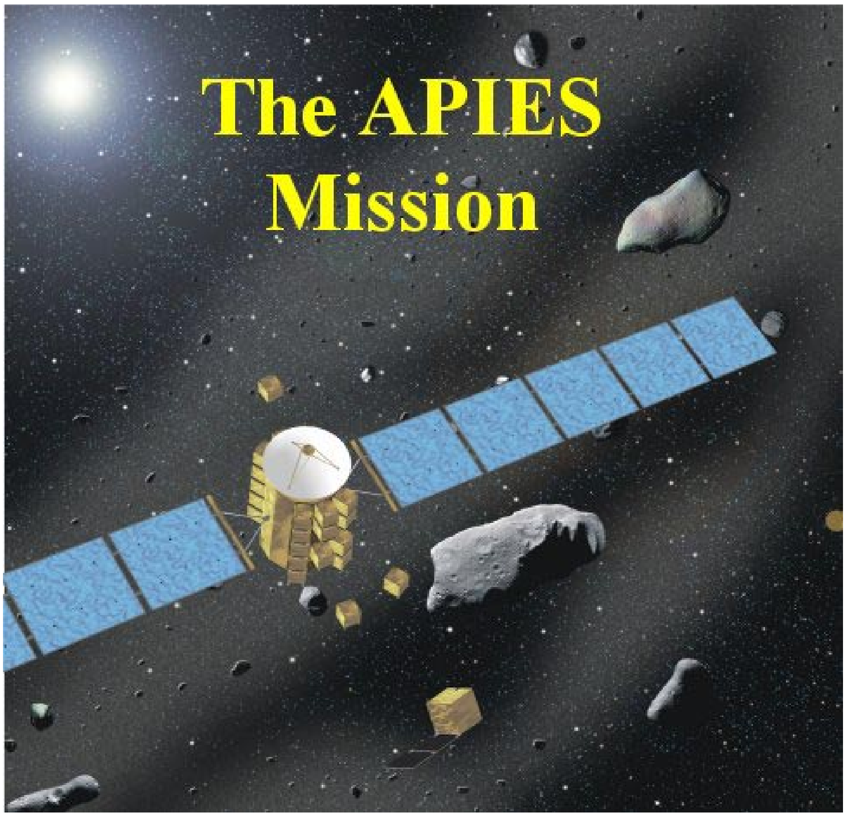


The APIES Mission
Executive Summary for Publication on ESA Web Pages

by Paolo D'Arrigo
Astrium Ltd

Prepared by:	*P. D'Arrigo*	*Date:*	*23/01/04*
Authorised by:	*M. Smith*	*Date:*	*23/01/04*

Astrium Limited
Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2AS, England

Mission Objectives

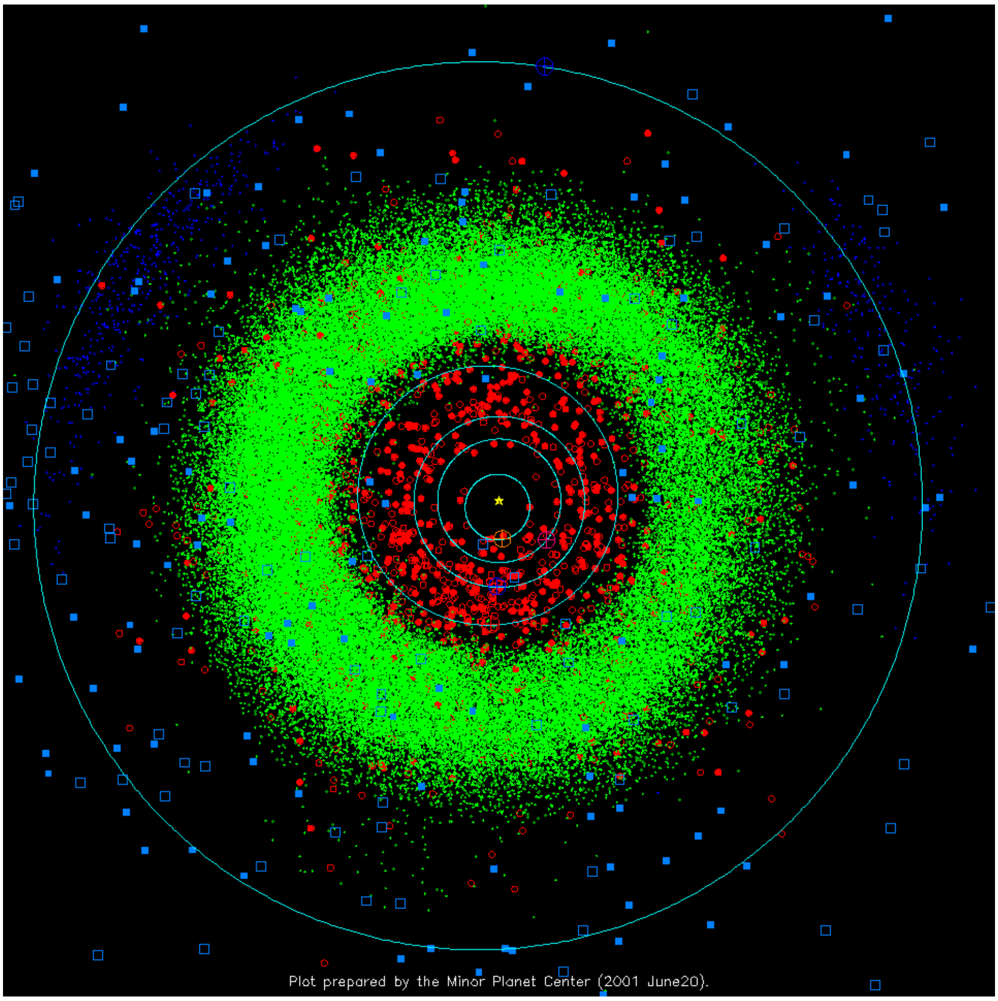
Asteroids are believed to be remnants of a planet that failed to form. They would then represent the last remnants of the swarm of planetesimals, which formed terrestrial planets. These bodies have such a small size that they should consist essentially of unaltered primitive material preserving important information about the structure of the protoplanetary nebula and the processes that produced planetary bodies. Their investigation will hence provide essential information about the physical and dynamical structure of the Solar protoplanetary disk, and help us in the explanation of their interaction with the rest of the Solar System. This interaction extends to our own Earth, where asteroids are now believed to have played a crucial role in the evolution of life, by triggering mass extinctions after collisions with Earth. In fact, the Earth continuously receives fragments of asteroids, in the form of meteorites.

