Image Credit: Endurosat 12U CubeSat Platform and Chassis Image

Analytical Cost-Optimization of Orbital Parameters and Propulsion Solutions for SPS in LEO

TEXAS SSPS

The University of Texas at Austin
Aerospace Engineering
and Engineering Mechanics
Cockrell School of Engineering

Undergraduates

Abdulbari Agboola

Peyton Burlington

Mark Dunn

Faculty Advisor

Adam Nokes

Agenda Overview

- Introduction
- Problem and Mission
- Methods and Analysis
- Economic Results
- Conclusion

Problem and Mission

Background

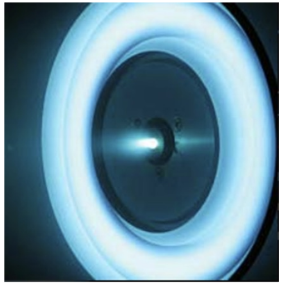
Space solar power has been considered ***technically feasible*** since the 1970s, provided sufficient technological development in **key areas:**

- In-space large structure assembly
- High-efficiency solar energy conversion devices (photovoltaics, batteries, etc.)
- Super-heavy reusable launch vehicles

There is a **select amount** of data on the economic merit of performance parameters. This project focuses on analysis of the following **design parameters:**

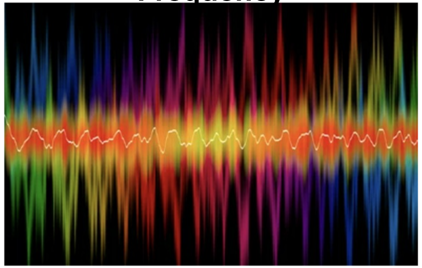
Orbital Configuration

Propulsion System



[1]

Power Transmission Frequency



Mission Objective

For a Solar Power Satellite (SPS) in Low Earth Orbit (LEO), we shall identify the most **economical** approach considering tradeoffs between:

Orbital Configurations

Power Transmission Frequency

Propulsion Systems

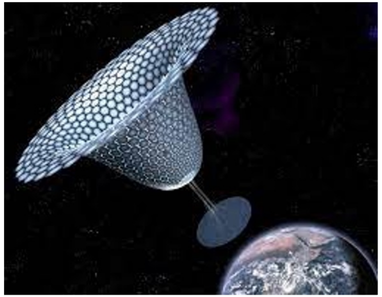


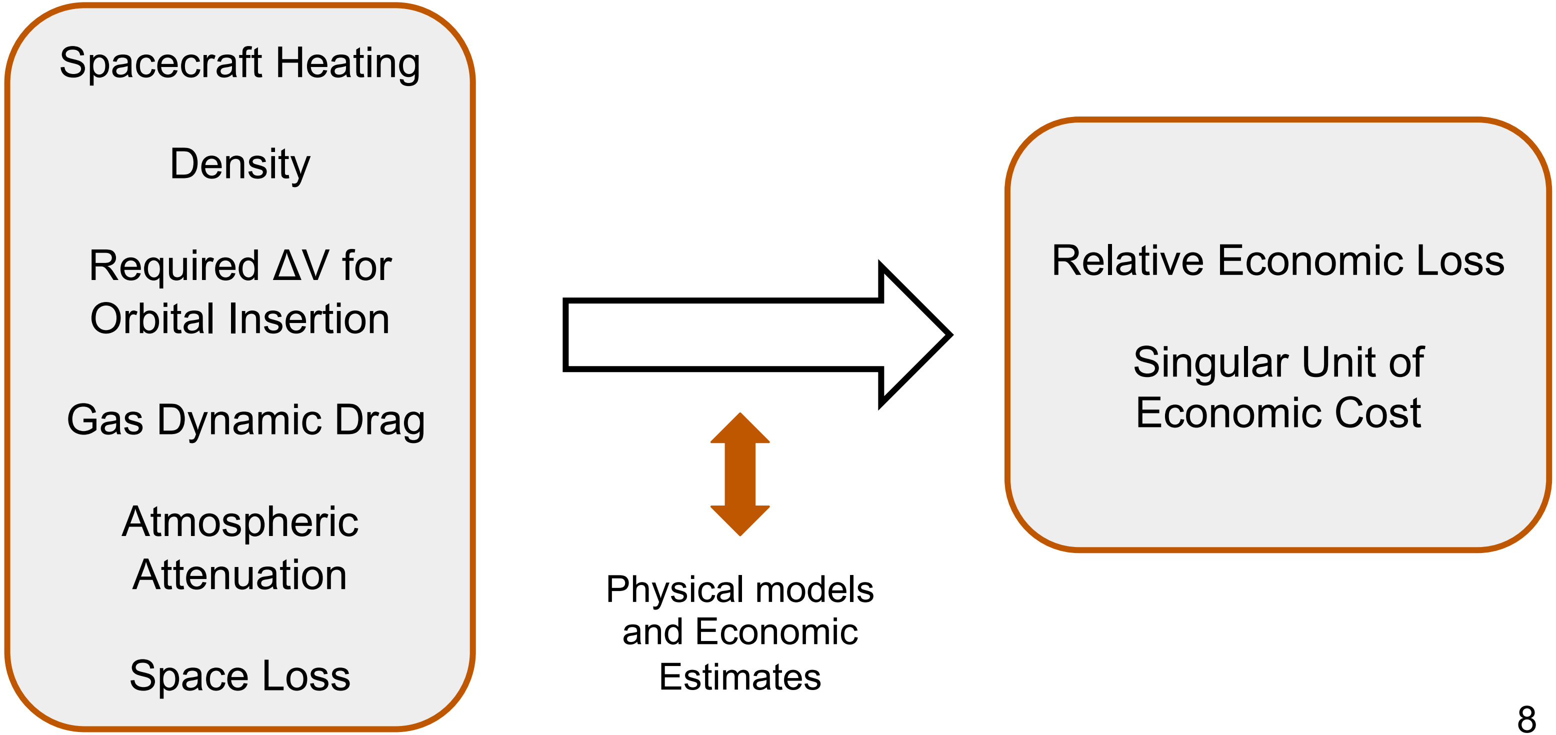
Figure 1: Conceptual image of a solar power transmission satellite

