INERTIA TENSOR ESTIMATION OF TETHERED DEBRIS THROUGH TETHER TRACKING

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- Outline
- Introduction
- Data Generation
- Unscented Kalman Filtering
- Conclusion

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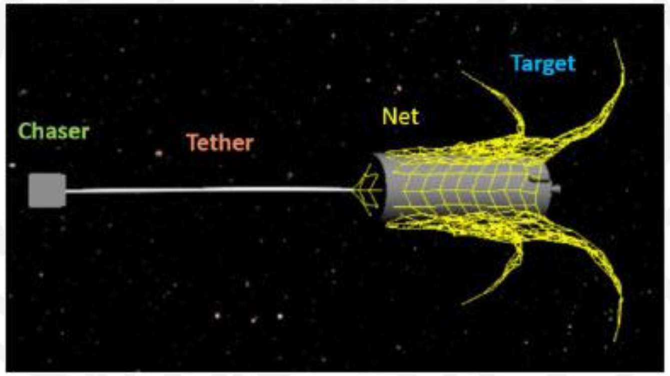
Introduction

Tether-based Capture of Debris

- Tether-based capture of debris include tether nets and harpoons
  - Safer capture of debris (longer distances can be maintained)
  - More difficult to control
    - De-tumbling, model prediction, collision prevention, etc.
    - Requires moments of inertia
      - Ratios are often found
- Principal moments of inertia estimated via UKF



(Botta et al. 2020)

- Outline
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Challenges

Moment of Inertia Observability

- Requires knowledge of acting moments on target
  - Most debris is freely rotating
  - Tension in tether creates a known moment
- Requires angular rate of target
  - Debris is unresponsive and uncooperative
  - Tracking features on the target provides angular rate estimates

- Outline
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- Introduction
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System Model

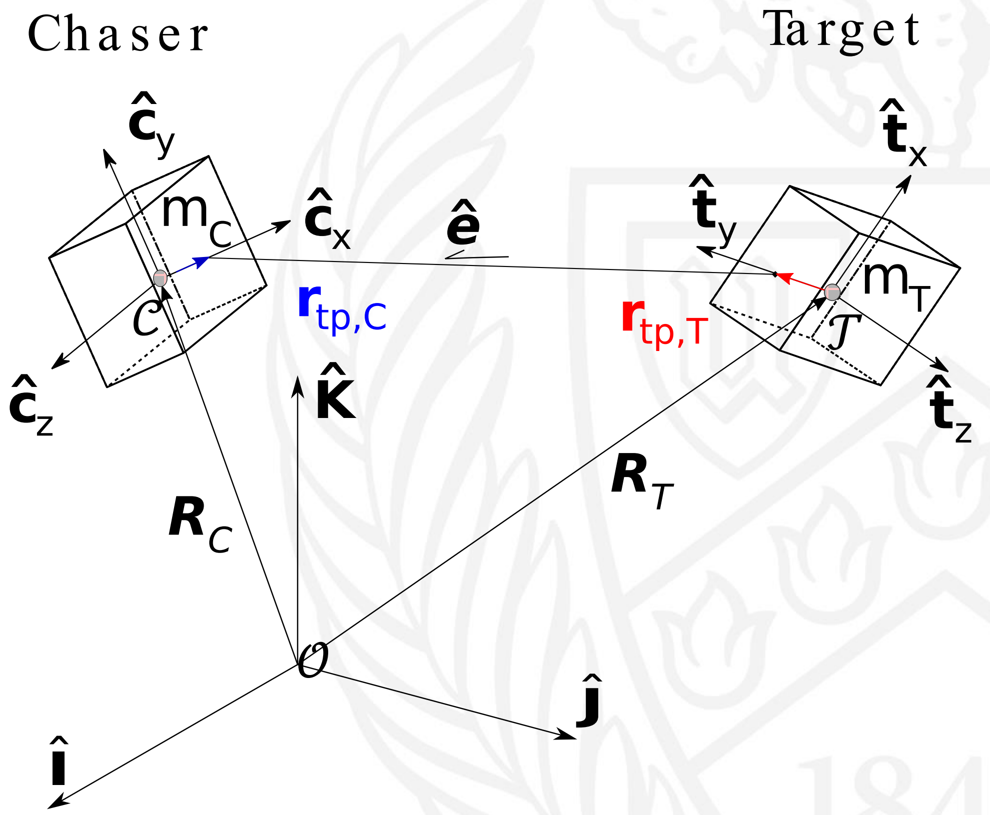
- Rigid body chaser and debris connected by massless, extensible tether treated as a single spring-damper