Unfortunately, the large asteroid population between the orbits of Mars and Jupiter is, at present, one of the least known parts of the Solar System. More than 45,000 asteroids have already been catalogued and there are millions more yet to be discovered. However, our knowledge of the physical and geological characteristics of the Main Belt asteroid population is restricted by the limited information obtainable from Earth-based remote observations and from the very small number of object of this class currently encountered by spacecraft. While ever-more detailed laboratory analyses of meteorites are currently achievable, the difficulty of reliably linking particular meteorite groups with parent bodies remains. For most asteroids, key physical parameters, like mass, bulk density, surface geology and composition can only be obtained by a close spacecraft flyby. Yet, to this date, only 7 objects have been visited by a spacecraft, with 5 more visits planned for the near future. Even if we only count the larger bodies (>10 km in diameter), this represents less than 0.05% of the entire Main Belt asteroid population.

The present poor knowledge of the nature of asteroids leads to great gaps in our knowledge of the internal structure, mineralogy, origin and evolution processes of the asteroid population. To complicate matters, there are at least 13 main asteroid classes, each subdivided into many subclasses, on the sole basis of ground-based spectroscopic observations. This suggests a high level of diversity in the asteroid population, reflecting different origin and/or evolution. Sending however spacecraft to one object of each asteroid type may answer many general questions about the asteroid population as a whole, but will not be able to assess the diversity of asteroids within each type. This would leave us largely unable to distinguish “unique” features from those shared by all asteroids of that type. Studying instead a more statistically significant sample of each asteroid type would produce a much better “ground truth” data set to allow more reliable assessment of their characteristics from Earth-based observations. For this reason, it has been estimated that only the exploration of a sample of about 100 asteroids will allow the unravelling of many mysteries of Main Belt asteroids.

The APIES mission concentrates therefore on measuring asteroid properties that cannot be easily obtained from ground observations, namely their mass, density and surface physical properties. A wealth of information can in fact be obtained with a very simple payload, centred on a microimager for surface properties and a radio science experiment for bulk mass and density determination. An IR spectrometer complements the imager for the provision of mineralogical information. The key APIES science objectives are then:

- To characterize the Main-Belt asteroid population, by measuring mass, density and the surface physical properties (Visible and IR spectral imaging).
- To analyse a statistically significant sample of the population, including several samples from all the major spectral classes and a few representatives from the rarer ones, for a total of 100 objects.



The asteroid belt contains over 45,000 objects with diameters greater than 5.0 km, yet only a handful has been visited by a spacecraft, and key properties like mass, composition and density are known for very few objects

Mission Concept & Payload

Given the large number of target objects, only a swarm mission as proposed here is capable of performing, in a reasonable timeframe, the required basic *in situ* measurements. The APIES mission goal is in fact to achieve over 100 close asteroid flybys during an operational period of 6 years in the asteroid belt. Although only a short time is available to make close measurements of each asteroid's parameters during a flyby, the large number of such flybys making similar measurements will provide the obtained data an extra dimension not attainable with a small number of rendezvous missions or opportunistic flybys by different spacecraft.

For the achievement of the envisaged 100 flybys, APIES relies on a fleet of 19 microsatellites equipped with the mission scientific payloads. Each of these BElt Explorers (BEEs) carries the combined imager & IR spectrometer and a Ka-band transponder & amplifier necessary for communications and for the mass measurement. Each BEE spacecraft has a mass of 45 kg. The BEE spacecraft are delivered to the asteroid belt by the HIVE (Hub and Interplanetary VEhicle), a carrier spacecraft that also acts, during the mission operational phase, as the central hub for the swarm and as a relay satellite to transmit the data back to Earth. The HIVE plays the vital roles of communications and Doppler tracking of the BEEs during flyby, swarm control, data storage and downlink to Earth. In particular, the HIVE is also equipped with some of the radio science experiment instruments package, including an Ultra-Stable Oscillator (USO) and Doppler extractors.

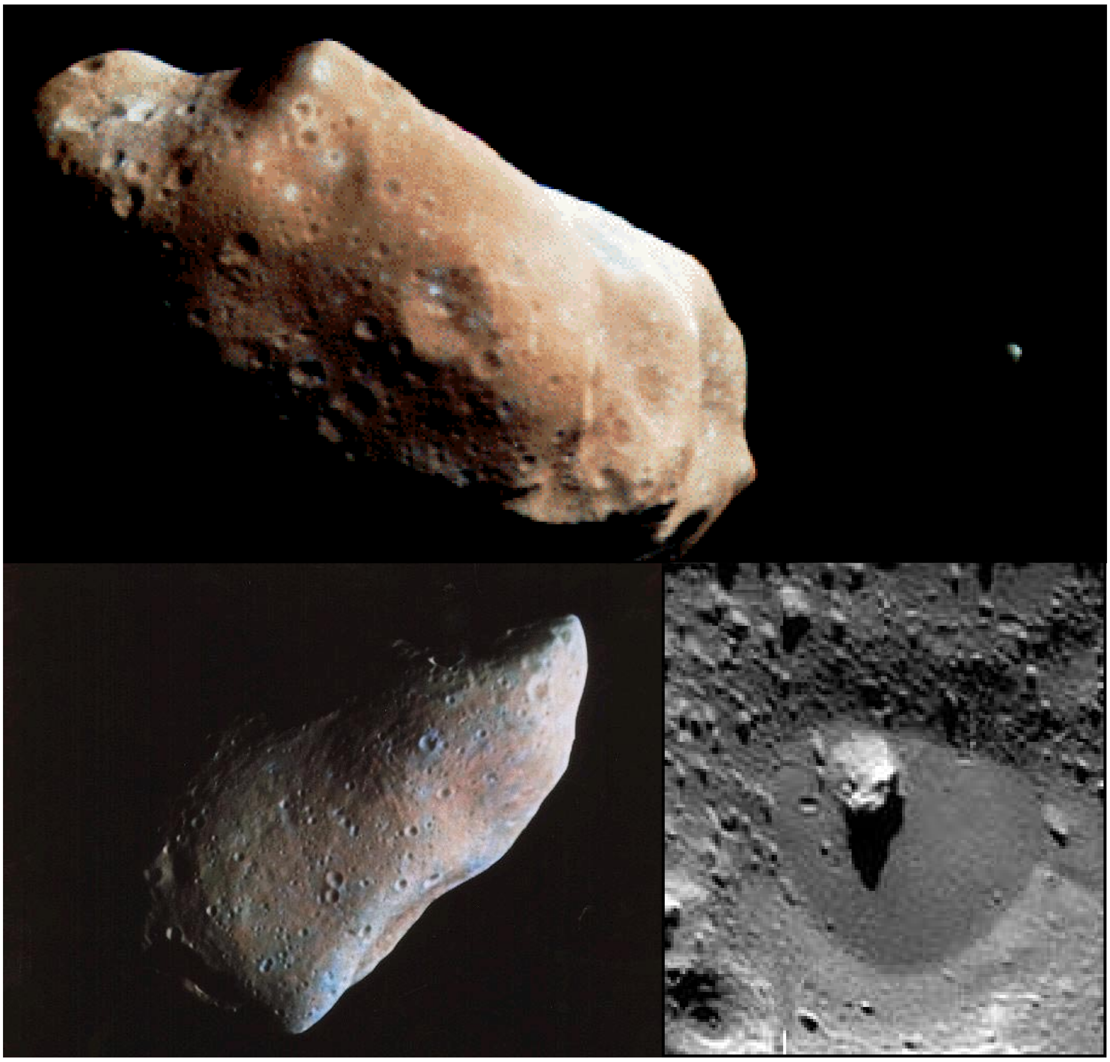
All the key parameters mentioned earlier can be measured with a small complement of instruments. This is the full set of instruments on board the BEE spacecraft:

- A Radio Science Experiment to measure the asteroid gravity field (mass & mass distribution)
- A Multispectral Imager to measure the surface properties
- An IR Spectrometer to measure the surface mineralogy

The Radio Science Experiment utilizes the spacecraft communication systems to transmit and receive radio beacons from/to the HIVE. This allows location of the BEE with respect to the HIVE and the reconstruction of the asteroid gravity field through the deflections in the BEE trajectory after flyby. The measurement is based on a Doppler Ranging technique that provides both the relative distance and the radial velocity of the BEE. The radio science experiment utilizes the Ka-band uplink and downlink also used for communications between the BEE and the HIVE. In addition an Ultrastable Oscillatior (USO) on-board the HIVE provides a frequency reference. This way, APIES will be able to measure the mass of the asteroid to within at least 10% (much higher accuracy can be achieved for larger asteroids).

The Multispectral Imager is based on a miniature CCD camera operating at visible wavelengths and provided with at least 3 broadband spectral filters to obtain colour information. This microcamera will map the surface of the asteroid to study its topology, geology and to measure the asteroid volume (necessary for the density measurement). The camera will also be able to measure the asteroid rotation and to search for surface regolith. The APIES camera will be able to achieve global imaging with at least 100 m/pixel resolution and to resolve details of the order of 10 m for selected surface regions. This would allow APIES to determine the asteroid density to at least 20% accuracy for the smallest objects (an accuracy to around 10% is expected to be the norm).

The IR Spectrometer will provide an IR spectrum of the asteroid surface in the wavelength region between 1.0 µm and 2.5µm, which can be used to determine the mineralogical composition and spectral classification of the asteroid surface.



A wealth of information can be derived from imaging of the asteroid surface at different resolutions and in different spectral bands, specially when combined with the asteroid bulk density and its IR spectrum.

Mission Design

The Interplanetary Cruise

In the baseline concept, the target orbit for the APIES swarm is based on a HIVE heliocentric circular orbit at 2.6 AU. This orbit selection is the result of a trade-off between the need of achieving a high rate of asteroid flybys (hence targeting a high-density region of the asteroid belt) and that of adequately sampling the diversity of the asteroid population (and so targeting a Main Belt zone where the population is mixed, with representatives of most of the known asteroid spectral classes).

To achieve the final operational orbit, it is envisaged that the APIES swarm will be transported by the HIVE carrier spacecraft, with the BEEs deployed only after reaching the asteroid belt. APIES is designed for a Soyuz/Fregat launch, capable of injecting a mass of up to 1420 kg into a Mars flyby trajectory. The HIVE, still carrying the BEEs, will take advantage of a Mars gravity assist and then use its own Solar Electric Propulsion (SEP) system to reach its 2.6 AU final circular heliocentric orbit. It has been estimated that with the Soyuz-Fregat launcher and Mars gravity assist, an SEP system can deliver about 850 kg of payload (total ad-up mass for the BEEs) to a circular orbit at 2.6 AU within a 3-year transfer time. An additional 3-4 years may then be needed for the deployment of the BEEs swarm to its nominal operational formation.

The Exploration Phase

After reaching the asteroid belt, the BEEs will separate from the HIVE and create a swarm “cloud” centred on the HIVE. In the APIES nominal formation, the BEEs are distributed in concentric rings in one plane at 60º to the ecliptic and containing the HIVE velocity vector (see Figure). The selection of this optimal swarm formation is resulting from the modelling of the asteroid population in the main belt. This free-drift formation can then be demonstrated to be stable and requiring minimal fuel consumption. The nominal formation will however evolve with time, as the BEEs are directed towards different asteroid flybys, during the belt exploration phase.

