18 Spacecraft Subsystems I—Propulsion

18.7 Alternative Propulsion Systems for In-Space Use

18.7.2 Solar Sail

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The concept of utilizing light pressure as a means of space propulsion is attributed to Konstantine Tsiolkovskii [1921], 5 years before Robert Goddard launched the first liquid-fueled rocket. Tsander [1924] coined the term "solar sailing" in the first technical publication on this topic. In that paper, Tsander calculated several interplanetary trajectories for solar sail spacecraft and identified several useful configurations. It wasn't until the 1950s that additional papers were published Wiley [1951] and Garwin [1958]. Leap forward 20 years to the 1970s before the possibility of rendezvousing with Halley's Comet triggered more analyses of solar sail applications Wright [1974 and 1976], Friedman [1978].

About the same time that the U.S. dropped trying to advance solar sail technology, a non-profit organization called the World Space Foundation was formed to promote a range of space related areas, among them advancing solar sail technology. During the period from 1977 to 1986, organization volunteers built 2 square solar sails, 225 m^2 and 900 m^2, respectively, and performed a ground deployment demonstration of the 225 m^2 sail in 1981 ["Solar Sail Unfurled," 1981]. A serious effort was initiated to perform a Space Shuttle deployment demonstration of the 900 m^2 sail, but it was shut down as a result of the loss of the Space Shuttle Challenger in 1986.

The Russians actually succeeded in deploying a 20-meter diameter spinning mirror from a Progress resupply spacecraft in 1993 that was called Znamya 2 (intended as an experiment to beam solar power to the ground, but unfurled in a way similar to how a solar sail would unfurl). However, a follow-on 25-meter diameter mirror failed to deploy in 1999 ["Projects, Organizations, and Missions," 2002]. The Planetary Society continued the hardware efforts begun by the World Space Foundation and with private funding built and attempted to launch Cosmos 1 in 2001. Unfortunately, the suborbital demonstration flight failed due to a launch vehicle failure ["Cosmos 1: The First Solar Sail," 2002]. A second attempt, this time for an orbital demonstration, also was unsuccessful because of another launch vehicle failure. In 2010, after nearly 90 years, the Japanese launched a solar sail spacecraft (Ikaros) as a secondary payload on an interplanetary mission to Mercury that validated what until then had been the theoretical ability of a solar sail to change its attitude in a controlled fashion and to change its acceleration. Now that the theory behind solar sailing has been validated, there are exciting and practical applications for solar sails that can become reality in the next 10 years. These missions include levitating payloads above and below the equatorial plane at geosynchronous altitude to make more efficient use of that crowded region and positioning payloads in "stationary" orbits above the poles for other interesting missions.

Technical Basis and Solar Sail Designs

Solar sailing **does not** involve the conversion of light into electrical energy (via solar cells), and **does not** utilize the transfer of momentum from solar wind (ionized particles ejected from the Sun)—due to the low density of the ionized particles, whose effect is < 0.1% that due to light pressure. Solar sailing **does** utilize the energy and momentum from light. The reflection of sunlight on a mirrored surface causes a change of momentum that is continuous, and the amount of "propellant" is limitless. Effectiveness falls off as the square of the distance from the Sun, so that solar sails are most effective for missions out to about the orbit of Mars.

Light generated thrust can be used to raise or lower an orbit altitude relative to any celestial object (e.g., Sun, planet, Moon, asteroid, comet), by inclining the sail to direct the component of thrust parallel to the orbit velocity vector. If the thrust is in the direction of the orbit velocity vector, posigrade thrust raises the orbit; if the thrust is in the opposite direction, the retrograde thrust lowers the orbit. Fig. 18-4 provides an overview of the geometrical relationship of solar sail orientation relative to the incoming light (shown orbiting the sun, but the vector relationship also applies to a solar sail orbiting a planet), and Fig. 18-15 is an expanded view of Fig. 18-14 that provides the details associated with the defining solar sailing equation below Eq. (18-34a):

The thrust, *F*, on a flat solar sail is perpendicular to the surface of the sail with a magnitude given by:

$$F = \left(2RSA/c\right)\sin^2\theta \tag{18-34a}$$

$$= 9.113\times10^{-6}\left(RA/D^2\right)\sin^2\theta \tag{18-34b}$$

where, in the second form, F is in Newtons, R is the fraction of incident (maximum of 1) light reflected by the sail, D is the distance from the Sun to the solar sail in AU, S is the solar flux, A is the sail area in m^2, c is the speed of light, and θ is the sail tilt angle – the angle between the Sun-Earth line and the sail. Eq. (18-34a) doesn't take into account all the factors that translate into the force resulting from light pressure because solar sail performance involves more than the single reflectance factor, Forward [1989, 1990] analyzed the effects of various optical properties on realistic "grey" solar sails that have finite transmittance and absorptance and non-perfect reflectance, which was further broken down into specular, diffuse, and back reflectance.

