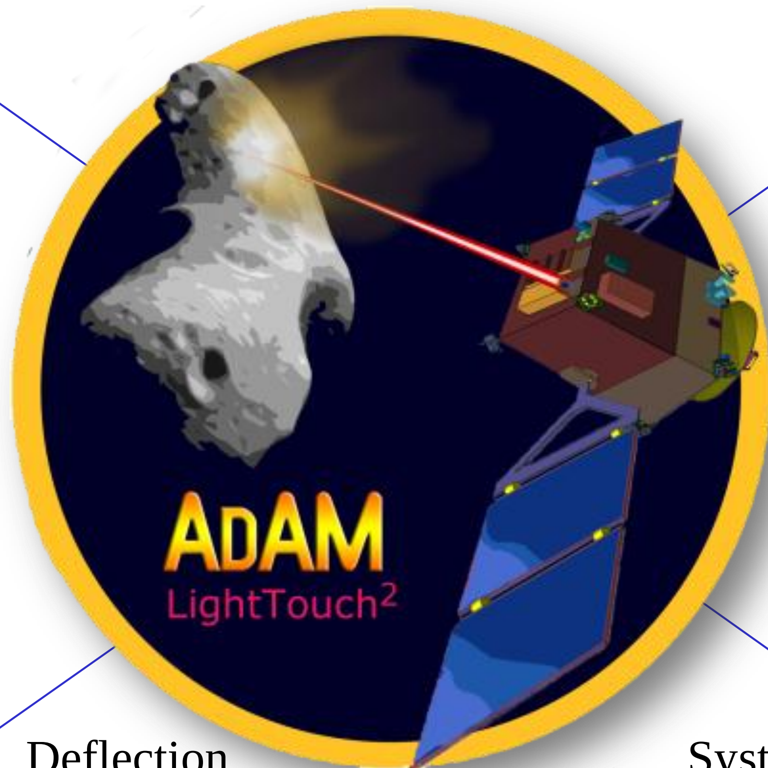
Light Touch^2

University of Strathclyde Glasgow

gmv INNOVATING SOLUTIONS

Joao Branco
GMV SKY-P, Portugal

GNC



Concept

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

Deflection

System

UNIVERSITY OF Southampton

Camilla Colombo
University of Southampton, UK

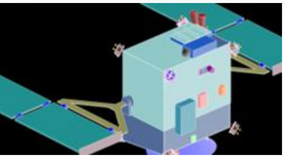
ASTRIUM AN EADS COMPANY

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

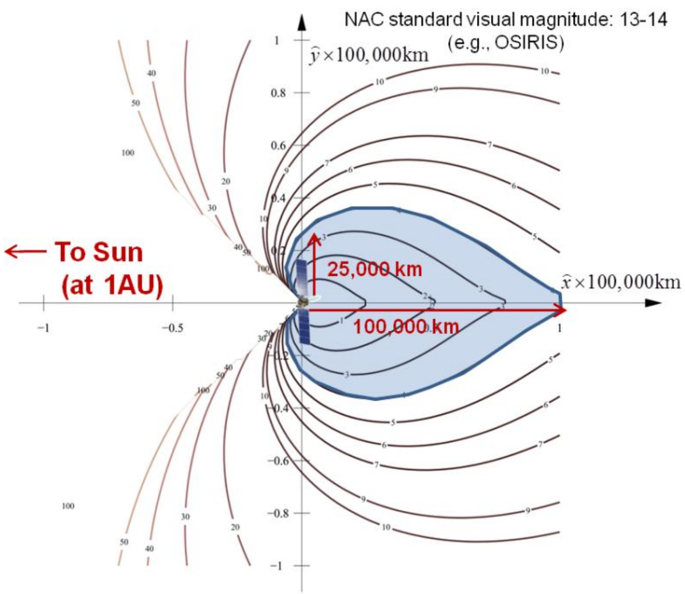
Target

- 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



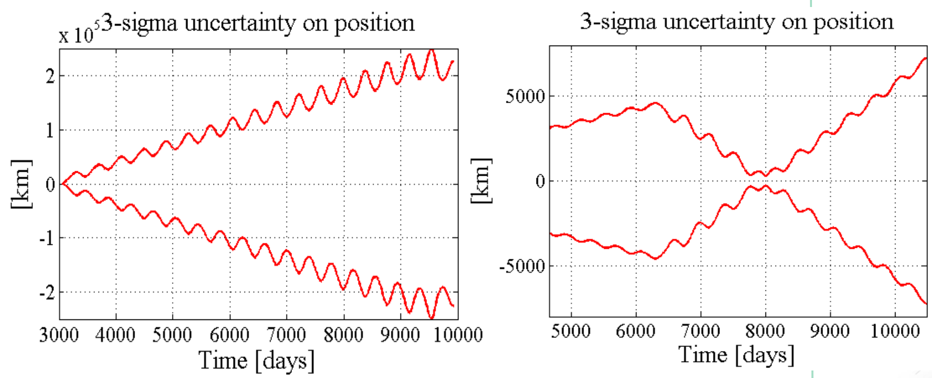
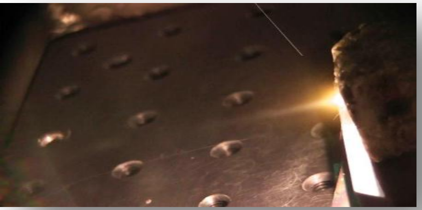


Fig: Uncertainty in asteroid position for 2008 JL24 (left) and 2006 RH120 (right) as a function of time (MJD2000).

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: $\bar{v} = \sqrt{\frac{8k_bT_s}{\pi M_a}}$

- 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:

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

University of Strathclyde

UNIVERSITY OF Southampton

gmv INNOVATING SOLUTIONS

ASTRIUM AN EADS COMPANY

ADAM LightTouch²

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:

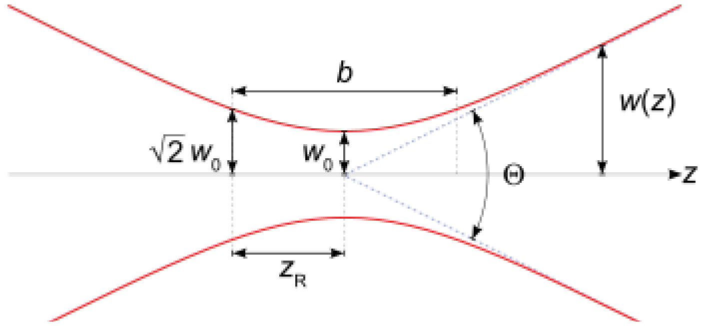
$$\frac{dh}{dt} = \frac{2\bar{v}\rho}{\rho_l}\cos\psi_{vf}$$

- Beer–Lambert law for light absorption:

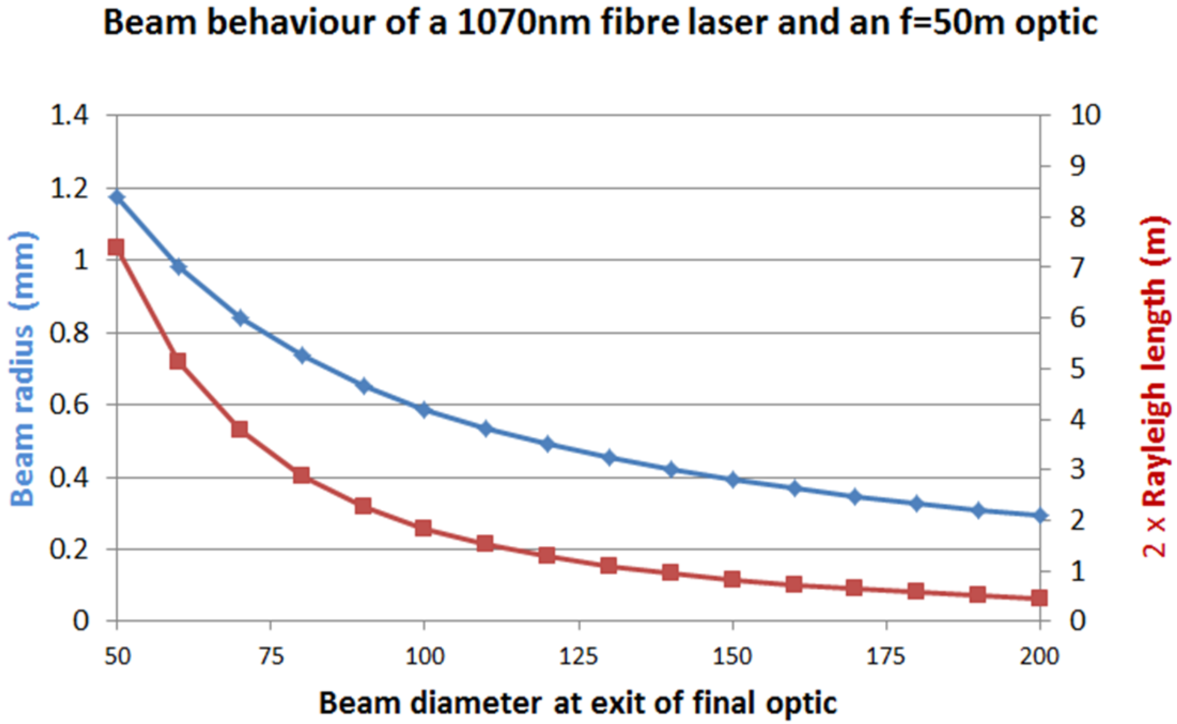
$$\tau = e^{-2\eta h}$$

- Key coefficients experimentally derived using asteroid analogous materials

Focusing and Beam Control

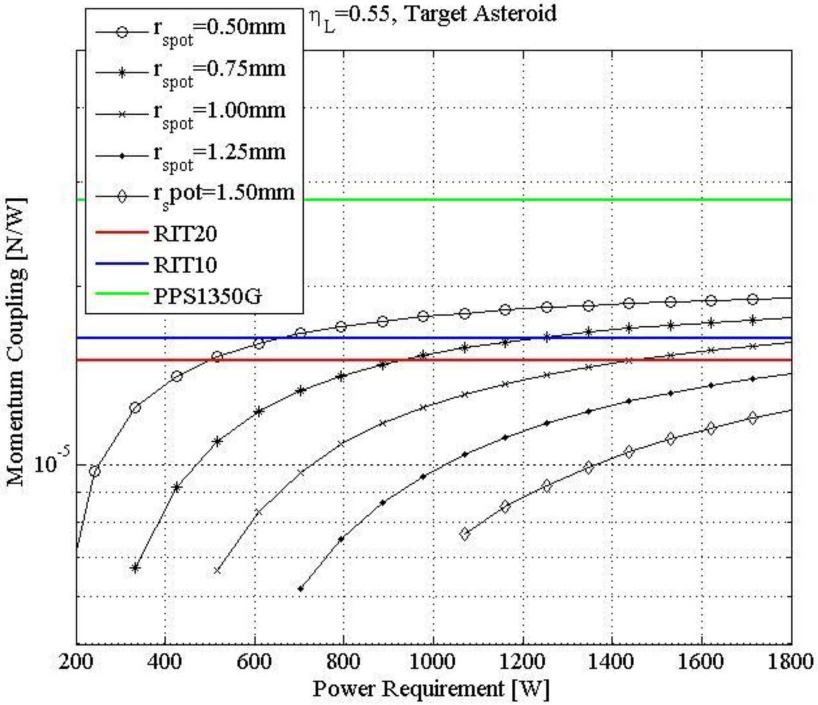


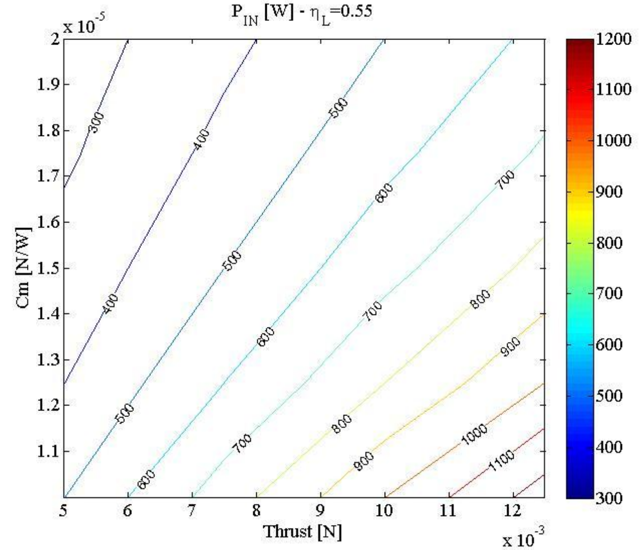
$$z_R = \frac{\pi w_0^2}{\lambda_b}$$

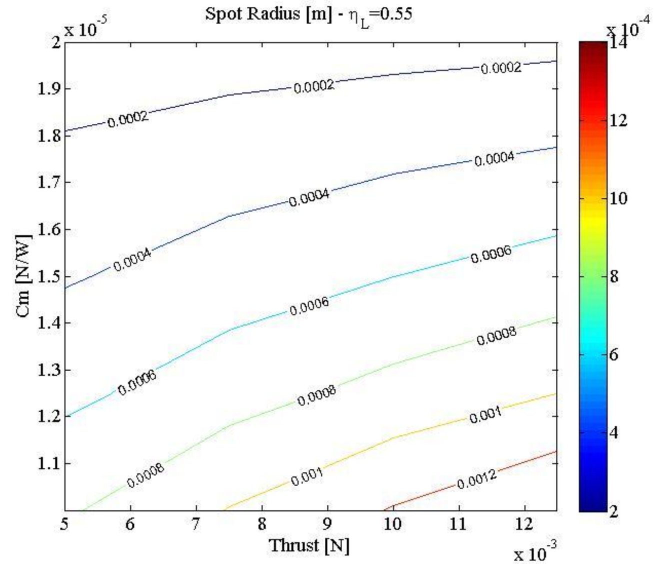


Momentum Coupling

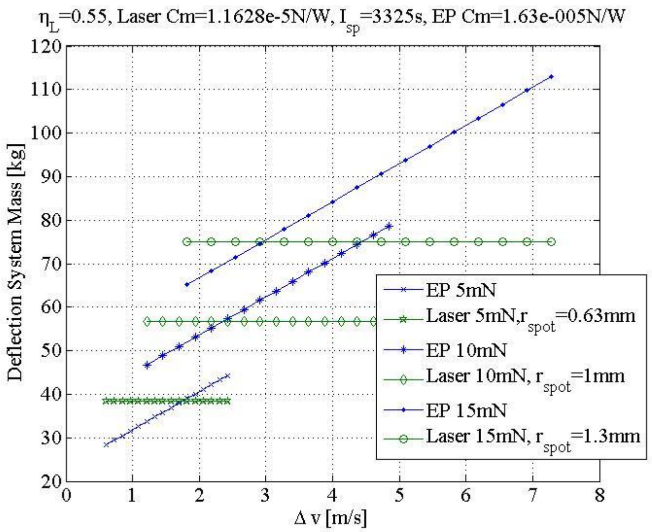
$$C_m = \frac{F_{sub}}{P_{IN}} \qquad P_{IN} = \tau \eta_P \eta_S \frac{P_{1AU} A}{R_{AU}^2}$$

