AUBURN UNIVERSITY

STUDENT SPACE PROGRAM

Orbit Control Using Aerodynamic Forces

Research By: Sanny Omar

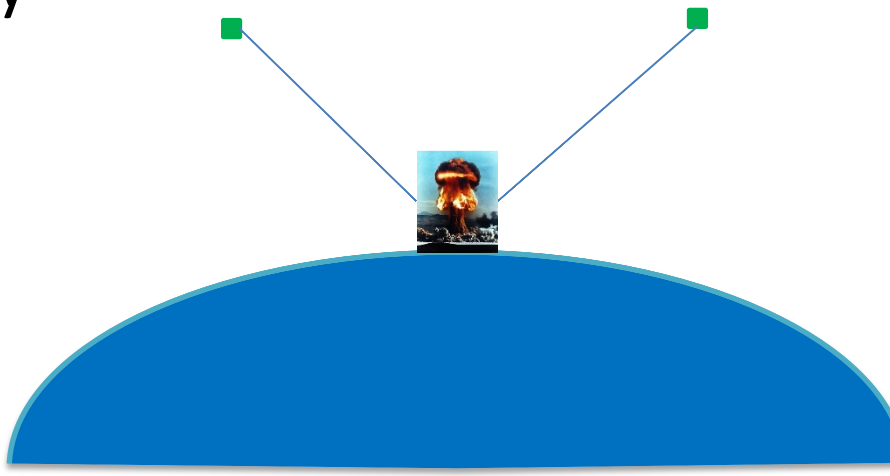
AubieSat CubeSat Program Member

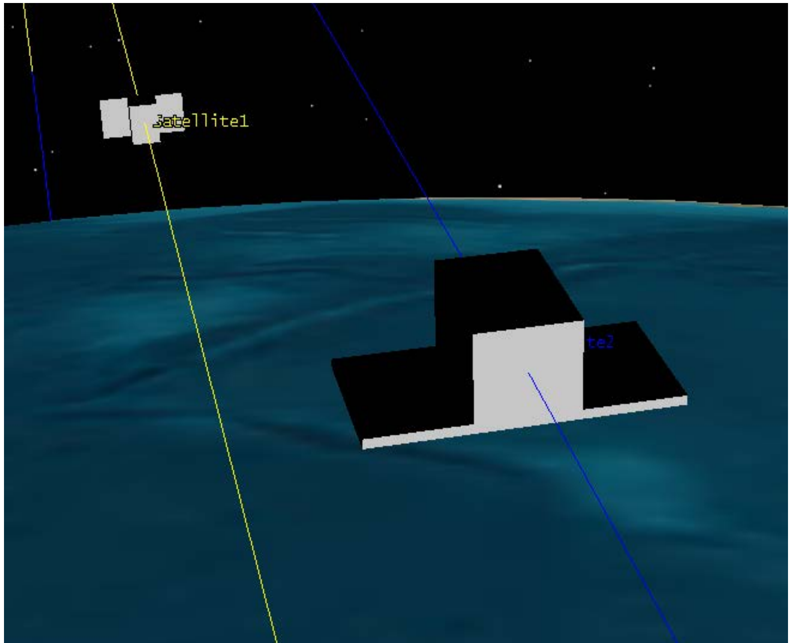
Advisor: Dr. JM Wersinger

AubieSat Program Director

Introduction/Purpose

- Research regarding use of solely aerodynamic forces for orbit control.
  - Drag characteristics of the satellites varied by changing attitudes
- Control relative position of multiple satellites in orbit.
  - Satellites could maintain constant separation without thrusters
- Allows for resolution over time and space
- Ability for observation with multiple satellites makes small satellites great!



