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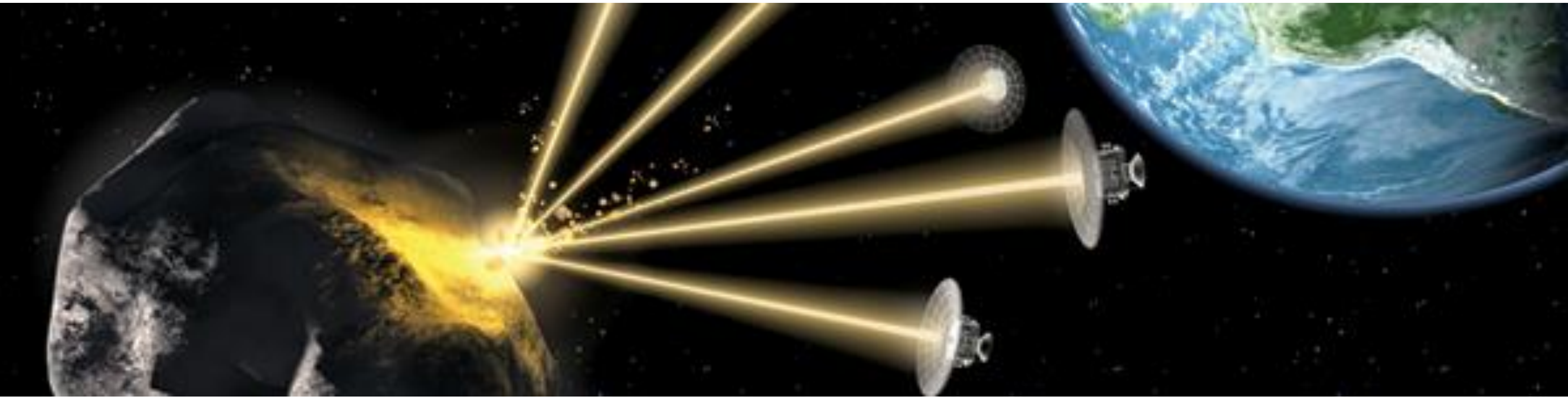

ATHENA: Astrodynamics Toolbox for High-Fidelity Error and Navigation Analysis

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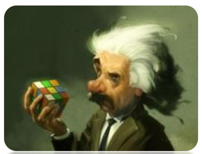
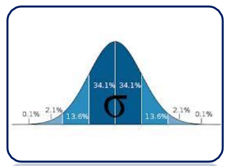


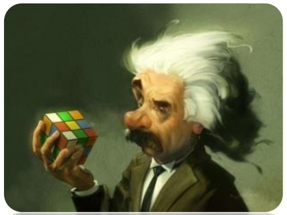
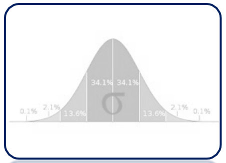


Toolbox Architecture

Main Components

Case Studies

Future Developments

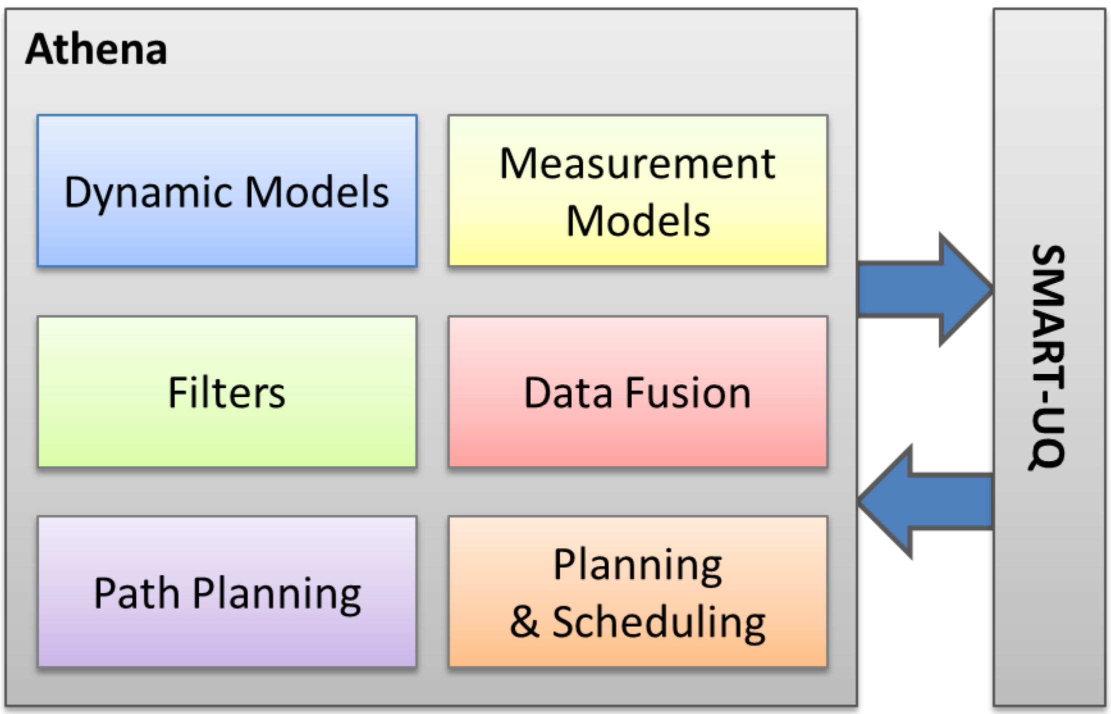



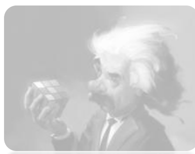
Toolbox Architecture

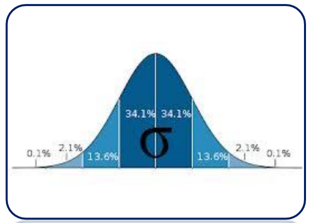
What is ATHENA?

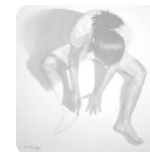
ATHENA is a toolbox for guidance, navigation and control of single an multiple coordinated platforms.

