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ASTEX: An in situ exploration mission to two near-Earth asteroids ☆

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Abstract

ASTEX (ASTeroid EXplorer) is a concept study of an in situ exploration mission to two Near-Earth-Asteroids (NEAs), which consists of an orbiting element and two individual lander units. The target candidates have different mineralogical compositions, i.e. one asteroid is chosen to be of "primitive" nature, the other to be a fragment of a differentiated asteroid. The main scientific goals of the ASTEX mission are the exploration of the physical, geological, and mineralogical nature of the NEAs. The higher level goal is the provision of information and constraints on the formation and evolution of our planetary system. The study identified realistic mission scenarios, defined the strawman payload as well as the requirements and options for the spacecraft bus including the propulsion system, the landers, the launcher, and assessed and defined the requirements for the mission's operational ground segment.

Keywords: NEO; NEA; Exploration; Interplanetary mission; Mission study

1. Introduction

This paper presents the results of a 10-months study led by the Max-Planck Institute for Solar System Research (MPS) with a support Grant from the German Space Agency (DLR). The study was performed in 2007/08 in close collaboration with scientific research institutes (DLR Berlin, DLR Oberpfaffenhofen) and industry (Astrium, Astos Solutions, LSE). The hereafter presented mission concept foresees to visit two different near-Earth asteroids (NEAs).

Beginning with the Galileo mission fly-bys of main-belt asteroids 243 Ida and 951 Gaspra in the early 1990s, a large amount of high-quality scientific data has been gathered on a number of main-belt and near-Earth asteroids by means of space missions. Spacecraft fly-bys and in-orbit or in situ exploration of asteroids can provide accurate information on shape, size, mass, bulk density, cratering, spatial distributions of surface structure, mineralogy, and the presence of natural satellites or moons. Data from space missions provide "ground truth", allowing the analysis techniques used on ground-based astronomical data to be checked and calibrated. To date there have been only two rendezvous missions to NEAs, NEAR-Shoemaker (Cheng et al., 1997; Bell et al., 2002) and Hayabusa (Fujiwara et al., 2006), the results from which highlight the diverse physical characteristics of NEAs.

2. Scientific background

Some 4.5 billion years ago the Solar System formed from a collapsing interstellar cloud. In the dense

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protoplanetary disk of dust and gas that surrounded the young Sun, grains of dust collided and coalesced. Over a period of a few million years material in the disk accumulated via collisions into 1–10 km-sized bodies, called planetesimals. At this size gravity began to play an important role and the planetesimals attracted more and more material until planet-sized bodies formed. Collisions between planetesimals, the precursors of present-day asteroids and comets, and growing planets forged the Solar System as we know it today. After the planets had formed, collisions with the remnant population of small bodies, i.e. asteroids and comets, continued, albeit at a declining rate, and probably deposited significant quantities of minerals, water and organic materials on the surfaces of the Earth and other planets. In later epochs impacts on the Earth may have abruptly altered the course of evolution and paved the way for mankind. Indeed, impacts of asteroids and comets are a natural phenomenon that continues to shape the surfaces of planets at the present time, and will do so in the future.

Most asteroids orbit the Sun in the main belt between Mars and Jupiter. The orbits of fragments arising from collisions between main-belt asteroids can evolve under the gravitational influence of Jupiter so that their perihelion distances decrease and they eventually cross the orbits of the terrestrial planets. The asteroid population known as near-Earth asteroids consists mainly of such objects, but probably includes also some nuclei of evolved or extinct comets. A near-Earth asteroid is defined as one having an orbit with a perihelion distance of 1.3 AU or less. The current total of known NEAs is 6300 (June 2009), of which about 900 have diameters larger than 1 km. Some NEAs pass very close to Earth. 99942 Apophis, a current well-known example, is due to pass within about 30,000 km of the Earth's surface on the 13th April 2029. At present, there are nearly 1000 NEAs in the category of potentially hazardous objects, i.e. objects that could collide with the Earth at some time in the future.

The known NEA population contains a large variety of objects: there are many different "animals in the zoo". Some NEAs are thought to be largely metallic, indicative of material of high density and strength, while some others are carbonaceous and probably of lower density and less robust. A number of NEAs may be evolved cometary nuclei that are presumably porous and of low density but otherwise with essentially unknown physical characteristics. In terms of large-scale structure NEAs range from monolithic slabs to "rubble piles" and binary systems (asteroids with natural satellites). An asteroid that has been broken up in a collision may survive under the collective weak gravitational attraction of the resulting fragments as a cohesionless, consolidated, so-called rubble pile. A rubble pile may become a binary system if its spin rate is accelerated as a result of the torque produced by photon reflection/radiation (the YORP effect), or if it makes a close approach to a planet and becomes (partially) disrupted by the gravitational perturbation. The proximity of NEA orbits to the Earth and close approaches provide us with a unique opportunity to study the products of collisions between planetesimals and related bodies that have governed the formation and evolution of our Solar System, and in particular, the development of the Earth and its inventory of water and organics vital for the emergence of life.

3. Scientific and technology goals

Space missions to NEAs are attractive for a number of reasons. NEAs have intimate links to the original "primitive" planetesimals and to the "evolved" population in the asteroid belt; they carry valuable information on the early formation phase and post-formation evolution of asteroids. In addition, the Δv requirement[1] for a single target mission to many NEAs is very low, enabling a significant complement of scientific instruments to be carried at reasonable cost. The uniqueness of the ASTEX mission scenario is to rendezvous with and perform in situ investigations on two asteroids during one mission.

The overall scientific goal of the ASTEX mission is the provision of information and constraints on the formation and evolution of our planetary system. This goal will be accomplished through studies of a primitive and an evolved planetesimal remnant. The following immediate mission objectives have been identified:

- the exploration of the inner structure of the NEAs,
- the determination of physical body parameters (spin vector, size, shape, mass, density, rotation) as well as the physical properties of the surfaces (thermal conductivity, roughness, strength),
- the determination of geology, chemistry, mineralogy, and the age of the surfaces,
- the exploration of the origin and collision history,
- the examination of the link between NEAs and meteorites.

The present work was initiated to study different mission scenarios and to identify those that are most compatible with the scientific goals of the ASTEX mission. The immediate study goals were:

- to identify suitable NEA targets, propulsion units, trajectories and launch options for the mission,
- to select suitable instrumentation to achieve the scientific goals,
- to propose suitable and affordable spacecraft and lander systems,
- to evaluate the required ground segment for mission operations and support,
- to assess the technology readiness level (TRL) of the spacecraft, payload, and ground segment.

[1] Δv is a measure for the required propellant to reach a target.

4. The mission concept

ASTEX would, for the first time, involve setting permanent landers down on two NEAs. The target asteroids are of different mineralogical composition: one asteroid being of "primitive" nature, the other being a fragment of an "evolved" (differentiated) asteroid. Thus the mission concept is certainly unique and would explore the diversity of the NEA population by examining two constraining examples. The Orbiter design features a Radio Reflection Tomographer (RRT) to probe for the first time the internal structure of an asteroid. Knowledge of the internal structure will shed light on the origin and evolution of asteroids, inform predictions of the consequences of asteroid impacts on the Earth's biosphere and strategies under consideration for mitigating hazardous objects. The use of an RRT experiment for asteroid tomography has been previously proposed by Asphaug et al. (2003) and Arrigo et al. (2002). Each lander will be equipped with identical scientific instrumentation, designed to investigate in situ the mineralogy and chemistry of the surfaces. The descent phase and landing will be controlled autonomously.

