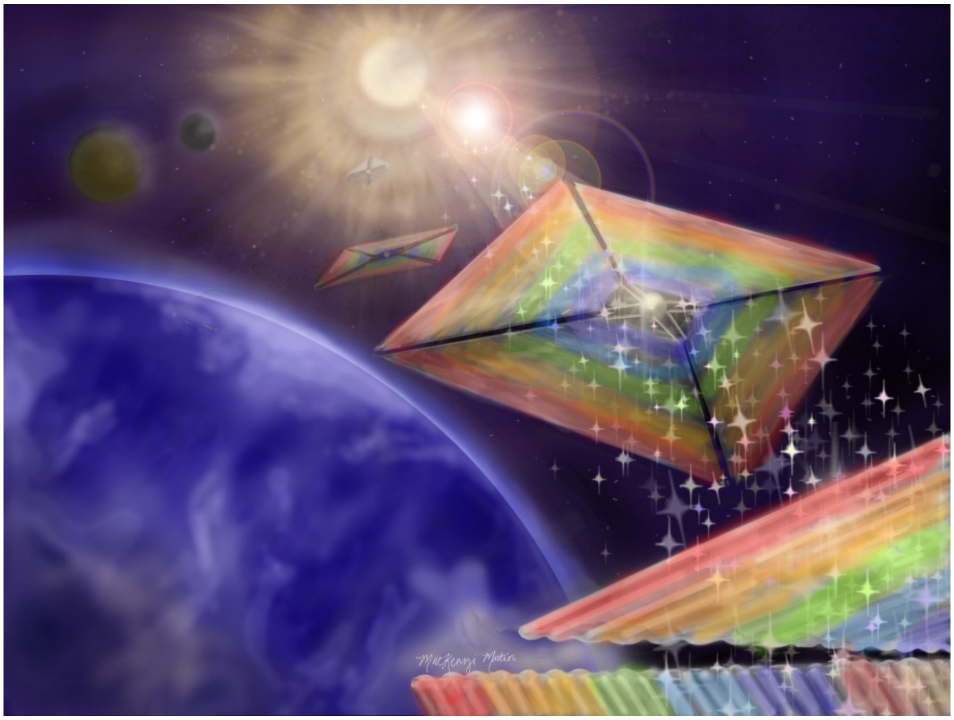
NIAC PHASE I FINAL REPORT



Project Title: Advanced Diffractive MetaFilm Sailcraft

NASA Award Number: 80NSSC18K0867

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Table of Contents

1. Abstract

A fast-tracked multifaceted approach that integrated NASA, industry, and academia was successfully executed to advance the novel concept of radiation pressure by means of a thin diffractive film. This pioneering new approach to light sailing was found to offer advantages over reflective sails – especially for missions that include close orbits or a close fly-by of the sun. The research effort included experiments, numerical modeling, and an "incubator meeting" that brought together over 35 researchers and stakeholders to uncover some of the most feasible means of advancing both the TRL and mission capabilities of diffractive sailcraft. One of the outcomes of the incubator meeting was to focus this Phase I research on a solar polar orbiter mission for heliophysics experiments. NASA decadal surveys and other reports have repeated pointed out that scientists have only a paucity of information about the sun beyond the ecliptic plane. The TRL has been advanced from 1 to 3 during this Phase I research with the help of experiments that have verified the predicted force and mechanical control afforded by diffractive sails. Knowledge gained from the experiments and numerical models was not only disseminated in peer reviewed publications and conferences, but it also resulted in a patent disclosure.

2. Objectives

Recognizing that the predicted force on a diffractive sail is characteristically different than that on a reflective sail we identified several overarching objectives needed to raise the Technical Readiness Level: (1) Experimentally verify that the predicted forces can be achieved; (2) Develop analytical and numerical models to predict the dynamics of a diffractive sail that includes a payload; (3) Experimentally demonstrate dynamical characteristics of a light-driven diffractive film; (4) Assess high-impact missions that are both important to NASA and that have the potential to outperform a reflective sail.

3. Executive Summary

Solar sails are propelled by the free and abundant momentum afforded by sunlight. Propulsion and navigation are achieved by directing reflected or diffracted light away from the natural direction of sunlight. The magnitude and direction of this radiation pressure force depends on factors such as the light deflection angle, the angle of the sail with respect to the sun, and the distance from the sun. Sail areas spanning hundreds of square meters have been envisioned for nearly 100 years for a wide range of space missions that are not practical for chemical rockets. If the momentum transfer efficiency is high and the mass per unit area of the sail is small, large velocity changes may be achieved over time owing to a continuous acceleration. The conventional means of collecting and redirecting sunlight, which makes use of a metal-coated polyimide film, is sub-optimal and mechanically cumbersome because the very large and very thin sail must be rapidly slewed away from the sun line for navigational purposes. What is more sail rigging and conventional attitude control devices add mass to the sailcraft, thereby reducing the acceleration. Engineered diffractive sails designed using metamaterial principles afford significant advantages over reflective sails such as enhanced momentum transfer efficiency, low-mass electro-optic attitude and navigation control, and superior heat tolerance. Diffractive metamaterial films allow both inclination cranking, orbit lowering (raising) toward (away from) the sun, and superior thermal management than a reflective sail, as well as other advantages such as the off-loading of mass and failure risk from mechanical systems such as gyros.

The fundamental theory and experimental verification of diffractive lightsailing principals were developed in this Phase I study. The study included an "incubator meeting" of more than 35 experts in solar sailing and metamaterial research. A target mission was identified during the incubator meeting which has been given prominence in various NASA Decadal Surveys: A constellation of solar polar orbiters for gathering in-situ heliophysics data such as images of the sun at different wavelength bands. To date no direct image of either solar pole has been recorded. A constellation could provide continuous radiometric information across 4π steradians, leading to vast increases of our understanding of the Sun across a wide range of spatial and temporal scales.

The TRL was increased from 1 to 3 during this Phase I study. This rapid acceleration was possible because the materials and fabrication technology is already being matured to the point where prototype experiments are possible. In addition, the PI had past experience with radiation pressure experiments, collaborators who were eager to provide samples, and colleagues at NASA having a long association with solar sailing. Fundamental experiments that verified the theory of radiation pressure on a diffraction grating were performed for the first time in history. Advanced measurements that demonstrated the dynamic control of a space-variant diffraction grating were also made. A patent application was submitted for this latter device, which also functions as a so-called "beam rider". We also developed sophisticated computer models to predict the attitude of a sailcraft having a diffractive sail, showing for example, that a bi-grating or radial grating pattern provides dynamic stability to a well-designed sailcraft. Finally, our computer model demonstrated that diffractive sails could be used more efficiently than reflective sails to place a constellation of science instruments in polar orbits around the sun.

A study of the feasibility and cost effectiveness of this novel approach to light sailing is recommended. Also recommended are design and fabrication studies for the development of large-scale electro-optically controlled diffractive films that provide efficient momentum transfer across the solar spectrum. Experiments verifying the predicted force and control afforded by such films are recommended, as well as space weathering studies. Finally, the preliminary roadmaps reported here (see Appendix) should be refined, based on the outcomes of these recommended studies.

4. Activities and Accomplishments

A. Visit to NASA (George C. Marshall Space Flight Center, Huntsville, Alabama)

The PI (Swartlzlander) and an RIT undergraduate research assistant (Amber Dubill) visited the NASA Marshall Space Flight Center, 18-29 June 2018 to discuss NASA requirements, concerns, and lessons learned from solar sailing scientists and engineers. The NASA visit was hosted by Les Johnson, Principal Investigator for the Near-Earth Asteroid Scout solar sail mission. We also met with NASA scientists Andrew Heaton, Roy Young, Paul Craven, and Jason Vaughn to discuss sailcraft momentum management issues, LEO satellites, and space environment degradations measurement facilities. Our visit coincided with the only full scale test deployment of the NEA-Scout sail (see photo below), which we attended to gain knowledge of the unfurling process of a cubesat-compatible sail.

During our visit we learned that it is highly desirable for the sail to face the sun (an advantage of diffractive sails) because it allows photovoltaic solar cells to continuously charge while also delivering power for communication, control, and navigation. We also found that having a small component of force along the sun line (as provided by a diffractive sail) is attractive for station keeping, e.g., for a fixed distance from the sun, or for a polar orbit around the Earth. Diffractive sails may also provide means of offsetting the unwanted angular momentum that is developed when the center of mass and center of pressure are displaced. An array of electro-optically controlled diffractive films could potentially be used to prevent "windmill" torque on a solar sail. We learned that momentum management is one of the most difficult parts of a sailcraft mission. However, a diffractive sail could become an integral part of the Attitude Determination and Control System. Finally we learned that a roll maneuver that keeps a sail facing the Earth is difficult, requiring angular momentum management (adding mass to the satellite). This latter point, NanoSail-D experiences, and concerns about the space environment in very low Earth orbit, made us reconsider the original Phase I focus mission, which was to counter LEO atmospheric drag with radiation pressure on an Earth-facing sail. A solar polar orbiter mission became the new focus.

Solar sail deployment test for NEA-Scout at NeXolve (Huntsville, AL). Left to Right: Amber Dubill (BS/MS Mechanical Engineering, RIT), Grover Swartzlander (Professor, Center for Imaging Science, RIT), Les Johnson (PI, NEA-Scout Mission, Science and Technology Office, NASA Marshall Space Flight Center). Background: $85m^2$, $2.5\mu m$ thick aluminized CP-1 at 90% reflectivity.

B. OSA Incubator Meeting on Diffractive MetaFilm Sails

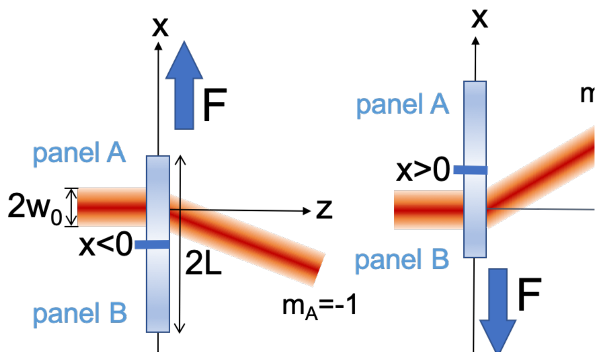
Over 35 key researchers and stakeholders from NASA facilities, the Planetary Society, the Breakthrough Starshot Initiative, industry, and academia were brought together during this Phase I period. The meeting conveyed the concept of diffractive sailing to the participants, proving a workshop forum for discussing the feasibility of fabricating films have desired properties and pinpointing missions where such metafilms could outperform other types of propulsion. A White Paper summarizing the key outcomes and recommendations of the meeting is attached in the Appendix. Incubator participants discussed both passive and active diffractive films designed to minimize spectral absorption and loss of light, provide passive sailcraft roll control/stability, and to have high broadband diffraction efficiency. Mission concepts and roadmap objectives were also discussed. Liquid crystal polymer and transparent oxide (e.g., titanium nitride or fused silica) based diffractive structures were identified as candidate materials. As evidence of the rapidly advancing TRL of these materials, electro-optic (non-mechanical) beam steering using high efficiency polarization diffraction gratings, and high efficiency passive dielectric gratings designed using metamaterial principles were both identified.

