Ambient Atmosphere Ion Thruster (AAIT) Proof-of-Concept Modeling

AIAA-2011-XXXX

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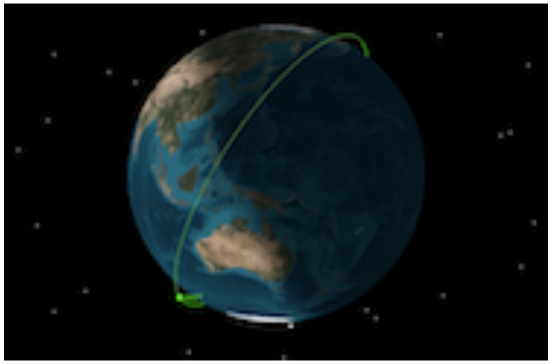
47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit

Motivation



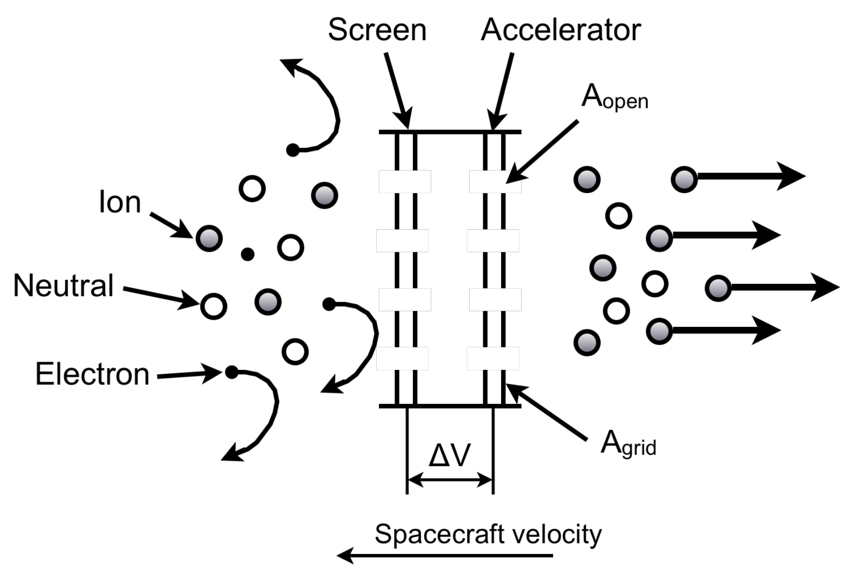
- Satellites growing more prevalent in military, communications, and science applications
- Satellite lifetime limited by amount of on-board propellant for drag makeup
- Design an alternative propulsion system which utilizes in-situ particles (ions)
- Presence of in-situ ions makes a case for using electric propulsion (EP)
- **Goal:** *Create tool to estimate on-orbit performance of EP that utilizes in-situ ions*

Introduction

- Ambient Atmosphere Ion Thruster (AAIT) utilizes in-situ ions to eliminate on-board propellant mass
    - G. Dressler (AIAA-2006-4650)
- Designed for electrostatic acceleration of ambient ions with two biased grids
    - Uses screen grid and accelerator grid to create electric field and accelerate ambient ions
- Use on-board power generation (e.g. solar arrays) to provide power for ion acceleration
- **Focus:** Predict AAIT performance by integrating thruster mathematical model with atmospheric model
    - Use orbit propagator to output orbit parameters

Electrostatic Thruster Model

- Created a mathematical model that estimates AAIT performance with an integrated atmospheric model
- Developed thrust, drag, and power from fundamental equations
- Requires given AAIT parameters:
  - Total grid area
  - Grid transparency
    - Ratio of open grid area to total grid area
  - Acceleration voltage



Model Assumptions

- Fixed spacecraft frame of reference
  - Incoming ion velocity is equal in magnitude but opposite in direction of spacecraft velocity
  - Neglect random thermal motion of ambient particles
  - Ion temperatures of approximately 0.2 eV result in thermal speeds much less than orbital speed
- Uniform particle number densities across grid area and satellite frontal area
- Grid transparency fixed at 90%
  - Assume 10% of all ions and neutrals impact screen grid
  - Neglect optical transparency of ions
- Electrons repelled by screen grid bias

