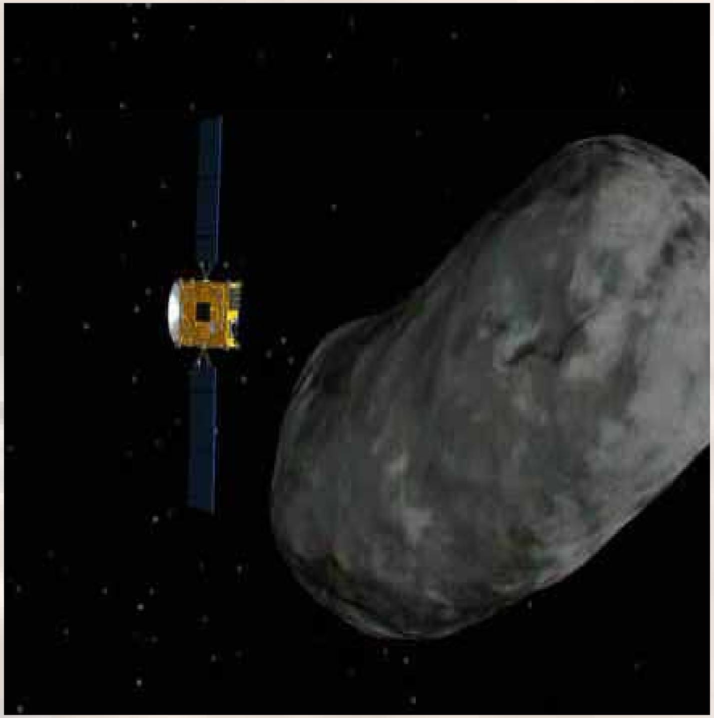

A-TRACK

A MISSION TO TAG ASTEROID APOPHIS

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Agenda

- **The Apophis Mission Design Competition**
- **Mission Scenario**
  - Mission Concept Selection
  - Minimal Mission Requirements
  - Apophis Properties
  - Mission Analysis
  - System Design
  - Operations Concept and Ground Segment
  - Tracking Strategies
  - Programmatics
- **Conclusions**