It forms one of the applications of the Strathclyde Mechanical and Aerospace Research Toolbox (SMART)









Main Components

Main Toolbox Components

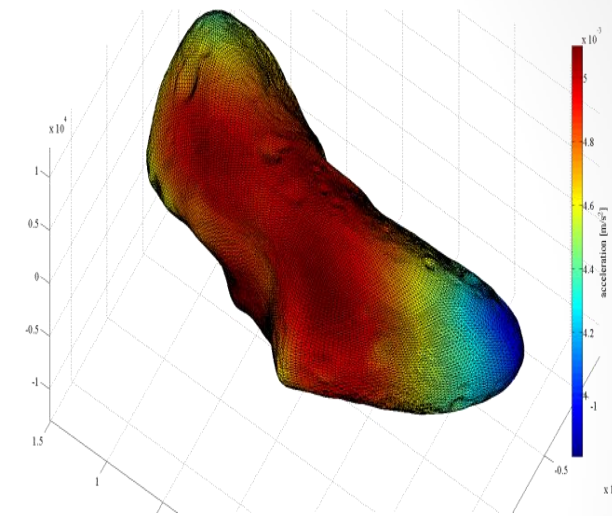
- **The toolbox collects a set of:**
  - High-fidelity **dynamic models** coupled with numerical integrators
  - **Measurement models**
  - **State Estimation and Filtering Techniques**
  - **Path and Operation Planning Algorithms**
  - **Control Algorithms**

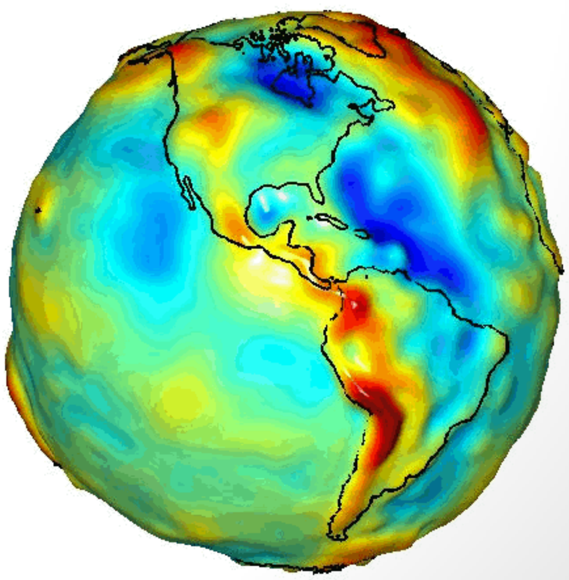
Dynamic Models

- Dynamics in Cartesian parameters in an inertial reference frame:

$$\ddot{\mathbf{r}} = -\frac{\mu}{r^3}\mathbf{r} + \mathbf{a}_d$$

- Full Earth, Moon, Mars gravity models in spherical harmonics
- Distributed mass model for asteroids
- Tetrahedron model from radar observations for single and binary asteroids
- N-body gravity effects
- Light pressure
- Atmospheric drag



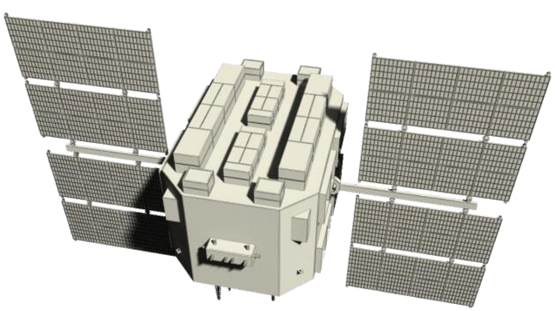


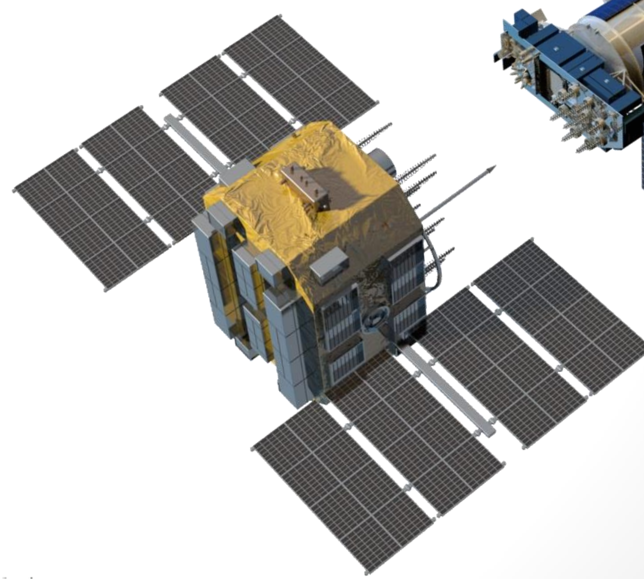
Dynamic Models

- Dynamics in Hill's reference frame for proximity motion:

$$\delta\ddot{\mathbf{r}}^h = -\ddot{\mathbf{r}}_a^h - 2\dot{\theta}^h \times \delta\dot{\mathbf{r}}^h - \dot{\theta}^h \times \delta\mathbf{r}^h - \dot{\theta}^h \times \left(\dot{\theta}^h \times \delta\mathbf{r}^h\right) +$$
$$- \frac{\mu_{Sun}}{r_{Sc}^3}\left(\delta\mathbf{r}^h + \mathbf{r}_a^h\right) + \nabla U_a + \frac{\mathbf{F}_{Sc}\left(\delta\mathbf{r}^h, \mathbf{r}_a^h\right)}{m_{Sc}}$$

- Same forces as in the inertial reference frame
- Coupled orbital and attitude dynamics of target and chaser
- Full 3D satellite shape