Thrust

- Development of thrust begins with conservation of momentum in fixed spacecraft reference frame:

$$T = \dot{m}v = \sum_i \dot{m}_i \left(v_{out,i} - v_{s/c} \right)$$

- Spacecraft velocity, $v_{s/c}$, determined with orbit propagator
  - Reduces computations within performance code
- Ion exit velocity, $v_{out,i}$, determined from energy conservation
  - Assume singly-charged ions (Z=1)

Thrust (continued)

- Inserting these relationships into thrust equation:

$$T = \sum_i m_i n_i A_{open} v_{s/c} \left(v_{out,i} - v_{s/c} \right) = \sum_i \dot{m}_i'' A_{open} \left(v_{out,i} - v_{s/c} \right)$$

- Thrust dependent upon:
  - Mass flux, $\dot{m}_i''$, term:
    - Particle mass, m_i
    - Ion and electron densities, n_i (from atmospheric model)
    - Spacecraft velocity, $v_{s/c}$ (from orbit propagator)
  - Ion exit velocity, $v_{out,i}$ (from energy conservation)
  - Open grid area, A_{open} (from AAIT design)

Drag

- Drag is due to neutral, ion, and electron impacts on both the spacecraft and AAIT
- Estimation begins with the classic continuum fluid mechanics equation from momentum conservation:

$$D = \frac{1}{2}\rho v^2 S C_D$$

$$D = D_{s/c} + D_{AAIT}$$

- Drag is dependent upon:
  - Drag areas, A_{grid} and $A_{s/c}$ (from AAIT and mission designs)
  - Spacecraft velocity, $v_{s/c}$ (from orbit propagator)
  - Atmospheric density, ρ_{atmo} (from orbit propagator)
  - Ion and electron densities, n_i (from atmospheric model)

