



Celestial and Spaceflight
Mechanics Laboratory



Dynamical Issues in Space Situational Awareness

D.J. Scheeres / K.T. Alfriend PIs

C. Frueh / J.W. McMahon Co-Is

A joint research collaboration with the University of
Colorado, Texas A&M University and Purdue University

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Overview of Research

- This talk provides a brief, high-level overview of research supported in part by an AFOSR grant entitled:
Modeling Observability and Change Detection in Space Situational Awareness
- Faculty involved:
 - The University of Colorado (CU): D.J. Scheeres (PI) & J.W. McMahon
 - Texas A&M University (TAMU): K.T. Alfrend (PI)
 - Purdue: C. Frueh
- Former Students & Post-docs involved with this research and prior AFOSR awards
 - C. Frueh (Asst. Prof. Purdue), I.-K. Park (post-doc TAMU), H.C. Ko (Korean Air Force), A. Albuja (Aerospace Corp.), D. Lubey (Aerospace Corp.), A. Rosengren (Asst. Prof. U Arizona), K. Fujimoto (Asst. Prof. Utah State), M. Holzinger (Asst. Prof. GATech)
 - Fellowship programs from the FAA, NSF and NASA leveraged as well
- Presentation focuses on work at CU



Review of Research at CU

- Active Satellites and Change Detection
 - Constraints on satellite intent based on optimal control theory
 - Maneuver detection and characterization methods
 - Generic representation of orbital events
- Dynamics and modeling of defunct satellites and orbit debris
 - Orbital dynamics over long time spans
 - Models to efficiently capture and estimate non-gravitational effects
 - Rotational dynamics of defunct satellites and orbit debris
- Mapping and constraints on orbital uncertainty distributions
 - Semi-analytical methods for mapping uncertainty rapidly and accurately
 - Determination of precision needed for accurately capturing uncertainty distributions
 - Fundamental constraints on orbit distribution mappings



Active Satellites

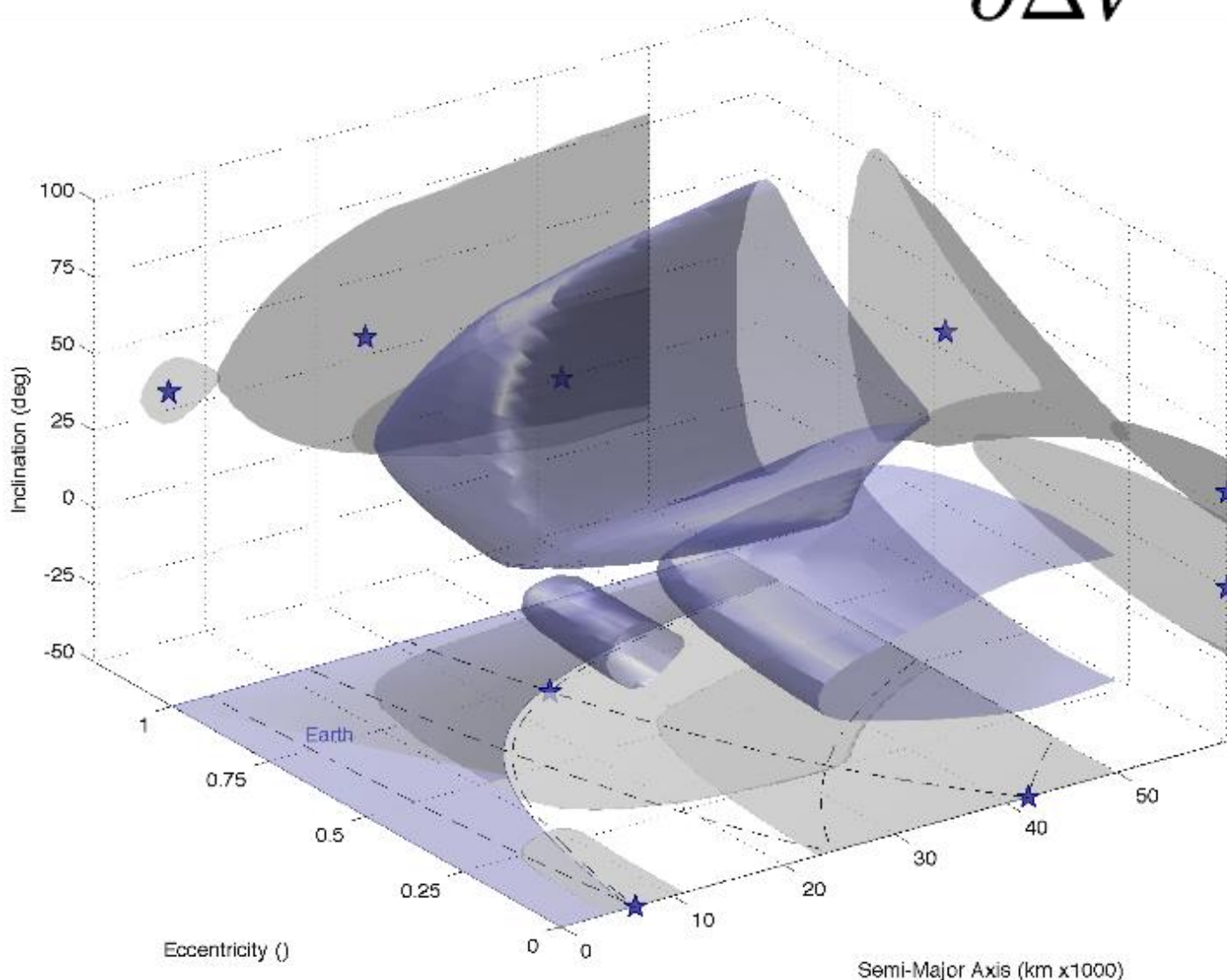
- How to quantify and constrain activity of an active satellite without direct observation or measurement?
 - What constraints can be placed on a maneuvering satellite with unknown capabilities? *Optimal control and reachability*
 - Can a series of unobserved maneuvers or deployments be detected and represented uniquely? *Averaging, optimal estimation and control*
 - What is the optimal response to forestall encroachment in orbit? *Game theory*
- More general topic of estimation and inference of the objectives of a non-cooperative vehicle
 - Rich set of questions amenable to fundamental research in the unique and richly dynamic orbital environment



Reachability Analysis in Orbit

- Similar to the Breuget “Range Equation” for aircraft as a function of fuel, we have developed a computational technique for finding the “Orbital Range” as a function of ΔV