The Apophis Mission Design Competition

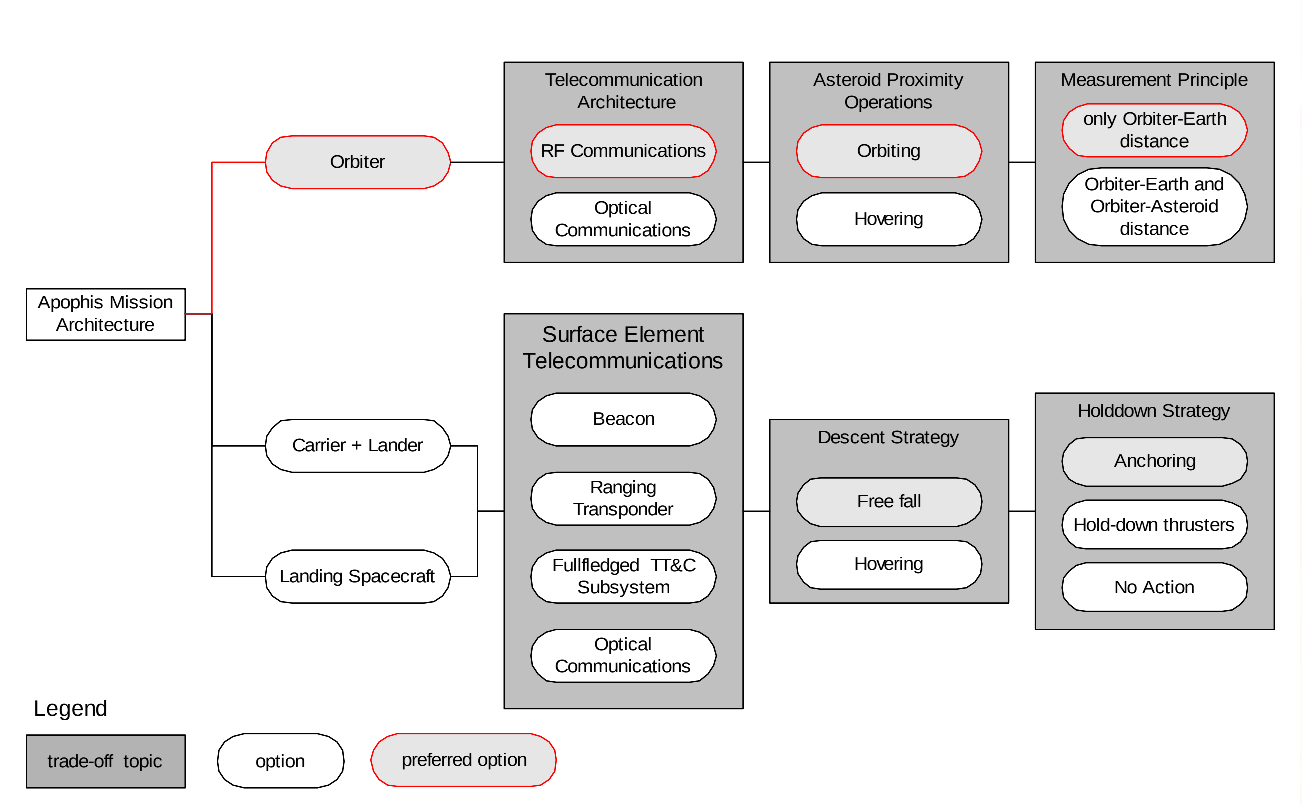
- **International competition promoted by the Planetary Society to develop ideas of missions to study Apophis**
- **DEIMOS Space formed a consortium with EADS Astrium in Germany, University of Pisa (Italy) and University of Stuttgart (Germany) for the preparation of a joint proposal:**
  - DEIMOS: Mission analysis, Operations and RTE
  - Astrium: Platform design and Launcher selection
  - Univ. Pisa: Support to scientific design
  - Univ. Stuttgart: Support to platform design
- **The Planetary Society has awarded the second prize of the contest to DEIMOS Space's consortium for its "A-Track" proposal**

The Apophis Mission Design Competition

- **The overall concept is based upon a dedicated orbiter in a so-called "foto-gravitational" orbit about Apophis that will actually allow determining the asteroid's orbit with high precision**
- **With this approach it is feasible to ascertain whether Apophis will pass by the daunting keyhole that would put it in collision path to Earth.**

Mission Concept Selection

- **Potential measurement concepts for an Apophis OD mission**
  - Surface element → carrier+lander / landing spacecraft
  - Orbiter



Mission Requirements

- **A minimum set of mission requirements were derived from the contest rules**

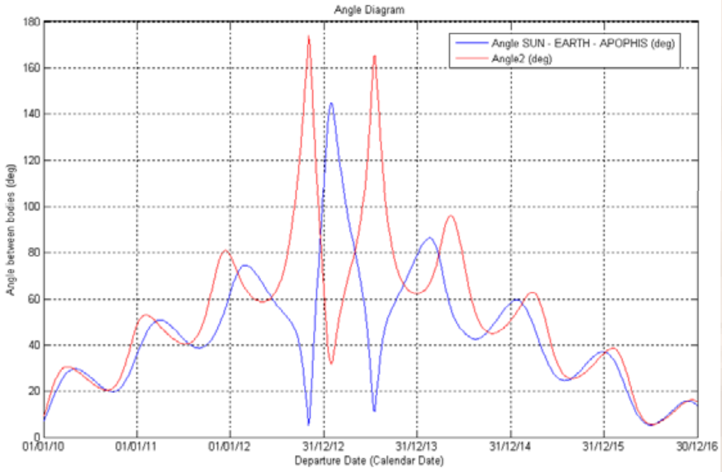
Mission Parameter	Value	Remarks
First launch date	Start of 2010	Assuming a minimum of 2 years for the development of the spacecraft, the earliest launch date could be at start of 2010
Mission end	End of 2016	2017 is specified in the contest rules as the latest year for the completion of the assessment mission and then allow a decision on the deflection mission
Last arrival date to asteroid	End of June 2016	Assuming a minimum 6 month period of tracking activity at Apophis and the 2017 deadline for the whole mission
Apophis tracking accuracy	Long dimension of 3σ error ellipse less than 14 km	Needed to prompt governments to launch a deflection mission as given in contest rules.
Mission complexity	Minimum	For development and cost reasons, minimum mission complexity shall be pursued
Cost	Minimum	Mission design shall ensure that optimal cost paths are followed in all fields to achieve an overall minimum mission cost (e.g. launcher, development, operations, etc.)

