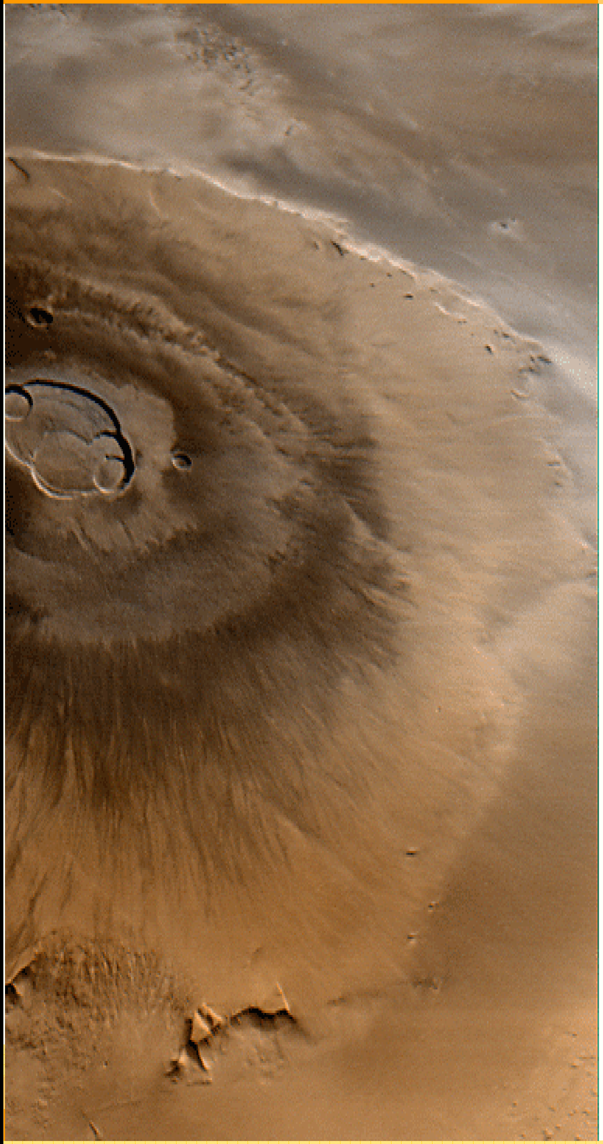

Small Body Proximity Operations Autonomous GNC Concepts Based on Novel Gravitational Field Modelling and Estimation Techniques

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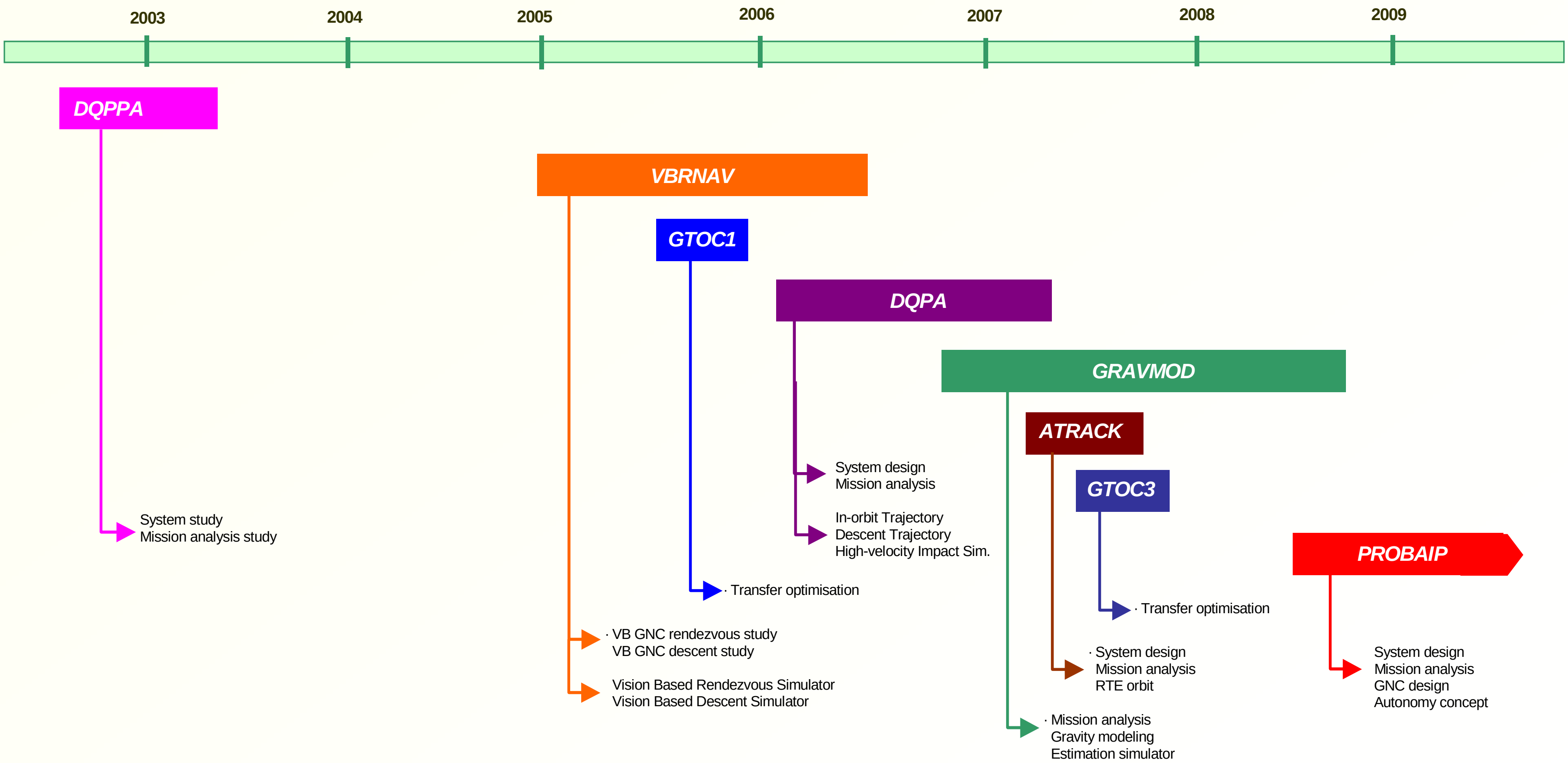
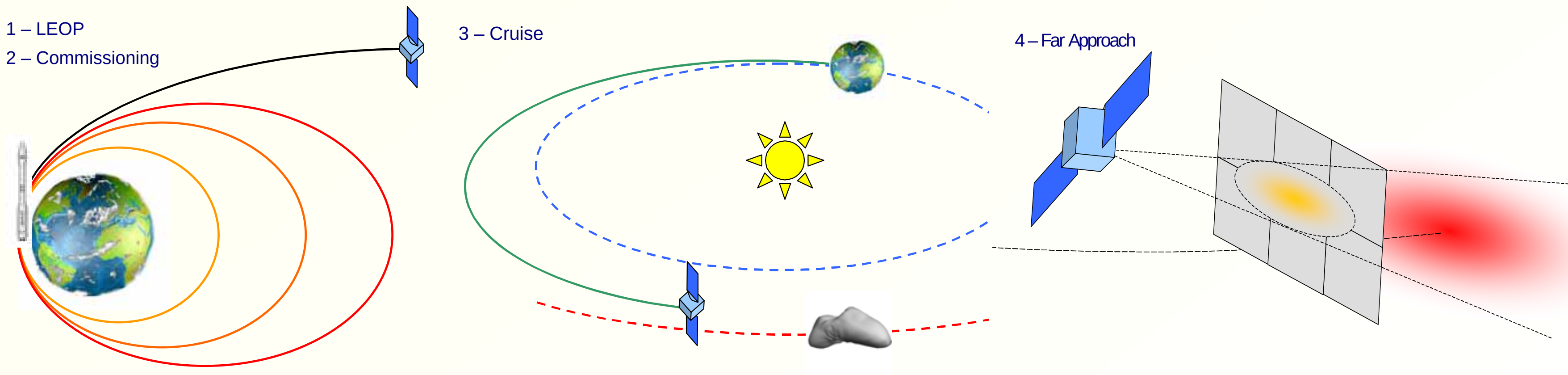
Outline

