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Differentiable Lighting Informed Trajectory Evaluation for On-Orbit Inspection

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[2] ARIAM

76TH INTERNATIONAL ASTRONAUTICAL CONGRESS SYDNEY

ROBOTIC IMAGING LAB


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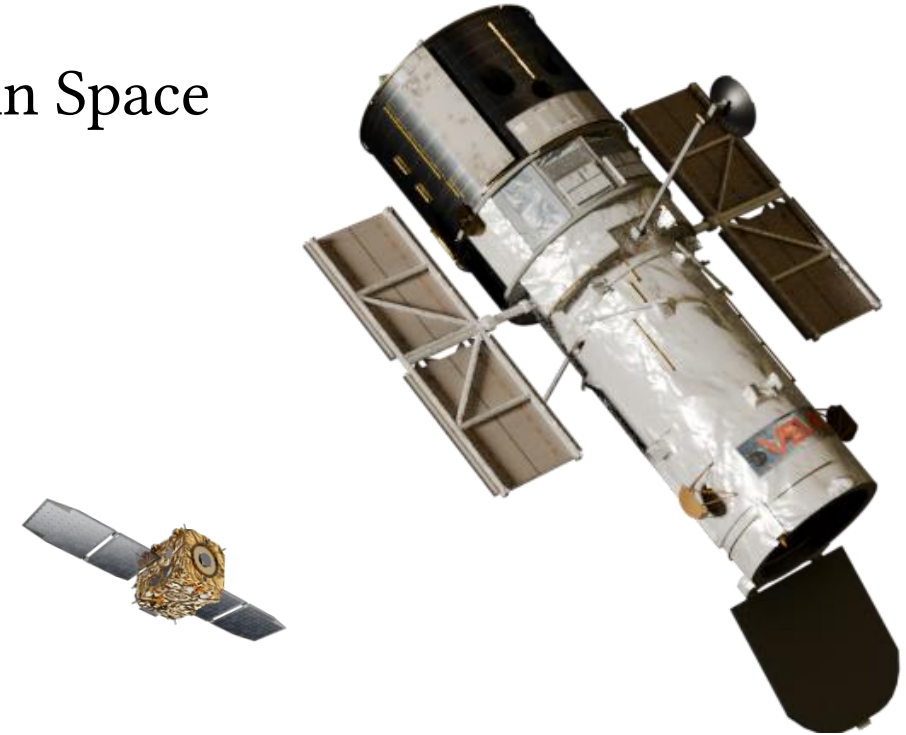
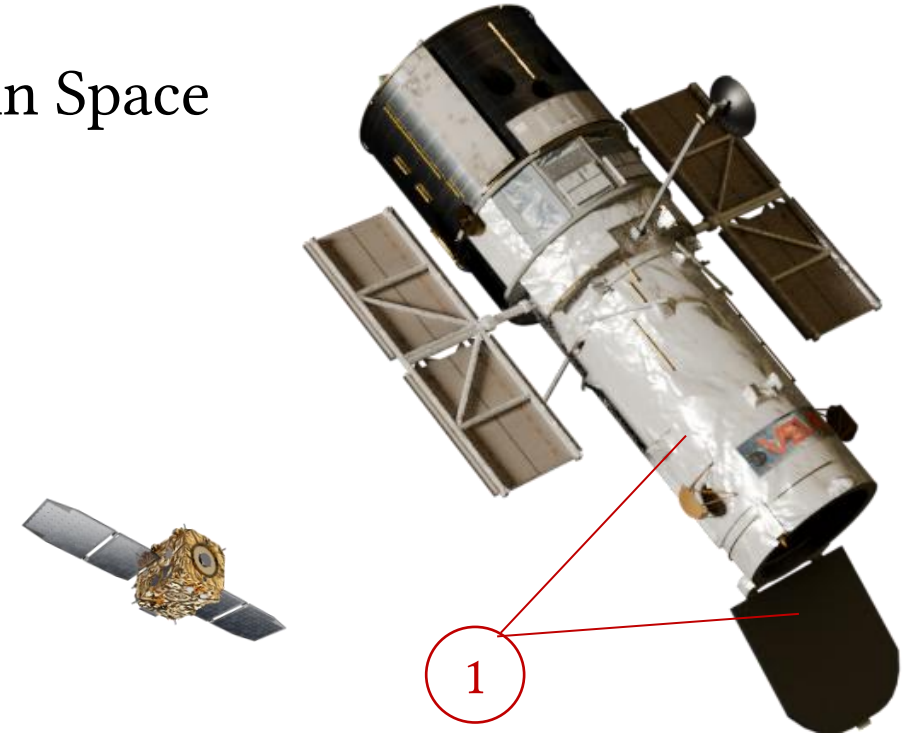
Some Challenges of Seeing in Space



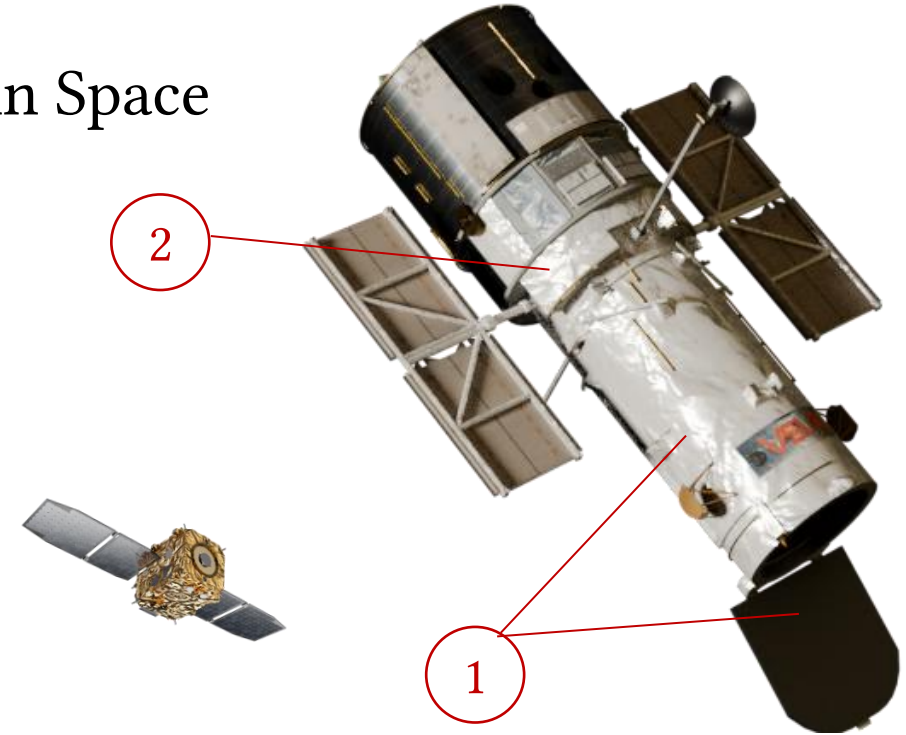
Some Challenges of Seeing in Space

1. High-dynamic range



Some Challenges of Seeing in Space

1. High-dynamic range
2. Specular objects



Some Challenges of Seeing in Space

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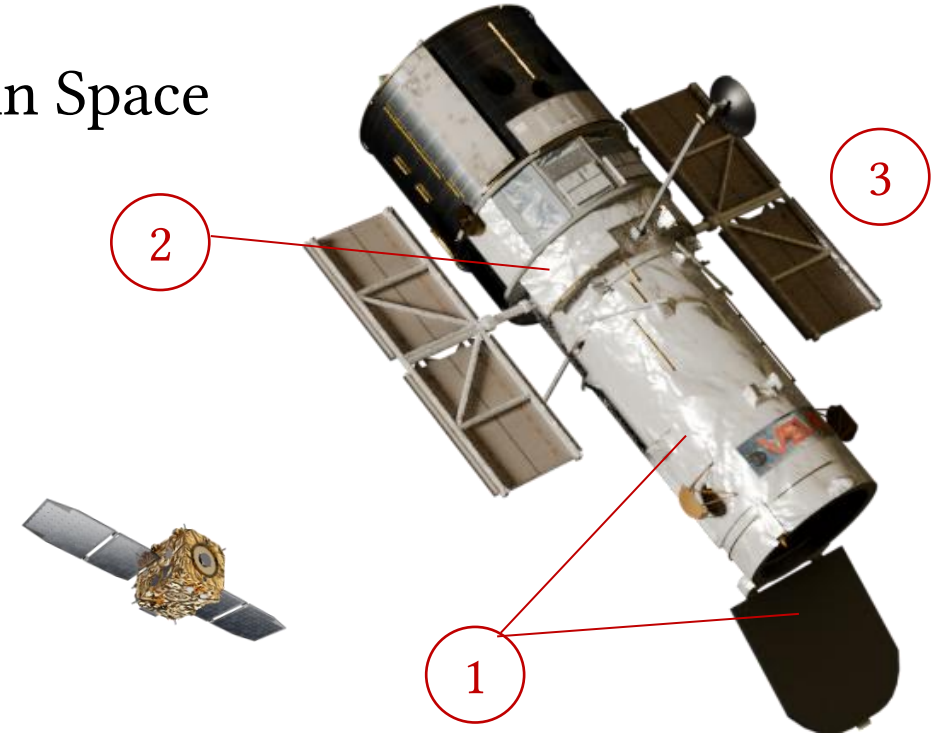
3. Self-shadowing