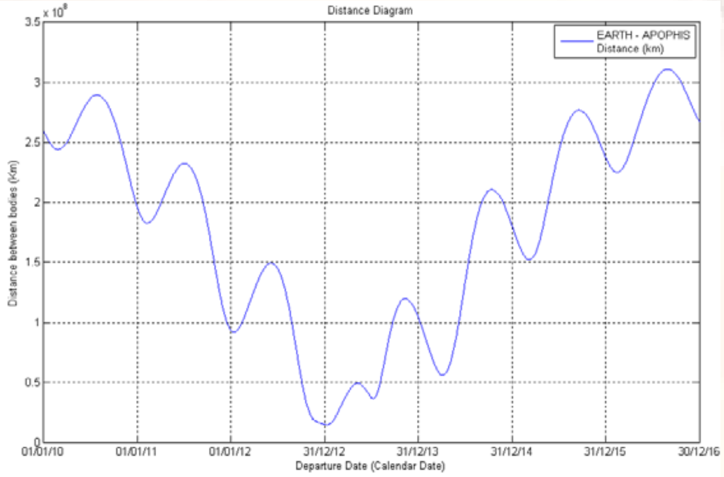
Apophis Characterisation

- **Orbital Properties**
  - 2010-2016 timeframe ≈ a synodic period
  - Solar conjunctions → 0 superior + 2 inferior

Feature	Value
Period (y)	0.886
Semi-major axis	0.922
Eccentricity	0.191
Inclination (deg)	3.33
R.A. of Ascending Node (deg)	204.5
Argument of perihelion (deg)	126.4
Synodic period (y)	7.772
Superior conjunctions	None in the period

- **Earth-Apophis distance between 0.3 and 3 AU**





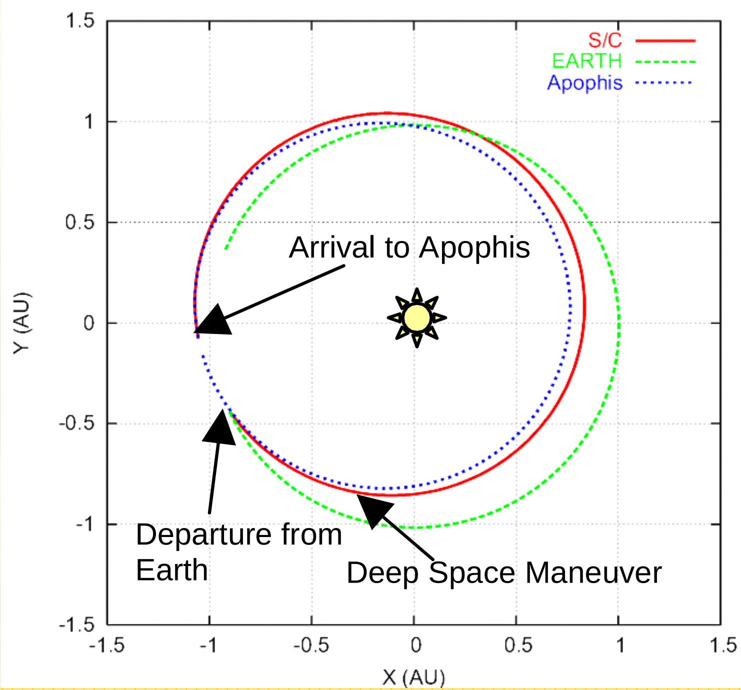
- **Physical Properties**
  - Principal axis rotator
  - Prolate spheroid (a>b≈c)