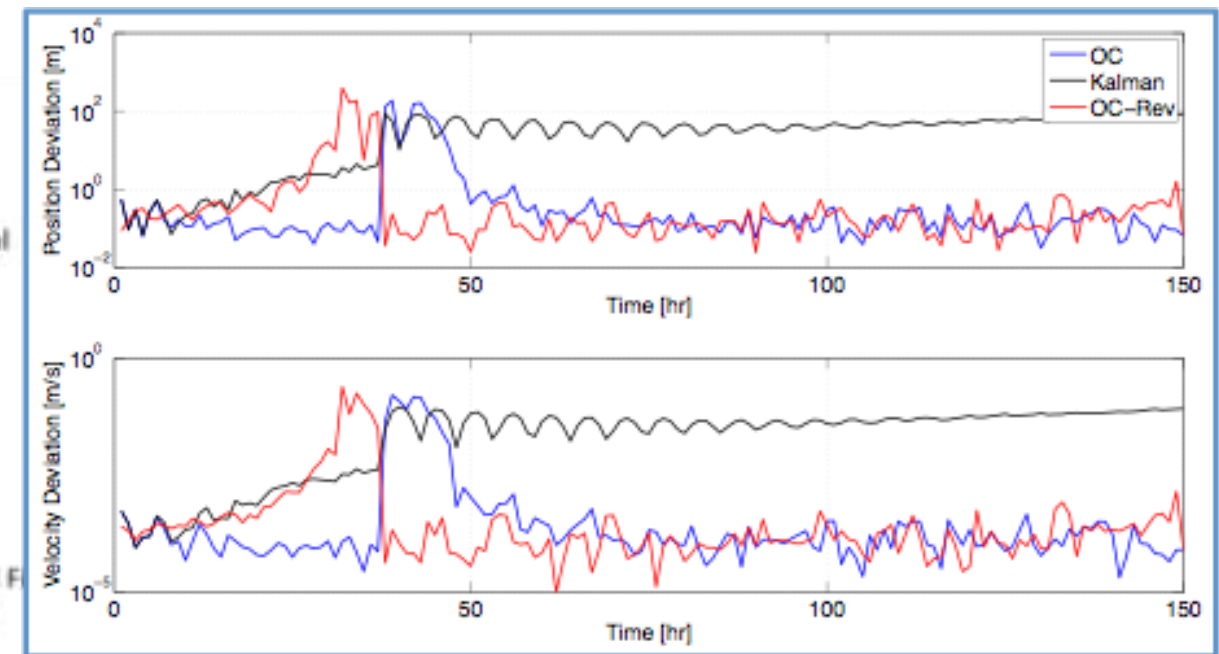
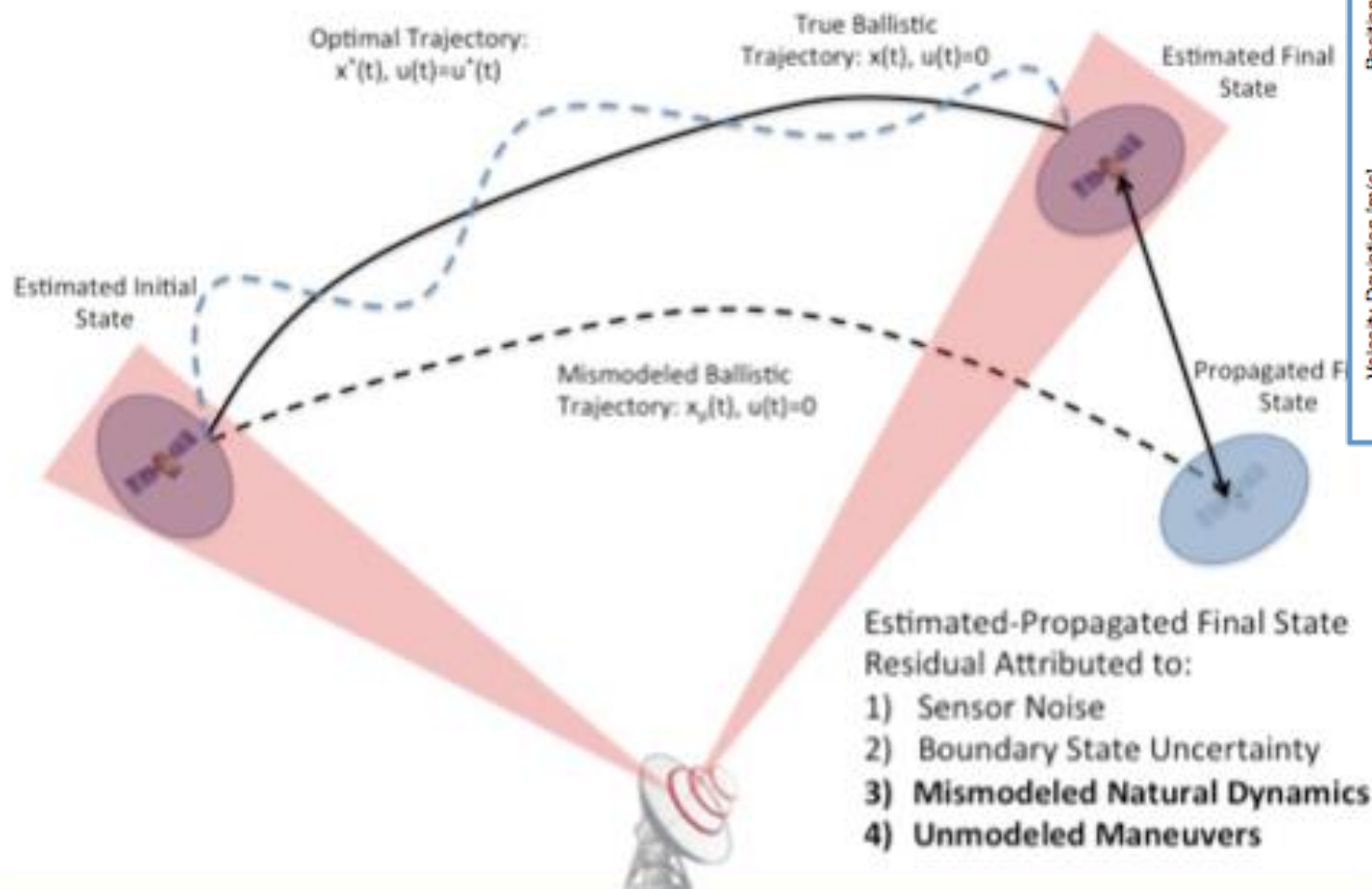
$$\frac{\partial \mathcal{V}}{\partial \Delta V} + \sup_{\mathbf{u} \in U} \left[\frac{\partial \mathcal{V}}{\partial \mathbf{x}} \mathbf{F}(\mathbf{x}, t) \cdot \frac{\mathbf{u}}{\Delta V} \right] = 0$$



Comparison of the range of different orbit radii and inclination that can be reached as a function of ΔV , can be strategically used to analyze “reachable orbits” for a given satellite.

Currently being applied to cooperative and non-cooperative game theory settings.