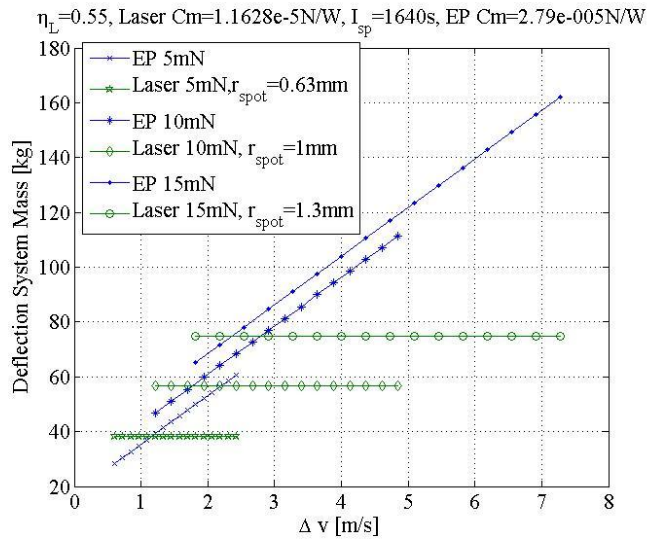


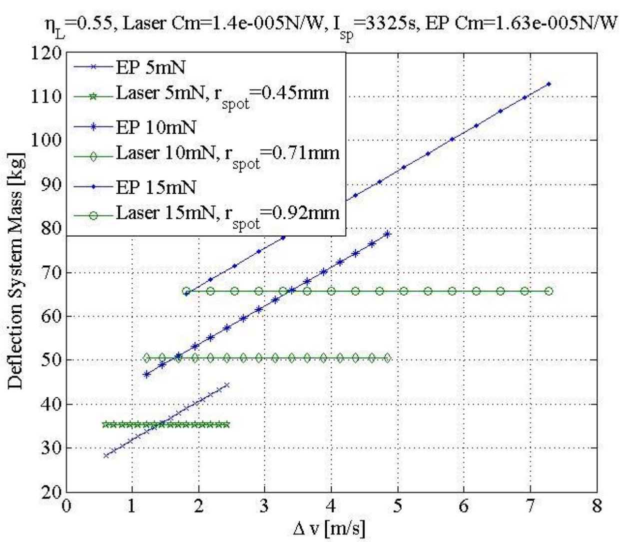


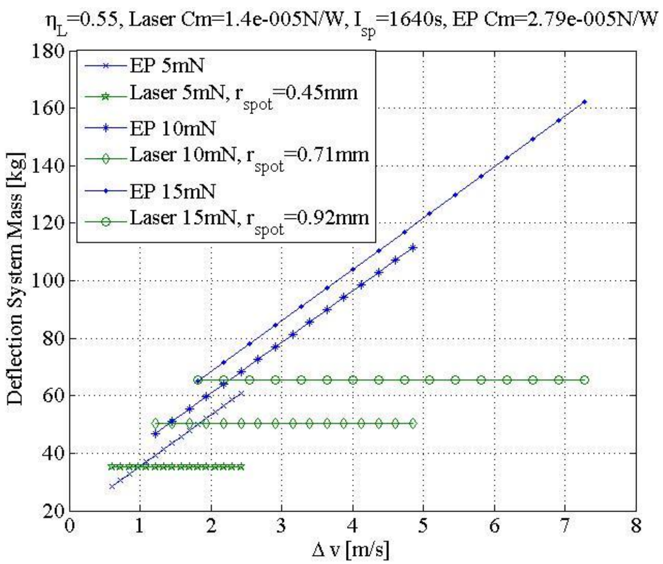


Mass Efficiency









University of Strathclyde

University of Southampton

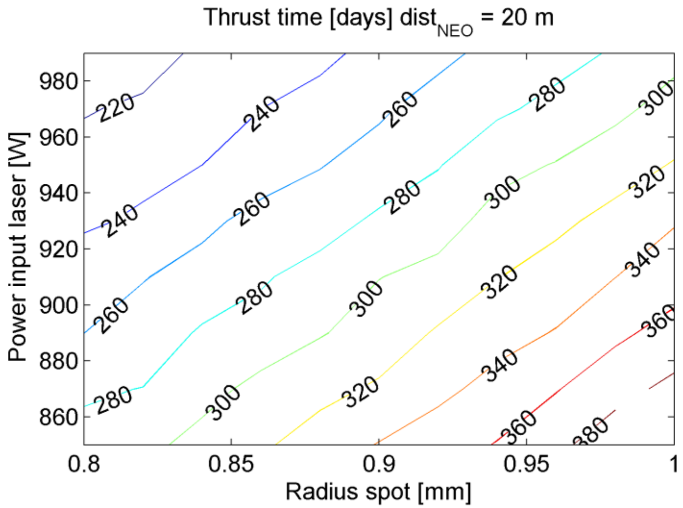
gmv INNOVATING SOLUTIONS

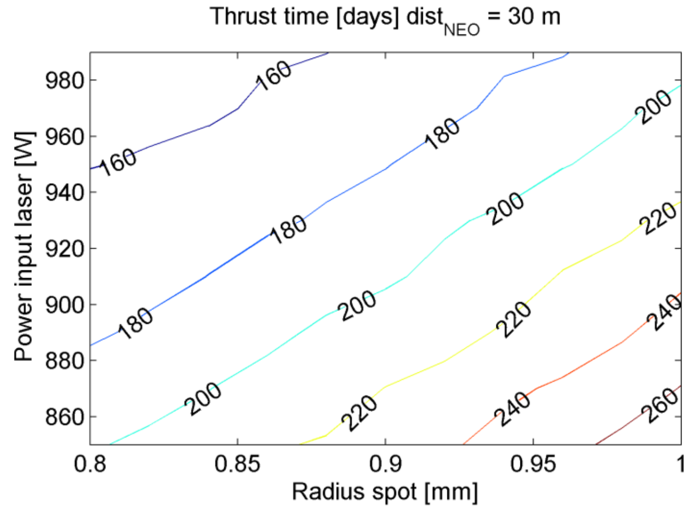
ASTRIUM AN EADS COMPANY

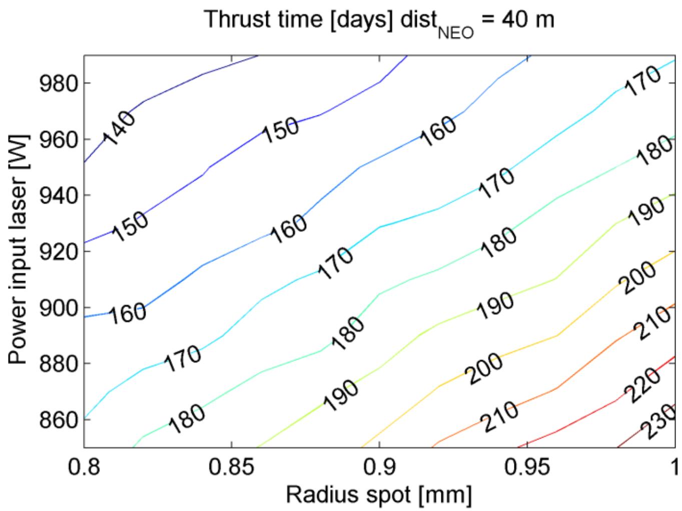
ADAM LightTouch^2

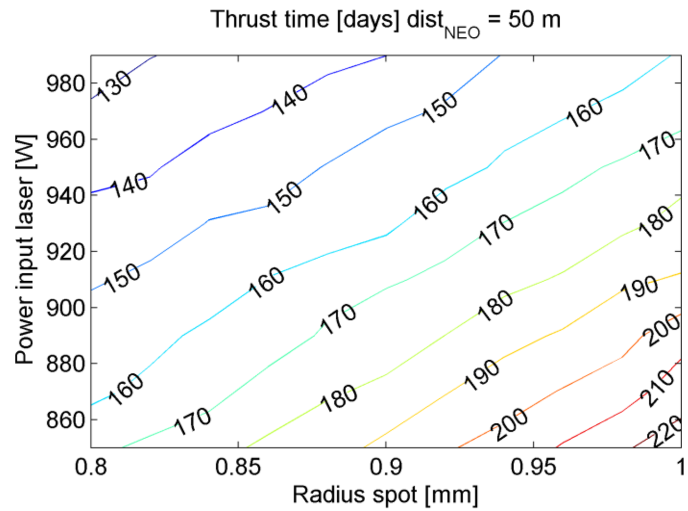
Efficiency analysis

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



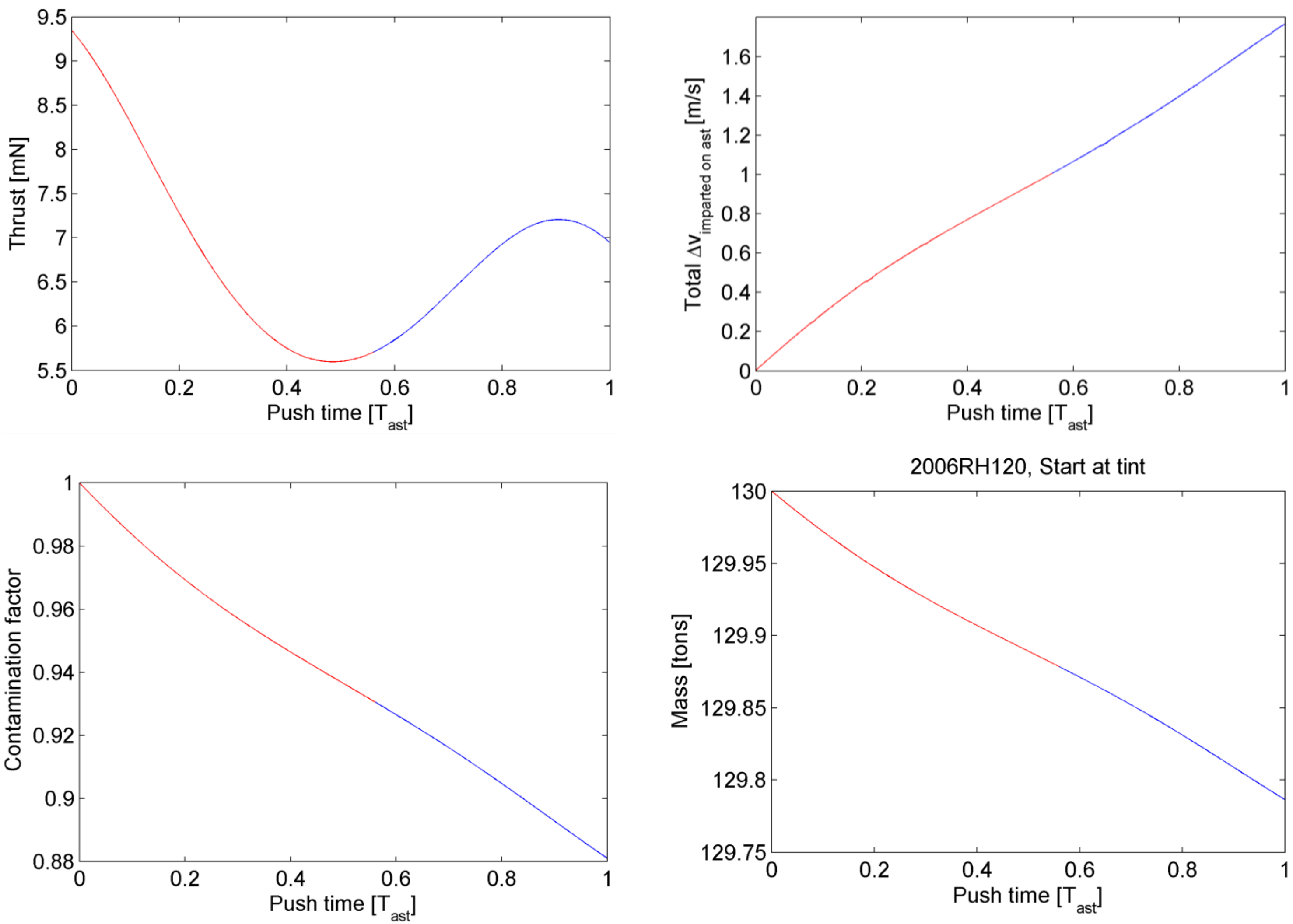






Deflection Result

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



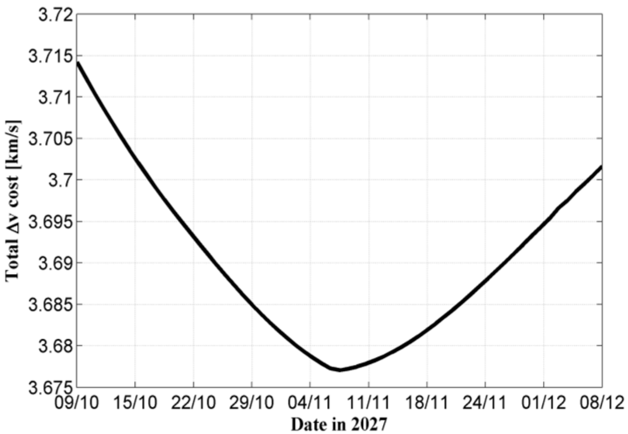
Mission, Control, Navigation

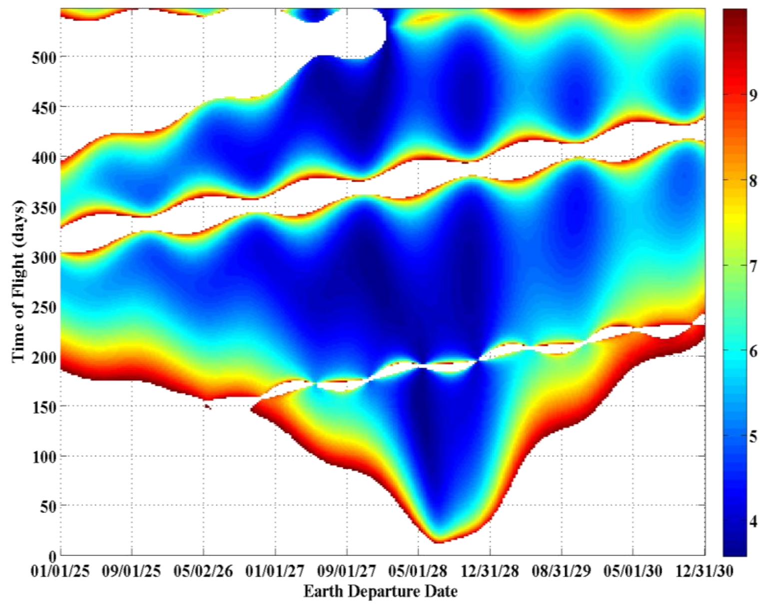
Mission: Interplanetary Trajectory and LW