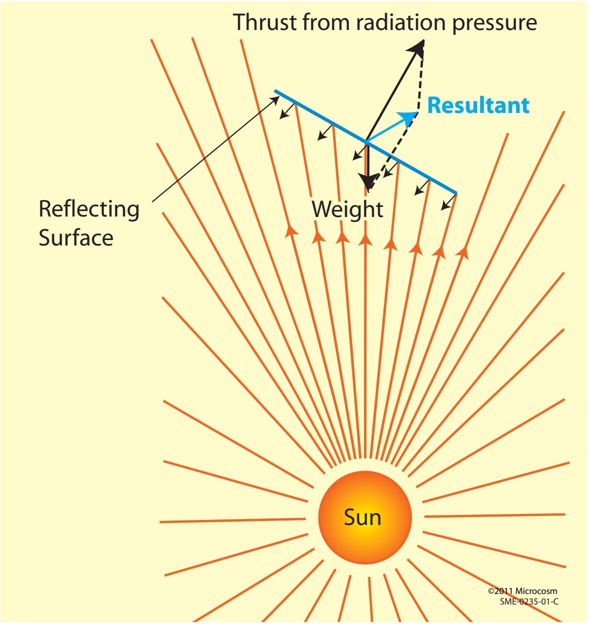

Fig. 18-14. General Depiction of How Solar Sails Maneuver.

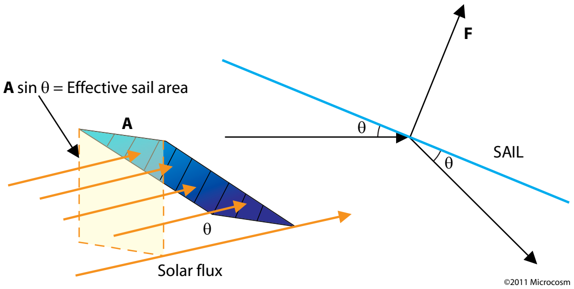

Fig. 18-15. Defining Solar Sail Equation Geometrical Relationships.

There are several factors to consider when designing a solar sail, starting with the decision on the sail material, including reflectivity, fragility, and lifetime. Aluminum is the best material because of a combination of its high reflectivity (86% - 97% for wavelengths from about 0.2 to 1.5 μm) and low density (2.70 g/cm^3) compared to gold (reflectivity 20% - ~100%, 19.32 g/cm^3), silver (reflectivity ~ 0% - ~100%, 10.49 g/cm^3), and copper (8.96 g/cm^3). At the thicknesses involved, all candidate materials are fragile, but rip stops can be incorporated to mitigate tearing, which is most likely to occur during deployment. Typically, the aluminum would be coated onto a backing material. Two candidate backing materials are Mylar® and Kapton®, but Mylar® degrades when exposed to ultraviolet light, so Kapton® currently is the better material.

Because solar sails for practical multi-hundred kilogram payloads could have dimensions of several kilometers, saving mass is a critical factor, even for such thin material. One option would be to coat the aluminum film on a polymer substrate that breaks down in ultraviolet light, leaving just the aluminum film (so Mylar® might actually be better than Kapton® in this case). Another interesting option for mass reduction that would make sense for very large solar sails, in the square kilometer range and larger, would be to perforate the sails with holes that are smaller than the wavelength of light ($< \approx$ 650 nm), which could reduce the solar sail mass by a factor of about 8 [Forward, 1984]. A third option to consider would be aluminum coated carbon fibers.