$\mathcal{O}[\hat{\boldsymbol{I}}, \hat{\boldsymbol{J}}, \hat{\boldsymbol{K}}]$: ECI frame

$\mathcal{C}[\hat{\boldsymbol{c}}_1, \hat{\boldsymbol{c}}_2, \hat{\boldsymbol{c}}_3]$: Chaser body frame

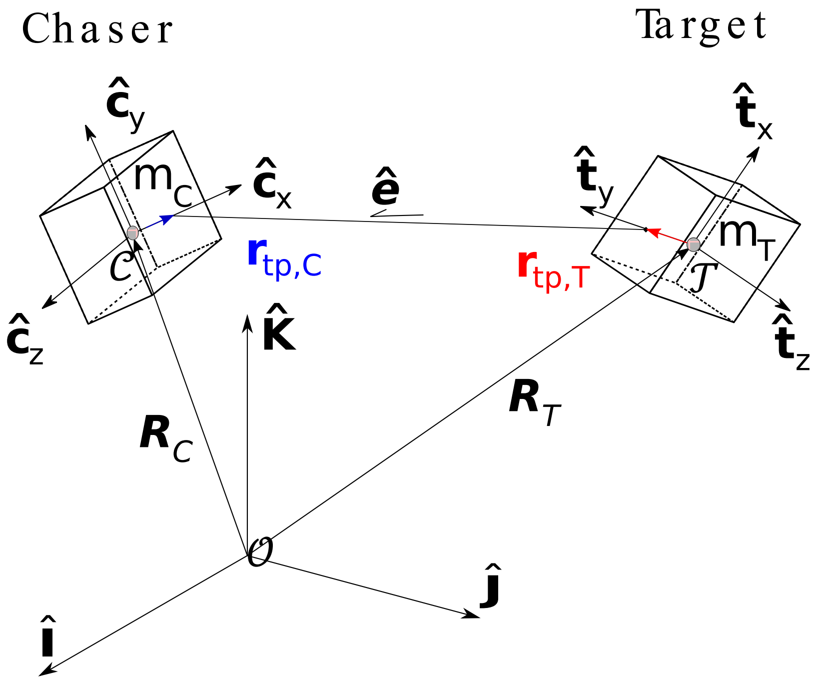
$\mathcal{T}[\hat{\boldsymbol{t}}_1, \hat{\boldsymbol{t}}_2, \hat{\boldsymbol{t}}_3]$: Target body frame