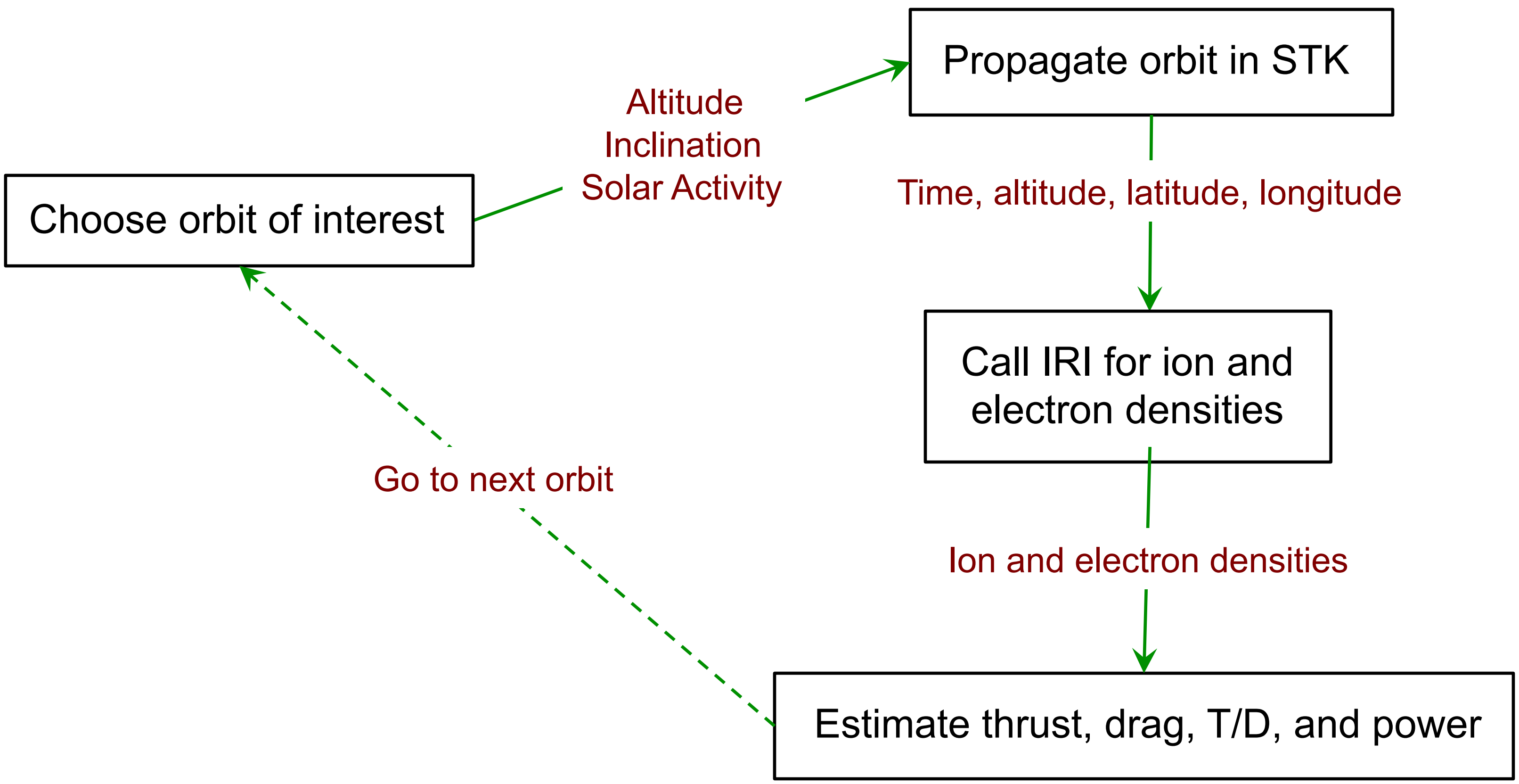
Power

- Power required by the AAIT is a sum of two powers:
  - Jet power – ions accelerated for thrust
  - Grid power – ions striking the screen grid (power loss)
    - Assumes 10% of ions strike the screen grid

$$P_{AAIT} = P_{jet} + P_{grid}$$

- Total AAIT power dependent upon:
  - Voltage applied to grids, V_{screen} and ΔV (from AAIT design)
  - AAIT grid areas, A_{grid} and A_{open} (from AAIT design)
  - Ion and electron densities, n_i (from atmospheric model)
  - Spacecraft velocity, $v_{s/c}$ (from orbit propagator)

AAIT Performance Code Flowchart

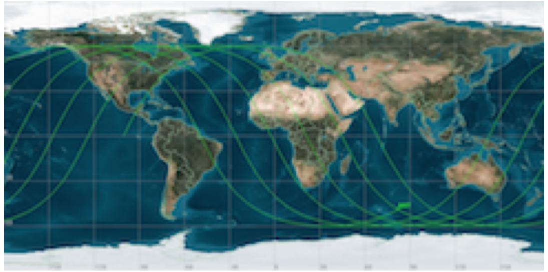


Atmospheric Model - IRI

- Use International Reference Ionosphere 2007 (IRI) from NASA as atmospheric model
  - State-of-the-art ionosphere model
  - D. Bilitza, and Reinisch, B., J. Adv. Space Res., 42, #4, pp. 599-609, 2008
- IRI models the ionosphere between 50 and 2,000 km
- IRI enforces quasi-neutrality by calculating ion densities as percentages of the electron density
- Model returns densities for AAIT performance estimation
  - O^+, O_2^+, N^+, NO^+, H^+, He^+, and e^-
- Inputs obtained from orbit propagator and include
  - Time, altitude, latitude, and longitude

Orbit Propagation in STK 9

- Orbit propagation interval is 60 seconds
  - Approximately 90 points in one complete orbit of Earth
  - Over 1 year orbit duration, approximately 550,000 points
  - Allows many data points to average over one full year while retaining orbit fidelity
- Considered circular orbits with no drag (used J2 perturbation propagator)
  - Assuming same altitude during entire orbit duration
  - Useful for first-order analysis without requiring specific knowledge of spacecraft characteristics
- STK outputs data required for IRI
  - Time, altitude, latitude, longitude



