Non-Keplerian Trajectory Planning Via Heuristic-Guided Objective Reachability Analysis

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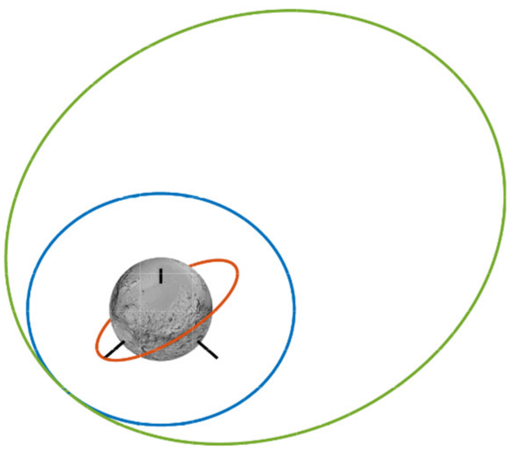
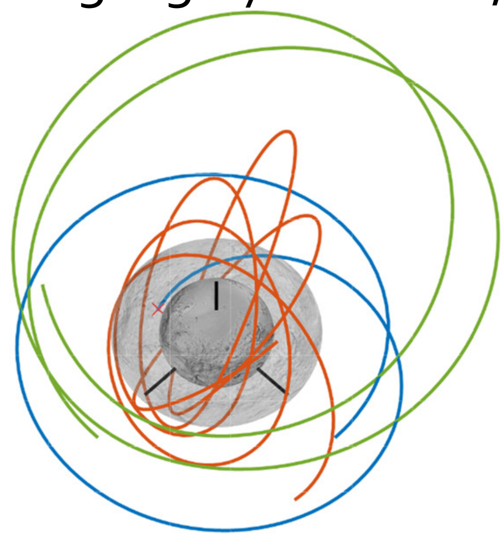
Small Body Orbit Dynamics

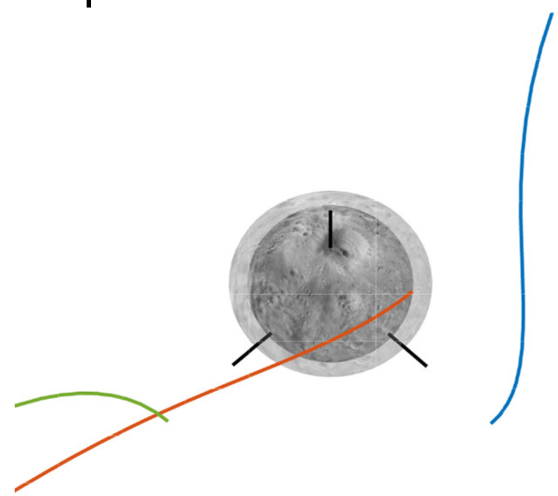
Irregular shapes and proportionally large external forces complicate mission design by producing highly sensitive, non-periodic motion.



Spherical Body



Asteroid Itokawa
(Highly elongated)



Martian moon Phobos
(Strong tidal forces)

NASA GNC Tech Report

- *A central need is "the ability to **rapidly design efficient and innovative trajectories**."*
- *"…more **complex** dynamical models must be used to perform **preliminary** designs."*

Test Scenario

System: Comet 67/P Churyumov-Gerasimenko (highly non-spherical)

Objective: perform close-range imaging of candidate landing sites A, C, and J with four different viewing geometries under appropriate solar phasing

Uncertainty in state estimation (10 m, 1 mm/s) and gravity model (64 vs 2500 vertices)

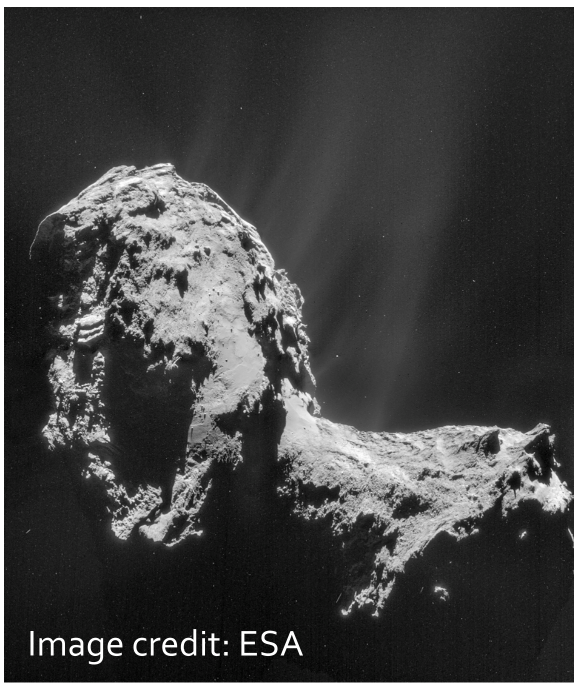
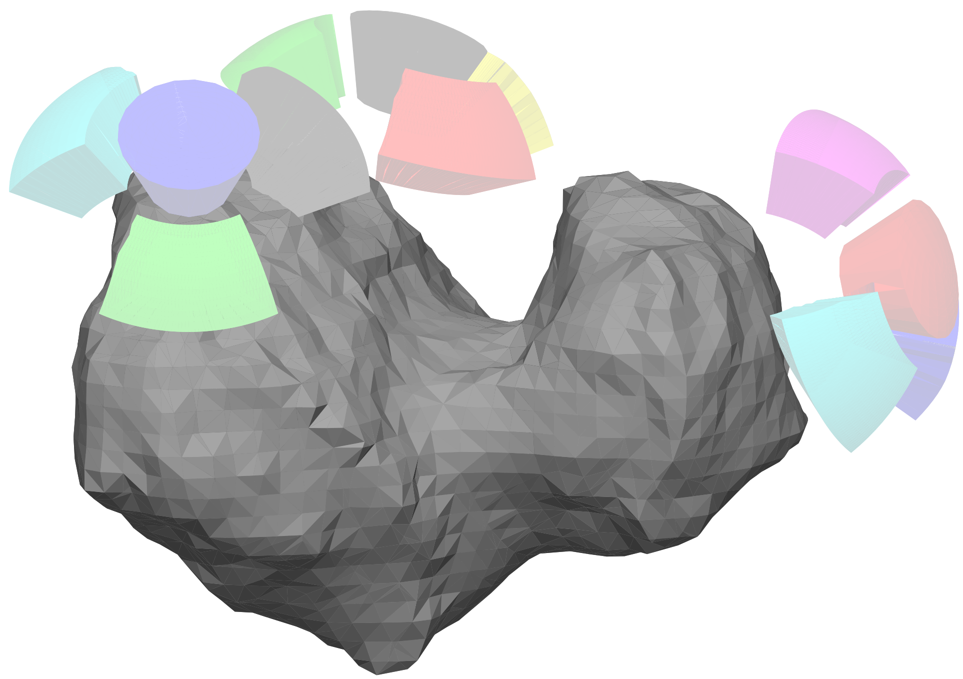


Image credit: ESA



Solution Strategy

Re-pose motion planning problem as regulation of an abstract state by an intermittently acting impulsive controller, via:

1. Robust predictive model for abstract outcomes
2. Heuristic search of single-impulse reachable set
3. Reactive receding-horizon implementation

Key Concepts

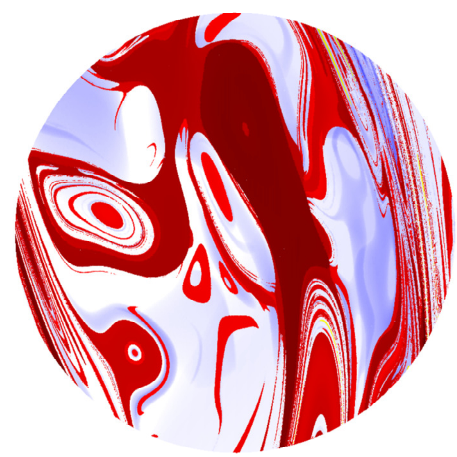
Abstraction

- Trajectories are incidental; objectives/constraints are fundamental.
- Separate treatment of two sequential problems can cause nuanced, unintuitive solutions to be overlooked (e.g. low-energy lunar transfers).

