Light Touch²

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GNC
Deflection
System
Concept
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.

<table>
<thead>
<tr>
<th>DESIGNATION</th>
<th>PHA (Y/N)</th>
<th>H</th>
<th>q (AU)</th>
<th>Q (AU)</th>
<th>i (deg)</th>
<th>D (km) ($p_v=0.154$)</th>
<th>OCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 JL24</td>
<td>N</td>
<td>29.572</td>
<td>0.927631</td>
<td>1.148906</td>
<td>0.550106</td>
<td>0.004124</td>
<td>3</td>
</tr>
<tr>
<td>2006 RH120</td>
<td>N</td>
<td>29.527</td>
<td>1.007964</td>
<td>1.058540</td>
<td>0.595266</td>
<td>0.004211</td>
<td>1</td>
</tr>
</tbody>
</table>


- **Rotation ~ 18 rev/h**
- **Rotation ~ 21.8 rev/h**
Target

- Target observability from Earth

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

<table>
<thead>
<tr>
<th>Object Designation</th>
<th>Orbit ID</th>
<th>( \Delta H ) (mag)</th>
<th>Estimated Diameter (m)</th>
<th>OCC</th>
<th>Min. delta-V [delta-V, dur.] (km/s), (d)</th>
<th>Min. Duration [delta-V, dur.] (km/s), (d)</th>
<th>Viable Trajectories</th>
<th>Next Optical Opportunity (yyyy-mm [Vp])</th>
<th>Next Arecibo Radar Opportunity (yyyy-mm [SNR])</th>
<th>Next Goldstone Radar Opportunity (yyyy-mm [SNR])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2008 JL24)</td>
<td>10</td>
<td>29.6</td>
<td>2.1 - 9.5</td>
<td>3</td>
<td>4.628, 394</td>
<td>11.791, 82</td>
<td>904797</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>(2006 RH120)</td>
<td>45</td>
<td>29.5</td>
<td>2.2 - 10</td>
<td>1</td>
<td>3.989, 450</td>
<td>11.323, 42</td>
<td>1283739</td>
<td>2026-06 [23.9]</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>

- 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 Touch²
Ablation Process

- Energy balance:

\[ \left( E_v + \frac{1}{2} \bar{V}^2 + C_p (T_s - T_0) + C_v (T_s - T_0) \right) \dot{m} = P_I - Q_{RAD} - Q_{COND} \]

- Ejection velocity dependent on temperature:

\[ \bar{V} = \sqrt{\frac{8k_b T_s}{\pi M_a}} \]

- Integrated mass flow over the spot including rotation:

\[ \dot{m} = 2V_{rot} \int_{0}^{\gamma_{max}} \int_{t_{in}}^{t_{out}} \frac{1}{E_v} \left( P_I - Q_{rad} \right) - \left( \frac{ckp}{\pi} (T_{subl} - T_0) \right) \sqrt{\frac{1}{t}} \, dt \, dy \]

- Thrust model includes a scattering factor:

\[ F_{sub} = \lambda \bar{V} \dot{m} \]

- Input power dependent on system efficiency:

\[ P_I = \tau g \alpha_M \eta_p \eta_L \eta_s \frac{P_{1AU} A_{SA}}{A_{spot} R_{AU}^2} \]
Contamination Model

- Density dependent on elevation angle distance:
  \[
  \rho(r, \theta) = \rho^* K_p \frac{d_{SPOT}^2}{(2r + d_{SPOT})^2} \left[ \cos \left( \frac{\pi \theta}{2 \theta_{MAX}} \right) \right]^{2/k-1}
  \]

- Thickness of the layer of contaminant dependent on view factor and mass flow:
  \[
  \frac{dh}{dt} = \frac{2\bar{v} \rho}{\rho_I} \cos \psi_{vf}
  \]

- Beer–Lambert law for light absorption:
  \[
  \tau = e^{-2\eta h}
  \]

- Key coefficients experimentally derived using asteroid analogous materials
Focusing and Beam Control

