Near-Term Beamed Sail Propulsion Missions: Cosmos-1 and Sun-Diver

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Abstract. In 2003, the Planetary Society plans to launch Cosmos-1, the first solar sail. We are planning an experiment to irradiate the sail with the Deep Space Network beam from Goldstone. This can demonstrate, for the first time, beamed propulsion of a sail in space. The 450 kW microwave beam from the large 70-m dish can show direct microwave beam acceleration of the sail by photon pressure, and we can measure that acceleration by on-board accelerometer telemetry. In addition, we describe a mission scenario called 'Sun-Diver' using a powerful microwave beam on a solar-driven sail, to both heat and push the sail, accelerating by "boil-off" of coated materials. Sublimation and desorption work well with the new carbon sail materials which can take very high temperatures (>2000 K), can use promising new materials for mass loss, and promise new classes of missions. These missions make a close pass near the Sun, hence the name, to take advantage of high temperature characteristics of the sail by using the large solar flux at perihelion, yielding high velocities of ~50 km/s for >40 A.U. missions. Within ~5 years, the sailcraft flies beyond Pluto, giving high velocity mapping of the outer solar system, the heliopause and interstellar medium.

Ideas of sailing in space by various forms of photon pressure have captured the imagination of many for years. Solar sailing as been studied theoretically for 30 years, but has never been demonstrated. Beam-driven sail acceleration has been studied for 20 years and has recently been demonstrated in the laboratory. That research has suggested enhanced means of propelling sails. This paper describes our plans to detect solar and microwave acceleration in orbit, which would give a robust proof of photon-driven sailing, and outlines a new mission concept for sails.

BEAM-DRIVEN ACCELERATION OF COSMOS-1

The Planetary Society, in partnership with Russian laboratories, plans to launch the first solar sail in low Earth orbit in 2003 (http://www.planetary.org/solarsail). We have requested time on the Deep Space Network for two tasks: 1) To track the telemetry on the sail to determine its velocity and acceleration accurately under solar radiation (photon) pressure. 2) To irradiate the sail with a high power microwave beam from a large aperture to show direct microwave beam acceleration of the sail by photon pressure, and to measure that acceleration from receipt of on-board accelerometer telemetry. This would be the first demonstration in space of both solar sailing and microwave beam propelled sailing.

The Cosmos 1 orbit will be polar, because the launch point is from a submarine in the Barents Sea. Its circular orbit is to be at 800 km. The orbital velocity is 7.4 km/s. The satellite moves across the sky at 0.06 deg/sec, so can be tracked readily. The orbital period is 101 minutes, so overhead time at most is 15 minutes. The orbital Doppler shift at the spacecraft telemetry carrier frequency (2.25 GHz) will be 56 kHz.

