Trajectory Design for Space Systems

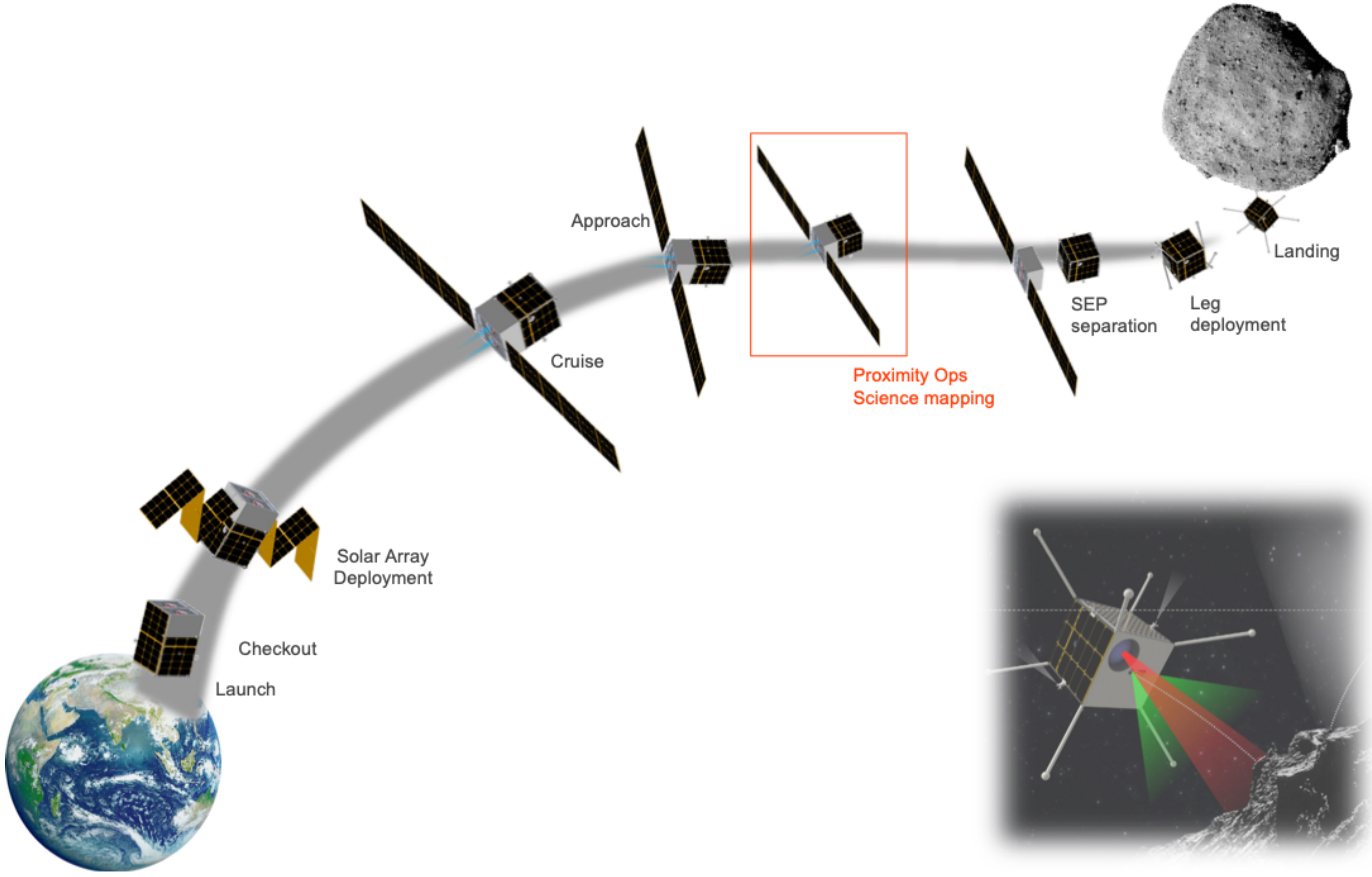
EN.530.626 (Fall 2025)

Lecture 24

Instructor: Prof. Abhishek Cauligi
Course Assistant 1: Arnab Chatterjee
Course Assistant 2: Mark Gonzales

Deep-space Autonomous Robotic Explorer (DARE)

- Mission concept for an autonomous small satellite mission for small body exploration



Reviewed and approved for public distribution via URS #329541

Deep-space Autonomous Robotic Explorer (DARE)

Modeling Considerations for Developing Deep Space Autonomous Spacecraft and Simulators

Project page: sites.google.com/stanford.edu/spacecraft-models

Christopher Agia[1*], Guillem Casadesus Vila[2], Saptarshi Bandyopadhyay[3], David S. Bayard[3], Kar-Ming Cheung[3], Charles H. Lee[3], Eric Wood[3], Ian Aenishanslin[4], Steven Ardito[3], Lorraine Fesq[3], Marco Pavone[2], Issa A. D. Nesnas[3]

[1]Department of Computer Science, Stanford University, California, U.S.A.
[2]Department of Aeronautics & Astronautics, Stanford University, California, U.S.A.
[3]Jet Propulsion Laboratory, California Institute of Technology, California, U.S.A.
[4]Institut Polytechnique des Sciences Avancées, Ivry-sur-Seine, France

*Corresponding author. Email: cagia@stanford.edu

***Abstract*— Over the last two decades, space exploration systems have incorporated increasing levels of onboard autonomy to perform mission-critical tasks in time-sensitive scenarios or to bolster operational productivity for long-duration missions. Such systems use *models* of spacecraft subsystems and the environment to enable the execution of autonomous functions (*functional-level autonomy*) within limited time windows and/or with constraints. These models and constraints are carefully crafted by experts on the ground and uploaded to the spacecraft via prescribed safe command sequences for the spacecraft to execute. Such practice is limited in its efficacy for scenarios that demand greater operational flexibility.**

To extend the limited scope of autonomy used in prior missions for operation in distant and complex environments, there is a need to further develop and mature autonomy that jointly reasons over multiple subsystems, which we term *system-level autonomy*. System-level autonomy establishes situational awareness that resolves conflicting information across subsystems, which may necessitate the refinement and interconnection of the underlying spacecraft and environment onboard models. However, with a limited understanding of the assumptions and tradeoffs of modeling to arbitrary extents, designing onboard models to support system-level capabilities presents a significant challenge. For example, simple onboard models that exclude cross-subsystem effects may compromise the efficacy of an autonomous spacecraft, while complex models that capture interdependencies among spacecraft subsystems and the environment may be infeasible to simulate under the real-world operating constraints of the spacecraft (*e.g.*, limited access to spacecraft and environment states, and computational resources).

In this paper, we provide a detailed analysis of the increasing levels of model fidelity for several key spacecraft subsystems, with the goal of informing future spacecraft functional- and system-level autonomy algorithms and the physics-based simulators on which they are validated. We do not argue for the adoption of a particular fidelity class of models but, instead, highlight the potential tradeoffs and opportunities associated with the use of models for onboard autonomy and in physics-based simulators at various fidelity levels. We ground our analysis in the context of deep space exploration of small bodies, an emerging frontier for autonomous spacecraft operation in space, where the choice of models employed onboard the spacecraft may determine mission success. We conduct our experiments in the Multi-Spacecraft Concept and Autonomy Tool (MuSCAT), a software suite for developing spacecraft autonomy algorithms.

979-8-3503-0462-6/24/$31.00 ©2024 IEEE. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was also supported by the National Aeronautics and Space Administration under the Innovative Advanced Concepts (NIAC) program.

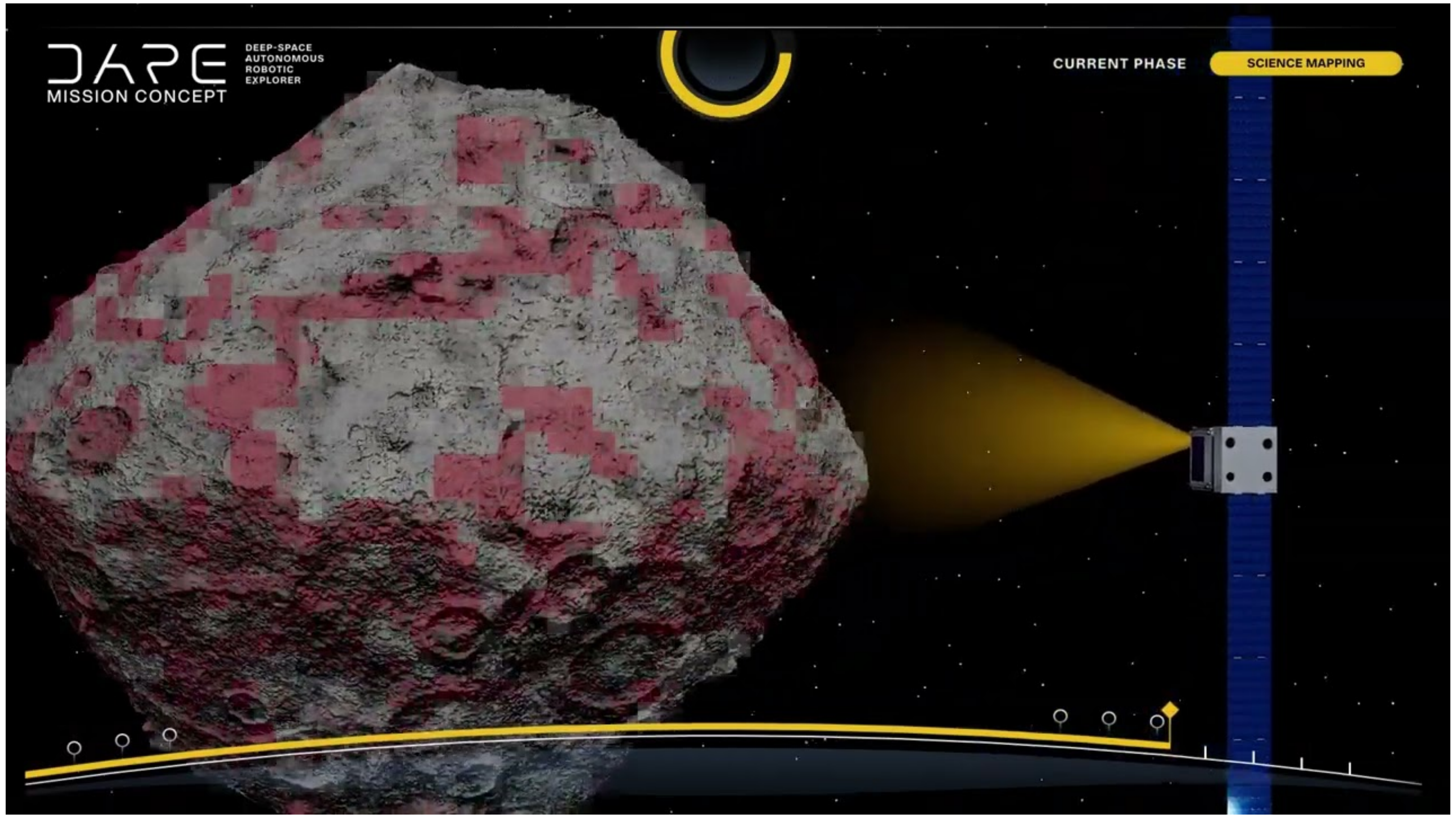
Table of Contents

1. Introduction 1
2. Related Work 2
3. Case Study: Autonomous Exploration of Small Bodies 3
4. Preliminaries 5
5. Power Subsystem 5
6. Attitude GNC Subsystem 8
7. Navigation Subsystem 10
8. Communication Subsystem 11
9. Discussion 13
10. Conclusion 14
Acknowledgments 15
Appendix 15
References 16
Biography 19

1. Introduction

There is an escalating demand for spacecraft that feature increasing levels of onboard autonomy, defined as the ability of the spacecraft to achieve mission goals independent of external control (*i.e.*, ground control) [1]. The need for spacecraft onboard autonomy is motivated by enabling new exploration missions, increasing productivity, enhancing robustness, and eventually reducing operations cost [2]. For example, the exploration of distant worlds with dynamic environments that are not well characterized *a priori* may not be feasible with state-of-the-practice ground-in-the-loop operations. In such situations, large uncertainties and communication constraints reduce the ability of ground experts to assess the states of the spacecraft and environment, predict outcomes, and prescribe command sequences in a timely manner. Some future missions may only be viable with onboard decision making, reasoning, and taking actions that achieve goals while assuring spacecraft safety, each of which is predicated upon establishing robust situational awareness. Other missions may benefit from increased productivity and robustness driven by onboard autonomy capable of reducing uncertainties and carrying out risk- and time-sensitive tasks across various mission phases.

