Solar Sails for Space Exploration – The Development and Demonstration of Critical Technologies in Partnership

M. Leipold
Institute of Space Sensor Technology and Planetary Exploration, DLR German Aerospace Centre, Cologne, Germany

D. Kassing
Systems Studies Division, ESA Directorate of Industrial Matters and Technology Programmes, ESTEC, Noordwijk, The Netherlands

M. Eiden
Mechanical Systems Division, ESA Directorate of Technical and Operational Support, ESTEC, Noordwijk, The Netherlands

L. Herbeck
Institute of Structural Mechanics, DLR German Aerospace Centre, Braunschweig, Germany

Introduction

Solar-sail technology holds the promise of significantly enhancing the interplanetary transportation infrastructure for space-exploration missions in the new millennium, by exploiting the freely available space resource of solar radiation pressure for primary propulsion.

This article presents results of a joint ESA/DLR effort to pre-develop the technologies required to validate the concept of space exploration by solar sailing. This co-operative effort is considered a prototype for a new form of partnership with other space agencies and industrial partners involved in technology R&D aimed at exploiting new application opportunities.

A solar sail consists of a large, lightweight and highly reflective surface that relies on the momentum transferred from solar photons for passive propulsion. By making use of this innovative means of low-thrust propulsion, extended missions in our Solar System which require a ΔV of several tens of kilometres per second would become possible. For missions needing such high propulsion energies, solar sails could either complement other more traditional means of space propulsion, or provide all of the propulsion needed. Typical examples might be a Mercury Orbiter, a (multiple) main-belt asteroid rendezvous, a small-body sample return, or a solar polar orbiter in a 90° inclined orbit (to the ecliptic) at about 0.5 AU solar distance.

Based on promising results obtained during system studies by DLR (in cooperation with NASA/JPL) and by ESA, a joint effort for the development of solar-sail technology on a co-funding basis was initiated in 1998.

Potential solar-sail mission applications

Solar sailing has been investigated as an alternative means of propulsion in several studies for planetary missions such as a Mercury Orbiter. Mission analysis has shown that solar sails can be utilised for a low-thrust spiral transfer to Mercury with essentially zero Earth-departure relative velocity, and allowing suitable rendezvous conditions at Mercury arrival. For the Earth-Mercury trajectory shown in Figure 1, the maximum acceleration delivered by the sail at 1 AU solar distance (referred to as the characteristic acceleration a_c) is large enough to provide a transfer flight time of 1.8 years. Departing from Earth in January 2003, therefore, would result in arrival at Mercury in November 2004.

An example for the associated sail size and mass would be a 125 m x 125 m sail carrying a spacecraft with a net mass of 110 kg, including the scientific payload. Assuming 8 g/m^2 for the sail itself, the launch mass of the complete spacecraft would be about 235 kg. This would mean that it could potentially be launched at relatively low cost as an Ariane-5 mini auxiliary payload.

Once at Mercury, solar sails would also allow a Sun-synchronous orbit about the planet to be established. The highly effective and basically endless propulsion capability of a solar sail could be used to produce a rotation of the orbital plane around Mercury, allowing the spacecraft to operate continuously near the planet's terminator.

Another promising solar-sail application is a mission to a close circular polar orbit at 0.3 AU to 0.5 AU solar distance, which would provide an interesting opportunity for solar observations and space-physics investigations. This would allow close-up observation of the solar poles, with a relatively short transfer time and a high repetition rate. The only observations to date of the Sun's polar regions have been made by ESA's Ulysses spacecraft, which passes above the poles at a distance of approximately 2 AU, as a result of the Jupiter Gravity Assist (JGA) trajectory used to position the spacecraft in its elliptic, polar orbit around the Sun.

The solar-sail transfer would be carried out in two flight phases:

- a spiral to a semi-major axis of 0.3 — 0.5 AU
- a spiral to increase the orbit's inclination to 90º (so-called 'orbit cranking').

The analysis shows that the trip time needed to reach a semi-major axis of 0.3 AU would be about 1.5 years, and the subsequent 'cranking orbit' to achieve a heliocentric inclination of 90º would take 2 years (Fig. 2).

