Drag De-Orbit Device (D3) Mission to Demonstrate Controlled Re-Entry using Aerodynamic Drag

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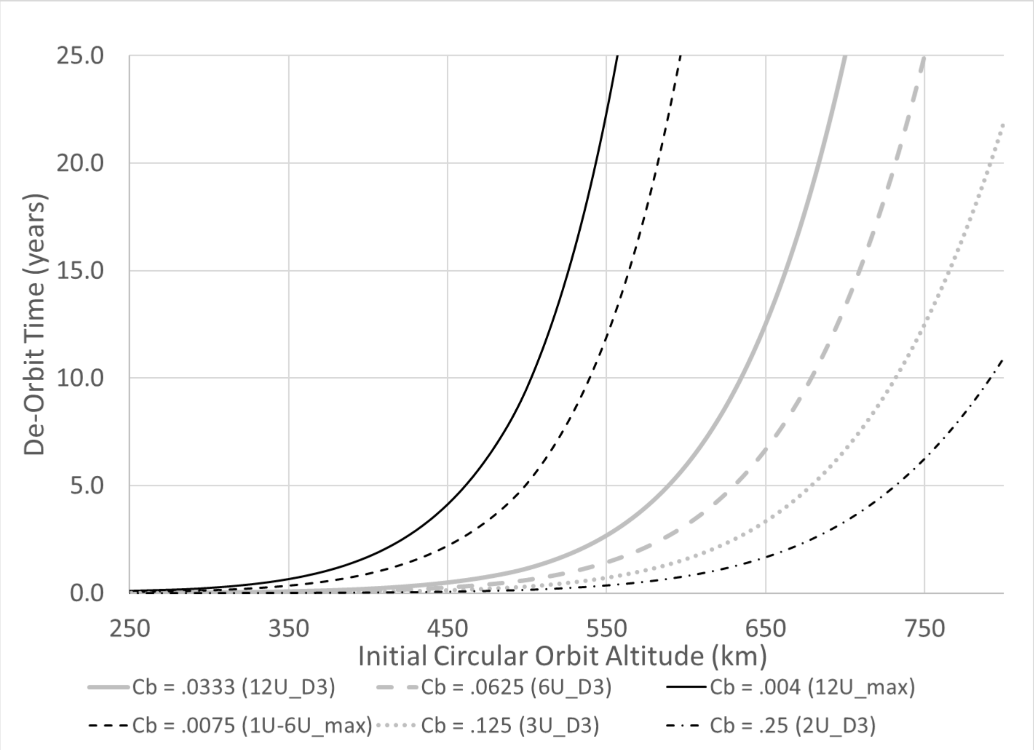
Drag De-Orbit Device (D3) Project Objectives

- Design a drag device to De-Orbit a 12U (15 kg) satellite from 700 km in 25 years (0.5 m^2 required)
  - Most Low Earth Orbit (LEO) spacecraft do not have thrusters to de-orbit with
- Design a control algorithm by which the drag device can be deployed and retracted to target a de-orbit location, perform collision avoidance, and maintain ram-alignment
- Manufacture drag device
- Test the Drag De-Orbit Device (*D3*) in flight

- Plot shows 12U, 6U, and 3U satellite orbit lifetimes with and without the .5m^2 drag device (D3)

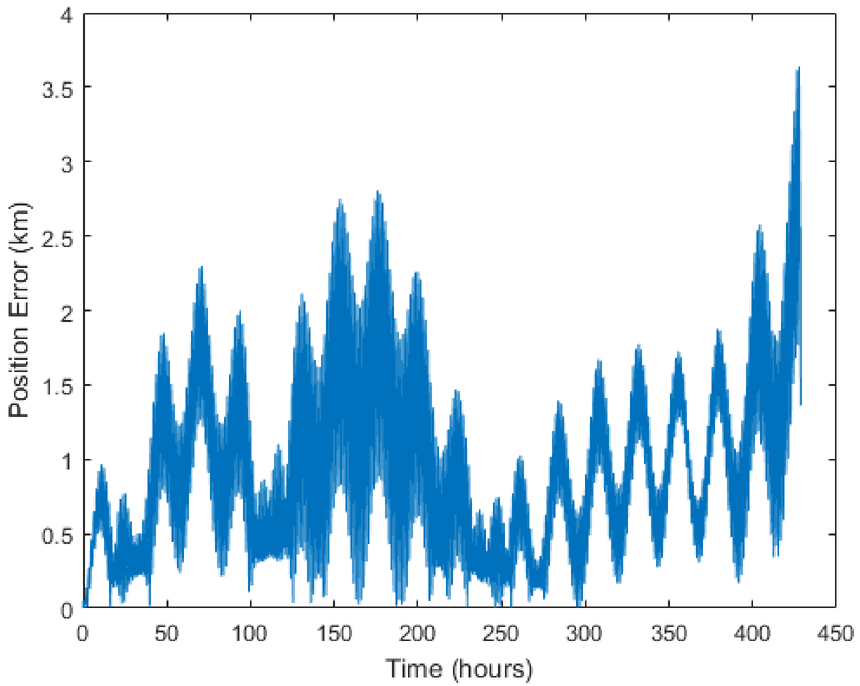


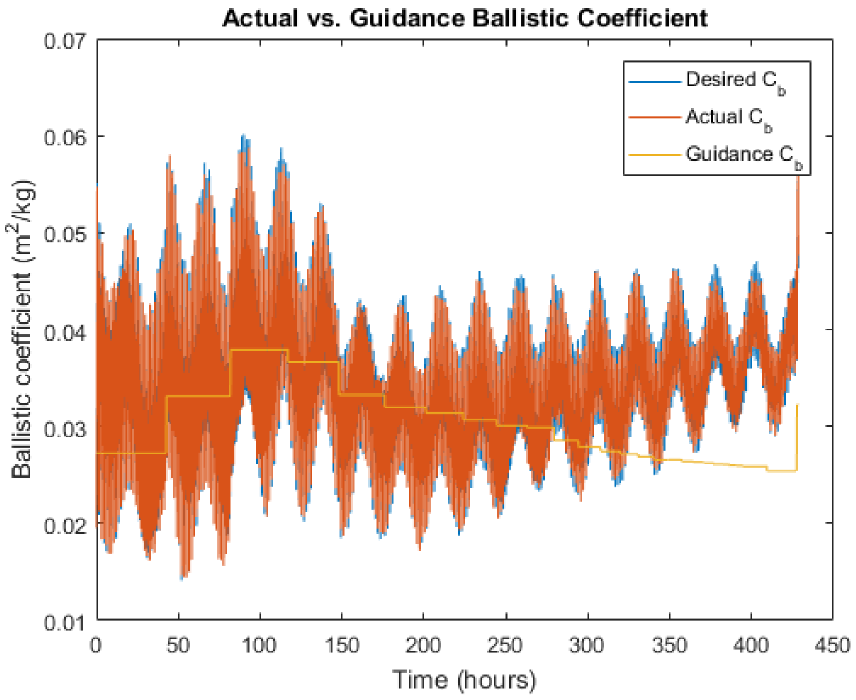
Algorithms Overview

- De-orbit point “Targeting Algorithm” has three components
- Guidance Generation Algorithm
  - Computes the ballistic coefficient (C_b) over time profile and corresponding trajectory that a satellite must follow to de-orbit in a desired location
- Navigation Algorithm with Kalman Filtering
  - Given noisy GPS measurements, estimates the position and velocity of the spacecraft relative to the guidance
- Guidance Tracking Algorithm
  - Based on the relative position and velocity, computes the ballistic coefficient that spacecraft must maintain to return to the guidance
    - Continues LQR-based full state feedback

Kalman Filter with Measurement Noise, Bias, and Density Error

- Motor runs 3.5% of the time assuming 240 seconds for full deployment
  - 5% actuator deadband
- Truly a “worst case”
- Tracking to 90 km altitude