Orbit-change maneuver → ***Force environment*** → Trajectory through space → ***Mission specifications*** → Outcomes of interest

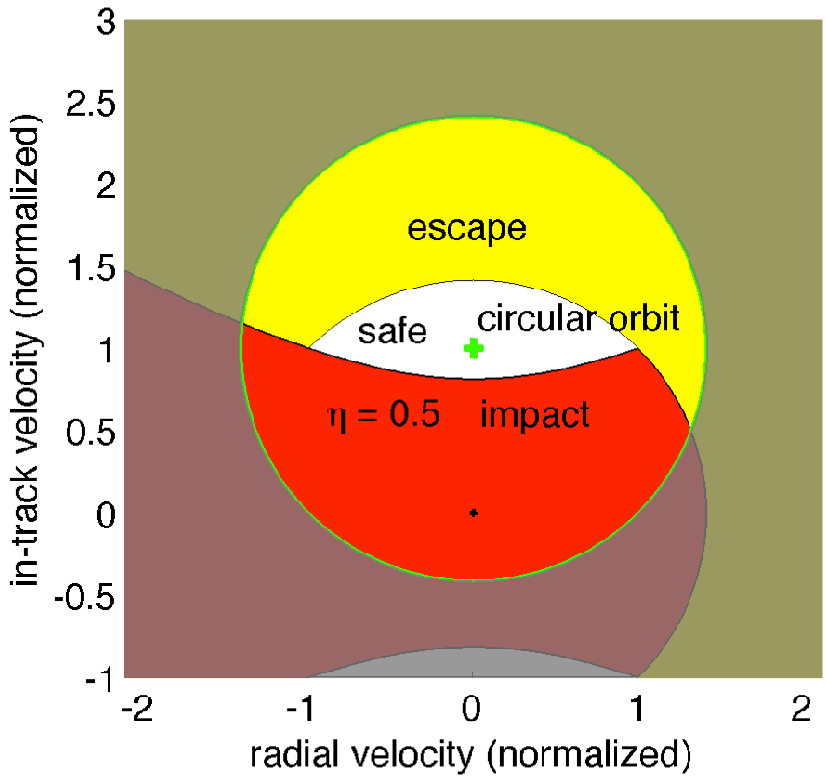
Reachability

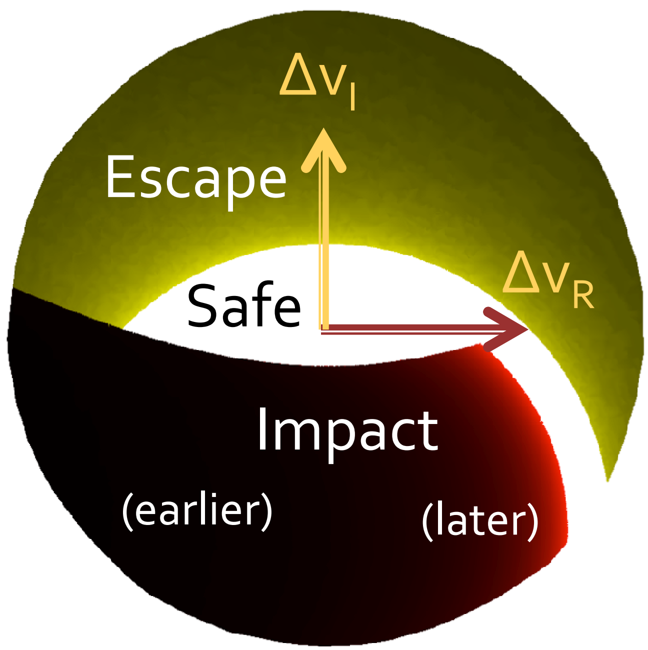
- In lieu of tractable reference solutions, reduce the large, complex design space via accessibility
- Naturally facilitates continuous re-planning, opportunism, and robustness to uncertainty



Keplerian Reachability

Kepler problem results (spherical body).
Position on map: selection of initial velocity
Color: safety outcome of resulting trajectory.

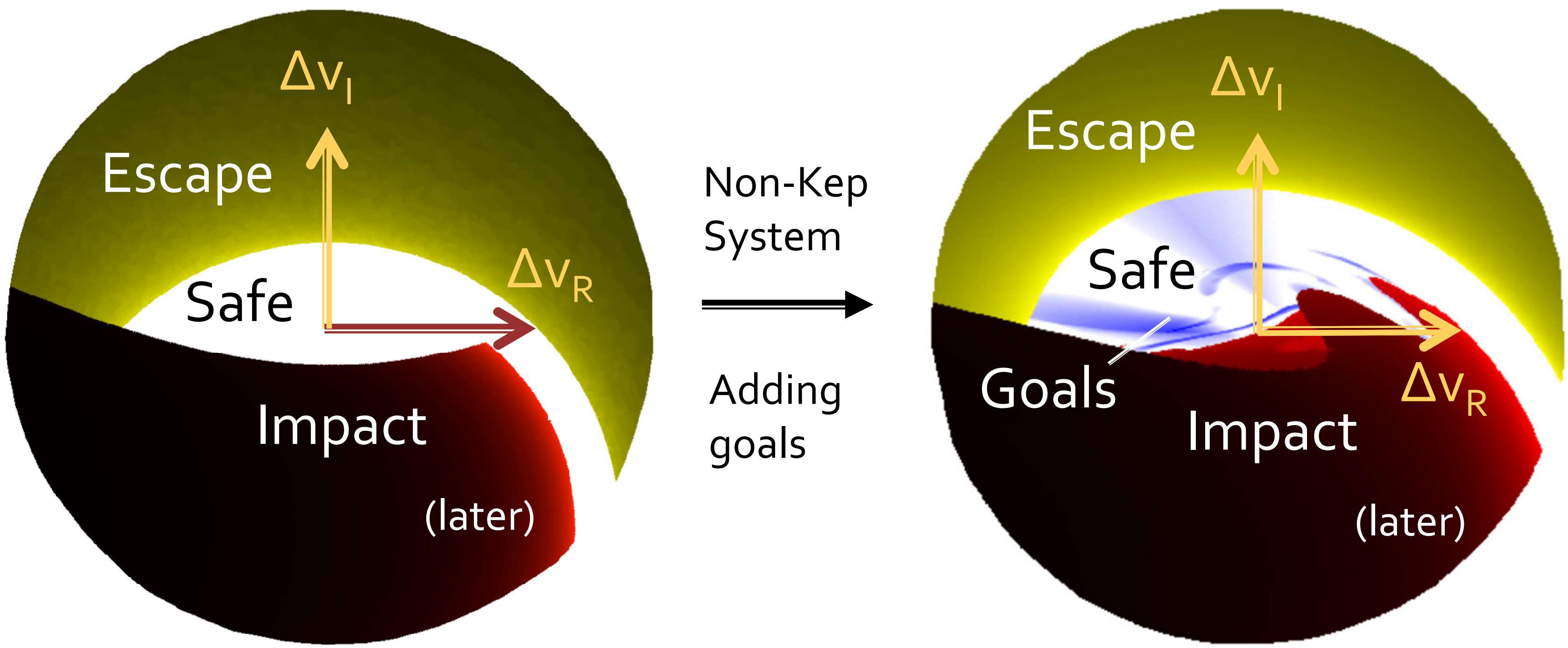




Non-Keplerian Reachability

Non-Keplerian system: Asteroid Itokawa (highly elongated)