Outcomes from the incubator meeting led to a revision of this Phase I target mission from a low-Earth orbit system to a solar polar orbiter mission for heliophysics science. NASA decadal surveys and other reports have repeatedly lamented the paucity of information about the sun beyond the ecliptic plane. Space-weathering experts at the meeting suggested that the originally proposed low-Earth orbit sailing mission might be short-lived owing to highly reactive oxygen molecules. NeXolve president James Moore stated that self-hardening polyimides can help mitigate the oxygen problem, but such materials are not yet well understood. The PI of this Phase I effort raised almost $30,000 from sponsors (NASA, NSF, the Gordon and Betty Moore Foundation, AFOSR, Thorlabs, and Sydor Optics) to help defray the cost of attendance. Two meeting co-hosts, Charles (Les) Johnson from NASA-Marshall and Nelson Tabiryan (BeamCo) provided advise and helped attract key participants. Johnson is instrumental in NASA solar sailing missions, including the upcoming NEA-Scout – the first true solar sail carrying a science payload. Tabiryan is developing advanced polarization diffraction gratings with potential use as a large gossamer space telescope. The 1-1/2 day meeting (7-9 October 2018, Optical Society of America headquarters, Washington, DC) included a small number of keynote talks, followed by panel discussions and working group meetings (see Agenda in Appendix). The meeting attracted roughly 35 attendees. Following the meeting, the three hosts compiled notes from both my RIT undergraduate research student and blogger, Amber Dubill and input from the working groups.

Incomplete group photo of the incubator meeting.

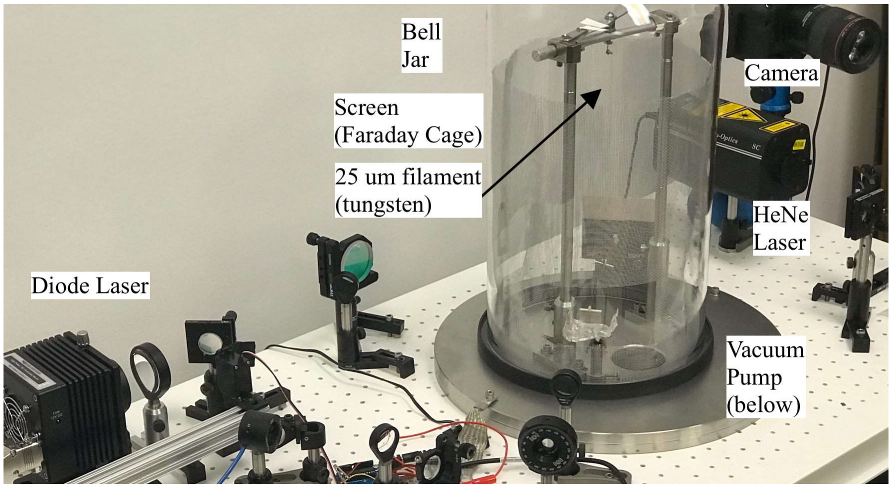
C. Experiments at RIT

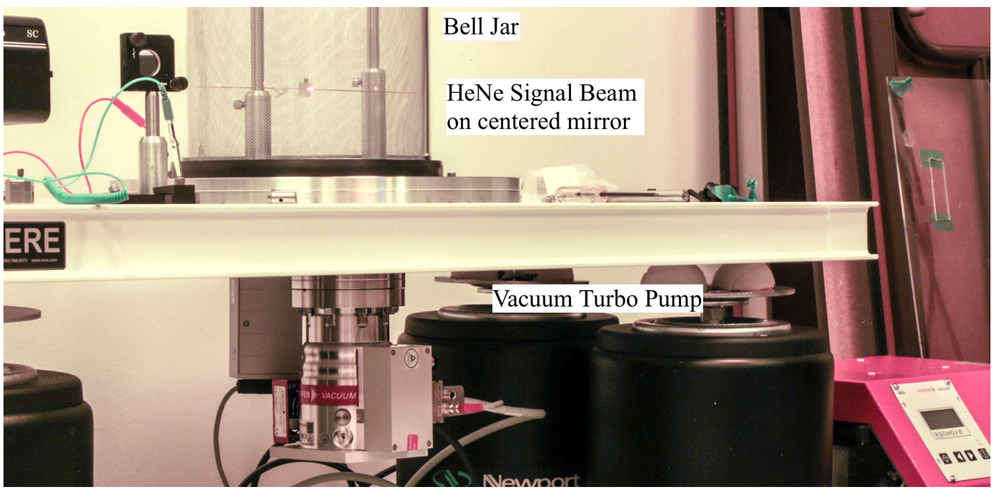
A sensitive and precise instrument was constructed to allow the determination of radiation pressure forces on materials based on experimental measurements. Those values were compared to theoretical predictions to verify the theory and assess the quality of the samples. We received diffractive samples fabricated using different techniques from two collaborators: Rajesh Menon (U. Utah) and Nelson Tabiryan (BeamCo). To demonstrate the fundamental dynamic functionality of diffractive films without the complexity of electro-optic control, RIT designed a bi-grating (patent pending) that provides position-dependent control (see Bi-Grating Sail Modeling section below). The bi-grating is designed to diffract light toward the central axis of the grating, as depicted below. When the laser exposes Panel-A, the beam is diffracted in the –x direction, resulting in an equal and opposite momentum transferred to the grating in the +x direction. Likewise, when the laser exposes Panel-B, the beam is diffracted in the +x direction, forcing the grating in the –x direction. Radiation pressure therefore provides a restoring force, returning the grating to the equilibrium position at x=0.



Position-dependent force on a bi-grating, resulting in a restoring force $F \approx -(P/c)(\lambda/\Lambda)\tanh(x/2w_0)$ and an equilibrium position at x = 0.
Beam power P, speed of light c, wavelength λ, grating period Λ, beam size w_0.

Torsion Oscillator Construction. We have constructed a vacuum torsion oscillator $(1.4\times10^{-6}$ Torr$)$ and placed it in the RIT nanofabrication facility, which was designed to have low vibrational flooring. We found that the addition of dampers such as tennis balls or Sorbothane™ hemispheres increases the coupling of low frequency noise into the system, so these were removed. The background noise level was found to be less than 0.01 nN (10^{-11} N), allowing precision measurements of radiation pressure. The discrepancies between our numerical model and experimental results where ~0.1 nN (2% of the measured values). The system was therefore well characterized for precision measurements. Systematic fluctuations over times scales much longer than the oscillation period (T=120 s) were attributed to ultralow frequency building disturbances. The oscillator was comprised of a 25 µm diameter tungsten filament of length 240 mm, a twist-hardened copper wire torsion arm of length 2R=220 mm, with an aluminum counter-balance on one side and the diffractive film on the other. To prevent spurious electrostatic forces the oscillator was surrounded by a grounded aluminum mesh Faraday cage. The system was encased in a glass bell jar and seated on a machined and polished steel vacuum plate. The bell jar was evacuated of air by means of a vacuum turbo pump (see below).





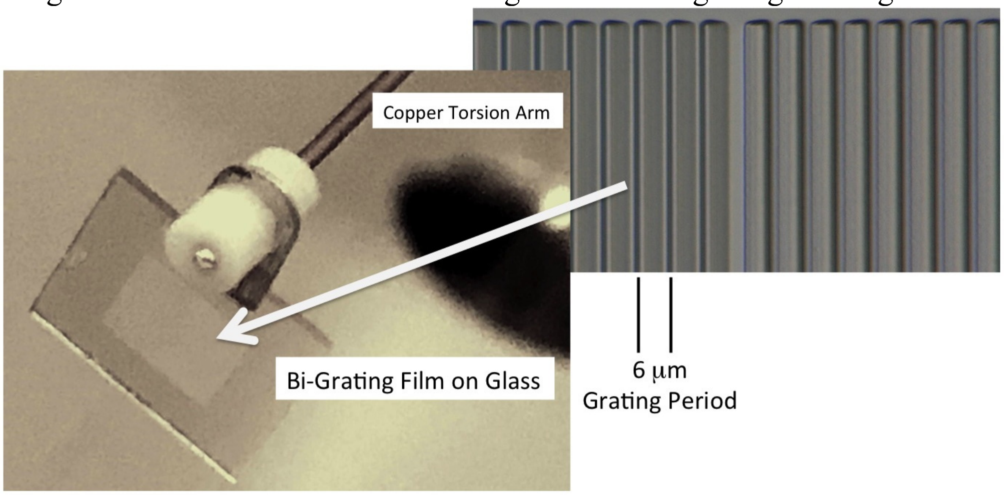
Top and side views of the RIT vacuum torsion oscillator encased in a glass bell jar for measuring nano-Newton scale radiation pressure forces on a diffractive film from a diode laser. Angular deviations are recorded by means of a low power HeNe laser beam.

LightSmyth Littrow Grating

A commercially available diffraction grating from LightSmyth (T-1850-800s-3210-93) was ground to a thickness of 190 [μm] to minimize the moment of inertia and thereby achieve large angular displacements when mounted on the torsion oscillator. Assuming perfect single order diffraction the components of radiation pressure force were predicted to be given by $F_p = (P/c)m\lambda/\Lambda$ and $F_n = (P/c)\left(\cos\theta_i \pm \sqrt{1-(m\lambda/\Lambda - \sin\theta_i)^2}\right)$. Torsion oscillator experiments were conducted to measure each of these, resulting in excellent agreement with the theory after accounting for the presence of multiple diffraction orders. These measurements represent the first time radiation pressure was measured with a diffraction grating and were therefore published in the prestigious journal Physical Review Letters (*Measurements of Radiation Pressure Owing to the Grating Momentum,* Phys. Rev. Lett. 121, 063903, 2018.) The experiment measured the step function response of the torsion oscillator to radiation pressure, allowing the determination of force values, which were in the nano-Newton range.

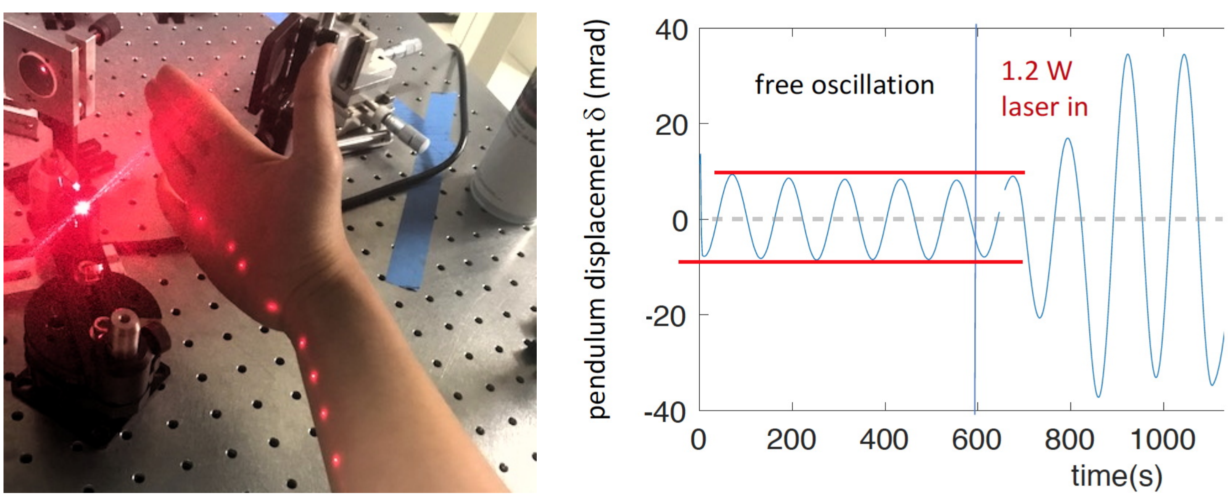
University of Utah Bi-Grating Sample

An RIT-designed bi-grating was fabricated by Rajesh Menon, a colleague at the University of Utah. A design grating period of $\Lambda = 6$ μm was specified. A series of microscopic prisms of height 1.3 μm were formed in photoresist having a refractive index of n = 1.6291 at $\lambda = 800$ nm. The prism angles were reversed on the left and right half of the grating as designed.