- **Additional Assumptions and Constraints**
  - Minimum Earth and Venus swing-by height of 300 km, in case swingbys are needed in transfer
  - Minimum Sun distance of 95% of the minimum Venus distance w.r.t. the Sun (this to comply with S/C design thermal constraints)
- **Most important performance figure of merit for the mission design is the goal to determine the long dimension of the 3σ error ellipse with accuracy of less than 14 km by 2017**
  - This will allow prompting the governments to launch a deflection mission if needed

Mission Analysis

- **Mission Options**
  - Tracking philosophy
    - It affects to the type of operational approach for the accurate determination of the asteroid orbit about the Sun.
    - Options: **tracking from orbit** or **tracking from the surface**.
  - Propulsion system selection
    - It affects the system design and the transfer to Apophis.
    - Options with **chemical** and **low-thrust** propulsion were considered.
    - Chemical propulsion was selected due to:
      - Higher level of maturity compared to electrical propulsion (EP) systems
      - EP system would not help much in reducing the useful mass at Apophis
  - Launcher selection
    - Medium size launchers → **Delta II**, **Soyuz**
    - Delta II was found to be the smallest suited launcher
      - To be revisited with NASA's recent announcement to phase out the Delta II by 2009
  - Earth escape strategy
    - Closely linked to the propulsion system selected
    - Options: **direct escape** and **escape from HEO**
    - Escape from HEO favors selection of a smaller launcher and the design of a spacecraft compatible with current designs at EADS Astrium → **cost savings**

- **Transfer to Apophis**
  - Analysis based on the use of a global search method of trajectory solutions → it allows considering missions with varied constraints and intermediate application of a DSM (optimized), gravity assist maneuvers (GAM) and both direct and delayed transfers to the target.
  - Departure from GTO orbit (185 km×35786 km×28.7º)
  - Delta II 7926 launcher → Payload mass in GTO is: 1660 kg
  - Baseline mission launched in April 2013
  - Back-up mission launched in March 2014
  - Escape from GTO
    - Own propulsion system
  - Transfer with DMS:
    - Direct for baseline
    - Delayed for back-up
  - Total mission duration:
    - 1.45 years for baseline
    - 1.86 years for back-up



Tracking Operational Orbit

- **Orbiter at Apophis in a photo-gravitationally stable orbit**
  - Locating the Orbiter in a self-stabilized orbit for long time (~180 days) that do not require of correction burns and presents a stable dynamic environment

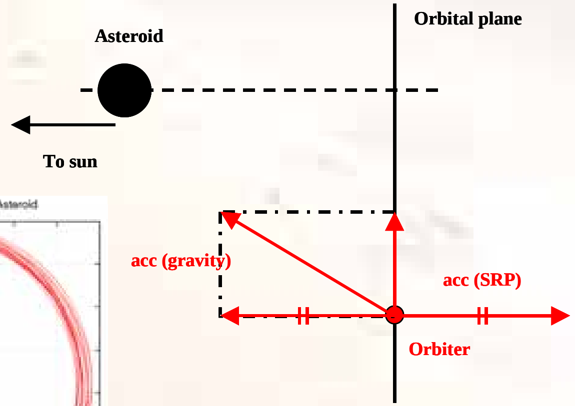
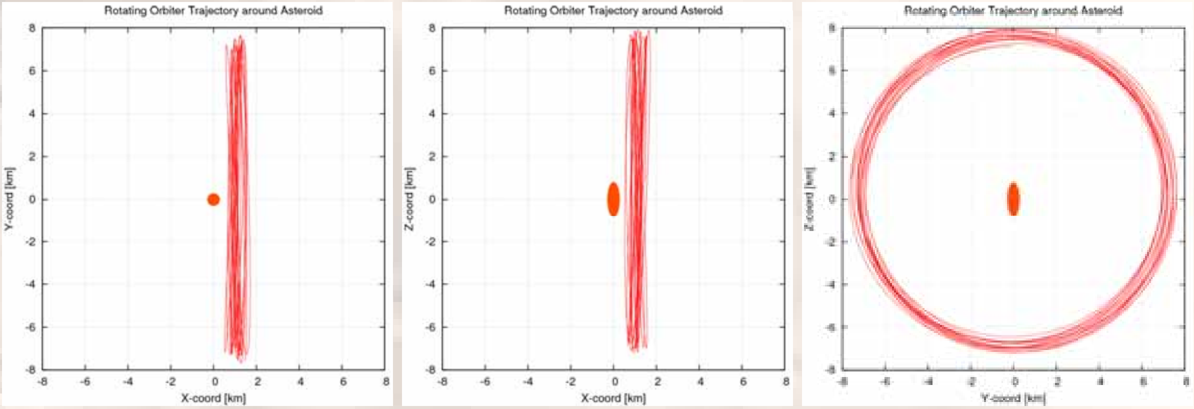