Methods and Analysis

Cost Optimized Orbit Analysis Approach

Performance Parameters

Output



Spacecraft Heating

Density

Required ΔV for Orbital Insertion

Gas Dynamic Drag

Atmospheric Attenuation

Space Loss

Physical models and Economic Estimates

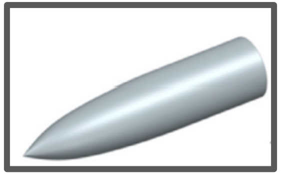
Relative Economic Loss

Singular Unit of Economic Cost

Preliminary Assumptions

Drag Calculation

- Spacecraft Frontal Area: 5, 25, and 125 m^2
- Mission duration: 50 years
- Launch Vehicle: SpaceX Falcon 9 ($2000/kg to LEO)
- Retail price of energy delivered: $0.23/kWh
- Coefficient of drag, C_D = 2.0



- Surface emissivity = 0.92 (Z93 coating)
- Accommodation coefficient, α = 0.05
- Dispersive collision fraction, g = 0.05

Figure 2: Streamlined Spacecraft Body Assumption [17]

Power Attenuation Calculation

- Antenna efficiency = 55%
- Altitude-averaged atmospheric thermodynamic parameters
  - Temperature = -44.2 ℃,
  - Water vapor density = 0.15 g/m^3
- Domain of analysis:
  - Frequency: [0, 50] GHz
  - Receiver Aperture Area: [0, 100] km^2
  - Altitude: [100, 2000] km

