Small Satellite Capability Analysis

Translational Performance in Small Satellites

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Objectives and Relevance

▪ ***Relevate Satellite Size and Delta-V:***

- Using minimum observables (size/vol) to determine available delta-v
- Find relationships between total delta-v, satellite size, propulsion system % of volume

What's the Point???

▪ ***SSA Applications:***

- Characterize maneuvering capability of possible RSO threats

▪ ***Combine with Other Sub-System Analyses:***

- Integrate studies of each system to make strong deductions about satellite capability based solely on size

Project Overview

- ***Propulsion Systems Selected:***
  - Cold Gas, and Monopropellant thrusters
  - Electric and Bipropellant not considered due to volume and possible power restrictions

- ***Satellite Mass in terms of System Components:***
  - Define component metrics in terms of satellite size

$$m_{sat} = m_{str} + m_{plumb} + m_{thr} + m_{\mathrm{tank}}$$

- ***Delta-V Equation:***
  - Determine satellite and fuel mass

$$\Delta V = I_{sp} g \ln\left(1 + \frac{m_{fuel}}{m_{sat}}\right)$$

Structure

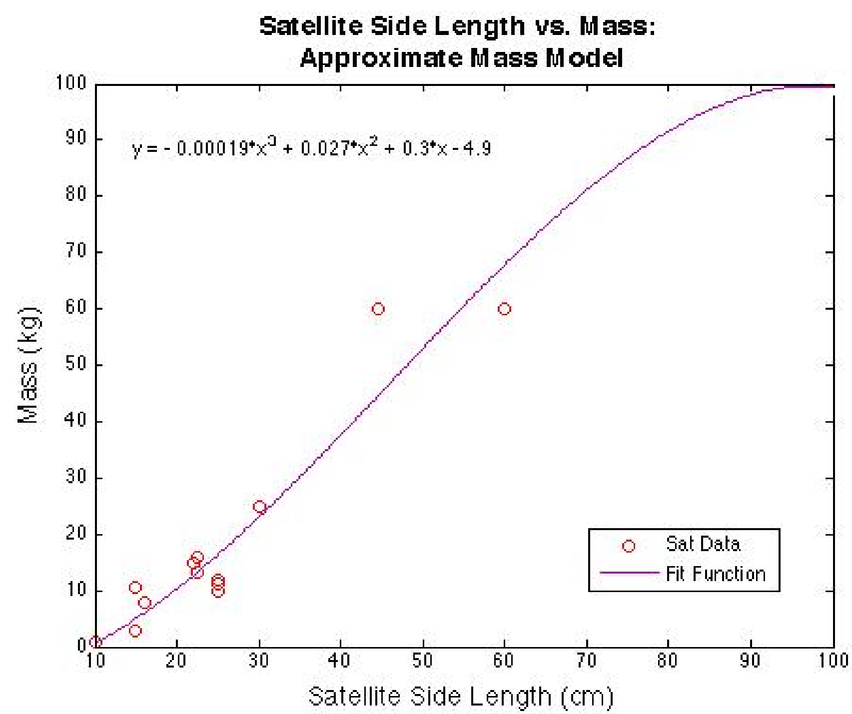
Structure Mass/Volume

- ***Percentage of Sat Mass:***
  - Define structure mass as percentage of total sat mass:

$$m_{str} = Pm_{sat}$$

Where: P= percentage of total mass
m_{sat}= mass estimate of satellite

- ***Plot:***
  - Red dots show cataloged data from real satellites
  - Line is best fit function used to estimate sat mass
  - Structure mass selected as 20% of fit function based upon real sat data