New mission opportunities applying solar-sail technologies are currently being addressed by NASA also. The Jet Propulsion Laboratory (JPL), for instance, has recently completed a study of a proposed Solar Polar Sail Mission that would use solar-sail propulsion to place a spacecraft in a circular 4-month orbit at a distance of 0.48 AU from the Sun with an inclination of 90º. The mission would provide data on the solar corona to complement observations of the Sun's disk and the solar-wind data obtained near Earth. Another potential solar-sail mission, proposed by NOAA in cooperation with NASA as well as by European scientists, is a sailcraft to be stationed sunward of the Sun-Earth Lagrangian point L1. Solar photon pressure on the sail would be required for the sailcraft to fly inside the L1 point whilst remaining on the Earth-Sun line (the outward radial force on the sail must compensate for the lower centrifugal force on the sailcraft). From this vantage point, the sailcraft would deliver a factor 2 improvement in solar-storm warning time (60 min compared to 30 min) over a conventional satellite stationed at L1. A similar mission concept called 'Vigiwind' was proposed in Europe by U3P and CNES in 1996.

Transfers to Pluto and beyond would also be possible with solar-sail propulsion. So-called 'indirect' or 'solar photonic assist' trajectories, investigated recently by DLR, allow short trip times to Pluto with solar sails. Figure 3 shows the ecliptic projection of a transfer to Pluto using a sailcraft with a characteristic acceleration of 0.7 mm/s^2 and a double swing-by at the Sun. The transfer time from Earth to Pluto flyby in this case is about 10.5 years, which compares favourably with conventional

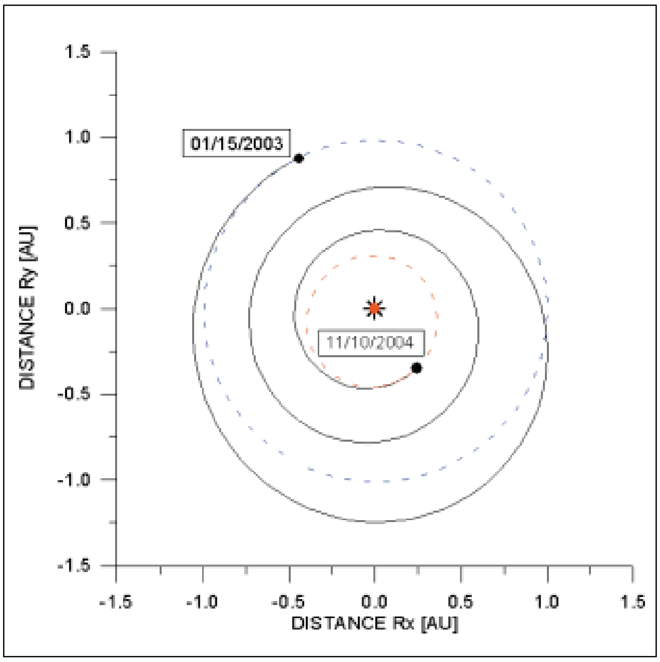

Figure 1. Interplanetary transfer from Earth to Mercury, with a characteristic acceleration a_c of 0.55 mm/s^2