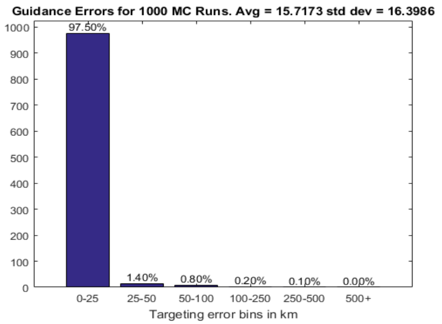
Monte Carlo Simulations

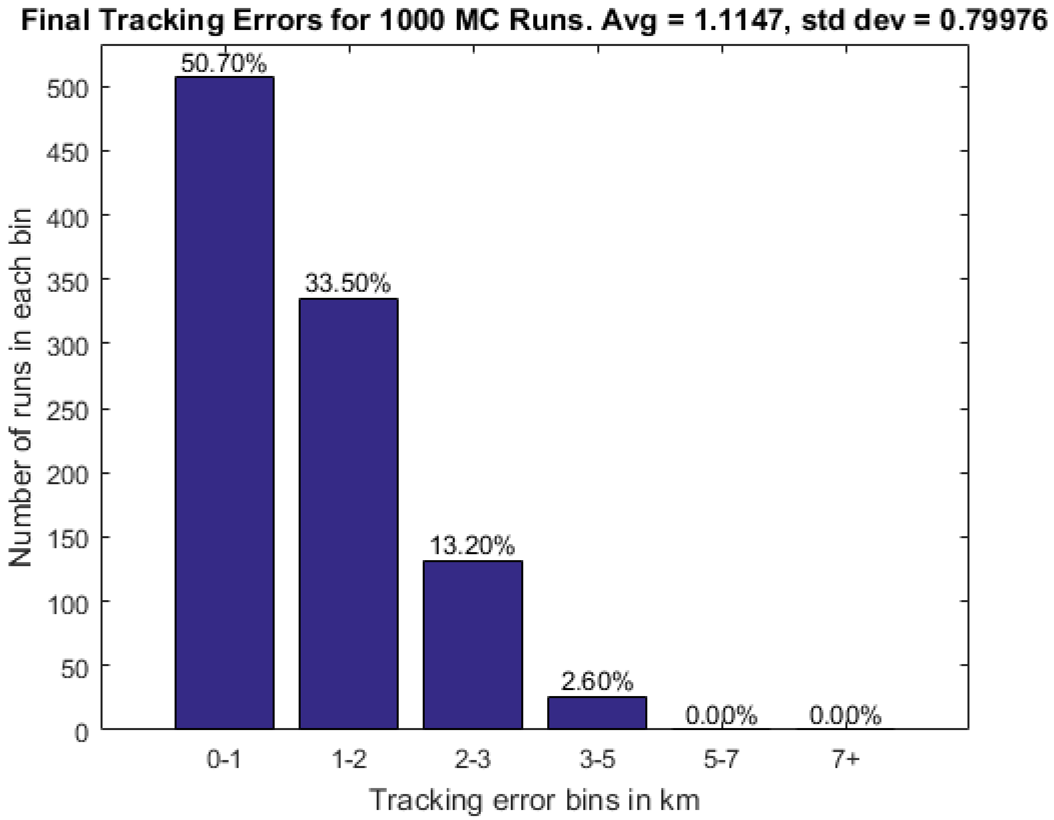
Variable	Range	Probability Distribution
Semi Major Axis	[6698, 6718] km	Uniform
True Anomaly	[0, 360] degrees	Uniform
Eccentricity	[0, .004]	Uniform
Right Ascension	[0, 360] degrees	Uniform
Argument of the Periapsis	[0, 360] degrees	Uniform
Inclination	[1, 97] degrees	Uniform
Impact Latitude	[0, max(inclination, 180-inclination)-. 1] degrees	Uniform
Impact Longitude	[-180, 180] degrees	Uniform
Cb_{max}	[.033, .067]	Uniform
Cb_{min}	[.0053, .027]	Uniform
epoch	[11/1/2003, 11/1/2014]	Uniform

1,000 guidance generation and tracking simulations were conducted for the randomly varying simulation parameters in the table above.

Guidance Generation and Tracking MC Results

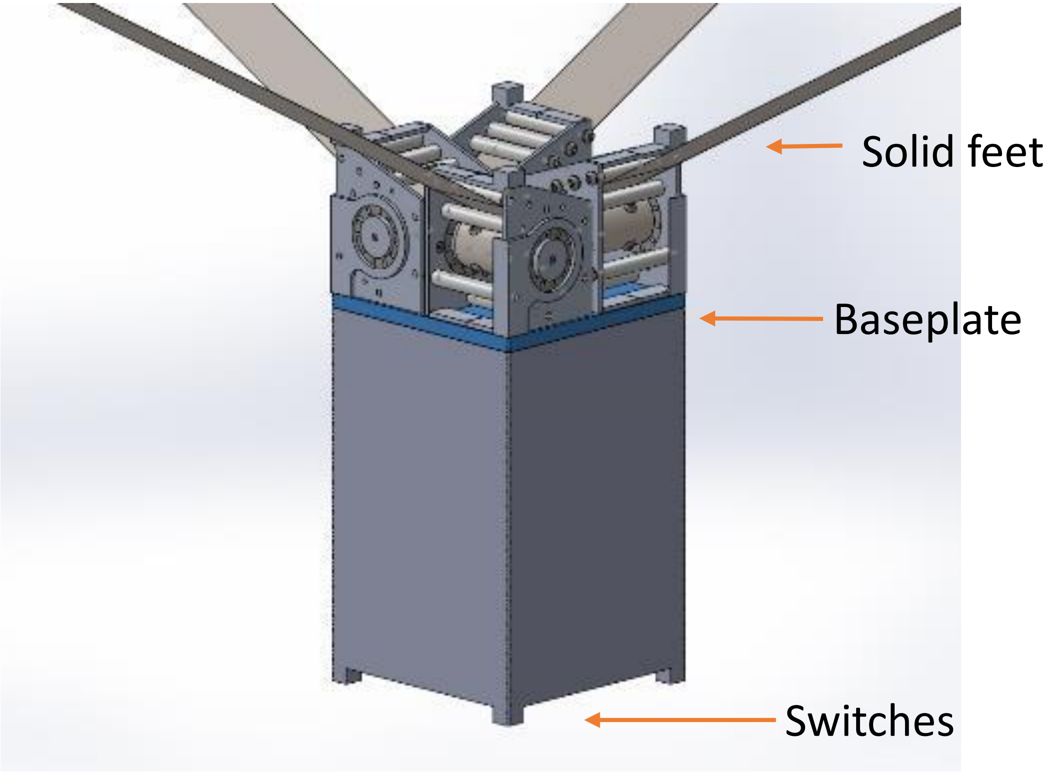
- Guidance generation algorithm calculates a trajectory that the spacecraft must follow to reach a desired de-orbit location
- Guidance tracking feedback control algorithm modulates ballistic coefficient to ensure this trajectory is followed despite drag force uncertainties
- Average guidance error of 16 km and average final tracking error of 1.1 km
  - Tracking down to 120 km geodetic altitude



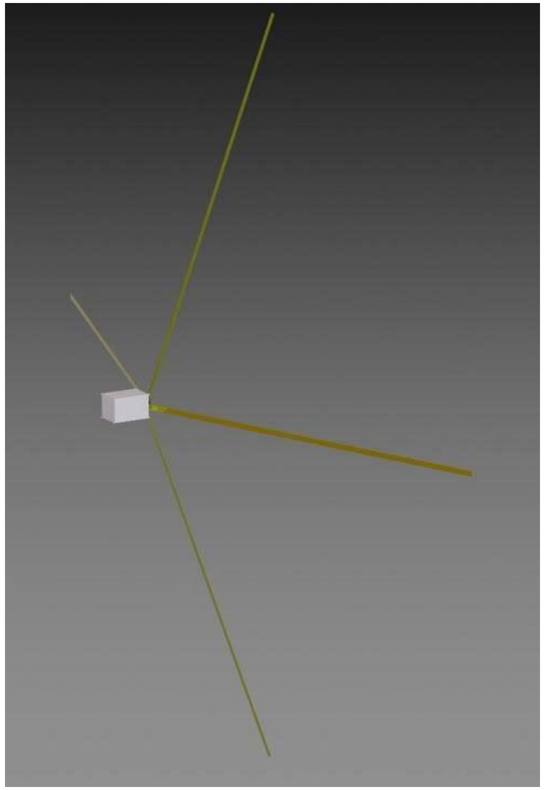


D3 Device Overview

- Drag De-Orbit Device (D3) attaches to existing CubeSats to facilitate de-orbit of a 12U, 15 kg satellite in 25 years from a 700 km circular orbit
- D3 is retractable and facilitates re-entry point targeting
- Re-entry point targeting algorithms run onboard D3 microcontroller