Thruster Mass/Volume

▪ ***Thruster Mass:***

$$m_{thr} = n_{thr} m_n$$

Where: n=number of thrusters
m_n= mass per thruster

▪ ***Cold Gas Valves:***

•Valve length is limiting factor for satellites below 15cm

•For rest of sat size range, valves chosen by increasing thrust

▪ ***Monopropellant Hydrazine Valves:***

•Will not fit into less than 13cm satellite

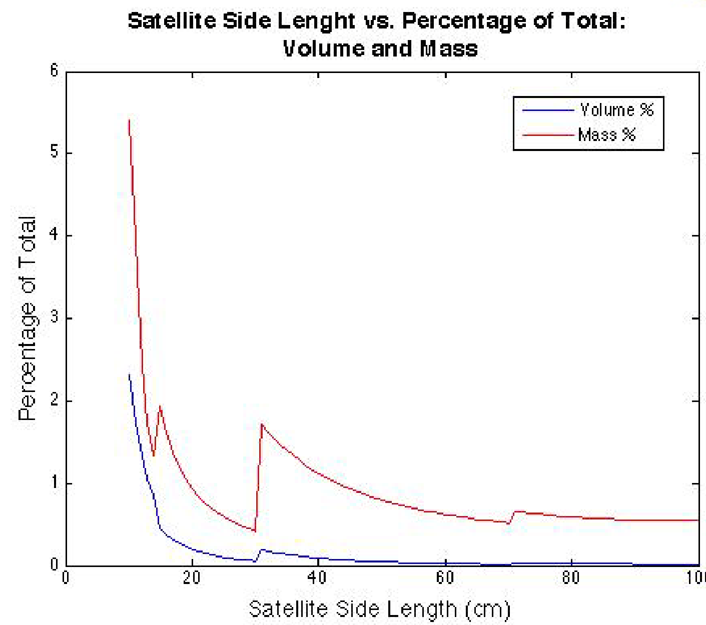
•Can be considered beginning at 21cm where thrusters account for 25% of volume and 10-15% of satellite mass

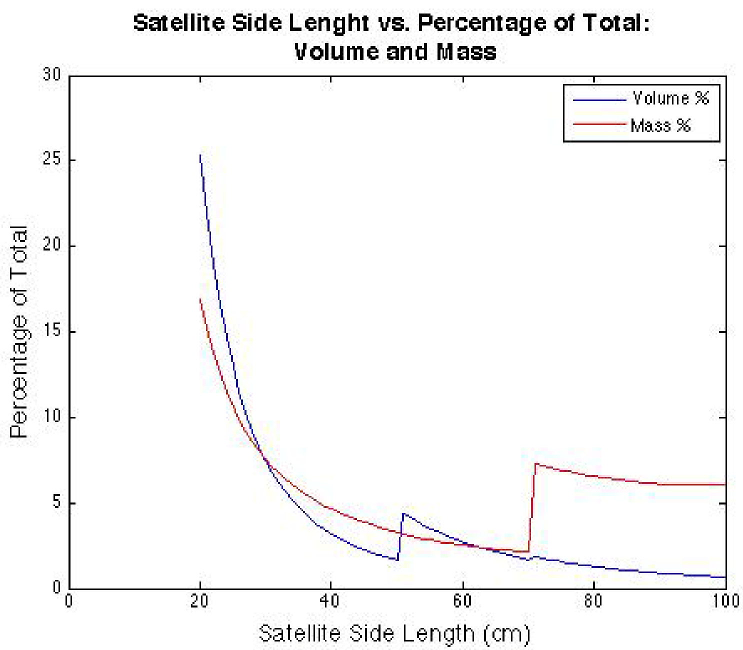
▪ ***Considerations:***

- Assumed 6 thrusters for this study (min for 3 translational DOF w/o attitude control)
- Minimum thrust levels may be an issue given environment

Cold Gas/Monopropellant Valves: Figures

- ***Volume:***
  - At CubeSat level valves are 2.5%
  - Largest valves could fit cubesat at 13% of total volume
- ***Mass:***
  - At CubeSat level 5.5% of total
  - Larger than 15cm valve mass is below 2% of total





- ***Volume:***
  - At 21cm valves are 25% of total
  - <5% of total past 35cm size
  - <2% of total past 70cm size
- ***Mass:***
  - At 21cm valves are 17% of total
  - Past 30cm <10% of total

Plumbing

Plumbing Mass/Volume

$$m_{plumb} = n_{thr}\mu_{tube}l_{thr} + m_{reg}$$

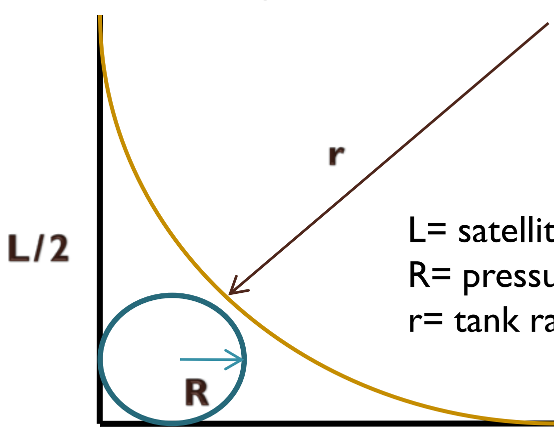
Where: m_{reg}= mass of pressure regulation system
n= number of thrusters
μ= linear density of tubing
l = length of tube needed per thruster

