



Terminal Guidance Navigation for an Asteroid Impactor Spacecraft

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Introduction

- On July 4, 2005, the Deep Impact impactor spacecraft successfully collided with comet 9P/Tempel 1, while the main spacecraft flew by and shuttered images which captured the impact
 - 1st hypervelocity impact of a primitive Solar System body
 - Not primary goal of mission, but it did demonstrate that such an impact could be accomplished with current technologies and relatively modest budget
- Increased concerns have been raised in recent years about the hazard posed to the Earth from impacts by Near Earth Objects
- Recent NASA report outlined mitigation strategies should a NEO be found that poses a hazard to Earth
- For relatively small asteroids and short turnaround times from detection to impact, kinetic energy technique recommended as the most practical and cost effective technique for deflection

Introduction (cont)

- DI impact made possible by onboard closed-loop autonomous navigation system (AutoNav)
- Parameter settings and sequence of events performed by AutoNav determined through simulations to optimize probability of impact for DI and Tempel 1 approach scenario
- Key differences in scenarios between DI and potential asteroid deflection

	DI	Asteroid Deflection
Approach velocity	10.5 km/s	~3 - > 20 km/s
Approach phase angle	62 deg	0 to 180 deg
Target diameter	~ 6 km	< 100 to > 300 m

Introduction (cont)

- In this paper, we broaden the experience base of AutoNav for use on the asteroid deflection scenario
- Use Monte Carlo simulations to assess performance for a wide range of scenarios
 - Determine range of parameters from literature
 - Vary key parameters to test their sensitivity
- Simulations include:
 - Generation of photorealistic images using triaxial shape model for asteroid
 - Orbit determination and maneuver targeting using AutoNav

Deep Space Navigation

- Step 1: design trajectory to intercept asteroid
 - Details of how this is done out of scope for this paper
 - Use other studies, in particular one by Hernandez and Barbee (2012), that found a candidate set of reference trajectories
- Step 2: navigate reference trajectory from launch to impact
 - General techniques of navigation from launch, cruise, and early approach out of scope of this study
 - Main focus of this paper is the terminal guidance, defined here as point when AutoNav takes control.
 - As for DI, we assume this takes place approximately 2 hours prior to impact

Asteroid Ephemeris

- Knowledge of precise target asteroid location an important consideration for deflection
- Asteroid orbits obtained from ground observations, primarily optical from telescopes, but also from radar for a limited number of cases
- Accuracy of ground-based asteroid ephemeris at time of deflection dependent on several factors (density, quality, geometry, types of observations, and length of time from last observation to the time of deflection)
- Generally, we can say it is good to the tens of km level
 - Good enough for targeting to general vicinity during deep space cruise
 - Not good enough for precision targeting of small asteroids
- Only way to achieve extremely high accuracy is to perform target relative navigation using onboard camera

Optical Navigation

- Optical navigation (OpNav) is the science of using onboard camera as navigation device
- Images of target object against star background
 - Stars provide accurate inertial orientation of image
 - Centroiding on target body provides angular measurement relative to spacecraft
 - Accuracy increases as distance decreases
 - Provides only target-relative navigation information (ground-based radiometric data provides Earth-referenced navigation information)

Camera

- Opnav images provided by onboard camera
 - Generally use framing camera CCDs with long focal lengths
- Key parameters for camera include IFOV (angular resolution of single pixel), sensitivity
 - IFOV set by focal length, pixel size, and determines angular accuracy of measurement
 - Sensitivity determined by CCD and electronics, and determines S/N of light source, and hence ability to detect objects

Camera (cont.)