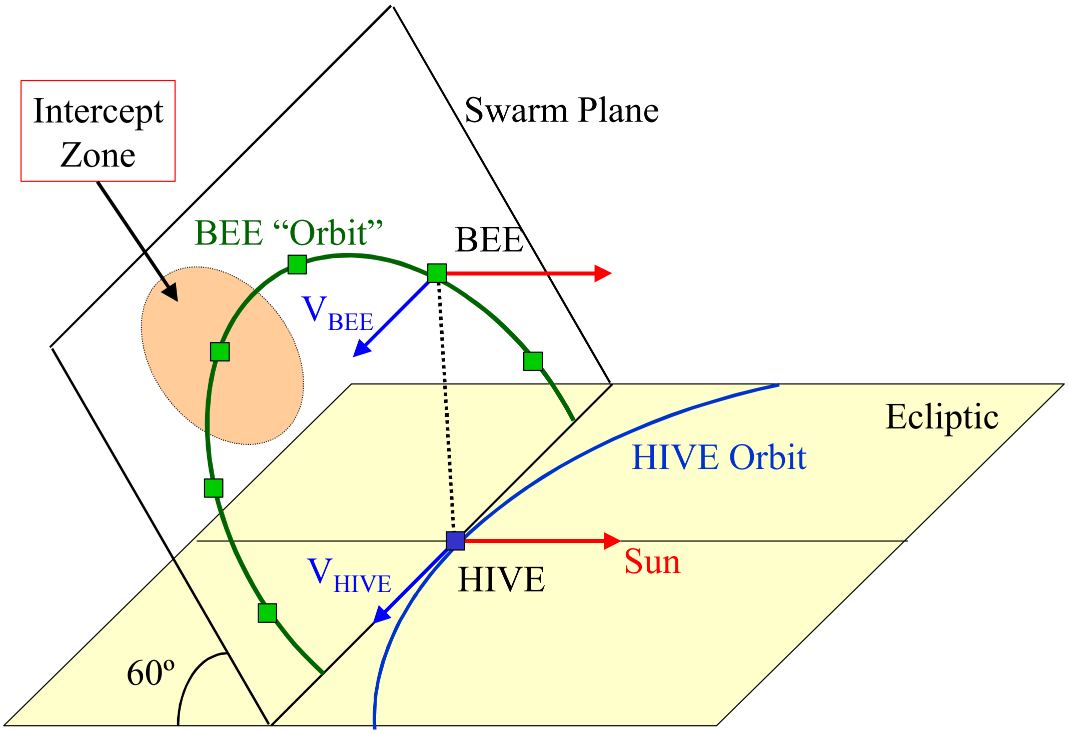
The swarm cloud is in fact meant to intercept the asteroid flux drifting through it by directing, in each case, the most appropriate BEE towards the target asteroid. Hence, the direction and magnitude of this asteroid flux has important implications for the size and configuration of the swarm formation. The asteroid flux has been modelled using orbital data from over 50,000 asteroids, down to magnitude 14.6, corresponding to a diameter of around 5.0 km. The results of this simulation work are:

a) The spatial density of objects larger than 5 km at 2.6 AU is around 1200 objects/AU^3,

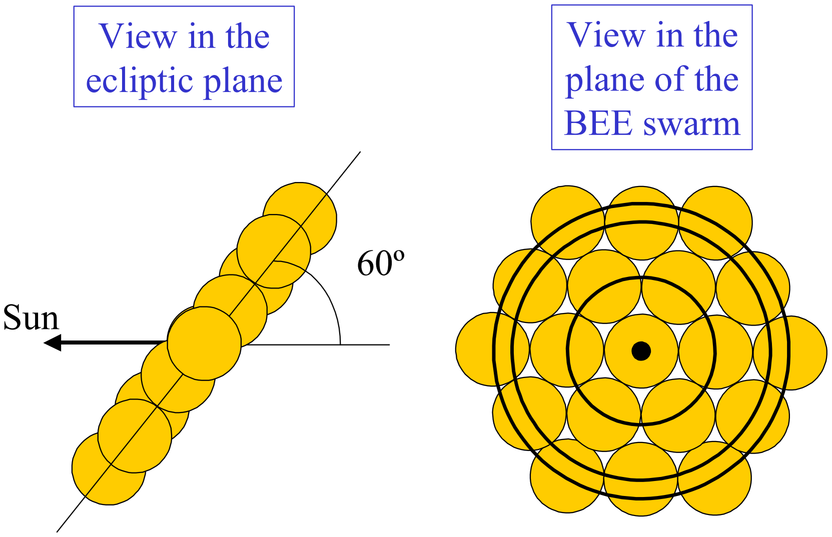
b) Their mean flyby velocity relative to the HIVE’s circular orbit is 2.2 km/s,

c) The asteroid flux is strongly peaked around the cross-track direction (mean relative velocity forming a 90º angle with respect to the HIVE’s orbital velocity).

With all the BEEs distributed in a single plane, it is hence possible to position them so that virtually every asteroid crossing the cloud can be intercepted, by assigning each BEE an "intercept zone" (see Figure). With a swarm size of 19 BEEs and about 100 asteroid flybys in 6 years, each BEE will have on average over 1.1 years between two successive flybys. This time is envisaged to be used to manoeuvre the BEE into position for its next expected encounter. The time between flybys and the size of the "intercept zone" can then be used to size the propulsion system on the BEE spacecraft.

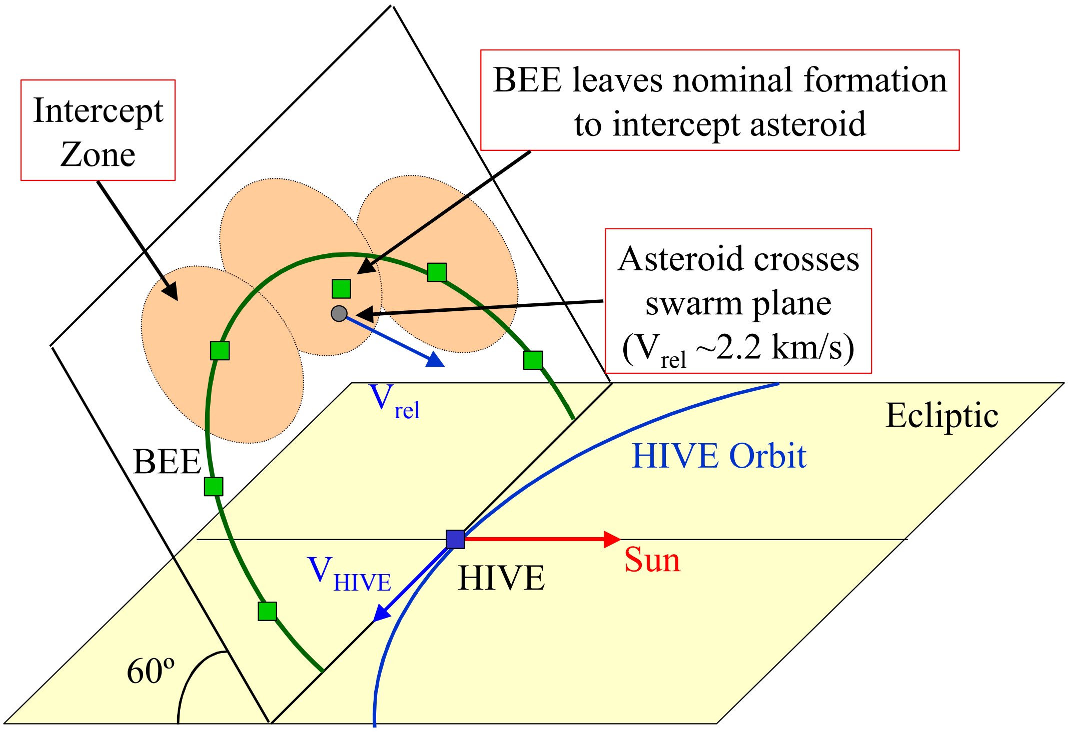


The APIES swarm is distributed in a plane at 60° to the ecliptic plane. The BEEs are distributed in concentric rings around the HIVE. As the HIVE revolves around the Sun, the BEEs appear to "orbit" the HIVE.