Some Challenges of Seeing in Space

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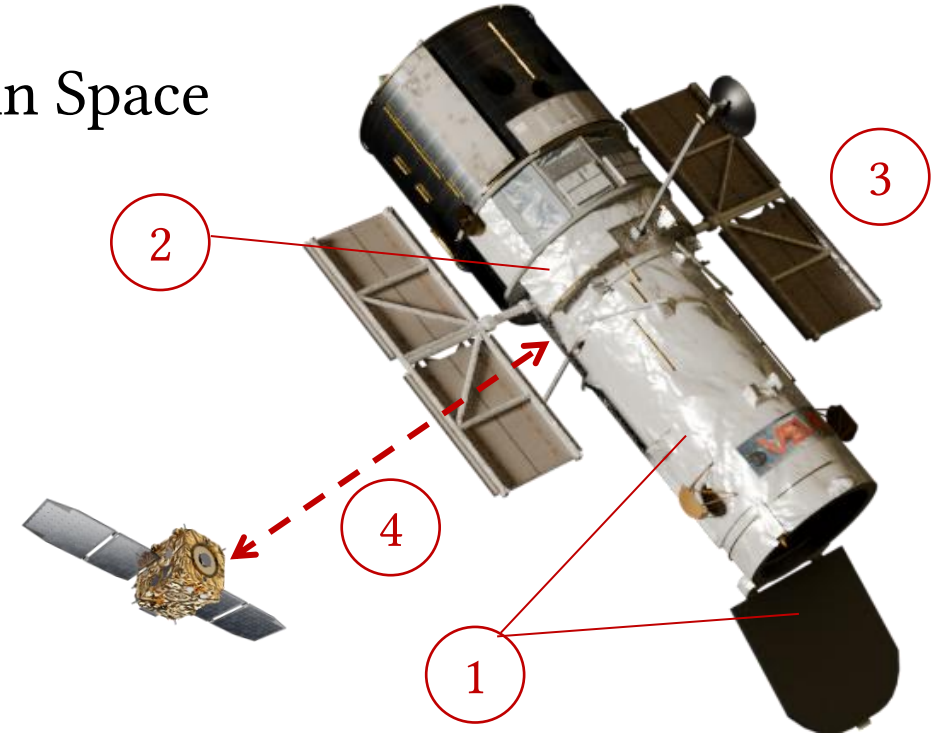
3. Self-shadowing
4. Dynamic lighting/imaging distances



Some Challenges of Seeing in Space

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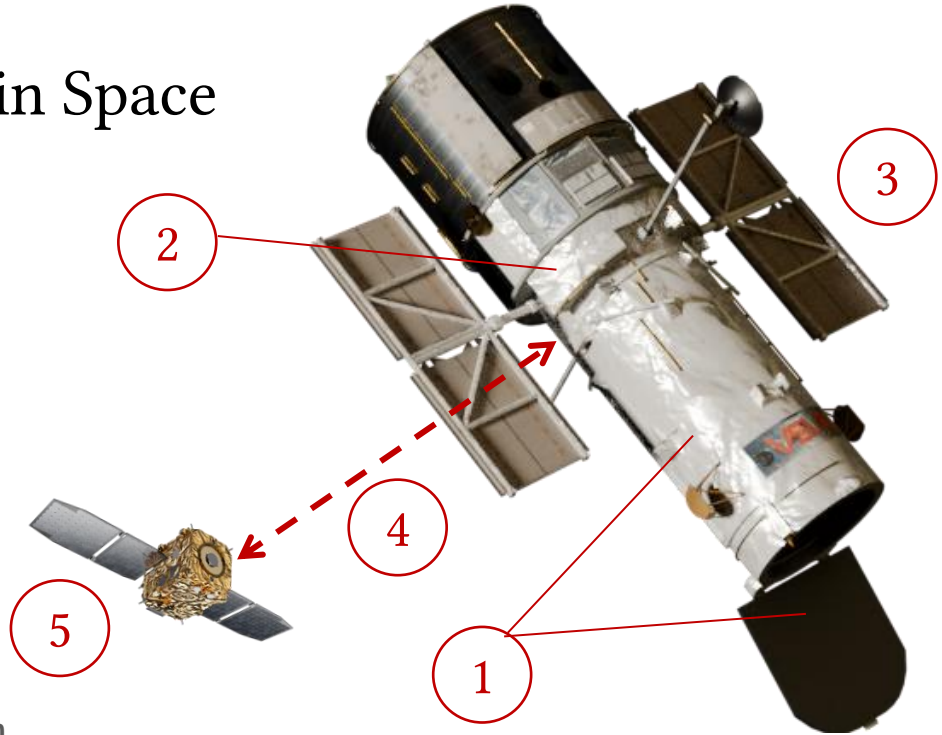
5. Cannot just move anywhere in an orbit to avoid these conditions



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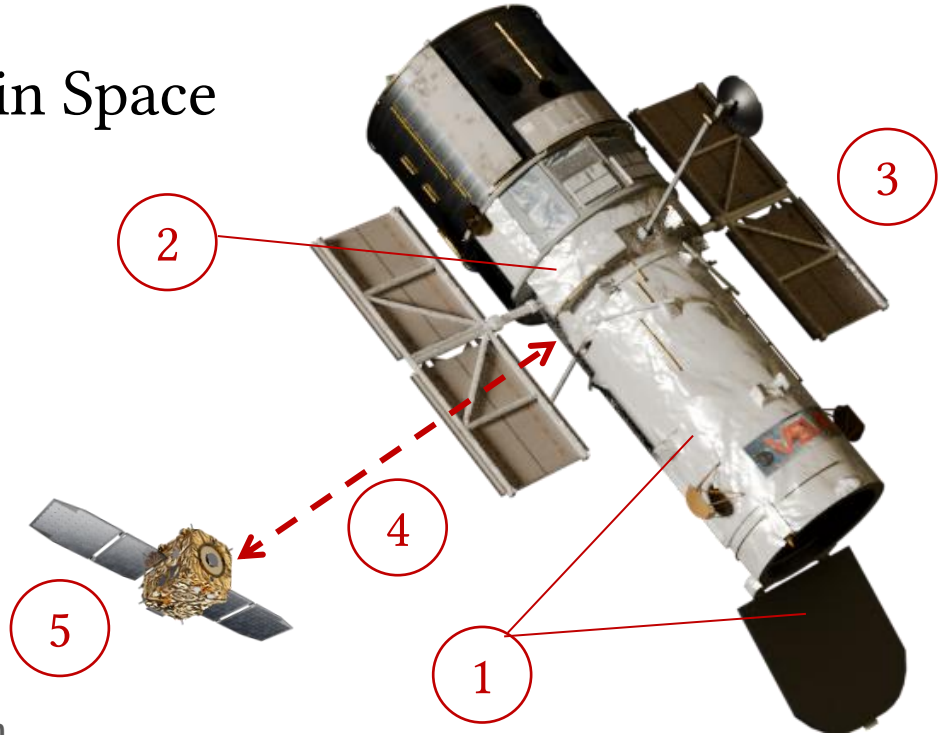
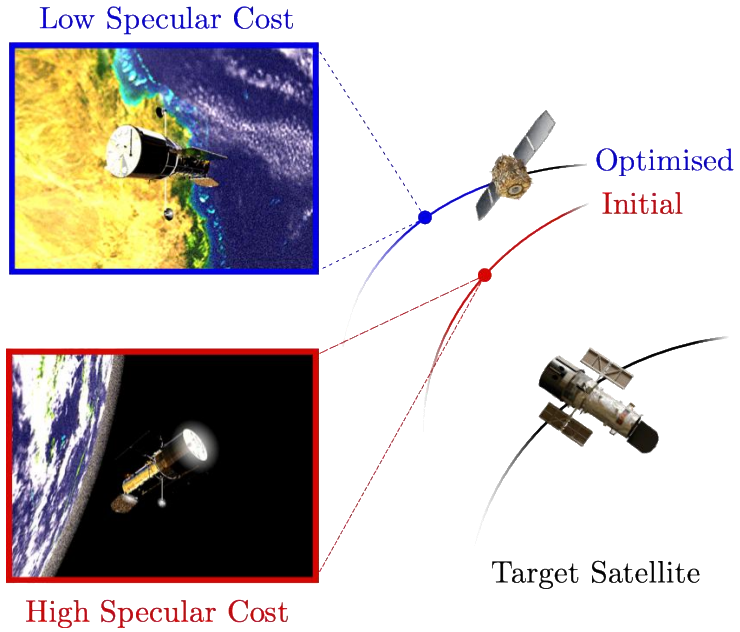


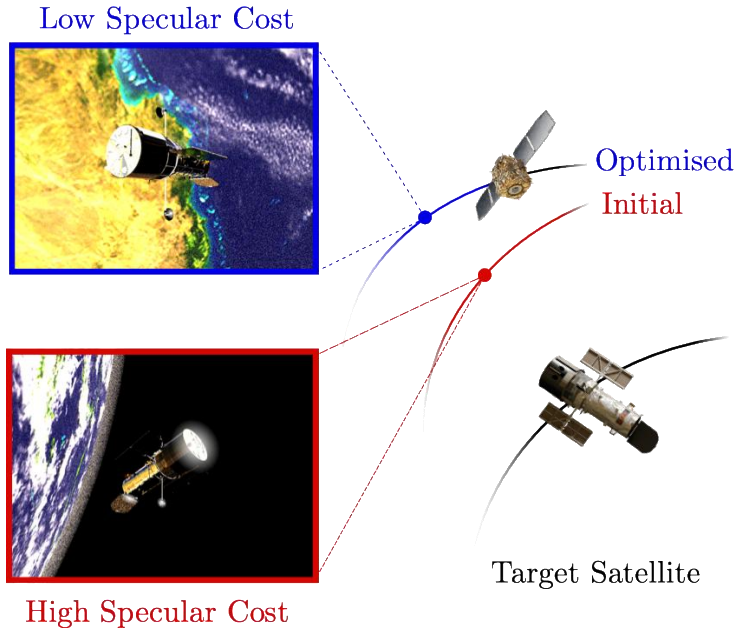
But what if you could plan ahead and choose your orbit?

