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SOLAR SAILCRAFT OF THE FIRST GENERATION
TECHNOLOGY DEVELOPMENT

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ABSTRACT

Based on the experience gained with the ground deployment demonstration of a 20 m x 20 m solar sail, performed in December 1999 at DLR, the future development of solar sails has been investigated recently by DLR on behalf of ESA within the PROPULSION 2000 – PHASE II study. The paper highlights some of the findings and gives recommendations for near-term actions. Solar sails are large and light-weight, generally deployable or inflatable, space structures that reflect solar radiation and thereby utilize the freely available solar radiation pressure (SRP) for propellant-free space propulsion. They have a characteristic length of several tens to hundreds of meters and specific masses of several grams to tens of grams per square-meter. Typically, the reflecting material consists of aluminum coated thin plastic films with a thickness of a few micrometers. The considered system design displays a three axes stabilized square sail with diagonal deployable or inflatable booms for tensioning the thin film. In order to derive the necessary technology development, the paper identifies minimum performance requirements for near-term solar sailcraft missions, using results from recent hardware developments and mission analyses, including trajectory simulation and optimization. A characteristic acceleration of 0.1 to 0.2 mm/s^2 seems to represent a 'lower bound' for useful acceleration levels within typical planetary missions. The DLR/ESA ground demonstration cannot achieve this required characteristic acceleration. Thus, to improve the performance, it seems necessary to go to larger and thinner sails, and to modify the design of the deployment module. A technology development roadmap on subsystem-level is outlined, represented by different sails with increasing performance. In-orbit deployment demonstration missions are proposed for low Earth orbit with an altitude of about 350 km, so that automatic de-orbiting takes place after the mission due to atmospheric friction. Other missions are proposed for deep space ($C_3 \geq 0\ km^2/s^2$), requiring a launcher that injects the sailcraft into an Earth escape trajectory.

INTRODUCTION AND GENERAL CONCEPT

Solar sails are large and light-weight, generally deployable or inflatable space structures that reflect solar radiation, thereby utilizing the freely available radiation pressure for propellant-free space propulsion. Solar sails provide a wide range of opportunities for low-cost interplanetary missions with large ΔV-requirements, many of which may be difficult or even impossible with other types of spacecraft.

With the exception of rotating configurations, which are difficult to control and steer, a typical system design features a three axes stabilized square sail with diagonal deployable or inflatable booms for tensioning the coated thin film (e.g. aluminized PEN or Kapton®). Attitude control could be achieved, e.g., with gas thrusters (especially for the deployment phase and as back-up), with control flaps at the boom tips or with a steerable control mast (see description below). Our baseline design is taken from the ODISSEE (Orbital Demonstration of an Innovative Solar Sail driven Expandable structure Experiment) proposal [Leipold et al. 1999a]. The sailcraft comprises a central deployment module for the sail and the four CFRP (Carbon Fiber Reinforced Plastics) booms that diagonally support the four sail segments, a micro-spacecraft – which is the "payload" to be transported – and a deployable control mast (see Figures 1 and 2). The control mast connects the micro-spacecraft with the sail structure and is attached to the deployment module via a 2-degree-of-freedom actuator gimbal, which allows to rotate the control mast and the attached micro-spacecraft with respect to the sail. This way, the center of mass (CM) can be offset from the center of pressure (CP) and, using light pressure as an external force, a torque can be generated to control the sail attitude. This attitude control concept was originally proposed by [Angrilli et al. 1990]. The length of the control mast would be optimized to achieve the required angular acceleration levels (for a 10 m control mast and a $(50\,\mathrm{m})^2$ sail, a 90° turn takes typically about 10 minutes at 1 AU). As an additional option, an active attitude control system with gas thrusters may be installed in the micro-spacecraft.