Developing adequate *models* of spacecraft subsystems (also referred to as *subsystem models*) is among the most impor-

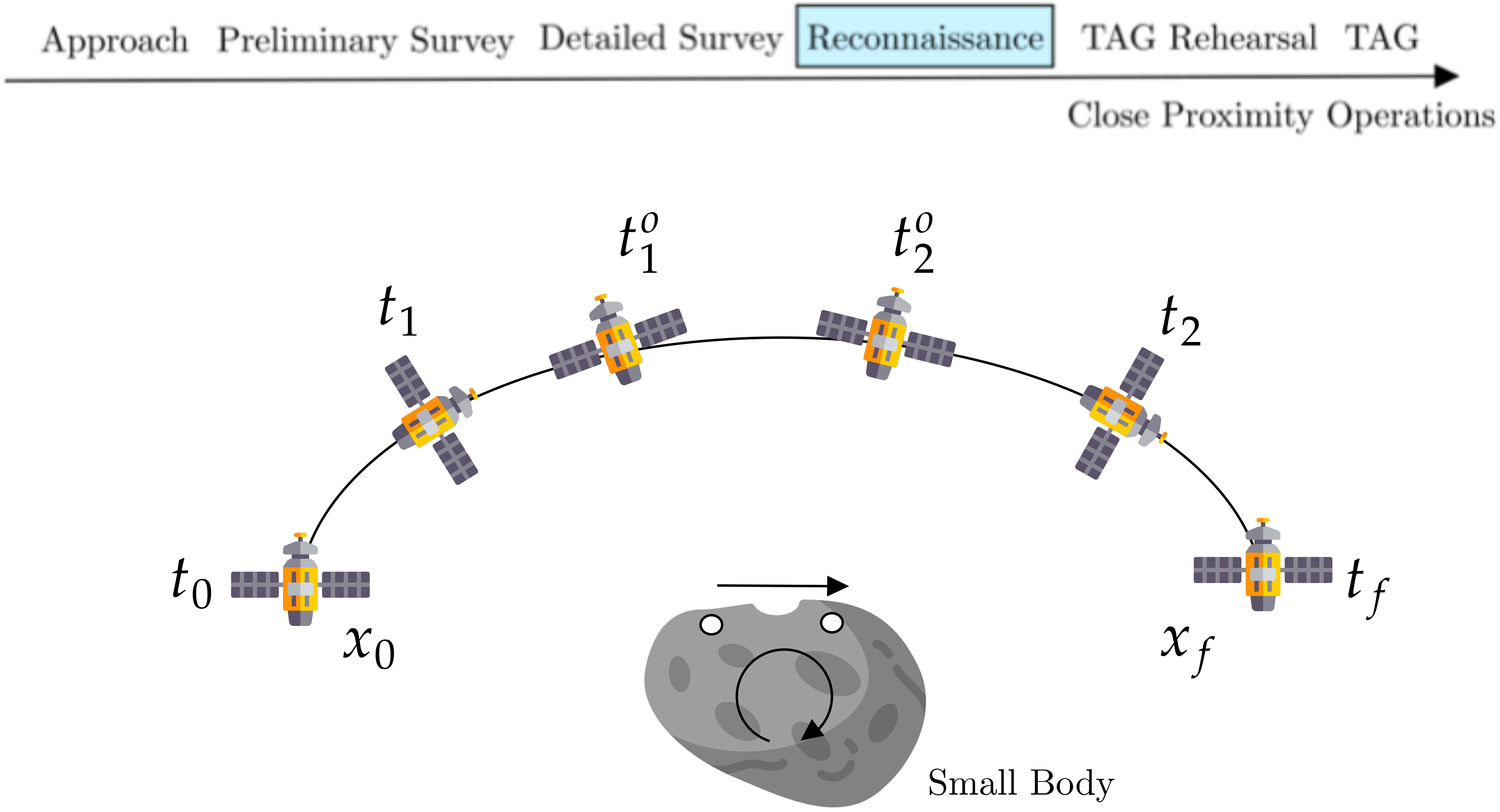


https://youtu.be/ejP_IDua6J0

Reviewed and approved for public distribution via URS #329541

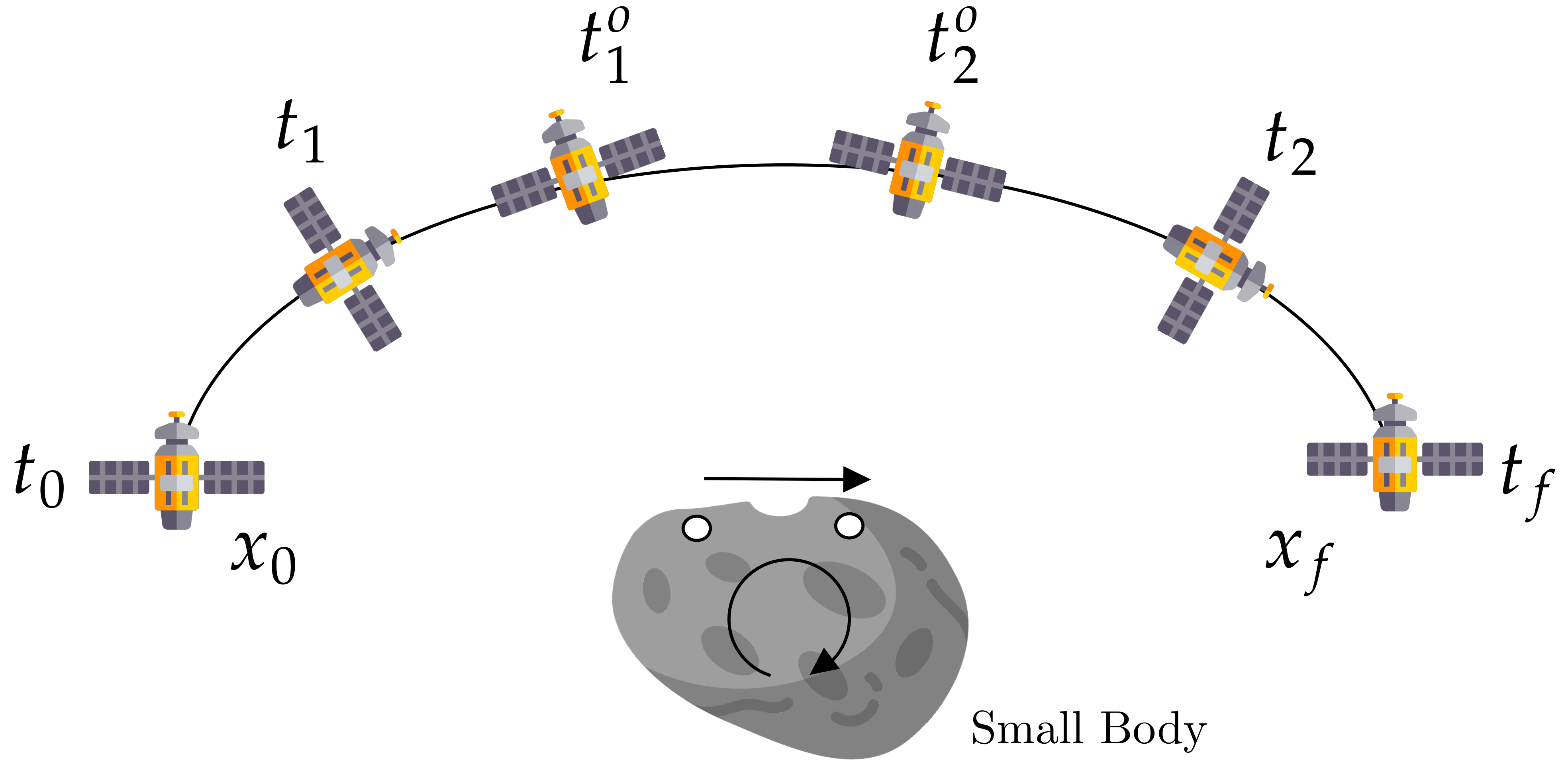
Autonomous trajectory planning

- Goal: autonomous trajectory planner considering uncertainty



Autonomous trajectory planning

Stochastic optimal control approach

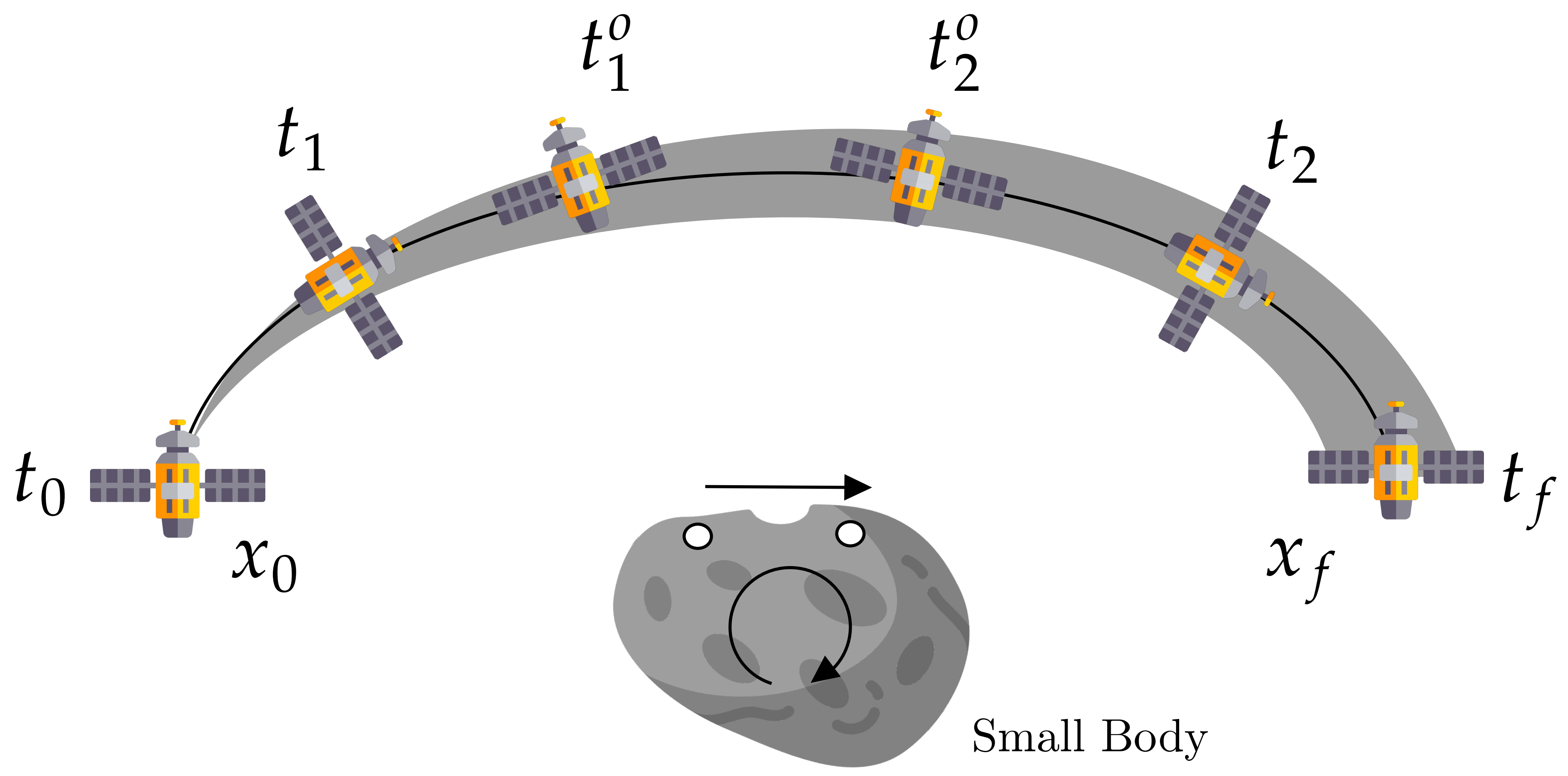


$$\min_{u} \quad \int_{t_0}^{t_f} \|u(t)\|_2 \, \mathrm{d}t$$
$$\text{s.t.} \quad \dot{x}(t) = f(x(t), u(t), t),$$
$$x(t) \in \mathcal{X}, \quad u(t) \in \mathcal{U}$$

Solution to the optimization problem is the nominal trajectory satisfying all mission constraints