Our Approach



Our Approach

Optimise orbit of inspection "chaser" satellite to minimise visual costs relative to a "target" satellite.

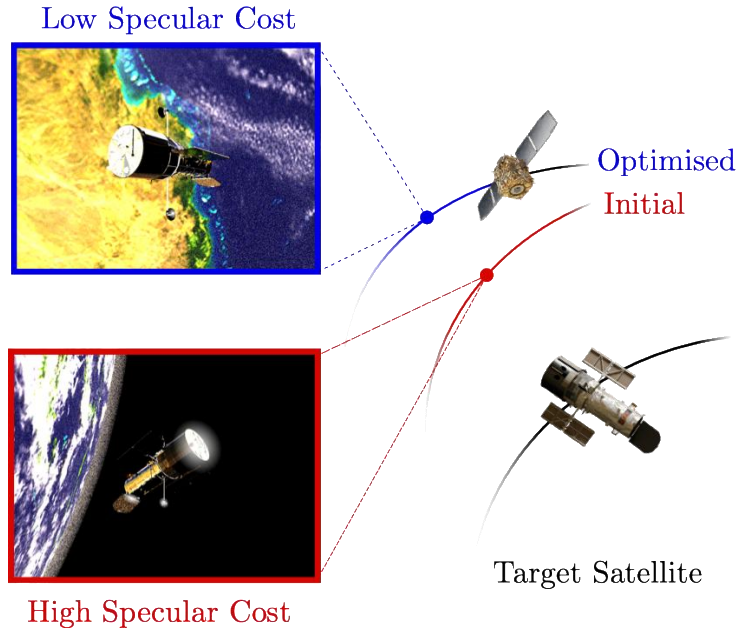


Our Approach

Optimise orbit of inspection "chaser" satellite to minimise visual costs relative to a "target" satellite.

How?

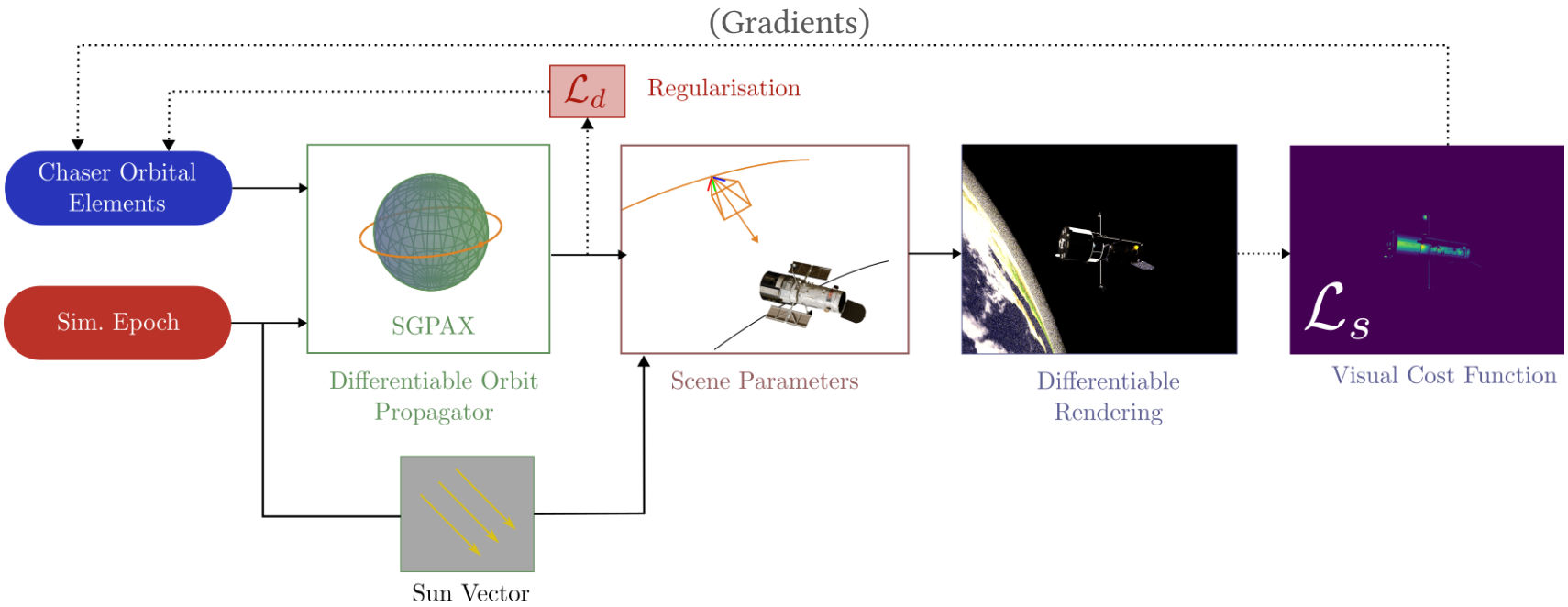
- Build an end-to-end differentiable simulator for on-orbit inspection
  - Differentiable orbit propagation
  - Differentiable rendering
- Minimise arbitrary costs via simple gradient descent.



Related Work

NAME	Diff. Orbits?	Diff. Rendering?	Photometric?	Optical Effects?	Photorealistic?
ALL-STAR [Li et al. 2024]					
SPIN [Montalvo et al. 2024]					
SISPO [Pajusalu et al. 2022]					
HySIM [Felicetti et al. 2024]					
∂LITE [Ours]					

End-to-End Differentiable Inspection



Building Differentiable Orbital Simulations

Building Differentiable Orbital Simulations

- Differentiable orbit propagation in JAX + Mitsuba 3 rendering

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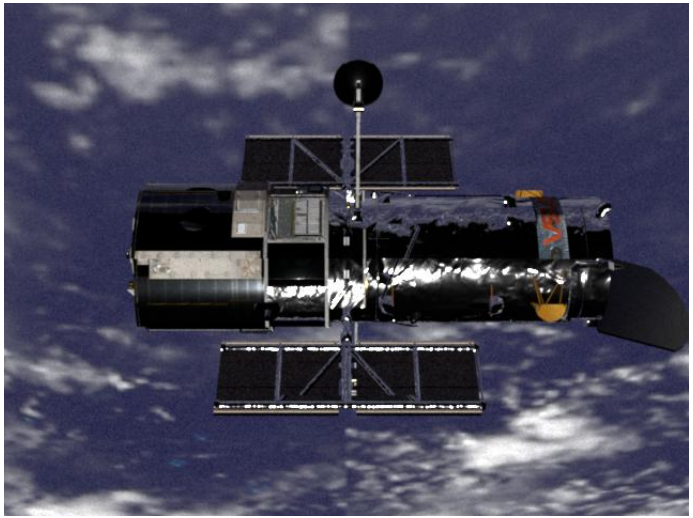

Building Differentiable Orbital Simulations

- Differentiable orbit propagation in JAX + Mitsuba 3 rendering

- Assume state & geometry are known (requires depths and surface normals)

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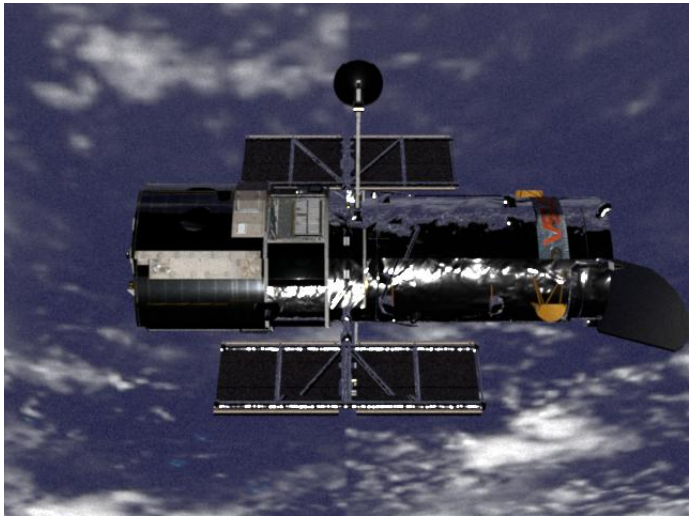
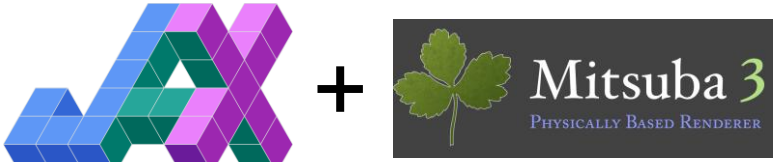


Building Differentiable Orbital Simulations

- Differentiable orbit propagation in JAX + Mitsuba 3 rendering
- Assume state & geometry are known (requires depths and surface normals)
- Assume always pointing at target



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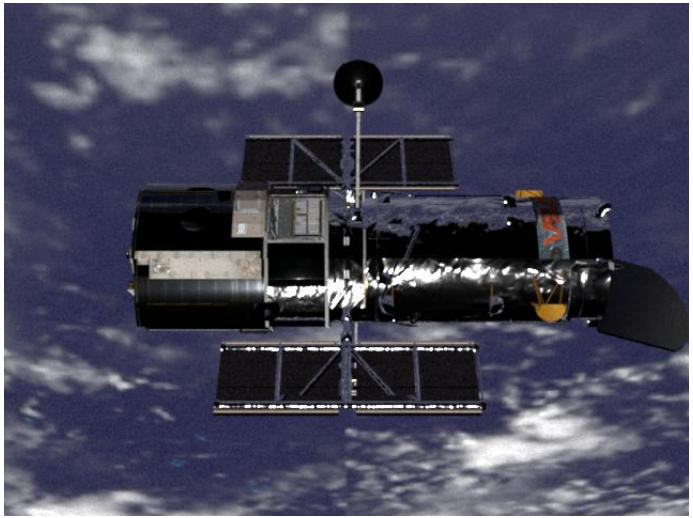