Analysis Parameters

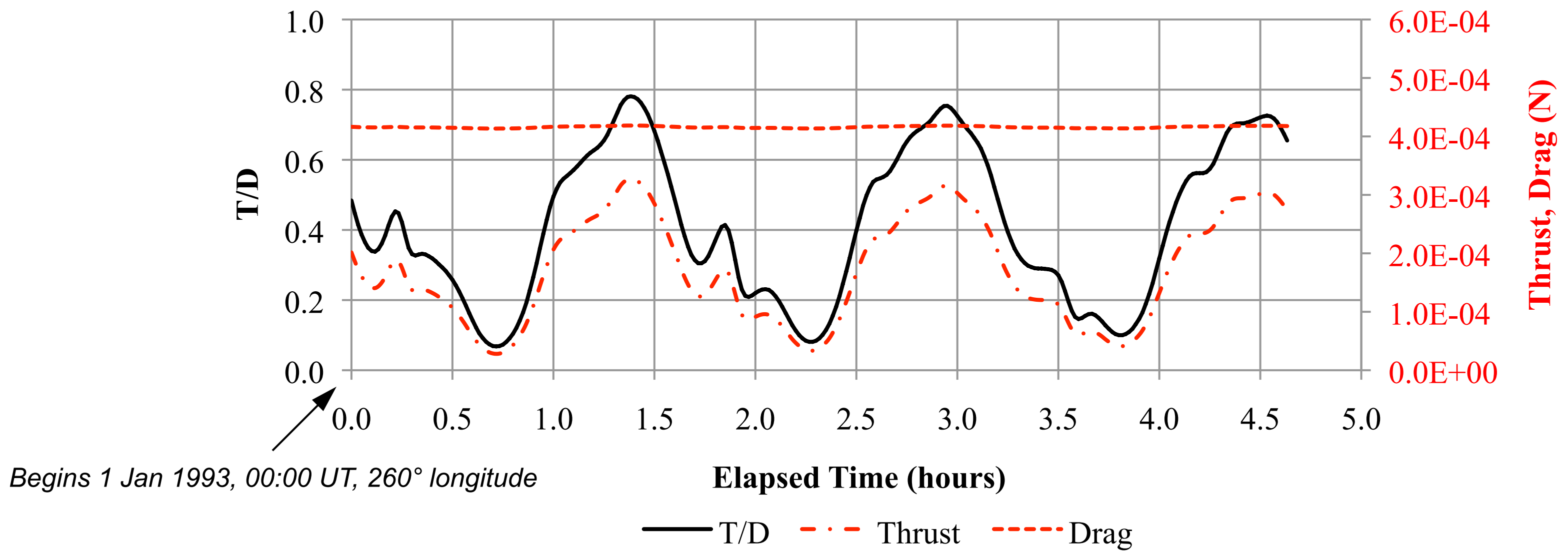
- Vary orbital, spacecraft, and AAIT parameters

	Minimum	Interval	Maximum
Altitude (km)	300	100	1000
Inclination (deg)	0	30	60
	Minimum	**Mean**	**Maximum**
Solar Activity Level (Year)	1996	1993	1991
Satellite Frontal Area (m^2)	0.1	1.5	5.0
AAIT Total Grid Area (m^2)	1	5	10
AAIT Acceleration Potential (V)	1000	5000	10000

- Two constants in this analysis
  - Coefficient of drag, C_D: 2.4
  - AAIT grid transparency, $A_{open}/(A_{open}+A_{grid})$: 90%

Transient Performance Verification

- Verify that IRI functions properly within code
  - Expect thrust peak during daylight (increase in ion density)
  - Drag change during these three orbits was less than 1.3%
- Transient modeling ability useful for mission analysis



