GLASS

Geo-Laser Accelerated Spacecraft Sail

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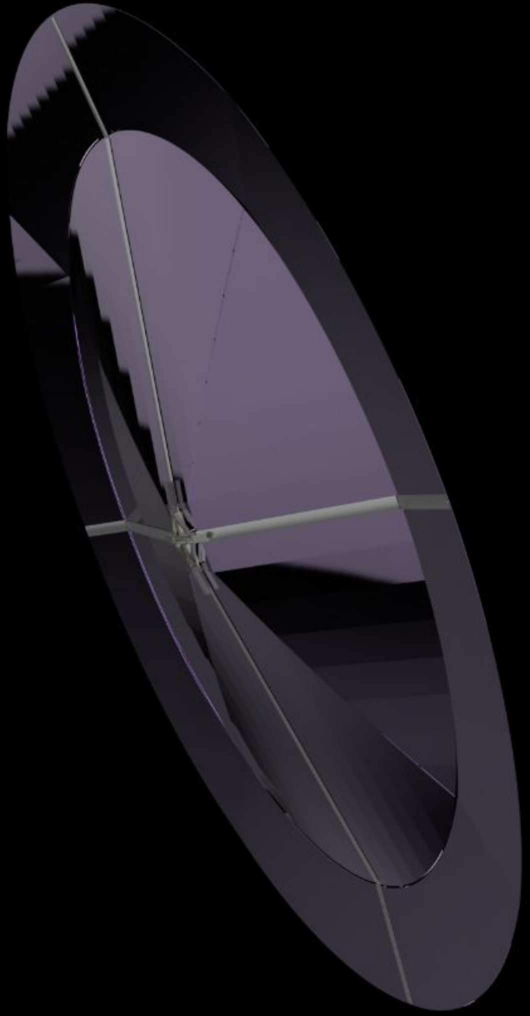


GLASS Introduction

What is GLASS?

Mission Statement:

- Our mission is to develop a platform for the high-speed acceleration of diverse payloads using ground-based laser propulsion technology, facilitated by a photon sail attachment, eliminating the requirement for onboard fuel or propulsion systems.

Objective:

- To design the mission architecture for spacecraft and other payloads powered by ground-based laser propulsion and develop compatible photon sails
- To also be a testbed for future development of laser-propelled relativistic probes

Requirements:

- Laser propulsion is successfully used to accelerate a payload from low-Earth orbit to further space targets using a photon sail

Why choose GLASS?

- Beyond-LEO, travel is expensive with chemical or electric propulsion. GLASS can enable post-LEO propulsion for up to 150x cheaper than current methods.
- Speeds beyond 10 km/s tend to be unachievable purely with traditional rockets (mass of fuel tanks, propulsion limitations, etc)
- Thrust is entirely determined by the available power at the ground and payload mass, not by the mass of onboard fuel and engine ISP.
- Available as a propulsion method for a variety of scientific, military, or industrial missions
- Adaptable for a number of applications including deep-space missions, Earth orbit boosting, satellite constellation maintenance, and other orbital transfers

The Team

Chicha Nimitpornsuko

First Year
Astrophysics

Zach Stellato

Sophomore
ScB CompSci

Ash Lassonde

First Year
Astrophysics

Dean Zweiman

First Year
MechE

Alex Khosrowshahi

First Year
CompE

Operations

Overview (Statement of Work)

1. Introduction

This statement of work outlines objectives, project scope, deliverables and management for a laser propelled photon sail mission. The mission aims to utilise ground based laser propulsion and provide transportation for various payloads.

2. Objectives
- Brainstorm and develop a photon sail system propelled by an array of lasers from ground stations
- Create and manage subsystems for mission
- Demonstrate potential for high speed interstellar travelling using photon sails
- Be a testbed for future development of laser-propelled relativistic probes

3. Scope

- Build a to-scale model of proposed design Fabrication and assembly of photon sail components
- Integration of sail system with base and deployment mechanism
- Test and validation of system
- Carry out an in-class demonstration

4. Deliverables

- Slide Deck for design concept of sail system (CDR)
- Fabricated components and subsystems
- Integrated base with sail system
- Astrodynamics simulation
- Mission operation report

Overview (Statement of Work)

5. Responsibilities:

- Project Management: Coordinates efforts, helps subsystem leads
- Engineering: design, develop and tests build prototype
- Fabrication: produce and assemble all 156 pieces of build project
- Integration: assemble sail and rest of craft
- Mission Operation: manages workload, scheduling

6. Cost: $2.2k-81k / kg

7. Conclusion:

Statement of Work highlights the key aspects of the mission. The team aims to implement and build this photon sail and help advance technology to ensure faster interstellar travel

Obstacles

Technical:

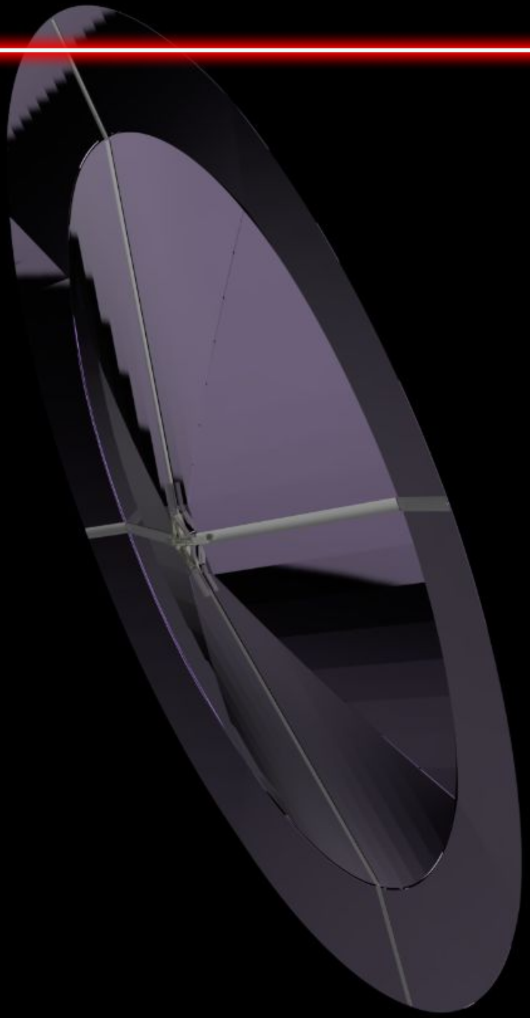
- Sail Optimisation Problem
- Thermodynamics and Chain Reaction Rapid Unscheduled Disassembly
- Reaction Wheels vs Sail Actuation
- Difficulty in budget prediction
- Astrodynamics and Orbital Science
- Time constraints
- Material costs and shipping
- Transporting finished prototype

Operational:

- Politics (limitations on ground station locations)
- Weather constraints
- Ecological damage
- Staff shortage
- Exclusion zone

Time Division

1. Brainstorming (1 week)
2. Research and Design (9 weeks)
3. Parts Acquisition (2 weeks)
4. Manufacturing (2-3 days)
5. Assembly (1 week)
6. Testing (4-5 days)
7. Demonstration (1 day)



Operations Timeline (Prototype Project)

Start of course and idea brainstorming

Research on sail shape, laser wavelength, ADCS systems

Sail optimisation, reaction wheel, sail overheating problems

Choosing sail materials, candidate locations for ground stations, creation of folding geometry

Preliminary CoDR

Build Project begins, slide deck creation: cost, time constraint, shipping time challenges, FEA, communications

Laser cut acrylic, assemble outer and inner panels, threaded rod inserts, motor function, base 3D print

Assembly, testing, astrodynamics problem

Presentation and Demonstration

Work Breakdown Structure

- Ash
  - Laser Lead and Communications Lead
- Dean
  - Project Manager, Structures Lead
- Alex
  - Ground Control Co-Lead, Software Lead
- Chicha
  - ADCS Lead, Operations Lead
- Zach
  - Ground Control Co-Lead and Policy Lead

Individual Tasks

Ground Station

- Number of ground stations
- Location for ground stations
- Complying with defence regulations
- Orbital simulations
- Reliability justification

Laser and Communications

- Laser Optics
- Laser Safety
- The case against thermoelectrics
- Link Budget
- Reliability justification

Structures

- CAD design and renders
- Design of photon sail and base
- FEA and sail optimisation
- Sail material
- Build project
- Reliability justification

ADCS:

- Reaction wheel vs sail actuation
- Reliability justification

Operations:

- Timeline
- Overseeing task completion
- Helping with misc tasks
- Taking notes to reflect on from meetings
- Drafting slides

Package Tasks

- Sail and body assembly (build project)
- Cost and budgeting
- Meetings with project supervisor (Marco)

Sample Mission Calculation

	Qty	Units
Wavelength	100	nm
Reflectance	0.998	%
Imparted Photon Momentum	1.32E-26	kg m s^-1
Target Speed	0.00	c
Target Mass	10000	g
Target Momentum	99930.81933	kg m s^-1
Photon Quantity	7.55E+30	
Total Laser Output	1.50E+13	J
Acceleration Period	21600	s
CV Laser Wattage	6.94E+08	W
Sail Area	20	m^2
Power Density	3.47E+07	W / m^2
Non-Reflected Power Density	6.94E+04	W / m^2
Percent Mass as Sail	0.80	%
Sail Thickness	3597.122	micron

Timeline (Full Scale)

GLASS is contacted by a payload provider

Working with them to integrate their payload with our sail, mass vs size of sail, etc

Launch day

Sail deployed

Stays in LEO until able to be accelerated by ground stations

Accelerated by the laser along LEO equatorial path

Accelerated until desired speed in desired direction

Communications throughout the mission until desired flyby/other target is achieved

Data from target relayed back

GLASS Phases

Phase I

Mission can use basic laser array

No deceleration beyond on-board propulsion

No highly complex mechanisms (mirrors)

Upper atmospheric sampling

Fly-by imagery

Asteroid Impact (high-speed)

Hard 'landings' on extraterrestrial bodies

Phase II

Heavier payloads

Aero-braking / gravity-assist

Complex planetary rendezvous

Inclusion of secondary mirrors

Orbital Placement around Solar bodies

Bigger Asteroid Impact (big-damage)

Soft landings on extraterrestrial bodies.

Phase III

Secondary laser for slowing down at a target location

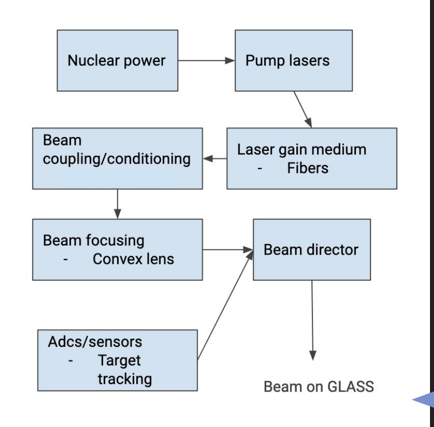
Possibility for interplanetary transportation and routine shipping

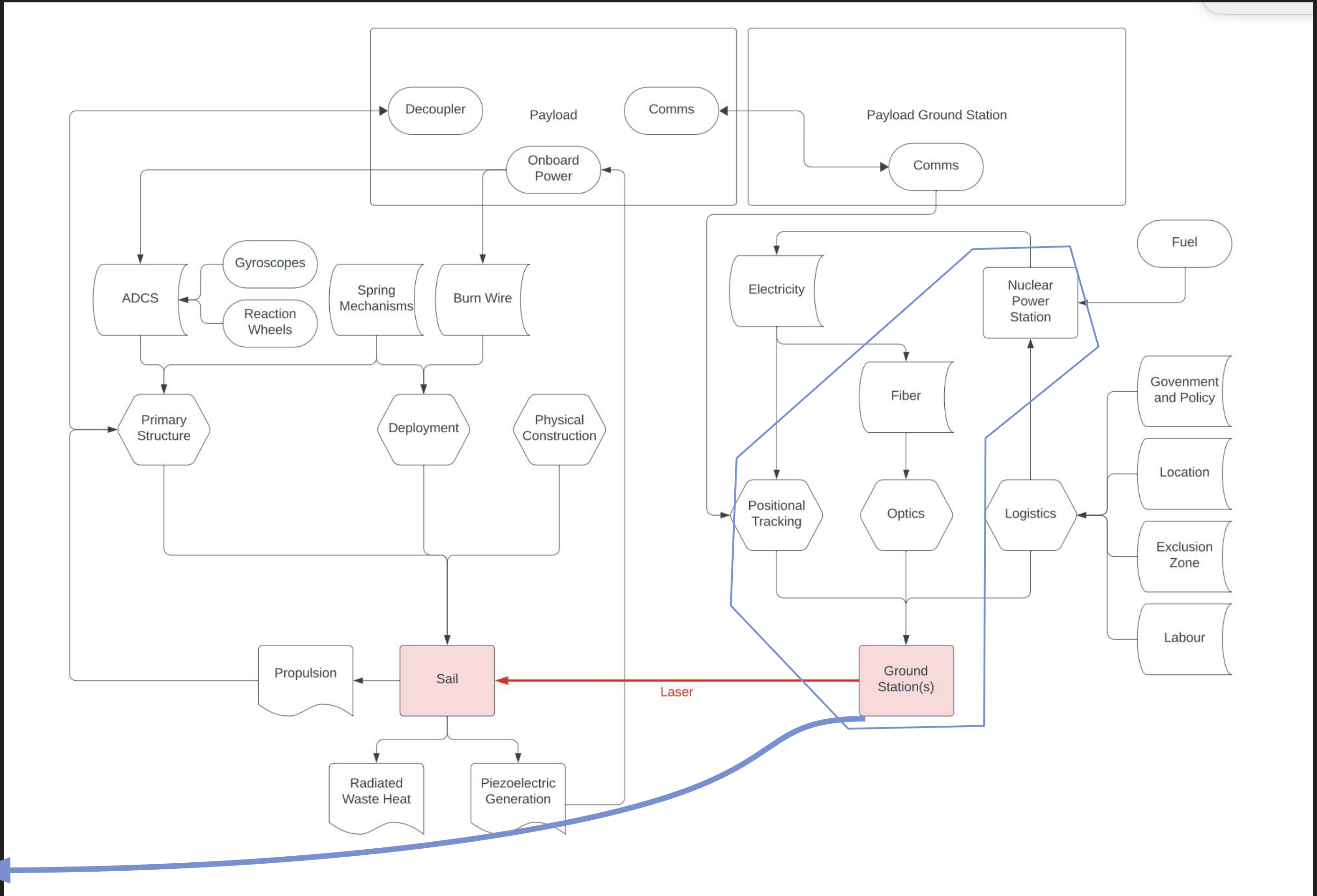
In tandem with other sci-fi tech such as space elevators, propulsion-less space travel is possible.

Possible extrasolar travel to nearby stars with pre-existing infrastructure.