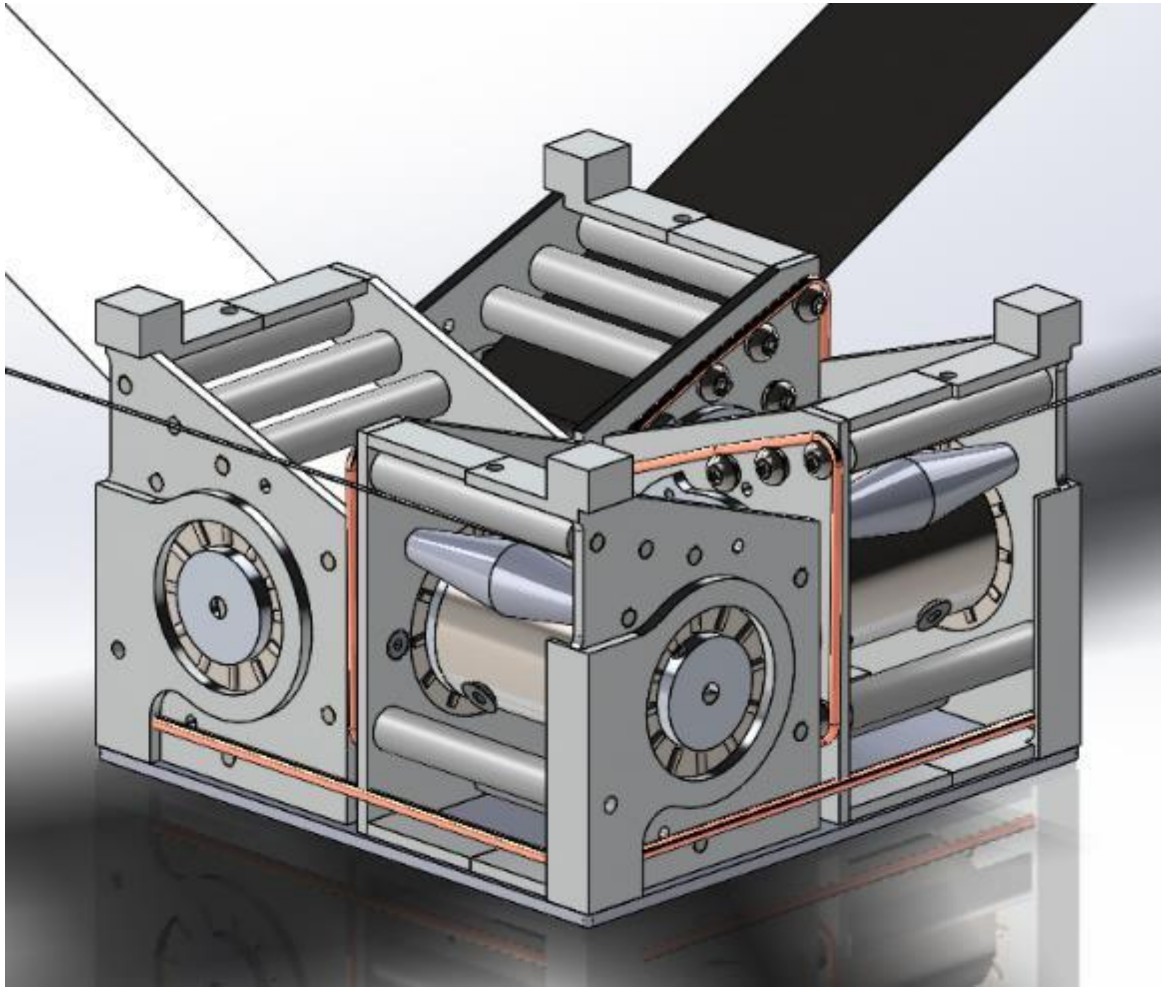


D3 is Compatible With CubeSat Design Spec



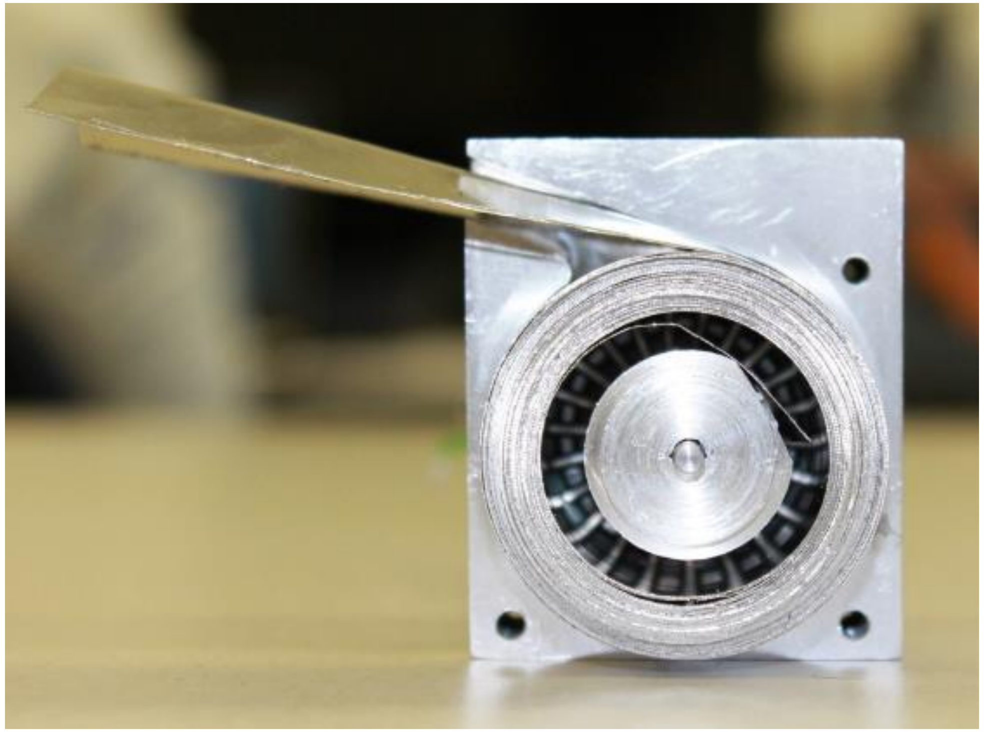
D3 Installed on CubeSat

Four deployers are attached to make the drag device

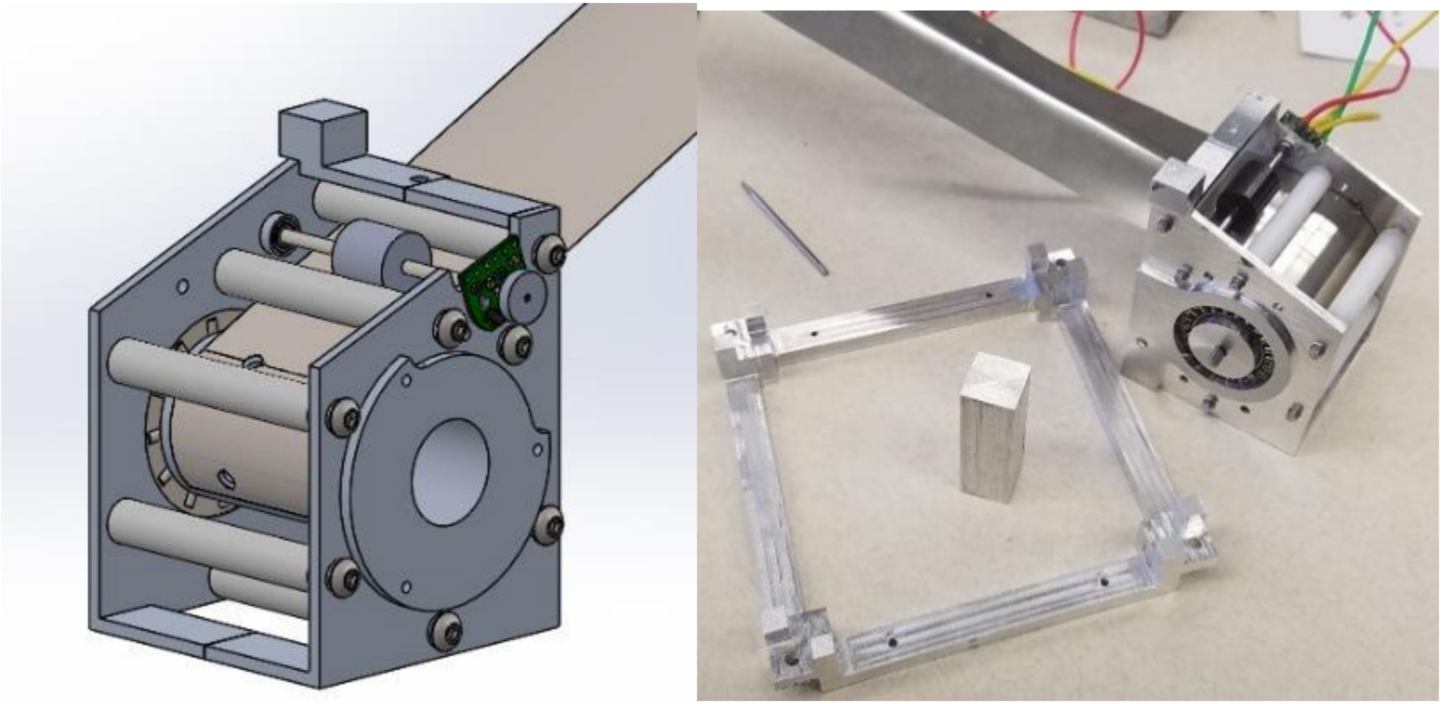


- Each deployer is actuated independently
- Five magnetorquers are used to damp rotational velocity