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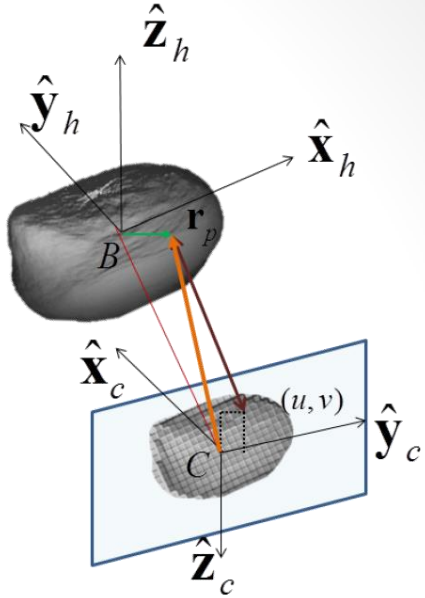
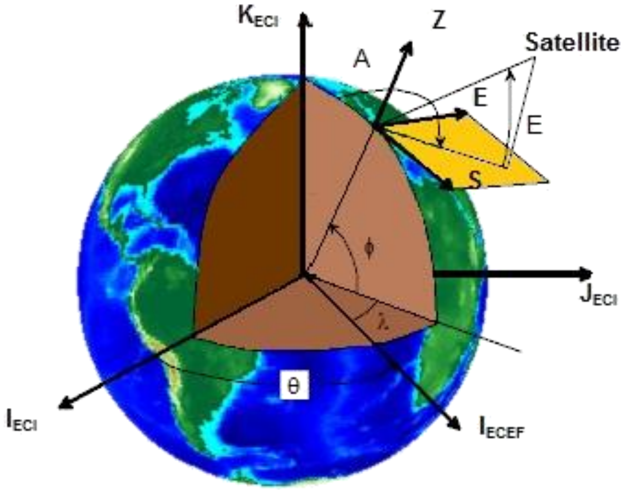
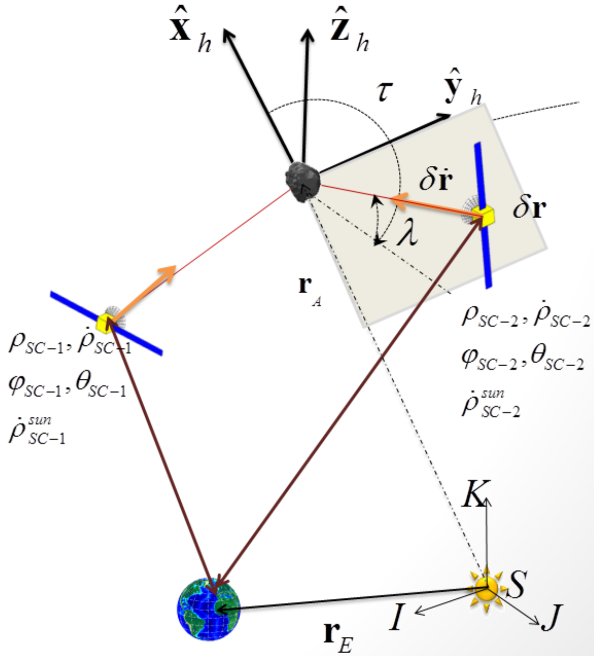
Measurement Models

The sensor model suite includes:

- Camera model
- Optical flow extraction and feature tracking
- LIDAR model
- Inter-satellite link model
- Solar Doppler effect
- Ground station range and range rate







State Estimation and Filtering

The main filtering techniques included in the toolbox are:

- Kalman Filter (KF)
- Extented Kalman Filter (EKF)
- Uncented Kalman Filter (UKF)
- Uncented H_∞ Filter (UHF)
- Extended H_∞ Filter (EHF)
- High-order semi-Analytic Extended Kalman Filter (HAEKF)

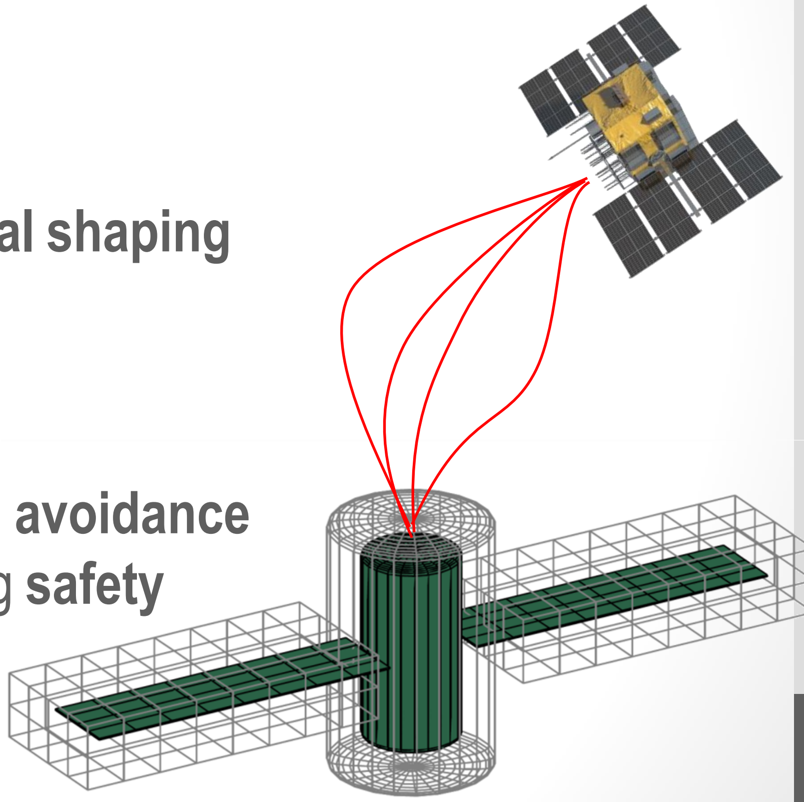
Filters have been extended to allow data-fusion sensor information

Path Planning

Implemented specially to provide Guidance for close proximity operations, autonomous rendezvous and docking (RVD)

Two Key Features:

- **High performance**
  - Path Planning based on **polynomial shaping**
  - Inverse optimization problem
  - Optimize to **minimize ΔV**
- **Safety**
  - Safety is provided by implementing **avoidance collision** with the target by defining **safety region**, Keep Out Coating



Operation Planning: AIDMAP

AIDMAP: Single objective **incremental decision making algorithm** for the solution of complex **combinatorial optimization problems** such as tasks planning and scheduling.

AIDMAP: decision making map using tree-like topology

- **Nodes:** Decision made
- **Edges:** Cost associated to decision

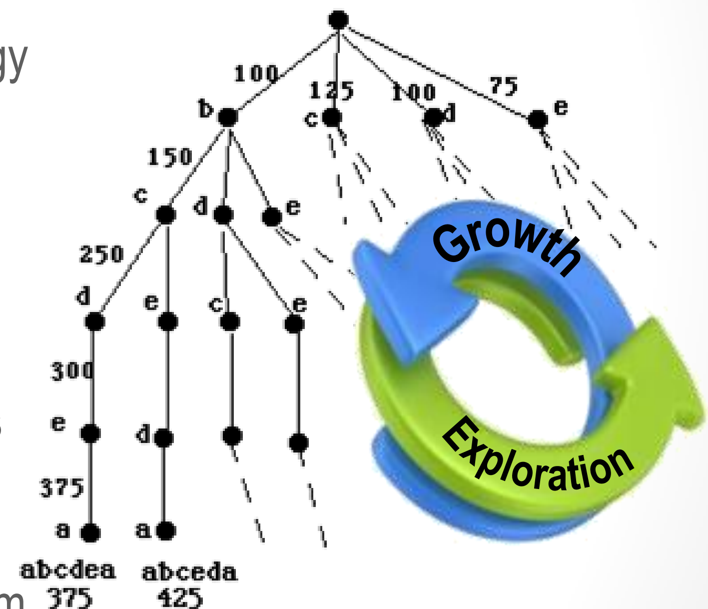
Decision Tree build

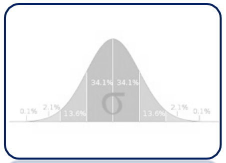
- **Incrementally** with time
- through **Exploration** and **Growth** by virtual agents