Autonomous trajectory planning

Stochastic optimal control approach



$$\min_{u} \quad \int_{t_0}^{t_f} \|u(t)\|_2 \ \mathrm{d}t$$

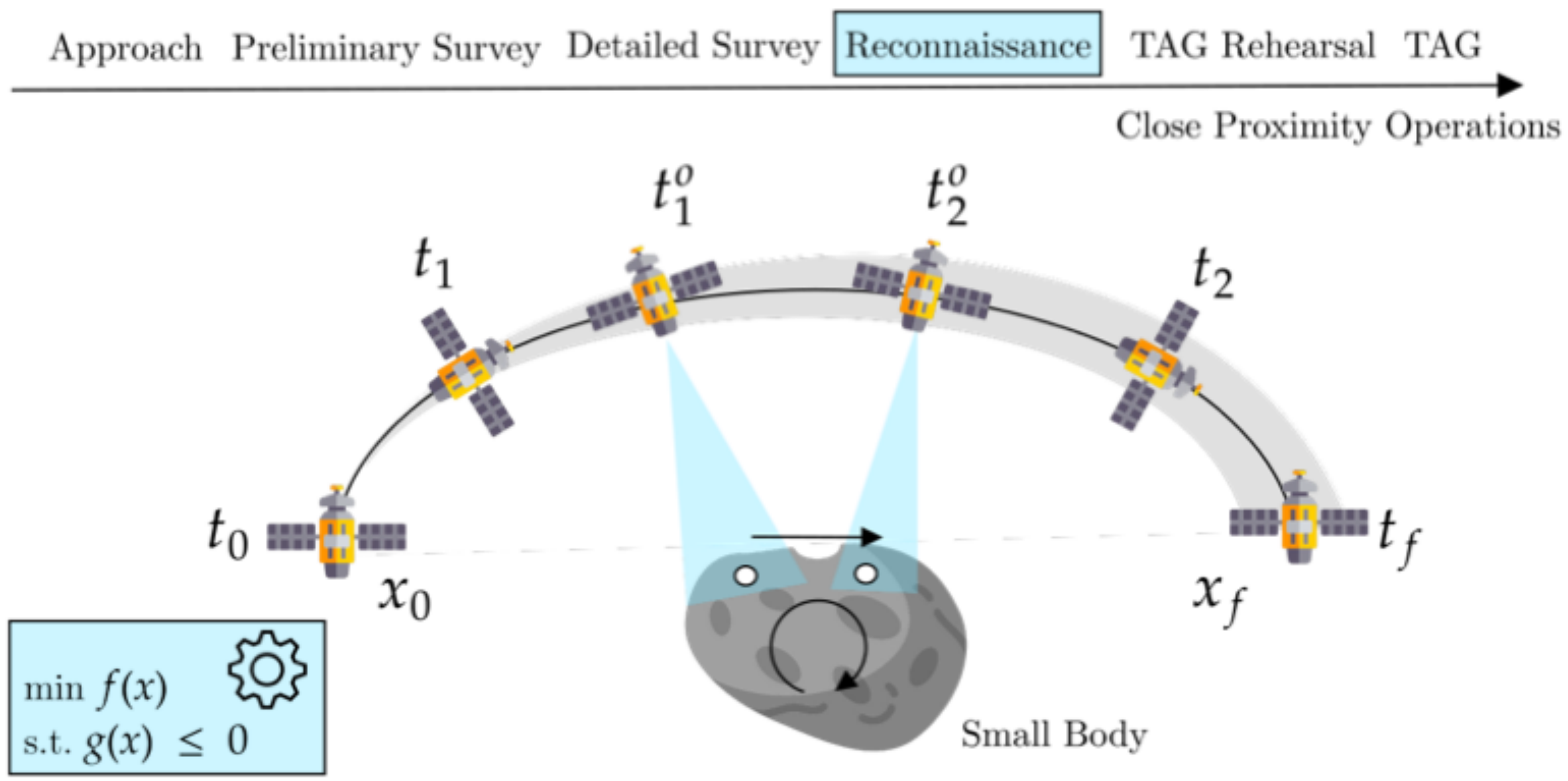
$$\text{s.t.} \quad \mathrm{d}x = f(x(t), u(t), t)\mathrm{d}t + G(x(t), u(t), t)\mathrm{d}\omega,$$

$$\rho(x(t)) \in \mathcal{X}, \quad u(t) \in \mathcal{U}$$

Solution to the stochastic optimal control problem is the nominal trajectory satisfying all mission constraints with its deviation also satisfying all safety constraints

Autonomous trajectory planning

Stochastic optimal control approach



- Minimize fuel usage
- Spacecraft satisfies dynamics under uncertainty
- Keep battery state-of-charge
- Enable thruster to fire four times
- Avoid the impact at *p* percentile
- Satisfy boundary conditions
- During $t_1^o < t < t_2^o$, spacecraft must meet all observation constraints more than *p*%

Validating model fidelity

min Fuel

s.t. $x_{sc}(t)$ follows 3DOF Stochastic Dynamics

1) Single Point Mass + J2
2) Cannonball SRP
3) Thruster & Localization Uncertainty
4) $x_{sc}(t)$ is Modeled as Gaussian
5) Model the Propagation as EKF

Thrust can fire 4 times, modeled as Dirac Delta

Boundary Conditions

Keep the Battery SoC above the Min Threshold during DeltaV

Avoid the asteroid with $p\%$

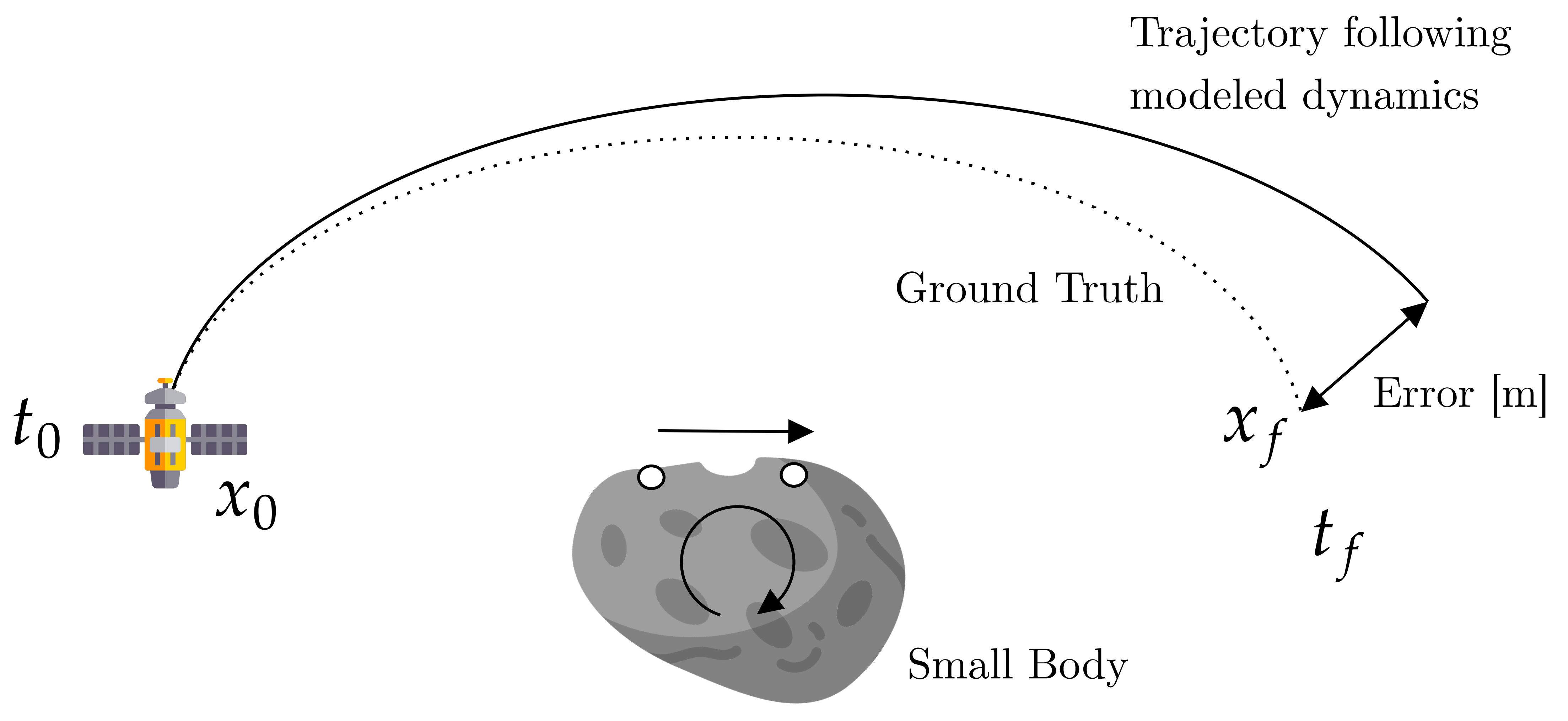
If $t_1^o \leq t \leq t_2^o$ (Observation)

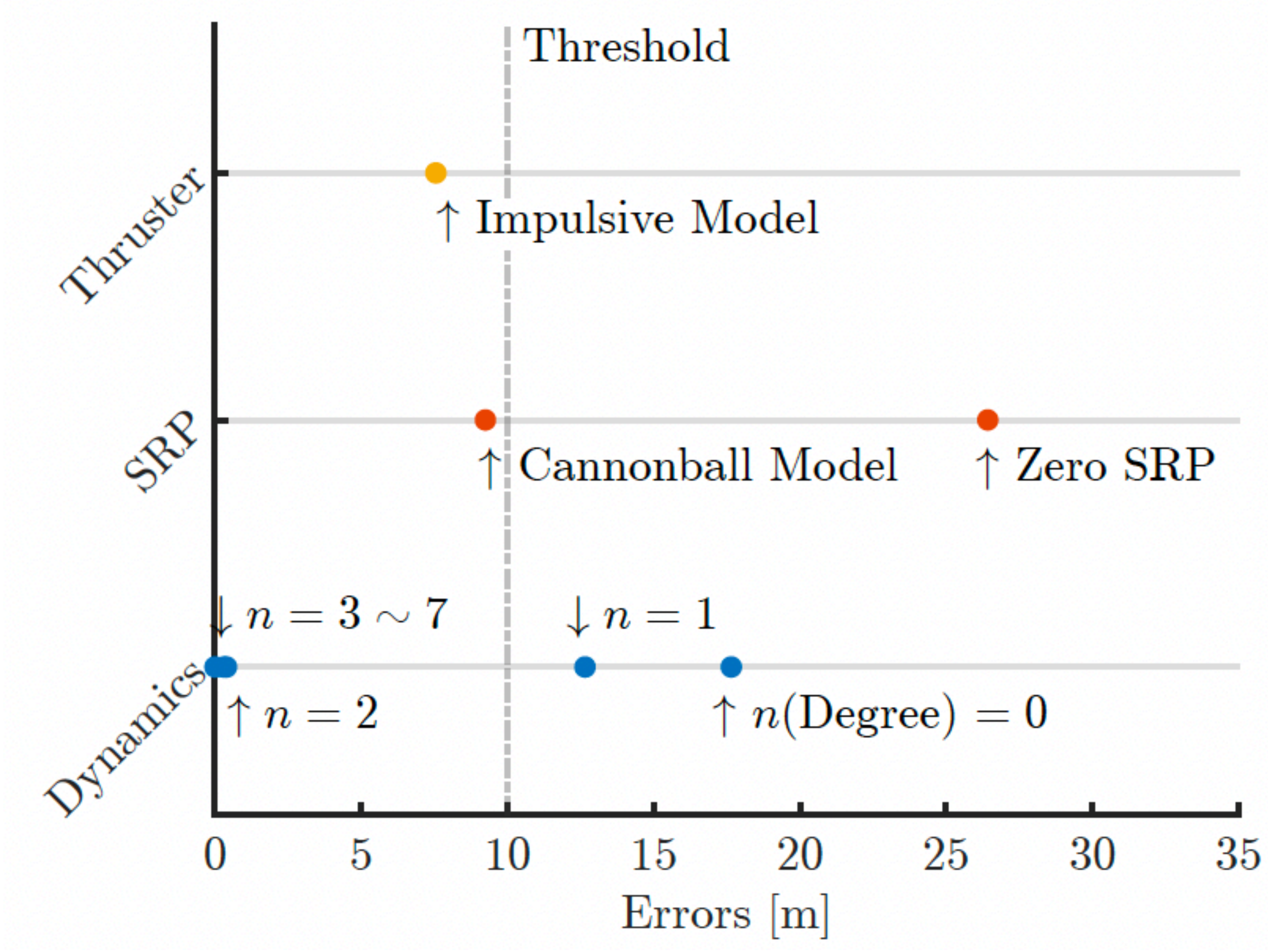
Remain in the observable region with $p\%$