- “Unresolved” objects
 - Angular extent of target body less than 1 pixel
 - Stars always unresolved
 - Light spread to multiple pixels due to diffraction and lens defocusing
 - Centerfind using Gaussian function
- “Resolved” objects
 - Angular extent of target body greater than 1 pixel
 - Shape becomes apparent as object increases in size
 - Use COB to do centerfinding
 - Offset of COB from true center of object can be large due to shape and lighting effects
- Note that for the deflection scenarios we are examining, the target object will almost always be unresolved at start of terminal guidance, and may remain so until < 5 minutes to impact

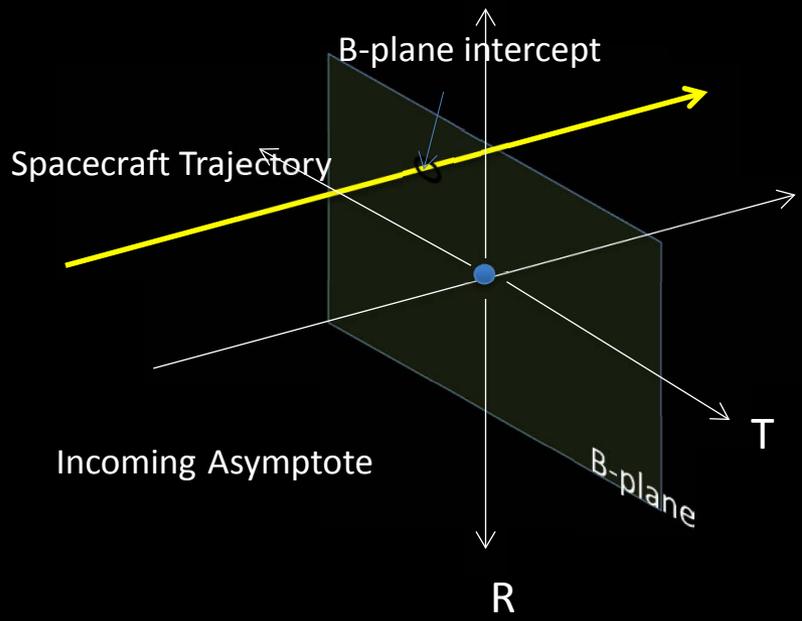
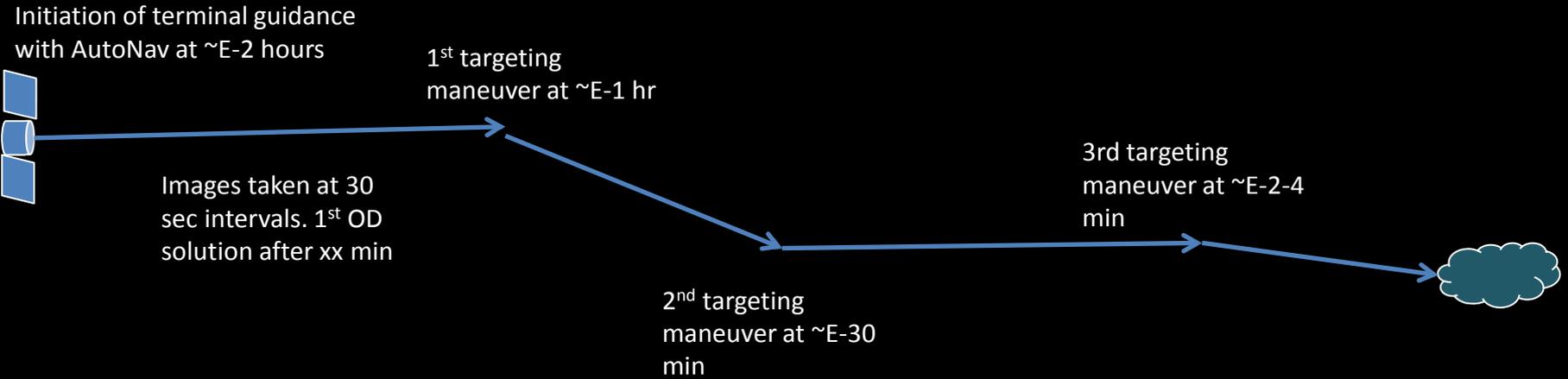
Camera (cont.)