- **Asteroid Proximity Operations Autonomy Concepts**
  - Small bodies proximity operations
  - Autonomous GNC concepts for proximity operations
  - In-orbit autonomous GNC challenges
- **Gravitational Field Modelling and Estimation**
  - Small body gravitational field needs and challenges
  - Gravitational field modelling techniques
  - Gravitational field estimation techniques
  - GRAVMOD Tool
- **Application of Gravitationl Field Techniques**
  - Application for in-orbit operations
  - Application for descent trajectories
- **Conclusions**

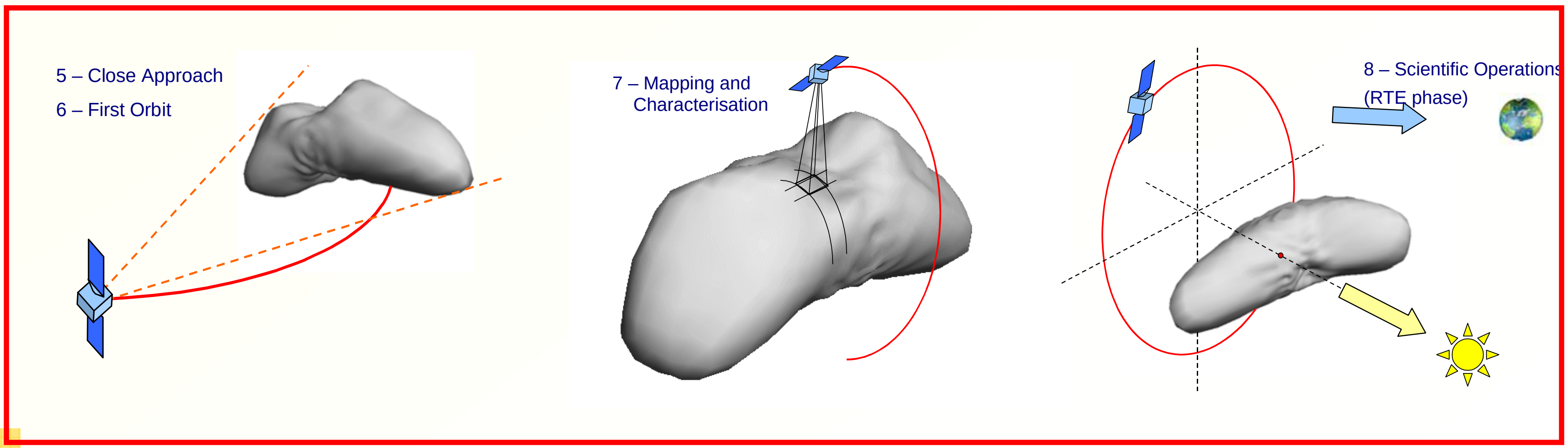
DEIMOS NEO Technology Related Activities



Small Body Mission Phases



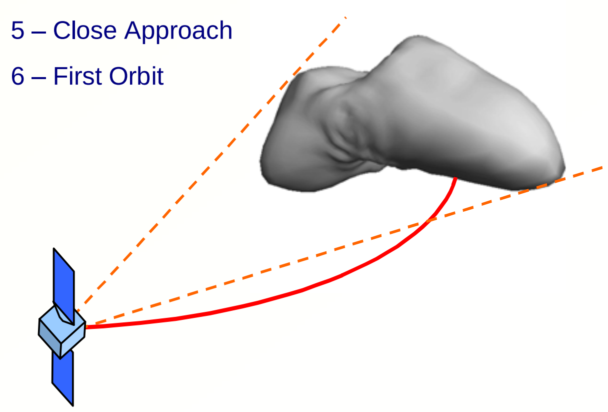
Proximity Operations



Autonomous GNC requirements

– Autonomous GNC during close approach and insertion:

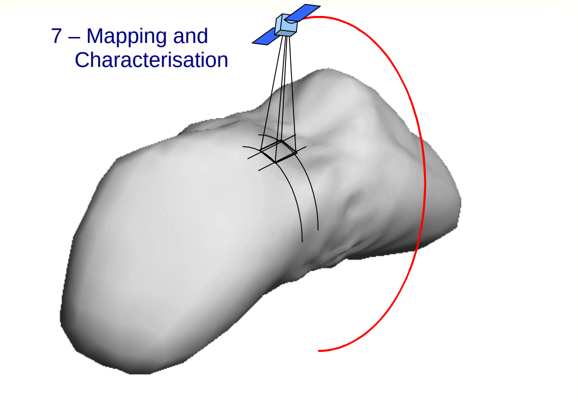
- Steering trajectory to the asteroid
- Inserting in asteroid safe orbit
- Autonomy requirements on:
  - ✓ Asteroid and S/C ephemerides generation
  - ✓ Target asteroid imaging planning and execution
  - ✓ Image processing (extended objects)
  - ✓ Navigation filtering
  - ✓ Approach guidance laws
  - ✓ Collision avoidance strategies

