Light Touch^2

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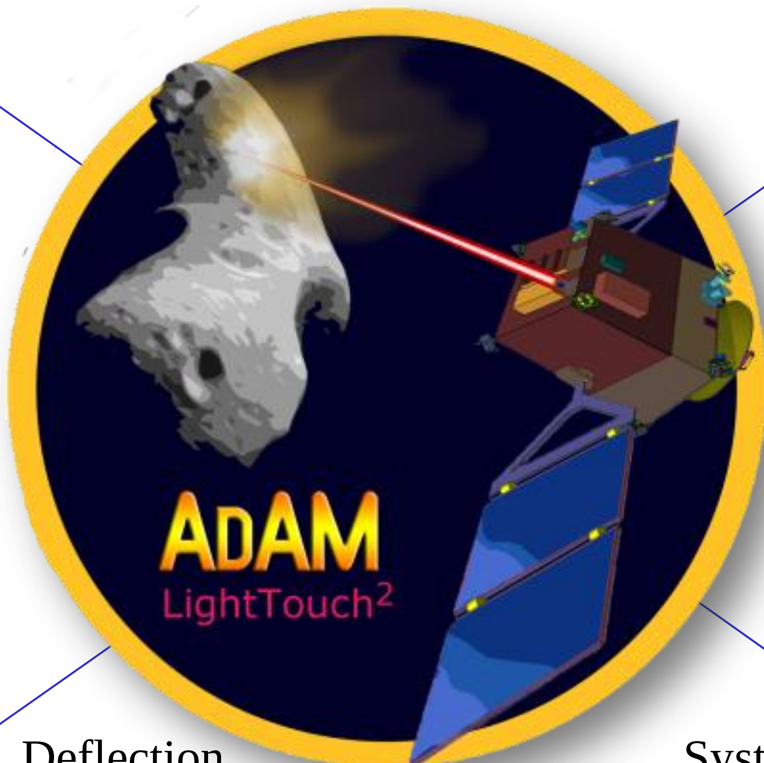


GNC

Concept

Deflection

System

INNOVATING SOLUTIONS

Joao Branco
GMV SKY-P, Portugal

Massimiliano Vasile, Alison Gibbings, Massimo Vetrisano, Pau Sanchez, Daniel Garcia, Colin McInnes & David Burns, John-Mark Hopkins
University of Strathclyde, UK

UNIVERSITY OF Southampton

Camilla Colombo
University of Southampton, UK

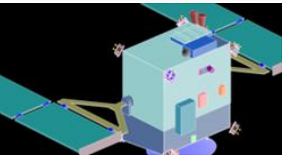
ASTRIUM AN EADS COMPANY

Steven Eckersley, Alastair Wayman
Astrium Ltd, UK

Target

Light Touch^2

Mission, Control, Navigation



AdAM

Roadmap

Target

Target

- Initial target selection based on orbital elements, size and Orbit Condition Code (OCC).
  - ~9,500 NEOS known today, 189 with Q<1.4 AU & q>0.7 AU, and only 10 with D~4m considering p_v=0.154.
  - OCC>4 are equivalent to “lost objects”. → Only 2 left.

DESIGNATION	PHA (Y/N)	H	q (AU)	Q (AU)	*i* (deg)	D (km) (p_v=0.154)	OCC
2008 JL24	N	29.572	0.927631	1.148906	0.550106	0.004124	3
2006 RH120	N	29.527	1.007964	1.058540	0.595266	0.004211	1

2008JL24

Orbital Elements at Epoch 2456200.5 (2012-Sep-30.0) TDB
Reference: JPL 10 (heliocentric ecliptic J2000)

Element	Value	Uncertainty (1-sigma)	Units
e	.106559869181477	7.2705e-06	
a	1.03826844970543	2.8956e-06	AU
q	.9276306995295643	5.0396e-06	AU
i	.5501064109470443	4.6053e-05	deg
node	225.822449694026	0.00026854	deg
peri	281.9655686889383	0.00038643	deg
M	124.186109529154	0.0073006	deg
t_p	2456067.198991958747 (2012-May-19.69899196)	0.0072788	JED
period	386.4229508179025 1.06	0.0016165 4.426e-06	d yr
n	.9316216835413743	3.8973e-06	deg/d
Q	1.148906199881296	3.2042e-06	AU

Rotation ~ 18 rev/h

2006RH120

Orbital Elements at Epoch 2456200.5 (2012-Sep-30.0) TDB
Reference: JPL 45 (heliocentric ecliptic J2000)

Element	Value	Uncertainty (1-sigma)	Units
e	.02447403062284801	4.2401e-05	
a	1.033252056035198	1.0251	AU
q	1.007964213574672	1	AU
i	.5952660003048117	9.4379e-05	deg
node	51.14334927580387	3.8304e-05	deg
peri	10.14353817485877	0.092984	deg
M	221.2498016727181	206.48	deg
t_p	2456348.356001016605 (2013-Feb-24.85600102)	1	JED
period	383.6258326667335 1.05	570.89 1.563	d yr
n	.9384143854377558	1.3965	deg/d
Q	1.058539898495724	1.0502	AU

Rotation ~ 21.8 rev/h

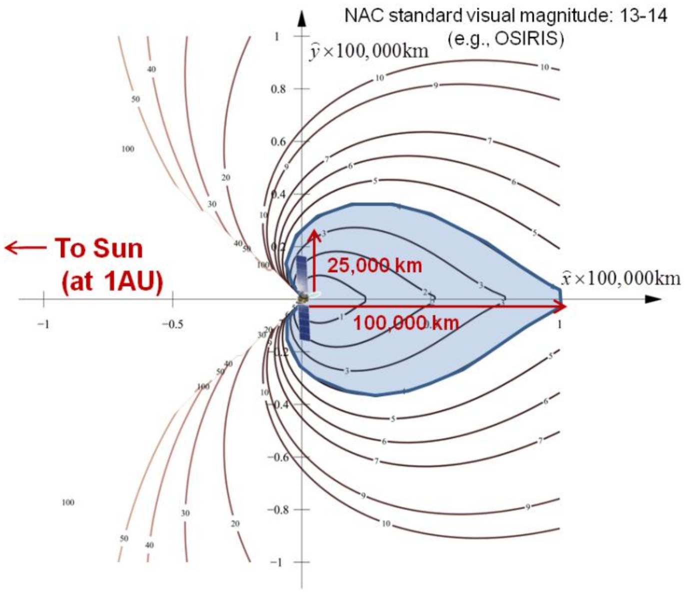
Target

- Target observability from Earth

Table 5: NEO properties and next observation opportunities according to NHATS[5]

Object Designation	Orbit ID	△H (mag)	Estimated Diameter (m)	OCC	Min. delta-V [delta-V, dur.] (km/s), (d)	Min. Duration [delta-V, dur.] (km/s), (d)	Viable Trajectories	Next Optical Opportunity (yyyy-mm [Vp])	Next Arecibo Radar Opportunity (yyyy-mm [SNR])	Next Goldstone Radar Opportunity (yyyy-mm [SNR])
(2008 JL24)	10	29.6	2.1 - 9.5	3	**4.628**, 394	11.791, **82**	904797	none	none	none
(2006 RH120)	45	29.5	2.2 - 10	1	**3.989**, 450	11.323, **42**	1283738	2028-06 [23.9]	none	none

- Target observability from S/C



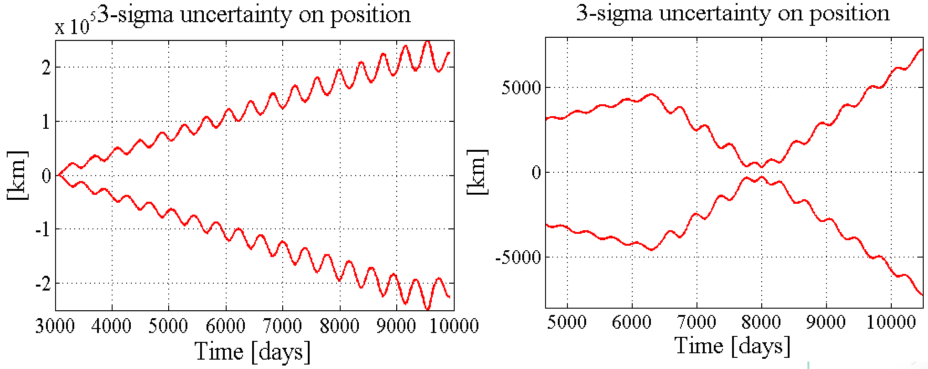
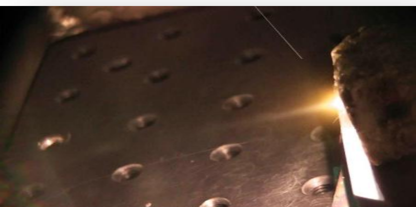


Fig: Uncertainty in asteroid position for 2008 JL24 (left) and 2006 RH120 (right) as a function of time (MJD2000).

2006 RH120 allows a reliable rendezvous considering both ephemeris uncertainties and future optical opportunities.



Light Touch^2

Ablation Process

- Energy balance:

$$\left(E_v + \frac{1}{2}\bar{v}^2 + C_p\left(T_s - T_0\right) + C_v\left(T_s - T_0\right)\right)\dot{\mu} = P_I - Q_{RAD} - Q_{COND}$$

- Ejection velocity dependent on temperature: $\bar{v} = \sqrt{\dfrac{8k_b T_s}{\pi M_a}}$

- Integrated mass flow over the spot including rotation:

$$\dot{m} = 2V_{rot}\int_0^{y_{max}}\int_{t_{in}}^{t_{out}} \frac{1}{E_v^*}\left(\left(P_I - Q_{rad}\right) - \left(\sqrt{\frac{c\kappa\rho}{\pi}}\left(T_{subl} - T_0\right)\right)\sqrt{\frac{1}{t}}\right)dt\,dy$$

- Thrust model includes a scattering factor:

$$F_{sub} = \lambda\bar{v}\dot{m}$$

- Input power dependent on system efficiency:

$$P_I = \tau\tau_g\alpha_M\eta_P\eta_L\eta_S\frac{P_{1AU}A_{SA}}{A_{spot}R_{AU}^2}$$

Contamination Model

- Density dependent on elevation angle distance:

$$\rho(r,\theta) = \rho^{*} K_P \frac{d_{SPOT}^2}{\left(2r + d_{SPOT}\right)^2} \left[\cos\left(\frac{\pi\theta}{2\theta_{MAX}}\right)\right]^{\frac{2}{k-1}}$$

- Thickness of the layer of contaminant dependent on view factor and mass flow:

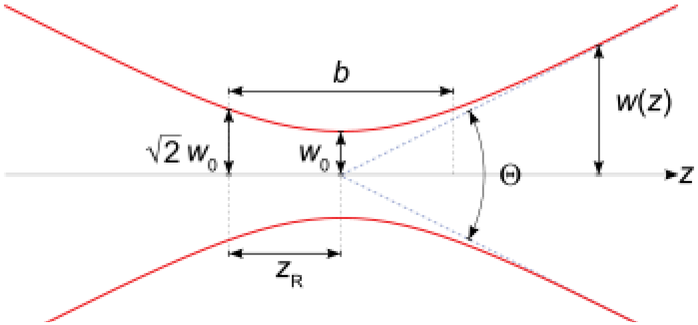
$$\frac{dh}{dt} = \frac{2\bar{v}\rho}{\rho_l} \cos\psi_{vf}$$

- Beer–Lambert law for light absorption:

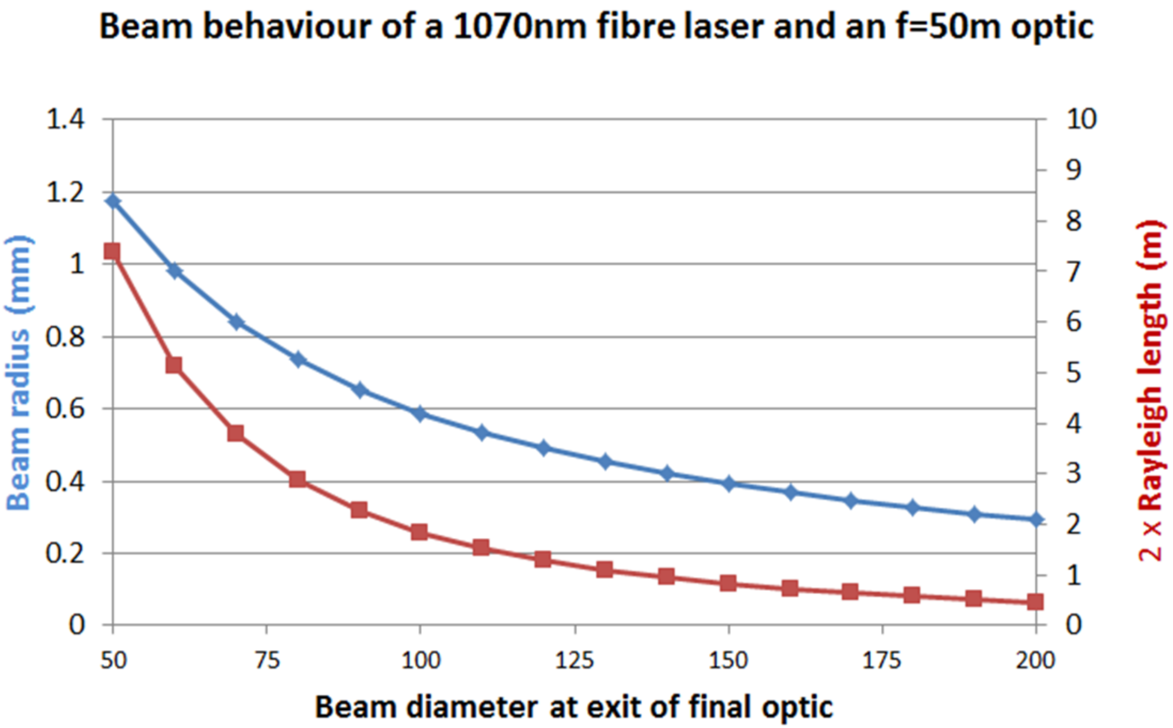
$$\tau = e^{-2\eta h}$$

- Key coefficients experimentally derived using asteroid analogous materials

Focusing and Beam Control

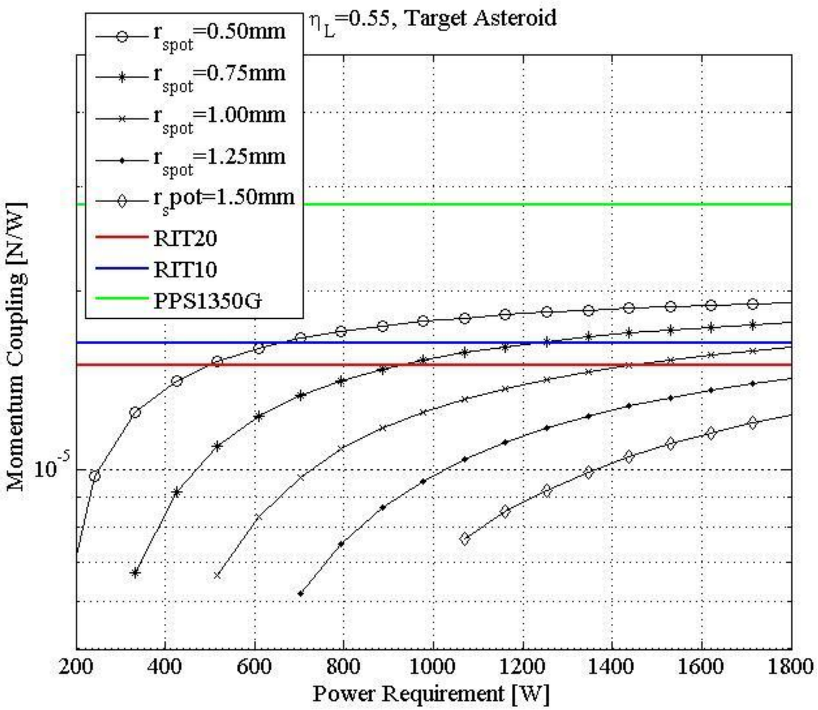


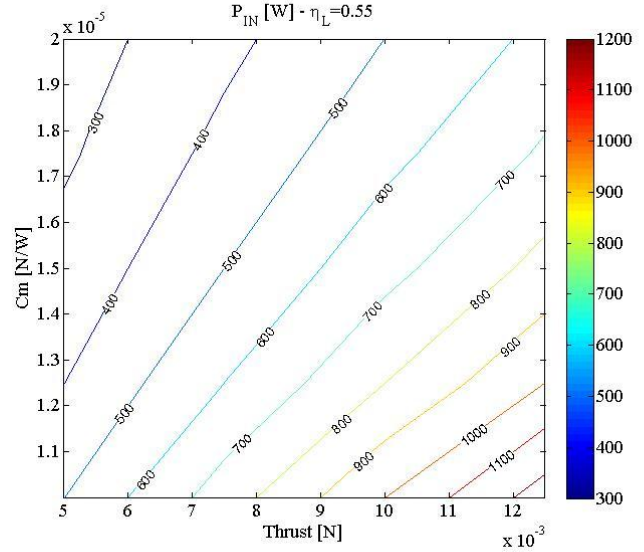
$$z_R = \frac{\pi w_0^2}{\lambda_b}$$

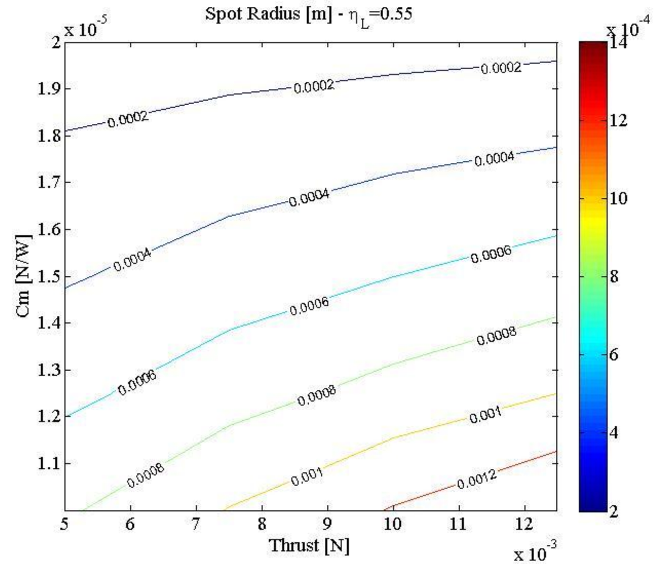


Momentum Coupling

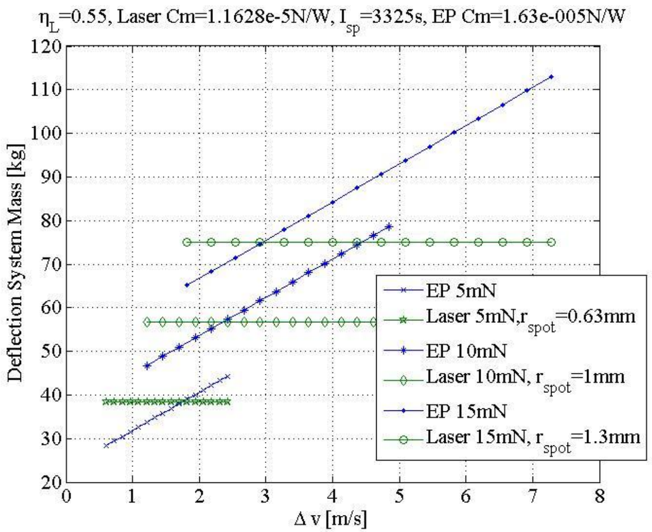
$$C_m = \frac{F_{sub}}{P_{IN}} \qquad P_{IN} = \tau \eta_P \eta_S \frac{P_{1AU} A}{R_{AU}^2}$$