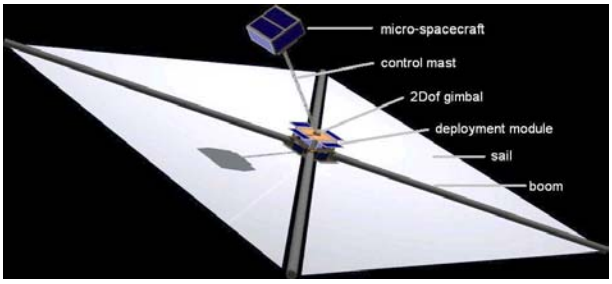
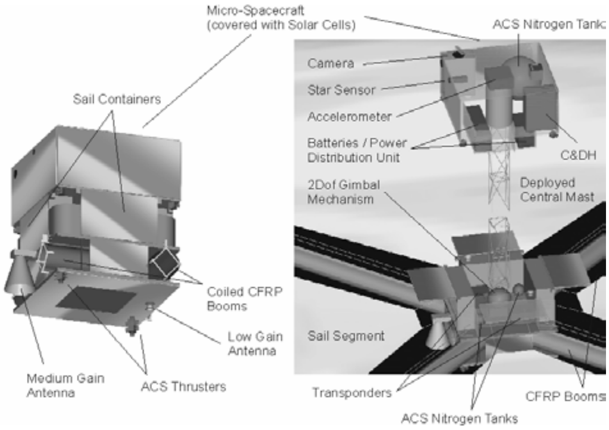


Figure 1: DLR design for a free-flying three-axis stabilized sailcraft with deployed control mast



a) b)

Figure 2: Solar sailcraft design a) launch configuration; b) deployed configuration (from ENEAS proposal [Jessberger et al. 2000])

To keep operation costs low, the sailcraft should have a high degree of navigational autonomy for the control of its attitude and trajectory. Therefore, the capability for on-board determination of the actual position and comparison with the reference trajectory is desirable (at least for certain flight phases) with subsequent automatic modification of the steering strategy – if necessary.

At 1 AU, the solar radiation pressure is $P_0 \doteq 4.563\,\mu\mathrm{N/m^2}$. Therefore, the effective pressure (force per unit area) acting on an ideally reflecting sail, normal to the sun-line, is twice the solar radiation pressure, $2P_0 \doteq 9.126\,\mu\mathrm{N/m^2}$ (Figure 3).

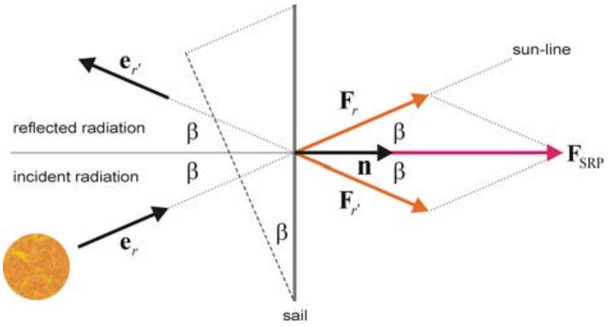


Figure 3: SRP force on a flat and ideally reflecting solar sail

Assuming a perfectly reflecting sail surface and a conservative sail efficiency of $\eta \approx 0.85$ (aluminum coated plastic film), we get

$$P_{\mathrm{eff},0} = 2\eta P_0 \doteq 7.757\,\mu\mathrm{N/m^2}$$

for the effective pressure acting at 1 AU on a solar sail that is oriented normal to the sun-line and

$$\mathbf{F}_{\mathrm{SRP}} = P_{\mathrm{eff},0}\left(\frac{1\mathrm{AU}}{r}\right)^2 A\cos^2\beta\,\mathbf{n}$$

for the respective SRP force in a distance r from the sun. Thus, to experience a reasonable acceleration, solar sailcraft must be large and very lightweight.

The orbital dynamics of solar sailcraft is in many respects similar to the orbital dynamics of other spacecraft, where a small continuous thrust is applied to modify the spacecraft's orbit over an extended period of time. However, other continuous thrust spacecraft may orient its thrust vector in any desired direction and vary its thrust level within a wide range, whereas the thrust vector of solar sailcraft is constrained to lie on the surface of the 'cos^{2}β-bubble' that is always directed away from the sun (see Figure 4). Nevertheless, by controlling the sail orientation relative to the sun, solar sailcraft can *gain* orbital angular momentum and spiral outwards – away from the sun – or *lose* orbital angular momentum and spiral inwards – towards the sun. Despite the relatively low thrust (see Figure 5), a significant reduction of flight times and increase in flexibility for high-ΔV missions seems possible, since planetary gravity-assist trajectories with their associated long transfer times and extremely reduced mission flexibility due to launch window restrictions can be avoided.