Systems Overview

Systems Overview





Architecture and Subsystems

- Mission architecture
  - Technology and infrastructure development: no formal orbit path/trajectory
  - First stage missions don't involve slowing down or entering orbit around other objects
- Major trade offs
  - Dielectrics vs Films
  - Annular vs Gaussian
  - Communications
  - Reaction Wheels vs Sail Actuation
  - High-n Ground Station Complexity
  - Costly circularization maneuvers
- Requirements (what the system does to be labeled a success)
  - Laser propulsion is successfully used to accelerate payloads from low-Earth orbit to further space targets using a photon sail
  - No individual mission-critical system (sail deployment, reflection, comms, ADCS) fails
  - Remains significantly price competitive with traditional propulsion systems

Subsystems

- Lasers and Optics
- Communications
- Ground Control
- Structures
- ADCS
- Operations

Laser and Communications

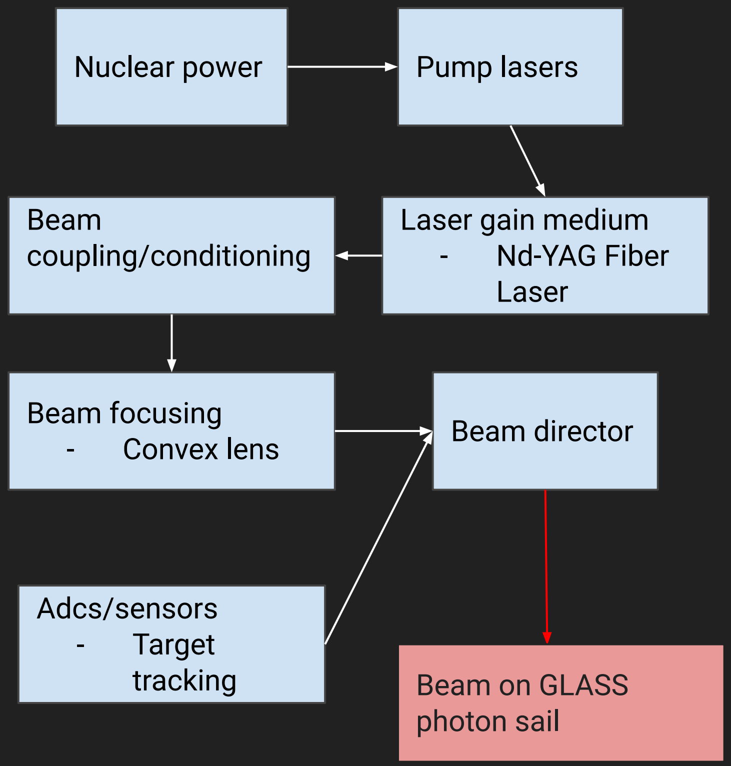
Laser Optics

Function

- Act as thrust for the payload during launch and acceleration and provide power

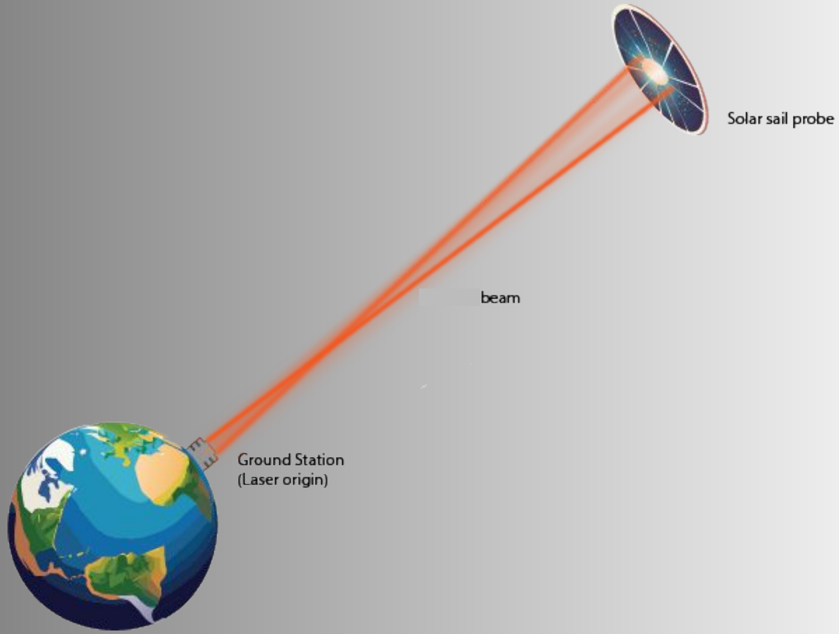
Requirements

- 500-1000 MW (1 Gigawatt max)
- Focus spot consistently on the sail
- 1064 nm wavelength
- Minimum atmospheric beam diameter dependant upon ionization of air: > 1.06 m diameter
- Gaussian beam



Trade Offs

- Gaussian beam vs annular beam
  - Both beams provide self-stabilization
  - The annular beam requires more intensive optics, would limit our distance in space that we can target in space because of heavier effects of diffraction and overall would make the cost higher than necessary
  - Using a Gaussian beam will allow future use of a laser array which will allow us to target further distances for deeper space missions



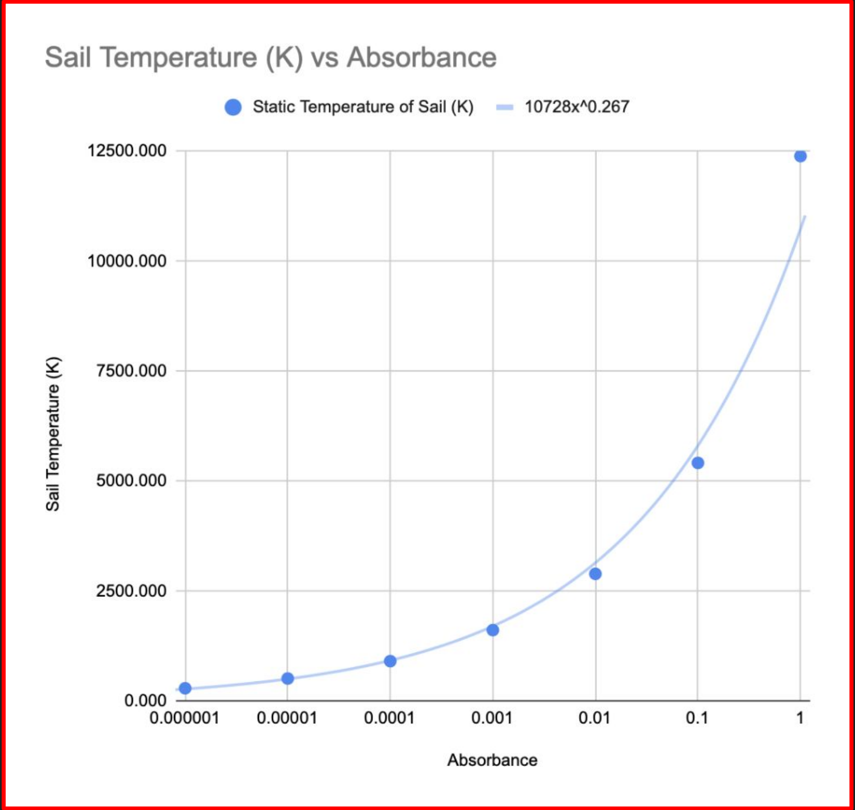
Laser Safety

- Determination of safe radius for a 1064 nm wavelength depending on irradiance and Maximum Permissible Exposure (MPE)
  - MPE for 1064 nm plateaus at around 0.07 $W/cm^2 \rightarrow 700\ m^2$
  - Calculated radius using adapted irradiance formula (r = 1.847 km) for a max power of 100,000 kW
  - Total area needed would be 10.72 km^2
  - Anything in this area would exceed the ANSIZ136.1 OSHA daily occupational safety limit for Nd-YAG indirect beam exposure

Thermoelectrics: The Case Against

- After consideration, we've elected not to include the thermoelectric generation system because the sail does not produce enough heat for system to be efficient while producing meaningful power for most payloads.

- At 10^-6 absorbance, static temperature is 285K in interplanetary space between Earth and Mars. (Cassini RTGs are ~1470K)



Reliability

- Atmospheric conditions
  - Although 1064 nm is usually transparent through the atmosphere, clouds or an especially humid day could affect its transparency causing delays and decreased efficiency
- Targeting accuracy
  - GLASS needs the targeting accuracy to remain incredibly high at far distances, even though the sail is self stabilizing, if at least 80% of the area of the sail isn't covered the sail will no longer self stabilize
- Hazards to other satellites
  - If the laser is deemed too hazardous to other satellites, GLASS might be forced to shut off the laser, in the worst case in the middle of a mission or while a payload is in acceleration

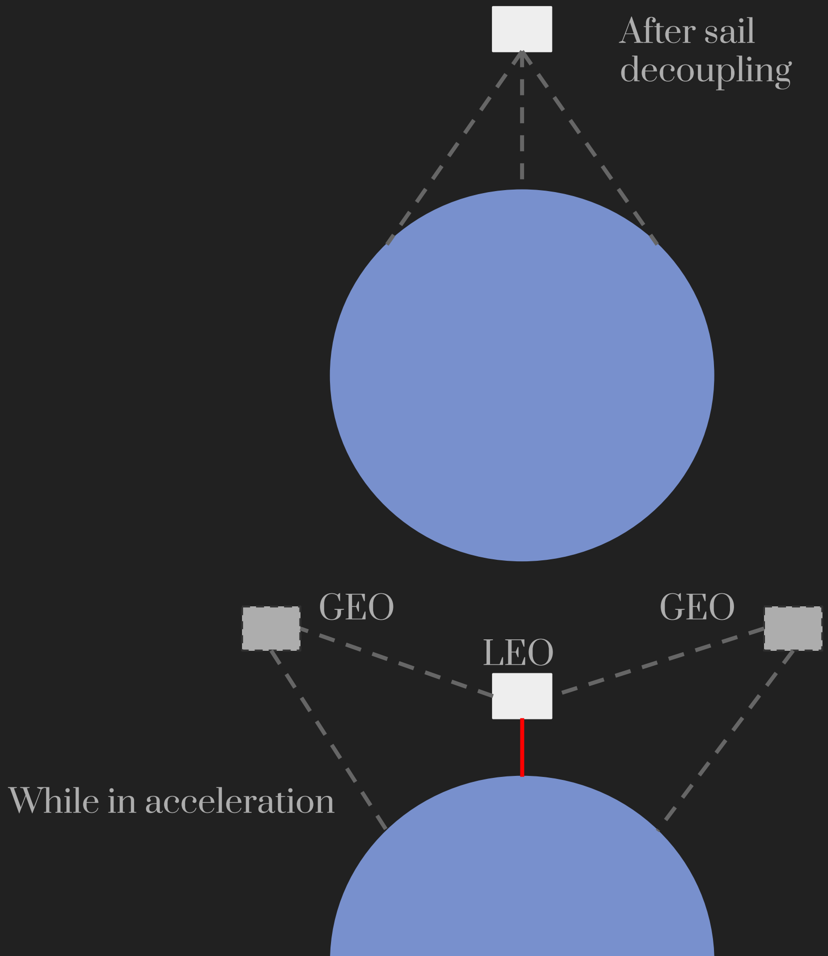
Radio Communications

Function

- To communicate ADCS functions with the satellite
- Radio, amplifier, S/X-band patch antenna on GLASS

Requirements

- S-band while in acceleration to match with TDRS satellites, 24/7 support at s-band, also omnidirectional antenna is only S-band
- X-band after sail decoupling
- 1-3 W during LEO, will increase as GLASS gets further out (Voyager 1 needs 22 W for reference)
- Ground station with 5 m antenna for S/X-band communications



Link Budget - Ground to TDRS

earth rad (km)	6371									
c (Gm/s)	0.3			note: only using third gen tdrs (K, L, and M)						
fpl general (dB)	190.78									
GEO d (km)	35888	tdrs satellite		K = 10log(Kb) (dB)	-228.6		groundstation			
				data rate (bps)	6000000			0.60775	wavelength*4 + a quarter of it	
antenna diam (m)	4.6	tdrs satellite					antenna diam (m)	5	groundstation	
wavelength (m)	0.13	c/f		Eb/No reqs for 10^-9 QPSK (dB)	13	based on graph	wavelength (m)	0.143	c/f	
carrier freq (GHz)	2.3	s-band uplink					carrier freq (GHz)	2.1	s-band downlink	
system noise (K)	290			GEO sat tx power (dBM)	30		bandwidth (MHz)	10		
antenna G/T (dB/K)	11.6	tdrs-L (SA East LHCP/RHCP)		for uplink	1 W		antenna gain (dB)	57.7	ground reciever	https://calculator.academy/antenna-gain-calculator/
antenna gain (dBi)	35.8	tdrs-L spec					system noise (K)	300		
occupied bandwidth (H	3570000	65.53					antenna G/T (dB)	32.93		
							Eb/No reqs 10^-9 MSK (dB)	12.5	graph	
final EIRP (dBW)	35.8	(tx power - 30) + gain, this is using antenna gain of tdrs					final EIRP (dBW)	57.7	idk should i use 50 dbm again, using gain of groundstation	
losses (dB)							losses (dB)			
RF losses	1						RF losses	1		
polarization losses	0	can either have RH or LH circular polarization					atmospheric loss	2		
demod loss	2						polarization loss	0	cirular polarization	
modulation loss	1						modulation loss	1		
atmospheric losses	1						demod loss	2		
pointing loss	2.5	estimate					pointing loss	6	estimate	
total losses (dB)	7.5						total losses (dB)	12		
path loss calculations										
tdrs elevation (deg)	0	5	15	30	60	90				
elevation (rad)	0	0.09	0.26	0.52	1.05	1.57				
slant range (km)	676.99	320.31	133.56	71.14	41.38	35.87	https://www.vcalc.com/wiki/slant-range			
fpl (dBW)	156.33	149.83	142.23	136.76	132.06	130.82				
margin to tdrs (dB)	14.75	18.62	23.14	26.39	29.19	29.93				
mardin to earth (dB)	38.3	42.16	46.68	49.94	52.74	53.47				

Link Budget - TDRS to GLASS

earth rad (km)	6371				eb/no for 10^-9 ber	13	qpsk, based on graph	
c (Gm/s)	0.3				data rate for tdrs	6000000	6 mbit/s max	
fpl (general)	189.5				bandwidth tdrs	2000000	20 mhz	63.01
GEO to LEO (km)	33888							
K = 10log(Kb) (dB)	-228.6							
on GLASS					on TDRS			
carrier freq (GHz)	2.1				carrier freq (GHz)	2.1		
wavelength	0.14				wavelength (m)	0.14		
system noise (K)	290				system noise (K)	290		
antenna gain (dBi)	25				antenna gain (dBi)	35.8		
amplifier gain	14				antenna G/T	11.6		
antenna G/T	14.38				tx power (dBm)	32		
tx power (dBm)	16				final EIRP (dBW)	37.8		
final EIRP (dBW)	11	(tx power - 30) + gain						
losses (dB)					losses (dB)			
RF losses	1				RF losses	1		
atmospheric losses	0				atmospheric losses	0		
polarization loss	0				polarization loss	0		
demod loss	2				demod loss	2		
modulation loss	1				modulation loss	1		
pointing loss	6	estimate			pointing loss	6		
total losses (dB)	10				total losses (dB)	10		
elevation (deg)	0	5	15	30	60	90		
elevation (rad)	0	0.09	0.26	0.52	1.05	1.57		
slant range (km)	676.99	320.31	133.56	71.14	41.38	35.87		
fpl (dBW)	155.69	149.19	141.59	136.12	131.41	130.17		
margin to GLASS (dB)	-1.03	1.13	3.67	5.49	7.06	7.47		
margin to TDRS (dB)	11.5	13.67	16.2	18.02	19.59	20.01		

Link Budget - Ground to GLASS after decoupling

earth rad (km)	6371		fpl (dBW)	318.12	
c (Gm/s)	0.3		Eb/No for 10^-9 BER	13	
K = 10log(Kb) (dB)	-228.6		datarate (bps)	16000000	
voyager 1 distance (km)	24,000,000,000	roughly	bandwidth (Hz)	6000000	67.78
on GLASS			groundstation		
			wavelength (m)	0.14	c/f
wavelength (m)	0.0375	c/f	carrier freq (GHz)	2.1	
carrier freq (GHz)	8		system noise (K)	300	
system noise (K)	290		antenna G/T (dB/K)	32.93	
antenna G/T (dB/K)	-14.62		antenna gain (dBi)	57.7	
antenna gain (dBi)	10	we're gonna need a rly big amp if we dont have a dish	antenna diameter (m)	5	
tx power (dBM)	43.6		tx power (dBM)	53	depends on how far, for this example lets say it's really far out, like where voyager 1 is (which takes 22 W right now)
final EIRP (dBW)	23.6	(tx - 30) + gain	final EIRP (dBW)	80.7	(tx - 30) + gain
losses (dB)			could hypothetically use DSN if needed, when it gets too far out		
RF losses	1		that way would have bigger aperature		
atmospheric losses	1				
polarization loss	0				
demod loss	2				
modulation loss	1				
pointing loss	5	estimate			
total loss (dB)	10				
margin to GLASS (dB)	-63.14				
margin to goundstation (dB)	-23.84	to fix this: bigger antenna area, good amplifiers, etc.			