There are 3 fundamental solar sail designs Fig. 18web-1: square (3-axis stabilized), circular, and heliogyro (multiple "helicopter blades"). For the three-axis stabilized configuration, booms are required to support the sail material. Boom material options include composite, open truss, and inflatable structures. The 4-boom version is the most structurally efficient, but there are significant mass and deployment reliability implications associated with this configuration. For attitude control, a combination of tip vanes that are essentially miniature solar sails (square shown, but could be triangular or other shapes) and a moveable center of mass can be used. The circular configuration requires movement of the center of mass relative to center of pressure to maintain control and may have lower mass than the heliogyro. The heliogyro configuration, which has blades analogous to those on a helicopter, requires substantial edge tendons along the blades to withstand centrifugal forces. The deployment is simpler than for the square sail configuration, but this configuration is not as mass efficient as a square sail. Relative to control, the heliogyro requires rotation to maintain stability, and the blades can be changed in pitch to control the rotation rate and attitude.

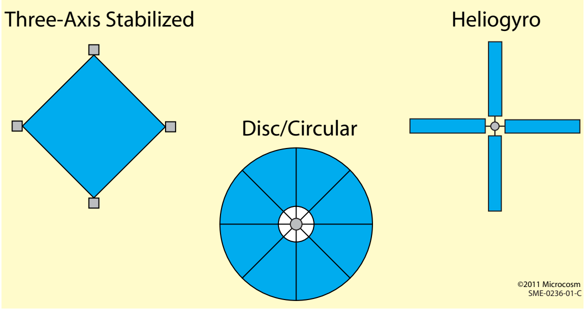

Fig. 18web-1. Candidate Solar Sail Designs.

Solar Sail Applications

Independent of the particular design of a solar sail, Table 18-15 lists their advantages and disadvantages of solar sails.

There is a wide range of missions that can benefit from the use of solar sails, as indicated by Table 18-16. Included are Earth-oriented missions, missions to the moon and planets, and supply/resupply missions in support of human missions to the Moon and Mars.

Regarding the disadvantage listed in Table 18-15 associated with chemical and nuclear propulsion, this one needs some amplification and expansion because the dis-

Table 18-15. Solar Sail Advantages and Disadvantages.

ADVANTAGES
Not propellant limited, as is the case for chemical, electric, and nuclear
Can achieve orbits not achievable by any other means or achievable only to a limited extent (e.g., cylindrical orbits, retrograde solar orbits)
Permits efficient use of geosynchronous altitude by allowing stacking of multiple satellites at the same longitude
Can perform dual roles [applies to, for example, transfers associated with going to and from geosynchronous Earth orbit (GEO) or transfers to and from another planet]: - Boost payload to desired orbit and maintain orbit - Boost payload to desired orbit, drop it off, and return for another payload
Minimal to no orbit debris - Can return payloads for repair - Can place payload on trajectory to burn up in the atmosphere or boost it into a safe orbit
Very large, thus very visible
For comparable missions, fewer spacecraft required (e.g., GEO communications satellite, see Fig. 18-16—levitated orbit allows cross pole communications with 2 spacecraft instead of 3 needed to send signals “around” the geosynchronous belt)
DISADVANTAGES
Very little operational experience when compared to chemical or electric propulsion
Complex deployment, independent of configuration
Requires continuous control to maintain desired orientation
Main benefit for inner planet missions (similar to solar electric)
Vulnerable - To attack - From orbital debris - From micrometeorites
Long time required to spiral out to desired orbit when compared to other propulsion technologies, such as chemical and nuclear (for interplanetary missions, an option is to use chemical propulsion for Earth escape)
Very large, thus very visible
Higher performance versions require space fabrication

Table 18-16. Solar Sail Mission Candidates.

EARTH ORIENTED	***SPACE EXPLORATION***
Commercial/Scientific • Weather • Communications • Miscellaneous - Solar storm warning - Payload repair/replacement Government/Military • Weather • Communications • Surveillance, especially at high latitudes—optical, signals • Satellite Inspection/Negation (i.e., anti-satellite) • Orbit transfer vehicle—transport payloads to/from desired orbits	• Solar—especially very high latitude • Retrograde orbit missions (e.g., Halley comet rendezvous) • Inner planets—Venus, Mercury, Earth, Mars • Human mission supply/resupply—Moon, Mars • Outer planets—combine sail capabilities with gravity assist • Interstellar missions—use gravity assist from close flyby of the Sun to accelerate sail to solar system escape velocity; replace solar light source with laser source to push sail