Beam behaviour of a 1070nm fibre laser and an f=50m optic

\[ z_R = \frac{\pi W_0^2}{\lambda_b} \]

\[ \sqrt{2} w_0 \quad w_0 \quad b \quad w(z) \quad z_R \]

\[ \Theta \quad \Theta \quad \Theta \quad \Theta \quad \Theta \]

2 x Rayleigh length (m)

Beam radius (mm)

Beam diameter at exit of final optic
Momentum Coupling

\[ C_m = \frac{F_{\text{sub}}}{P_{IN}} \quad P_{IN} = \tau \eta_P \eta_S \frac{P_{1AU} A}{R_{AU}^2} \]

\[ \eta_L = 0.55, \text{ Target Asteroid} \]

\[ r_{\text{spot}} = 0.50 \text{mm}, \quad r_{\text{spot}} = 0.75 \text{mm}, \quad r_{\text{spot}} = 1.00 \text{mm}, \quad r_{\text{spot}} = 1.25 \text{mm}, \quad r_{\text{spot}} = 1.50 \text{mm} \]

- RIT20
- RIT10
- PPS1350G

\[ \text{Momentum Coupling [N/W]} \]

\[ \text{Power Requirement [W]} \]

\[ \text{Thrust [N]} \]

\[ \text{Spot Radius [m]} \]

\[ \eta_L = 0.55 \]

\[ \times 10^{-3} \]

\[ \times 10^{-4} \]
Efficiency analysis

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

- Thrust time [days] dist\text{NEO} = 20 m
- Thrust time [days] dist\text{NEO} = 30 m
- Thrust time [days] dist\text{NEO} = 40 m
- Thrust time [days] dist\text{NEO} = 50 m
Deflection Result

Assuming 860W at 1AU the target $\Delta v$ can be achieved in about half a year.
Mission, Control, Navigation
Mission: Interplanetary Trajectory and LW

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

<table>
<thead>
<tr>
<th>Earth Departure</th>
<th>$V_{\text{inf}}$ (km/s)</th>
<th>DSM date (Fraction ToF)</th>
<th>DSM $\Delta v$ (km/s)</th>
<th>Asteroid Arrival</th>
<th>Arr $\Delta v$ (km/s)</th>
<th>ToF (Days)</th>
<th>Total $\Delta v$ (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/11/2027</td>
<td>0.5403</td>
<td>N/A</td>
<td>0</td>
<td>9/09/2028</td>
<td>0.4871</td>
<td>306.5</td>
<td>3.677</td>
</tr>
</tbody>
</table>

- Preliminary analysis assumes escape 400x400 orbit
- Low $\Delta v$ requirements during transfer and arrival

- Wide LW
  - 1 month $\rightarrow$ less 1% extra costs
Mission: Launcher & Propulsion Trade-off

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

- Refined trajectory

<table>
<thead>
<tr>
<th>Non-Sphericity</th>
<th>8 Zonal, 8 Tesseral</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/C Initial Mass</td>
<td>1074 kg (maxi for PSLV XL)</td>
</tr>
<tr>
<td>Third Body</td>
<td>Moon, Earth</td>
</tr>
<tr>
<td>SRP</td>
<td>A: 7.4 m², $C_R = 1.5$</td>
</tr>
<tr>
<td>Dep. Conditions</td>
<td>GTO: 200 x 36 000 km, 18°</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>321 sec</td>
</tr>
<tr>
<td>Thrust</td>
<td>450 N</td>
</tr>
</tbody>
</table>

- Final mass > 690 kg

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>$\Delta v$ [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Departure</td>
<td>792</td>
</tr>
<tr>
<td>DSM</td>
<td>186</td>
</tr>
<tr>
<td>Arrival</td>
<td>395</td>
</tr>
</tbody>
</table>
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
      - Dynamics 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 ×10³ Km - Don Quijote’s 160-meter-wide 2002AT4 could be detected from 2500 ×10³ 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, $\Delta v$ 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
  - Approach 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

3σ ephemeris uncertainty

Range for detection

SC (early detection)

SC (late detection)
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
- Acquisition 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, Rotational 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