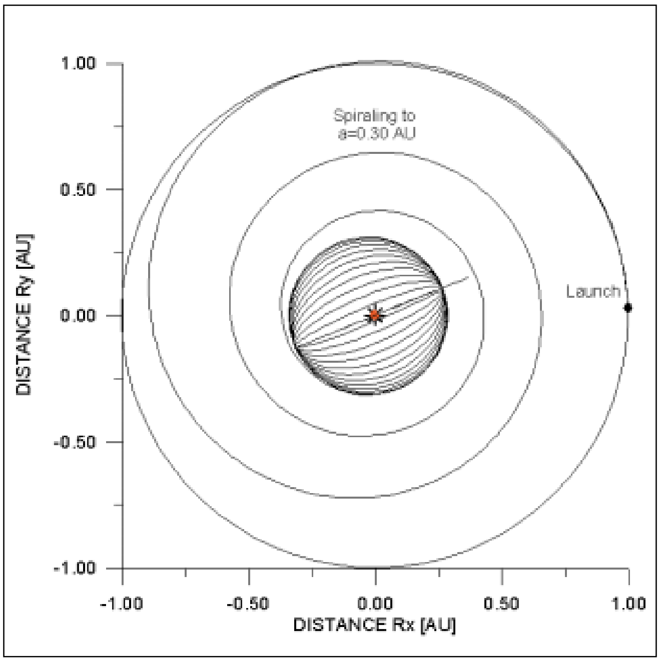

Figure 2. Spiral trajectory to a close solar-polar orbit (ecliptic projection) a_c = 0.50 mm/s^2

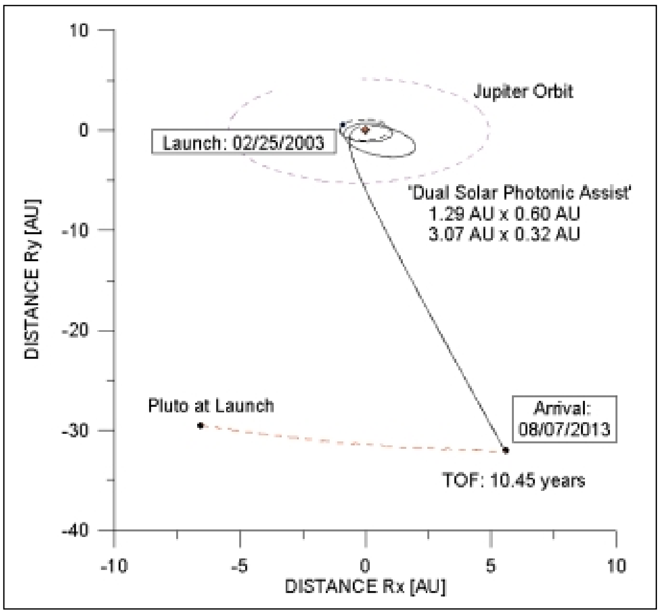

Figure 3. A solar-sail 'dual solar photonic assist' transfer to Pluto

transfers of 11 to 13 years using multiple-gravity-assist trajectories at Venus and Jupiter.

By extending the principle of single or multiple 'solar photonic assist' trajectories, advanced solar sails might be capable of achieving high enough speeds to propel spacecraft out of our Solar System. Assuming that 'second-generation' solar sails might have characteristic accelerations (a_c) in the order of 1 to 3 mm/s^2 and ultra-light sail structures of 1 to 5 g/m^2, very high speeds could indeed be achieved. By using close solar approaches to within 0.3 AU or even less, using special sail coatings and high-performance materials capable of handling the very high temperatures, escape velocities of 50 to 100 km/s or more might be achievable.