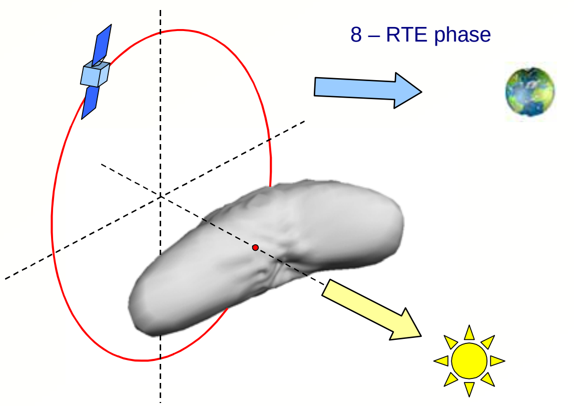


Autonomous GNC requirements

– Autonomous GNC during in-orbit operations:

- Safe orbiting
- Asteroid mapping
- Scientific orbits demonstration
- Autonomy requirements on:
  - ✓ S/C ephemerides generation
  - ✓ Mission planning and execution
  - ✓ Image processing of extended objects and landmarks
  - ✓ Navigation filtering
  - ✓ Orbit maintenance strategies
  - ✓ Collision avoidance strategies

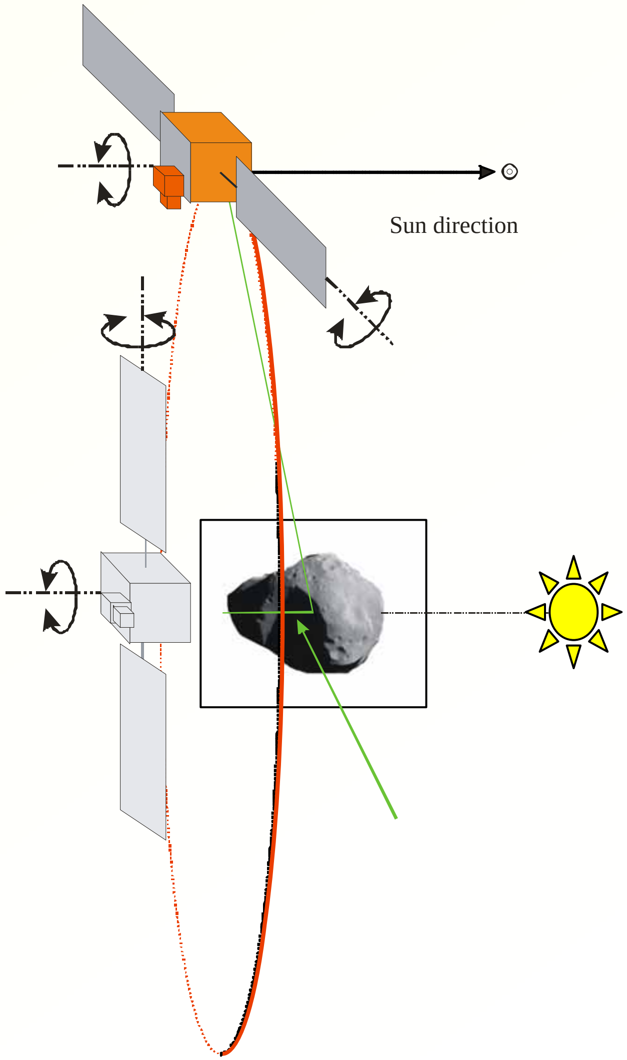




Strategies for In-Orbit Operations

– **Strategies for in-orbit operations:**

- Orbiting:
  - ✓ Stable photo-gravitational terminator-plane orbits for small sized asteroids
  - ✓ Frozen asteroid orbit-plane orbits (highly eccentric for small bodies)
  - ✓ Stable equatorial retrograde orbits for larger sized bodies
  - ✓ Non-stable orbits controlled with propulsion (polar, equatorial, etc.)
- Hovering:
  - ✓ Both body-fixed and inertial hovering are technologically feasible (Hayabusa)



– Proximity Operations Autonomous GNC challenges

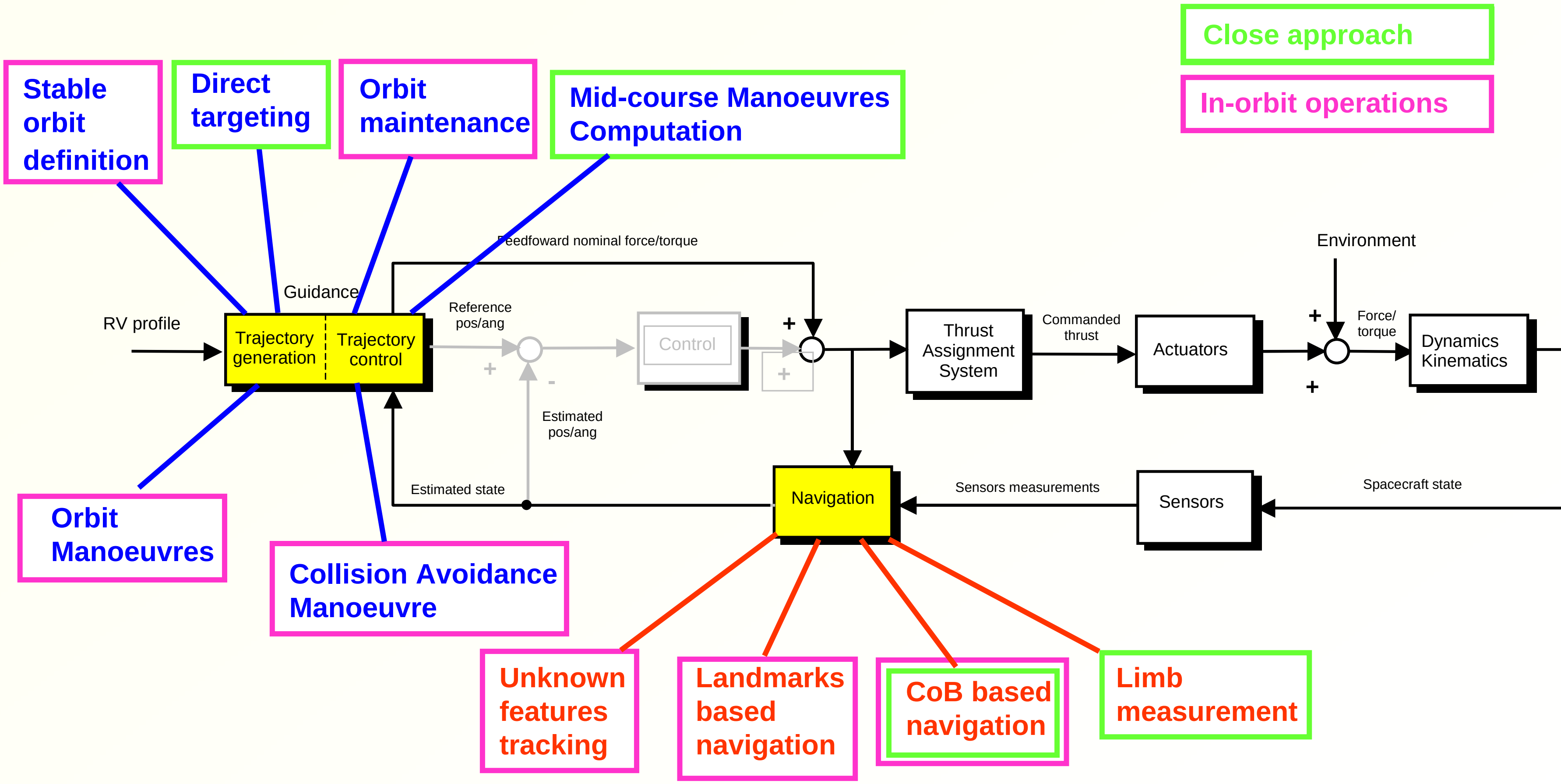
- The uncertain knowledge of target characteristics
  - ✓ Orbit size
  - ✓ Mass
  - ✓ Rotational state
  - ✓ Gravity field
- Highly perturbed dynamic environment:
  - ✓ Very irregular gravity field, second order and degree terms may cause relevant perturbations
  - ✓ Solar Radiation Pressure (SRP), particularly relevant for smaller asteroids with orbits closer to the Sun
  - ✓ Sun third body perturbation (solar tide)
- The Orbiter low altitude
  - ✓ Increases the collision risks
  - ✓ Imposes imaging constraints