D3 Deployer

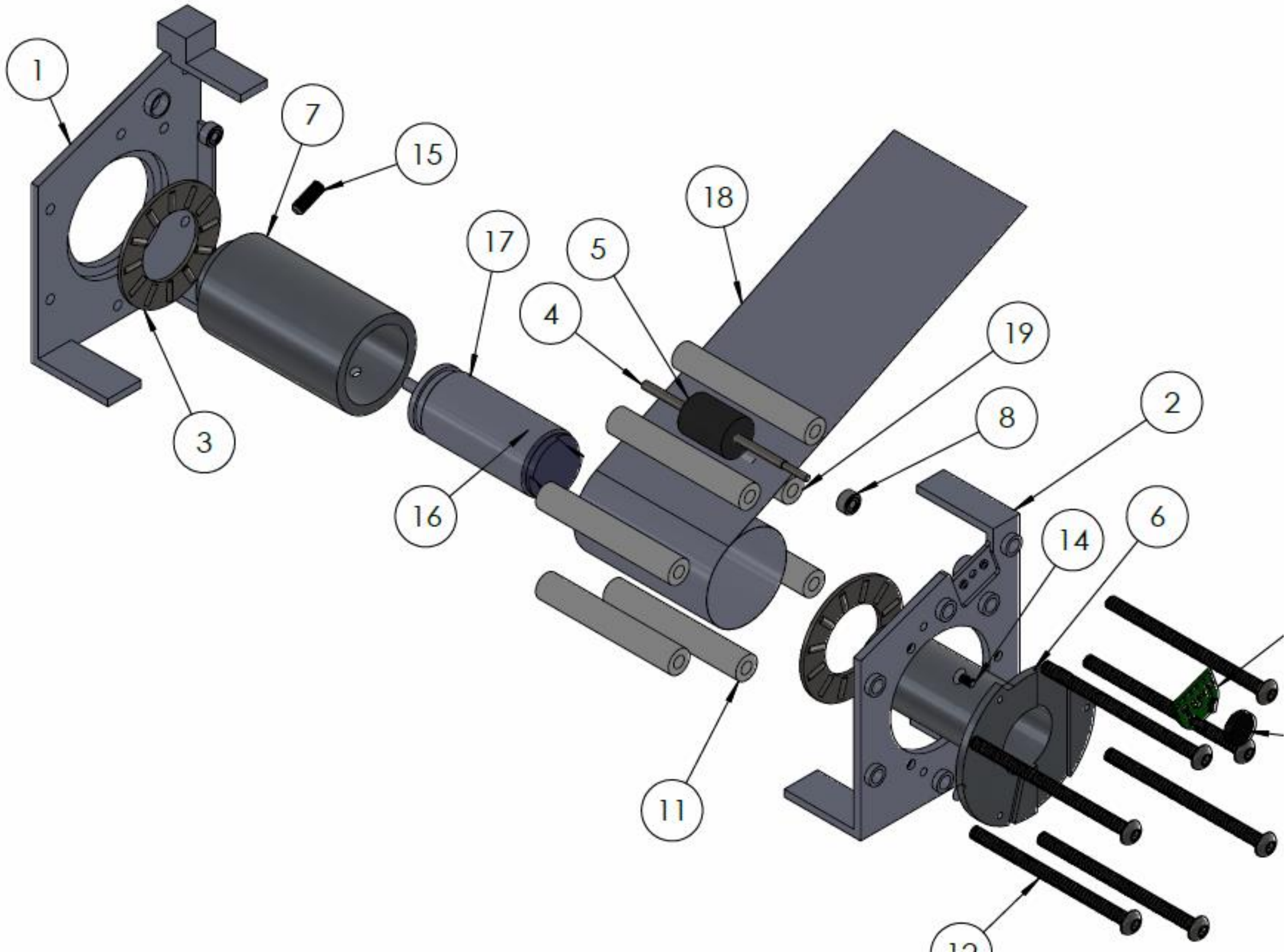


Original Version of Deployer

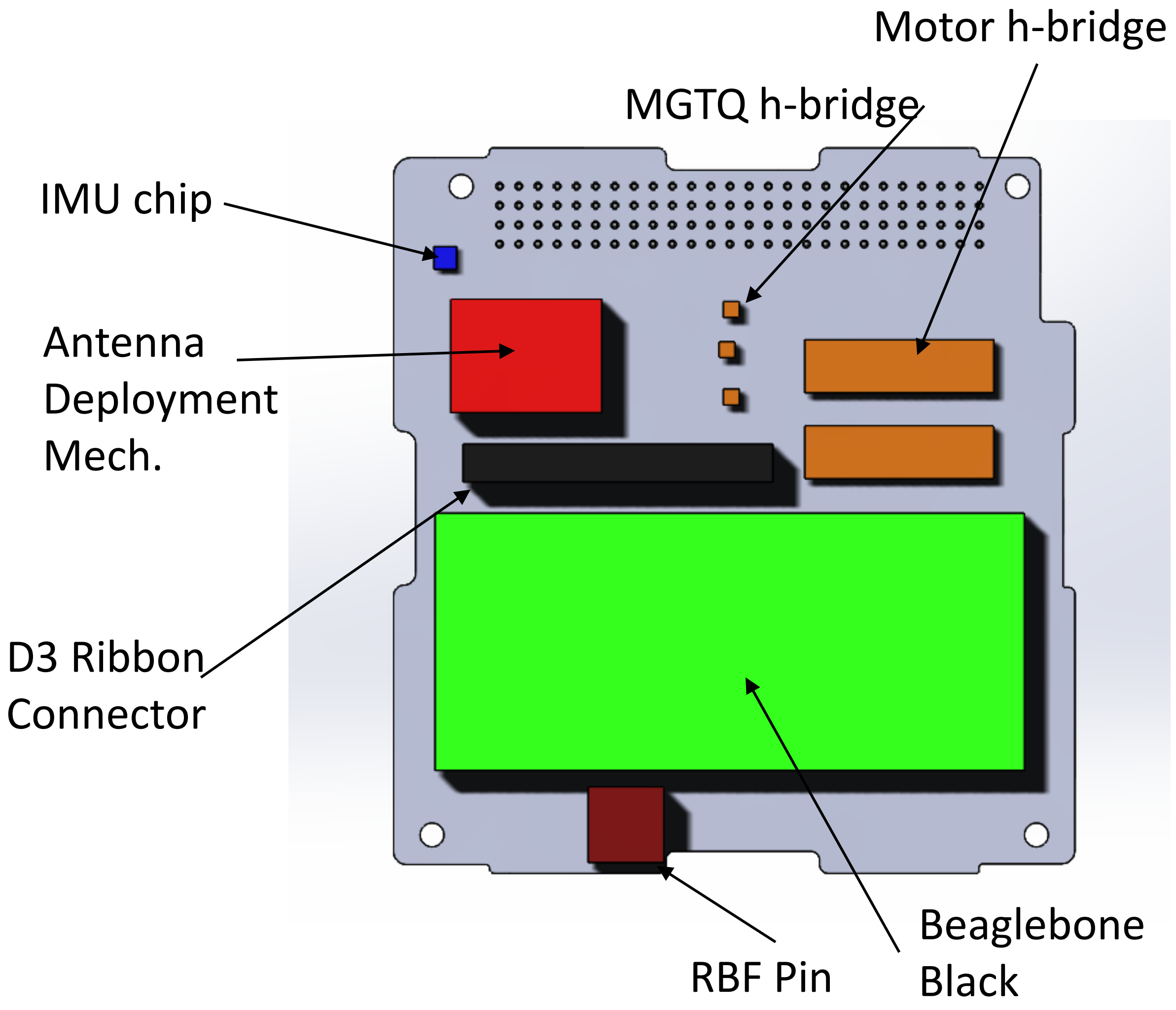


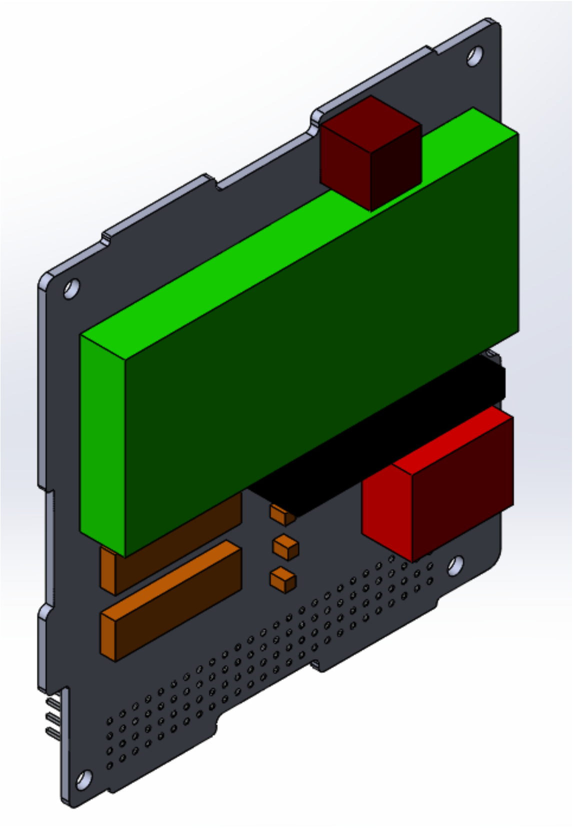
Latest Version Includes Rollers and Encoder