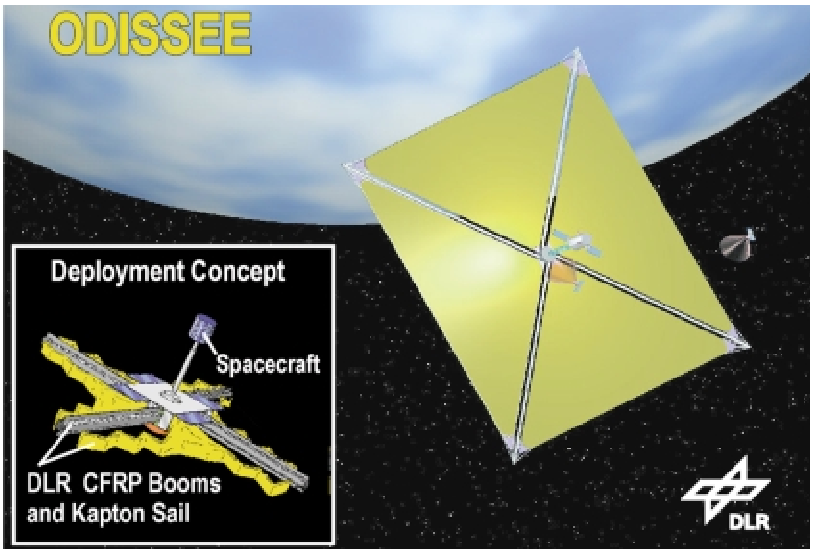

Figure 4. Conceptual design for the deployed square sail

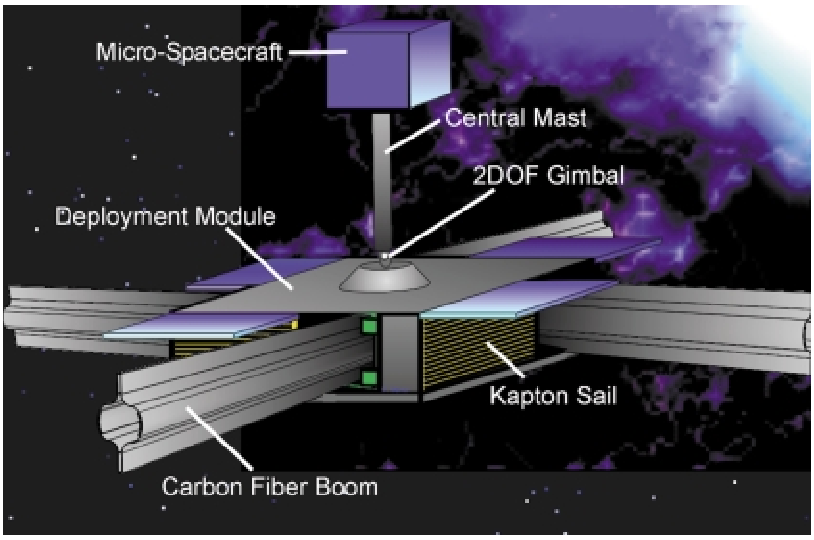

Figure 5. Sailcraft baseline concept, partially deployed

The mission concept envisages a sailcraft that is injected into a heliocentric orbit at 1 AU, in which the solar sail is then deployed. In a corresponding NASA study, the mission trajectory would carry the sailcraft to 2 AU approximately one year after launch and then sunward to a perihelion distance of 0.25 AU to exit the Solar System with a velocity of 10.9 AU/year. At this velocity, a Jupiter orbital distance would be achieved within 2.1 years after launch, and 200 AU within 20 years.

The sailcraft concept

Various solar-sail design concepts have been proposed in the past. For the joint ESA-DLR technology development effort, a square sail with diagonal booms supporting four triangular segments was chosen as the baseline configuration. The sail structure is composed of three major elements: the booms, the sail film segments, and a central deployment module. The four supporting CFRP (Carbon Fibre Reinforced Plastic) booms are unrolled from the central deployment module and the folded sail film segments are released from storage containers. Figure 4 shows a conceptual design for the square sail in Earth orbit, together with a partially deployed sail (lower left). The concept is based on the ODISSEE proposal (Orbital Demonstration of an Innovative, Solar Sail driven Expandable structure Experiment).

Figure 5 shows the partially deployed CFRP booms, with the storage containers for the sail film segments. The film segments are folded in two directions ('accordion fashion', also referred to as 'frog-leg folding' due to the unfolding behaviour), thereby minimising storage volume and allowing controlled sail release. Once in orbit, the micro-spacecraft and sail module are separated from each other by a collapsible 10 m mast, which is housed inside the spacecraft in its stowed configuration. This structure is referred to here as the 'central mast', or 'sailcraft control mast', connecting the spacecraft and the sail structure. The central mast is attached to the sail deployment module via a two-degree-of-freedom (2 DOF) actuator gimbal, which allows the control mast and attached spacecraft to be rotated with respect to the sail. In this way, the center-of-pressure (CP) can be offset from the centre-of-mass (CM), and using solar radiation pressure as an external force a torque can be generated to control the sail's attitude.

The carbon-fibre booms, developed by DLR, combine high strength and stiffness with low density, and can be stored in a small volume. They consist of two laminated sheets, which are bonded at the edges to form a tubular shape (Fig. 6). They can be pressed flat around a central hub for storage, and uncoil from the hub during deployment. Once deployed, they resume their original tubular shape and exhibit high bending stiffness.