Physical Model: Density and Drag Calculation

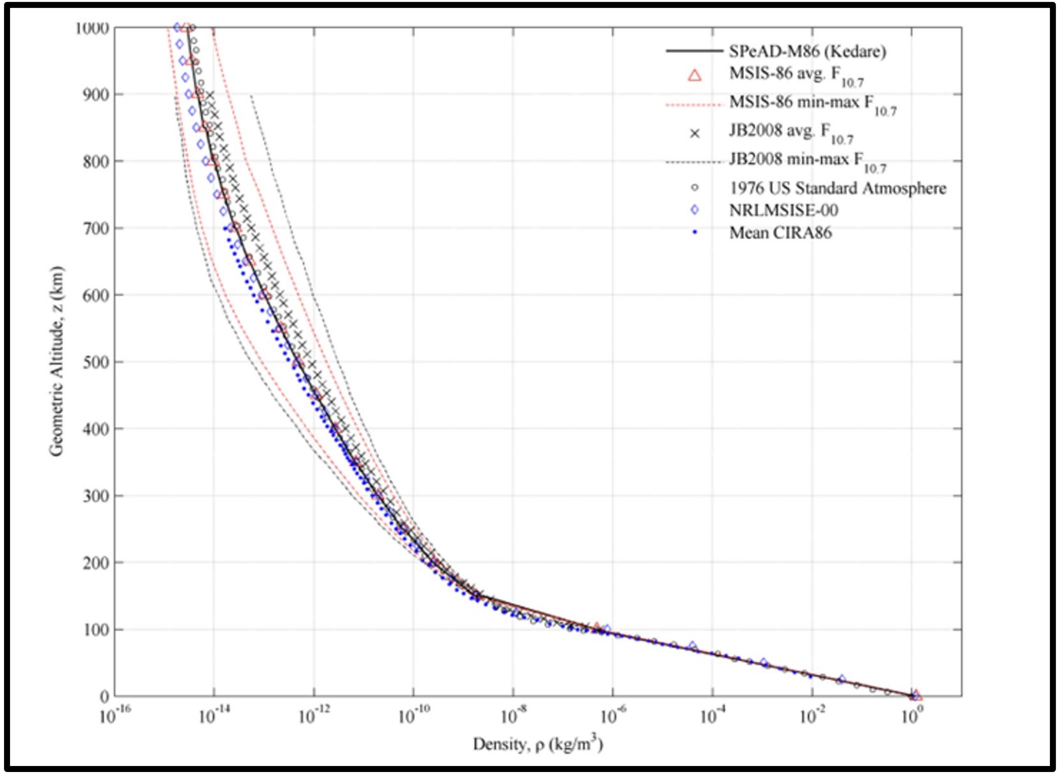


Figure 3

$$ma_{x,aero} = -\frac{1}{2}\rho V_R^2 A_{ref} C_X(\alpha,\beta,S,\sigma,T_w)$$

ρ_∞ = freestream density, u_∞ = freestream gas speed

h_0 = stagnation enthalpy, h = enthalpy

ε_r = spacecraft reflectivity

σ_{SB} = Stefan-Boltzmann constant

Relating Drag to Propulsive Requirements

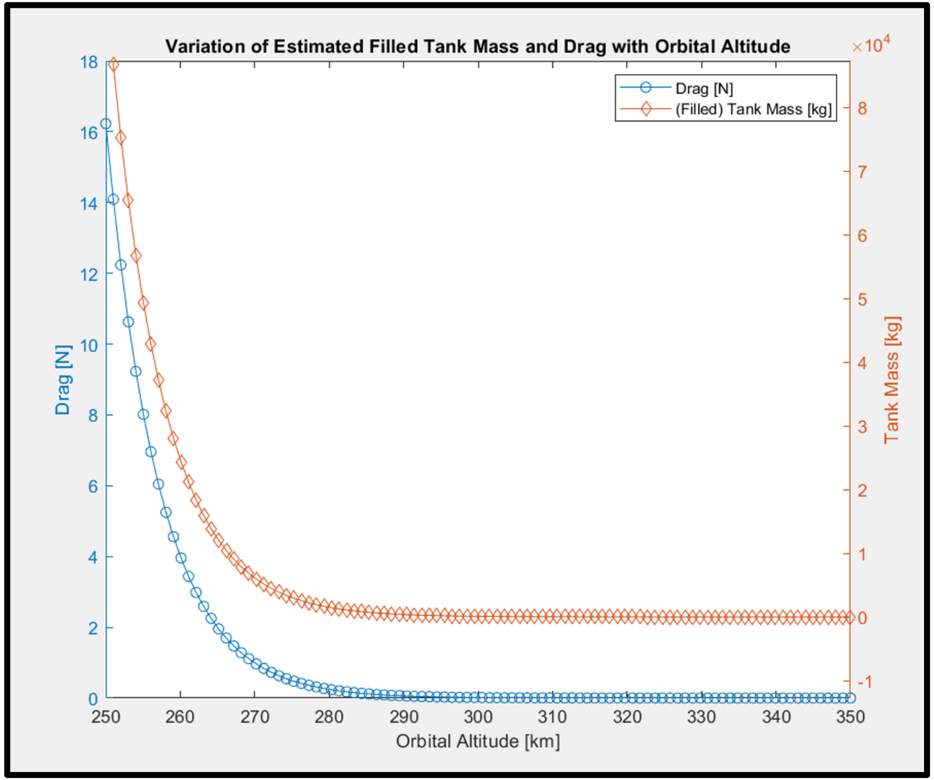


Figure 4

The following ideal gas rocket sizing equations were used for Xenon storage as a compressed gas (150 bar, 300K):

$$M_{tank} = \rho_w \cdot V_{tank} = \rho_w \cdot (4\pi R^2 \cdot t)$$

$$t = \frac{R \cdot P_{G0}}{2 \cdot \sigma_{allow}}$$

$$R = \left(\frac{1}{4} \cdot V_{gas}\right)^{1/3}$$

M_t = tank mass
ρ_w = tank wall density
t = tank wall thickness
P_{Go} = Initial tank internal Pressure
V = Volume

Physical Model: Launch Cost

Assumptions:

- This model calculates the launch cost as a function of altitude and eccentricity
- Keplerian orbital mechanics.
- The initial orbit is a circular orbit of 100 km altitude ($\Delta v \sim 8$ km/s).
- ‘Cost per Δv’: ~$1000 per 1 m/s (from SpaceX Falcon 9 payload to LEO launch cost) [3]

$$\boxed{\Delta v \approx \sqrt{\left(\frac{2\mu}{r_i}\right) - \left(\frac{\mu}{r_f}\right)}}$$

μ = gravitational parameter
r_i = initial radius at apogee
r_f = final radius at apogee
v = spacecraft speed