Desired operation: close-range fly-over of target sites



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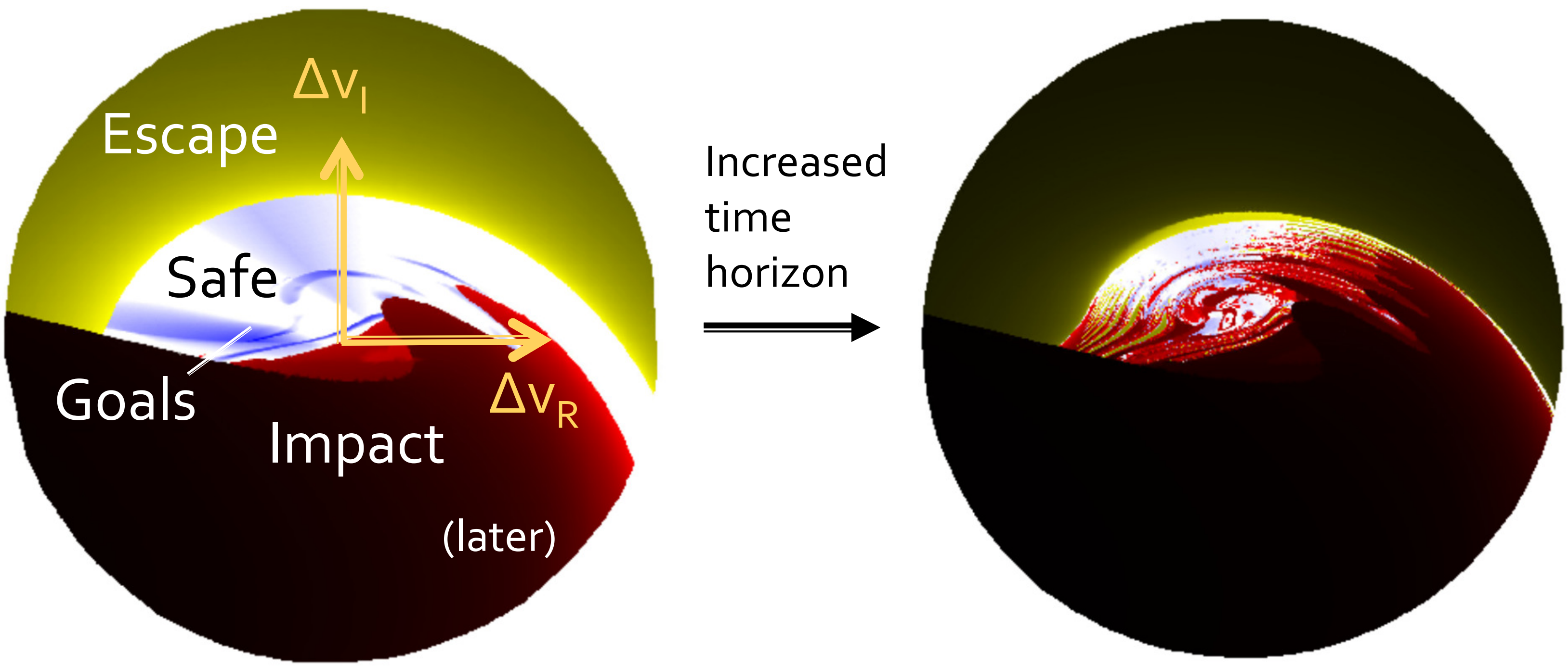

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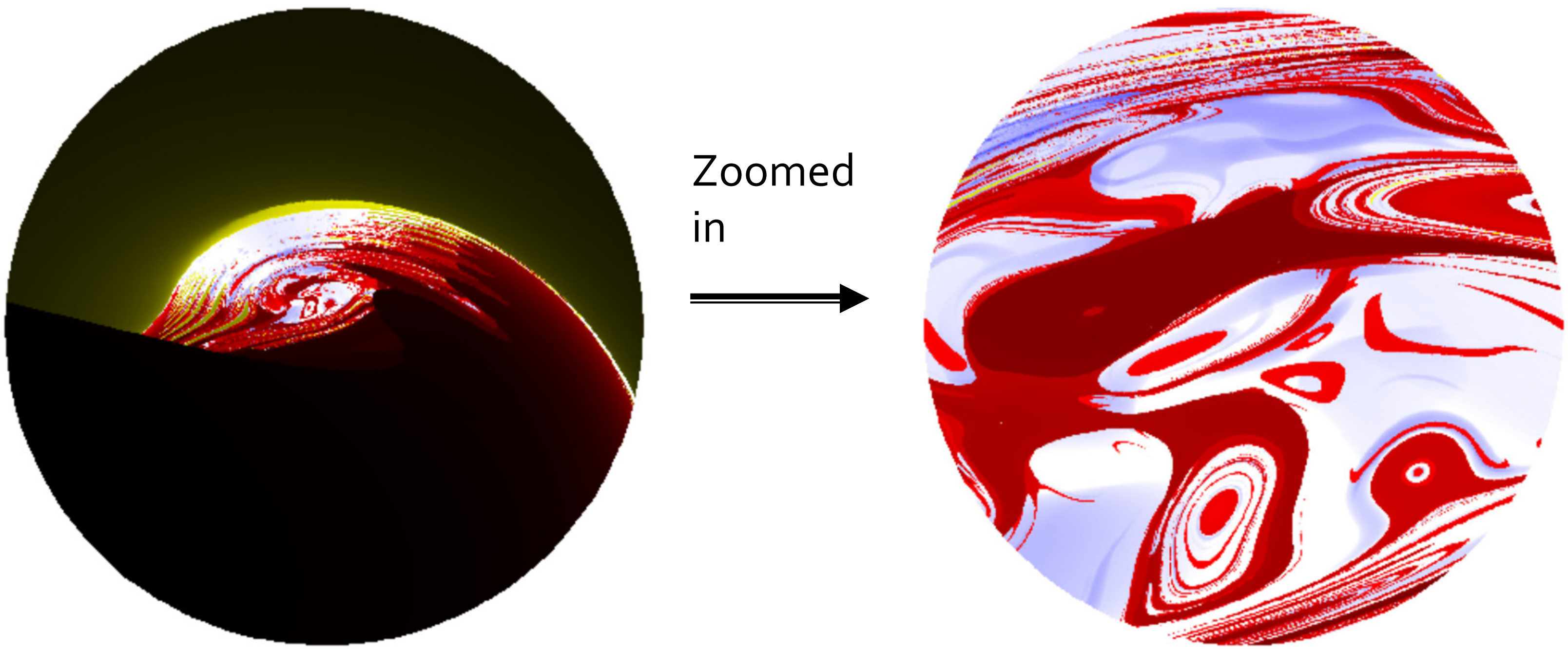

Non-Keplerian Reachability

Non-Keplerian system: Martian moon Phobos (strong tides)