In conclusion of the performed investigations of several scenarios for the ASTEX mission a baseline of a mother satellite carrying two identical lander units is recommended. The concept includes redundancy, i.e. even in the case of total loss of one lander more than 50% of the mission goals can still be accomplished. In this case the mother craft can at least perform remote sensing investigations at the target where in situ measurements are no longer possible due to the lander loss. Furthermore, after completion of the nominal science investigations at both targets the mother satellite can be "parked" at a certain distance to the asteroid in order to perform long-term monitoring of the asteroid's orbit by means of radio tracking.

5. Target selection

The selection of the ASTEX targets is one of the most important aspects of the mission preparation. The targets are intended, as far as possible, to reflect the diverse nature of the NEA population in order to satisfy the scientific mission goals. The selection of examples of both types, primordial and processed, will best serve the objectives of the mission. For example, many of the M-type asteroids are believed to be composed of almost pure metal and thus represent an extreme of the asteroid population; most likely these asteroids are remnants of the cores of large differentiated asteroids which have been destroyed by catastrophic collisions. However, due to the high radar reflectivity of M-type asteroids, radar investigations of the inner structure of these objects will not be possible and therefore M-type asteroids have not been considered as potential mission targets. Basaltic fragments are also remnants of a differentiated asteroid, originating from either the mantle or the crust of a large asteroid. Fragments of the crust/mantle region probably make up the V-type class and some of the S-class asteroids and thus these are amongst the most interesting objects for the mission. Undifferentiated, primitive objects make up the C-type class and its subclasses. The primitive objects carry information on the origin and very early evolution phase of the solar system, while the evolved fragments are witnesses of a subsequent phase. Potential targets with technically unacceptable physical or dynamical properties were excluded in the first phase of the target selection process by applying the following constraints: (1) distance to the Sun larger than 0.7 AU and less than 2 AU, (2) asteroid diameter >200 m, (3) exclusion of extremely fast and extremely slow rotators, (4) total mission $\Delta v < 11$ km/s, and (4) stay time at each target >180 days.

For guidance of the target selection a software tool was developed that enables the selection of NEA pairs based on basic target and mission parameters which are computed by the software. The incorporated data base with 5000 objects contains information from NASA's NEA data base (http://neo.jpl.nasa.gov/cgi-bin/neo_elem), DLR's EARN data base (http://earn.dlr.de/nea/) as well as further asteroid taxonomy information provided by R. Binzel (personal communication). The overall database contained taxonomy information for 431 Amor, Apollo and Aten objects.

In order to identify the targets best suited to the ASTEX mission, we applied the following constraints: (1) Amors were removed since their orbits do not intersect that of the Earth,[2] (2) the absolute magnitude was limited to 22.5 *mag* to exclude targets with diameters of less than about 200 m, (3) the impulsive Δv required for the first rendezvous was limited to a maximum of 7 km/s. As a result, 4793 NEAs were deselected but the remaining 207 asteroids still represent more than 40,000 possible target combinations. Further down-selection was performed by excluding all asteroids with unknown taxonomy and by constraining the total mission Δv (assuming Hohmann transfers) to a realistic value of 11 km/s; leading to 1210 pairs. In a next step, the ephemerides of the Earth and the two target asteroids were considered. Using a patched conics approach and a genetic algorithm for the optimization, all missions were computed under the following constraints: (1) mission time frames 2015–2040, and (2) maximum mission duration <15 years. The 1210 missions were optimized using the POINT software (Program to Optimize Interplanetary Trajectories, Astos, 2003) in order to find out whether realistic mission geometries would still lead to a mission Δv of 11 km/s or less. It turned out that this is the case for only 210 combinations. We then identified target combinations which likely consist of a "primitive" NEA, or fragment thereof (taxonomic types C, D, P, B and F) and a fragment of a differentiated body (taxonomic types E, V, Q, S, A, and R). V-type asteroids are scientifically of particular interest due to their rarity and possible relation to the main-belt asteroid 4 Vesta that is likely fully differentiated

[2] Self-defined constraint.

and hence target pairs including V-types were given highest priority. For the remaining 29 (so far still impulsive) missions each transfer leg was optimized by using GESOP (Graphical Environment for Optimization and Simulation, Astos, 2004) under the assumption of solar electrical propulsion (SEP). We found that all 29 missions can be carried out with a low-thrust propulsion system.

In the last step of our selection process we identified three priority missions from which one was selected as baseline mission of the study. This final selection step considered the following information: (1) expected NEA mineralogy, (2) mission duration <10 years, and (3) comparatively low mission Δv. The selected 3 primary missions, including the baseline mission, are presented in Table 1 and Fig. 1.

6. Mission analysis

In the following we describe the mission analyses which were performed within the ASTEX study, i.e. the details of the transfer orbits from Earth to the first and second target asteroid. The propellant mass is the key parameter of the transfers and hence this parameter was optimized during our analyses. After launch, the spacecraft leaves the Earth with a hyperbolic excess energy $C3 = 0\ \mathrm{km^2/s^2}$. The transfer starts at the border of the Sphere of Influence (SOI) of the Earth, which is assumed to be at a distance of 1 million km. It should be noted that the mission start dates given in the present paper always refer to the date on which the spacecraft leaves the Earth's SOI and not to the actual launch date, which would be about 8 days earlier. The position and velocity of the first target was used as the final state of the first transfer leg and as the initial state of the 2nd transfer leg (first to second asteroid), under consideration of the corresponding times.

As will be described in detail in the following sections the spacecraft consists of an Orbiter and two landers. The spacecraft is driven by a SEP which is powered by solar panels of $40\ \mathrm{m^2}$ size. For our mission analysis the starting wet mass of the spacecraft was assumed to be 1600 kg. After the first rendezvous the mass is lowered by 100 kg due to the fuel burning and the undocking of the first lander unit. The SEP consists of four thrusters; three of these can provide a Δv of 11 km/s, although only 1 thruster is operated at a time. The 4th thruster is for redundancy. The maximum thrust at which the engine operates is limited to 170 mN to ensure a lifetime of at least 10,000 h per engine. According to "optimal control theory" it is known that the best strategy is to fly always with maximum thrust interrupted by coasting arcs.

Table 1
Selected ASTEX primary mission targets (the baseline mission is in bold letters).

1st Target	Taxonomy of 1st	2nd Target	Taxonomy of 2nd
99942 Apophis	**Sq**	**1996 FG3**	C
162173 1999 JU3	Cg	3361 Orpheus	S, V
65679 1989 UQ	B	3361 Orpheus	S, V

The computed mission profiles of the three selected primary missions are presented in Table 2 and are further detailed in Nathues et al. (2009). As an example we show in Fig. 2 the orbit geometry and in Fig. 3 the thrust profile of our baseline mission to 99942 Apophis and 1996 FG3.[3]

During the rendezvous phase the Lander is released to descend to a pre-defined surface area. For the in situ measurements a 6-months period is foreseen at each target, with the possibility of extending the mission at the 2nd target for a further 6-months period. Remote observations of planetary targets are usually performed while the spacecraft is in orbit. Due to the very low gravity of our targets and the comparatively high solar radiation pressure, stable orbiting may not be feasible, or at least an achievable stable orbit may not be useful, for example, a quasi terminator orbit (photo gravitational orbit) for imaging.