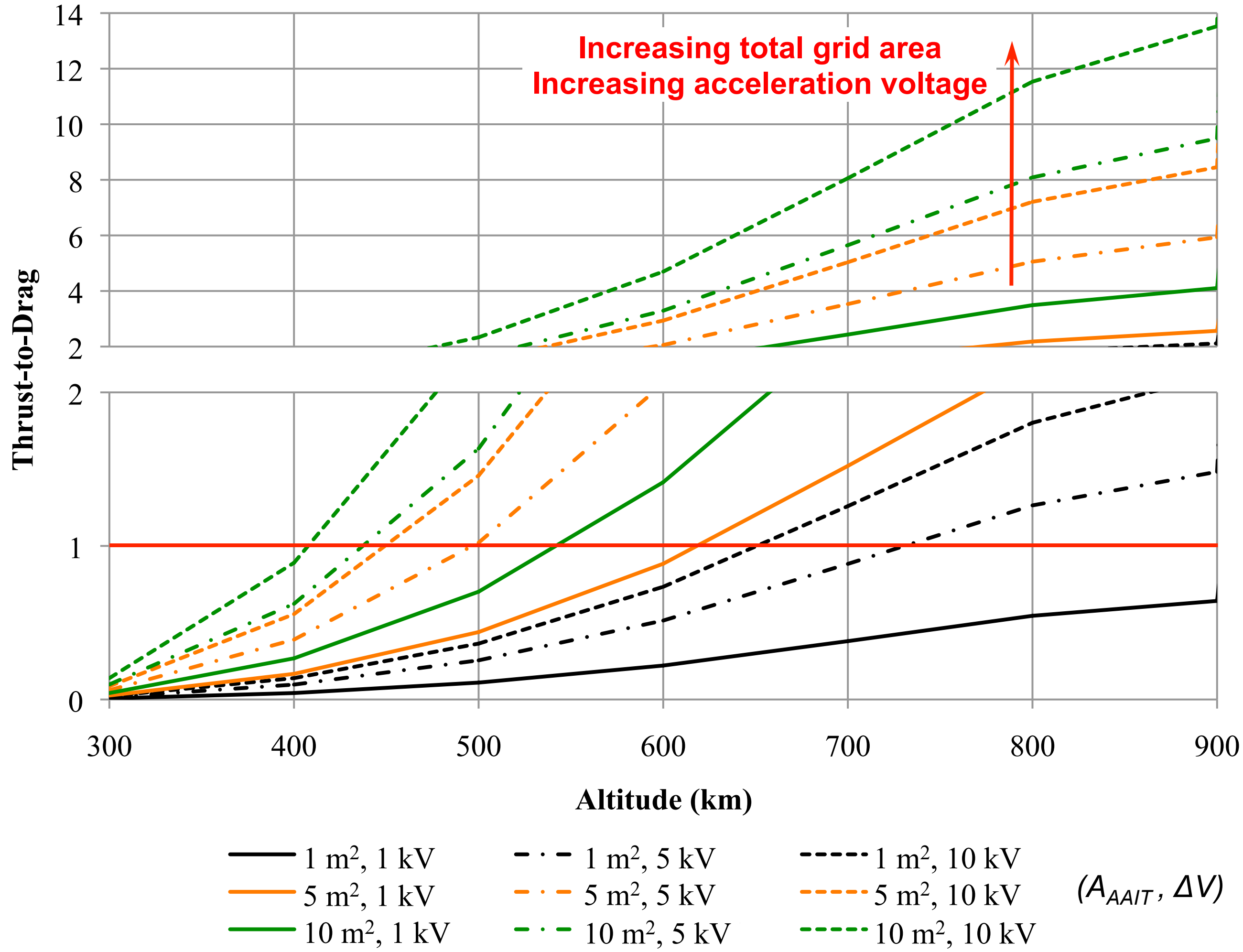
400 km, circular, equatorial orbit with mean solar activity
1.5 m² satellite frontal area, 5 m² AAIT total grid area, 5 kV acceleration voltage

AAIT Performance Analysis

- Analyze two cases averaged over one full year to identify trends in thrust-to-drag (T/D) and total power
- Case 1 identifies performance trends due to changes in AAIT grid area and acceleration voltage
  - Fixed
    - Circular, equatorial orbit with mean solar activity
    - 1.5 m^2 satellite frontal area
    - 90% grid transparency
  - Variable
    - Altitude
    - AAIT total grid area
    - AAIT acceleration voltage