- We have developed a novel estimation algorithm that accounts for model errors and which can be used for automatic maneuver detection:
 - Our “Optimal Control” filter is a generalization of the Kalman filter
 - Utilizes the “control distance” and optimal control concepts to efficiently reconstruct and detect unmodeled dynamics while fitting observations



- Demonstration computations showing our filter's ability to follow a changing, maneuvering body



Maneuver / Event Representation

- We have developed a methodology that can reduce any maneuver or S/C event to a finite basis of coefficients

$$\vec{\ddot{x}} = \bar{G}(\vec{x}) \cdot \vec{\tau}$$

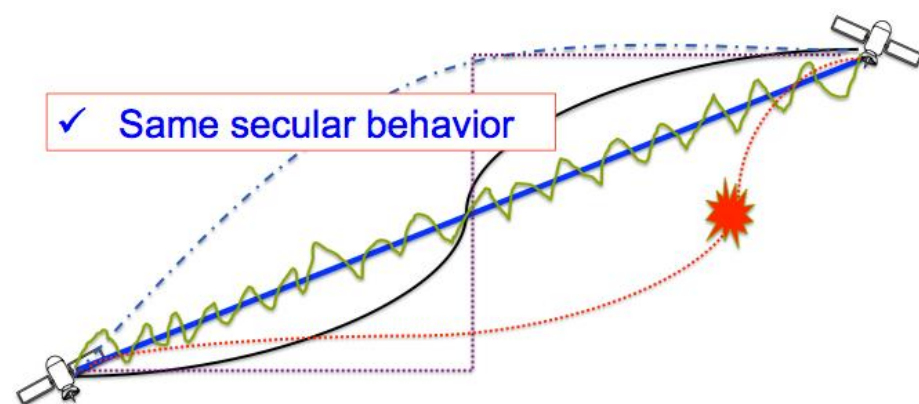
$$\vec{x} = [a \ e \ i \ \Omega \ \omega \ \sigma]^T$$

$$\bar{G} = \begin{pmatrix} 0 & 0 & 0 & G_{1,4} & G_{1,5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{2,4} & G_{2,5} & G_{2,6} & G_{2,7} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{3,10} & G_{3,11} & G_{3,12} & G_{3,13} & G_{3,14} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & G_{4,10} & G_{4,11} & G_{4,12} & G_{4,13} & G_{4,14} \\ G_{5,1} & G_{5,2} & 0 & 0 & 0 & 0 & 0 & G_{5,8} & G_{5,9} & G_{5,10} & G_{5,11} & G_{5,12} & G_{5,13} & G_{5,14} \\ G_{6,1} & G_{6,2} & G_{6,3} & 0 & 0 & 0 & 0 & G_{6,8} & G_{6,9} & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

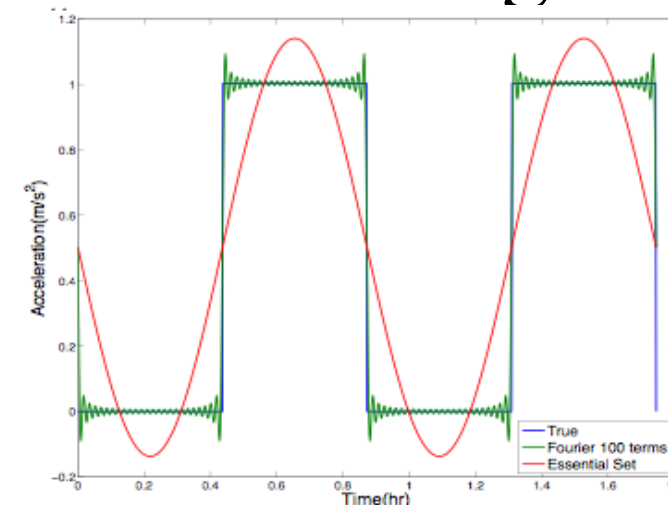
$$\vec{\tau} = [\alpha_0^R \ \alpha_1^R \ \alpha_2^R \ \beta_1^R \ \alpha_0^S \ \alpha_1^S \ \alpha_2^S \ \beta_1^S \ \beta_2^S \ \alpha_0^W \ \alpha_1^W \ \alpha_2^W \ \beta_1^W \ \beta_2^W]^T$$

Example of the “essential set” of thrust coefficients in terms of classical orbit elements

- Enables trajectories to be fit and estimated in the absence of detailed information on maneuvers and thrusting



Equivalent representations





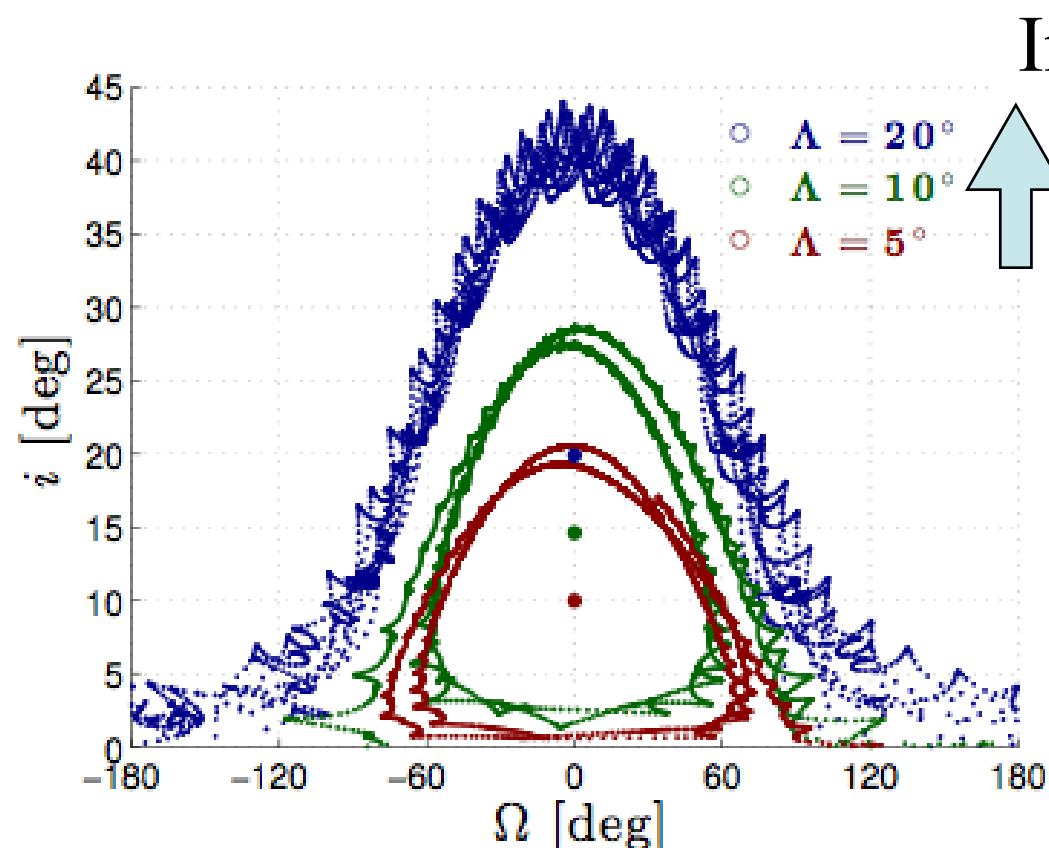
Natural Dynamics of Debris

- What is the long-term stability of important orbital assets or defunct satellites in graveyard orbits? *Recent work shows that almost all GNSS satellites will eventually impact the Earth — analysis done with methods we developed.*
- Can on-orbit interaction with defunct satellites or debris be definitely planned? *Our work has shown that defunct satellites can be forced to spin rapidly or go through chaotic spin evolution due to solar radiation pressure torques.*
- Are taking more SSA measurements always the best strategy? *We have shown that improved and generalized models can outperform dense measurements.*

