Diffractive Solar Sailing

NIAC Phase III 2022-2024

PI: Amber Dubill (JHU/APL)
Contact: amber.dubill@jhuapl.edu

Co-I's: Dr. Grover Swartzlander (RIT), Les Johnson (NASA MSFC)
Collaborators: Dr. Angelos Vourlidas (JHU/APL), Dr. George Ho (JHU/APL), Dr. David Shrekenhamer (JHU/APL)

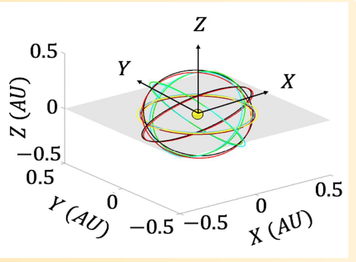


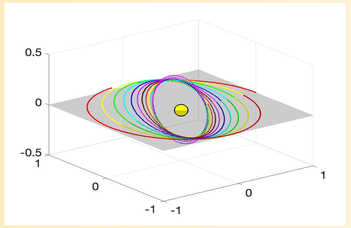
Graphic Credit: Jillian Duma

Solar sails, which require no propellant, provide significant in-space propulsion advantages over traditional spacecraft propulsion systems, allowing spacecraft to attain novel orbits such as high solar inclination angles above the ecliptic. Whereas the law of reflection has traditionally governed solar sailing technology, our research indicates that the law of diffraction provides significant enhancements that out-perform reflective sails. A sail based on diffraction can provide a transverse radiation pressure force optimal for low thrust spiraling trajectories. We determined in Phase-II that a higher efficiency sail provides multiplier effects, including a simpler attitude control scheme, a simpler heat management configuration, and a smaller sail that lessens the risk of boom buckling. The resulting mass reduction of the spacecraft may provide enhanced acceleration, affording shorter transit times. In Phase I and II we made first principles studies of the radiation pressure and orbital path of a diffractive sail, verification measurements using a laser, space weathering experiments involving prolonged electron and gamma ray bombardment, and spacecraft architecture comparisons, advancing the technology to TRL-3.

Solar Polar Orbiter Diffractive Sailcraft

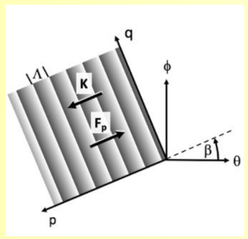
- Need for solar sailing and solar polar missions outlined in Decadal Survey for Solar and Space Physics 2013
- Submitted to Decadal Survey for Solar and Space Physics 2024
- NASA's Ulysses and ESA's Solar Orbiter are the only two missions to significantly leave the ecliptic
- To gain useful information on the solar poles behavior, target above 65 degrees within 0.5 AU as shown in previous NIAC Phase II
- Goal is to expand into constellation for simultaneous, multi-view – complete coverage of the Sun
- Aligns with current NASA strategic programs: LWS, Helio 2050
- Expected trajectory is to spiral in towards the Sun and out of the ecliptic plane
- Higher efficiency diffractive sail provides: a simpler attitude control scheme, a simpler heat management configuration, and a smaller sail that lessens the risk of boom buckling. The resulting mass reduction of the spacecraft may provide enhanced acceleration, affording shorter transit times

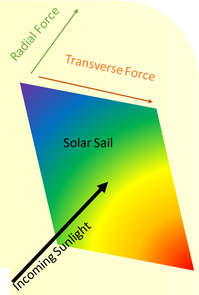


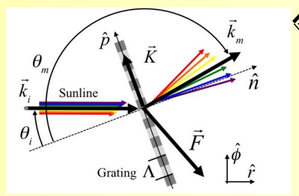


Diffractive Solar Sailing Theory

- Diffractive solar sails use the radiation pressure force produced by the optical mechanism of diffraction rather than the traditionally used method of reflection
- This produces an "in plane" or transverse thrust force from the sail that is otherwise not possible per reflection
- This enables unique control solutions that cannot be performed with reflective sails to circumnavigate current challenges and is theoretically more efficient for low thrust trajectories
- Instead of having to tilt the sail back and forth, the transverse thrust vector can be controlled simply by rotating the sail around the normal plane of the sail