Trade Offs

- Modulation type
  - Using QPSK rather than others, minimizes effects of non-linear amplification in high-power amplifier, using rather than a higher one (8PSK, 16PSK, 16QAM) because although it will make it a lower data rate, it will also leave it less sensitive to signal impairments so it'll be more reliable
- Wavelength
  - Using S-band for while in acceleration (using TDRS satellites), allows for small and high gain antennas (good for adding onto satellite), good bandwidth, but very crowded and requires gain antennas
  - After sail decoupling, can communicate directly with the payload, most likely to use X-band (8-9 GHz) as it's already heavily used for deep space research, we can easily find compatible S and X-band transmitters, and it's less crowded, but it is higher cost and has lower efficiency (<50%)

Reliability

- Comms are mission critical
  - If Earth cannot communicate with GLASS, we have no way of getting data from the mission, no way to track it with the laser if needed, and no way of knowing it's still intact at all, will be considered a mission failure
- Relies on Tracking and Data Relay Satellites (TDRS) already in place
  - Anything further than TDRS range or the critical angle for the field of view of Earth of satellite relies on the decoupling mechanism working so that we can communicate with it at further distances
  - If the sail fails the decoupling, the sail will block all radio communication and we will have no way of communicating with it at all

Ground Control

Ground Control

Purpose:

- Power for laser, direct laser, launch site, to receive and process communication links

Requirements:

- Remote location (large area) based on laser safety, staffed, large power source
- Close to equatorial location

Trade Offs:

- Atmosphere conditions for clear skies and equatorial locations
- Large area requires places where wildlife are likely present, potentially damaging to environment
- Political standings with the US eliminate many good candidates

1.847 km radius circle overlaid on Brown University

Within this range, laser light exceeds the ANSIZ136.1 OSHA daily occupational safety limit for Nd-YAG indirect beam exposure

Candidate Locations

British Indian Ocean Territory

Pros:

- Extremely low population.
- British Military Base - Allies provide protection
- Extremely close to the equator, great for early orbit boosting
- Dry air, low humidity.
- Hundreds of feet from satellite tracking station

Cons:

- Remote location - expensive supply chains

Candidate Locations

French Guiana

Pros:

- Proven record of amicable relations and collaboration with EU/US, including in Aerospace.
- Low population density
- Located close to the equator
- Growing aerospace industry looking to expand, likely friendly to infrastructure development related to project.
- France has existing nuclear power production infrastructure (unlike US)

Cons:

- Growing tourism industry may prove a challenge as population density increases
- Small land area (32,433 km^2) will prove a challenge, as a ground station would require a fairly large safe area.
- High humidity could pose issues for laser operation

The GLASS Orbit Problem

- Main orbital challenge of the GLASS Mission is effective orbital maneuvering with burns originating from ground stations.
  - Unlike ordinary orbital craft, GLASS-driven probes cannot boost at any orientation, and rely on ground station locations for maneuvers
  - We compromised in our simulation efforts by not having impulse vectors actually originate from the ground (technical limitations)
- Missions specifications can change massively based on number of ground stations, payload weight, inclination, etc.
  - For the astrodynamics portion of the project, we decided to focus on two main configurations as, others present mission complexity out of scope for our project
    - One-station orbital maneuvers for lightweight payloads
    - Two-station orbital maneuvers for heavier payloads and complex applications
  - We also decided to primarily focus on deep-space applications of the GLASS system

Astrodynamics Simulation

Purpose: Create a tool for simulating GLASS-driven Probe maneuvers within the poliastro framework, a toolkit built on top of astropy for astrodynamics simulations.

Conclusion: Simulation efforts proved extremely difficult but warrant further exploration—possible future endeavors include building new simulation infrastructure from the ground up (more likely) or on top of NASA's existing SPICE (Spacecraft, Planet, Instrument, C-matrix, Events) Toolkit. Despite difficulties, efforts toward simulation led to valuable astrodynamics insights.

```python
def get_altitude(orb: Orbit, time: datetime):
    orb_x = orb.r.value[0]
    orb_y = orb.r.value[1]
    orb_z = orb.r.value[2]
    un = u.m
    _, _, ret_alt = eci2lla2(orb_x, orb_y, orb_z, time, un)
    return ret_alt

def compute_eci_vec(dv, orb: Orbit, epoch):
    cart_coords = (orb.r.to(u.m)).value

    lo, la, al = eci2lla2(cart_coords[0], cart_coords[1], cart_coords[2], epoch, u.m)
    ned = [0, dv, 0]
    lat_ref = la
    lon_ref = lo
    alt_ref = al
    ecefRep = ((navpy.ned2ecef(ned, lat_ref, lon_ref, alt_ref)) << u.m / u.s).to(
        u.km / u.s
    )
    print(ecefRep)

    gcrs = coord.ITRS(
        x=orb.r[0],
        y=orb.r[1],
        z=orb.r[2],
        v_x=ecefRep[0],
        v_y=ecefRep[1],
        v_z=ecefRep[2],
        representation_type="cartesian",
        differential_type="cartesian",
        obstime=epoch,
    )
    itrs = gcrs.transform_to(coord.GCRS(obstime=epoch))
    return itrs.cartesian.differentials['s'].d_xyz

def apply_maneuver_evil(orbit: Orbit, di: float, dv: float, epoch) -> None:
    disc_vel = dv / di
    temp_orbit = orbit
    prev_orbit = None

    for i in range(0, math.floor(di)):
        prev_orbit = temp_orbit
        temp_orbit.apply_maneuver(
            (i * u.s, compute_eci_vec(disc_vel, orbit, epoch + i))
        )
```

```python
def ned2ecef(ned,lat_ref,lon_ref,alt_ref,latlon_unit='deg',alt_unit='m',model='wgs84'):
    """
    Transform a vector resolved in NED (origin given by lat_ref, lon_ref, and alt_ref)
    coordinates to its ECEF representation.

    Parameters
    ----------
    ned : {(N,3)} input array, units of meters
    lat_ref : Reference latitude, unit specified by latlon_unit, default in deg
    lon_ref : Reference longitude, unit specified by latlon_unit, default in deg
    alt_ref : Reference altitude, unit specified by alt_unit, default in m

    Returns
    -------
    ecef : {(N,3)} array like ned vector, in the ECEF frame, units of meters

    Notes
    -----
    The NED vector is treated as a relative vector, and hence the ECEF representation
    returned is NOT converted into an absolute coordinate.  This means that the
    magnitude of `ned` and `ecef` will be the same (bar numerical differences).

    Examples
    --------
    >>> import navpy
    >>> ned = [0, 0, 1]
    >>> lat_ref, lon_ref, alt_ref = 45.0, -93.0, 250.0 # deg, meters
    >>> ecef = navpy.ned2ecef(ned, lat_ref, lon_ref, alt_ref)
    >>> print("NED:", ned)
    >>> print("ECEF:", ecef)
    >>> print("Notice that 'down' is not same as 'ecef-z' coordinate.")
    """
    lat_ref,N1 = _input_check_Nx1(lat_ref)
    lon_ref,N2 = _input_check_Nx1(lon_ref)
    alt_ref,N3 = _input_check_Nx1(alt_ref)

    if( (N1!=1) or (N2!=1) or (N3!=1) ):
        raise ValueError('Reference Location can only be 1')

    ned,N = _input_check_Nx3(ned)

    ned = ned.T

    C = np.zeros((3,3))

    if(latlon_unit=='deg'):
        lat_ref = np.deg2rad(lat_ref)
        lon_ref = np.deg2rad(lon_ref)
    elif(latlon_unit=='rad'):
        pass
    else:
        raise ValueError('Input unit unknown')

    C[0,0]=-np.sin(lat_ref)*np.cos(lon_ref)
    C[0,1]=-np.sin(lat_ref)*np.sin(lon_ref)
    C[0,2]= np.cos(lat_ref)

    C[1,0]=-np.sin(lon_ref)
    C[1,1]= np.cos(lon_ref)
    C[1,2]= 0

    C[2,0]=-np.cos(lat_ref)*np.cos(lon_ref)
    C[2,1]=-np.cos(lat_ref)*np.sin(lon_ref)
    C[2,2]=-np.sin(lat_ref)

    # C defines transoformation: ned = C * ecef.  Hence used transpose.
    ecef = np.dot(C.T,ned)
    ecef = ecef.T

    if(N == 1):
        ecef = ecef.reshape(3)

    return ecef
```

```python
def eci2lla2(x, y, z, t, unit):
    """Convert Earth-Centered Inertial (ECI) cartesian coordinates to latitude, longitude, and altitude, using astropy.

    Inputs :
    x = ECI X-coordinate
    y = ECI Y-coordinate
    z = ECI Z-coordinate
    t = UTC time (datetime object)
    unit = units the coordinates are in

    Outputs :
    lon = longitude (degrees)
    lat = geodetic latitude (degrees)
    alt = height above WGS84 ellipsoid (m)
    """
    # position of satellite in GCRS or J20000 ECI:
    cartrep = coord.CartesianRepresentation(x, y, z, unit=u.m)
    gcrs = coord.GCRS(cartrep, obstime=t)
    itrs = coord.GCRS(cartrep, obstime=t).transform_to(coord.ITRS(obstime=t))
    loc = coord.EarthLocation(*itrs.cartesian.xyz)
    return loc.lat.value, loc.lon.value, (loc.height.to(u.m)).value

def get_tan_vel(orb: Orbit, time):
    orb_x = orb.r.value[0]
    orb_y = orb.r.value[1]
    orb_z = orb.r.value[2]
    lon, lat, height = eci2lla2(orb_x, orb_y, orb_z, time, u.m)
    return navpy.ecef2ned(orb.r.value, lon, lat, height)[1]

def compute_time_off(dt: float) -> datetime:
    """Returns a datetime object with an offset from J2000 Epoch (Default)

    Args:
        dt - float: The time passed since initial orbit creation (Assumed in J2000 frame)

    Returns:
        datetime: a new datetime object
    """
    return datetime.datetime(2000, 1, 1, 12, 0) + datetime.timedelta(seconds=dt)

def get_altitude(orb: Orbit, time: datetime):
    orb_x = orb.r.value[0]
    orb_y = orb.r.value[1]
    orb_z = orb.r.value[2]
    un = u.m
    _, _, ret_alt = eci2lla(orb_x, orb_y, orb_z, time, un)
    return ret_alt
```

Challenges: GLASS Astrodynamics Simulation

- The main issue encountered with simulation within Poliastro came when applying impulses to orbiting objects
  - Poliastro is an extremely useful library for simulating objects in keplerian orbits & natural perturbations, but lacks infrastructure for unnatural impulses
- Poliastro places coordinates in ECI (Earth-Centered Inertial) frames, while astrodynamics simulations supporting artificial perturbations benefit most from NED (North East Down) frames, which Poliastro does not support.
  - Attempts at frame conversion proved extremely obtuse and costly
- Potential frameworks for future progress include:
  - Orekit, a library built in Java
  - NASA's SPICE Library
  - Kerbal Space Program
  - A self-built framework (current main idea)

```python
def eci2lla2(x, y, z, t, unit):
    """Convert Earth-Centered Inertial (ECI) cartesian coordinates to latitude, longitude, and altitude, using astropy.

    Inputs :
    x = ECI X-coordinate
    y = ECI Y-coordinate
    z = ECI Z-coordinate
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    Outputs :
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    return navpy.ecef2ned(orb.r.value, lon, lat, height)[1]

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    orb_y = orb.r.value[1]
    orb_z = orb.r.value[2]
    un = u.m
    _, _, ret_alt = eci2lla(orb_x, orb_y, orb_z, time, un)
    return ret_alt
```

Modeling the Problem

- For the simulation, we simplified the problem to burning within a range that we could reasonably burn prograde with an incident angle from the laser less than 35°
- Further steps include more accurate derivations for calculating acceleration, including radial-out to prograde burns

$$\Delta t = \frac{2(\frac{A}{tan(10)} - A \cdot tan(55))}{V_i + (\sqrt{\frac{4 \cdot 10^9 W \cdot \Delta t}{m}} + V_i)}$$

$$V_f = \sqrt{\frac{4 \cdot 10^9 W \cdot \Delta t}{m} + V_i^2}$$

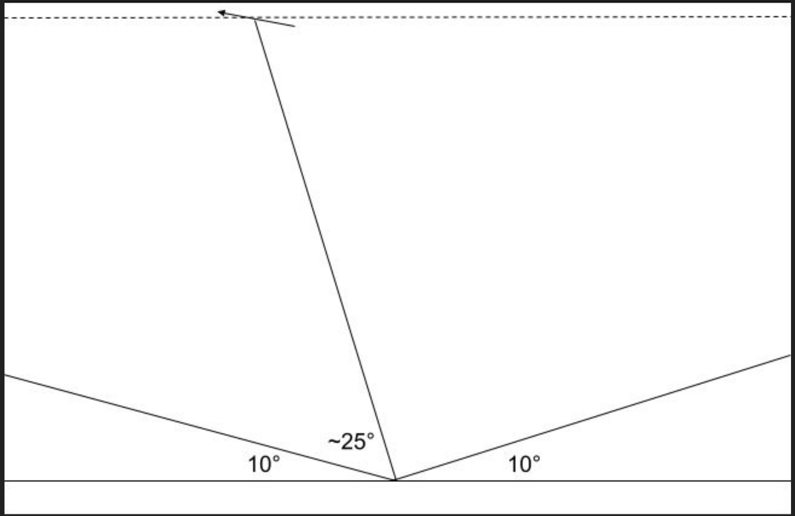


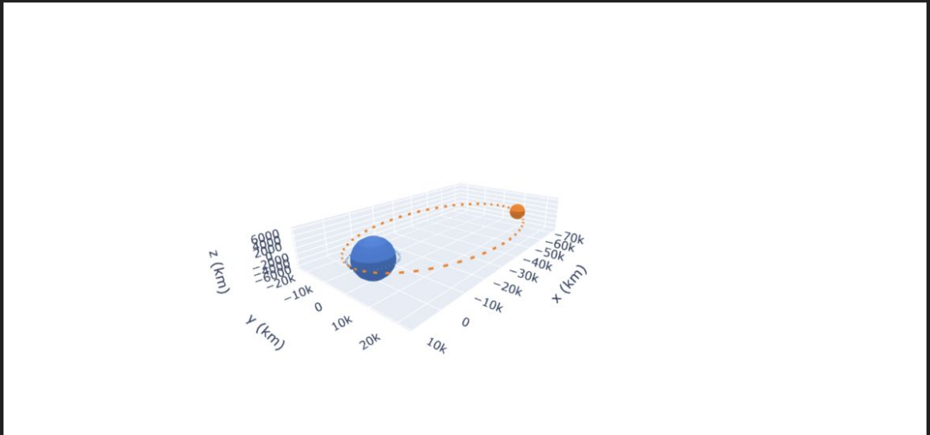
*Diagram not to scale

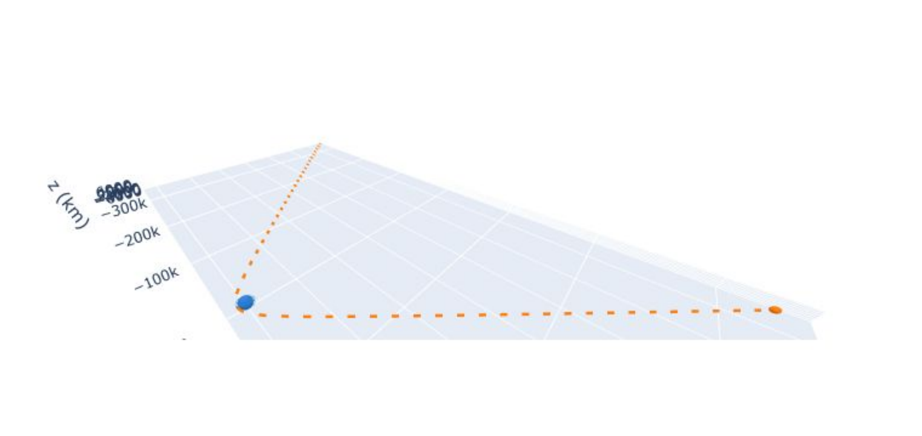
1-Station Configuration

Shown to the right:

(Top): Demonstration of a boost to geo-height. Additional burns would be needed to circularize, but could be done within 1-2 passes for small satellites.