19-BEE Swarm

The 19 BEEs of the swarm are distributed in concentric rings at the centre of their own (circular) intercept zone. The intercept zones are distributed so as to minimize overlap.



During the operational phase the BEEs continuously move within their intercept zones to encounter passing asteroids.

System Design

A swarm mission like APIES, involving the flight of a formation of a large number of spacecraft in a deep space environment, requires a complex system optimization process involving the swarm size and operational orbits, the propulsion system choice on both the HIVE and the BEEs, but also the knowledge of the spatial density of target asteroids, the time available for the main belt exploration, the total number of flybys, etc. From the selection of the scientific objectives, in the form of target HIVE orbit and total flybys' number, it is possible to derive the key trade-off for the BEE spacecraft propulsion system, determining the optimum number of BEEs in the swarm. The figure of merit used in this analysis is the residual mass of each BEE, defined as the total spacecraft wet mass minus the mass of the propulsion system (engine + propellant for the chemical/SEP options, sail + deployment mechanism for the solar sailing case).

Five main propulsion system options have been considered for the BEEs: conventional mono- and bi-propellant chemical propulsion, arcjet technology (assuming Isp = 600 s) and two options (conservative & advanced) for solar sailing. The used sail sizing parameters were 4.0 mm film thickness, 6 g/m2 area mass and 100 g/m boom mass for the more pessimistic conservative case, reduced by 50% for the more advanced option (2.0 mm film and 50g/m booms). It should be noted here that, although solar sailing is still untested in space, these scaling parameters are well within the capability of technology currently undergoing on-ground testing. Although solar sailing can potentially deliver a competitive performance, for this mission it was felt that the technology was not sufficiently mature. A more conservative approach to solar sail mass would instead lead to a less competitive option.

On a general basis, the adoption of a chemical propulsion system would provide lower performances with respect to those achievable with the other propulsion systems, but has the advantage of simplicity and of being feasible with current technology. The most promising option uses a bipropellant system and it leads to a swarm size of ~25 BEEs with a total mass of around 35 kg each.

The chosen baseline option utilises however a miniature arcjet system, which delivers the best match between the provided Isp (600 sec) and the DV requirement (around 2000 m/s). while keeping the dry mass of the propulsion system to a very low level. In this case, the swarm would be composed of 19 BEEs, each having a mass in the 45 kg range.

The arcjet propulsion baselined for APIES delivers a thrust of 15 mN for a power input of 100W. Since the BEE solar arrays can only deliver a maximum of around 40W of power, the arcjet is operated in pulsed mode off the battery, with relatively short thrusts (~1 hour maximum) separated by longer battery recharge times (~5 hours). This solution provides the best mass-efficient solution as it does not significantly increase the size of the BEE solar arrays, while still performing trajectory correction manoeuvres in near-impulsive fashion: the total time for thrusting/recharging is only around 11% of the total time available for the manouvres.

Swarm communications are also critical to the success of the mission. In the baseline operational mode, APIES will have one BEE performing one asteroid flyby at a time.

The flybys are envisaged to be scheduled beforehand using asteroid orbital data known from ground based observations, so that no encounters will occur simultaneously. As already introduced, for the achievement of the overall mission goal of over 100 flybys in 6 years, the mean time interval between successive encounters is 2-3 weeks. To prevent the accumulation of stored data, all the data volume produced during each flyby needs to be downloaded back to Earth in this period of time. This implies the transmission of all the acquired scientific data from the BEE to the HIVE and then from there back to Earth.

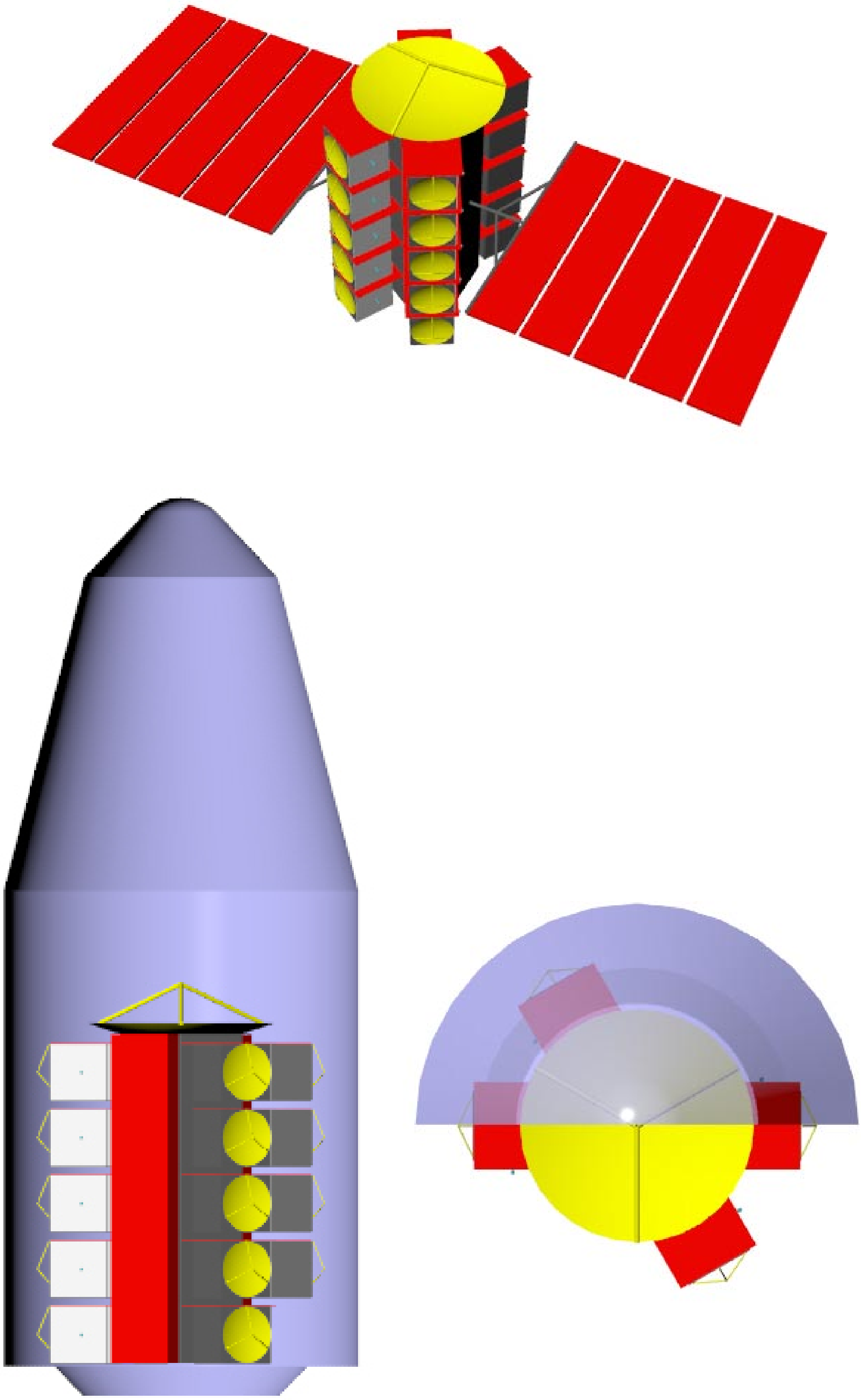
Given the involved distances, the HIVE needs to point its HGA towards the relevant BEE during each flyby and then towards Earth for data downlink. Low data rate communications between the BEEs and the HIVE via the MGA onboard the HIVE will be possible, but should be limited to housekeeping data and swarm control (e.g. monitoring distress signals from BEEs experiencing faults, etc.). It should be noted, however, that the data from the various BEEs do not need to be transmitted straight after each flyby. In fact, provided that the time available is utilized to the full, it may be advantageous in some cases to schedule the BEE data download to a more suitable time from the point of view of HIVE operations, even if before the next flyby scheduled for the relevant BEE. In the current communications scheme, about 8 days are envisaged to be required for the download to the HIVE of the 70 Mbit of scientific data acquired, during each asteroid flyby, by a BEE at the edge of the swarm.