The design for the deployment module housing the rolled-up booms and folded sail film is driven mainly by the severe volume constraints of the Ariane-5 ASAP (Ariane Structure for Auxiliary Payloads) launch option.

To analyse the baseline configuration further and to test the deployment behaviour of folded sail segments, an 8 m x 8 m solar-sail mock-up (Fig. 7) was built at DLR. The four diagonal booms are made of aluminium and are not deployable. The sail itself was manufactured from 12-micron Mylar film, aluminised on one side. The upper triangular sail segment was 'frog-leg-folded' and stored in a sail container sized to match the storage volume available for the proposed ODISSEE orbital test flight. The sail segment was deployed successfully in several ground tests involving motors and deployment ropes to unfurl and tighten the sail.

Figure 6. A CFRP deployable boom

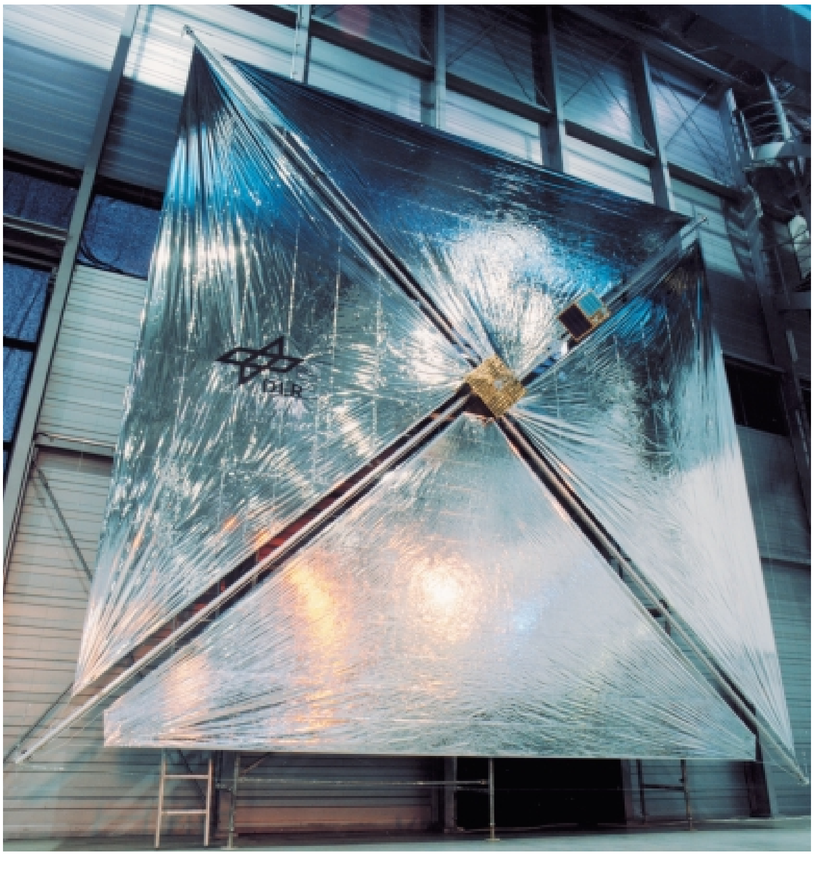

Figure 7. The DLR solar-sail mock-up

Technological challenges of solar-sail deployment

Although the basic idea behind solar sailing appears simple, challenging engineering problems have to be solved to exploit photonic propulsion for orbit transfer. Since the spiral orbit-raising efficiency depends basically on the overall spacecraft mass to solar sail area ratio, lightweight technological solutions for large in-orbit deployed sail surfaces are required. The technical challenges are:

- to fabricate the sails using ultra-thin films and lightweight deployable booms able to carry the in-orbit loads
- to package the sails and booms into a small volume
- to deploy these lightweight structures successfully in space, and
- to control the large but low-mass structure.

The solutions to these challenges must first be demonstrated to the greatest possible extent on the ground in 1 g, and subsequently via an in-orbit demonstration mission, before solar-sail propulsion can be considered viable for any mission.