advantage is not necessarily a true disadvantage. Regarding flight time, as solar sail technology improves, and assuming for interplanetary missions that chemical propulsion is used to achieve Earth escape, absolute flight times can approach achievable flight times possible from chemical propulsion. McInnes [2004] in a figure originally created by NASA/JPL provides data on flight times to Mars as a function of solar sail acceleration. From that figure, representative flight times to Mars are listed in Table 18web-1 for chemical, nuclear thermal, nuclear electric, and solar sail propulsion. For example, the minimum flight time to Mars for a solar sail capable of achieving an acceleration of 1 mm/s^2 is 370 days (+ about 100 days for capture and spiral down to a useful altitude). The corresponding minimum energy (chemical propulsion) coplanar Hohmann Transfer time to Mars is approximately 259 days. The characteristic Hohmann Transfer is representative of a flight time to Mars, but is not what realistically would be implemented. However, if the launch date is missed (as was the case for the Mars Science Laboratory mission), the impact will be a wait of 780 days for Earth and Mars to be aligned for another Hohmann Transfer trajectory flight opportunity.

Table 18web-1. Representative Earth-Mars Flight Times.

Propulsion Method	Earth-Mars Flight Time (Days)
Chemical (Hohmann Transfer)	259[1]
Chemical (Type I-min/ave/max)	131/196/228[2]
Chemical (Type II-min/ave/max)	286/313/334[2]
Nuclear Thermal	170–210[3]
Nuclear Electric	179–221[4]
Solar Sail (1 mm/s^2 acceleration)	370[5]
Solar Sail (1.5 mm/s^2 acceleration)	320[5]

1. Representative coplanar Hohmann Transfer; 2. NASA Mars Exploration Program Web Site; 3. [Norris, 2010]; 4. [Clark, et. al., 1994], 5. Minimum times [McInnes, 2004]

There are 2 Earth oriented missions that are particularly fascinating, are extremely challenging technologically, and demonstrate the unique capabilities of solar sails. They were chosen also because of the increased focus on the utilization of space to better understand the Earth's environment that is certain to be an area of continuously increasing interest over time. Both of them were devised by Forward. In the first instance, solar sails can use light pressure to *levitate* a payload (e.g., communications) above or below the geosynchronous plane and maintain it there indefinitely **at a fixed longitude, called a** *cylindrical orbit* [Forward, 1984, 1990]. More specifically, a levitated orbit allows continuous communications with and/or observation of latitudes not possible with equatorial geosynchronous satellites or with high inclination low altitude satellites. Even more intriguing, but technologically extremely challenging, for levitation distances > 1 Earth radius, only 2 satellites are required for cross-Earth communications (180 deg separation), rather than the three minimum required for geosynchronous equatorial communications satellites (120 deg separation).

Looking at levitated orbits using non-perforated sails (i.e., sails whose sail material does not have perforations that are smaller than the wavelength of light, but which have a significant impact on reducing the mass of the sail), levitation distances of practical payloads are limited by total sail and payload mass. However, performance is still sufficient to allow stacking of communications satellites with separations sufficient to avoid signal interference and essentially eliminates the problem of crowding of the equatorial plane. Perforated sails significantly alleviate the limitations of non-perforated sails so that practical payloads become possible and also permit additional stacking.

Fig. 18-16 illustrates the overall levitated orbit geometry. The maximum altitude achievable, Z (km) is provided in Eq. (18-35) and is a function of the tilt angle θ Eq. (18-36), that results in the maximum force normal to the equatorial plane, F_P; and is inversely proportional to the sail mass m (kg) to sail area A ratio. The tilt angle is the angle between Sun-Earth line and the sail as a function of φ, the angle between Sun-Earth line and Earth's equatorial plane, both angles measured in radians. The other parameters shown are considered to be constants. Besides R, S, and c, already defined, there are the constants r, the geosynchronous radius; G, the universal gravitational constant (m^3/kgs^2); and the mass of the Earth, M (kg).