Physical Model: Atmospheric Attenuation & Space Loss

- Atmospheric Attenuation calculated using:
  - International Telecommunication Union (ITU-R P.676-10)

- Free Space Path Loss calculated using:

$$FSPL(dB) = 20\log_{10}(d) + 20\log_{10}(f) + 92.45$$

Figure 5:

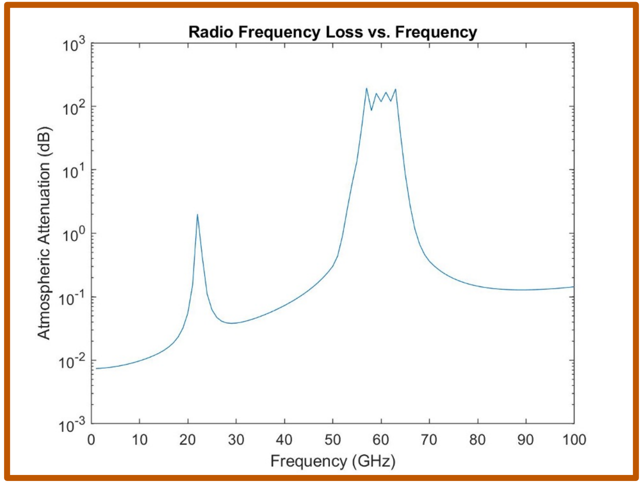
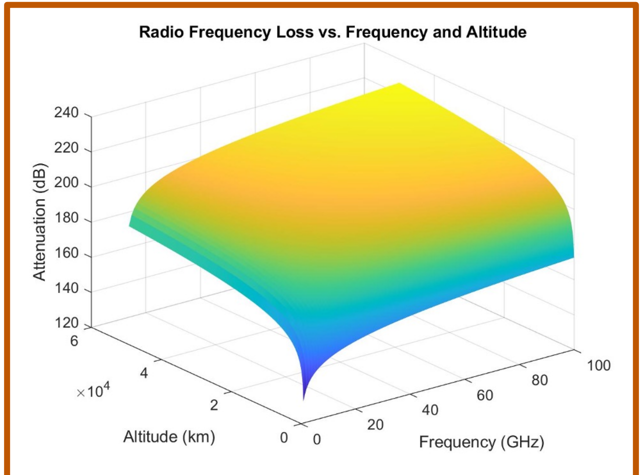


Figure 6:



Cost-Optimized Frequency

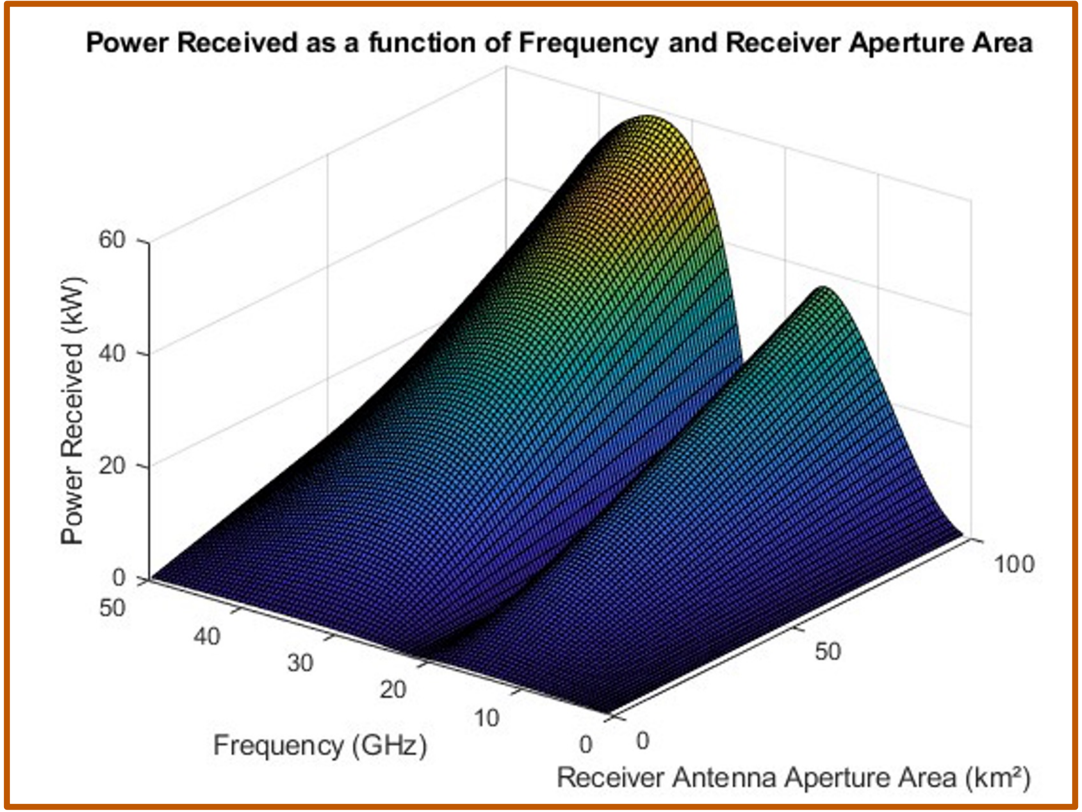


Figure 7

- Current technology with high efficiencies exist currently under 50 GHz.
- The optimal frequency is **33.67 GHz.**
- A secondary peak occurs at **15.78 GHz.**