Possible heuristics to evaluate Decision Tree:

- **Deterministic:** Classical Branch-and-Cut Algorithm
- **Probabilistic:** New Bio-inspired Physarum Algorithm

Decision Tree



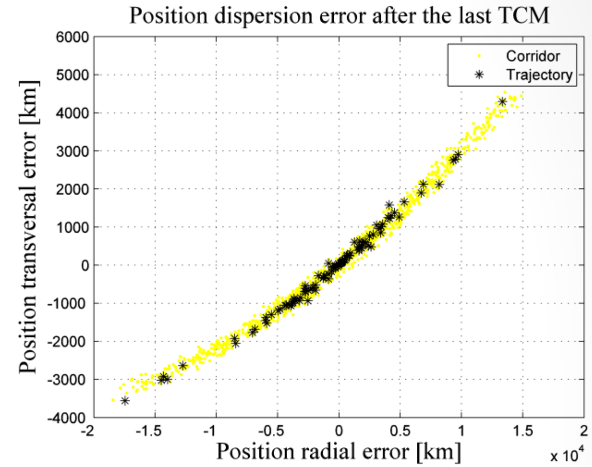


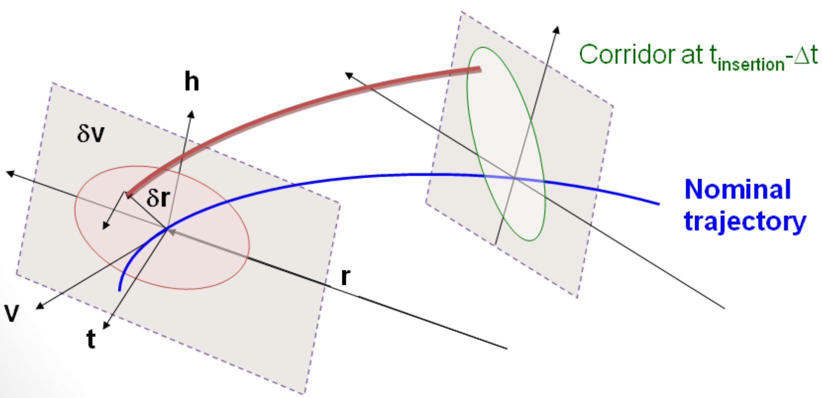
Case Studies

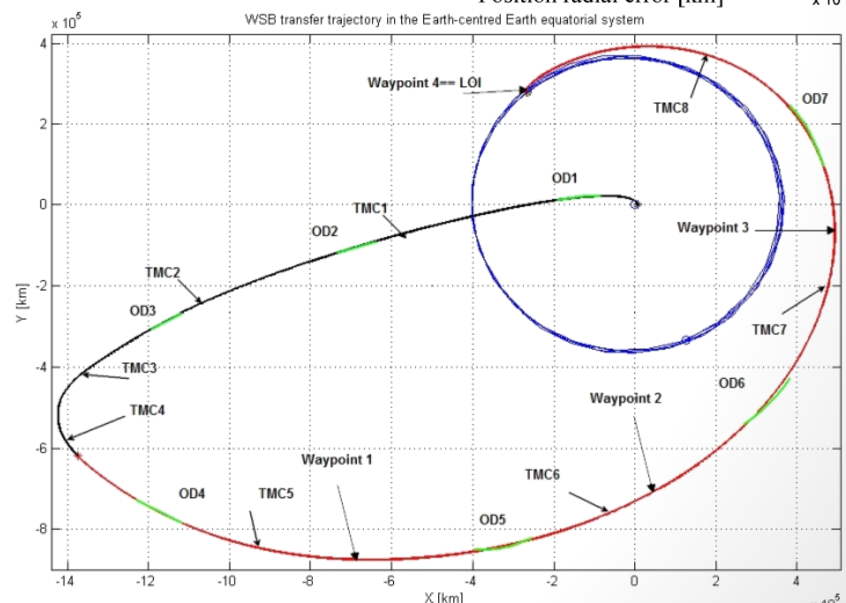
Navigating to the Moon

Navigation and OD system for ESMO:

- Full ephemerides 4 body dynamics
- **OD** and **Navigation based** on **ground station measurements** and **UKF**
- TCM allocation and optimisation to target capture conditions at the Moon
- Analysis of **High Order semi-Analytic Extended Kalman Filter**







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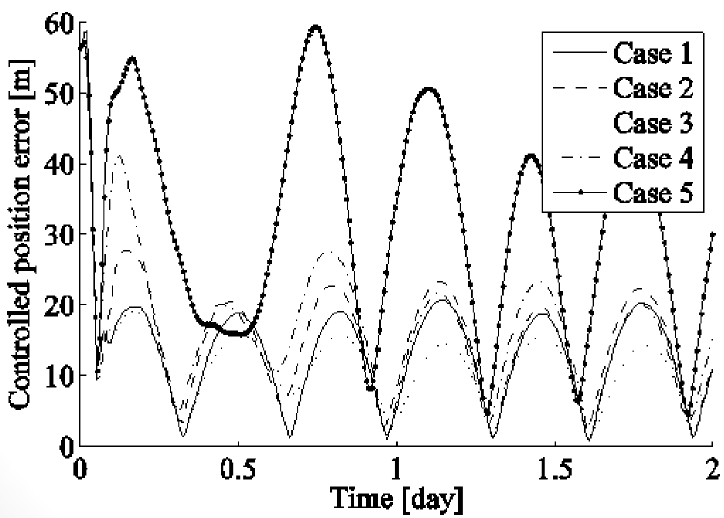
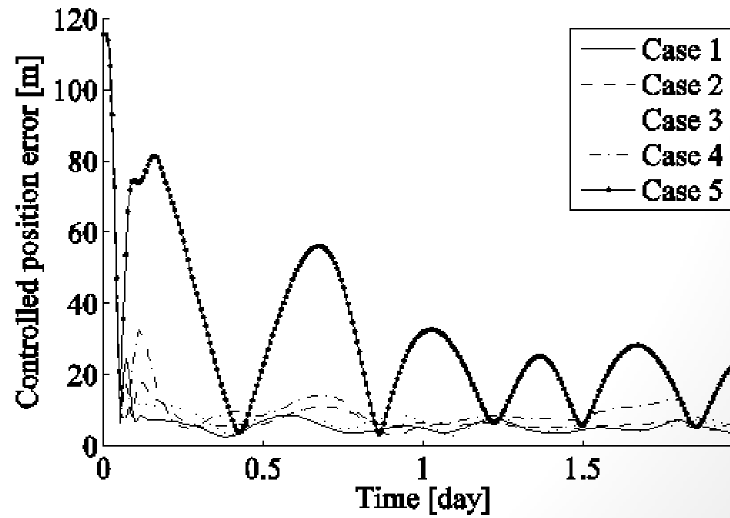
Collaborative Formation GNC