• Trade-off in-orbit Navigation Concepts

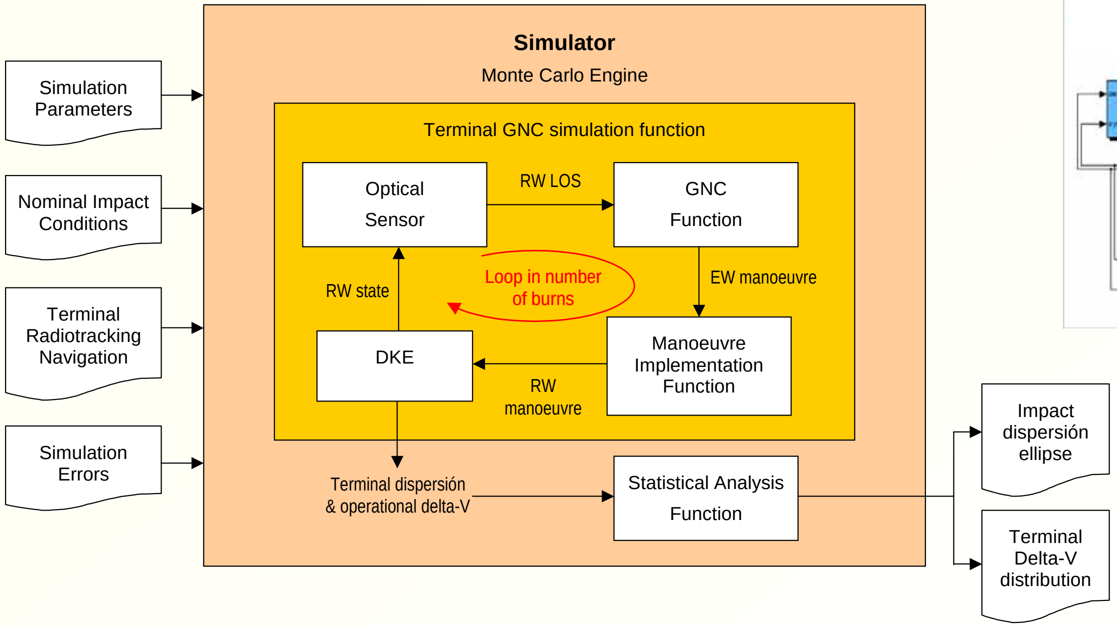
Technology	Advantages	Disadvantages	Comments
Inertial navigation	Simple implementation	Poor navigation performance due to bad estimation of horizontal velocity.	Simple and well known for descent and landing. Requires IMU. Poor performances
COB-based navigation	Simple implementation	The camera FOV shall contain the entire asteroid	It can be used only far away from the target body
Limb measurement	It can work even if the asteroid is larger than the FOV	Complex (and unknown) shape of asteroid	Very complex validation. It can be used most of all for planet approach
Camera + Radiotracking navigation	Does not strictly requires altimeter or range finder, high TRL	It is not autonomous.	It is safe, proven but not autonomous
Unknown landmark tracking	Good performance in navigation, high TRL	Feature point tracking HW required Possibly also altimeter	Complex validation versus various illumination conditions, asteroid rotation, etc. Technology is TRL 4-5
Landmarks based navigation	Best accuracy Instantaneous measurement	Intensive use of on-board resources	Requires characterization of the target body

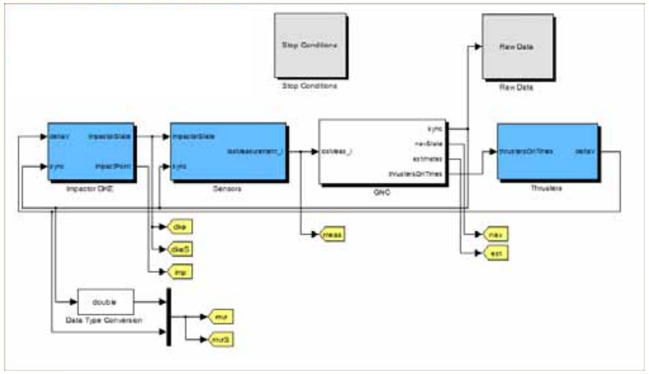
Proximity Operations GNC Concept

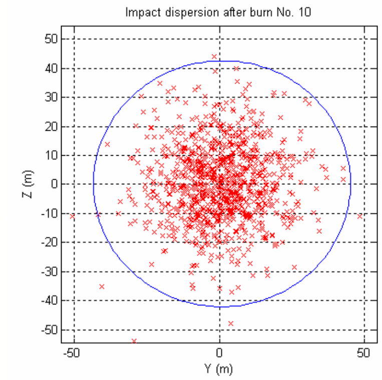
- **Addressed proximity operations GNC concept**