$$G_{db} = 10\log_{10}\left(\frac{4\pi\eta A}{\lambda^2}\right)$$

Eq: Antenna Gain

[9]

Economic Results

Performance Data to Economics

A **Monte Carlo analysis** was used to quantify the economic merit associated with the following physical parameters for 15,000 orbital configurations for a space-based solar power system.

SpaceCraft Heating

Density

Required Delta V for Orbital Insertion

Gas Dynamic Drag

Atmospheric Attenuation

Space Loss

×

$2000/kg for orbital insertion

$0.23/kWh price of energy

=

Economic merit of **orbital configuration** & **power transmission frequency**

Results - Mission Cost

Legend

- ● 125 m^2 frontal area
- ● 5 m^2 frontal area

Total Mission Cost as a Function of Altitude and Eccentricity

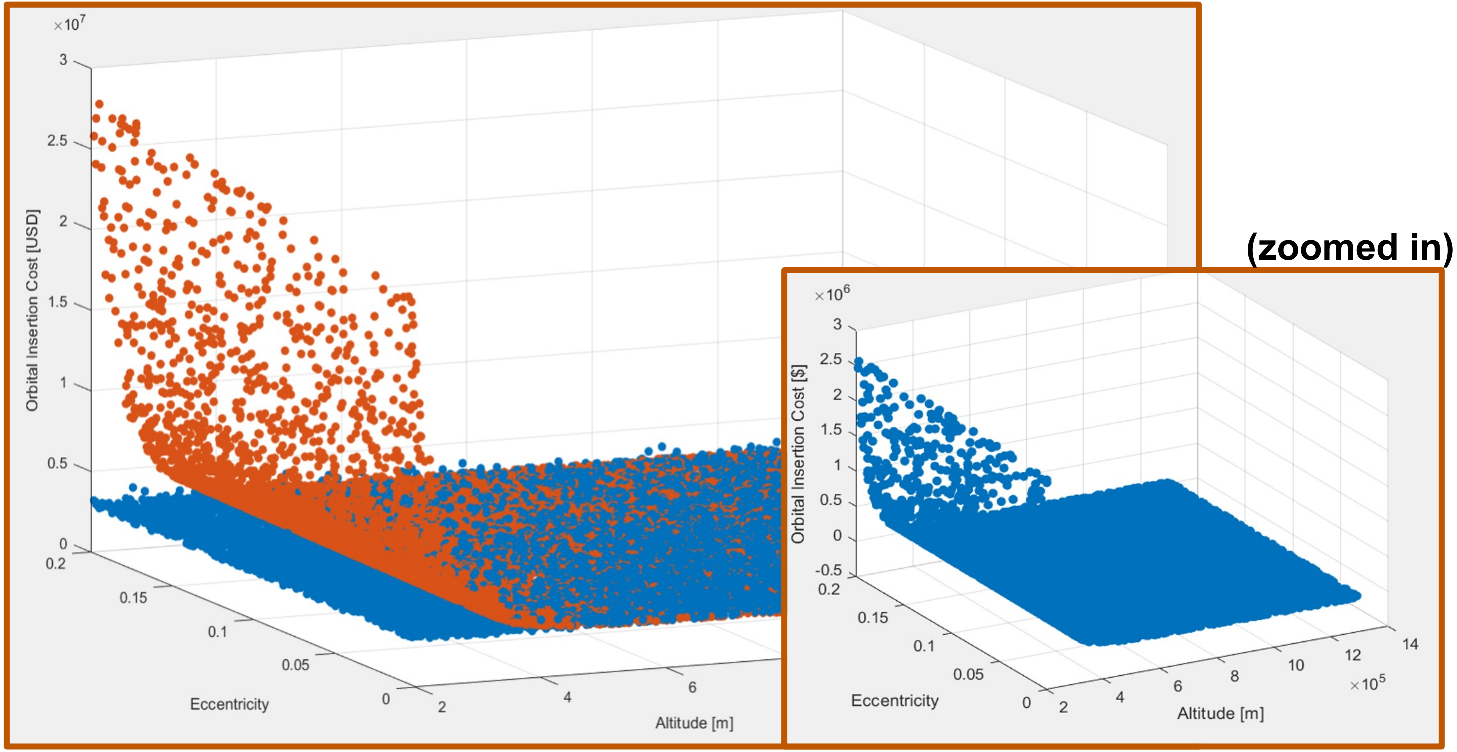


