Exploring Further: Advances in Autonomy for Small Body Missions

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COMET-ORB

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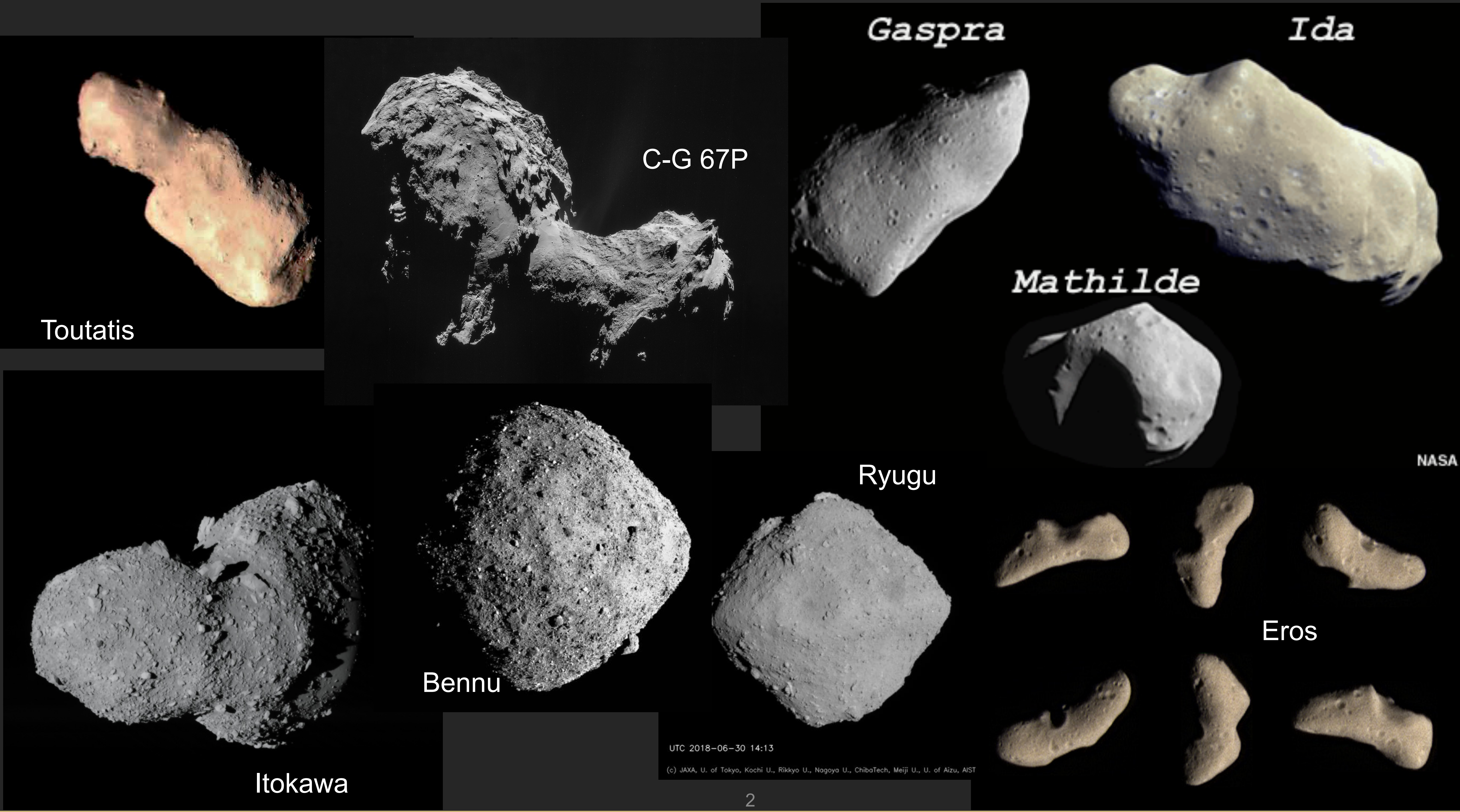
Toutatis
C-G 67P
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Mathilde
NASA
Ryugu
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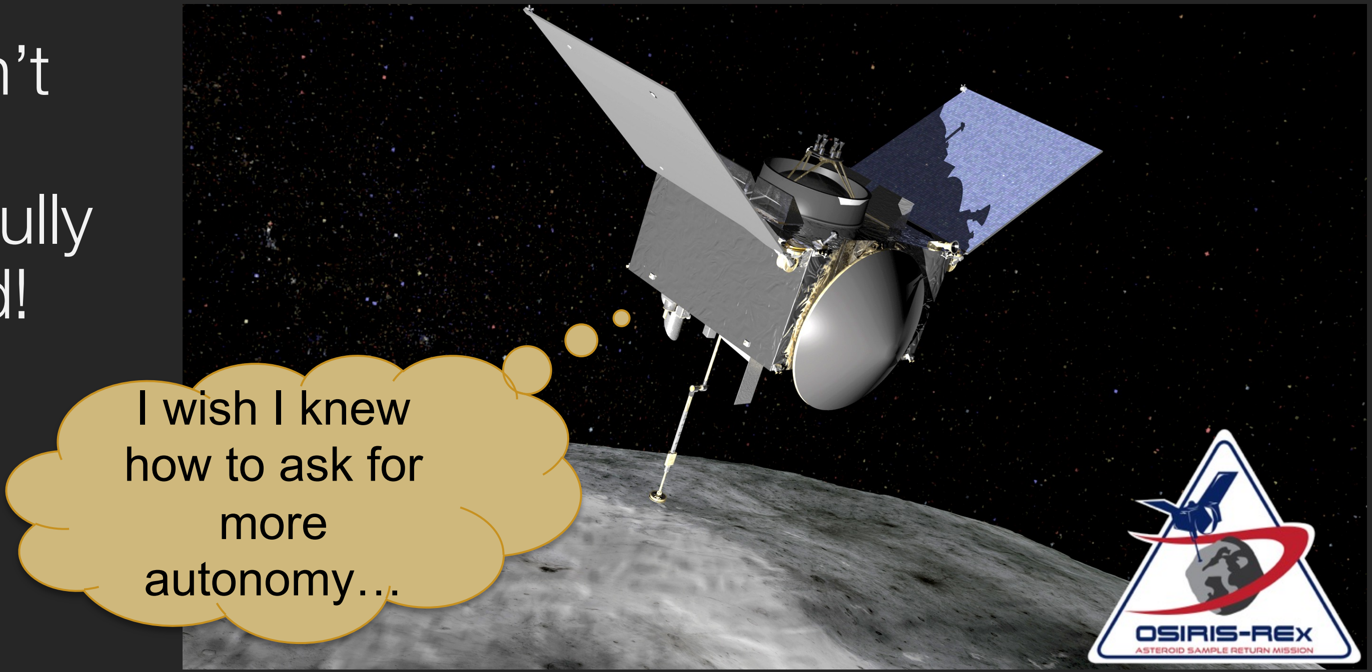
Current Asteroid Mission Con-ops

- Small body missions today require a slow, deliberate acquisition of knowledge about the body to enable proximity operations
  - OSIRIS-REx: approach -> distant flybys -> high orbit -> lower orbit -> TAG
- Navigation accuracy is largely driven by *prediction* requirements
- This accuracy is achieved today with precise landmark tracking which requires high-resolution shape models
- Many useful exploration modes don't necessarily require high precision shape models to navigate successfully IF navigation can be done on-board!
  - Partial exceptions: landing, TAG, very low-altitude hovering/orbits
- Maneuvers are almost exclusively planned on the ground
  - Exceptions: back-away, TAG



TAG autonomy had to be re-worked to handle Bennu!

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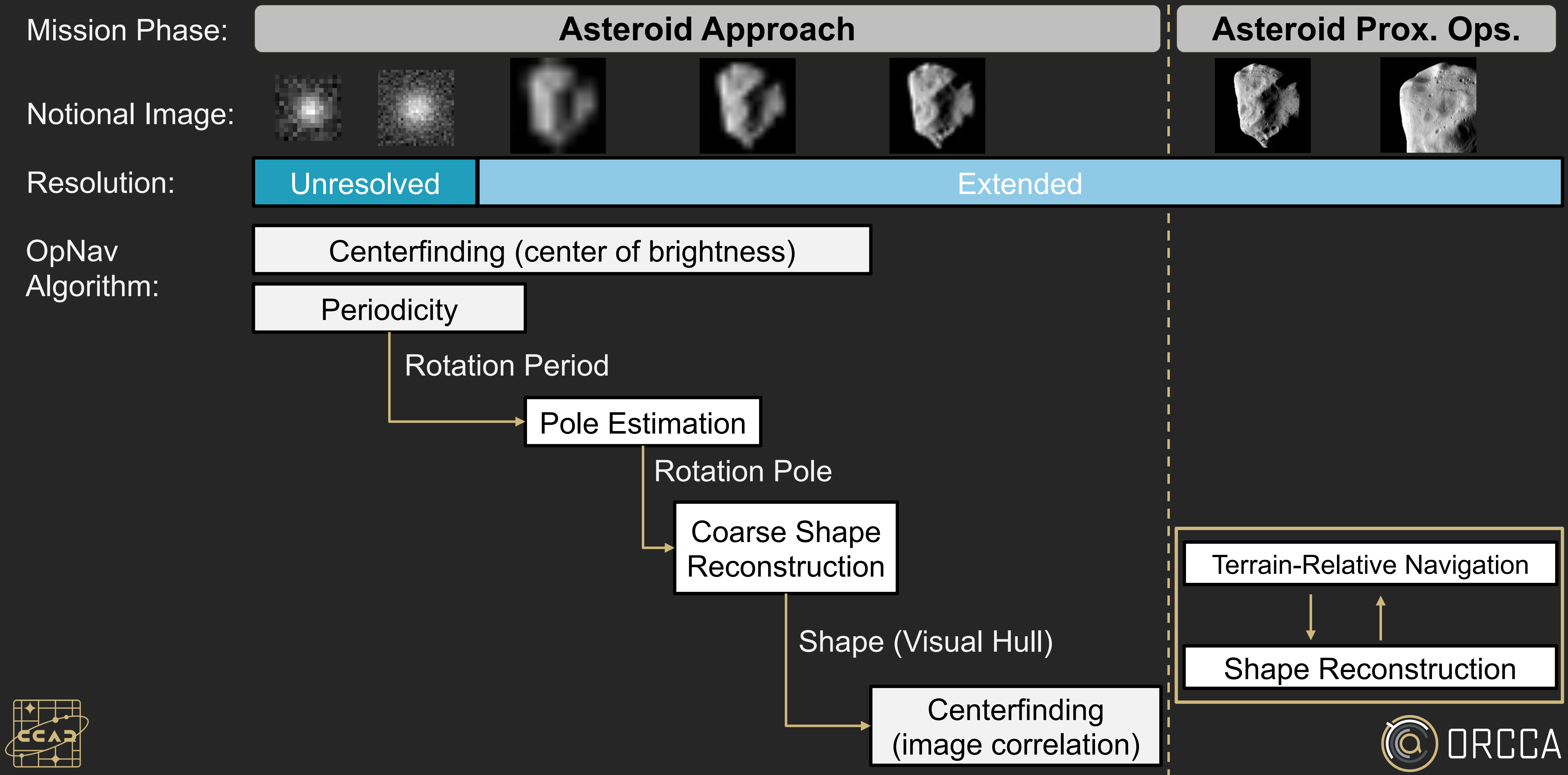
NAVIGATION AROUND SMALL BODIES

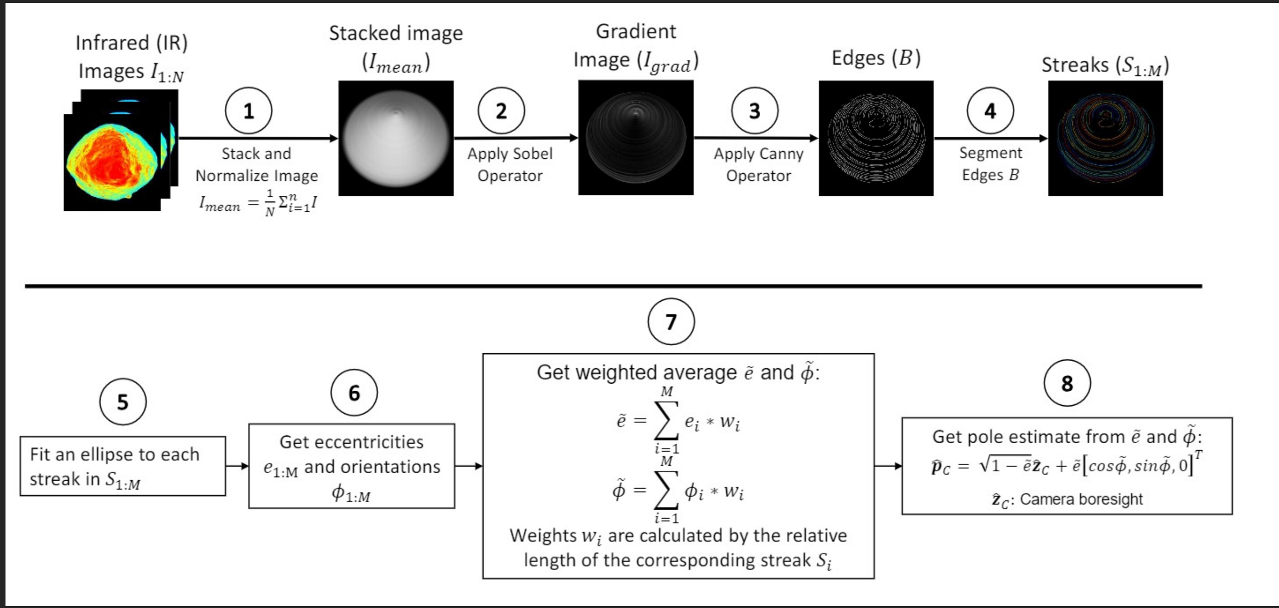
Work of Dr. Jacopo Villa, Dr. Benjamin Bercovici, and Ken Kuppa shown

Asteroid Approach and Proximity Operations, Waterfall Pipeline



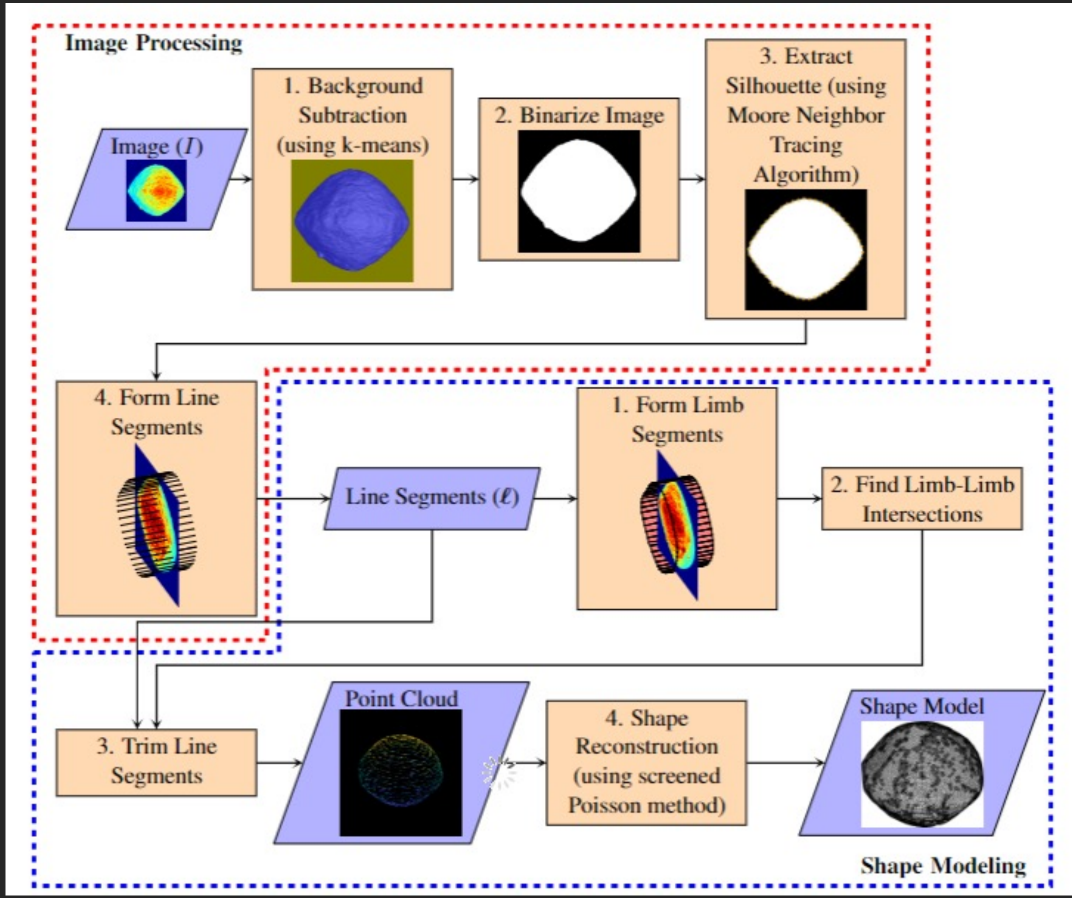
Pole Estimation

- A recently proposed algorithm [Kuppa et al., 2024] is used to generate a pole estimate from on-board infrared images
- Method leverages the observed geometry between pole axis and a camera

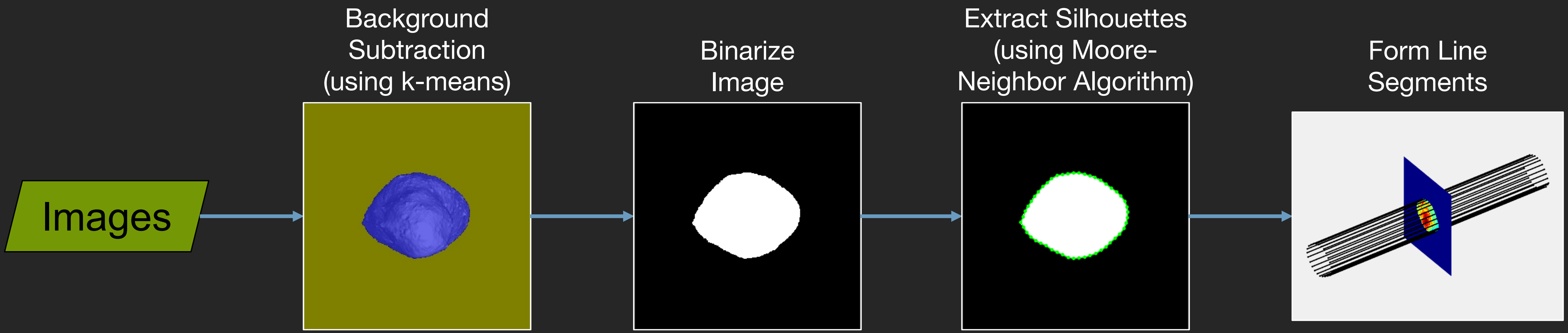


Shape from Silhouette (SfS) Overview

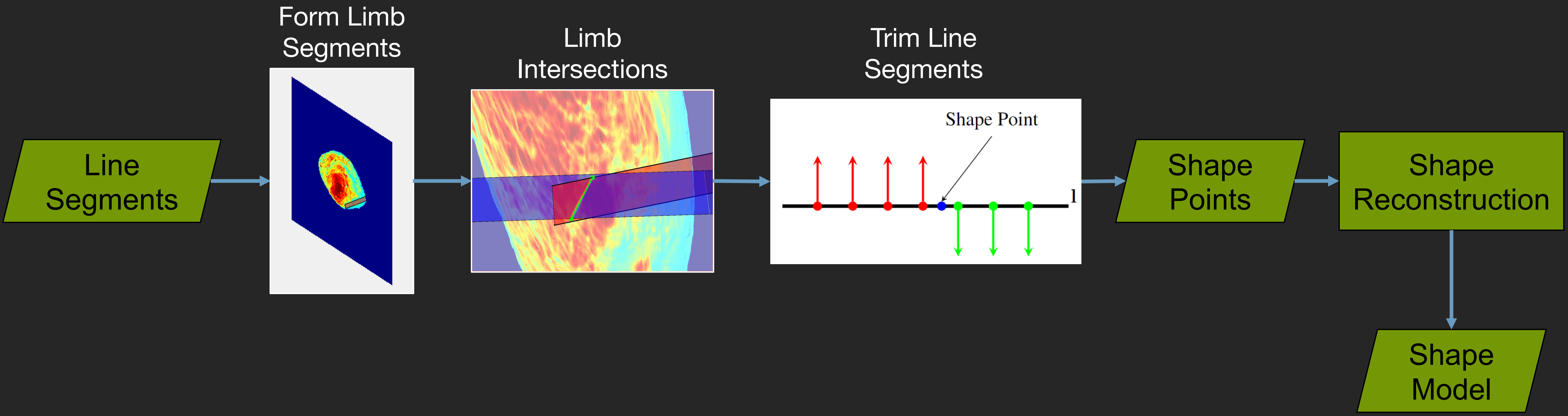
- Using the silhouettes of a body in a sequence of images, a shape model can be derived
- Using infrared images simplifies the image processing pipeline
  - Improves robustness to illumination geometries
- This method we used is an improved version of a ray-trimming approach [Baker and McMahon, 2020]
  - Improvements to the image processing steps