(Bottom): Demonstration of a boost out of Earth orbit for a small satellite, feasible with light payloads.



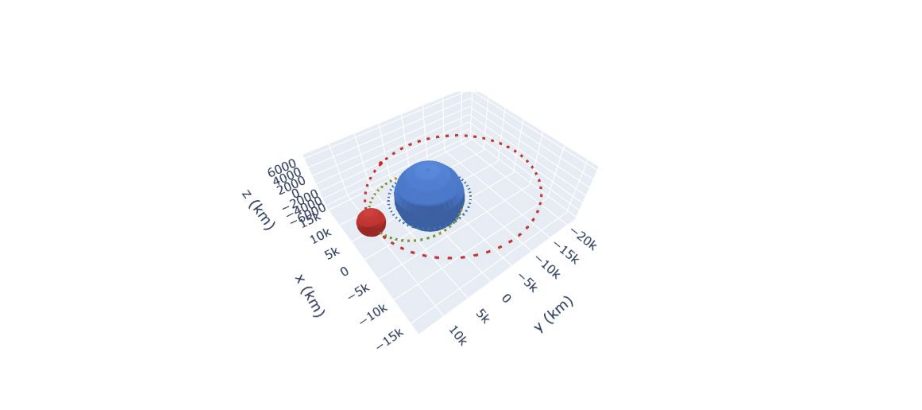


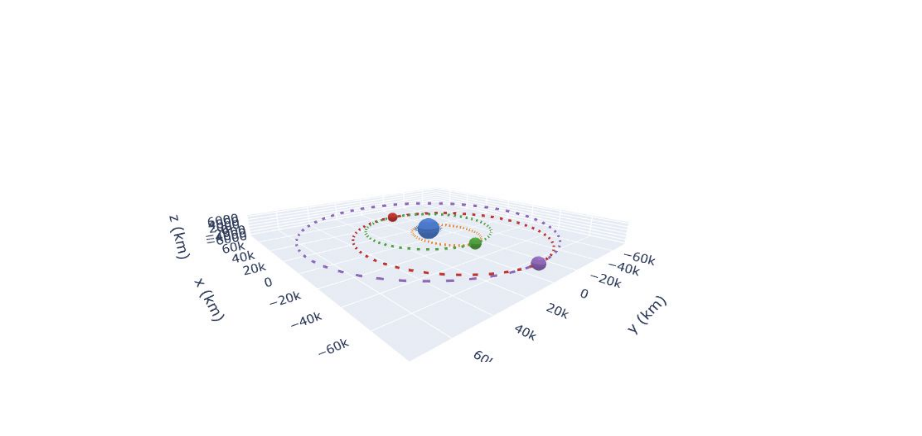
2-Station Configuration

Shown to the right:

(Top): Demonstration of radial burn followed by circularization with burn at apogee

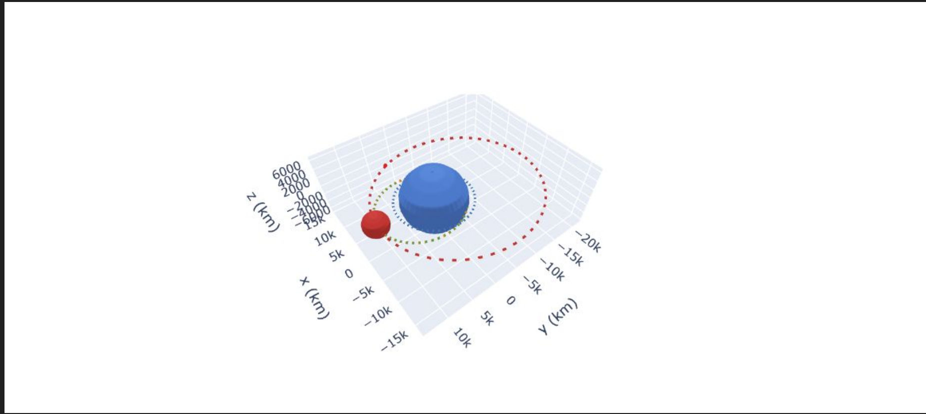
(Bottom): This strategy can be extended further, with incremented radial-to-prograde burns followed by apogee burns





Maneuvers: Orbit Circularization with Multiple Stations

1. Burn radial out to prograde, extending apogee and shortening perigee
2. Burn at apogee to circularize orbit, wasting some energy without extending orbit
3. Repeat to further extend orbit



Other Potential Applications - Inclination Change

- Inclination Change
    - Ground stations and the GLASS system could be used to correct and change satellite inclinations without the need for onboard propulsion systems and fuel.
    - This could prove extremely useful for commercial satellites in equatorial orbits, allowing for launches from sites with greater variance from the equator due to low correction cost
    - Unexplored simulation wise due to technical limitations, but could be a future path of research.

Drawbacks/Advantages of Proposed Configurations

One Station:

Advantages:

- Much less complex
- Effective for light-medium payloads
- Lower cost

Drawbacks:

- Not feasible for upper medium-heavy payloads
- Advanced maneuvers (circularization for geostationary transfer, etc.) not possible or very difficult

Two Station

Advantages:

- Allows for the boosting of light-medium payloads within less orbital cycles
- For heavier payloads, allows for far transfers using circularization techniques described

Drawbacks:

- Massively increased complexity
- Higher cost
- Difficulty in placing ground stations

Expanding to 3-n Station Configurations

- Due to the effectiveness of 2-station configurations in accelerating heavy payloads, the advantages of 3 - n station configurations are primarily in flexibility of mission specifications
- Use cases could include
  - Equatorial stations for launch, additional stations for adjustments of inclination
  - Capability to launch and support multiple payloads simultaneously
- Complexity of 3 - n station configurations expands massively, heavily mission dependent
- Inconclusive if a relationship can be established between number of stations and mission efficiency, more work needs to be done.

Reliability

- Reliability of ground stations is conditional to tolerance of outside factors such as inclement weather, humidity, etc.
- Other concerns include the ability for ground stations to track payloads (after initial boosts, payloads can be extremely fast moving).
    - Targeting is also a major priority—major considerations include whether or not stations could adequately avoid potential obstacles while tracking probes.
- Despite maneuvers like the circularization shown earlier being possible, there is still existent risk with heavy payloads potentially falling back to Earth if the apogee burn is rendered ineffective for any reason.

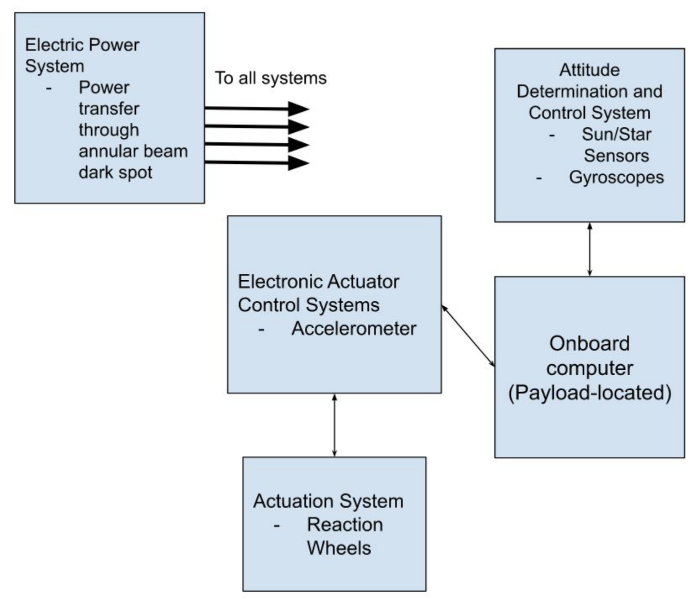
Altitude Determination Control System (ADCS)

Function

Stabilize and direct/orient the satellite and sail

Requirement

- Reaction wheels, gyroscopes, sun sensors, star sensors
- Point accurately during acceleration
- Can turn sail sideways to avoid debris
- Mission critical during lasing for steering



Why not Sail Actuation? (Trade Offs)

After consideration, we chose a reaction wheel over sail actuation

Reaction Wheel	Sail Actuation
Reaction wheels are lighter, final sail mass will be lighter	Sail actuation could control sail orientation to optimize photon pressure and contribute to propulsion
Reaction wheels allow for finer control which makes it easier to maintain a specific angle with earth	Sail actuation would allow for a more dynamic control of orientation which would accelerate the sail better than reaction wheels
Reaction wheels have a much less complex system than sail actuation	Sail actuation can passively maintain attitude control, only consuming power when actively maneuvering
The sail orientation could be adjusted more easily and rapidly, making it easier to maneuver out of the way of debris	

Reliability

- A reaction wheel failure has the potential to jeopardize a mission (especially if during a burn)
- Redundant reaction wheels could be a potential advantage
- Rotational and translational stability within a laser beam is passive, and therefore reliable so long as the sail and its frame remain in working condition

Structures

Structures

- Function
  - Transfer incoming photon momentum to the payload
- Requirements
  - Self-stabilizing, highly reflective, deployable without failure
- Size
  - Mass < 5kg (26 lbs in acrylic for build-project demo)
  - Irradiation Area ~ 2-5 m^2 (3.46m^2 for demo)
- Materials
  - Sail: 70 um keronite coating, silver, 0.6 mm CaF with 266 nm dielectric mirror coating (acrylic w/ mirror tape for demo)
  - Rails, Base: Magnesium (Aluminum, Carbon Fiber reinforced PETG w/ Brass inserts for demo)
  - Compliant Mechanisms: Titanium 6Al-4V (Replaced by Steel Hinges for demo)
  - Screws: 316 Stainless Steel

Requirements

- Deployable (Mission Critical)
  - Foldable without damaging reflecting layer
  - Reliable
  - Structurally sound when deployed
- Highly reflective
  - Specific material choice
  - Thermal stability
- Self-stabilizing
  - Requires highly specific geometry

Parts List (Actual)

Sail

- 156 segment articulating mirror
  - CaF_2 substrate dielectric bonded to silver with black keronite coating
- 170 degree compliant mechanism (4x)
  - Titanium 6Al-4V
- 195 degree compliant mechanism (4x)
  - Titanium 6Al-4V
- Long Rail (4x)
  - Magnesium
- Short Rail (4x)
  - Magnesium
- Base
  - Magnesium
- Screws (40x)
  - 316 Stainless Steel (M3x0.5 various lengths)
- Neodymium Magnets (8x)

Required Payload Components

- Reaction Wheels
- Gyroscopes
- S-Band Patch Antenna
- Attachment Points (8x M3)
- (Decoupling Bolts/Mechanism)
- Deployer
  - Burn wire or mechanical equivalent

Parts List (Build Project)

Sail

- 156 segment articulating mirror
  - Laser cut acrylic, mirror tape, electrical tape
- Spring Loaded Cabinet Hinge (8x)
  - Steel
- Long Rail (4x)
  - Aluminum
- Short Rail (4x)
  - Aluminum
- Base
  - 3D Printed Carbon Fiber Reinforced PETG
- Screws (32x)
  - Alloy Steel (M3x0.5 various lengths)
- Threaded Rods (8x)
  - Alloy Steel
- Nuts (24x)
  - Steel (M3x0.5)

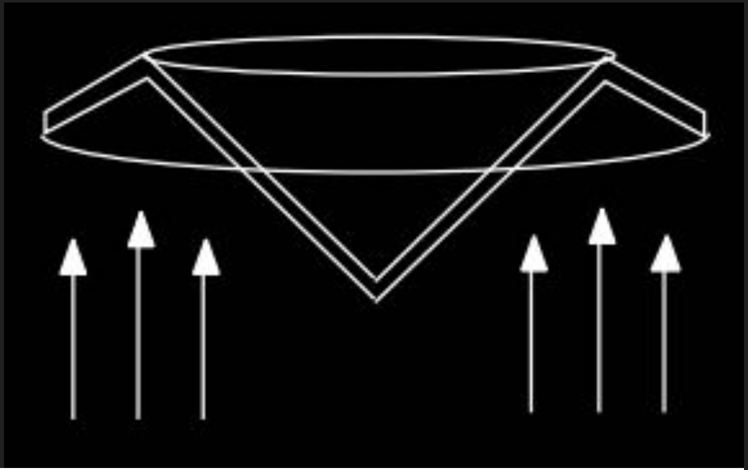
Motorized Deployer

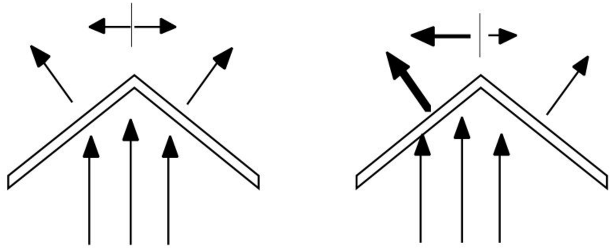
- 6ft Steel Beam
- Hold Bolts (2x)
  - M8 250mm
- M8 Nuts (2x)
- Hold Bracket (3x)
  - Laser cut acrylic
- Breadboard
- Battery
- High-Torque Motor
- Switch (4x)
- Keycap (4x)
- Spindle
  - 3D Printed PLA
- Electrical Cable (Weight Bearing)

Sail Optimization

Requirements:

- Self stabilizes against moment upsets
- Self stabilizes against translational upsets
- Minimizes overall sail area for given thrust (small angles)





Region of stable sails

$$\sin(z)\left(2x^2\cos^{-1}\left(\frac{D}{2x}\right)-D\sqrt{x^2-\frac{D^2}{4}}-\pi\right)>\pi\sin y\left\{\frac{1}{2\cos y}\left(\cos^2(y-E)-\cos^2(y+E)\right)>\frac{x^2-1}{2x\cos z}\left(\cos^2(z-E)-\cos^2(z+E)\right)\right\}\{z<(45-E)\}\{y<(45-E)\}$$

