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What Is a Space Sailcraft?

Chapters 1–4 discussed the importance of the rocket propulsion in the first 50 years of spaceflight, and its limitations with respect to what space-faring nations (augmenting in number and quality) would want to accomplish in the solar system and beyond. Chapter 5 discussed the concept of sailing, first on Earth seas with conventional sailboats, then by extending the concept to space; there, the first similarities and differences between sea sail craft and space sailcraft were emphasized. Chapter 6 detailed the principles of space sailing. Now this chapter will discuss what a space sail actually means, through the great impact it can have on the design of the different systems, which is not as obvious as it might seem.

One may think of the space sailcraft as the sum of two pieces: something like a conventional spacecraft (containing the payload) and a sail system consisting of a sail with booms, rigging, tendons and a device controlling its orientation in space. That's correct, in principle. However, such an oversimplified description may induce someone to believe that building a sailcraft means merely adding a sail to something that already is well known. In Chap. 5, basic analogies and differences between terrestrial sailboats and space sailcraft were mentioned. Here there is another important difference—the relative size: *In the space sailcraft, the two-dimensional size of the sail system overwhelms that of any other system.* This is due to three reasons:

1. Earth orbits the Sun at about 1 astronomical unit (AU).
2. The Sun's power emitted from its surface (technically called the **solar radiant emittance** or **exitance**) amounts to about 63.1 million W/m^2.
3. The linear momentum a photon transports is scaled by the factor 1/c, where c denotes the speed of light in vacuum. As a result, an object of 1 m^2 that is 1 AU distant from the Sun and perpendicular to the sunlight's direction can receive about 1,366 W (on average during a solar cycle).

What does it mean? If this object were a perfect mirror, it would experience a force equal to $2*1366/c=0.0000091$ newtons (or about 0.000002 lbf). If the mass of such a body were 91 g, the ensuing acceleration would amount to 0.1 mm/s^2. At 1 AU again, the solar

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gravitational acceleration (which allows Earth to orbit stably about the Sun) is 5.93 mm/s^2. In other words, the solar light pressure acceleration on this particular object would be about 1/60 of the solar gravity at 1 AU.

The previous example (a typical one in solar sailing books) tells us two important things. First, such an acceleration level would be sufficient for many space missions (especially the first ones) and would correspond to an object having a mass-to-area ratio of 91 g/m^2; second, if we aim at ambitious missions, we have to lessen this ratio by a factor of ten, at least. Despite the significant advancement in materials technology, key space systems (including the whole sail system) cannot be designed by decreasing their mass arbitrarily. As a result, a sailcraft has to have a large sail, from a few thousand to tens of thousands of square meters to begin with. (At the end of this chapter, we will discuss the micro-sailcraft concept.)

Now that we understand the above statement about relative size, we can analyze some implications of the major spacecraft systems. In this chapter, we adopt the following nomenclature: Sailcraft = Sail System + Spacecraft. Some of the topics briefly discussed here complement the discussion in Chaps. 11 and 12.

SAIL DEPLOYMENT

Normally, once the whole sail system is manufactured on the ground, it should be folded and placed in a box. Subsequently, it will be unfolded in an initial orbit and, then, some initial orientation will be acquired. It is easy to guess that the sail system is considerably delicate. The sail configuration and the related deployment method affect the performance of the solar sail thrust, which is still a work in progress; some 20 m by 20 m sails have been unfolded in important experiments on the ground. This research area is considerably broad, and any deployment method must pass future tests in space. Let us mention just a few issues related to sail performance. Suppose that the sail is unfolded by means of telescopic booms, which slowly come out of the box. This means that the sail, either squared or polygonal in shape, has been divided into smaller (e.g., triangular) sheets. These sheets could be considered as a membrane subjected to two-dimensional different tensions in their plane. If the sheet undergoes a tension that it is much lower than the other-dimension tension, wrinkles develop. However, a sail divided into parts presents advantages from the construction and handling viewpoint.

Wrinkles should be avoided as much as possible because multiple reflections of light can occur among them. These wrinkles cause two undesirable effects: (1) locally, the sail can absorb much more energy than it would in normal conditions, and so-called hot spots develop; (2) if wrinkles cover a large fraction of the sail, the solar-pressure thrust decreases with respect to what is expected for a flat smooth surface. In one view, wrinkles increase the sail's intrinsic roughness (coming from the sail manufacturing process), which lessens the surface's ability to reflect the light in specular way.