The deployment module uses a square sail design with diagonal booms to support four triangular sail film segments, which are stowed in small containers next to the coilable-boom compartment. The volume constraint of an anticipated Ariane-5 piggy-back launch places extreme demands on the engineering ingenuity of the four-boom deployment solution, while the in-orbit loads due to solar pressure and the effects of manufacturing tolerances call for boom-stiffness performances in excess of the solutions known today. As a consequence of the high stiffness requirements for the booms, their release from a central deployment mechanism has to have proper position guidance components at the exit of the module, whilst still aiming for limited contact to achieve low friction in order to limit the power requirement for the actuation unit.

There are other technical reasons for supporting this field of technology development and demonstration. Engineers would learn through synergy how to deploy and control very large, but extremely lightweight structures for, for example, antennas and solar generators. Micro/nano-technologies, like the micro-machined propulsion thrusters being developed by ESA, could play a complementary but essential role in attitude control.

Planned demonstrations

Two major milestones are foreseen in terms of demonstrations:

– Currently a 20 m x 20 m breadboard model of a fully deployable sail structure is being developed on a co-funding basis by DLR and ESA.

– Recent cooperative pre-Phase-A studies by DLR together with NASA/JPL, as well as an ESA feasibility study, have concluded that a low-cost technology-demonstration mission in Earth orbit is the best approach to demonstrate and flight-validate the basic principles of sail fabrication, packaging, storage, deployment, and control.

The breadboard model is intended to demonstrate the feasibility of a fully deployable lightweight structure via a ground demonstration in a 1g environment under ambient environmental conditions. This breadboard model will provide experience with the deployment of lightweight booms and sail segments, as well as the manufacture, folding and storage of large areas of reflective film.

Following successful completion of the ground demonstration, a low-cost technology-demonstration flight to validate solar-sail technology in Earth orbit is proposed. A ‘piggy-back’ launch on an Ariane-5 would minimise launch costs. This launch vehicle offers the ASAP-5 (Ariane Structure for Auxiliary Payloads) ring structure, which can accommodate up to 8 micro-spacecraft, each with a maximum mass of 100 kg. The volume for each ASAP payload is restricted to 60 cm x 60 cm x 80 cm. Once Ariane-5 had reached its standard Geostationary Transfer Orbit (GTO), with a perigee of 620 km and an apogee of 35 883 km, the sailcraft would be ejected, the sail fully deployed, and performance and manoeuvrability tests performed as part of the primary mission objectives. Sail deployment would be observed with several wide- and narrow-field micro-cameras mounted on the spacecraft.

Two alternative mission routes are being studied:
Route 1 (DAEDALUS): The sailcraft performs a number of orbit changes in Earth orbit to explore its potential for Earth-directed applications. The mission would end with a controlled re-entry of the sailcraft after several months in orbit.
Route 2 (ODISSEE): The sailcraft performs an orbit transfer to the Moon. A high-resolution camera on the sailcraft could explore lunar areas during a polar flyby or from lunar orbit.

The performance for spiral orbit-raising using low-thrust solar-sail propulsion depends on the overall mass-to-area ratio, which for ODISSEE would be about 48 g/m^2. Reaching lunar distance from GTO would take approximately 550 days. Depending on the navigation strategy chosen, the sailcraft could perform a lunar polar flyby to continue its journey to Earth escape and possibly a near-Earth asteroid rendezvous, or the sail might be used for a weak orbit capture into a highly elliptical lunar orbit. Figure 8 shows a typical steering profile for the sail attitude for one orbit. An acceleration and drift phase can be identified. During the acceleration phase, the solar sail raises the orbit, whereas during the drift phase almost ‘edge-on’ sailing is required in order to avoid deceleration. In the baseline scenario only one side of the sail is used for ‘primary propulsion’, reflecting the incident light. Therefore, the front side of the sail, facing the spacecraft, has to be reoriented towards the Sun.

