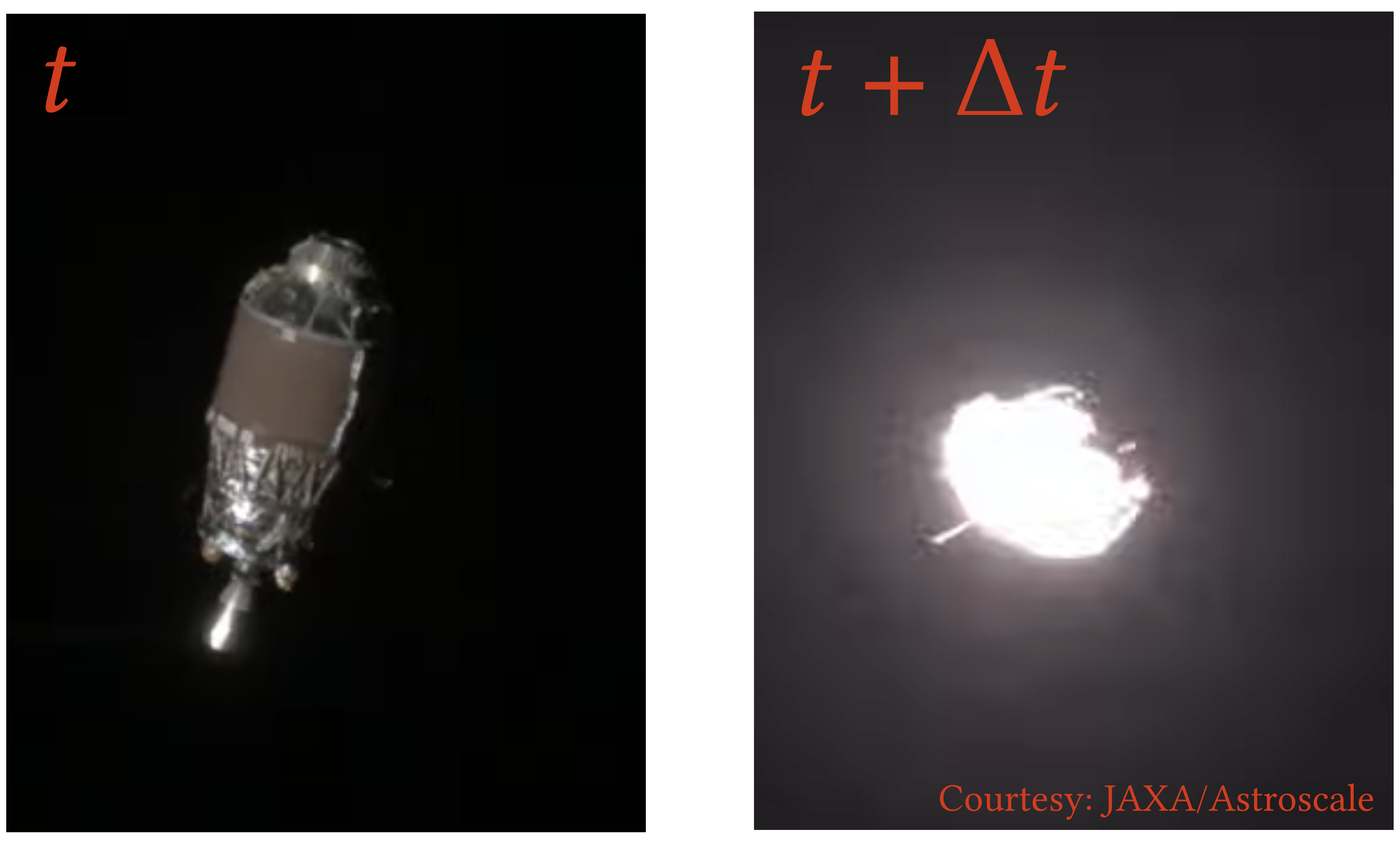
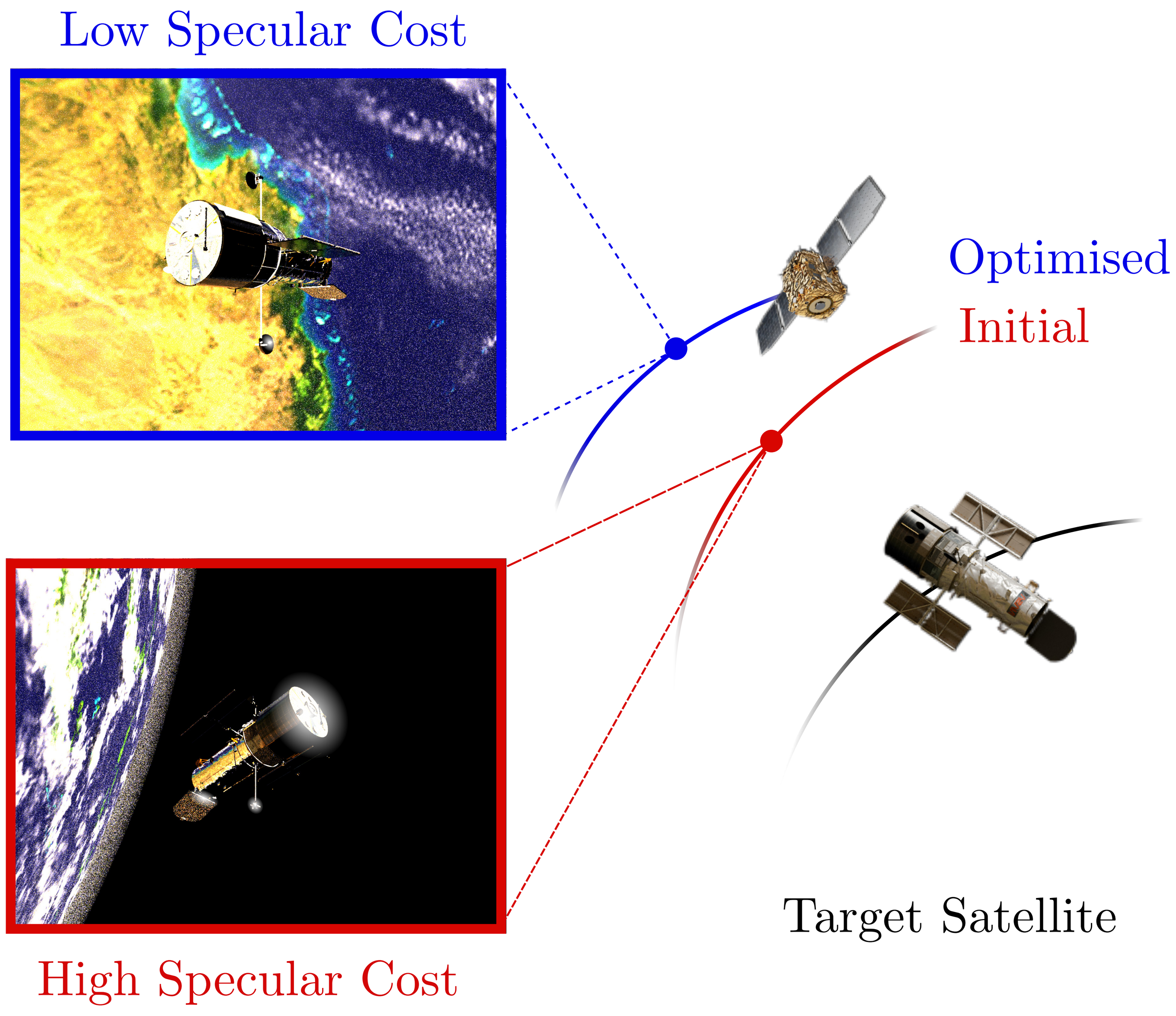
Motivation & Contributions