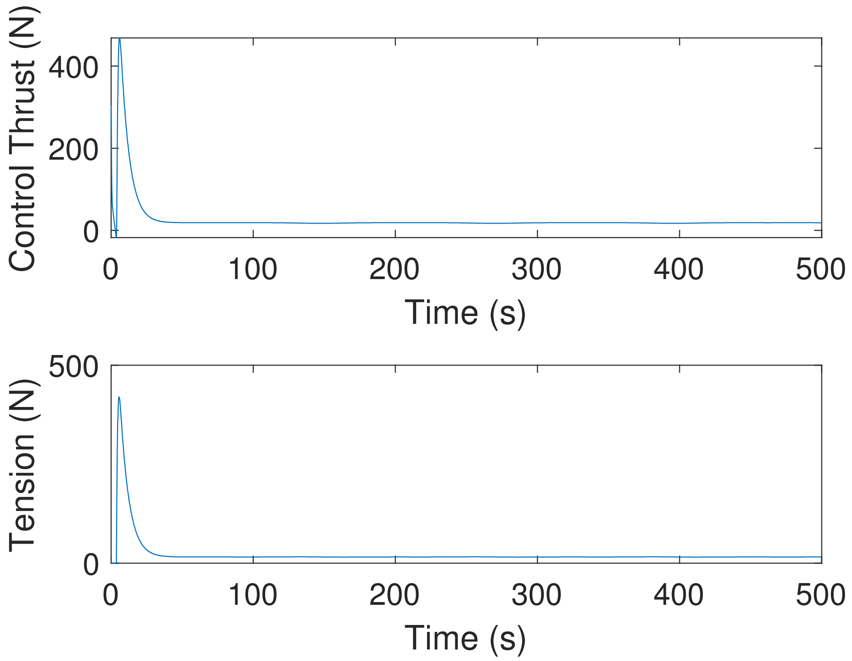
r_{tp}: Tether attachment point



Model Simulation and Control

- Full dynamics simulated with sliding mode and PID control
  - Chaser remains pointed down tether direction via SMC
- Relative distance between chaser and target maintained by PID control





- Outline
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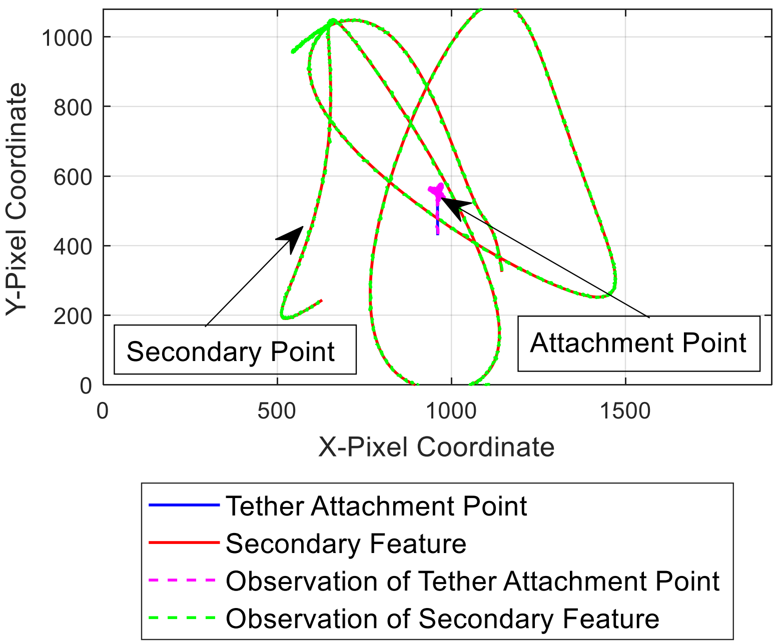
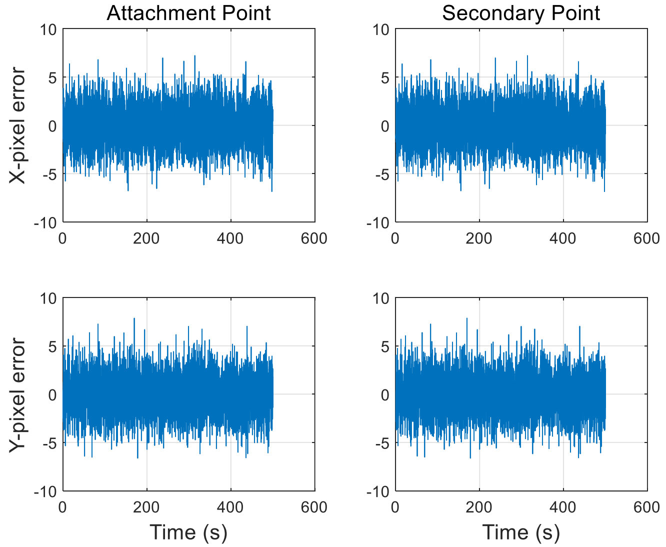
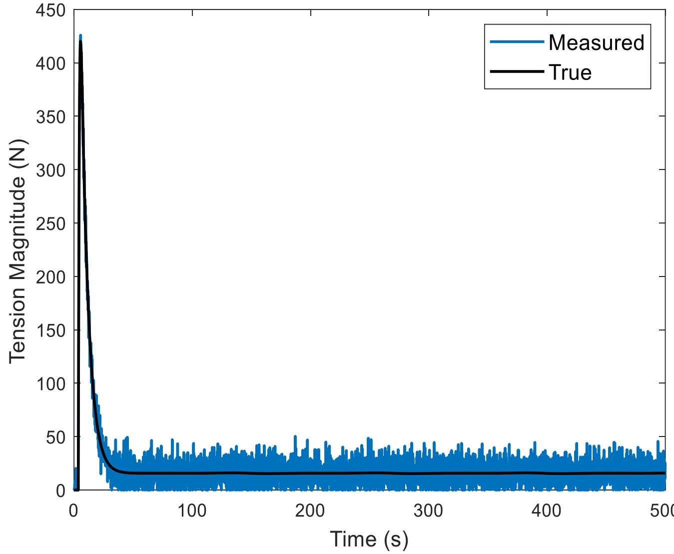
Synthetic Data Generation