- 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





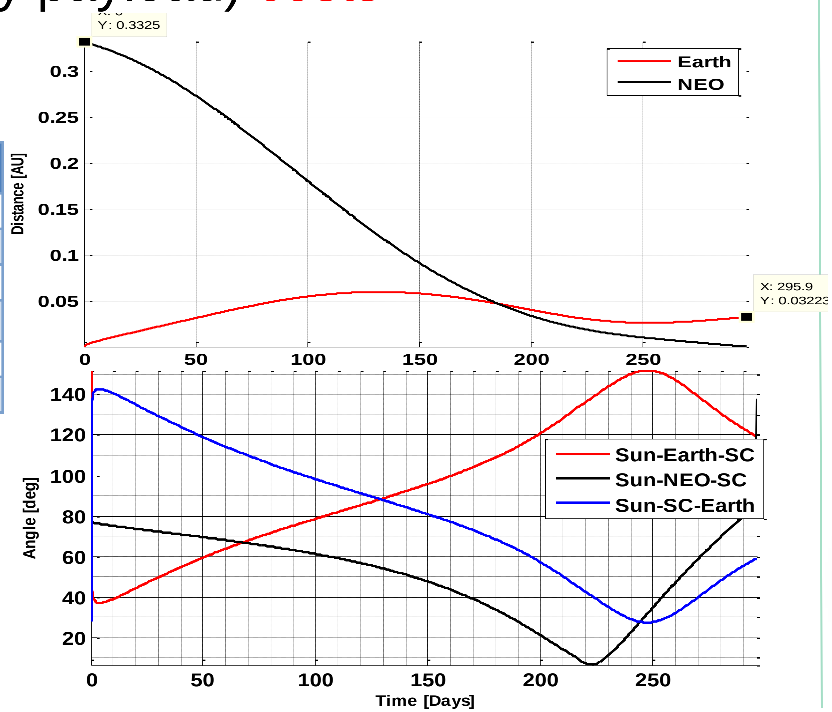
Mission: Launcher & Propulsion Trade-off

- 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

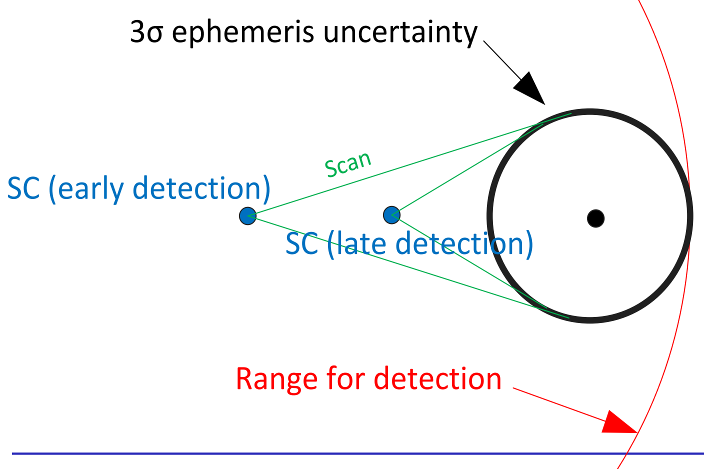
- NEO Mission
  - References - Hayabusa, Marco Polo, Rosetta, NEAR, Stardust
  - Relies heavily in optical navigation
  - Dynamics – 3 body problem, SRP, asteroid rotation,
  - Need for combined approach strategy definition and GNC analysis
- AdAM
  - 2006RH120 is approximately 4 m diameter, 130 Ton, 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)

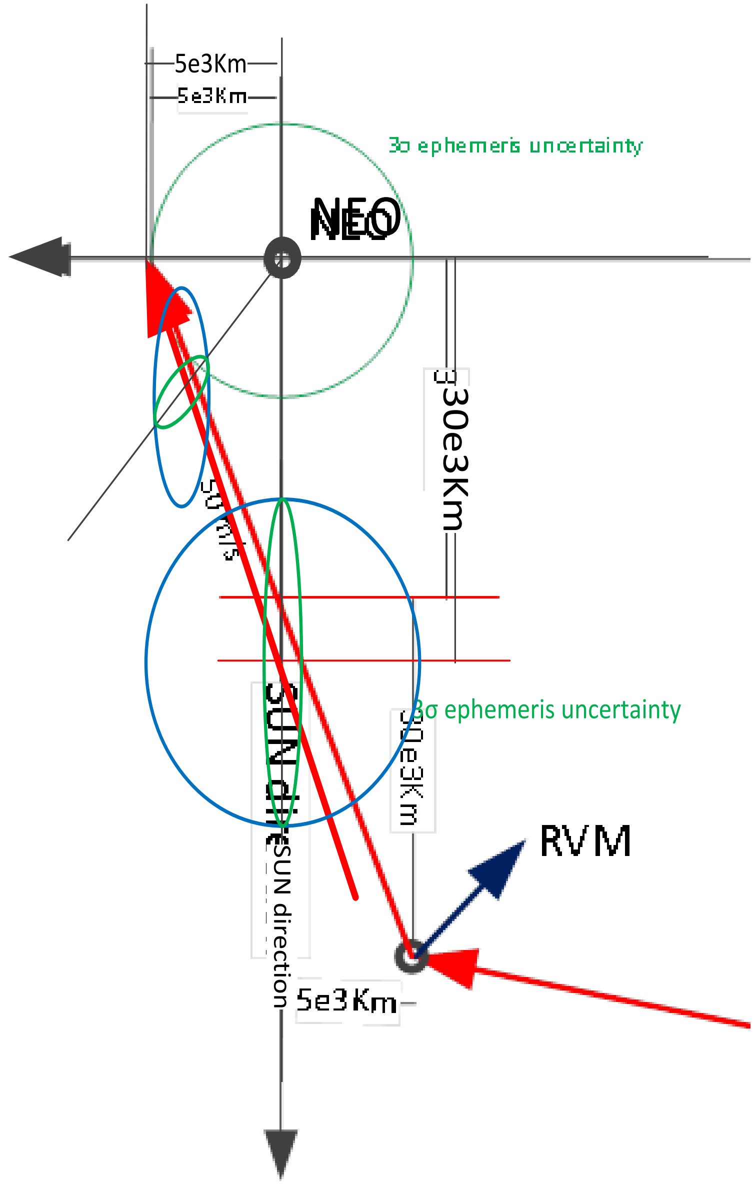
GNC Strategy

- **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

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

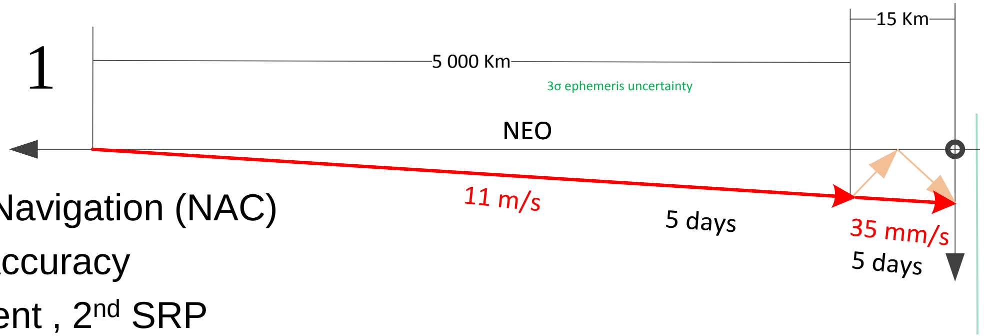




Approach

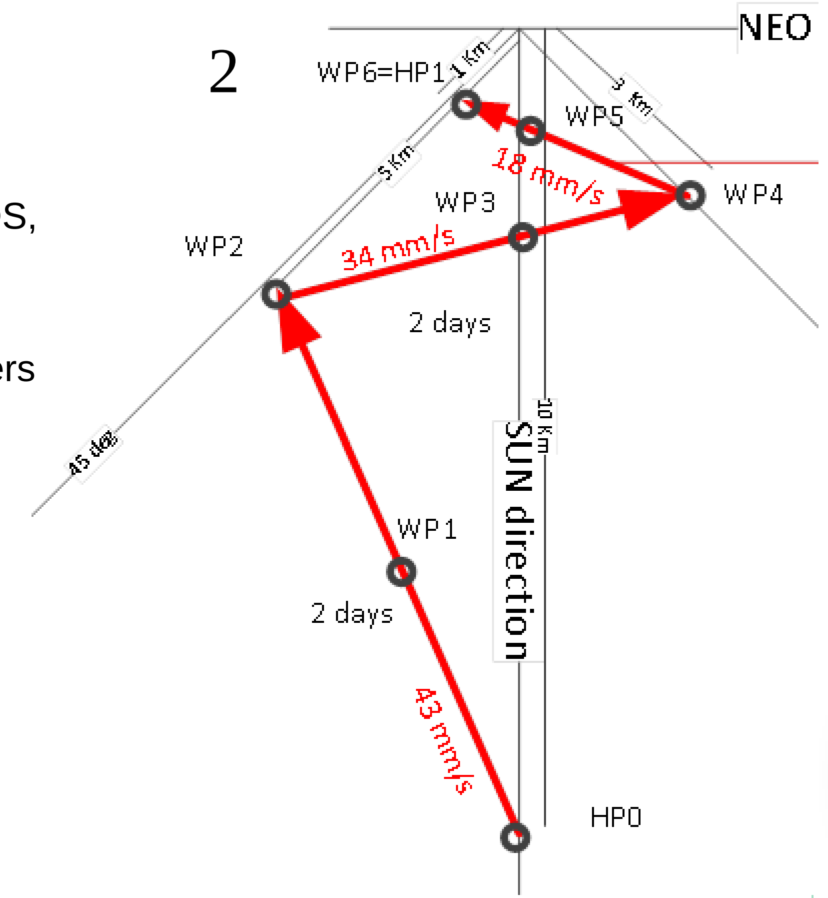
Far Approach

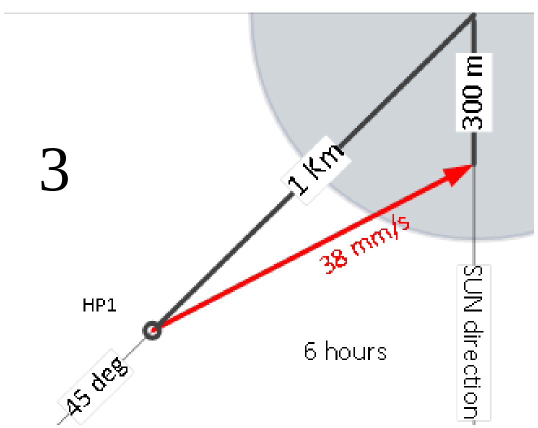
- LOS + Radiometric - based Navigation (NAC)
- Lower the Range, Improve Accuracy
- 1st Segment – Gravity-Gradient , 2nd SRP



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

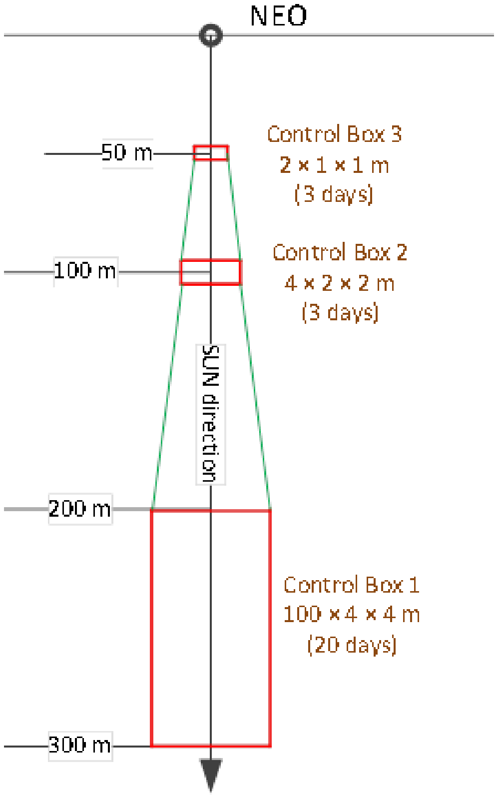




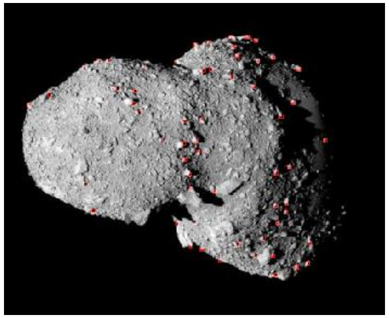
Transition to Operations

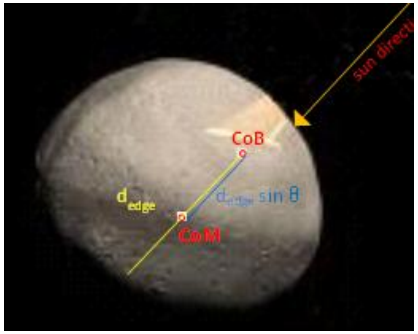
- Full Metrology Acquired
- Asteroid is 300 000 pixels in NAC, 10 in WAC
- Autonomous Station-Keeping