Live Calc

$$Z = \{[(2RSr^3)/(GMc)]\sin^2\theta\cos(\theta - \varphi)\}[1/(m/A)] \tag{18-35a}$$

$$= [1.715 \times 10^3\sin^2\theta\cos(\theta–\varphi)][1/(m/A)] \tag{18-35b}$$

$$\theta = \text{atan}[[3\tan\varphi + \text{sqrt}(9\tan^2\varphi + 8)]/2] \tag{18-36}$$

Note that there is an equatorial component to the force (not shown in Fig. 18-16, but parallel to the Earth's equatorial plane). It is much less than the gravitational attraction of the Earth, but it does have the effect of displacing the near-circular orbit to the side of the Earth away from the Sun. As is the case with current GEO satellites, it will be necessary to separate solar sail spacecraft that will be stacked at the same longitude, which means that Z for each will have to be held relatively constant throughout the year. To maintain a constant Z, the tilt angle, θ, will have to vary from the value that results in the maximum force normal to the equatorial plane, which means that the sail angle will have to be trimmed over time.

Results of applying the above equations to a sail whose mass is assumed to be equal to its payload/bus mass are listed in Table 18web-2. Further, for ease of traceability, the payload mass is assumed to be the same as the total spacecraft mass for a GEO satellite, since the Sail/Payload/Bus will still require such subsystems as solar cells for power and a communications subsystem (e.g., if the actual "payload" is an imager). Launch masses for GEO satellites range from about 1,000 kg to 6,500 kg [Union of Concerned Scientists (UCS) Satellite Database, 2010]. Assuming no change in launch capability would imply a maximum bus/payload mass of 3,250 kg, which is what has been chosen. Clearly, very large sails are required.

As can be seen from Table 18web-2, levitation distances vary between 50 km and 11,000 km as the sail thickness varies from 1 μm to less than 0.01 μm. (0.5 μm translates into a levitation distance of 150 km, and 0.02 μm represents the practical limit to sail thickness) Note that the minimum physical satellite separation at GEO is about 0.2 deg or 150 km, and in a few cases even 0.01 deg [Hudgins, 2002; UCS Satellite Database, 2010].

Stationary polar orbits represent another unique capability for solar sails (Fig. 18web-2). Here, the force on the sail counteracts Earth's gravitational force. By equating the force from light pressure, as given in Eq. [18web-1a], with Earth's gravitational force, it is possible to solve for the range, R_S, from the center of the Earth to the sail (Eq. 18web-1b). The range squared is a function of tilt angle and directly proportional to the spacecraft mass-to-area ratio. In this instance, a solar sail maintains its position

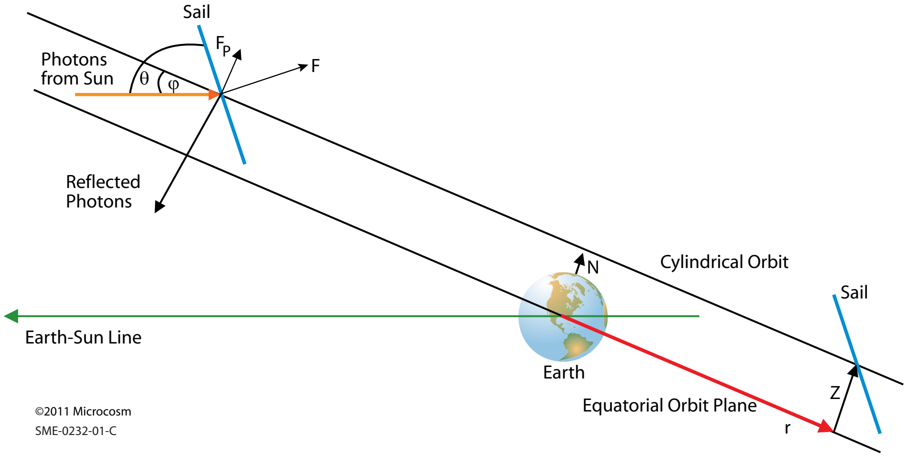

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Fig. 18-16. Levitated Geosynchronous Orbit Overview and Detailed Geometry.

Table 18web-2. Solar Sail Technology Impacts on Sail Size and Achievable Levitation Distances.