- On-orbit inspection is subject to challenging illumination conditions, e.g. high dynamic range, variable distances

- Reflections from the sun can saturate the sensor, substantially reducing information available to downstream tasks



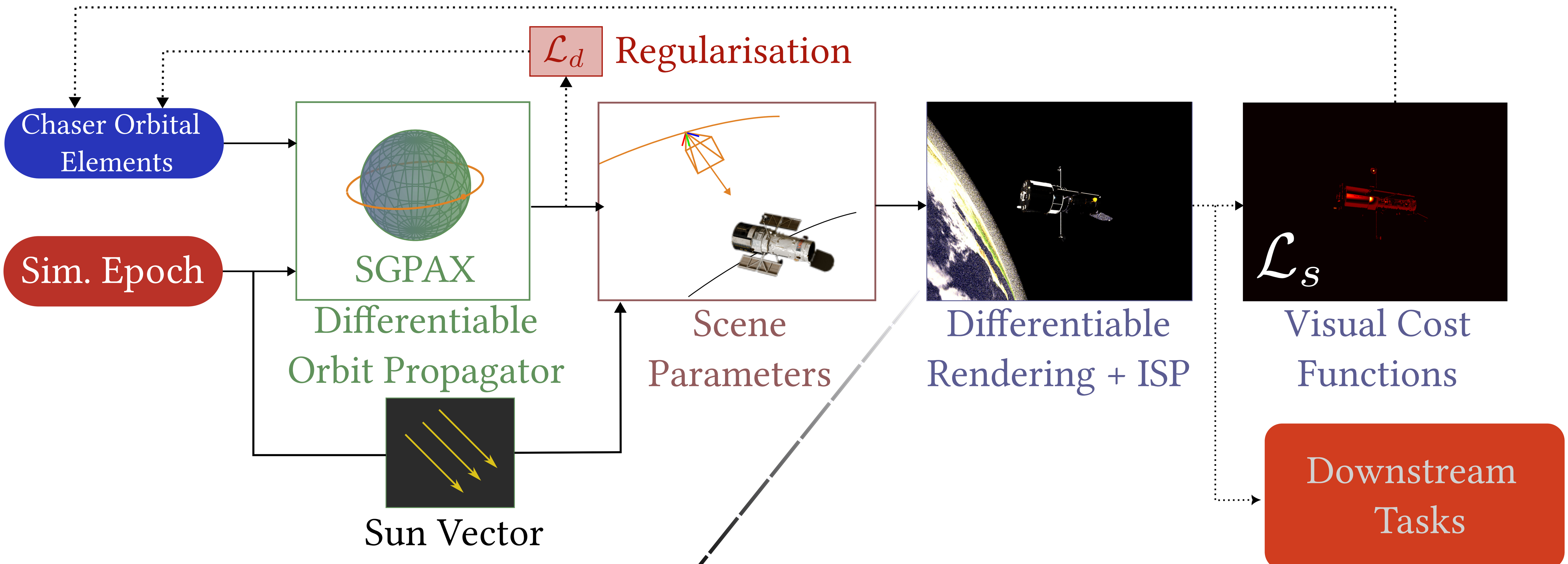


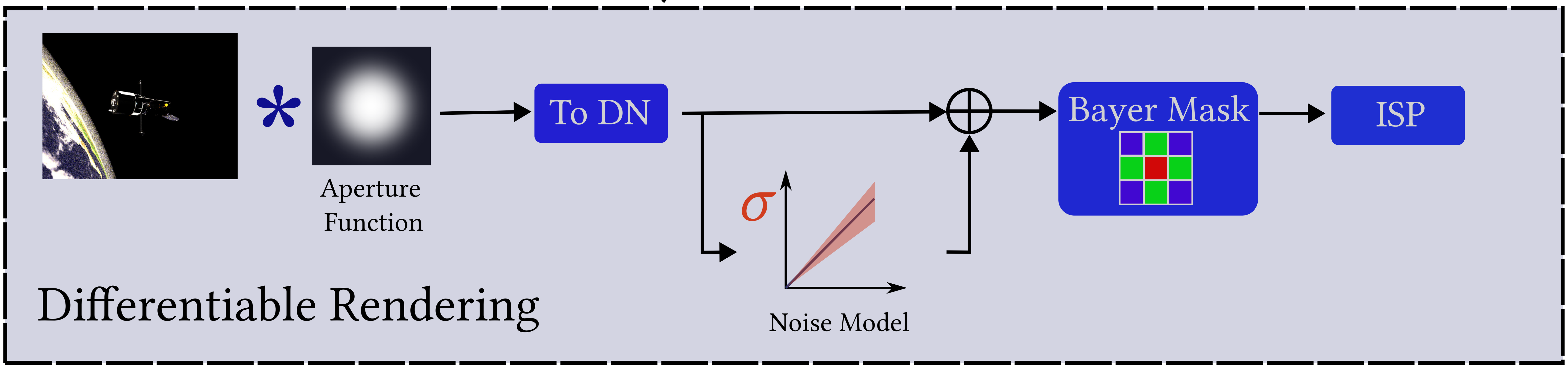
- Optimising for trajectories that are appearance-aware can avoid visually challenging conditions in observations