Photoresist bi-grating on glass, mounted in the RIT radiation pressure test-bed. Micro-fabrication by Rajesh Menon, U. Utah. Grating period: 6 μm.

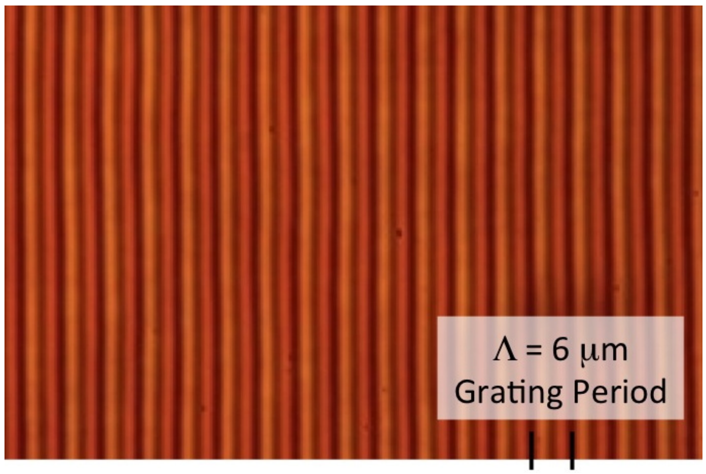
The grating produced multiple diffraction orders, as shown on the left below. Though the grating provided radiation pressure as indicated in the displacement plot (below right), it was unable to demonstrate bi-grating dynamics, as predicted by the RIT team, owing to the multiple orders on both sides of the grating normal. When light is diffracted on both sides of the beam axis, the desired momentum transfer is diminished. The Menon group used our measurements to adopt a different fabrication technique that may provide a single dominant diffraction order. That work is ongoing as of the date of this report.



Left: Multiple diffraction orders of a low power HeNe laser beam from the U. Utah diffraction grating. Right: at t > 600 s a 1.2W diode laser ($\lambda = 808$ nm) provided significant radiation pressure, changing free oscillations into a forced oscillation state.

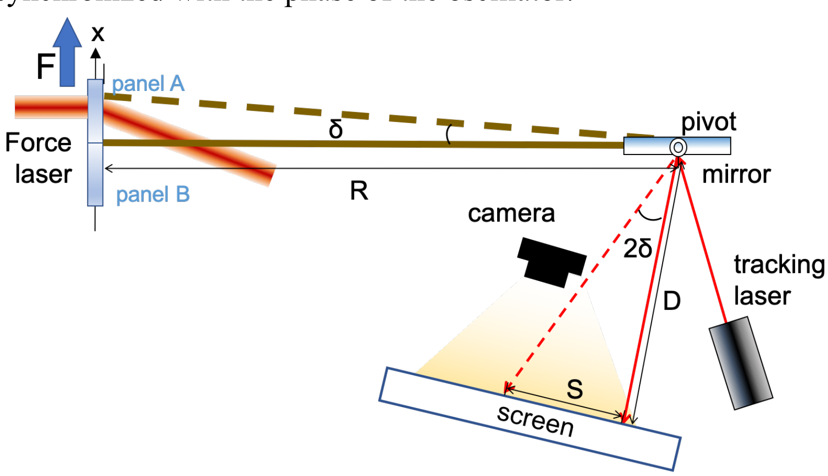
BEAMCo Bi-Grating Sample

The RIT-designed $\Lambda = 6\mu m$ bi-grating was also fabricated by Nelson Tabiryan's team at BEAMCo (Orlando, FL). This grating was made using polarization hologram techniques that afforded a high diffraction efficiency of almost 100% into a single dominant diffraction order. These gratings belong to a class of non-metallic metamaterials that are nearly lossless, provide spatially variant features at the wavelength scale, and admit electro-optic control owing the liquid crystal polymer and transparent conductive film. The sample was a 100μm thick film, mounted on a thin glass plate for rigidity and handling. In principle the film thickness may be as small as ~1 μm.



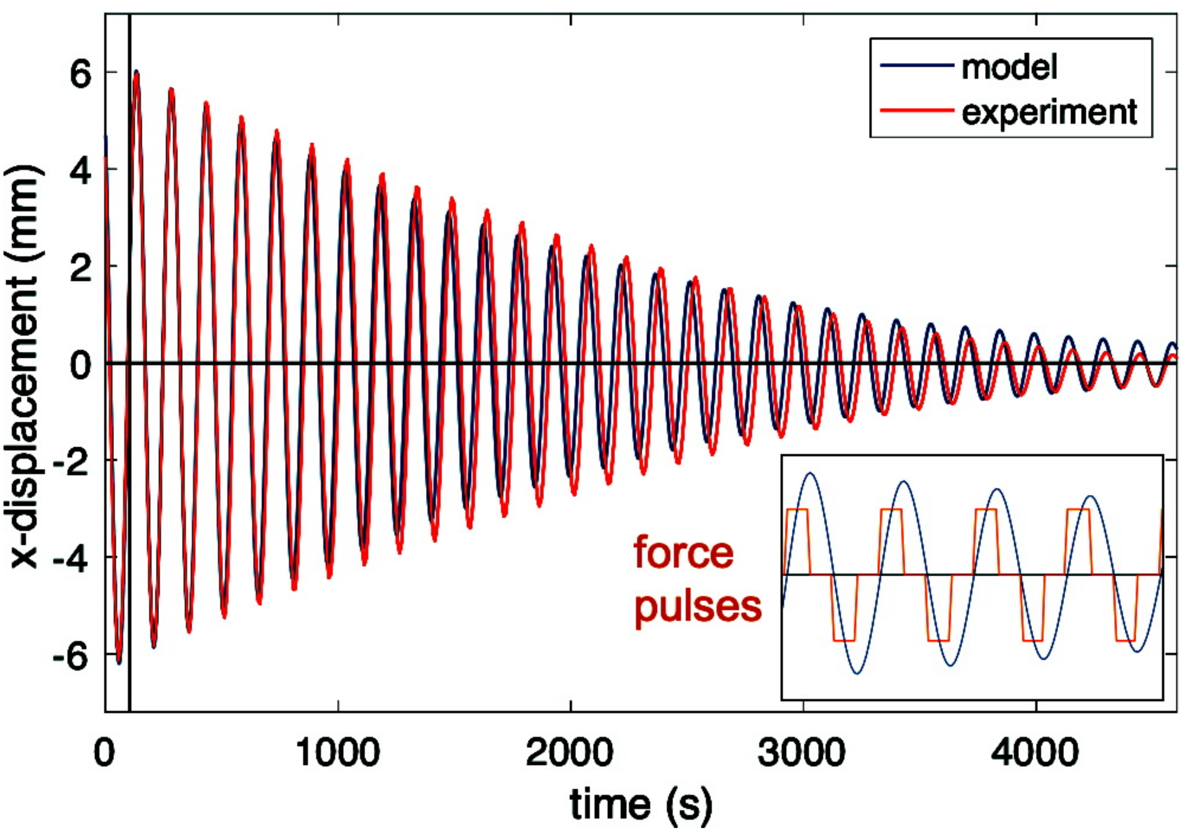
Magnified section of the BEAMCo diffractive film with grating period L = 6 μm.

The BEAMCo bi-grating produced a single dominant diffraction order $m_A = -1$ when Panel A was exposed, and $m_B = +1$ when Panel B was exposed. The grating was position on the RIT torsion oscillator and exposed with a P=1.5 W laser beam (λ = 808 nm) at normal incidence as depicted below. A shutter was placed between the laser and the grating, allowing the radiation pressure to be synchronized with the phase of the oscillator.



Experimental configuration showing the key components of the torsion oscillator, including a forcing laser (1.5W diode laser, λ = 808 nm), torsion arm (length R = 110 mm), mirror at the pivot point, tracking laser (5 mW HeNe laser, λ = 633 nm), observation screen with beam displacement S, and camera for time-lapsed recordings, pivot-to-screen distance D = 170 mm. Oscillator angular displacement $\delta \approx S/2D$.

An example of the dynamic control afforded by radiation pressure is shown in the following plot. The oscillator initially exhibits free sinusoidal motion, with period T_0 = 151.4 s and displacement amplitude S = 6 mm. At t=104 s the laser is turn on for 1/4 of the oscillator period, and periodically thereafter at half-period intervals. The restoring force attributed to radiation pressure decelerates the grating, resulting in a "laser cooling" phenomenon. **This remarkable experimental result provides great confidence in the ability of a grating to provide attitude and navigational control to a diffractive sail.** In the future, this experiment should be repeated with an electro-optically controlled grating whereby the diffraction order is switched from the +1 to the -1 order by means of an applied voltage. The experimental results are in good agreement with our theoretical model and numerical integrations by means of a Runga-Kutta algorithm. The model approximates the radiation pressure force: $F \approx -(P/c)(\lambda/\Lambda)\tanh(x/2w_0)$, as described above.

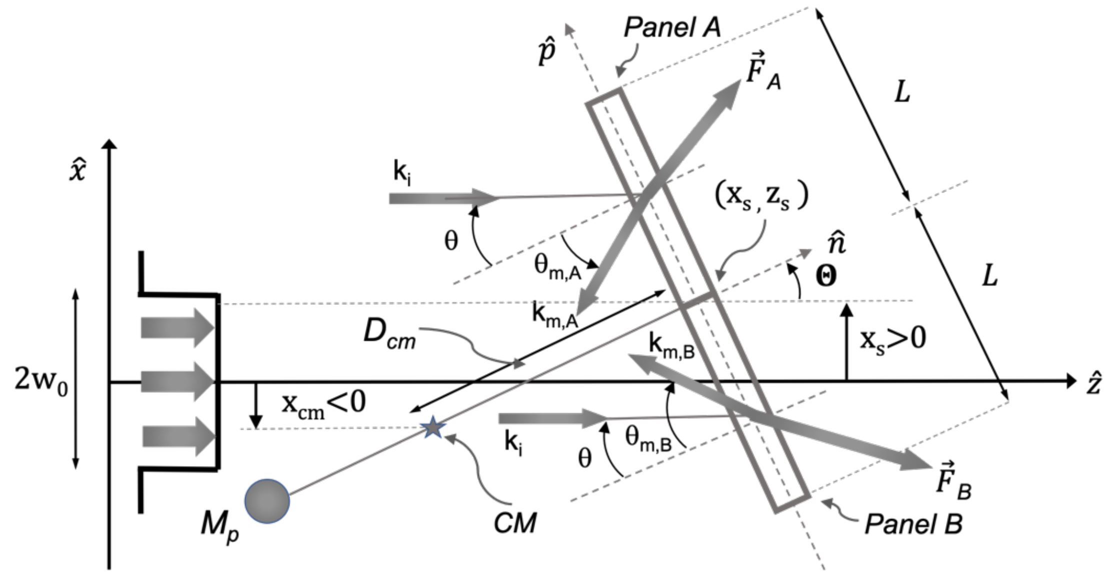


Radiation pressure "cooling" of an excited torsion oscillator. Inset shows laser pulses synchronized with the oscillation phase.