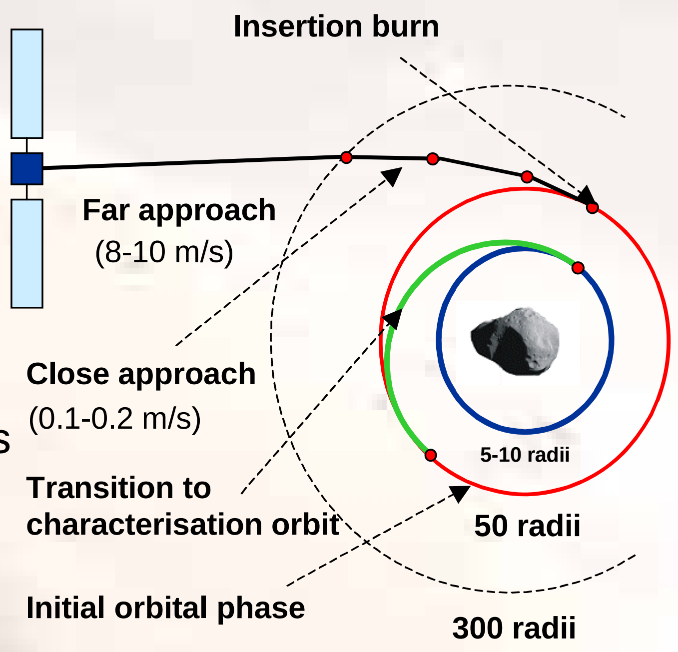
Foto-gravitational equilibrium



- **No required maintenance at orbit**
- **High degree of perturbation-free conditions for tracking**
- **Tracking with a dual-band system in X & Ka bands**
- **Use of range & Doppler**

Mission Timeline

- **LEOP of 12 days, escape from GTO**
- **Commissioning of 4 weeks after escape**
- **Cruise phase:**
  - 10.9 months baseline
  - 15.8 months back-up
- **Far approach phase of 2 weeks**
  - Braking → Relative orbiter V at 8-10 m/s
  - Rel. knowledge improved by optical images
  - Precise determination of asteroid's rotation
- **Close approach phase of 2 weeks**
  - Planning of first operational orbit
  - Definition of Orbit Insertion Point
- **Initial orbital phase of 1 month**
  - Precise determination of far gravity field and asteroid environment
  - Preparation of operations at closer distances
- **Characterisation phase of 3 months**
- **Precise tracking phase of 6 months (priori), 1 month (final)**



Mission ΔV

- **Rationale and assumptions:**
  - The deterministic delta-V budget is composed of:
    - Escape burn
    - DSM
    - Arrival excess velocity
    - Delta-V for asteroid operations
  - The stochastic delta-V is composed of the navigation delta-V:
    - 30 m/s for launcher dispersion reduction
    - 15 m/s for arrival dispersion reduction
    - 1% of the DSM for its implementation error corrections
  - Gravity losses of 10% of departure impulse for escape from GTO
  - For asteroid in-orbit operations up to 25 m/s are considered
  - A delta-V margin of 5% is added to the overall delta-V