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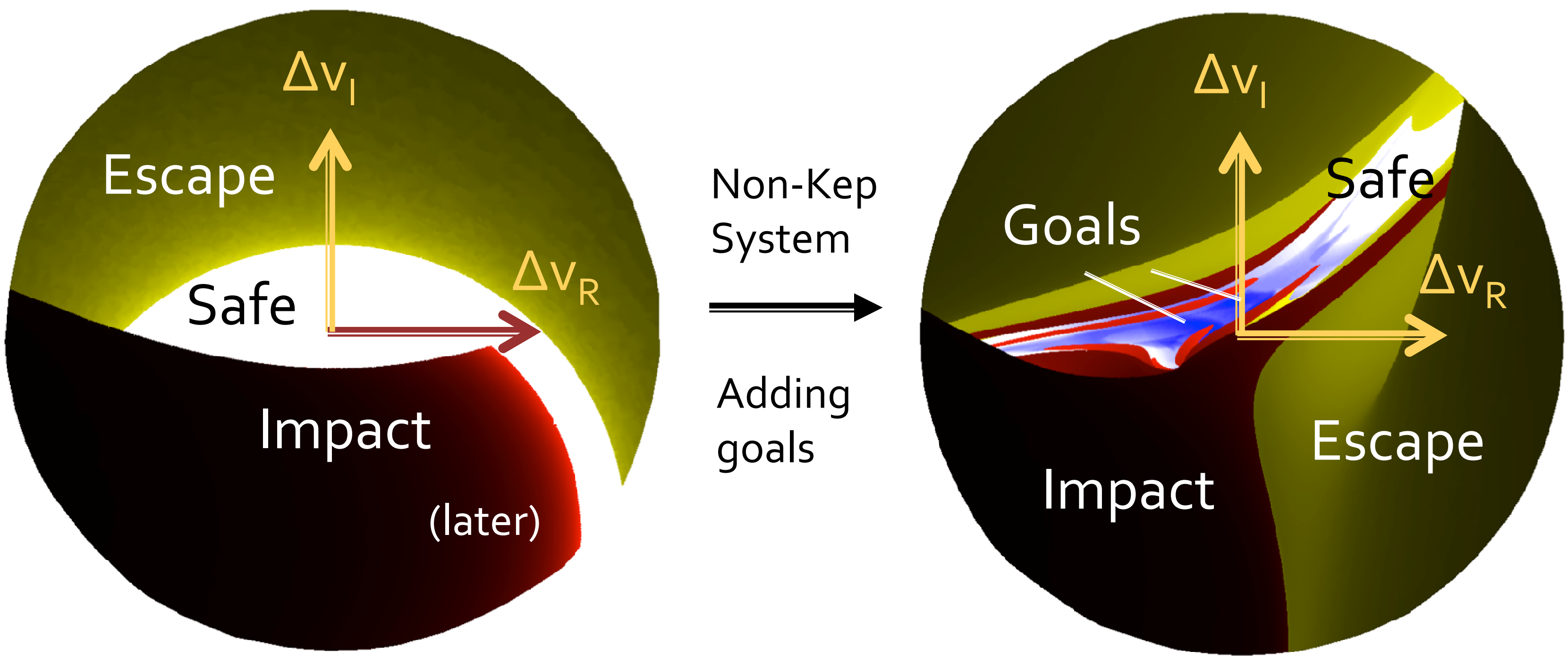

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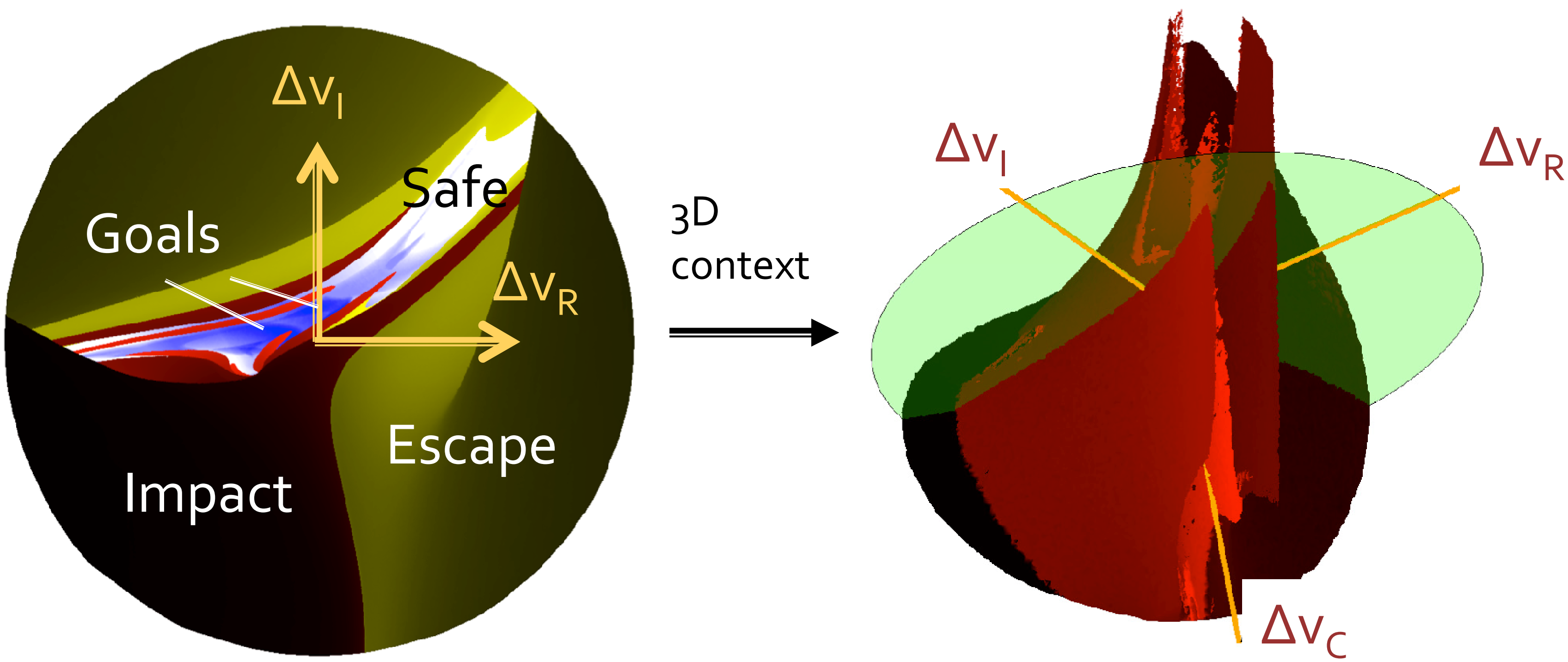
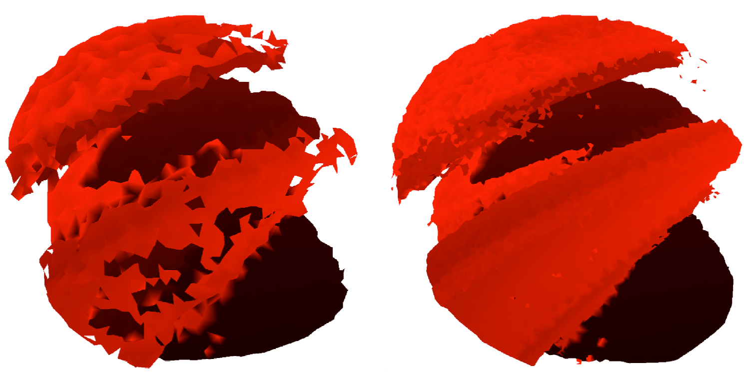
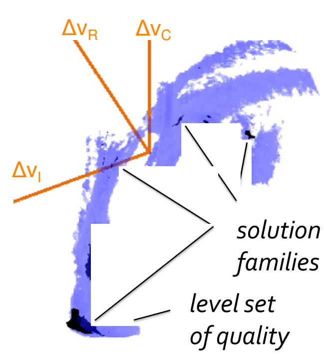