HIVE Design

As already introduced, the main functions of the HIVE are to transport the swarm to the target orbit in the asteroid belt and, once there, to act as communication and coordination centre for the swarm. In particular, the HIVE will perform all the radio tracking and data downloading from the BEEs swarm, thereby greatly reducing the need for ground operations. Thanks to the much higher data rate allowable for the HIVE-Earth communications, in fact, the duration of ground tracking for each flyby is reduced by 97% with respect to what would be necessary in the case of a direct BEE-Earth link, from 8-10 days to less than 6 hours.

Given the target HIVE orbit at 2.6 AU, the need to keep transfer times relatively short and the total launch mass of less than 1420 kg, the only reasonable option for the HIVE propulsion is SEP (either Ion or Plasma), with a total solar array area of about 25 m2 estimated to be needed for the required power generation. The use of SEP on the HIVE has also the indirect advantage of providing plenty of power for communications once it has reached its final operational orbit.

The HIVE's communication system relies on a 2.0 m fixed HGA for high data rate downlink and on MGAs/LGAs for swarm monitoring purposes. A dual X- and Ka-band transmission system will be used for communications with Earth, while communication with the BEEs will be exclusively in Ka-band.



The HIVE design combines accommodation of 19 BEEs on the structure as well as complying to the Fregat-ST fairing of the Soyuz launcher

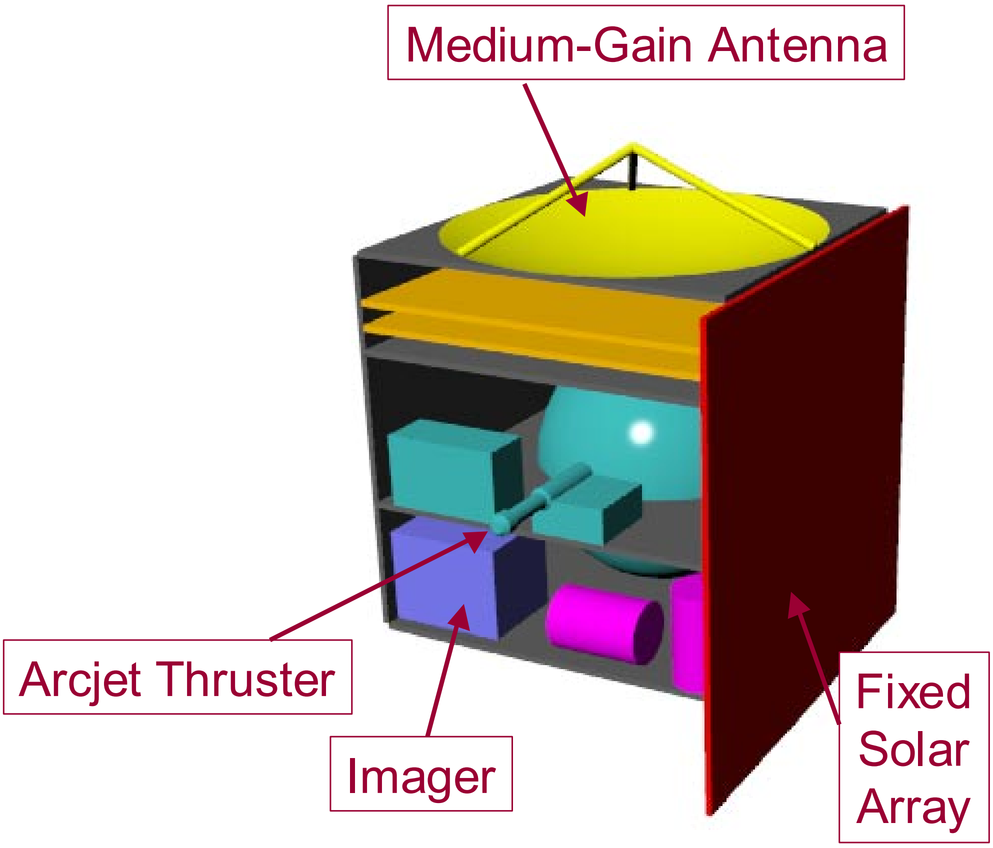
BEE Design

Each BEE spacecraft (see Figure 4) carries the critical payload for the exploration of the asteroid belt. The BEEs are also extremely constrained in mass, with a total (wet) mass of 45 kg (10% system margin), and up to 40-45% of this taken up by their own propulsion system. As such, the BEE design is critical for the success of the APIES mission. Apart from the arcjet propulsion system, the key drivers in the BEE spacecraft design are the mass constraint, the required high level of onboard autonomy, the attitude control system and the power generation system.