- Optimising alongside downstream tasks (e.g. localisation, pose estimation) can yield informative new task-specific capabilities for proximity operations

Methodology

- Formulate costs in the image frame or at scene level
- Flexible to sensing modality e.g. noise models, blur, camera models & types including infrared and polarisation





- Customisable blur kernels (incl. depth dependent) and image processing

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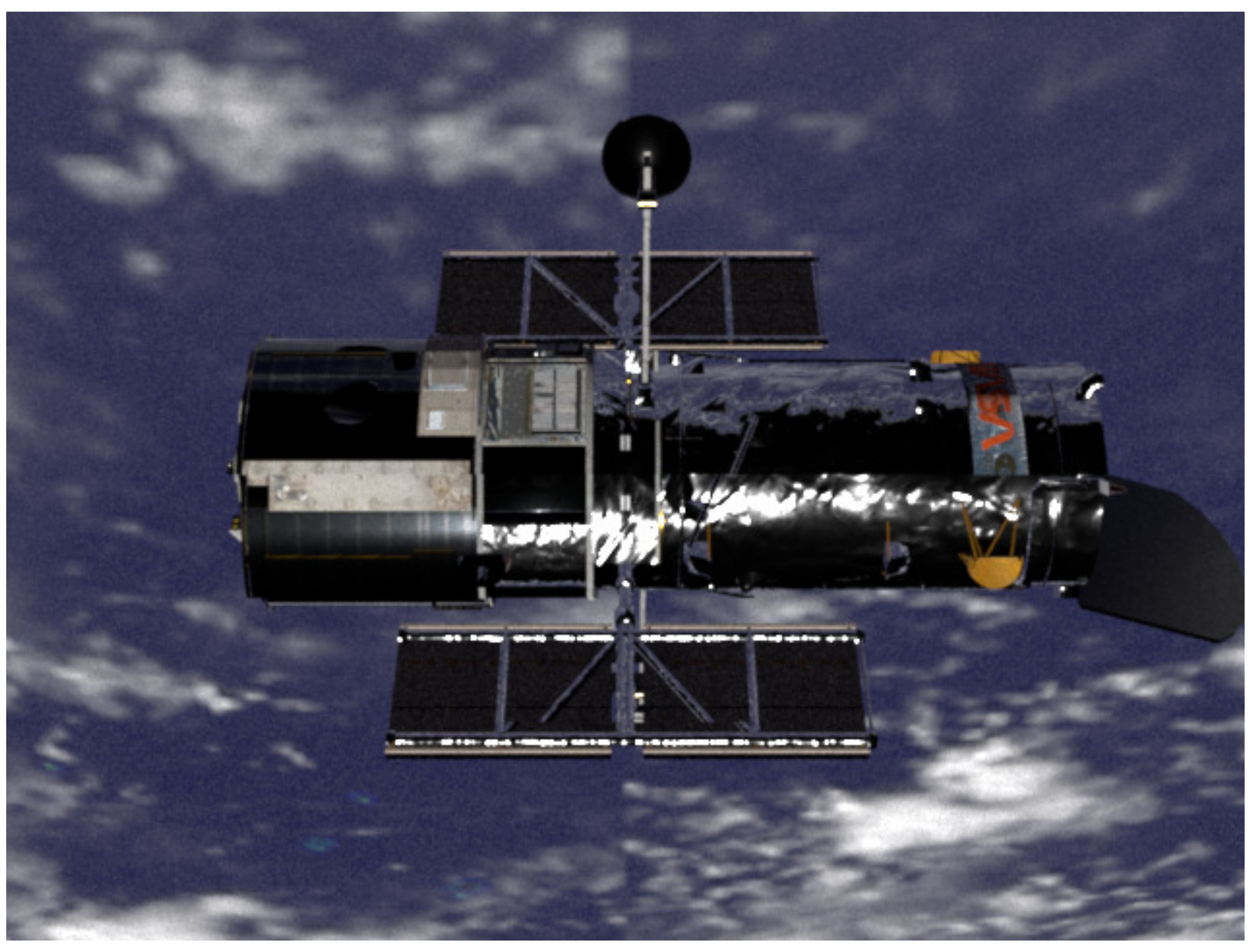
Results

- Photorealistic synthetic data that is end-to-end differentiable and customisable to different 3D models