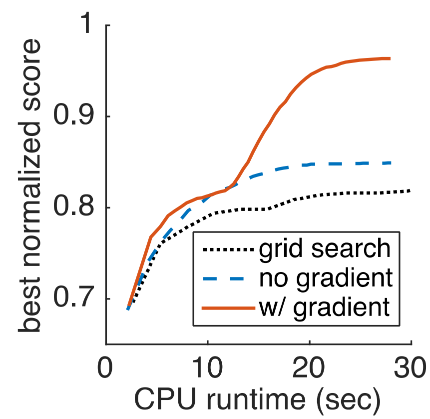
Reachability Computation

Heuristic-guided refinement

- Numerically propagate results of sample control inputs
- Bias distribution of next sample set toward promising areas







(goal: maximize target viewing duration)

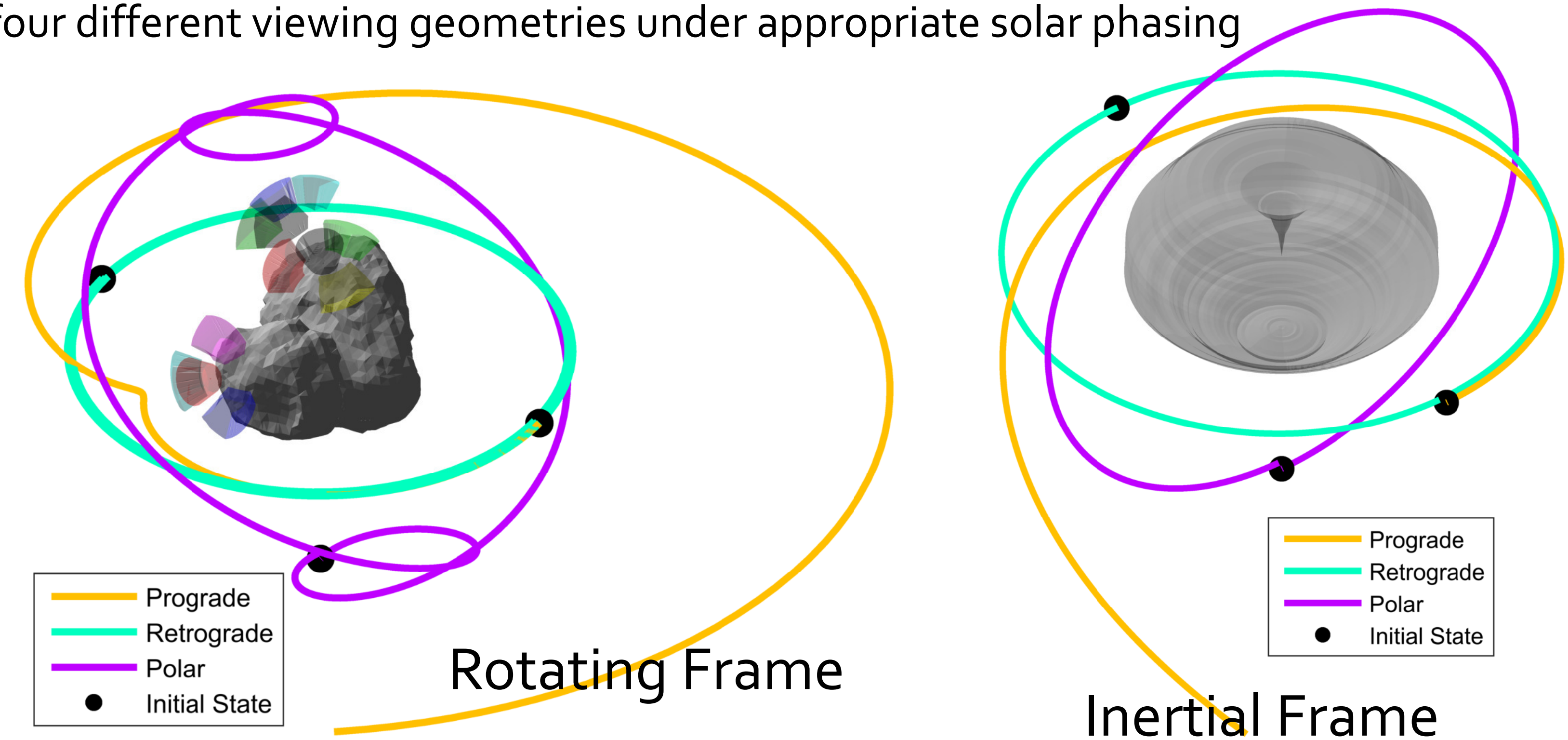
For visualization

For objective maximization during online planning

Temporal Reachability Analysis

System: Comet 67/P Churyumov-Gerasimenko (highly non-spherical)

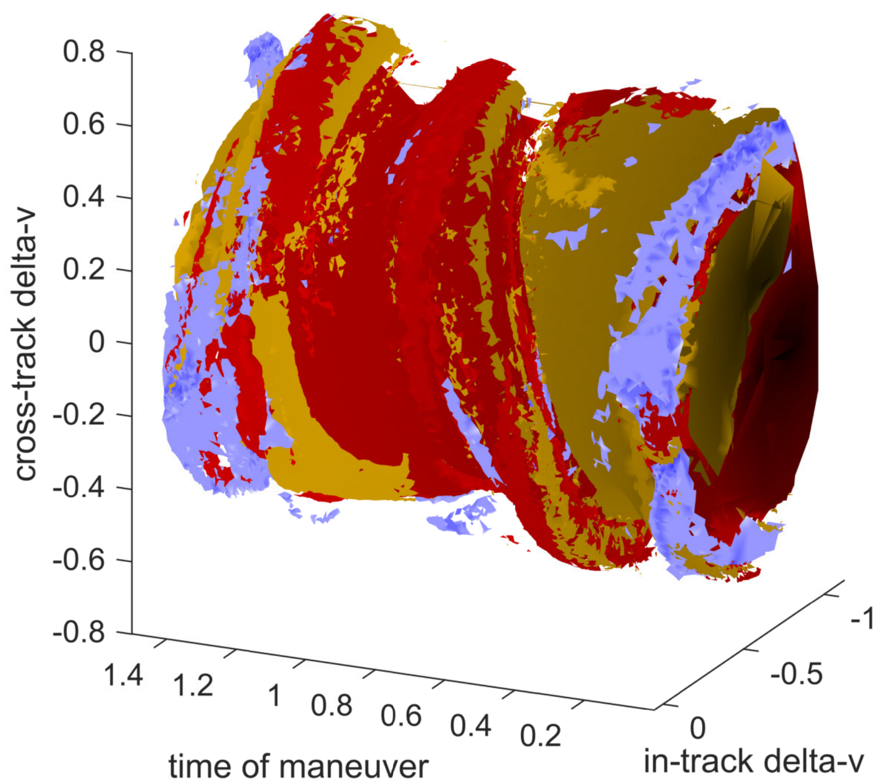
Objective: perform close-range imaging of candidate landing sites A, C, and J with four different viewing geometries under appropriate solar phasing

