

Improved Methods for Tracking and Characterizing Inactive Space Objects



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Advanced Sciences and Technology Research Institute for Astrodynamics*



<u>Charter:</u> Research entity combining government in-house and contractor expertise in astrodynamics with a consortium of universities performing research in relevant areas of interest to the U.S. Air Force Research Laboratory and Department of Defense.

Research Topics:

- Data Association and Tracking
- Initial Orbit Determination
- Maneuver Detection and Reconstruction
- Satellite Characterization
- Data/Sensor Fusion for SSA
- Orbital Debris Tracking and Characterization
- Astrodynamics Applications to High Performance Computing

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- Astrodynamics Tools:
- General Mission Analysis Tool (GMAT)
- Satellite Tool Kit (STK)
- Orbit Determination Tool Kit
 (ODTK)
- Goddard Trajectory Determination System (GTDS)
- •MATLAB (various analysis models and algorithms)

Current Academic Members:

- Purdue University
- University of Colorado, Boulder
- Texas A&M
- University of Texas , Austin
- State University of New York, Buffalo
- Utah State University
- Embry-Riddle Aeronautical University
- Missouri University of Science & Technology
- Penn State University
- Georgia Tech
- US Air Force Academy
- Naval Postgraduate School





- Every Space Object (SO) is not exhaustively surveyed and the number of objects is increasing
 - Data Exploitation: We must maximize the information we can extract from all sources of collected data (i.e. minimize ambiguity)
 - Data Collection: We must gather data in a way that maximizes its information content (i.e. maximize efficiency)
- Unrealistic and/or too large of an ambiguity leads to erroneous decisions, inability to discern, and overall lack of knowledge and confidence. All decisions are based upon knowledge.
 - The knowledge that we have need not be perfect, but must be realistic and predictable





- Decisions are based upon what we believe to know
 - Inferring space environment effects from object behavior
 - Gravity fields, Solar Activity, Atmospheric Density, etc.
 - Identifying Conjunctions
 - Computing Collision Probabilities
 - Correlating tracked objects to a catalog
 - Correctly Identifying and Discriminating between one and other Space Objects
- Flawed knowledge leads to flawed or no decisions





- Developed method based upon probabilistic approach
- Developed a realistic and quantifiable measure of association based upon SO ambiguity
- Employed a method that can readily process data of various types and disparate sensors
- Developed and implemented a method that can adaptively approximate the actual SO state error distribution
- Developed the Adaptive Entropy Gaussian Information Synthesis (AEGIS) method as an enabling technology
 - Exploits Gaussian Sum approximations for a given probability density function (pdf)
 - Adaptive coarsening and refining of components
 - Exploits Information-Theoretic measures of ambiguity (i.e. entropy)
 - Leverages contemporary advanced estimation strategies (e.g. Sigma-Point Filters)



Propagation Test



Dynamical models taken to be

- ▶ 8×8 spherical harmonics gravity
- $\blacktriangleright~3^{\rm rd}$ body perturbations from Sun and Moon
- SRP acceleration and moment on 8-plate macro model

Nominal orbit described by

 $a = 42165.91 \text{ km} \,, \ e = 0.0002429 \,, \ i = 0.83^{\circ} \,, \ \Omega = 0^{\circ} \,, \ \omega = 0^{\circ} \,, \ M = 0^{\circ}$

Apply the EKF, UKF, and SGMUKF and evaluate performance of each method

- note that trace $\{F(\hat{x}(t), t)\} = 0$
- the differential entropy of the linearized system is constant
- implement 3-component and 5-component splitting libraries

Initial uncertainty is taken to be

- 1 km for position
- 1 m/s for velocity
- 1° for attitude
- ▶ $0.1 \circ$ /hr for angular velocity



Strategy Definitions



- Extended Kalman Filter (EKF)
 - Based upon linearized dynamics
 - Linear covariance (assumes Gaussian error distribution)
 - Observations update propagated mean and covariance
- Unscented Kalman Filter (UKF)
 - Non-linear dynamics
 - Non-linear covariance (computes error distribution second moment)
 - Observations update computed mean and covariance (second order effects or higher captured)
- Adaptive Entropy Gaussian Information Synthesis (AEGIS)
 - Non-linear dynamics
 - Does not assume a Gaussian error distribution, but error distribution is approximated by sum of individually weighted Gaussian components
 - Each Gaussian component is a UKF
 - Observations update each Gaussian component based upon Bayesian likelihoods



Spacecraft Model















Likelihood Agreement Measure: UKF and AEGIS PDFs vs Monte Carlo









- Generate measurement data of topocentric right ascension and declination
- Observer located at the Maui GEODSS complex

 $\phi = 20.708074^{\circ}$, $\lambda = -156.257486^{\circ}$, and h = 3060.74 m

- Measurement arc is taken to be
 - 20 minutes in duration
 - 20 seconds between measurements
 - total of 61 measurements
- Each of the measurements is subjected to a Gaussian, white-noise sequence with a standard deviation of 1 arc-second on both the right ascension and declination angles.
- Test the update capabilities of the UKF, and 5-component SGMUKF on a single stress-case.







Estimated SO Ambiguity vs True SO: 1 Rev Propagation





Estimated SO Ambiguity vs True SO After Measurement Update: 1 Measurement





Estimated SO Ambiguity vs True SO After Measurement Update: 10 Measurements





Estimated SO Ambiguity vs True SO After Measurement Update: 61 Measurements





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- Action: Developed the Adaptive Entropy Gaussian Information Synthesis (AEGIS) method as an enabling technology
 - Based upon probabilistic approach
 - Yields realistic and quantifiable measure of SO knowledge (ambiguity)
 - Adaptively approximates the actual SO state error distribution
- Impact: Realistic measure of ambiguity improves SO data/track correlation and allows for more accurate trajectory estimation and prediction