Deployer Uses Faulhaber 1516-006SR Motor with 15/5S 262:1 gearbox to Drive Boom



D3 Control Board Design





D3 Control Board Pin Header Interface

2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	H2
1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	H1
1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43	45	47	49	51	

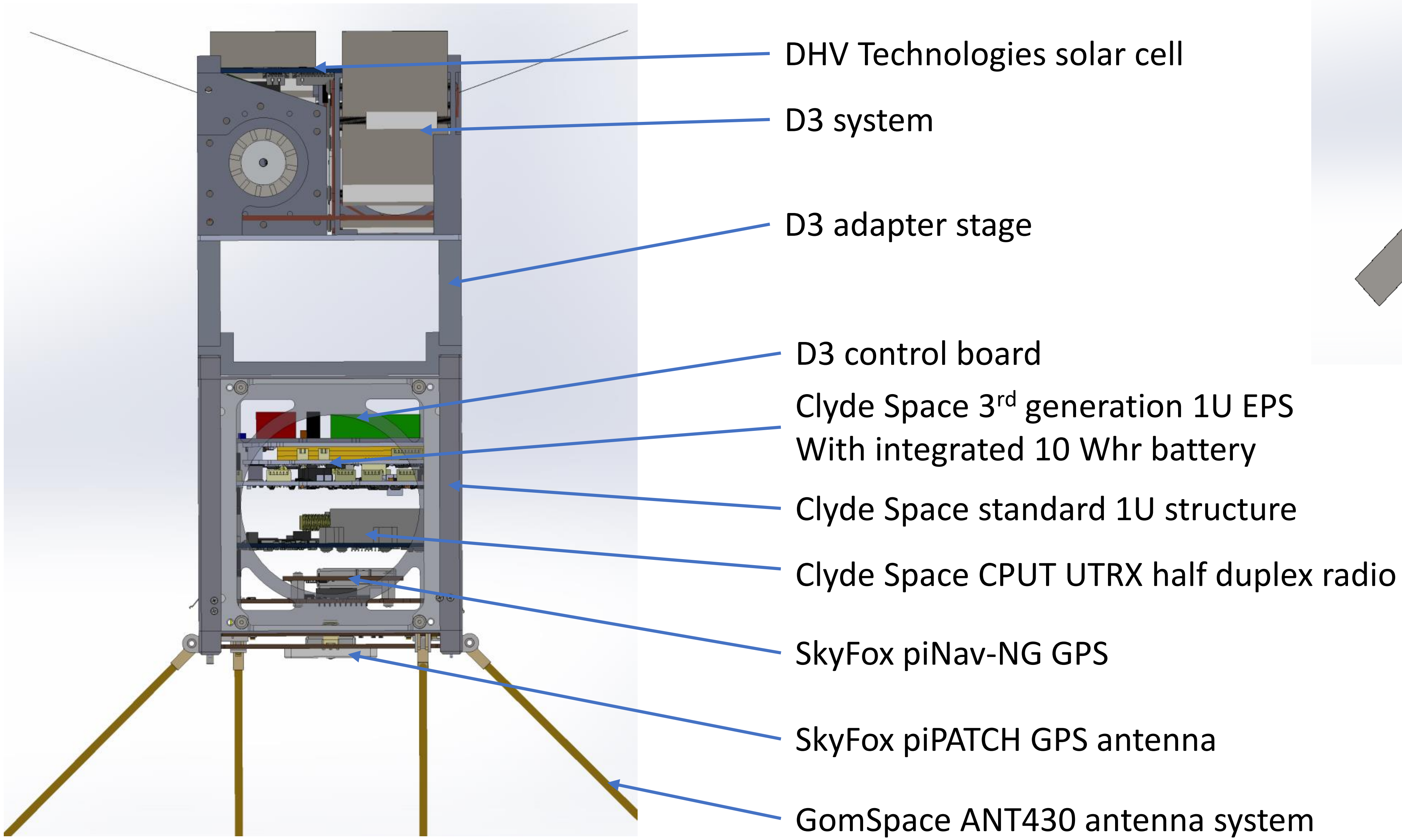
Key

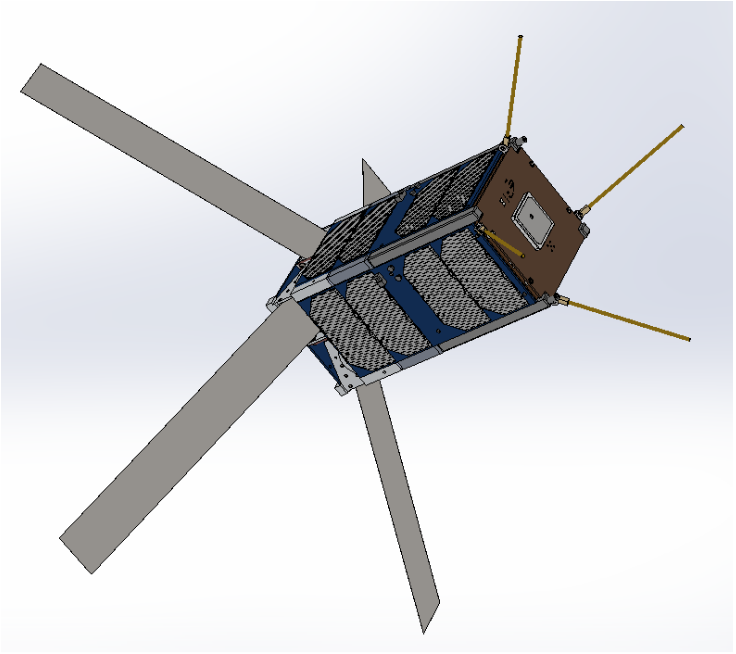
- USB Charge (H1-32)
- I2C Data (H1-41)
- I2C Clock (H1-43)
- Ground (H2-(9, 14, 17, 29, 30, 32, 47, 48))
- 5V Regulated Power (H2-25, H2-26)
- 3.3V Regulated Power (H2-27, H2-28)
- GPS Serial data receiver pin (H1-19)
- GPS Power on Signal (H1-23)
- GPS Power off Signal (H1-21)
- GPS Timing Pin (H1-45)
- GPS Position Fix Indicator (H1-49)
- Transmit Empty (H1-1)
- Transmit Ready (H1-5)
- Receive Ready (H1-6)
- Radio Reset (H1-2)
- Independent DTMF Pins (H2-(49-52))

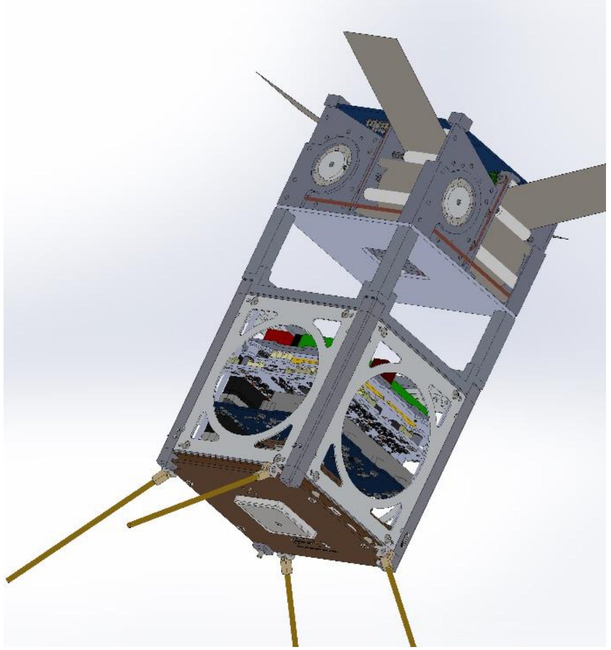
CubeSat Mission Requirements

Success Level and Description	Demonstration	Verification Criteria
Required: D3 CubeSat ejects from deployer	Prerequisite.	• Track CubeSat with radar. • Confirmation of launch from vehicle.
Required: Ground systems make contact with CubeSat	Prerequisite.	Make radio contact.
D3 booms are used to change the cross-wind area of the CubeSat	Boom can operate in LEO.	• Commanded motor position telemetry. • Track CubeSat with radar and look for drag changes.
D3 stabilizes attitude of CubeSat	Booms and magnetorquers can be used to stabilize attitude in LEO.	• Commanded motor position telemetry. • Magnetometer telemetry.
D3 device is used to actuate a desired maneuver	D3 can be used to actuate a desired maneuver.	JSpOC radar data and CubeSat GPS data.
D3 device is used to deorbit within a desired interval	Ability of D3 to deorbit a CubeSat as desired.	JSpOC radar data and CubeSat GPS data.
Maximum: d3 deorbits to within 1300km of a desired target interface point at 90km altitude.	Ability of D3 to deorbit the CubeSat to a safe location.	Track CubeSat with radar.