A series of innovative approaches to mission and spacecraft design will allow the achievement of the ambitious goal of designing a microsatellite for deep space exploration at 2.6 AU, namely:

- Simple science payload, focussed on a small number of key objectives, and consisting of an integrated imager/spectrometer and of a radio science experiment.
- Dual use of payload for science measurements and other tasks, namely the communication system also used for radio tracking and the imager also used as a highly sensitive star tracker for visual navigation and feedback for the Attitude and Orbit Control System (AOCS).
- Highly autonomous operation of the BEE spacecraft for navigation, AOCS and scheduling of flyby measurements.
- Use of advanced technology best suited to the mission needs, like miniature arcjets for the propulsion system, solid-state Ka-band amplifiers and transponders for communications, miniature wheels and star trackers for the AOCS, 28% efficiency triple-junction solar cells.
- Communication with Earth mediated through a high data rate satellite (the HIVE), reducing both the power & mass requirements for the communication system on the BEE and the time necessary for ground contact.
- Zero redundancy on the BEE, redundancy being provided by the high number of used BEE spacecraft (approach calling for a reduction of systematic design faults, rather than improving reliability).

Because of the very stringent time and power limitations, each BEE spacecraft needs to be highly autonomous for most of its operation. Although information about the selected target asteroid position and about the early targeting manoeuvres can be uploaded from the HIVE, each BEE needs to navigate to the asteroid largely by itself. The BEEs are intended to achieve this goal using an autonomous navigation system, calculating relative positions and directing the final Trajectory Correction Manoeuvres (TCM). This approach is similar to what has been achieved during the Deep Space 1 (DS1) spacecraft's flybys of asteroid Braille and comet Borrelly. The autonomous navigation system will use the science camera to acquire and track the motion of the case-by-case target asteroid relative to the background stars and will use this information to predict the approach miss distance. Once this is known with sufficient accuracy, a TCM is planned to achieve the desired 20 km flyby distance.



The BEE design is based on a simple cubic structure, with fixed solar arrays and a fixed 60-cm medium-gain antenna.

The visual navigation system is also envisaged to be used to point the BEE's imager towards the asteroid during its close flyby. Since the flyby velocity can vary between 2.0 and 4.0 km/s, during the last stages of a 20 km flyby, the target can move across the imager's field of view at speeds of more than 5 deg/s. Moreover, as the flyby distance is not known with high accuracy until after the event, the imager slew cannot be entirely programmed in advance. The solution proposed for APIES is to use an asteroid closed-loop tracking system, as was tested on DS1. The advantage of closed-loop tracking is that the drift of the image across the field of view can be monitored in real-time and the pointing corrected to keep the asteroid in the centre of the image itself. For the few seconds or tens of seconds near closest approach the tracking system will probably not be able to follow the asteroid, but in this case a prediction of the asteroid position in the sky can be quite accurate, allowing recovery of the target after closest approach.

The tracking system for the BEE relies on the fact that the spacecraft inertia is sufficiently small to allow the imager to be rigidly mounted to the BEE's structure and pointed by changing the attitude of the whole spacecraft. Performed calculations show that the required fast slew and the maintenance of sufficient pointing accuracy are possible with the combination of small reaction wheels and micro star trackers. This AOCS design is accurate to a 20-30 arcsec up to slew rates of 2-3 deg/sec, allowing high-resolution imaging of the asteroid surface. The same AOCS system, can then be used, with different operational modes, for the accurate pointing of the imager when far from the target, with an achievable pointing accuracy of better than 20 arcsec with up to 30 sec integration times.

Up to about 70 Mbit of data are estimated to be generated during each asteroid flyby. To avoid data accumulation, this volume of information will need to be transmitted from the relevant BEE to the HIVE and then relayed back to Earth in the 2-3 weeks between two successive asteroids' encounters. This leads to data rates for the BEE-HIVE link in the 100 bps range for distances of up to 0.15 AU. The requirement for relatively high data rates at low system mass and power led to the selection of Ka-band for the BEE communication system. With a 60 cm parabolic antenna on the BEE and a 2.0 m receiving antenna on the HIVE, and with a technology similar to that already flown on DS1, these data rates can be achieved with 1.1 W of RF power on each BEE. The use of Ka-band at 32 GHz for communications has also the additional advantage of providing better position and velocity accuracy for the radio tracking and avoiding perturbations from the solar wind. Position accuracies of the order of 100 m and BEE velocity changes of less than 0.1 mm/s are estimated to be achievable.

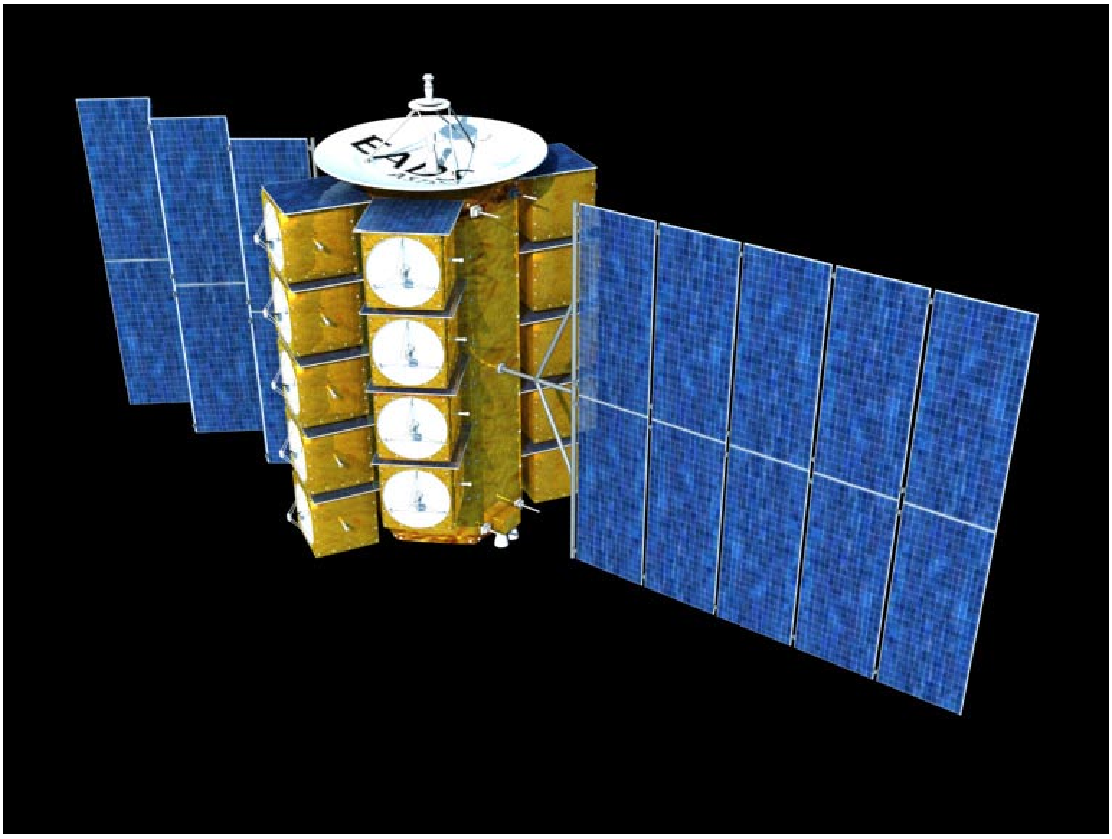
Low mass power generation at 2.6 AU from the Sun is also a critical aspect in the BEEs' design. Most of the BEEs' high power demand systems (wheels for fast slewing, imager/spectrometer, arcjet propulsion) are however only used for brief periods of time, the first two usually near closest approach. The envisaged solution is hence to run the BEEs' subsystems off battery power in the 10-15 hours centred on each close flyby and rely on fixed solar arrays for all the other mission phases. As explained earlier, the arcjet engine is also operated off battery power, in a pulsed mode. The total energy needed for the battery-powered phases near closest approach is less than 60 W-hr, while the battery capacity needed to drive the arcjet is 130 W-hr, well within the capabilities of a small battery.