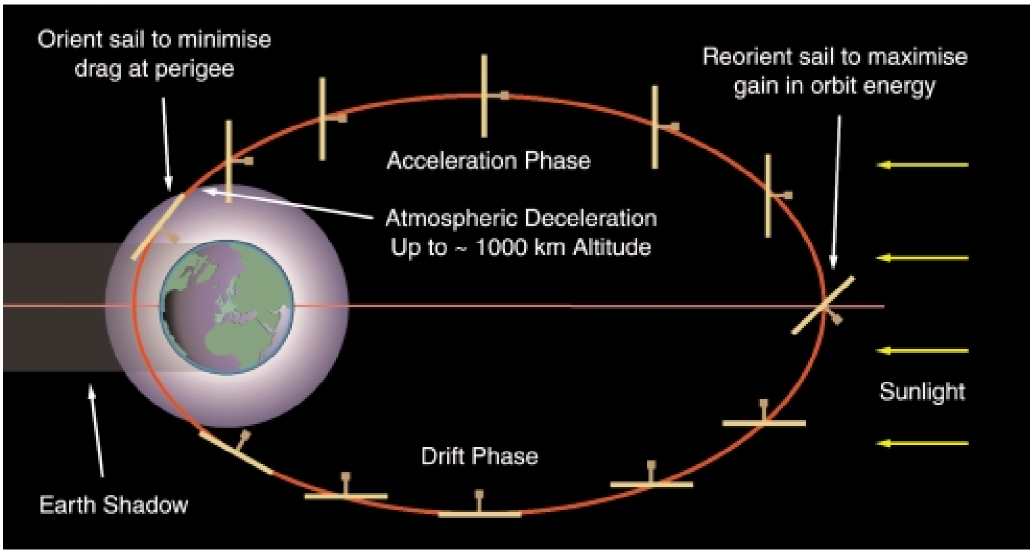

Figure 8. Sail steering profile in GTO

The breadboard-model development is foreseen to bridge the gap between the largely theoretical feasibility study and flight-hardware development. This philosophy fosters early hardware development and extensive testing where possible in order to reduce the inherent project risks. The envisaged low-cost flight validation of a solar sail in Earth orbit by the beginning of the new millennium is seen as an example of rapid prototyping for emerging advanced, breakthrough technologies. Such a validation flight is being proposed as a means of ensuring technology readiness for post-2000 space-science missions utilising solar sails.

A trial case for technology development and demonstration in partnership

Co-funding of concerted activities in this field of technology development and demonstration is the agreed option for ESA and DLR because of:

- the interest in solar-sail propulsion for future interplanetary missions and the applicability of associated large-structure technology for future Earth-directed space services
- the fact that such technology has not been flown before on any space mission, nor has it been demonstrated in space
- the promising results obtained in system studies by both DLR and ESTEC
- the high technological interest on the part of ESA and DLR in the advanced technologies required by the solar-sail concept, which has led ESA to include relevant activities in its technology programme.

ESA has been involved in co-funding initiatives with its industrial partners for ten years or more, particularly in the technology research and development area. Since 1993, a few ESA programmes have formally introduced the idea that the Agency and industry (or another partner organisation like DLR willing to work with ESA) could co-fund all or some of their activities, two early examples being Artes-4 and GSTP.

At an ESA Council Meeting at Ministerial Level in March 1997, a Resolution was finalised and approved which promoted the idea of further improving European industry's world-wide competitiveness as well as the concept of 'partnership' (in this context, partnership is seen as a concept, and co-funding as a mechanism). The partnership scheme applied to the solar-sail activity brings together the Agency, the German Aerospace Centre DLR as an interested institutional partner, and Invent GmbH, a small German SME which is developing the deployment module.

Conclusion

The emerging economic and political environment for space activities initiated by ESA and other space agencies in Europe calls for more and better co-operation and partnership between them and with industry. ESA has developed a set of guidelines for co-funding arrangements, which should help the industrial partners to improve their international competitiveness in the area of technology R&D.

The proposal of a co-operation agreement in the field of solar-sail development and demonstration has been welcomed by both ESA and DLR. The current activity is considered a prototype for a partnership in the development of strategic technology. Solar-sail technology holds the promise of significantly enhancing, or even enabling, space-exploration missions in the new millennium, by exploiting the space-pervading resource of solar radiation pressure.