Figure 8

Mission Cost: 2D View

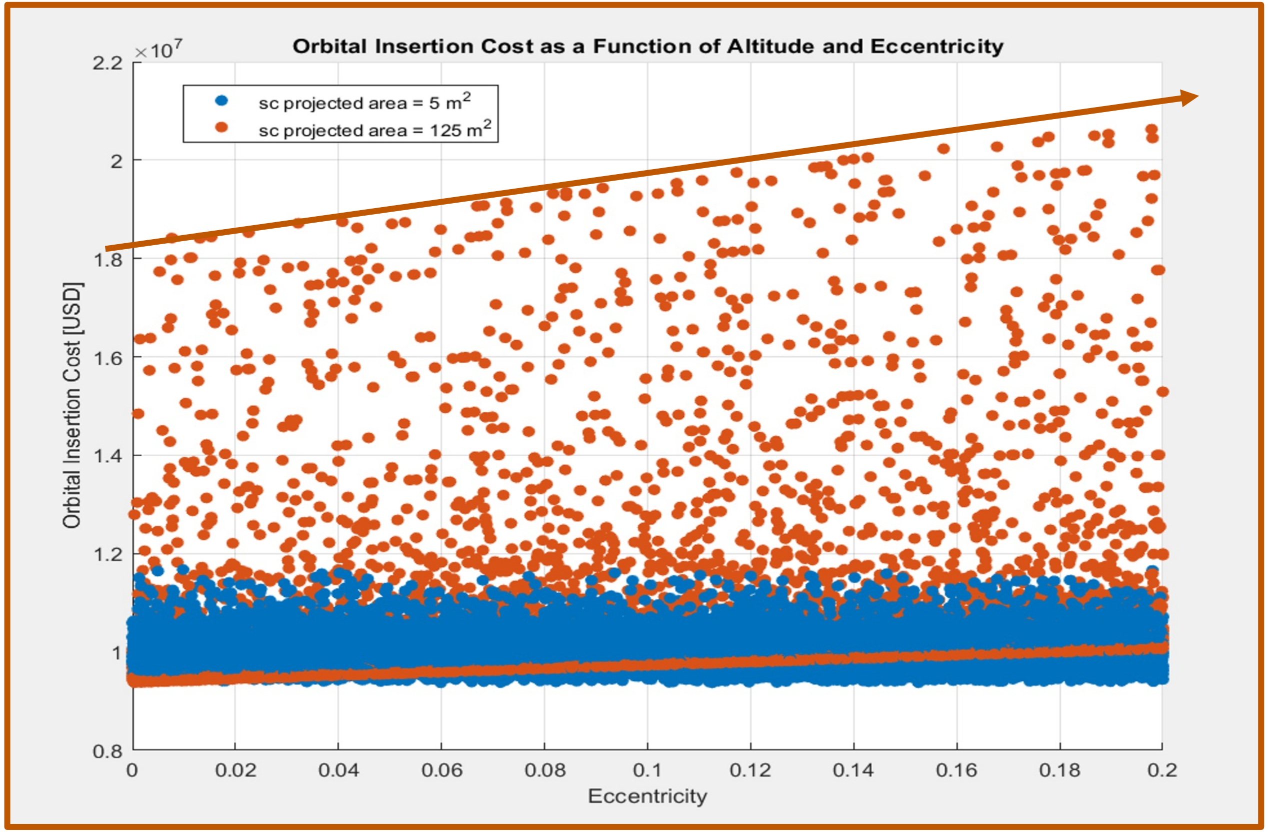


Figure 9:

Results Continued

Spacecraft Projected Area [m^2]	5	25	125
Optimal Orbital Altitude [km]	301	377	461
Optimal Eccentricity	~0	~0	~0
Total Projected Cost [Billions of USD]	9.38	9.73	9.94

Orbital Inclination Determination - Oblateness Perturbations

- Precession of the **ascending node, Ω**, due to J2.

$$\frac{d\Omega}{dt} = \frac{-3}{2} \cdot J_2 \cdot \left(\frac{R_E}{a(1-e^2)}\right)^2 \cdot \sqrt{\frac{\mu_E}{a^3}} \cdot \cos(i)$$

- Critical ***inclinations*** of **63.43 or 116.57 deg** minimizes perturbative effects [58].

- The delta-v required for an inclination change of 5.99 deg, as necessary for a launch from the Pacific Spaceport Complex, is 801 m/s.