SfS Image Processing

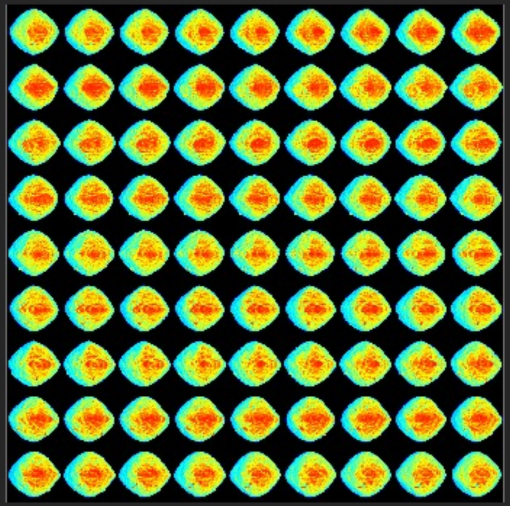


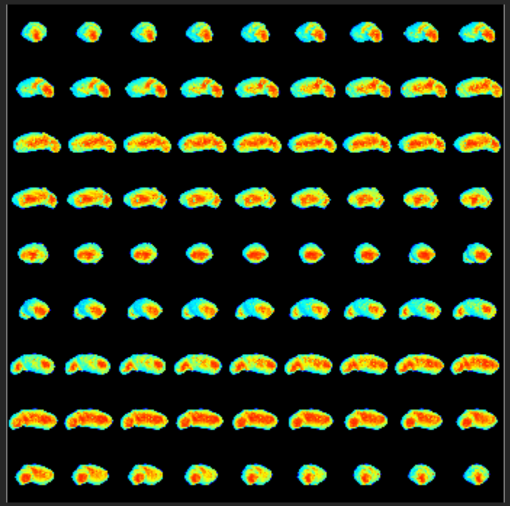
SfS Shape Modeling

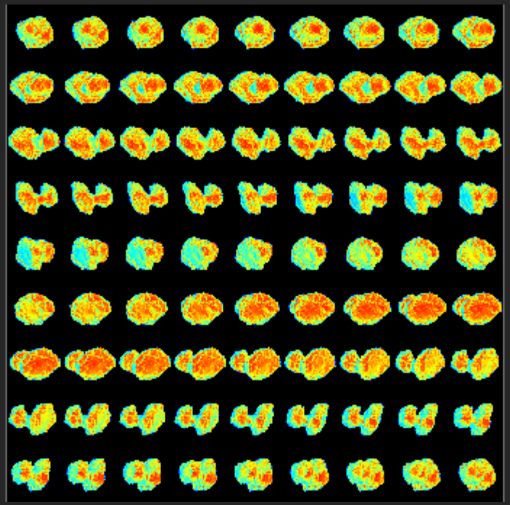


Results

- Synthetic IR images of Bennu, Itokawa, and 67P/C-G were generated
  - SPC based reference shape models
    - Bennu: [Barnouin et al., 2019]
    - Itokawa: [Gaskell et al., 2008]
    - 67P/C-G: [Capanna et al., 2013]
  - A simplified thermal model [Kuppa et al., 2024]
  - Camera FOV of $0.3°$and resolution of $550px \times 550px$
  - Camera is viewing along equatorial plane at 100 body radii
- 81 images taken over 1 spin period
  - Bodies rotate $4.5°$ between images
- From each silhouette, 50 points are sampled from the ordered set of pixels (for computational efficiency)

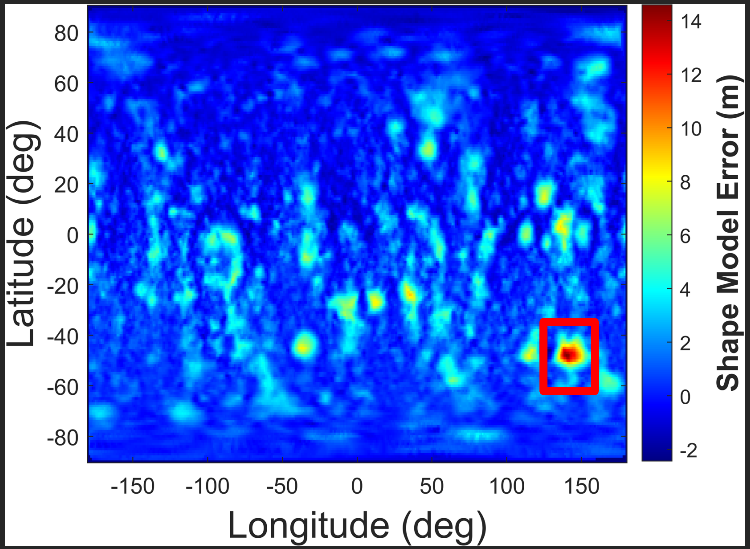


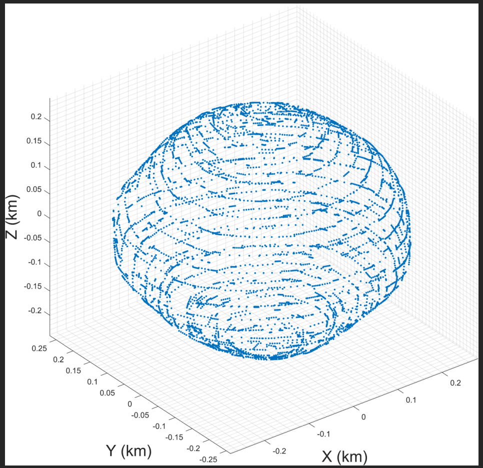


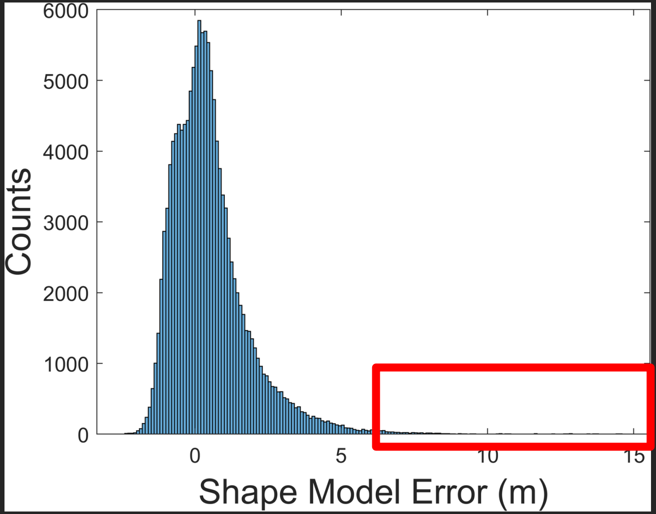


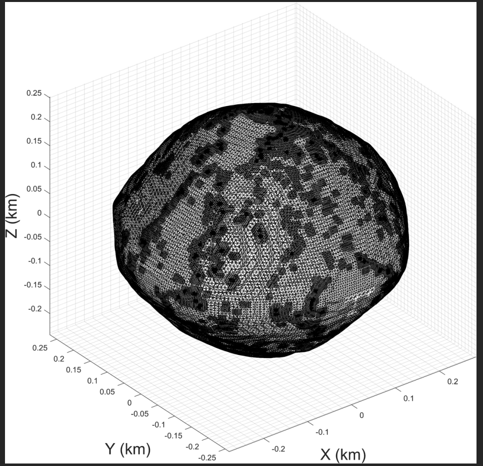
Results – Bennu

- Assuming known pole orientation
- SfS generates a point cloud with $6{,}118$ points (and associated normal vectors)
- Reconstructed shape contains $137{,}009$ vertices and $274{,}014$ facets
- RMS Error is $1.44\ m$ $(0.6\%$ of body radius)
- Results are worse in the region around Benben (long tail in the histogram)
  - Unobservability of the surface slopes in this region due to observer geometry and silhouettes









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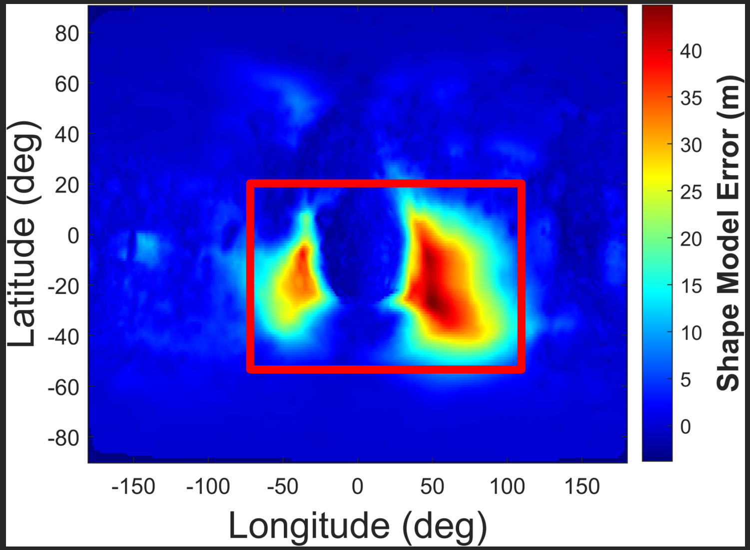
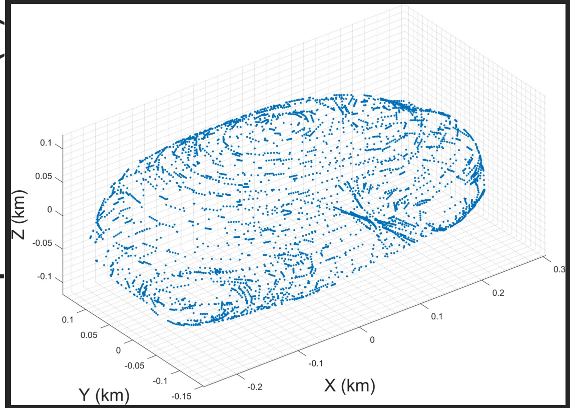
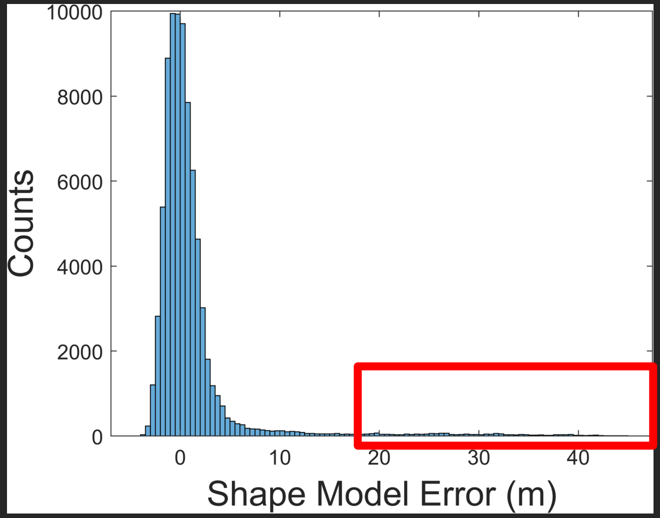
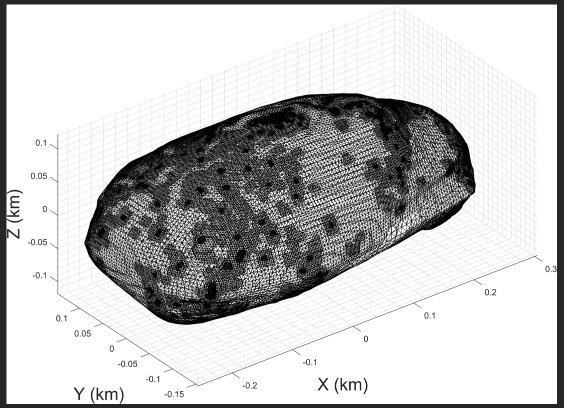
Results – Itokawa

- Assuming known pole orientation
- SfS generates a point cloud with $4{,}515$ points (and associated normal vectors)
- Reconstructed shape contains $159{,}682$ facets and $79{,}843$ vertices
- RMS Error is $5.07\ m$ $(1.7\%$ of body radius)
- Results are worse in the region around neck



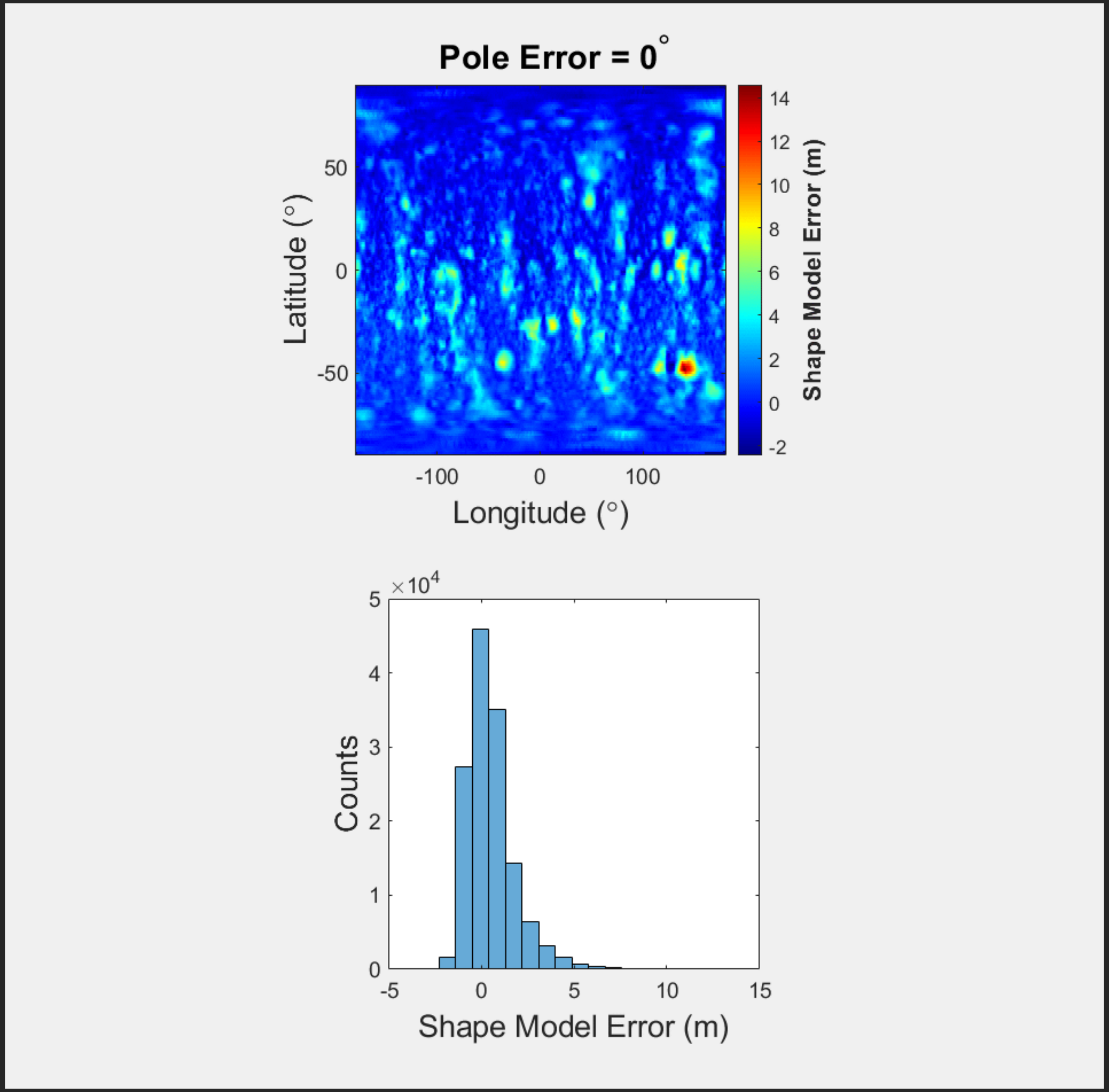






Results – Effects of Pole Errors

- A parametric study of the effect of pole errors on Bennu
  - Induced pole errors between $2° - 20°$ (in increments of $2°$) as a latitude error
- As expected, increase in errors mostly occurs around the pole
- Using the pole estimation algorithm, an error of $2.5°$ is expected
  - Corresponds to an RMS error of $1.6\ m$



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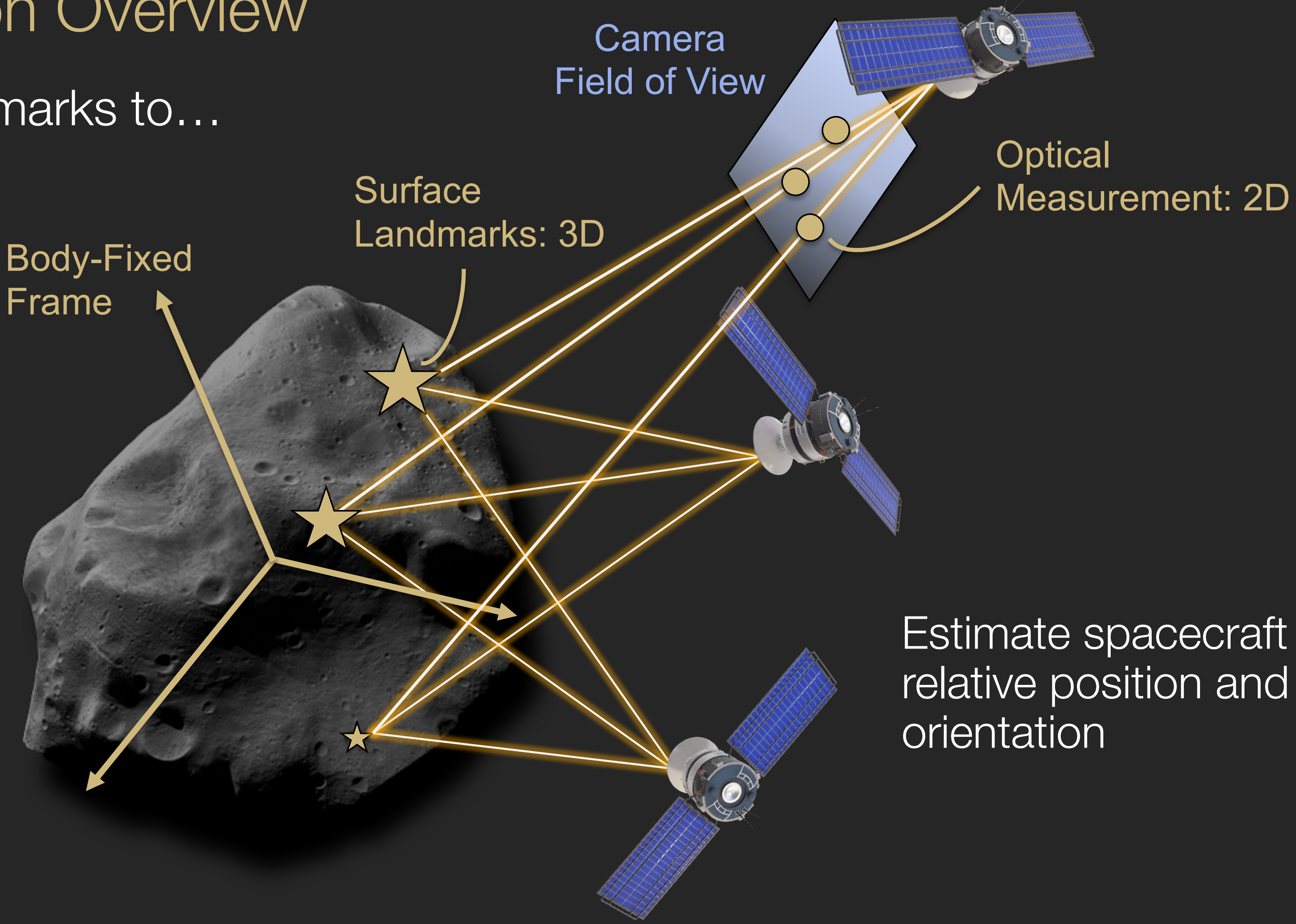
Optical Navigation Overview

Tracking surface landmarks to…

Estimate target body's physical parameters (pole, rotation period, center of mass, etc.)

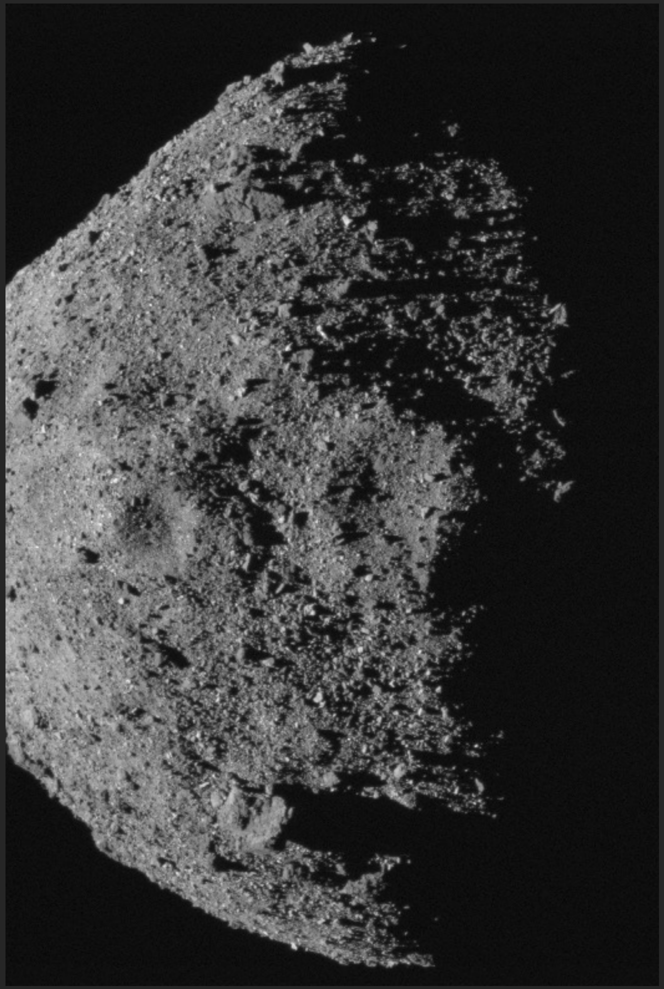
Reconstruct the shape



Estimate spacecraft relative position and orientation

Challenges of Landmark Matching

Asteroid Bennu example: how to identify the *same* landmarks in both images?