D. Sail Modeling

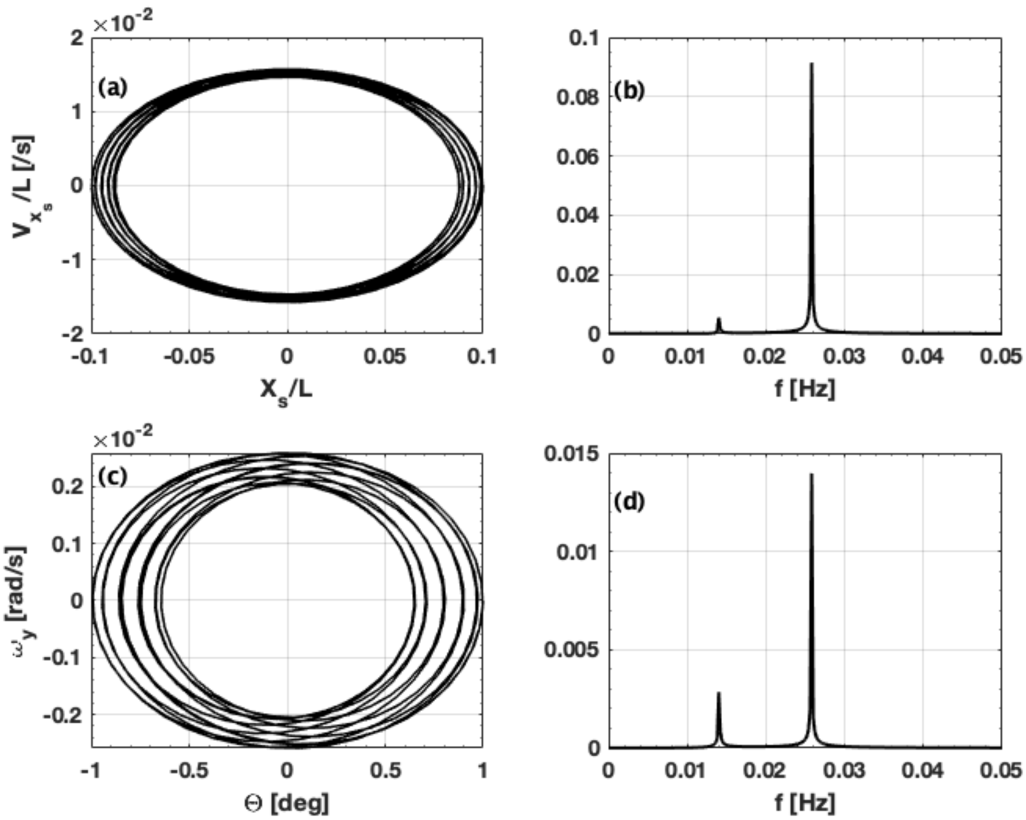
Attitude Control Bi-Grating Model

The dynamic control of a diffractive sail may be achieved by varying the diffraction angle of each element of a diffractive array. We have established the foundations of this approach in this Phase I study by exploring a two-element bi-grating.



Fundamental elements of a diffractive bi-grating beam rider (patent pending).

A light beam of half-width w_0 is incident upon a bi-grating comprised of Panel A of length $L = 2w_0$ which diffracts light into the m_A = -1 order and Panel B of length $L = 2w_0$, which diffracts light into the m_B = +1 order. The entire sailcraft is comprised of a sail, boom, and payload. It is assumed to be rigid, having an attitude θ and displacement from the beam axis, x_s. The sailcraft is designed to have an equilibrium position and angle ($x_s = \theta = 0$) while simultaneously providing acceleration in the z-direction. This system may be called a beam rider if it remains in the beam path as it accelerates. For small linear and angular displacements we have discovered that the acceleration along the beam path is nearly constant: $\ddot{z}_s \approx (P/Mc)\left(1+\sqrt{1-\lambda^2/\Lambda^2}\right)$. On the other hand, we have discovered that the transverse degrees of freedom, x_s and θ, are governed by two coupled linear equations that admit stable oscillatory solutions when the boom length is greater than a critical value: $D_{cr} = (L\Lambda/\lambda)\left(1+\sqrt{1-\lambda^2/\Lambda^2}\right)$, where $\lambda/\Lambda < 1$. The natural oscillation frequency is given by $\omega_0 = \sqrt{P\lambda/L\Lambda Mc}$, which generally splits into two neighboring frequencies owing to coupling between the degrees of freedom. These results have been verified for the both the linearized and un-linearized models by means of Runge-Kutta numerical integration techniques, as well as for a full three-dimensional system (work in progress). **These results provide guidance for the design of advanced electro-optically controlled diffractive sails that may be comprised of an array of individually addressable diffractive panels.** What is more, these results are directly applicable to a laser-driven diffractive sailcraft for both laboratory studies (see above) as well as potential in-space missions.



Phase diagrams (left) for the transverse displacement x_s and attitude θ for the full sailcraft model (without linearization) showing stable oscillations when no damping or cooling mechanisms are introduced. Fourier analysis (right) reveals two oscillation frequencies as expected from our linearized theory.

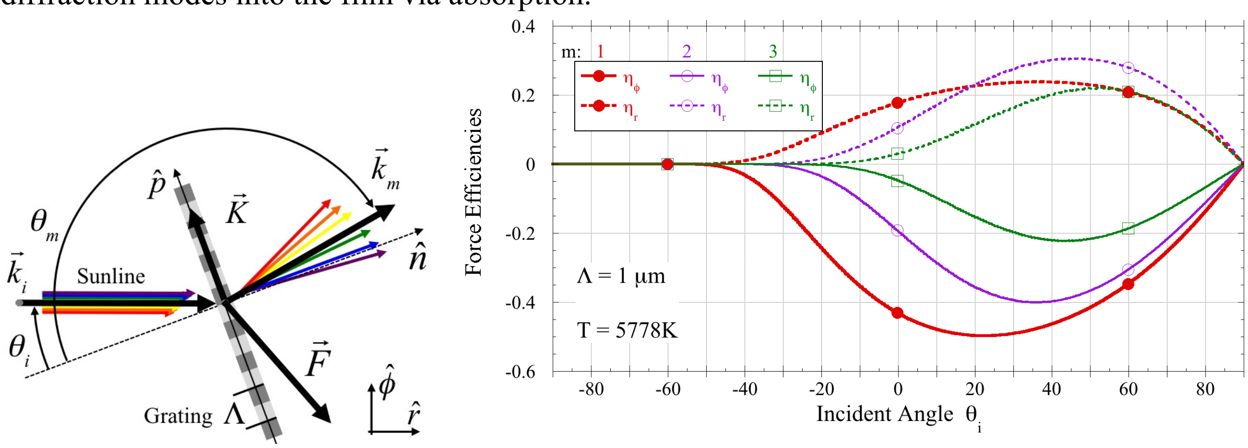
Orbital Dynamics Model

The forcing law of a diffractive sail is characteristically different from that of a reflective sail, owing to the difference between diffraction (which depends on engineered properties like the grating period Λ) and reflection. Both systems may be simplified as having two components of force: parallel to the sail surface F_p, and normal to the sail surface F_n. For ideal systems (100% reflection and 100% diffraction efficiency), the values of these components are determined from the expression $\vec{F} = (IA/c)\left(\eta_p \hat{p} + \eta_n \hat{n}\right)$ where I is the solar irradiance, A is the sail area, c is the speed of light, and the efficiencies η are given by

	η_p	η_n
Diffractive Sail	$-(1+\sin\theta_m)$	$1+\cos\theta_m$
Reflective Sail	0	$-2\cos^2\theta_i$

where we have assumed the diffractive sail faces the sun, diffracting light at the angle θ_m defined by the grating equation $\sin\theta_m = m\lambda/\Lambda$, and the reflective sail makes an angle θ_i with the sun line.

A great advantage of a diffractive sail is provided by the non-zero value of the parallel force component F_p. This component allows a diffractive sail to face the sun, collecting its the full power, while also experiencing a force perpendicular to the sun line; this allows the most efficient means of spiraling toward or away from the sun. We discovered that this advantage is maintained after accounting for the solar spectrum. The integrated force on a diffractive sail depends on the spectral irradiance of the source (e.g., the solar black body distribution at 5778 K). As illustrated in the figure below (left), red light diffracts as a larger angle than blue light, resulting in a more efficient transfer of momentum. The wavelength-integrated efficiency components in the direction of the sunline η_r and perpendicular to the sunline η_ϕ are plotted below (right) for different diffraction orders. We discovered that a simple (un-optimized) diffraction grating having a period L = 1 μm, oriented at $\theta_i = 20°$ provides an orbit-raising or orbit-lower efficiency of $\eta_\phi \approx 50\%$ and a radial efficiency of $\eta_r \approx 25\%$. Since a radial force only disturbs the ellipticity of an orbit, a small value of η_r is often desirable. The azimuthal efficiency η_ϕ may be optimized in future work by engineering the grating to better diffract blue light. Metamaterials principles are currently being devised to optimize the diffracted light. We also propose an additional means of enhancing the force parallel to the film: coupling evanescent diffraction modes into the film via absorption.



Left: Broadband sunlight is diffracted at different angles. Right: Components of force efficiency along the sun line η_r , and at right angle η_ϕ for different diffraction orders m, calculated for a grating period Λ = 1 μm and the solar black body spectrum at temperature T = 5778 K.