– Small Bodies Proximity Operations Simulator





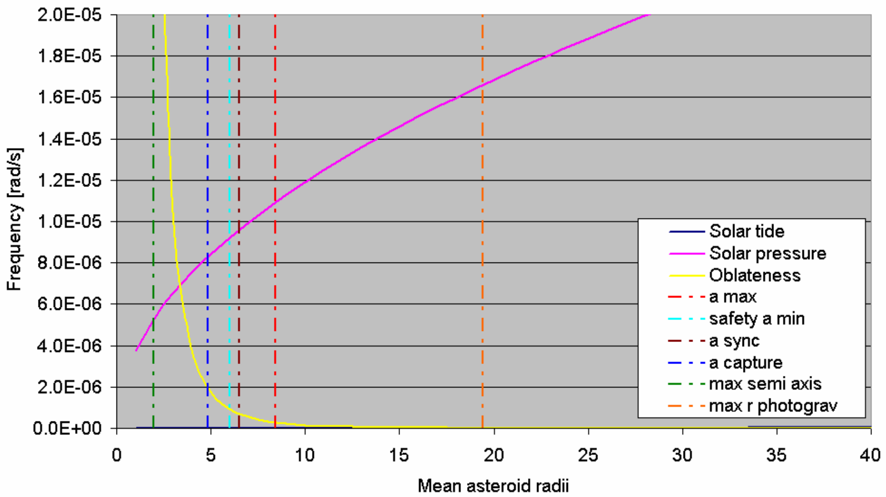


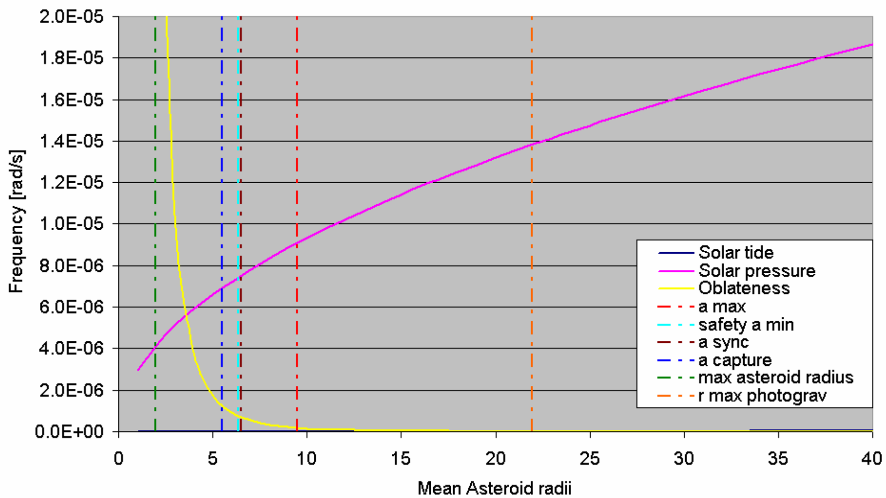
Example of Asteroid Dynamic Environment

Parametric stability analysis: Apophis

Small asteroid (Upper plot)	
Smaller semi-axis [m]	70.29
Larger semi-axis [m]	196.81
Mean radius [m]	99.07
Mass [kg]	1.30E+10
Large asteroid (Lower plot)	
Smaller semi-axis [m]	89.79
Larger semi-axis [m]	251.42
Mean radius [m]	126.56
Mass [kg]	2.72E+10

- For both cases the slow rotation period (high resonance radius) is a major issue
- Even the photo-gravitational terminator-plane orbits may require control





– Asteroids Gravitational Field Challenges

- Gravitational characteristics of Asteroids
  - ✓ Not very detailed or even known before in-situ observations
  - ✓ Preliminary geometrical information from Earth-based images
- A successful mission requires gravity models for:
  - ✓ Far approach
  - ✓ Close approach
  - ✓ In-orbit operations
  - ✓ Descent and landing operations
- Fidelity of gravitational representation impacts on:
  - ✓ Mission design
  - ✓ System-level budgets and margins
  - ✓ GNC design and performances
  - ✓ Scientific operations

Role of Gravitional Fields

- **Pre-flight**
  - Preliminary derivation of Gravitational Fields:
    - ✓ Regular bodies → Geometrical models
    - ✓ Irregular bodies → Parametric representations
  - Simulation of S/C orbit and measurements and obtention
    - ✓ Estimated Gravity Field (Spherical Harmonics)
    - ✓ Achievable accuracy of the estimated Gravity Field
    - ✓ Analysis of parameters defining a future mission in order to achieve an expected accuracy → requirements on GNC
- **Mission operations**
  - Processing of real data to derive a representation of a gravity field with a given degree of accuracy
    - ✓ Generation of gravitational models suitable for on-board processing
    - ✓ Periodical updates of both on-board and ground gravity representation
- **Post-flight**
  - Post-processing of scientific data

Gravitational field modelling techniques

- **Gravitational field model:**
  - Mathematical representation of the actions produced by a gravity field
- **Different methods are suitable:**
  - Geometrical
    - ✓ Based on surface integrals for all faces of a polyhedron
  - Multiple Point Mass Modelling
    - ✓ Potential expressed as a sum of ‘point masses’
    - ✓ It presents clear advantages → suitable for very complex shapes
    - ✓ Body is replaced by a topologically different body:
      - » High discontinuities in density
    - ✓ Geometry is one of the first measurements taken on target bodies
  - Spherical Harmonics Expansion
    - ✓ Harmonic potential function outside the attracting body → $\Delta V(x, y, z) = 0$
    - ✓ Expansions as solution of Laplace equation in different coordinate systems
    - ✓ Solving Laplace equation in spherical coordinates → Legendre polynomials