- Customisable attitude dynamics, on top of differentiable SGP4

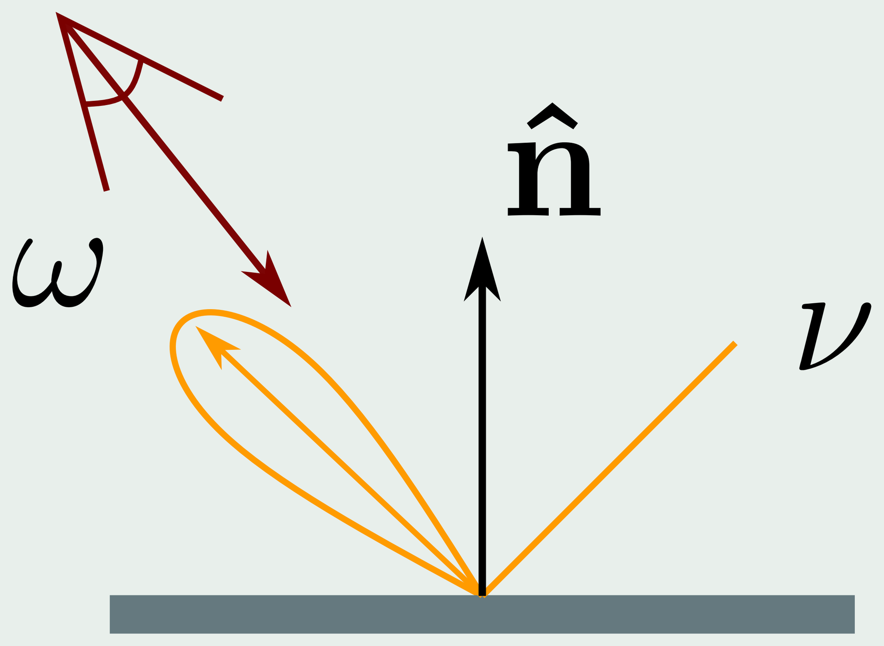


Appearance-aware Optimisation

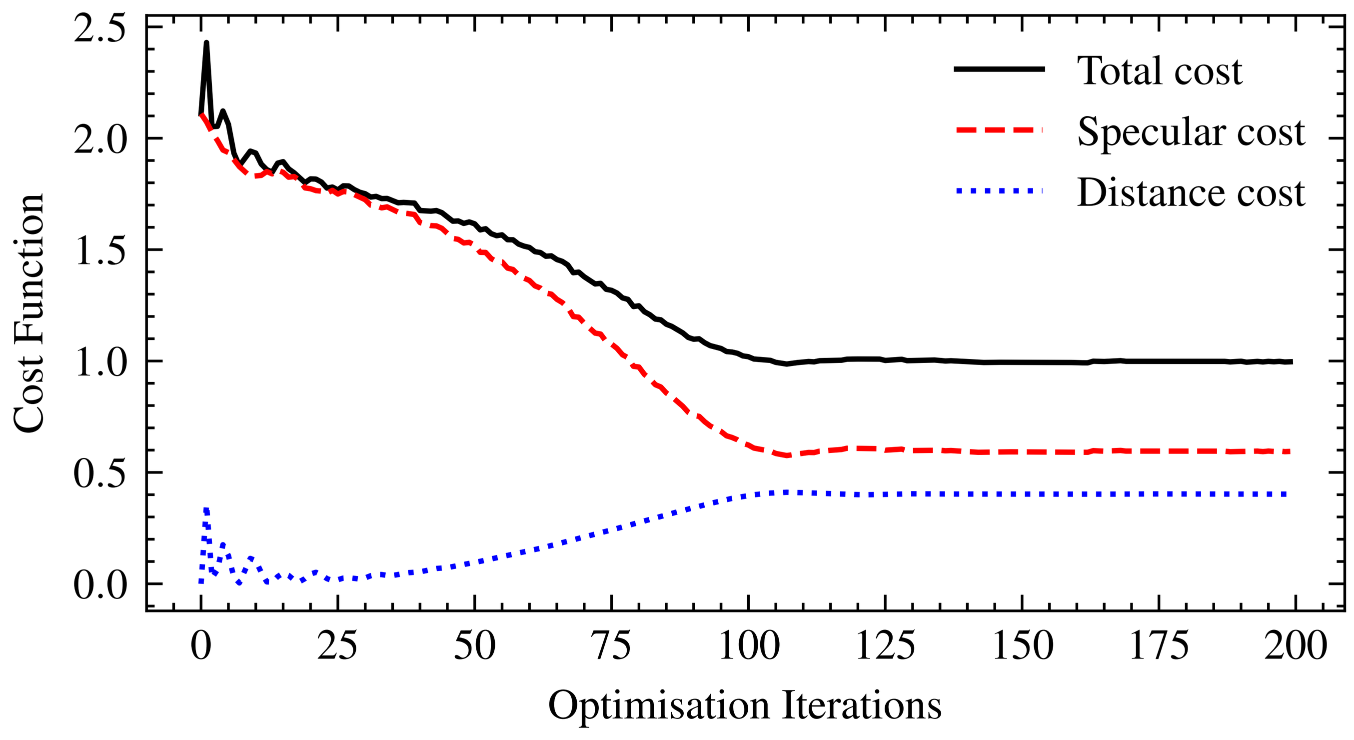
- Apply physics-based cost function to minimise reflection