- ***Plumbing Volume = Tube Length x Cross-sectional Area***
  - Add pressure regulator size specs (if necessary)
- ***Pressure Regulator:***
  - Determined by operating pressure
  - Sizing considerations:

Regulator size may limit tank radius
Relation between regulator rad, tank rad & sat side:

$$r_{\text{tank}} \leq \frac{\sqrt{2L^2}}{2} - \sqrt{2a^2} - 2r_{reg}$$

$$a = r_{reg} - \sqrt{\frac{r_{reg}^2}{2}}$$



L= satellite side length
R= pressure regulator radius
r= tank radius

Tank Mass/Volume

- ***Selected System Percentage:***
  - Subtract volume of other system components from selected percent of total volume to obtain total tank volume:

$$V_{\text{tank}} = p_{sys} V_{sat} - V_{sys}$$

Where: p= propulsion system volume percentage
V_{sys}= volume of plumbing and thrusters
V_{sat}= total satellite volume

- ***Tank Thickness:***
  - Radius found from total volume
  - Thickness estimated using stress equation for sphere
  - Defines tank mass

$$\sigma_y = \frac{2pr}{t} \times SF$$

SF= safety factor (2.0) p=tank pressure
t= tank thickness r=tank radius

Tank Mass/Volume Continued

▪ ***Cold Gas Tank:***

•Increase by 10x in pressure results in 10x increase in mass

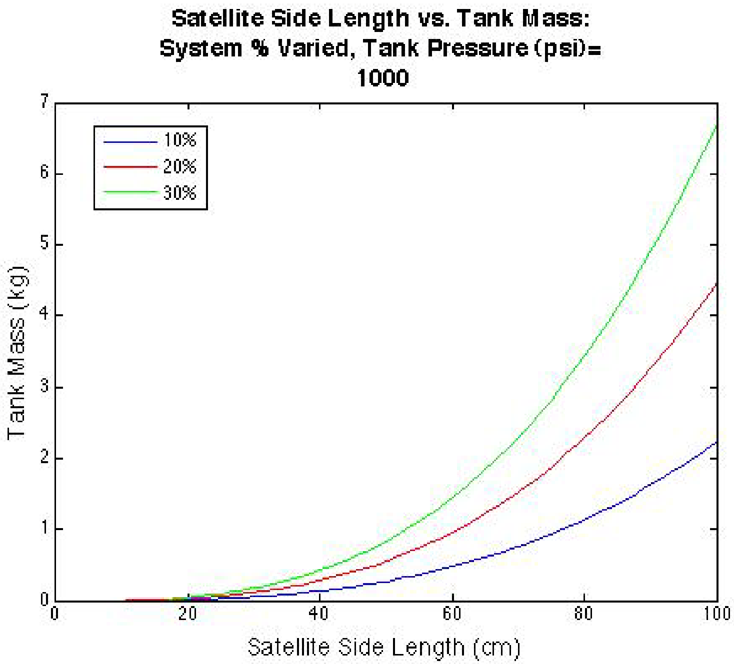
•Reduction in fuel volume with increase in pressure

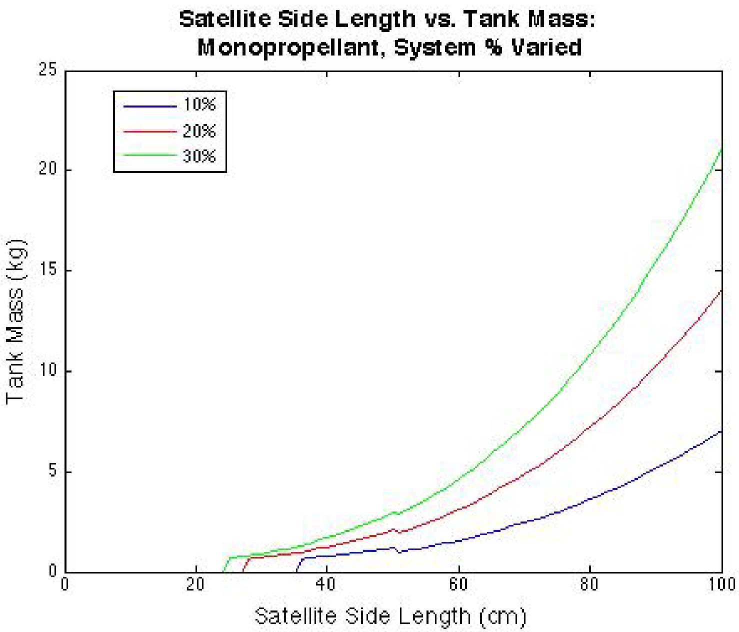
•Volume increases linearly with system percent