- **Collaborative** and **distributed navigation** of a formation in the proximity of an asteroid.
- Distributed sensor fusion
- Evaluation of different filters: EKF, UKF, UHF, EHF

Case	SC-1	SC-2	SC-3	SC-4
1	I	C,L/R, I	C, L/R, I	C, L/R, I
2	I	I	C, L/R, I	C, L/R, I
3	I	C, L/R, I	C, L/R, I	C, L/R*, I
4	I	I	C, L/R*, I	C, L/R*, I
5	I*	I*	C, L/R*, I	C, L/R*, I

C-camera, L/R LIDAR, I-inter-satellite, * worst condition

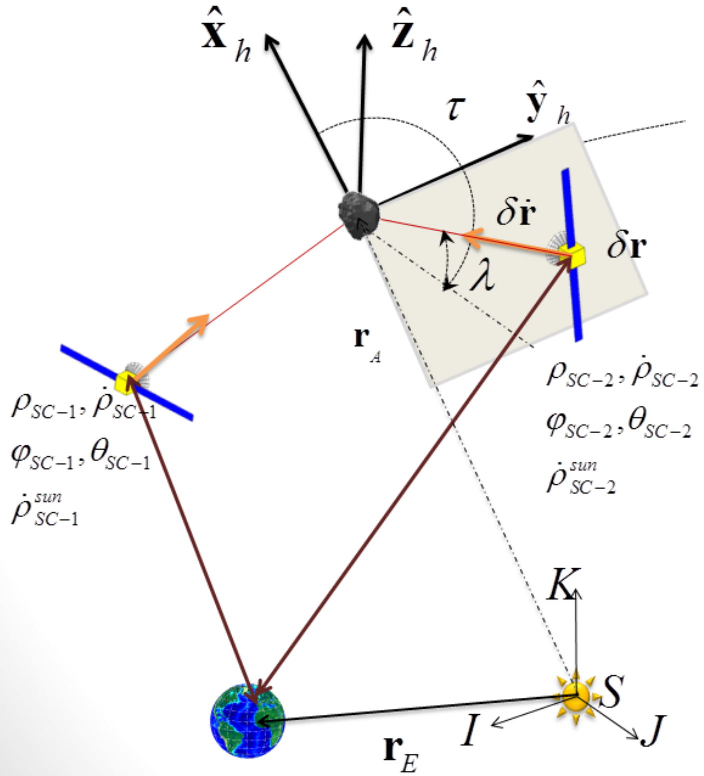




Collaborative Formation GNC

Improve Asteroid ephemerides during rendezvous:

- **Case 1:** Spacecraft-to-Ground tracking data **WITH** Sun Doppler Shift Sensor
- **Case 2:** Spacecraft-to-Ground tracking data **WITOUT** Sun Doppler Shift Sensor

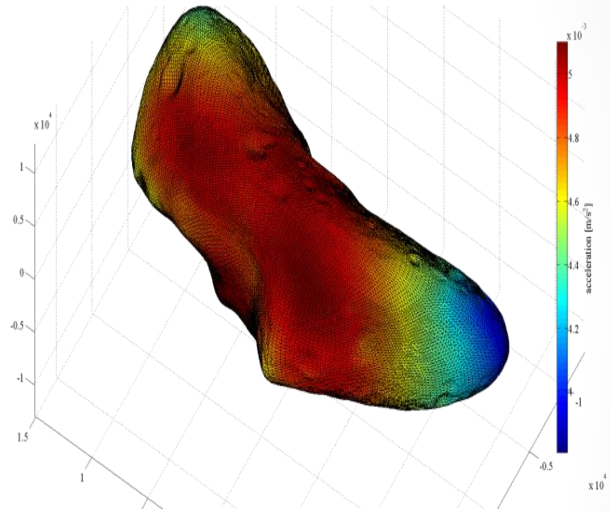


Analysed Configuration and Final Estimated error with and without Doppler Shift

	SC-1	SC-2	No Doppler		Doppler	
	τ [deg] λ [deg]	τ [deg] λ [deg]	Pos. Error [Km]	Vel. Error [mm/s]	Pos. Error [Km]	Vel. Error [mm/s]
1	90 0	270 3	31.38	100.90	26.89	90.87
2	180 0	270 3	5.66	19.36	5.79	19.05
3	135 0	270 3	8.04	19.61	8.09	19.15
4	135 0	139 0	17.50	62.63	17.09	62.88
5	135 0	136 3	25.14	801.00	25.67	82.27
6	135 0	135.5 3	26.25	82.69	26.48	84.05
7	135 0	135.5 0.5	115.25	374.90	101.97	358.10

Detumbling Asteroids and Space Debris

- Coupled **12DOF control** of proximity motion and attitude motion of an asteroid using laser ablation.