Building Differentiable Orbital Simulations

- Differentiable orbit propagation in JAX + Mitsuba 3 rendering
- Assume state & geometry are known (requires depths and surface normals)
- Assume always pointing at target
- Simulate passive inspections – e.g., circular "football" orbits

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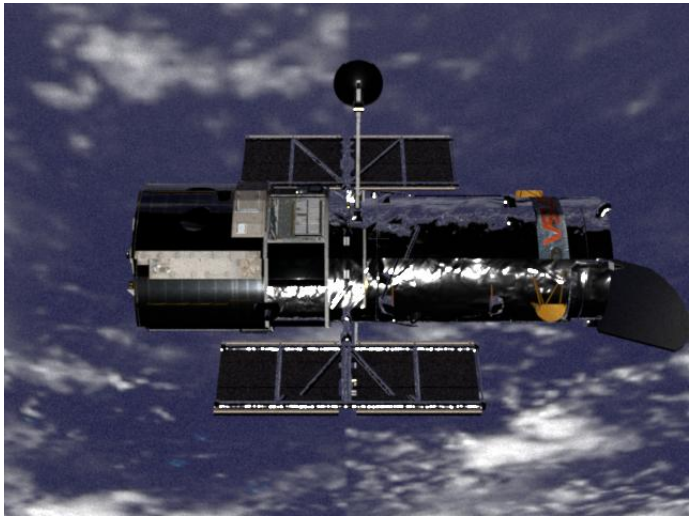

Cost Function: Minimising Specular Reflection

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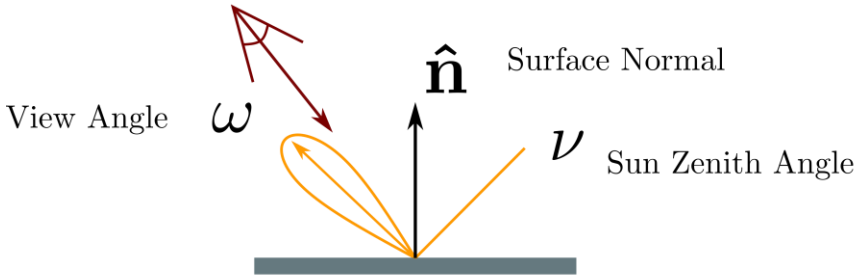
    - Model sun illumination direction, use known geometry
    - Use physically-based reflection model, model strength of reflection from surface seen by the camera



Phong Reflection Model

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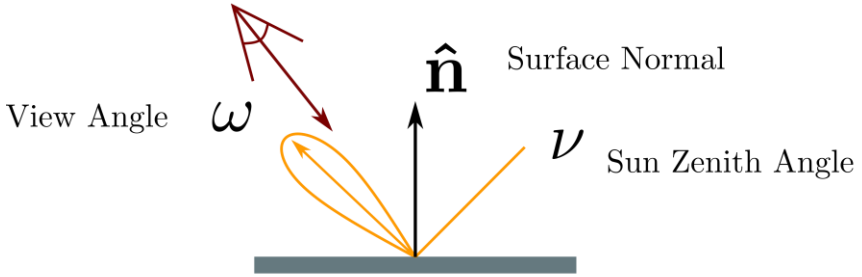

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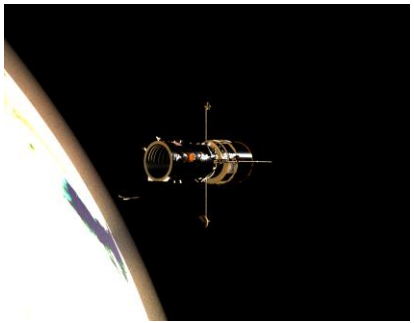
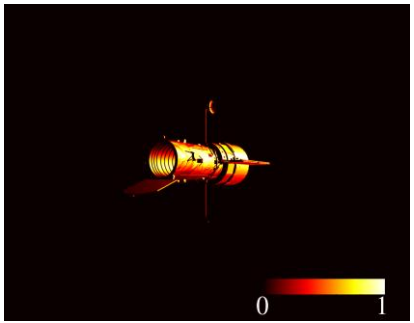


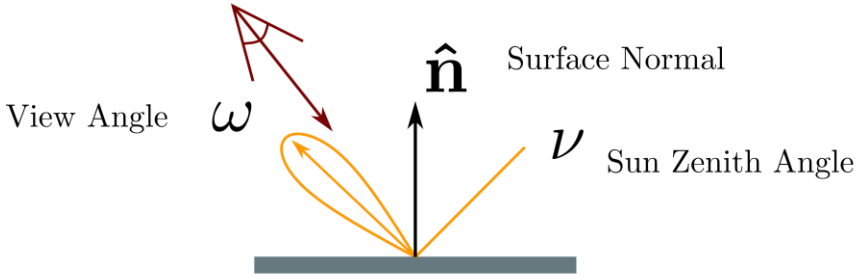
RGB



Specular Cost

Cost Function: Minimising Specular Reflection

- Main cost: reduce direct specular reflections seen by the camera
    - Model sun illumination direction, use known geometry
    - Use physically-based reflection model, model strength of reflection from surface seen by the camera
- Additional cost: relative distance between chaser and target to avoid drift



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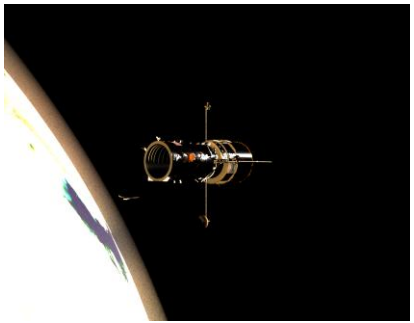

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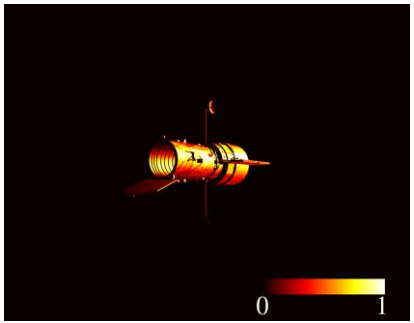
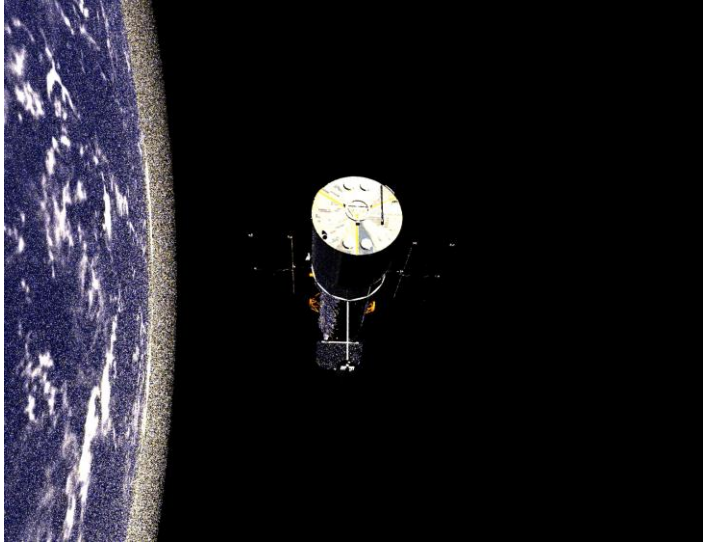


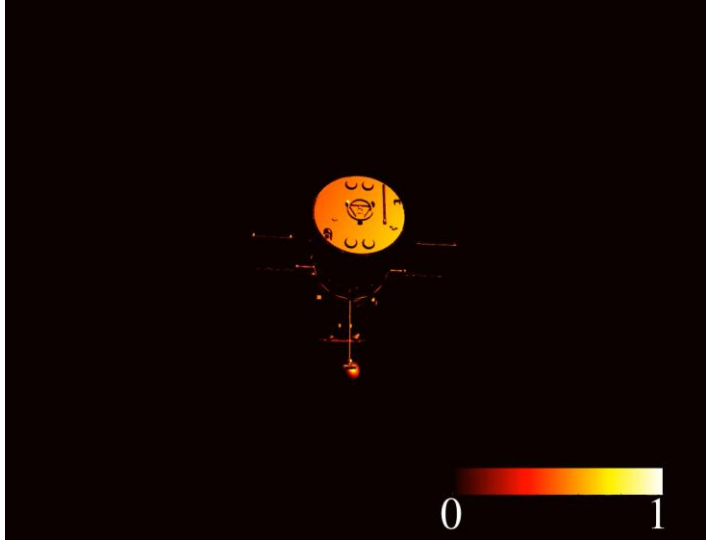
Specular Cost

Results

Results

Before Optimisation





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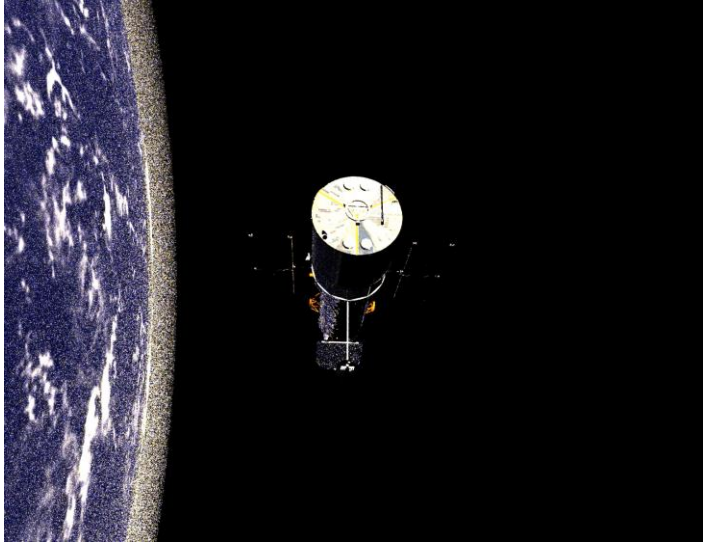