The following proximity operations have been analyzed: (1) orbiting in a close and stable orbit, (2) orbiting in an unstable orbit with active orbit keeping, (3) high-altitude flyovers, (4) low-altitude flyovers, (5) inertial hovering,[4] (6) body-fixed hovering, and (7) landing. The performed computations considered the individual target parameters, such as diameter, expected mass range, and the Sun as a gravitational point mass, and the solar radiation pressure as a perturbing force. From an energetic point of view (stable) target orbiting is often preferred since this type of proximity operation minimizes fuel consumption. An analytical analysis, introduced by Scheeres et al. (2002 and 2004) and performed within the present study revealed that for some potential mission targets orbiting may be feasible, while for others it will not (see Table 3). The analytical approach parameterizes the effect of asteroid gravity and rotation as well as the solar radiation pressure. For the binary target asteroid 1996 FG3 we found that a stable spacecraft orbit inside the orbit of the secondary is impossible, whereas stable orbiting is feasible outside the orbit of the secondary. Often the terminator orbit is the only possible stable orbit around a small body but unfortunately this kind of orbit is not suited for remote imaging since the spacecraft is orbiting on the night side. However, the terminator orbit might be used for the RRT observations which do not require an illuminated surface. Flyovers in general can be used to precisely measure the non-spherical gravity field of the asteroid but are less suited to remote sensing due to the variation of instrument spatial resolution and relative velocity. However, high-altitude flyovers, for example, could be flown at the very beginning of the asteroid characterization phase, at a time when it still may not be clear whether safe orbiting is possible or not. Hovering requires more fuel but for many small bodies this is the only type of proximity operation suited for surface map-

[3] 1999 FG3 is a binary asteroid system.

[4] For inertial (sub-solar) hovering the spacecraft is located at a position between the Sun and the target.

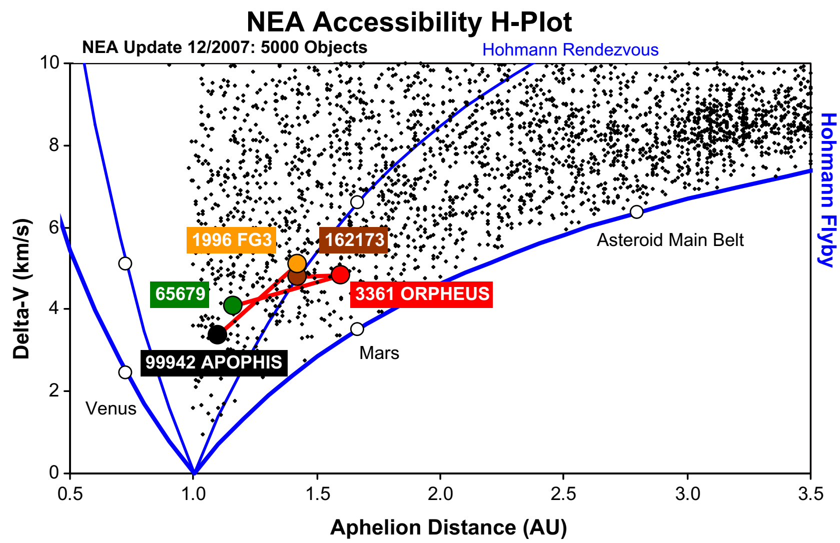

Fig. 1. H-plot showing the three ASTEX primary mission pairs.

Table 2
Parameters of the ASTEX primary missions.

1st Target	99942 Apophis	162173 1999 JU3	65679 1989 UQ
2nd Target	1996 FG3[a]	3361 Orpheus	3361 Orpheus
Start mission	20 May 2023	06 December 2020	01 March 2017
Arrival 1st	08 June 2027	30 December 2024	04 July 2021
Departure 1st	05 December 2027	28 June 2025	31 December 2021
Arrival 2nd	30 December 2031	16 August 2027	20 August 2024
End mission	27 June 2032	12 February 2028	16 February 2025
1st Transfer Time	1480 d	1485 d	1587 d
Stay Time 1st	180 d	180 d	180 d
2nd Transfer Time	1486 d	779 d	963 d
Stay Time 2nd	180 d	180 d	180 d
Mission duration	9.11 years	7.19 years	7.97 years
Delta-V to 1st	3.838 km/s	4.219 km/s	4.577 km/s
Delta-V to 2nd	5.276 km/s	4.614 km/s	5.512 km/s
Delta-V mission	9.114 km/s	8.833 km/s	10.090 km/s
Fuel mass	287.3 kg	280.3 kg	315.3 kg

[a] Binary asteroid system.

ping. In general the weaker the target gravity, the more attractive especially inertial hovering becomes. Table 4 lists the required Δv for a 6-month period of sub-solar (inertial) hovering at the ASTEX targets.

Body-fixed hovering is much more fuel-intensive than inertial hovering, as the distance between the spacecraft and the asteroid surface is usually very small (several hundreds of meters or less). This kind of hovering is suited for the lander separation. The spacecraft hovers above a certain surface location that has been selected as landing site. The position of the spacecraft is fixed relative to the rotating asteroid. In order to remain in this position, the spacecraft has to compensate the gravity force of the body, the centrifugal force, and the solar radiation pressure. Since the gravitational attraction is strongest close to the surface, the total velocity of such a manoeuvre is of the order of several m/s per hour. Hovering in a body-fixed frame is very demanding and requires a closed-loop hovering control. Nevertheless, the hovering location is unconstrained and it is also possible to move the spacecraft over the surface. In this way, several possible landing areas can be investigated from close proximity.

For the release of the landers two possible scenarios are considered: (1) de-orbiting and (2) body-fixed hovering release. In the first case the Orbiter (with Lander) has established a stable orbit. The lander then separates from the Orbiter and performs a de-orbit burn to lower its periapsis close to the surface. After half an orbit period, during periapsis passage, the lander has to align its remaining orbit velocity with the rotating body. In this situation the lander is close to a body-fixed hovering position. In the second scenario the spacecraft is already in a body-fixed hovering position from which the lander is released; this is the baseline scenario for ASTEX. Both landing strategies