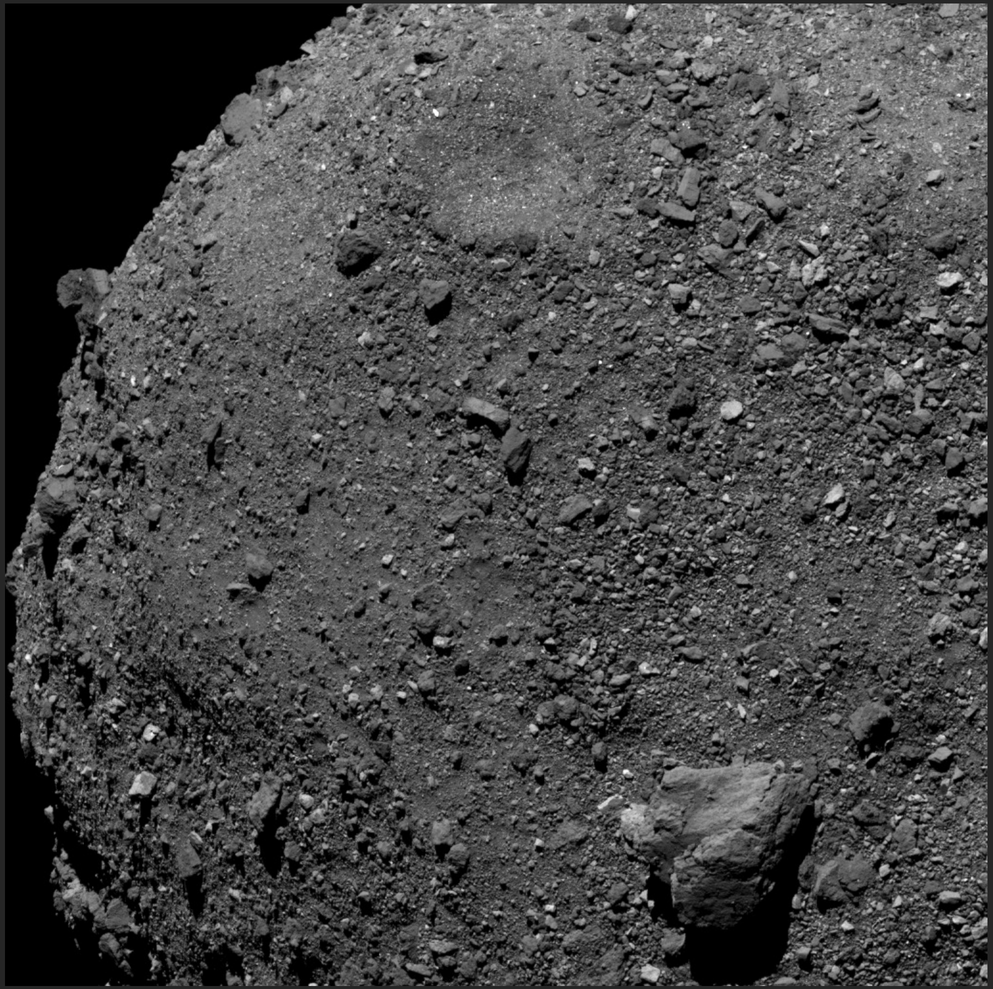


Same surface region

Appearance changes in…

- Resolution
- Viewpoint
- Lighting

Failure of most state-of-the-art feature matching techniques



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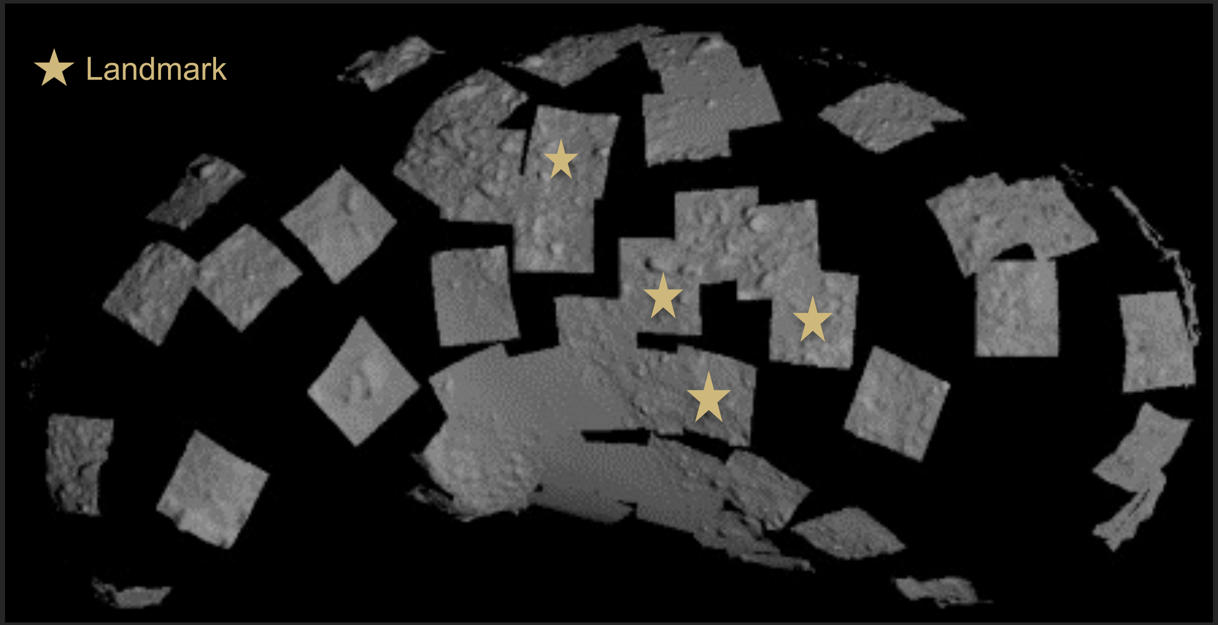
State of The Practice

High level of human intervention, iterations, and oversight:



Map-Stitching output

Shape Team

Selection/rejection of images…

Concurrent Solution

Stitching surface local maps…

OpNav Team

Orbit Team

Tracking surface landmarks…

Visual Point Clouds

Key Principle: Tracking features over a <u>small stereo baseline</u>, to estimate a 3D point cloud.

Leveraging 3D structure for localization.

Strengths

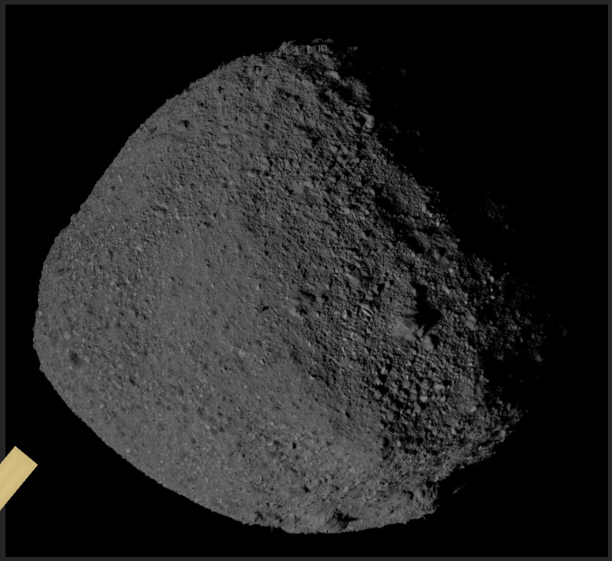
- Avoids landmark **detection** and **matching**
- Small baseline: robust to changes in surface appearance (lighting, viewpoint)
- Navigation and mapping are concurrently performed
- Simplicity
- Agnostic to body type and resolution

Limitations

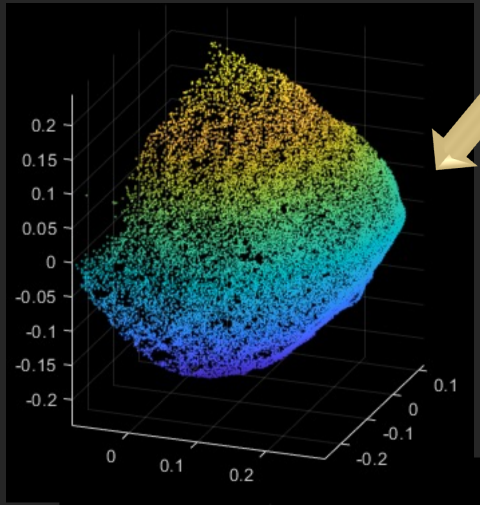
- Best suited for proximity scenarios
- Lower mapping resolution than photometry-based techniques

Assumptions

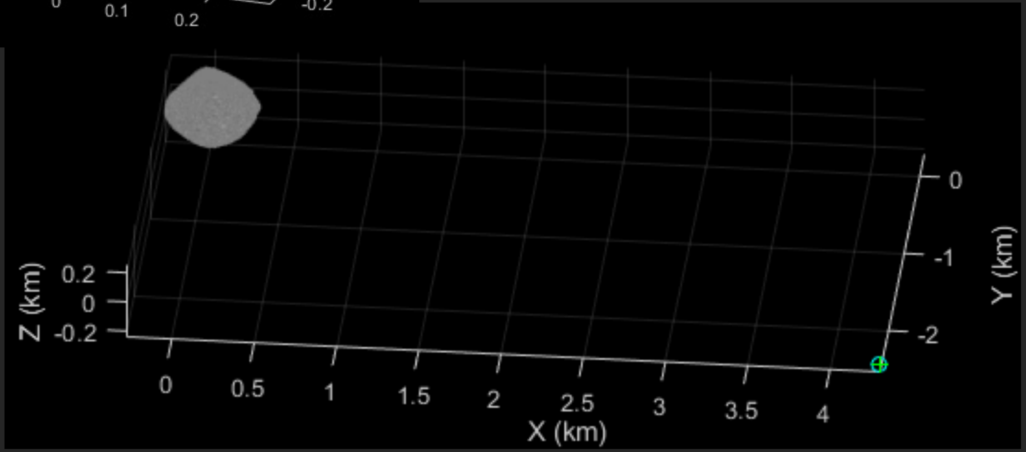
- Some prior knowledge of the small-body orientation, as well as spacecraft trajectory and attitude
- Higher-frequency imaging (~ minutes between frames)



Surface Point Cloud



Relative Camera Pose



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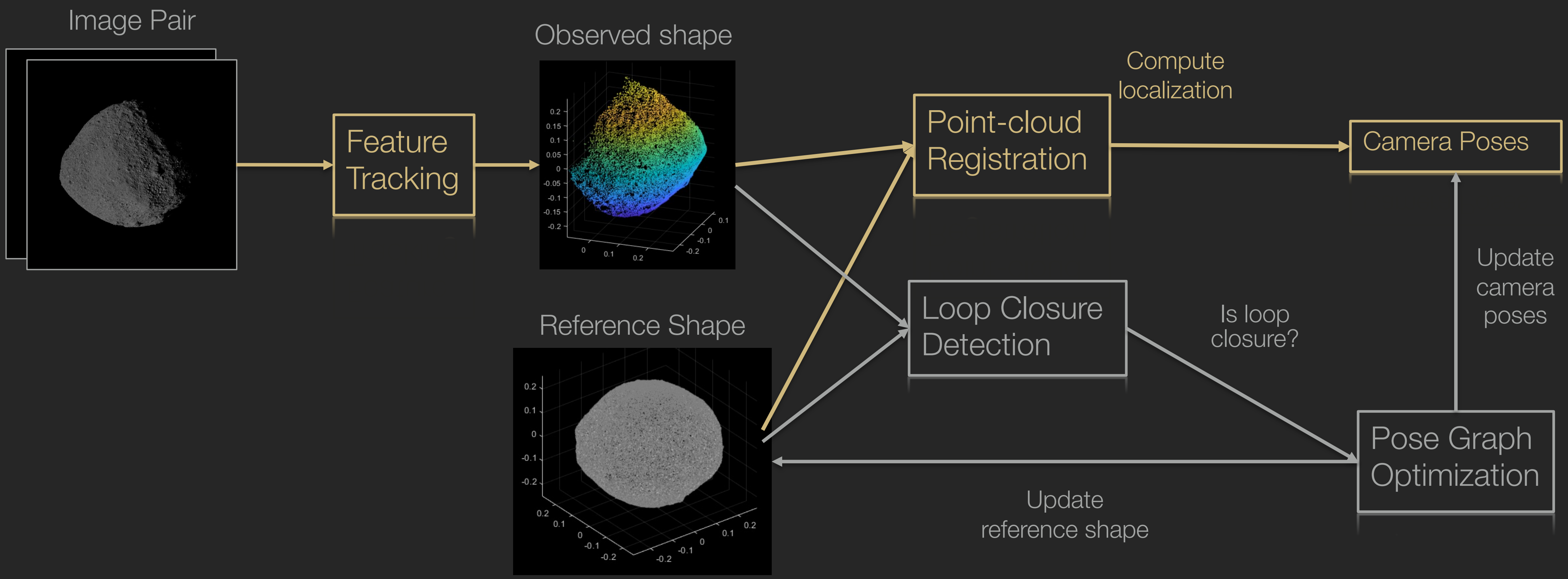
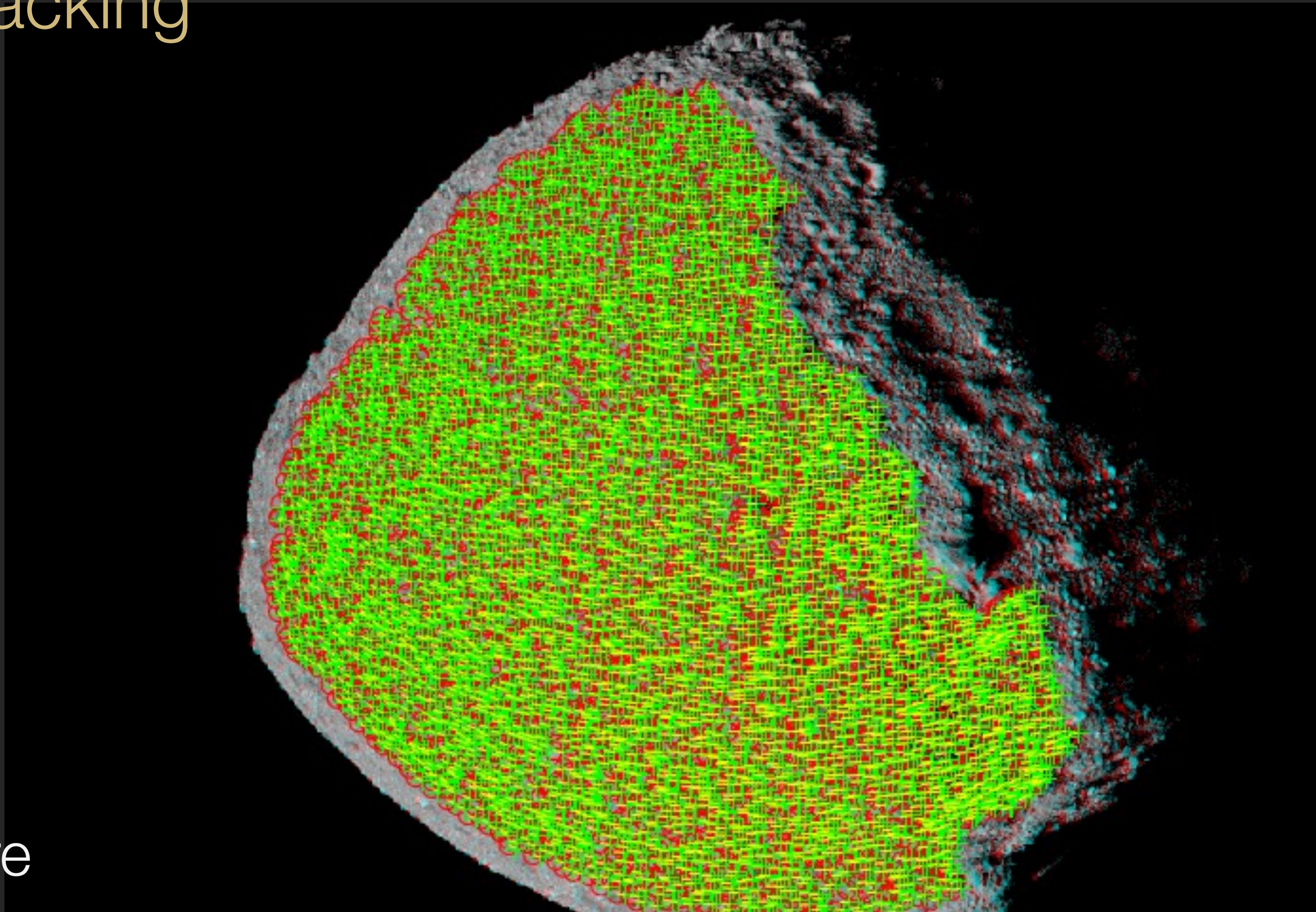
Visual Point Cloud SLAM (VPC-SLAM) Overview



Small-Baseline Feature Tracking

- Kanade-Lucas-Tomasi(KLT) tracking, small baseline
- Estimating camera essential matrix. Returns:
  - 3D point estimates
  - Camera pose estimate
- Scale factor is normalized
- Features can be downsampled
- Features close to the limb are discarded using a distance transform

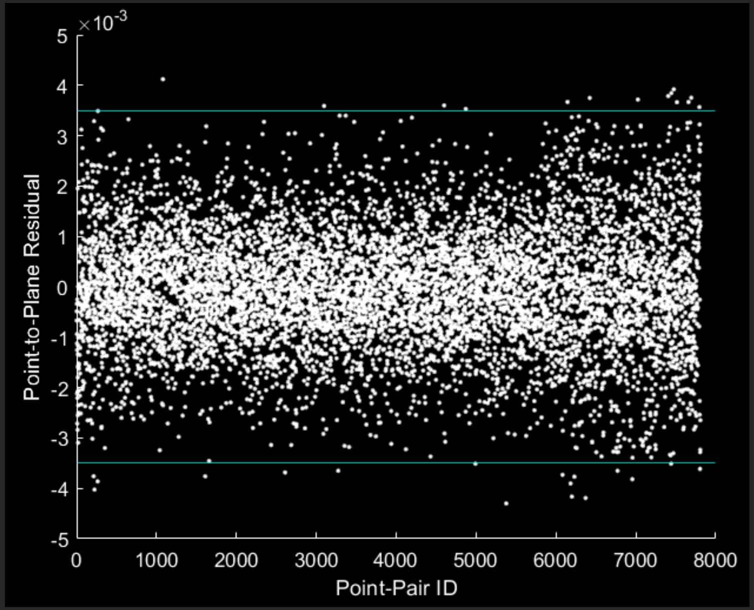


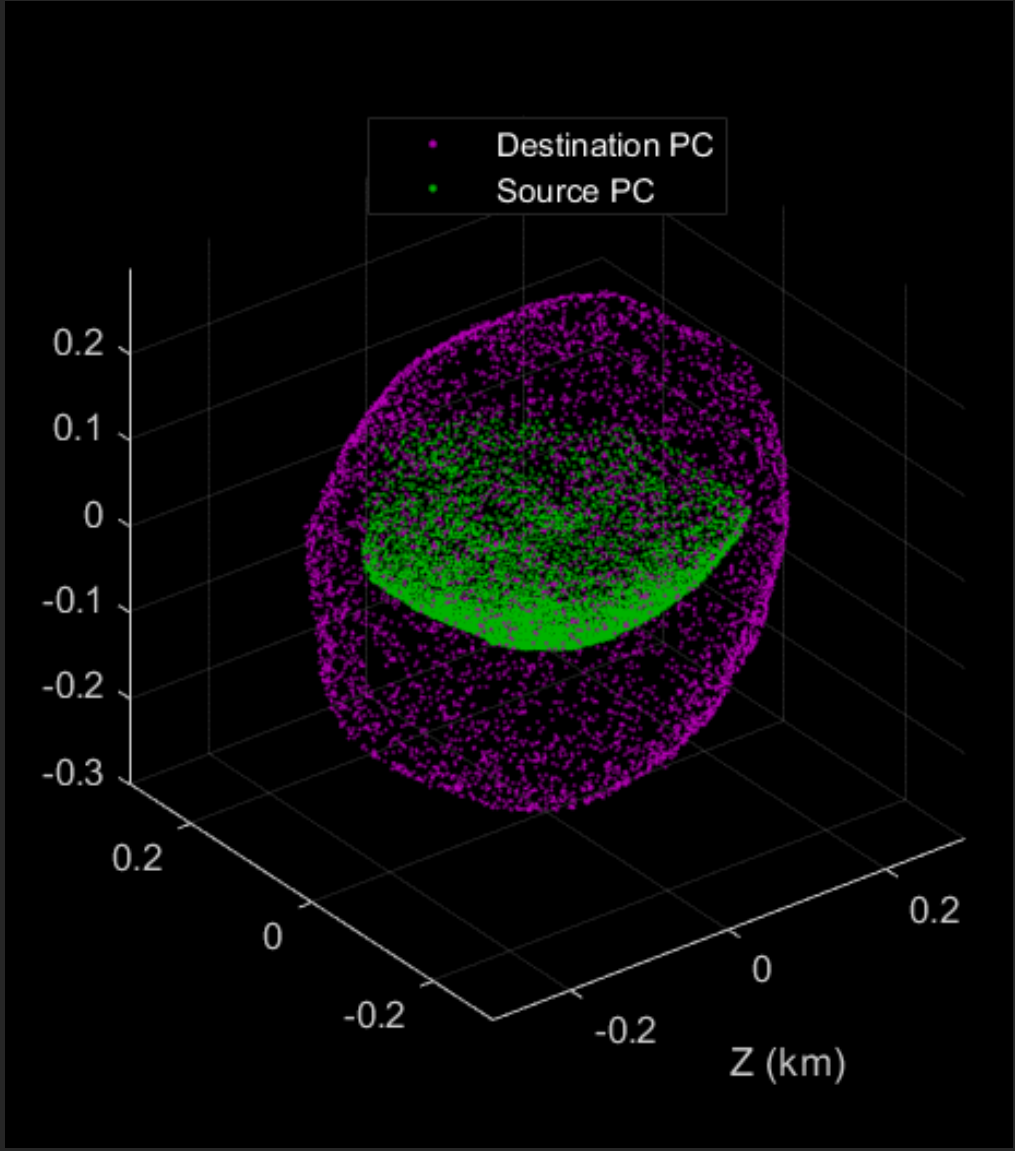
Feature Tracks
on asteroid Bennu

Registration Results

Example case study

- Initial errors:
  - MRP: $[0.01, 0.01, 0.01]$
    - $\sim[3,3,3]°$ Euler-angle rotation
  - Position: $[100,100,100]$ m
  - Scale: $\sim 1\%$ (from depth error)