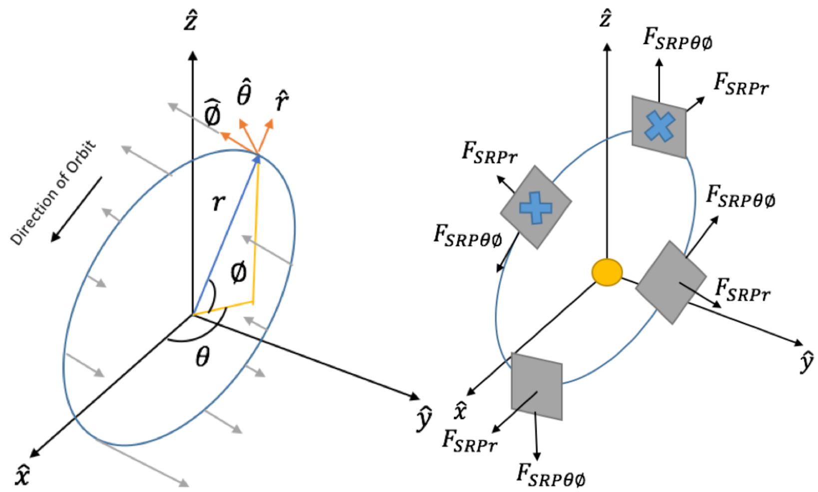
The orbit of a diffractive sailcraft of mass m_s has been numerically determined by use of Runge-Kutta numerical integration of the equations of motion, expressed in spherical coordinates:

$$F_r / m_s = \mu G(\alpha - 1) / r^2 = \ddot{r} - r\dot{\psi}^2 - r\dot{\theta}^2 \sin^2\psi$$

$$F_\theta / m_s = \mu\beta \left|\sin\theta\right| / r^2 = r\ddot{\theta}\sin\psi + 2\dot{r}\dot{\theta}\sin\psi + 2r\dot{\theta}\dot{\psi}\cos\psi$$

$$F_\psi / m_s = \mu\delta\cos\theta / r^2 = r\ddot{\psi} + 2\dot{r}\dot{\psi} - r\dot{\theta}^2\sin\psi\cos\psi$$

where $\phi = 90 - \psi$, α, β, and δ are respectively related to the radial, azimuthal, and polar efficiencies and the lightness number: $\alpha = \eta_r \sigma^* / 2,\ \beta = \eta_\theta \sigma^* / 2,\ \delta = \eta_\phi \sigma^* / 2$, and where $\sigma^* = \sigma_{cr} A_s / m_s$ is the lightness number, $\sigma_{cr} = 1.54$ [g/m^2] is the solar equivalent areal density at 1 AU, A_s is the sail area, and μ is the product of the solar mass and the gravitational constant. The forcing laws above are written for a sun-facing sail.

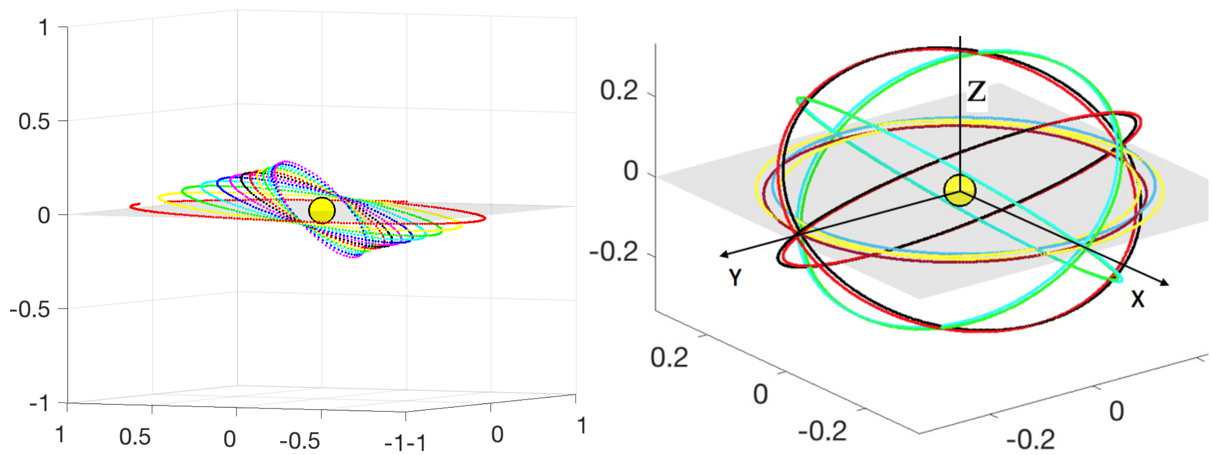


Left: Sun-centered spherical coordinate system with x,y ecliptic plane, azimuth θ, polar angle above the ecliptic ϕ, and radius r. Arrows represent radiation pressure force vectors. Right: Attitude of a diffractive sail with respective force components.

To compare diffractive and reflective sails for a solar polar orbiter mission we assumed sail size and sailcraft mass similar to the NASA Near-Earth Asteroid Scout mission – a 6U cubesat package planned for the future test launch of the Space Launch System rocket. The mass and area of the NEA Scout sailcraft are m_s = 14 kg and A_s = 86 m^2, respectively, yielding a lightness number of $\sigma^* \sim 0.010$. With an eye toward the future technological advancements, we take the liberty of assuming a diffractive sail area A_s = 400m^2, and lightness number $\sigma^* \sim 0.044$. Both the diffractive and reflective sails are given a constant attitude with respect to the sunline, optimizing for acceleration perpendicular to the sun line. Relative modest efficiencies and lightness numbers were assumed, with (α,β,δ) = (0.022, -0.022, 0.022) for the diffractive sail and (0.022, -0.017, 0.017) for the reflective sail. The lower values of β and δ for the reflective sail are attributed to need to a reflective sail away from the sun to achieve a transverse force. We discovered that whereas the diffractive sail reached an inclination of 60° and 0.3 AU within 5 years (see numerically calculated trajectory below left), the reflective sail reached smaller values (33° and 0.42 AU). Given the foregoing reasonable assumptions, **our calculations demonstrate the advantage of using a diffractive sail over the reflective one.** The diffractive sail provides a short transfer time to a near-sun orbit. From another point of view, the more efficient diffractive sail may be made smaller or more massive than a reflective sail, with both reaching the desired orbit in the same time. It should be kept in mind that these calculations are representative of ideal sails that do not account for inefficiencies attribute to absorption, heating, and spectral variations.

E. Constellation of Solar Polar Orbiters

Based on the recommendations of National Academy of Sciences Decadal Surveys (e.g., the 2013 Helio-Physics Decadal Survey) and NASA scientists, we explored a potential of mission that inserts 12 solar polar orbiters around the sun at 0.3 AU to provide constant full-sun monitoring. There is surprisingly little solar data from beyond the ecliptic plane. For example, direct images of either solar pole do not exist. Inclination cranking is energy intensive, but may be aided with multiple gravitational assists and highly elliptic orbits. Radiation pressure overcomes the complexity of such orbits, reaching the desired perihelion in the same time frame. Assuming a sailcraft mass of m_s = 30 kg (11 kg of which corresponds to the mass of a science instrument like the Solar Parker probe Wide Field Imager), area A_s = 780 m^2, and the same force coefficients as above (α,β,δ) = (0.022, -0.022, 0.022), we find that a constellation of 12 solar polar orbiters could be inserted throughout the year to provide full coverage with four on the equator and eight in inclined quadrants (see below right). The equatorial orbits would reach 0.3 AU in 3.6 years and the inclined orbits would require 4.75 years.



Left: Example of simultaneous inclination cranking and orbit lowering over a five year period, staring from 1 AU. Each color represents a one year time span. Right: Constellation of 12 solar orbiters providing full-sun monitoring above, below, and along the ecliptic at 0.3 AU. An inclination of 45° is reached in 4.75 years.

5. List of Publications and other Disseminations

Peer Reviewed Publications
Y.J. Chu, E. M. Jansson, and G. A. Swartzlander, Jr.
Measurements of Radiation Pressure Owing to the Grating Momentum,
Phys. Rev. Lett. 121, 063903 (1-6, plus supplement) (2018).

G. A. Swartzlander, Jr.,
Flying on a Rainbow: A Solar-Driven Diffractive Sailcraft,
J. British Interplanetary Society 71 (4) 130-132 (2018).

Other Publications
Grover A. Swartzlander, Jr.,
Flying on a Rainbow: A Solar-Driven Diffractive Sailcraft,
arxiv.org/abs/1805.05864 (May, 2018)

In Preparation for Peer Reviewed Publication
A. Dubill and Grover A. Swartzlander, Jr,
Circumnavigating the Sun with Diffractive Solar Sails in Spherical Coordinates

Y.J. Chu, , N.V. Tabiryan, and G.A. Swartzlander, Jr.
Experimental Observations of a Diffractive Beam-Rider

P.R. Srivastava, Y.J. Chu, and G.A. Swartzlander, Jr.
Theory of a Diffractive Beam-Rider

P.R. Srivastava, Y.J. Chu, and G.A. Swartzlander, Jr.
Three-Dimensional Analysis of a Diffractive Beam-Rider

Patent Disclosure
G. A. Swartzlander, Jr., Prateek Srivastava, Ying-Ju Chu
Diffractive Optical Beam Rider
RIT provisional (2018)

Popular Media
Diffractive Light Sail, Rochester First TV and WXXI Radio spots, July 2018,
www.rochesterfirst.com/news/local-news/rit-researchers-test-out-new-tech-for-nasa/1323943122

New Solar Sailing Technology for NASA, Science Daily, July 2018,
www.sciencedaily.com/releases/2018/07/180719165034.htm

Intersections: The RIT Podcast Ep. 8: *Space Travel and Toaster-sized Boats in the Sky*,
soundcloud.com/rittigers/intersections-the-rit-podcast-ep-8-space-travel-and-toaster-sized-boats-in-the-sky

Presentations
Grover A. Swartzlander, Jr. (Host), *Introduction to MetaFilms for Radiation Pressure,*
OSA Incubator: Metamaterial Films for In-Space Propulsion by Radiation Pressure,
Washington, DC 7-9 Oct. 2018

Amber Dubill, *Circumnavigating the Sun with Diffractive Solar Sails,*
RIT Undergraduate Research Symposium, 8 March 2018

P.R. Srivastava, A.Dubill, Y.J. Chu, G.A. Swartzlander, Jr.
Application of Radiation Pressure forces on Diffraction Grating
Frontiers in Optics (FiO) + Laser Science (LS) 2018 Conference
Washington, DC, 16-20 Sept. 2018

Ying-Ju Lucy Chu, Eric M. Jansson, and Grover A. Swartzlander Jr.
Verification of Radiation Pressure owing to the Grating Momentum
SPIE Optics and Photonics, San Diego, Aug 2018

Ying-Ju Lucy Chu
Sailing on a Rainbow: Optical Radiation Pressure on a Diffractive Solar Sail
IONS (International OSA Network of Students) Orlando, FL, March 2019

Upcoming Presentations
G.A. Swartzlander, Jr. (invited talk)
NIAC Inventive Genius lecture, *From Science Fiction to Science Fact*, at the Museum of Science and Industry, Chicago, IL 13 Apr 2019

Ying-Ju Lucy Chu
Sailing on a Rainbow: Optical Radiation Pressure on a Diffractive Solar Sail
RIT 3 minute Presentation Competition, Rochester, NY, April 2019

G.A. Swartzlander, Jr. (invited talk)
Radiation Pressure on a Diffractive Film
5th International Conference on Optical Angular Momentum, Ottawa, Canada, 17-21 June 2019

G.A. Swartzlander, Jr. (invited talk)
Sailing on a Rainbow with a Diffractive Metafilm
10th International Conference on Metamaterials, Photonic Crystals and Plasmonics, META 2019
Lisbon, Portugal, 23-26 July 2019

G.A. Swartzlander, Jr. (invited talk)
Radiation Pressure on a Diffractive Metafilm
SPIE, Optical Trapping and Optical Micromanipulation XVI
San Diego, CA, 11 - 15 Aug. 2019

Collaborations
Charles (Les) Johnson, George C. Marshall Space Flight Center, Huntsville, AL
Andrew Heaton, George C. Marshall Space Flight Center, Huntsville, AL
Nelson Tabiryan, BeamCo, Orlando, FL, Consultant
Rajesh Menon, University of Utah

Participating Students
Ying-Ju Lucy Chu (PhD Candidate, Center for Imaging Science, RIT)
Prateek R. Srivastava (PhD Candidate, Center for Imaging Science, RIT)
Amber Dubill (Bachelor/Master Program, Mechanical Engineering, RIT)
Eric Jansson (High School Student, Charter School of Wilmington, DE)

Appendix A

White Paper on Diffractive Metamaterial Sailcraft (v2, 30 Oct 2018)

Grover Swartzlander[1], Les Johnson[2], and Nelson Tabiryan[3]

1. Rochester Institute of Technology, Rochester, NY; 2. NASA-Marshall, Huntsville, AL; 3. BeamCo, Orlando, FL

The synopsis and recommendations listed below have been distilled by the organizers of the 2018 OSA Incubator: *Metamaterial Films for In-Space Propulsion by Radiation Pressure*. This incubator brought together aerospace engineers, space materials manufacturers, and university and national laboratory scientists to discuss how mission-focused developments of diffractive metamaterials may advance the efficiency and functionality of solar and laser driven light sails for in-space propulsion.