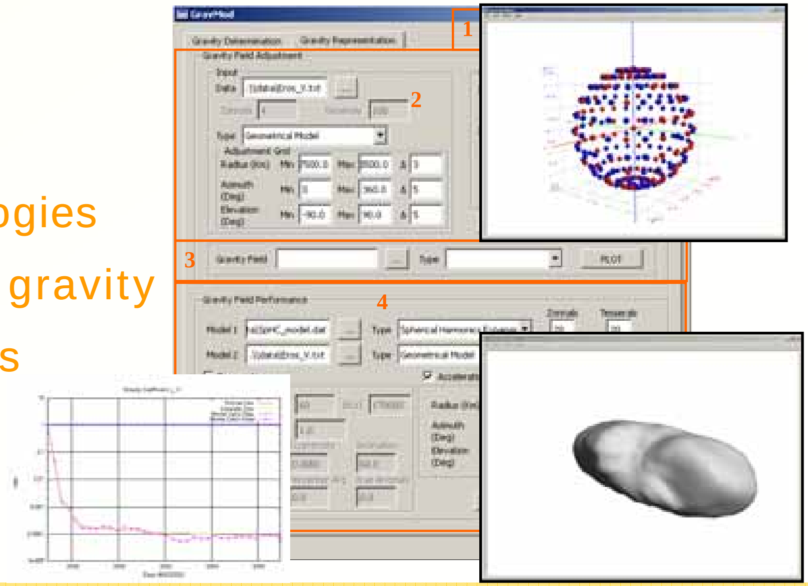
Gravitational field estimation techniques

– **Objective:**
- Determation of gravitational fields from satellite tracking data
- It requires the following capabilities:
  - ✓ Precise orbit propagation
  - ✓ Measurements pre-processing and generation
  - ✓ Filtering scheme → Estimation of the parameters associated to a given representation of the gravity field

– **Two levels of applicability:**
- Mission design with simulated/synthetic tracking data
  - ✓ Definition of reference trajectory
  - ✓ Determination of guidance profile
  - ✓ Derivation of requirements and performance on GNC system
- Operations with real data
  - ✓ Refinement of gravity field model based on measurements

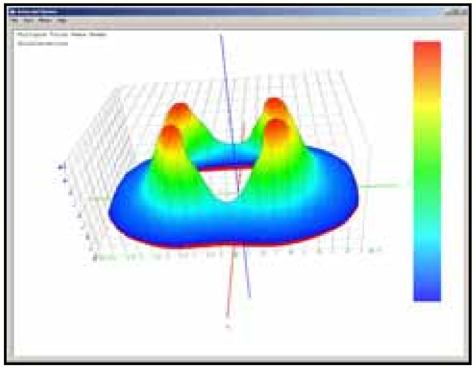
The GRAVMOD Tool

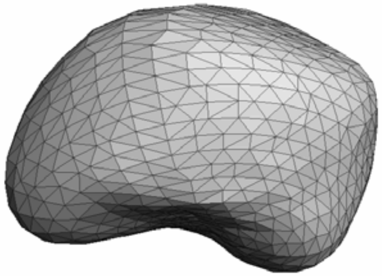
- **GRAVMOD is a SW tool allowing:**
  - Modelling and comparison of different gravity field representations
  - Computation of gravity fields
  - High accuracy propagation of orbits about irregular bodies
- **GRAVMOD comprises two mutually inter-related modules:**
  - **Representation Module**, mathematical way in which the actions produced by a gravity field are represented:
    - ✓ Spherical Harmonics
    - ✓ Multiple Point Masses
    - ✓ Geometrical representation
  - **Determination Module**, methodologies allowing the optimal estimation of a gravity field once a mission around a body is defined
    - ✓ From simulated data
    - ✓ Obtained from real data

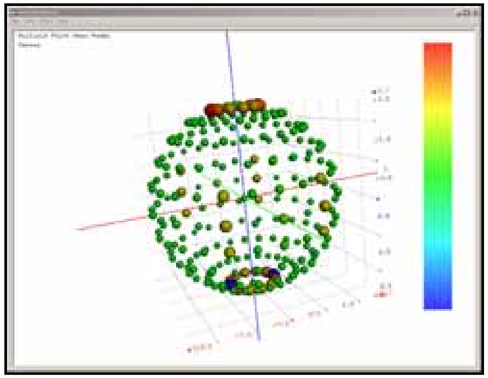


Representation Module

- **Gravity Representation module :**
  - Comparing different gravity representations of the same field
  - Computing the field that best fits to a set of external measurements
- **Two possible operation modes:**
  - Gravity Field Adjustment → Computation of the field that better fits:
    - ✓ Gravity field specification
    - ✓ Set of external accelerations
  - Gravity Field Performance Evaluation
    - ✓ Comparison of performances of several gravity fields in terms of accelerations and propagation capabilities
    - ✓ Accuracy, Efficiency and Computational effort → for O/B implementation