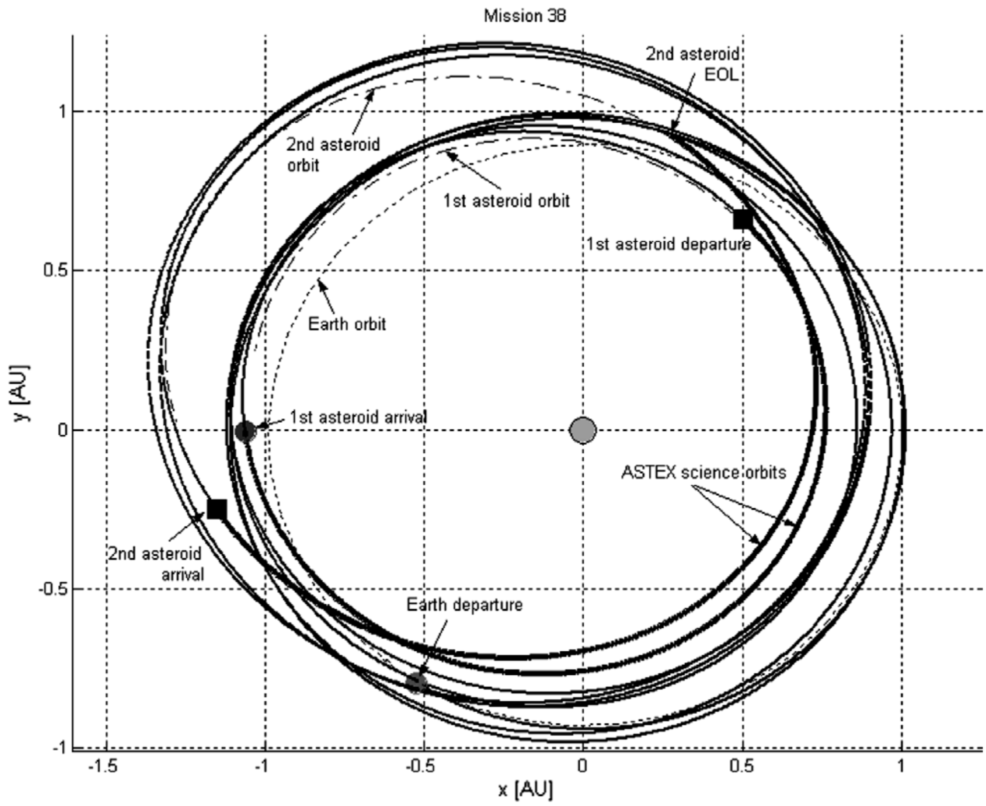

Fig. 2. Orbit geometry of the mission to 99942 Apophis and 1996 FG3.

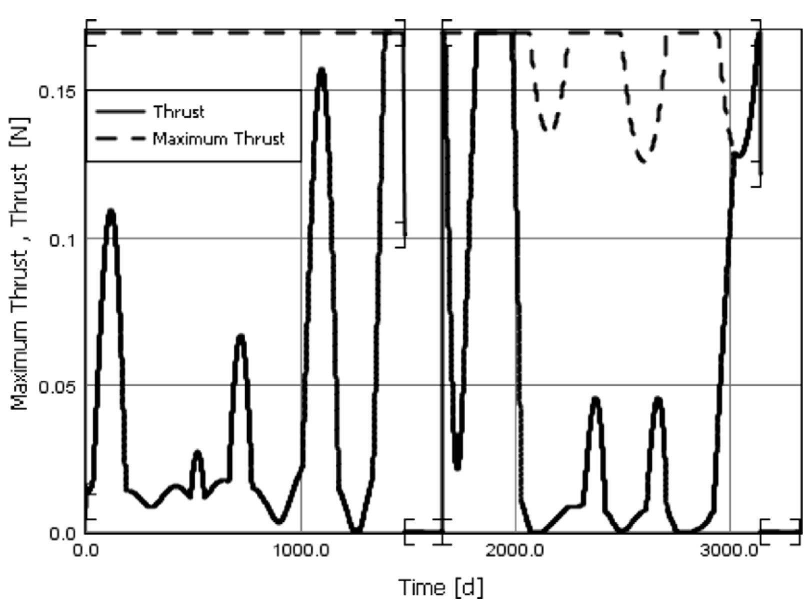

Fig. 3. Optimum thrust profile of the mission to 99942 Apophis and 1996 FG3 and maximum available thrust (dashed).

foresee an actively controlled descent to ensure precise landing. Due to the weak gravity of the targets there is no need for a deceleration burn immediately before touch down. Typically the total required Δv for lander release and descent is on the order of 1 m/s. Based on our analysis a Δv budget of 50 m/s for the proximity operations at each target appears reasonable.

7. Mission operations concept and timeline

The mission requirements are always derived from the defined scientific and technological objectives. Operationally relevant requirements can then be extracted or be merged, leading to conceptual and architectural designs of the operations and ground segment for the mission.

Table 3
Results from an analytical investigation of the feasibility of stable orbits around the primary ASTEX targets.

Asteroid	Statement	Orbit radius*	Orbit period
3361 Orpheus	Stable orbiting is feasible	1–5 km	19–200 h
65679 1989 UQ	Stable orbiting is feasible	2–8 km	40–175 h
99942 Apophis	No stable orbits	None	None
162173 1999 JU3	Stable orbiting is feasible	2–11 km	40–250 h
1996 FG3	Stable orbiting is feasible	9–23 km	90–360 h

* Strongly depends on the asteroid's physical properties and distance to the Sun.

The baseline mission profile to the asteroids 99942 Apophis and 1996 FG3 has been used to develop the ASTEX mission operations concept. In this context the following flight operations phases were identified: (1) LEOP, (2) commissioning, (3) cruise phase 1, (4) arrival[5] at Target 1, (5) Approach, (6) Orbiter operations, (7) landing on Target 1, (8) Orbiter and lander Ops, (9) Orbiter departure, (10) cruise phase 2, (11) arrival at Target 2, (12) approach, (13) Orbiter Ops, (14) landing on Target 2, (15) Orbiter and lander Ops, and (16) extended Ops at Target 2. The deduced timeline of the baseline mission that includes information from mission analysis is presented in Fig. 4.

Link budget calculations (see Table 5) have been performed to ensure the telemetry/telecommand and tracking signal availability and quality during the different phases of the ASTEX mission. In order to guarantee an adequate data rate we need to ensure that during the science phases, especially during the lander release and the lander in situ measurements communication is unconstrained. The upper and lower conjunctions of the spacecraft with the Sun pose a risk of losing communication capability for certain periods of time. Thus calculations were performed to estimate the impact on the communication link budget. For the downlink we chose the Ka-Band in order to increase the available bit rate and reduce the solar conjunction effects on the communication. In fact, the Ka-Band provides in general a 6 dB advantage compared to the X-Band. Moreover, an X-Band link starts to be influenced by solar interferences at an apparent angular distance of 4° while a Ka-Band link will experience perturbations for angles less than 1° (Morabito et al., 2003 and 2000).

For orbit determination purposes, the ASTEX mission foresees to use Doppler, Ranging and Delta-DOR measurements in order to achieve high orbit accuracy at all mission phases. The so-called hybrid navigation mode, where in addition optical navigation and laser ranging is used, is foreseen for periods in which the distance between the asteroid and the spacecraft are sufficient low. For this purpose the orbiter is equipped with two cameras and a laser ranger.

[5] Actually there are two approach stages: the initial approach to the arrival point at a safe distance, followed by a second stage bringing the spacecraft nearer to the NEA. Only the second approach has been stressed explicitly as the approach phase since here the asteroid is actually encountered. Here, arrival is used in the sense of the termination of the cruise element, while the final approach continues from this (initial) arrival phase. There is no final arrival that could be localized or timed as there are multiple options for how to proceed to the final encounter (various hover points, orbits, fly-bys).

8. Ground segment

The ground segment is designed according to the operational requirements deduced from the scientific payload operations objectives; it involves the mission operations system plus backup, and a world-wide ground station network (e.g. the Deep Space Network 120° degree longitude-separation for Goldstone, Madrid, and Canberra stations). Baseline for the present study is the availability of a Ka-Band antenna and the WHM3 ground station X-Band (backup) 30-m antenna (DLR GSOC) with down- and uplink capability.