- **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



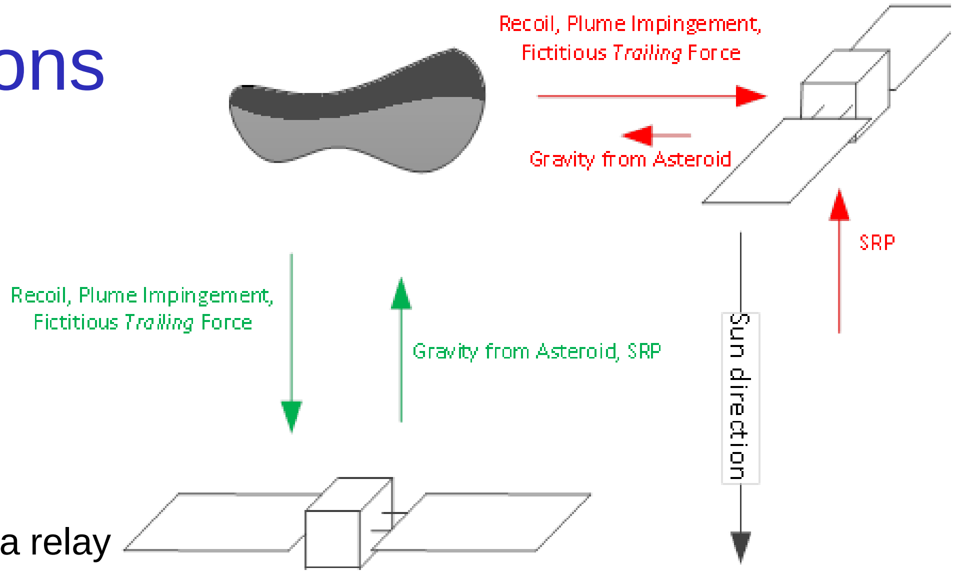
Followed by series of Ablation Tests

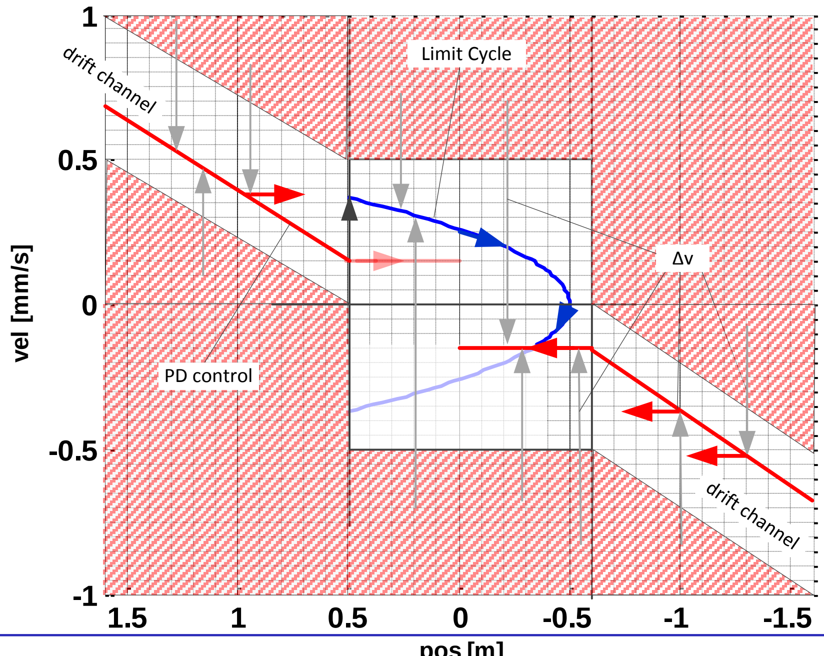




Proximity Operations

- **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





	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		

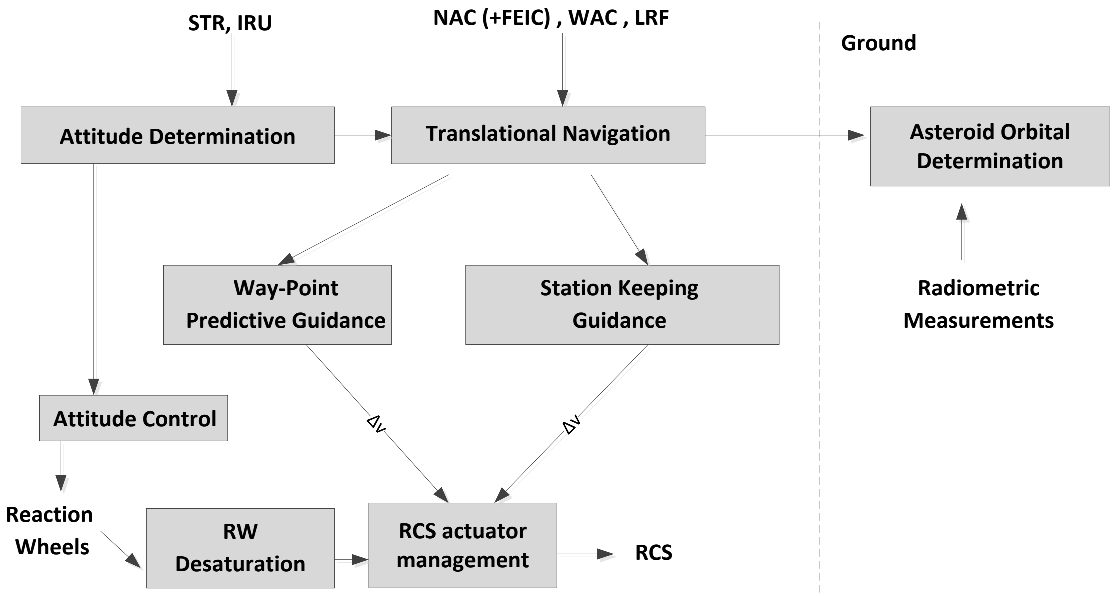
University of Strathclyde
UNIVERSITY OF Southampton
gmv INNOVATING SOLUTIONS
ASTRIUM AN EADS COMPANY
ADAM LightTouch²

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

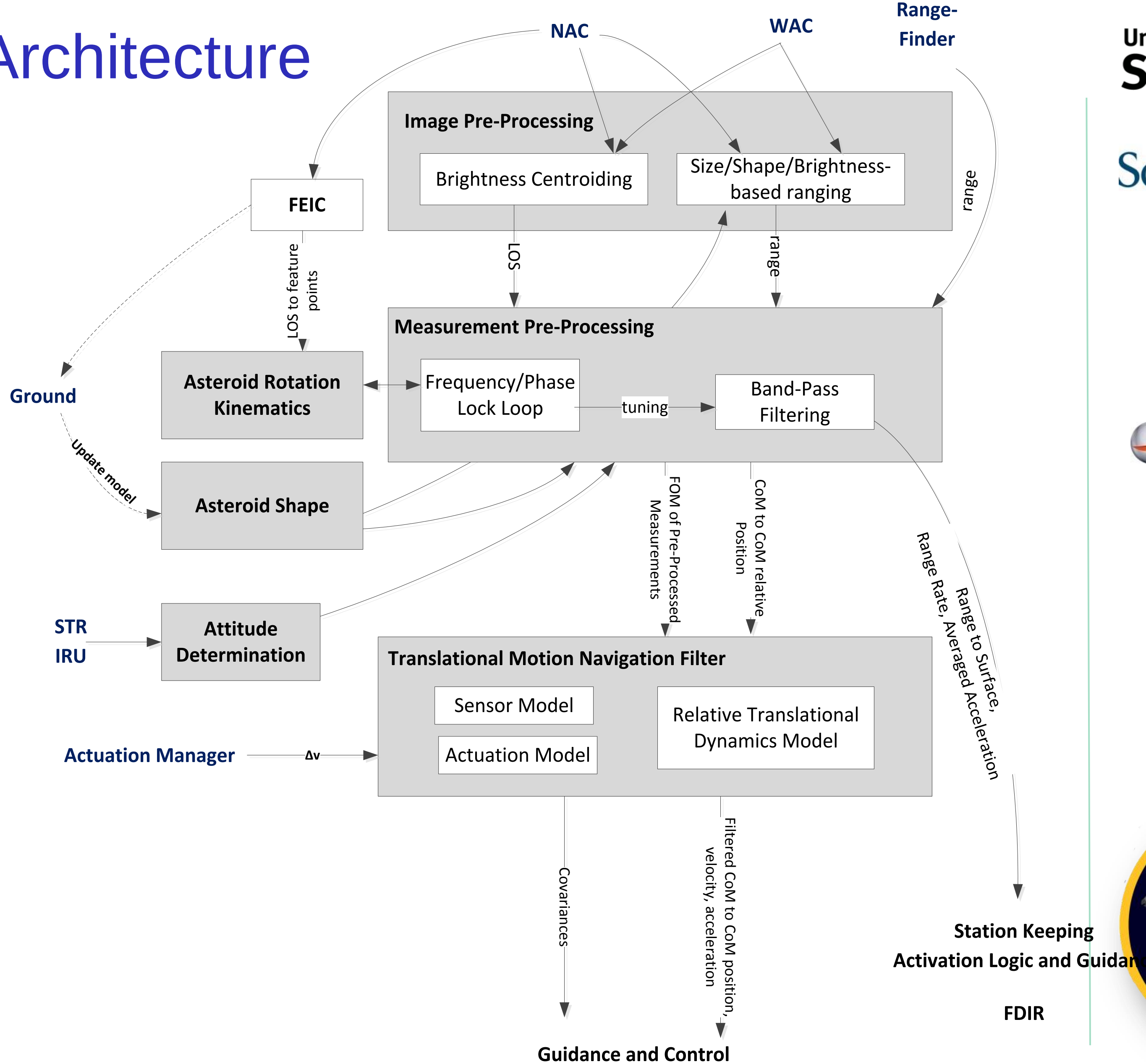
Camera	Pixel [µrad]	FOV	Range [Km] (worst case)	Mass
Galileo Avionica VBNC	200	70	10	0.6 kg
Marco Polo R NAC	15	1.7	30 000	6 kg

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



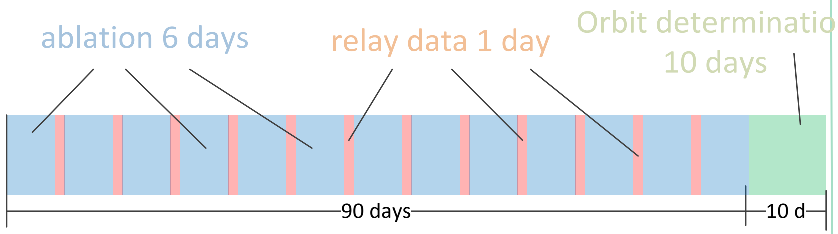
GNC Architecture

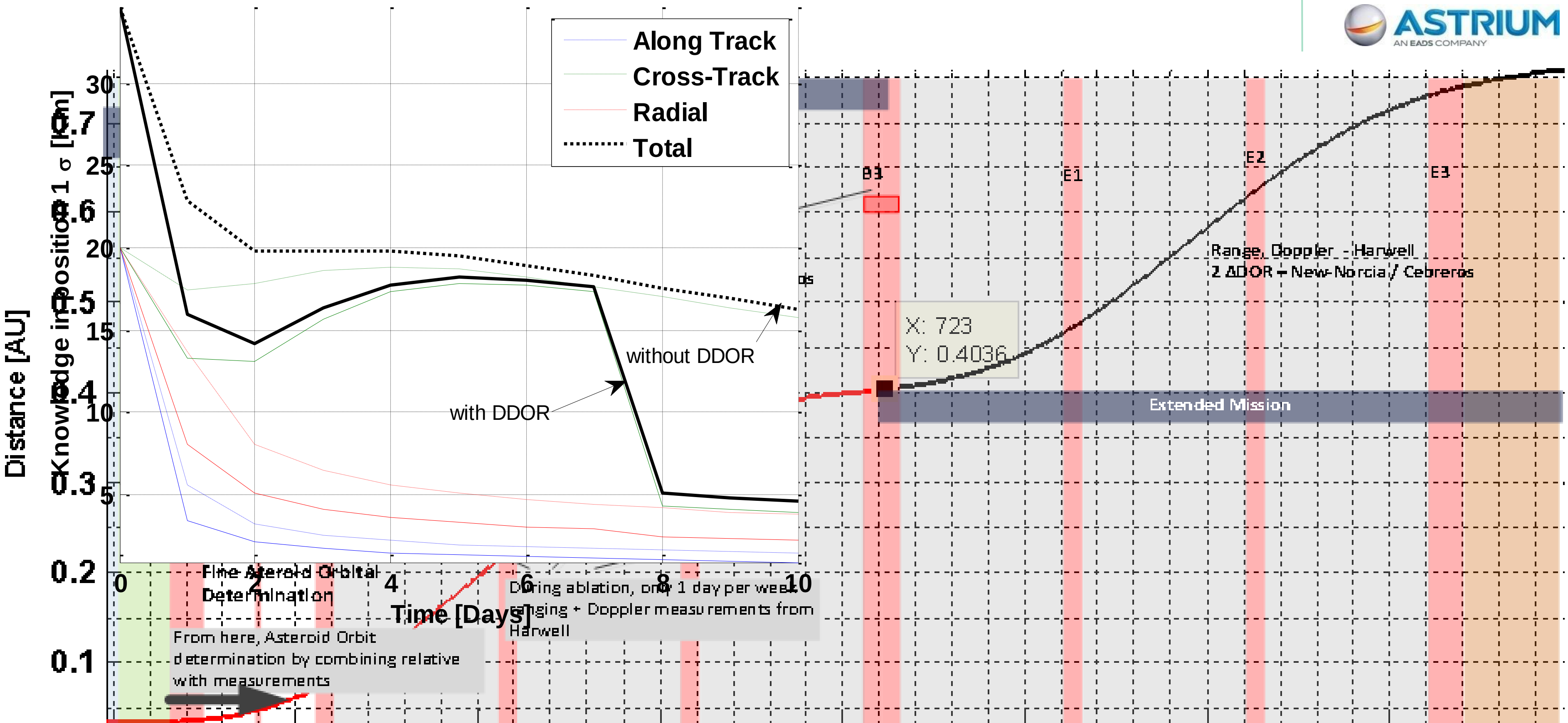
- Modular
- Robust



Radiometric Orbit Determination

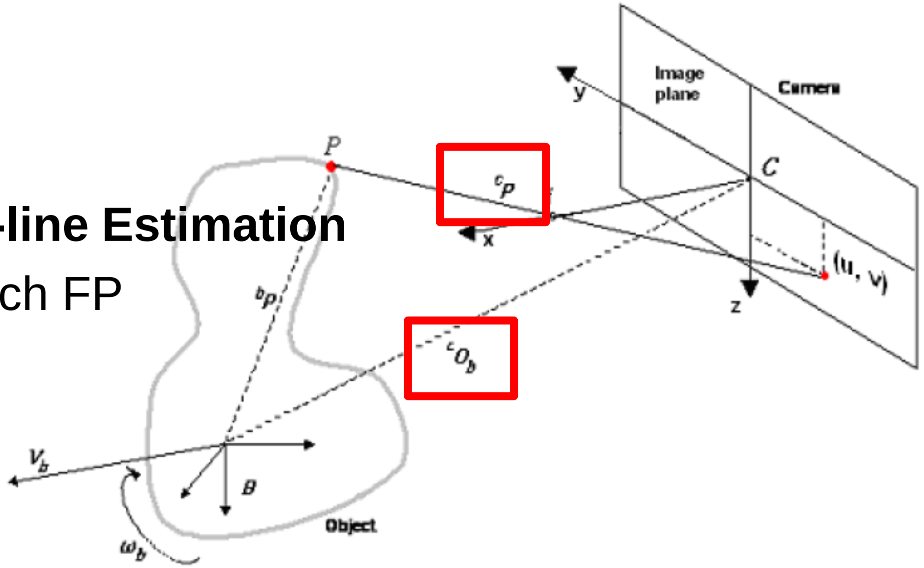
- Range, Doppler from Harwel*
- ΔDOR from DSA
  - (3 x 2 in nominal mission)
- Combined with relative metrology to obtain NEO orbit