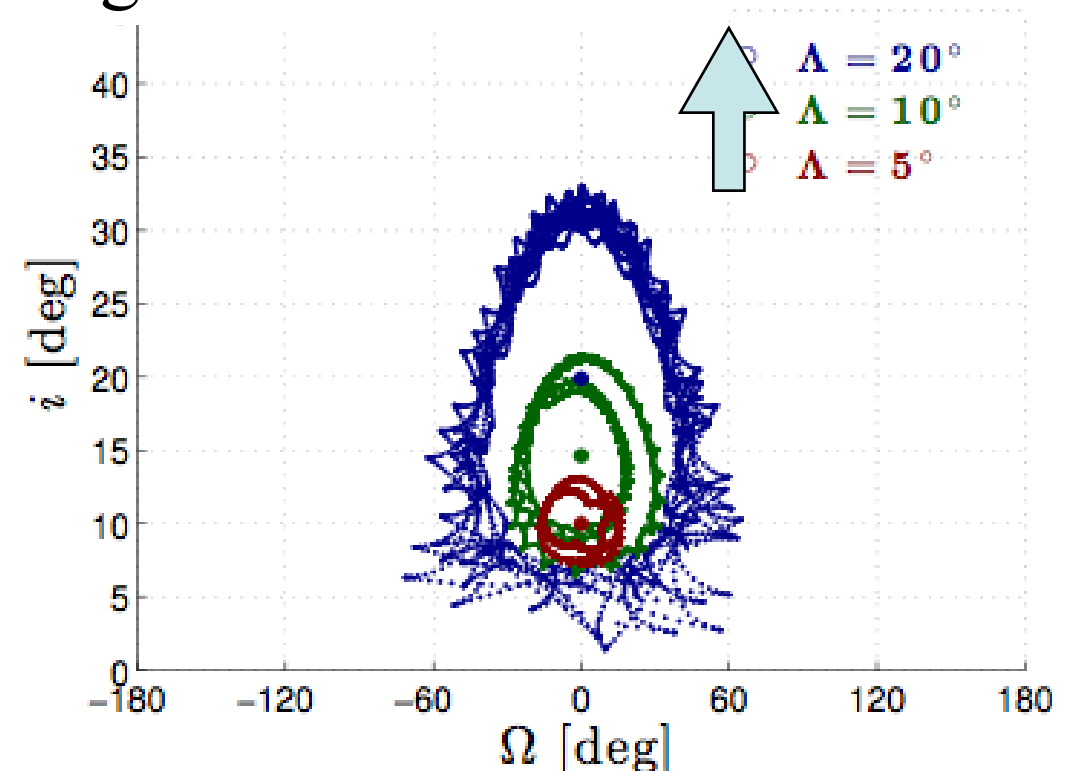


Long-Term Debris Dynamics

- Developed a combined analysis to rigorously propagate high area mass ratio (HAMR) objects in GEO, defining the “modified Laplace Plane”
 - Identified new resonances that create chaotic orbit evolution
 - Defined preferred GEO disposal orbit strategies
 - Paper awarded the *COSPAR Outstanding Paper Award for Young Scientists*.
 - Methodology used to identify that all GNSS satellites are ultimately unstable and will impact the Earth