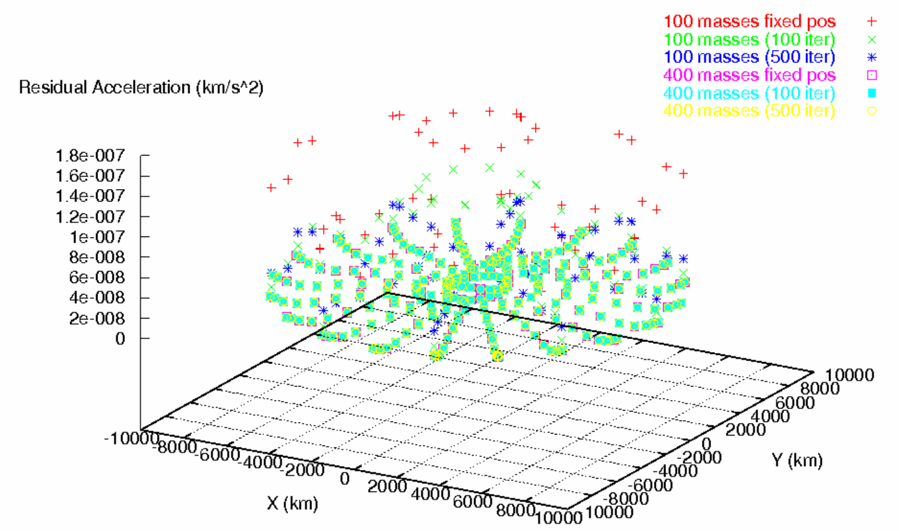


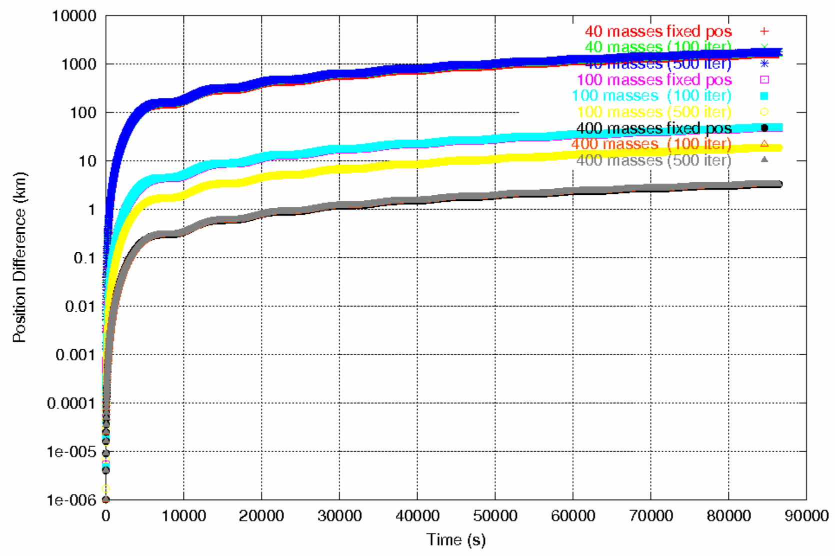


Gravity Field Representation Comparison

– Gravity Field Performance Comparison

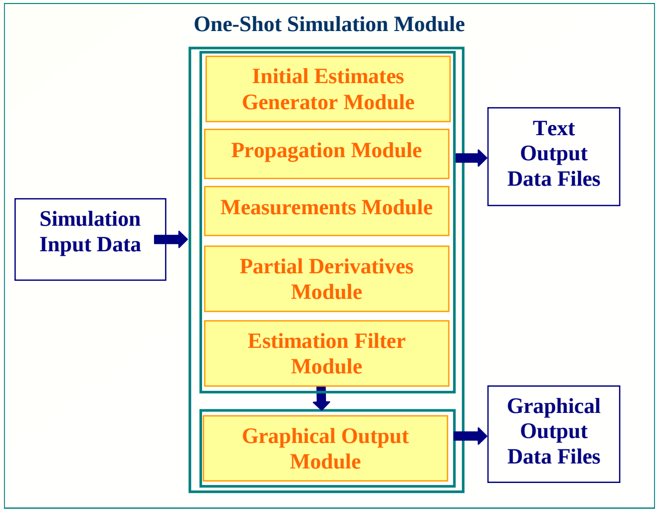
- MPM vs. Spherical Harmonics Coefficients
  - ✓ Accelerations comparison
  - ✓ Position and velocity accuracy





Determination Module

- **It derives coefficients of a gravitational representation by using satellite tracking data and a filtering scheme**
- **It comprises high-fidelity simulation of:**
  - Satellite dynamics → precise orbit propagation
  - Environment → measurements generation
- **Estimation scheme based upon two main modes:**
  - One-Shot Mode:
    - ✓ Covariance Analysis
    - ✓ Full determination process of a single shot
  - Monte-Carlo Mode:
    - ✓ Executions based on initial random variables
    - ✓ Statistical analysis of most important figures

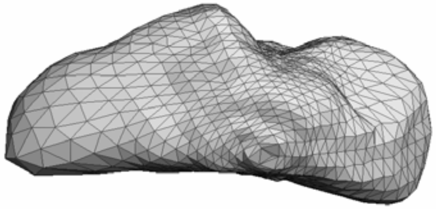


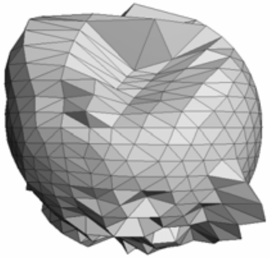
- **Main output consists of:**
  - Estimated gravity field and associated accuracy
  - Propagated orbit and measurements considered in the process

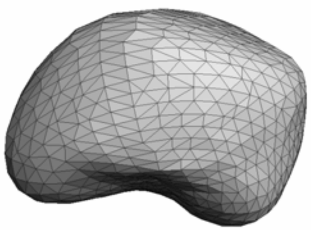
Examples

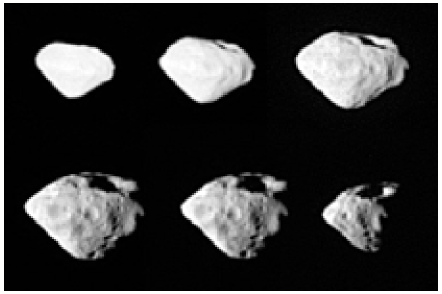
– From Geometrical to Spherical Harmonics Model

- Normalised spherical harmonics up to 6th order and degree
- Eros Geometry from NEAR Shoemaker Laser Rangefinder
  - ✓ 809 discretisation points
- Mathilda
  - ✓ Geometry given by 7381 discretisation points
- Deimos
  - ✓ Geometry given by 3829 discretisation points
- Steins
  - ✓ Diamond shaped (5.9x4 km)
  - ✓ Random errors added to radii in order to obtain more realistic results









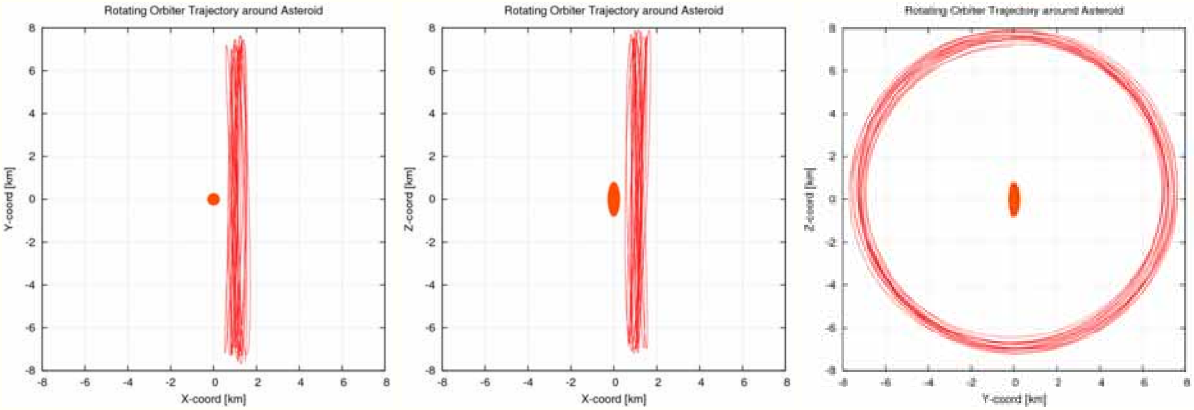
– **Examples of treated gravitational fields models :**