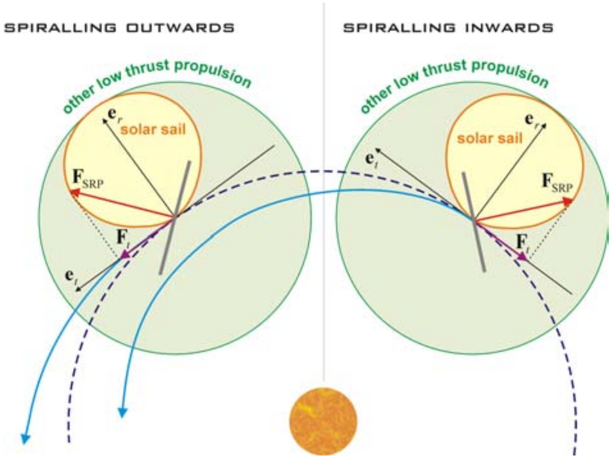


Figure 4: Spiraling inwards and outwards

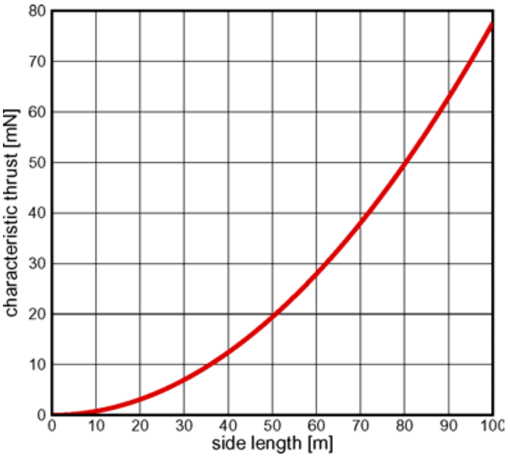


Figure 5: Characteristic thrust (at 1AU) versus square sail side length

As for all spacecraft with continuous thrust, finding flight-time optimized solar sailcraft trajectories is typically a time-consuming and difficult task that involves a lot of experience and expert knowledge. However, recent developments at DLR Institute of Space Simulation show that a new method for low-thrust trajectory optimization, using artificial neural networks and evolutionary algorithms, yields much better results than previously achieved. The developed software can be handled even without the involvement of an expert in astrodynamics and optimal control theory [Dachwald et al. 2002b, Dachwald 2003 / 2003a].

In a paper entitled “Solar Sailcraft of the First Generation – Mission Applications to Near-Earth Asteroids” and submitted in parallel to the 54th International Astronautical Congress, it is shown that challenging scientific missions are feasible at relatively low cost even with moderate performance solar sailcraft of the first generation [Dachwald et al. 2003].

SOLAR SAILCRAFT PERFORMANCE PARAMETERS

The performance of solar sailcraft can be expressed by the following parameters:

Sail Assembly Loading

The sail assembly loading

$$\sigma_{\mathrm{SA}} = \frac{m_{\mathrm{SA}}}{A}$$

is defined as the mass of the sail assembly (the sail film and the required structure for storing, deploying and tensioning the sail, index 'SA') per unit area. Thus, the sail assembly loading is the key parameter for the performance of a solar sail and the efficiency of its structural design.

Sailcraft Loading

The sailcraft loading

$$\sigma = \frac{m}{A} = \frac{m_{\mathrm{SA}} + m_{\mathrm{PL}}}{A} = \sigma_{\mathrm{SA}} + \frac{m_{\mathrm{PL}}}{A}$$

is defined accordingly as the specific mass of sailcraft including the ‘payload’ (index 'PL'). It should be noted, that the term ‘payload’ stands for the total sailcraft except the solar sail assembly (i.e. except the propulsion system).

Characteristic Acceleration

The characteristic acceleration a_c is defined as the maximum acceleration at 1 AU solar distance. It can be calculated via

$$P_{\text{eff},0}A = ma_c = \sigma A a_c = \left(\sigma_{\text{SA}} + \frac{m_{\text{PL}}}{A}\right)Aa_c$$

$$\Rightarrow a_c = \frac{P_{\text{eff},0}}{\sigma_{\text{SA}} + m_{\text{PL}}/A}$$

Using the characteristic acceleration, the SRP force acting on the sail can be written as

$$\mathbf{F}_{\text{SRP}} = ma_c\left(\frac{1\,\text{AU}}{r}\right)^2\cos^2\beta\,\mathbf{n}$$

PRELIMINARY SOLAR SAIL REQUIREMENTS

Solar sailcraft of the first generation will have a relatively moderate performance. They should, however, offer at least a characteristic acceleration of about 0.1 to 0.2 mm/s^2, which seems to represent a 'lower bound' for useful acceleration levels within typical high-energy planetary missions [Dachwald et al. 2002a]. This is demonstrated in Figure 6, where two Mercury transfers are shown with 0.1 and 0.55 mm/s^2 characteristic acceleration, respectively. In the first case, the transfer time of about 10 years represents obviously an upper limit for an acceptable mission duration, while in the second case a transfer time of one year and a half appears very promising.