- Sensitivity of camera determines time of initial detection and ability to have both stars and target object visible in single frame
- Initial detection
 - Early detection ($> E-1$ day) - initial OD and 1st targeting maneuver can be done with ground in the loop
 - Detection $< E-1$ day – all OD/maneuvers done onboard
- Stars and object in single camera frame
 - May be difficult because target brightness will vary considerably from initial detection to last image used for targeting
 - If possible – precise attitude knowledge available, which greatly improves OD performance
 - If not possible – rely on star tracker/IMU for attitude knowledge. Errors in this one of the largest contributors to targeting errors
 - Can use some techniques to mimic single star/target frames

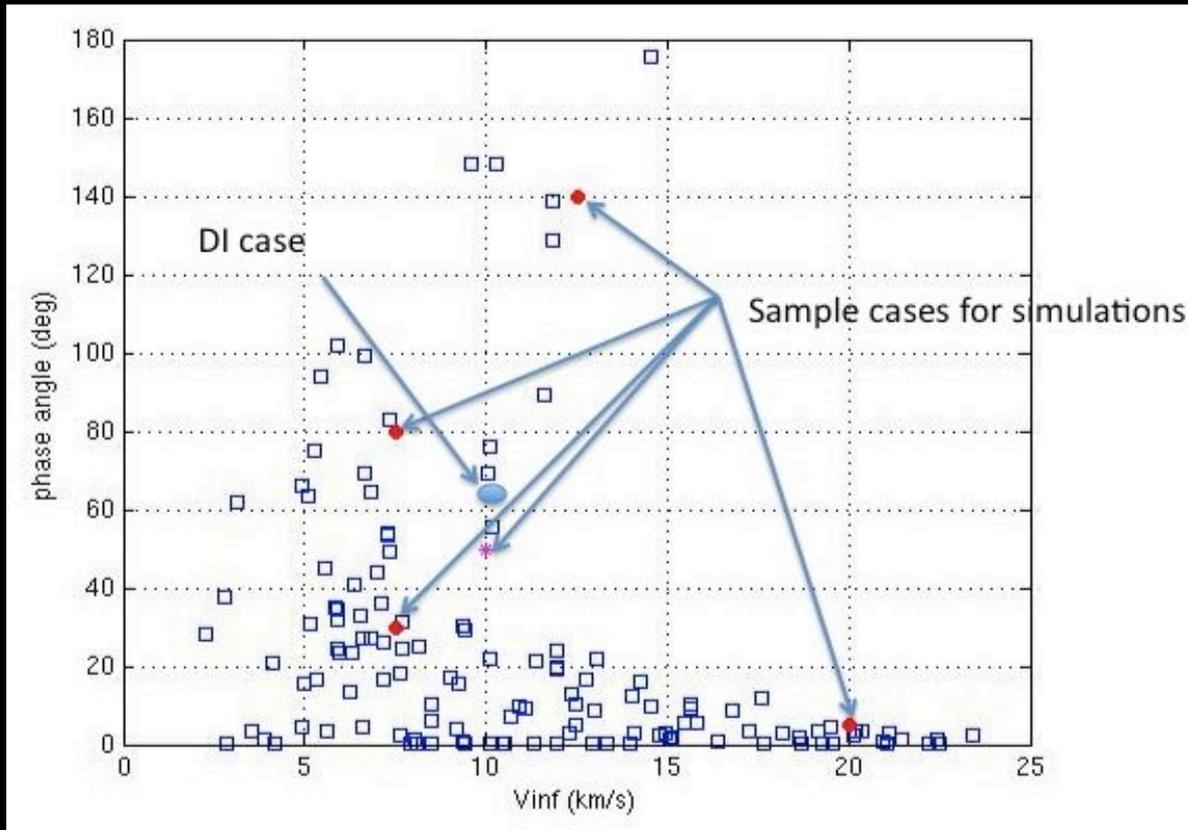
AutoNav Description

- Entirely self-contained system uses onboard camera to take images of target body to compute target relative navigation solution
 - Does not require radio link to other s/c or the Earth
- 3 main components of AutoNav
 - Image processing element to extract target center-of-figure information
 - Orbit determination element to combine set of target centroid information in least-squares filter estimate of s/c trajectory
 - Maneuver planning and execution element to compute delta-V needed to hit target

Targeting Scenario



Case Study Scenarios



	Vinf (km/s)	Phase angle (deg)
1	7.5	30
2	7.5	80
3	12.5	140
4	20	5

Reference for data: Hernandez, S. and Barbee, B. "Design of Spacecraft Missions to Test Kinetic Impact for Asteroid Deflection", Paper AAS 12-129, presented at the AAS/AIAA Spaceflight Mechanics Meeting, Feb. 2012.