- Quasi-regular bodies:
  - ✓ Mercury → Kaula's rule
  - ✓ Europa → Kaula's rule
  - ✓ Venus → simulated mission
  - ✓ Earth → simulated mission
  - ✓ Mars → simulated mission
  - ✓ Moon → simulated mission
- Irregular bodies:
  - ✓ Eros → Geometrical to spherical harmonics
  - ✓ Deimos → Geometrical to spherical harmonics
  - ✓ Mathilde → Geometrical to spherical harmonics
  - ✓ Comet Churyumov-Gerasimenko → Geometrical to spherical harmonics
  - ✓ Asteroid Steins → Geometrical to spherical harmonics

Application for In-orbit Operations

– Orbiter at Apophis in a photo-gravitationally stable orbit

- Locating the Orbiter in a self-stabilized orbit for long time (~180 days)
- It does not require correction burns
- It presents a stable dynamic environment



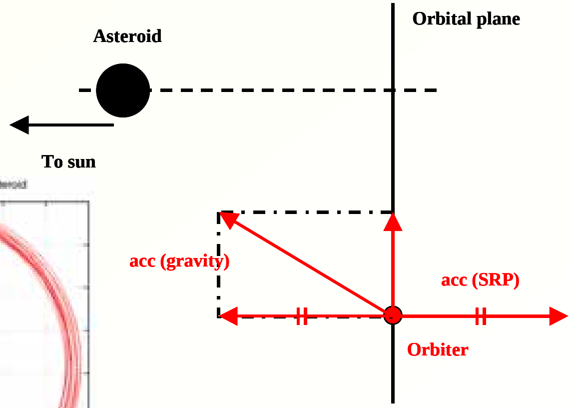


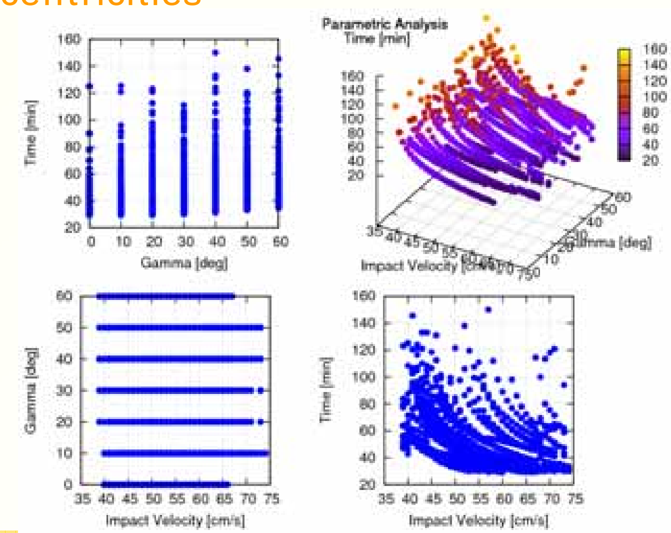
Foto-gravitational equilibrium

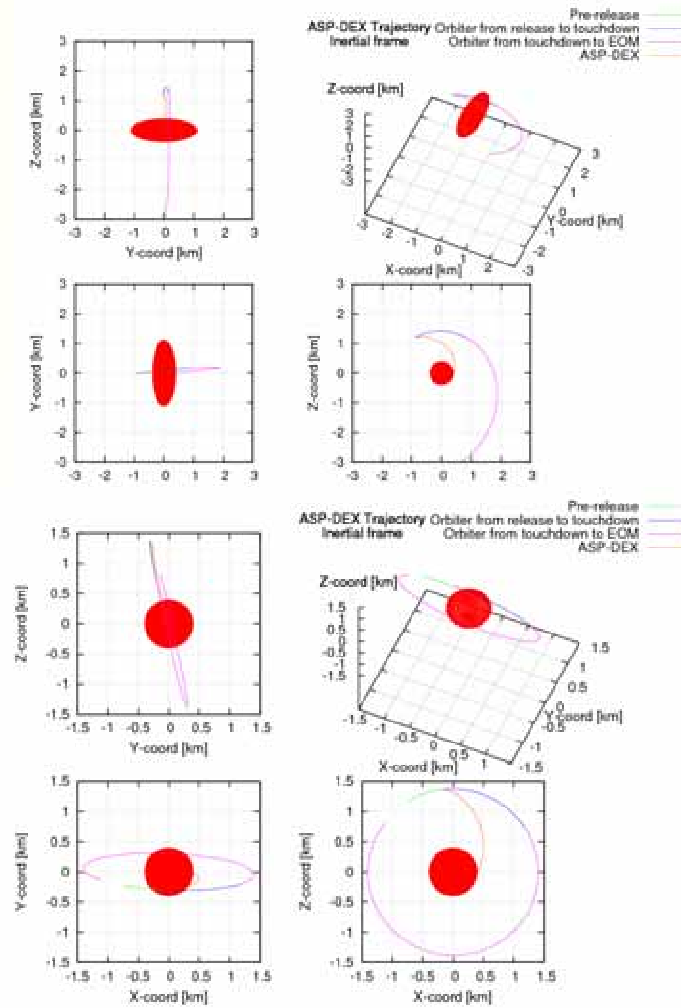
– Knowledge of gravitational field is of paramount importance

- Stability is result of equilibrium between gravity and solar radiation
- Non-homogeneities of gravitational field impacts:
  - ✓ Long-term stability
  - ✓ Minimum altitude above NEO surface

Application for Descent Trajectories

- **Descent module for Don Quijote mission (phase A)**
  - Ellipsoid asteroid
  - Equatorial landing site
- **Mission scenario**
  - Passive and self-stabilised free-fall
- **Gravitational field up to 4th order**
  - Spherical configurations calls for circular orbits, while ellipsoid might require big eccentricities





– Conclusions

- Small Body missions GNC for proximity operations require precise and well known gravity models for...
  - ✓ Pre-flight for mission and GNC design
  - ✓ Operations for on-board autonomous GNC
  - ✓ Post-flight for performance analysis and scientific return
- Different gravitational models can be used depending on the mission phase and requirements
  - ✓ Geometrical Model
  - ✓ Multiple Point Mass Modelling
  - ✓ Spherical Harmonics Expansion
- GRAVMOD is a SW tool allowing:
  - ✓ Comparison between several different methods for gravity modelling;
  - ✓ Computation of gravity fields;
  - ✓ High accuracy propagation of orbits about irregular bodies
- Application
  - ✓ In-orbit operation GNC
  - ✓ Descent and landing GNC

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