The Mission Ops System (MOS) has to fulfil the operational requirements imposed on the ground segment by the mission objectives. The top-level MOS architecture as illustrated in Fig. 5 could be applied for the ASTEX mission. Generally, a centralized-decentralized approach for mission operations may utilize the advantages of both the generic compactness of the existing mission control centre architectures and the specificity of de-central support facilities. The central establishment usually brings along basic networks and ground monitoring and command systems for comprehensive spacecraft bus operations, including operations preparation, launch and early orbiting phase, and special or contingency operations. External facilities, on the other hand, may be preferable for the control of scientifically dedicated payload control units and for hosting their supervising teams.

In total, the ground segment will consist of: (1) the ground data system (GDS) which is responsible for providing, driving, and maintaining the communication networks and link systems, (2) the flight dynamics system (FDS) that is responsible for mission analysis and in-flight trajectory/attitude determination and maintenance, (3) the flight operations system (FOS) with the spacecraft health monitoring and command control systems, the offline data processing systems, and the procedure preparation facilities, (4) the payload operations system (POS). The latter is considered to coordinate or integrate payload planning and control activities from the de-central payload centres and the science coordinators with those activity plans resulting from continuous spacecraft operations planning as well as operations performance and constraint analyses performed centrally within the MOS.

9. Space segment – Lander –

The landing units represent the most important and central part of the mission. They carry the in situ payload which will be used to perform numerous measurements to characterize the surface material of the NEAs. Thus the Lander

Table 4
Δv requirement for 6-months of inertial sub-solar hovering at several distances at each target.

Asteroid	Delta-V requirement in a certain sub-solar hovering distance of						
	1 km	3 km	5 km	7 km	10 km	15 km	20 km
3361 Orpheus	210 m/s	29 m/s	14 m/s	10 m/s	8 m/s	7 m/s	7 m/s
65679 1989 UQ	802 m/s	97 m/s	41 m/s	25 m/s	17 m/s	13 m/s	11 m/s
99942 Apophis	40 m/s	11 m/s	9 m/s	8 m/s	8 m/s	8 m/s	7 m/s
162173 1999 JU3	1028 m/s	118 m/s	45 m/s	25 m/s	15 m/s	9 m/s	7 m/s
1996 FG3	4461 m/s	504 m/s	187 m/s	100 m/s	53 m/s	29 m/s	20 m/s

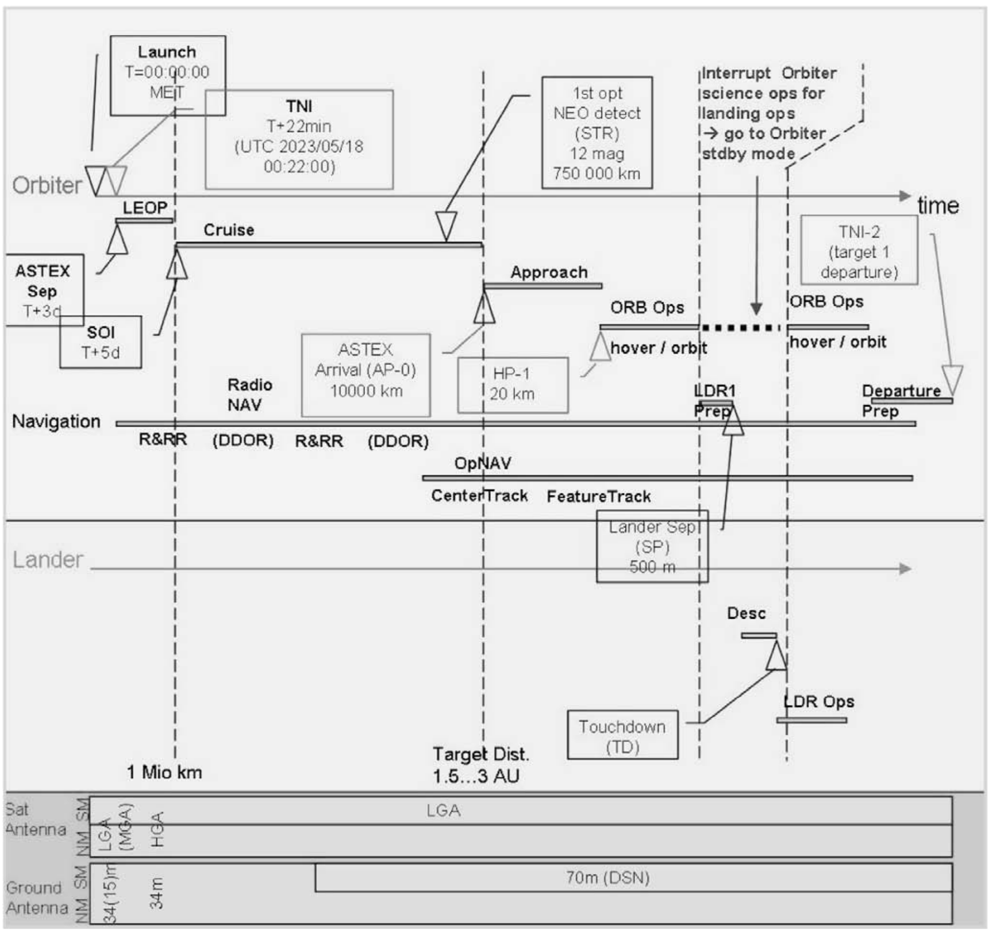

Fig. 4. Obiter and lander operations timeline (qualitative view); antenna usage vs. distance is indicated in the bottom box: 34 m and HGA communicating together in nominal mode (NM); initially 34 m, later in the cruise phase 70 m and LGA used in safe mode (SM) operations; MGA can also communicate with 15 m (ground backup) for the initial flight period (for safe mode this possibility ends early). Further abbrev.: TNI = Trans-NEO injection, STR = star camera, AP = arrival point, HP = Hover point, SP = separation point, ORB = Orbiter, LDR = lander, Sep. = separation, R&RR = range and range rate, DDOR = Delta-differential one way ranging, MET = mission elapsed time, Desc = descent, SOI = sphere of influence.

units provide the ground truth for the remote sensing instruments used onboard the Orbiter. The lander strawman payload consists of a panoramic stereo camera, a close-up camera, an optical microscope, an electron microscope, a Moessbauer spectrometer and a thermal measurement suite. Table 6 summarizes the scientific goals of each payload and lists the basic instrument parameters. The total wet mass of one lander unit has been determined to be 103 kg.

In order to enable investigations of the asteroid's subsurface, the Lander is equipped with a rake which allows the removal of the uppermost (heavily weathered) regolith layer. The rake is mounted on an instrument platform (see Figs. 6 and 7) at the stop of a robotic arm that houses also the in situ payload. The robotic arm assures the correct positioning of each payload above the selected surface area. Some of the in situ experiments (close-up camera, optical microscope, electron microscope) require night time operation. In addition, safety heater usage during night time is mandatory, and thus the determination of the required capacity of the lander battery is of special

Table 5
Reference link budget for 1.5 AU (Apophis reference case), 34 m DSN antenna.