Region of sails that withstand a given moment

$$\left(\frac{1}{2\cos y}\left(\cos^2(y-E)-\cos^2(y+E)\right)-\frac{x^2-1}{2x\cos z}\left(\cos^2(z-E)-\cos^2(z+E)\right)\right)\cdot F>EG\left\{\sin(z)\left(2x^2\cos^{-1}\left(\frac{D}{2x}\right)-D\sqrt{x^2-\frac{D^2}{4}}-\pi\right)>\pi\sin y\right\}\left\{\frac{1}{2\cos y}\left(\cos^2(y-E)-\cos^2(y+E)\right)>\frac{x^2-1}{2x\cos z}\left(\cos^2(z-E)-\cos^2(z+E)\right)\right\}\{z<(44-E)\}\{y<(44-E)\}$$

Sail Optimization

Inner sail is rotationally stable

Inner sail is translationally unstable

Outer sail is rotationally unstable

Outer sail is translationally stable

Under rotational upset, inner sail area on the moment integral must exceed that of the outer sail

Under translational upset, outer sail must have greater area * cos(ϕ) than inner sail area * cos(Θ)

These two inequalities drive design constraints, with mass and size as free variables

Optimization covers ratio of inner to outer radii, angle of inner sail, and angle of outer sail

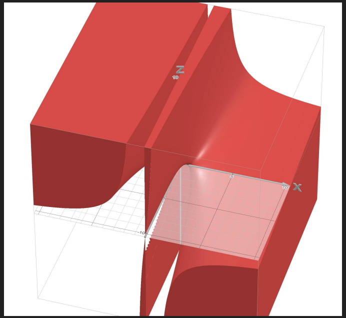
Region of stable sails

$$\sin(z)\left(2x^2\cos^{-1}\left(\frac{D}{2x}\right)-D\sqrt{x^2-\frac{D^2}{4}}-\pi\right)>\pi\sin y\left\{\frac{1}{2\cos y}\left(\cos^2(y-E)-\cos^2(y+E)\right)>\frac{x^2-1}{2x\cos z}\left(\cos^2(z-E)-\cos^2(z+E)\right)\right\}\{z<(45-E)\}\{y<(45-E)\}$$

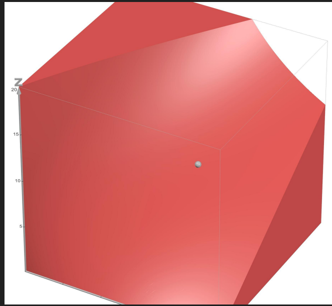
Region of sails that withstand a given moment

$$\left(\frac{1}{2\cos y}\left(\cos^2(y-E)-\cos^2(y+E)\right)-\frac{x^2-1}{2x\cos z}\left(\cos^2(z-E)-\cos^2(z+E)\right)\right)\cdot F>EG\left\{\sin(z)\left(2x^2\cos^{-1}\left(\frac{D}{2x}\right)-D\sqrt{x^2-\frac{D^2}{4}}-\pi\right)>\pi\sin y\right\}\left\{\frac{1}{2\cos y}\left(\cos^2(y-E)-\cos^2(y+E)\right)>\frac{x^2-1}{2x\cos z}\left(\cos^2(z-E)-\cos^2(z+E)\right)\right\}\{z<(44-E)\}\{y<(44-E)\}$$

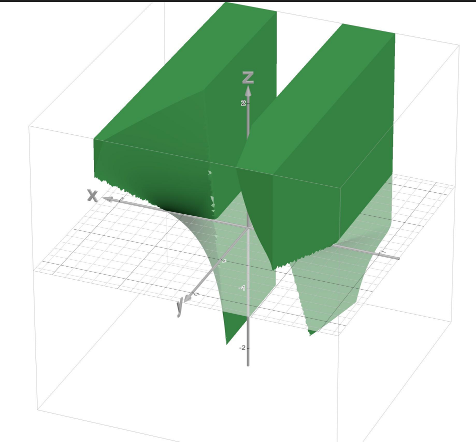
Sail Optimization



Inequality geometry for rotational stability

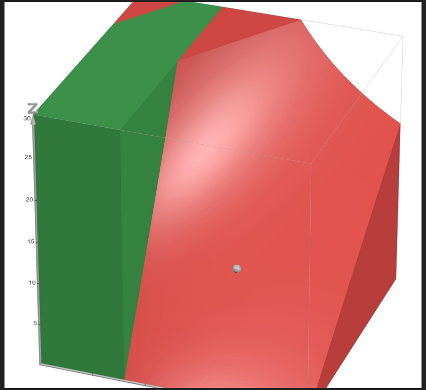


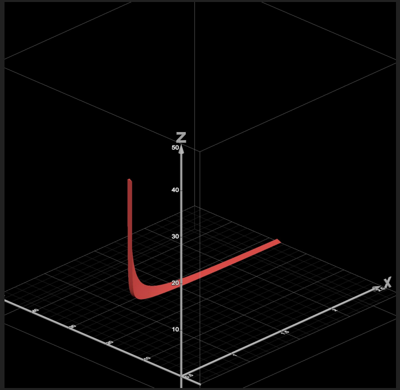
Inequality within our working region



Inequality geometry for translational stability

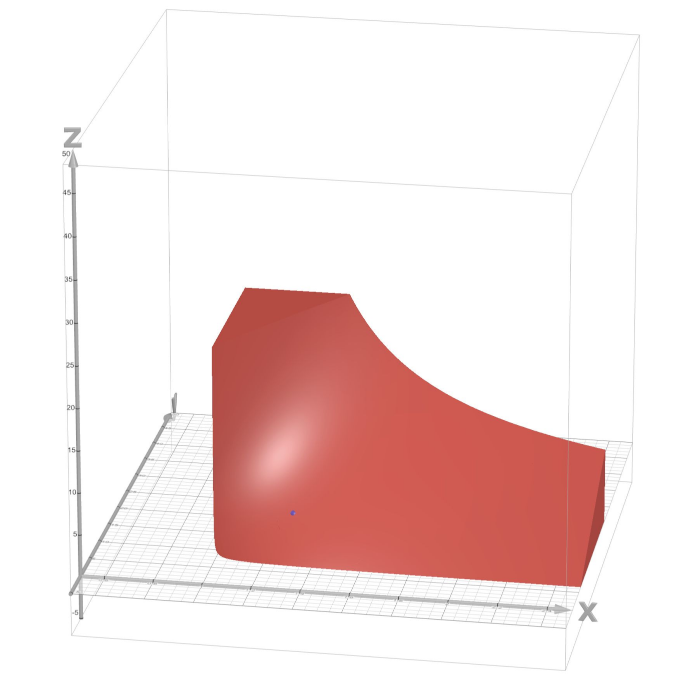
Combined regions within our working region





Region of the most stable sails

Sail Optimization



Region that our sail sits in
(accounting for size and mass)

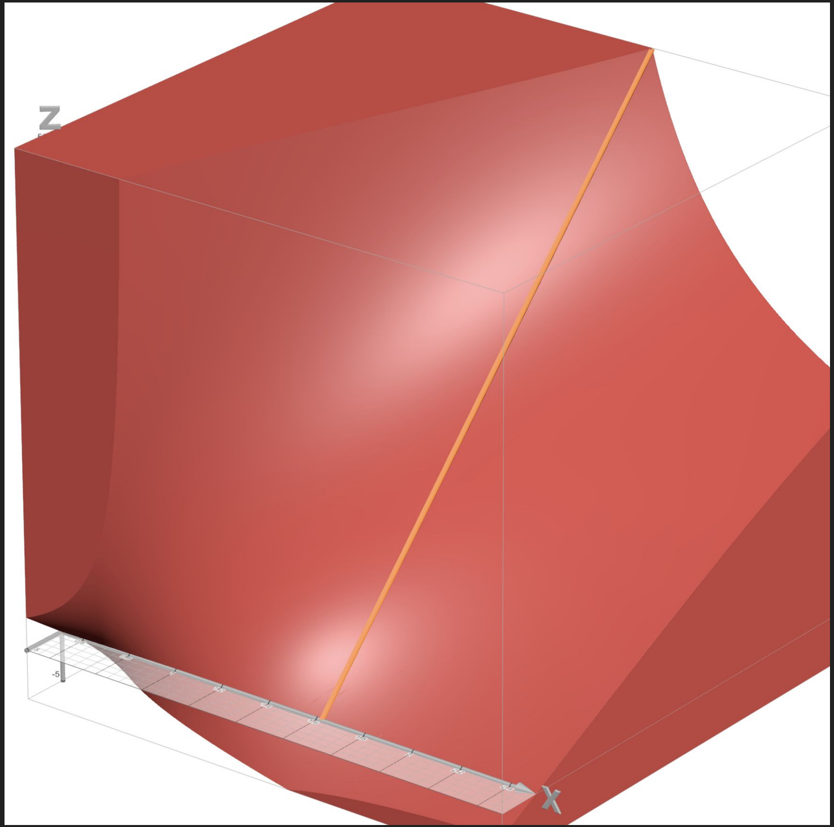
We chose 1.3 ratio, inner angle of 10 deg, outer angle of 5 deg.

it seems that the y angle (for moments) is ideal at just below the difference between the maximum disturbance torque and the maximum allowable angle. As such we find that x of 1.1-1.3 is ideal, and the angles should be close to their maximums. This maximum angle should be determined by the maximum torque expected.

Weird Math Quirk

The bounding line on rotational stability is a line given as (ϕ, t, t). The golden ratio appears in sail geometry optimization!

Note on overall optimization:
For rotational stability, sail was approximated as a 2D cross section, assumed standard gaussian beam profile.



Materials

- Sail area estimated to be between 2- 5m^2
- Sail mass target < 5 kg
- One side reflective coating, other blackbody coating to equalise temperature from constant IR (~2kW / m^2)
- Dielectric mirror reflectivity target: 99.9999% (for optimal thermals and feasibility of the mission)
- Reflective thin-film dielectric material coating: non reactive, durable, withstands oxidation and cracking, good surface stability (silver)
- Black Keronite coating (developed from PEO coatings): extremely resistant, ultra-low friction, been tested on ISS MEDET system

Reliability

Thermodynamics and Rapid Unscheduled Disassembly

Critical Question:
Would impact from space debris or a mirror imperfection threaten the mission?

Key points:

@ .999999 reflectance, steady state is 285K

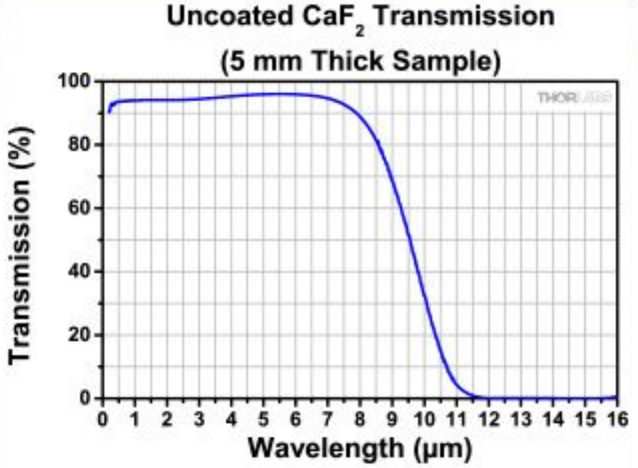
@ .9997 reflectance, steady state is 1235K (=silver T_{melt})

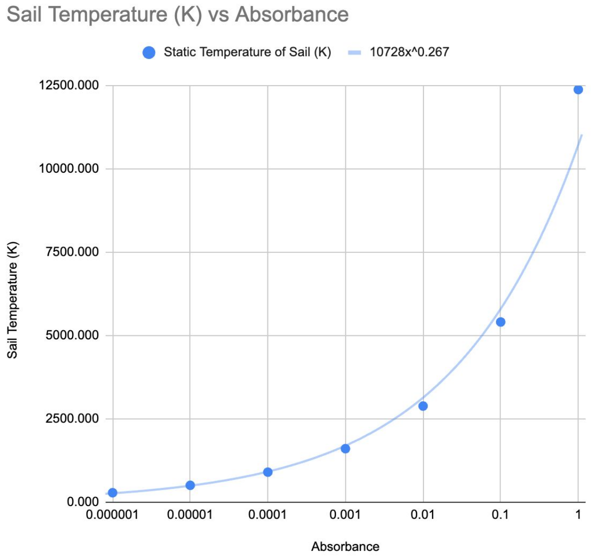
@ .999 = CaF_2 T_{melt}

Panels with cracks likely to melt, but not vaporize instantly

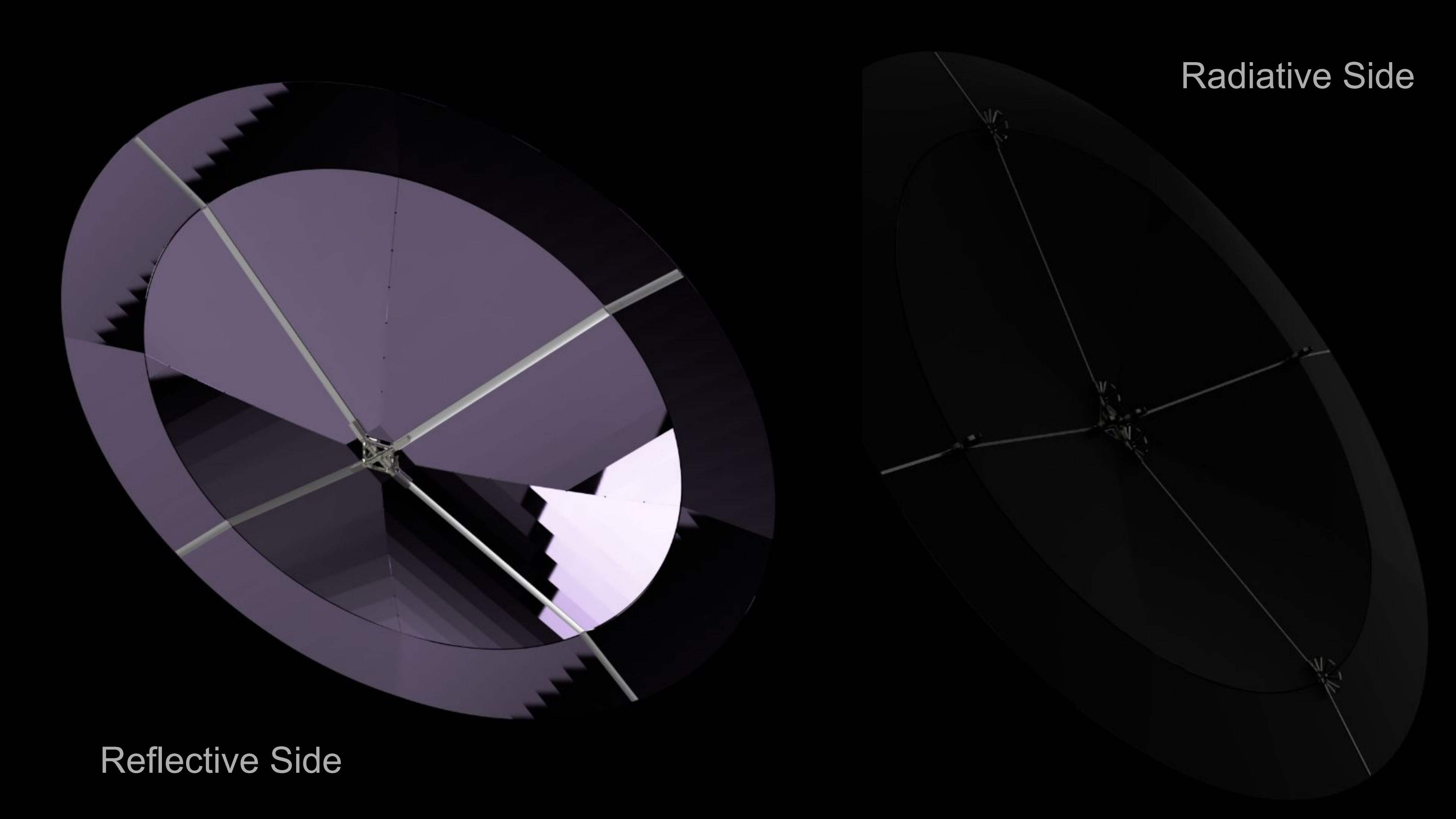
Chain reaction unlikely

Debris below .995 reflectance becomes plasma very, very fast, though unlikely to severely impact mission