Although the in space advantages of light sailing have been studied by space mission specialists for nearly a century, the last decade has seen the first set of demonstration missions by JAXA, NASA, and the Planetary Society. In all cases, the sail was comprised of a thin metallic layer deposited on a thin plastic film. The recent proposal to replace this structure with an optimized thin diffractive film offers navigation, propulsion, and stability advantages not afforded by reflective films. Another practical advantage of a diffractive sail is the ability to maintain an arbitrary navigational force vector while facing the sun, thereby obviating the need to change attitude to recharge onboard batteries.

Incubator participants discussed both passive and active diffractive films designed to minimize spectral absorption and loss of light, provide passive sailcraft roll control/stability, and to have high broadband diffraction efficiency. Mission concepts and roadmap objectives were also discussed. Liquid crystal polymer and transparent oxide (e.g., titanium nitride or fused silica) based diffractive structures were identified as candidate materials. As evidence of the rapidly advancing TRL of these materials, electro-optic (non-mechanical) beam steering using high efficiency polarization diffraction gratings, and high efficiency passive dielectric gratings designed using metamaterial principles were both identified.

The advancement of diffractive light sails requires further research and development – particularly for the design, manufacture and testing of broadband, transparent, polarization independent gratings having a high diffraction efficiency and a low ratio of mass to area (areal density). As outlined below, this begins with laboratory testing of currently available diffractive films, e.g., radiation pressure measurements and space environment assessments for thermal cycling, resistance to ionizing radiation, and static charge mitigation. Radiation hardened materials having a high thermal emissivity would afford exciting mission opportunities that take advantage of the extraordinarily large radiation pressure force during perihelion passage. The forcing laws for a diffractive film may be optimized for particular missions, such as station-keeping near a Lagrange point. What is more, modest sized diffractive panels may be useful for offloading the mass and risk of mechanical attitude control devices. A passive roll-control diffractive device was identified to manage momentum imparted from sunlight or laserlight that cannot be controlled by center-of-mass / center-of-pressure offsets to a conventional reflective sail.

In summary, the group identified the following themes in need for R&D funding.

Currently available diffractive films:

- Measure radiation pressure at different wavelengths
- measure and optimize heat characteristics (emissivity, heat cycle tolerance, thermal expansion)
- characterize and optimize mechanical and optical properties with space-relevant ionizing radiation
- measure stress-strain characteristics and film integrity under tension
- comparative mechanical measurements of bulk and thin (~1 micrometer) material films
- measurements at extreme irradiance values

Design/fabricate ultrathin broadband polarization-independent diffractive films with

- high efficiency and large diffraction angles at normal incidence
- high efficiency back reflection at normal incidence
- high efficiency and large diffraction angles at oblique incidence
- robustness to space-relevant temperature cycling (high long wave emissivity)
- robustness to ionizing radiation
- electro-optic switchable diffraction order
- attitude-dependent switchable diffraction

Space mission integration into reflective solar sail

- design single-purpose passive diffractive panel to counter roll torque
- design passive and active diffractive panels for attitude and navigation control
- design active diffractive trim tabs for satellites

Advanced mission concepts

- large-scale passive or active diffractive films to replace reflective sails
- multifunctional diffractive films (antenna, sensors, radiator, spectrometer, photovoltaic)
- photon recycling for transmissive diffractive film sail
- large area scalable fabrication (nano-imprint lithography, roll-to-roll laser writers)
- in-space assembly of diffractive panels, on-orbit fabrication
- in-space technology demonstrator (International Space Station)
- in-plane radiation pressure for sail tensioning or unfurling
- sail geometry (sphere, multi-sheet, complex)
- autonomously stable sails, low mass dampers
- self-healing films
- hybrid propulsion (solar, laser, ablation, solar-electric, ion, …)
- sail dynamic driven by an in-space kW class laser

Target space missions

- Solar polar orbiter (60° inclination, 0.5AU perihelion)
- Solar sentinel (advanced sunspot imager)
- L1 space weather monitor
- Solar gravitational lens mission with extremely close (<0.1 AU) perihelion passage (for exoplanet imaging)
- Heliopause sensors with extremely close (<0.1 AU) perihelion passage
- Laser-driven chip sails to Mars, Venus, asteroids, or Moons
- Solar driven constellations to commercially valuable targets (water, metals, methane)
- Laser-driven chip sails to distance stars
- Reconfigurable multifunctional films (sail becomes antenna, rectenna, sensor)

- LEO sail driven by earth laser (e.g., Redstone 50 kW HELSTF) and solar
- Earth pole sitter for communication and earth monitoring

Other

- Economic model of single launch/multiple sailcraft concept
- Standards and benchmarks for space sails (ionizing radiation, shock, oxygen, thermal)
- Spin-off commercial opportunities

A notional roadmap for metamaterial development is shown in Table 1.

Table 1. Attempt to capture breakout team notes into a single cohesive roadmap for metamaterials in sailcraft

Mission Space	<5 years	<10 years	<20 years	<50 years

Inner Solar System (Near Sun & Near Earth)	• passive/active lightweight roll control (risk reduction?)
	• Test flights
	  • Space environments
	  • Thermal control
	• Thermal test at 0.5 AU
	• L1
	• NEA
		• fine roll control of big sails
		• large manufacturing of metamaterials/ diffractive gratings
		• Pole-sitters
		• Solar Polar Imager
			• passive/active control with sunlight
			• making whole sail of meta- material
			• Larger manufacturing	

Outer Solar System & Beyond	• Killer app → perihelion passage at 0.1AU. • Passive diffractives/ metasurfaces • Layering as top material degrades, it can be jettisoned. • Momentum management with lightsails. • Efficiency as a function of angle	• Ultra-high area to mass ratios. • Reconfigurable lightsail to modulate transmitting starlight for comms. (similar to exoplanet transits) • Ultra-thermally stable materials • Active control of passive diffractives/metasurfaces • Compact antenna ; reconfigurable antenna • Getting rid of adhesives with metamaterials • Manufacturing/Assembling in space	• Ultra-strong materials for structure (eg. mechanical metamaterials • Can the lightsail itself store energy (replace the nuclear generator, which is heavy). • Space squid: autonomously changing its geometry based on environment. • Self healing. Self morphing lightsail, antenna, solar cell. • Reconfigurable lightsail. • Engineer near-field gradient forces using nanophotonics. • Small compact X-ray telescope • Entrepreneurial/Commercial drive to smaller devices, launches, missions.	• High power density nuclear power for push in the outer solar system. • Infrastructure outside earth • Massive aperture for communication
Laser-Light Driven Sail	• Wafer sized (45 cm) sail, ~kW class laser can do great science in solar system • Develop NIST standards and benchmarking for space qualification of metamaterials	• demonstrate laser driven metamaterial based (small) sail. Piggy back on larger sail for range finding - dual test opportunity	• Early test of laser-driven: 1 GW station located in the US. Many interesting targets: Venus, Kuiper Belt, Enceladus, … combination of quick turn-around tests and long/far destinations	• Breakthrough Starshot

OSA Incubator: Metamaterial Films for In-Space Propulsion by Radiation Pressure

7-9 October 2018
Washington, DC USA

HOSTED BY:
Grover Swartzlander, Rochester Institute of Technology, United States
Les Johnson, NASA Marshall Space Flight Center, United States
Nelson Tabiryan, BeamCo, United States

AGENDA

Sunday 7 October 2018

Afternoon — Arrival/Hotel Check-in
Hotel Palomar, 2121 P Street, NW

18:00 — Welcome Dinner
OSA Headquarters, 2010 Massachusetts Ave, NW

Monday 8 October 2018

8:00 — Breakfast
OSA Headquarters, 2010 Massachusetts Ave, NW

8:30 — Welcome
Elizabeth Rogan, CEO, OSA

8:45 — Program Overview and Goals
Grover Swartzlander, Rochester Institute of Technology

The Big Picture on In-Space Propulsion

9:10 — Solar Sailing
Bruce Betts, Planetary Society, United States

9:30 — Polarization Gratings
Nelson Tabiryan, Beamco, United States

9:50 — Beamed
Harry Atwater, California Institute of Technology, United States

10:10 — Dielectric Metafilms
Vladimir Shalaev, Purdue University, United States

10:30 Coffee Break

Panel Presentations and Discussions

11:00 Sailcraft Mission
Panelists: Les Johnson, NASA, United States
Nathan Barnes, L'Garde, United States

11:20 Moderated Discussion: Sailcraft Mission

11:50 Radiation Pressure on a Solar or Laser Driven Sailcraft
Panelists: Bruce Betts, Planetary Society, United States
Peter Klupar, Breakthrough Initiatives, United States
Edward Montgomery, Mont. Tech, LLC, United States

12:10 Moderated Discussion: Radiation Pressure on a Solar or Laser Driven Sailcraft

12:40 Lunch, provided

13:40 Metamaterial Films
Panelists: Wei-Ting Chen, Harvard University, United States
Rajesh Menon, University of Utah, United States
Vladimir Shalaev, Purdue University, United States
Nelson Tabiryan, Beamco, United States

14:00 Moderated Discussion: Metamaterial Films

14:30 **Breakout Session Introductions (approx. 13 minutes each)**

15:10 Coffee Break

15:40 Breakout Session Time

Inner Solar System (Near Sun & Near Earth) Mission
Leader: Ben Diedrich, Dynamic Concepts, Inc., United States

Outer Solar System & Beyond Mission
Leader: Darren Garber, NXTRAC, United States

Laser-Light Driven Sail Mission
Leader: Peter Klupar, Breakthrough Initiatives, United States

18:00 Dinner
Bistrot du Coin, 1738 Connecticut Ave NW

Tuesday 9 October 2018

8:00	Breakfast OSA Headquarters, 2010 Massachusetts Ave, NW
8:30	Space Environment Requirement *Panelists: Harry Atwater, California Institute of Technology, United States* *James Moore, Nexolve, United States* *Joe Minow, NASA, United States*
8:50	Moderated Discussion: Space Environment Requirement
9:30	Coffee Break