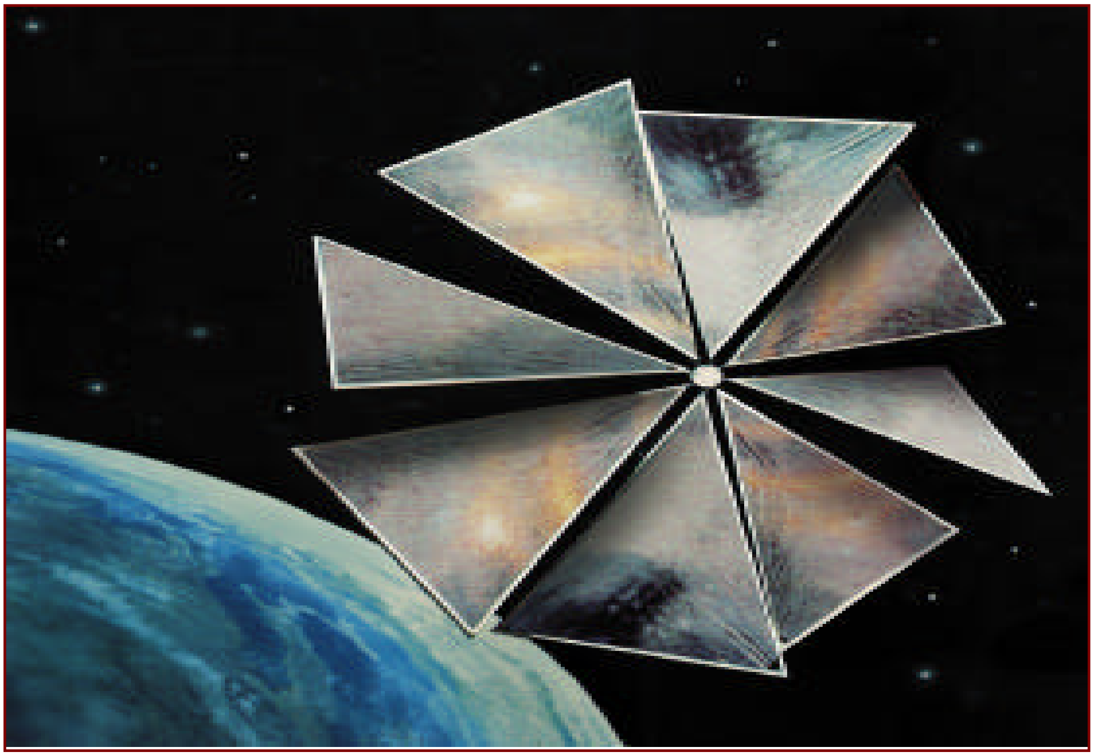

FIGURE 1. Cosmos-1 in orbit. The sail is ~100 feet across and has two independent sets of vanes which are to be steered to raise the orbit using solar pressure.

Solar-Driven Sailing

A clear measurement of solar thrust in orbit on a real Sailcraft will be a significant scientific contribution, the first step in the experimental study of solar sailing. Doppler tracking as a supplement to accelerometer measurements, adds confidence and robustness to the experiment, and gives a direct measure of velocity to use in modeling the sail orbit.

The sail diameter is 30m. The solar flux will give a maximum acceleration to the ~100-kg sail of 10^{-4} m/s^2. There are on-board accelerometers with sensitivity down to 10^{-7} m/s^2 and sample rates which can be varied from 10 to 100 Hz. Moreover, the delta-v from solar flux will produce a shift of the carrier of 10^{-3} Hz/sec. (This shift from solar acceleration should be detectable by the DSN: the DSN frequency resolution for carrier determination is 0.1 Hz, so tracking for ~ 100 sec is necessary for detection to be possible.)

We will model the rate of change of frequency for the few hundred seconds of track, incorporating orbital dynamics [including drag] and ionospheric propagation effects, and then see to what extent reality deviates from the model, thereby extracting the effect of solar pressure. The atmospheric and ionospheric calibration similar to that used for the Cassini gravity wave experiment may be needed. As both the shift of the carrier frequency and receipt of the accelerometer telemetry measure the acceleration of the sail, these can then be compared to each other and to modeling.

Microwave Beam-Driven Acceleration of Cosmos-1

There are two very different modes for accelerating the sail, the Tracking mode and the Impulse mode, with the former more attractive.

Impulse Mode

As the Cosmos sail passes overhead of Goldstone, the beam, directed to almost vertical, hits the sail at its minimum distance from the dish. The Goldstone 500 kW, 8.5 GHz microwave beam from its 70 m aperture will produce a beam width at the orbit about 0.5 km across at 800 km altitude. The impulse from the beam is applied in 0.07 seconds as the sail passes through the beam. The beam accelerates the sail at about 10^{-7} m/s^2, giving a total impulse of 10^{-8} newton-seconds. For this to be detectable, sail electronics must be optimized to give the maximum sensitivity on the accelerometers.

The on-board accelerometers are derived from a gravitational wave experiment in Moscow and can measure accelerations to 10^{-12} m/s^2. The baseline for the Cosmos-1 accelerometers is to sample at 10 Hertz and integrate over 1 second. So the impulse will be sensed as a single pulse and then be integrated with lower accelerations, reducing its detectability. A faster cycle rate should be used to help the signal-to-noise ratio (S/N).

Tracking Mode

Consider an orbit taking the sail directly overhead Goldstone. As the sail rises above the horizon, its angular rate of motion is 0.13 degrees per second. The Goldstone dish has in a slew rate of 0.25 degrees per second, therefore it can track the sail until it reaches 23 degrees, where it moves faster than the dish can follow. The range at the horizon is 6270 km and the acceleration from the beam on the sail will be 10^{-8} m/s^2, for normal incidence on the sail. The sail will be inclined to the beam, with 30 degrees as a typical value. The acceleration on the sail will be reduced by the cosine of this angle. Although acceleration is lower than for the impulse mode, it occurs over a far longer time, about 200 seconds. Integrating over the trajectory, the total impulse is 2.5 x 10^{-6} newton-seconds, 250 times the impulse of the other mode.