Monte Carlo Simulations

- Impactor targeting accuracy assessed through Monte Carlo simulations
- Methodology of simulations
 - “Truth” trajectory generated by taking random samples from a normal distribution of parameters which describe the trajectory.
 - At varying intervals, truth trajectory and attitude used to create photorealistic image of target
 - Image data fed to AutoNav to perform image processing and orbit determination using least-squares batch filter
 - At predetermined maneuver times, maneuver to target impact computed based on filtered OD solution
 - As the truth trajectory either crosses surface of triaxial ellipsoid or is determined to have passed by without impacting, simulation stopped and relevant parameters describing hit or miss stored
 - DI MRI camera, with 10 microrad IFOV, used in the sims

Simulation Parameters

Initial asteroid-relative state error	Position: 30 km Velocity: 5 cm/s
Gates model maneuver execution error	Fixed magnitude: 4.3 mm/s Proportional magnitude: 10% Fixed direction: 4 mm/s Proportional direction: 3.1%
Gyro errors (MIMU class)	Rate bias: 0.005 deg Angle random walk: 0.005 deg/sqrt(hr)
Gyro errors (SSIRU class)	Rate bias: 0.0005 deg Angle random walk: 0.0005 deg/sqrt(hr)
Asteroid size	130 x 90 x 90 m 390 x 260 x 260 m
Asteroid pole orientation	RA: 0 to 360 deg, uniform Dec: -90 to 90 deg, uniform

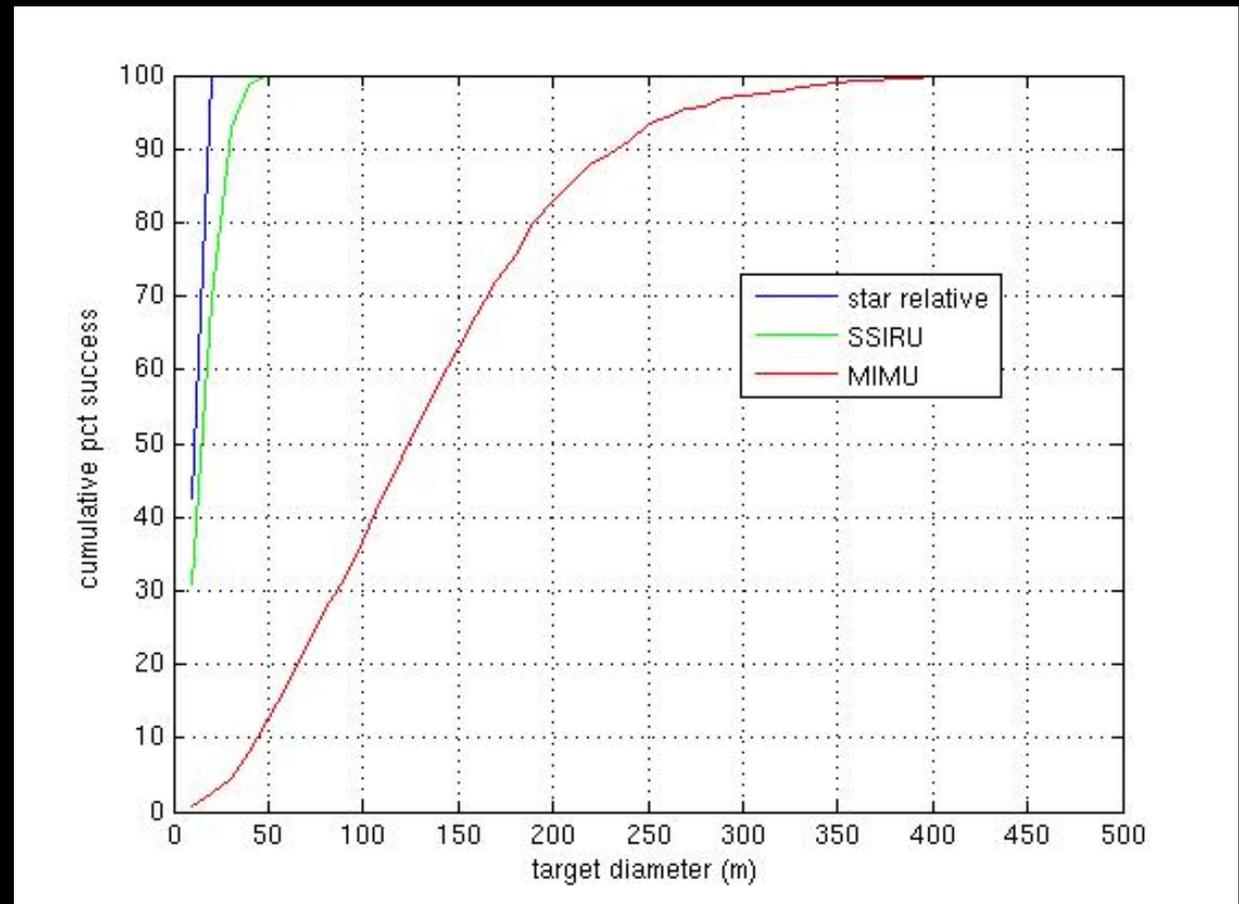
All errors values are 1 sigma unless otherwise noted