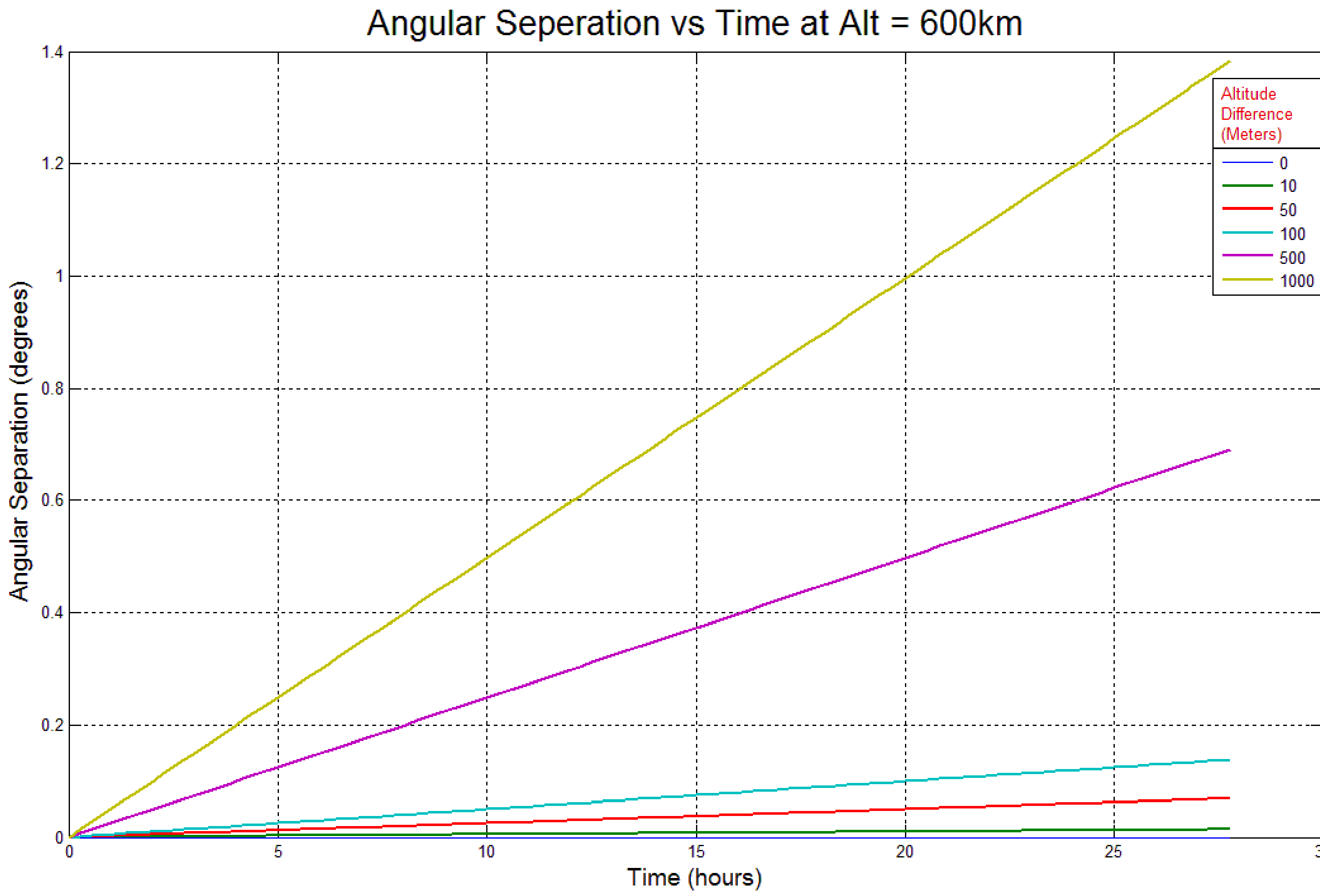


Circular Orbit Analysis

T = Orbital Period
μ = Gravitational Parameter
R = Average Orbital Radius
δ = height difference
θ = Angular Separation

- $\omega =$ orbital angular velocity = $\frac{2\pi}{T} = \sqrt{\frac{\mu}{R^3}}$
- $\Delta\theta(\text{radians}) = (\omega_1 - \omega_2)\Delta t = \Delta t\sqrt{\mu}(R_1{}^{-\frac{3}{2}} - R_2{}^{-\frac{3}{2}})$
- $\Delta\theta(\text{radians}) = \frac{3}{2}\mu^{\frac{1}{2}}\Delta t\left(\frac{\delta}{R^{5/2}}\right)$ (by binomial expansion)
- The change in angular separation($\Delta\theta$) with respect to time between two satellites in circular orbits at different altitudes is:
  - Governed solely by altitude difference (δ) and orbital radius (R).
    - The altitude difference will be the significant variable.
- $\Delta X = R\Delta\theta$ (distance between satellites)
- If we can manipulate δ, we can manipulate ΔX.

Visual Aid

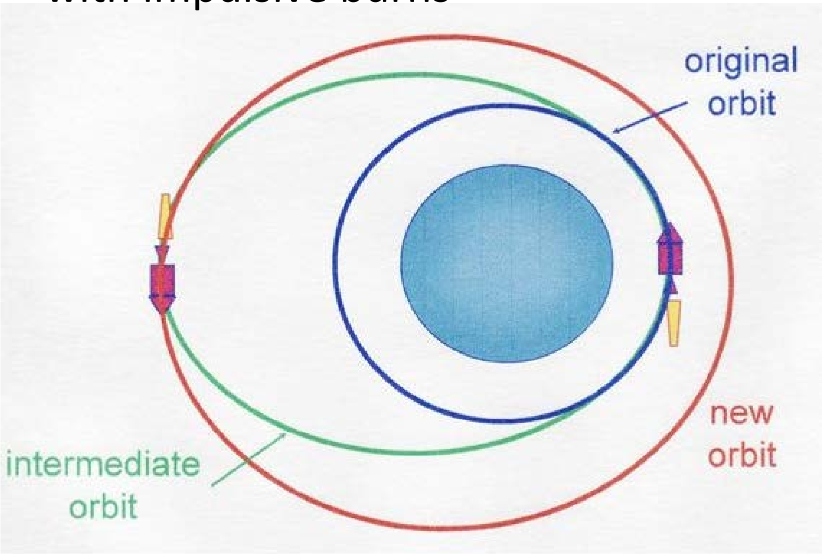


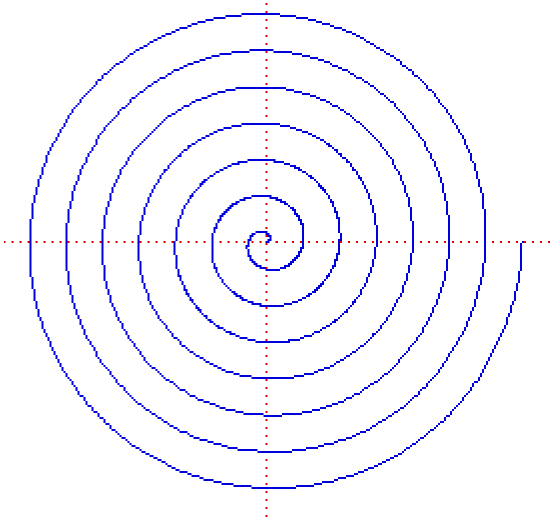
1 degree = about 122km at alt = 600 km (R = 6978km)

Aerodynamic Forces

- Aerodynamic drag used to vary satellite altitudes, thereby varying δ (altitude difference)
  - $F_d = \frac{1}{2}\rho v^2 S c_d = ma$
  - F = force, ρ = density, v = velocity, S = surface area orthogonal to velocity, c_d = drag coefficient, m = mass, a = acceleration
  - Essentially an ongoing in-plane orbit transfer
    - Aero drag vector always parallel to velocity vector (will reduce orbit energy)
  - Satellite will spiral toward Earth's center.
  - Altitude loss per spiral very small
    - Can be approximated as series of circular orbits with progressively lower altitudes