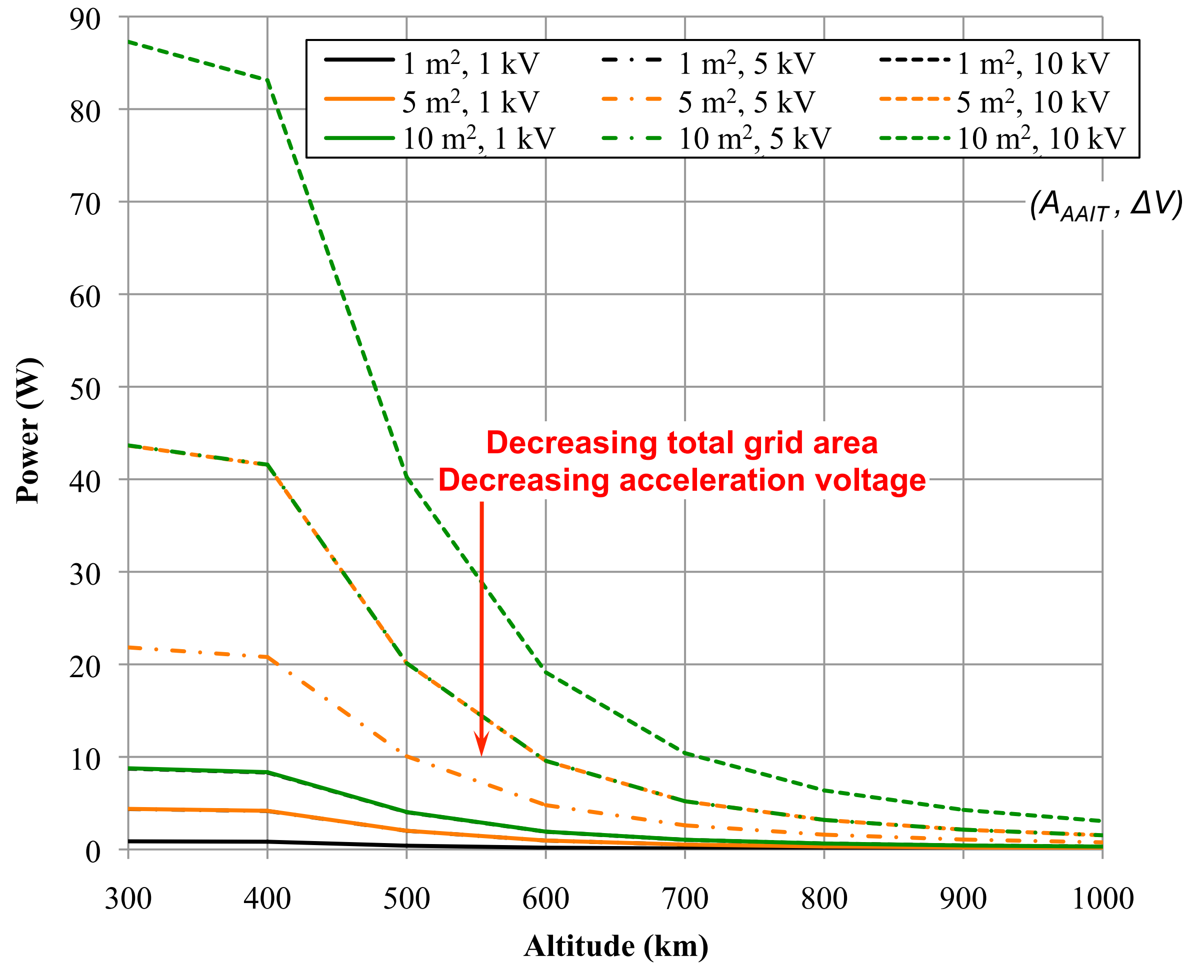
Results - Thrust (Case 1)

- T/D increases with greater:
  - Total grid area
  - Acceleration voltage
  - Altitude (mainly due to decreasing neutral density)
- T/D first reaches 1 just over 400 km
- Almost every case with T/D greater than 1 by 800 km



Results - Power (Case 1)

- Cases with same numerical (m^2-kV) appear very similar, but differ by less than 1%
- Power decreases with:
  - Lower total grid area
  - Lower acceleration voltage
  - Higher altitude
- Power peaks just under 90 W
- Most cases show AAIT power less than 40 W