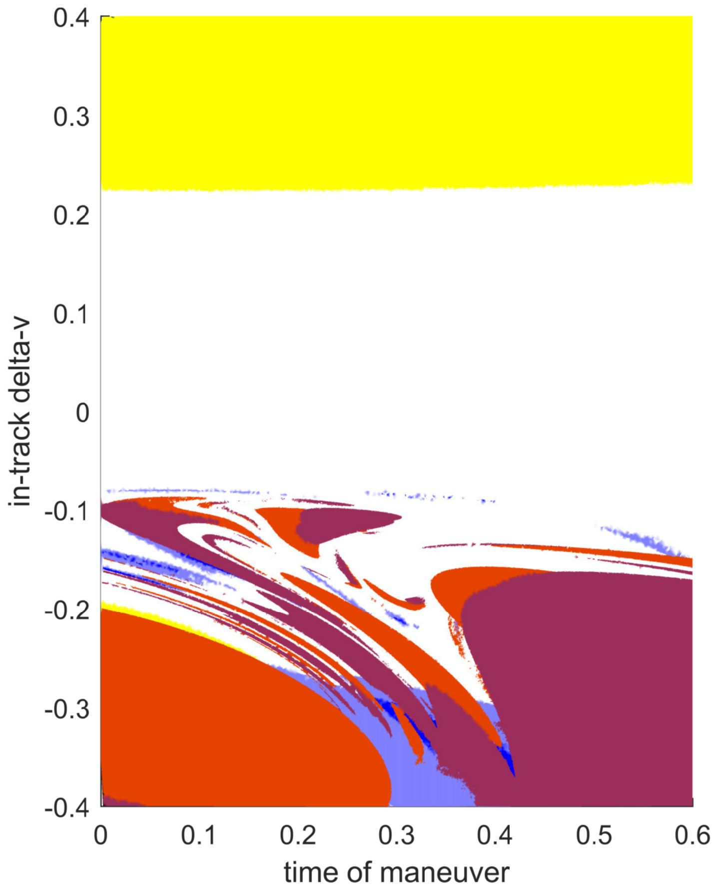


Nominal trajectories associated with reachability analysis domains

Temporal Reachability Analysis

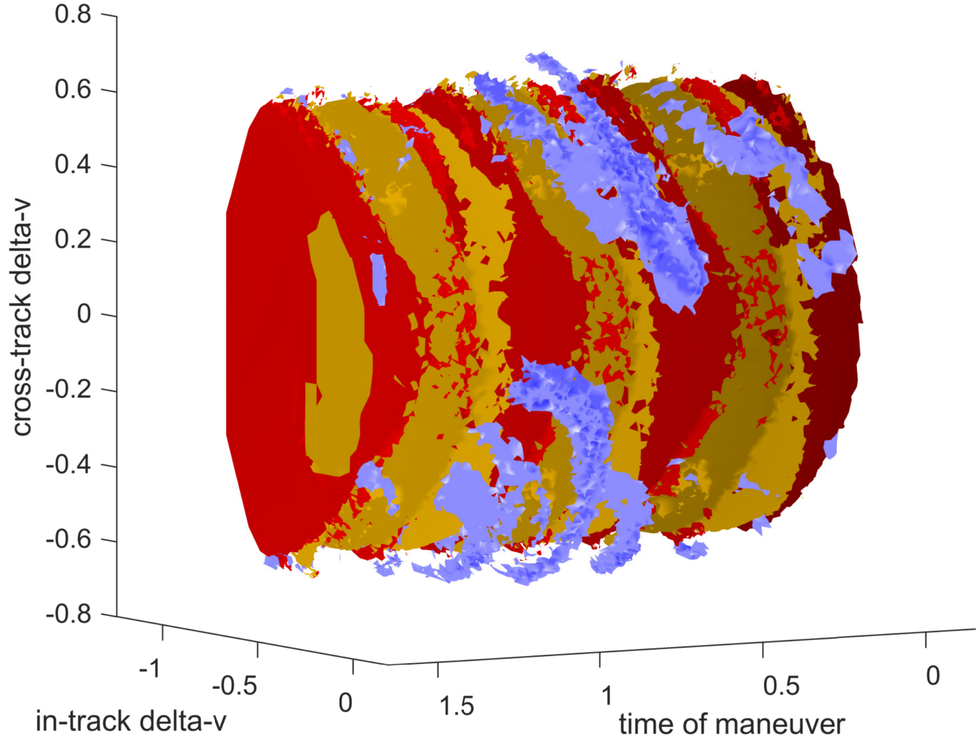
Reachability from polar orbit

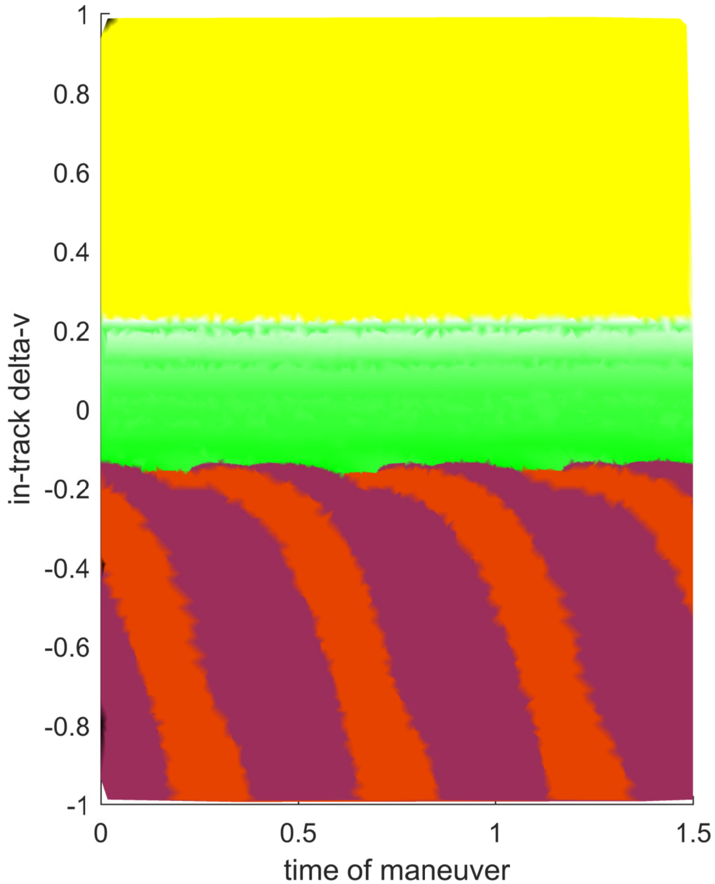




Temporal Reachability Analysis

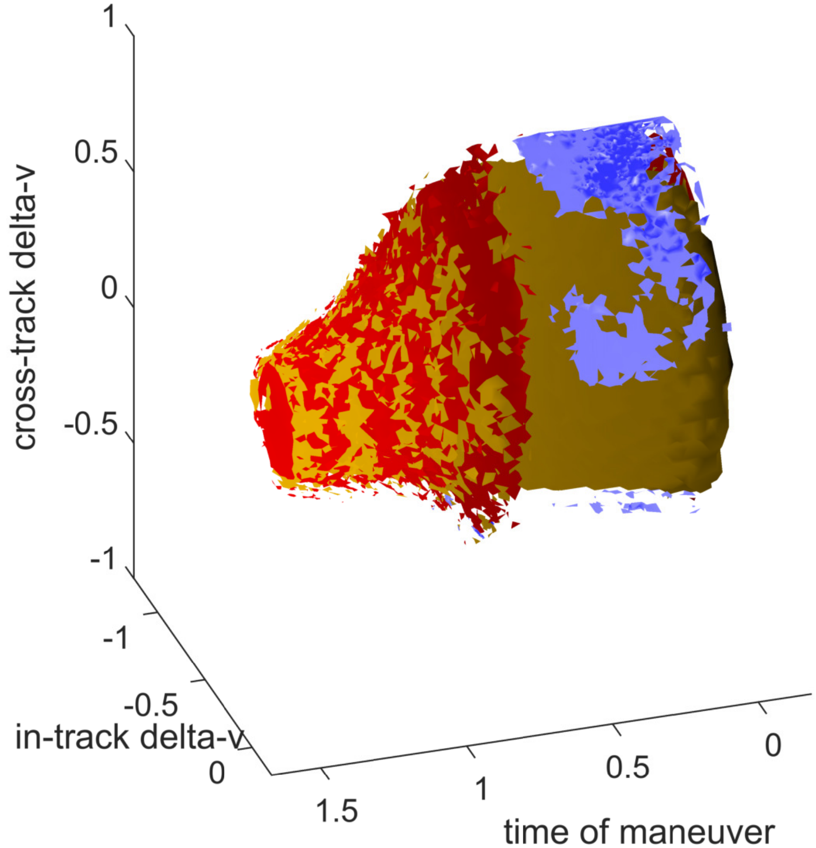
Reachability from retrograde orbit

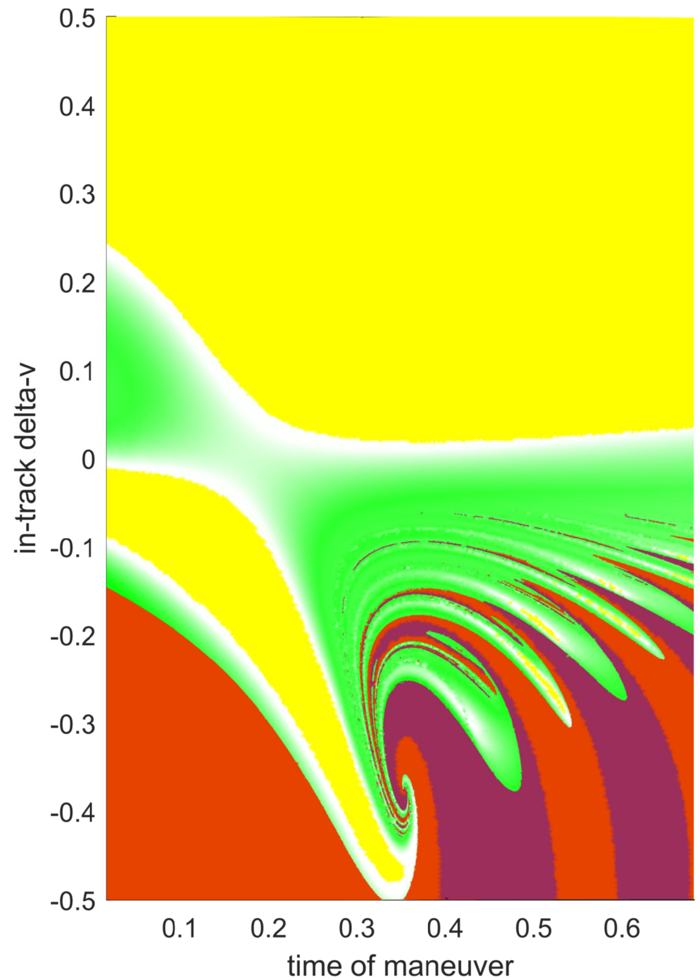




Temporal Reachability Analysis

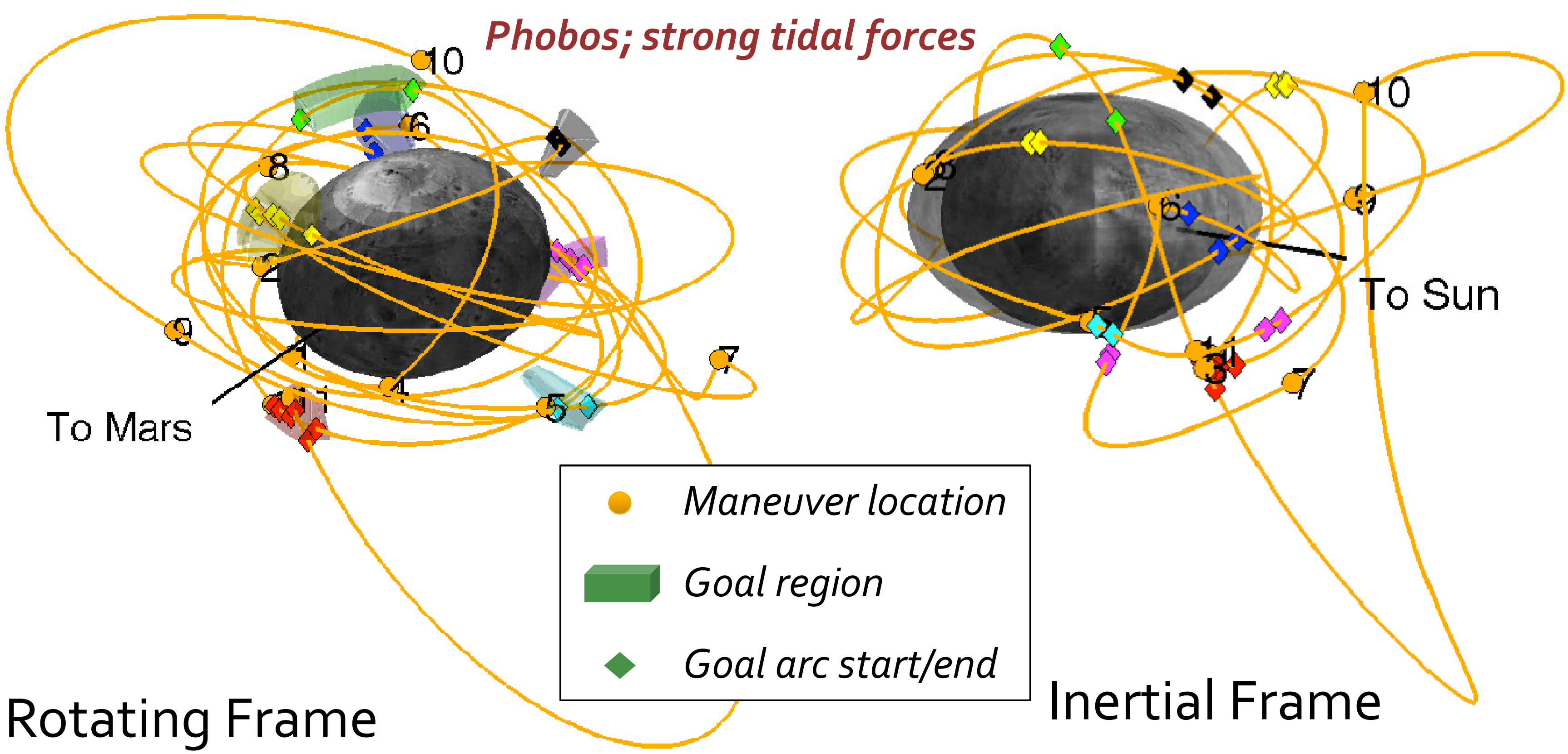
Reachability from prograde orbit





Receding Horizon Scheme

Decision metric: balance new progress within planning horizon against heuristic indicators of future prospects



Robust Planning

- State Transition Matrix gives a linearized description of divergence

$$\Phi(t;t_0) \quad \int_{t_0}^{t} \frac{\mathrm{d}\mathbf{f}}{\mathrm{d}\mathbf{x}}\bigg|_{\mathbf{x}(\tau)} \mathrm{d}\tau \quad \begin{bmatrix} \phi_{\mathbf{rr}}(t) & \phi_{\mathbf{rv}}(t) \\ \phi_{\mathbf{vr}}(t) & \phi_{\mathbf{vv}}(t) \end{bmatrix}$$