Absorbance	Reflectance	Temperature Difference (K)	Static Temperature of Radiative Layer (K)	Static Temperature of Sail (K)	Emissivity of coating	0.86			
1	0	3363.760	9021.295	12385.055	Thermal conductivity	429	W m^-1 K^-1	For CaF2	9.71
0.1	0.9	336.376	5073.047	5409.423	Cross Sectional Area	3.0963	m^2		
0.01	0.99	33.638	2852.784	2886.421	Silver Thickness	0.00005	m		0.0001
0.001	0.999	3.364	1604.238	1607.602	Input Laser Wattage	1000000000	W		
0.0001	0.9999	0.336	902.129	902.466					
0.00001	0.99999	0.034	507.305	507.338					
0.000001	0.999999	0.003	285.278	285.282					


Radiative Side
Reflective Side

Design

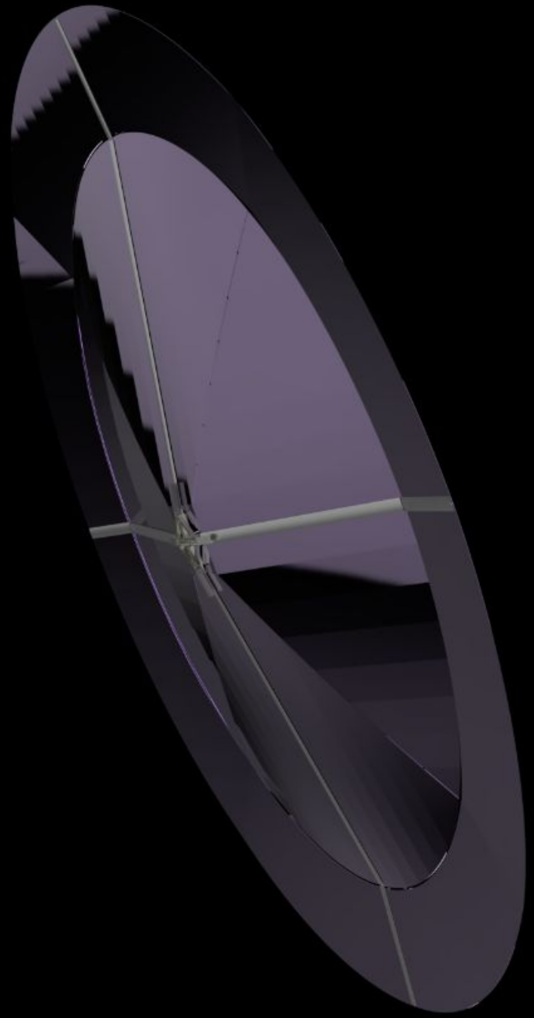
Design

Sail Geometry

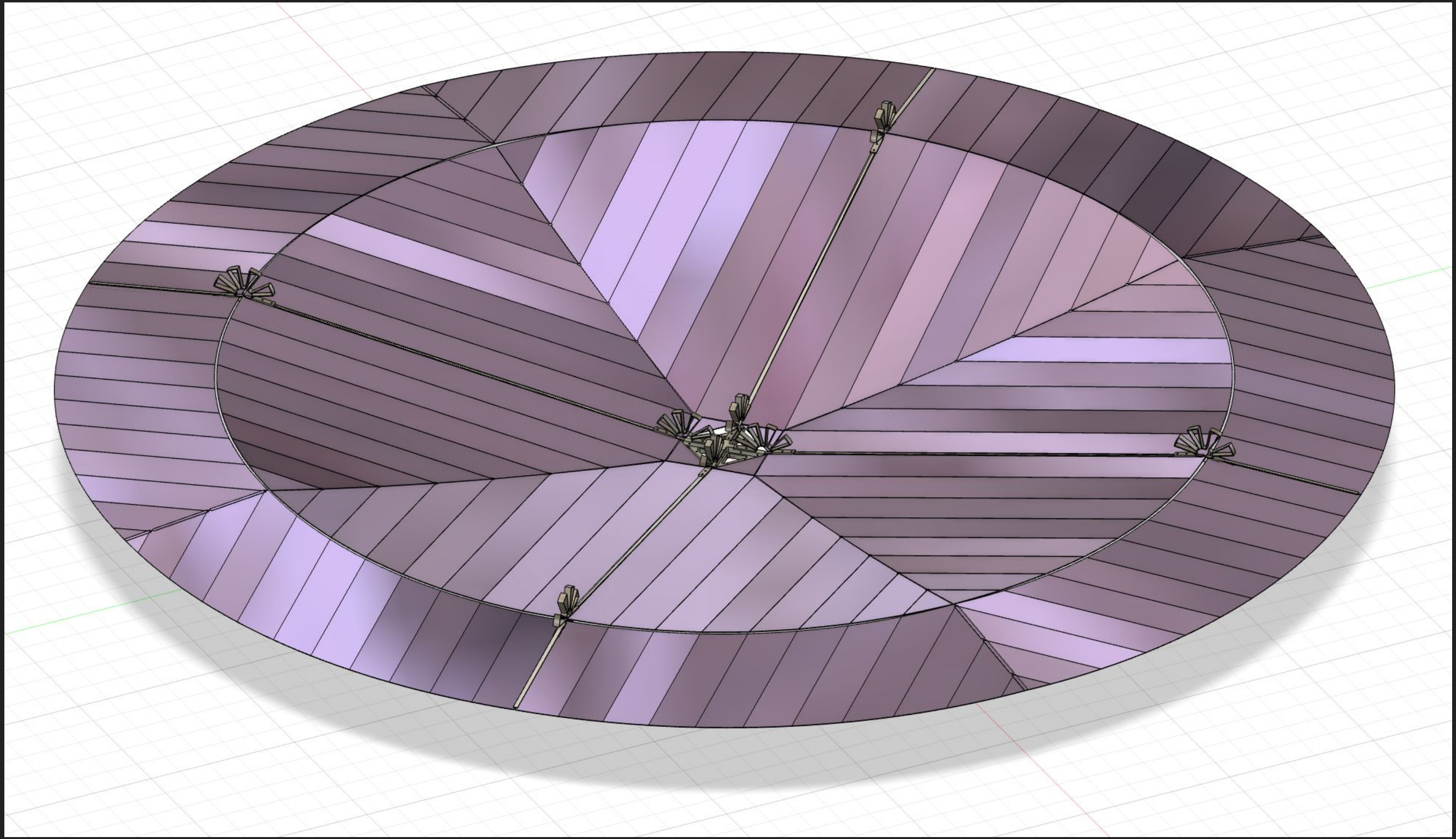
Deployability

Rigidity and Safety of Mirrors

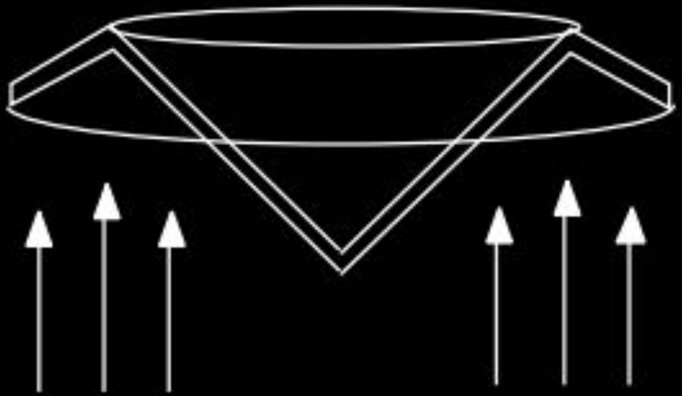
Using Factor of Safety: 1.25



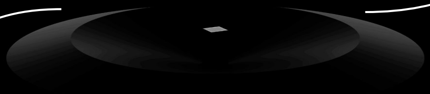
CAD



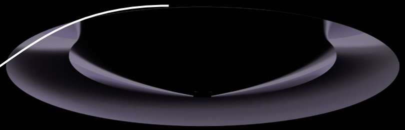
Concept



Proposed self-stabilizing
sail cross-section

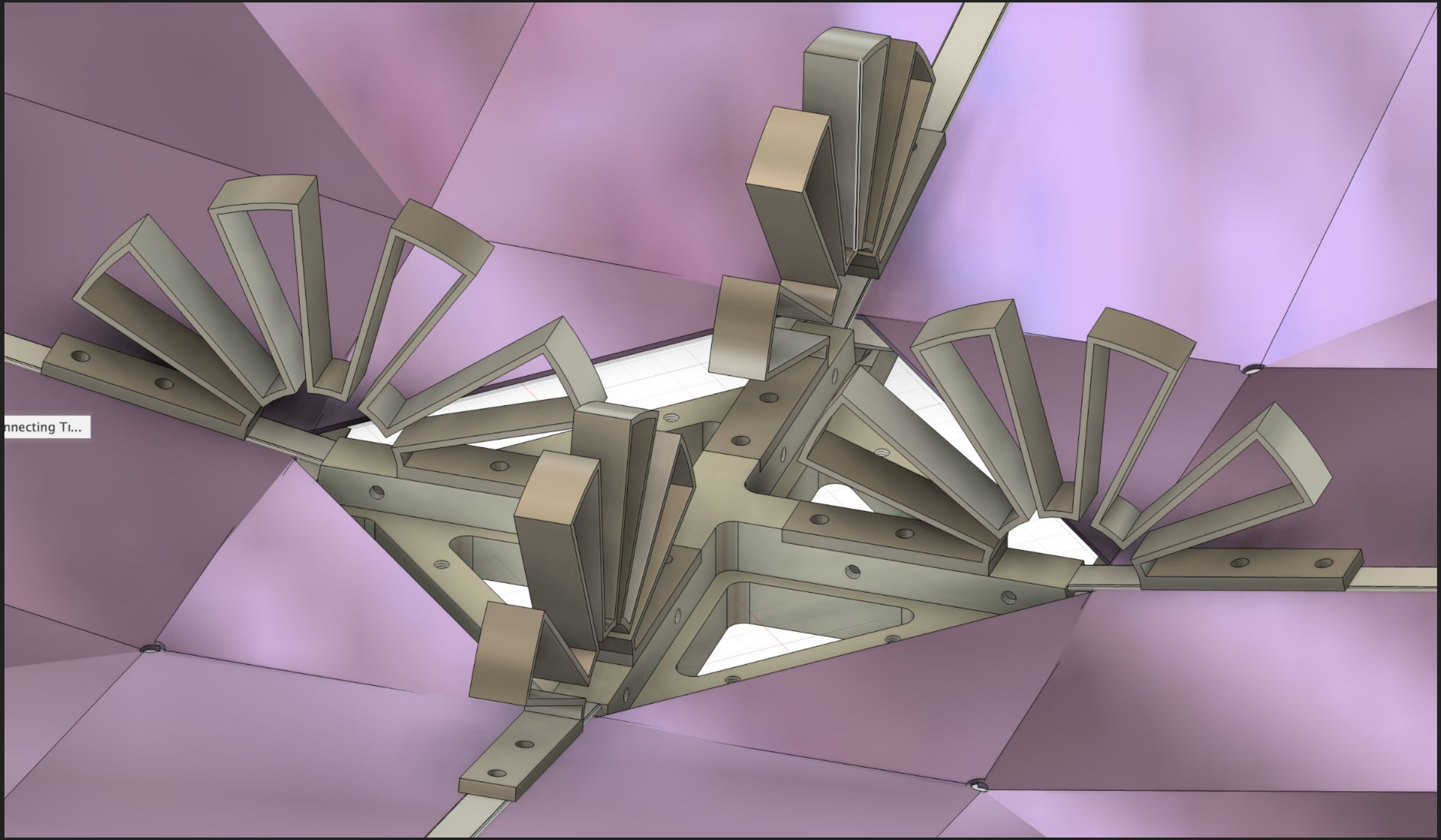


Concept render
(radiative side)

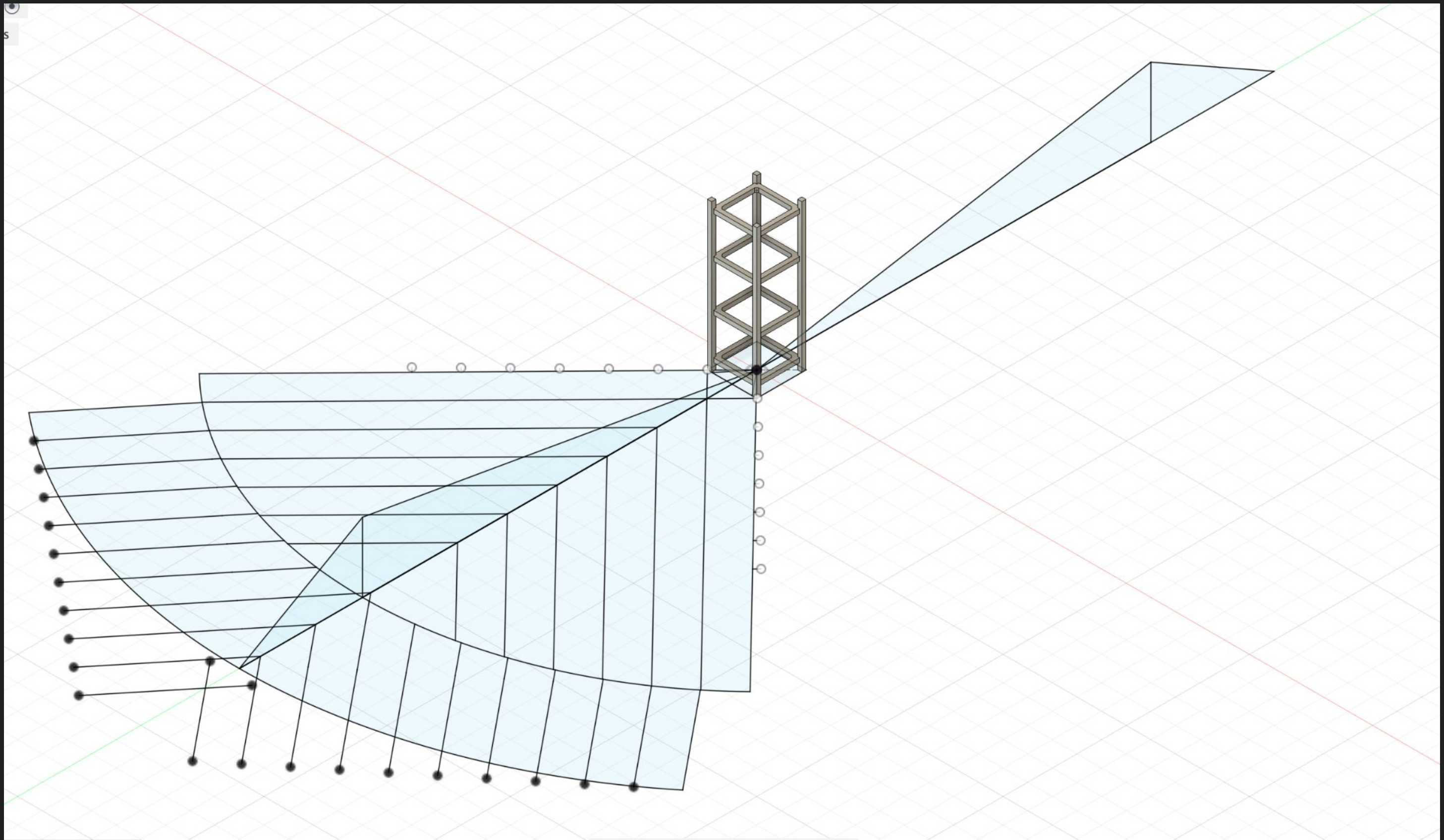


Concept render (mirror
side)