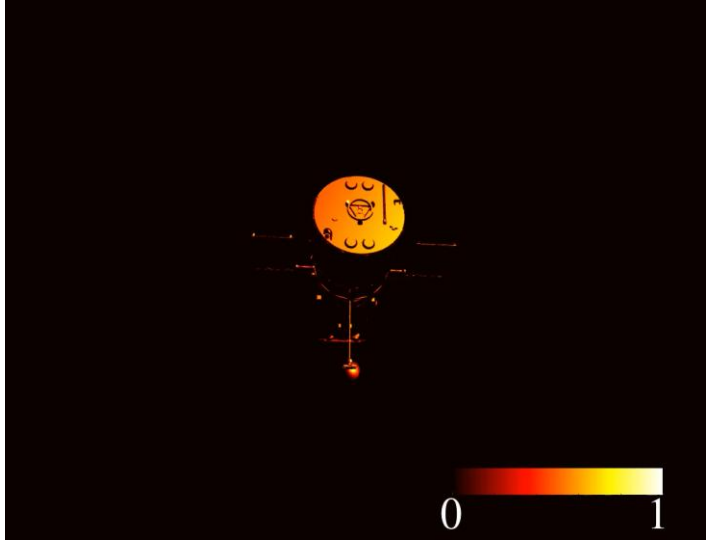

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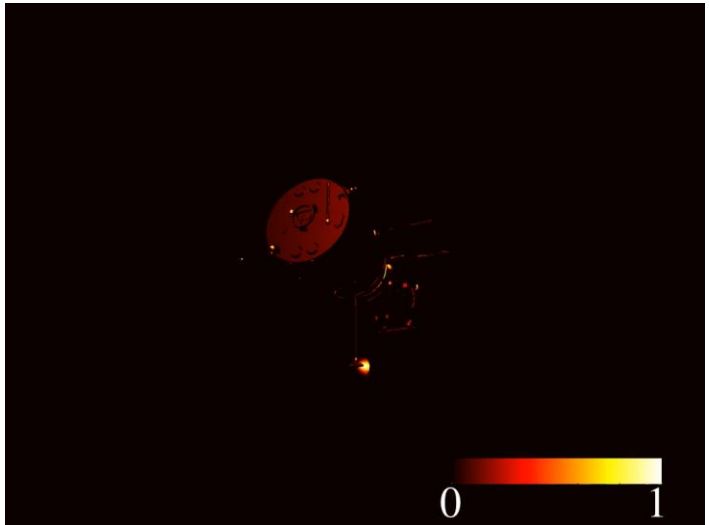

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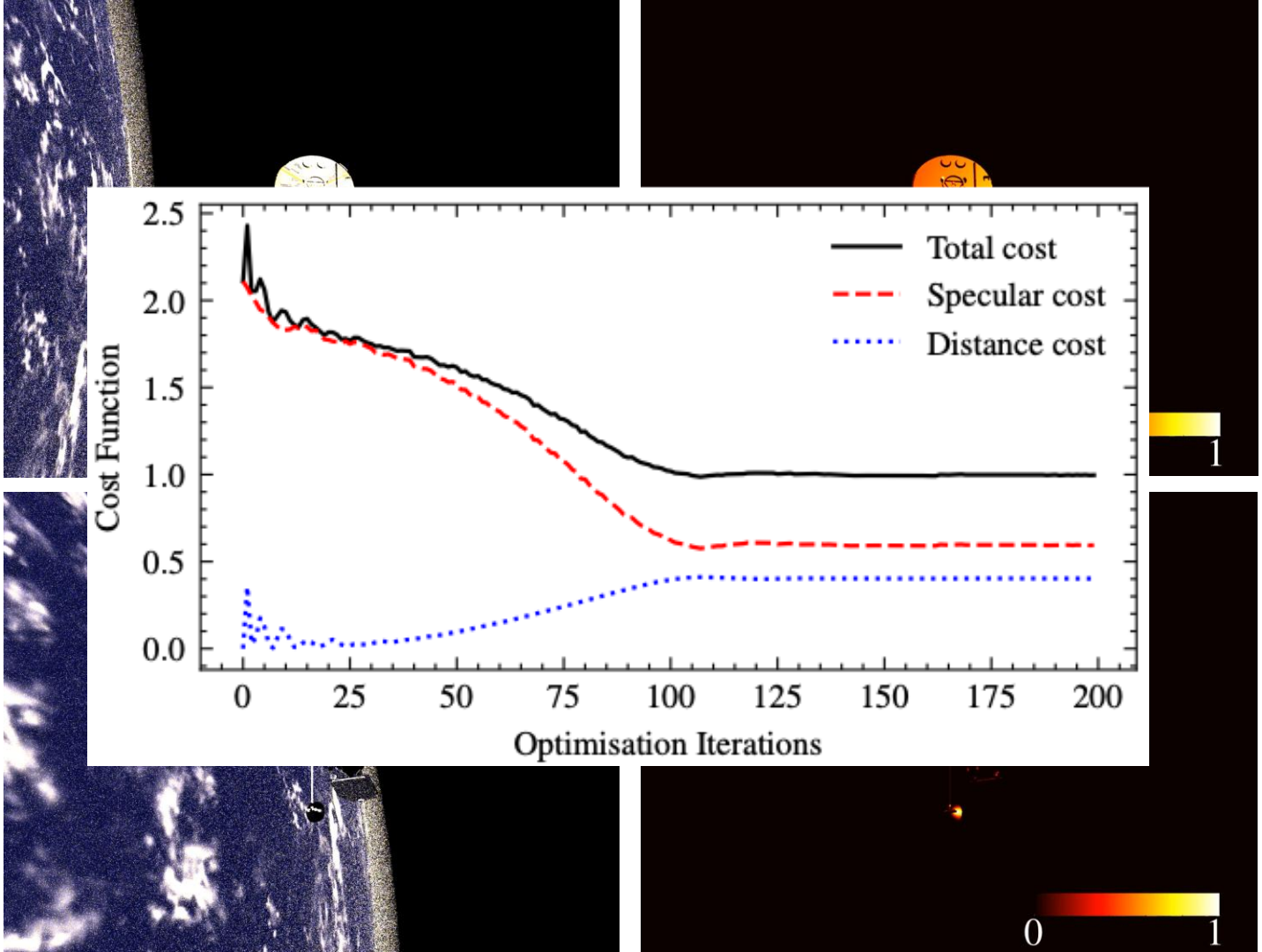

Pixel Saturation

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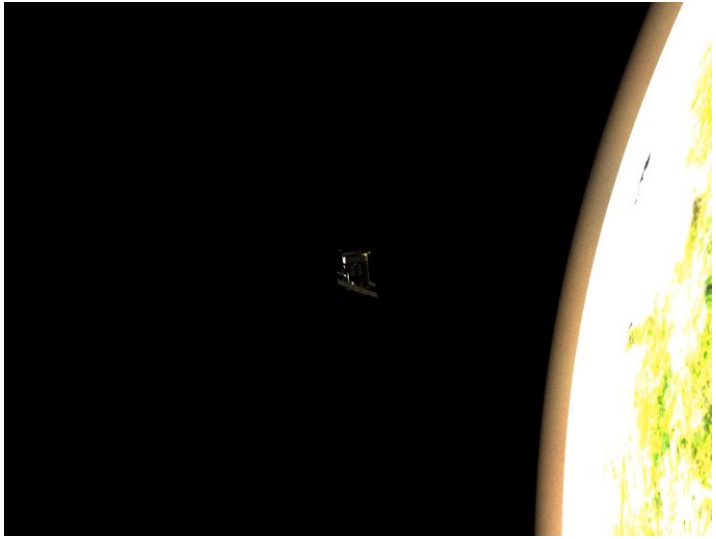