Link budget type	Scientific data downlink	
Earth radius	6378.145	km
Max transfer Orbit Apogee	224396806	km
Elevation	5	Degree
Distance GES S/C (rouded to 1000)	224402628	Km
Station	NASA DSN 34 m	
TM bit rate	200	Kb/s

	Ka-Band	X-Band	Unit
Downlink TLM			
S/C EIRP	57	48	dBW
Path loss	289.57	283.97	dB
Atmospheric Attenuation	0.6	0.25	dB
Polarization mismatch loss	0.1	0.1	dB
Pointing losses	0.8	0.2	dB
Received power	−234.07	−236.52	dBW
Station G/T	64.5	54	dB/K
S/N0	59.03	46.08	dBHz
Implementation Loss	1	1	dB
10 × Log (bit rate)	53.01	53.01	dBHz
BPSK demodulation losses	1.50	1.50	dB
Eb/N0 at receiver	3.52	−9.43	dB
Required Eb/N0	0.5	0.5	dB
Margin	3.02	−9.93	dB

Link budget type	TC (X-Band)	
Earth radius	6378.145	Km
Max transfer Orbit Apogee	224396806	Km
Elevation	5	Degree
Distance GES S/C	224402628	Km
Station G/T @5 (X-Band)	54	dB/K
Station EIRP	110	dBW
TC Bit rate	2	Kb/s

	Nominal	Unit
UPLINK TC		
GES EIRP	110	dBW
Path loss	276.61	dB
Atmospheric Attenuation	0.25	dB
Polarization mismatch loss	0.1	dBi
Pointing losses	0.2	K
Received Power@Antenna	−167.16	dBW
S/C G/T	6.00	dB/°K
S/N0	67.439	dBHz
Implementation loss	1	dB
10 × Log (bit rate)	33.01	dBHz
Modulation losses	4.12	dB
PM demodulation loss	1.5	dB
BPSK Demodulation loss	1.5	dB
Eb/N0 at receiver	26.31	dB
Required Eb/N0	10.6	dB
Margin	15.71	dB

importance. To estimate the required capacity and hence the required battery mass we have detailed the lander power budget for each primary target and found that for dark times exceeding 15 h the battery becomes a major driver for the lander mass, i.e. the battery mass exceeds 15 kg. In order to ensure sufficient battery charging during day time we have examined the consequences of residing at different locations on a model asteroid and computed the required dimension of the lander solar panels. Our results indicate that an area of 2 m^2 is required; the optimum orientation and shape of the panels can be seen in Fig. 7.

After touch-down the lander unit has to be kept stable in its position in order to perform the in situ investigations. This is a particular challenge because the surface properties are not or only poorly known. A suitable method for all conceivable cases is the use of hold-down thrusters. How-

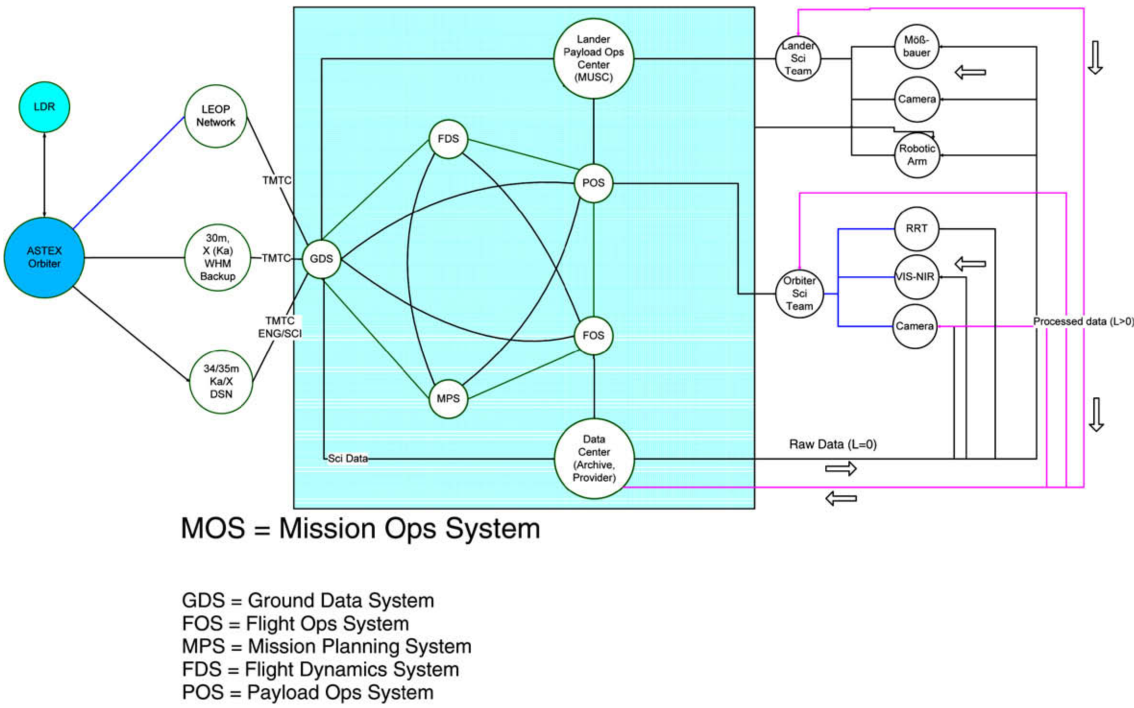

Fig. 5. The mission operations system interfacing between the external science coordinators and the ground-space communication links. It fulfils tasks in the areas of flight dynamics, ground data, mission planning, payload and flight operations.

Table 6
ASTEX lander strawman payload. The payloads have a common data storage device as well as a common data processing unit.

Instrument	Science goal	Mass (kg)	Size (mm^3)	Power (W)
Close-up camera	High-resolution close-up imaging of surface materials. 4-band illumination device foreseen	0.5	90 × 60 × 80	6 (peak)
Panoramic stereo camera	Stereo mapping and characterization of landing and sampling sites. Aid and monitor robotic arm investigations (Stereo and DTM products)	2 × 0.5	2 × 90 × 60 × 80	2 × 2.5 (peak)
Optical microscope	Studies the geophysical and structural properties of the surface, studies luminescence phenomena (UV excited emission in the VIS), and provides the context for electron microscopy	0.3	125 × 60 × 50	5 (peak)
Electron microscope	Micron-scale characterization and elemental/mineralogical analysis of surface materials. Potential detection of micro-structures, e.g. chondrules (could link NEA material with meteorites)	0.5	50x50x80	3 (peak)
Moessbauer spectrometer	Identify Fe bearing minerals in the regolith, determine degree of oxidation of iron (II, III)	0.8	90 × 50 × 40	5 (peak)
Thermal measurement suite	Measure surface/subsurface temperature and thermal conductivity of surface materials	16 × 0.02	10 × 10 × 3	16 × 0.01

ever, this method requires significant amounts of propellant even for short stays. For the ASTEX case where the Lander is supposed to stay and operate on the surface for durations of the order of weeks to months this method is thus not suitable. An anchor/harpoon approach based on the Rosetta heritage is probably inapplicable as well since this method relies on a certain cohesion and weight of the surface material above the anchor, which would most likely be inadequate in the case of the ASTEX targets. Since we could not identify any qualified anchoring method on bare rock, (harpoons are considered as inapplicable as well) landing on bare rock shall be avoided. At this stage no specific hold-down system except the compensation of the occurring momenta and torques caused by the mechanical motion of the robotic arm is foreseen. Increased friction between the lander bottom and the asteroid surface by using multiple spikes has been proposed to enhance the passive stability.