Altitude Required for Repeating Ground Tracks

$$a_{RGT} = \mu^{1/3}\left(\frac{M}{N\omega_B}\right)^{2/3}$$

$a_{RGT} = Orbital\ Radius$

$\mu = Gravitational\ Parameter$

$M = \#\ of\ Rotations\ of\ Earth$

$N = \#\ of\ Spacecraft\ Revolutions$

$\omega_B = Rotational\ Sidereal\ Frequency\ [1/s]$

Summary: Resulting Orbit and Targeted Customers

1. Altitude: 404 km.
2. Eccentricity: 0.
3. Inclination: 63.43.
4. Longitude of the ascending node (LAN) contingent on specific customer's location.
5. Repeat period: 2 days.
6. Launch site: Pacific Spaceport Launch Complex (latitude: 57 deg.).

Plots of Orbital Trajectory

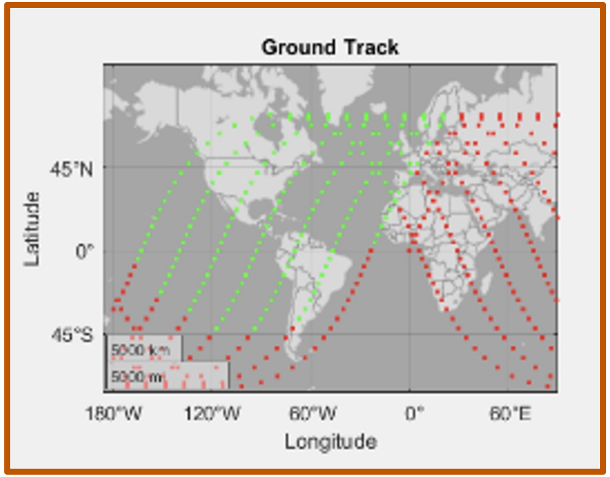


Figure 10

Off-the grid Canadian communities host more than 200,000 people.

- Whitehorse (latitude: 60.72 deg N).
- Yellowknife (62.45 deg N).
- Arviat (latitude: 61.1078 deg N).

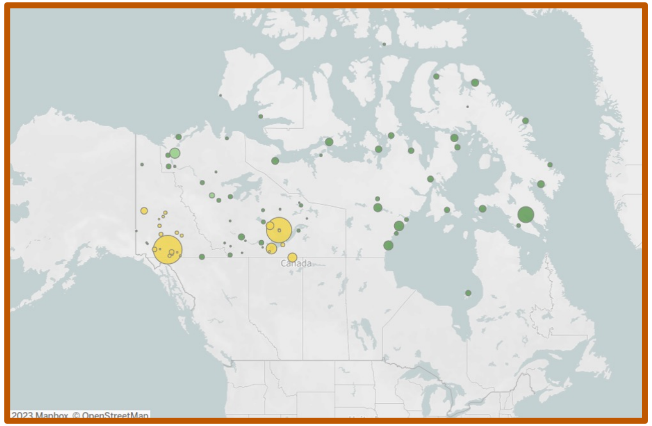


Figure 11: Map of Off-the-Grid Canadian Communities [27]