Keep the Battery SoC above the Min Threshold with $p\%$

Validating model fidelity

Dynamics modeling





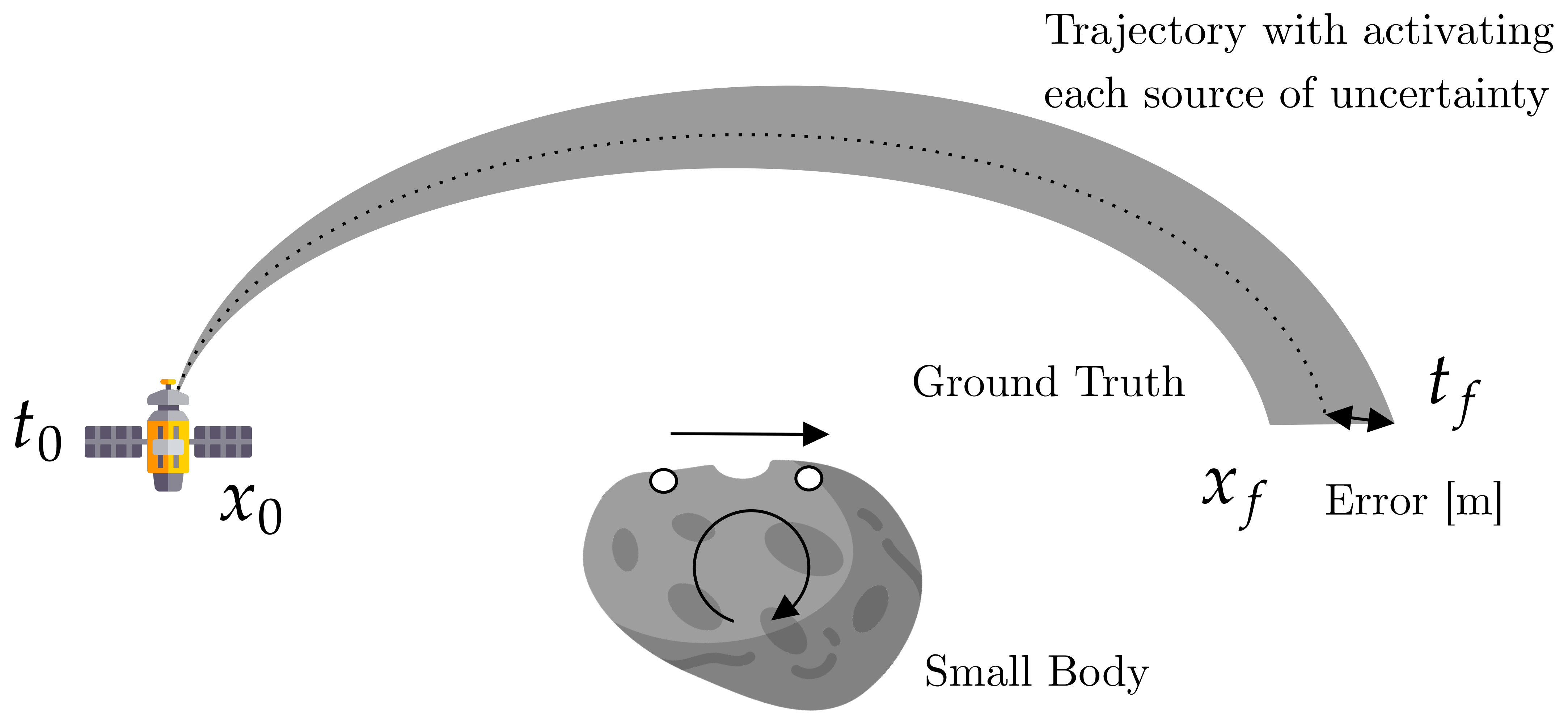
Chosen model: impulsive thrusts + cannonball model + J2 perturbation

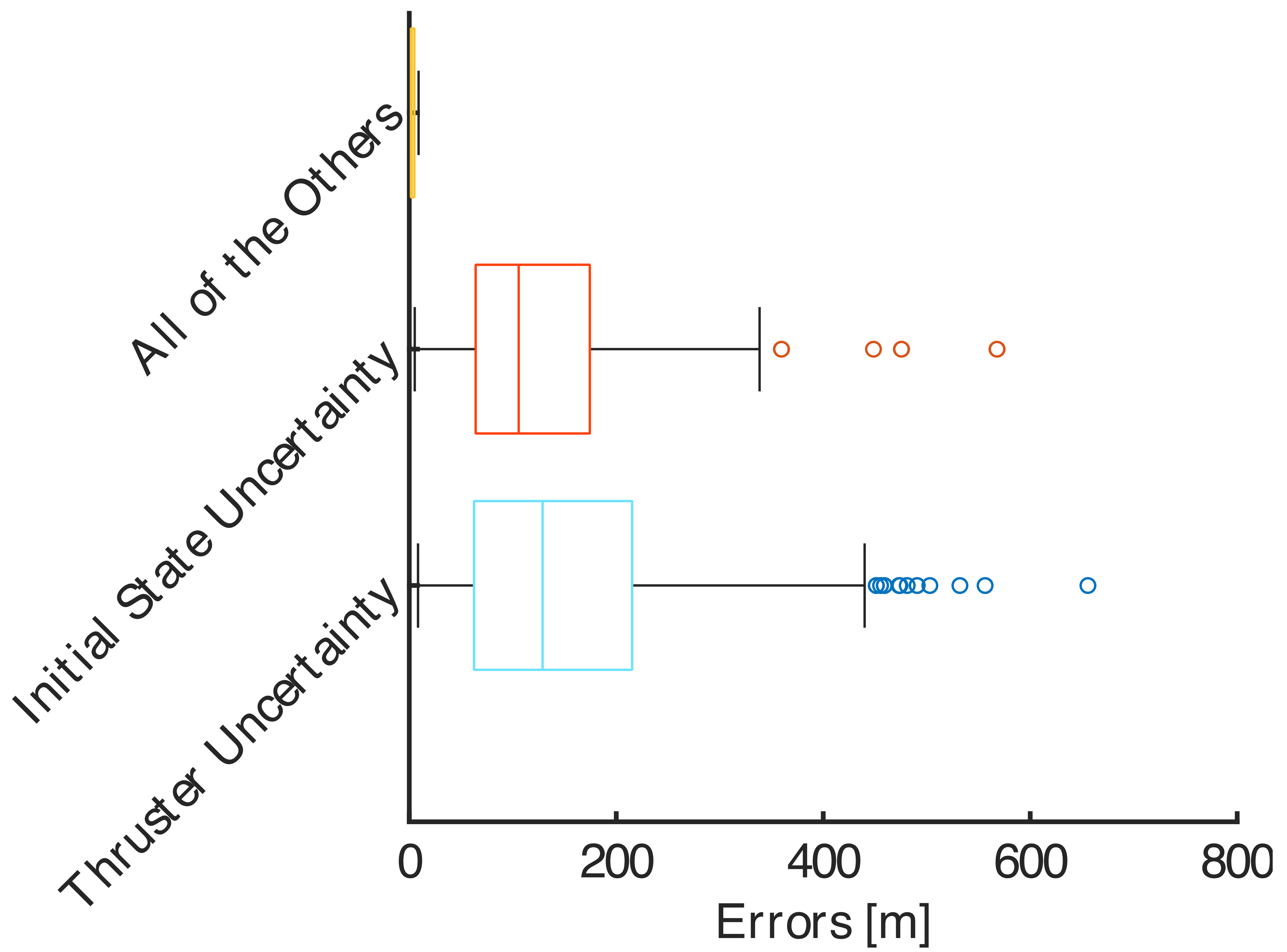
Validating model fidelity

min	Fuel
s.t.	$x_{sc}(t)$ follows 3DOF Stochastic Dynamics
	1) Single Point Mass + J2
	2) Cannonball SRP
	3) Thruster & Localization Uncertainty
	4) $x_{sc}(t)$ is Modeled as Gaussian
	5) Model the Propagation as EKF
	Thrust can fire 4 times, modeled as Dirac Delta
	Boundary Conditions
	Keep the Battery SoC above the Min Threshold during DeltaV
	Avoid the asteroid with $p\%$
	If $t_1^o \leq t \leq t_2^o$ (Observation)
	Remain in the observable region with $p\%$
	Keep the Battery SoC above the Min Threshold with $p\%$

Validating model fidelity

Dispersion from uncertainties





Initial state and thruster uncertainties are main sources of dispersion

Validating model fidelity

min Fuel

s.t. $x_{sc}(t)$ follows 3DOF Stochastic Dynamics

1) Single Point Mass + J2
2) Cannonball SRP
3) Thruster & Localization Uncertainty
4) $x_{sc}(t)$ is Modeled as Gaussian
5) Model the Propagation as EKF

Thrust can fire 4 times, modeled as Dirac Delta

Boundary Conditions

Keep the Battery SoC above the Min Threshold during DeltaV

Avoid the asteroid with $p\%$

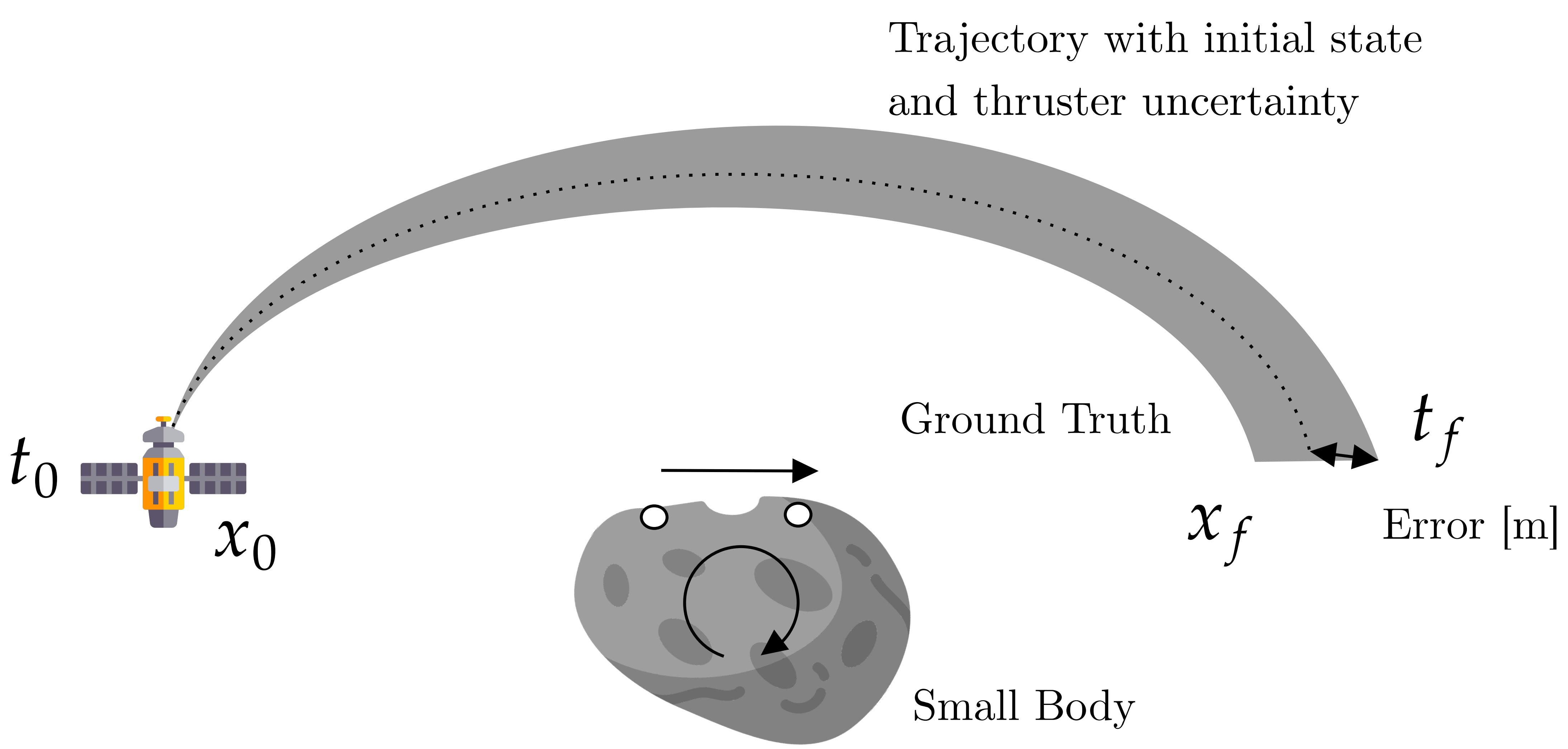
If $t_1^o \leq t \leq t_2^o$ (Observation)