For a square solar sail (area $A = s^2$), the performance depends on three design parameters, defining a three-dimensional design space: the sail assembly loading σ_{SA}, the payload mass m_{PL} and the side length s. Figure 7 displays a section of this design space for fixed characteristic acceleration $a_c = 0.1$ mm/s^2. The diagram shows that the sail used for the ground demonstration, with $s = 20$ m and $\sigma_{\text{SA}} = 87.5$ g/m^2, cannot achieve a characteristic acceleration of 0.1 mm/s^2, even without payload (payload could, however, be accommodated for a smaller a_c). To improve the performance with respect to sail assembly loading substantially, it seems necessary on the one hand to go to larger and thinner sails and on the other hand to modify

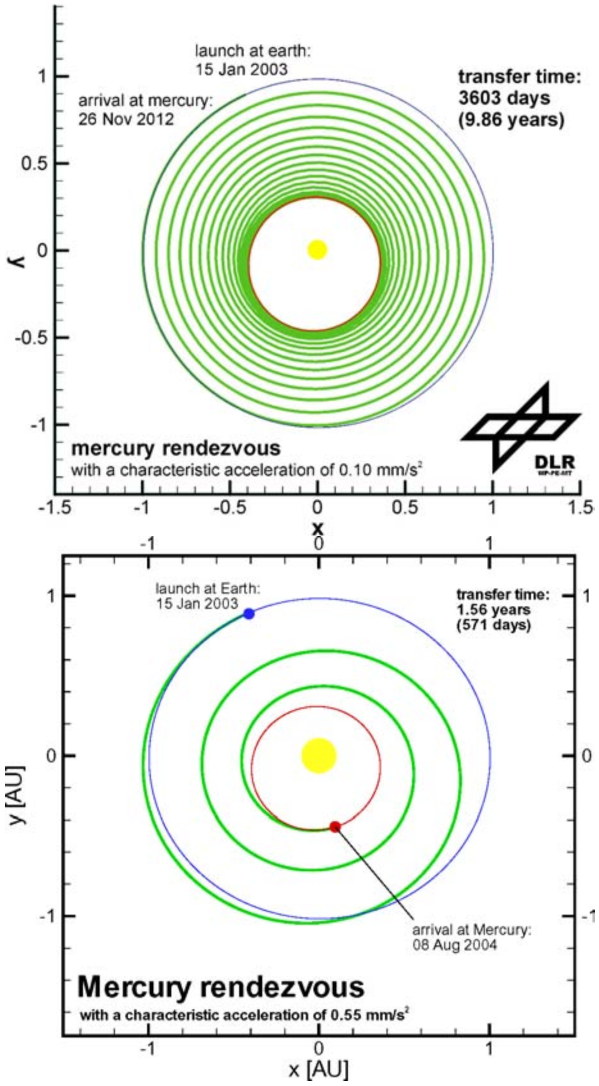


Figure 6: Mercury rendezvous mission with different solar sailcraft ($a_c = 0.1$ and 0.55 mm/s^2)

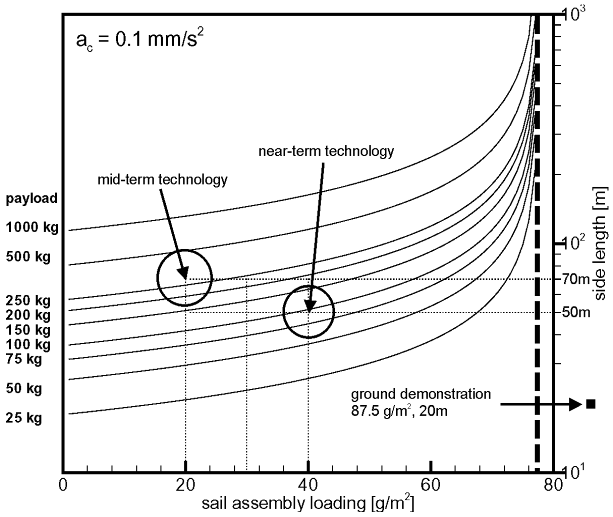


Figure 7: Required sail assembly loading σ_{SA} for fixed $a_c = 0.1$ mm/s^2 with parametric dependence on side length s and payload mass m_{PL}