	Baseline (2013)		Back-up (2014)	
	Min	Max	Min	Max
Escape delta-V (m/s)	1745	2113	1541	1961
DSM value (m/s)	61.9	515.6	312.9	787.3
Arrival velocity modulus (m/s)	702	816	188	1048
Navigation budget (m/s)	45.6	50.2	48.1	52.9
Total DV + margin (m/s)	**3091.3**	**3277.6**	**2988.7**	**3184.2**

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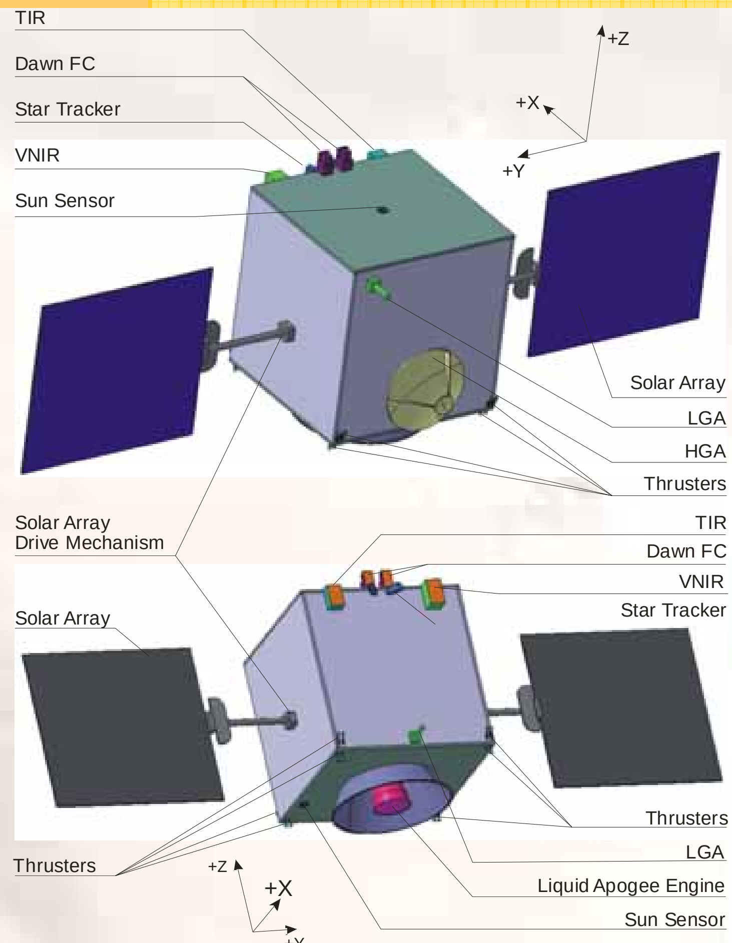
System Design

- **Spacecraft Design**
  - 3-axis stabilized Orbiter
  - Dimensions 1.7 x 1.7 x 1.8 m
  - Dry mass: 540 kg
  - Wet mass: 1520 kg
  - 6 m² Solar array
- **Conservative spacecraft design**
  - Maximum reliability
- **Strong recurrence to EUROSTAR and MarsExpress platforms**
  - Minimising cost
- **High-performance bi-propellant system with a ΔV of 3 km/s**



- **NAV camera for visual navigation during asteroid approach**
- **Autonomous collision avoidance for asteroid proximity operations**

Operations Concept and Ground Segment

- **The LEOP and transfer operations based on the established practice for previous interplanetary missions**
  - 3 X-band ground stations of the 10-15 m class in order to ensure good ground contact for initial check-out and the Earth escape maneuvers
- **Ground contacts every fortnight: 35 m DSN or 34 m Estrack station**
  - More frequent contacts around DMS → use of DDOR is foreseen
- **Far approach will be supported by navigation camera.**
- **Close approach 2 ground stations are foreseen**
- **Initial asteroid characterisation phase and the radio-tracking**
  - Daily ground contact for data downlink and the radio tracking
  - During the radio tracking phase dual-band X/Ka-Band tracking
    - A ground station with Ka-Band capability is required → DSN Goldstone station (DSS-25) or the ESA New Norcia (DSA-1) or Cebreros (DSA-2) ground stations.