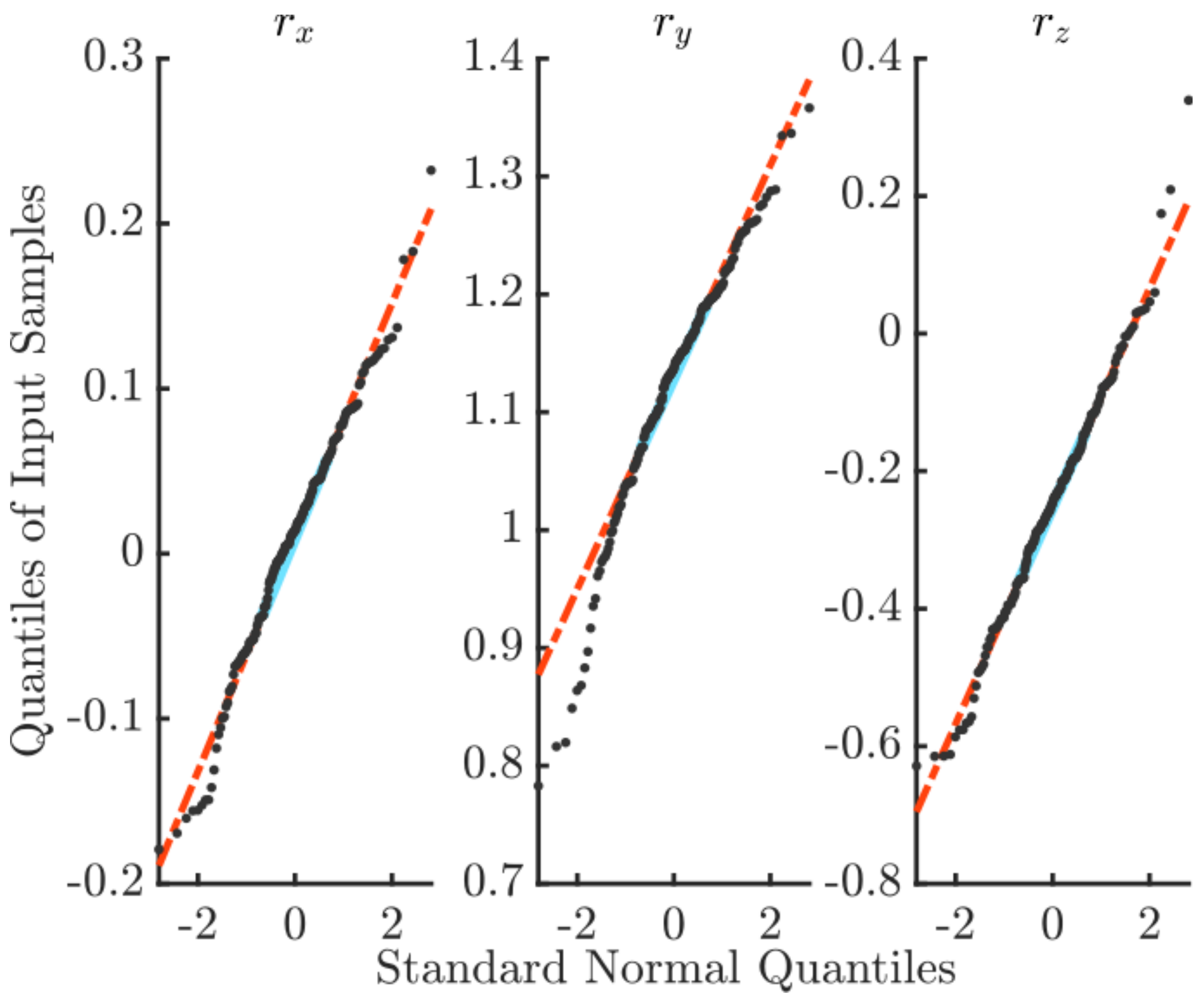
Remain in the observable region with $p\%$

Keep the Battery SoC above the Min Threshold with $p\%$

Validating model fidelity

Gaussian uncertainty quantification





Sate uncertainty can be reasonably modeled as Gaussian

Hierarchical Asteroid Reconnaissance Planner (HARP)

$$
\begin{aligned}
\min_{\boldsymbol{\Delta v}_k, \Delta t} \quad & \sum_{k \in \{k_0, k_1, k_4, k_5\}} \|\boldsymbol{\Delta v}_k\|_2, \\
\text{s.t.} \quad & \mathbf{x}_k = \begin{cases} F(\mathbf{x}_{k-1},\ k-1) + [\mathbf{0}_{3\times1},\ \boldsymbol{\Delta v}_k^\top]^\top + \beta[\mathbf{0}_{3\times1},\ (\boldsymbol{\Delta v}_k \circ \boldsymbol{\omega}_k)^\top]^\top & (k \in \{k_0, k_1, k_4, k_5\}) \\ F(\mathbf{x}_{k-1},\ k-1) & (k \notin \{k_0, k_1, k_4, k_5\})' \end{cases} \\
& \|\boldsymbol{\Delta v}_k\|_2 \leq \Delta v_{\max}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \mathbf{x}_0 \sim \mathcal{N}(\mathbf{x}_{t_0}, \boldsymbol{\Sigma}_{t_0}), \quad \mathbb{E}(\mathbf{x}_N) = \mathbf{x}_{t_f}, \\
& \frac{(\boldsymbol{\Delta v}_k)^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\boldsymbol{\Delta v}_k\|_2} \leq \cos\theta_{\text{deltaV}}, \quad \frac{(\boldsymbol{\Delta v}_k)^\top (-\hat{\mathbf{r}}_{\text{center}\to\text{sun}})}{\|\boldsymbol{\Delta v}_k\|_2} \leq \cos\theta_{\text{deltaV}}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \Pr(\|\mathbf{r}_k\|_2 \geq h_{\min}) \geq p_{\text{chance}}, \quad k = 0, \dots, N, \\
& \Pr\left(\frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{\text{obs}} \right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3, \\
& \Pr(d_1 \leq \|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2 \leq d_2) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3, \\
& \Pr\left(\cos\theta_{e2} \leq \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \mathbf{r}_{s\perp,k}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{e1} \right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3, \\
& \Pr\left(\cos\theta_{p2} \leq \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{p1} \right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3, \\
& \Delta t_i \leq 190, \quad \forall i = 0, \dots, 6, \\
& \Delta t_0 k_0 + \Delta t_1 (k_1 - k_0) + \Delta t_2 (k_2 - k_1) = t_1^o, \quad \Delta t_3 (k_3 - k_2) = t_2^o - t_1^o, \\
& \Delta t_j (k_j - k_{j-1}) \geq 2\Delta t_{\text{attitude}} + \Delta t_{\text{heat}} + \Delta t_{\text{SoC}}, \quad j = 1, 4, 5, \quad \Delta t_2 (k_2 - k_1) \geq 2\Delta t_{\text{attitude}} + \Delta t_{\text{SoC}}.
\end{aligned}
$$

Hierarchical Asteroid Reconnaissance Planner (HARP)

$$\min_{\boldsymbol{\Delta v}_k, \Delta t} \sum_{k \in \{k_0, k_1, k_4, k_5\}} \|\boldsymbol{\Delta v}_k\|_2,$$

Minimum fuel

$$\begin{aligned}
\text{s.t.} \quad & \mathbf{x}_k = \begin{cases} F(\mathbf{x}_{k-1},\ k-1) + [\mathbf{0}_{3\times1},\ \boldsymbol{\Delta v}_k^\top]^\top + \beta[\mathbf{0}_{3\times1},\ (\boldsymbol{\Delta v}_k \circ \boldsymbol{\omega}_k)^\top]^\top & (k \in \{k_0, k_1, k_4, k_5\}) \\ F(\mathbf{x}_{k-1},\ k-1) & (k \notin \{k_0, k_1, k_4, k_5\})' \end{cases} \\
& \|\boldsymbol{\Delta v}_k\|_2 \le \Delta v_{\max}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \mathbf{x}_0 \sim \mathcal{N}(\mathbf{x}_{t_0}, \boldsymbol{\Sigma}_{t_0}), \quad \mathbb{E}(\mathbf{x}_N) = \mathbf{x}_{t_f}, \\
& \frac{(\boldsymbol{\Delta v}_k)^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\boldsymbol{\Delta v}_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad \frac{(\boldsymbol{\Delta v}_k)^\top (-\hat{\mathbf{r}}_{\text{center}\to\text{sun}})}{\|\boldsymbol{\Delta v}_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \Pr(\|\mathbf{r}_k\|_2 \ge h_{\min}) \ge p_{\text{chance}}, \quad k = 0, \dots, N, \\
& \Pr\left(\frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{\text{obs}}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr(d_1 \le \|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2 \le d_2) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr\left(\cos\theta_{e2} \le \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \mathbf{r}_{s\perp,k}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{e1}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr\left(\cos\theta_{p2} \le \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{p1}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Delta t_i \le 190, \quad \forall i = 0, \dots, 6, \\
& \Delta t_0 k_0 + \Delta t_1 (k_1 - k_0) + \Delta t_2 (k_2 - k_1) = t_1^o, \quad \Delta t_3 (k_3 - k_2) = t_2^o - t_1^o, \\
& \Delta t_j (k_j - k_{j-1}) \ge 2\Delta t_{\text{attitude}} + \Delta t_{\text{heat}} + \Delta t_{\text{SoC}}, \quad j = 1, 4, 5, \quad \Delta t_2 (k_2 - k_1) \ge 2\Delta t_{\text{attitude}} + \Delta t_{\text{SoC}}.
\end{aligned}$$

Hierarchical Asteroid Reconnaissance Planner (HARP)

$$\min_{\boldsymbol{\Delta v}_k, \Delta t} \sum_{k \in \{k_0, k_1, k_4, k_5\}} \|\boldsymbol{\Delta v}_k\|_2,$$

$$\text{s.t.} \quad \mathbf{x}_k = \begin{cases} F(\mathbf{x}_{k-1},\ k-1) + [\mathbf{0}_{3\times1},\ \boldsymbol{\Delta v}_k^\top]^\top + \beta[\mathbf{0}_{3\times1},\ (\boldsymbol{\Delta v}_k \circ \boldsymbol{\omega}_k)^\top]^\top & (k \in \{k_0, k_1, k_4, k_5\}) \\ F(\mathbf{x}_{k-1},\ k-1) & (k \notin \{k_0, k_1, k_4, k_5\})\text{'} \end{cases}$$

Dynamics constraints

$$\|\boldsymbol{\Delta v}_k\|_2 \leq \Delta v_{\max}, \quad k \in \{k_0, k_1, k_4, k_5\},$$

$$\mathbf{x}_0 \sim \mathcal{N}(\mathbf{x}_{t_0}, \boldsymbol{\Sigma}_{t_0}), \quad \mathbb{E}(\mathbf{x}_N) = \mathbf{x}_{t_f},$$

$$\frac{(\boldsymbol{\Delta v}_k)^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\boldsymbol{\Delta v}_k\|_2} \leq \cos\theta_{\text{deltaV}}, \quad \frac{(\boldsymbol{\Delta v}_k)^\top (-\hat{\mathbf{r}}_{\text{center}\to\text{sun}})}{\|\boldsymbol{\Delta v}_k\|_2} \leq \cos\theta_{\text{deltaV}}, \quad k \in \{k_0, k_1, k_4, k_5\},$$

$$\Pr(\|\mathbf{r}_k\|_2 \geq h_{\min}) \geq p_{\text{chance}}, \quad k = 0, \ldots, N,$$

$$\Pr\left(\frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{\text{obs}}\right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Pr(d_1 \leq \|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2 \leq d_2) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Pr\left(\cos\theta_{e2} \leq \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \mathbf{r}_{s\perp,k}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{e1}\right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Pr\left(\cos\theta_{p2} \leq \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{p1}\right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Delta t_i \leq 190, \quad \forall i = 0, \ldots, 6,$$

$$\Delta t_0 k_0 + \Delta t_1(k_1 - k_0) + \Delta t_2(k_2 - k_1) = t_1^o, \quad \Delta t_3(k_3 - k_2) = t_2^o - t_1^o,$$

$$\Delta t_j(k_j - k_{j-1}) \geq 2\Delta t_{\text{attitude}} + \Delta t_{\text{heat}} + \Delta t_{\text{SoC}}, \quad j = 1, 4, 5, \quad \Delta t_2(k_2 - k_1) \geq 2\Delta t_{\text{attitude}} + \Delta t_{\text{SoC}}.$$