the design of the deployment module. Some hardware components and mechanisms necessary to deploy the sail could, e.g., be jettisoned after completion of the deployment process. The successful handling of ultra-thin sail materials and fabrication of large sail segments in the ground demonstration indicates that even thinner advanced film materials on the order of 1 µm to 3 µm can be handled. Furthermore, it is obvious that for different combinations of the three design parameters any desired characteristic acceleration can be achieved. An increase in payload mass can, for example, be offset with a proportional increase of s^2 or with an adequate decrease of σ_{SA}. It should be noted that – strictly speaking – only m_{PL} and s can be chosen independently, whereas – for fixed design and technology – $\sigma_{SA}(s)$ is a function of s with $\partial\sigma_{SA}/\partial s < 0$ (i.e. the mass of the booms and the deployment module scale less than linearly with the sail area). In Figure 7, the required technology development to reach acceptable acceleration levels and payload masses is identified. A characteristic acceleration of $a_c \approx 0.1$ mm/s^2 is assumed, corresponding to an overall sailcraft loading of $\sigma \equiv P_{\text{eff},0} / a_c \cong 77\,\text{g/m}^2$.

Displayed are two technology levels:

- Near-term technology:
  Sail assembly loading $\sigma_{SA} \cong 40\,\text{g/m}^2$; square sail side length $s \approx 50$ m (characteristic thrust 19 mN). These design parameters allow a "payload-mass" of about 90 kg.

- Medium-term technology:
  Sail assembly loading $\sigma_{SA} \cong 20\,\text{g/m}^2$; square sail side length $s \approx 70$ m (characteristic thrust 38 mN). These design parameters allow a "payload-mass" of about 275 kg.

It should be noted, however, that higher accelerations can also be achieved if the "payload-mass" is reduced accordingly (see Figure 8).

SUBSYSTEM TECHNOLOGY ANALYSIS

Within this section a high-level technology analysis for the most important subsystems (including development requirements, roadmaps, feasibility, and technology readiness) is performed. As a reference for 'existing technology' the DLR/ESA ground demonstration has been taken (see Figure 9). Necessary or recommended technology development is described with respect to this reference.

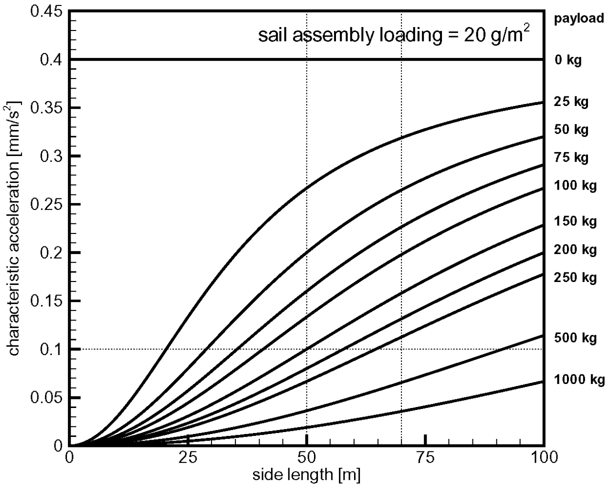


Figure 8: The characteristic acceleration a_c as a function of side length s and payload mass m_{PL} for a sail assembly loading $\sigma_{SA} = 20$ g/m^2