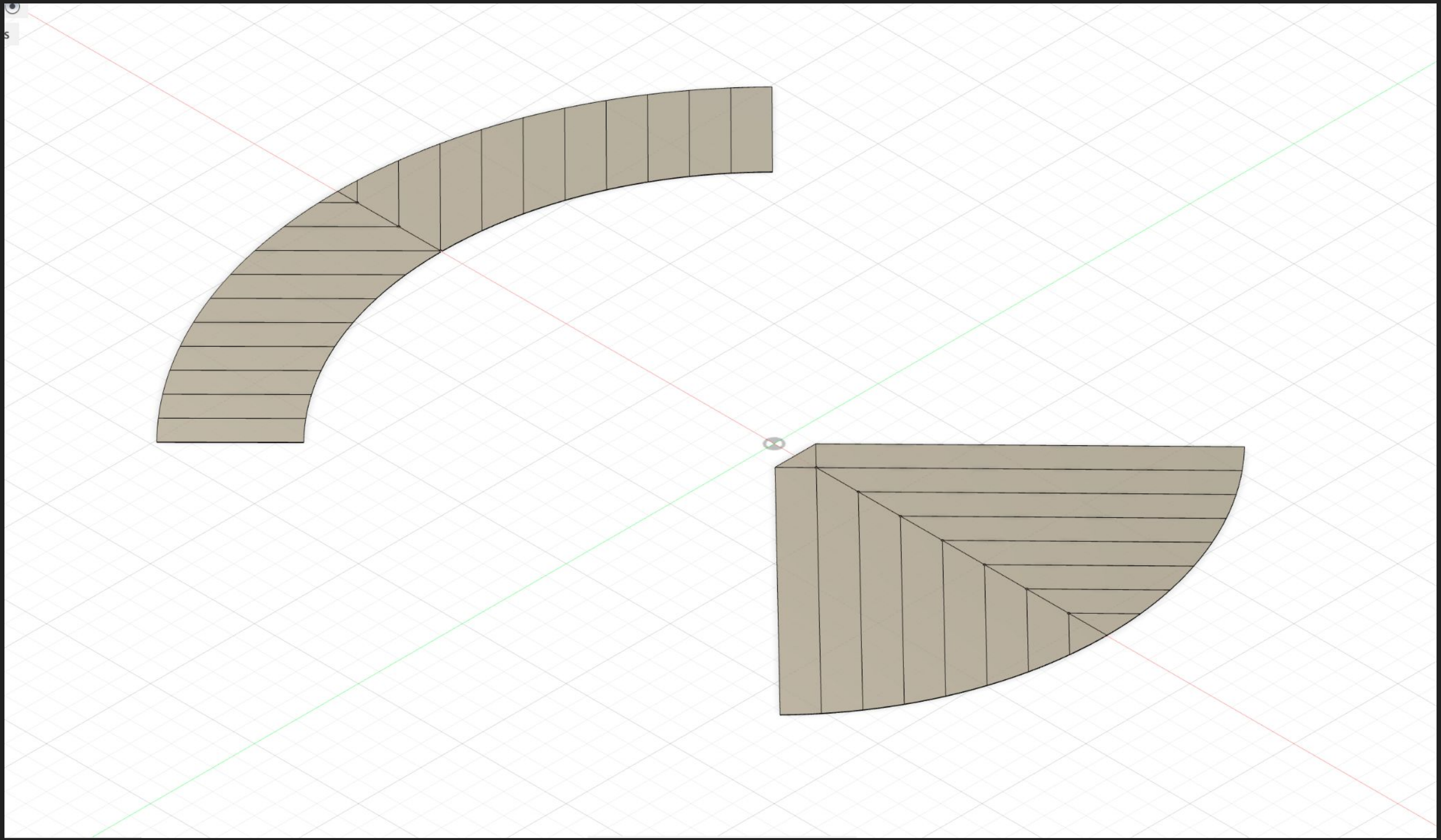
Drawings and Renders



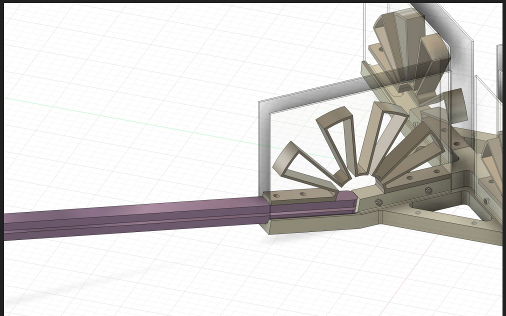
Drawings and Renders

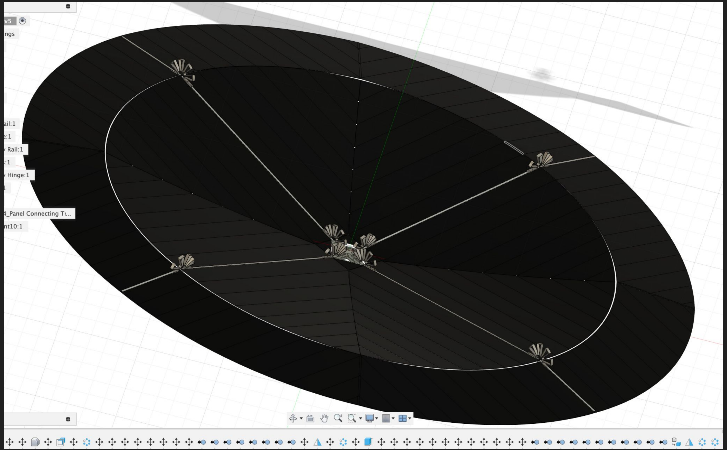


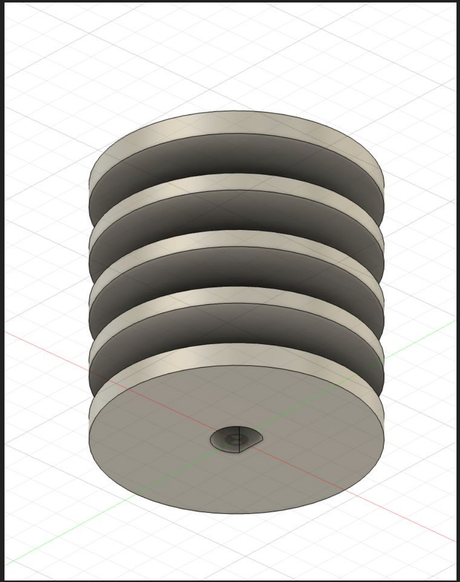
Drawings and Renders

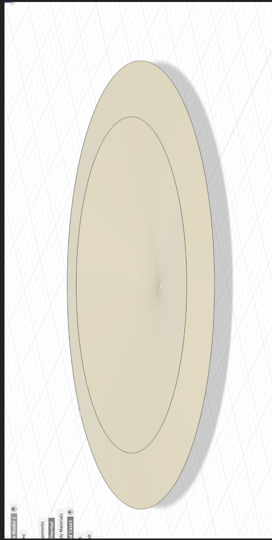


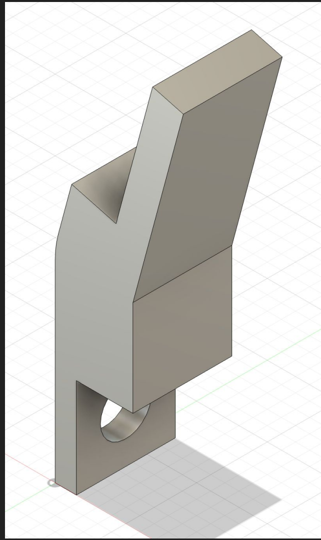
Drawings and Renders

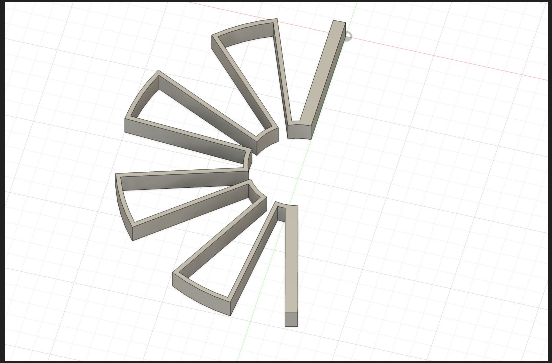


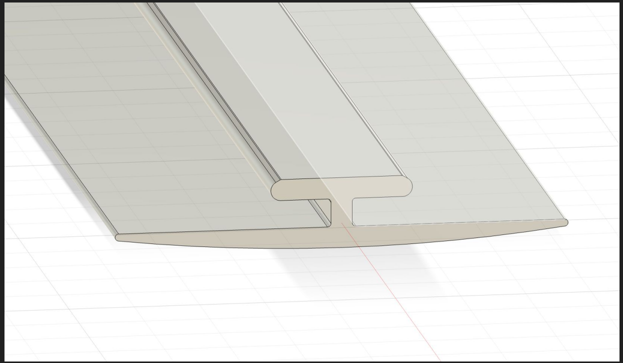




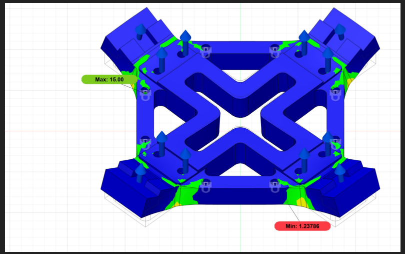


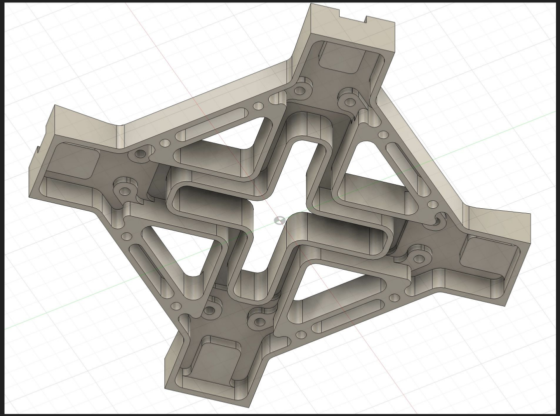




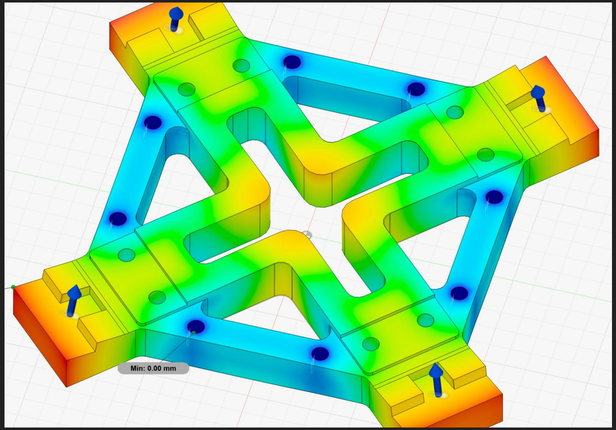


Base Part (Root) w/FEA (Thermal, Stress, Static, & Dynamic have been completed)