Hierarchical Asteroid Reconnaissance Planner (HARP)

$$\min_{\Delta \boldsymbol{v}_k, \Delta t} \sum_{k \in \{k_0, k_1, k_4, k_5\}} \|\Delta \boldsymbol{v}_k\|_2,$$

$$\text{s.t.} \quad \mathbf{x}_k = \begin{cases} F(\mathbf{x}_{k-1},\ k-1) + [\mathbf{0}_{3\times 1},\ \Delta \boldsymbol{v}_k^\top]^\top + \beta[\mathbf{0}_{3\times 1},\ (\Delta \boldsymbol{v}_k \circ \boldsymbol{\omega}_k)^\top]^\top & (k \in \{k_0, k_1, k_4, k_5\}) \\ F(\mathbf{x}_{k-1},\ k-1) & (k \notin \{k_0, k_1, k_4, k_5\})' \end{cases}$$

$$\|\Delta \boldsymbol{v}_k\|_2 \leq \Delta v_{\max}, \quad k \in \{k_0, k_1, k_4, k_5\},$$

$$\mathbf{x}_0 \sim \mathcal{N}(\mathbf{x}_{t_0}, \boldsymbol{\Sigma}_{t_0}), \quad \mathbb{E}(\mathbf{x}_N) = \mathbf{x}_{t_f},$$

$$\frac{(\Delta \boldsymbol{v}_k)^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\Delta \boldsymbol{v}_k\|_2} \leq \cos\theta_{\text{deltaV}}, \quad \frac{(\Delta \boldsymbol{v}_k)^\top (-\hat{\mathbf{r}}_{\text{center}\to\text{sun}})}{\|\Delta \boldsymbol{v}_k\|_2} \leq \cos\theta_{\text{deltaV}}, \quad k \in \{k_0, k_1, k_4, k_5\},$$

Battery constraints

$$\Pr(\|\mathbf{r}_k\|_2 \geq h_{\min}) \geq p_{\text{chance}}, \quad k = 0, \ldots, N,$$

$$\Pr\left(\frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{\text{obs}}\right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Pr(d_1 \leq \|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2 \leq d_2) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Pr\left(\cos\theta_{e2} \leq \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \mathbf{r}_{s\perp,k}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{e1}\right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Pr\left(\cos\theta_{p2} \leq \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \leq \cos\theta_{p1}\right) \geq p_{\text{chance}}, \quad k_2 \leq k \leq k_3,$$

$$\Delta t_i \leq 190, \quad \forall i = 0, \ldots, 6,$$

$$\Delta t_0 k_0 + \Delta t_1(k_1 - k_0) + \Delta t_2(k_2 - k_1) = t_1^o, \quad \Delta t_3(k_3 - k_2) = t_2^o - t_1^o,$$

$$\Delta t_j(k_j - k_{j-1}) \geq 2\Delta t_{\text{attitude}} + \Delta t_{\text{heat}} + \Delta t_{\text{SoC}}, \quad j = 1, 4, 5, \quad \Delta t_2(k_2 - k_1) \geq 2\Delta t_{\text{attitude}} + \Delta t_{\text{SoC}}.$$

Hierarchical Asteroid Reconnaissance Planner (HARP)

$$
\begin{aligned}
\min_{\boldsymbol{\Delta v}_k, \Delta t} \quad & \sum_{k \in \{k_0, k_1, k_4, k_5\}} \|\boldsymbol{\Delta v}_k\|_2, \\
\text{s.t.} \quad & \mathbf{x}_k = \begin{cases} F(\mathbf{x}_{k-1},\ k-1) + [\mathbf{0}_{3\times1},\ \boldsymbol{\Delta v}_k^\top]^\top + \beta[\mathbf{0}_{3\times1},\ (\boldsymbol{\Delta v}_k \circ \boldsymbol{\omega}_k)^\top]^\top & (k \in \{k_0, k_1, k_4, k_5\}) \\ F(\mathbf{x}_{k-1},\ k-1) & (k \notin \{k_0, k_1, k_4, k_5\})' \end{cases} \\
& \|\boldsymbol{\Delta v}_k\|_2 \le \Delta v_{\max}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \mathbf{x}_0 \sim \mathcal{N}(\mathbf{x}_{t_0}, \boldsymbol{\Sigma}_{t_0}), \quad \mathbb{E}(\mathbf{x}_N) = \mathbf{x}_{t_f}, \\
& \frac{(\boldsymbol{\Delta v}_k)^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\boldsymbol{\Delta v}_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad \frac{(\boldsymbol{\Delta v}_k)^\top (-\hat{\mathbf{r}}_{\text{center}\to\text{sun}})}{\|\boldsymbol{\Delta v}_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \Pr(\|\mathbf{r}_k\|_2 \ge h_{\min}) \ge p_{\text{chance}}, \quad k = 0, \ldots, N, \\
& \Pr\left(\frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{\text{obs}}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr(d_1 \le \|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2 \le d_2) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr\left(\cos\theta_{e2} \le \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \mathbf{r}_{s\perp,k}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{e1}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr\left(\cos\theta_{p2} \le \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{p1}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Delta t_i \le 190, \quad \forall i = 0, \ldots, 6, \\
& \Delta t_0 k_0 + \Delta t_1(k_1 - k_0) + \Delta t_2(k_2 - k_1) = t_1^o, \quad \Delta t_3(k_3 - k_2) = t_2^o - t_1^o, \\
& \Delta t_j(k_j - k_{j-1}) \ge 2\Delta t_{\text{attitude}} + \Delta t_{\text{heat}} + \Delta t_{\text{SoC}}, \quad j = 1, 4, 5, \quad \Delta t_2(k_2 - k_1) \ge 2\Delta t_{\text{attitude}} + \Delta t_{\text{SoC}}.
\end{aligned}
$$

Probabilistic safety constraints

Hierarchical Asteroid Reconnaissance Planner (HARP)

$$
\begin{aligned}
\min_{\boldsymbol{\Delta v}_k, \Delta t} \quad & \sum_{k \in \{k_0, k_1, k_4, k_5\}} \|\boldsymbol{\Delta v}_k\|_2, \\
\text{s.t.} \quad & \mathbf{x}_k = \begin{cases} F(\mathbf{x}_{k-1},\ k-1) + [\mathbf{0}_{3\times1},\ \boldsymbol{\Delta v}_k^\top]^\top + \beta[\mathbf{0}_{3\times1},\ (\boldsymbol{\Delta v}_k \circ \boldsymbol{\omega}_k)^\top]^\top & (k \in \{k_0, k_1, k_4, k_5\}) \\ F(\mathbf{x}_{k-1},\ k-1) & (k \notin \{k_0, k_1, k_4, k_5\})' \end{cases} \\
& \|\boldsymbol{\Delta v}_k\|_2 \le \Delta v_{\max}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \mathbf{x}_0 \sim \mathcal{N}(\mathbf{x}_{t_0}, \boldsymbol{\Sigma}_{t_0}), \quad \mathbb{E}(\mathbf{x}_N) = \mathbf{x}_{t_f}, \\
& \frac{(\boldsymbol{\Delta v}_k)^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\boldsymbol{\Delta v}_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad \frac{(\boldsymbol{\Delta v}_k)^\top (-\hat{\mathbf{r}}_{\text{center}\to\text{sun}})}{\|\boldsymbol{\Delta v}_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad k \in \{k_0, k_1, k_4, k_5\}, \\
& \Pr(\|\mathbf{r}_k\|_2 \ge h_{\min}) \ge p_{\text{chance}}, \quad k = 0, \dots, N, \\
& \Pr\left(\frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{\text{obs}}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr(d_1 \le \|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2 \le d_2) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr\left(\cos\theta_{e2} \le \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \mathbf{r}_{s\perp,k}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{e1}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Pr\left(\cos\theta_{p2} \le \frac{(\mathbf{r}_k - \mathbf{r}_{\text{site},k})^\top \hat{\mathbf{r}}_{\text{center}\to\text{sun}}}{\|\mathbf{r}_k - \mathbf{r}_{\text{site},k}\|_2} \le \cos\theta_{p1}\right) \ge p_{\text{chance}}, \quad k_2 \le k \le k_3, \\
& \Delta t_i \le 190, \quad \forall i = 0, \dots, 6, \\
& \Delta t_0 k_0 + \Delta t_1 (k_1 - k_0) + \Delta t_2 (k_2 - k_1) = t_1^o, \quad \Delta t_3 (k_3 - k_2) = t_2^o - t_1^o, \\
& \Delta t_j (k_j - k_{j-1}) \ge 2\Delta t_{\text{attitude}} + \Delta t_{\text{heat}} + \Delta t_{\text{SoC}}, \quad j = 1, 4, 5, \quad \Delta t_2 (k_2 - k_1) \ge 2\Delta t_{\text{attitude}} + \Delta t_{\text{SoC}}.
\end{aligned}
$$

Thruster firing constraints

Hierarchical Asteroid Reconnaissance Planner (HARP)

Design Firing Timings and Attitude Mode Profile

Initial Guess

$$
\begin{aligned}
\min_{u} \quad & \int_{t_0}^{t_f} \|u(t)\|_2 \ \mathrm{d}t \\
\text{s.t.} \quad & \mathrm{d}x = f(x(t), u(t), t)\mathrm{d}t + G(x(t), u(t), t)\mathrm{d}\omega, \\
& \rho(x(t)) \in \mathcal{X}, \quad u(t) \in \mathcal{U}
\end{aligned}
$$

Design an Attitude Profile

Deterministic reformulation

$$\min \quad \text{Fuel}$$

$$\min_{\Delta v_k} \sum_{k\Delta t \in \{0, t_1, t_2, t_f\}} \|\Delta v_k\|_2,$$

Deterministic reformulation

$$
\begin{aligned}
\min \quad & \text{Fuel} \\
\text{s.t.} \quad & x_{sc}(t) \text{ follows 3DOF Stochastic Dynamics} \\
& \quad 1) \text{ Single Point Mass + J2} \\
& \quad 2) \text{ Cannonball SRP} \\
& \quad 3) \text{ Thruster \& Localization Uncertainty} \\
& \quad 4) \; x_{sc}(t) \text{ is Modeled as Gaussian} \\
& \quad 5) \text{ Model the Propagation as EKF} \\
& \text{Thrust can fire 4 times, modeled as Dirac Delta}
\end{aligned}
$$

$$
\begin{aligned}
\min_{\Delta v_k} \quad & \sum_{k\Delta t \in \{0, t_1, t_2, t_f\}} \|\Delta v_k\|_2, \\
\text{s.t.} \quad & \mu_k = \begin{cases} F(\mu_{k-1}, k-1) + [0_{3\times 1},\ \Delta v_k^\top]^\top & (k\Delta t \in \{0, t_1, t_2, t_f\}), \\ F(\mu_{k-1}, k-1) & (k\Delta t \notin \{0, t_1, t_2, t_f\}), \end{cases} \\
& \Sigma_k = \begin{cases} \nabla_x F \Sigma_{k-1} \nabla_x F^\top + [0_{3\times 6};\ 0_{3\times 3},\ \beta v_k \circ I] I [0_{3\times 6};\ 0_{3\times 3},\ \beta v_k \circ I]^\top & (k\Delta t \in \{0, t_1, t_2, t_f\}), \\ \nabla_x F \Sigma_{k-1} \nabla_x F^\top & (k\Delta t \notin \{0, t_1, t_2, t_f\}), \end{cases} \\
& \|\Delta v_k\|_2 \le \Delta v_{\max}, \quad k\Delta t \in \{0, t_1, t_2, t_f\}
\end{aligned}
$$