Localization Scenarios

Camera:

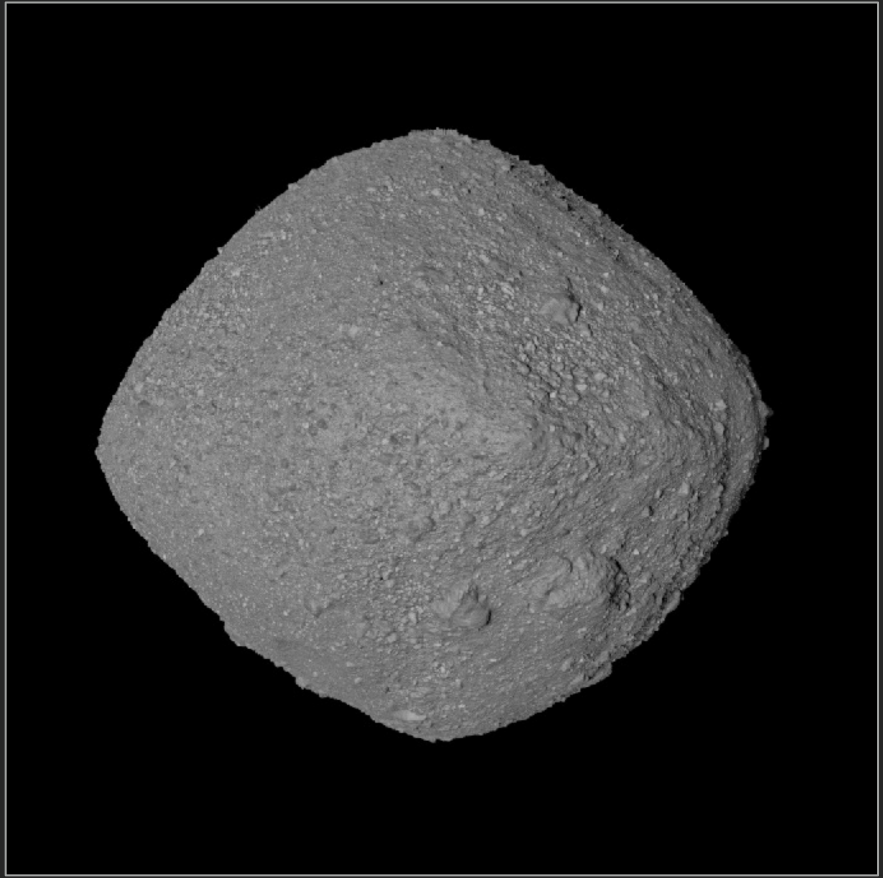
- FOV: $40°$
- Resolution: 1024×1024

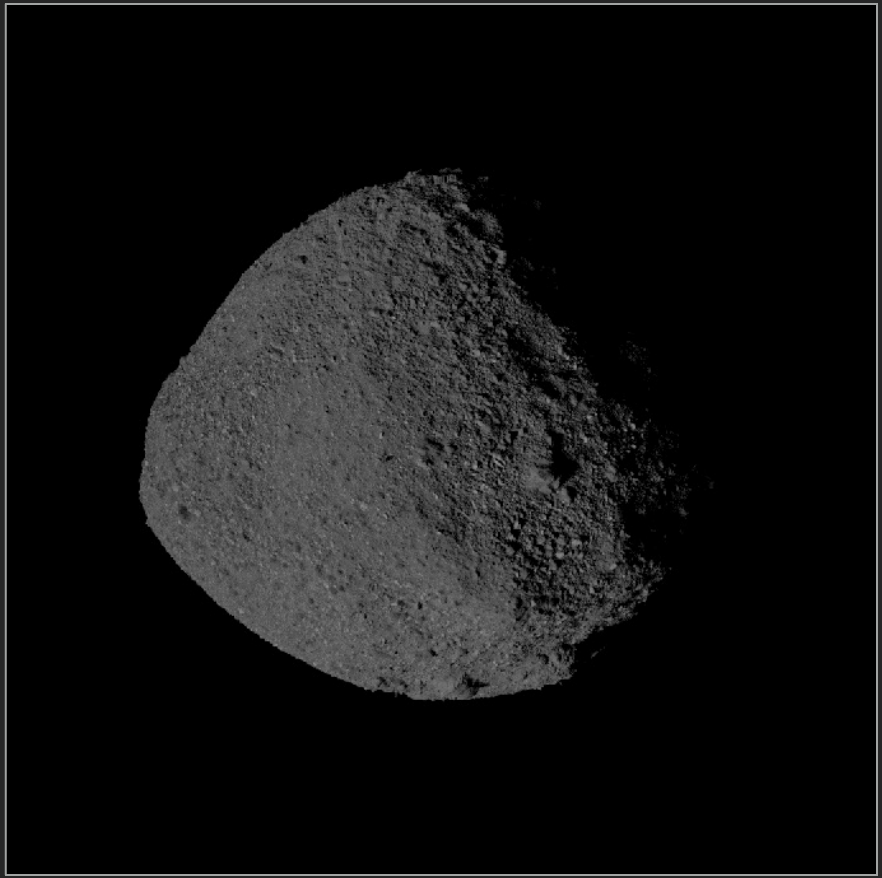
Perfect hovering
(i.e., steady observer)

Imaging cadence:

- 1-deg longitudinal displacement
- **Note:** this cadence is arbitrary and likely sub-optimal. This should be considered in assessing performance

Sun phase: $0°$
Latitude: $0°$
Distance: 1 km





Sun phase: $45°$
Latitude: $45°$
Distance: 1.1 km

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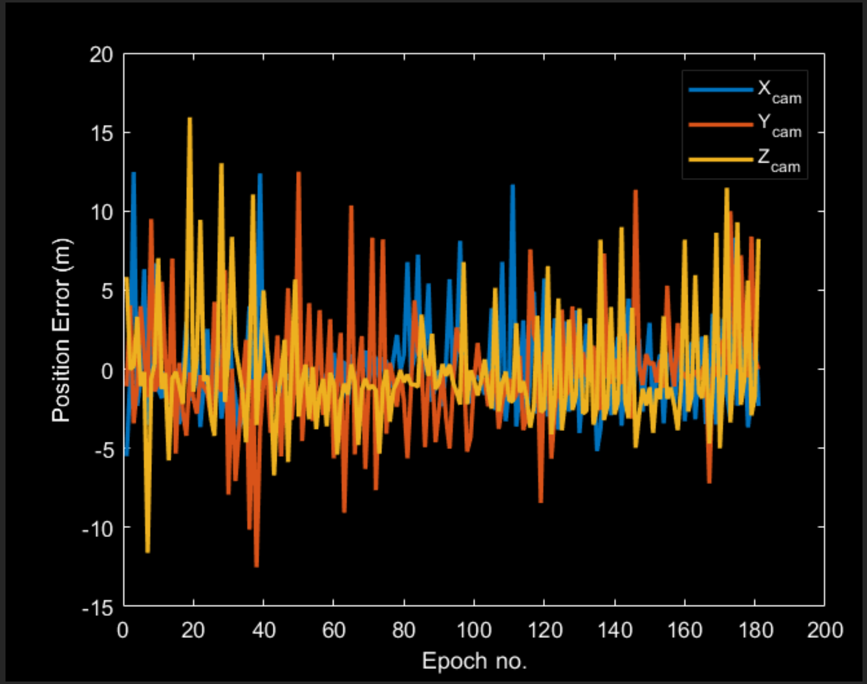
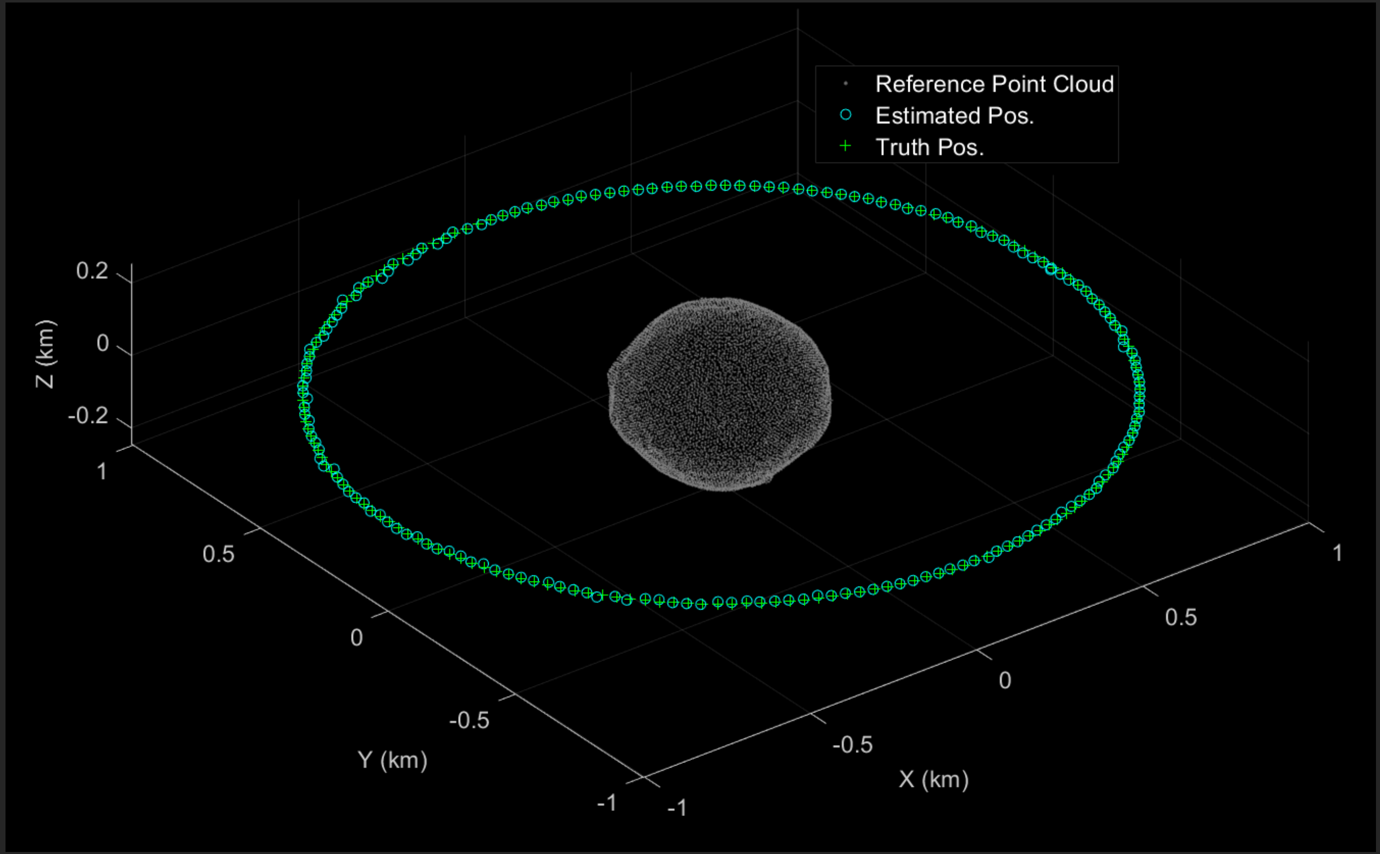
Initial Localization Scenario

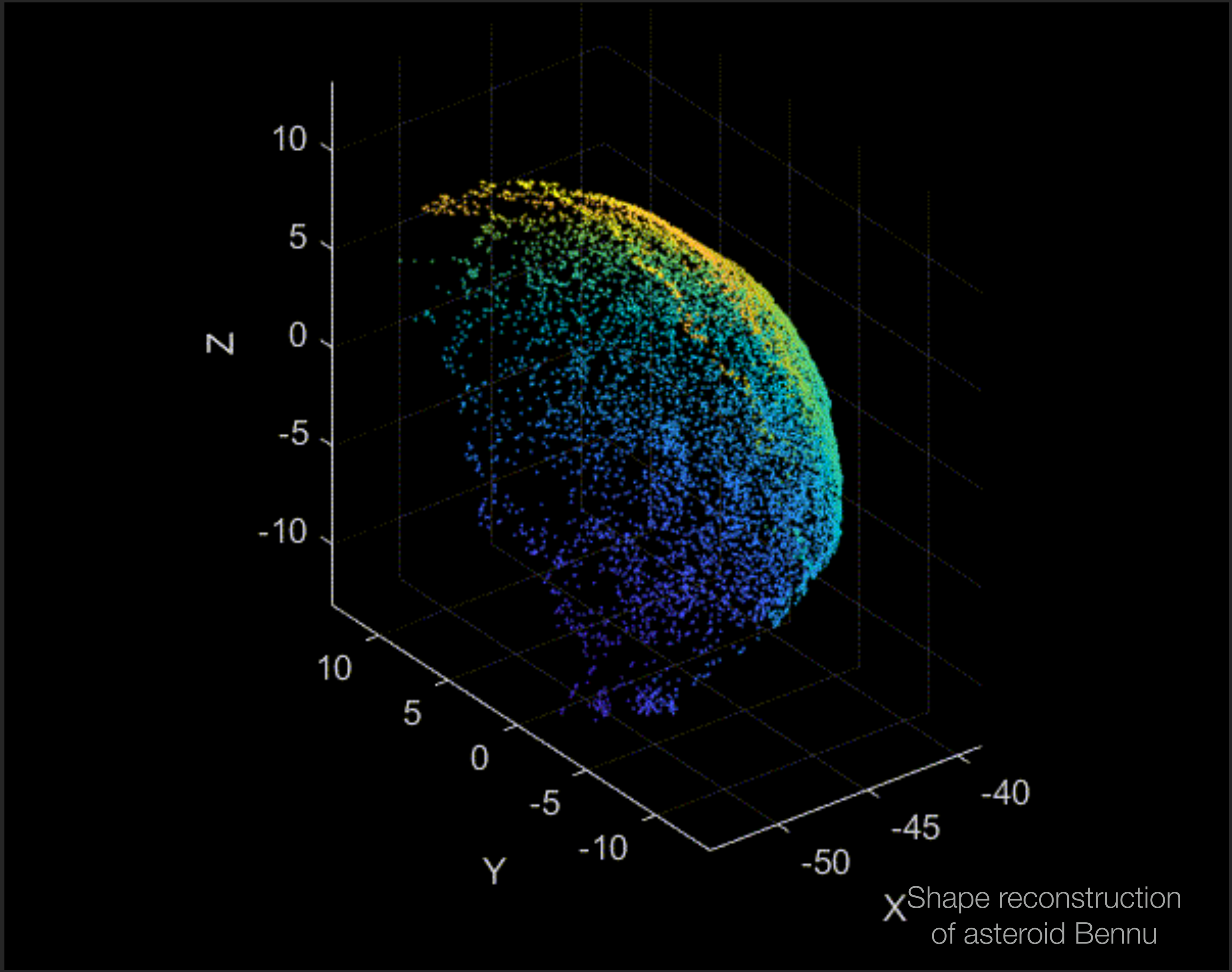
- Position errors mostly < 1% of radial distance
- Using truth scale to compare the estimate
- Have a reference point cloud, but not necessarily a shape model





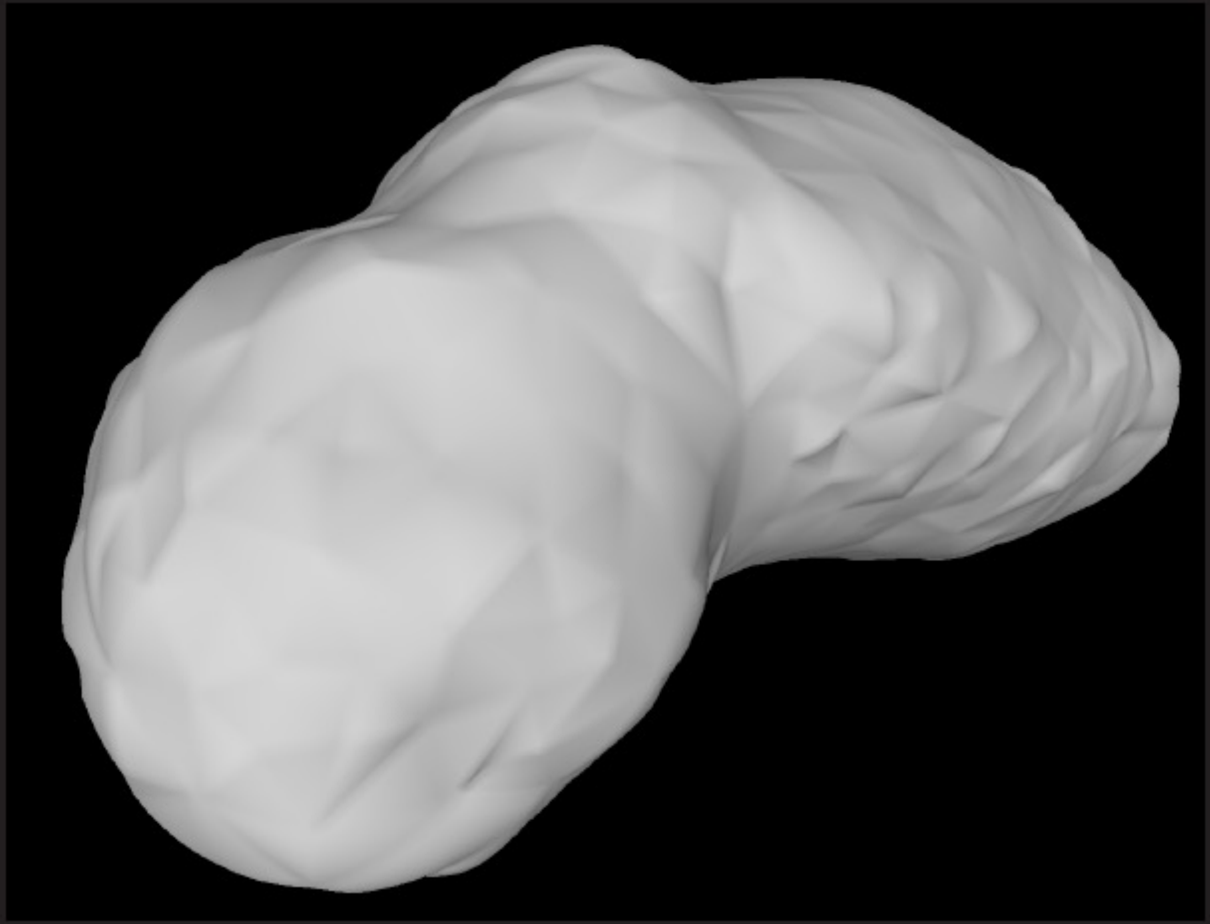
Mapping Results

- Consecutive point-cloud registration for map building (odometry)
- Ongoing work: loop closure and bundle adjustment



Shape reconstruction of asteroid Bennu

Efficient Shape Representation with Bezier shapes



A-priori

hedron

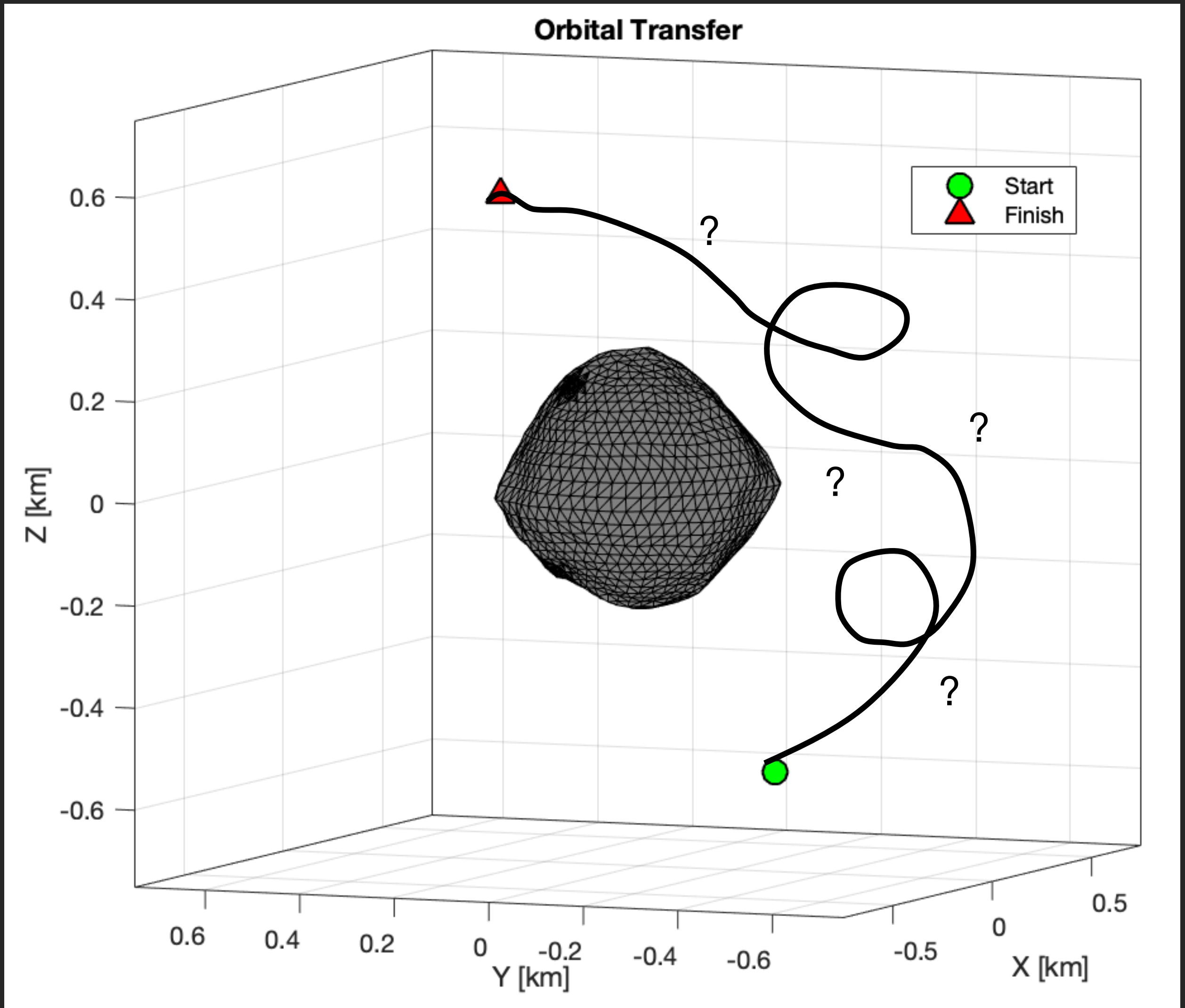
Fit Bezier shape: 1500 quadratic Bezier patches, 1998 control points