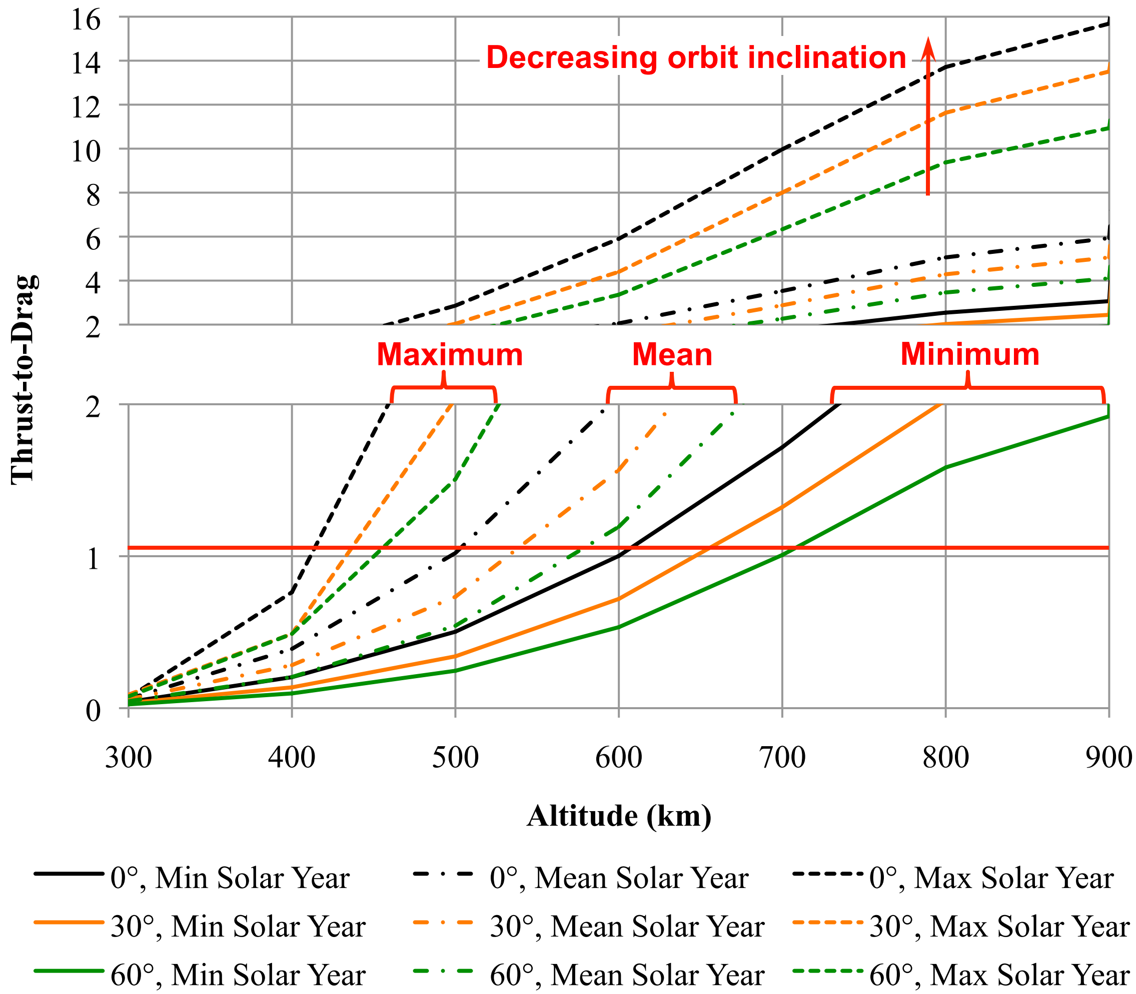


AAIT Performance Analysis

- Case 2 identifies performance trends due to changes in orbit inclination and solar activity level
  - Fixed
    - Circular orbit
    - 1.5 m^2 satellite frontal area
    - 5 m^2 total grid area
    - 5 kV acceleration voltage
    - 90% grid transparency
  - Variable
    - Altitude
    - Orbit inclination
    - Solar activity level