Traditional Hohmann orbit transfer with impulsive burns

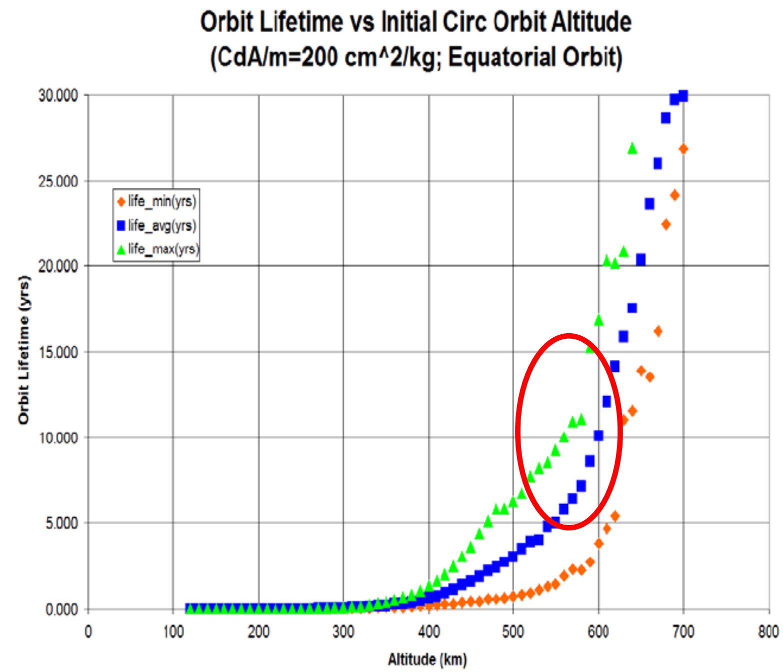


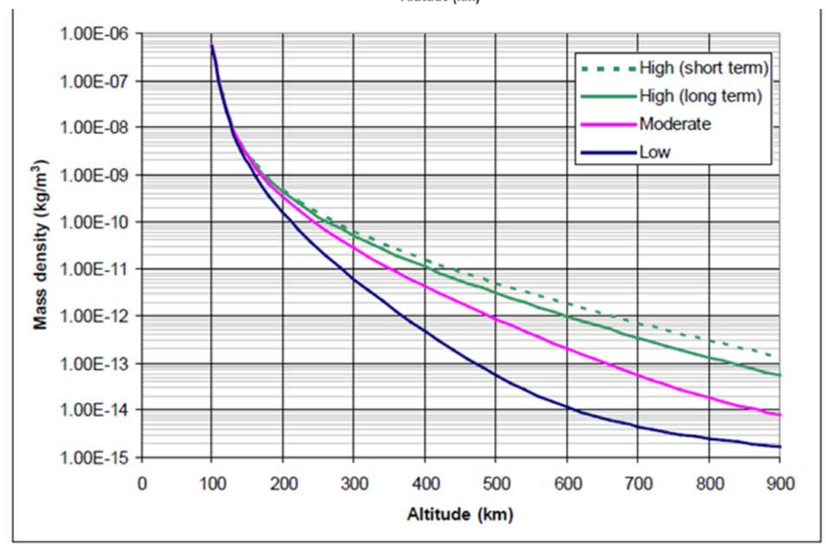


Finding Density

Note: Polar orbits have longer lifespans

- Density is dependent on:
  - Altitude
  - Geomagnetic and Solar activity
    - Can cause drastic density changes (2 orders of magnitude)
- Advanced atmospheric models for obtaining density
  - NRLMSISE-00
  - JB2008
- 1976 US Standard atmosphere tables used for initial calculations
- Orbits between 500 and 600 km popular for CubeSats
  - 5 < lifespan < 25 years





'igure A.3 — JB2008 mean air density with altitude for low, moderate, and high long- and short-term solar and geomagnetic activity

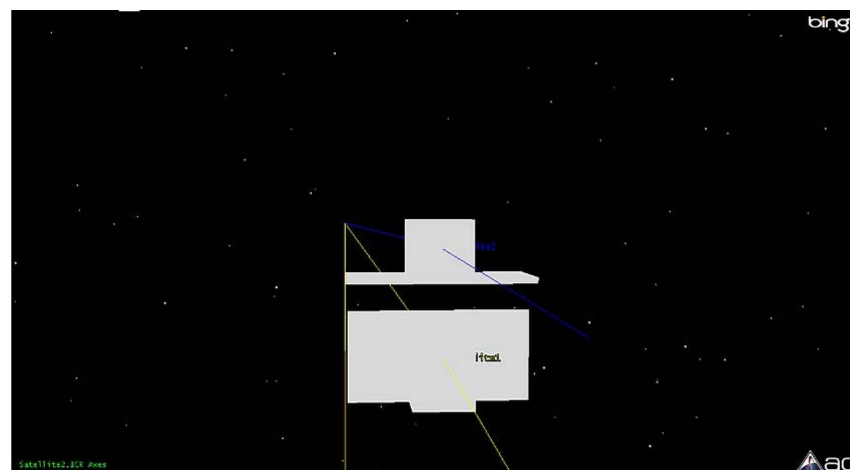
Software Modeling

- Numerical integrator software written in java
  - Can account for external forces
  - Does not make simplifying assumptions (circular orbits, constant density)
- Forces that affect both satellites equally or cancel out over time ignored (J2 (Earth oblateness), Sun/Moon gravity, Solar pressure) .

Force Model Verification With STK

- STK and Java Simulator models of two 1.5U CubeSats initially in identical 600km circular orbits.
- One satellite in max drag configuration, other in min drag configuration.
  - 1976 Standard atmosphere model used in both sims
- Angular separation over time results from both simulators compared.
  - Less than 1% difference in sim values with same density models
  - Shows that forces that effect both satellites equally can be safely ignored when calculating separation over time

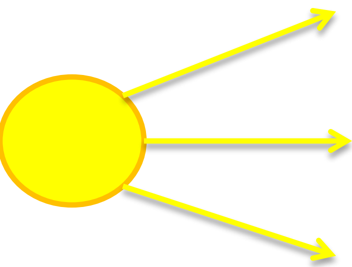
Date	STK Separations (deg)	Java Sim Separations (deg)
8/1/13 16:00	0	0
8/6/13 16:00	0.385	0.3833
8/11/13 16:00	1.536	1.535
8/16/13 16:00	3.479	3.457
8/21/13 16:00	6.169	6.153
8/26/13 16:00	9.648	9.623
8/31/13 16:00	13.987	13.872