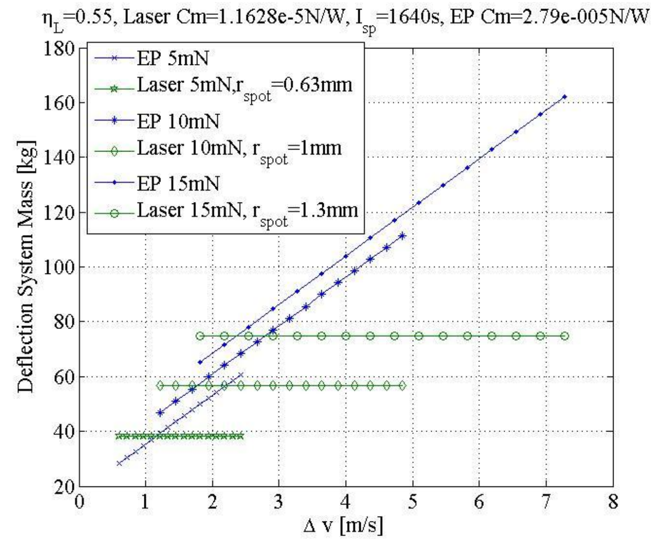


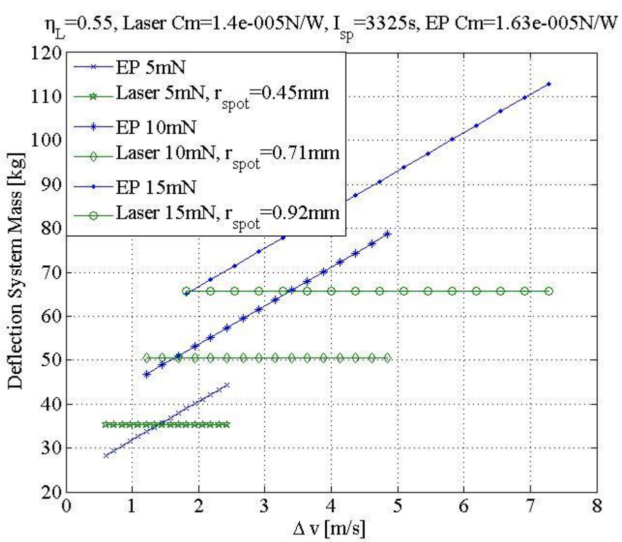


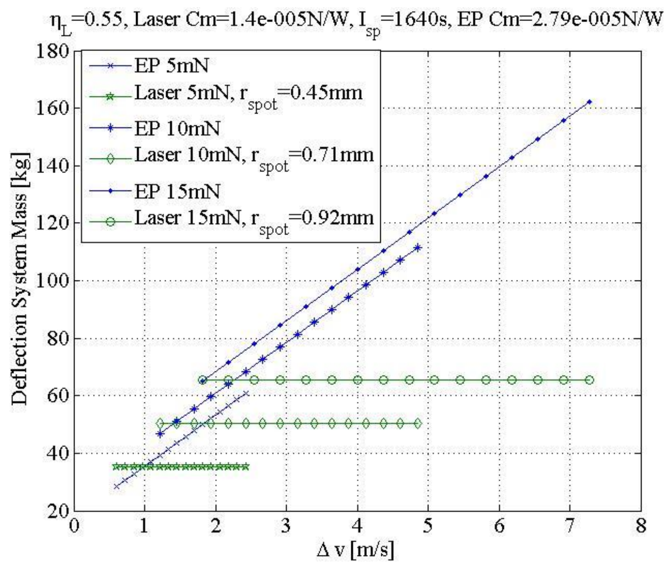


Mass Efficiency



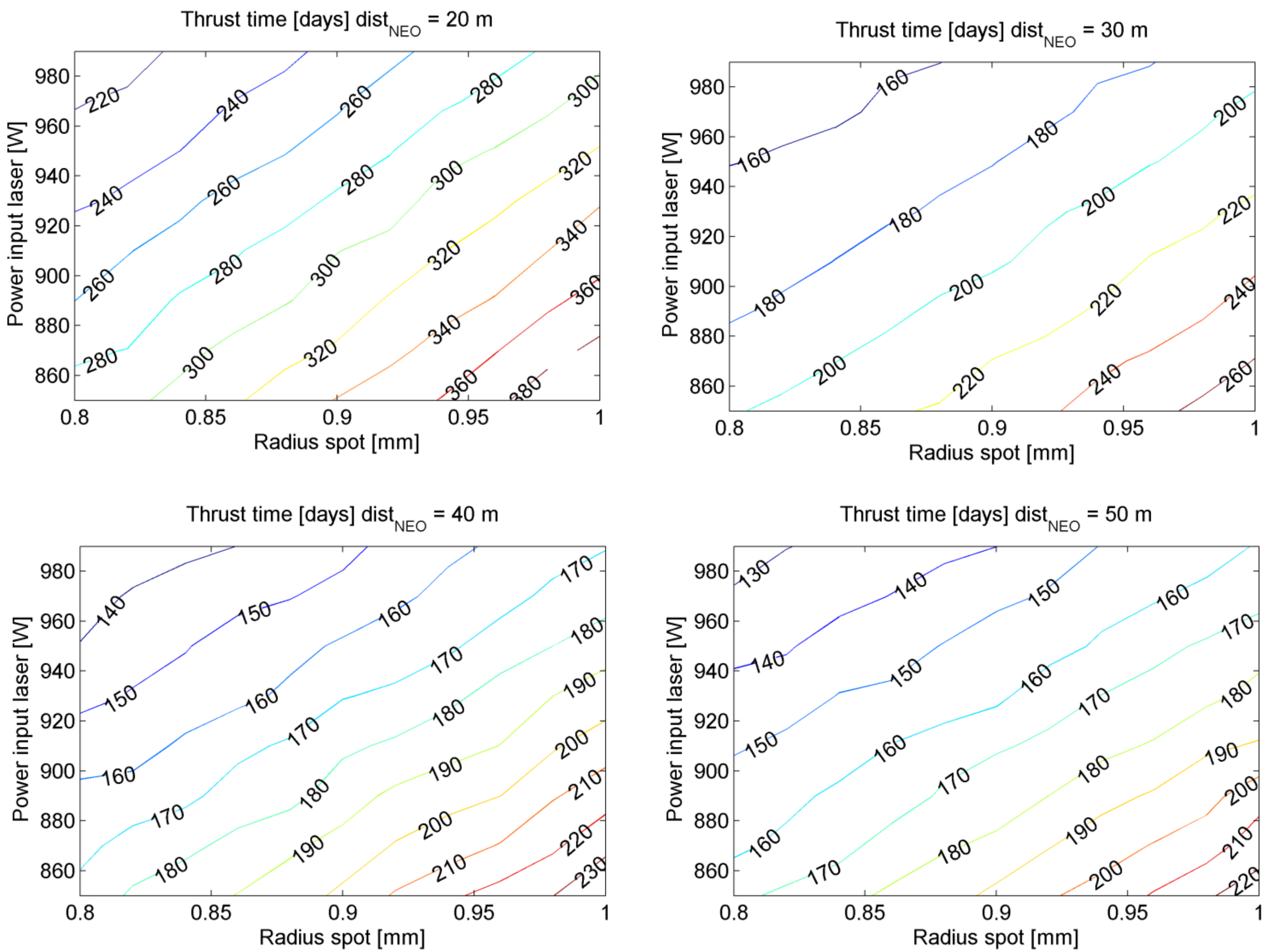






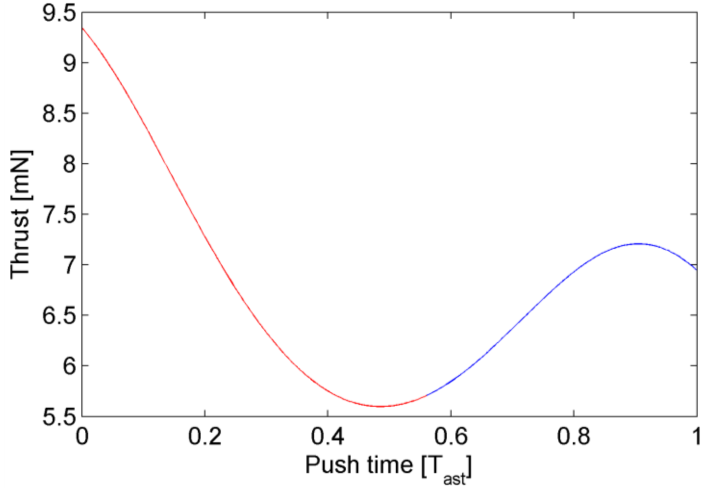
Efficiency analysis

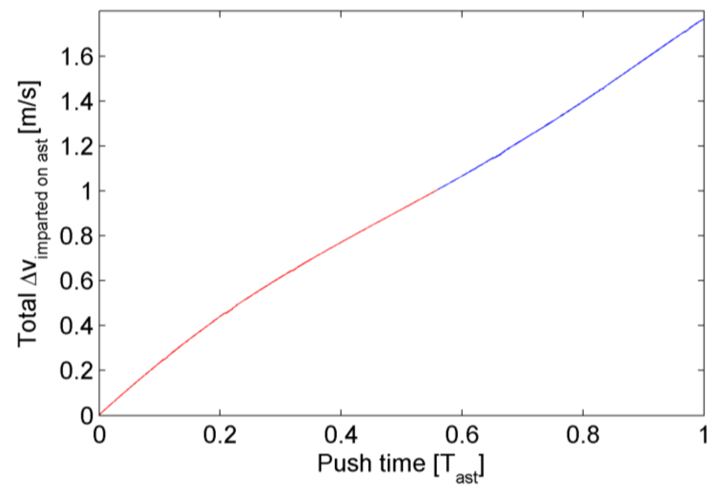
Thrusting time required to achieve 1 m/s for different shoot shooting distances

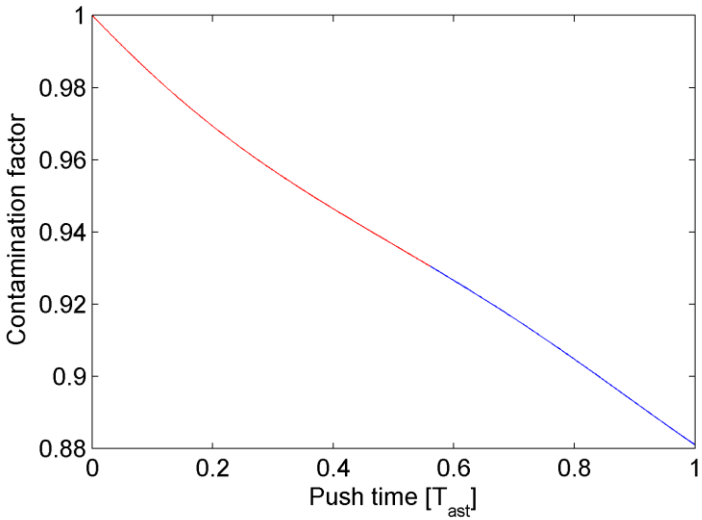


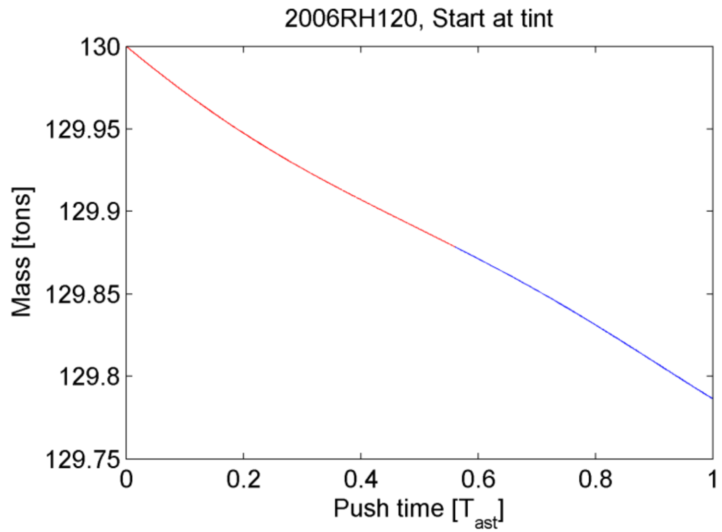
Deflection Result

Assuming 860W at 1AU the target Δv can be achieved in about half a year.









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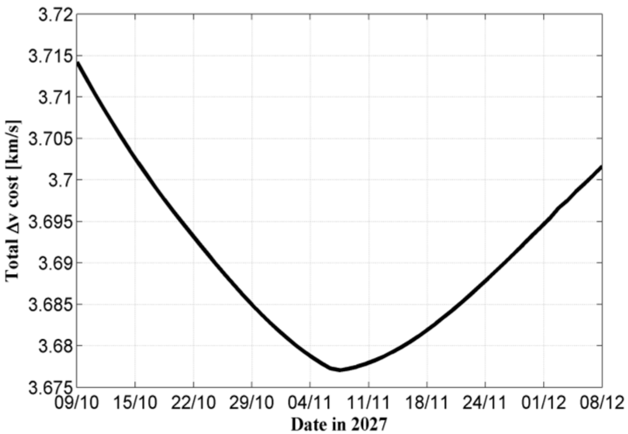
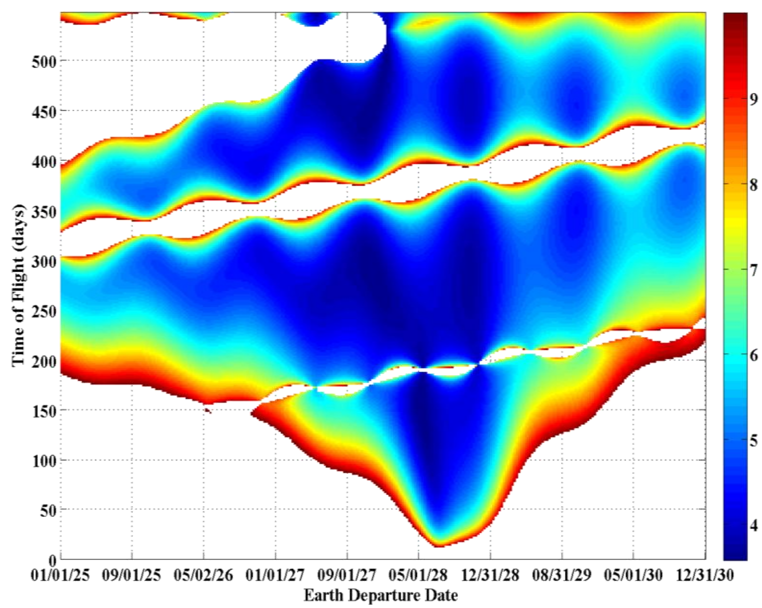
Mission: Interplanetary Trajectory and LW

- Opportunities in 2027 (nominal) and 2028 (backup)

Earth Departure	V_{inf} (km/s)	DSM date (Fraction ToF)	DSM Δv (km/s)	Asteroid Arrival	Arr Δv (km/s)	ToF (Days)	Total Δv (km/s)
8/11/2027	0.5403	N/A	0	9/09/2028	0.4871	306.5	3.677

  - Preliminary analysis assumes escape 400x400 orbit
  - Low Δv requirements during transfer and arrival
- Wide LW
  - 1 month → less 1% extra costs





Mission: Launcher & Propulsion Trade-off

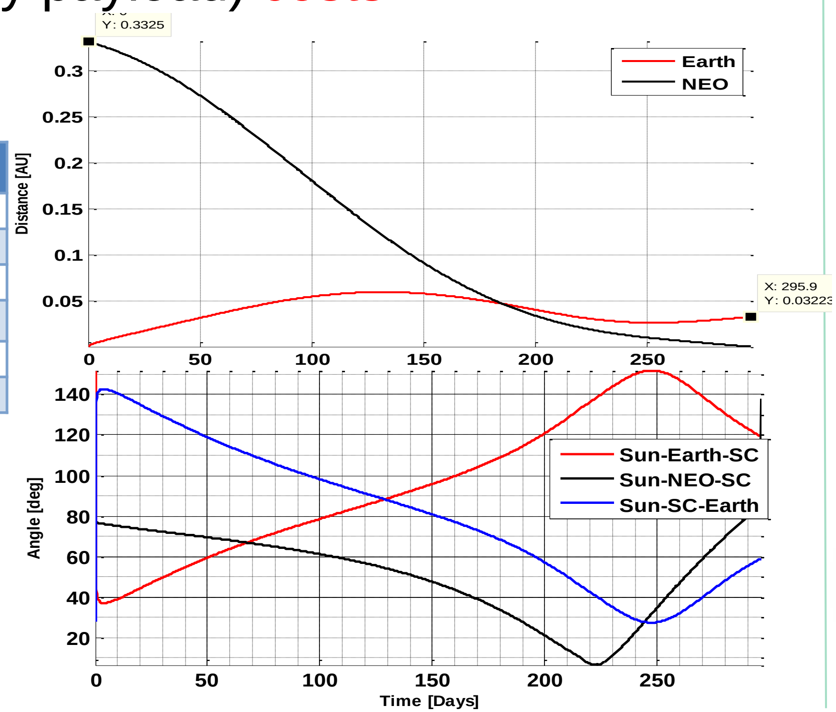
- Launcher and propulsion trade-off:
  - VEGA to LEO / PSLV to LEO *with* Off-the shelf PRM / Integrated SC / Solid motor
  - **PSLV XL to GTO** *with* **Biprop** / EP
  - (Ariane 5 ECA tertiary payload) costs