<table>
<thead>
<tr>
<th>Force μN</th>
<th>Variation</th>
<th>τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRP 38</td>
<td>20%</td>
<td>7 d</td>
</tr>
<tr>
<td>Recoil 3.3</td>
<td>1%</td>
<td>1 m</td>
</tr>
<tr>
<td>Gravity 1.7</td>
<td>10%</td>
<td>5 m</td>
</tr>
<tr>
<td>Impingement 20 (6)</td>
<td>20%</td>
<td>1 h</td>
</tr>
<tr>
<td>Deflection 42.3</td>
<td>20%</td>
<td>1 d</td>
</tr>
<tr>
<td>Total (trailing) 62.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (radial) 25.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**GNC Architecture and Hardware**

- **NAC**
  - Main Approach Sensor
  - Rotational State
  - Fitted with FEIC

- **WAC**
  - Proximity (LOS)
  - Calibration

- **Laser Rangefinder**
  - Low-Power, Low-weight (wrt to LIDAR, Radar)
  - Proximity – range to surface

---

**Camera**

<table>
<thead>
<tr>
<th></th>
<th>Pixel [μrad]</th>
<th>FOV</th>
<th>Range [Km] (worst case)</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galileo Avionica/ VBNC</td>
<td>200</td>
<td>70</td>
<td>10</td>
<td>0.6 kg</td>
</tr>
<tr>
<td>Marco Polo R/ NAC</td>
<td>15</td>
<td>1.7</td>
<td>30 000</td>
<td>6 kg</td>
</tr>
</tbody>
</table>

**LRF**

- Accuracy: 10 cm
- Power: <2 W
- Mass: 0.5 K
- Rate: 1 MHz
- Range: 500 m
- Bandwidth: 920 nm

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**Ground**

- Asteroid Orbital Determination
- Radiometric Measurements

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**Translational Navigation**

- Way-Point Predictive Guidance
- Station Keeping Guidance

**Attitude Determination**

- Attitude Control

**RCS**

- RCS actuator management

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**Reaction Wheels**

- RW Desaturation

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**Light Touch² – Final Review Meeting – 21-22 January 2013 – ESA/ESTEC**
GNC Architecture

- Modular
- Robust

![Diagram of GNC Architecture]
Radiometric Orbit Determination

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

![Graph showing knowledge in position over time with and without DDOR](image)

*Harwel: Reference station for Doppler measurements.
GNC Modules

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

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

\[
\begin{bmatrix}
\dot{u} \\
\dot{v}
\end{bmatrix} = M \begin{bmatrix} f, cP, cO_B \end{bmatrix} \begin{bmatrix} cV_{B/C} \\
c\omega_{B/C}
\end{bmatrix}
\]

- Invert Matrix (or LSQ, etc)

\[
\begin{bmatrix}
cV_{B/C} \\
c\omega_{B/C}
\end{bmatrix} = M(f, cP_1, cO_B) \cdots M(f, cP_N, cO_B) + \begin{bmatrix}
\dot{u}_1 \\
\dot{v}_1 \\
\vdots \\
\dot{u}_N \\
\dot{v}_N
\end{bmatrix}
\]

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

\[
p' = a \cos(\theta_1) + b \sin(\theta_1) + c \cos(\theta_2) + d \sin(\theta_2) + \\
e \cos(\theta_1 + \theta_2) + f \sin(\theta_1 + \theta_2) + g \cos(\theta_1 - \theta_2) + h \sin(\theta_1 - \theta_2) + i
\]

- 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
- \( z_{\text{est}} = [0.009 \ 0.054 \ 0.998] \);
- \( y_{\text{est}} = [0.317 \ 0.948 \ 0.000] \);
Proximity Navigation and Control

- Relative perturbed spacecraft motion described in the Hill reference frame:
  \[
  \ddot{\mathbf{x}} = -\mathbf{a}_r - 2\mathbf{v} \times \dot{\mathbf{v}} - \mathbf{v} \times (\mathbf{v} \times \mathbf{x}) - \frac{\mu_{\text{sun}}}{r_{\text{Sc}}^3} (\mathbf{x} + \mathbf{x}_{\text{e}}) - \frac{\mu_s}{\partial r^3} \mathbf{x} + \nabla U + \frac{\mathbf{F}_{\text{sc}}(\mathbf{x}, \mathbf{x}_{\text{e}})}{m_{\text{sc}}}
  \]
  