Tracking Strategies

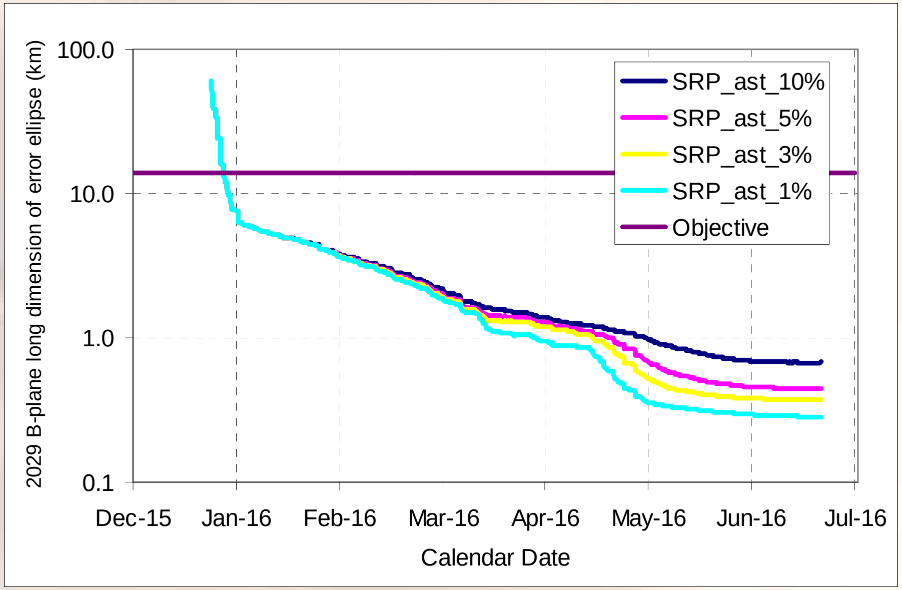
- **Main objective: "***Tracking capability of the system must ensure the reduction (by 2017) of the long dimension of the ±3σ error ellipse of the 2029 encounter down to 14 km***"**
- **Tracking of Apophis is indirectly derived by tracking the Orbiter.**
- **Simulation of tracking experiment by means of Covariance Analysis**
- **Main dynamic effects considered:**
  – Asteroid gravity field: gravity field coefficients up to 4th degree are used as a function of the shape of the asteroid.
  – Radiation forces on the asteroid: Sum of the impinging radiation, the direct reflection and the thermal radiation Force (Yarkovsky effect).
  – Radiation forces on the Orbiter: SRP from the Sun and radiation emitted from the asteroid are also accounted for
  – RCS non-propulsive fuel leakage:
    - Non-propulsive fuel expulsion from the RCS ($\approx 7\cdot10^{-7}$ N).
    - Additional non-propulsive fuel leakage immediately after the maneuver
  – WOL maneuver → parasitic ΔV generated by the wheel desaturation
- **Use of range and Doppler from New Norcia ground station**

Tracking Strategies (2)