Upper Atmosphere Gas Dynamic Drag - Monte Carlo Analysis at 400 km

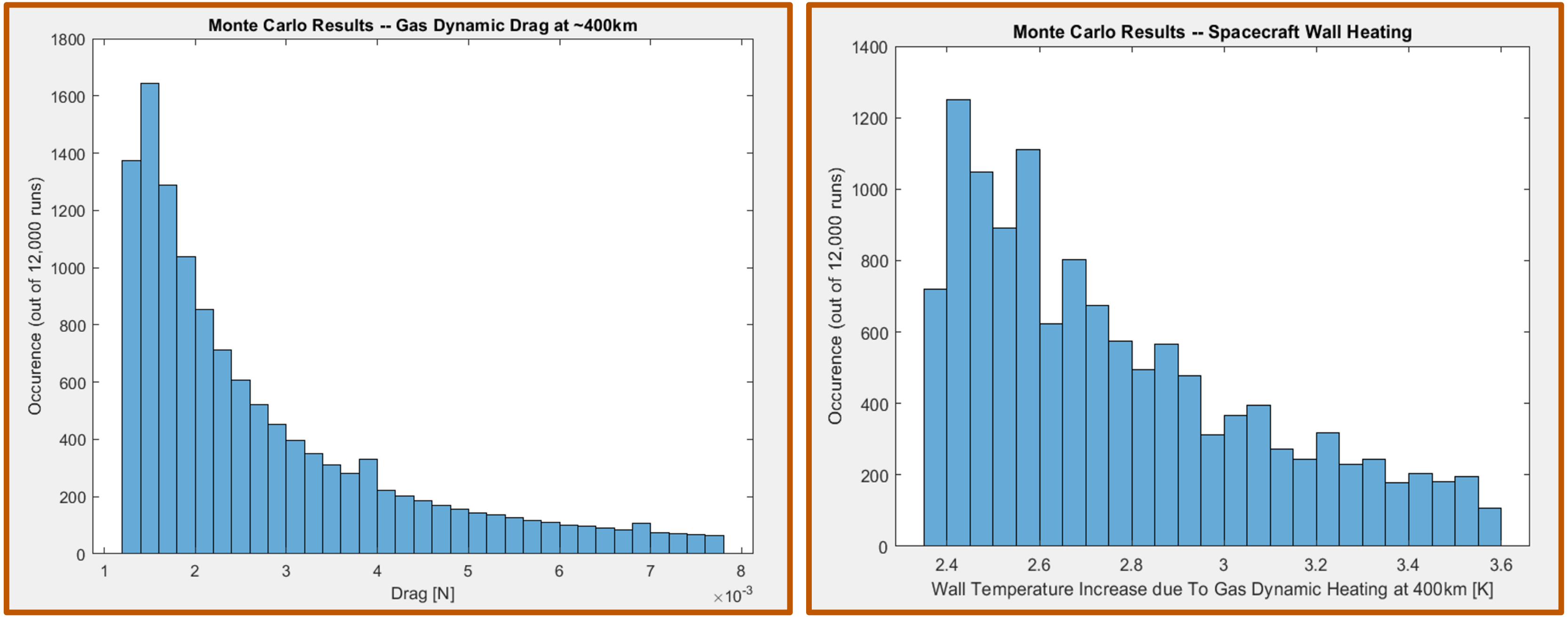


Figure 12 [3, 37].

Optimal Propulsion Engine Given Altitude

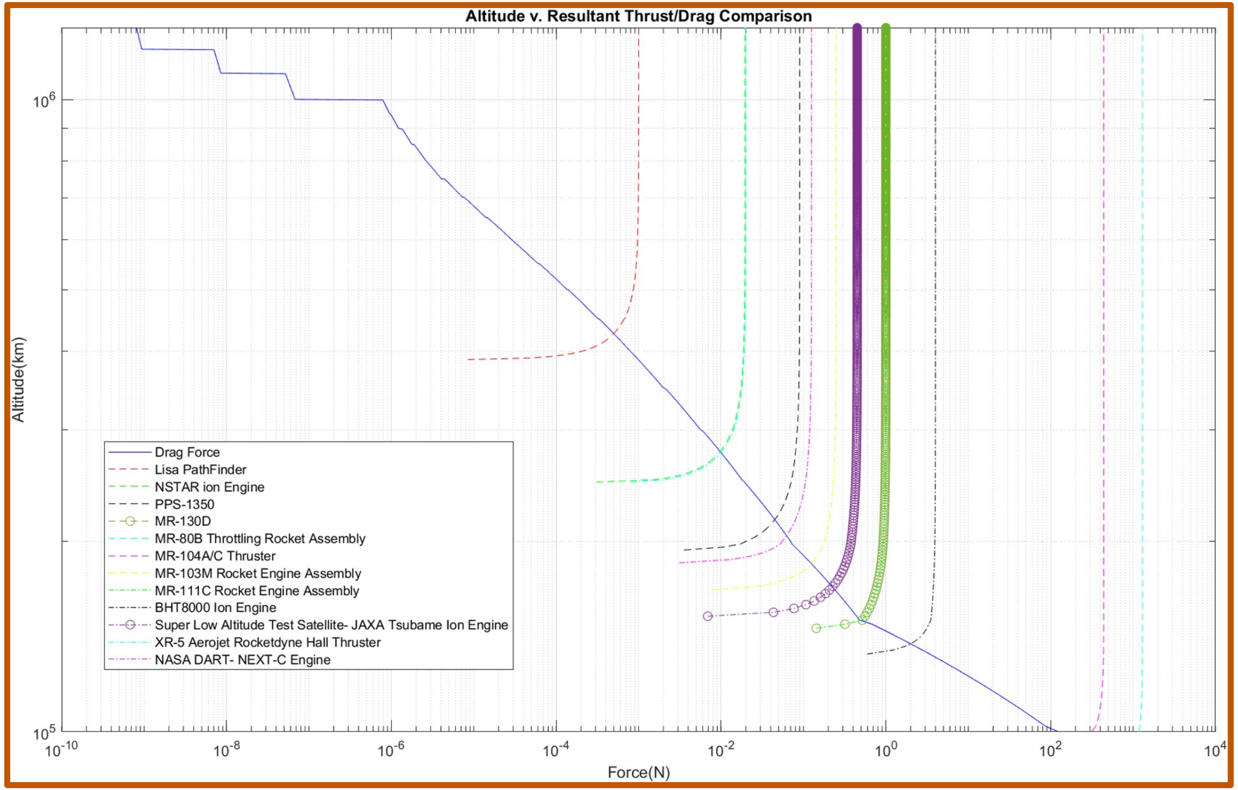


Figure 13

Thank You! | Questions?

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