Diffractive Solar Sailing : A Modern Method of Solar Sailing

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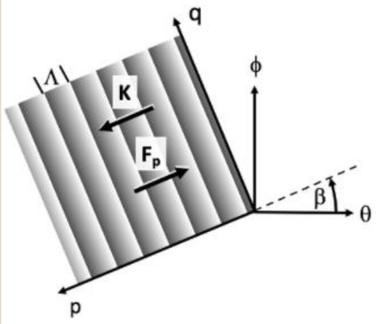
Phase III - 2022

Summary

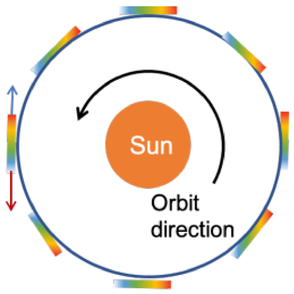
Solar sails have been of interest to the solar and space science community since the 1980s. The concept of a massless, near infinite propulsion method provides significant advantages over traditional spacecraft propulsion systems in that they allow spacecraft to escape the constraints of Keplerian orbits and attain novel orbits such as high solar inclination angles or stationed above the Earth's poles. Presently, the law of reflection has traditionally governed solar sailing technology, but our NASA Innovative Advanced Concepts (NIAC) Phase I and II indicated that the law of diffraction provides significant enhancements that out-perform reflective sails as well as traditional propulsion. Our Phase III plans to optimize the diffractive sail material and explore the use of a constellation of diffractive sail-craft for 4π coverage of the Sun to empower transition from the NIAC program.

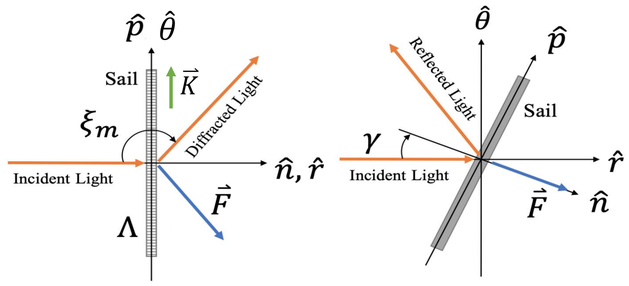
Diffractive Solar Sailing Concept

For radial and inclination changing heliocentric orbits, the optimal theoretical force efficiency of a solar sail is achieved when (1) the sail is facing the sun and (2) when light is redirected at a right angle. Unlike a reflective sail, both conditions can be met with a theoretical diffractive sail. The thrust from a reflective sail is controlled by changing the angle γ of the sail normal n with respect to the incoming solar light along r. Alternatively, a transmissive diffractive sail with a grating momentum vector K derived from the grating period Λ can be controlled by changing the diffraction angle ξm instead.



(Left) Perspective of a diffractive sail optical fully facing the sun. Radiation pressure force in the plane of the sail Fp is antiparallel to K . The thrust direction is directed by the roll angle control parameter β, allows orbit lowering (angular deceleration) when sunlight is incoming normal to the sail plane. (Right) An example of a circular orbit with a sun facing diffractive sail





Diffractive Solar Sailing

Reflective Solar Sailing

(Left) Sun-facing transmissive diffractive sail with sun line along $\hat{r}$.
(Right) Reflective sail with angular offset γ from the sun line along $\hat{r}$.

The higher efficiency of a diffractive sail owes a smaller sail, or alternatively a larger payload mass for the same size sail. An entirely sun facing sail can yield less complex guidance, navigation, and control schemes with less massive systems. Potential solar cells can take advantage of full, direct sunlight at all times to either reduce the required power system mass or increase power margin for potential payloads. The direction of force on a fixed sun-facing diffractive sail can be controlled by rotating the sail about the sunline.

Contributors

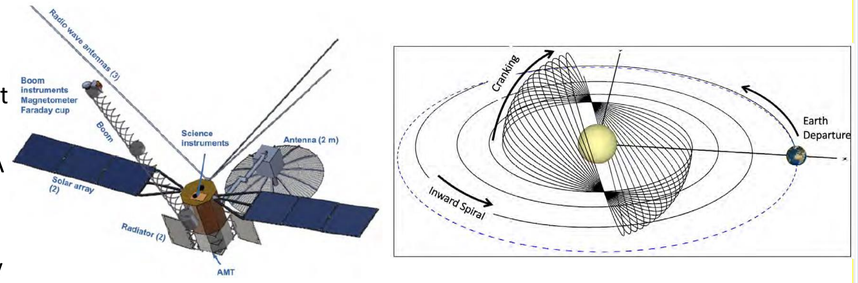
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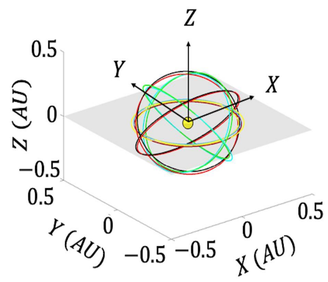