Spacecraft Design CAD Model







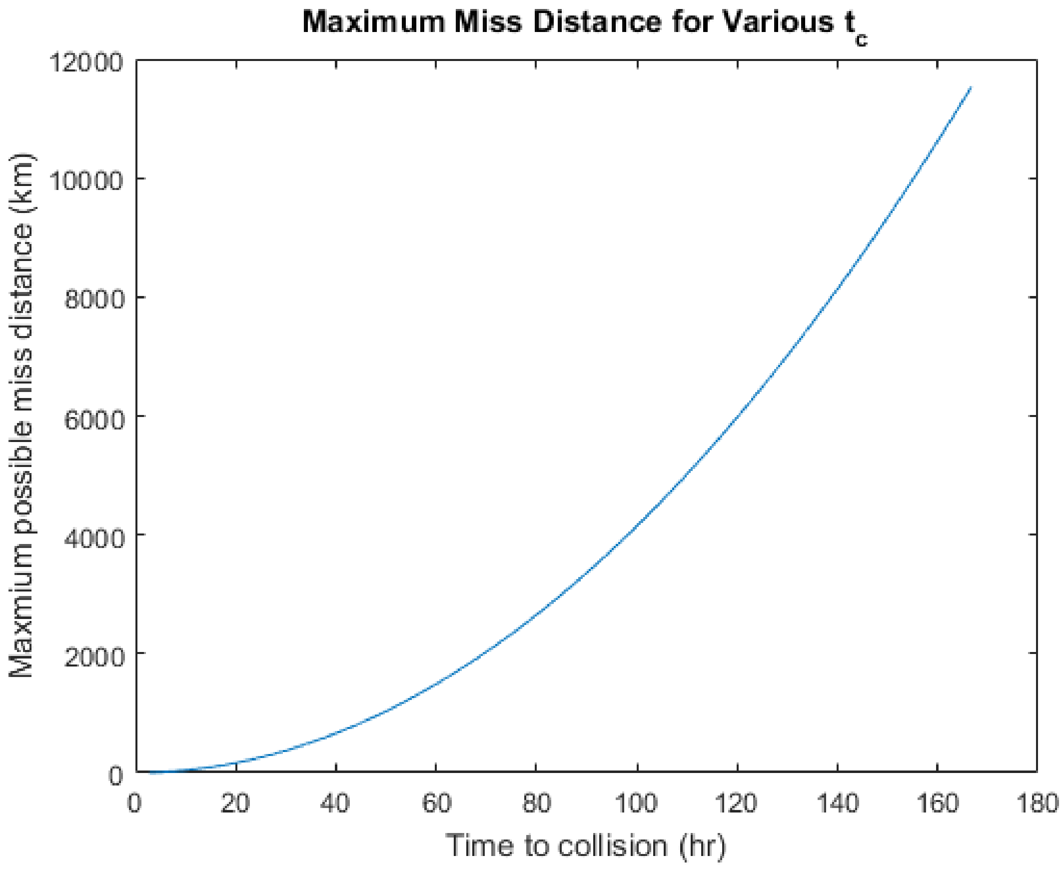
Hardware Configuration

Component	Options	Mass (g)	Avg power use (mW)	Size (mm^3)	Cost (USD)
EPS	Clyde Space 3rd generation 1U EPS	86	160	95 x 90 x 15.4	4400
Battery	Clyde Space 10 Whr Battery	156	0	95 x 90 x 10	1800
Radio	Clyde Space CPUT UTRX half duplex radio	90	250 rx, 4000 tx, 333 avg with 30 min daily tx	96 x 90 x 10	8600
Comm. Antenna	GomSpace NanoCom ANT430	30	0	100 x 100 x 4	6325
D3 deployers	Custom	1100	200 avg, 15000 peak	100 x 100 x 69	2000
D3 magnetorquers	Custom	101	Variable	Integrated	100
D3 Microcontroller	BeagleBone Black Industrial	24	1000	87 x 55 x 10	100
Solar Panels	DHV Technologies four 1.5U panels on long edges	100	-4240 max gen	170.25 x 83 x 1	21150
	DHV Technologies two 1U panels on short edges		-2120 max gen	98 x 98 x 1	
Structure	ClydeSpace 1U structure	200	0	100 x 100 x 113.5	2560
D3 adapter stage	Custom	200	0	100 x 100 51	200
Navigation	SkyFox piNav-NG	100	139	75 x 35 x 12.5	9300
GPS Antenna	SkyFox piPATCH	25	100	98 x 98 x 14.5	2237
Totals		2212	1932 avg cont use	10 x 10 x 227	58722

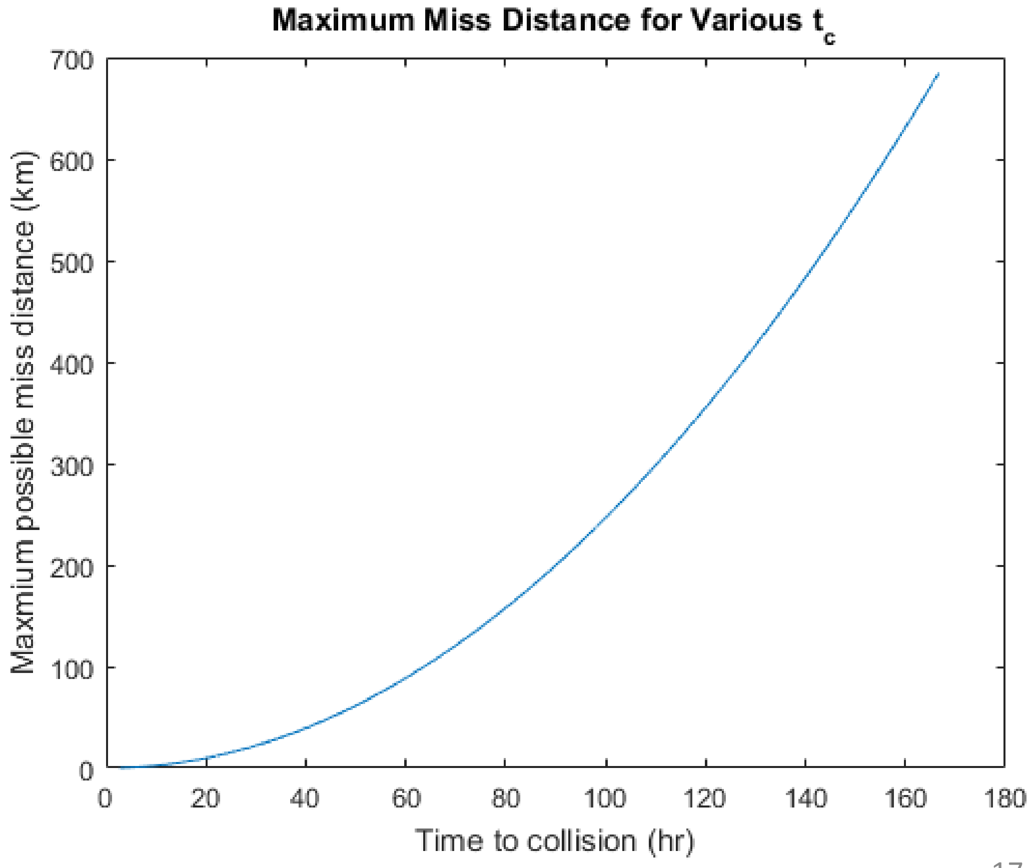
Backup slides

Maximizing Miss Distances using Aerodynamic Drag for 400 and 600 km Circular Orbits