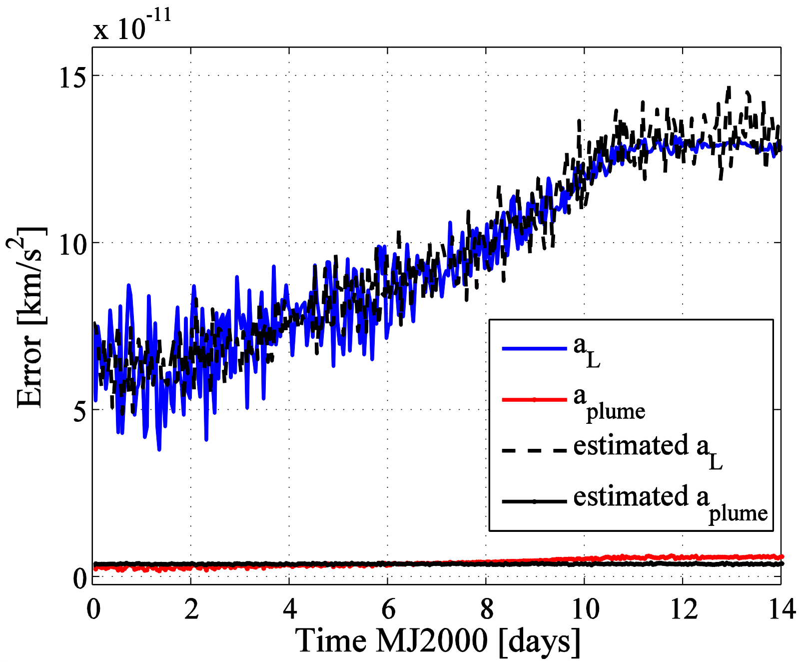


- Rich Dynamics:
  - Irregular gravity of the asteroid
  - Light pressure
  - Recoil of the laser
  - Plume impingement

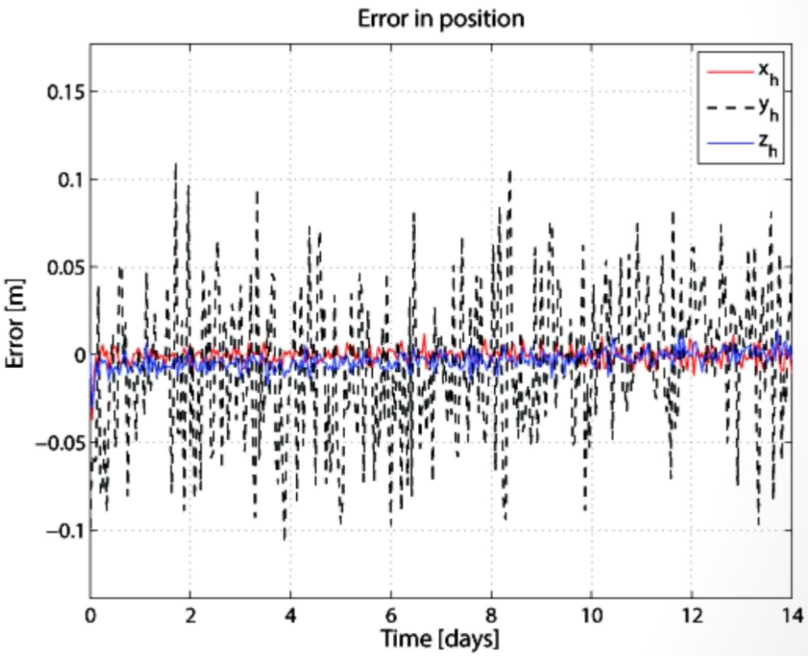
- UKF to fuse optical camera and LIDAR information

Detumbling Asteroids and Space Debris

- **Optical flow** and feature extraction to **track the attitude motion** of the asteroid.
- **Online estimation** of the **acceleration** induced by the laser



Estimated acceleration from the laser and plume force vs actual acceleration

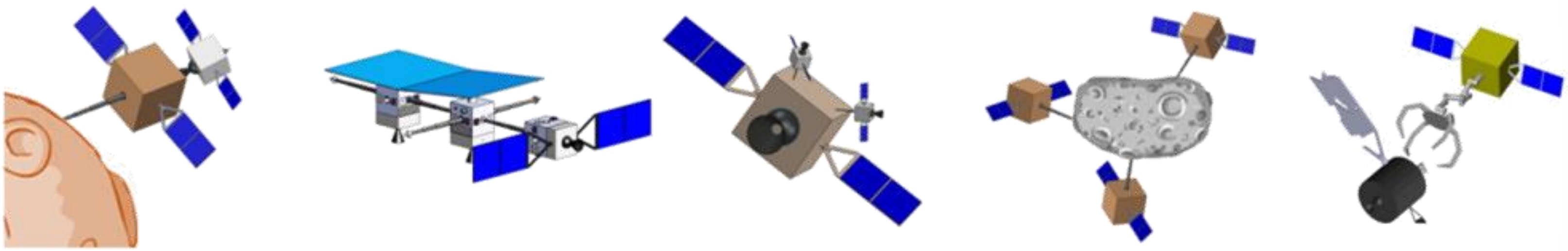


Actual Controlled position and velocity error

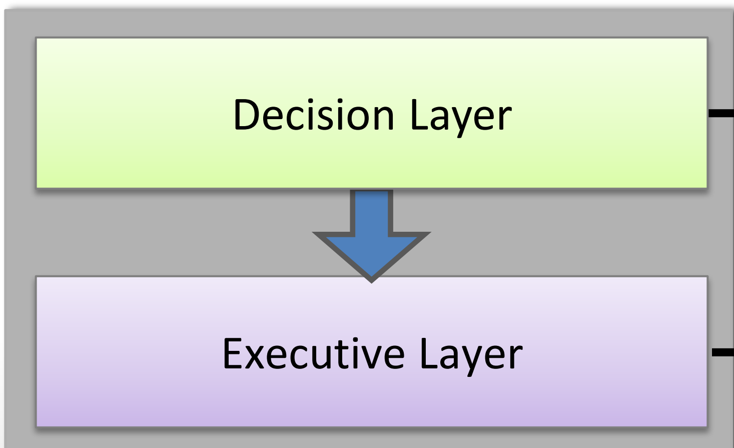
Autonomous Collaborative On-Orbit Servicing

ACO²SF an **Autonomy Framework** for Autonomous **Collaborative On-Orbit Servicing** (OOS)

- **Plan and Schedule** the execution of elementary pre-defined **actions** to fulfill complex OOS missions for a swarm of spacecraft: proximity operations, rendezvous, docking & undocking operations



Cascade Flow Procedure Architecture:



Decision Layer → Allocate the resources & generate optimal *execution plan:* plan and schedule actions for each of the servicing spacecraft