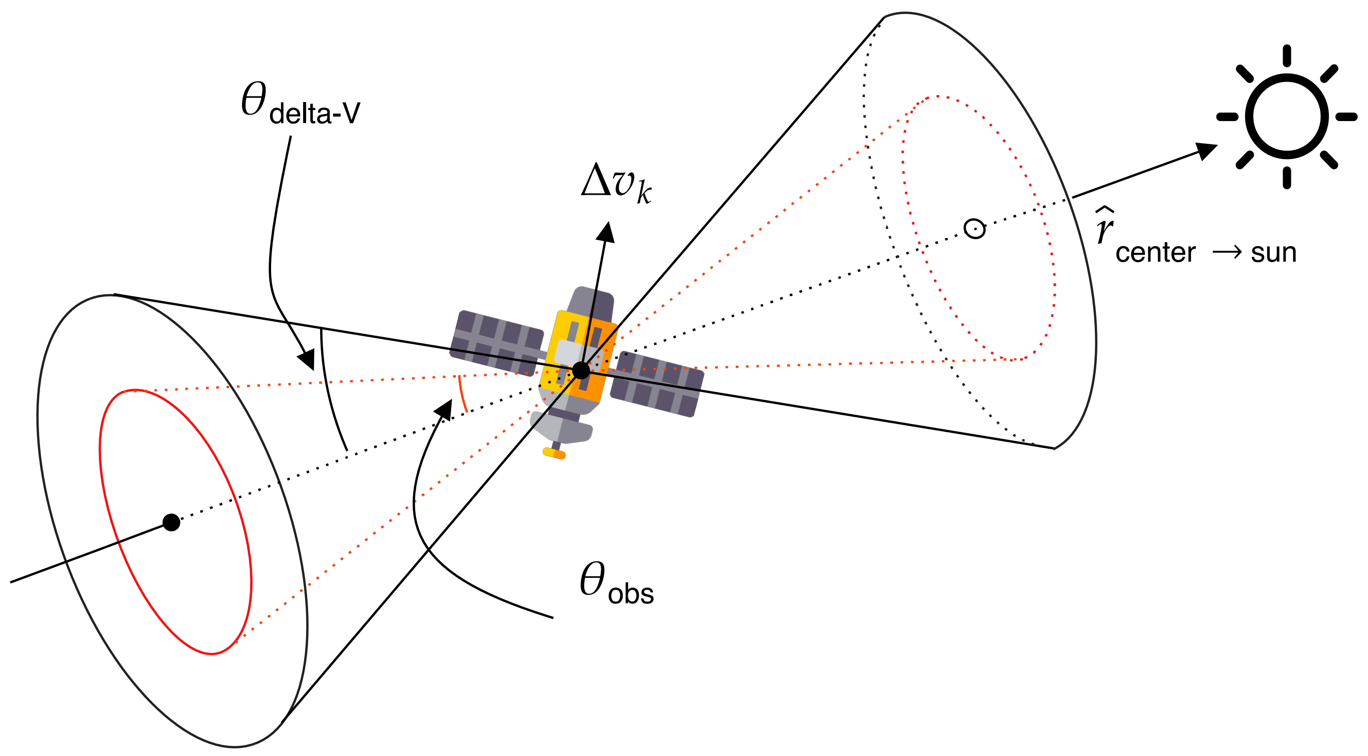
Deterministic reformulation

$$\begin{aligned}
\min \quad & \text{Fuel} \\
\text{s.t.} \quad & x_{sc}(t) \text{ follows 3DOF Stochastic Dynamics} \\
& \quad \text{1) Single Point Mass + J2} \\
& \quad \text{2) Cannonball SRP} \\
& \quad \text{3) Thruster \& Localization Uncertainty} \\
& \quad \text{4) } x_{sc}(t) \text{ is Modeled as Gaussian} \\
& \quad \text{5) Model the Propagation as EKF} \\
& \text{Thrust can fire 4 times, modeled as Dirac Delta} \\
& \text{Boundary Conditions}
\end{aligned}$$

$$\begin{aligned}
\min_{\Delta v_k} \quad & \sum_{k\Delta t \in \{0, t_1, t_2, t_f\}} \|\Delta v_k\|_2, \\
\text{s.t.} \quad & \mu_k = \begin{cases} F(\mu_{k-1}, k-1) + [0_{3\times 1},\ \Delta v_k^\top]^\top & (k\Delta t \in \{0, t_1, t_2, t_f\}), \\ F(\mu_{k-1}, k-1) & (k\Delta t \notin \{0, t_1, t_2, t_f\}), \end{cases} \\
& \Sigma_k = \begin{cases} \nabla_x F \Sigma_{k-1} \nabla_x F^\top + [0_{3\times 6};\ 0_{3\times 3},\ \beta v_k \circ I] I [0_{3\times 6};\ 0_{3\times 3},\ \beta v_k \circ I]^\top & (k\Delta t \in \{0, t_1, t_2, t_f\}), \\ \nabla_x F \Sigma_{k-1} \nabla_x F^\top & (k\Delta t \notin \{0, t_1, t_2, t_f\}), \end{cases} \\
& \|\Delta v_k\|_2 \le \Delta v_{\max}, \quad k\Delta t \in \{0, t_1, t_2, t_f\} \\
& x_0 \sim \mathcal{N}(x_{t_0}, \Sigma_{t_0}), \quad \mathbb{E}(x_N) = x_{t_f}
\end{aligned}$$

Deterministic reformulation

$$
\begin{array}{ll}
\min & \text{Fuel} \\
\text{s.t.} & x_{sc}(t) \text{ follows 3DOF Stochastic Dynamics} \\
& \quad \text{1) Single Point Mass + J2} \\
& \quad \text{2) Cannonball SRP} \\
& \quad \text{3) Thruster \& Localization Uncertainty} \\
& \quad \text{4) } x_{sc}(t) \text{ is Modeled as Gaussian} \\
& \quad \text{5) Model the Propagation as EKF} \\
& \text{Thrust can fire 4 times, modeled as Dirac Delta} \\
& \text{Boundary Conditions} \\
& \text{Keep the Battery SoC above the Min Threshold during DeltaV}
\end{array}
$$



$$
\min_{\Delta v_k} \sum_{k\Delta t \in \{0, t_1, t_2, t_f\}} \|\Delta v_k\|_2,
$$

$$
\text{s.t.} \quad \mu_k = \begin{cases} F(\mu_{k-1}, k-1) + [0_{3\times1},\ \Delta v_k^\top]^\top & (k\Delta t \in \{0, t_1, t_2, t_f\}), \\ F(\mu_{k-1}, k-1) & (k\Delta t \notin \{0, t_1, t_2, t_f\}), \end{cases}
$$

$$
\Sigma_k = \begin{cases} \nabla_x F \Sigma_{k-1} \nabla_x F^\top + [0_{3\times6};\ 0_{3\times3},\ \beta v_k \circ I] I [0_{3\times6};\ 0_{3\times3},\ \beta v_k \circ I]^\top & (k\Delta t \in \{0, t_1, t_2, t_f\}), \\ \nabla_x F \Sigma_{k-1} \nabla_x F^\top & (k\Delta t \notin \{0, t_1, t_2, t_f\}), \end{cases}
$$

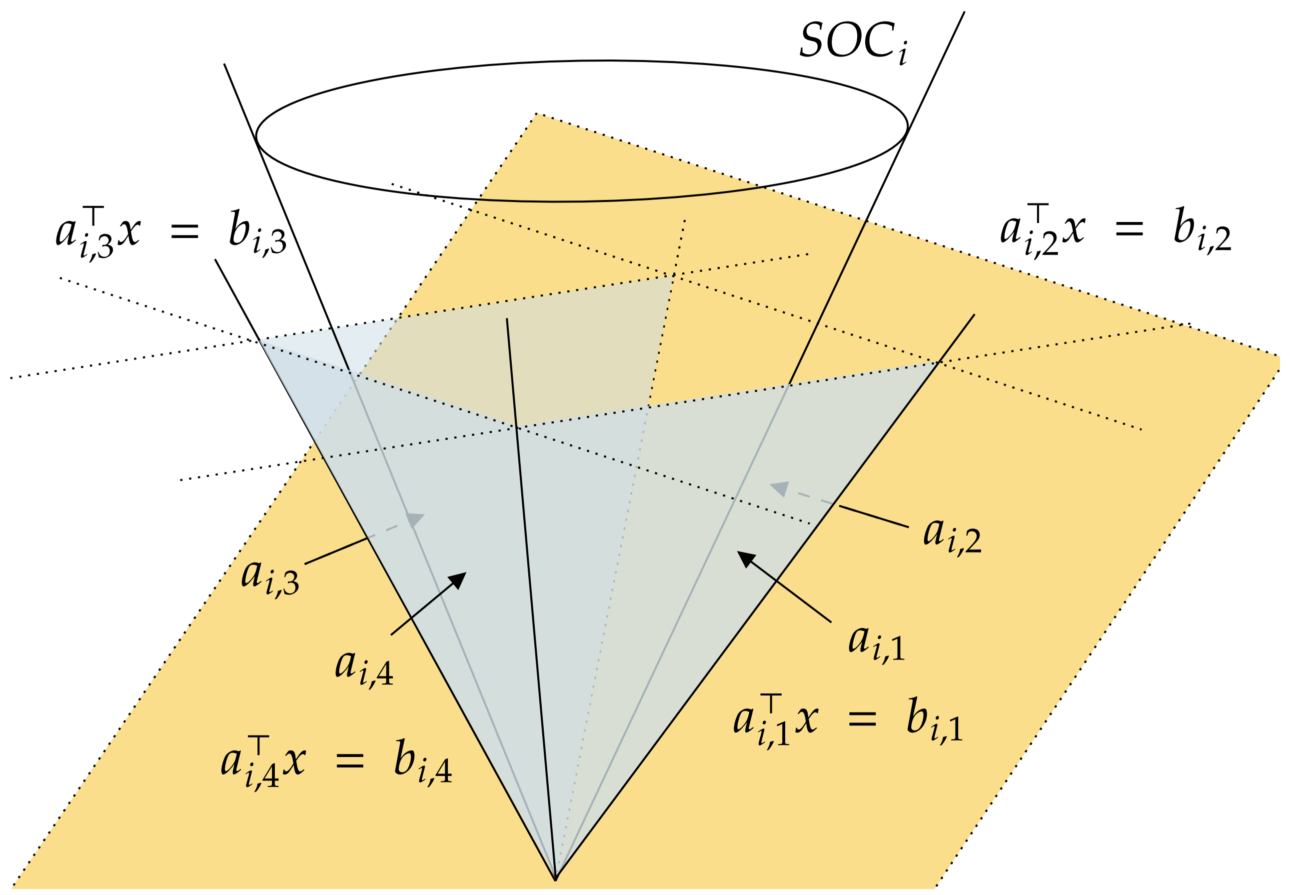
$$
\|\Delta v_k\|_2 \le \Delta v_{\max}, \quad k\Delta t \in \{0, t_1, t_2, t_f\}
$$

$$
x_0 \sim \mathcal{N}(x_{t_0}, \Sigma_{t_0}), \quad \mathbb{E}(x_N) = x_{t_f}
$$

$$
\frac{(\Delta v_k)^\top \hat{r}_{\text{center}\to\text{sun}}}{\|\Delta v_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad \frac{(\Delta v_k)^\top (-\hat{r}_{\text{center}\to\text{sun}})}{\|\Delta v_k\|_2} \le \cos\theta_{\text{deltaV}}, \quad k\Delta t \in \{0, t_1, t_2, t_f\}
$$