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

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

  - Invert Matrix (or LSQ, etc)

from nav

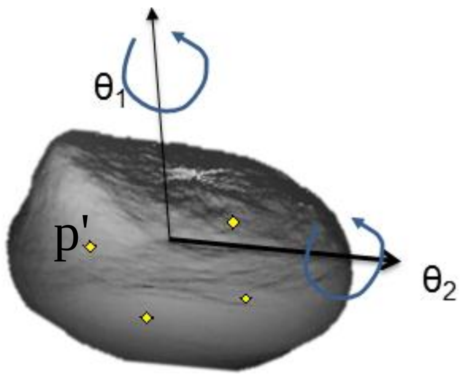
10 tracked points (only need to track from 2 instants)

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

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)

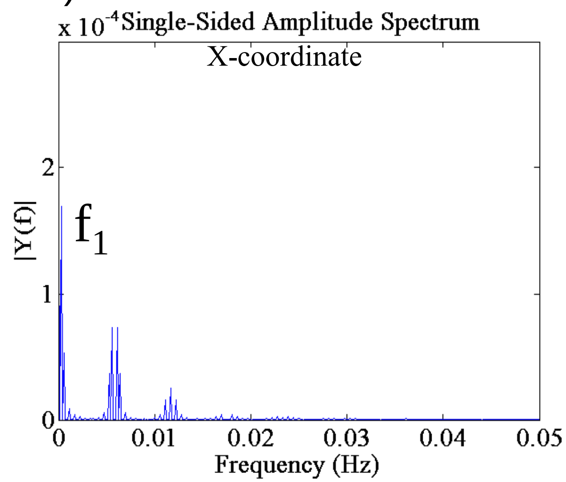
$$\mathbf{p}' = \mathbf{a}\cos(\theta_1) + \mathbf{b}\sin(\theta_1) + \mathbf{c}\cos(\theta_2) + \mathbf{d}\sin(\theta_2) + \mathbf{e}\cos(\theta_1+\theta_2) + \mathbf{f}\sin(\theta_1+\theta_2) + \mathbf{g}\cos(\theta_1-\theta_2) + \mathbf{h}\sin(\theta_1-\theta_2) + \mathbf{i}$$

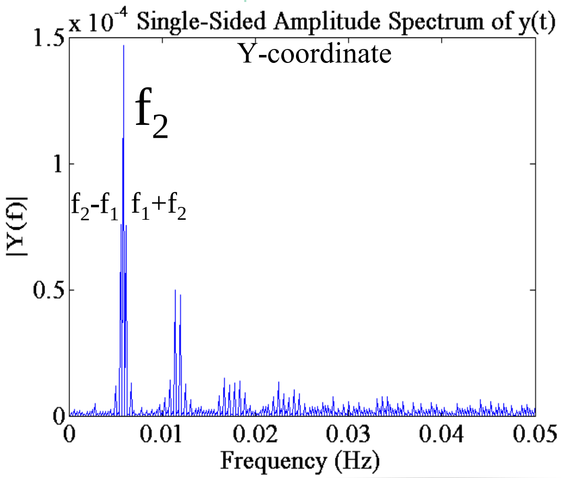


- Intersection of the two axis identifies the CG
- No needs to know inertia and mass of the asteroid

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

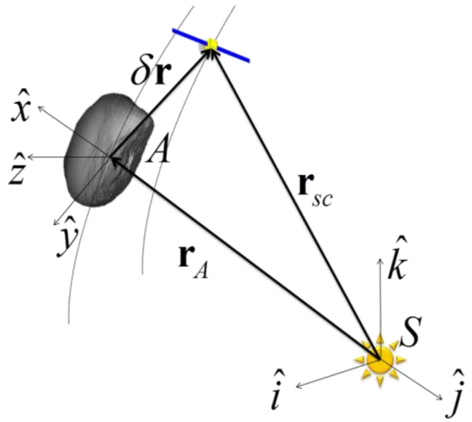
- Relative perturbed spacecraft motion described in the Hill reference frame:

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

- 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

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

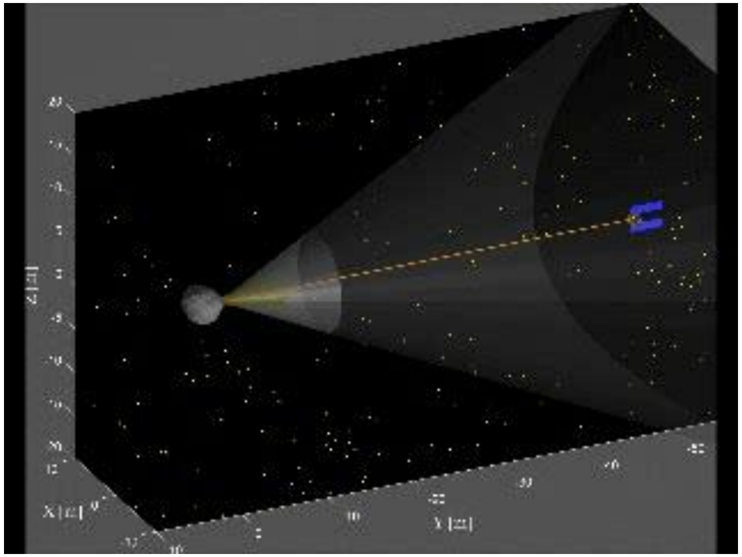
$$\mathbf{d}_f = \mathbf{d}_{in}^{est} + (\mathbf{v}_{in}^{est} + \Delta\mathbf{v}_{corr})t + \mathbf{a}_{est}\frac{t^2}{2}$$

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

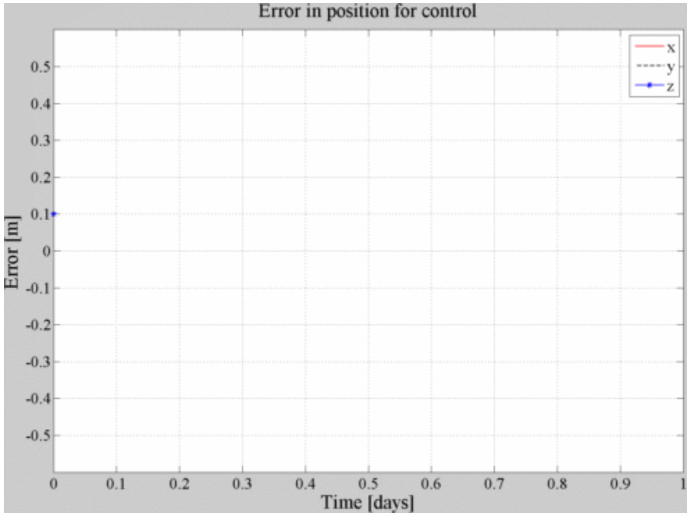
Need to estimate
- Spacecraft relative position and velocity
- Perturbative acceleration acting

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

Proximity Navigation and Control

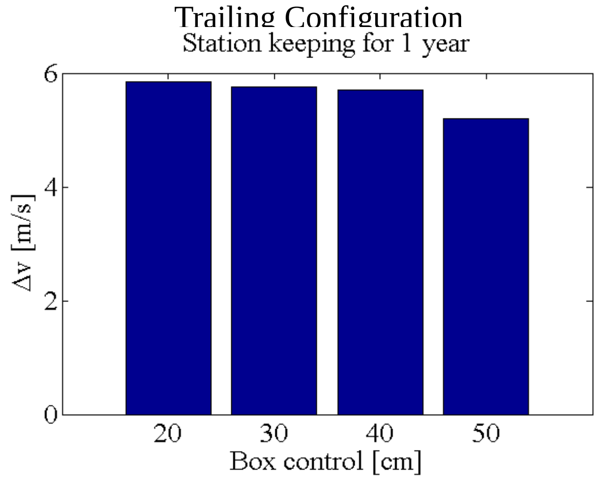


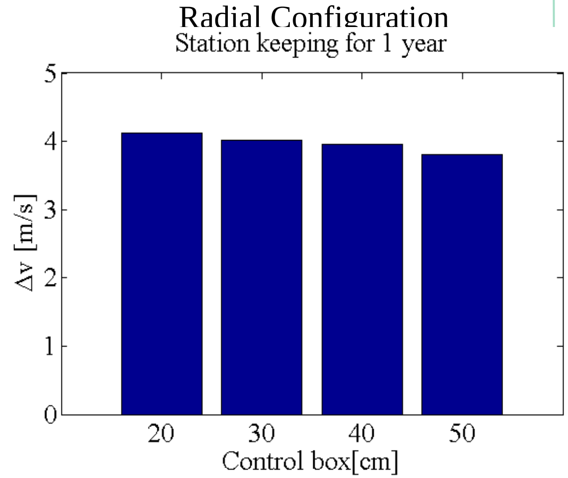
- Example Trailing Configuration



- Control Δv

-Radial configuration less demanding than the trailing one





How to measure the efficiency of a deflection strategy?

Two quantities can be measured:

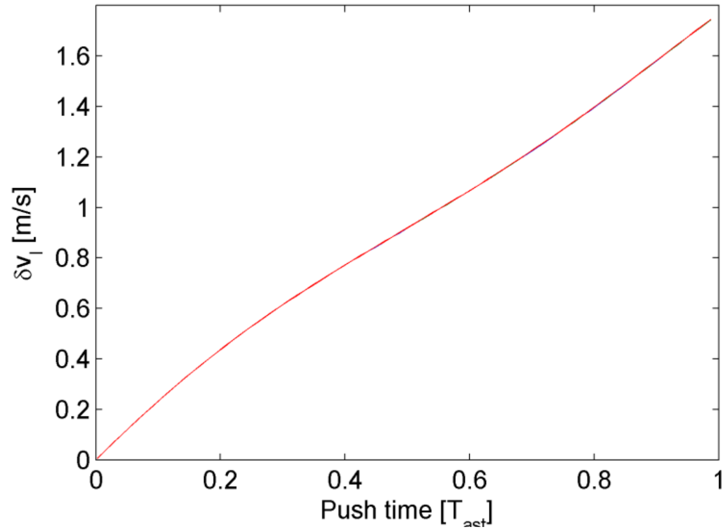
- Integral of the acceleration imparted onto the asteroid

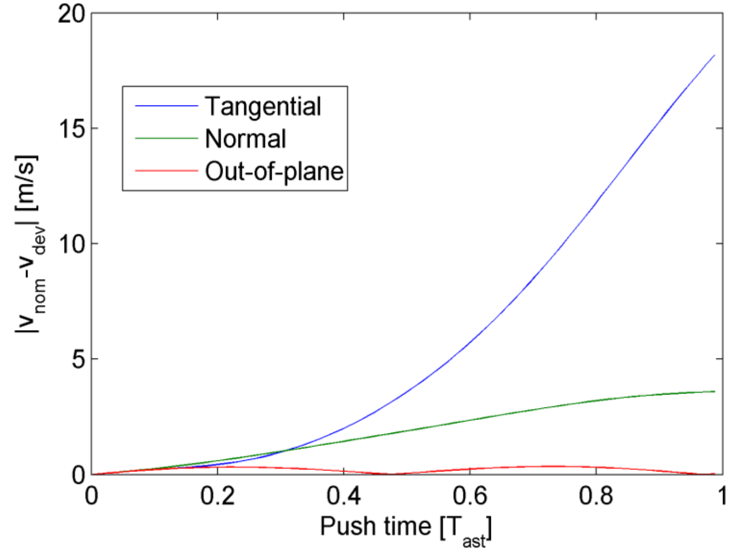
$$\delta v_I = \int_{\text{start ablation}}^{\text{stop ablation}} \frac{F_{\text{sub}}(t)}{m_{NEO}(t)}\, dt$$

- 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.

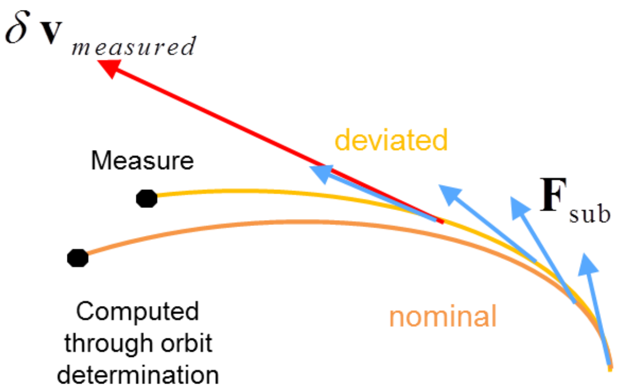




Estimating Δv imparted onto the asteroid

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

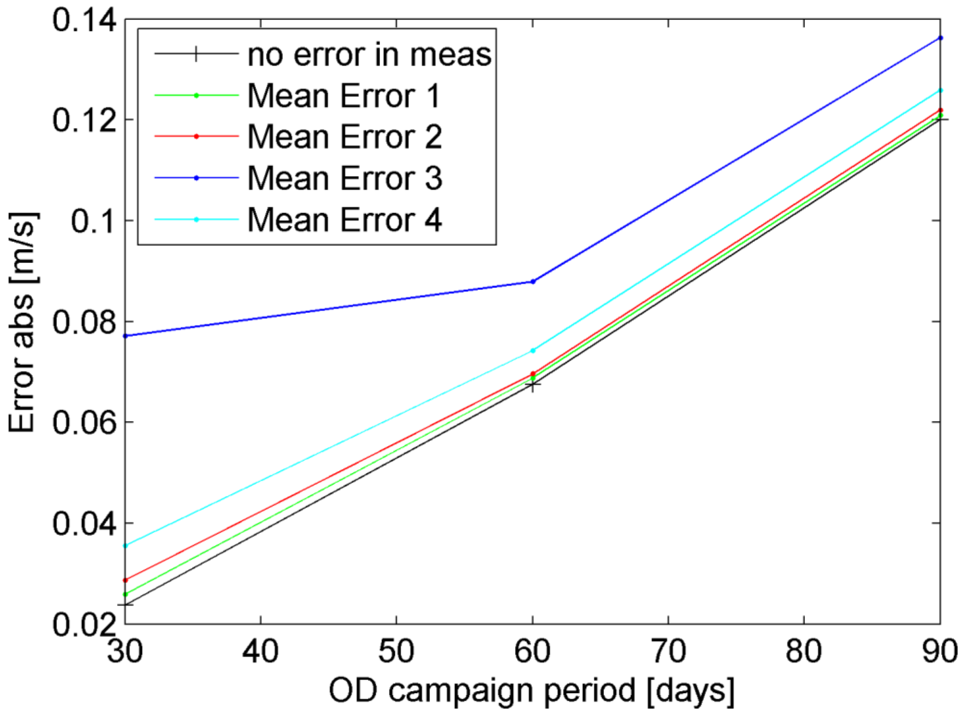
relative position of the asteroid with respect to its nominal one at the time of measure