Executive Layer → Execute the *execution plan* and monitor for unforeseen events

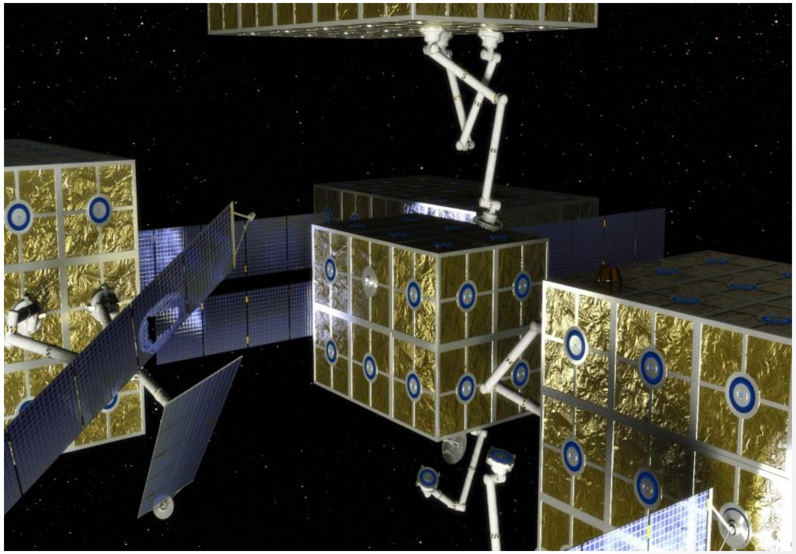
Autonomous Collaborative On-Orbit Servicing

ACO^{2}SF provides an Autonomy Framework for Autonomous Collaborative On-Orbit Servicing (OOS)

- capable of Plan and Schedule the execution of elementary pre-defined actions to fulfill complex OOS missions for a swarm of spacecraft:

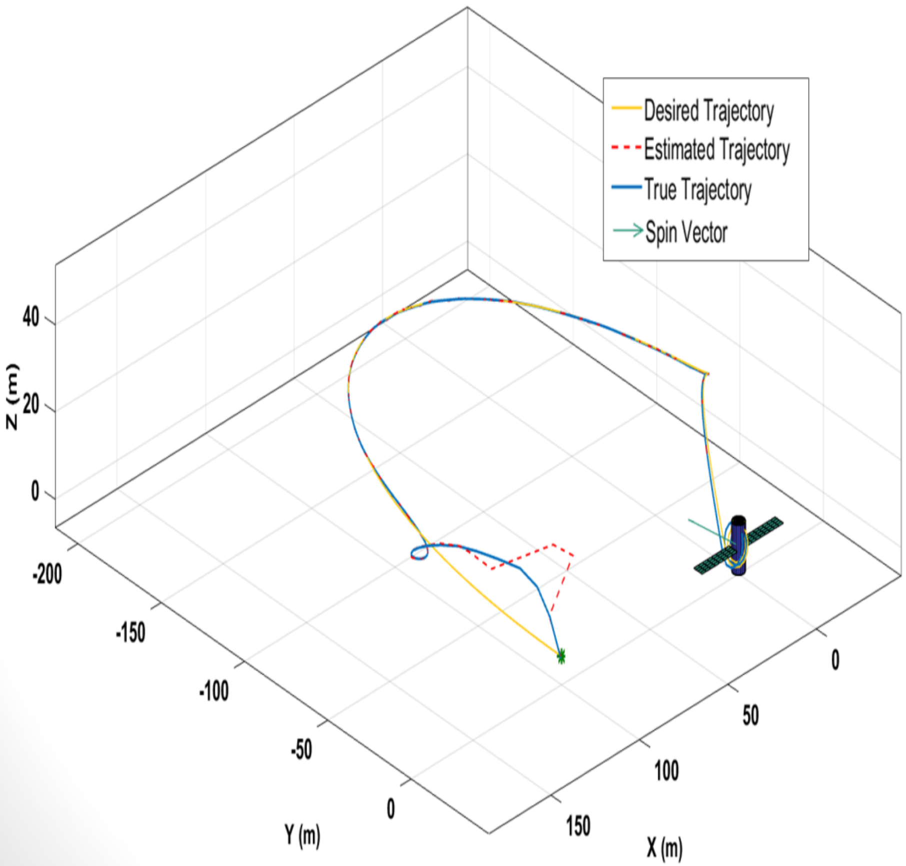
ACO^{2}SF responsible for:

- Allocate resources across the system
- **Plan** and **schedule actions**
- **Execute** the made **decision**
- Monitor the performance during the execution phase
- **Provide contingency reactions** to overcome any unforeseen event during the execution phase.

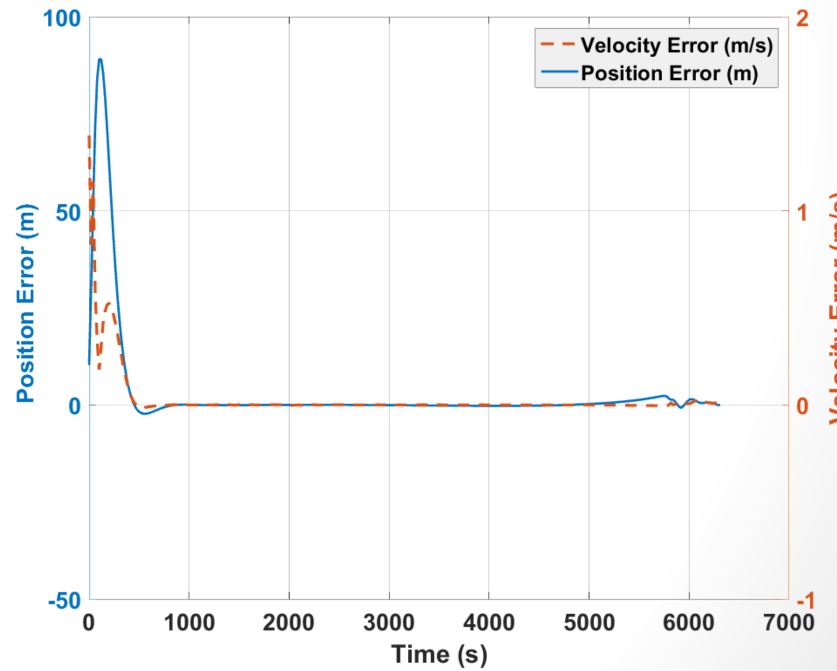


Autonomous Collaborative On-Orbit Servicing

Optimal and **Safe Docking Path** for a **triaxial tumbling** non-cooperative target (ω_x= 0.01 rad/s, ω_y= 0.02 rad/s, ω_z= 0.01 rad/s)