- Refined trajectory

Non-Sphericity	8 Zonal, 8 Tesseral
S/C Initial Mass	1074 kg (maxi for PSLV XL)
Third Body	Moon, Earth
SRP	A: 7.4 m^2 C_R = 1.5
Dep. Conditions	GTO: 200 x 36 000 km , 18º
Specific Impulse	321 sec
Thrust	450 N

  - Final mass > 690 kg

Manoeuvre	Δv [m/s]
Departure	792
DSM	186
Arrival	395



GNC Strategy and Analysis

- NEO Mission
  - References - Hayabusa, Marco Polo, Rosetta, NEAR, Stardust
  - Relies heavily in optical navigation
  - Dynamics – 3 body problem, SRP, asteroid rotation,
  - Need for combined approach strategy definition and GNC analysis
- AdAM
  - 2006RH120 is approximately 4 m diameter, 130 Ton, 31 Visual Mag
    - Gravity pull at 50 m range is 2 μN, 1 order of magnitude below SRP 40 μN), 6 orders of magnitude lower than for Hayabusa's Itokawa (382 mN). Implications
      - Dyamics modelling/decoupling → GNC algorithms modularity
      - Strategy – no stable terminator orbits → unstable hold points
      - Safety → spacecraft is barely pulled towards asteroid
    - Can be detected at 40 $\times 10^3$ Km - Don Quijote's 160-meter-wide 2002AT4 could be detected from 2500 $\times 10^3$ Km
  - Duration of operations Hayabusa/Marco Polo – Sample Return; Rosetta – Orbit, Release Lander; NEAR – Orbit, Touch-Down; Stardust - Flyby. AdAM - Actively perturbing the asteroid from a hold point for 2 years (while counter-acting forces and trailing the asteroid) → component life-time, robustness
- FF / RV / Debris Removal as add. reference (ATV, Proba, MSR)

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GNC Strategy

- **Early Encounter** (Launch + 296 Days)
  - RVM (main engine, Δv 391 m/s) @60 000 Km distance
  - Scan, Acquire LOS, relative accuracy from ~5000 Km to 10 Km
- **Far Approach** (11 Days)
  - Reduce relative distance from **5000 Km to 10 Km**
  - Improve relative accuracy from **10 Km to 1 Km** , 1 mm/s
  - (accuracy improves through Dog leg LOS observation + Radiometric)
- **Close Approach** (11 Days)
  - Acquire Ranging Sensor, early validation of GNC functions, tackle SRP
  - Aproach from **10 Km to 1 Km** through dog-leg in 6 days through 6 WP
    - Accuracy in range direction improves to **20 m , 0.1 mm/s**
  - Final approach segment from **1 Km to 300 m** in 6 hours, where ranging sensor is acquired.
    - Accuracy in range direction improves to **<1 m , < 0.1 mm/s**
  - SRP causes 5 Km drift in 4 days → close approach is autonomous (through station keeping hold points)
- **Transition to Operation** (26 days)
  - GNC callibration, Test Station Keeping, Fine Asteroid Ephemeris Characterization
  - Station keeping with increasingly narrow boxes, from 300 to 50 m to NEO
- **Operations – Testing and Callibration** (2 months)
  - Supervised used of laser for periods of minutes, then hours, weeks and month
- **Operations – Nominal** - 90 days ablation + 10 days orbital determination campaigns

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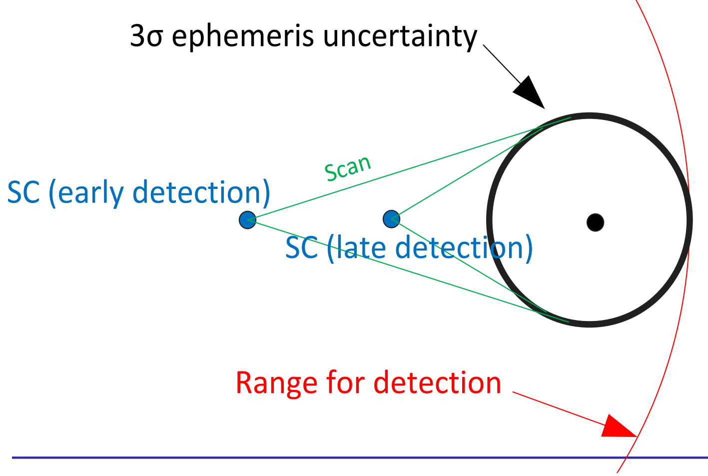
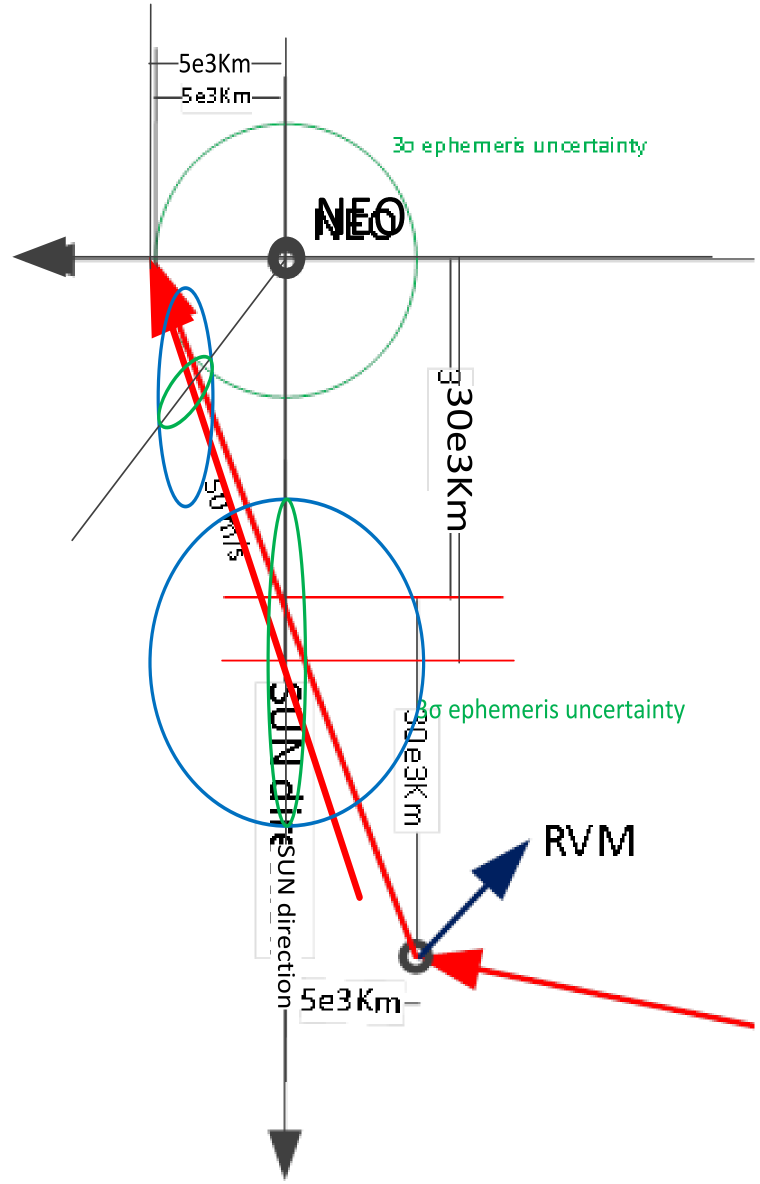
Early Encounter

- **Ephemeris Uncertainty**
  - 5 000 Km
  - 2 m/s
- **Detection/Scanning** (13.5 rel mag)
  - 60 000 Km Nominally
  - 30 000 Km Worst Case
- **RVM**
  - Illuminated approach
  - Minimize drift in the FOV
  - Observe NEO from 90(+30) deg





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Approach

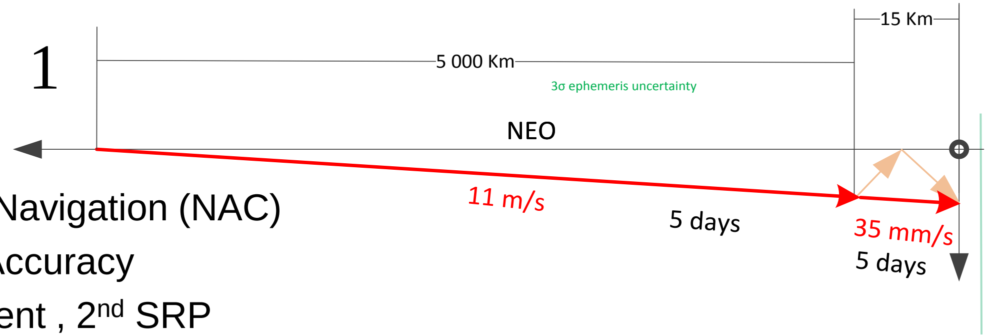
Far Approach

- LOS + Radiometric - based Navigation (NAC)
- Lower the Range, Improve Accuracy
- 1st Segment – Gravity-Gradient , 2nd SRP

Close Approach

- Autonomous GNC
- Dog-leg manoeuvres
- Improvement on range through LOS, Δv / LOS rate , brightness/size
- Predictive Guidance through WP
- **HP** at 1 Km, approach to 300 meters
- Acquisiton of ranging sensor

1



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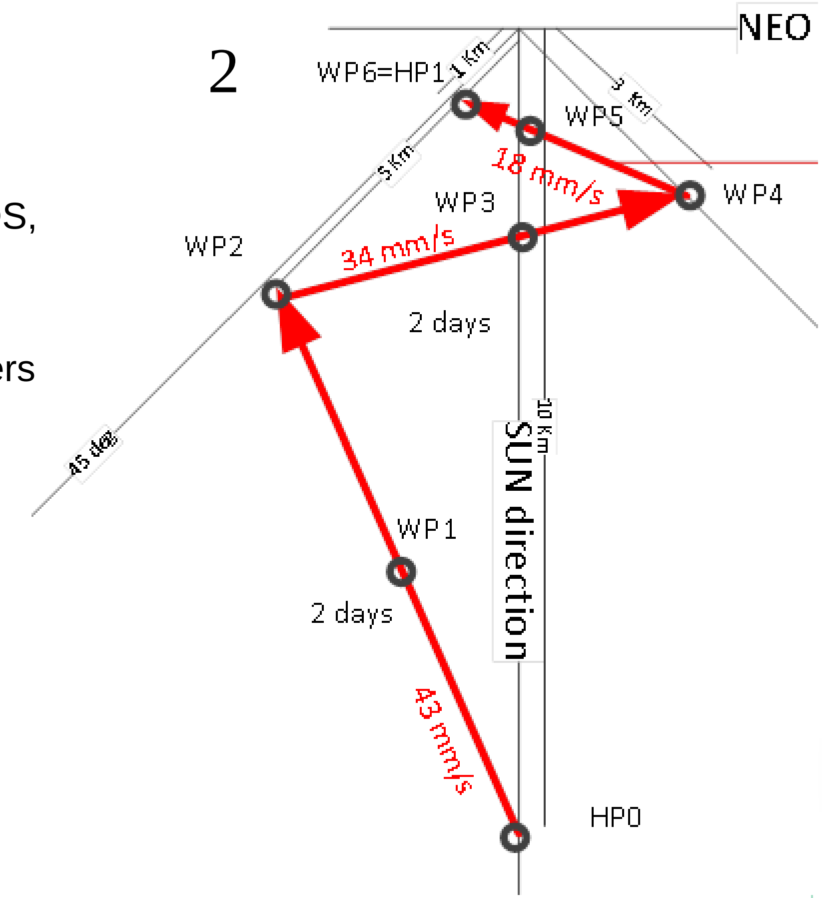

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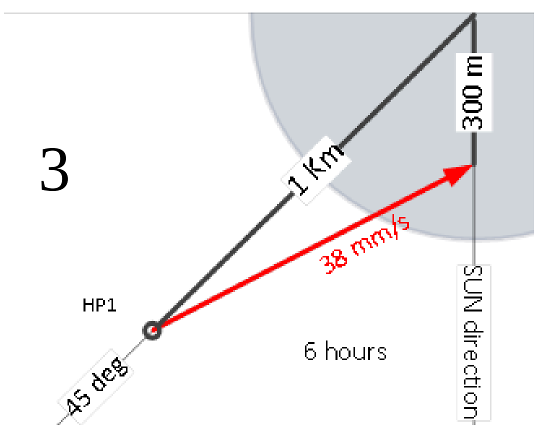
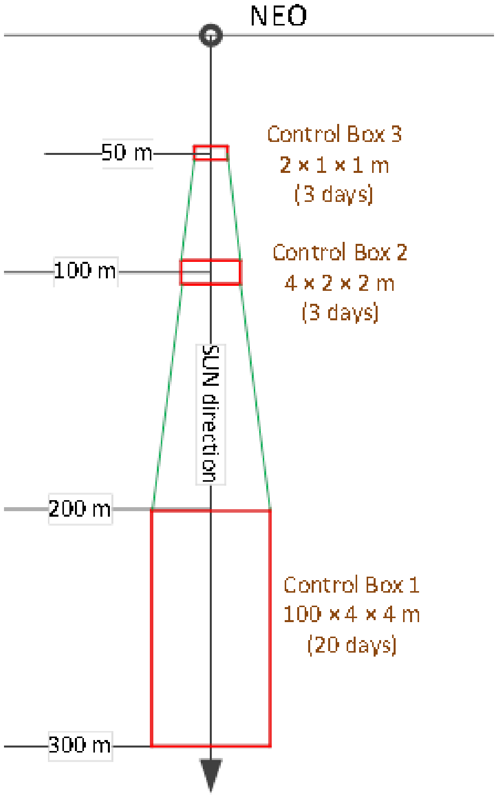
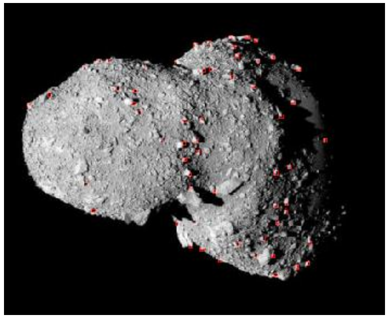


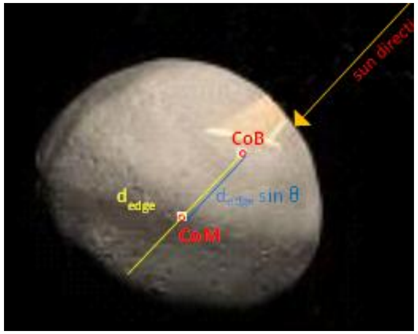
Transition to Operations

- Full Metrology Acquired
- Asteroid is 300 000 pixels in NAC, 10 in WAC
- Autonomous Station-Keeping

- **Calibrate**
  - WAC , NAC , STR for LOS, starry background
  - Range/Range Rate – (size of asteroid, rangefinder, shadow)
- **Characterize Asteroid**
  - Size, Rotatinal State
  - Features
- **Build Thrust**
  - Validate Procedures,
  - Assess GNC Algorithms Performances
- **Orbit Determination**
  - Radiometric measurements
  - Relative metrology
  - <0.4 AU from Earth



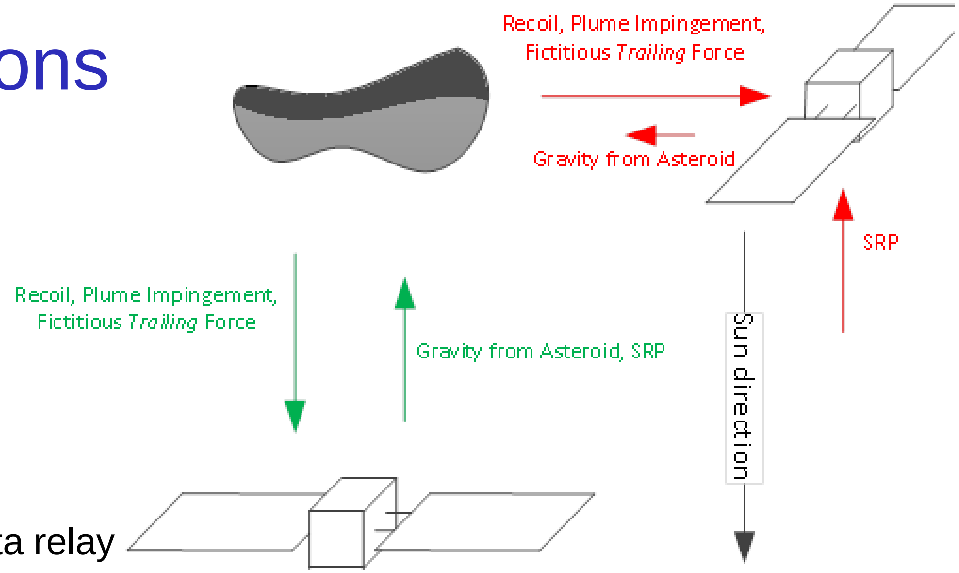




Followed by series of Ablation Tests

Proximity Operations

- **Control Box**
  - ±1m range wrt surface
    ±0.5 m lateral
- **Metrology**
  - Image - LOS to CoB
  - Range to Surface
- **Strategy**
  - 6 Days Ablation, 1 day data relay
  - For 90 days, then 10 days radiometric nav



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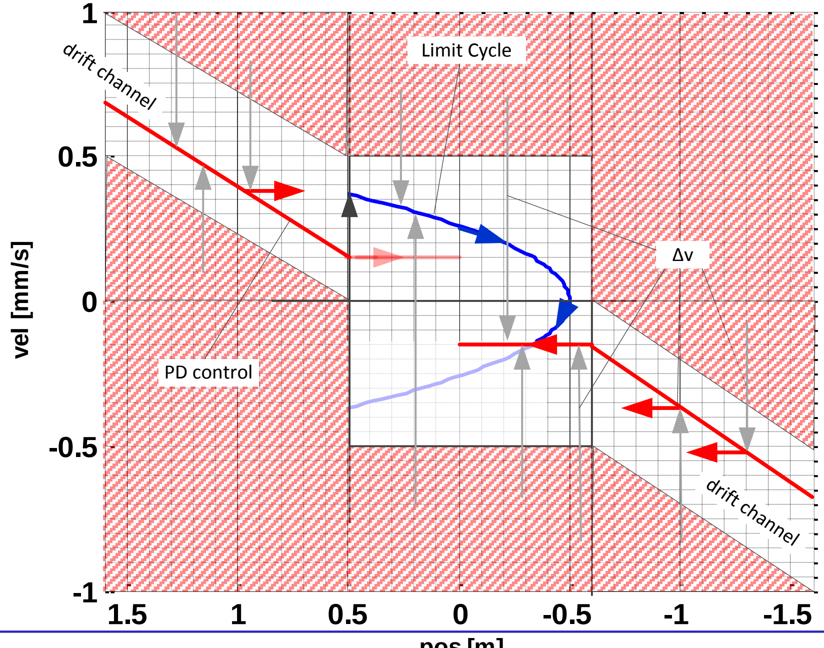
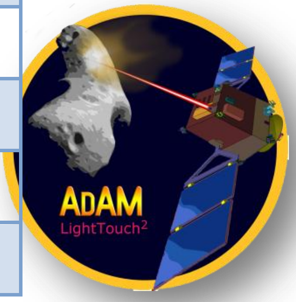