- **Figure of Merit for the Apophis Orbit knowledge:**

$$FoM = \sqrt{s_x^2 + s_y^2 + s_z^2 + s_{Vx}^2 + s_{Vy}^2 + s_{Vz}^2}$$

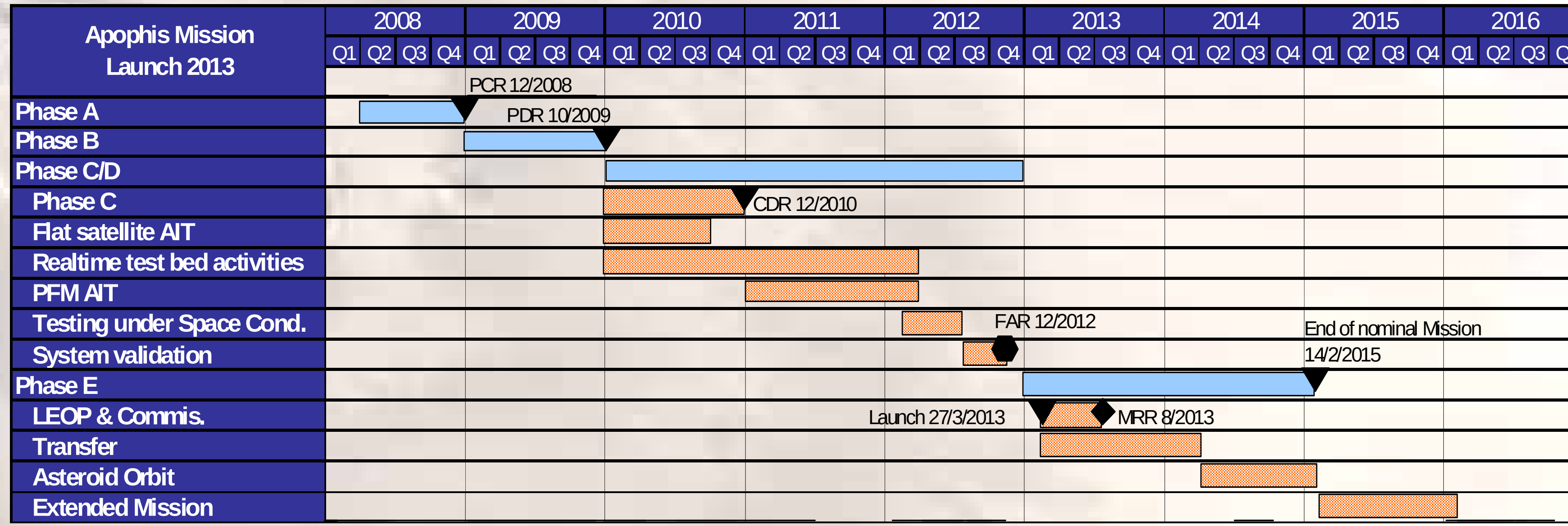
  - sx, sy and sz: dimensionless uncertainty in asteroid position
  - s_{Vx}, s_{Vy} and s_{Vz}:dimensionless uncertainty in asteroid velocity
- **The mission objective is set to a maximum value of this FoM corresponding to a 23% of the value at the beginning of the mission**



- **Tracking objective is achieved in less than one month** deimos SPACE

Programmatics

- **Mission development plan:**
  - Phase A in last 3 quarters of 2008
  - Phase B during 2009
  - Phase C during 2010
  - Phase D during 2011 and 2012
  - Phase E from first quarter of 2013
  - Mission cost at completion estimated at 387 M$



Conclusions (1)

- **A complete study on a mission to track Apophis has been performed fully compliant with required OD performance.**
- **The tracking goals are widely achieved by means of an Orbiter placed at a photo-gravitationally stable orbit behind Apophis as seen from the Sun**
  - This solution was found easier to implement and more effective than a lander mission.
- **Conservative design based on flight qualified equipment and strong heritage → high reliability of the SC**
- **The payload for the mission is composed of a dual band (Ka and X) tracking system, a narrow angle camera (as the one for Dawn), a thermal radiometer, and a visible and near infrared spectrometer.**
- **High thrust transfers to Apophis were systematically analysed, leading to the proposal of a baseline transfer to Apophis in April 2013 and a back-up transfer in March 2014.**
- **Preferred launcher is Delta II (7926 version)**
  - Alternatives are Falcon 9, Taurus II, Soyuz or a dual launch with a larger launcher.

Conclusions (2)

- **The spacecraft on-board propulsion is used for escape from GTO and Apophis rendezvous.**
- **Total mission duration is 1.45 years for baseline mission and 1.86 years for back-up making use of one month to achieve the tracking mission goal.**
- **Tracking experiment simulation has shown that the required performance can be achieved in less than one month of operations (worst case scenario)**
- **A mission development plan was established compatible with the proposed baseline launch window:**
  - phase A along the last 3 quarters of 2008
  - 3-year implementation phase from 2009 to 2012.
- **Mission cost at completion is estimated at 387 M$.**
  - At the lower end of the cost range for interplanetary mission
  - Mission cost is below the cost caps for both NASA Discovery missions and ESA Cosmic Vision medium class science missions.