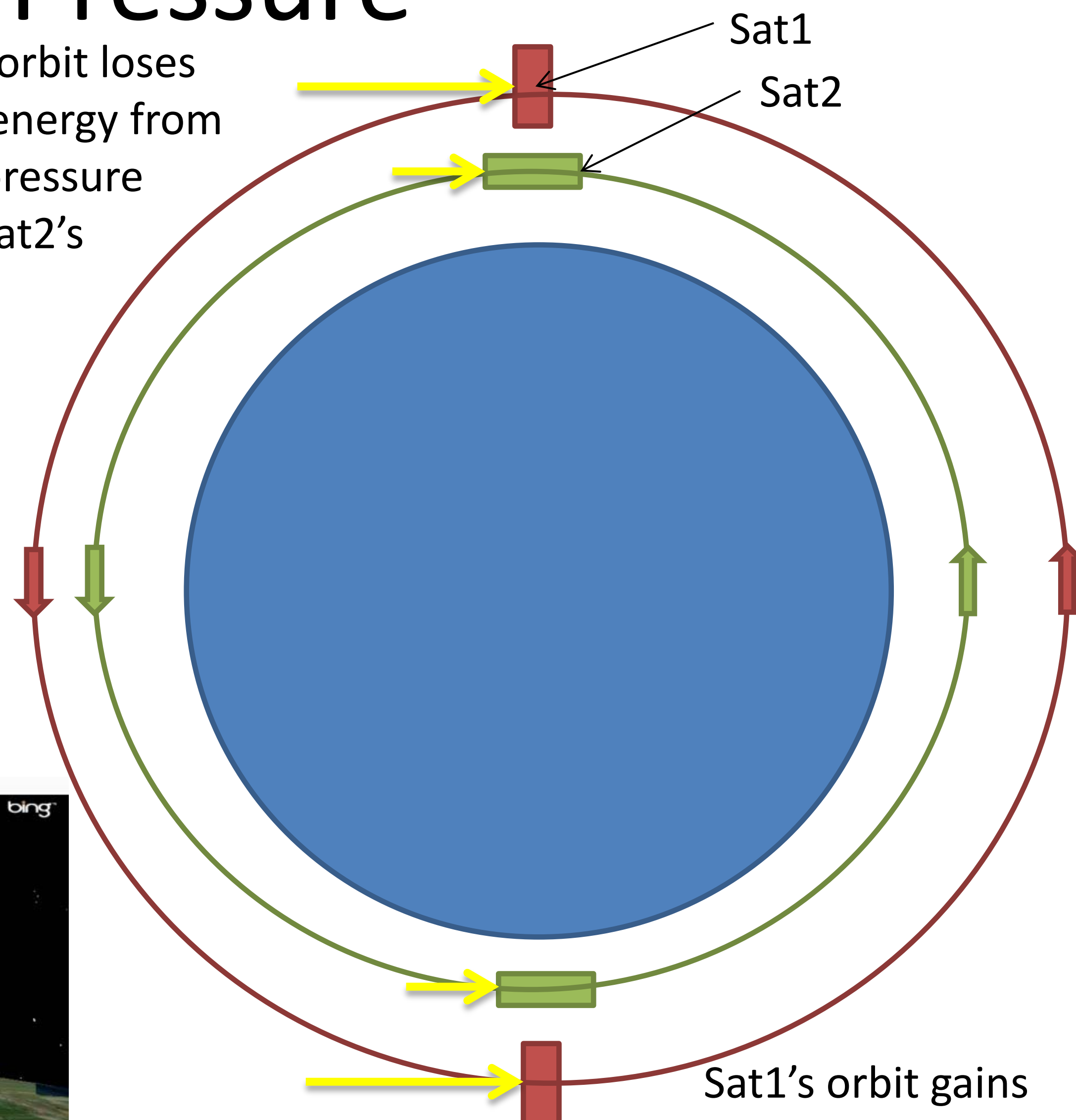


Solar Pressure

Sat1's orbit loses more energy from solar pressure than Sat2's

Energy Gains and Losses from already weak solar pressure forces roughly cancel out, so orbits are not significantly perturbed





Sat1's orbit gains more energy from solar pressure than Sat2's

Video: No drag, max SP sat 1, no SP sat 2

Solar Pressure Verification With STK

- Two identical satellites in identical initial orbits
  - Solar pressure simulation turned on for sat1 (4.5U panel array facing sun at all times) and turned off for sat2.

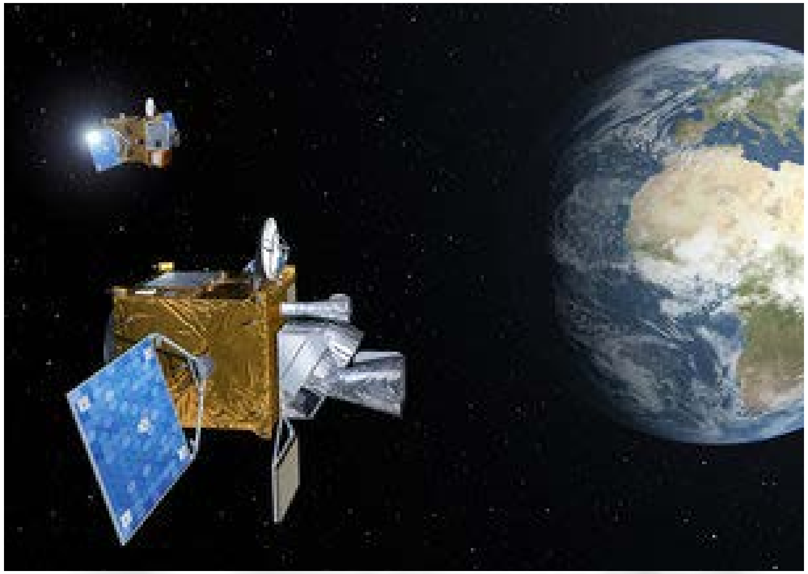
Sat2, No Drag, No Solar Pressure					Arg. Of Perigee + True Anomaly
Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	
8/1/2013 16:00	6978.14	0	28.5	0	360
8/6/2013 16:00	6974.013371	0.001411	28.428	327.842	257.264
8/11/2013 16:00	6977.240326	0.000144	28.421	295.591	154.591
8/16/2013 16:00	6975.394913	0.002147	28.397	263.419	51.948
8/21/2013 16:00	6975.471316	0.001468	28.414	231.12	309.084
8/26/2013 16:00	6977.254738	0.001743	28.464	198.98	206.711
8/31/2013 16:00	6973.953169	0.002083	28.483	166.779	103.702