Maneuver Δ**V**= 8 m/s,
Maneuver Time = 96.6 min



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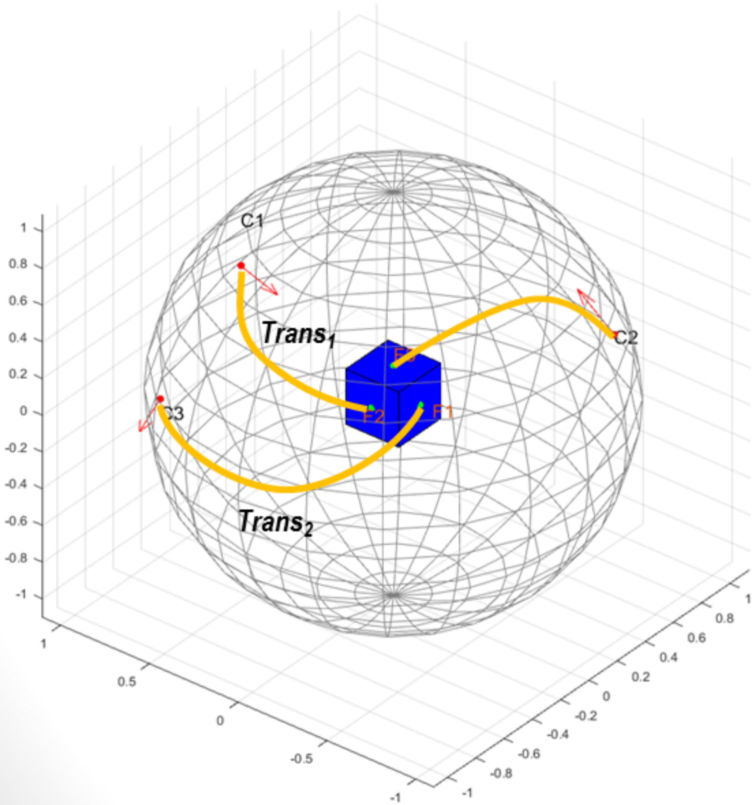
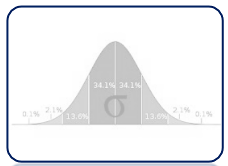
Autonomous Collaborative On-Orbit Servicing

Multi-Spacecraft operations for a **triaxial tumbling** non-cooperative target (ω_x= 0.01 rad/s, ω_y= 0.02 rad/s, ω_z= 0.01 rad/s)



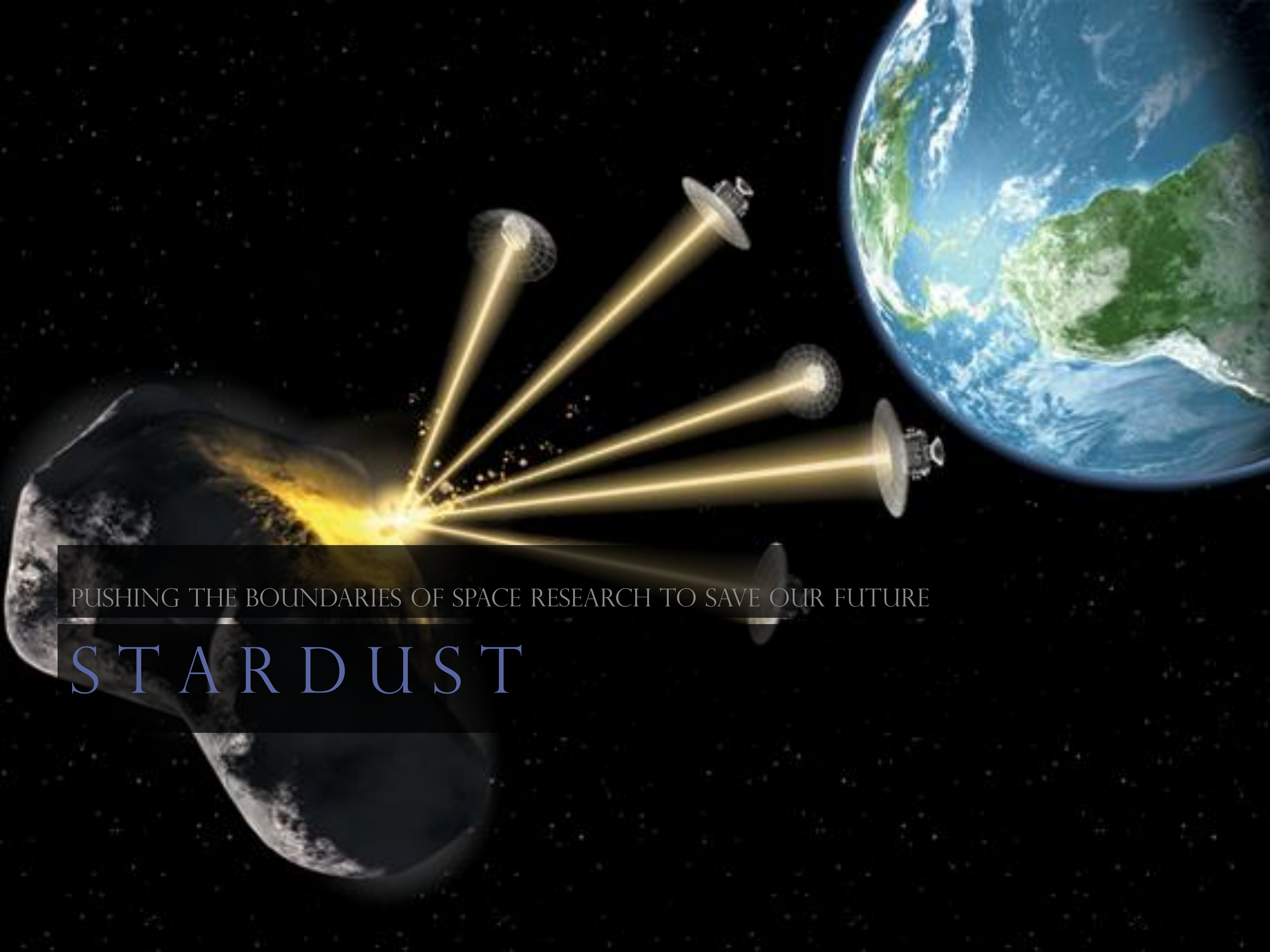
	Chaser	Docking Point	ΔV (m/s)
1st Docking, Operation & Undocking Phase	C_3	DP_3	16.8
	C_1	DP_2	19.3
	C_2	DP_1	16.7
2nd Docking, Operation & Undocking Phase	C_2	DP_2	16.4
	C_1	DP_3	26.8
	C_2	DP_1	17.3
		Total ΔV	**113.2**



Future Developments

Future Developments

- Orbital Dynamics with Unknown Drag Component:
  - This estimation allows us to extrapolate the prediction over a time span that is 2 times the one over which the measurements are available
- New Measurement Models: **GPS** measurements, **FLASH LIDAR Model + 3D Shape Reconstruction** techniques
- New **Docking Path Planning** Techniques for **unknown target shape**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