Other deployment methods, some of which have been tested on the ground, apply to circular sails. For instance, the sail would be unfolded by a small-diameter inflatable tube attached around the sail circumference; once deployed, the tube has to be rigidized (in the space environment) to retain its shape without the need of keeping the tube under pressure (a thing impossible to do for a long time). Although some corrugation may arise from such a method, it is expected that the sail could be almost wrinkle-free. One should note, however, that, replacing telescopic booms by inflatable tubes does not avoid wrinkles; the important thing is the circumferential geometry of the supporting beam (see the discussion of the Aurora collaboration in Chap. 13).

SAIL CONTROL

This topic is discussed in detail in Chap. 11, but just a few issues that characterize a sailcraft are stressed here. After the separation of the *packed* sailcraft from the launcher, the first maneuver, the related commands and procedures (the so-called attitude acquisition) are performed in order to begin the planned mission time sequence. The first part of the sequence includes sail deployment. After sail unfolding and checkout (e.g., via the television cameras of the sail monitoring system) have been completed, the sail has to be oriented stably toward the Sun (not necessarily normal to the sunlight). The sail's first orientation maneuver (which can be considered the second **attitude acquisition**) is probably accomplished via some traditional equipment such as cold-gas thrusters, rotating wheels and extendable booms. Other ways can be developed. When the solar photons impinge on the sail, the center of pressure rises, as the sea wind does when it swells the sails of a conventional sailboat (see Chap. 5). From that moment on, two objects—the spacecraft and the sail system—are both subjected to gravity and will move through the action of the sail on the spacecraft and the reaction of the spacecraft upon the sail. However, since the spacecraft and sail do not form a rigid body, it should be possible to accomplish relative movement between the center of mass (of the sailcraft) and the center of pressure (of the sail). (This operation will involve only small electric motors.) The result will be a change in the sail orientation. Whereas Chap. 11 focuses on sail attitude control, here it is noted that small mass variations of the sailcraft cannot be excluded in a mission.

COMMUNICATION SYSTEM

Let us consider the communication between the sailcraft and the ground station(s). Communications between the spacecraft and the ground control center are fundamental in a space mission, but the control center is not the only base. The spacecraft has to be tracked periodically from other ground stations with different tasks. NASA's Deep Space Network, ESA set of stations, and national centers (from different countries) are examples of ground stations. Both the station(s) and the control center receive and send electromagnetic waves to and from the spacecraft in different frequency bands. To do so, the spacecraft has to be "electromagnetically visible," and the onboard antennas have to point to Earth. Here is another implication of relative size. Where do we allocate the onboard antennas? This depends not only on the sail configuration, but also on the sail orientation along the sailcraft trajectory. On a spacecraft, there may be different types of antennas: scientific-data-return high-gain antennas, telemetry and command antennas, emergency and low-gain antennas. Normally, a high-gain dish antenna works in different bands and thus performs different functions. Although it is very thin, the sail can cause obstruction of the antenna waves. It would not be very wise to put antennas close to the sail rim, as it could cause mechanical and electrical problems, induce sail instability, and make the normal sail control much more difficult. A possible solution may be to use the structure that normally forms the "axis" of the sail; for each antenna type necessary for the mission, we can place one on the front side of the sail and (a copy of) this one on the back side. In future advanced missions beyond the solar system, a small part of a wide sail might be designed to function as a big antenna, so large amounts of scientific data may be downloaded to Earth-based or Moon-based receiving antennas from distances as large as hundreds of astronomical units.

SAILCRAFT TEMPERATURE

As for the power system on board a sailcraft, it is obvious that the required amount of watts depends on the mission type and purposes. The power system has to supply energy also to the thermal-control system. Space vehicles have to be designed to withstand the temperatures of space environments. Sail temperature can be adjusted solely by changing its orientation with respect to the incident light, but not too much, otherwise the sailcraft trajectory would change considerably. One has to design a trajectory by satisfying the temperature requirements of the sail materials and the mission target(s). The nonreflected photon energy is absorbed by the sail and then re-emitted almost uniformly. Therefore, if the sailcraft is sufficiently close to the Sun, other spacecraft systems may be hit not only by part of the light diffused by the sail, but also by a significant amount of energy in the form of infrared radiation, almost independently of their positions with respect to the sail. Therefore, the thermal control of such systems requires additional power in order to keep their range of operational temperatures.