Super-synchronous disposal orbit



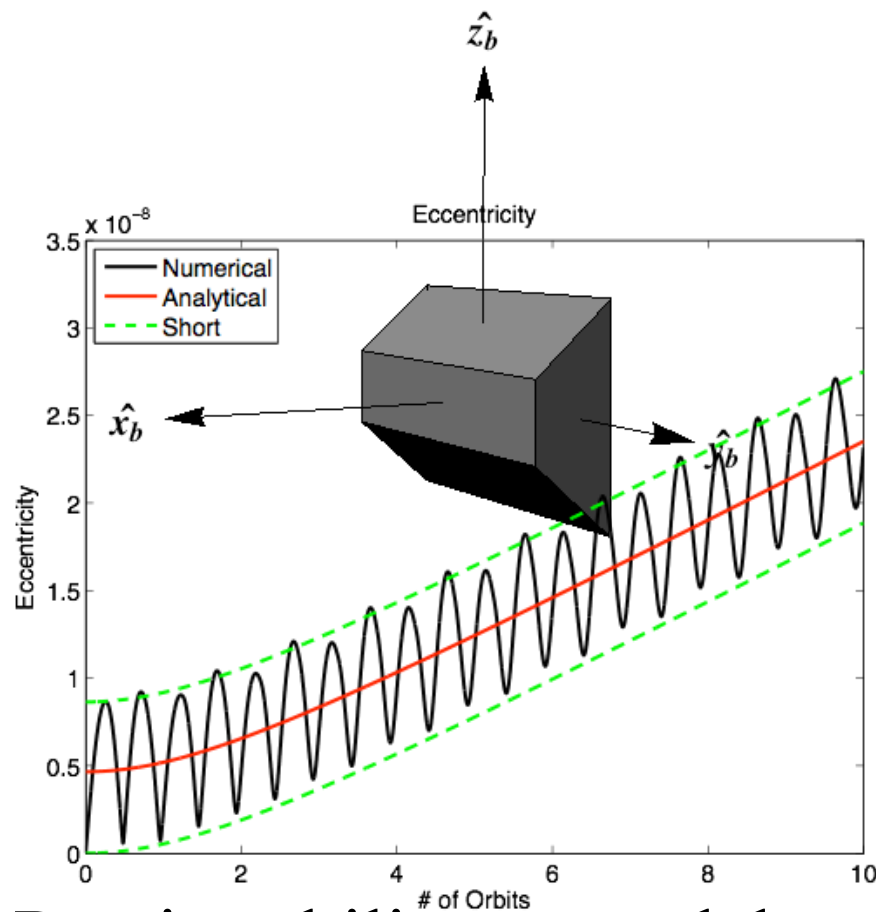
Laplace plane disposal orbit



Improved Models for Estimation

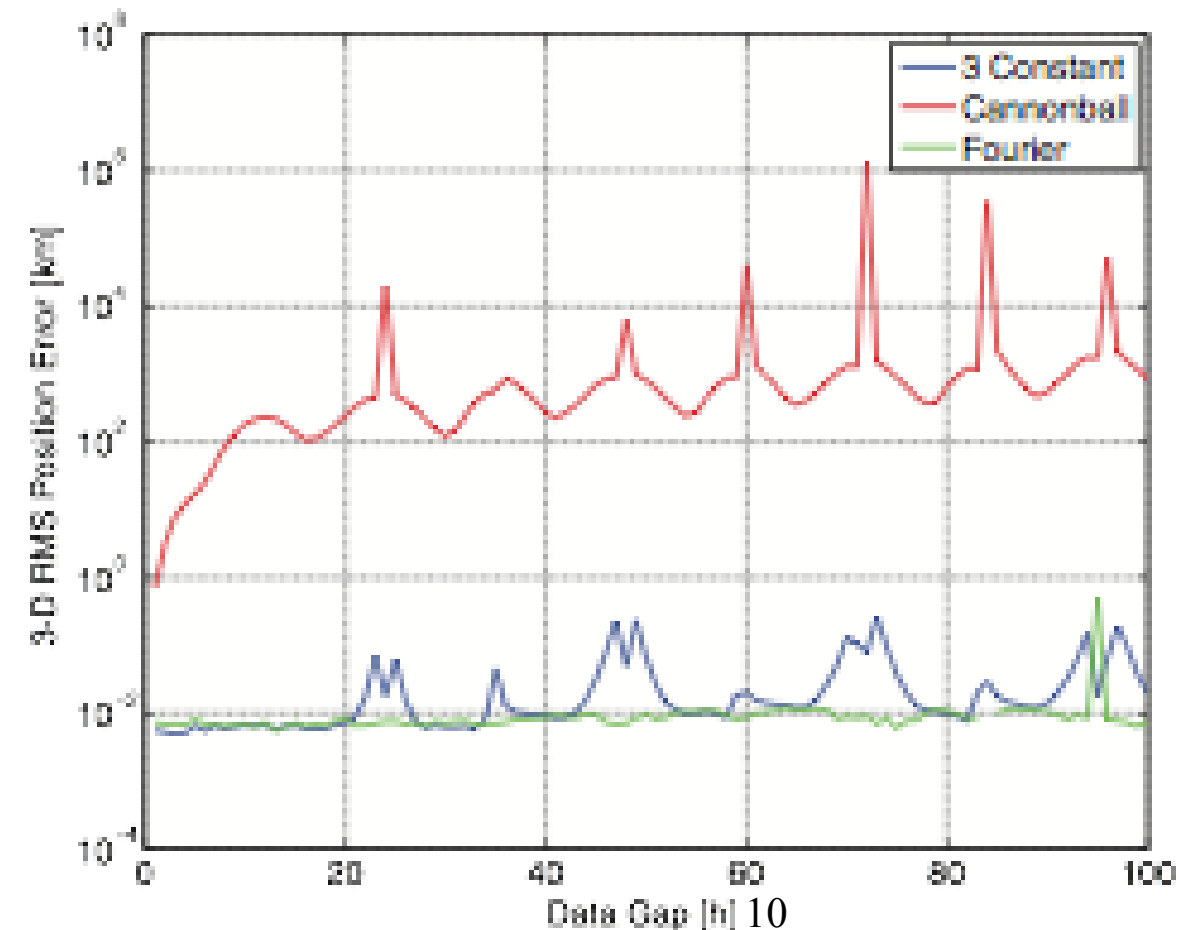
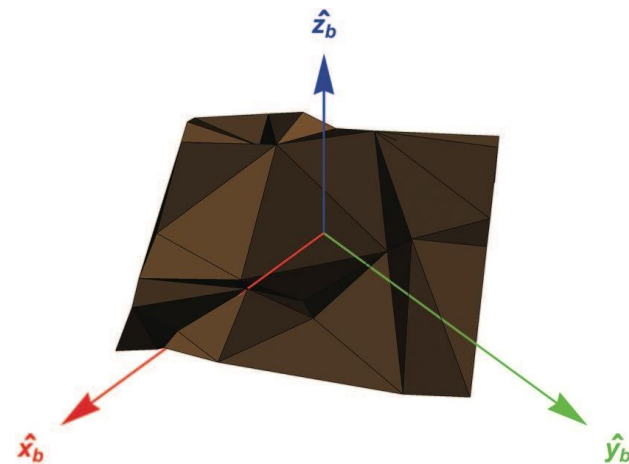
- Developing an improved modeling approach for capturing SRP forces, enabling improved orbit estimation and prediction with only modeling updates

Impact of improved SRP model on orbit determination and prediction for a wrinkled-plate HAMR object: comparison of “cannonball” model with simple extensions defined from our new model



Precise ability to model SRP effects analytically with improved approach.

D.J. Scheeres, A. Richard Seebass Chair, University of Colorado at Boulder

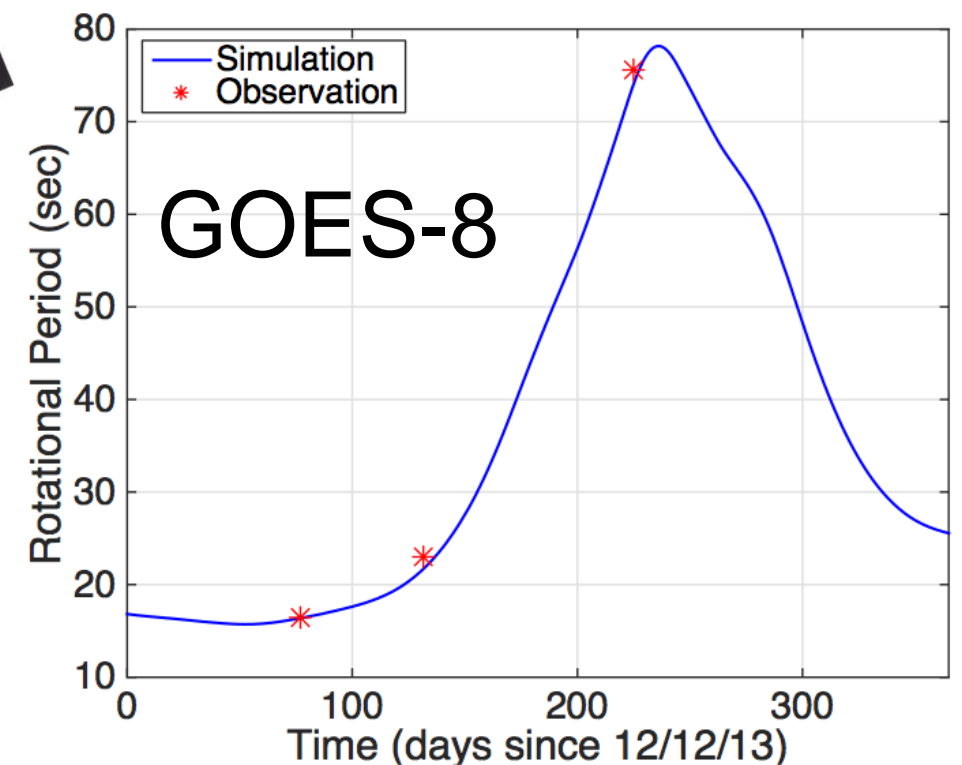
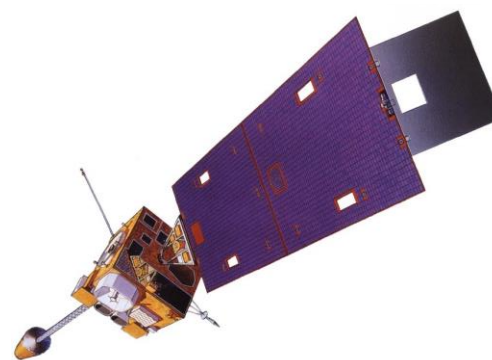
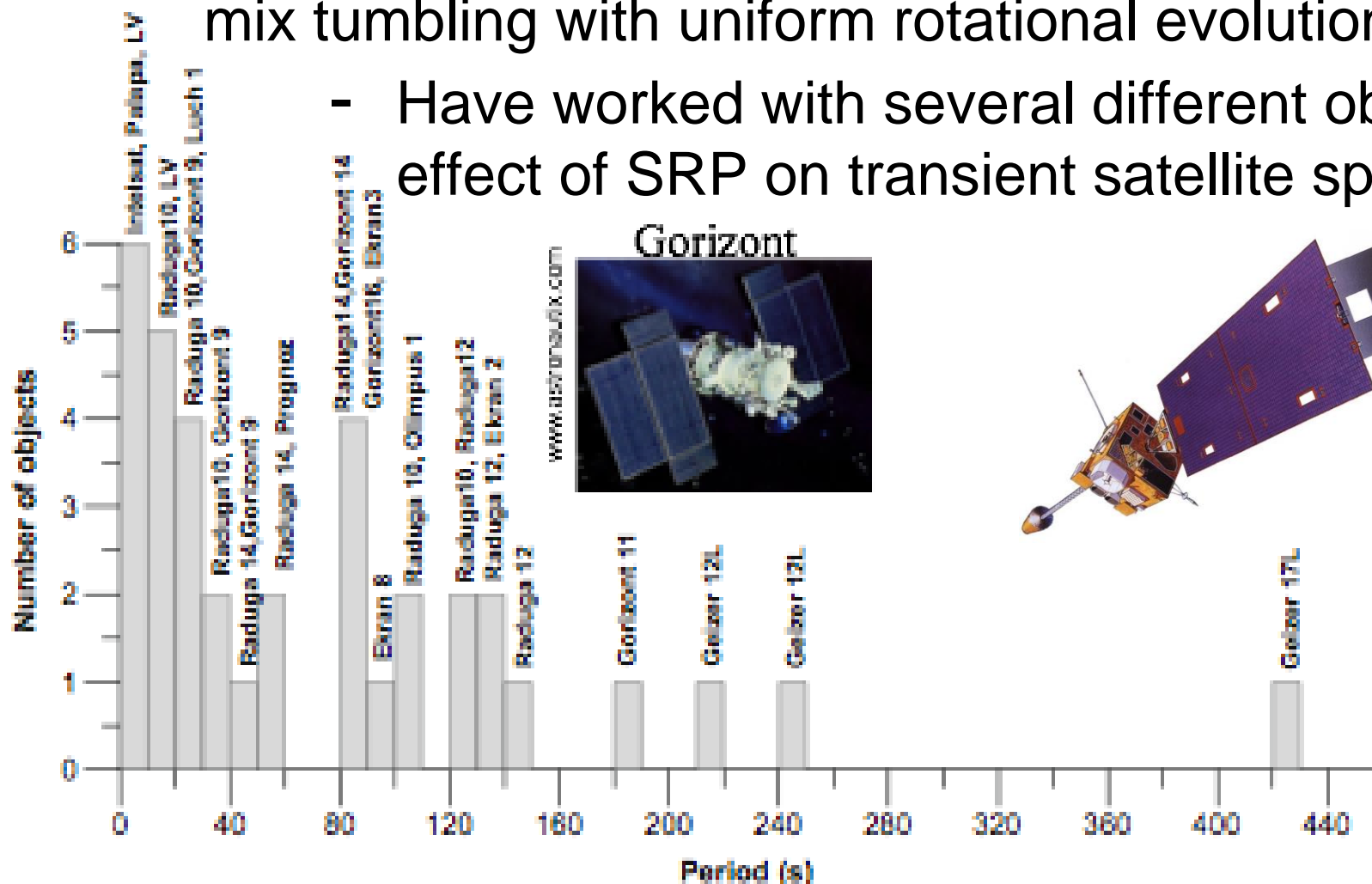