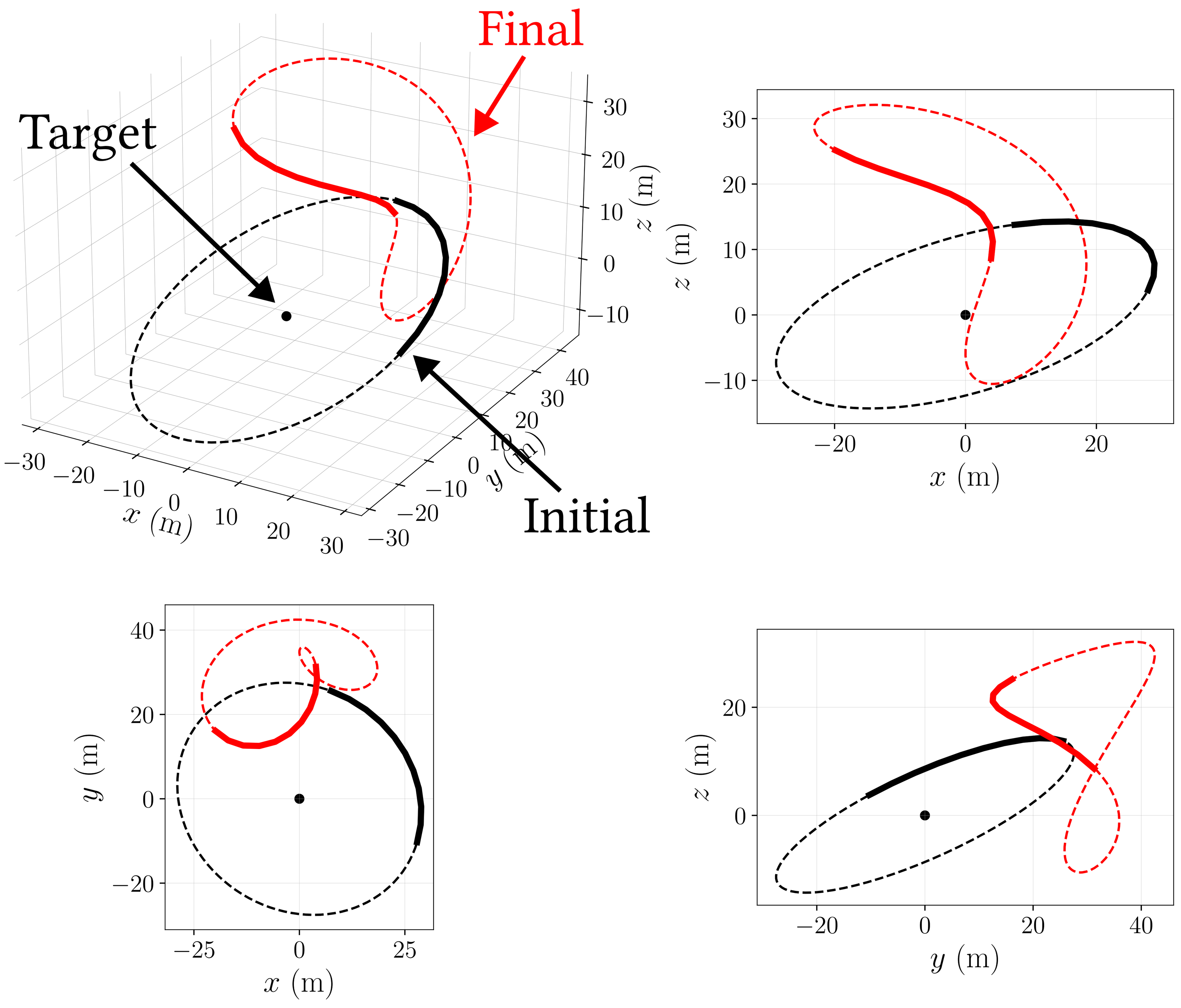
$$\omega_r = 2(\nu \cdot \hat{\mathbf{n}})\hat{\mathbf{n}} - \nu$$

$$\mathcal{L}_s = \frac{\sum_{i,j} M_{i,j} \max(0, \omega_r \cdot \omega)^\alpha}{\sum_{i,j} M_{i,j}}$$

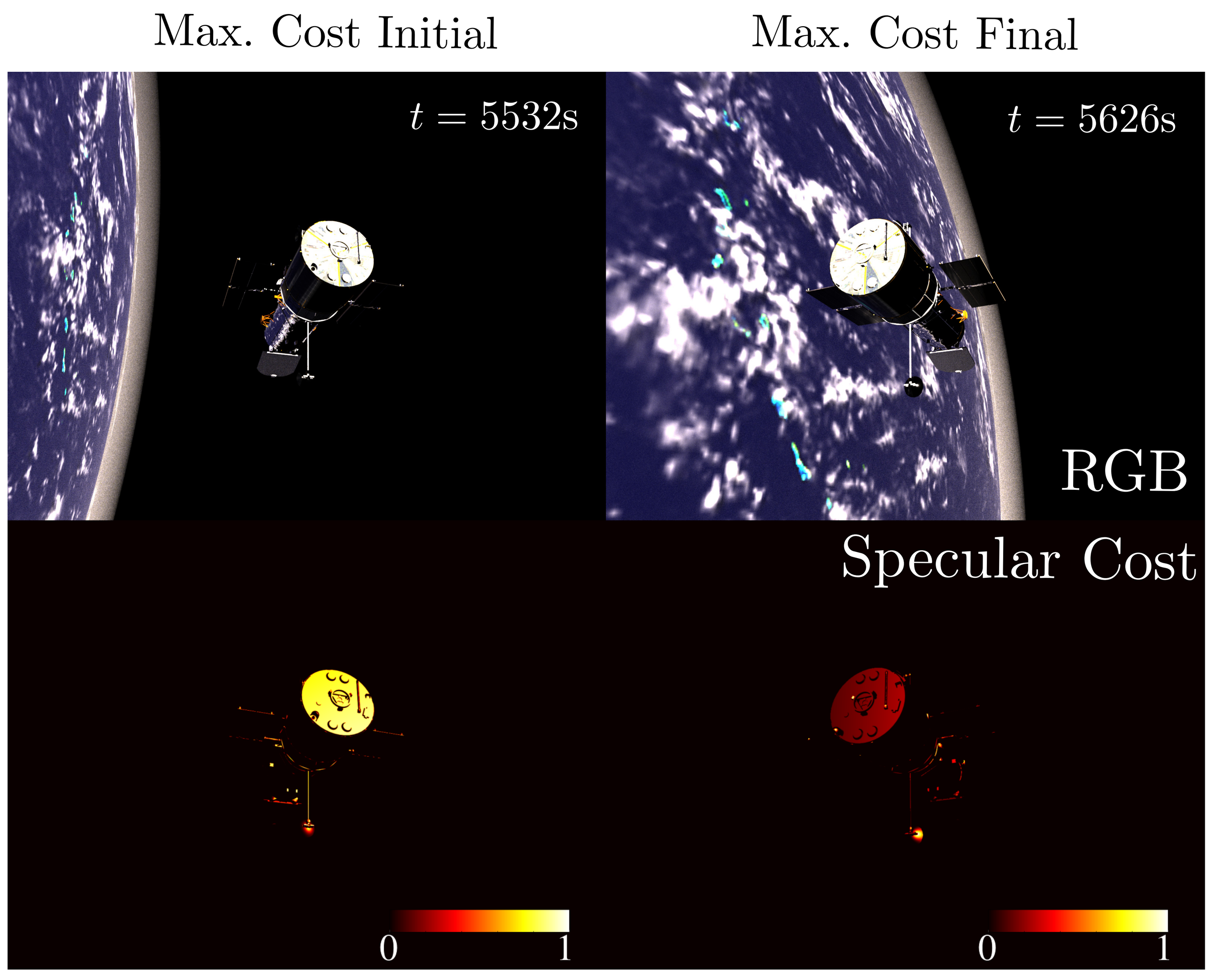


ν Sun Zenith Angle
ω View Angle
$\hat{\mathbf{n}}$ Surface Normal





Satellite	Approach	$d = 30$m Sat. % ↓	$d = 30$m MR↑	$d = 150$m Sat. % ↓	$d = 150$m MR↑
HST	Initial	26.0	0.759	30.8	0.716
	∂LITE (Ours)	**20.5**	**0.861**	**12.5**	**0.732**
Sentinel-6	Initial	1.20	0.583	1.69	**0.95**
	∂LITE (Ours)	**0.04**	**0.632**	**1.07**	†0.235
CloudSat	Initial	5.76	0.614	**5.52**	0.934
	∂LITE (Ours)	**2.72**	**0.801**	*5.61	**0.974**