▪ ***Monopropellant Tank Mass:***

•Takes into account mass of pressurant and diaphragm

•85% of tank volume available for fuel





Component Comparison to Dry Mass

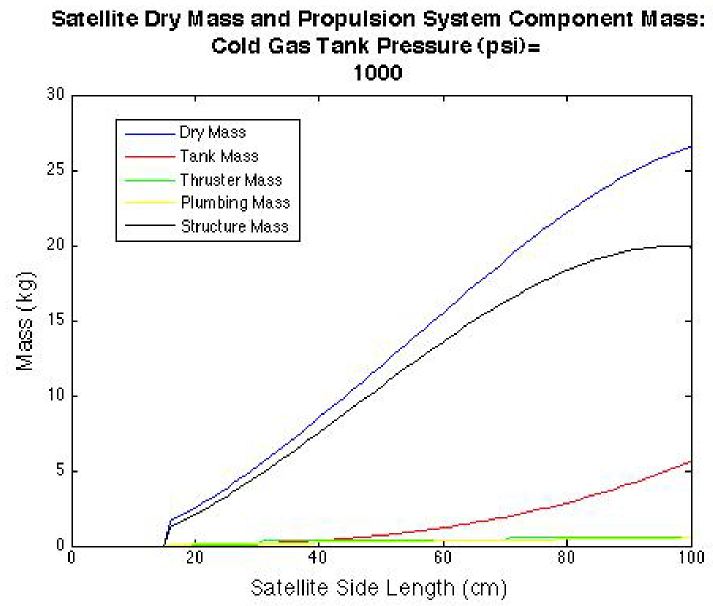
▪ ***Low Pressure (100's psi):***

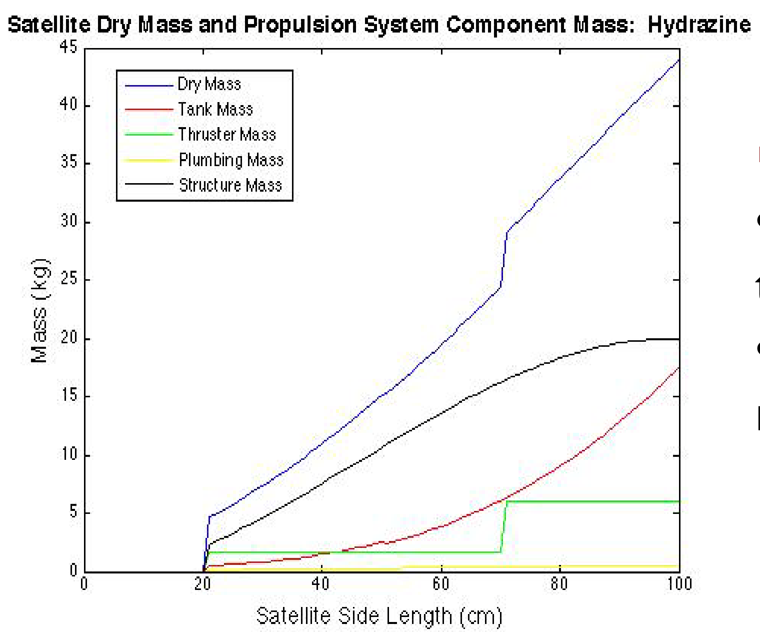
• Tank, thrusters, plumbing relatively same, low percentage of total

▪ ***High Pressure (>1000 psi):***

• Tank begins to dominate dry mass

• Shift in min sat size





▪ ***Monopropellant (System at 25%)***

• Tank and thrusters account for >50% of total mass

• Plumbing mass very small… almost negligible near 100cm

Fuel Mass/Volume

- ***Fuel Volume:***
  - Equal to total tank volume minus tank material volume
- ***Cold Gas:***
  - Entire volume assumed to be available for fuel
  - Mass defined as:

$$m_{fuel} = \frac{P_t V_t}{RT}$$

Where: P= tank pressure
V= fuel volume
R= gas constant
T= tank temperature

- ***Mass Example:***

•Cold gas at 1000 psi
•Maximum mass ~35kg

- ***Volume Example:***

•Largest volume ~450 liters
•Very small reduction in vol with increase in tank pressure