  - \(U\) second order gravity field potential
  - \(\mathbf{F}_{\text{sc}}\) force acting on the spacecraft
    - Laser recoil
    - Solar radiation pressure
    - Plume impingement

- \(a_r\) relative acceleration of the reference frame
  \[
  \ddot{\mathbf{r}}_r = -\frac{\mu_{\text{sun}}}{r_r^3} \mathbf{r}_r - \frac{\mu_{\text{sc}}}{\partial r^3} \mathbf{x}_r + \mathbf{a}_{\text{laser}}
  \]
  - tugging effect
  - \(\mathbf{a}_{\text{laser}}\) acceleration from laser ablation

- Control box to maximize the effectiveness of laser
  \[
  f' = v_{in}^{\text{est}} + \Delta v_{\text{corr}} + a_{\text{est}} t = 0
  \]
  \[
  d_f = d_{in}^{\text{est}} + (v_{in}^{\text{est}} + \Delta v_{\text{corr}}) t + a_{\text{est}} \frac{t^2}{2}
  \]
  - \(\Delta v_{\text{corr}}\) 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

- Control $\Delta v$

- Radial configuration less demanding than the trailing one

Example Trailing Configuration

Radial Configuration

Station keeping for 1 year

Control box [cm] 20 30 40 50

$\Delta v$ [m/s] 4 2 0

Trailing Configuration

Station keeping for 1 year

Box control [cm] 20 30 40 50

$\Delta v$ [m/s] 6 4 2 0
How to measure the efficiency of a deflection strategy?

Two quantities can be measured:

- Integral of the acceleration imparted onto the asteroid

\[ \delta v_1 = \int_{\text{start ablation}}^{\text{stop ablation}} \frac{F_{\text{sub}}(t)}{m_{\text{NEO}}(t)} dt \]

- 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 $\Delta v$ 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

$$\delta v_{\text{measured}} = \Phi^{-1} \delta r(t_{\text{measure}}) \quad [1]$$

- 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

Estimating $\Delta v$ 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 $\Delta v$ imparted onto the asteroid

- Proposed methods:
  - $\Delta v$ given by the integral of the acceleration from the laser ablation
    
    $$\delta v_I = \int_{\text{start ablation}}^{\text{stop ablation}} \frac{F_{\text{sub}}(t)}{m_{\text{NEO}}(t)} \, dt$$
    
    $$\delta v_I = \int_{\text{start ablation}}^{\text{stop ablation}} a_{\text{laser}}^{\text{estimated}} \, dt$$
  
  - 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

<table>
<thead>
<tr>
<th></th>
<th>Radial Configuration</th>
<th>Trailing configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control box</td>
<td>20 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Integral error</td>
<td>1.6%</td>
<td>0.68%</td>
</tr>
<tr>
<td></td>
<td>50 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td></td>
<td>1.2%</td>
<td>0.49%</td>
</tr>
</tbody>
</table>
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/m²
  - 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

Fibre | Initial collimator | 6mm diam beam | Mirror position drive | Positionable right-angle reflector |

Beam Expander telescope | Turret | 100mm diam beam |

XY Mirror mount
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 $\Delta v$
  - Limit transfer time and passes through radiation belts
  - Bipropellant propulsion system
  - Relatively high fuel mass
  - Relatively high structure mass
### Mass Budget