- Achieve appearance-aware trajectories that are non-obvious and substantially improve imaging quality

- Not passively stable, but cheap to correct (small deviation from initialisation)

- Guaranteed local minima that are robust to initialisation

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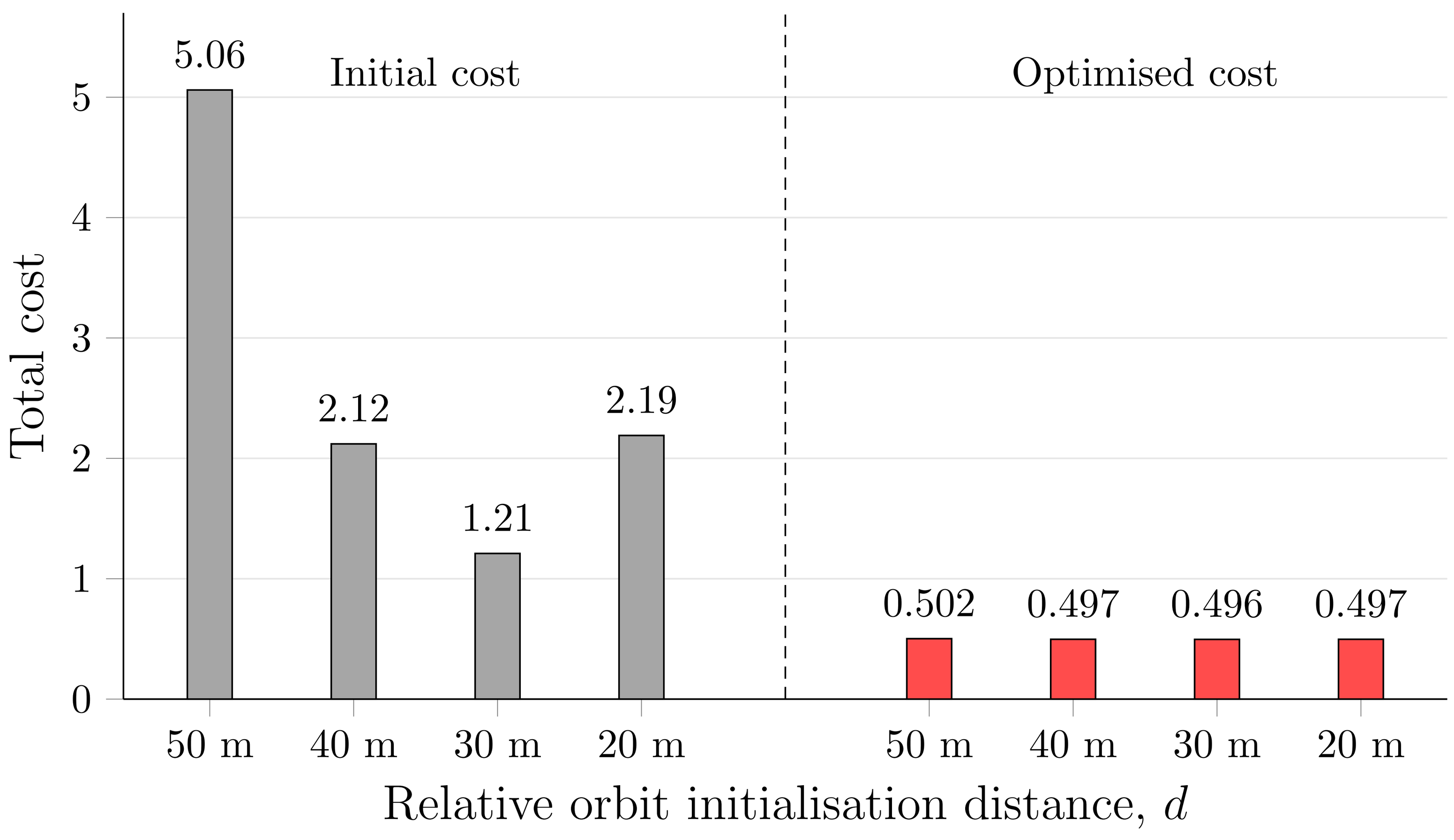
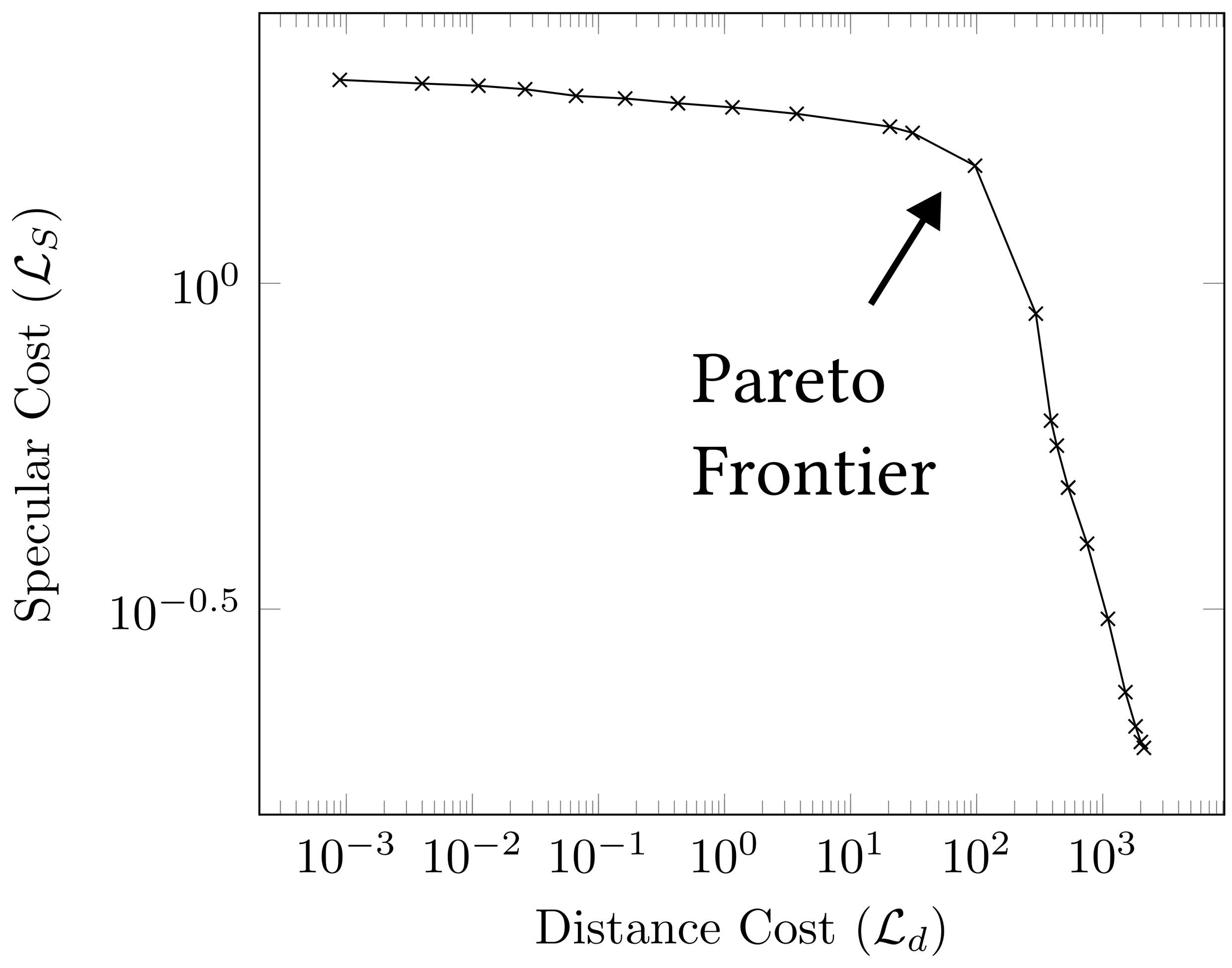
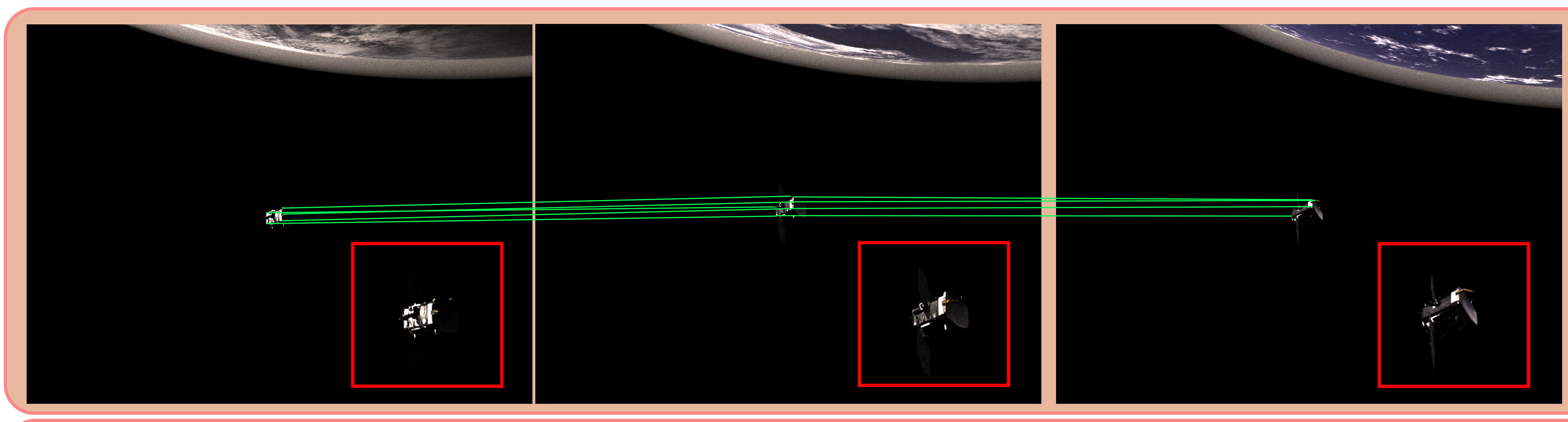
Sensitivity Analysis