Spin Evolution of Defunct Satellites



- What is the expected rotational evolution of defunct satellites and debris?
 - Observations of defunct GEO satellites shows that their rotation periods change over time, and that many of them rotate rapidly
 - Understanding the physical evolution of defunct satellites is crucial for developing mitigation approaches
 - Solar radiation pressure torques, known as “YORP” in planetary science, can cause satellites to spin rapidly or undergo complex rotational behaviors that mix tumbling with uniform rotational evolution
 - Have worked with several different observers that clearly show the effect of SRP on transient satellite spin rates



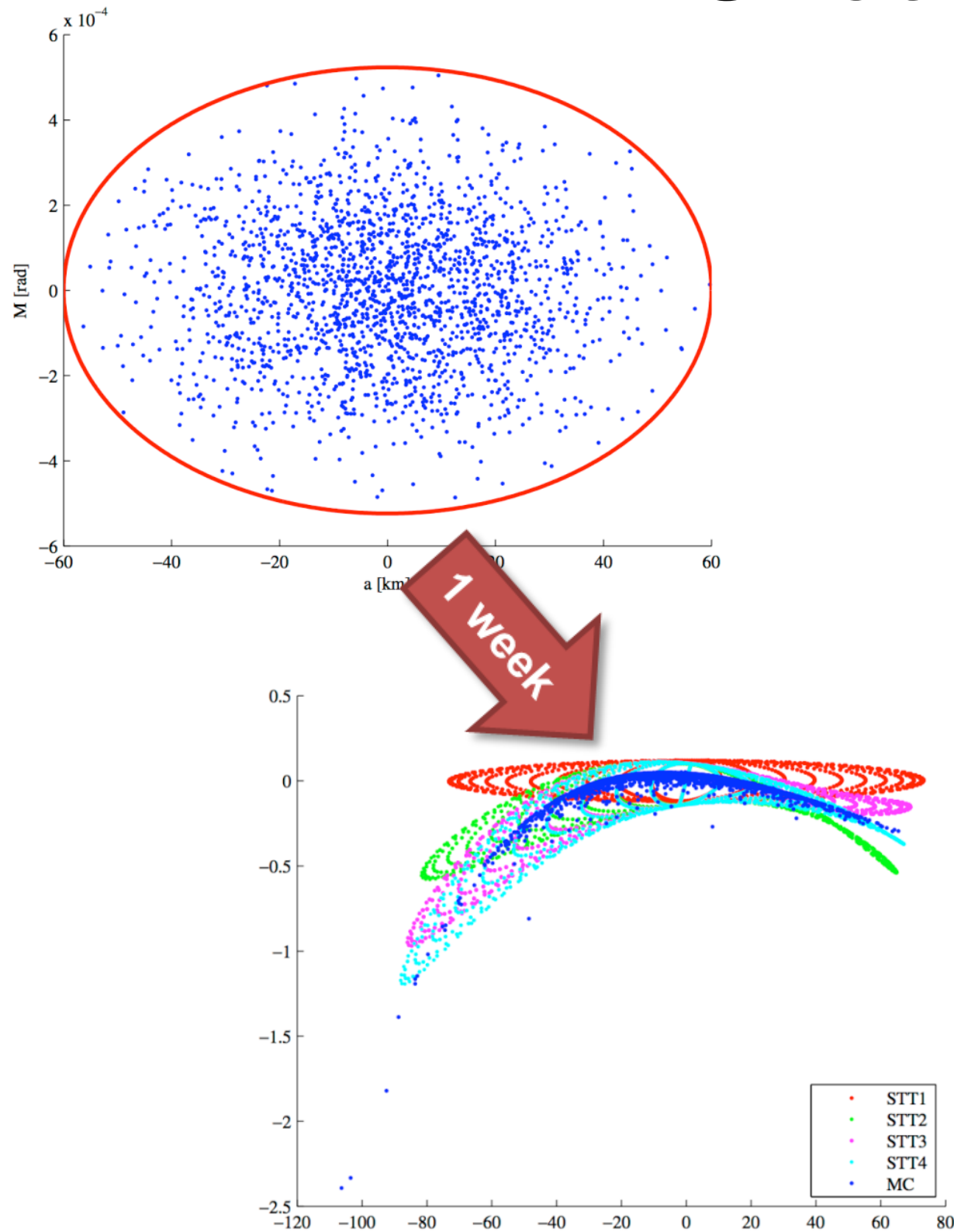


Constraints on and Mapping Methods for Orbit Uncertainty



- Orbit uncertainty distributions are subject to similar constraints as particles in quantum mechanics. *A fundamental uncertainty principle applies for a given orbit uncertainty distribution — provides a lower limit on predicted knowledge as a function of measurements.*
- The level of orbit dynamics modeling needed to capture statistical information is driven by the level of orbit knowledge of a body. *A precisely tracked satellite requires precision dynamics to capture its uncertainty evolution while a poorly known satellite with large uncertainty can be modeled with lower fidelity models.*
- Application of classical celestial mechanics techniques can be leveraged to speed orbit uncertainty mapping by several orders of magnitude. *Motivates research into analytical orbital mechanics to develop methods to deal with arbitrary numbers of tracked objects.*