Solar Polar Orbiter Missions

The NIAC Phase I and II advanced a novel means of circumnavigating the entire sun by means of diffractive solar sails. The first was the exploration of a NEA Scout sized Solar Polar Orbiter with a non optimized trajectory to 0.32 AU and 60 degrees above the ecliptic. This was expanded to a constellation of 12 satellites. A constellation of spacecraft with diffractive solar sails could provide simultaneous multi-view observations of the sun, thereby providing unprecedented perspectives across 4π steradians of the solar surface, is to be further explored by the Phase III activities. This aligns with NASA's heliophysics strategic objective "to understand the sun and its interactions with Earth and the solar system, including space weather". NASA MSFC's Advanced Concepts Office further explored the use of diffractive solar sailing in their Solar Polar Imager concept. The mission concept provides at least three years of high latitude data after a 13-15 year cruise phase that continuously cranks the inclination angle while approaching a circular orbit at 0.5 AU. They found that the innovative use of diffracted rather than reflected sunlight affords a higher efficiency sun-facing sail with multiplying effects such as a smaller sail, less complex guidance, navigation, and attitude control schemes, reduced power requirements, and a non-spinning bus.



(Left) Conceptual configuration of the fully deployed Solar Polar Imager (without the sail shown)
(Right) Typical solar sail mission trajectory from Earth to 0.48 AU and 75 inclination.

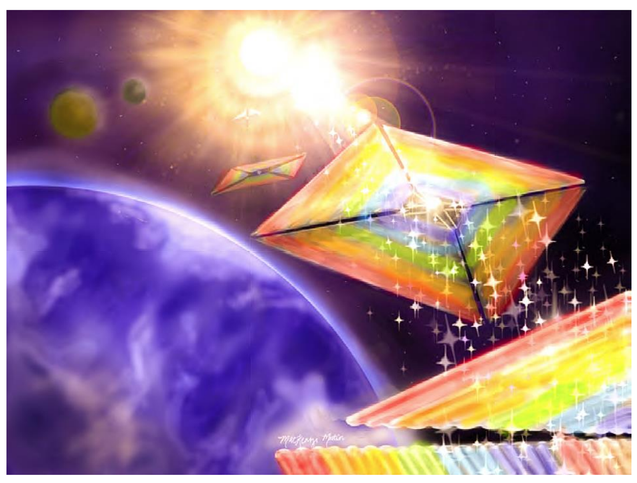


Full constellation of twelve satellites around the sun. There is one satellite in each octant at 60◦ inclination and four distributed about the ecliptic. Each colored orbit represents the final destination orbit of one satellite in the constellation.

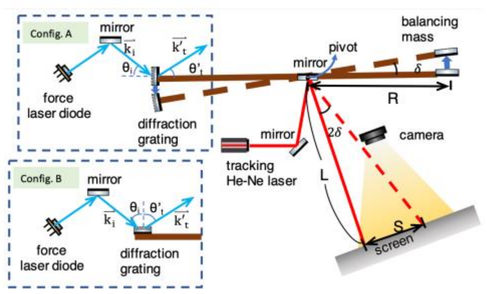
Phase III Goals

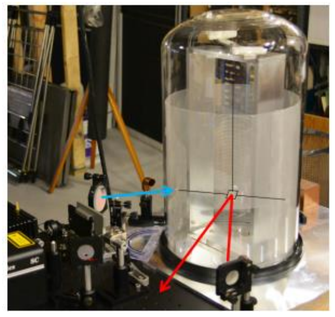
- Improvement in efficiency of gratings for broadband solar spectrum
- Manufacturing of sail material and scaling to large areas
- Complete characterization of realistic diffractive sail dynamics
- Space qualification of diffractive sail materials

Year 1	Year 2
• Design, optimize, and analyze broad band diffractive grating samples x2 • Manufacture samples x2 • Perform optical and radiation pressure measurements x2 • Subject samples to space weather testing • Fully characterize the force from grating designs	• Selection of heliophysics payload suite • Mission trajectory and design for constellation of Solar Polar Orbiters • High level sail-craft design • Attitude control and determination trades of sails



Diffractive Grating Testing





(Left) Schematics showing configurations for measuring components of radiation pressure force as a function of the incidence angle
(Right) Photo of experimental set up for measuring radiation pressure in a vacuum bell jar

Activities in the NIAC Phase II included the design, fabrication, and testing of thin liquid crystal polymer (LCP) diffractive gratings to demonstrate that LCP sails provided radiation pressure characteristics that are consistent with our theoretical and numerical models. These gratings were subjected to radiation pressure, opto-mechanical, and characterization experiments. Different samples completed a campaign of space weather testing with electron flux, UV, and gamma ray sources to understand the material's degradation in performance due to the space environment.

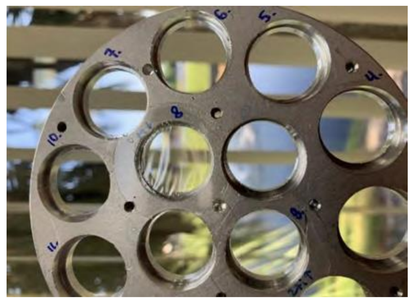


Photo of the sample holder with a single free-standing diffractive film mounted for space weather testing.

APL JOHNS HOPKINS APPLIED PHYSICS LABORATORY

RIT Rochester Institute of Technology

NIAC NASA Innovative Advanced Concepts

NASA