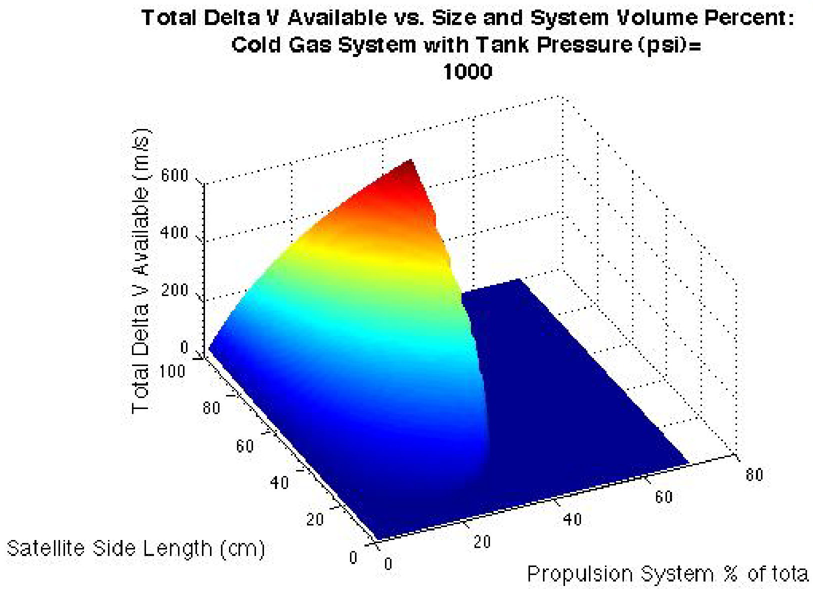
- ***Monopropellant:***

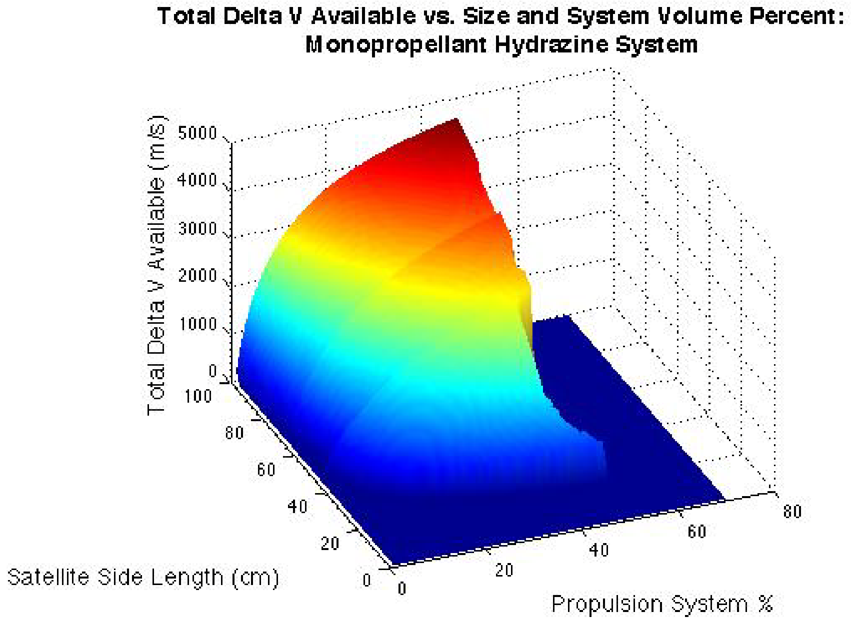
•Only 85% of volume available for fuel
•Mass found using total fuel volume and density
•Nearly 10x larger mass than cold gas