400 km orbit

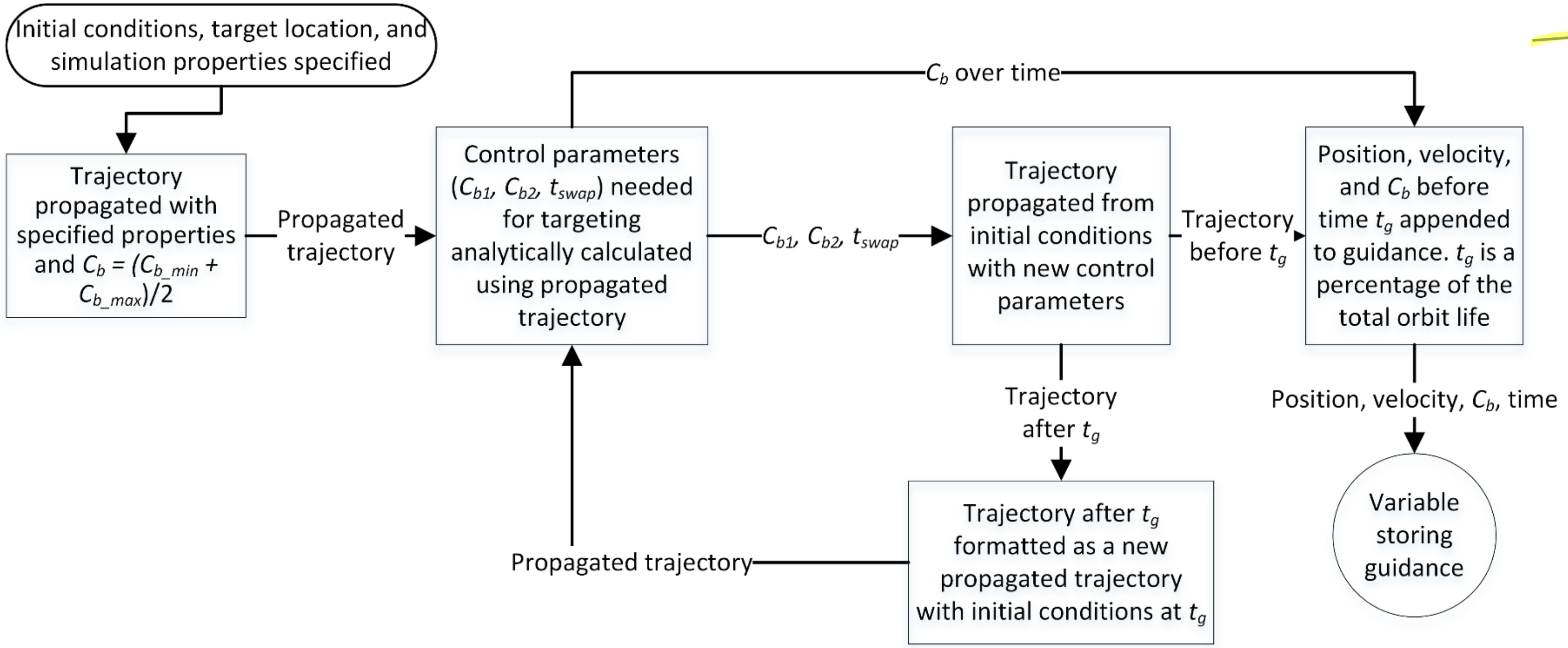


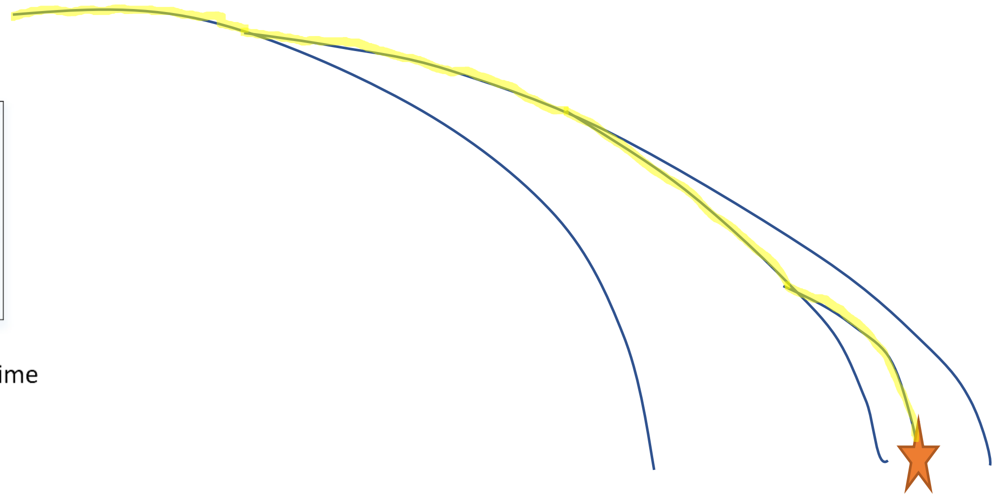
600 km orbit



Guidance Generation Algorithm

- Given a numerically propagated decay trajectory, it is possible to analytically estimate the C_b profile needed to de-orbit in a desired location
- Receding horizon guidance generation strategy
  - Trajectory propagated with analytical C_b profile for t_g seconds comprises first part of guidance
    - t_g is 1/10 of orbit life on each step
    - C_b is adjusted during propagation to ensure work done by drag consistent with analytical solution
  - New C_b profile analytically calculated, propagated for t_g seconds, and resulting trajectory appended to guidance
  - Procedure continues until trajectory found that yields low enough guidance error or less than certain amount (1 day) of orbit life remaining





Guidance Generation Analytical Solution

- Must control de-orbit latitude and longitude at given geocentric altitude
  - Final time free
- Control parameters are
  - t_{swap} = time until ballistic coefficient is changed
  - C_{b1} = ballistic coefficient from t_0 to t_{swap}
  - C_{b2} = ballistic coefficient from t_{swap} to t_{term}
    - Spacecraft maintains some predetermined drag profile after t_{term}
- Given enough time, variation of these parameters is sufficient to target any de-orbit point with latitude below the orbit inclination
- Analytical Solution Assumptions
  - Circular orbit around spherical Earth
  - Density is a function of semi major axis
    - If density is a function of altitude in a circular orbit around a spherical Earth, density is also a function of semi major axis
  - De-Orbit point is before aerodynamic forces exceed gravitational forces (~70 km altitude)
    - orbital elements still valid
- Receding horizon strategy eliminates errors resulting from these assumptions

Analytical Mapping from Initial to Final State

- Fundamental building block of analytical solution
- If a satellite with C_{b1} takes time t_1 to achieve some change in semi major axis and experiences a change in true anomaly $\Delta\theta_1$ during this time, then for a satellite with the same initial conditions and C_{b2}

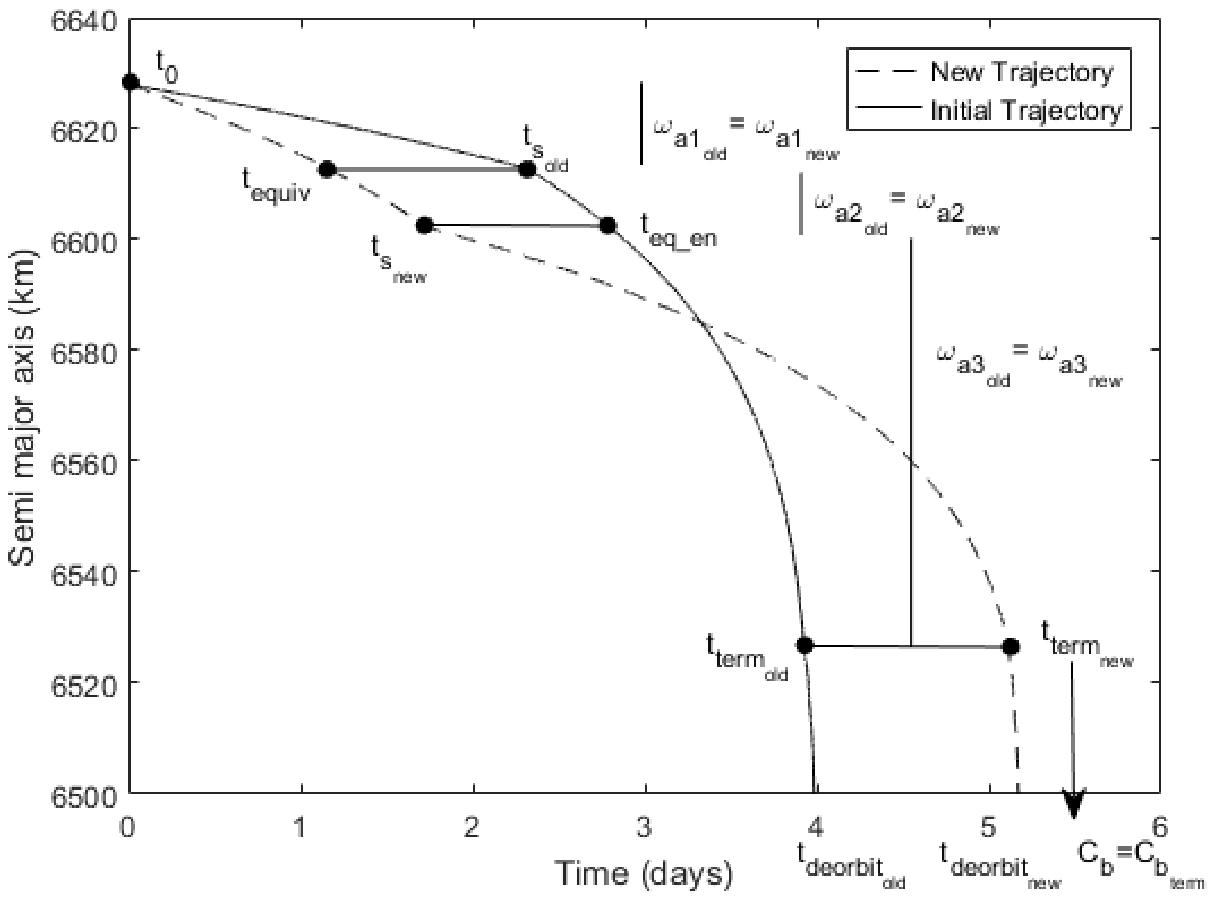
$$t_2 = \frac{C_{b1} t_1}{C_{b2}}$$

$$\Delta\theta_2 = \frac{C_{b1} \Delta\theta_1}{C_{b2}}$$

- It also proves that the average orbital angular velocity $\omega_{avg} = \frac{\Delta\theta}{\Delta t}$ for a given change in semi major axis is independent of ballistic coefficient