	Force μN	Variation	τ
SRP	38	20%	7 d
Recoil	3.3	1%	1 m
Gravity	1.7	10 %	5 m
Impingement	20 (6)	20%	1 h
Deflection	42.3	20%	1 d
Total (trailing)	62.8		
Total (radial)	25.5		

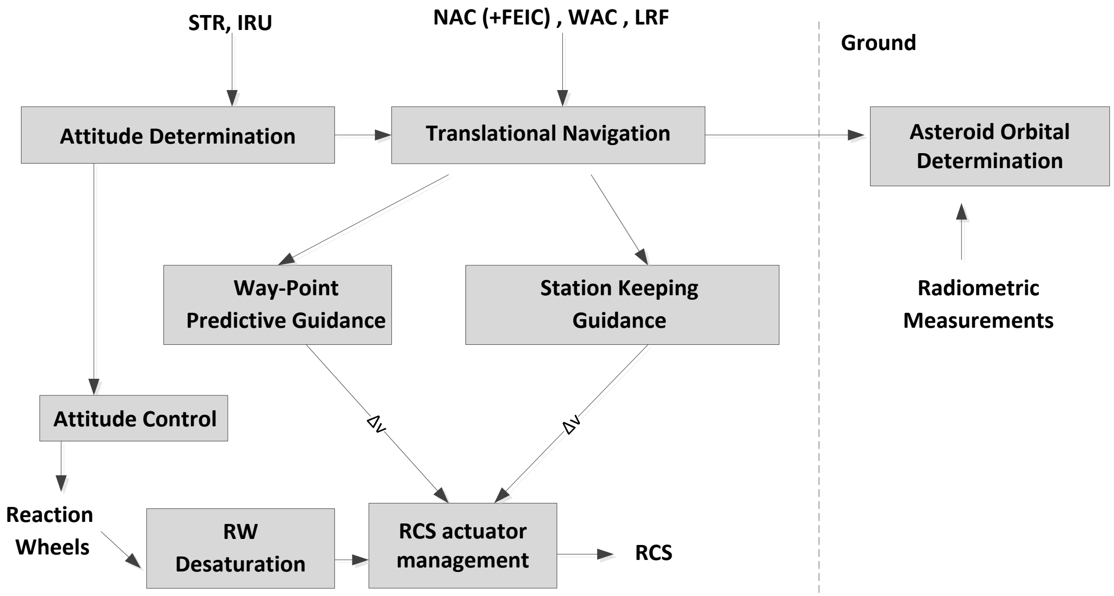


GNC Architecture and Hardware

- **NAC**
  - Main Approach Sensor
  - Rotational State
  - Fitted with FEIC
- **WAC**
  - Proximity (LOS)
  - Callibration
- **Laser Rangefinder**
  - Low-Power, Low-weight (wrt to LIDAR, Radar)
  - Proximity – range to surface

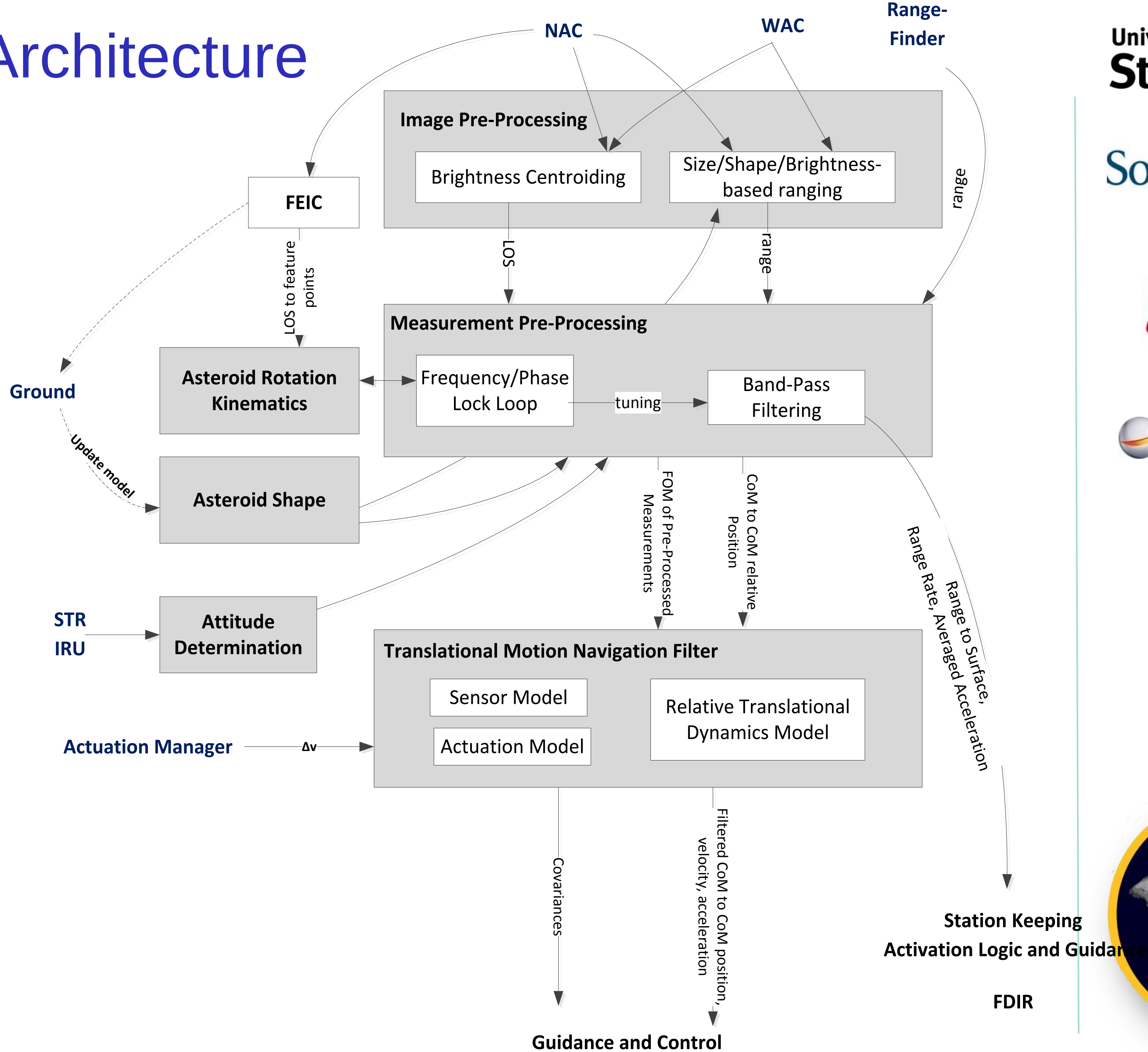
Camera	Pixel [μrad]	FOV	Range [Km] (worst case)	Mass
Galileo Avionica VBNC	200	70	10	0.6 kg
Marco Polo R NAC	15	1.7	30 000	6 kg

LRF	To qualify
Accuracy	10 cm
Power	<2 W
Mass	0.5 K
Rate	1*MHz
Range	500 m
Bandwidth	920 nm



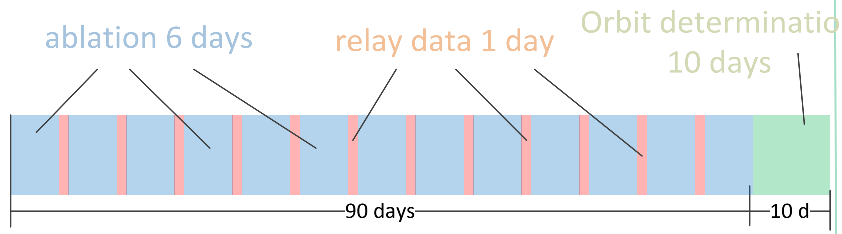
GNC Architecture

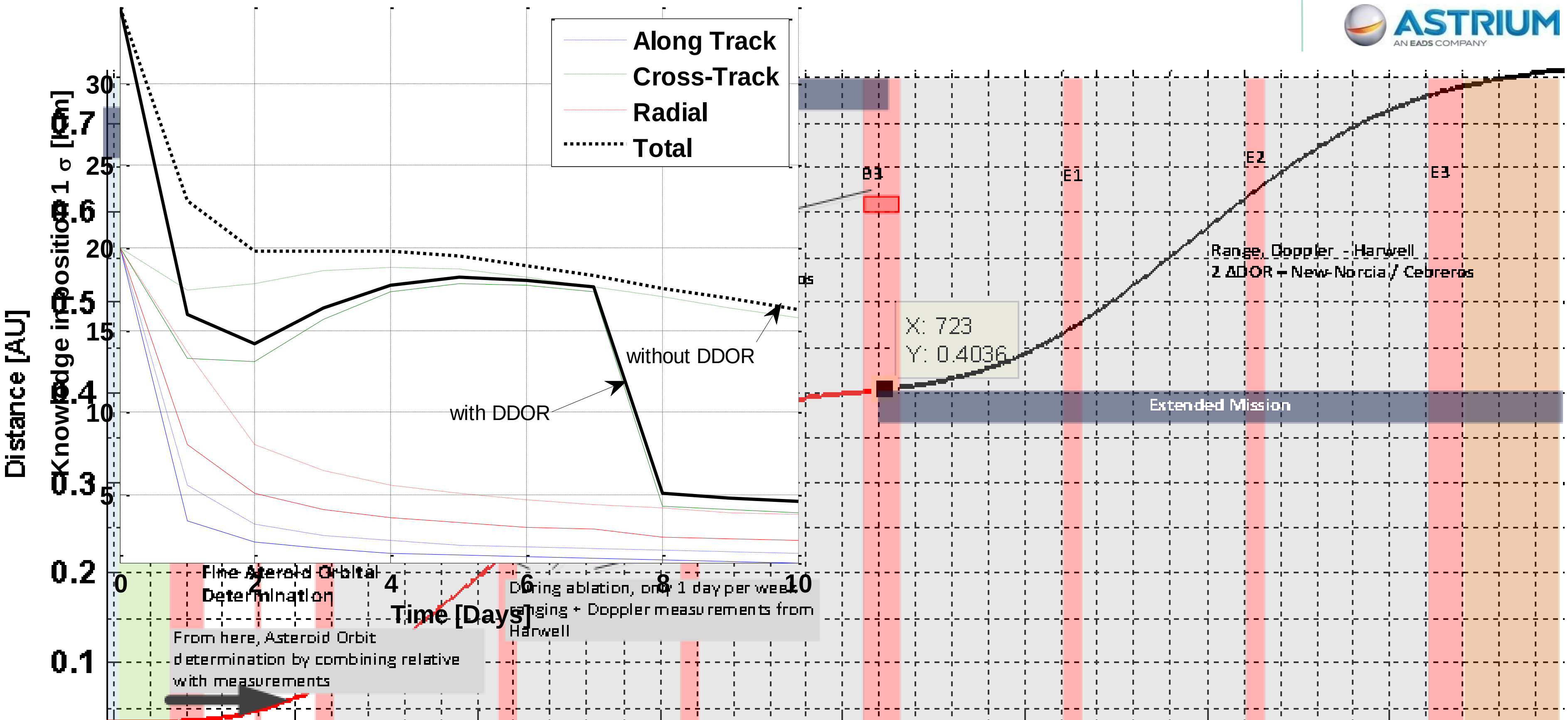
- Modular
- Robust



Radiometric Orbit Determination

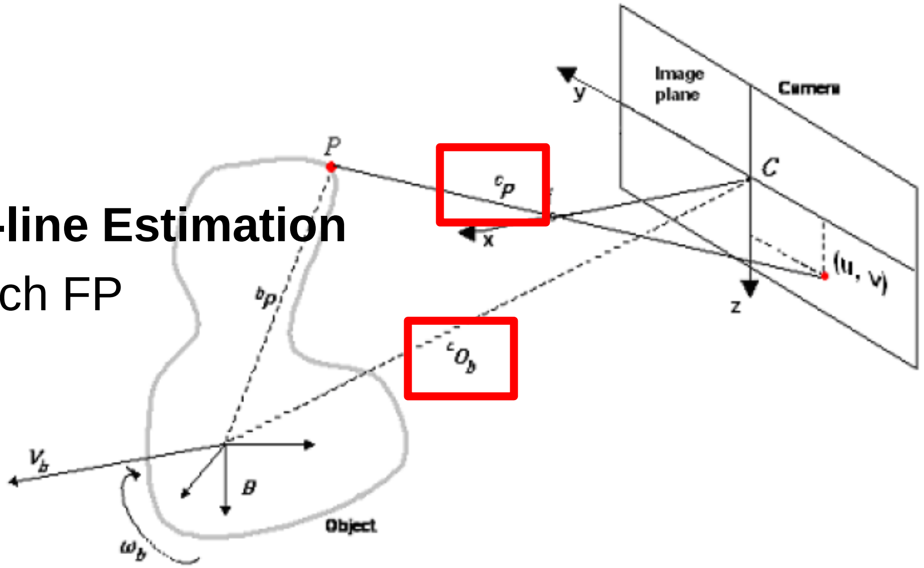
- Range, Doppler from Harwel*
- ΔDOR from DSA
  - (3 x 2 in nominal mission)
- Combined with relative metrology to obtain NEO orbit





GNC Modules

- **Asteroid Rotation On-line Estimation**
  - Displacement of each FP



$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{f}{x_C} \begin{bmatrix} y_C \\ z_C \end{bmatrix}$$

from nav

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = M\left(f, \boxed{{}^{C}P, {}^{C}O_B}\right) \begin{bmatrix} {}^{C}V_{B/C} \\ {}^{C}\omega_{B/C} \end{bmatrix}$$

  - Invert Matrix (or LSQ, etc)

from nav

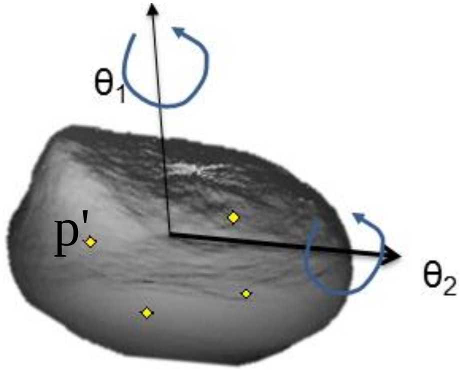
10 tracked points (only need to track from 2 instants)

$$\begin{bmatrix} \boxed{{}^{C}V_{B/C}} \\ {}^{C}\omega_{B/C} \end{bmatrix} = \begin{bmatrix} M(f, {}^{C}P_1, {}^{C}O_B) \\ \vdots \\ M(f, {}^{C}P_N, {}^{C}O_B) \end{bmatrix}^{+} \boxed{\begin{bmatrix} \dot{u}_1 \\ \dot{v}_1 \\ \vdots \\ \dot{u}_N \\ \dot{v}_N \end{bmatrix}}$$

Rotation Estimate FFT Approach

- Complex Spectrum of Position of points on the body (Fourier transform)
- Camera and LRF to detect points' relative position
- Rotations around two axis
- 2 distinct frequencies (4 frequencies in the spectrum)

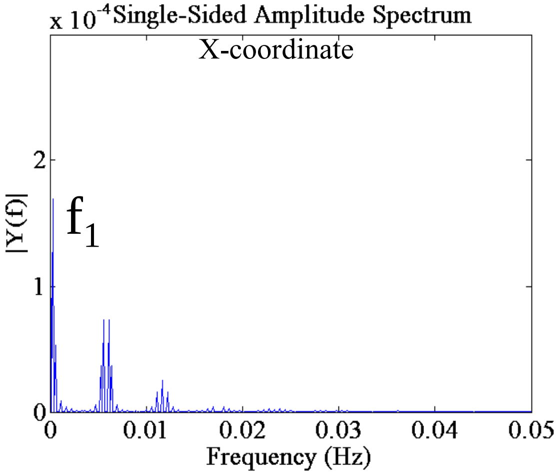
$$\mathbf{p}' = \mathbf{a}\cos(\theta_1) + \mathbf{b}\sin(\theta_1) + \mathbf{c}\cos(\theta_2) + \mathbf{d}\sin(\theta_2) +$$
$$\mathbf{e}\cos(\theta_1+\theta_2) + \mathbf{f}\sin(\theta_1+\theta_2) + \mathbf{g}\cos(\theta_1-\theta_2) + \mathbf{h}\sin(\theta_1-\theta_2) + \mathbf{i}$$

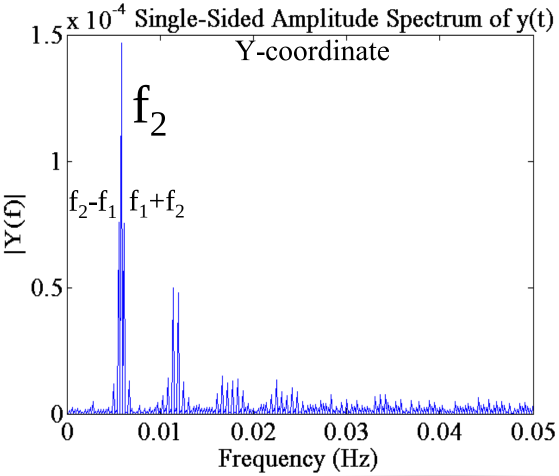


- Intersection of the two axis identifies the CG
- No needs to know inertia and mass of the asteroid

Example

- 21 rotations/hour around z-axis (5.833E-3Hz)
- 1 rotation/hour around y-axis (2.778E-4Hz)
- One image every 10 seconds
- 4 points tracked per image
- Observation period 2 hours





- Exact determination of frequency
- Rotational axis
- z_est = [0.009 0.054 0.998];
- y_est = [0.317 0.948 0.000];

Proximity Navigation and Control

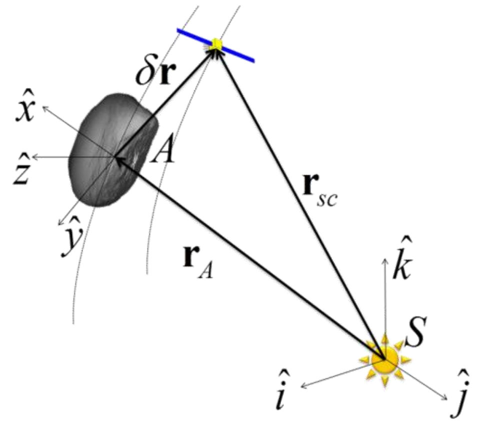
- Relative perturbed spacecraft motion described in the Hill reference frame:

$$\ddot{\mathbf{x}} = -\mathbf{a}_{r_a} - 2\mathbf{v}\times\dot{\mathbf{x}} - \dot{\mathbf{v}}\times\mathbf{x} - \mathbf{v}\times(\mathbf{v}\times\mathbf{x}) - \frac{\mu_{sun}}{r_{Sc}^{3}}(\mathbf{x}+\mathbf{x}_{r_a}) - \frac{\mu_a}{\delta r^3}\mathbf{x} + \nabla U + \frac{\mathbf{F}_{sc}(\mathbf{x},\mathbf{x}_{r_a})}{m_{sc}}$$