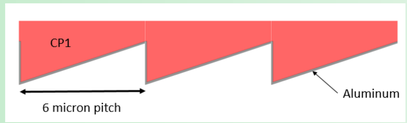


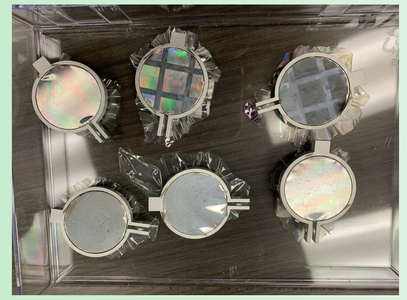


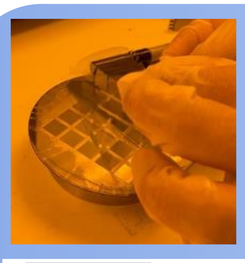


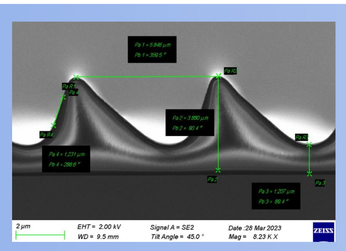
Current Phase III Status

- Orchestrated workshop with solar sailing and heliophysics community members (largely including other NIAC members) in December 2023 in tandem with NIAC Phase III kickoff meeting
- Developed, modeled, and analyzed a reflective diffractive saw tooth grating design
- Continued exploration of diffractive grating methods outside of a saw-tooth prism grating design, ie metasurfaces, procurement of Beam Co unpolarized samples
- Performed grating sample fabrication trades on material, resolution, feature size, to inform design for transition from theoretical to manufacturable
- Continued participation in relevant conferences and publications
- Manufactured first set of test grating samples in CP-1 with aluminum layer
- Continue to work within institution exploring opportunities for post-NIAC development
- Currently finishing optical characterization at JHU APL of the samples before sending to NASA MSFC's Combined Environmental Effects Facility for space environmental testing
- Currently modifying previous torsion oscillator set up at RIT for radiation pressure testing for use with broadband source
- Preparing for Solar Polar Orbiter Constellation study



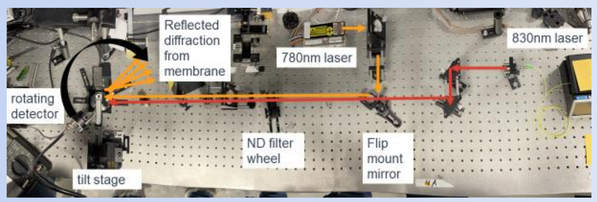


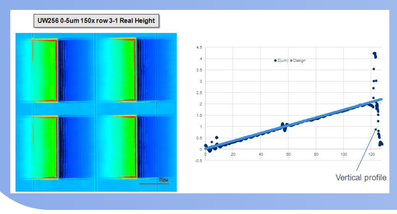




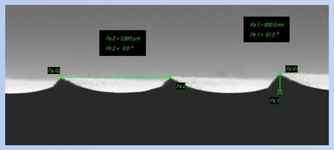
Broad-brand Diffractive Sail Material Samples

- Single layer saw-tooth grating design with reflective layer
- Sail material is CP-1 resin (under 10 microns thick) with an aluminum layer (currently ~100 nm thick)
- Design intent is to capture as much of solar spectrum as possible – aiming to center at the peak of ~880 nm wavelength, though this largely depends on feature resolution – currently 6 micron pitch
- First iteration of samples estimated to have transverse efficiency of ~30%
  - Target samples are 1" x 1" size, can create up to 6" diameter wafers
  - Process creates a master mold in a Si wafer, then CP1 is spun onto mold, cured, and removed. Aluminum layer is added via evaporative process.
  - Samples with various parameters were manufactured in effort to understand limitations of chosen fabrication process and effect on momentum transfer efficiency
    - Steepness of cut off
    - Smoothness
    - Rounding
    - Step Size
    - Feature Resolution





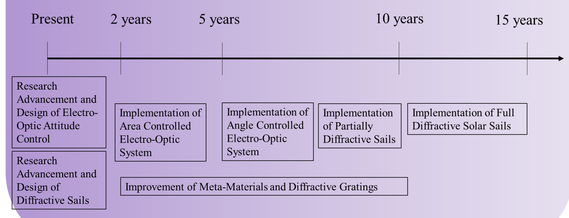




- Preliminary optical testing before sending to NASA MSFC for understanding baseline behavior of samples
- This testing is performed at two different wavelengths, (780 nm and 830 nm) unlike future radiation pressure testing at RIT
- Testing is also to inform thickness of aluminum to decrease transmission

Key Areas of Development for NIAC Phase III

- 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



Acknowledgements: We'd like to acknowledge the NASA Innovative Advanced Concept Program for their continued support in each phase of our work. We'd also like to acknowledge continued support form Johns Hopkins Applied Physics Laboratory's Space Sector and Research and Exploratory Development Area as well as the Rochester Institute of Technology and Marshall Space Flight Center.