Again, the signal level will be much more detectable if the accelerometers are made more sensitive.

We can enhance the S/N ratio of the accelerometers by pulsing the beam (by modulating the input to the klystron amplifier), thus modulating the sail acceleration up and down, and use signal processing of the telemetry to bring the structure in the signals above noise. We can further improve S/N by choosing to modulate the beam amplitude at frequencies to excite resonant acoustic modes in the sail structure, then look for enhancement of those modes in the frequency spectrum of the accelerometer data. If the sail were rigid, the fundamental oscillation frequency would be about 10 Hz. Preliminary modeling of sail oscillations by our Russian colleagues say that the lowest-frequency oscillation mode is at 0.2 Hz, which corresponds to a gentle flapping of the sail. The fact that the sail, attached to its spars, is not a rigid body complicates attempts to make the system resonate acoustically. The highest frequency is that of waves propagating along the spars, typically ~10 Hz. Therefore, we need to identify the resonant modes of the actual sail to understand what spectrum of oscillations we would be imposing our thrust upon.

So, calculations of resonant mode frequencies and their Q's are essential. We will attempt to measure the spectrum in flight by Fourier analyzing the data we get from the accelerometers. For this, the sampling time would have to be short to pick up the oscillations. We can oscillate the sail by varying be klystron power in amplitude between a fraction of a Hz to tens of Hz, depending upon which modes are typically excited in orbit and their damping rates.

Flight Preparation

From the above, since if the sources of noise are random (i.e., Poisson distribution), the signal scaling is $S \sim t/R^2$, noise $N \sim t^{0.5}$, so $S/N \sim t^{0.5}/R^2$, where t is the acceleration time and R is the distance from Goldstone to Cosmos. Calculations show that *the Tracking mode will have a S/N 15 times that of the Impulse mode.* Thus, we emphasize that mode.

We need observations of the amplitude and frequency spectrum of the sail every time it can be observed. We should gather data to understand modes of oscillation of the sail. The most useful measurement of the spectrum of oscillation will be as the sail is deployed. The typical case will be when the sail passes in and out of the Earth's shadow, and modes are excited and, eventually, damped. To see these acoustic oscillations of the sail, we need to have a sampling time ~100 Hz levels, compared to the present design level of 10 Hz.

Further, optimization of this experiment requires that the accelerometers be *as sensitive as possible*. A key factor for these accelerometers is the acceleration that gives an S/N = 1.

Another issue is the possible effect on electronics of the microwave electric field on the sail. The maximum field on the sail at closest range will be 30 V/m, which typically does not cause interference. Cosmos electronic equipment will be tested to this level at the X-band frequency of the Goldstone beam.

In summary, the power beaming experiment to the Cosmos sail will be optimized by

- Making the accelerometers as sensitive as possible,
- Operate the accelerometers at fast sample rate,
- Modulating beam amplitude to excite resonant modes in the sail.

We plan to conduct the beam/sail experiment about a month into the mission.. During this period, when the sail passes over Goldstone we plan for a DSN 34-m antenna to measure the solar acceleration by Doppler tracking, and for the Goldstone Solar System Radar 70-m dish to test the predictions for microwave acceleration. (Since the Cosmos 1 orbit will be polar, tracking can be done in several, if not all, DSN locations.)

Implications

Demonstration of feasibility of a sail driven by the sun or a beam from a ground station will:

- Show the basic principle of solar and beam-driven propulsion in action in space, quantify the propulsion, and compare it with predictions.

- Demonstrate the potential of a higher-power DSN in future, when beam-driven sail experiments can be done at much higher accelerations. The proposed demonstration is synergistic with ongoing investigations into DSN upgrades.

- Synergize with the Space Solar Power (SSP) Program. In current SSP concepts, microwave beams from SSP will be used to accelerate sails as space probes to very high velocities for outer Solar System missions. In the next section, we explore new ways to do this.