- U second order gravity field potential
- $\mathbf{F}_{sc}$ force acting on the spacecraft
  - Laser recoil
  - Solar radiation pressure
  - Plume impingement
- $\mathbf{a}_{r_a}$ relative acceleration of the reference frame

$$\ddot{\mathbf{r}}_a = -\frac{\mu_{sun}}{r_a^3}\mathbf{r}_a - \frac{\mu_{Sc}}{\delta r^3}\mathbf{x}_a + \mathbf{a}_{laser}$$

  - tugging effect
  - $\mathbf{a}_{laser}$ acceleration from laser ablation



- Control box to maximize the effectiveness of laser

$$f' = \mathbf{v}_{in}^{est} + \Delta\mathbf{v}_{corr} + \mathbf{a}_{est}t = 0$$

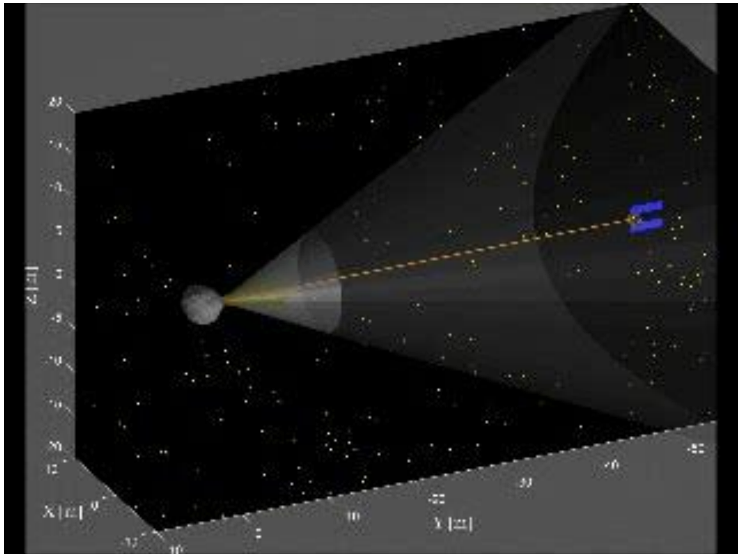
$$\mathbf{d}_f = \mathbf{d}_{in}^{est} + (\mathbf{v}_{in}^{est} + \Delta\mathbf{v}_{corr})t + \mathbf{a}_{est}\frac{t^2}{2}$$

  - $\Delta\mathbf{v}_{corr}$ corrective impulse bit

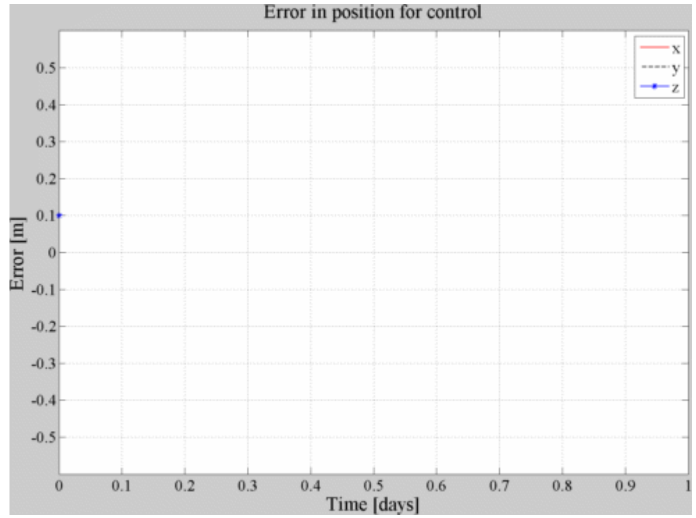
Need to estimate
- Spacecraft relative position and velocity
- Perturbative acceleration acting

- On board orbit determination by processing measurements from
  - Camera
  - Lidar Range Finder

Proximity Navigation and Control

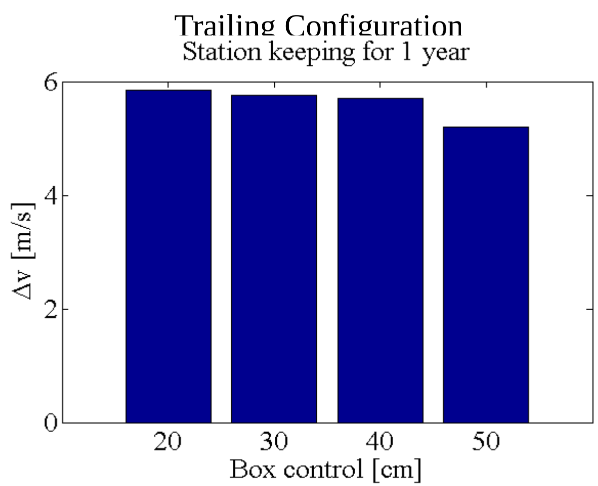


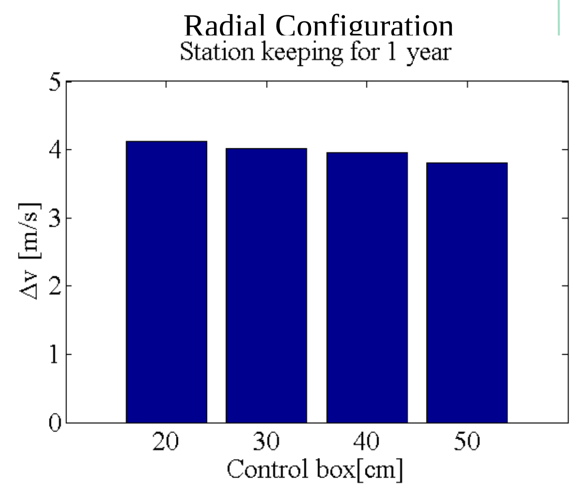
- Example Trailing Configuration



- Control Δv

-Radial configuration less demanding than the trailing one



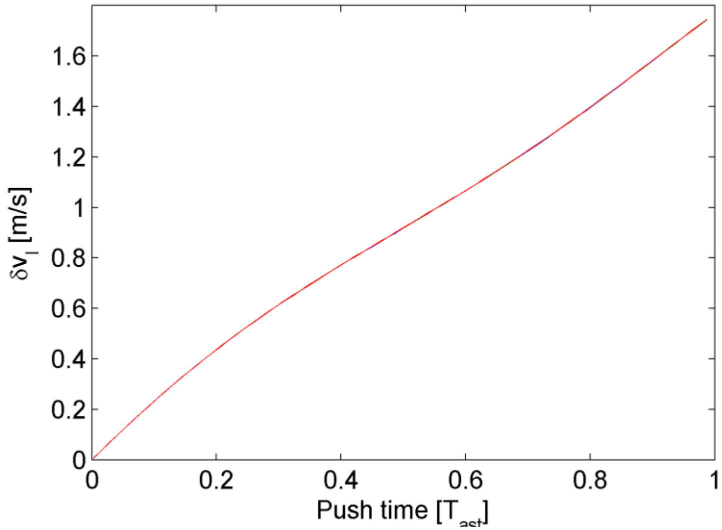


How to measure the efficiency of a deflection strategy?

Two quantities can be measured:

- Integral of the acceleration imparted onto the asteroid

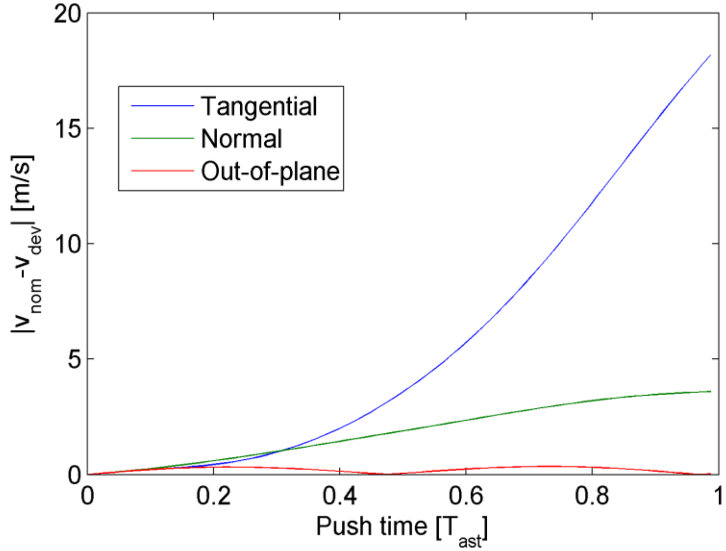
$$\delta v_I = \int_{\text{start ablation}}^{\text{stop ablation}} \frac{F_{\text{sub}}(t)}{m_{NEO}(t)} dt$$



- Variation of position and velocity with respect to the nominal orbit of the asteroid

Quantity of interest in an actual deflection mission

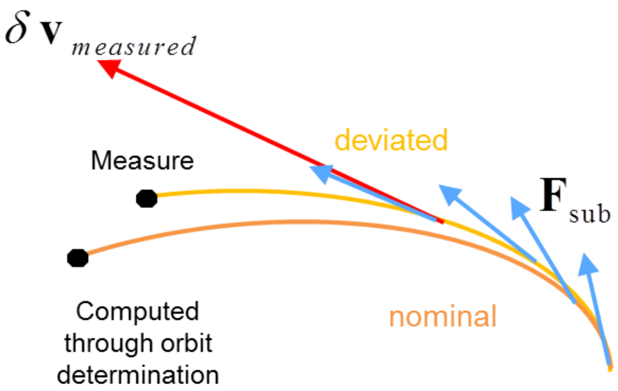
  - strongly affected by the thrust direction
  - the starting point of the deflection action and the orbital characteristics of the asteroid.



Estimating Δv imparted onto the asteroid

2. Measurement from OD

- Measurement of the deflected position of the asteroid at the end of the thrusting arc, with respect to its nominal position (through orbit determination campaign).
- Compute the delta velocity equivalent to a continuous thrust arc through the use of relative motion equations



$$\delta v_{measured} = \mathbf{\Phi}^{-1} \delta r \left(t_{measure} \right)$$ [1]

transition matrix of the relative motion equations

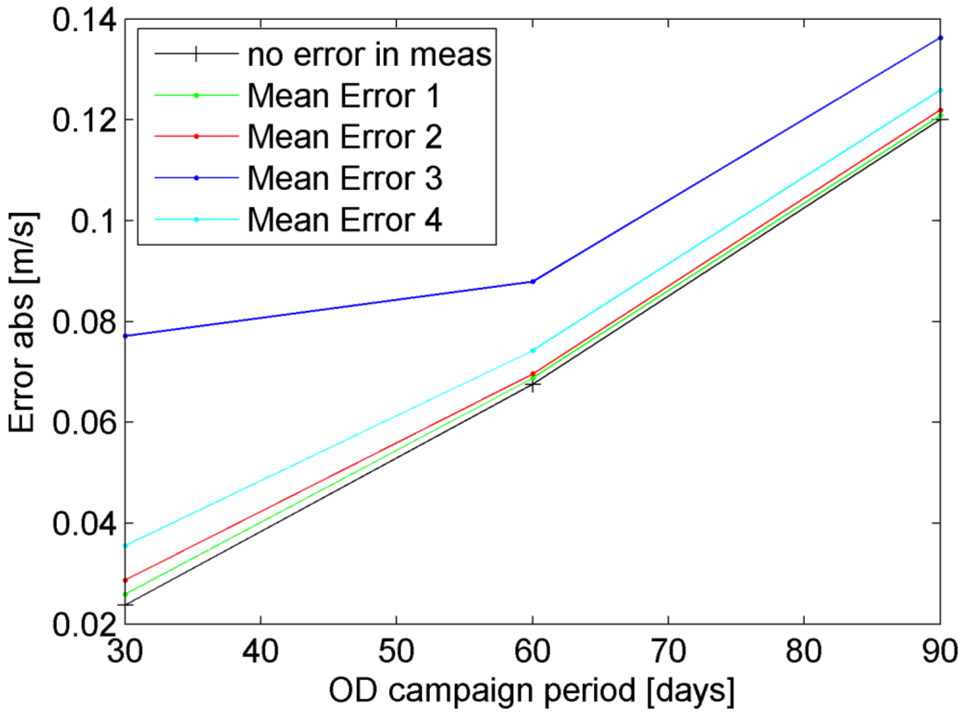
relative position of the asteroid with respect to its nominal one at the time of measure

- Dependent on range measurements
- Dependent on time interval between ODS
- Dependent on thrust direction

[1] Vasile M. and Colombo C., “Optimal Impact Strategies for Asteroid Deflection”, Journal of Guidance, Control and Dynamics, Vol. 31, No. 4, July–Aug. 2008, pp. 858–872, doi: 10.2514/1.33432.

Estimating Δv imparted onto the asteroid

- Monte Carlo analysis considering errors in the determination of position and velocity at each orbit determination campaign:
  - (Error 1) 500 m in position and 0.5 mm/s in velocity
  - (Error 2) 1.5 km in position and 1 mm/s in velocity
  - (Error 3) 10 km in position and 10 mm/s in velocity
  - (Error 4) 5 km in position and 2 mm/s in velocity



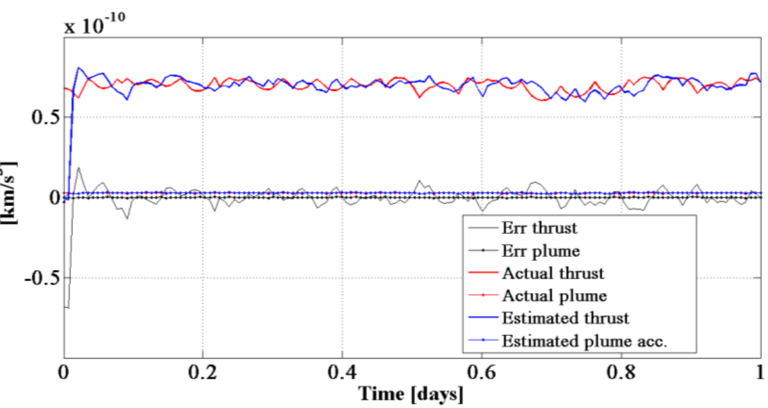
Estimating Δv imparted onto the asteroid

- Proposed methods:
  - Δv given by the integral of the acceleration from the laser ablation

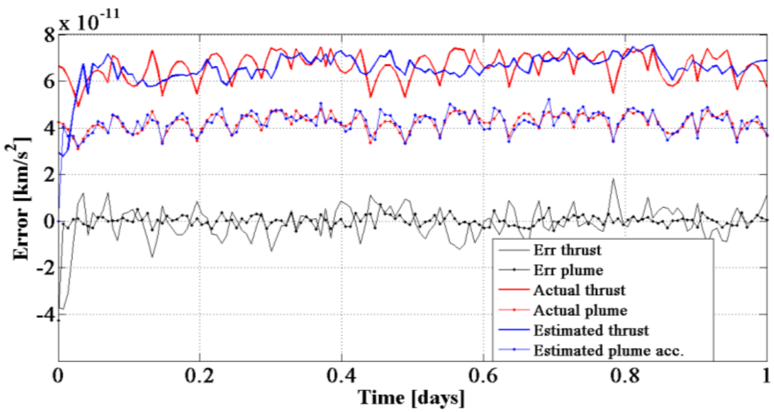
$$\delta \mathbf{v}_I = \int_{\text{start ablation}}^{\text{stop ablation}} \frac{\mathbf{F}_{sub}(t)}{m_{NEO}(t)} dt \quad \Longrightarrow \quad \delta \mathbf{v}_I = \int_{\text{start ablation}}^{\text{stop ablation}} \mathbf{a}_{laser}^{estimated} dt$$

  - High fidelity model for perturbations (recoil, asteroid's gravity, and solar radiation pressure)
  - Force from the plume exerted on the same direction of the asteroid acceleration
  - Camera+LRF+ impact sensor to estimate plume ejecta force

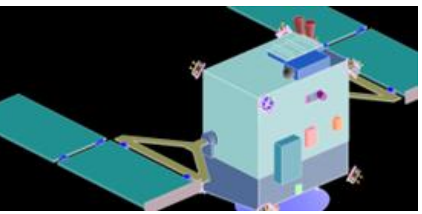
Acceleration - Trailing Configuration



Acceleration - Radial Configuration



	Radial Configuration		Trailing configuration	
Control box	20 cm	50 cm	20 cm	50 cm
Integral error	1.6%	1.2%	0.68%	0.49%