ORBITAL GUIDANCE AND CONTROL

Work of Dr. Don Kuettel, Dr. Kenshiro Oguri, and Dr. Spencer Boone shown

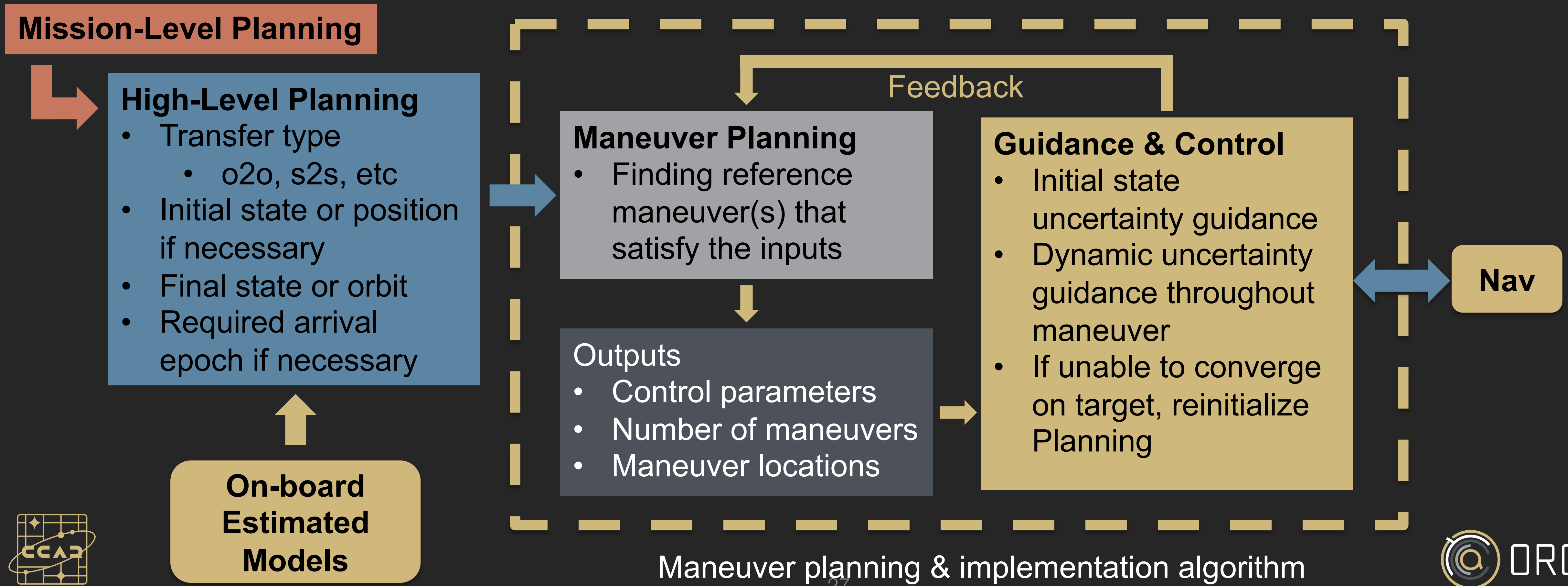
How to autonomously & robustly move around small bodies?

- Developing a robust, autonomous, onboard algorithm
- Guidance must deal with complicated natural dynamics
  - SRP
  - Gravity Field
  - Solar Gravity
- Options to control a spacecraft
  - Impulsive vs finite burns
  - Constant vs variable thrust
- Different target requirements
  - e.g. position vs full state targeting
- May have path constraints, such as avoiding particles/secondary bodies



Maneuvering Architecture

- Goal is to develop autonomous algorithms to plan and execute maneuvers based on input directions and navigation
  - Encompasses the control law, maneuver targeting, and guidance
  - Must be fault tolerant – triggers re-planning etc



Maneuver planning & implementation algorithm

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Autonomous Low-Thrust Maneuvers (ALTm)

- Plans the continuous, BLT maneuvers
  - Multiple Burn Configurations: Single Burn, Burn-Coast, Burn-Coast-Burn
  - Orbital Transfers: o2o, o2s, s2o, s2s
  - Intercept Maneuvers: s2r, o2r
- Optimal impulsive Lambert used for initial guess
  - Lambert trajectory optimized for total $\Delta V_T = \Delta V_1 + \Delta V_2$
- **MEOE Predictor-Corrector Algorithm** turns impulsive initial guess into continuous, BLT maneuver

Input → Impulsive Initial Guess → Predictor-Corrector → Final Maneuvers

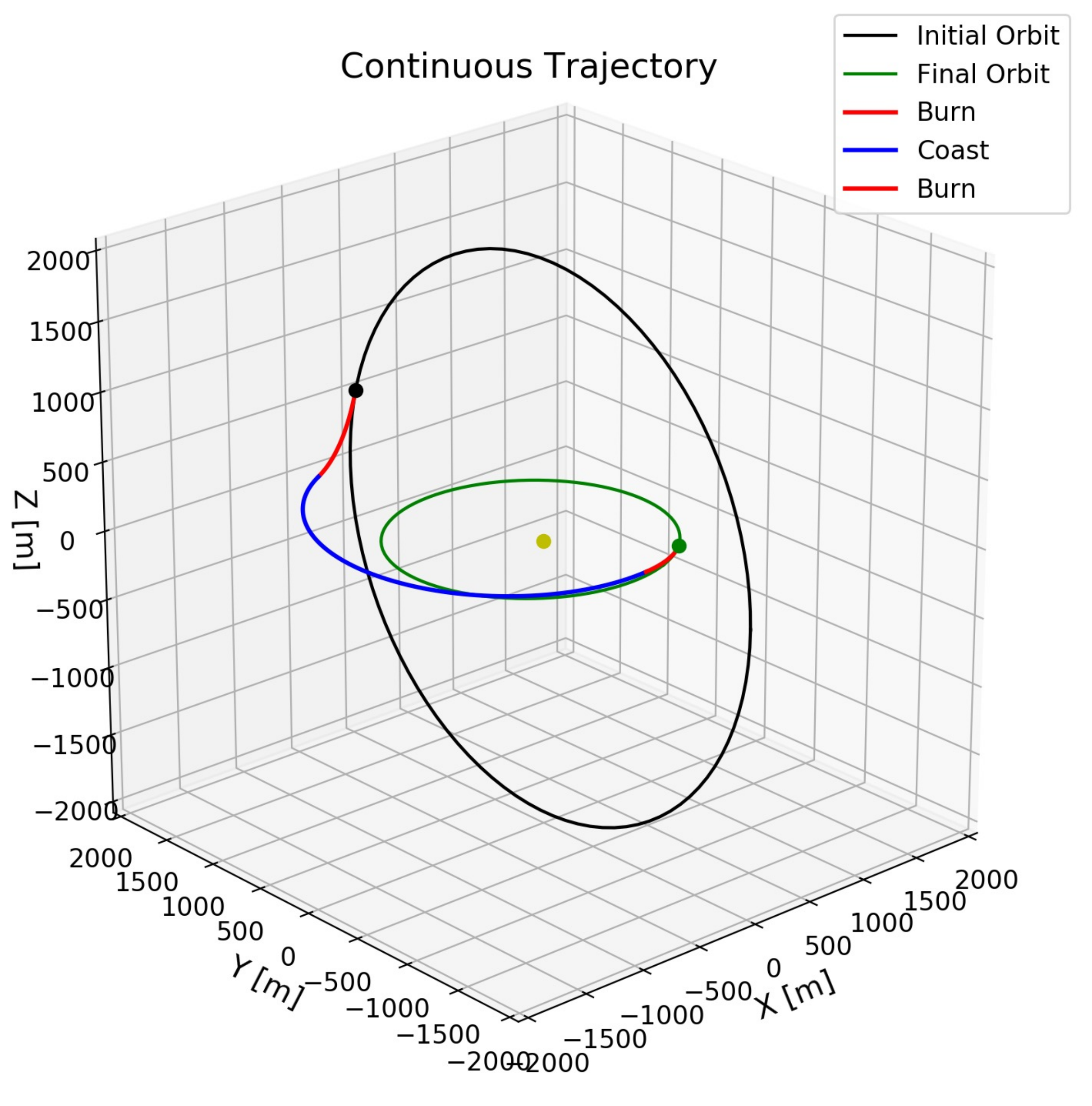
Input ↓
Initial and Final OE
Transfer Type
Transfer Time

Impulsive Initial Guess ↓
Optimal Lambert

Predictor-Corrector ↓
Normalized MEOEs
B – Single Shooter
BCB – 3-seg Multiple Shooter
Intercept – 2-seg Multiple Shooter

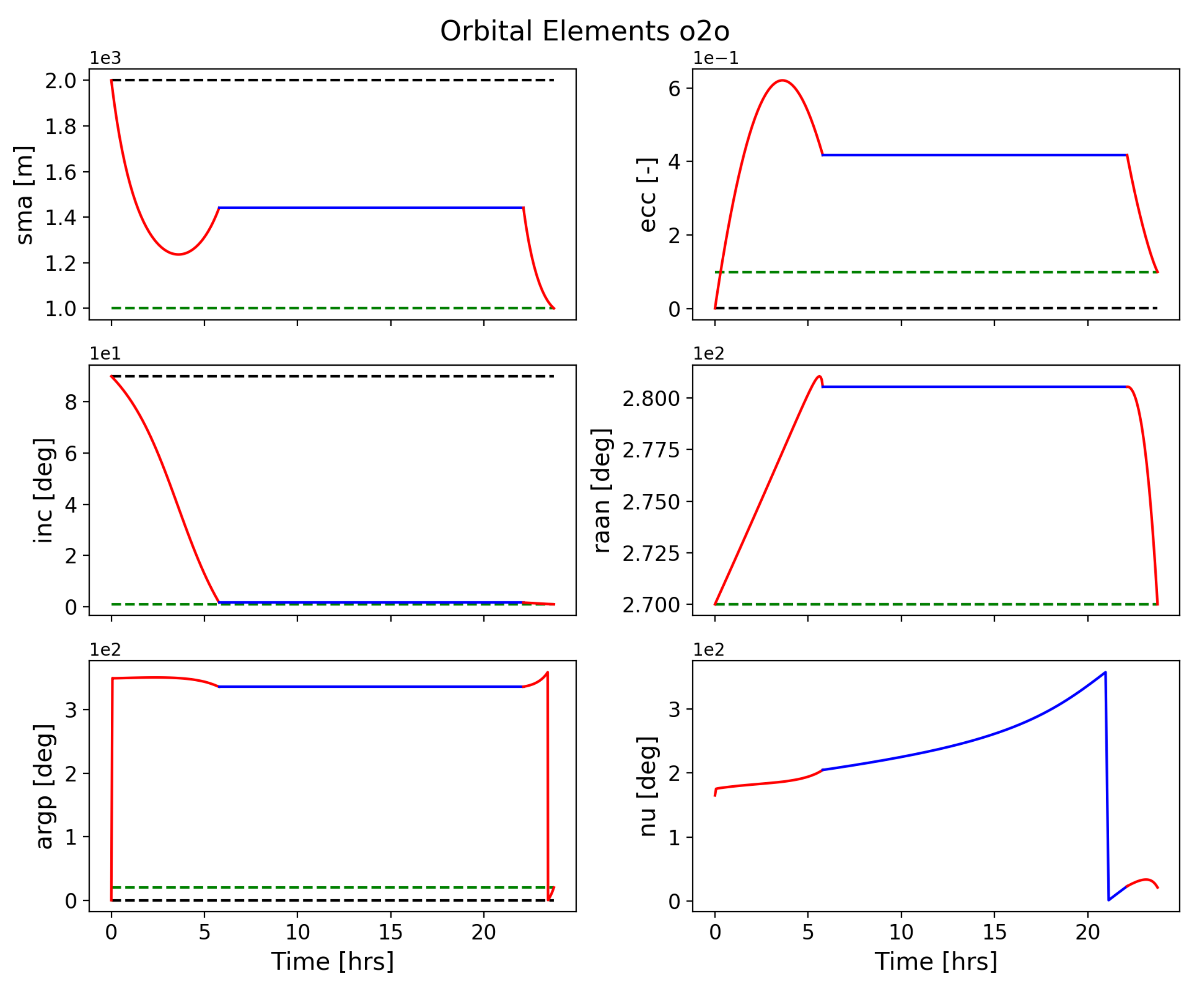
Final Maneuvers ↓
Converged BLT parameters
Initial and final OE

Orbit-2-Orbit 90-Degree Plan Change Maneuver

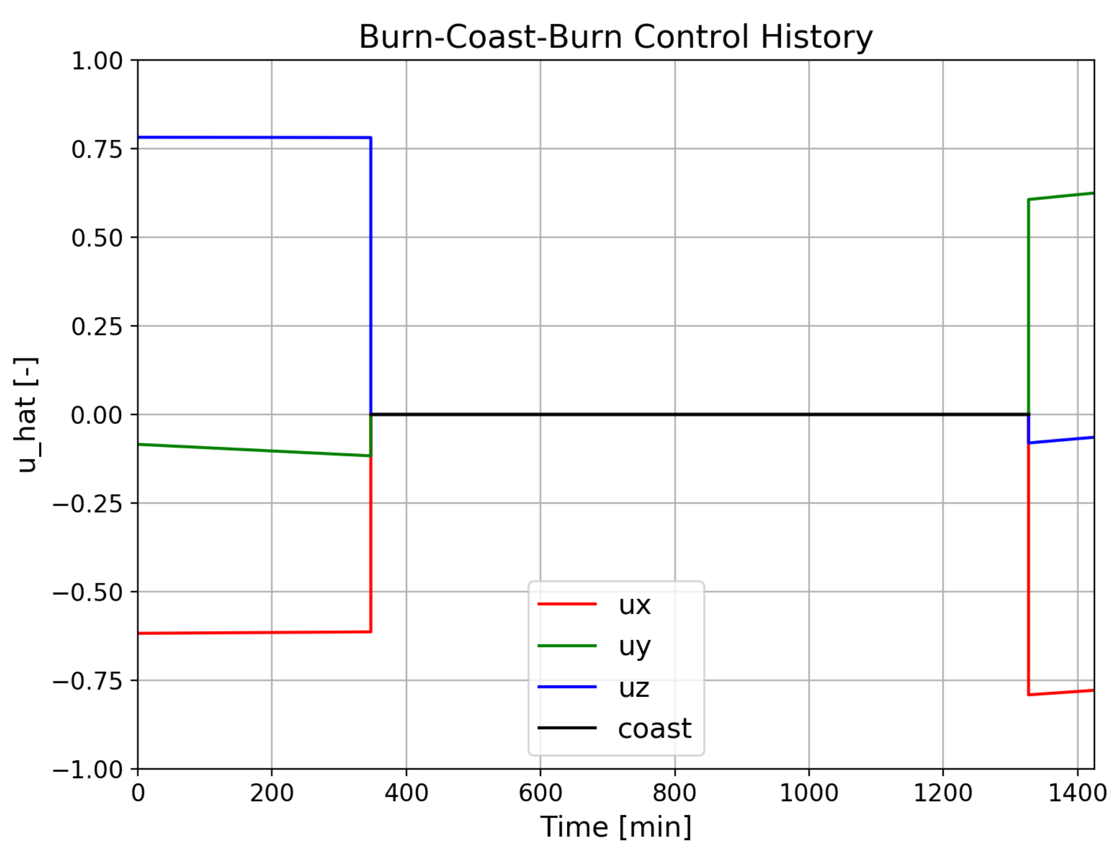


OE	Initial Val	Final Val
a	2000 m	1000 m
e	0.1	0.001
i	90º	0º
ω	0º	0º
Ω	270º	270º
ν	-	-

Orbit-2-Orbit 90-Degree Plan Change Maneuver

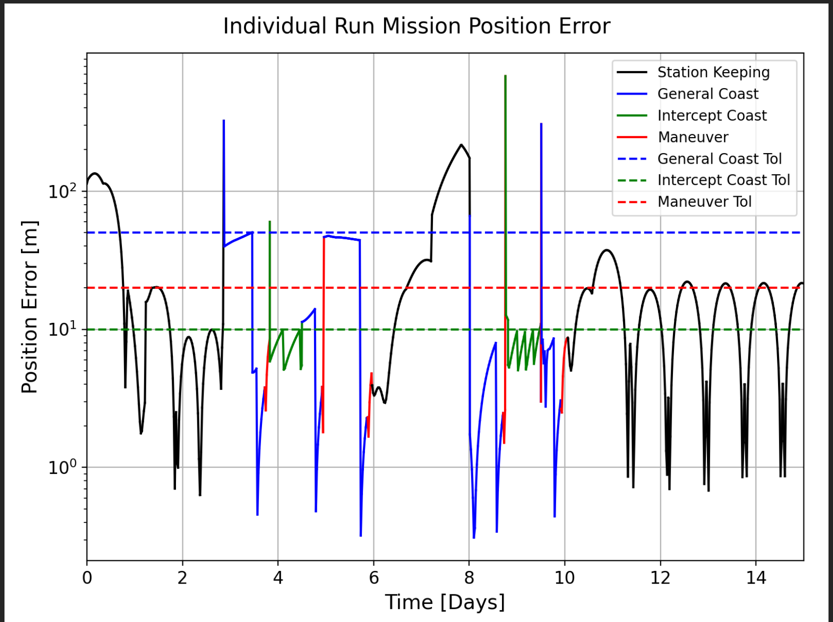


- ΔV_1 = 6.09 cm/s
- ΔV_2 = 1.02 cm/s
- ΔV_T = 7.11 cm/s
- ΔT = 1425 min
- Δm = 5.45 g



Implementation of Complicated Orbital Planning Scenarios

- Full implementation includes autonomous maneuver planning and execution with guidance for a variety of scenarios
  - Orbit-to-orbit transfers
  - State specific targets
  - Intercept targets



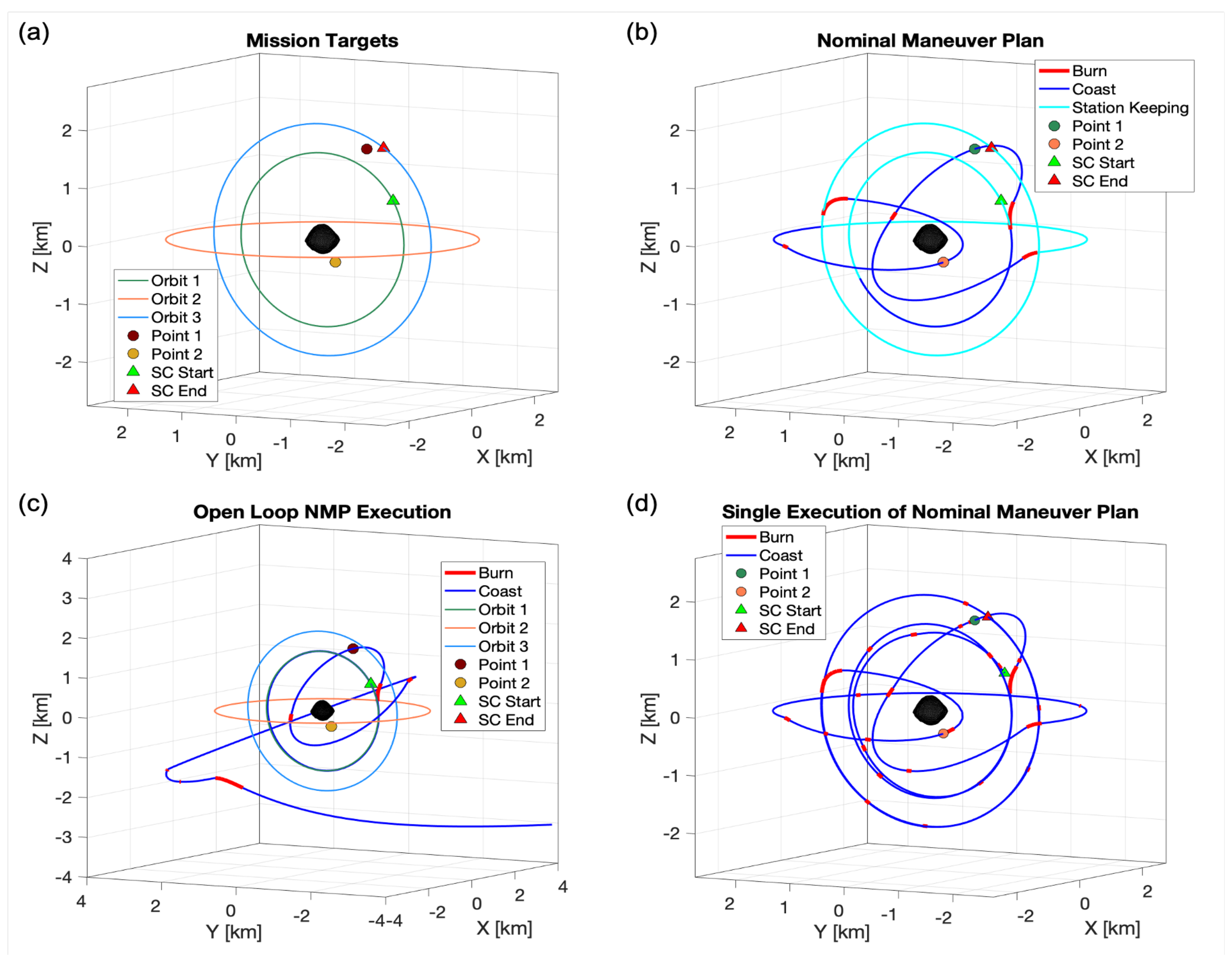


Fig. 17 A single instance of the ACTA algorithm planning and executing an intercept maneuver, an orbital transfer to an intermediate orbit, another intercept maneuver, and a last orbital transfer to the final orbit around Bennu. (a) The mission targets. (b) The nominal mission plan calculated by ACTA-t. (c) An open-loop execution of the nominal mission plan. (d) An ACTA-e execution of the nominal mission plan.