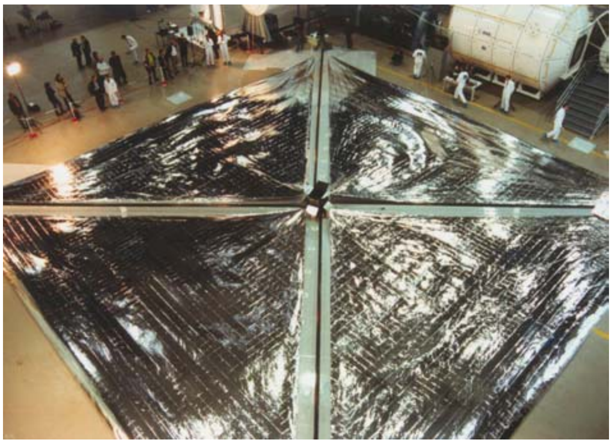


Figure 9: Solar sail ground demonstration at DLR Cologne 1999

Deployment Module

The DLR/ESA deployment module has been designed for square sails up to a side length of $s \approx 40$ m, corresponding to a boom length $l \approx 28$ m. For accommodation and deployment of larger booms and sails, a redesign of the deployment module is necessary. This will eventually result in both larger volume and mass. Further mass savings might be gained by designing the deployment module in such a way that jettisoning some parts of the deployment system after sail deployment is possible (e.g. sail canisters etc.)

Deployable CFRP-Booms

For larger sails ($s > 40$ m), a redesign of the booms (with $l > 28$ m) is necessary due to increased bending and buckling strength requirements. However, at the time being, the production of booms larger than about 20 m seems difficult due to restrictions in the dimensions of easily accessible autoclaves.

Sail Segments

For future enhanced missions with large sails the sail mass must be reduced (via reducing the thickness of the film, e.g., even up to 1 µm or less). Up to now, space qualified Kapton® is commercially available only down to a thickness of 7.5 µm. Using PEN-films with reduced thickness might be an option, but for specific missions (e.g. towards the sun) PEN might not be the optimal choice due to its properties/sensitivity at higher temperatures. Problems might arise with the sail manufacture due to difficulties in handling Al|Cr coated films (warping etc.). The degradation properties of metallized thin films during long deep space missions are not sufficiently understood and should be studied in more detail.

Attitude Control

Different attitude control (AC) concepts must be investigated (e.g. with central mast, flaps at boom tips, cold gas, etc.). The technology for a lightweight collapsible control mast housed in a canister to be stored inside the micro-spacecraft is not available in Europe. A corresponding space proven technology has been developed in USA by AEC-Able Eng, Goleta, CA (e.g. a 10 m boom requires a deployment canister with a length of about 35 cm and a mass of about 4 kg). AC using an ultra-lightweight central mast has not been elaborated and demonstrated yet. Especially, the control of the sail with a steerable mast is a difficult engineering and control problem that requires the development of smart software. An integrated 6DOF simulation environment must be developed. On-board software must be autonomous to a certain extent.

SUBSYSTEM TECHNOLOGY DEVELOPMENT ROADMAPS

Within this section, a technology development roadmap on subsystem-level is outlined for the solar sail technology represented by sails A, B, C and D. Described are four development steps with increased sail performance (see Table 1 and Figure 10). Compared to A, sails B to D are significantly improved versions to be developed within a near to medium timeframe (2004 to about 2014).

Sail A gives the design parameters already realized in the DLR/ESA ground demonstration in 1999. The sail assembly mass is 35 kg, the sail assembly loading is 87 g/m^2.

Sail B (improvements over A):
The sail side length is 50 m; the booms with a length of 35 m are redesigned and have a slightly increased specific mass; the sail film is Al|Cr coated; the deployment module is redesigned and scaled-up with an assumed mass increase by a factor of two; sail assembly mass is 94 kg; sail assembly loading is 38 g/m^2.

	Sail A (20 m x 20 m)	**Sail B** (50 m x 50 m)	**Sail C** (50 m x 50 m)	**Sail D** (70 m x 70 m)
Sail Film	4µm PEN **a)** Al|Al coated **a)** 10.5 g/m^2 **a)**	4µm PEN **a)** Al|Cr coated **b)** 10.5 g/m^2 **a)**	3µm PEN **a)** Al|Cr coated **b)** 7.5 g/m^2 **a)**	3µm PEN **a)** Al|Cr coated **b)** 7.5 g/m^2 **a)**
Booms	length 14 m **a)** 100 g/m **a)**	length 35 m **b)** 125 g/m **b)**	length 35 m **b)** 125 g/m **b)**	length 50 m **c)** 150 g/m **c)**
Deployment Module	mass 25 kg **a)**	mass 50 kg **b)**	mass 36.5 kg **c)** (w/o AC syst.)	mass 45 kg **c)** (w/o AC syst.)