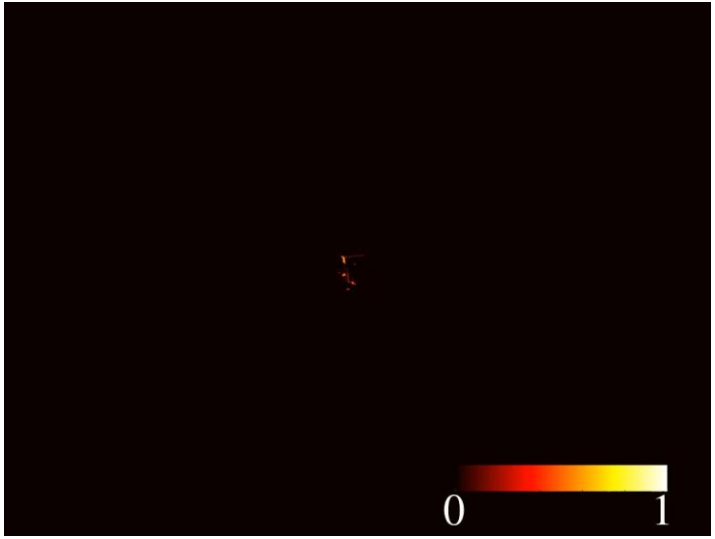

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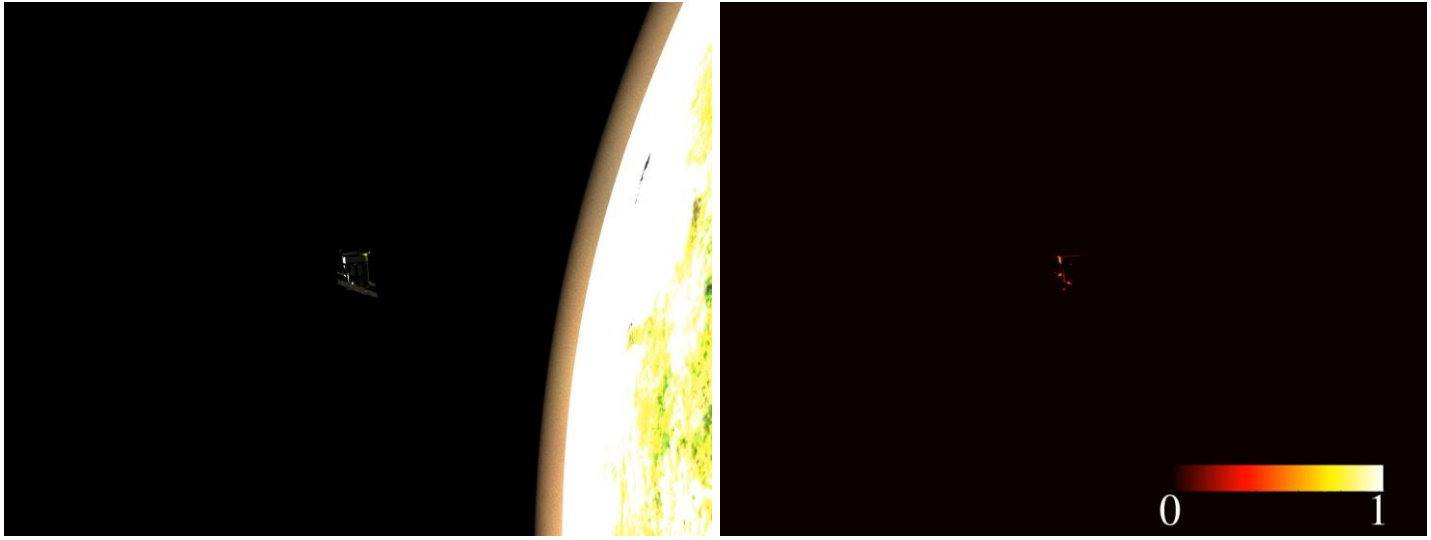

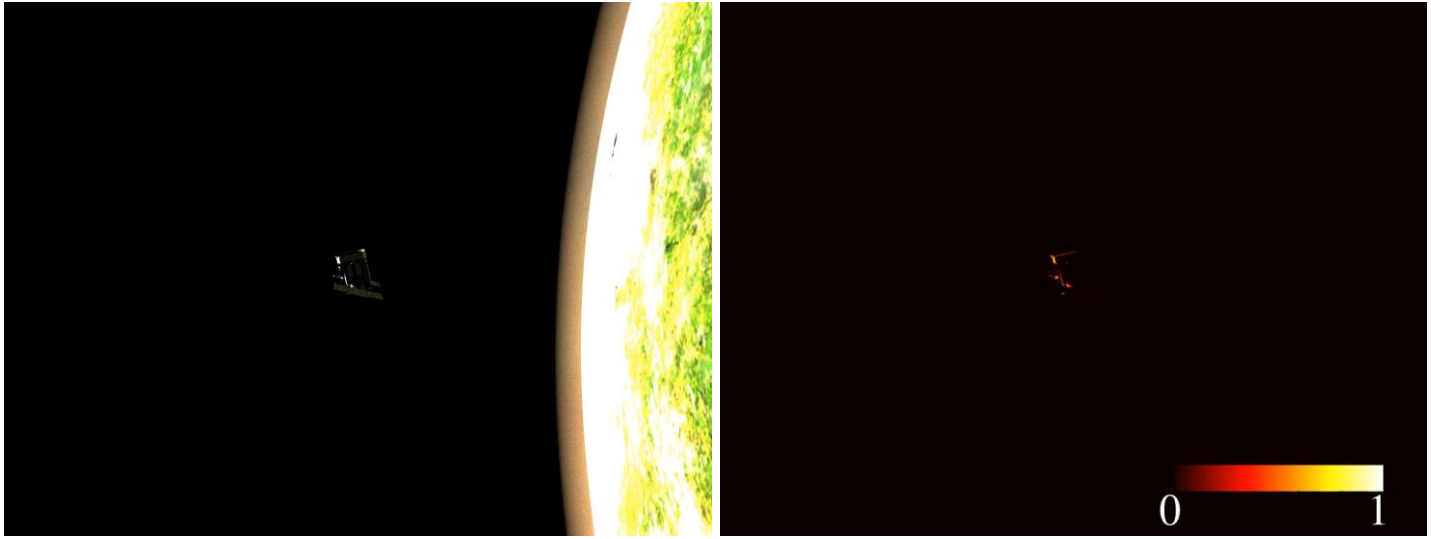

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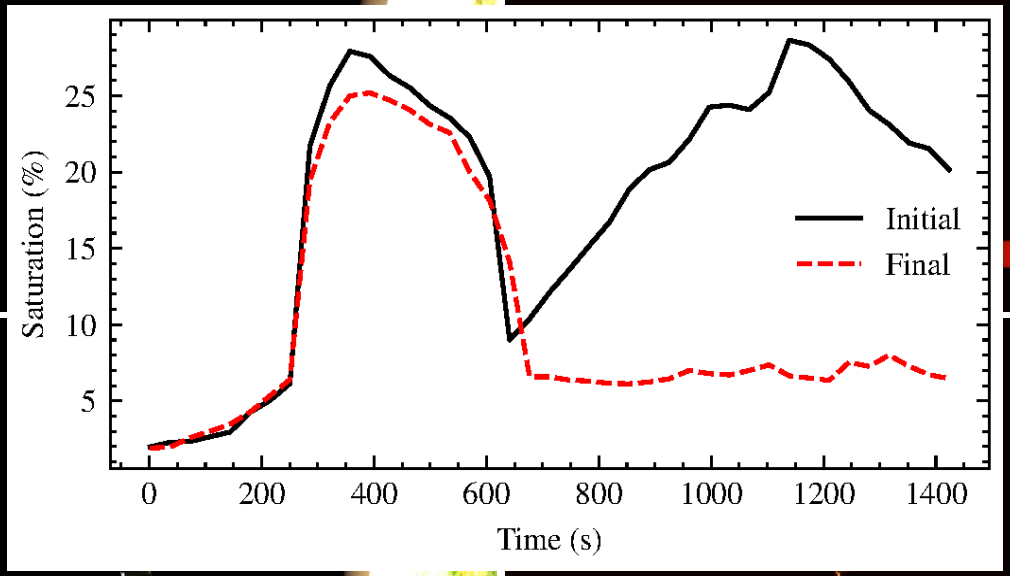
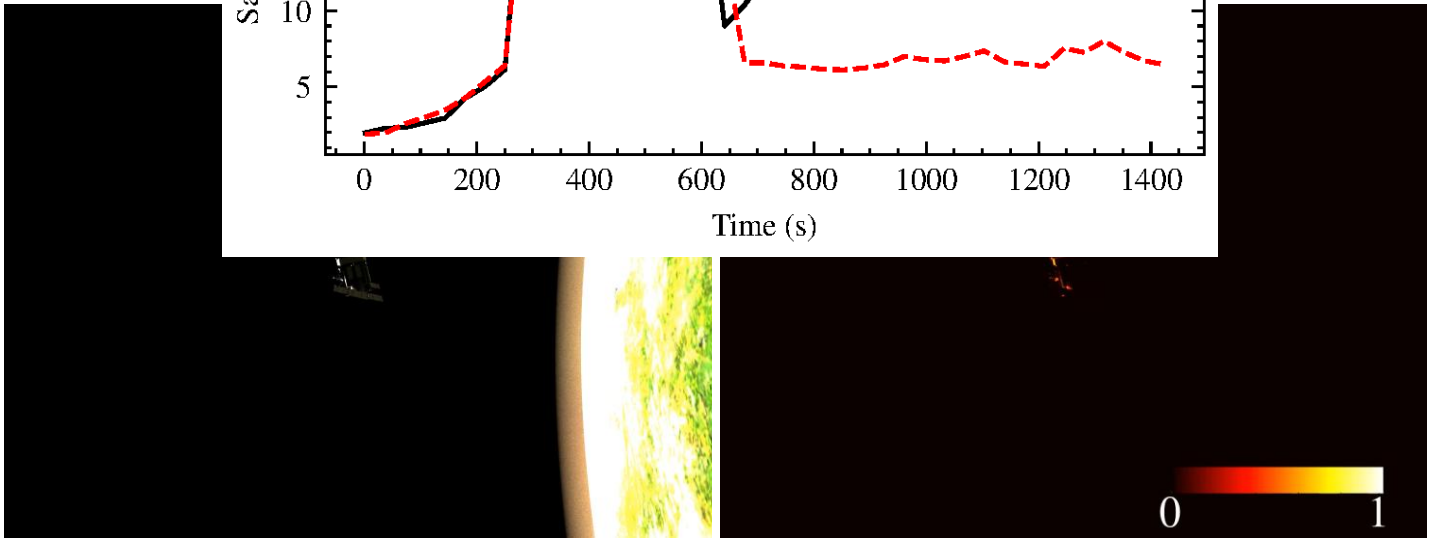
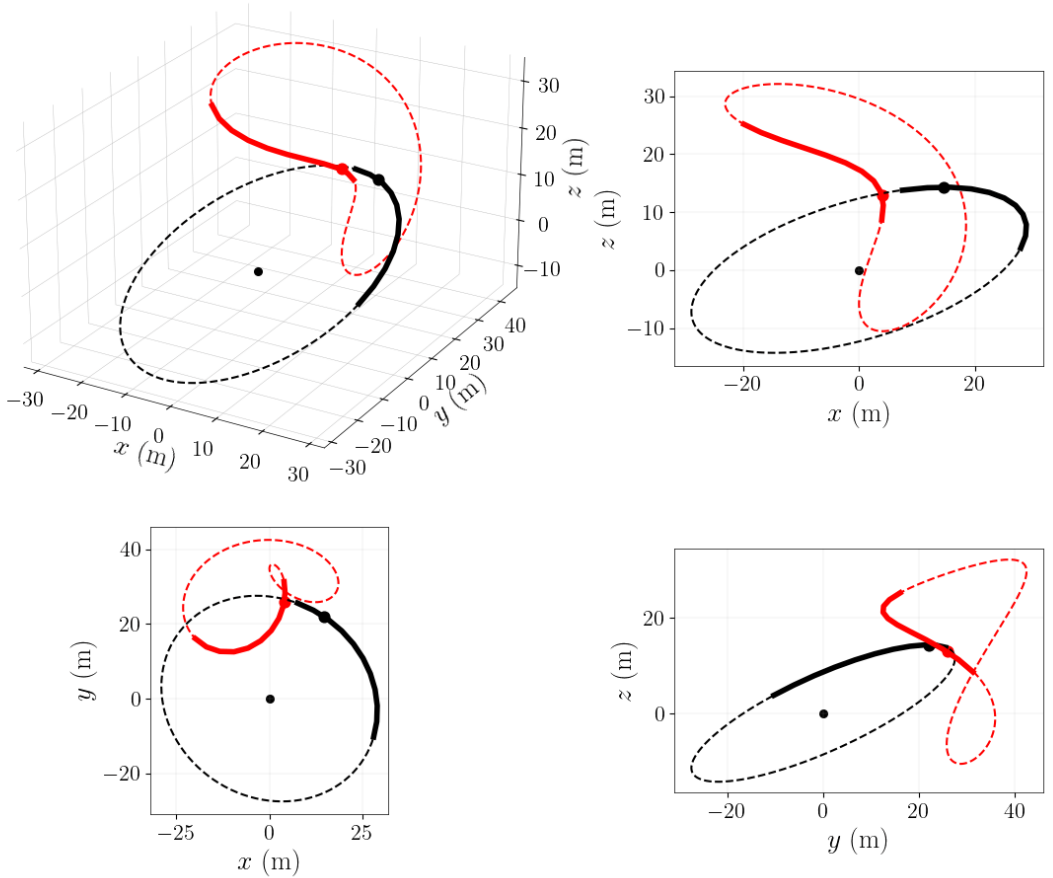