Simulation Results – Effects of Attitude Knowledge Mode

In this setup:

- No scene generated – observables were simulated with no errors to eliminate phase effects
- No maneuver execution errors

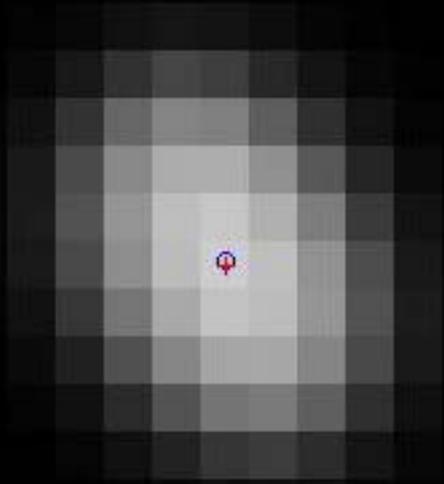
Results show that MIMU level gyro inadequate for objects $< \sim 300$ m



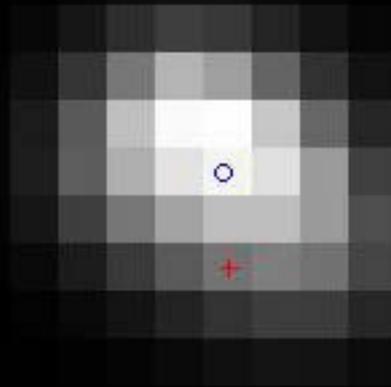
Simulation Results – All Inclusive

Case	Vinf (km/s)	Phase angle (deg)	Stellar reference		SSIRU	
			100 m	300 m	100 m	300 m
1	7.5	30	98.8%	100.0%	85.5%	100.0%
2	7.5	80	96.5%	100.0%	73.8%	99.2%
3	12.5	140	56.6%	99.4%	53.8%	90.6%
4	20	5	100.0%	100.0%	75.4%	99.6%