During the remaining periods the power budget is dominated by the communication system demands during tracking and data download. Even so, the total amount of power needed does not exceed 40 W, a value achievable with a 0.6m2 solar array (although solar radiation at 2.6 AU is much reduced, the solar cells can be kept very cold, to around 200 K, with increased efficiency).

Table 2 shows the BEE spacecraft mass budget assuming the use of an arcjet propulsion system with a specific impulse of 600 sec. Margins of typically around 10% have been included in each subsystem, with an additional system margin of 10%. The total mass of one BEE comes to 43.4 kg, corresponding to a total of 825 kg for the whole swarm. Although the HIVE design was not optimized as part of this study, the total (wet) HIVE mass is estimated at 450-550 kg depending on the transfer strategy. The total HIVE + BEE swarm launch mass adds up to less than 1420 kg, the predicted launcher capability.

BEE Mass Budget Summary	Arcjet BEE	
Payload	2.50	kg
Structure	3.30	kg
Propulsion	7.30	kg
Thermal	0.32	kg
Harness	0.50	kg
Power	4.07	kg
Communications	5.28	kg
AOCS + Electronics	6.28	kg
System Mass Margin	2.96	kg
Total s/c Dry Mass	**32.51**	**kg**
Propellants	10.88	kg
Total Mass @ Launch	**43.39**	**kg**

Mass budget summary for the BEE spacescraft



View of the HIVE carrying the BEE swarm during solar array deployment

Critical Technologies

A number of technologies have been identified as critical to the mission success, covering a wide range of areas, from propulsion, guidance, navigation and control, to communications technology.

For a deep-space microsatellite mission like APIES, the selection of the propulsion system is obviously fundamental in determining the mission performance. The mission analysis showed that with near-term technology the optimum propulsion for the BEE spacecraft is a low-thrust system with a specific impulse of 600-800 sec. The ideal candidate for such a system is a low-power arcjet using hydrazine, delivering a thrust of ~15 mN and a specific thrust of ~600 sec with 100 W input power. In the longer term it was also found that a solar sail could outperform the arcjet, but for the purpose of this study, it was felt that it was not sufficiently mature, particularly in the field of attitude control.

Another area of critical technology for APIES is in the fields of autonomy and navigation: because of the swarm operation at 2.6 AU from the Sun, each BEE needs to be able to navigate to its asteroid targets largely autonomously and the size of the swarm in itself is an obstacle to controlling each individual spacecraft directly. When we consider that one of the mission goals is also to minimize contacts with the ground to reduce costs, we can see that a high level of autonomy on the BEE becomes an imperative. There are two main areas of spacecraft autonomy, which are particularly critical to APIES:

- Autonomous Navigation. Each BEE needs to manoeuvre to move from one asteroid target to the next and calculate its position relative to the target. Autonomous visual identification of the target and position determination are then essential for the mission success.
- Autonomous Housekeeping Monitoring. To minimize contact with the HIVE, the BEE needs to be able to monitor its health status largely autonomously and transmit more information only when necessary.

The third area of critical technology for APIES is in the field of communications: because of the limited mass and power available and the distances involved, an efficient communication link between the BEE and the HIVE is critical. In the study it was found that communications in the Ka-band frequency range would offer the optimal solution, both in terms of reducing mass (through miniaturized deep space transponders and solid-state amplifiers, but also smaller antennas) and power consumption (thanks to the higher signal frequency) for a given data rate. The technology for Ka-band communication equipment under development at ESA and it will greatly benefit the APIES mission.

Conclusion

The APIES mission represents a novel approach to Solar System exploration: instead of relying on very large spacecraft packed with many different types of instruments, APIES takes the opposite route of limiting the payload to what is strictly needed for the achievement of few key objectives and distributing it over several microsatellites. A carrier “mother” spacecraft is then used for the swarm coordination, but even this is a relatively small spacecraft, with a wet mass in the 450-550 kg range.

For a mission like APIES, whose main objective is to cover a large number of bodies with a relatively small number of measurements, this is an ideal approach, but it is possible to envisage other cases where this strategy may be applicable. For example, just in the field of planetary science, “swarm” missions could be considered for the exploration of satellite systems of the outer planets, of planetary atmospheres (using aeroprobes rather than satellites) or for the monitoring of dynamic processes, like magnetic fields, the Solar wind or the Sun’s photosphere.

In the APIES case, the swarm approach allows the achievement of the very ambitious target of 100 asteroid flybys within a total mission duration of less than 12 years, a total launch mass within the capability of medium-sized launchers (Soyuz-Fregat) and with minimum levels of ground control. In addition, the production of spacecraft on a relatively large scale (at least 19) is envisaged to enable a significant reduction of manufacturing costs, though mass production of components