Delta-V

Delta-V Results: Unrestricted Plots

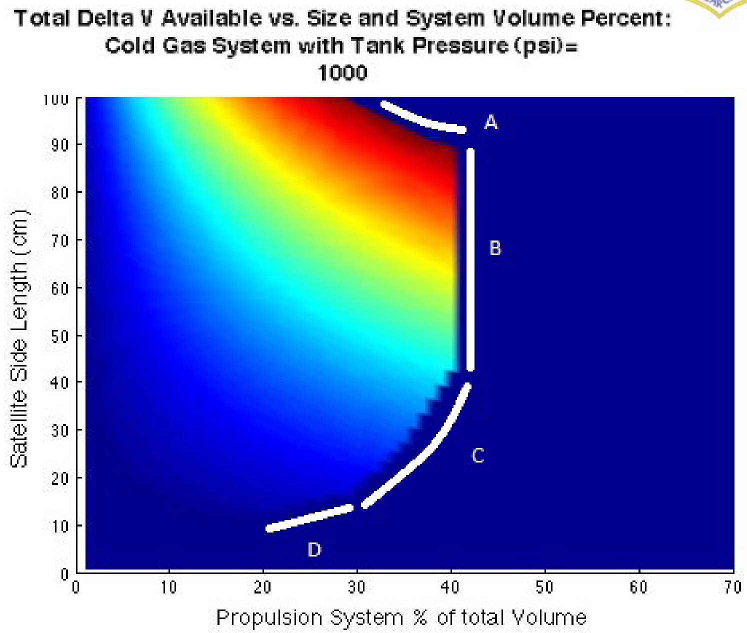
- *100 Psi:*
  - •Max delta-v ≈100 m/s
  - •Max sat mass ≈25 kg
- *1000 Psi:*
  - •Max delta-v ≈500 m/s
  - •Max sat mass ≈70 kg
- *10,000 Psi:*
  - •Max delta-v ≈900 m/s
  - •Max sat mass ≈400 kg!
- *Monopropellant:*
  - •Max delta-v ≈4.6 km/s
  - •Max sat mass ≈ 450 kg!
- *Cut Plots:*
  - •Limit propulsion system to 30% of total mass budget and 40% of total volume

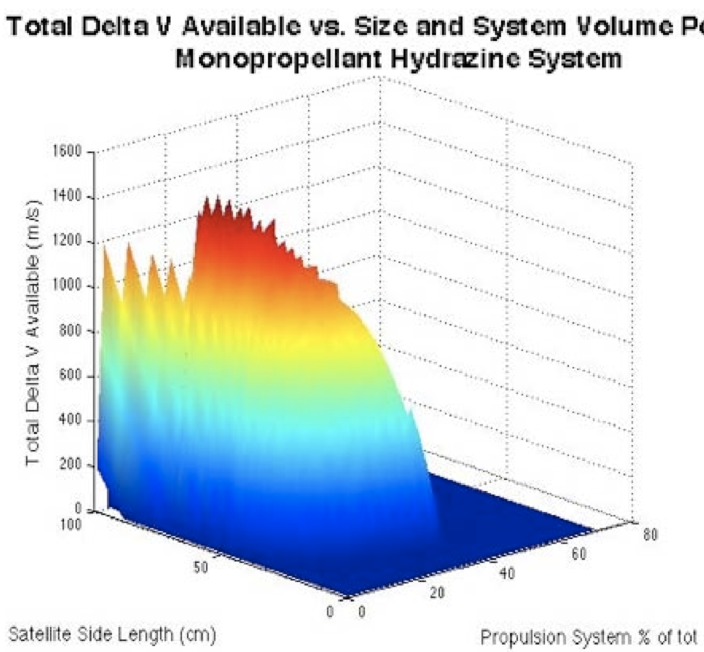




Delta-V Results: Plots w/limits

- ***Example (1000 psi):***
  - •Max delta-v ≈397 m/s
- ***Contour A & C:***
  - •Sat mass= 30% of mass budget
- ***Line B:***
  - •40% max volume cut-off
- ***Contour D:***
  - •Represents regime where max tank rad is limited by regulator





- ***Monopropellant Example:***
  - •Max delta-v ≈1.5 km/s
  - •Decreased delta-v in sats >70cm due to mass restriction
  - •Spikes seen due to incremental increase in tank radius

Conclusions

- ***Cold Gas:***

•Cold gas will not exceed 400 m/s for practical tank pressures
•Cold gas can be considered for entire size range
•Below 15cm Cold gas works for station-keeping only for any tank pressure (for low pressure: below 40cm)

- ***Monopropellant:***

•Monopropellant will not exceed 1.5 km/s for practical satellite mass
•Monopropellant system not practical for satellites >21cm in side length

- ***Other Findings:***

•Limited capability due to large increases in tank mass with increase in tank pressure
•Reasonable method for determining Delta-V for given satellite size

Possible Extensions

1) ***'Reachability'***
   - Connect maximum delta-v capability to reachable orbits

2) ***Pointing Accuracy***
   - Analyze slewing capabilities of the same systems

3) ***Other Propulsion Systems***
   - Electric and/or bipropellant systems
   - Theoretical or systems in development

4) ***Pressure Considerations***
   - Performance degradation in cold gas system
   - Pressure regulation system in hydrazine system

5) ***Tank Shape***
   - Compare spherical tanks with cylindrical or other shaped tanks

6) ***Satellite Shape***
   - Consider non-cubic shaped satellites