Table 1: Technology requirements and readiness on subsystem level for sails A to D

Sail C (improvements over B):

The sail film thickness is reduced; the mass of the deployment module is also reduced (eventually via mechanisms for jettisoning some parts after sail deployment); an ACS is integrated for scientific deep space mission; sail assembly mass is 73 kg; sail assembly loading is 29 g/m^2.

Sail D (improvements over C):

The sail side length is 70 m; the booms with a length of 50 m are redesigned and have a slightly increased specific mass; the deployment module is redesigned and scaled-up with some assumed mass increase; sail assembly mass is 111 kg; sail assembly loading is 23 g/m^2.

Feasibility up to 2020

The result of a very preliminary feasibility analysis at subsystem levels is also shown in Table 1 with the following classification:

a) Available now (well known technology that can be developed without large effort)
b) Amenable to improvements (work in progress, technology with technological improvements possible)
c) Potentially advanced (technology at conceptual level, large effort needed to develop and demonstrate it)

Criticalities and challenges

The list below summarizes the identified most critical and challenging technology aspects:

- building large sails (order of 100 m) with low sail assembly loading (around or less than 10 g/m^2)
- developing autonomous sailcraft navigation and attitude control
- dealing with short time-scales for attitude maneuvers in planetocentric orbits
- keeping sail degradation due to electromagnetic and particulate radiation within acceptable limits
- establishing long system and component lifetimes (order of 5-10 years)
- solving conflicting pointing requirements for communication, observation and propulsion
- handling the restricted payload capability

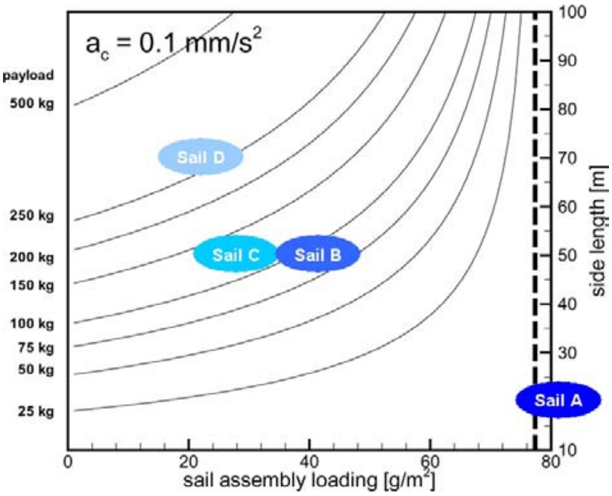


Figure 10: Performance parameters for sails A to D with assumed characteristic acceleration of 0.1 mm/s^2

SYSTEM DEVELOPMENT ROADMAP

The future development of solar sails is currently under investigation at DLR and ESA. As a possible next step for solar sail technology verification a space experiment is considered in cooperation between DLR and ESA [Leipold et al. 2000, Seboldt et al. 2000, Leipold et al. 2001]. On a longer timescale we have identified four steps for solar sail development as outlined below. Figure 11 shows the corresponding proposed mission roadmap.

Step 0 (Ground Deployment Demonstration with Sail A)

This step has been already achieved in 1999. Main characteristics are: (20 m)^2, $\sigma_{SA} \approx 80$ g/m^2, structure not space qualified.

Step 1a (In-Orbit Deployment Demonstration with Sail A$^+$)

($^+$ means space qualified)

Orbit altitude would be ~350 km. Main characteristics are: (20 m)^2, $\sigma_{SA} \approx 80$ g/m^2. This corresponds to the proposed cooperative demonstration project between ESA and DLR.

Step 1b (Ground Deployment Demonstration with Sail B

Main characteristics are: (50 m)^2, $\sigma_{SA} \approx 40$ g/m^2. The structure *might be* space qualified, the design should be scalable to even larger dimensions.

These two demonstrations (possibly performed in parallel) would be followed by:

Step 2 (In-Orbit Deployment Demonstration with Sail B$^+$) ($^+$ means space qualified)
Orbit altitude would be ~350 km. Main characteristics are: $(50\ \text{m})^2$, $\sigma_{SA} \approx 40\ \text{g/m}^2$.

Step 3 (Free Flight Demonstration / Solar Sailing with Sail C)
The free flight in deep space with $C_3 \approx 0\ \text{km}^2/\text{s}^2$ would include the validation of attitude control and navigation. Main characteristics are: $(50\ \text{m})^2$, $\sigma_{SA} \approx 30\ \text{g/m}^2$.

