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# MAX-MICROWAVE ACCELERATION EXPERIMENT WITH COSMOS-1

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The Planetary Society planned to launch Cosmos-1, the first solar sail in 2005. We planned an experiment to irradiate the sail with the Deep Space Network beam Goldstone Solar System Radar. This could demonstrate, for the first time, beamed propulsion of a sail in space. 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 provide direct microwave beam acceleration of the sail by photon pressure. We can measure that acceleration by telemetry from on-board accelerometers. We planned to modulate the beam to excite resonant oscillatory modes of the sail, enhancing the signal-to-noise ratio. We discuss issues affecting this experiment: how to track the sail and put the beam on it, download the accelerometer data and analyze it.

**Keywords:** Beam driven sail, solar sail, Cosmos-1

## 1. INTRODUCTION

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 [1]. That research has suggested enhanced means of propelling and handling (spinning) sails. Here we describe our plans to detect solar and microwave acceleration in orbit, which would give a robust proof of photon-driven sailing.

## 2. BEAM-DRIVEN ACCELERATION OF COSMOS-1

The Planetary Society, in partnership with Russian laboratories, planned to launch the first solar sail in low Earth orbit in June 2005. Called Cosmos-1 (Fig. 1), the spacecraft featured a sail 30 m across and had two independent sets of vanes, which are rotated about the axis to steer and to raise the orbit using solar pressure.The attempt failed because of some missing upgrades to the Russian launcher's first stage. The Planetary Society, pushed by many thousand enthusiasts over the world, wants to retry the basic adventure of the first real solar-sail mission. For such an aim, its president declared that a different, really reliable, launcher will be selected.

This paper describes our plans for the experiment. We requested time on the Deep Space Network (DSN) 70-m antenna at Goldstone, California to irradiate the sail with a high power 450 kW microwave beam from to show direct microwave beam acceleration of the sail by photon pressure, and to measure that acceleration from receipt of on-board accelerometer telemetry. We call it MAX-Microwave Acceleration eXperiment. This would be the first demonstration in space of both solar sailing and microwave beam propelled sailing [2].

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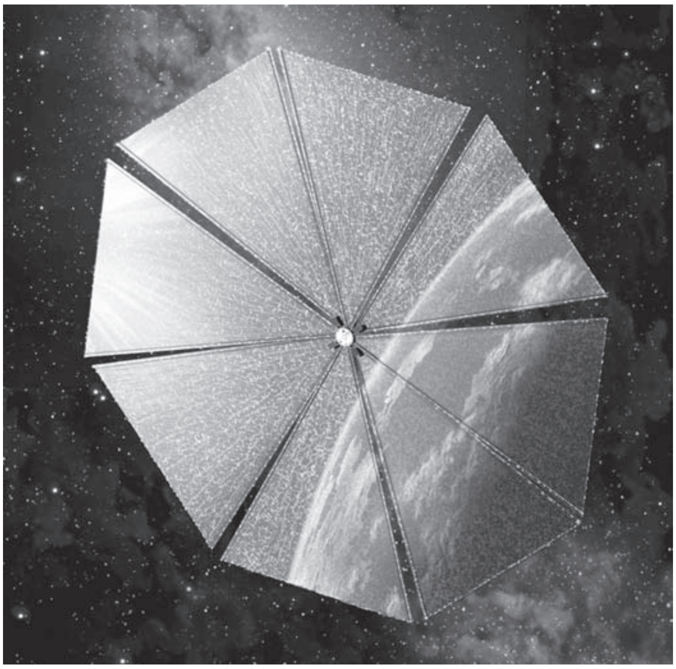

**Fig. 1 Cosmos-1 sail in Earth orbit. (Rick Sternbach, The Planetary Society (c).)**

The Cosmos 1 orbit was to be polar, because the launch is from a submarine in the Barents Sea. Its almost circular orbit is to be at approximately 800 km. There the orbital velocity is 7.4 km/s. The satellite moves across the sky at 0.06 deg/sec (a function of azimuth and elevation), so can be tracked readily. The orbital period is 101 minutes, so overhead time is at most 15 minute, and is typically much less. The sail diameter is 30 meters. The sail material is 5 micron thick polymer film (PET) aluminized on one side and with rip-stop reinforcement. The sail areal density is about 11 g/m$^2$ including the rip-stop and seaming adhesive. The boom tubes are made of 38 micron polyethylteraphtalate material. The tubes are inflated with nitrogen, and pull the sail from its initial folded configuration, to gradually deploy it and to hold it rigid. Because of the diaphanous nature of the sail material, the ~ 100 kg craft is 80% payload, 20% sail.

A clear measurement of beam-driven thrust in orbit on a real Sailcraft will be a significant scientific contribution, the first step in the experimental study of beam-driven sailing. The solar flux will give a maximum acceleration to the 100-kg sail of $10^{-4}$ m/s$^2$. The measurement of the orbital energy increase from solar photon pressure can come directly from Doppler radar and/or GPS tracking of the spacecraft, or inferred from onboard 3-axis accelerometer measurements. There are on-board accelerometers [3], derived from gravitational wave detectors, with sensitivity down to 2-20 x $10^{-7}$ m/s$^2$ (2-20 nanogees) sample at 10 Hertz and integrate over 2 seconds.