Rapid and Accurate Propagation of Uncertainty



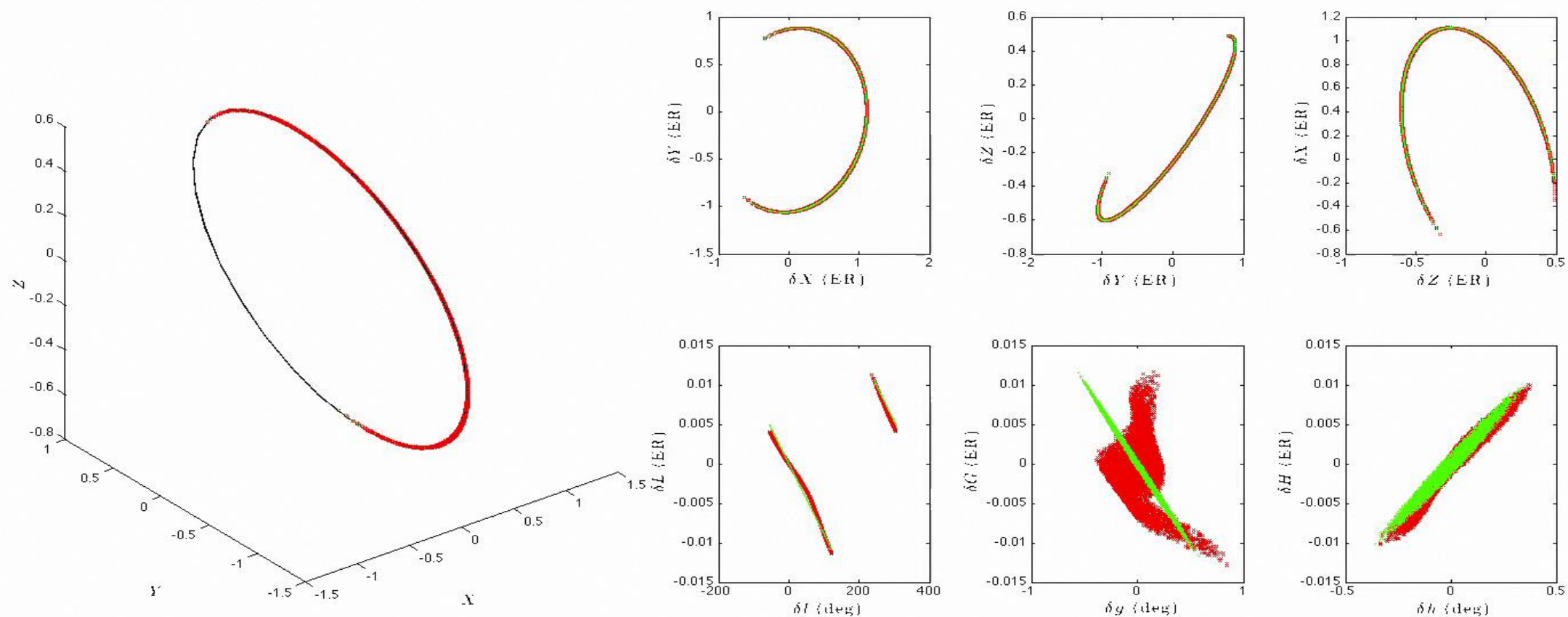
- Rapid semi-analytical uncertainty propagation
 - Utilize rigorous higher order averaging methods to develop analytical models for uncertainty propagation
 - Incorporate higher order effects of Earth gravity, 3rd body perturbation, simple drag and SRP models
 - Utilize Taylor Series expansions of the models to speed computations
- Allows new and rigorous approaches to conjunction analysis
 - Utilizes GMMs to leverage analytical expressions for Gaussian statistics
 - End-to-end analytic or semi-analytic method as accurate as numerical MC computations but many orders of magnitude faster
 - Papers published in JGCD and presented at AAS/AIAA Conferences



Necessary Accuracy for Uncertainty



- A fundamental question –
“What level of precision is needed in describing satellite dynamics to ensure an accurate determination of propagated orbit uncertainty?”
- Answer: Secular dynamics approximations can fully capture the first few moments of a statistical PDF distribution
- Implications: Can use computationally faster algorithms with lower accuracy dynamics to model debris uncertainty, the key is in properly defining the simplified models
- Papers published in JGCD and presented at AAS/AIAA and international conferences





Summary

- The field of Space Situational Awareness (SSA) poses fundamentally difficult problems that requires integration between the fields of:
 - Celestial Mechanics
 - Estimation theory
 - Optimal control theory
 - Statistical mechanics
 - Physical modeling
- New theoretical approaches are being developed to address core SSA issues and define fundamental research topics for future development
- Our AFOSR supported research has trained and transitioned many new academic and research faculty focused on these issues