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

<table>
<thead>
<tr>
<th>SysNova Power Budget</th>
<th>Current Power (W)</th>
<th>Design Maturity Margin (%)</th>
<th>Maximum Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>895.0</td>
<td>19.7%</td>
<td>1071.0</td>
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<tr>
<td>GNC &amp; AOCS</td>
<td>159.3</td>
<td>8.1%</td>
<td>172.2</td>
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<tr>
<td>Data Handling</td>
<td>46.9</td>
<td>11.0%</td>
<td>52.1</td>
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<tr>
<td>Power</td>
<td>0.0</td>
<td>0.0%</td>
<td>0.0</td>
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<tr>
<td>Communications</td>
<td>57.0</td>
<td>5.0%</td>
<td>59.9</td>
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<tr>
<td>Thermal</td>
<td>40.0</td>
<td>20.0%</td>
<td>48.0</td>
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<tr>
<td>Propulsion</td>
<td>0.0</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1198.2</strong></td>
<td><strong>17.1%</strong></td>
<td><strong>1403.1</strong></td>
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<tr>
<td>PCDU</td>
<td></td>
<td></td>
<td>140.3</td>
</tr>
<tr>
<td>Harness</td>
<td></td>
<td></td>
<td>28.1</td>
</tr>
<tr>
<td><strong>Total Including PCDU and Harness</strong></td>
<td><strong>1571.5</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Power Margin</td>
<td></td>
<td>20.0%</td>
<td>314.3</td>
</tr>
<tr>
<td><strong>Total Including 20% System Margin</strong></td>
<td><strong>1885.8</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

Asteroid

Laser Electronics

Impact Sensor

Laser Rangefinder

Raman Spectrometer

Laser Optics

NAC

WAC

Sun
Trailing/Leading Configuration

- Laser Electronics
- Laser Optics
- Raman Spectrometer
- Impact Sensor
- Laser Rangefinder
- NAC
- WAC
- Asteroid
- Sun
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

<table>
<thead>
<tr>
<th>SysNova Mass Budget</th>
<th>Current Mass (kg)</th>
<th>Design Maturity Margin (%)</th>
<th>Maximum Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Handling Subsystem</td>
<td>17.1</td>
<td>10.9%</td>
<td>18.9</td>
</tr>
<tr>
<td>Power Subsystem</td>
<td>46.0</td>
<td>14.6%</td>
<td>52.8</td>
</tr>
<tr>
<td>Harness</td>
<td>25.8</td>
<td>20.0%</td>
<td>30.9</td>
</tr>
<tr>
<td>Communications Subsystem</td>
<td>37.7</td>
<td>8.8%</td>
<td>41.0</td>
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<tr>
<td>GNC &amp; AOCS Subsystem</td>
<td>44.5</td>
<td>12.6%</td>
<td>50.0</td>
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<tr>
<td>Structure and Mechanisms</td>
<td>83.0</td>
<td>20.0%</td>
<td>99.6</td>
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<tr>
<td>Thermal Subsystem</td>
<td>12.4</td>
<td>20.0%</td>
<td>14.8</td>
</tr>
<tr>
<td>Propulsion Subsystem</td>
<td>59.9</td>
<td>12.3%</td>
<td>67.3</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td><strong>20.0</strong></td>
<td><strong>19.0%</strong></td>
<td><strong>23.8</strong></td>
</tr>
</tbody>
</table>