Breakout Group Reports & Full Discussion

10:00	Inner Solar System (Near Sun & Near Earth) Mission *Leader: Ben Diedrich, Dynamic Concepts, Inc., United States*
10:40	Outer Solar System & Beyond Mission *Leader: Darren Garber, NXTRAC, United States*
11:20	Laser-Light Driven Sail Mission *Leader: Peter Klupar, Breakthrough Initiatives, United States*
12:00	Final Discussions & Next Steps *Incubator Hosts*
13:00	Lunch, provided
14:00	Adjourn

Appendix C

OSA Incubator: Metamaterial Films for In-Space Propulsion by Radiation Pressure				
First Name	**Last Name**	**Affiliation**	**Country**	**Email**
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Wei-Ting	Chen	Harvard Univeristy	United States	weitingchen@seas.harvard.edu
Lucy Ying-Ju	Chu	Rochester Institute of Technology	United States	lucychu@mail.rit.edu
Artur	Davoyan	University of California, Los Angeles	United States	davoyan@seas.ucla.edu
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Darren	Garber	NXTRAC	United States	darren.garber@nxtrac.com
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Les	Johnson	NASA George C. Marshall Space Flight Center	United States	les.johnson@nasa.gov
Hyun Jung	Kim	NASA Langley	United States	hyunjung.kim@nasa.gov
Seongsin Margaret	Kim	University of Alabama	United States	seongsin@eng.ua.edu
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Howard (Ho Wai)	Lee	Baylor University	United States	Howard_Lee@baylor.edu
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Vladimir	Shalaev	Purdue University/Birck Nanotechnology	United States	shalaev@purdue.edu
Grover	Swartzlander	Rochester Institute of Technology	United States	gaspci@rit.edu
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Qi-Huo	Wei	Kent State University	United States	qihuo@lci.kent.edu

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Appendix D

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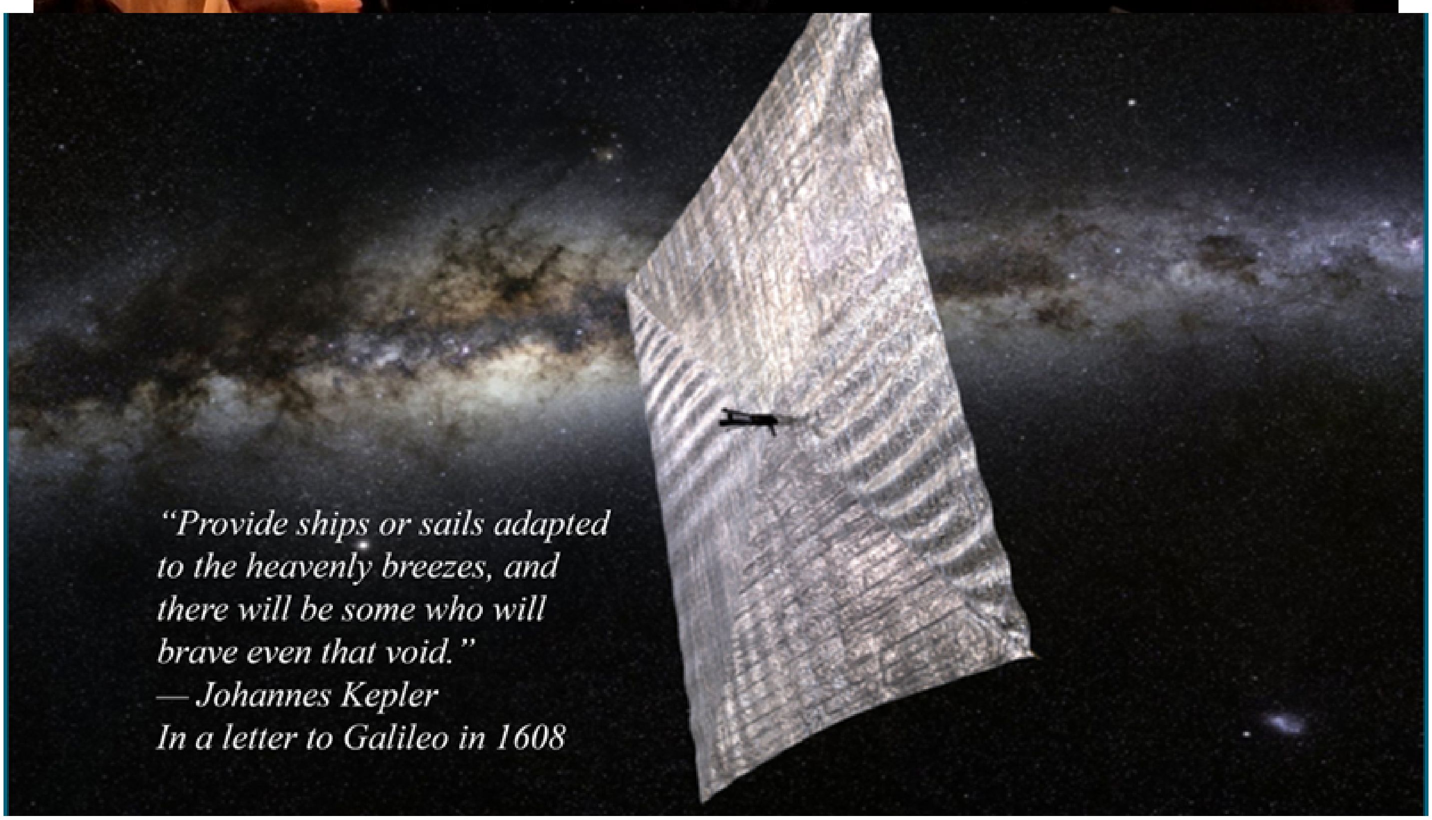
Day 1 of the Metamaterial Films for In-Space Propulsion by Radiation Pressure Incubator

Day 1 of the Metamaterial Films for In-Space Propulsion by Radiation Pressure Incubator

By Amber Dubill, RIT

The Optical Society's CEO, Liz Rogan started off the conference by reminding everyone that this week is the 60th anniversary of NASA, a fitting coincidence for the conference. Optics and photonics has and continues to enable our understanding of the universe, the center goal of this OSA Incubator (**Metamaterial Films for In-Space Propulsion by Radiation Pressure**). Dr. Grover Swartzlander, RIT, (right) one of the hosts, called this Incubator a chance to bring three diverse groups together: aerospace, optical, and materials scientists. The goal of the incubator is to create a roadmap for using diffractive metamaterials in solar sailing. This will be accomplished by documenting of ideas from the three participating groups as well as building enthusiasm in the communities for solar sailing applications.

The idea of solar sailing is to use the change of momentum of light as a propulsive force. The use of metamaterials can optimize the use of this force. Solar sails are advantageous over conventional propulsion methods because they use a massless and abundant propellant: light. This is not without challenges.



(Photo courtesy of Bruce Betts, The Planetary Society.)

Dr. Swartzlander, Bruce Betts, The Planetary Society, and other experts called to attention the issues with the current state of solar sailing technology. Large sail areas are needed with very small masses, which in turn produces very thin sails. The packaging, deployment, ability to withstand the harsh space environment, and attitude control of these thin material sails is yet to be perfected. The dependency of mass and area of the sail is a challenging engineering requirement for these sail-craft and missions towards the sun deal with extreme temperature environments. They challenged the three communities to discuss solutions to these issues.

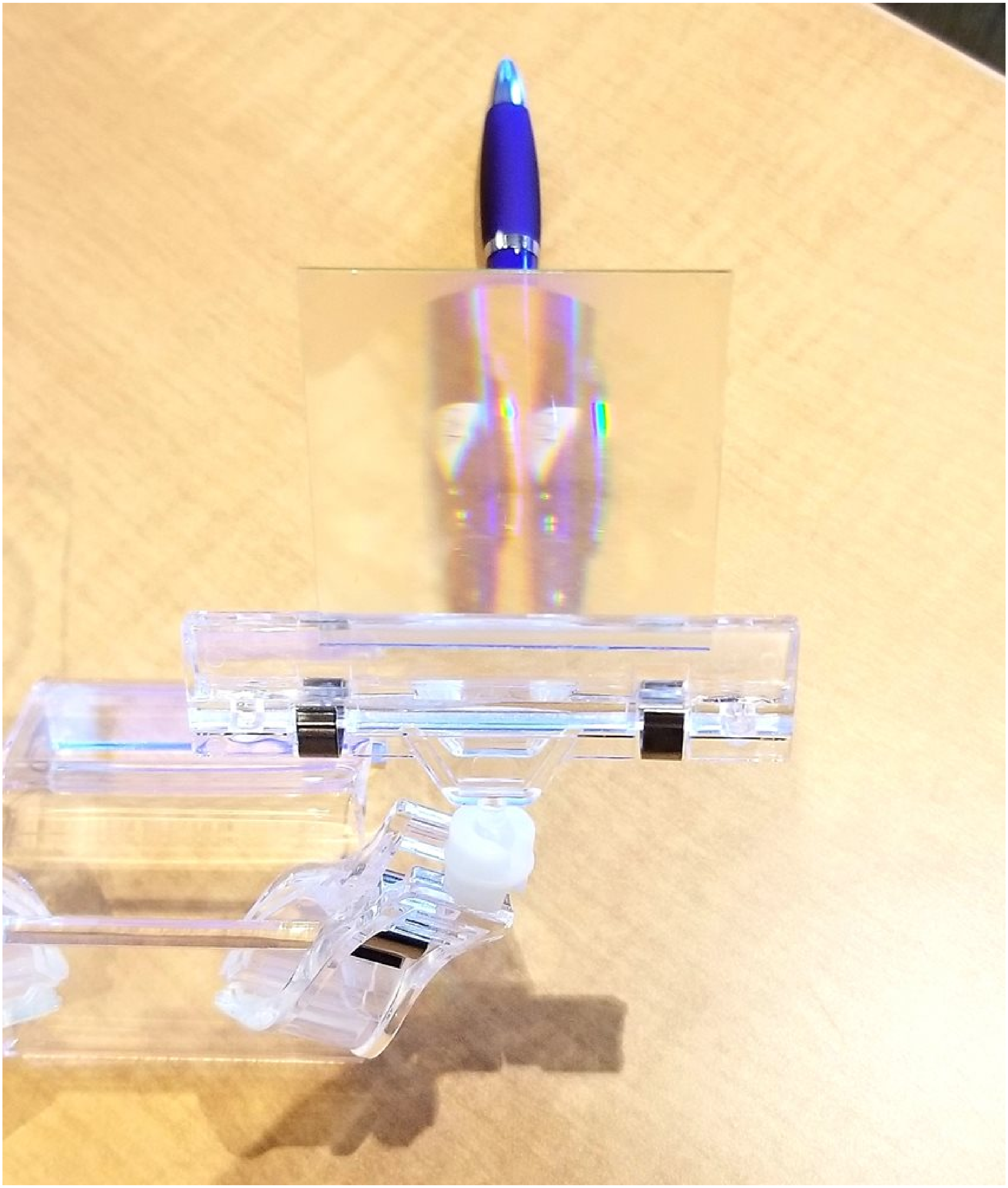
Solutions to these issues were proposed using current technology. Switchable gratings and reflectivity devices were seen as an important technology that could enable less complex methods of attitude control of large sails. The state of transparent conductors was discussed in in the context of minimizing mass on the sails and minimizing the chance of sail boom buckling. In space, assembly of these sails may bypass the problems with sail deployment and packaging. Thermally, sail materials are being manufactured that can survive within 0.5 AU, but more advancement in the thermal properties of these metamaterials is needed for closer approaches.