Comparing Relative Orbits



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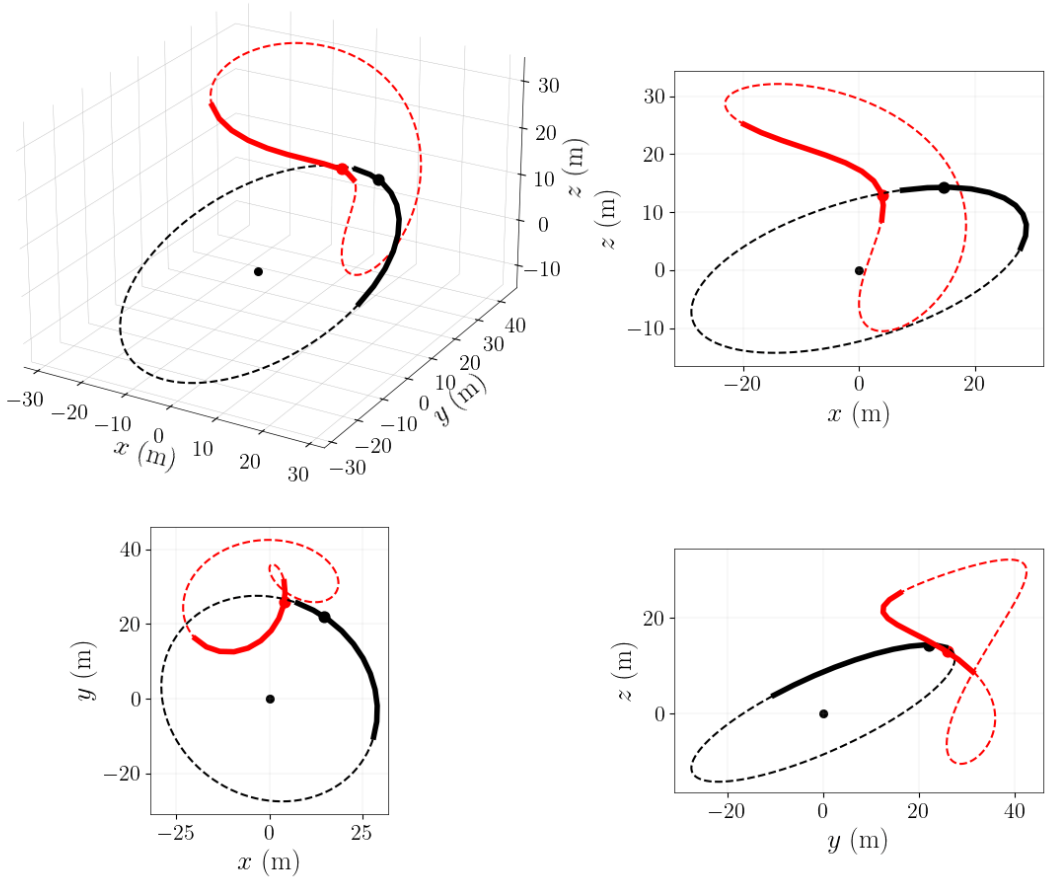
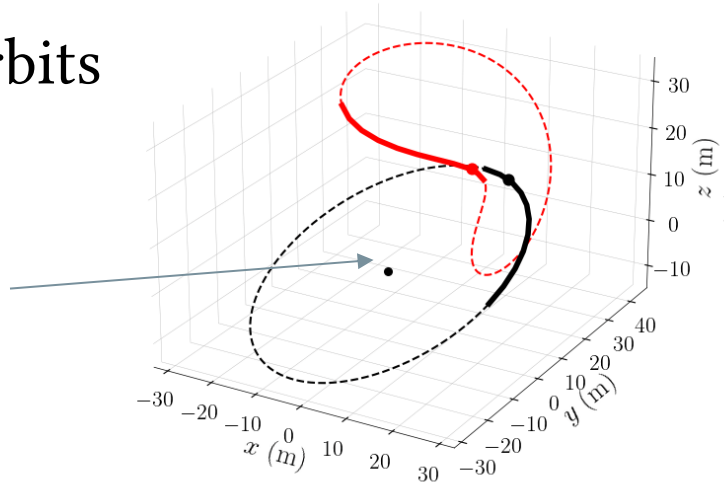
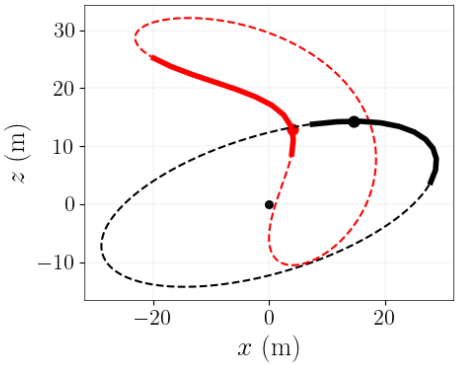
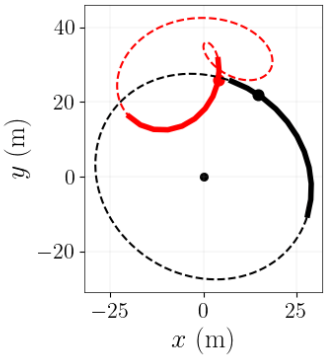


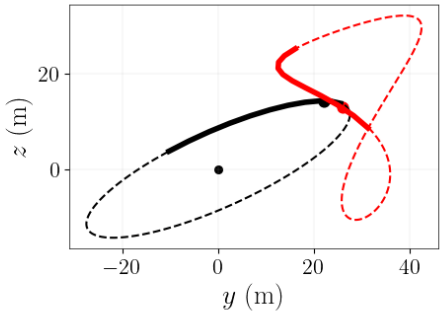
Comparing Relative Orbits

Target satellite (e.g., Hubble)





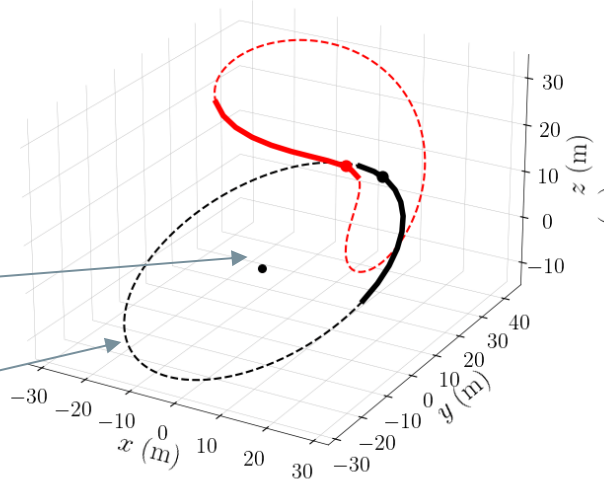


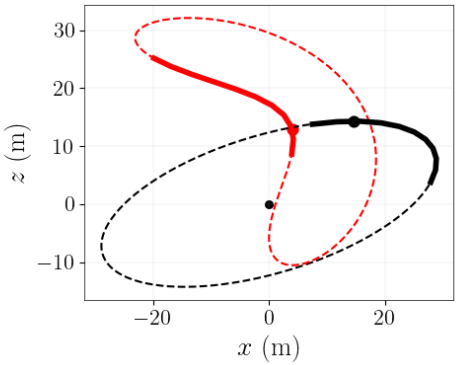


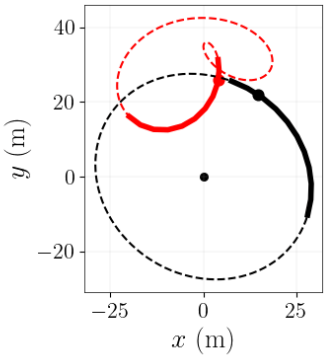
Comparing Relative Orbits

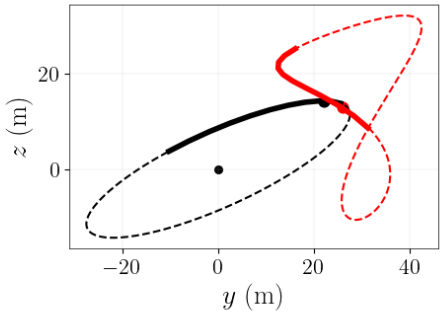
Target satellite (e.g., Hubble)