**SPACECRAFT DRY TOTAL**

| System Mass Margin | 20%                | 79.8              |

**DRY TOTAL (incl. System Margin)**

| Propellant | 351.9 |

**SPACECRAFT WET MASS**

| Launch Adapter | 0.0 |

**WET MASS + LA**

| 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

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

<table>
<thead>
<tr>
<th>Technology</th>
<th>TRL</th>
<th>Activity</th>
<th>Target Date</th>
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</thead>
<tbody>
<tr>
<td><strong>Laser system</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRL4</td>
<td>Lab demonstration of improved diode stack efficiency</td>
<td>2014</td>
</tr>
<tr>
<td></td>
<td>TRL4</td>
<td>Coherent combining for high power high efficiency laser</td>
<td>2016</td>
</tr>
<tr>
<td></td>
<td>TRL5/6</td>
<td>Lab space qualification of fibre-diode coupled laser (vacuum, thermal, radiation tests)</td>
<td>2018</td>
</tr>
<tr>
<td></td>
<td>TRL6</td>
<td>In space testing of adaptive optics</td>
<td>2018</td>
</tr>
<tr>
<td></td>
<td>TRL7/8</td>
<td>In-space testing of fibre-diode coupled system</td>
<td>2020</td>
</tr>
<tr>
<td><strong>Ablation process</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRL4</td>
<td>Lab experiments and model completion for both ablation and contamination</td>
<td>2013</td>
</tr>
<tr>
<td></td>
<td>TRL5/6</td>
<td>In Earth orbit demonstrator with dummy asteroid.</td>
<td>2020</td>
</tr>
<tr>
<td></td>
<td>TRL7/8</td>
<td>Asteroid material extraction and analysis mission</td>
<td>2025</td>
</tr>
<tr>
<td></td>
<td>TRL8/9</td>
<td>AdAM</td>
<td>2027</td>
</tr>
<tr>
<td><strong>In-space OD</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TRL3</td>
<td>Concept demonstrated in simulation environment</td>
<td>2012</td>
</tr>
<tr>
<td></td>
<td>TRL7/8</td>
<td>Multi asteroid discovery and tracking mission</td>
<td>2024</td>
</tr>
<tr>
<td></td>
<td>TRL8/9</td>
<td>AdAM</td>
<td>2027</td>
</tr>
<tr>
<td><strong>In-space rotation estimation</strong></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>TRL3</td>
<td>Concept demonstrated in simulation environment</td>
<td>2012</td>
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<tr>
<td></td>
<td>TRL6/7</td>
<td>In Earth orbit demonstration with dummy asteroid or space debris</td>
<td>2020</td>
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<tr>
<td></td>
<td>TRL7/8</td>
<td>Multi asteroid discovery and tracking mission</td>
<td>2024</td>
</tr>
<tr>
<td></td>
<td>TRL8/9</td>
<td>AdAM</td>
<td>2027</td>
</tr>
<tr>
<td><strong>In-space deflection estimation</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>TRL3</td>
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<td>2012</td>
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<tr>
<td></td>
<td>TRL8/9</td>
<td>AdAM</td>
<td>2027</td>
</tr>
</tbody>
</table>
Follow **Stardust**, the asteroid and space debris research and training network:
www.stardust2013.eu
https://twitter.com/stardust2013eu

Questions?
Back Up - Rotation Estimate FFT Approach

- Hirai et Al. 1998:
  \[ p' = R(k_1, \theta_1)R(k_2, \theta_2)\hat{p} + p_0 \]
  \[ p' = a \cos(\theta_1) + b \sin(\theta_1) + c \cos(\theta_2) + d \sin(\theta_2) + e \cos(\theta_1 + \theta_2) + f \sin(\theta_1 + \theta_2) \]
  \[ + g \cos(\theta_1 - \theta_2) + h \sin(\theta_1 - \theta_2) + i \]
  \[ \Rightarrow i = C_1 C_3 k_1 + p_0 \]
  \[ a = -C_1 C_2 k_1 + C_3 k_2 \quad e = \{ (1 + C_1)\hat{p} + (C_1 C_3 - C_2)k_1 - (C_2 + C_3)k_2 \} / 2 \]
  \[ b = C_3 (k_1 \times k_2) \quad f = \{ -C_2 k_1 - C_3 (k_1 \times k_2) + (k_1 \times \hat{p}) + (k_2 \times \hat{p}) \} / 2 \]
  \[ c = -(C_1 C_3 - C_2)k_2 \quad g = \{ (1 + C_1)\hat{p} + (C_1 C_3 - C_2)k_1 + (C_2 - C_3)k_2 \} / 2 \]
  \[ d = C_4 k_1 \quad h = \{ C_4 k_1 - C_3 (k_1 \times k_2) + (k_1 \times \hat{p}) - (k_2 \times \hat{p}) \} / 2 \]

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

- \[ f_1 \rightarrow a = 2 / N \Re(P(f_1)) \]
  \[ f_2 \rightarrow c = 2 / N \Re(P(f_1)) \]
  \[ i = 1 / N \cdot P(0) \]
  \[ f_1 \rightarrow b = -2 / N \Im(P(f_1)) \]
  \[ f_2 \rightarrow d = -2 / N \Im(P(f_1)) \]