- 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



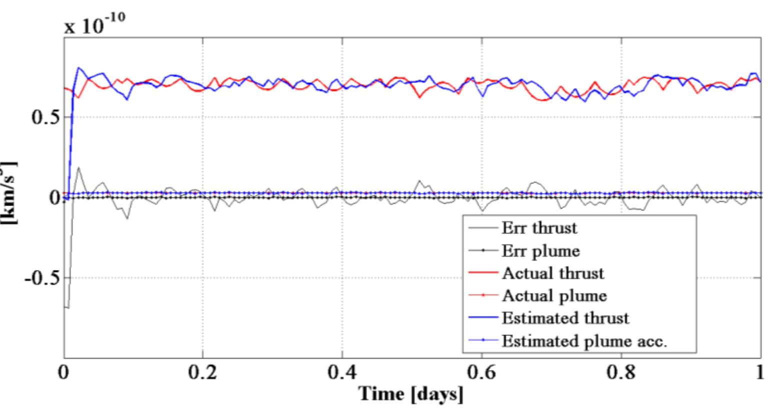
Estimating Δv imparted onto the asteroid

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

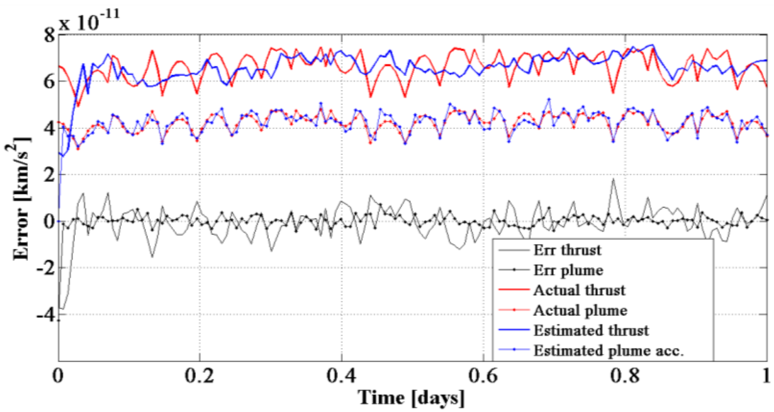
$$\delta \mathbf{v}_I = \int_{\text{start ablation}}^{\text{stop ablation}} \frac{\mathbf{F}_{sub}(t)}{m_{NEO}(t)} dt \quad \Rightarrow \quad \delta \mathbf{v}_I = \int_{\text{start ablation}}^{\text{stop ablation}} \mathbf{a}_{laser}^{estimated} dt$$

  - 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

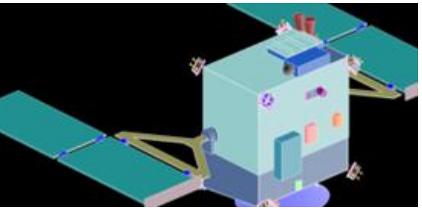
Acceleration - Trailing Configuration



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%

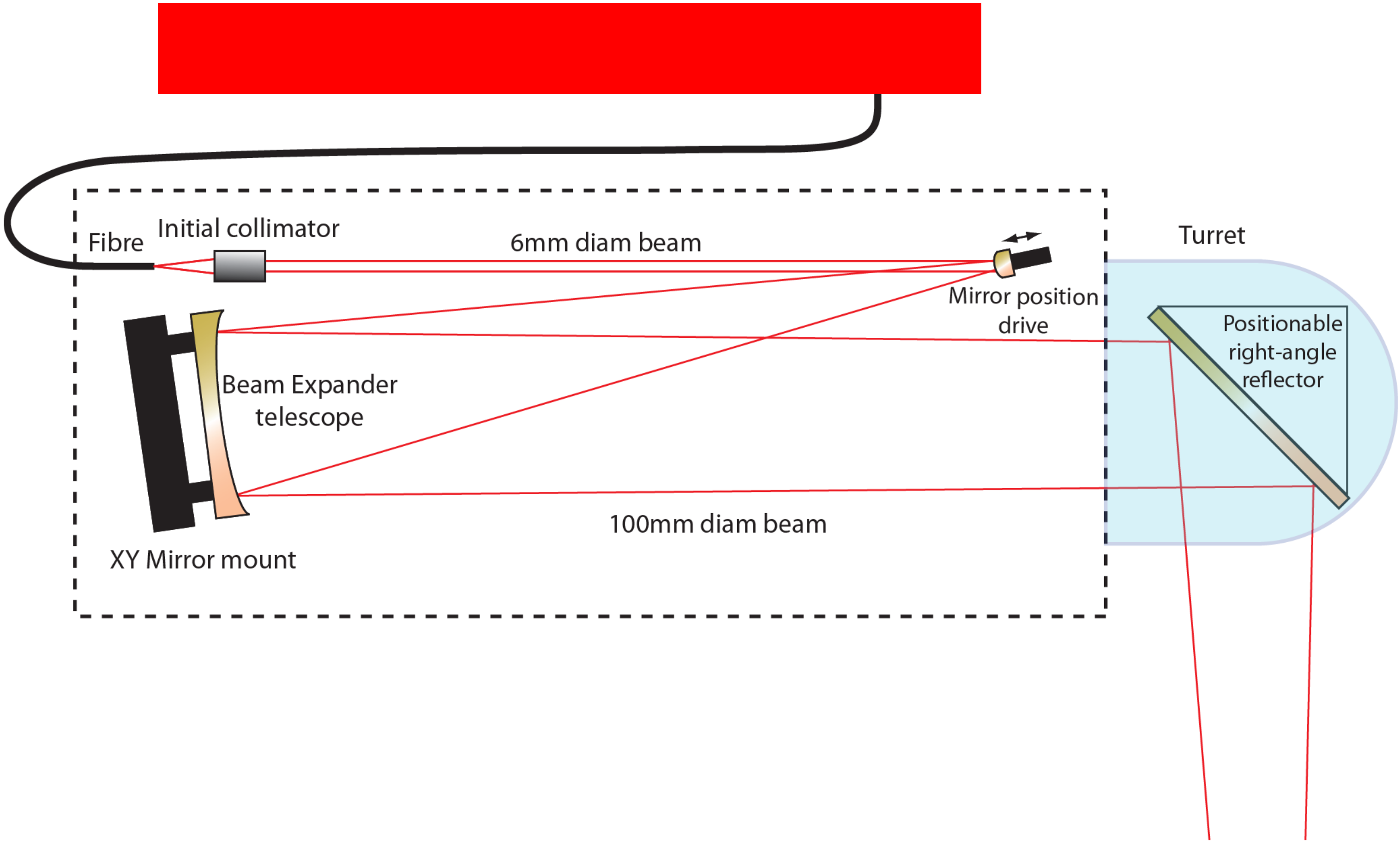


AdAM

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%**

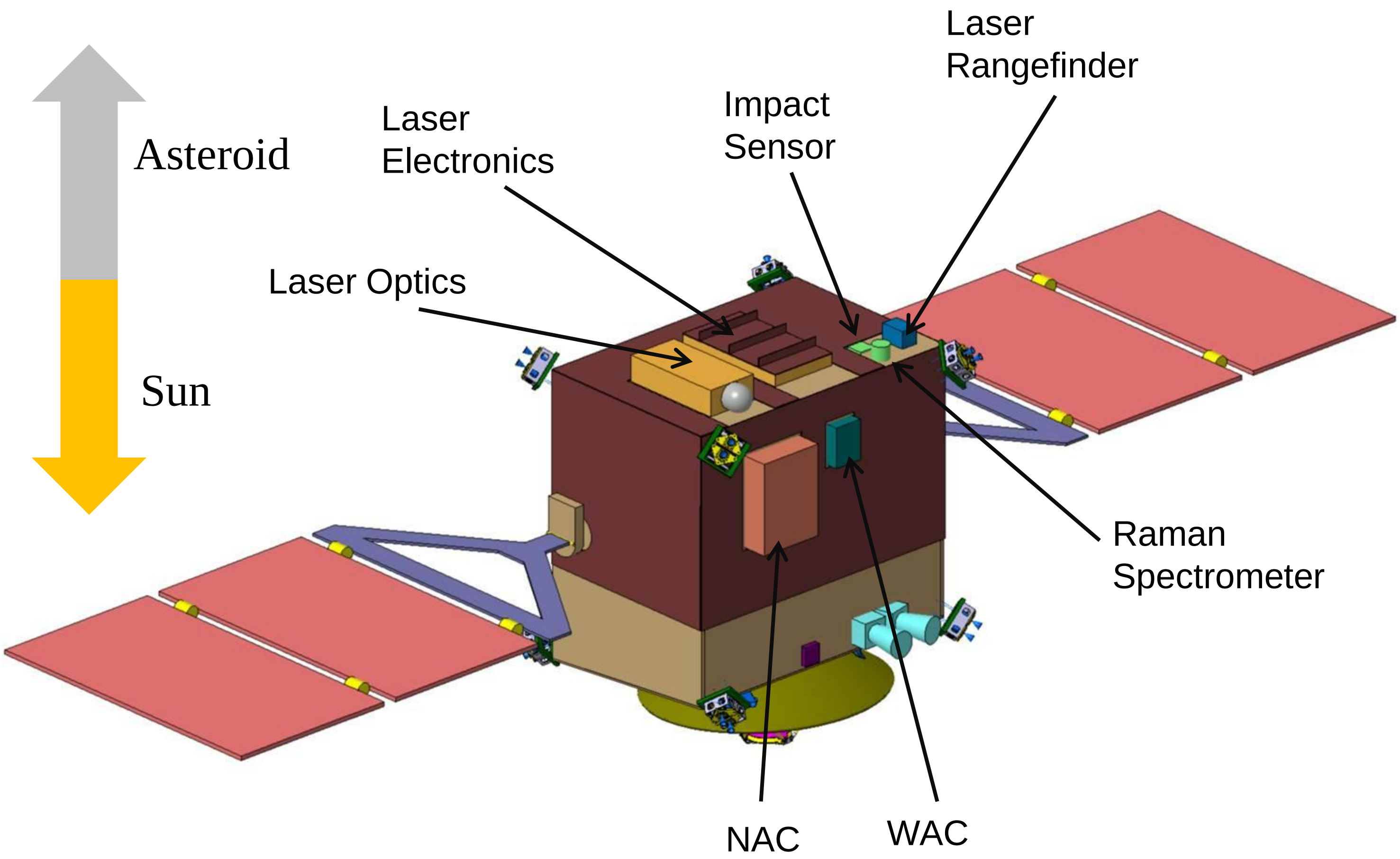
Power Budget

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**

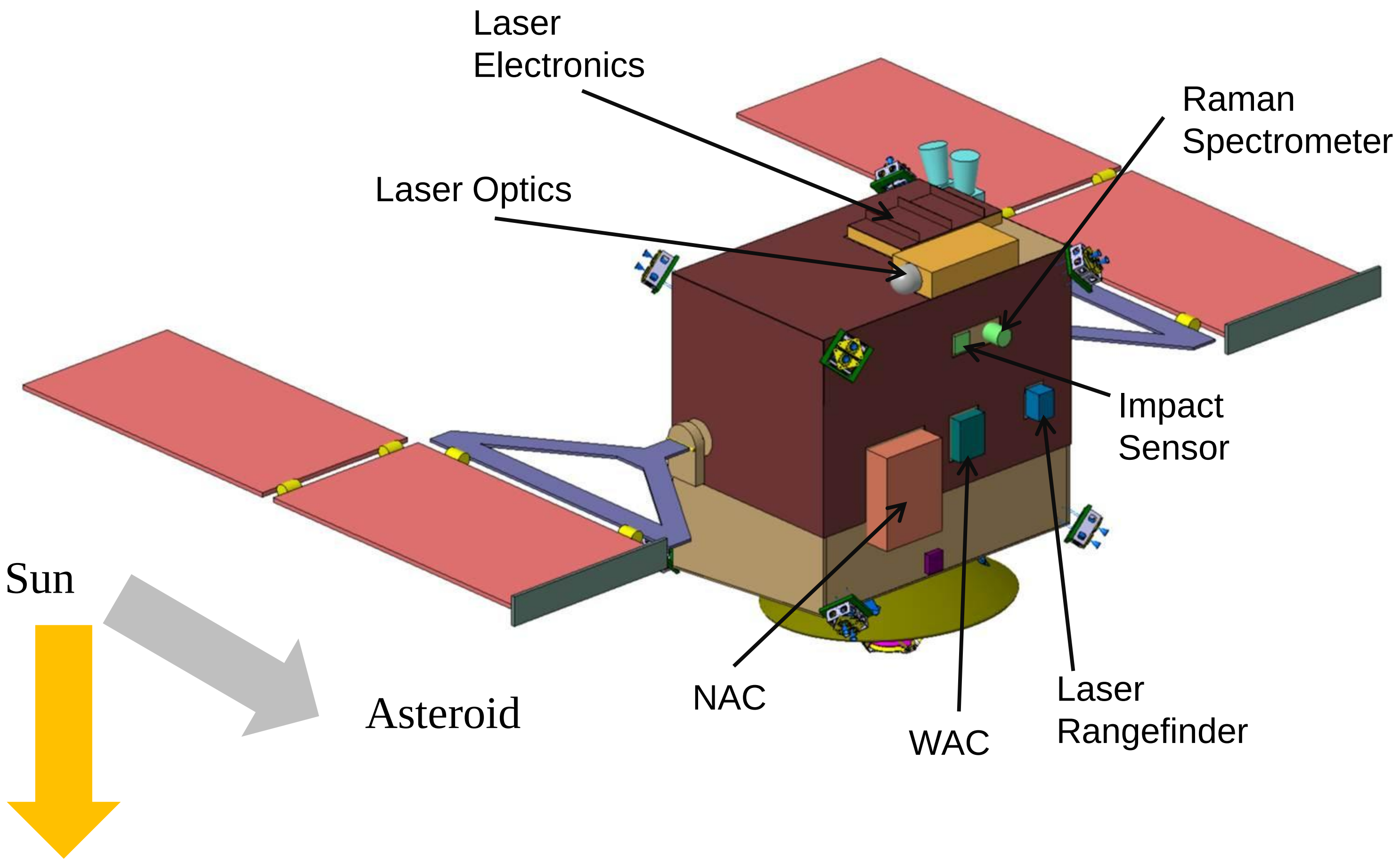
Downlink and Ground Segment

- 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

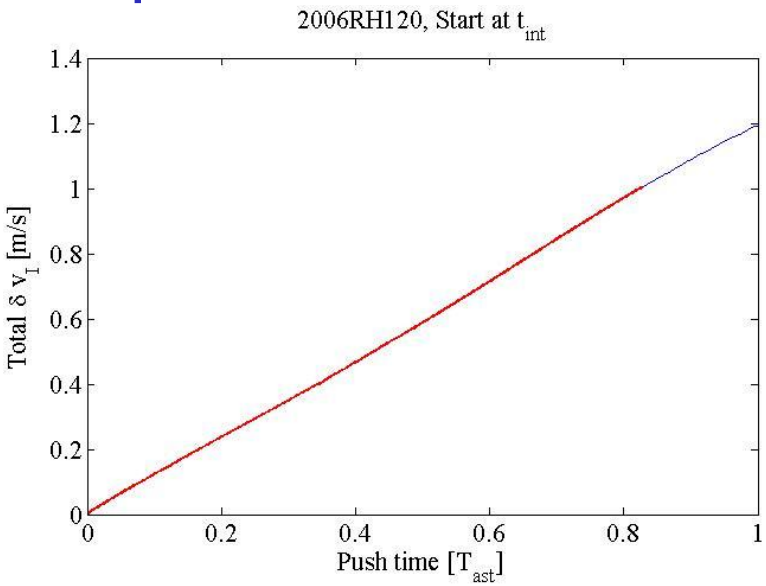
1. Low-mass low-power laser range finder instead of the LIDAR