From the Hayabusa mission and ground-based thermal investigations of NEAs it is expected that most NEAs are covered by coarse regolith or bare rock rather than fine, dusty regolith. In order to prevent the Lander from setting

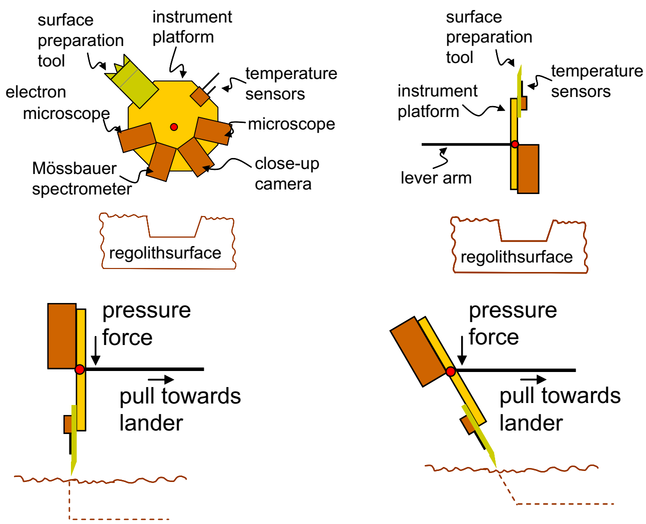

Fig. 6. Sketch of instrument platform with surface preparation tool (rake) and scientific experiments. The rotatable instrument platform is mounted on the stop of the robotic arm that is used to position the experiments correctly above the surface element.

down on bare rock, an autonomous active landing system is required which guides the lander units to the selected landing sites. The following components of an active attitude control for the descent of the Lander have been identified: (1) a cold gas thruster system, including one thruster for hold-down and four thrusters for attitude control, (2) a miniaturized radar altimeter, (3) a compact wide angle camera for visual navigation, and (4) a momentum wheel for the spin-stabilisation of the Lander's vertical axis. The cold gas system is part of the reaction control system which is operated by the on-board processing unit. The firing of these thrusters depends on the necessary correction maneuvers calculated from the imaging information of the visual navigation camera, as well as the distance to the surface measured by the altimeter. Cold gas has been chosen to avoid contamination of the asteroid surface with organic molecules resulting from combustion processes in chemical thruster systems. The radar altimeter's measurement accuracy is about 12 cm and hence qualified to support the accurate Lander descent. In order to stabilise the vertical axis of the Lander, a momentum wheel has been chosen as baseline. This will ensure that the lander unit is always in an upright position and does not need any additional means of orientation alignment after touch-down. This approach will also offer stability against forces acting on the Lander during the descent such as radiation pressure.

The lander telemetry including science data and the commanding will be uplinked/downlinked using the orbiting mother spacecraft as relay station. Thus, for the short communication path between Lander and Orbiter of up to about 100 km an UHF communication system is sufficient, which typically uses the frequency bands around 401 MHz and 437 MHz, respectively. The maximum transmission power has been fixed at 1 W allowing an adequate transmission rate when the Orbiter is at least at a distance of a few tens of kilometres to the target. Typical downlink rates (Orbiter to Lander) are in the order of 2–8 kbit/s while uplink rates are between 2 and 128 kbit/s.

10. Space segment – spacecraft –

In the following we present the ASTEX Orbiter concept. The main technical driver is the use of electric propulsion which requires a large solar array for efficient power generation. The Orbiter carries both landers and the remote sensing payload (see Fig. 8) which consists of an RRT, two cameras, VNIR spectrometer and a laser ranger. The Orbiter comprises all essential subsystems: power subsystem, SEP, chemical propulsion, attitude and orbit control system, data handling, communication, harnesses, structure, and thermal control system. The calculated wet mass of the ASTEX spacecraft is 1597 kg (for mass breakdown see Table 7). This system wet mass contains maturity margins between 5% and 20% depending on the individual component TRLs. In addition, an overall system margin of 20% is considered. Based on the preliminary system concept hardware matrixes listing the masses of the individual subsystems as well as their TRLs have been elaborated.

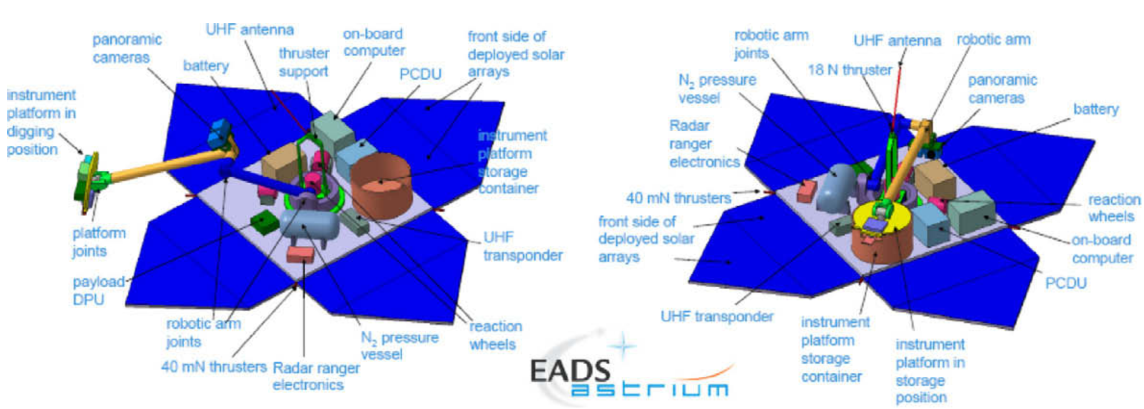

Fig. 7. The ASTEX Lander in landed configuration (thermal cover removed). The solar arrays are deployed, the robotic arm (length: 1.4 m) is in storage configuration (right) and in measurement configuration (left).

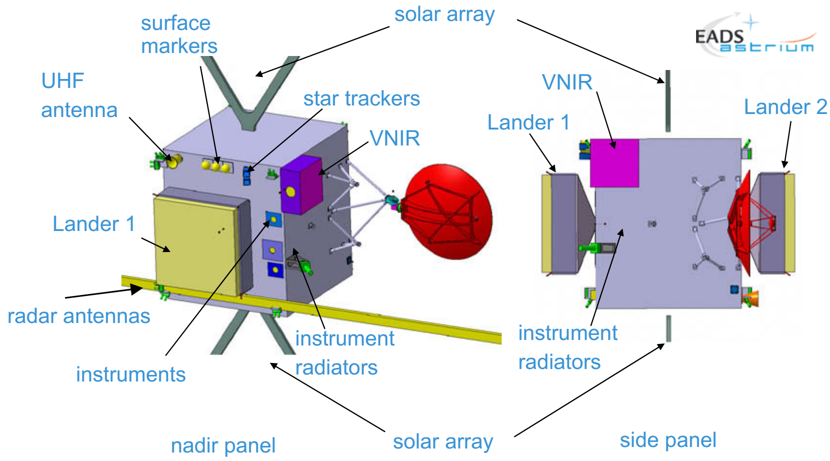

Fig. 8. ASTEX spacecraft design schema (solar array and RRT antennas are cut for a better overview).

Table 7
ASTEX spacecraft mass budget.