- Tension measurements through noise ~(0,10) N
- Pixel coordinate position measurements of 2 tracked features ~(0, 2) pixels







Outline

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Kalman Filter Dynamics

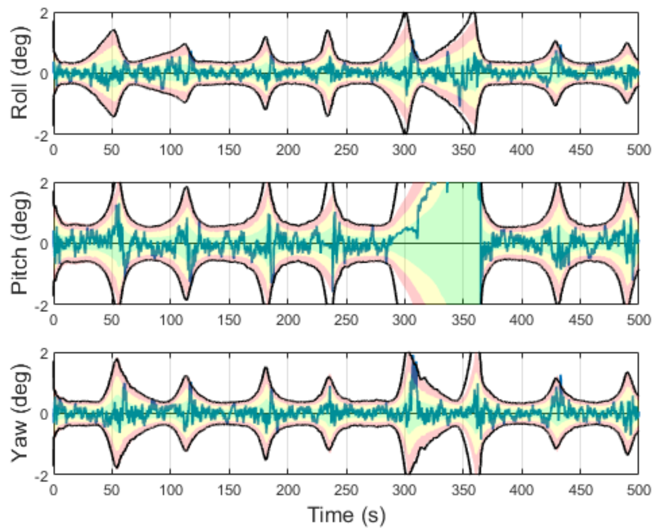
- Assume tether attachment points in target and chaser body frames are known
- Tether tension is measured and used as true
- Measurement model utilizes only pixel coordinate measurements ($\boldsymbol{h}(\boldsymbol{x}) = [p_x, p_y]^T$)
- Using an Unscented Quaternion Estimator UKF, States: $\boldsymbol{X} = [\delta p_x, \delta p_y, \delta p_z, \omega_x, \omega_y, \omega_z, J_x, J_y, J_z]^T$
- Monte-Carlo simulation of 1000 runs