Solar Sail Technology	Sail Thickness (μm)	Sail Mass/Area Ratio (g/m^2)	Square Sail Area (m^2)/(km^2)	Levitation Distance (km)
Aluminized Kapton	1	3	1,083,333/1.083	50*
Aluminized Kapton—Practical limit to unfurlable sails	0.5	1	3,250,000/3.250	150
Aluminum Film—Space fabrication	0.1	0.3	10,833,333/10.833	500
Aluminum Film—Practical limit to sail thickness	0.02	0.08	40,625,000/40.625	2,000
Representative Perforated Sail	—	0.015	216,666,667/216.667	11,000

* Minimum physical separation is about 0.2 degrees or 150 km, and in a few cases even 0.01 degrees [Hudgins, 2002, UCS Satellite Database, 2010]

over a pole and can provide continuous service (e.g., broadcast, data transmission, weather services, and various types of observation) to any region on the Earth, including polar regions, with only 1 spacecraft, called a *statite* orbit [Forward, 1989, 1991, 1993]. However, because of a round trip delay time of several seconds, there is a disadvantage for two-way voice communications.

$$R_S^2 = [GMc/(2RS\sin^2\theta)](m/A) \qquad (18web\text{-}1a)$$

$$= [4.371 \times 10^{16}/\sin^2\theta](m/A) \qquad (18web\text{-}1b)$$

There are some interesting general operational issues/challenges associated solar sails in general and with each of these orbit types in particular. In the general category, reflection from the sails is not specular since the sail material is not a perfect reflector. Hence some light is absorbed and some light is transmitted through the sail material. Also, the sail is not perfectly flat. In the case of the levitated orbits, 2 times/day the sail is approximately edge-on to the Earth so that there is potential communications impairment due to the physical blockage of the spacecraft antenna by the sail itself. Candidate solutions to this situation include cutout in the sail to permit an unobstructed communications path and putting the antennas on the tip vanes (at least for square sail configurations).

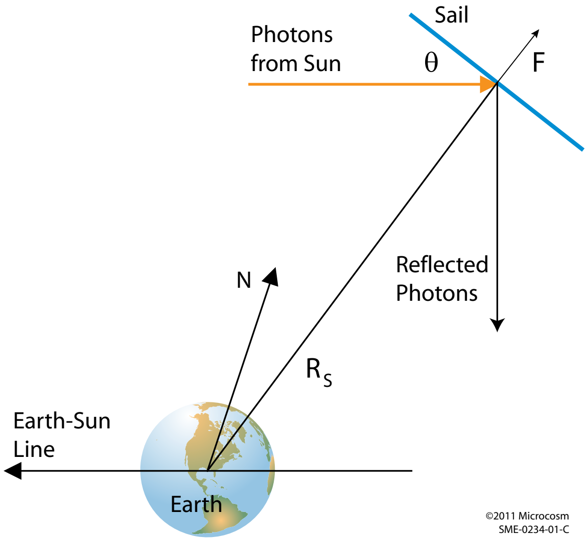

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Fig. 18web-2. Stationary Polar Orbit.

Additionally, 1 or 2 times/year the sail is shadowed by the Earth once/day at all levitated altitudes that are less than about 4 Earth radii. The worst case time in the shadow is about 70 minutes, during which the levitated altitude decreases by about 5%, which is not a major impact. Besides the long round trip light time of several seconds previously mentioned, another operational issue for stationary polar orbits is the need for a clock drive for the ground station antennas. However, the electronics is still relatively simple because the spacecraft remains at almost the same range.

Finally, there are some regulatory issues to consider, in particular for the levitated orbits. Since multiple satellites can be stacked at the same longitude, some regulation will be required relative to stacking separation distances. Related to the stacking issue is who will control the physical separation of the satellites at a particular longitudinal location to ensure that separation distances are maintained. Finally, as is already the case, care will be needed to avoid communications interference.

A number of enabling technologies required to field a functionally useful solar sail are listed in Table 18-17.

Solar sails can perform unique scientific, commercial, and military missions, and the stage is set for near-term space missions to validate deployment and control methodologies. Enabling technologies are still required to permit high performance missions (e.g., levitated geosynchronous, stationary polar).

Table 18-17. Enabling Technologies and Related Events.

SPACE FABRICATION
• Sail material • Supporting structure/deployment methods
CAPABILITY TO REPAIR/UPGRADE SPACECRAFT
• Periodically replace part or all of sail • Perforated substituted for part or all of non-perforated sail material • Carbon fiber replacement for aluminized Kapton
UPGRADE/REPLACE PAYLOADS
• Change of mission • Take advantage of technology improvements—continued advances in electronics will cause payload components to shrink in mass/volume, while capabilities increase