- \[ f_1 + f_2 \rightarrow e = 2 / N \Re(P(f_1 + f_2)) \]
  \[ |f_1 - f_2| \rightarrow g = 2 / N \Re(P(|f_1 - f_2|)) \]
  \[ f_1 + f_2 \rightarrow f = -2 / N \Im(P(f_1 + f_2)) \]
  \[ |f_1 - f_2| \rightarrow h = -2 / N \Im(P(|f_1 - f_2|)) \]

- Spin axes \( k_1, k_2 \) and centre of gravity \( p_0 \)
  \[ k_1 = \frac{e \times f}{|e|^2} \]
  \[ k_2 = \frac{(e + g + c) \times (f - h + d)}{|e + g + c|^2} \]
  \[ p_0 = \frac{(k_1 \times k_2)' \times (a \times k_1)}{|e|^2} k_2 + a + i \]
Back Up- Proximity navigation and control

- Angular velocity
  \[ \mathbf{x}_u \times (\dot{\mathbf{v}} \times \mathbf{x}_u) + 2 \mathbf{x}_u \times (\dot{\mathbf{v}} \times \mathbf{x}_u) = \mathbf{x}_u \times \mathbf{a}_{\text{laser-local}} \]

- Potential from ellipsoid body
  \[ U_{20,22} = \frac{\mu A}{\delta r^3} \left( C_{20} \left(1 - \frac{3}{2} \cos^2 \gamma \right) + 3C_{22} \cos^2 \gamma \cos 2\lambda \right) \]

- Perturbative forces
  \[ F_{\text{Solar}} = C_{k} S_{\text{srp}} \left( \frac{r_{\text{AU}}}{r_{\text{sc}}} \right)^2 A_M \frac{x_a}{r_{\text{sc}}} ; \]
  \[ F_{\text{recoil}} = \eta_{\text{sys}} S_{\text{srp}} \left( \frac{r_{\text{AU}}}{r_{\text{sc}}} \right)^2 A_M \frac{\delta x}{\delta r} ; \]
  \[ F_{\text{plume}} = \rho_{\text{plume}} (\delta r) \mathbf{v}_{\text{plume}}^2 (\delta r) A_{eq} \frac{\mathbf{x}}{\delta r} \cdot \mathbf{i} \]

- Number of actuations

![Trailing Configuration](image1)

![Radial Configuration](image2)

Back Δv imparted onto the asteroid

- Gauss’ equations
  \[
  \delta a = \frac{2a^2}{\mu} \delta v_i \\
  \delta e = \frac{1}{e} \left[ 2(e + \cos f) \delta v_i - \frac{r}{a} \sin f \delta v_n \right] \\
  \delta i = \frac{r \cos \vartheta}{h} \delta v_{ih} \\
  \delta \Omega = \frac{r \sin \vartheta}{h \sin i} \delta v_{ih} \\
  \delta \omega = \frac{1}{e v} \left[ 2 \sin f \delta v_i + \left( 2e + \frac{r}{a} \cos f \right) \delta v_n \right] - \frac{r \sin \vartheta \cos i}{h \sin i} \delta v_{ih}
  \]

- Variation in mean anomaly

\[
\delta M = -\frac{b}{e a v} \left[ 2 \left( 1 + \frac{e^2 r}{p} \right) \sin f \delta v_i + \frac{r}{a} \cos f \delta v_n \right] + \Delta n \left( t_{MOID} - t_d \right)
\]
Back $\Delta v$ imparted onto the asteroid

\[
\begin{align*}
\delta r(t_{\text{measure}}) &= A_{\text{measure nominal}} \delta \alpha(t_{d-\text{measure}}) \\
\delta \alpha(t_{d-\text{measure}}) &= G_d \delta v(t_d)
\end{align*}
\]