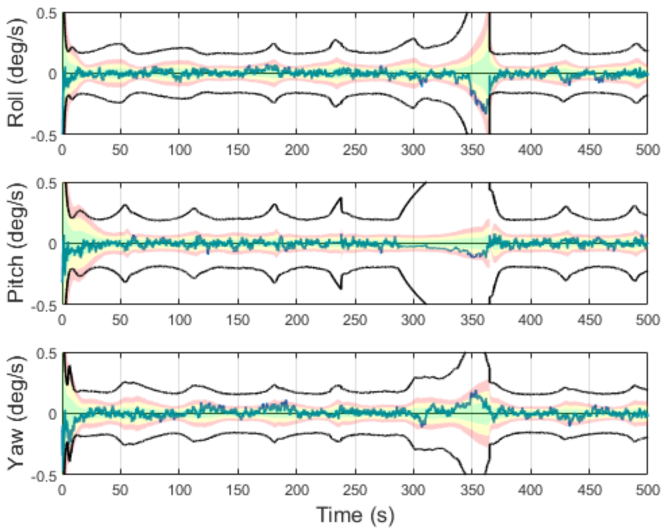
$$\begin{bmatrix} \dot{\hat{q}}_1 \\ \dot{\hat{q}}_2 \\ \dot{\hat{q}}_3 \\ \dot{\hat{q}}_4 \\ \dot{\hat{\omega}}_x \\ \dot{\hat{\omega}}_y \\ \dot{\hat{\omega}}_z \\ \dot{\hat{J}}_x \\ \dot{\hat{J}}_y \\ \dot{\hat{J}}_z \end{bmatrix} = \begin{bmatrix} (\hat{q}_4\hat{\omega}_x - \hat{q}_3\hat{\omega}_y + \hat{q}_2\hat{\omega}_z)/2 \\ (\hat{q}_3\hat{\omega}_x + \hat{q}_4\hat{\omega}_y - \hat{q}_1\hat{\omega}_z)/2 \\ (\hat{q}_1\hat{\omega}_y - \hat{q}_2\hat{\omega}_x + \hat{q}_4\hat{\omega}_z)/2 \\ (-\hat{q}_1\hat{\omega}_x - \hat{q}_2\hat{\omega}_y - \hat{q}_3\hat{\omega}_z)/2 \\ (r_y\hat{T}_z - r_z\hat{T}_y - \hat{\omega}_y\hat{J}_z\hat{\omega}_z + \hat{\omega}_z\hat{J}_y\hat{\omega}_y)/\hat{J}_x \\ (r_z\hat{T}_x - r_x\hat{T}_z - \hat{\omega}_z\hat{J}_x\hat{\omega}_x + \hat{\omega}_x\hat{J}_z\hat{\omega}_z)/\hat{J}_y \\ (r_x\hat{T}_y - r_y\hat{T}_x - \hat{\omega}_x\hat{J}_y\hat{\omega}_y + \hat{\omega}_y\hat{J}_x\hat{\omega}_x)/\hat{J}_z \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Attitude and Angular Rate Estimation

- Attitude estimate accurate within 2 degrees
- Angular rate estimates accurate within 0.1 deg/s
- Accuracy loss from loss of tracked feature

- Attitude bounds Match monte-Carlo bounds
- Angular rate bounds too conservative





- Outline
- Introduction
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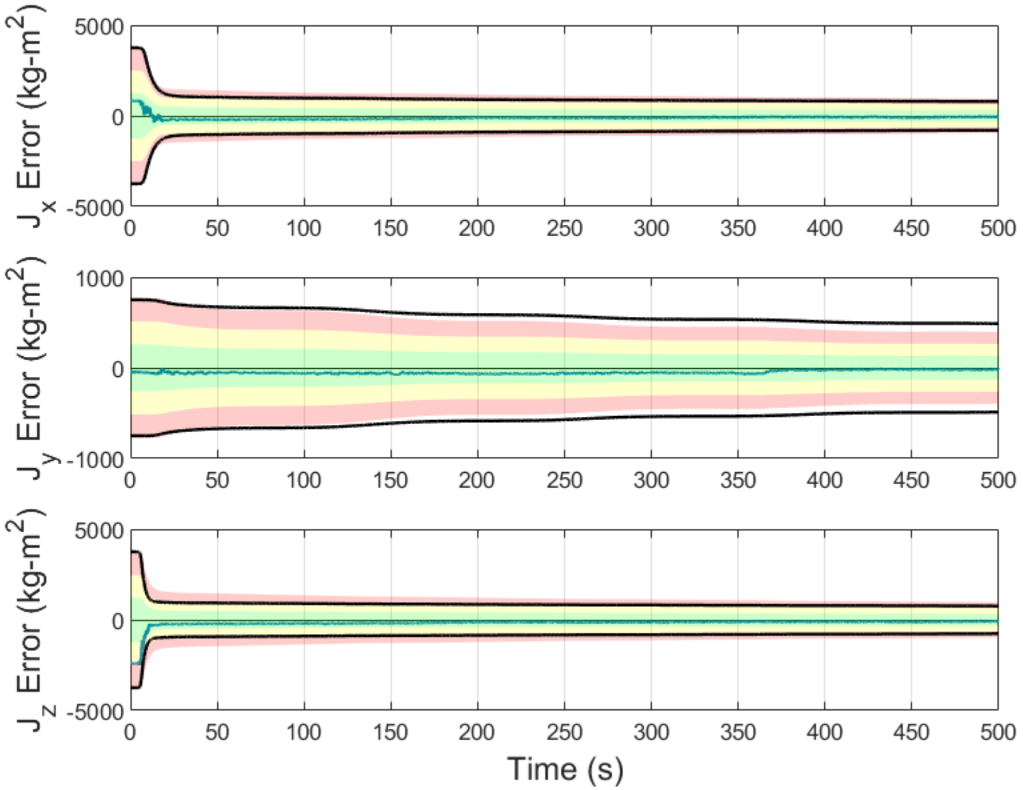
Moment of Inertia Estimation