- Consider position deviation only

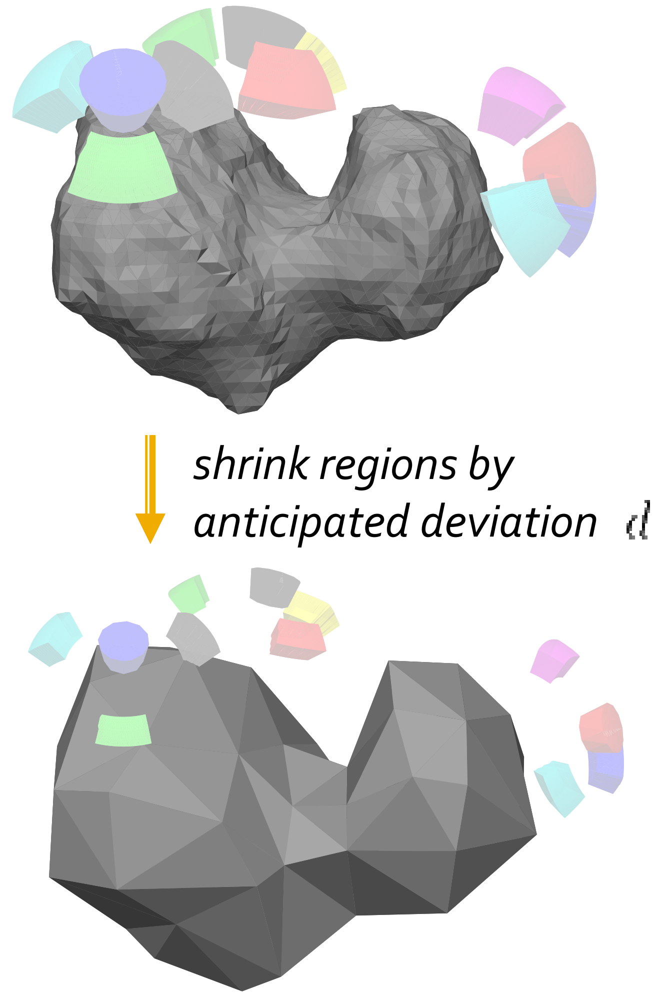
$$\mathbf{\Lambda}(t) \quad \phi_{\mathbf{rr}}(t;t_0)\delta\mathbf{r}(t_0) + \phi_{\mathbf{rv}}(t;t_0)\delta\mathbf{v}(t_0)$$

- Describe largest deviation magnitude expected under given uncertainty

$$\Lambda(t) \quad \lambda_{max}(\phi_{\mathbf{rr}})\sigma_r + \lambda_{max}(\phi_{\mathbf{rv}})\sigma_v$$

- Predict the worst-case outcome under an anticipated amount of deviation

$$d \quad \eta\Lambda \quad (\text{scaled}) \qquad d \quad \zeta \quad (\text{constant})$$



Results – Example Solutions

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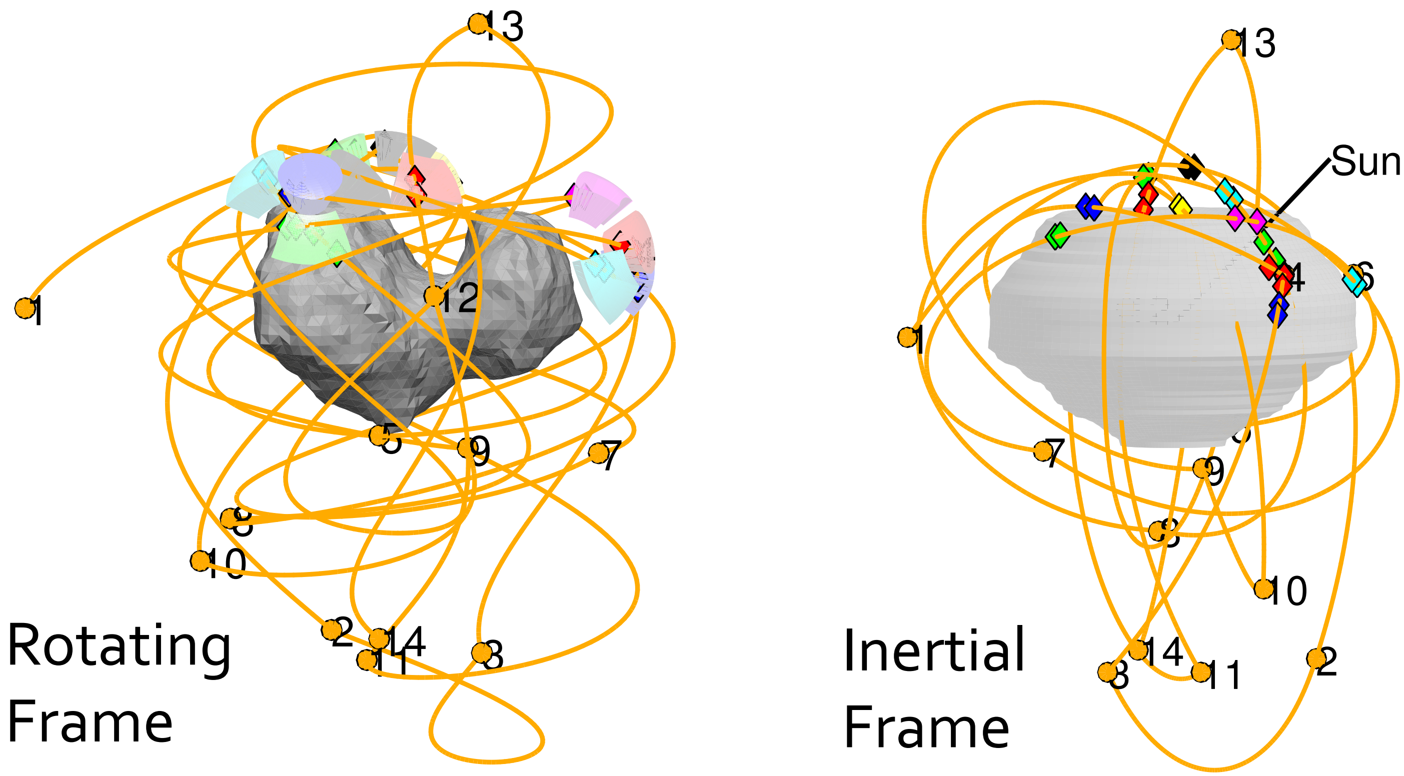

Conclusion

- Heuristics and a black-box predictive model enable a sampling-based approach to design complex operations in non-Keplerian systems without exhaustive search
- Single-impulse reachability analyses are useful for creating visualizations that aid preliminary mission design and analysis
- Receding-horizon implementation can be conducted onboard to construct a many-impulse solution profile
- A balance of robustness and feedback can be used to mitigate realistic levels of error in such a scenario

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Publications

[1] **D. A. Surovik** and D. J. Scheeres, "Reactive and robust paradigms for autonomous mission design at small bodies," *Journal of Guidance, Control, and Dynamics*, (submitted).

[2] **D. A. Surovik** and D. J. Scheeres, "Abstraction predictive control for chaotic spacecraft orbit design," in *IFAC Conference on Nonlinear Model Predictive Control*, Sep. 2015, (67% acceptance rate).

[3] **D. A. Surovik** and D. J. Scheeres, "Heuristic search and receding-horizon planning in complex spacecraft orbit domains," in *International Conference on Automated Planning and Scheduling*, Jun. 2015, (33% acceptance rate).

[4] **D. A. Surovik** and D. J. Scheeres, "Adaptive reachability analysis to achieve mission objectives in strongly non-keplerian systems," *Journal of Guidance, Control, and Dynamics*, vol. 38, no. 3, pp. 468–477, Mar. 2015.