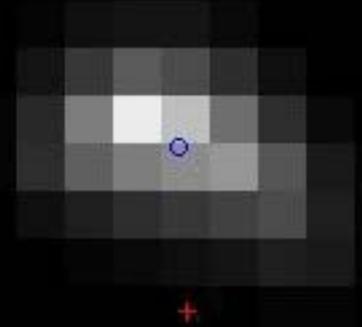
Example of Phase Effects in Final Image



Phase = 5 deg

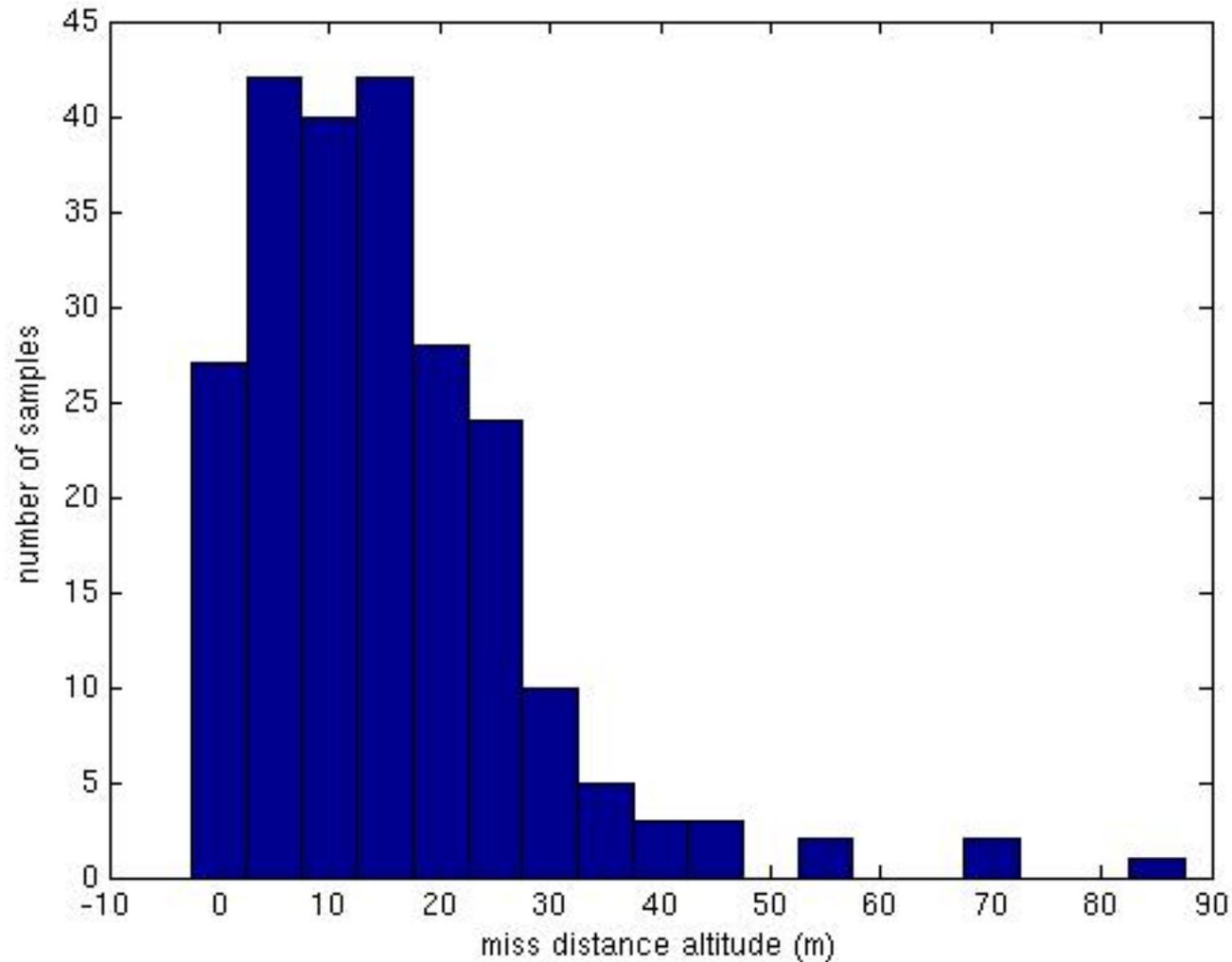


Phase = 80 deg



Phase = 140 deg

Histogram of Miss Distances for Case 3



Conclusion and Recommendations

- Attitude knowledge mode is the single biggest factor in determining impact success
 - With stellar reference, probability of success fairly high
 - Otherwise, must have very stable IMU
- Phase angle second largest effect
 - High value in designing reference trajectories which lower approach phase angle
- Higher V -infinity not concern if phase angle is low
- Still need to examine
 - Improving filter performance for IMU cases
 - More complex shape models
 - Finite duration burns