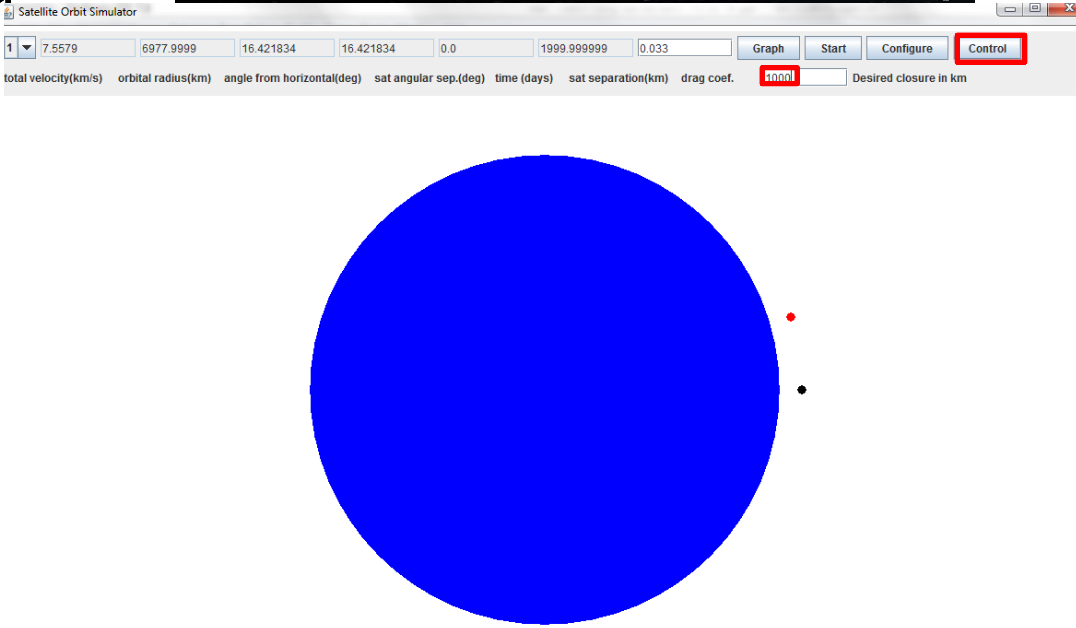
Sat1, No Drag, Same initial conditions as Sat2, Solar Pressure On					Arg. Of Perigee + True Anomaly
Time (UTCG)	Semi-major Axis (km)	Eccentricity	Inclination (deg)	RAAN (deg)	
8/1/13 16:00	6978.14	0	28.5	0	360
8/6/13 16:00	6974.013123	0.001425	28.428	327.842	257.266
8/11/13 16:00	6977.239368	0.000116	28.422	295.591	154.594
8/16/13 16:00	6975.393728	0.002175	28.398	263.419	51.961
8/21/13 16:00	6975.470757	0.00152	28.414	231.121	309.091
8/26/13 16:00	6977.251892	0.00178	28.464	198.981	206.736
8/31/13 16:00	6973.953364	0.002159	28.483	166.78	103.723

Solar pressure makes little difference in terms of satellite separation over time and can be safely ignored!

Separation Control Simulation

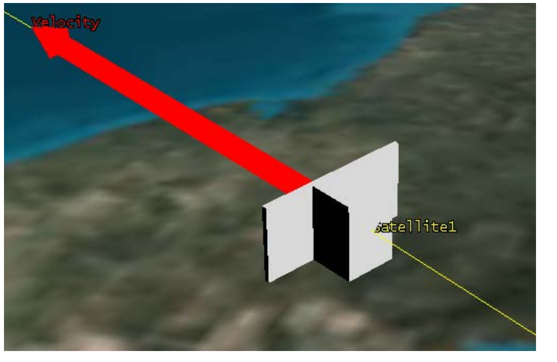
- Two satellites in identical circular orbits with a given distance between them
- User wants to change satellite separation by a desired amount
- Satellite Orientations controlled autonomously by software to produce desired changes

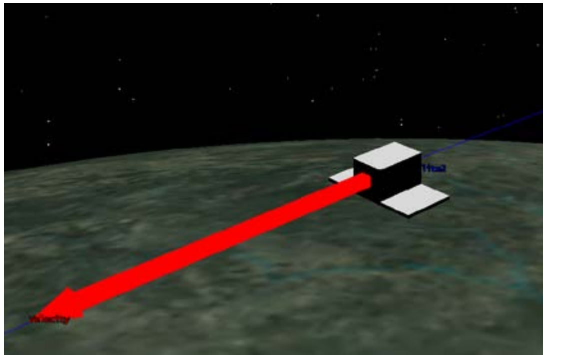




Simulation Procedures

- Drag coefficient for CubeSat with 2 single deployed long edge solar panels ≈ 2.2
- Density function to fit 1976 US standard atmosphere values.
  - $1.137*10^{-13}\ {}^{\mathrm{kg}}/_{\mathrm{m}^3}$ at 600 km altitude
- Max drag configuration:
  - $\frac{A}{m} = \frac{.045\mathrm{m}^2}{1.5\mathrm{kg}} = .0300\,\frac{\mathrm{m}^2}{\mathrm{kg}}$
- Min drag configuration:
  - $\frac{A}{m} = \frac{.01\mathrm{m}^2}{1.5\mathrm{kg}} = .0067\,\frac{\mathrm{m}^2}{\mathrm{kg}}$