The current state of diffractive optics and metamaterials was discussed by co-host Nelson Tabiryan, BeamCO. Metamaterials are used to produce very high efficiency gratings with very thin films. Diffractive waveplate optics are smooth and continuous, with thin coatings that could be very applicable to diffractive solar sails. The gratings needed for diffractive sailing need to have broadband capabilities and high efficiency across a range of wavelengths. These high efficiency gratings can be designed to be mission specific. Electrically switchable optics are already being developed. The metamaterial community is developing gratings and materials that could survive harsh space environments. Optimization techniques could be used to develop the best sail material for the mission requirements. These materials have tradeoffs thermally and structurally for their use as optical surfaces. In addition to these desired properties, the materials must also be thin and lightweight. In response to the role of advancing technology for solar sailing applications Valdmir Shalaev, Purdue University, responded “We are not talking about new physics, diffractive physics is well known - we are talking about new material challenges, manufacturing challenges.”

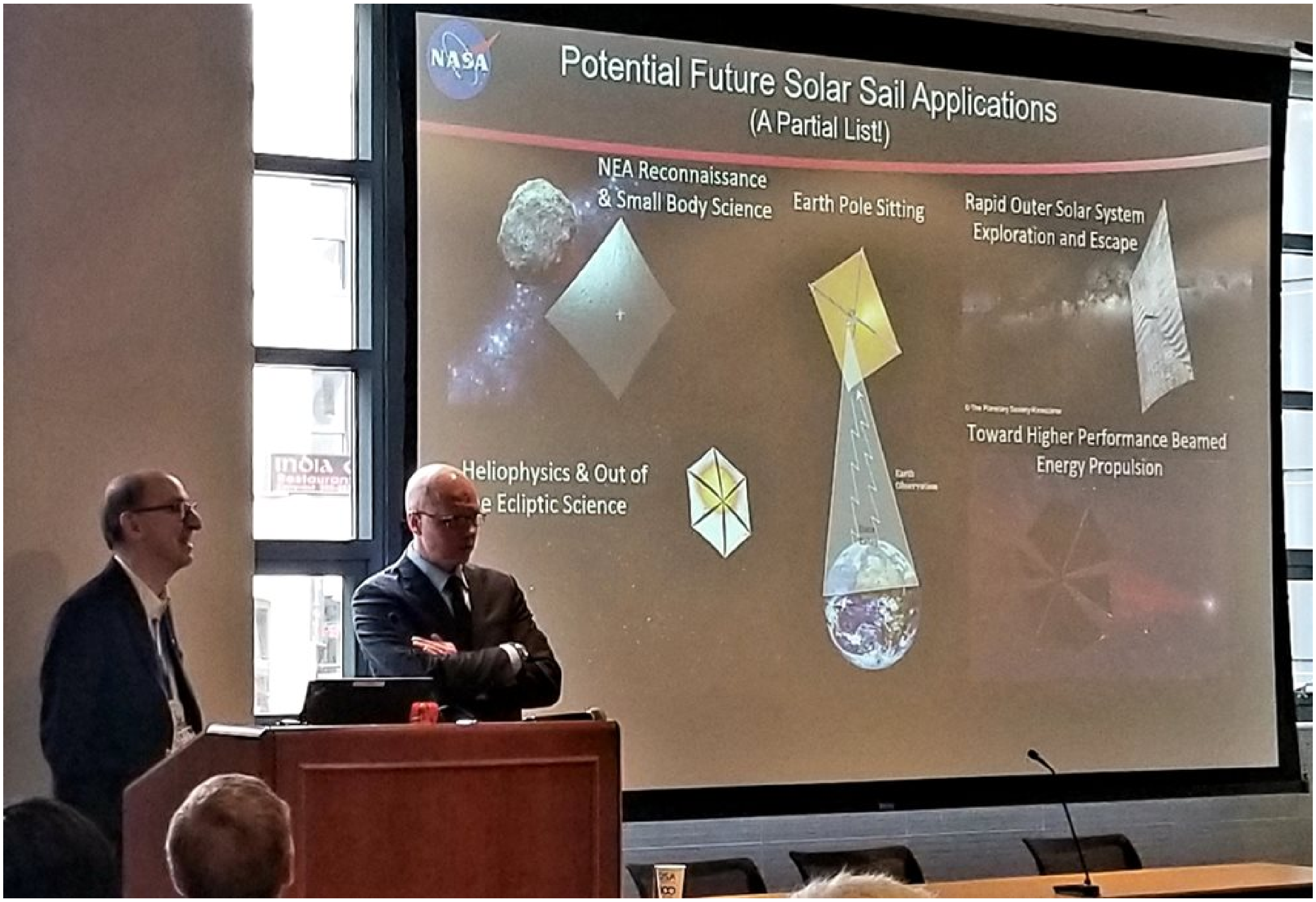
Laser driven sails were discussed as a subsection of solar sailing capabilities. For further out future missions, laser driven sails may be a way to enable interstellar travel. Harry Atwater, California Institute of Technology, stated “If you want to develop a space craft to travel near the speed of light, then the only viable propellant is light itself”. Breakthrough Starshot was discussed, a proposed laser driven sail that will get to 20% the speed of light to get to the nearest promising exoplanets within a lifetime. This consists of a 1 m^2 sail driven from a 100 GW laser array based on Earth. Discussions from this Incubator may find solutions for some of the challenges with this mission architecture.

Solar sails could enable more efficient deep-space missions that would gather useful information to further our understanding of the universe. Co-host Les Johnson, NASA and Nathan Barnes, L’Garde, discussed some of these desired missions. Near-Earth-Asteroid Reconnaissance and Small Body Science missions, Helio-physics and Out of the Ecliptic Science missions, Earth Pole Sitting, Rapid Outer Solar System Exploration and Escape missions, and missions Toward Higher Performance Beamed Energy Propulsions could all be enabled by solar sailing technology. Specifically, Earth Pole Sitting is a highly-desired opportunity for both the scientific community and industry for space weather stations at an artificially made L1 point. These solar sailing-based missions are not as mainstream because of risk aversion. The ideas from this Incubator could reduce the risk from these missions.

The program continues this afternoon with breakout sessions that will explore inner solar system, outer solar system, and laser-light driven missions so stay tuned tomorrow for additional updates and a look at what’s next for these efforts.



Incubator host Nelson Tabiryan, BeamCo, demonstrated a diffractive optic lens with an OSA pen.



Host Les Johnson, NASA and Nathan Barnes, L'Garde, discuss the Sailcraft Mission.

Tags:

Lasers (http://www.osa.org/blog/filter/?tagname=Lasers&groupid=)

OSA Incubator (http://www.osa.org/blog/filter/?tagname=OSA Incubator&groupid=)

Posted: 8 October 2018 by **Amber Dubill, RIT** | with 0 comments (http://www.osa.org/en-us/the_optical_society_blog/2018/october/day_1_of_the_metamaterial_films_for_in-space_propu/)

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Appendix E

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Day 2 of the Metamaterial Films for In-Space Propulsion by Radiation Pressure Incubator

Day 2 of the Metamaterial Films for In-Space Propulsion by Radiation Pressure Incubator

By Amber Dubill, RIT

The first day of the OSA Incubator **Metamaterial Films for In-Space Propulsion by Radiation Pressure** ended with breakout sessions for brainstorming ideas for different types of lightsail missions: **Inner Solar System, Outer Solar System, and Laser Driven**. Each group developed a roadmap for the development of solar sail technology and metamaterials to enable these types of missions. The integration of the two technologies are one key to furthering exploration of space.

Day 2 of the program kicked off with a panel discussing the harsh environments of space. Joe Minow, NASA, and James Moore, Nexolve, discussed the engineering requirements that need to be taken into account when developing materials for interplanetary spacecraft. The metamaterials that may be used in solar sails need to survive long mission durations while maintaining structural and optical integrity. There is concern about large temperature gradients across sails, fast thermal cycles, electrical charging of the spacecraft, and radiation effects. Joe showed that the environment closer to the sun is exponentially harsher in regards to radiation and solar wind. Harry Atwater, Cal Tech, discussed the space environment scenarios that a laser-driven sail would see over a Breakthrough: Starshot mission lifetime.

The breakout sessions yielded reports to share with the rest of the assembly.

- **Inner solar system missions** using solar sails would greatly benefit from using metamaterials to offset roll disturbance torques due to imperfections in sails. Near term, a passive method of attitude control using diffractive gratings could be implemented on current reflective sails. This could be crucial to offload mass from the design of a spacecraft. In longer term applications, an actively controlled system using diffractive gratings and reflectivity control devices to enable complete attitude control of sail craft could be developed. These metamaterials will need to be tested to the space environment limits, as many of them have not been considered for use in space. New materials could be developed to mitigate active thermal gradients in the sails, as emissivity properties can be tuned to different wavelengths and desired temperatures.
- **Outer solar system missions** cannot effectively use solar radiation pressure once outside of asteroid belt. For outer solar sail missions, solar sails are useful in gaining delta v for outer solar system transfers by going towards the sun at first. This community calls for metamaterials to enable multifunctionality of these sails, so that once their use for propulsion is finished, they can be used for sensors, antennas, and other capabilities that are needed for further out missions. Again, angular momentum management using diffractive gratings would be useful. In the long term these sails could enable grand tours of the solar system that are not limited by timeline windows. Darren Garbe, NXTRAC, ended on by noting "We are running out of tricks from the 60s and 70s - we need a new bag of tricks to get out past the outer solar system and beyond."
- **Laser sailing missions** may be a bit more far out, but the intermediate steps along the way can provide useful knowledge and technological advancement. There is a need to test these metamaterials and their interactions with the high-power lasers that are needed to provide large propulsive forces. Something like an established laser sailing system may be feasible in our lifetime, but full scale demonstrations could be possible within 20 years. The large cost for the development of these systems may be offset by interest in the other applications of metamaterials in cell phones, UV protection, and passive cooling.

Testing is the next big step for these metamaterials to become mainstream in space missions. The metamaterials need to be tested on the ground to extreme space environment limits and they could be tailored to specific missions. The manufacturing of these materials in larger areas would follow. Integration of these metamaterials into space missions within the next few years is crucial to proving the reliability and efficiency of this technology and can occur as solar sail technology is advancing. The product of the two technologies together could support further advancement of these light sails. Light sails are one enabling technology that could allow humans to explore the universe within this lifetime.

The hosts are looking forward to going through all the detailed notes from the working groups and, with help from the participants, continuing the discussions and work. Stay tuned for more on this topic from OSA, including an overview of the work and details on next steps, in a future issues of Optics & Photonics News.

One of three working sessions during the program on: Inner Solar Systems, Outer Solar Systems and Laser-Light Driven Sail Missions.

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