Journal Publications @ CU



- 2016:
 - H.C. Ko and D.J. Scheeres. 2016. “Tracking Maneuvering Satellite Using Thrust- Fourier-Coefficient Event Representation,” *Journal of Guidance, Control and Dynamics* in press.
 - I.-K. Park and D.J. Scheeres. “A Hybrid Method for Uncertainty Propagation of Orbital Motion,” *Journal of Guidance, Control and Dynamics*, in press 9/2016.
 - H.C. Ko and D.J. Scheeres. 2016. “Orbit determination across unknown maneuvers using the essential Thrust-Fourier-Coefficients,” *Acta Astronautica* 118: 90-95. **2**
 - H.C. Ko and D.J. Scheeres. 2016. “Maneuver Detection with Event Representation using Thrust-Fourier-Coefficients,” *Journal of Guidance, Control and Dynamics* 39(5): 1080-1091. **2**
- 2015:
 - I.-K. Park, K. Fujimoto and D.J. Scheeres. 2015. “Effect of Dynamical Accuracy for Uncertainty Propagation of Perturbed Keplerian Motion,” *Journal of Guidance, Control and Dynamics* 38(12): 2287-2300. doi: 10.2514/1.G000956
 - A. Albuja, D.J. Scheeres and J.W. McMahon. 2015. “Evolution of Angular Velocity for Defunct Satellites as a Result of YORP: An Initial Study,” *Advances in Space Research* 56: 237-251. **2**
 - K. Fujimoto and D.J. Scheeres. 2015. “Tractable Analytical Expressions for Non- Linearly Propagated Uncertainties,” *Journal of Guidance, Control and Dynamics* 38(6): 1146-1151. doi: 10.2514/1.G000795 **2**
 - J.W. McMahon and D.J. Scheeres. 2015. “Improving Space Object Catalog Maintenance Through Advances in Solar Radiation Pressure Modeling,” *Journal of Guidance, Control and Dynamics* 38(8), 1366-1381. **6**
 - M.J. Holzinger, D.J. Scheeres and J. Hauser. 2015. “Reachability Using Arbitrary Performance Indices,” *IEEE-Transactions on Automatic Control* 60(4): 1099-1103.
 - A.A. Albuja and Daniel J. Scheeres. 2015. “Analytical solution for the normal emission portion of the averaged Yarkovsky-O’Keefe-Radzievskii-Paddack coefficient for a single facet,” *Monthly Notices of the Royal Astronomical Society* 446 (4): 4029-4038 doi: 10.1093/mnras/stu2379 **1**
- 2014:
 - D.P. Lubey and D.J. Scheeres. 2014. “Identifying and Estimating Mismodeled Dynamics via Optimal Control Policies and Distance Metrics,” *Journal of Guidance, Control and Dynamics* 37(5): 1512-1523. doi: 10.2514/1.G000369 **6**
 - H.S. Ko and D.J. Scheeres. 2014. “Essential Thrust-Fourier-Coefficient Set of Averaged Gauss Equations for Orbital Mechanics,” *Journal of Guidance, Control and Dynamics* 37(4): 1236-1249. **8**
 - A.J. Rosengren, D.J. Scheeres and J.W. McMahon. 2014. “The classical Laplace plane as a stable disposal orbit for geostationary satellites,” *Advances in Space Research* 53: 1219-1228. **4**
 - A.J. Rosengren and D.J. Scheeres. 2014. “On the Milankovitch Orbital Elements for Perturbed Keplerian Motion,” *Celestial Mechanics and Dynamical Astronomy* 118(3): 197-220. **18**
 - M. Holzinger, D.J. Scheeres and R.S. Erwin. 2014. “On-Orbit Range Computation using Gauss’ Variational Equations with J2 Perturbations,” *Journal of Guidance, Control and Dynamics* 37(2): 608-622. **3**
 - J.W. McMahon and D.J. Scheeres. 2014. “General Solar Radiation Pressure Model for Global Positioning System Orbit Determination,” *Journal of Guidance, Control and Dynamics* 37(1): 325-330. **3**
 - K. Fujimoto, D.J. Scheeres, J. Herzog and T. Schildknecht. 2014. “Association of optical tracklets from a geosynchronous belt survey via the direct Bayesian admissible region approach,” *Advances in Space Research* 53: 295-308. **11**



Conference Papers @ CU



- A. Albuja, R. Cognion, W. Ryan, E. Ryan and D.J. Scheeres. “Rotational Dynamics Of The Goes 8 And Goes 10 Satellites Due To The Yorp Effect,” paper presented at the AAS/AIAA Spaceflight Mechanics Meeting, Napa Valley, California, February 2016. Paper AAS 16-416
- D. Lubey and D.J. Scheeres. “State Estimation and Maneuver Reconstruction with The Nonlinear Adaptive Optimal Control Based Estimator,” paper presented at the AAS/AIAA Spaceflight Mechanics Meeting, Napa Valley, California, February 2016. Paper AAS 16-423
- I. Park and D.J. Scheeres. “A Hybrid Method for Uncertainty Propagation of Orbital Motion around the Earth,” paper presented at the 25th International Symposium on Spacecraft Dynamics, Munich, Germany, October 2015.
- H.C. Ko and D.J. Scheeres. “Orbit Determination and Maneuver Detection Using Event Representation with Thrust-Fourier-Coefficients,” paper presented at the 2015 AMOS Conference, Wailea, Maui, September 2015.
- D.P. Lubey and D.J. Scheeres. “Towards Real-Time Maneuver Detection: Automatic State and Dynamics Estimation with the Adaptive Optimal Control Based Estimator,” paper presented at the 2015 AMOS Conference, Wailea, Maui, September 2015.
- I. Park and D.J. Scheeres. “Analytical Conversion of Mean Orbital Elements into Osculating Elements for Frozen Orbit About Asteroids,” paper presented at the AAS/AIAA Astrodynamics Meeting, Vail, Colorado, August 2015. Paper AAS 15-803
- H.C. Ko and D.J. Scheeres. “Maneuver Detection with Event Representation using Thrust-Fourier-Coefficients,” paper presented at the AAS/AIAA Astrodynamics Meeting, Vail, Colorado, August 2015. Paper AAS 15-631
- D. Lubey and D.J. Scheeres. “Automated State and Dynamics Estimation in Dynamically Mismatched Systems with Information From Optimal Control Policies,” paper presented at the 18th International Conference on Information Fusion, Washington, D.C., July 2015. Paper AAS 15-252
- A.A. Albuja and D.J. Scheeres. “Representation of Short Period Variations in an Inactive Satellite’s Rotational State Due to the YORP Effect,” paper presented at the International Symposium on Space Technology and Science, July 2015.
- D. Lubey, A. Doostan and D.J. Scheeres. “Estimating Object-Dependent Natural Orbital Dynamics with Optimal Control Policies: A Validation Study,” paper presented at the AAS/AIAA Spaceflight Mechanics Meeting, Williamsburg, Virginia, January 2015. Paper AAS 15-252
- D. Lubey and D.J. Scheeres. “Robust Tracking and Dynamics Estimation with the Automated Optimal Control Based Estimator,” paper presented at the AAS/AIAA Spaceflight Mechanics Meeting, Williamsburg, Virginia, January 2015. Paper AAS 15-251
- A. Albuja and D.J. Scheeres. “Short Period Variations in Angular Velocity and Obliquity of Inactive Satellites Due to the YORP Effect,” paper presented at the AAS/AIAA Spaceflight Mechanics Meeting, Williamsburg, Virginia, January 2015. Paper AAS 15-264
- H.C. Ko and D.J. Scheeres. “Orbit Determination Across Unknown Maneuvers Using The Essential Thrust Fourier Coefficients,” paper presented at the 2014 International Astronautical Congress, Toronto, Canada, September 2014. Paper IAC-14.C1.5.1
- R. Cognion, A. Albuja and D.J. Scheeres. “Tumbling Rates Of Inactive Geo Satellites,” paper presented at the 2014 International Astronautical Congress, Toronto, Canada, September 2014. Paper IAC-14.C1.2.12
- H.C. Ko and D.J. Scheeres. “Spacecraft Orbit Anomaly Representation Using Thrust-Fourier-Coefficients with Orbit Determination Toolbox,” paper presented at the 2014 AMOS Conference, Wailea, Maui, September 2014.
- A. Albuja and D.J. Scheeres. “Effects of Optical and Geometrical Properties on YORP Effect for Inactive Satellites,” paper presented at the 2014 AMOS Conference, Wailea, Maui, September 2014.
- I.-K Park and D.J. Scheeres. “Simplified Propagation of Uncertainty in the Non-Keplerian Problem,” paper presented at the 2014 AMOS Conference, Wailea, Maui, September 2014.
- D.P. Lubey and D.J. Scheeres. “Combined Optimal Control and State Estimation for the Purposes of Maneuver Detection and Reconstruction,” paper presented at the 2014 ACC Conference, Portland, Oregon, June 2014.