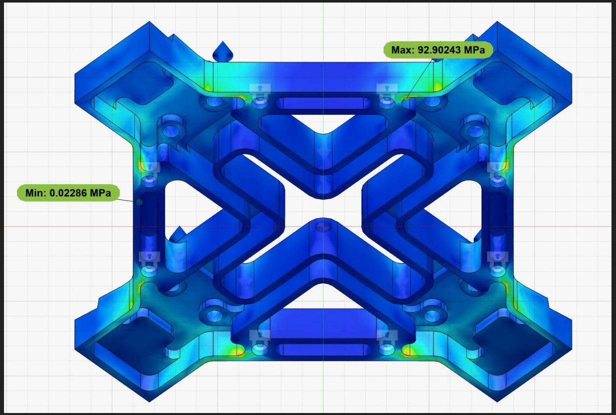




Base CAD Model



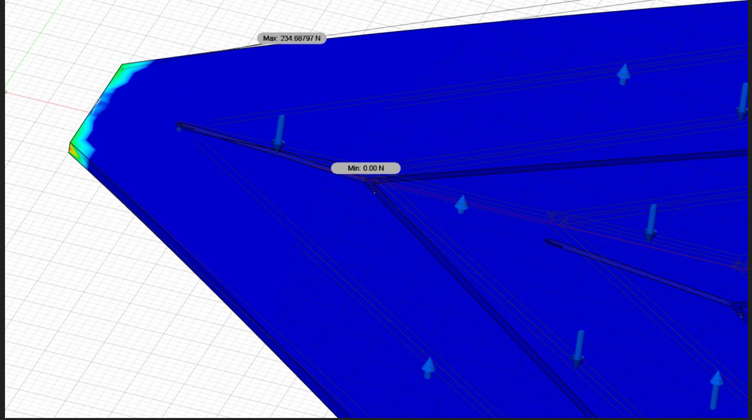
Base CAD Model with FEA



Base CAD Model under maximum thrust

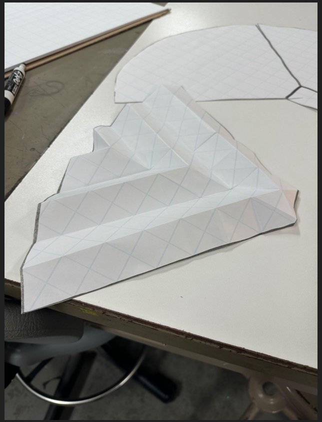
Prototyping

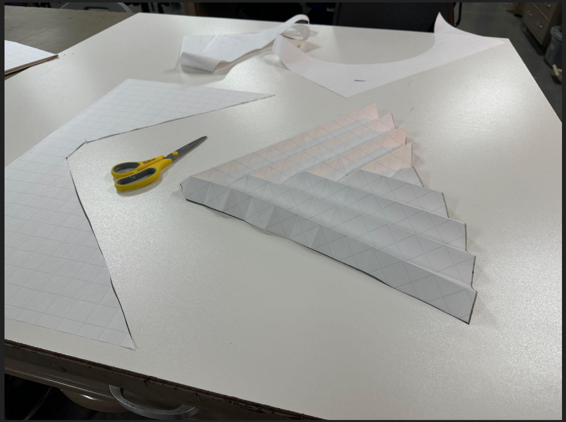
Concept render



Basic reaction force FEA for deployment

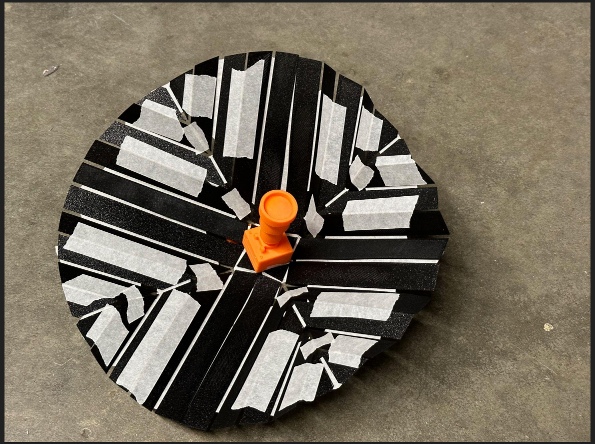
Paper sail folding mockups



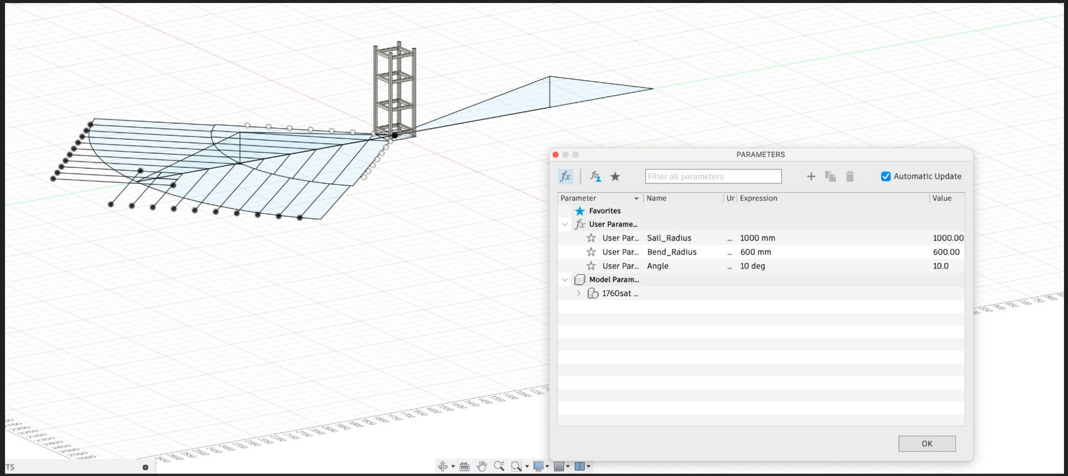


Prototype: Step 1

3D Printed Folding Mechanism

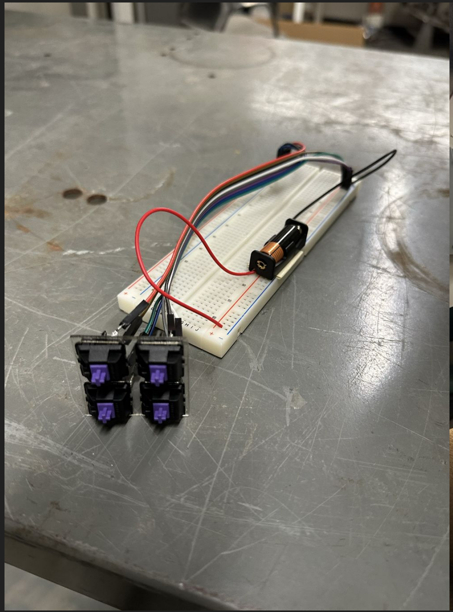


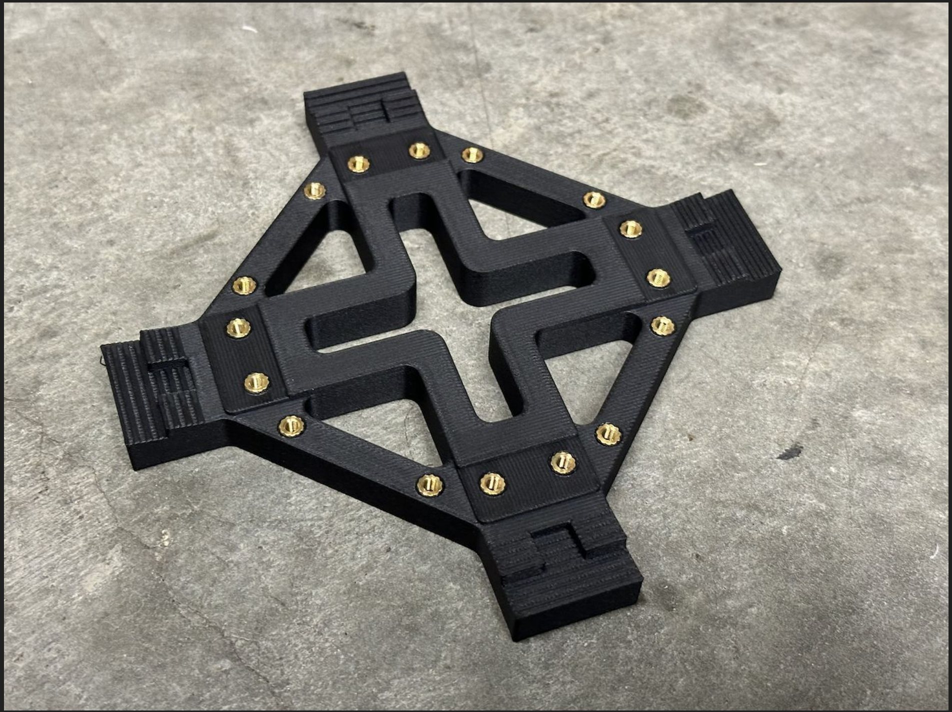
Parametric CAD model



Prototyping: Step 2

Build Project





Build Project

Demonstration and Proof of Concept

Final prototype: large-to-full scale solar sail prototype with deployment system

Caveat: At 1.25 FoS, this design does not fully function at 1.00G! We expect a maximum acceleration when deployed of 0.67g. As such, we only intend to demonstrate the inner sail deployment, which incidentally has a higher FoS.

Outer section collapses under Earth gravity >>>>>>>>>>>>>>>>>>>>>>>>>>>>>

Sources of Funding

- Private Companies and Investors
- Government Grants and Contracts
- Academic Institutions
- Crowdfunding
- International Collaborations
- Military Funding
- Prizes from Competitions

Budgeting and Costs

Overview

Laser Stations	$11.2b per laser array
Sail Material	~$70k / m^2
Manufacturing	~$500k
Integration and Labour	~$3m
Nuclear Energy	$8.1m per 17 days of acceleration
Estimated Program Infrastructure Cost	$100-150b
Price Per Launch	$4-20m (including rocket to LEO)

GLASS would provide a price of **$2.2k-81k / kg** - ($16.1m for 100kg, $30m for 10MT)

Note: 100kg can be accelerated to 10 km/s for just $4m, $16.1m figure is for 1000 km/s

Cost Breakdown: Subsystems

Subsystem	Cost ($)
Structures and Materials	~$740,000
ADCS	$7,000-$1M Dependent on Payload
Ground Control	$200k
Laser and Communications	$8.1M for 17 day acceleration
Management and Operations	$4M

Cost Breakdown: Parts

Part	**Cost ($)**
Sail Material (Mirror + Coatings)	$70,000 / m^2
Rails	$2,650
Base	$850
Misc Parts	$450
Deployment Mechanism	$3,000-$10,000
Payload Connector	Dependent on Payload

Cost Breakdown: Mass

Subsystem/Part	**Mass (kg)**
Mirror	2.9-3.8kg dependent on payload
Rails	0.136kg
Base	0.076kg
Misc Parts	0.038kg
Deployment Mechanism	0.5-1.0kg dependent on payload
Payload	100kg-10MT

Cost Breakdown: Orbital Mechanics

Situation	Cost/Risk
Multiple Payloads	Ground Stations (at this point) are single target. Would require some adaptation or building of more.
Heavy Payloads	Heavy payloads pose a risk of re-entering if unsuccessfully targeted
Inclement Weather	Inclement weather can affect laser effectiveness
Rotation of Earth	As the Earth rotates, targeting capabilities of ground stations change

Cost Breakdown: Power

Subsystem/Part	Power (W)
Nuclear Station	+2.5GW
Laser	1.0GW (-1.5GW efficiency loss)
Atmospheric Loss	-0GW (negligible)
Sail	Converts 1.0GW Laser to Thrust
Communications	1-3 W while using TDRS, once further out will use continue to increase
Payload is powered on internal battery, would be a separate power budget	

Policy and Geopolitics

Ground-Based Lasers: A Geopolitical Double-Edged Sword

Powerful laser + satellite targeting capabilities

Weapon capable of destroying enemies' satellite infrastructure

Utopian future of sustainable space travel

- Laser capable of ablating or disabling satellites in orbit
- Building laser could be perceived as a threat and could raise geopolitical tensions between countries
- Remote location increases potential for hijackings
- Skirts boundaries related to regulation on the peaceful use of outer space

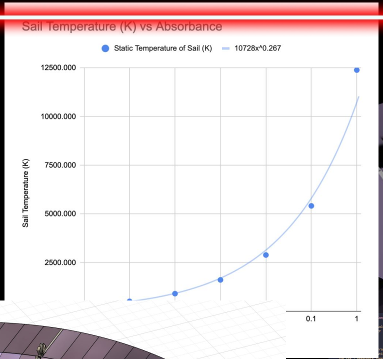
Policy on Space Laser Systems

- 1967 Outer Space Treaty
  - Only specifies that weapons of mass destruction cannot be placed **in orbit**
  - Clarifies that any use of space must be for the benefit of mankind
- Committee on Peaceful Uses of Outer Space (COPUOS)
  - Wrote the Liability Convention of 1972 treaty, which would hold any country that authorized the use of a ground-based laser to be liable for any destruction it caused
- Lack of Precedent
  - Powerful laser systems capable of targeting satellites are still in the early stages (at least publicly)
  - It is unclear how a laser system will be received by other world powers
  - The absence of established norms increases risks of misuse

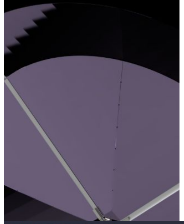
Nuclear Power Complications

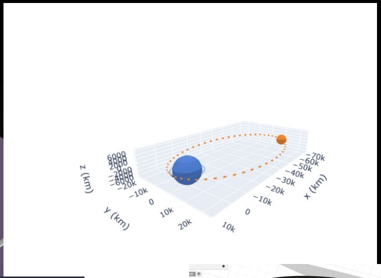
- Fuel Transportation Risk
  - Radioactive material is volatile and dangerous to transport
  - Transportation will require tight security measures
- Nuclear power hasn’t crossed the chasm
  - Although nuclear power is the best energy source for our power usage specs., nuclear is still mired in regulation and politics that can make building them expensive and full of delays
  - No new nuclear plants have been created in Britain since 1990
  - France is pioneering Small Modular Reactors capable of producing half our power requirement. Building two of these would lower the cost and be more feasible to build in remote regions.

Thanks!

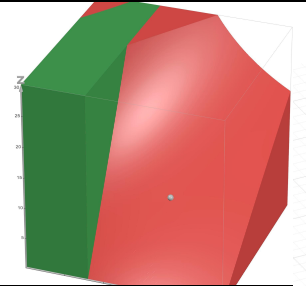


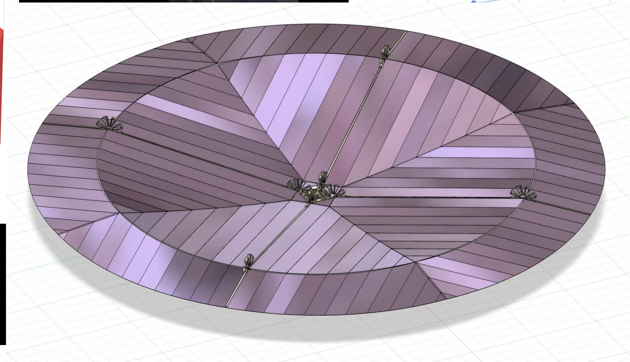
Sail Temperature (K) vs Absorbance
Static Temperature of Sail (K)
10728x^0.267
12500.000
10000.000
7500.000
5000.000
2500.000
Sail Temperature (K)
0.1
1

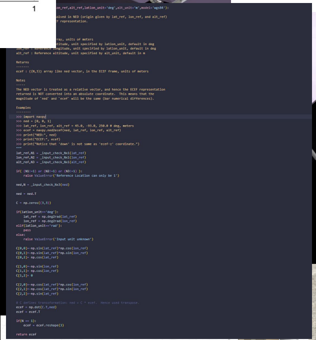


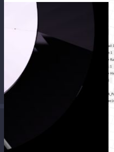


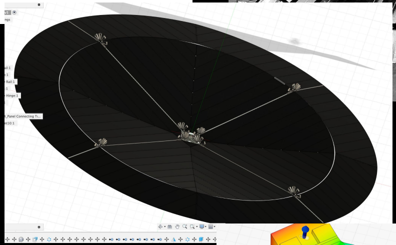
z (km)
y (km)
x (km)

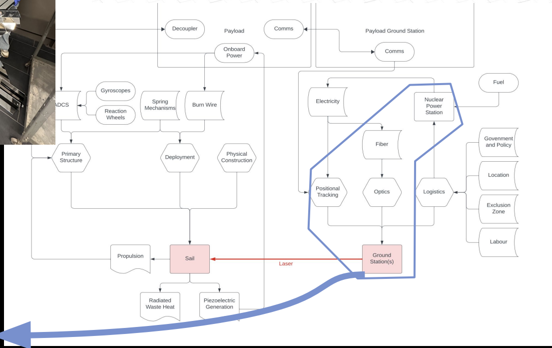




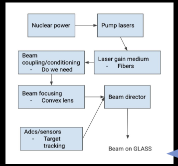




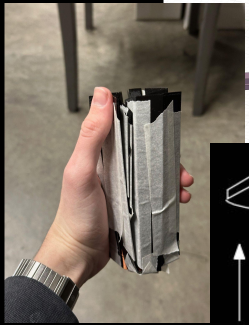


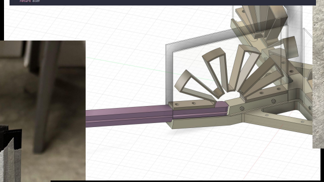


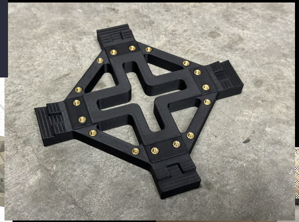
Decoupler
Payload
Comms
Payload Ground Station
Onboard Power
Comms
Fuel
ADCS
Gyroscopes
Reaction Wheels
Spring Mechanisms
Burn Wire
Electricity
Nuclear Power Station
Government and Policy
Fiber
Primary Structure
Deployment
Physical Construction
Location
Positional Tracking
Optics
Logistics
Exclusion Zone
Labour
Propulsion
Sail
Laser
Ground Station(s)
Radiated Waste Heat
Piezoelectric Generation

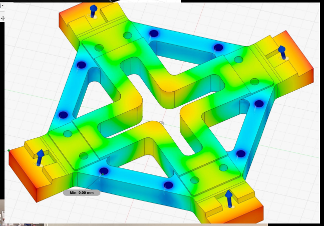


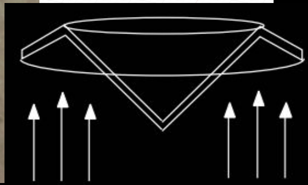
Nuclear power
Pump lasers
Beam coupling/conditioning
- Do we need
Laser gain medium
- Fibers
Beam focusing
- Convex lens
Beam director
Adcs/sensors
- Target tracking
Beam on GLASS











Acknowledgements and References

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BDW Staff

Dan Marella

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