Step 4 (Scientific Deep Space Mission with Sail C/D)
The free flight in deep space (including attitude control) with $C_3 \geq 0\ \text{km}^2/\text{s}^2$ could aim at a fly-by or rendezvous with a planetary target body (e.g. NEO) or even a sample return. Main characteristics are: $(50\text{-}70\ \text{m})^2$, $\sigma_{SA} \approx 20\text{-}30\ \text{g/m}^2$.

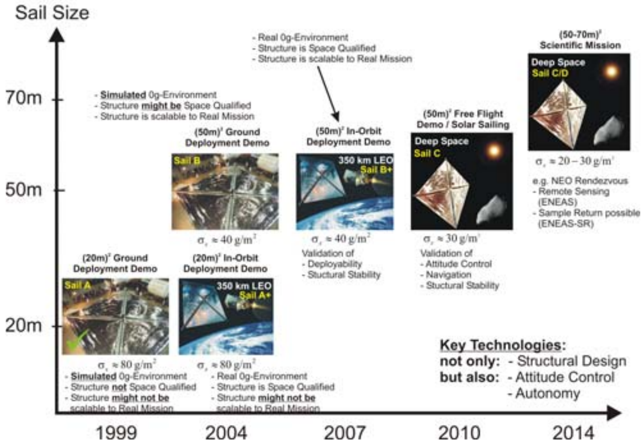


Figure 11: Solar Sail Development & Mission Roadmap

The in-orbit deployment demonstration missions are proposed for a low Earth orbit with an altitude of about 350 km, so that automatic de-orbiting takes place after the mission due to atmospheric friction.

The other two missions are in deep space ($C_3 \geq 0\ \text{km}^2/\text{s}^2$), requiring a launcher which injects the sailcraft into Earth escape trajectory. Free-flying solar sail demonstration missions in higher Earth orbits (≥ 1000 km altitude) are not recommended. Due to the possibility of creating dangerous space debris, they should be avoided if a controlled de-orbiting is not guaranteed.

PROBABLE SPIN-OFFS AND SPIN-ONS

There is potentially a larger market in the future for applications of light-weight structure technology (deployable plus inflatable), e.g.

- large light-weight solar arrays (with thin film PV technology)
- large concentrating mirrors (e.g. solar concentrators) for power production, large antennas for communication and space-based astronomical telescopes
- integrated *multi-functional* large and extremely light-weight structures for "Gossamer" spacecraft

COST ESTIMATES

The development plan in Figure 11 comprises twelve years (2003–2014) with one ground demonstration and four demonstration missions in space (including two deep space missions). The total costs during this timeframe are estimated to be around 100 M€ including accompanying basic research and software development. This rough cost estimate is based (i.e. scaled-up accordingly) on the experience gained from the DLR/ESA $(20\ \text{m})^2$ ground deployment demonstration.

SUMMARY AND RECOMMENDATIONS

To realize solar sail propulsion, the most important recommendations for near-term actions are as follows:

- Start as soon as possible with technology development of larger booms and sails including space qualification.
- Start as soon as possible with development of software for autonomous sailcraft navigation and attitude control.
- As the next important step the technology development and demonstration of a solar sail with a side length of about 50 m has been identified. A corresponding $(\sim 50\ \text{m})^2$ ground deployment demonstration seems indispensable. But different from the $(20\ \text{m})^2$ ground demon-

stration performed at DLR in 1999, the necessary hardware should be designed and fabricated already with regard to space qualification requirements.

- In order to keep the development risks low, two steps for in-orbit deployment demonstrations may be foreseen: the deployment of a $(20\ \mathrm{m})^2$ and a $(50\ \mathrm{m})^2$ sail, respectively. Cancellation of the $(20\ \mathrm{m})^2$ in-orbit deployment demonstration would be possible and could save some money and time. However, in this case, the risks for the $(50\ \mathrm{m})^2$ in-orbit deployment demonstration would increase.
- The degradation of sails due to electromagnetic and particulate radiation should be tested with ground experiments as far as possible (incl. estimate of component life times etc.).
- Identify and study promising scientific (and eventually commercial) missions with solar sails.
- Due to the possibility of creating dangerous space debris, free-flying solar sail missions in near-Earth orbits ($\geq$ 1000 km altitude) should be avoided if a controlled de-orbiting can not be guaranteed.

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