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

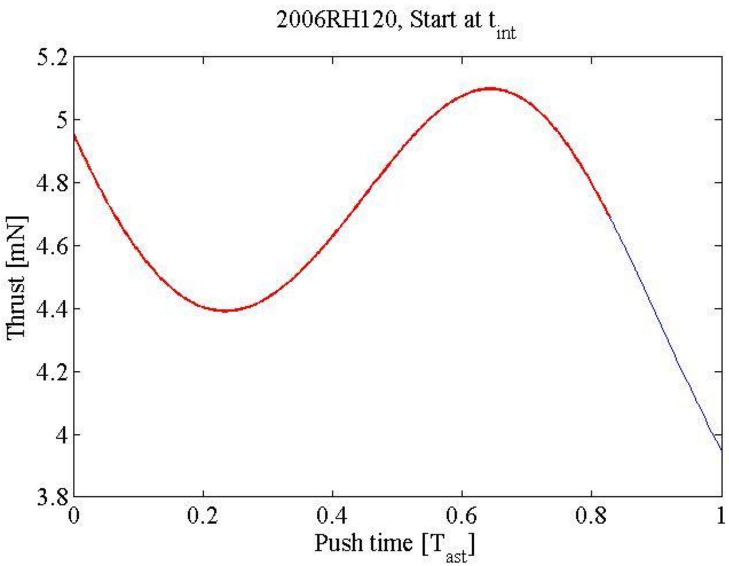
4. Same margin approach as for the second iteration

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

University of Strathclyde
UNIVERSITY OF Southampton
gmv INNOVATING SOLUTIONS
ASTRIUM AN EADS COMPANY

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

Follow **Stardust**, the asteroid and space debris research and training network:

www.stardust2013.eu

https://twitter.com/stardust2013eu

Questions?

Backup Slides

Back Up- Rotation Estimate FFT Approach

- Hirai et Al. 1998:

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

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

$$\mathbf{a} = -C_1C_2\mathbf{k}_1 + C_3\mathbf{k}_2 \qquad e = \{(1+C_1)\hat{\mathbf{p}} + (C_1C_3 - C_2)\mathbf{k}_1 - (C_2+C_3)\mathbf{k}_2\}/2$$
$$\mathbf{b} = C_3(\mathbf{k}_1\times\mathbf{k}_2) \qquad f = \{-C_4\mathbf{k}_1 - C_3(\mathbf{k}_1\times\mathbf{k}_2) + (\mathbf{k}_1\times\hat{\mathbf{p}}) + (\mathbf{k}_2\times\hat{\mathbf{p}})\}/2$$
$$\mathbf{c} = -(C_1C_3 - C_2)\mathbf{k}_2 \qquad g = \{(1+C_1)\hat{\mathbf{p}} + (C_1C_3 - C_2)\mathbf{k}_1 + (C_2 - C_3)\mathbf{k}_2\}/2$$
$$\mathbf{d} = C_4\mathbf{k}_1 \qquad h = \{C_4\mathbf{k}_1 - C_3(\mathbf{k}_1\times\mathbf{k}_2) + (\mathbf{k}_1\times\hat{\mathbf{p}}) - (\mathbf{k}_2\times\hat{\mathbf{p}})\}/2$$

$$\mathbf{i} = C_1C_3\mathbf{k}_1 + \mathbf{p}_0$$
$$C_1 = \mathbf{k}_1{}^T\mathbf{k}_2$$
$$C_2 = \mathbf{k}_1{}^T\hat{\mathbf{p}}$$
$$C_3 = \mathbf{k}_2{}^T\hat{\mathbf{p}}$$
$$C_4 = \mathbf{k}_1{}^T(\mathbf{k}_2\times\hat{\mathbf{p}})$$

- 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

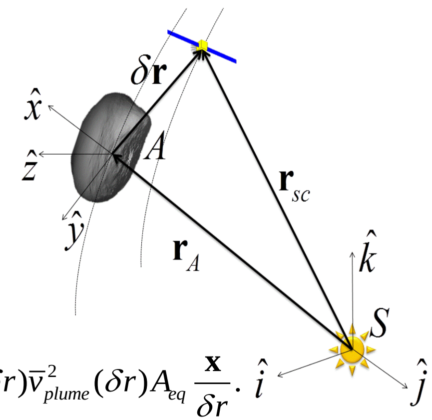
$$\mathbf{x}_{r_a} \times (\ddot{\mathbf{v}} \times \mathbf{x}_{r_a}) + 2\dot{\mathbf{x}}_{r_a} \times (\dot{\mathbf{v}} \times \mathbf{x}_{r_a}) = \mathbf{x}_{r_a} \times \mathbf{a}_{laser-local}$$

- Potential from ellipsoid body

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

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

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

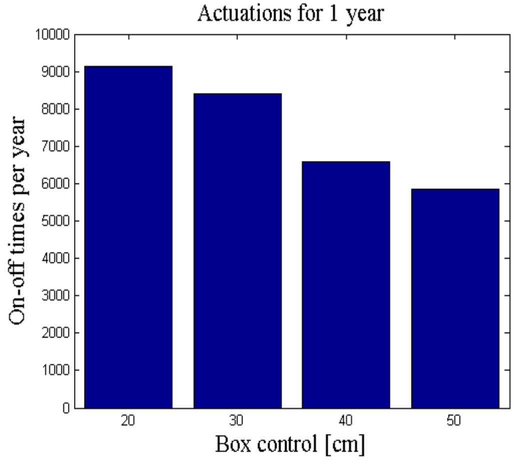


- Perturbative forces

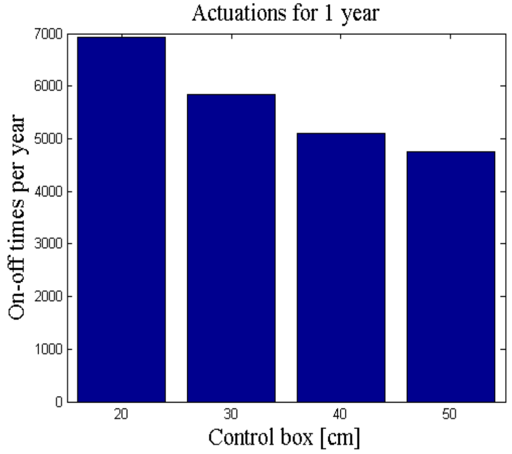
$$F_{Solar} = C_R S_{srp}\left(\frac{r_{AU}}{r_{sc}}\right)^2 A_M \frac{\mathbf{x}_a}{r_{Sc}}; \quad F_{recoil} = \eta_{sys} S_{srp}\left(\frac{r_{AU}}{r_{sc}}\right)^2 A_M \frac{\mathbf{x}}{\delta r}; \; F_{plume} = \rho_{plume}(\delta r)\bar{v}_{plume}^2(\delta r)A_{eq}\frac{\mathbf{x}}{\delta r}.$$

- Number of actuations

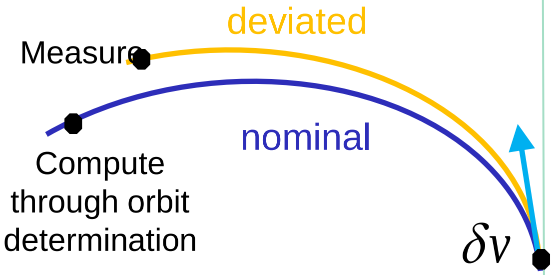
Trailing Configuration



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

through Gauss' equations — due to a variation in a

$$\delta M = -\frac{b}{eav}\left[2\left(1+\frac{e^2 r}{p}\right)\sin f\,\delta v_t + \frac{r}{a}\cos f\,\delta v_n\right] + \Delta n\left(t_{MOID} - t_d\right)$$

Back Δv imparted onto the asteroid

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

Proximal motion between nominal and deviated

Gauss' equations (also orbit perturbation can be included)

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

Get Δv

Measure position displacement

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)

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

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?

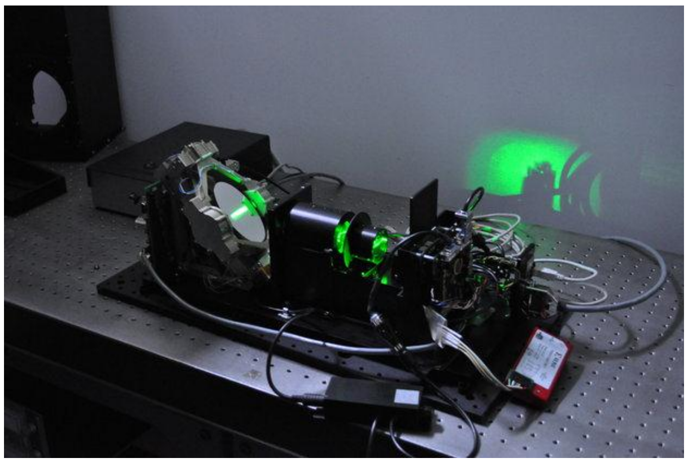
- Escaping from LEO with a solid motor was also considered
- Several issues were identified
- No European solid motor exists
  - American solid motor would need to be used
- No European heritage for the use of solid motors
- Significant additional mass would be required
  - Structure between solid motor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

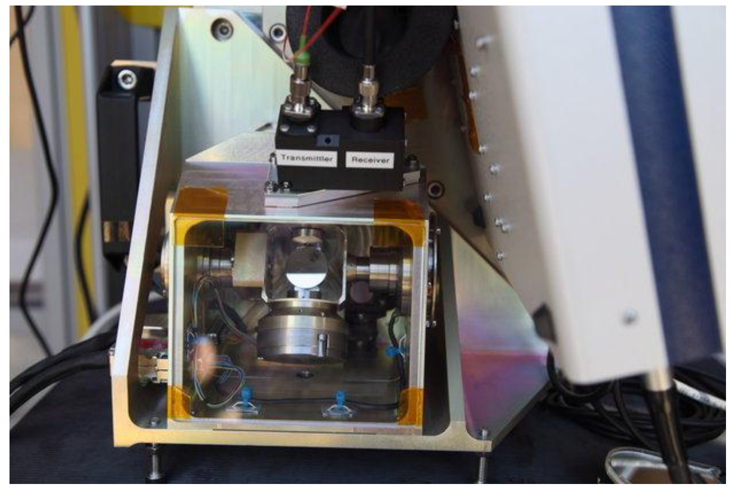
PSLV XL Mass Budget

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)

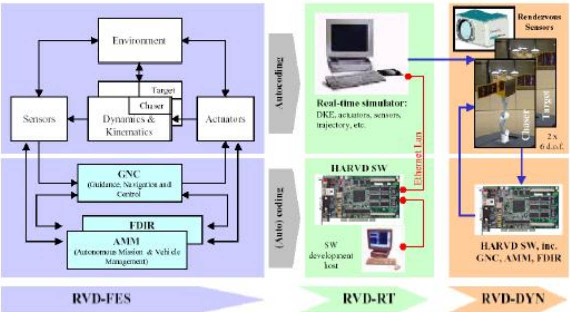


Figure 9. HARVD development and validation environments

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

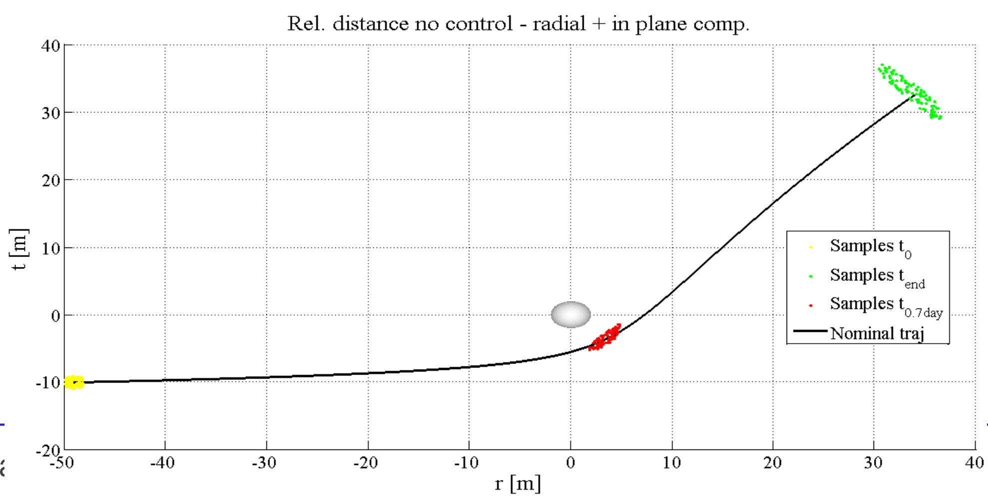
Autonomy

- 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

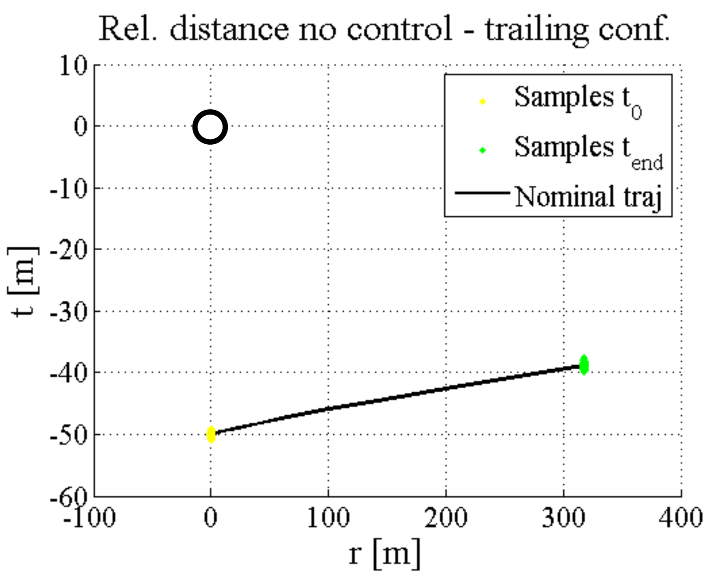
- Not a typical NEO mission
  - Gravity pull from asteroid < 2 μN
  - SRP ~40 μN
  - **Collision Avoidance Design – SC is 10 m offset to asteroid's orbital plane**
    - (offset has negligible effect of <1 pN due to differential gravity)
- Larger Concerns:
  - Evaporation
  - No illumination angle (SC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