Original relative orbit







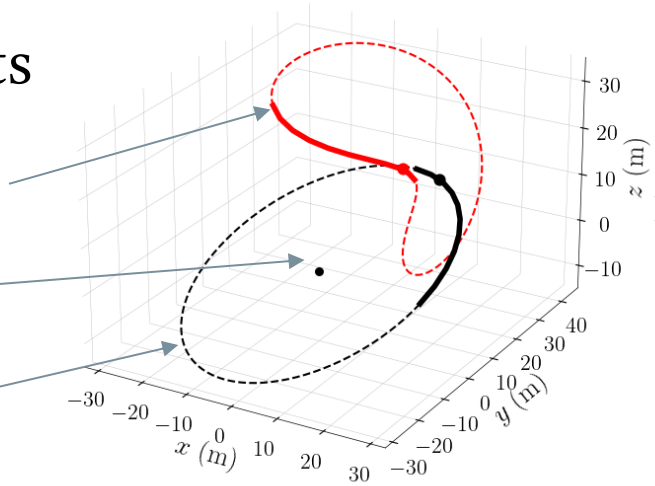


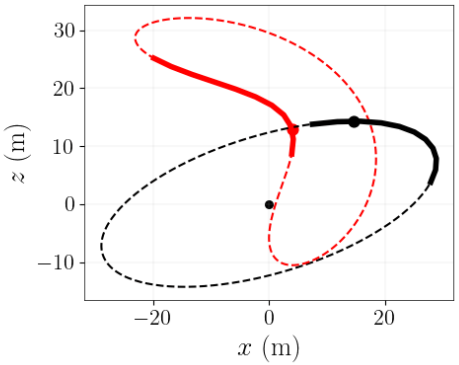
Comparing Relative Orbits

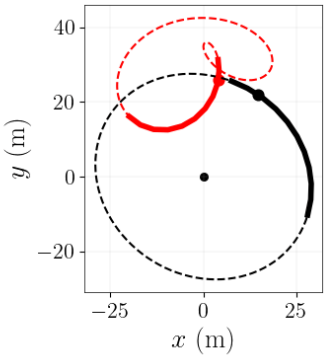
Optimised relative orbit

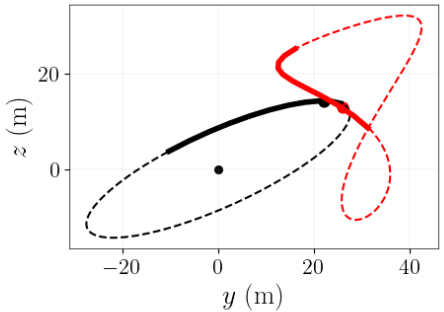
Target satellite (e.g., Hubble)

Original relative orbit









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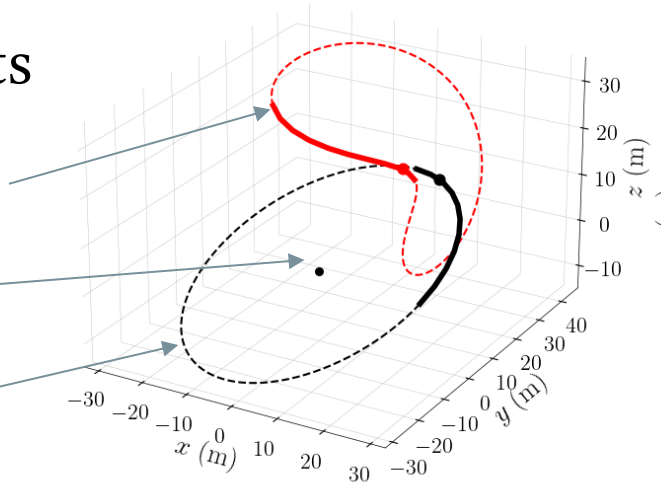
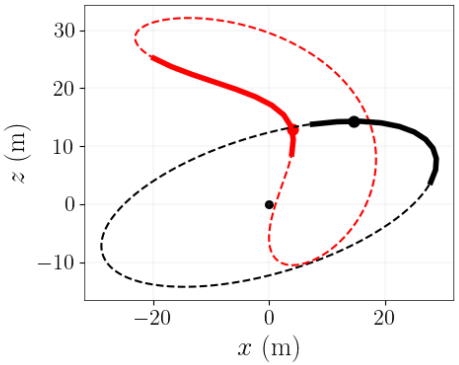
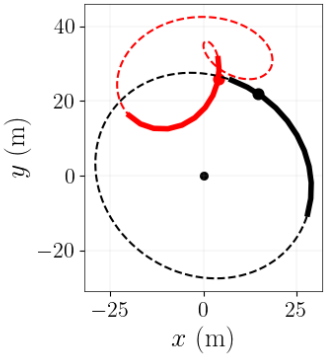
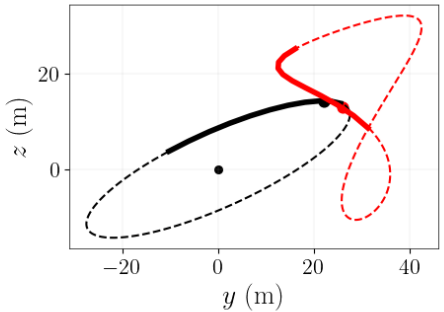




- Optimising the orbital elements to improve visual costs leads to new, specialised inspection trajectories in the relative frame.



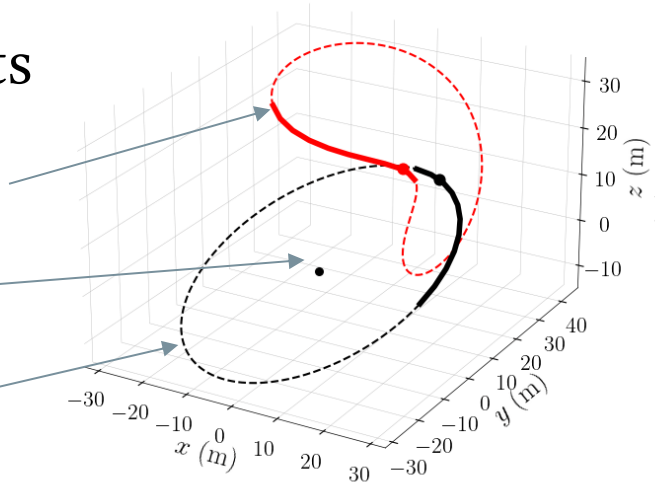


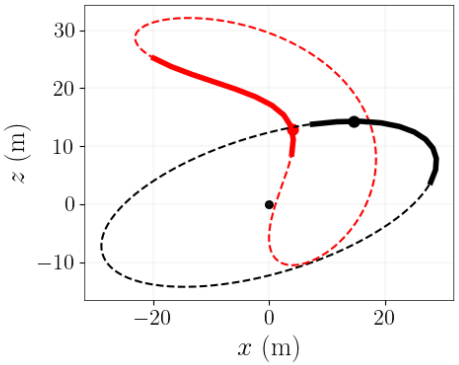
Comparing Relative Orbits

Optimised relative orbit

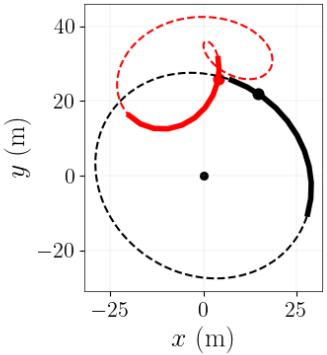
Target satellite (e.g., Hubble)

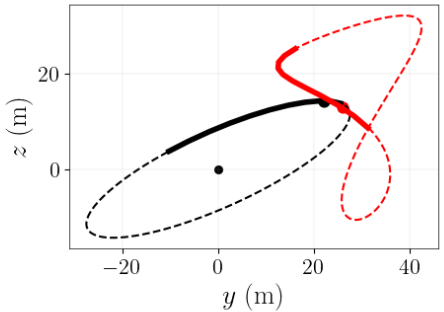
Original relative orbit





- Optimising the orbital elements to improve visual costs leads to new, specialised inspection trajectories in the relative frame.
- Deviation from the initial orbit is very small, so delta V costs are low.





Conclusions

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- Fully-differentiable vision-to-planning pipeline.
- Demonstrated capability in optimising inspection trajectories.

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Future Work

Conclusions

- Fully-differentiable vision-to-planning pipeline.
- Demonstrated capability in optimising inspection trajectories.

Future Work

- Integrate attitude dynamics & materials, add uncertainty quantification
- Apply to mission planning & operations.
- Other applications combining imaging & orbits (e.g., Earth observation tasking).

Q & A

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Project Page