- Jx/Jz estimated well
  - Rapid convergence ~ 6s – 20 s
  - Small change ~ 20 s – 500 s
- Jy estimated well with lower accuracy
  - Bounds remain relatively large
  - Majority of convergence

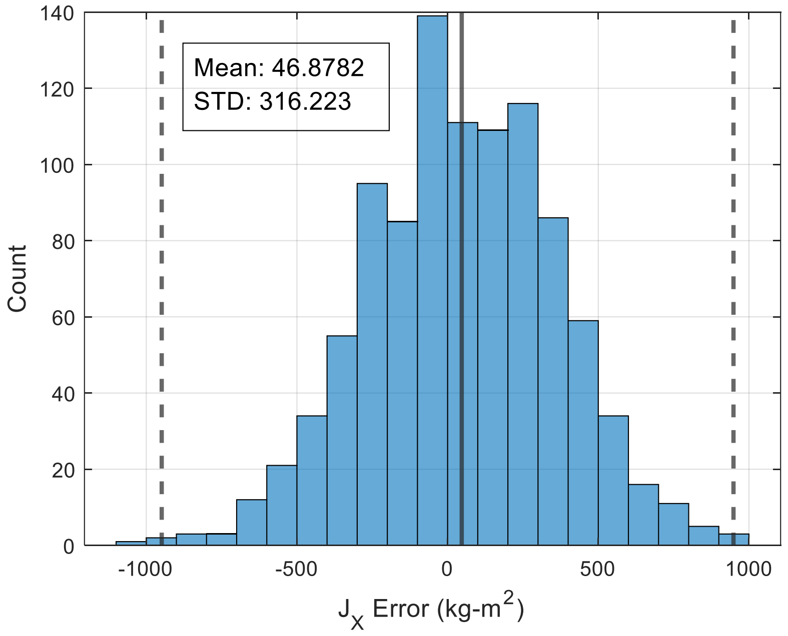
    ~ 360 s – 380 s

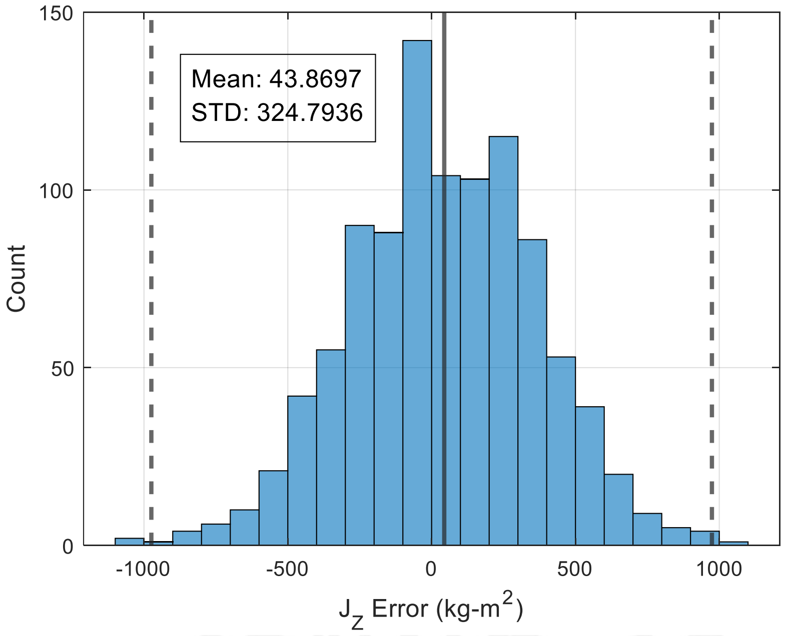


Jx and Jz Distribution

- Estimates within 6.8% of true values of 15000 $\mathrm{kg\,m^2}$ (with std. dev.) ~ 1018 $\mathrm{kg\,m^2}$

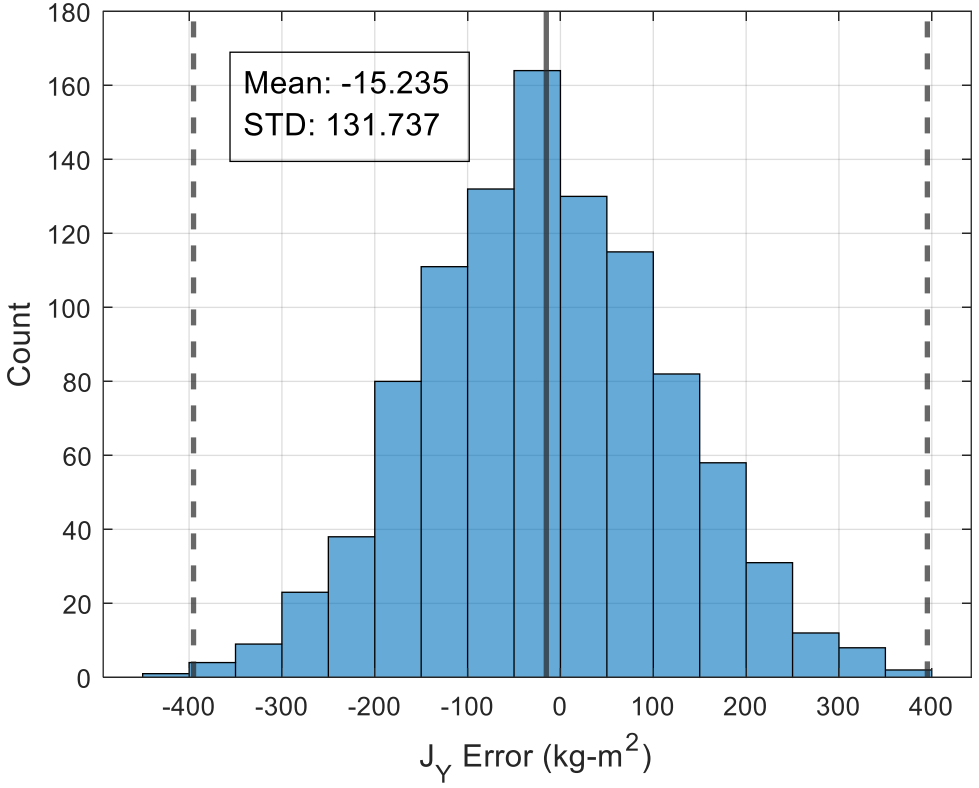
- Bi-modal distribution:
  - -100 – 0 $\mathrm{kg\,m^2}$
  - 200 – 300 $\mathrm{kg\,m^2}$





Jy Distribution

- Normal distribution
- Accurate within 13.7% of true value of 3000 $\mathrm{kg\,m^2}$ (with std. dev.) ~ 400 $\mathrm{kg\,m^2}$



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Conclusion

- Synthetic data generated to estimate moments of inertia
- UKF accurately and precisely estimates debris attitude, angular rate, moments of inertia
  - Requires at least two tracked features for attitude/angular rate
  - Conservative with angular rate estimates
  - Within 7% and 14% of true principal moment of inertia

- Outline
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Questions?:

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