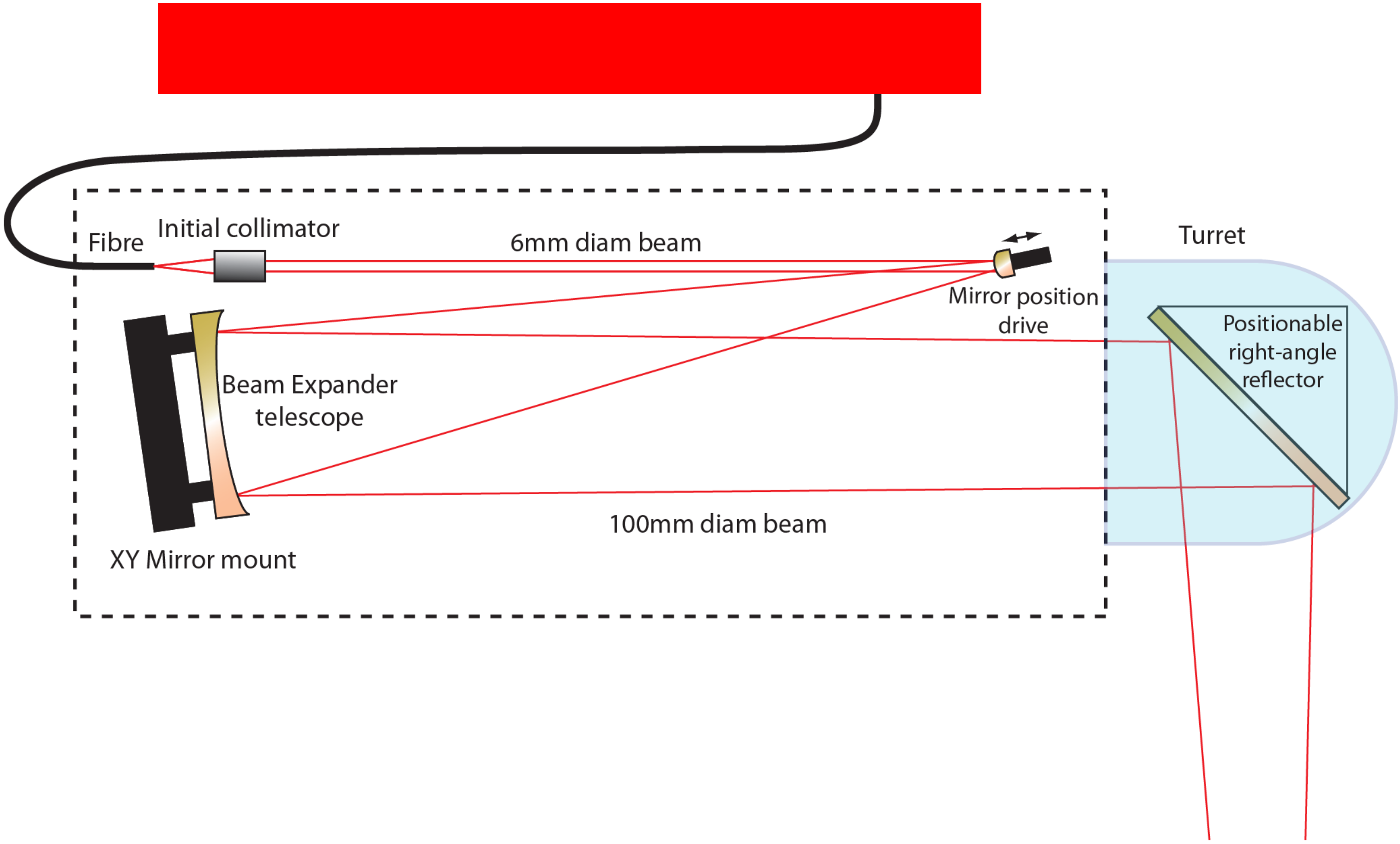


AdAM

Primary Payload

- Diode-pumped fibre laser system
  - Overall efficiency of 55 %, operating temperature 10 C
  - Focal length of 50 m [spacecraft-to-asteroid distance]
  - 860 W, with a spot size radius between 0.8-1 mm
    - Surface power density 428-274 MW/m^2
  - Mass derived from space qualified reflective telescopes [HiRise reflective telescope] and perceived laser development for the 2025+ timeframe [DARPA, nLIGHT]
    - Optics 10 kg, laser 9.9 kg
  - Optical scheme is based on a simple combined beam expansion and focusing telescope
- Impact Sensor
  - Upon impact, used to measure the momentum created by the ejecta
    - Consist of a thin aluminium diaphragm with piezoelectric transducers
    - Heritage from Rosetta (GIADA) and PROBA-1 (DEBIE instrument)
    - 2.5 kg, 4 W

Laser System Schematic



Opportunistic Payload Selection

- Ablation results in the volumetric removal and ejection of deeply situated and currently inaccessible subsurface material. [Gibbings, Vasile et al, 2012]

- Raman/Laser-Induced Breakdown Spectrometer
  - Best complements the laser ablation process
  - Single science objective
    - Measure the spectral emission and intensity of the ejecta plume
    - Measure the elemental composition, quality and concentration
    - Heritage from the ExoMars Rover, flight model [2 kg, 30 W] and pioneering technological development in laser sources, optical elements and spectrometers

- Supported by the operations of the WAC and NAC
  - Shape model, topographical profile, rotational state
  - Derivation of bulk density and mass

Design Drivers

- Cost
  - Low cost launch/transfer
    - Vega to LEO + LISA PRM not possible due to mass
    - PSLV to GTO offers sufficient mass and low cost
  - Low cost ground station
    - High performance communications subsystem
- Escaping from GTO
  - Relatively high Δv
  - Limit transfer time and passes through radiation belts
  - Bipropellant propulsion system
  - Relatively high fuel mass
  - Relatively high structure mass

Mass Budget

SysNova Mass Budget	Current Mass (kg)	Design Maturity Margin (%)	Maximum Mass (kg)
Data Handling	17.1	10.9%	18.9
Power	68.8	16.4%	80.1
Communications	37.7	8.8%	41.0
GNC & AOCS	39.5	7.9%	42.5
Structure and	100.0	20.0%	120.0
Thermal	13.0	20.0%	15.6
Propulsion	59.9	12.3%	67.3
Payload	**35.5**	**19.4%**	**42.4**
SPACECRAFT DRY TOTAL	**371.4**	**15.2%**	**427.9**
Harness	30.0	20.0%	35.9
DRY TOTAL (incl. Harness)			**463.8**
System Mass Margin		20.0%	92.8
DRY TOTAL (incl. 20% System Margin)			**556.6**
Propellant			405.2
SPACECRAFT WET MASS			**961.8**
Launch Vehicle Capability - PSLV GTO			**974.0**
Launch Vehicle Margin - PSLV GTO			**12.2**
Mass Margin % - PSLV GTO			**1.3%**

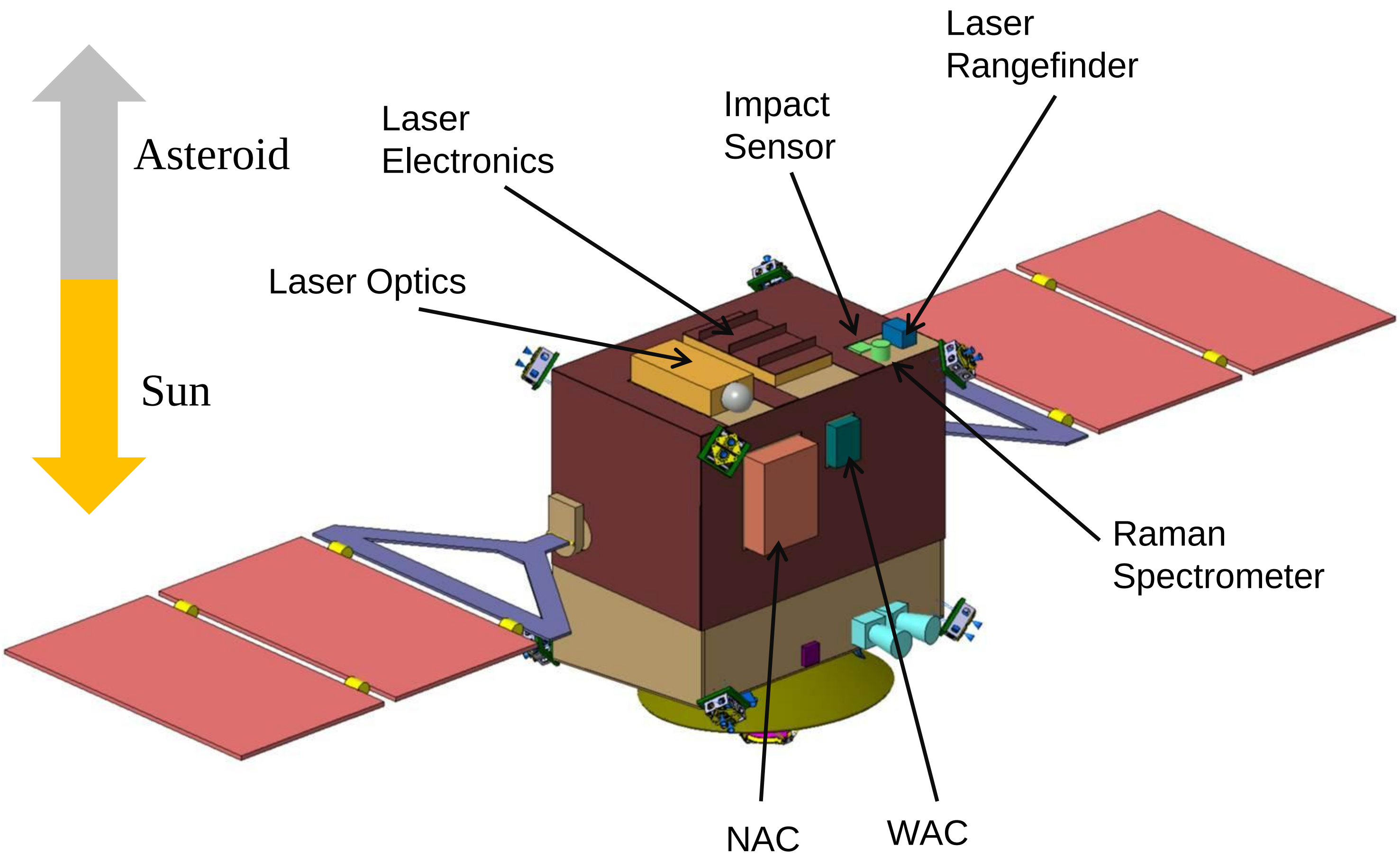
Power Budget

SysNova Power Budget	Current Power (W)	Design Maturity Margin (%)	Maximum Power (W)
Payload	895.0	19.7%	1071.0
GNC & AOCS	159.3	8.1%	172.2
Data Handling	46.9	11.0%	52.1
Power	0.0	0.0%	0.0
Communications	57.0	5.0%	59.9
Thermal	40.0	20.0%	48.0
Propulsion	0.0	0.0%	0.0
Total	**1198.2**	**17.1%**	**1403.1**
PCDU		10.0%	140.3
Harness		2.0%	28.1
Total Including PCDU and Harness			**1571.5**
System Power Margin		20.0%	**314.3**
Total Including 20% System Margin			**1885.8**

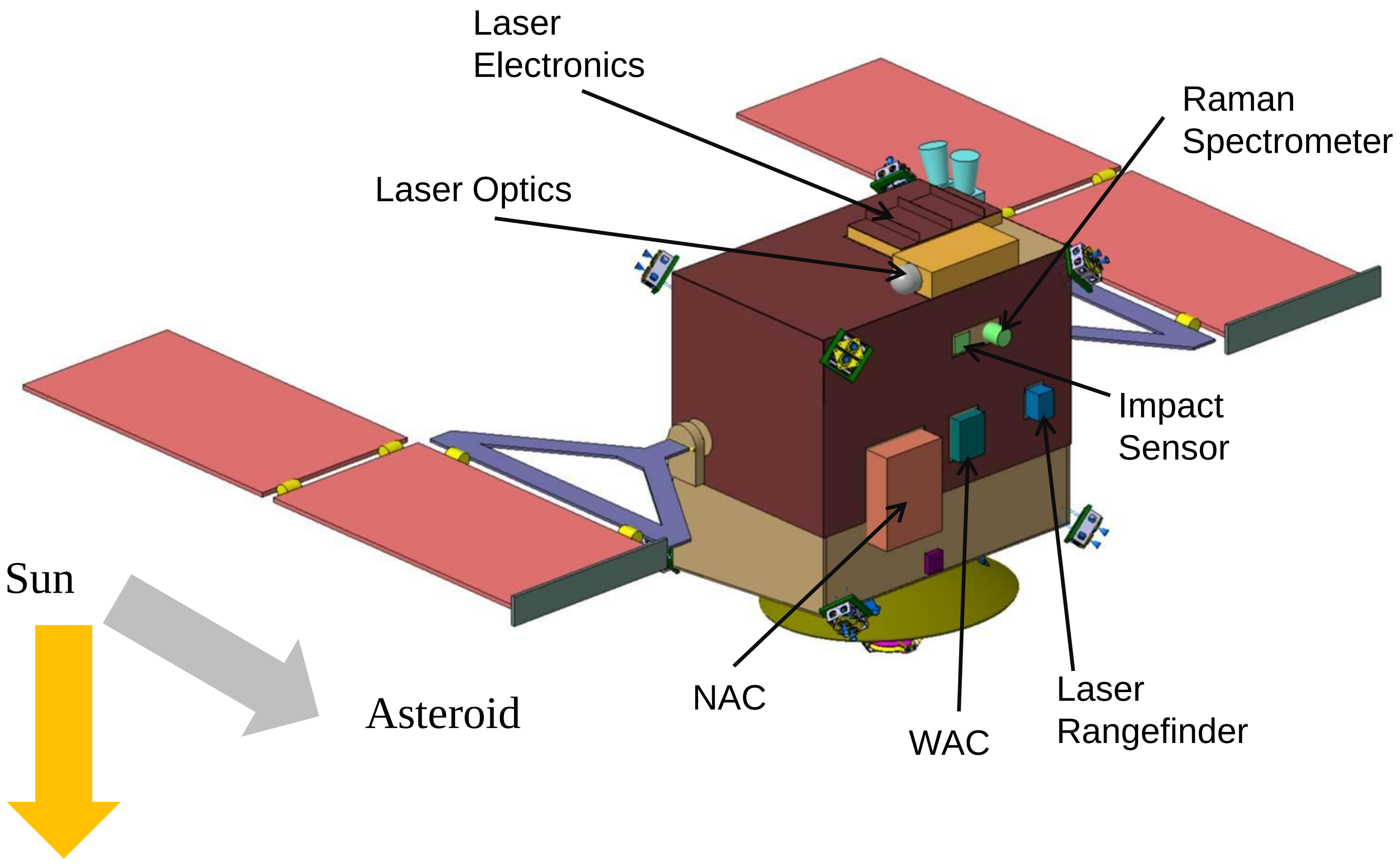
Downlink and Ground Segment

- Nominal science operations is the driving case with an 8 hour downlink once every 7 days
- Baseline system includes:
  - 1.3m X-band HGA
  - 160W Tx Output Power
  - 12m Rx antenna at Harwell
- Supports the required data rate of 23.5kbps at end of nominal operations
  - Link margin of 9.2dB
- Can also support the required data rate of 8kbps until the end of the 3 year mission lifetime
  - Link margin of 8.5dB

Radial Configuration



Trailing/Leading Configuration



Improved Solution

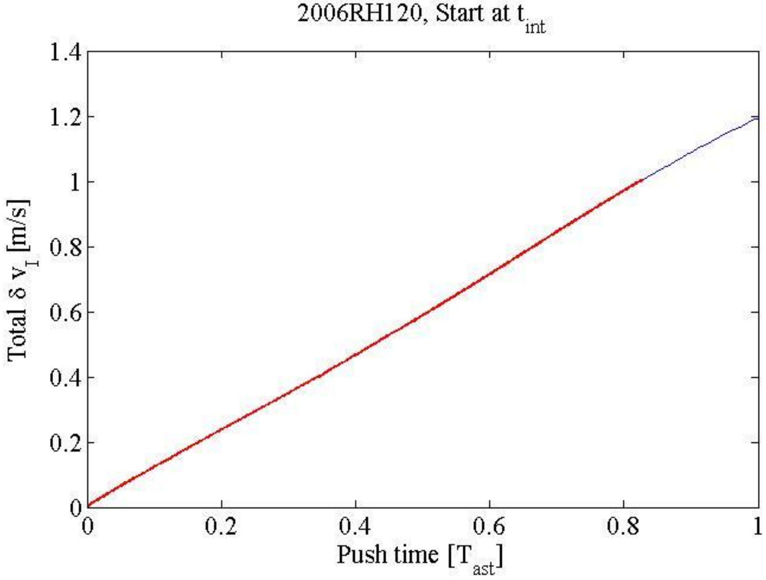
1. Low-mass low-power laser range finder instead of the LIDAR

2. Reduced power input to the laser down to 480W

3. Optimised spacecraft mass:
   a. Improved thermal system mass
   b. Improved structural mass
   c. Optimised propellant mass
   d. Improved power system mass

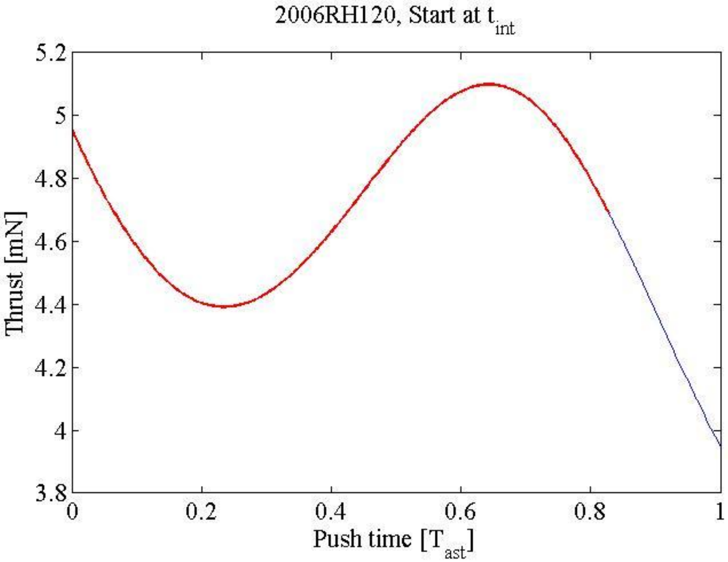
4. Same margin approach as for the second iteration

Improved Solution



A reduction in the input power to the laser leads to an increase of the deflection time to over 80% of the period of the asteroid.

The delivered thrust level fluctuates between 4 and 5.1 mN



Improved Solution

SysNova Mass Budget	Current Mass (kg)	Design Maturity Margin (%)	Maximum Mass (kg)
Data Handling Subsystem	17.1	10.9%	18.9
Power Subsystem	46.0	14.6%	52.8
Harness	25.8	20.0%	30.9
Communications Subsystem	37.7	8.8%	41.0
GNC & AOCS Subsystem	44.5	12.6%	50.0
Structure and Mechanisms	83.0	20.0%	99.6
Thermal Subsystem	12.4	20.0%	14.8
Propulsion Subsystem	59.9	12.3%	67.3
Payload	**20.0**	**19.0%**	**23.8**
SPACECRAFT DRY TOTAL			**399.2**
System Mass Margin		20%	79.8
DRY TOTAL (incl. System Margin)			**479.0**
Propellant			351.9
SPACECRAFT WET MASS			**831.0**
Launch Adapter			**0.0**
WET MASS + LA			**831.0**
Launch Vehicle Capability - PSLV XL GTO			**1074.0**
Launch Vehicle Margin - PSLV XL GTO			**243.0**
Mass Margin % - PSLV XL GTO			**22.6%**

Roadmap

Technology Readiness Level

PLATFORM	TRL	Heritage	Expected Modifications
Payload			
Laser	**3/4**	**Ground-based**	**Design and Space Qualification**
Laser Optics	**3/4**	**Ground-based**	**Design and Space Qualification**
Impact Sensor	5	Rosetta (GIADA payload)	Modification and Space Qualification
Raman Spectrometer	5	ExoMars	Modification and Space Qualification
Power Subsystem			
Solar Array Assembly	5	IMM Cells - E3000 development	Further Cell Development/Qualification
Whipple Shield	5	ISS and ATV derivative	Significant modification
GNC & AOCS Subsystem			
Narrow Angle Camera	4	MarcoPolo-R	Continued development
Laser Rangefinder	9	ARP, ATV, HTV	Not tested for non-collaborative target

Roadmap

Technology	TRL	Activity	Target Date
Laser system	TRL4	Lab demonstration of improved diode stack efficiency	2014
	TRL4	Coherent combining for high power high efficiency laser	2016
	TRL5/6	Lab space qualification of fibre-diode coupled laser (vacuum, thermal, radiation tests)	2018
	TRL6	In space testing of adaptive optics	2018
	TRL7/8	In-space testing of fibre-diode coupled system	2020
Ablation process	TRL4	Lab experiments and model completion for both ablation and contamination	2013
	TRL5/6	In Earth orbit demonstrator with dummy asteroid.	2020
	TRL7/8	Asteroid material extraction and analysis mission	2025
	TRL8/9	AdAM	2027
In-space OD	TRL3	Concept demonstrated in simulation environment	2012
	TRL7/8	Multi asteroid discovery and tracking mission	2024
	TRL8/9	AdAM	2027
In-space rotation estimation	TRL3	Concept demonstrated in simulation environment	2012
	TRL6/7	In Earth orbit demonstration with dummy asteroid or space debris	2020
	TRL7/8	Multi asteroid discovery and tracking mission	2024
	TRL8/9	AdAM	2027
In-space deflection estimation	TRL3	Concept demonstrated in simulation environment	2012
	TRL6/7	In Earth orbit demonstration with dummy asteroid or space debris	2020
	TRL7/8	Asteroid material extraction and analysis mission	2024
	TRL8/9	AdAM	2027

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www.stardust2013.eu

https://twitter.com/stardust2013eu

Questions?