Spacecraft Guidance using Higher-Order Methods

- Higher-order **state transition tensors** (STTs) can be used for on-board spacecraft guidance in highly nonlinear dynamical systems (e.g. small bodies, multiple bodies) where the linearized dynamics may not be sufficiently accurate.
- Reference trajectory STTs can be repeatedly evaluated analytically (i.e. fast) in order to predict the effect of any perturbation or control on the spacecraft's state

Solution flow

$$\mathbf{x}(t) = \phi(t; \mathbf{x}_0, U^*_{(t_f,t_0)}, t_0)$$

STTs

$$\phi^{i,\gamma_1\ldots\gamma_p}_{(t_f,t_0)} = \frac{\partial^p \phi^i(t_f; \mathbf{x}_0, U^*_{(t_f,t_0)}, t_0)}{\partial x_0^{\gamma_1}\ldots\partial x_0^{\gamma_p}}$$

Control influence in terms of STTs

$$\delta x_f^i \simeq \sum_{p=1}^{m} \frac{1}{p!}\phi^{i,\gamma_1\ldots\gamma_p}_{(t_f,t_0)}\delta x_0^{\gamma_1}\ldots\delta x_0^{\gamma_p} + \sum_{\tau=t_0}^{t_f-1}\left[\sum_{q=1}^{m}\frac{1}{q!}\beta^{i,\kappa_1\ldots\kappa_q}_{(t_f,\tau)}\delta u_\tau^{\kappa_1}\ldots\delta u_\tau^{\kappa_q} + \sum_{q=1}^{m-1}\sum_{p=1}^{m-q}\frac{1}{p!q!}\Xi^{i,\kappa_1\ldots\kappa_q,\gamma_1\ldots\gamma_p}_{(t_f,\tau)}\delta u_\tau^{\kappa_1}\ldots\delta u_\tau^{\kappa_q}\delta x_\tau^{\gamma_1}\ldots\delta x_\tau^{\gamma_p}\right]$$

$$\Delta C_f^i = \sum_{r=1}^{s}\frac{1}{r!}\Psi^{i,\eta_1\ldots\eta_r}\left[h_x^{\eta_1}(\delta\mathbf{x}_0) + h_u^{\eta_1}(\delta\mathbf{u}_0) + h_{xu}^{\eta_1}(\delta\mathbf{x}_0,\delta\mathbf{u}_0)\right]\ldots \left[h_x^{\eta_r}(\delta\mathbf{x}_0) + h_u^{\eta_r}(\delta\mathbf{u}_0) + h_{xu}^{\eta_r}(\delta\mathbf{x}_0,\delta\mathbf{u}_0)\right]$$

Variation in targeting constraints

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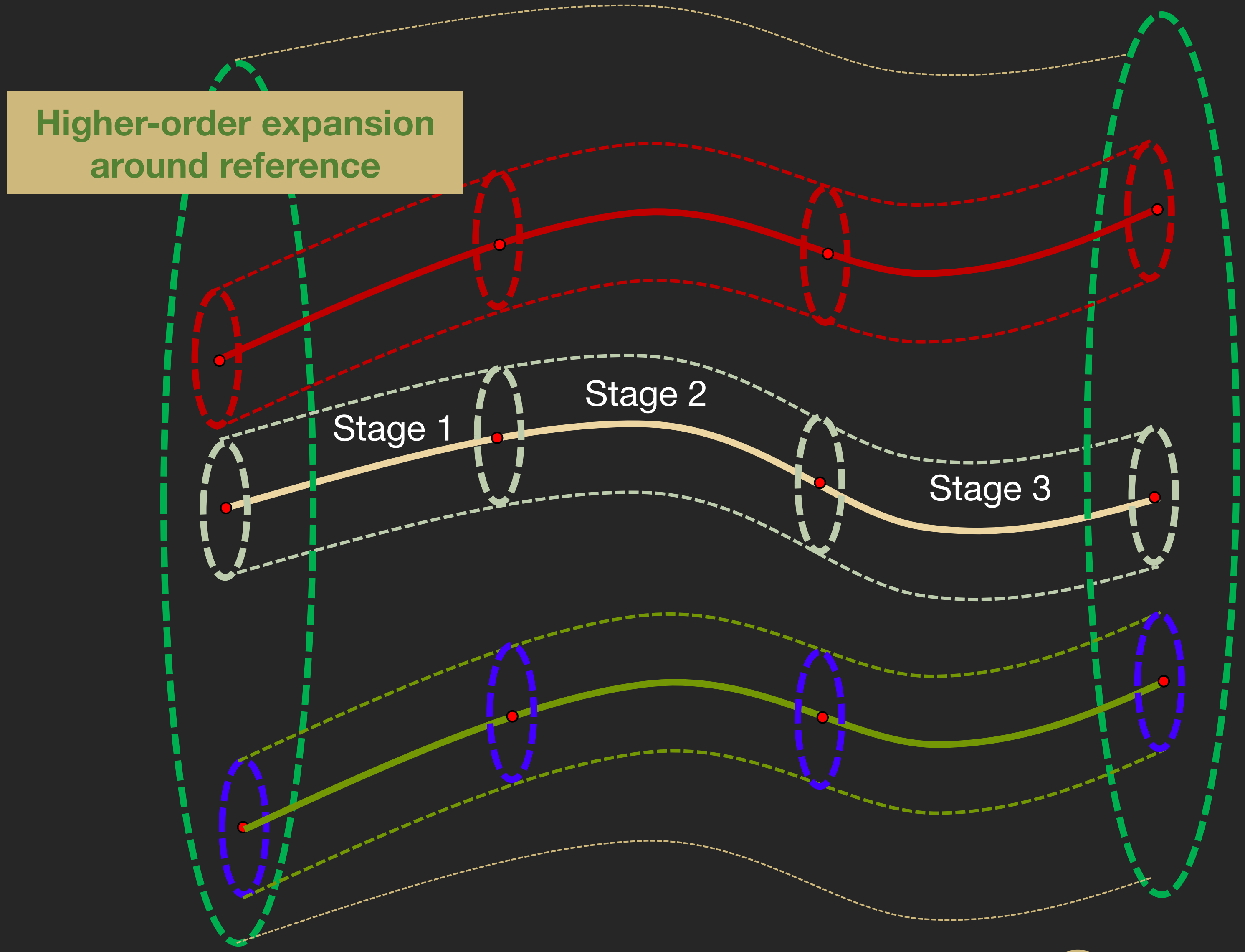
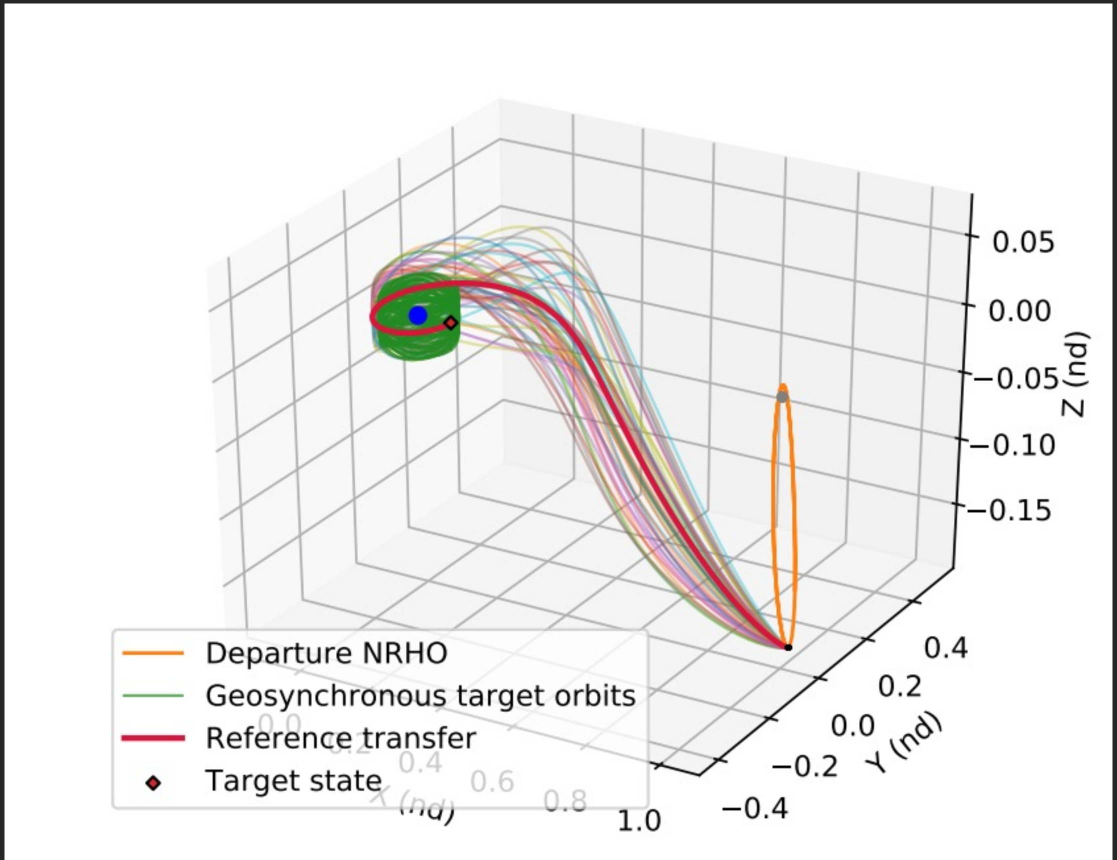
STT/DDP

- We propose **STT/DDP**
- Higher-order STTs of reference trajectory are integrated for each stage
- Successive second-order expansions can be accurately approximated using the higher-order STTs of this reference
- Resulting algorithm is **fully analytical** after reference STTs have been integrated
  - Very fast!



NRHO to Geosynchronous Orbit Transfer

- Vary target GSO parameters:
  - Inclination: [0, 15] deg
  - RAAN: [0,360] deg
- Compute 50 new trajectories with 2nd, 3rd, 4th order STT/DDP and compare with numerical DDP



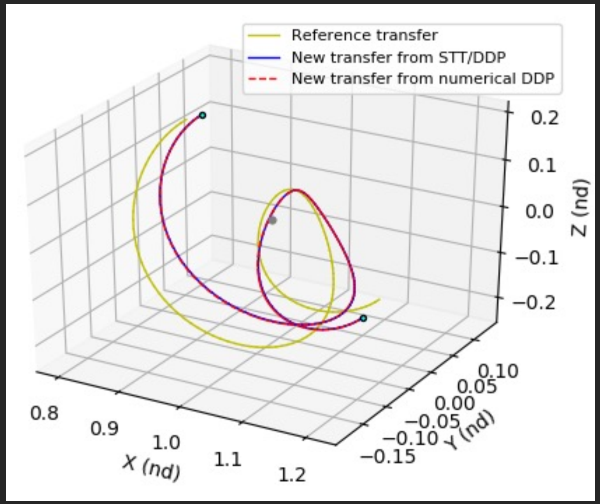
Computation time significantly decreases with STT/DDP

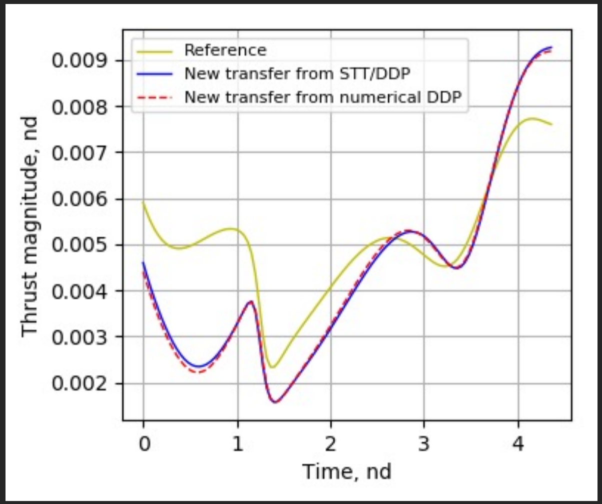
Algorithm	Final cost J	Computation time (s)	Number of iterations	Final state error $\|\psi\|$ with feedback law
STT/DDP, $m = 2$	0.139014	4.96	30.9	1.35e-3
STT/DDP, $m = 3$	0.069420	6.46	32.4	2.58e-4
STT/DDP, $m = 4$	0.065928	8.14	31.8	4.45e-5
Numerical DDP	0.065789	291.04	32.4	4.47e-13

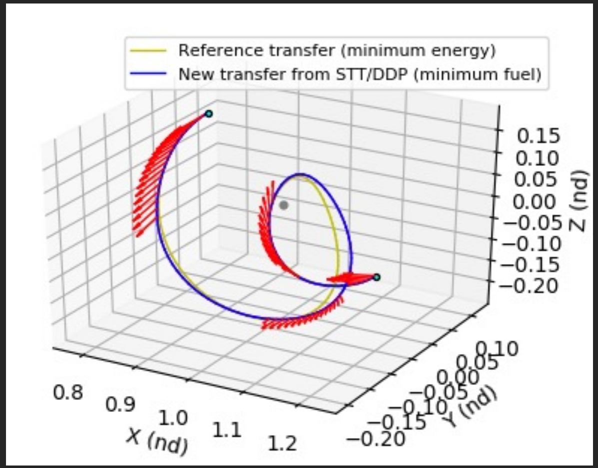
Other Applications

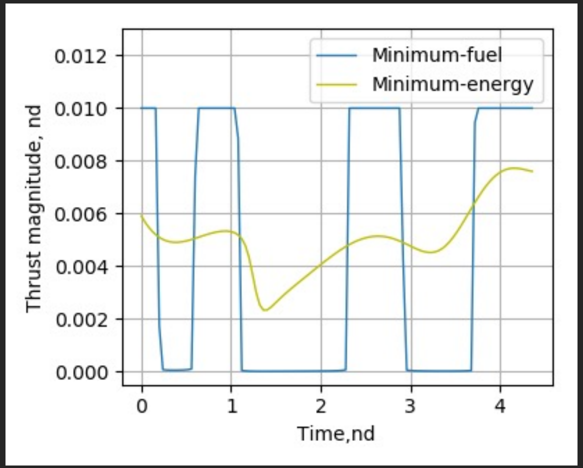
- The STT/DDP algorithm is promising for rapid local trajectory optimization around a reference
  - No need to integrate the dynamics and the first/second-order derivatives
  - Time to evaluate the STTs does not increase as the dynamics become more complex
  - Potential for use on flight hardware with limited resources
  - Frontloading of computations - integrate reference STTs prior to mission execution, and rapidly evaluate them at a later time
- Could be used to expedite sensitivity analyses in the preliminary mission design process

New target AND initial conditions





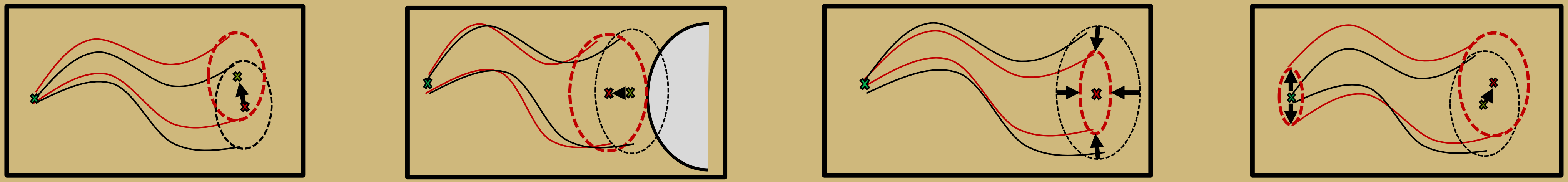




New cost function

Stochastic Formulations

- Derived expressions to analytically express various forms of stochastic maneuver design **strictly as a function of reference STTs**
  - Mean state constraint
  - State chance constraint
  - Minimum-covariance cost function (at final time)
  - Maximum-covariance cost function (at initial time)
  - Control-linear noise
- Derived **analytical gradients** for these formulations in terms of STTs
  - Useful for gradient-based optimization algorithms

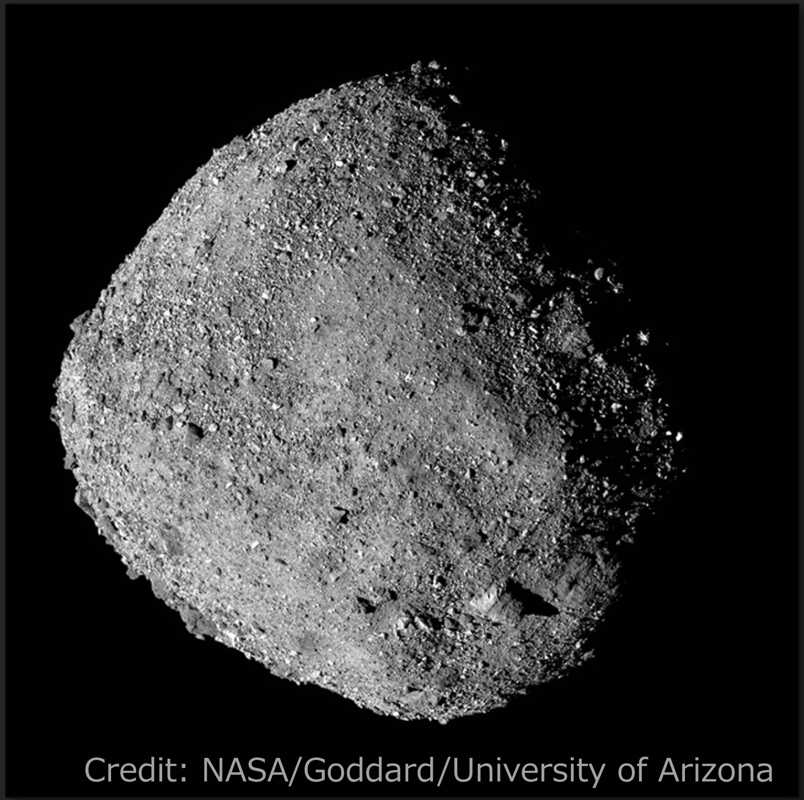


Mean state constraint | *State chance constraint* | *Minimum-covariance* | *Maximum-covariance*

Autonomous Spacecraft Guidance around Small Bodies

Astrodynamics ✕ **Stochastic Optimal Control** ✕ **Convex Optimization**

- Small-body dynamical environment:
  - Complex & uncertain
- Stochastic optimal control approach:
  - Designs feedback policies for future TCMs: *"controller of state distribution"*
  - Each FB policy maps "state estimate" $\mapsto$ "TCM" that probabilistically ensures the state feasibility under uncertainty



Bennu observed by OSIRIS-REx

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Stochastic Optimal Control in Robotics

Hard-Constrained Approach[1,2]

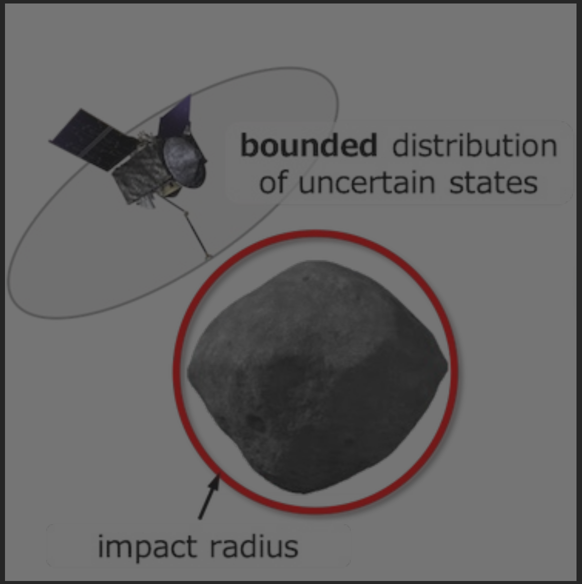
- Assume *bounded* distributions
- Feasibility for *all possible realizations*:

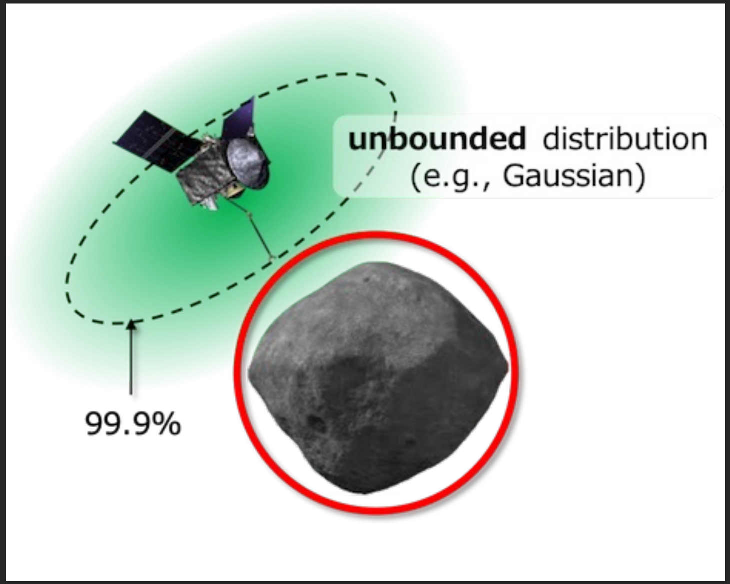
$$\forall\, x \in \mathcal{S}_{\text{safe}}$$

Chance-Constrained Approach[3,4]

- Handle both *bounded* & *unbounded* distributions
- Bound *probability* of failure δ

$$\Pr[x \in \mathcal{S}_{\text{safe}}] \geq 1 - \delta$$





1. Robust MPC with uncertain plant (M.Kothare, V. Balakrishnan, and M. Morari, Automatica, 1996)
2. Constraint tightening for robust MPC (Y.Kuwata, A.Richards, J.How, IEEE ACC, 2007)
3. Risk allocation for chance-constrained MPC (M.Ono, B.Williams, IEEE CDC, 2008)
4. Chance-constrained dynamic programming (M.Ono, et.al., Autonomous Robots, 2015)

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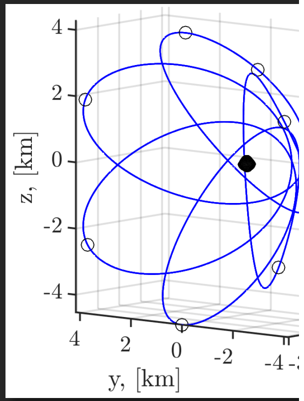
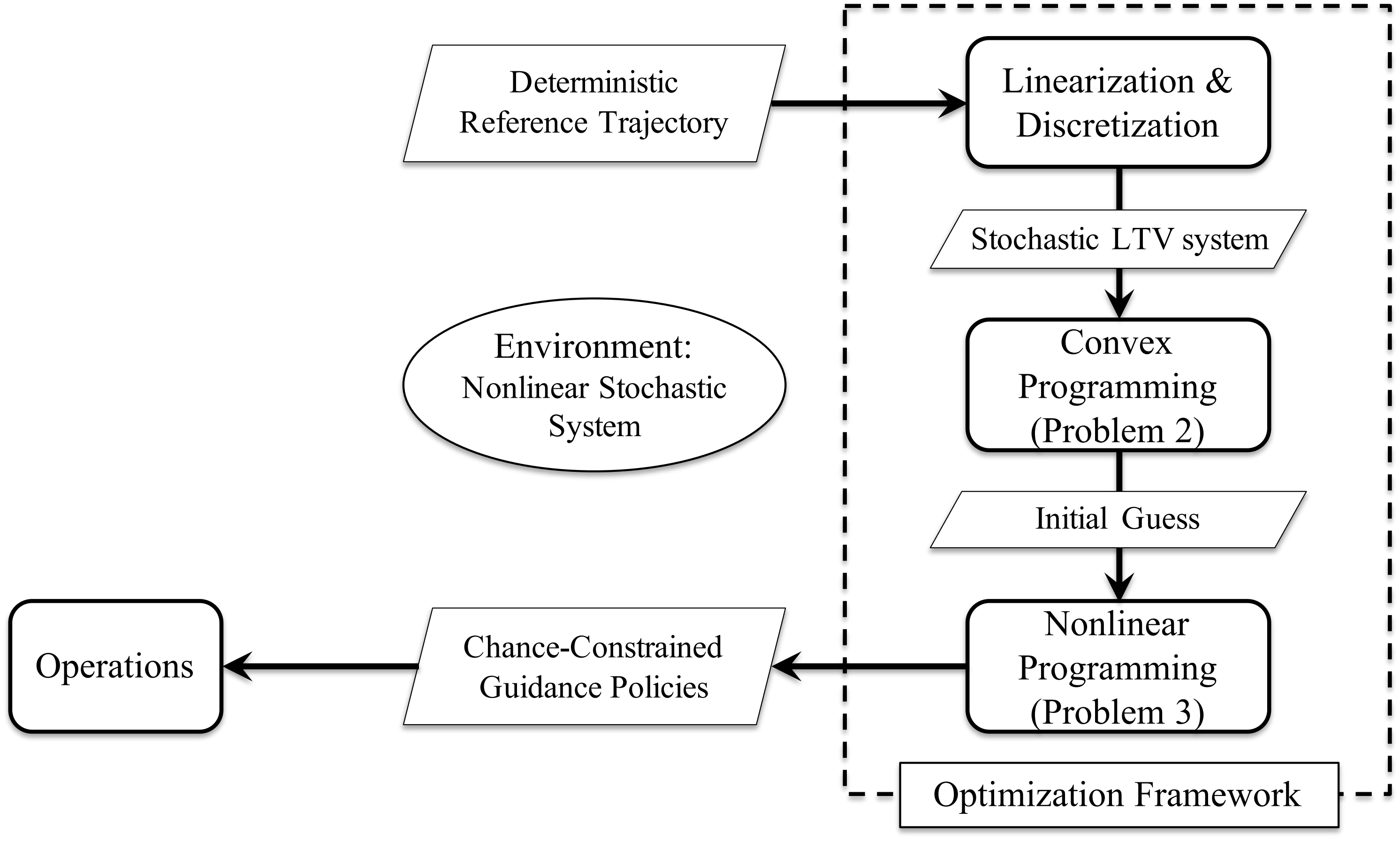
Chance-Constrained Control for Robust Guidance

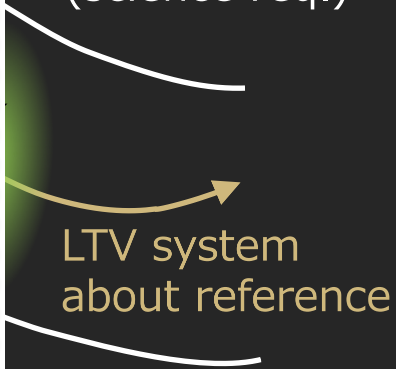
- Convex formulation to solve for chance-constrained guidance[1,2]
  - based on LTV system around nonlinear reference

Nonlinear

on LTV system







Original,

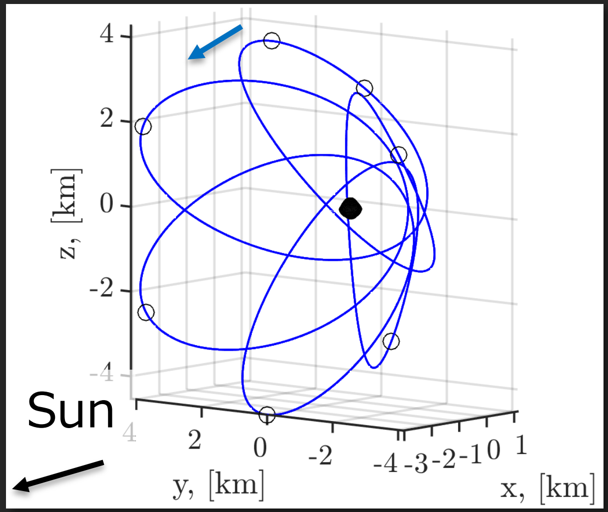
tion

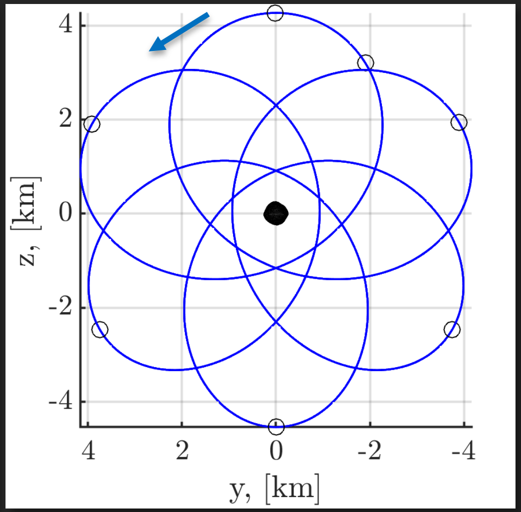
1. K.Oguri, M.Ono, J.McMahon, IEEE Conference on Decision and Control (CDC), 2019
2. K.Oguri, J.McMahon, AAS Guidance, Navigation, and Control conference, 2020

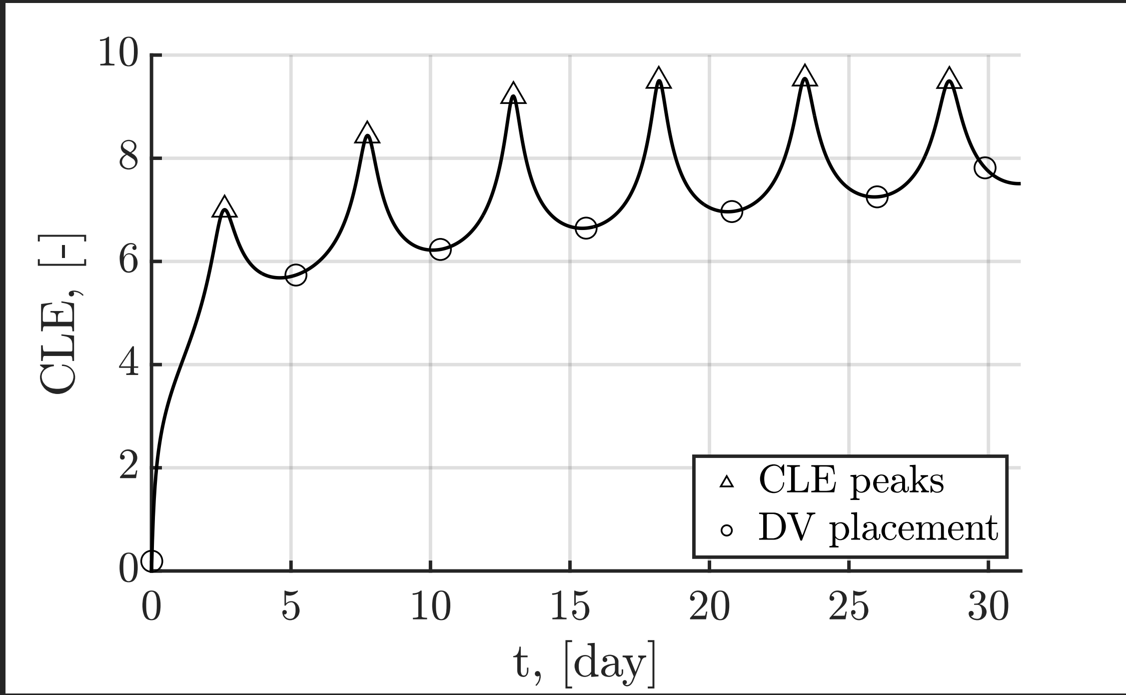
Global Mapping Scenario

- Reference science orbit
  - Sun-side 5:1 RTO (OREx at Bennu)
  - ~30-day period (5 revs)

- Autonomous guidance
  - FB policies for all TCMs designed based on the initial knowledge
  - Uncertainties: orbit insertion error, SRP strength, unmodeled accel., TCM execution error
  - Each FB policy linearly maps "state estimate" $\mapsto$ "TCM": light onboard computation

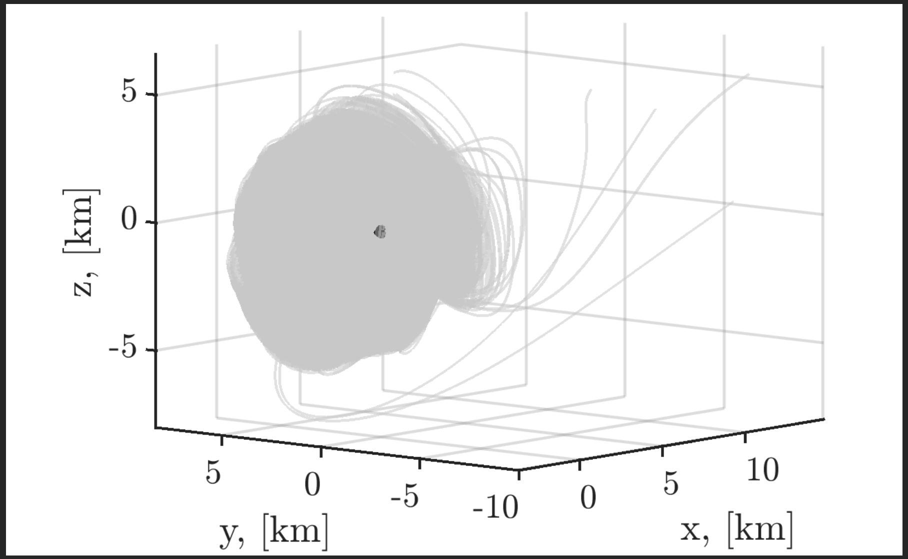


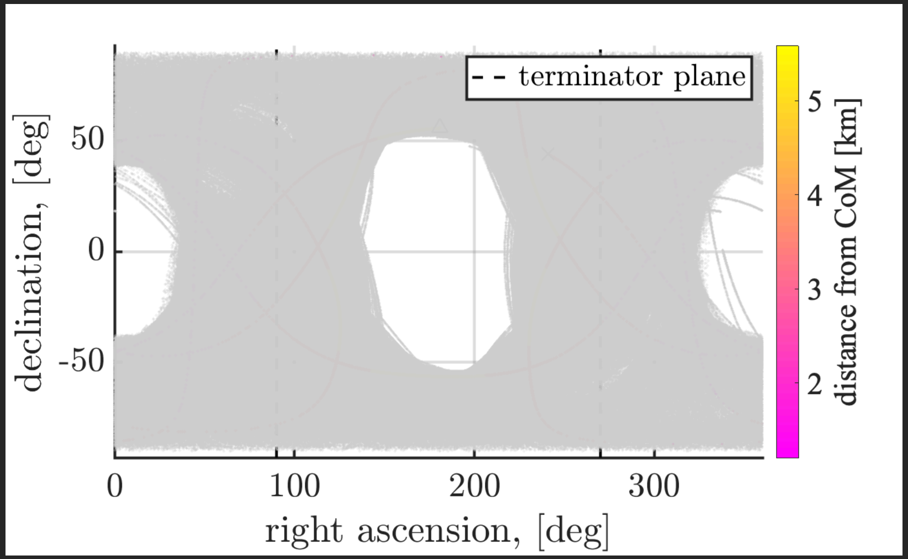




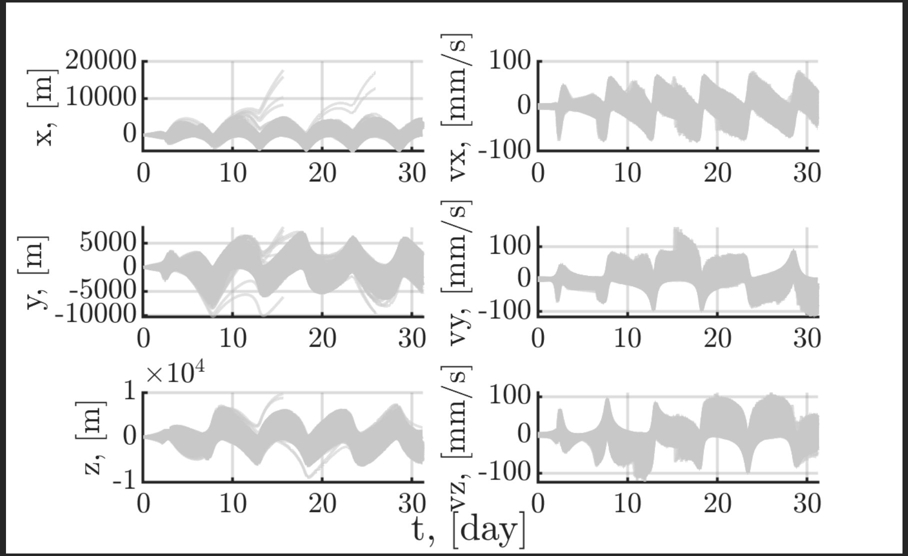
Numerical simulation: no control (ballistic)

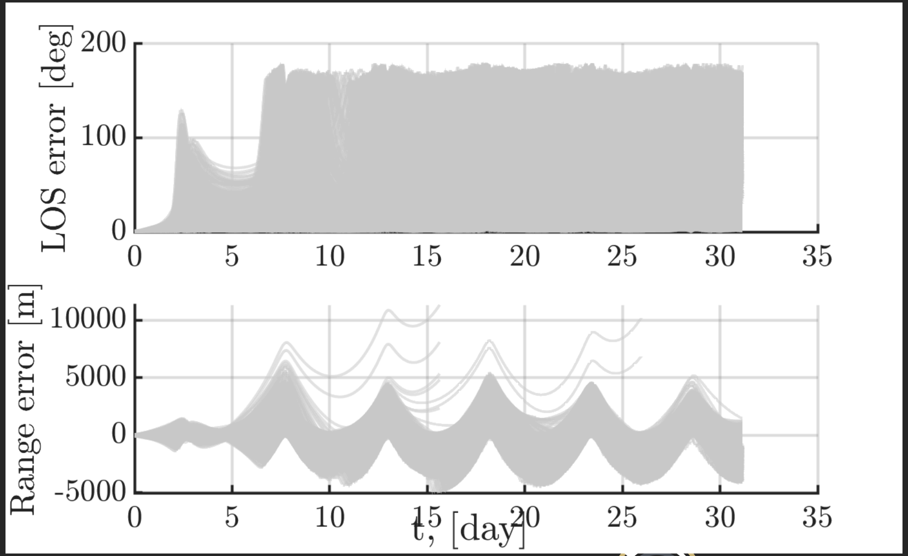
Nonlinear sim
w/ uncertain
errors
(N=2000)





deviation
from reference

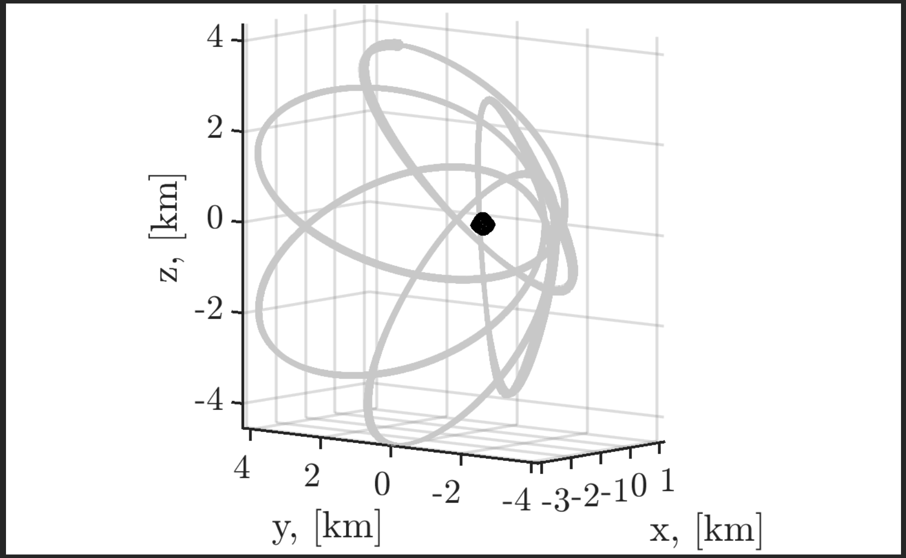


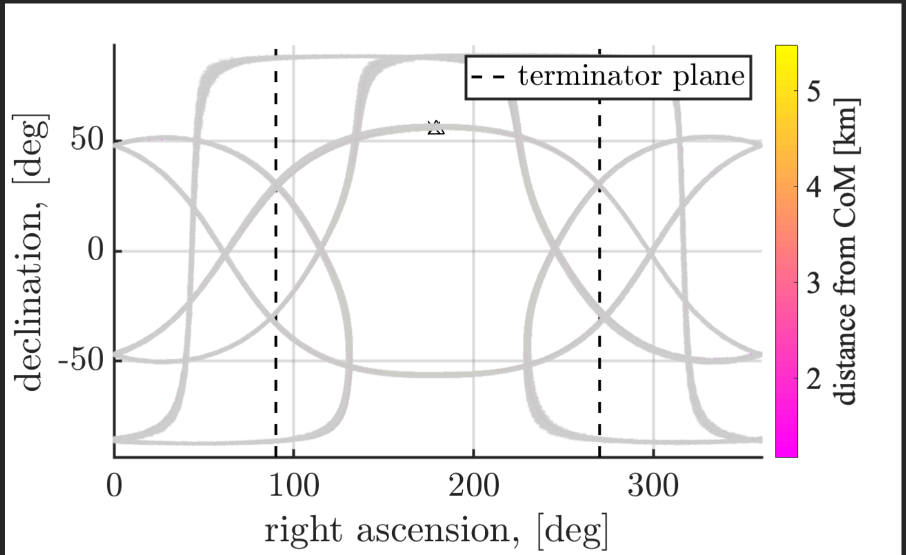


0% Success

Numerical simulation: chance-constrained guidance

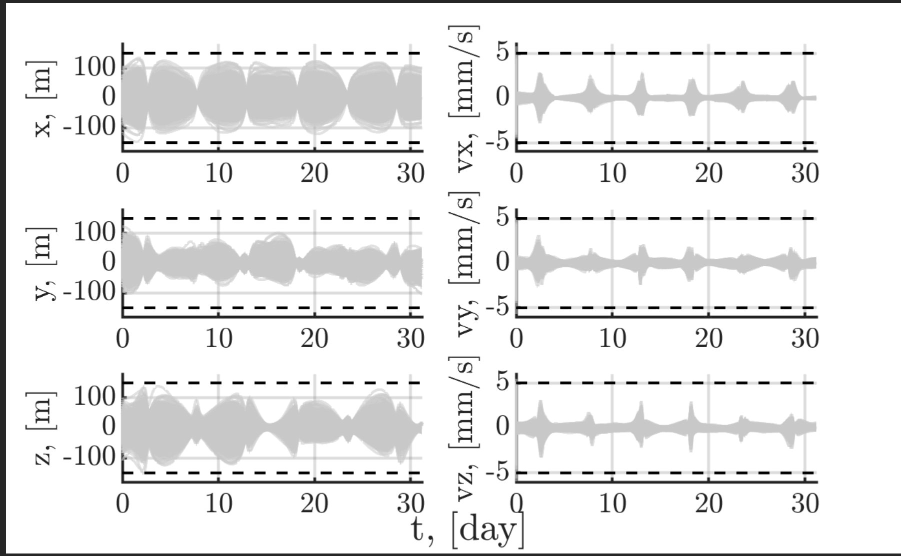
Nonlinear sim
w/ uncertain
errors
(N=2000)