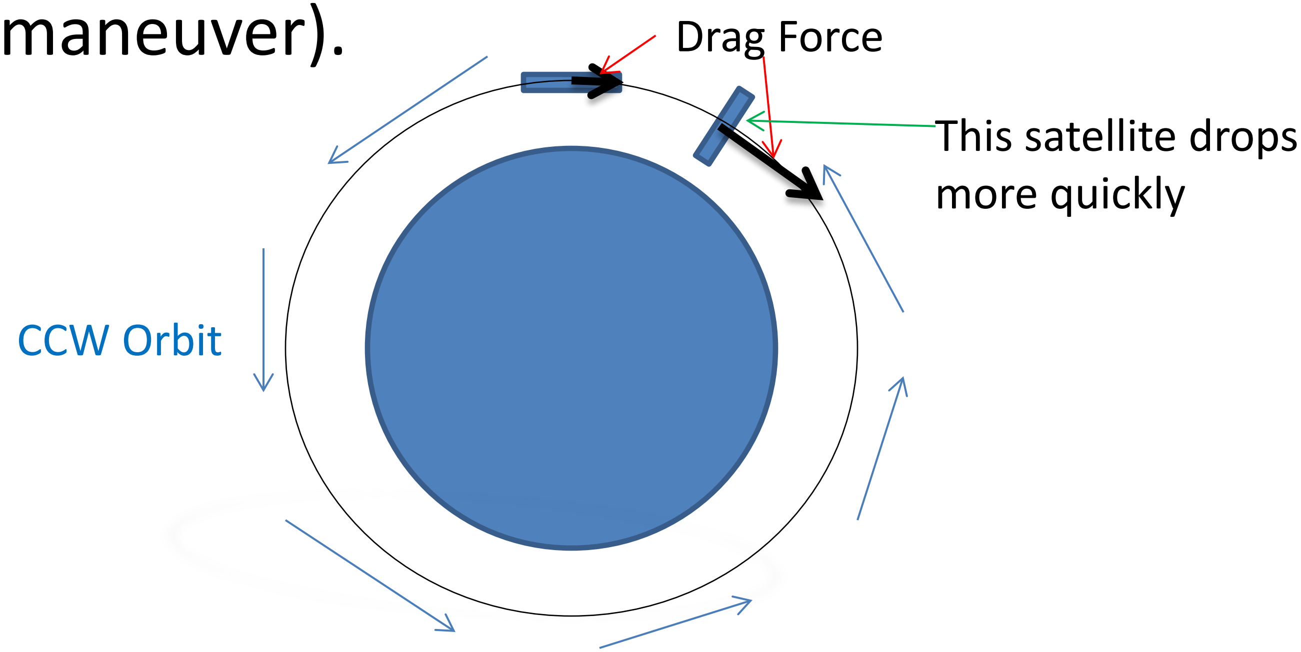




Control Algorithm Step 1

Chasing satellite set to max drag configuration while leading satellite set to min drag configuration

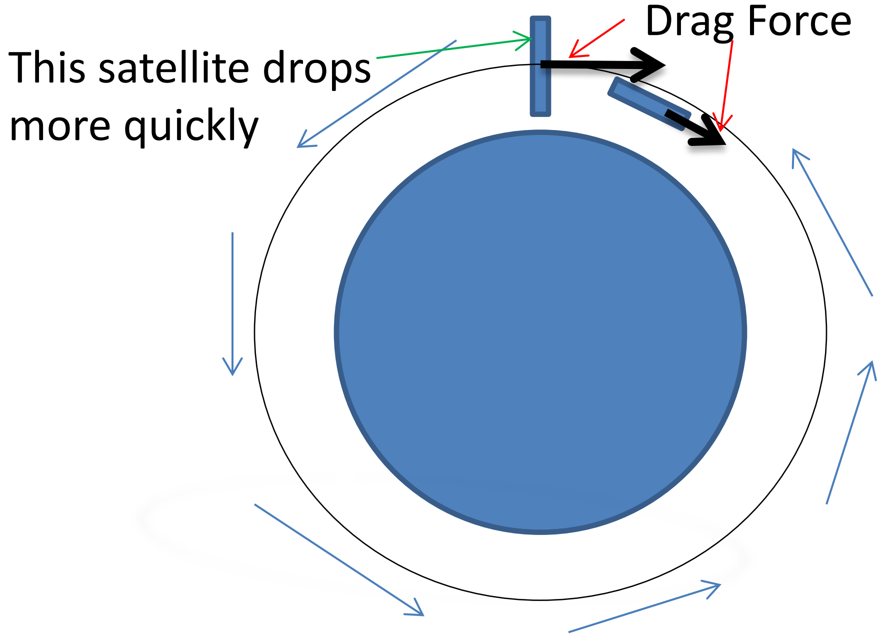
– Allows chasing sat to drop to a lower altitude and catch up to leading sat (similar to phasing maneuver).



Control Algorithm Step 2

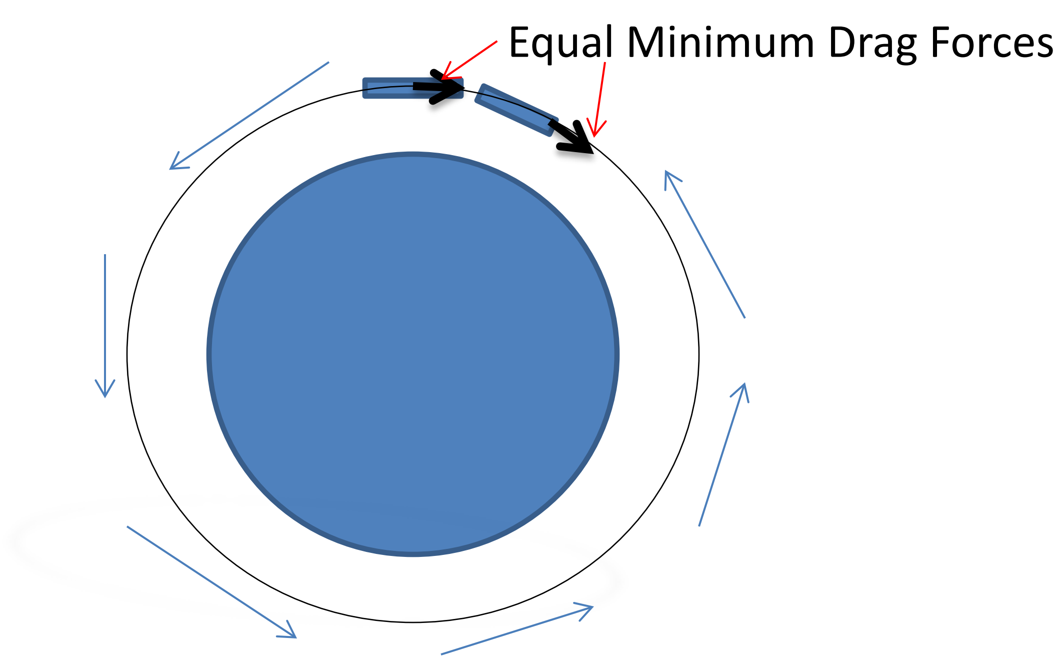
When half desired distance closed, swap satellite configurations (leader has max drag while chaser has min drag).