Backup Slides

Back Up- Rotation Estimate FFT Approach

- Hirai et Al. 1998:

$$\mathbf{p}' = \mathbf{R}(\mathbf{k}_1, \theta_1)\mathbf{R}(\mathbf{k}_2, \theta_2)\hat{\mathbf{p}} + \mathbf{p}_0$$

$$\mathbf{p}' = \mathbf{a}\cos(\theta_1) + \mathbf{b}\sin(\theta_1) + \mathbf{c}\cos(\theta_2) + \mathbf{d}\sin(\theta_2) + \mathbf{e}\cos(\theta_1 + \theta_2) + \mathbf{f}\sin(\theta_1 + \theta_2)$$
$$+\mathbf{g}\cos(\theta_1 - \theta_2) + \mathbf{h}\sin(\theta_1 - \theta_2) + \mathbf{i}$$

$$\mathbf{a} = -C_1 C_2 \mathbf{k}_1 + C_3 \mathbf{k}_2 \qquad e = \{(1 + C_1)\hat{\mathbf{p}} + (C_1 C_3 - C_2)\mathbf{k}_1 - (C_2 + C_3)\mathbf{k}_2\}/2$$
$$\mathbf{b} = C_3(\mathbf{k}_1 \times \mathbf{k}_2) \qquad f = \{-C_4 \mathbf{k}_1 - C_3(\mathbf{k}_1 \times \mathbf{k}_2) + (\mathbf{k}_1 \times \hat{\mathbf{p}}) + (\mathbf{k}_2 \times \hat{\mathbf{p}})\}/2$$
$$\mathbf{c} = -(C_1 C_3 - C_2)\mathbf{k}_2 \qquad g = \{(1 + C_1)\hat{\mathbf{p}} + (C_1 C_3 - C_2)\mathbf{k}_1 + (C_2 - C_3)\mathbf{k}_2\}/2$$
$$\mathbf{d} = C_4 \mathbf{k}_1 \qquad h = \{C_4 \mathbf{k}_1 - C_3(\mathbf{k}_1 \times \mathbf{k}_2) + (\mathbf{k}_1 \times \hat{\mathbf{p}}) - (\mathbf{k}_2 \times \hat{\mathbf{p}})\}/2$$

$$\mathbf{i} = C_1 C_3 \mathbf{k}_1 + \mathbf{p}_0$$
$$C_1 = \mathbf{k}_1{}^T \mathbf{k}_2$$
$$C_2 = \mathbf{k}_1{}^T \hat{\mathbf{p}}$$
$$C_3 = \mathbf{k}_2{}^T \hat{\mathbf{p}}$$
$$C_4 = \mathbf{k}_1{}^T (\mathbf{k}_2 \times \hat{\mathbf{p}})$$

- a, b, .,.,i can be obtained from the Fourier transform of the time sequence data of p’

$$f_1 -> \mathbf{a} = 2/N\,\mathrm{Re}[P(f_1)] \qquad f_2 -> \mathbf{c} = 2/N\,\mathrm{Re}[P(f_1)] \qquad \mathbf{i} = 1/N \cdot P(0)$$
$$f_1 -> \mathbf{b} = -2/N\,\mathrm{Im}[P(f_1)] \qquad f_2 -> \mathbf{d} = -2/N\,\mathrm{Im}[P(f_1)]$$
$$f_1 + f_2 -> \mathbf{e} = 2/N\,\mathrm{Re}[P(f_1 + f_2)] \qquad |f_1 - f_2| -> \mathbf{g} = 2/N\,\mathrm{Re}[P(|f_1 - f_2|)]$$
$$f_1 + f_2 -> \mathbf{f} = -2/N\,\mathrm{Im}[P(f_1 + f_2)] \qquad |f_1 - f_2| -> \mathbf{h} = -2/N\,\mathrm{Im}[P(|f_1 - f_2|)]$$

- Spin axes $\mathbf{k}_1$ $\mathbf{k}_2$ and centre of gravity $\mathbf{p}_0$

$$\mathbf{k}_1 = \frac{\mathbf{e} \times \mathbf{f}}{|\mathbf{e}|^2}$$

$$\mathbf{k}_2 = \frac{(\mathbf{e} + \mathbf{g} + \mathbf{c}) \times (\mathbf{f} - \mathbf{h} + \mathbf{d})}{|\mathbf{e} + \mathbf{g} + \mathbf{c}|^2}$$

$$\mathbf{p}_0 = \frac{(\mathbf{k}_1 \times \mathbf{k}_2)^T \times (\mathbf{a} \times \mathbf{k}_1)}{|\mathbf{e}|^2}\mathbf{k}_2 + \mathbf{a} + \mathbf{i}$$

Back Up- Proximity navigation and control

- Angular velocity

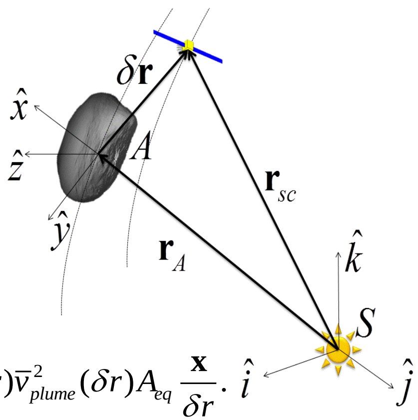
$$\mathbf{x}_{r_a} \times (\ddot{\mathbf{v}} \times \mathbf{x}_{r_a}) + 2\dot{\mathbf{x}}_{r_a} \times (\dot{\mathbf{v}} \times \mathbf{x}_{r_a}) = \mathbf{x}_{r_a} \times \mathbf{a}_{laser-local}$$

- Potential from ellipsoid body

$$U_{20+22} = \frac{\mu_A}{\delta r^3}\left(C_{20}(1 - \frac{3}{2}\cos^2\gamma) + 3C_{22}\cos^2\gamma\cos 2\lambda\right)$$

$$C_{20} = -\frac{1}{10}(2c_l^2 - a_l^2 - b_l^2)$$

$$C_{22} = \frac{1}{20}(a_l^2 - b_l^2)$$

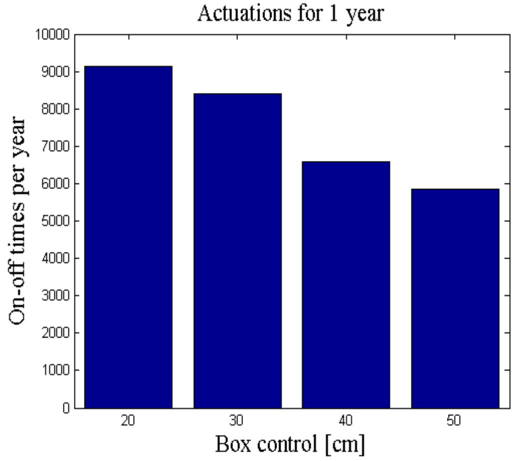


- Perturbative forces

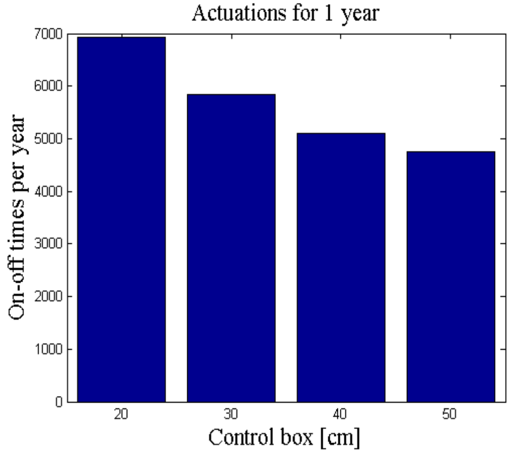
$$F_{Solar} = C_R S_{srp}\left(\frac{r_{AU}}{r_{sc}}\right)^2 A_M \frac{\mathbf{x}_a}{r_{Sc}}; \quad F_{recoil} = \eta_{sys} S_{srp}\left(\frac{r_{AU}}{r_{sc}}\right)^2 A_M \frac{\mathbf{x}}{\delta r}; \; F_{plume} = \rho_{plume}(\delta r)\bar{v}^2_{plume}(\delta r) A_{eq}\frac{\mathbf{x}}{\delta r}.$$

- Number of actuations

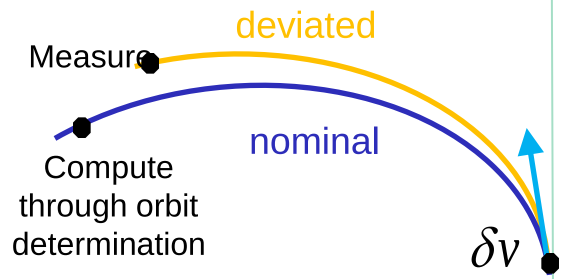
Trailing Configuration



Radial Configuration



Back Δv imparted onto the asteroid



- Gauss' equations

$$\delta a = \frac{2a^2 v}{\mu}\delta v_t$$

$$\delta e = \frac{1}{v}\left[2\left(e+\cos f\right)\delta v_t - \frac{r}{a}\sin f\,\delta v_n\right]$$

$$\delta i = \frac{r\cos\vartheta}{h}\delta v_h$$

$$\delta\Omega = \frac{r\sin\vartheta}{h\sin i}\delta v_h$$

$$\delta\omega = \frac{1}{ev}\left[2\sin f\,\delta v_t + \left(2e+\frac{r}{a}\cos f\right)\delta v_n\right] - \frac{r\sin\vartheta\cos i}{h\sin i}\delta v_h$$

- Variation in mean anomaly

$$\delta M = \overbrace{-\frac{b}{eav}\left[2\left(1+\frac{e^2 r}{p}\right)\sin f\,\delta v_t + \frac{r}{a}\cos f\,\delta v_n\right]}^{\text{through Gauss' equations}} \overbrace{+\Delta n\left(t_{MOID}-t_d\right)}^{\text{due to a variation in a}}$$

Back Δv imparted onto the asteroid

$$\begin{cases} \delta r\left(t_{measure}\right) = A_{\text{measure nominal}}\,\delta\alpha\left(t_{d-measure}\right) \\ \delta\alpha\left(t_{d-measure}\right) = G_d\,\delta v\left(t_d\right) \end{cases}$$

Proximal motion between nominal and deviated

Gauss' equations (also orbit perturbation can be included)

$$\delta r\left(t_{measure}\right) = T\,\delta v\left(t_d\right)$$

$$\delta v\left(t_d\right) = T^{-1}\,\delta r\left(t_{measure}\right)$$

Measure position displacement

Get Δv

Absolute error on the measurement of the velocity imparted onto the asteroid (mean and standard deviation in m/s).

	OD after 30 days	OD after 60 days	OD after 90 days
Error 1	0.025899 ±0.001112	0.06877 ±0.00071162	0.12086 ±0.00053259
Error 2	0.028674 ±0.0026812	0.069602 ±0.0014648	0.12194 ±0.0011782
Error 3	0.077114 ±0.015354	0.087915 ±0.010835	0.13626 ±0.012386
Error 4	0.035589 ±0.006973	0.074227 ±0.0032254	0.12588 ±0.0024126

GNC-Estimating Δv imparted onto the asteroid

- Augmented state vector $[x, y, z, v_x, v_y, v_z, a_{laser}, a_{plume}]$
- Acceleration considered as bias (no time variation)

$$\dot{a}_{laser} = 0 + v_{laser}$$
$$\dot{a}_{plume} = 0 + v_{plume}$$

Why not Electric Propulsion from GTO?

- Moderate Mission ΔV from GTO of ~1.4km/s
  - Propellant savings from EP are not compelling
- Only have 3 years in total for SySNOVA:
  - EP for escape incurs a time and significant Δv penalty
  - Mass penalty for high thrust & power for rapid escape
- Every orbit in GTO passes through radiation belts
  - Need to escape quickly or accept high radiation dose
  - Mass (for faster escape) or Cost (radiation) penalty
- All up EP (for transfer & AOCS) is heavy & expensive
  - Separate EP (for transfer) & chemical RCS is inefficient and still expensive
- A combined CPS is significantly cheaper and simpler than EPS options

Why not LEO?

- PSLV to LEO also considered
    - Total available mass of 789-3760kg dependent on altitude and inclination of orbit
- The LISA PRM could be used in 2 ways:

1. To provide all of the Δv to escape
    - Would need significant modification to accommodate fuel mass
2. To provide as much Δv as possible with no modification with spacecraft providing remainder
    - Spacecraft mass is potentially over the design limit of PRM, again requiring modifications

Why not LEO?

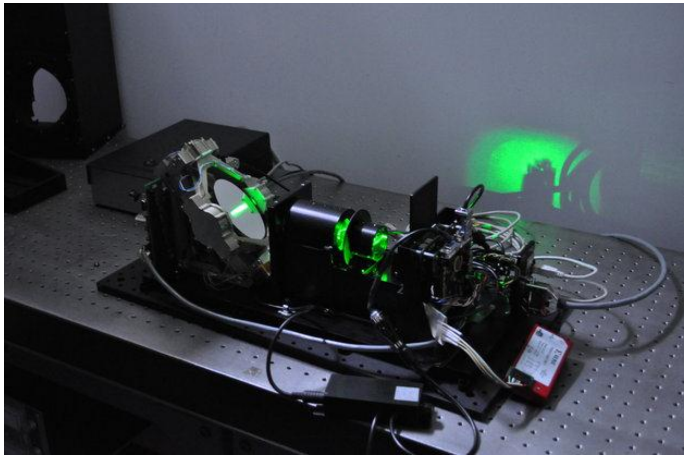
- Escaping from LEO with a solid motor was also considered
- Several issues were identified
- No European solid motor exists
    - American solid motor would need to be used
- No European heritage for the use of solid motors
- Significant additional mass would be required
    - Structure between solid motor and spacecraft
    - Spin table
- Further unknown complexities that add mass

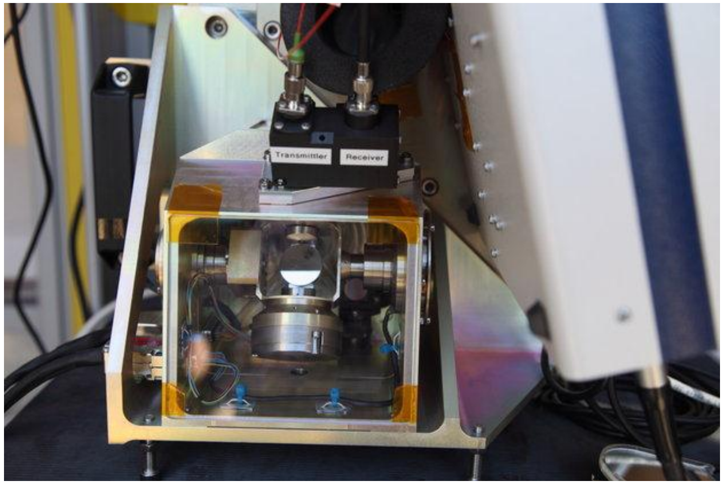
PSLV XL Mass Budget

SysNova Mass Budget	Current Mass (kg)	Design Maturity Margin (%)	Maximum Mass (kg)
Data Handling	17.1	10.9%	18.9
Power	68.8	16.4%	80.1
Communications	37.7	8.8%	41.0
GNC & AOCS	39.5	7.9%	42.5
Structure and	100.0	20.0%	120.0
Thermal	13.0	20.0%	15.6
Propulsion	59.9	12.3%	67.3
Payload	**35.5**	**19.4%**	**42.4**
SPACECRAFT DRY TOTAL	**371.4**	**15.2%**	**427.9**
Harness	30.0	20.0%	35.9
DRY TOTAL (incl. Harness)			**463.8**
System Mass Margin		20.0%	92.8
DRY TOTAL (incl. 20% System Margin)			**556.6**
Propellant			442.2
SPACECRAFT WET MASS			**998.8**
Launch Vehicle Capability - PSLV GTO			**1074.0**
Launch Vehicle Margin - PSLV GTO			**75.2**
Mass Margin % - PSLV GTO			**7.0%**

Laser Range Finder

- ESA ILT – undergoing programmes miniaturization of LIDAR technology – Jena Optroniks and ABSL





- Roadmap

Δ in ILT (LRF-only) → Ground test on non-collaborative target (asteroid mockup)

prototype → Ground test in GNC system (PLATFORM)

Δdevelopment of fligh model → Debris Removal Mission

Roadmap

- LRF
  - BB Model tested
  - Range (at 5000 Km)
  - Accuracy <10 cm
  - Scanning and processing are the heavy/power-hungry
  - Sensor head 1.7 Kg
  - Power (30 W) – moving mirror

- Jena ILT Tested in GNC testbed in real time with FF Algorithms (PLATFORM)