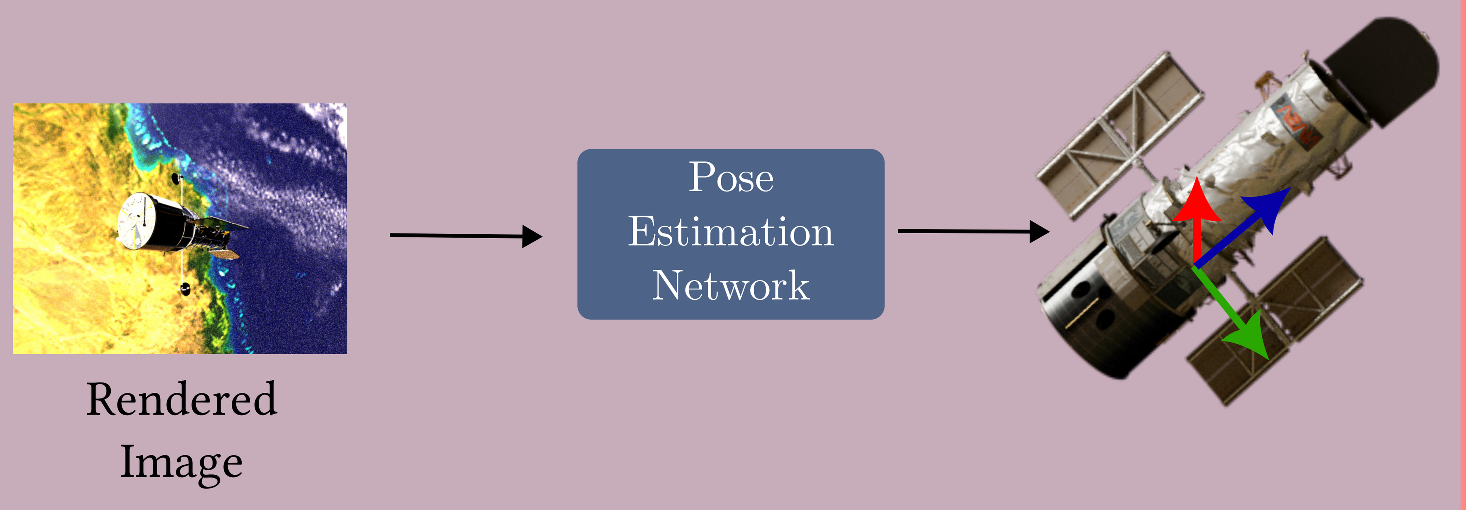


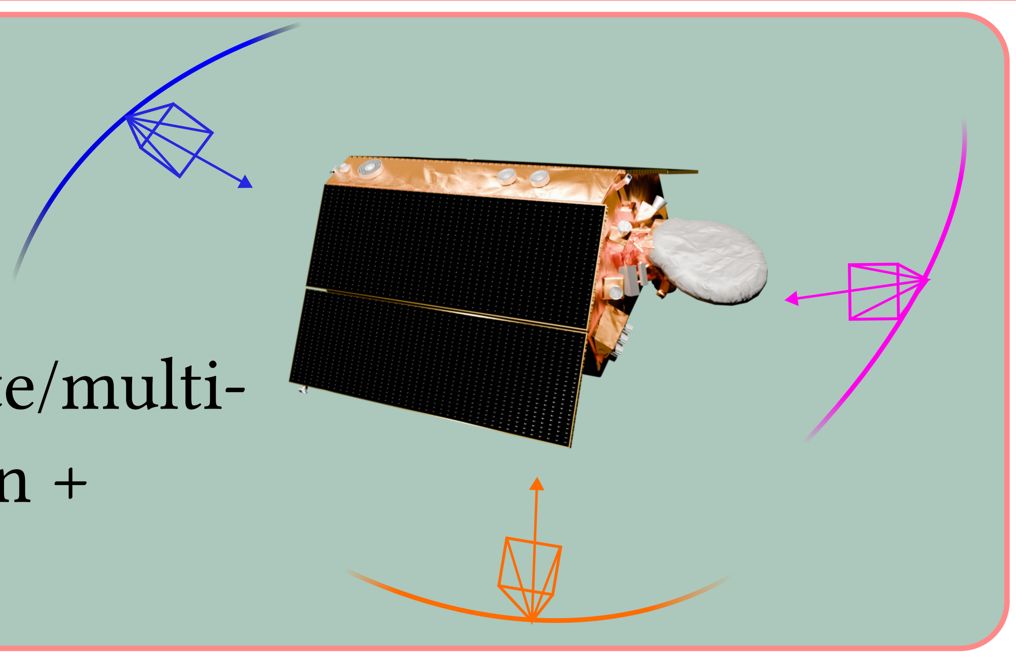
Task Specific Capabilities



- Localisation
- Relative navigation
- 3D Reconstruction

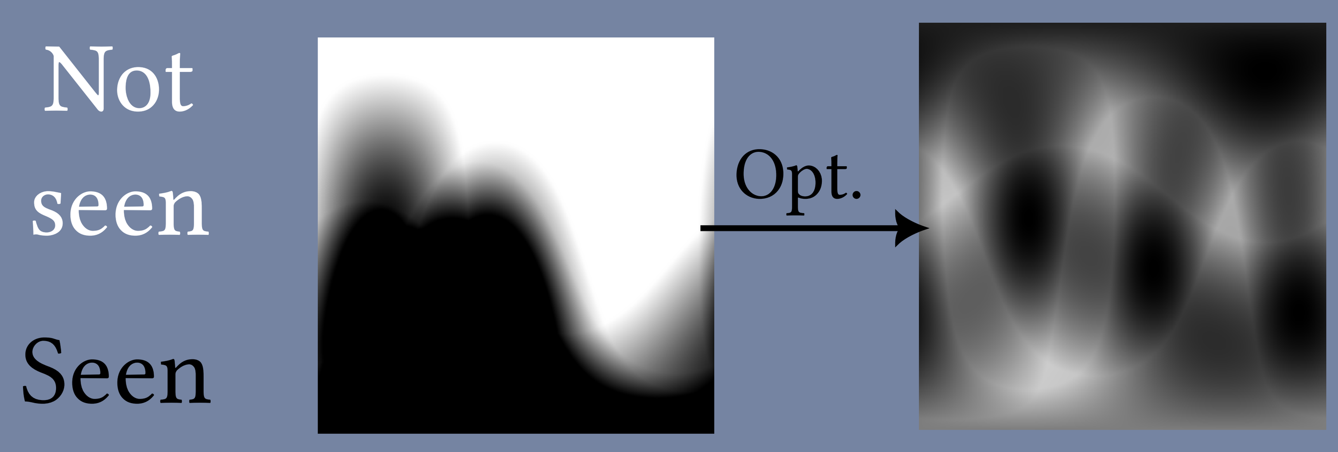
- Fine-tune networks under image processing, varying lighting and materials (e.g. pose determination)
- Benchmark other sensor measurements + reconstruction algorithms (e.g. polarisation)





- Multi-satellite/multi-pass inspection + teaming

- Optimising coverage vs. quality of data



Conclusions & Future Work

- Leverage differentiable pipeline for downstream applications
- Different sensor configurations, e.g. stereo
- Multi-satellite capture and teaming simulations

+ we anticipate more!

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Project Page

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Lab Website

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