	No. of units	Mass (kg)
Lander units		
Payload	9	8.8
Mechanics	4	5.2
Structure	3	14.1
Power system	4	26.3
Communication system	3	1
Thermal system	3	8.4
Data handling system	1	5.4
Harness	1	1.8
cold gas system	1	10.8
Attitude control system	1	4.5
Lander total mass (incl. margin)	2	206
Orbiter + landers		
Payload	9	52.1
Power system	10	183.6
SEP	24	163.6
Chemical propulsion	20	28.1
AOCS	13	38.0
Data handling	2	27.3
Communication system	17	66.5
Harness	1	57.7
Structure	5	143.3
Thermal control system	6	11.8
Landers	2	206.0
Propellant (Xenon and Hydrazine)	2	465.8
Orbiter total mass at Earth escape (incl. margin)	1	1597

The scientific instruments onboard the Orbiter and their objectives are presented in Table 8. The number of the orbiter experiments can be kept to a minimum because the diverse lander payload is so well suited to a precise analysis of the asteroid's chemical and mineralogical composition. The key payload of the Orbiter is the RRT experiment that probes the interior of the NEA. The measurement technique utilizes changes in the dielectric properties of internal materials and structures. Modeling the scattering and reflection of electromagnetic waves via tomographic inversion in the light of additional information on the body, such as gravity field, mass, size, and shape, can provide a detailed picture of the internal structure of the NEA, or at least provide evidence for a basic structural type (monolithic homogeneous body, fractured body, porous body, rubble pile, etc.).

Within the present study we have investigated the need for a SEP system and identified which of the available systems is most suited for the ASTEX mission. The total required mission Δv for the primary missions (9–11 km/s) is rather demanding. In general the selection of a propulsion system is driven by the following design criteria: (1) high specific impulse (I_{sp}), which reduces the required fuel mass, (2) high thrust, which reduces the flight time, (3) high specific efficiency, which reduces the energy supply, and (4) long life time, which reduces the required number of engines. The relation between fuel mass and Δv clearly favours electrical over chemical propulsion systems. Basic calculations show that the required fuel mass of a chemical system would be about five times larger than that of the electrical one, i.e. one would require a fuel mass exceeding by far 90% of the total ASTEX system launch mass. We identified the following SEPs as candidates for ASTEX: RIT-22 (Astrium), T6 (Qinetiq), and HEMP (Thales). The RIT-22 has been chosen as baseline due to the fact that it combines high thrust (≈150–170 mN) with high I_{sp} and high efficiency. The extremely large I_{sp} of the RIT-22 leads to a reduced Xenon consumption and thus to reduced fuel mass.

The ASTEX reaction control thruster configuration is capable of producing pure torques and pure forces in any direction. Pure torques are necessary for reaction wheel off-loading while in orbit around the asteroid and during cruise. Similarly vectored thrust is necessary during orbital operations to perform small orbit corrections without slewing the satellite, which may take several minutes in some cases. In addition, the maintenance of the hovering position will be performed by generating a vector thrust. The suggested configuration comprises 8 redundant thrusters capable of 6-DOF (six-degrees-of-freedom) control. A mono-propellant system has been chosen for the reaction

Table 8
ASTEX orbiter strawman payload science goals and parameters.

Instrument	Science goal	Mass (kg)	Size (mm^3)	Power (W)
Radar Reflection Tomographer	Determines the inner structure of the targets	12	Antennas: 15 m length electronics: 160 × 250 × 110	100 (peak)
2 Cameras	Determination of the global physical parameters of the targets (shape, size, spin vector, rotation period, etc.). Determines also the geological context	2 × 5.5	160 × 190 × 380	18 (average)
VNIR spectrometer	Determines the mineralogical composition of the surfaces	15	500 × 500 × 380	20 (average)
Laser ranger	Measures the distance between spacecraft and target. Can be possibly used also for topography	5	140 × 120 × 120	9 (peak)
Radio science	Determination of the target mass, centre of gravity and estimation of the target's gravitation field	–	–	–

control system for emergency recovery, fast manoeuvres and wheel unloading.

The power system of the ASTEX Orbiter consists of solar arrays and a power storage unit. The power consumption is mainly determined by the required power for the SEP. For the remaining spacecraft systems without payloads a total consumption of 300 W has been estimated. In contrast to the lander battery, the orbiter battery only has the purpose to supply the orbiter systems in emergency or eclipse cases for a maximum period of 1 h. This leads to a battery mass of about 10 kg. The size of the solar arrays is mainly determined by the SEP power requirement. The assumed maximum thrust level of 170 mN at a distance of 1.3 AU and about 100 mN at 1.7 AU defines therefore the size of the solar arrays. Based on typical solar array sizing parameters the power generation per unit area is 241.7 W/m^2 at 1 AU or 98.1 W/m^2 at 1.5 AU. With these parameters a total power of 9667 W or 4852 W can be generated at 1 AU or 1.5 AU, respectively. Thus a total area of 40 m^2 for the solar panels is required.

The ASTEX communication scenario with Earth is as follows: the mother satellite carries a High Gain Antenna (HGA) for communication with the ground stations in Ka- and X-Band (see also Section 7). Both frequency bands will also allow for precise radio tracking. The Ka-Band preference arises from link budget calculations performed within the present study, which are dominated by the large science data rates generated by the orbiter cameras and the imaging spectrometer. The proximity communication with the Lander in the target vicinity will be performed in the UHF frequency band. A beacon mode option for the landers, in order to track the asteroid's orbital drift, was analysed and finally excluded from the strawman payload due to the anticipated extra mass of about 28 kg per lander. However, an alternative is to foresee an extended lifetime of the spacecraft at the second target. As the Orbiter will carry the X- and Ka-Band equipment combined with an HGA it remains possible to track its position while the spacecraft remains in the vicinity (potentially in a close orbit, e.g. a photo-gravitational orbit) of the second target. In this configuration, exact monitoring of the asteroid's orbit would be possible and might, given a sufficient active lifetime, reveal orbital drifting due to the relative force exerted by the asymmetric emission of thermal photons (the Yarkovsky effect). Further more, with the help of the remote sensing cameras and the laser ranger, it might be possible to measure the related YORP effect, which influences the rotation rate.

Soyuz-Fregat has been identified as today's most applicable launcher for ASTEX since it is the only low-cost launcher in Europe which offers the required performances. The Soyuz-Fregat is capable of injecting up to 1600 kg into a direct Earth escape trajectory and even up to 2200 kg of payload mass when using a lunar gravity assist maneuver for Earth escape. The costs of the entire ASTEX mission are expected to be in the scale of ESA's L-class missions.

11. Conclusions and outlook

Near-Earth asteroids, fragments of remnant planet embryos, carry a wealth of information on the history of the Solar System. Despite their profound significance, the characteristics of the vast majority of asteroids are largely unknown. Impacts of NEAs on the Earth and other planets have shaped their surfaces and contributed to the conditions necessary for the evolution of life. Future impacts of NEAs pose a hazard to the future of our civilization.

The ASTEX mission to two NEAs of very different composition and histories would represent a giant step forward in the exploration of the Solar System, and revolutionize our understanding of the physical properties of asteroids. The overall technical feasibility of the ASTEX mission concept has been demonstrated and technological challenges have been highlighted in the ASTEX study report (Nathues et al., 2009). Based on the conclusions drawn we recommend further investigations, in particular: (1) spectral classification of those target pairs which are most easily accessible, (2) more detailed investigations of operations in the vicinity of small bodies, (3) Lander design detailing (robotic arm, in situ platform, guidance navigation control system, hold-down strategy) and (4) detailed quantitative planning of the science phases (telemetry rates, on-board memory capacity, timeline, etc.)

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