SUN-DIVER MISSIONS

In work reported in this session (see J. Benford et. al., this session) an intense microwave beam drove an ultralight carbon sail to liftoff and flight against gravity[1]. Although there was photon pressure, it wasn't strong enough to explain the observed accelerations. The most plausible explanation for the bulk of the observed accelerations greater than gravity is fast evaporation of heated absorbed molecules from the hot side of the sail on timescales short compared to that of thermal diffusion. This suggests development of sails that fly due to loss of "paint" from their illuminated side. Microwaves do not damage sail materials as short-range lasers do, and so can heat them less destructively. This approach promises to make microwave-riding sails greatly superior to both solar sails and laser-driven sails, because it uses the best features of both. After the coats desorb away, a sail can perform as a conventional solar sail, using an aluminum coat beneath. Solar sails are plagued in mission plans by low accelerations, which dictate long orbital times. Laser sails have problems with atmospheric distortion if the laser beam is fired from the ground, which microwave beams do not. *A natural collaboration emerges between subliming sails driven by beams in LEO, converting to greatly accelerated solar sails for the long mission.*

For a schematic of the approach, see Figure 2. For a full treatment, see Reference 5. This deployment takes advantage of high temperature characteristics of the sail to dive to within a few radii of the sun, where it achieves a high velocity by using the large solar flux at perihelion. The planned Solar Probe mission, flying to within 0.01 A.U., is an extreme example. For the near term use of beamed power, note that beam illumination at ~kW/cm^2 in LEO can simulate conditions any solar grazer mission will experience to within 0.01 A.U.

Conventional solar sail missions lower perihelion by adding and subtracting energy from the orbit over several revolutions around the sun[2]. Adding mass to a sail to be lost at the sun will generally lengthen this perihelion lowering time, because of lower accelerations. *Sublimation (or desorption) thrust from LEO into interplanetary orbit can omit the several-year orbits conventional solar sails need to reach ~0.1 AU. A second "burn" at perihelion, the highest available orbital velocity in the inner solar system, and thus optimum point for a delta-V, then yields high velocities for >40 A.U. missions.*

The mission phases are:

(1) Deployment in Low Earth Orbit by conventional rocket.

(2) Launch by a microwave beam from nearby in orbit. Beam heating makes a "paint" (*layer #1*) desorb from the sail. Under this enhanced thrust in repeated shots at perihelion in steepening elliptical orbits, the sail attains ~15 km/s velocity, canceling most of its solar orbital velocity, and so can fall edge-on toward the sun immediately. (This is far faster than using solar pressure to spiral down, which takes years.) It approaches the sun edge-on, to minimize radiation pressure on it in the inward fall.

(3) At perihelion, the spacecraft rotates to face the sun. Under intense sunlight ~20 times Earth insolation, the sail *desorbs away layer #2,* getting a ~50 km/s boost at its maximum (infall) velocity.

(4) It then sails away as a conventional, reflecting solar sail, with the final Aluminum layer revealed. Its final speed is ~ 10 AU/year. Within ~5 years, it sails beyond Pluto, giving high velocity mapping of the outer solar system, the heliopause and interstellar medium.