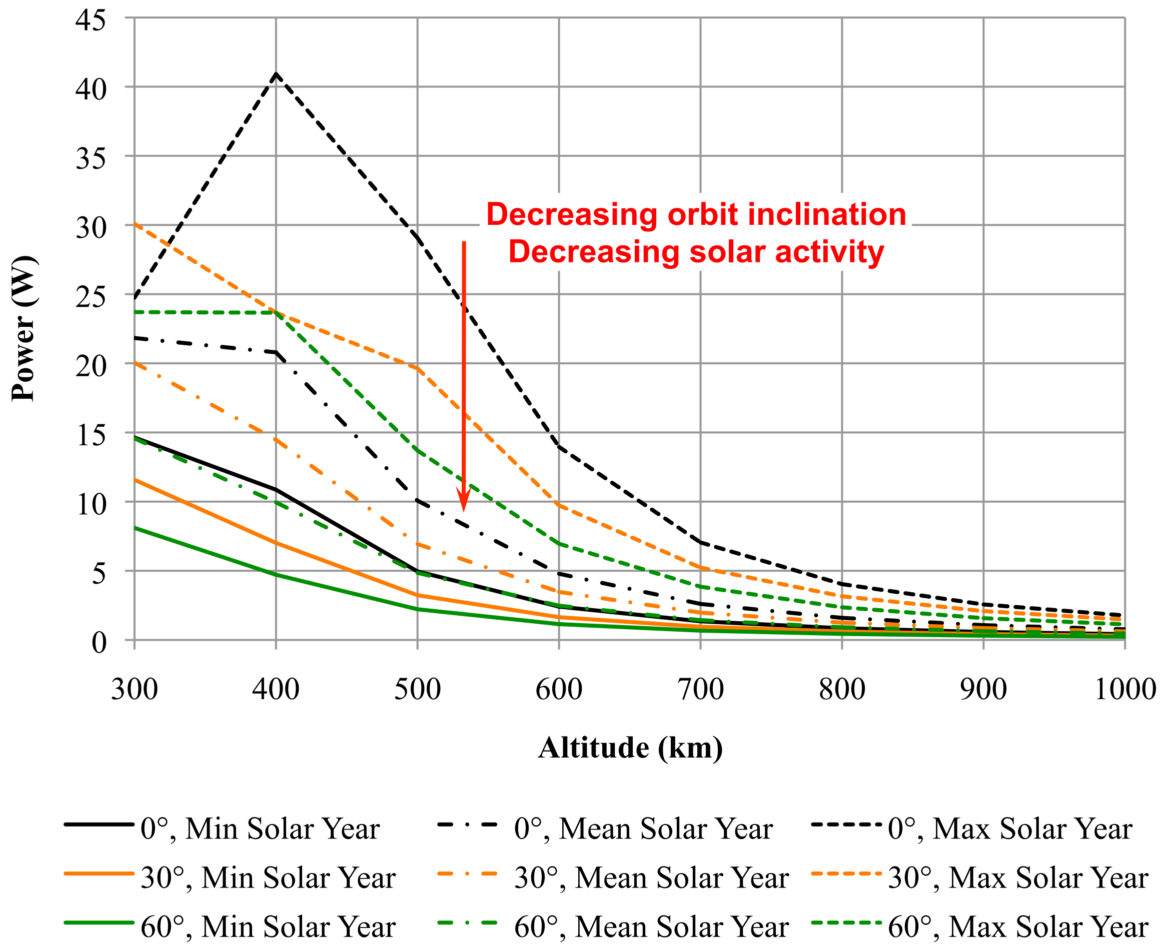
Results - Thrust (Case 2)

- T/D increases with:
  - Lower orbit inclination
  - Higher solar activity
  - Higher altitude (mainly due to decreasing neutral density)
- T/D first reaches 1 just over 400 km
- T/D greater than 1 for every case by 700 km



Results - Power (Case 2)

- Power decreases with:
  - Higher orbit inclination
  - Higher altitude
  - Lower solar activity
- Power peaks just over 40 W
  - Peak in power on this line due to densities from IRI
  - May be consequence of maximum solar year, as minimum and mean years show trends similar to all other cases
- Most cases show AAIT power less than 30 W



Conclusions

- Configurations studied show T/D greater than 1 is possible at orbit altitudes greater than 400 km
- T/D less than 1 may still lengthen satellite missions
  - Analysis for specific missions will determine if this is months or perhaps years
- Estimated power requirements less than 100 W
  - Would not pose large burden on state-of-the-art satellite bus power systems
- Created a useful tool for predicting on-orbit EP performance
  - Can be modified for alternative EP model or orbit propagator
- AAIT could also help satellites de-orbit faster

Questions?