- Allows satellites to return to same altitudes
- Descent and ascent paths will be roughly symmetric

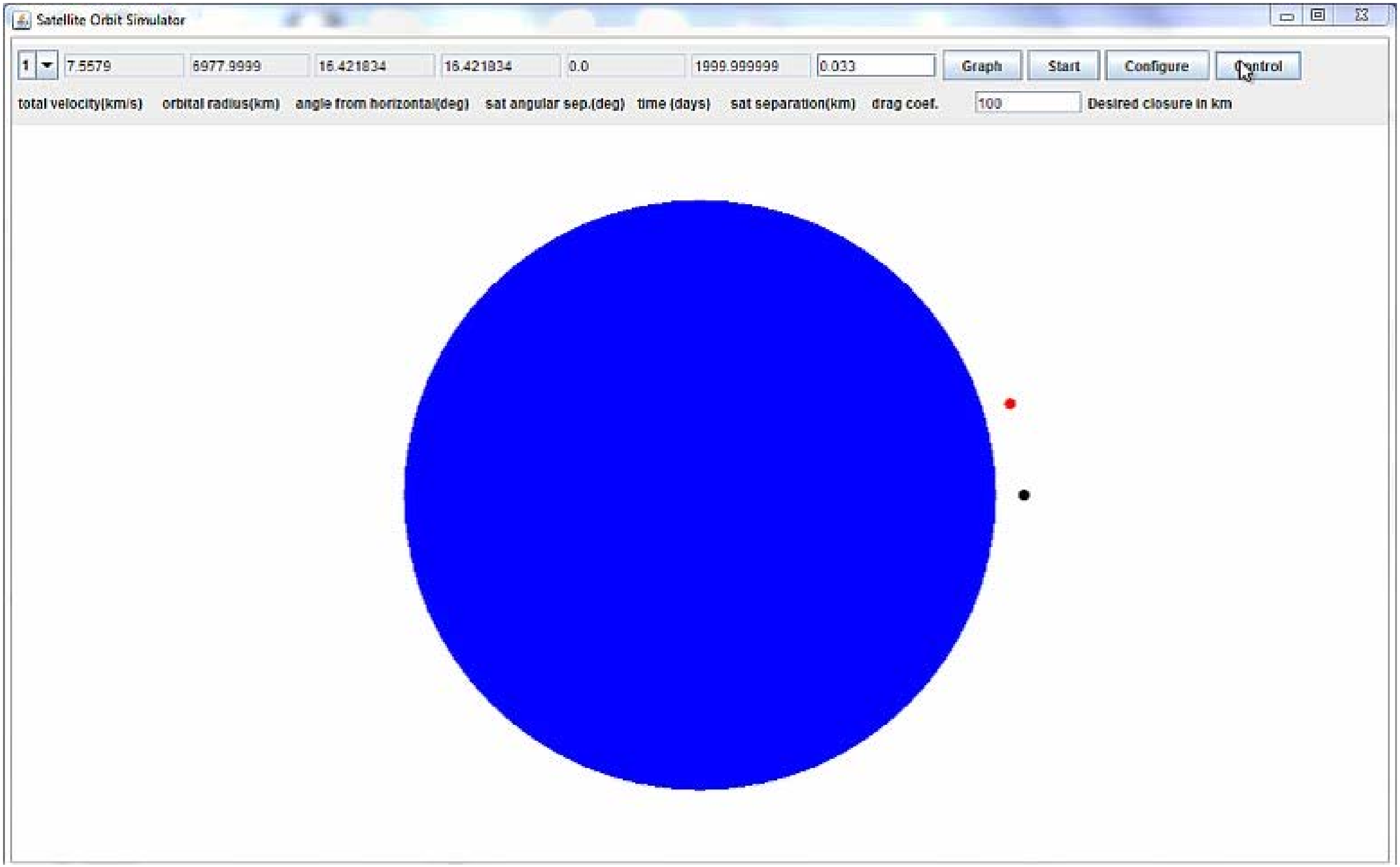


Control Algorithm Step 3

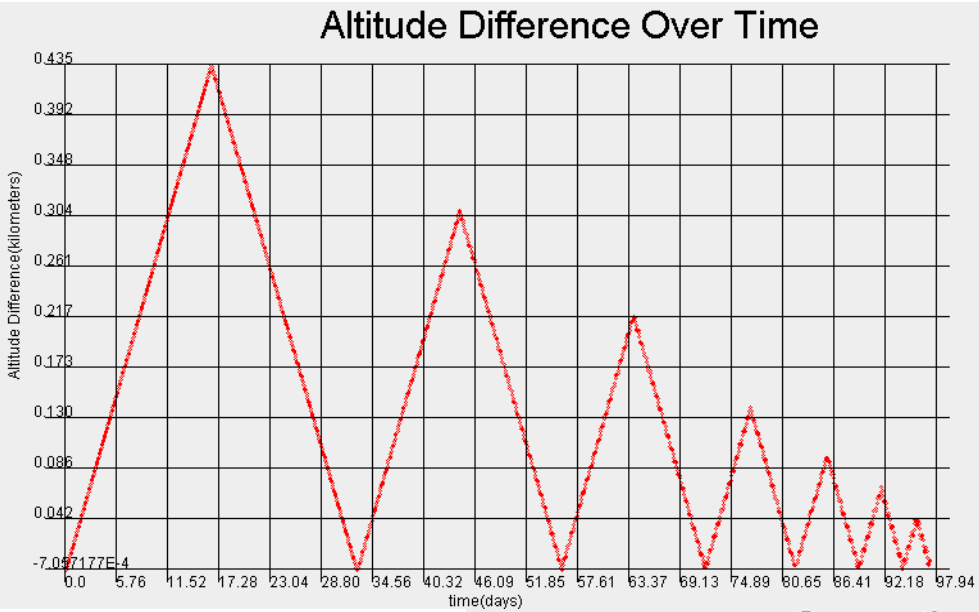
- When satellites have reached the same altitude, set satellites to same minimum drag configurations.