Proximal motion between nominal and deviated

Gauss’ equations (also orbit perturbation can be included)

\[
\delta r(t_{\text{measure}}) = T \delta v(t_d) \quad \quad \quad \delta v(t_d) = T^{-1} \delta r(t_{\text{measure}})
\]

Get $\Delta v$ Measure position displacement

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

<table>
<thead>
<tr>
<th>Error</th>
<th>OD after 30 days</th>
<th>OD after 60 days</th>
<th>OD after 90 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error 1</td>
<td>0.025899 ±0.001112</td>
<td>0.06877 ±0.00071162</td>
<td>0.12086 ±0.00053259</td>
</tr>
<tr>
<td>Error 2</td>
<td>0.028674 ±0.0026812</td>
<td>0.069602 ±0.0014648</td>
<td>0.12194 ±0.0011782</td>
</tr>
<tr>
<td>Error 3</td>
<td>0.077114 ±0.015354</td>
<td>0.087915 ±0.010835</td>
<td>0.13626 ±0.012386</td>
</tr>
<tr>
<td>Error 4</td>
<td>0.035589 ±0.006973</td>
<td>0.074227 ±0.0032254</td>
<td>0.12588 ±0.0024126</td>
</tr>
</tbody>
</table>
GNC-Estimating $\Delta v$ 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 789-3760 kg dependent on altitude and inclination of orbit
- The LISA PRM could be used in 2 ways:
  1. To provide all of the $\Delta v$ to escape
     - Would need significant modification to accommodate fuel mass
  2. To provide as much $\Delta v$ 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

<table>
<thead>
<tr>
<th>SysNova Mass Budget</th>
<th>Current Mass (kg)</th>
<th>Design Maturity Margin (%)</th>
<th>Maximum Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Handling</td>
<td>17.1</td>
<td>10.9%</td>
<td>18.9</td>
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<td>Power</td>
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<td>Communications</td>
<td>37.7</td>
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<td>GNC &amp; AOCS</td>
<td>39.5</td>
<td>7.9%</td>
<td>42.5</td>
</tr>
<tr>
<td>Structure and</td>
<td>100.0</td>
<td>20.0%</td>
<td>120.0</td>
</tr>
<tr>
<td>Thermal</td>
<td>13.0</td>
<td>20.0%</td>
<td>15.6</td>
</tr>
<tr>
<td>Propulsion</td>
<td>59.9</td>
<td>12.3%</td>
<td>67.3</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td><strong>35.5</strong></td>
<td><strong>19.4%</strong></td>
<td><strong>42.4</strong></td>
</tr>
<tr>
<td><strong>SPACECRAFT DRY TOTAL</strong></td>
<td><strong>371.4</strong></td>
<td><strong>15.2%</strong></td>
<td><strong>427.9</strong></td>
</tr>
<tr>
<td>Harness</td>
<td>30.0</td>
<td>20.0%</td>
<td>35.9</td>
</tr>
<tr>
<td><strong>DRY TOTAL (incl. Harness)</strong></td>
<td><strong>463.8</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Mass Margin</td>
<td></td>
<td>20.0%</td>
<td>92.8</td>
</tr>
<tr>
<td><strong>DRY TOTAL (incl. 20% System Margin)</strong></td>
<td><strong>556.6</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propellant</td>
<td></td>
<td></td>
<td>442.2</td>
</tr>
<tr>
<td><strong>SPACECRAFT WET MASS</strong></td>
<td></td>
<td></td>
<td>998.8</td>
</tr>
<tr>
<td>Launch Vehicle Capability - PSLV GTO</td>
<td></td>
<td></td>
<td>1074.0</td>
</tr>
<tr>
<td>Launch Vehicle Margin - PSLV GTO</td>
<td></td>
<td></td>
<td>75.2</td>
</tr>
<tr>
<td><strong>Mass Margin % - PSLV GTO</strong></td>
<td></td>
<td></td>
<td><strong>7.0%</strong></td>
</tr>
</tbody>
</table>
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)
- Development of flight model
- Debris Removal Mission
- Ground test in GNC system (PLATFORM)
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)**

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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
- 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-stable 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 $\Delta$position = 1m. $\Delta$velocity = 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