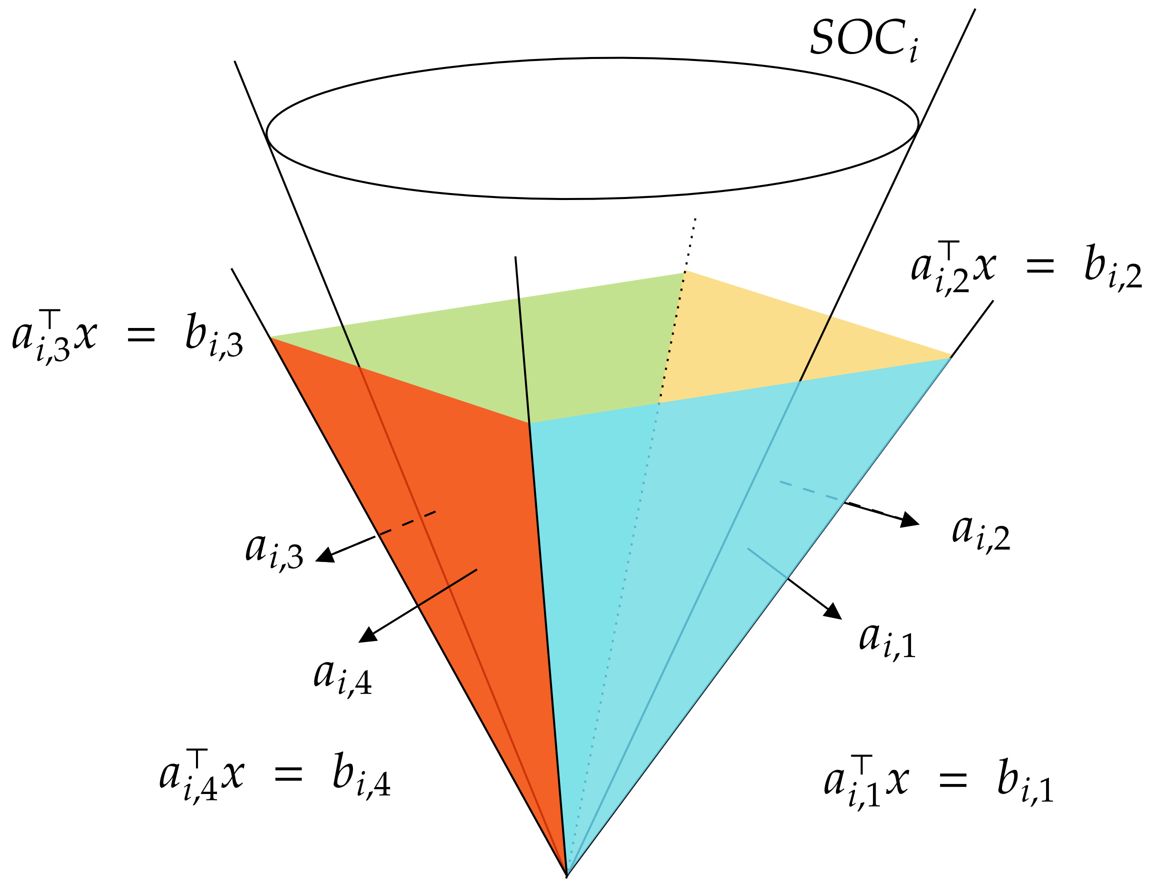
Deterministic reformulation

$$\Pr(x \notin SOC_a) \geq p_a$$



$$a_{i,\hat{j}}^\top \mu_k + \Psi^{-1}(1-(1-p_i))\sqrt{a_{i,\hat{j}}^\top \Sigma_k a_{i,\hat{j}}} \leq b_{i,\hat{j}}$$

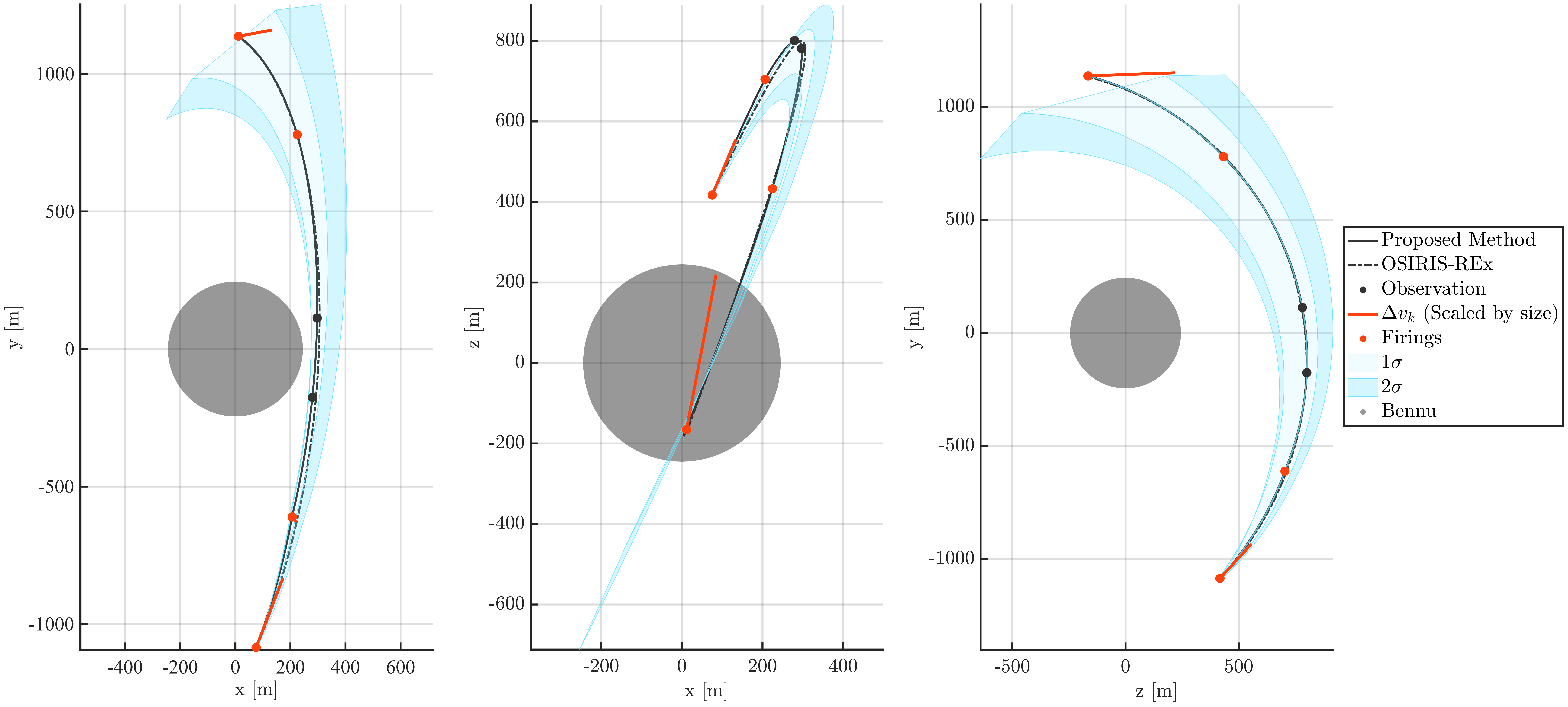
$$\Pr(x \in SOC_b) \geq p_b$$



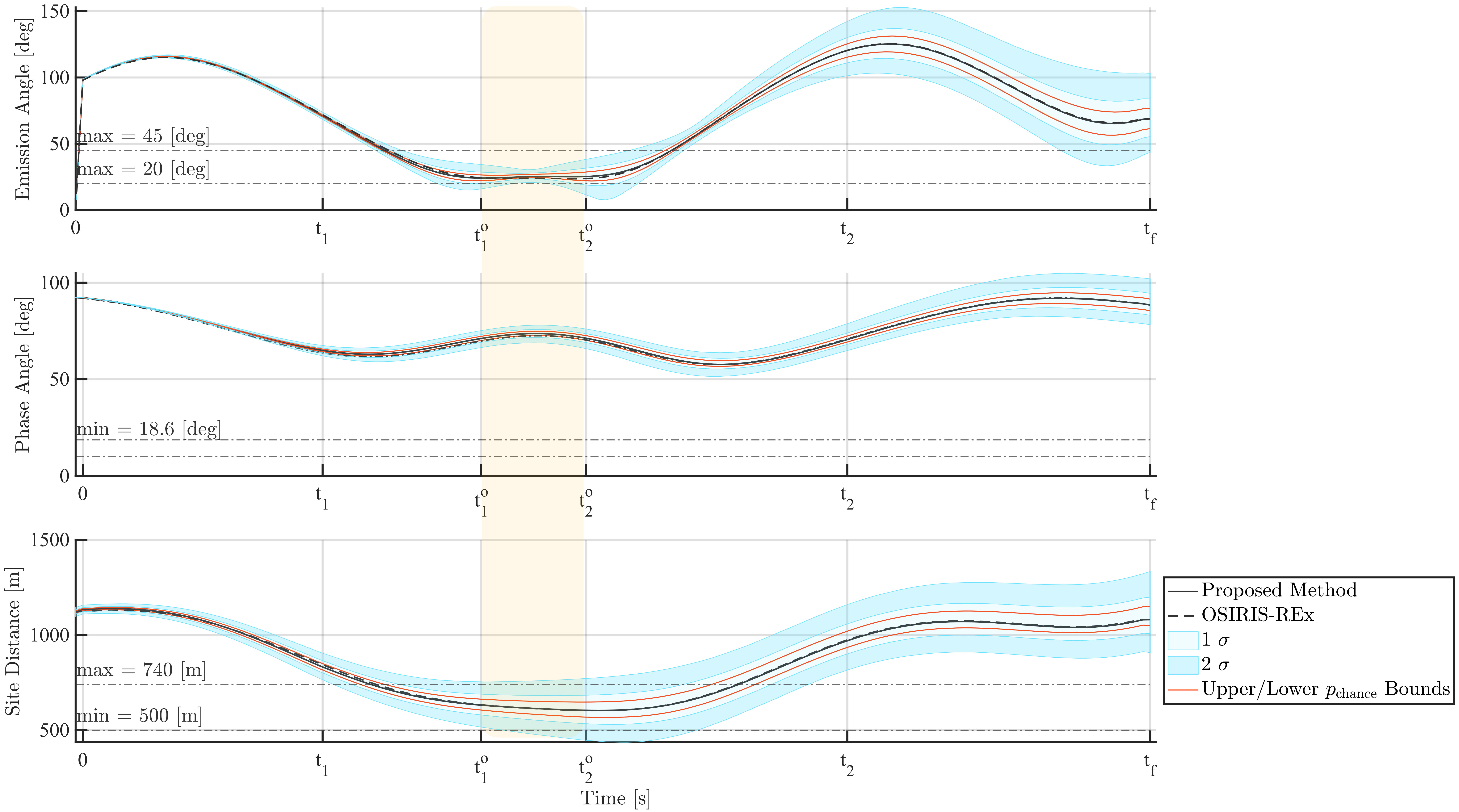
$$a_{i,j}^\top \mu_k + \Psi^{-1}(1-\frac{(1-p_i)}{n_i})\sqrt{a_{i,j}^\top \Sigma_k a_{i,j}} \leq b_{i,j},$$

$$j = 1, ..., n_i,$$

Simulation results



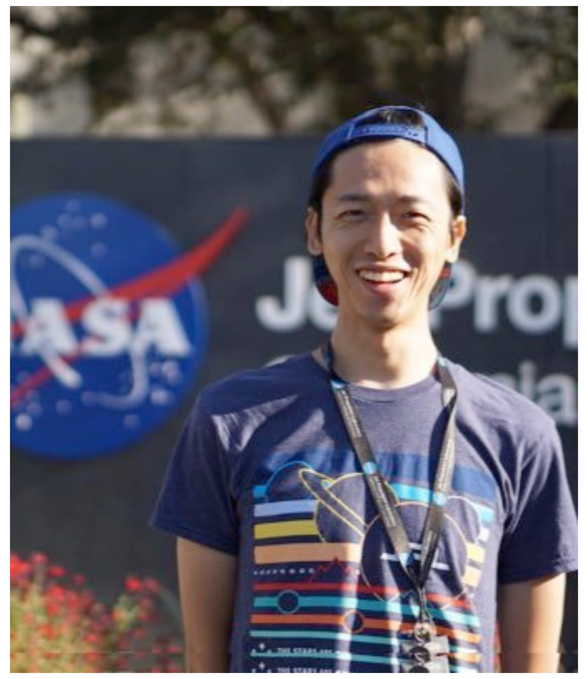
Simulation results




Rigorous uncertainty quantification
Constraint enforcement under uncertainty

Acknowledgements

HARP researchers



Kazuya Echigo

Issa Nesnas

Behcet Acikmese

Dan Scharf

Saptarshi Bandyopadhyay

Greg Lantoine

References

- K. Echigo, A. Cauligi, S. Bandyopadhyay, D. Scharf, G. Lantoine, B. Acikmese, and I. Nesnas, “Autonomy in the Real-World: Autonomous Trajectory Planning for Asteroid Reconnaissance via Stochastic Optimization,” in *AIAA Scitech Forum*, 2025.
- K. Echigo, A. Cauligi, S. Bandyopadhyay, D. Scharf, G. Lantoine, B. Acikmese, and I. Nesnas, “Principled Stochastic Trajectory Planning for Asteroid Reconnaissance,” in *AIAA Journal of Guidance, Control, and Dynamics*, 2025.