A different situation occurs from sailcraft entering planetary shadows (penumbra and umbra). Since the sail is extended and very thin, the sail temperature drops and adapts to the space environment. When the sailcraft returns to light, the sail temperature rises more quickly. Although the space environment around a planet is very different from the interstellar medium, the sail's temperature jumps may achieve over 200 K (in some planetary missions close to the Sun). Therefore, the sail materials have to be selected to withstand many high–low–high temperature cycles during their years of operational life.

PAYLOAD

Usually, the mission payload consists of a set of instruments for detecting particles and fields, for receiving and sending signals, for taking pictures of objects, etc. Can the payload be affected by the sail? Suppose we design a planetocentric sailcraft, the payload of which will measure the detailed structure of the planet's magnetic field, if any, in a large volume around the planet itself. The solar wind, interacting with such a magnetic region, continuously changes its shape and properties. One of the next-generation sailcraft missions will probably be of a similar kind, for which the planet is Earth. Incidentally, although space satellites such as the NASA IMAGE spacecraft (March 2000–December 2005) and the ESA four-satellite CLUSTER (in operation since August 2000) have discovered fundamental phenomena in Earth's magnetosphere, there are still many physical quantities to be measured better and longer in our magnetosphere.

How does a sailcraft behave inside a large region of magnetic and electric fields, and with many flows of charged particles? (Earth's magnetosphere does not protect the planet completely.) If the sail size is wider than characteristic plasma lengths, then one of the expected effects consists of space plasma surrounding the sail's front side by a positively charged sheath, whereas a wake of negatively charged flow extends beyond the sail's back side significantly. Such a charge distribution changes the local properties of what the payload instruments can measure. Therefore, it is important to locate the scientific sensors sufficiently *ahead* of the sail system, where the plasma will be *undisturbed* by the sailcraft's presence.

Since each mission has its own features, the payload-sail arrangement should be analyzed on a case-by-case basis.

THE MICRO-SAILCRAFT CONCEPT

In Chap. 12, nanotechnology and its potential impact on solar sails will be discussed. Here, the discussion is limited to the following questions: If the ratio between the sailcraft mass and its effective area were kept fixed with the same sail orientation, would the motion of the vehicle remain unchanged, regardless of the sail size? What would happen if the sailcraft were scaled down further? In other words, how much can one reduce the size of the sailcraft? Is it only a technological problem or is there any physical limit that prevents having an (almost) arbitrarily small vehicle?

Let us start by noting that about 98 % of the solar irradiance is due to photons with wavelengths from 0.25 μm to 3.5 μm (micrometers) (μm). The visible part of the spectrum (from 0.4 to 0.8 μm) carries about 49 % of the total solar irradiance. If one wants to utilize the solar energy at its best, it is difficult to think of building a sail with a diameter less than 10 μm. Thus far, the telecom system has been based mainly on microwaves. Even if one envisages a complete system transmitting information at 100 gigahertz (GHz), the only antenna could not be smaller than 3 mm. If one turns to telecom system via laser, small lasers are possible, but there are other problems (e.g., pointing accuracy and receiving ground telescope) to be taken into account.

Consider a scientific payload. Interstellar spacecraft of 1 kg have been proposed; however, if one wishes to accomplish some high-performance deep-space mission science by tiny volume detectors, the probability of interaction between any space particle and the detector decreases dramatically. Even if we have one-event (large) detectors, getting a sufficiently high number of events is fundamental for analyzing data the mission is seeking. The minimum size of scientific instruments can vary significantly; it depends not only on technology, but also on the underlying physics.

What about nanoscience and nanotechnology for solar sailing? These quite intriguing topics deserve attention; they will be discussed in Chap. 12 with regard to sailcraft.

Here, it is noted that a few years ago, author Matloff discussed the possibility of a swarm of many tiny spacecraft, or nanoprobes, that collectively behave like a large spacecraft. As the reader can see, this is a very advanced concept; in principle, the probe might look like many small antennas that act together as a very large non constructible antenna, but much more intricate. This concept will be analyzed more deeply as nanoscience develops.

CONCLUSION

Most of the above mentioned problems can be solved, as many other problems have been in the history of spaceflight. This chapter has shown that the sailcraft represents something considerably different from the satellites and probes launched into space so far, and it is just the beginning.