Characterizing New Trajectory Based on Old Trajectory

- Divide trajectories into four phases
- Phases go from same initial to final semi major axes in old and new trajectories
  - C_b values are unchanging in each phase
- Average angular velocity in each phase constant between old and new trajectories
- Time, raan change, and change in true anomaly associated with each phase in the new trajectory calculated based on corresponding phase in old trajectory and analytical relations
- Both spacecraft assumed to follow the same decay profile after t_{term} (terminal point)
- Time and orbital elements of the new spacecraft at de-orbit point can be calculated and used to calculate de-orbit latitude and longitude.



Calculating New Control Parameters

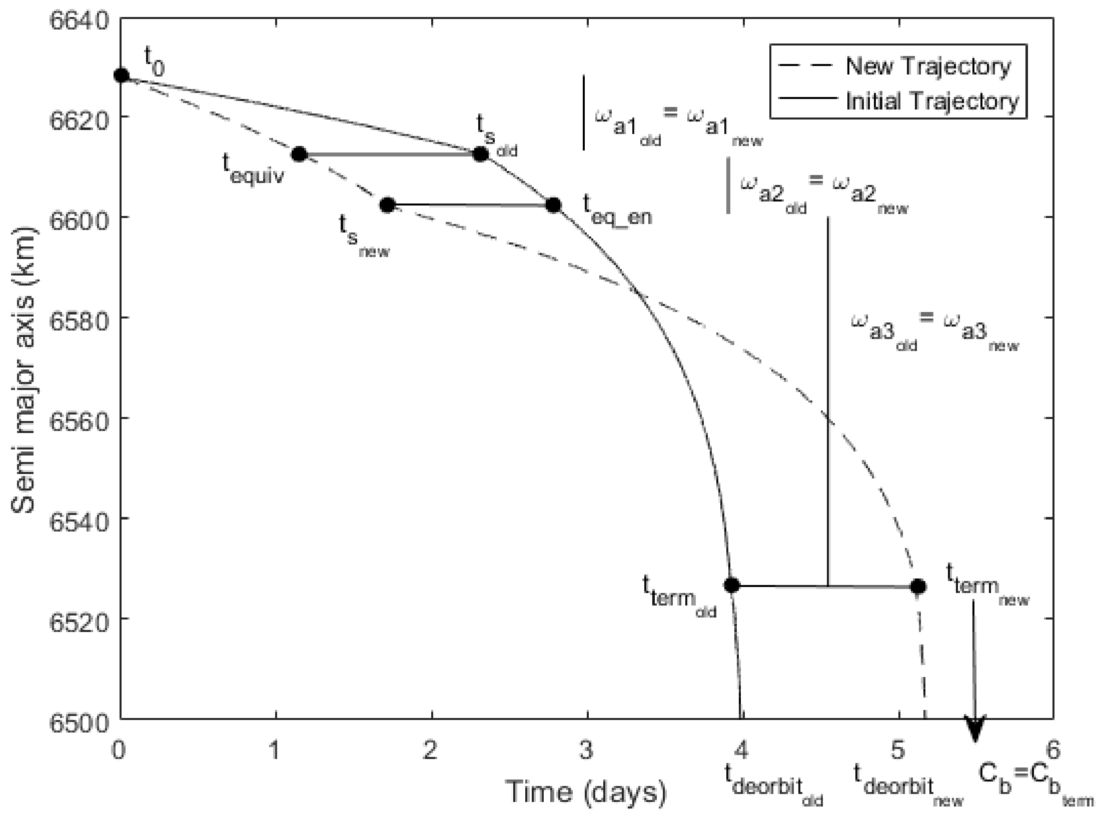
- Control parameters to achieve desired $\Delta\theta_t$ and Δt_t

$$C_{b2} = \frac{C_{b20}(\Delta t_{20}\Delta\theta_{10} - \Delta t_{10}\Delta\theta_{20})}{\Delta t_t \Delta\theta_{10} - \Delta t_{10}\Delta\theta_t}$$

$$C_{b1} = \frac{C_{b10}(\Delta t_{10}\Delta\theta_{20} - \Delta t_{20}\Delta\theta_{10})}{\Delta t_t \Delta\theta_{20} - \Delta t_{20}\Delta\theta_t}$$

$$t_{swap} = \frac{\Delta t_{10} C_{b10}}{C_{b1}}$$

- Compute control solution for multiple initial values of t_{swap} to explore full control space
- Select solution with maximum remaining orbit lifetime controllability



Discrete Time Extended Kalman Filter for LQR Guidance Tracking

- State will be relative position and velocity
  - Measurement $z =$ relative position and velocity derived from GPS measurement and guidance state

$$z_i = Gx_i,\ x_i \approx \Phi_i x_{i-1}$$
$$G = [I]_{4x4}, \Phi_i = e^{(A-BK)t}$$

W = measurement noise covariance

Q = Process noise covariance

Λ = Fading term

f represents numerical propagation from t_i to t_{i-1}

x_1^- and P_i^- are a-priori state and state error covariance estimates

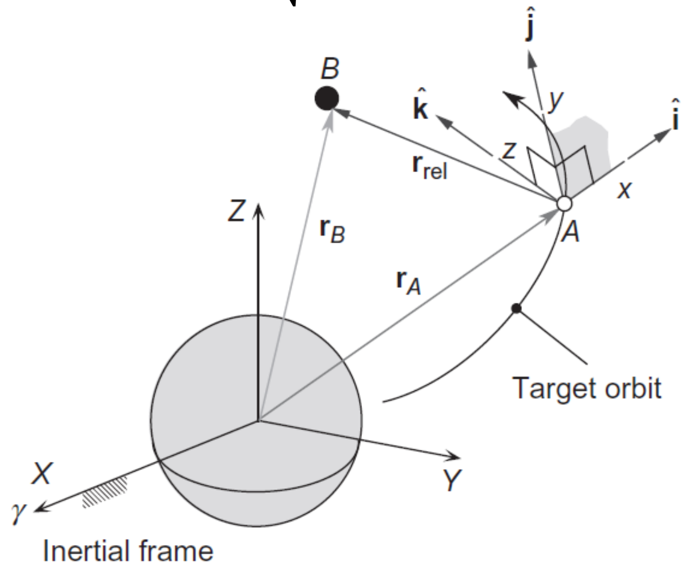
$$x_i^- = f(t_i, t_{i-1}, x_{i-1}^+)$$
$$P_i^- = \Phi_i P_{i-1}^+ \Phi_i^T + Q$$
$$S = GP_i^- G^T + W$$
$$K_i = P_i G^T (S)^{-1}$$
$$x_i^+ = x_i^- + K_i(z_i - Gx_i^-)$$
$$P_i^+ = (I - K_i G)P_i \Lambda$$

Schweighart Sedwick Relative Motion Equations with Differential Drag

$$\begin{bmatrix}\delta\dot{x}\\ \delta\dot{y}\\ \delta\ddot{x}\\ \delta\ddot{y}\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ b & 0 & 0 & a\\ 0 & 0 & -a & 0\end{bmatrix}\begin{bmatrix}\delta x\\ \delta y\\ \delta\dot{x}\\ \delta\dot{y}\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 0\\ -\rho v^2\end{bmatrix}\left(C_{b_{sc}} - C_{b_{guid}}\right)$$

$$\delta\ddot{z} = -n^2\delta z\ (uncontrolled)$$

$$a = 2nc, b = (5c^2 - 2)n^2, c = \sqrt{1 + \frac{3J_2R_e^2}{8a^2}[1 + 3\cos(2i)]}, n = \sqrt{\frac{\mu}{a^3}}$$



Full State Feedback Control

$$C_{b_{sc}} = C_{b_{guid}} - K\boldsymbol{x}$$
$$K = lqr(A, B, Q, R, 0)$$

- System of form $\dot{\boldsymbol{x}} = A\boldsymbol{x} + Bu$
- R is a 1x1 control weighting matrix
- Q is a 4x4 error penalty matrix
- Gain value *K* minimizes cost function $J = \int_0^\infty (\boldsymbol{x}^t Q\boldsymbol{x} + u^t Ru)\, dt$