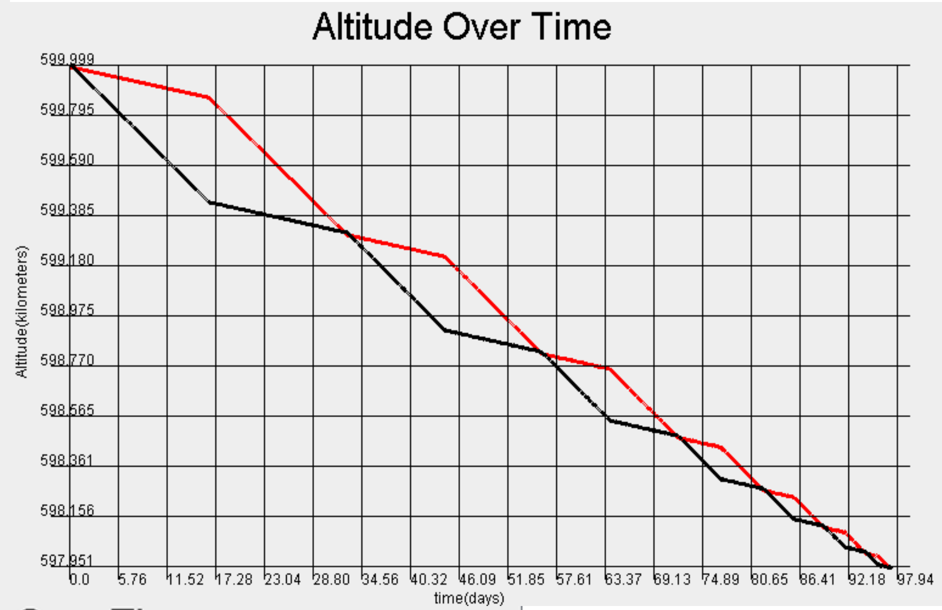


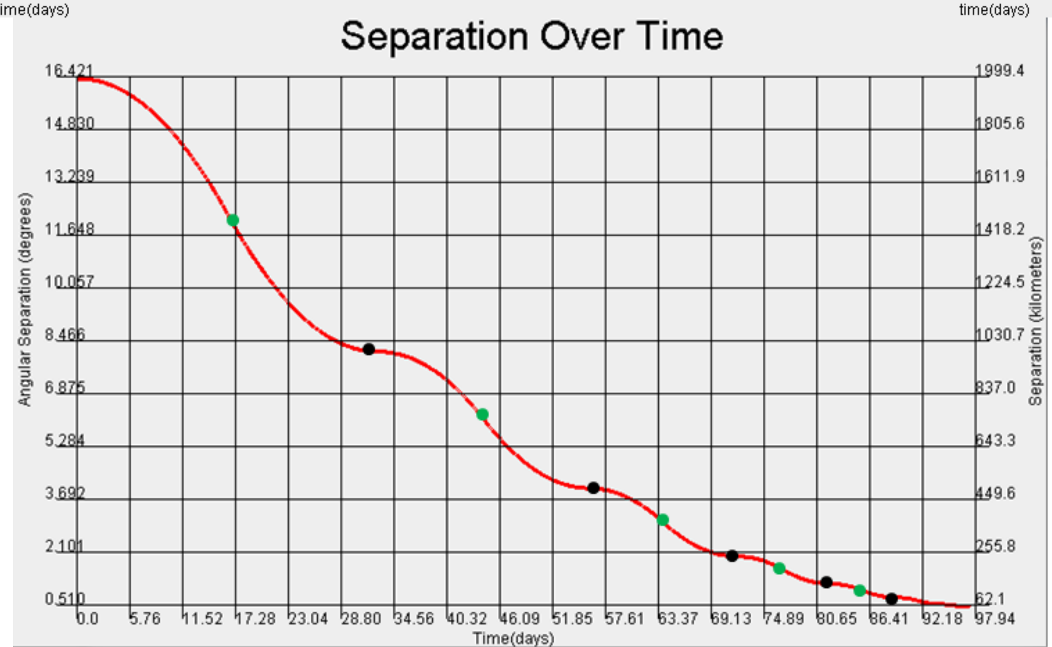
Orbit Simulator Demo



Graphs of Results







Simulation Conclusions

$$\Delta\theta = \frac{3}{2}\mu^{\frac{1}{2}}\Delta t\left(\frac{\delta}{R^{5/2}}\right)$$

Desired Distance Closed(km)	Time required(days)	Total Altitude loss(meters)	Max Altitude Difference (δ) (meters)	Estimated Closure (km) Based on average δ and Δϕ Eq.
1000	32.697	686.191	436.456	1001.603
500	22.975	485.868	309.891	499.703
250	16.146	342.935	217.842	246.862
100	10.417	216.482	137.637	100.629
50	7.350	153.014	97.383	50.236
25	5.208	108.309	69.207	25.297
10	3.299	68.729	43.342	10.035

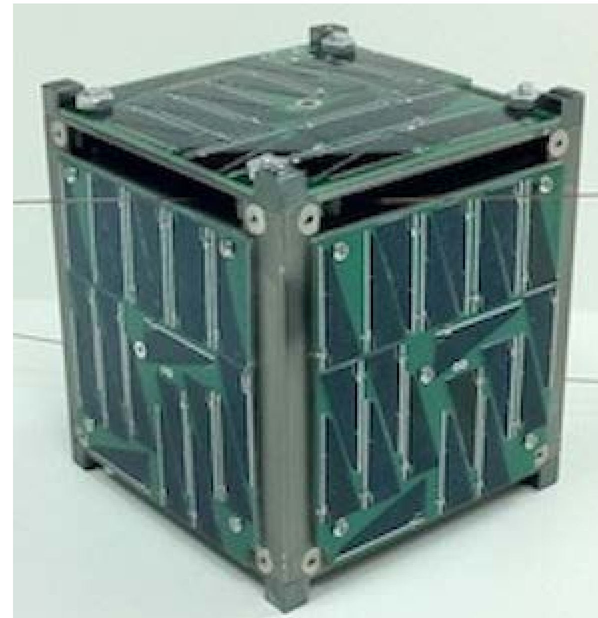
- It is more efficient to wait as long as possible before initiating control algorithm
  - average altitude difference will be greater.
- If it takes time t_1 to change satellite separation by a distance x_1, then the time t_2 it will take to change separation by a distance x_2 can be calculated by $t_2 = \sqrt{\frac{x_2}{x_1}}\, t_1$

  (about 10.4 days to close 100 km. $\sqrt{\frac{1000}{100}}(10.4) \approx 32.9$ days to close 1000km)
- Times calculated above would be ideal for simple CubeSat missions
- NORAD radar could be used to track satellites, and all orbit control commands could be issued from the ground
  - Satellites would not need to communicate with each other or know their positions.

Future Goals

- Improve software user interface
- Improve density estimation
  - Effects of solar and geomagnetic activity
  - Effects of night and day
  - Use existing simulation software/algorithms
- Improve drag coefficient estimation
- Possible simulation of out of plane transfers using aerodynamic lift

Questions?



- Contact:
- Sanny Omar
  - AubieSat Team
- sanny.omar@gmail.com

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