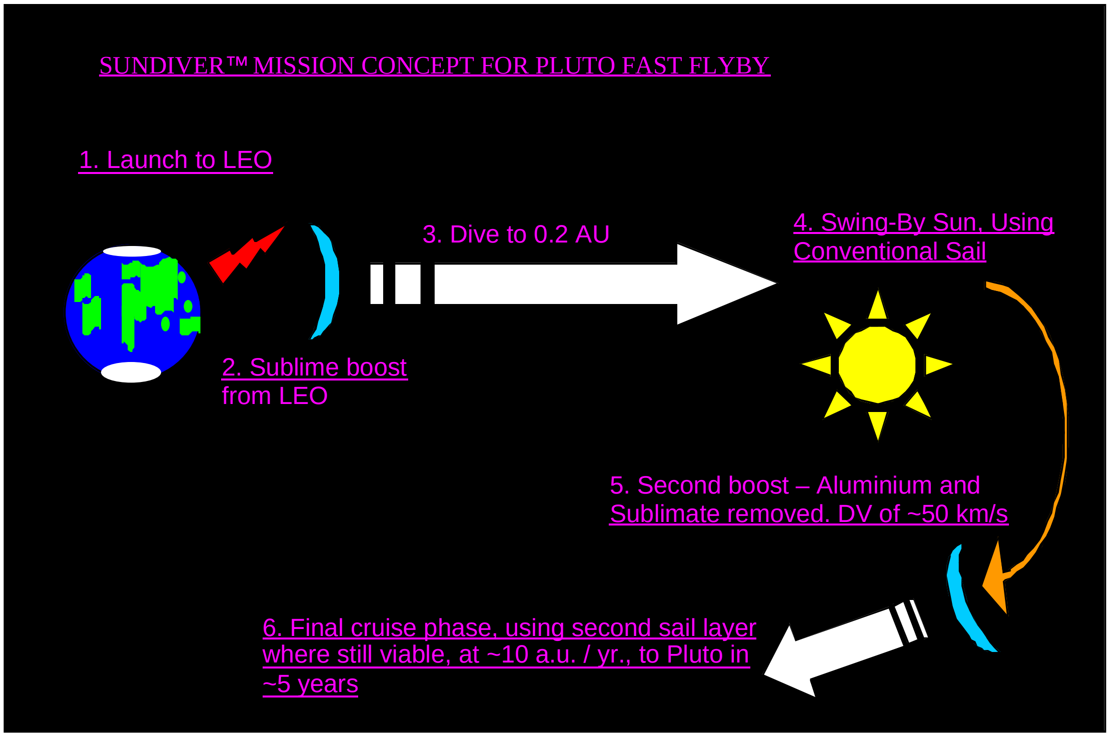

FIGURE 3. Phases of a Desorption-Assisted Sun-Diver Mission.

Obviously one needs a detailed orbital integration such as Sweetzer's[3] with plausible rates of mass loss gained from laboratory work, before judging the overall credibility of such a mission.

An Interstellar Sun-Diver

As a simple example, consider a sail falling sunward on a parabolic orbit. It will be accelerated by

- the ΔV imparted by desorption at perihelion
- ordinary solar sail acceleration on the outward-bound leg, once the desorped layer is gone, leaving a reflecting sail.

We can find an approximate expression for the final velocity V^F with respect to the sun, following energy analysis, as in Matloff[4]. The sail's parabolic velocity at distance R is

$$V = 1.4\ (GM/R)^{1/2} = 93\ \text{km/s}\ (R/0.1\ \text{AU})^{-1/2} \qquad (1)$$

At perihelion of 0.1 A.U. the sail reaches a temperature (for plausible values of absorption and emissivity)

$$T = 927\ \text{K}\ [(\alpha/0.3)(\varepsilon/0.5)^{-1}]^{1/4}\ (R/0.1\ \text{AU})^{-1/2} \qquad (2)$$

For such temperatures, a considerable $\Delta V >$ km/s is plausible for a range of desorption materials. Losing its mass load at perihelion, the sail thereafter works as an ordinary solar sail, attaining a *final exit speed* from the solar system

$$V^F = 19.5\ \text{km/s}\ [(\Delta V/2\ \text{km/s}) + (3\sigma)^{-1}\ ]^{1/2} \qquad (3)$$

$$V^F = 3.9\ \text{AU/year}\ (\Delta V/2\ \text{km/s})^{1/2}\ [1 + 0.33\ /(\Delta V/2\ \text{km/s})(\sigma')]^{1/2} \qquad (4)$$

Here σ is the sail areal mass density in units of 100 gm/m^2. In the brackets, the first term comes from acceleration (a), the ΔV imparted by desorption at perihelion and the second from (b), ordinary solar photon acceleration on the outward-bound leg, once the desorped layer is gone, leaving a reflecting sail.

The sail's speed as it passes through the outer planets will exceed V^F. The linear sum of ΔV and the ordinary solar sailing momentum in the square root above means there will be a simple tradeoff in missions between the two effects, which are equal when the last term in brackets above is unity.

This is only a rough calculation, omitting many mission details, such as sail maneuvering near the sun. We assumed a perfectly reflecting sail on the outward leg, and that desorption would occur quickly at perihelion. For a full treatment, see Reference 5.

Conclusions

Using mass loss for thrust is not a new idea, but it is new to apply this idea, together with a powerful microwave beam, to both heat and push a sail. It is worth pursuing because sublimation and desorption

- work well with the new carbon sail materials, which can take very high temperatures (>2000 K),
- can use promising new materials for mass loss so far not studied for thrusting applications,
- hold the promise whole new classes of missions.

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