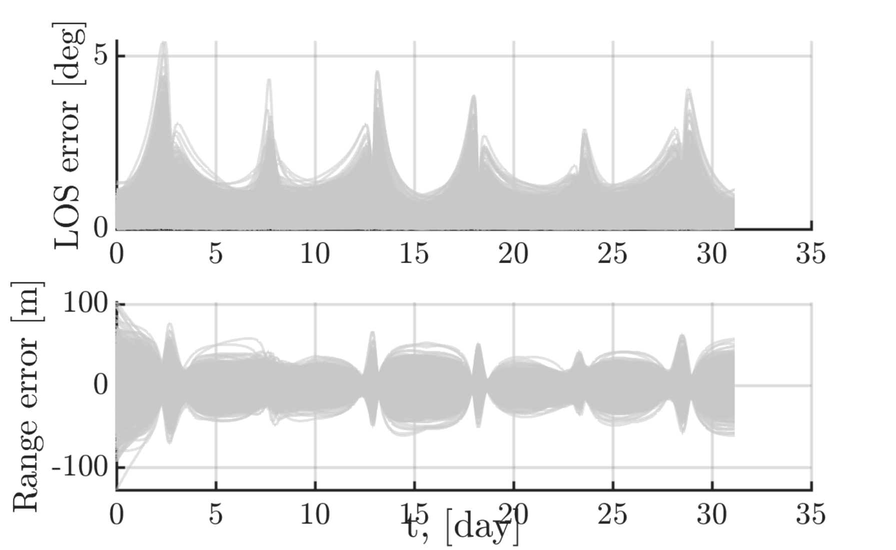




deviation
from reference

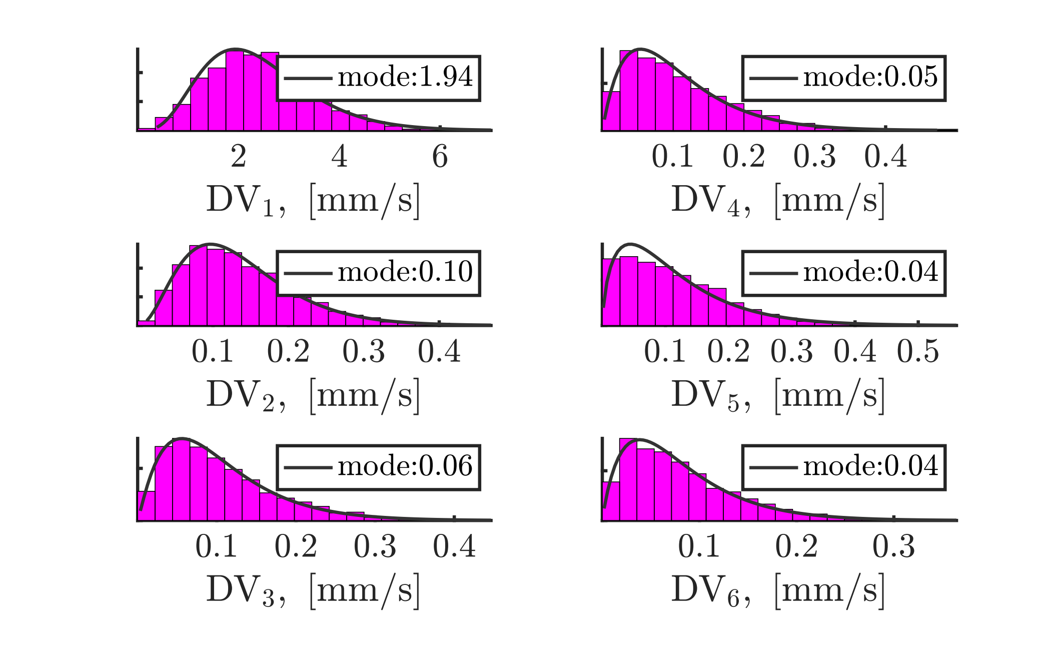
100% Success

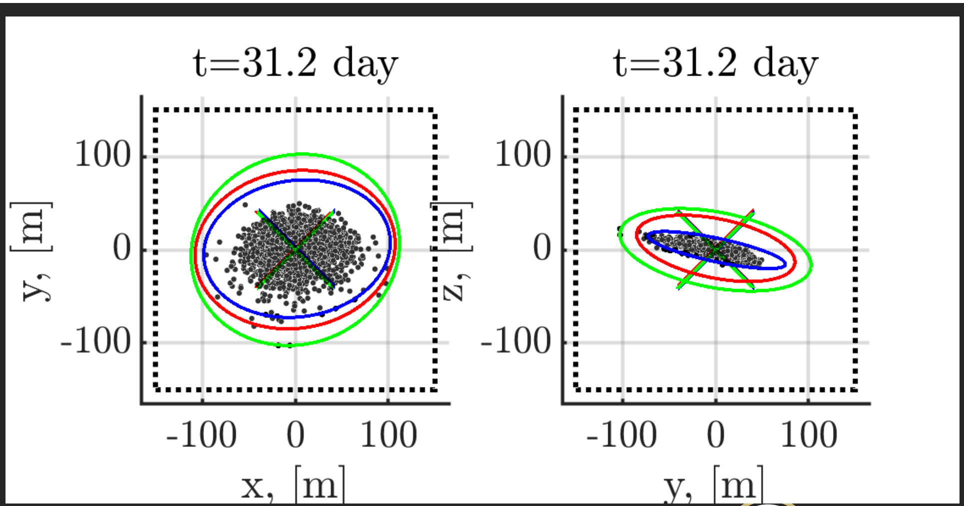




Chance-Constrained Guidance Performance

- Solution performs one larger maneuver first, then smaller maneuvers to correct for stochastic perturbations
- Solution uncertainty matches non-linear results close enough to allow for good performance
  - Blue = MC
  - Green = Linear
  - Red = UT (used)
  - Dotted black – requirements
- Guarantees 99.9% constraint satisfaction over 31 days
- These results use perfect navigation to perform TCMs – addressed in later work.



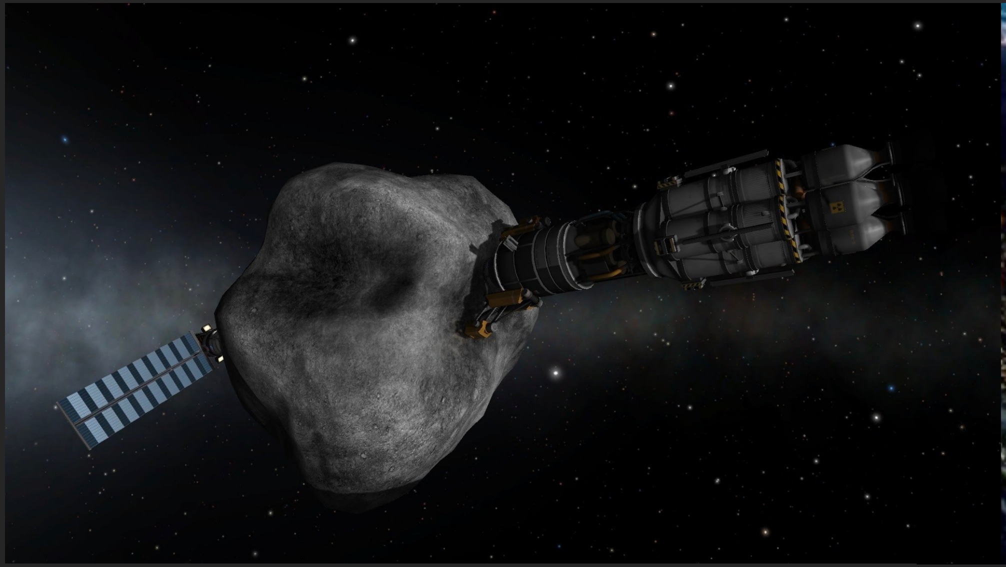


Why asteroids?

Science

Economics

Planetary Defense



Area-of-Effect Softbots

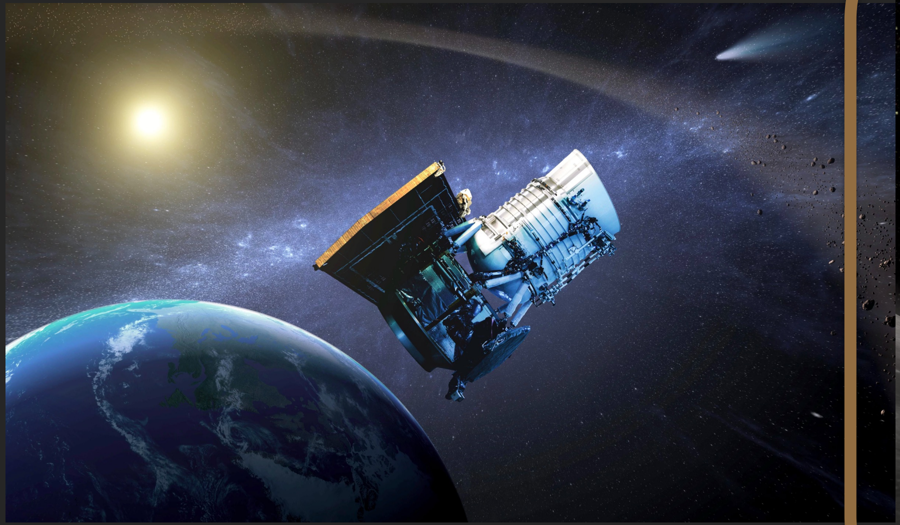
HOW TO OPERATE ON ASTEROID SURFACES

Work of Dr. Ken Oguri, Jesse Tambornini, and Dr. Shane Mitchell shown

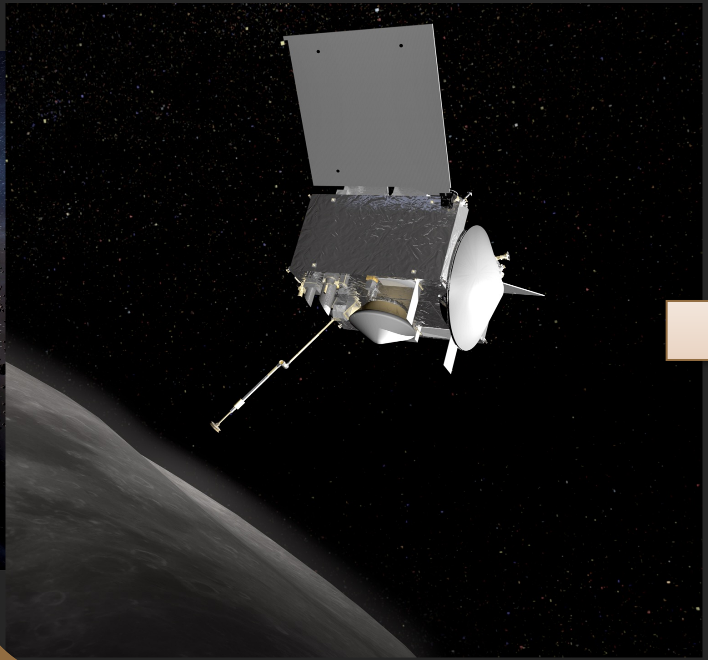
Collaboration with Prof. Christoph Kepliner, now of Max Planck

The Asteroid Mining Cycle

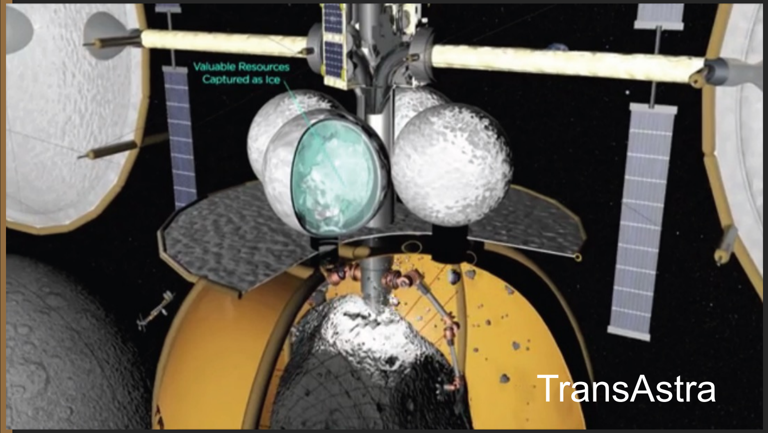
Prospect



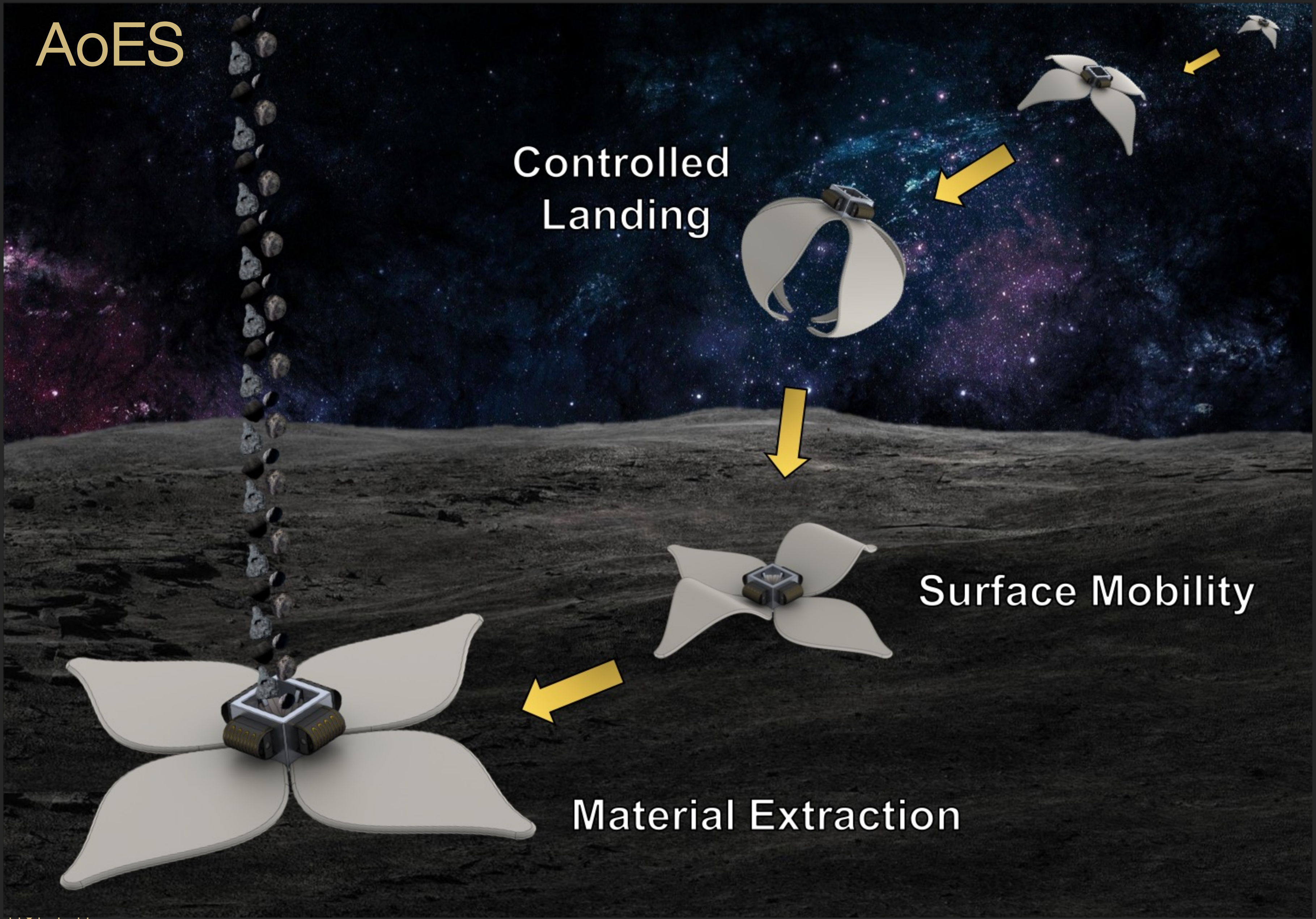
Extract



Refine



How do we get a lot of material from the surface to the refinery efficiently?



- What are Area-of-Effect Softbots?
- Soft robotic spacecraft (AoES) with a large, flexible, actuated surface area uses electroadhesion to anchor to asteroid surfaces
- Large surface area also allows for solar sailing orbit control and hopping across the asteroid surface
- AoES support an ISRU mission by dismantling rubble pile asteroids by lofting material from the surface to be collected by an orbiting processing vehicle for resource extraction

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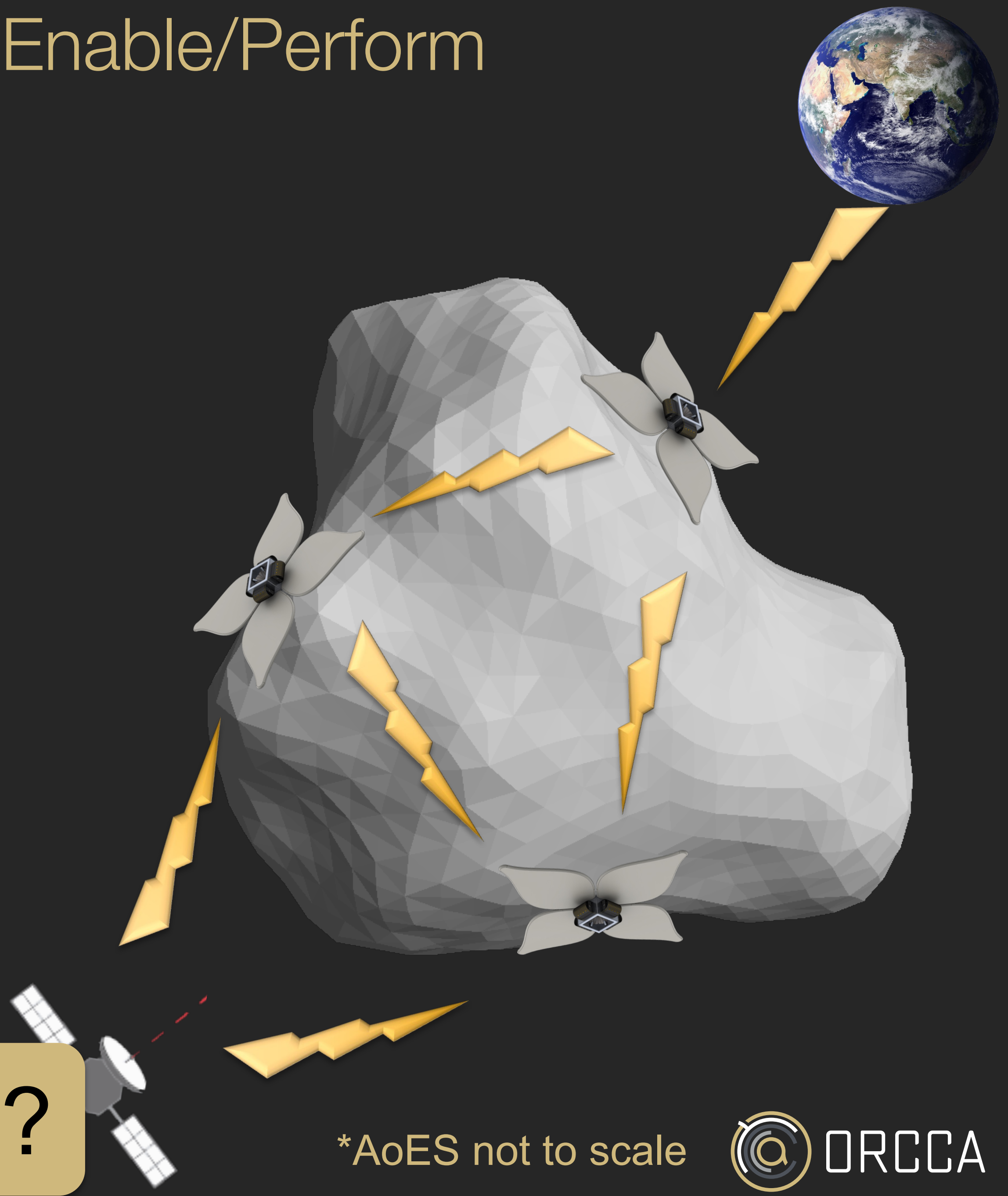
Scientific Experiments AoES Could Enable/Perform

- Landed transponder (adhesion, mobility)
  - during closest approach could also use TDRSS or GPS as well as ground-based assets
- Antenna for radar (long deployable arms)
- Seismometer (adhere to surface)
- Surface motion or strain
  - Relative measurements with multiple - range, interferometry (adhesion, mobility)
  - Measure leg stretching (adhesion)
  - Retroreflectors (adhesion, attitude control)
- Gravity science
  - Controlled orbit, viewed by Earth or orbiting s/c
  - Act as excellent landmarks for orbiting s/c
  - Surface gravity gradiometer



Thank you!!

Questions?

*AoES not to scale

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