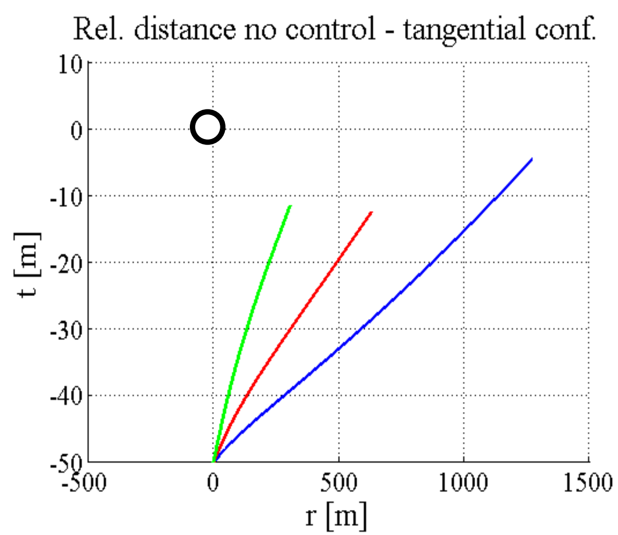
- **Passive Safety – Worst case – loss of control (position, attitude, tumbling)**

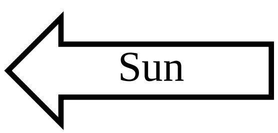


Trailing Configuration

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

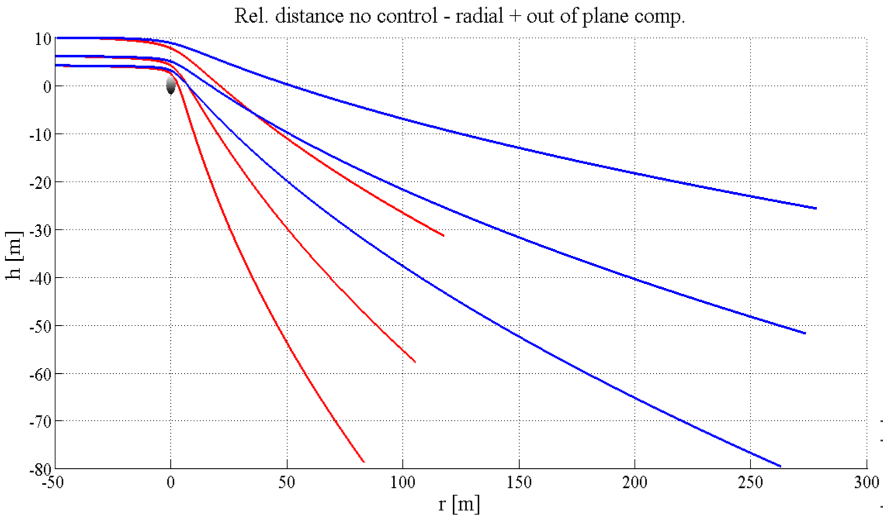


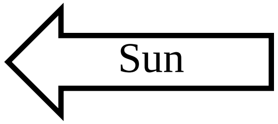


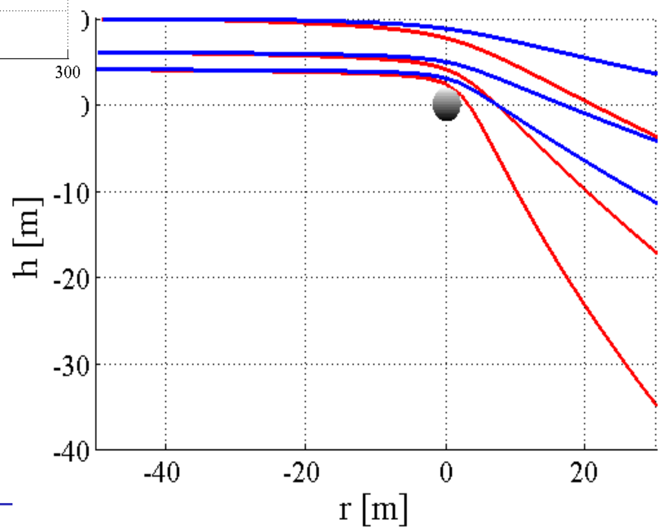


Radial Configuration Configuration

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

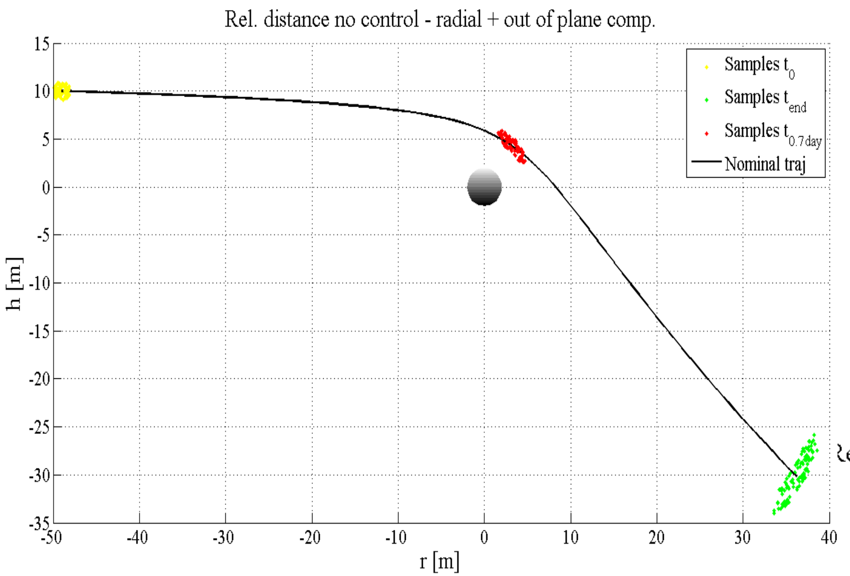


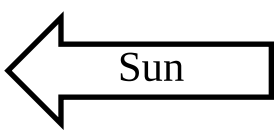


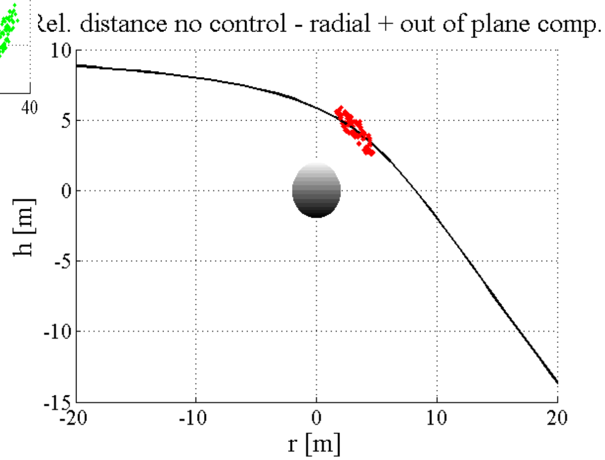


Radial Configuration Configuration

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







CEAM / FDIR

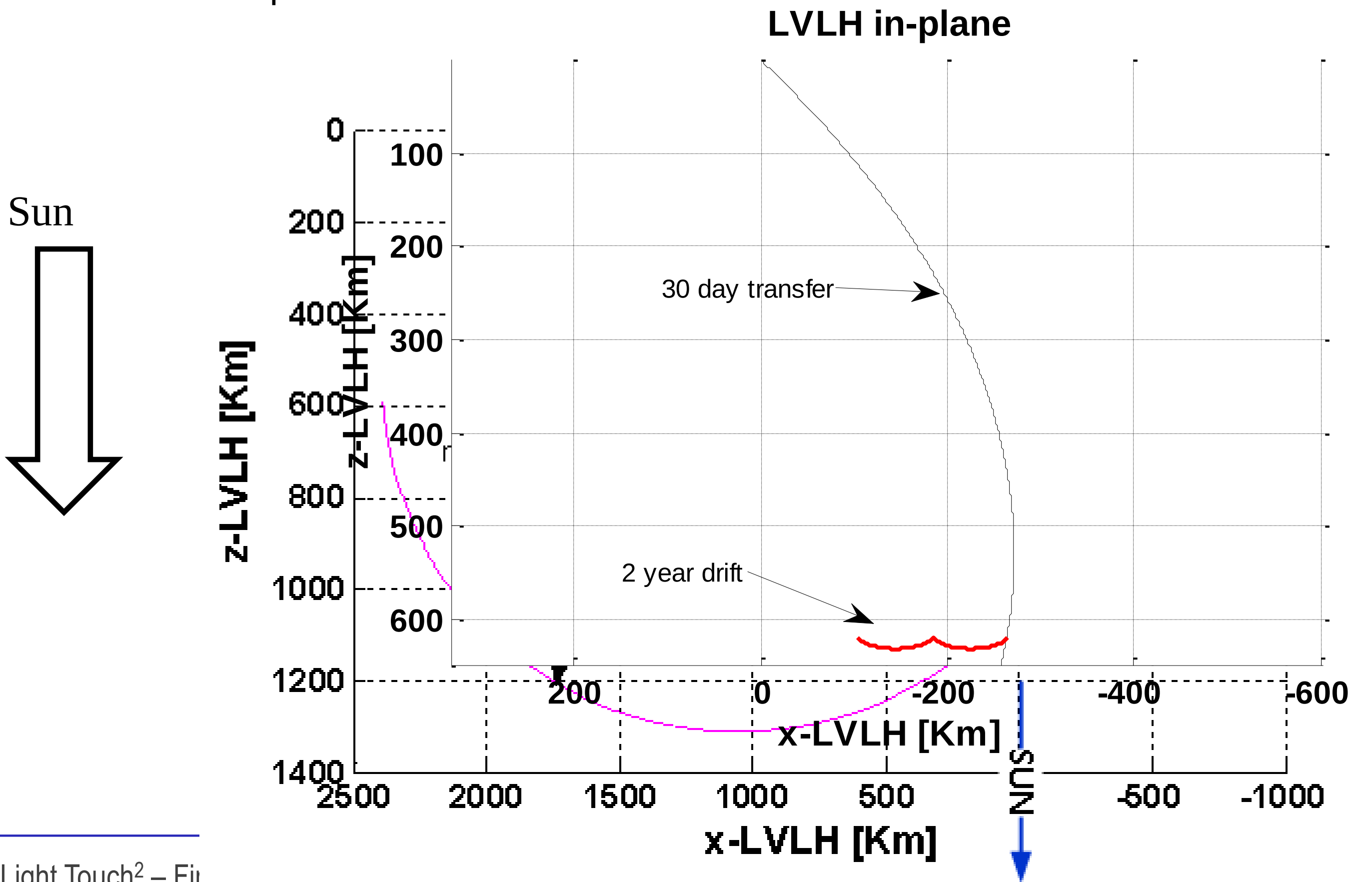
- Detection of failure / Contingency
  - Fault/Failure in component detected by component (hardware) – sensor actuator – failure flag
  - Incoherent measurements/data detected in cross-checking (pre-processing) in the GNC chain
  - Contingency – raw algorithms for CAEM
    - LRF raw measurement exceeds 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

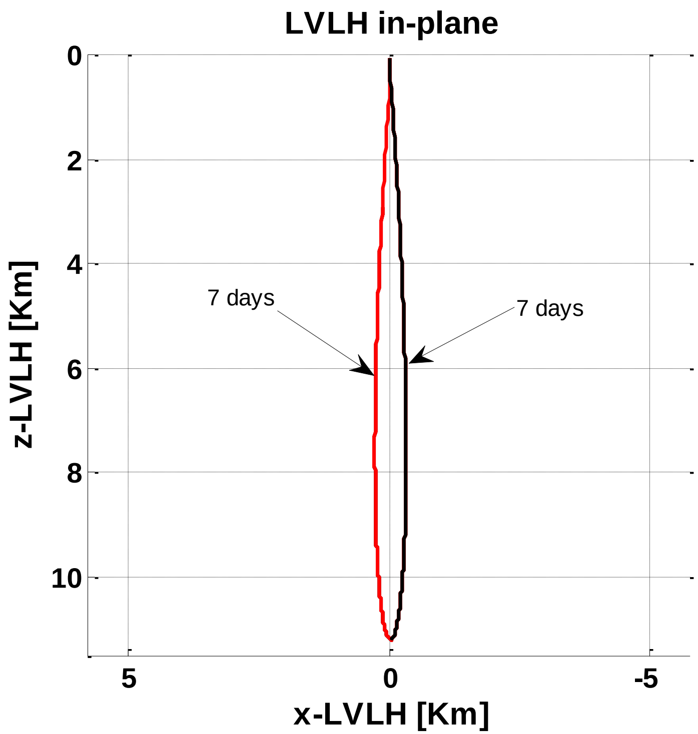
University of Strathclyde

UNIVERSITY OF Southampton

gmv INNOVATING SOLUTIONS

ASTRIUM AN EADS COMPANY

- 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

ADAM LightTouch2