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 4 x $10^{-8}$ 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. Acceleration occurs over about 240 seconds, as the sail rises and nears the Goldstone site. The average acceleration will be 8.5 $10^{-8}$ m/s$^2$; over the entire trajectory, the total impulse is 2 x $10^{-6}$ newton-sec. The basic signal-to-noise ratio S/N~1. It will be improved by integrating over the entire trajectory. We estimate that the S/N will be about 10. Clearly we'd like to improve it further.

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 modulating 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. The typical case will be when the sail passes in and out of the Earth's shadow, and modes are excited and, eventually, damped. If the sail were rigid, the fundamental oscillation frequency would be about 10 Hz. The fact that the sail, attached to the tubes, is not a rigid body complicates attempts to make the system resonate acoustically. Calculations show that the fundamental frequency of sail oscillation is 0.147 Hz, which corresponds to a gentle flapping of the sail. There should also be odd numbered harmonics (0.44 Hz, 0.735 Hz, etc.). Corresponding periods are 6.8 sec, 2.26 sec, 1.36 sec. Because of limited bandwidth (due to onboard integration at 0.5 Hz, 2 sec) only the first two modes may be observed in the accelerometer data. We will attempt to measure the spectrum and the phase of the oscillations in flight by Fourier analyzing the data we get from the accelerometers.

## 3. FLIGHT PREPARATION

Microwave power beaming was to occur late in the mission because of the remote possibility of interference with spacecraft electronics.

There is not likely to be any effect on Cosmos-1 by the DSN beam. The beam intensity on the solar sail typically varies from 0.1-0.4 W/m$^2$, and cannot exceed 1 W/m$^2$ for firing at the sail broadside as it passes directly overhead.

Cosmos-1 had several electronics systems in the central payload section. The frequencies of the links with the ground run from 0.4-2.25 GHz. The DSN X-band at 8.56 GHz is far from being in-band to any of these, nor is it a harmonic multiple of them. Therefore there will be no in-band interference through the external antennas of the spacecraft (so-called "front-door" paths). There remains the possibility of front-door out-of-band effects, where the beam goes into antennas and no front-end filtering attenuates the signal. Consequences of electromagnetic interference (EMI)-caused failure mechanisms are divided into three categories: 1) damage or permanent effects, 2) upset and 3) interference. In X-band, permanent damage has a threshold at about 10 kW/m$^2$, far above our levels. Likewise upset, which means that the system has to reboot in order to restore itself, has a threshold at about 10 W/m$^2$, also below our levels. Interference means that electronic activities are interrupted while the EMI is present. In X-band, the threshold is at about 0.1 W/m$^2$, so interference might occur while the beam is on, but only if the receivers have no filtering on the front end. Any filtering will increase the threshold, of course.

The most important electronics for our experiment is the accelerometers. (Note that no data reception will be attempted during beaming. While DSN beams at Cosmos-1, the accelerometer data will be recorded on-board and will be downloaded later.) The quartz sensor is enclosed in the metal housing, and is unlikely to be sensitive to EMI.

We conclude that the power density on the sail will not damage and or upset Cosmos-1 electronics. Interference while the beam is on is possible but not likely.

Tracking the LEO Cosmos-1 is not what the Solar System Radar 70-m dish was designed for. It's normally used for sidereal targets, meaning ones that move little in the sky, such as planets and asteroids. To quickly acquire and track Cosmos-1 requires modifications to software and operating procedures. The system will have to frequently furnish the dish with updated orbital elements. This procedure is now being put in place.

Unless Cosmos-1 is boosted into significantly higher orbit by solar sailing, the mission will last for about two months before drag-induced re-entry. During this period, when the sail passes over Goldstone, the beam from the Goldstone 70-m dish will test the predictions for microwave acceleration.

## 4. IMPLICATIONS

Following the loss of Cosmos-1, we feel that it was the first attempted sail mission, but not the last. There are stirrings to use the Cosmos-1 design to try again. There will be future sail missions, we just do not know when. To prepare for the next attempt to accelerate a sail with a beam, we have thought of ways that Cosmos-1 could have been built that would make MAX much easier, these are:

1) The onboard transmitter should be a very stable oscillator. With that we could establish a phase-locked loop with Cosmos-1, enabling a sensitive measure of velocity changes. X-band would be better that the Cosmos-1 S-band, because there would be more cycles to detect.

2) Adding a retro-reflector would make possible a phase-locked loop with a ground-based laser, such as OCTL. With a 1-micron laser, there would be many 100,000 times more cycles to detect.
3) Conduct EMI tests on the electronics, early on in fabrication/assembly of the sail, to get assurance there will be no problems, as we expected on Cosmos-1. Then we can start beaming much earlier in the mission.

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, larger-aperture array 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 other papers we have explored new ways to do this [4-5].

## 5. CONCLUSIONS

The future first flight of a solar sail will be an opportunity to also show the effects and promise of beamed power for space applications.

## 6. ACKNOWLEDGMENTS

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