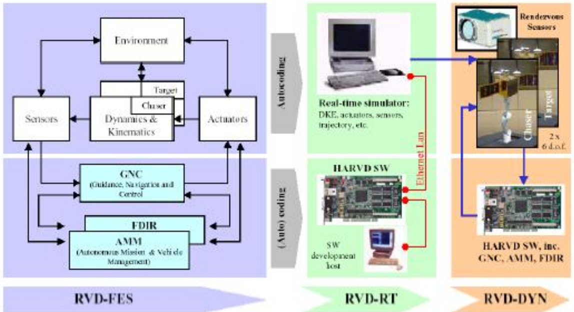


Figure 9. HARVD development and validation environments


Figure 11. Sensors mounted on the mock-up

Roadmap for GNC technology maturation

- Optical Navigation
  - Proba-3 (main system and RV experiments), Rosetta experience
- LRF
  - ILT, Prototype, test with PLATFORM
  - 2013 – 4 developments in Europe (GSTP Debris Removal, Science – Marco Polo (hayabusa-like 3 beams), ABSL, NEPTEC? still developing for Lunar Lander, DLR supporting qualification of Jena's RVS
- GNC algorithms for RV / Asteroid state identification / FEIC
  - Virtual simulations (PANGU) , tests with PLATFORM
- Test of full system in orbital debris removal

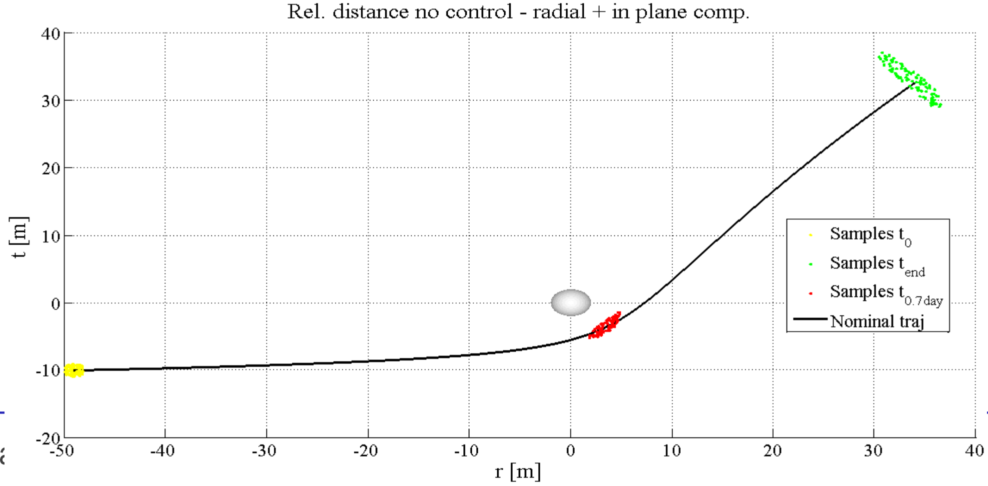
Autonomy

- Autonomous GNC reduced to a minimum – NO AutoNAV!
  - NO autonomous detection, NO autonomous GNC up to 10 Km, Hold Points, Modular Design
- Imperative for Station Keeping (non-stabe station keeping point)
- Same algorithms and techniques widely used for Pointing (Attitude Control)
- GNC for Close Approach (<10 Km)
  - 6 days
  - Hold Points waiting for "Go" from ground
  - Quick response is needed for safety (SRP moves SC 5 Km in 3 days)
  - Final segment is supervised from ground
  - Heritage of procedures from PROBA; ATV

Collision Avoidance

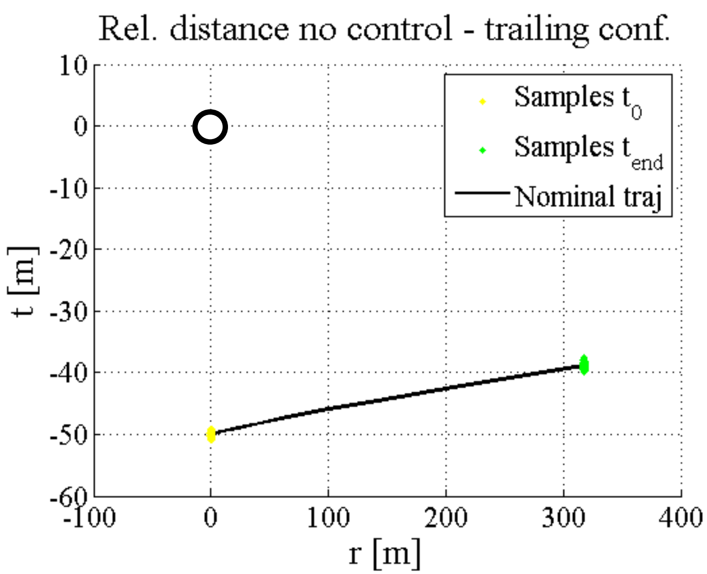
- Not a typical NEO mission
  - Gravity pull from asteroid < 2 μN
  - SRP ~40 μN
  - **Collision Avoidance Design – SC is 10 m offset to asteroid's orbital plane**
    - (offset has negligible effect of <1 pN due to differential gravity)
- Larger Concerns:
  - Evaporation
  - No illumination angle (SC is pushed to the dark side of the asteroid)
- This happens only in case of failure (FDIR field)

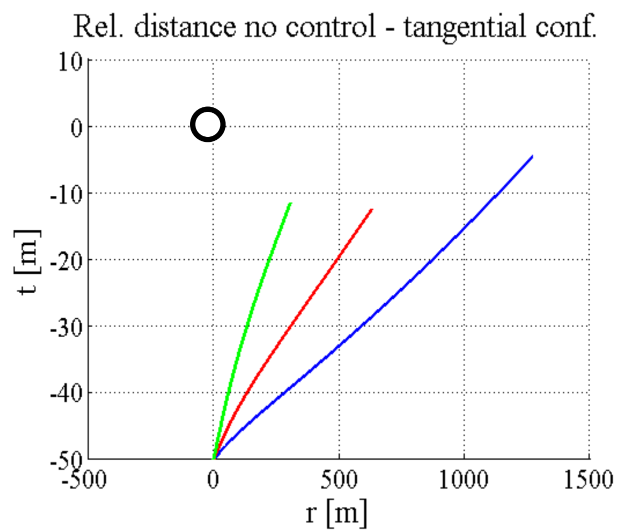
- **Passive Safety – Worst case – loss of control (position, attitude, tumbling)**

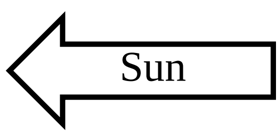


Trailing Configuration

- No Collision – Safe with 25% to 100% SRP , 2 day propagation

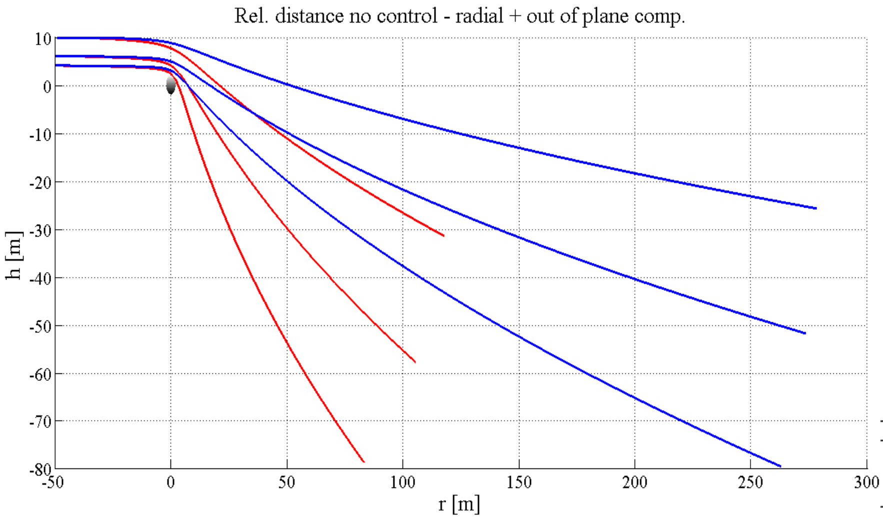


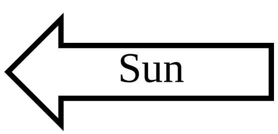


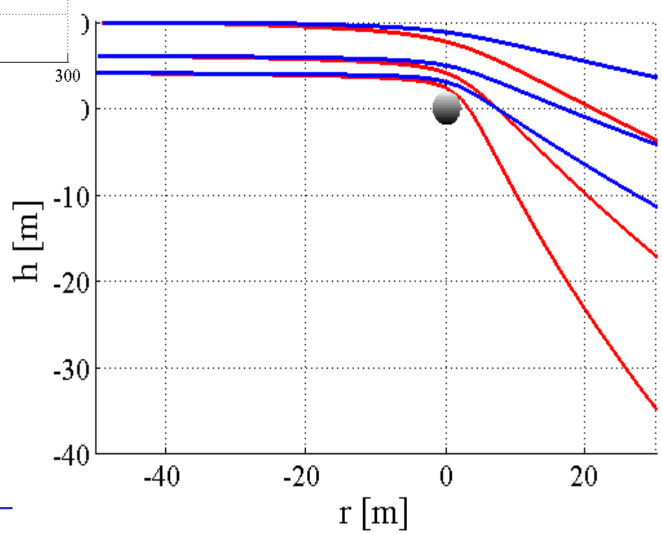


Radial Configuration Configuration

- No Collision – Safe with 25% to 100% SRP
- Safe with offset of 10 meters

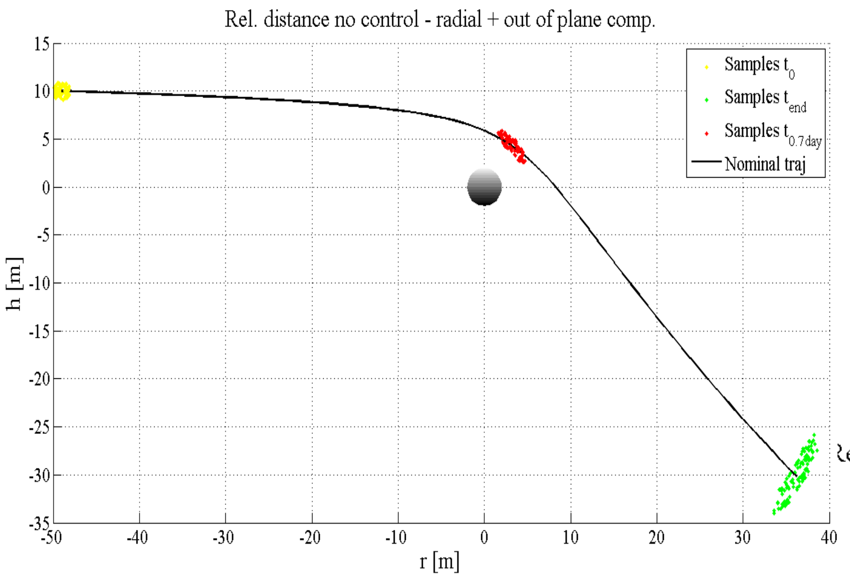


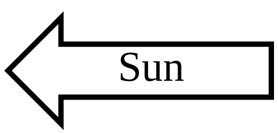


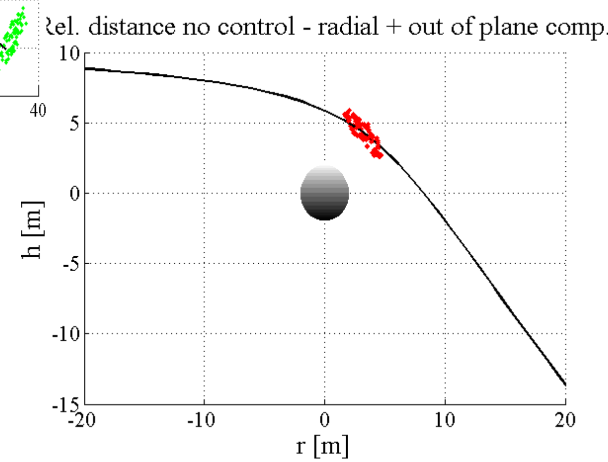


Radial Configuration Configuration

- Worst case – error in position Δposition = 1m . Δvelocity = 1 mm/s, 25% SRP







CEAM / FDIR

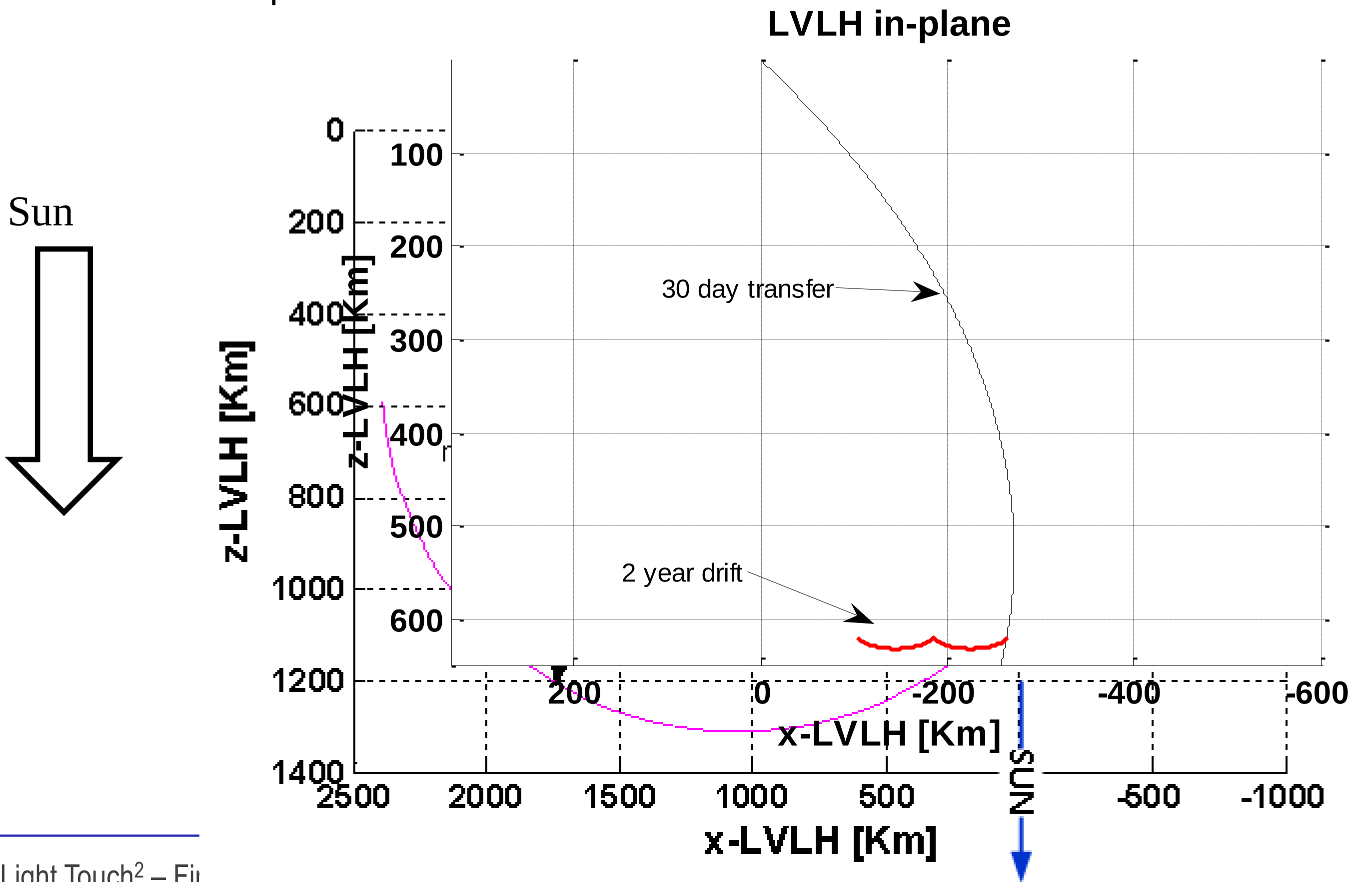
- Detection of failure / Contingency
  - Fault/Failure in component detected by component (hardware) – sensor actuator – failure flag
  - Incoherent measurements/data detected in cross-checking (pre-processing) in the GNC chain
  - Contingency – raw algorithms for CAEM
    - LRF raw measurement exceeds limit
    - SC spans more than 10000 pixels in WAC
  - Contingency – GNC solution shows phase angle >30 deg (radial) or > 120 (trailing)

- Classification → Contingency plan / FDIR
  - No failures, immediate recovery to operational conditions
  - Supervised recovery (boost in Sun direction - 3 days safe, 14 days safe), send to further away SK
  - Safe mode with 3 months of opportunity
  - Safe mode to equilibrium point
  - Worst-Case – Attitude Control with RCS, Sun-Pointing, Boost of towards* Sun

Safe Hold Points

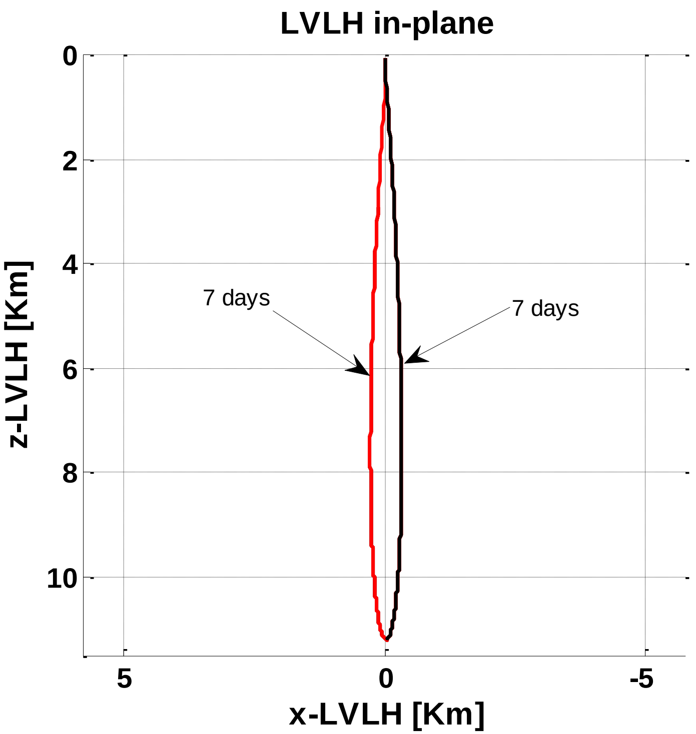
- No terminator Orbits – asteroid gravity << SRP
- No stable orbits due to SRP

- However, **~615 Km** distance, gravity gradient balances SRP
- In case of failure ~0.4 m/s boost brings SC in 30 days to point where breaking leaves the SC in an equilibrium orbit with little drift.



Non-Critical CEAM - Reconfiguration

- Hops – 50 mm/s provides 14 days for diagnostic/reconfiguration



- Pure CEAM (no failure) -> 3 day hop
- Failure in redundant system (eg LRF) - > Reconfiguration (ranging from camera) 14 day hop
- Failure in Critical system (eg Attitude Control, RCS) -> 300 mm/s hop to SAFE orbit