THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

Improved Methods for Tracking and Characterizing Inactive Space Objects

8 April 2011

Moriba Jah[1], Kyle DeMars[2] , and Robert Bishop[3]

(1) Air Force Research Laboratory, Space Vehicles Directorate
(2) NRC Research Fellow (AFRL)
(3) Marquette University

Distribution A; Public Release.

By SAF/IA 12/13/2010

"This briefing, presentation, or document is for information only. No US Government commitment to sell, loan, lease, co-develop or co-produce defense articles or provide defense services is implied or intended."

Advanced Sciences and Technology Research Institute for Astrodynamics*

Charter: 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.

ASTRIA

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*

*Dr. Moriba Jah, Director

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*

Background/Motivation

- 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

Knowledge Realism: Why?

- 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

Knowledge Realism: How?

- **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
- 3^{rd} body perturbations from Sun and Moon
- SRP acceleration and moment on 8-plate macro model

Nominal orbit described by

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

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

- note that $\text{trace}\{\boldsymbol{F}(\hat{\boldsymbol{x}}(t), t)\} = 0$
- 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

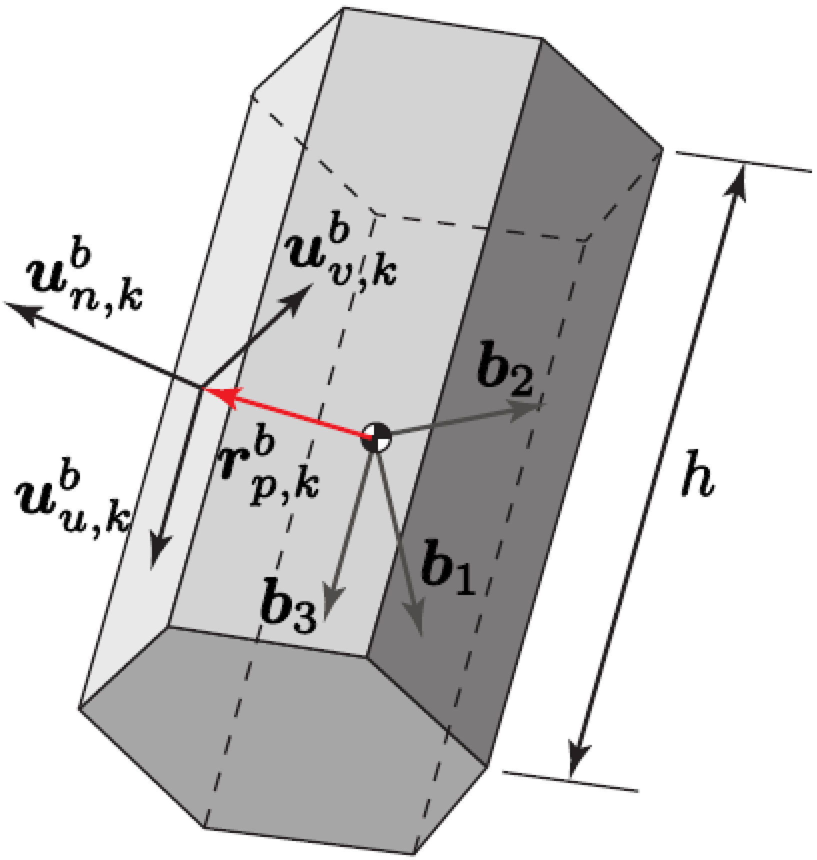
Strategy Definitions

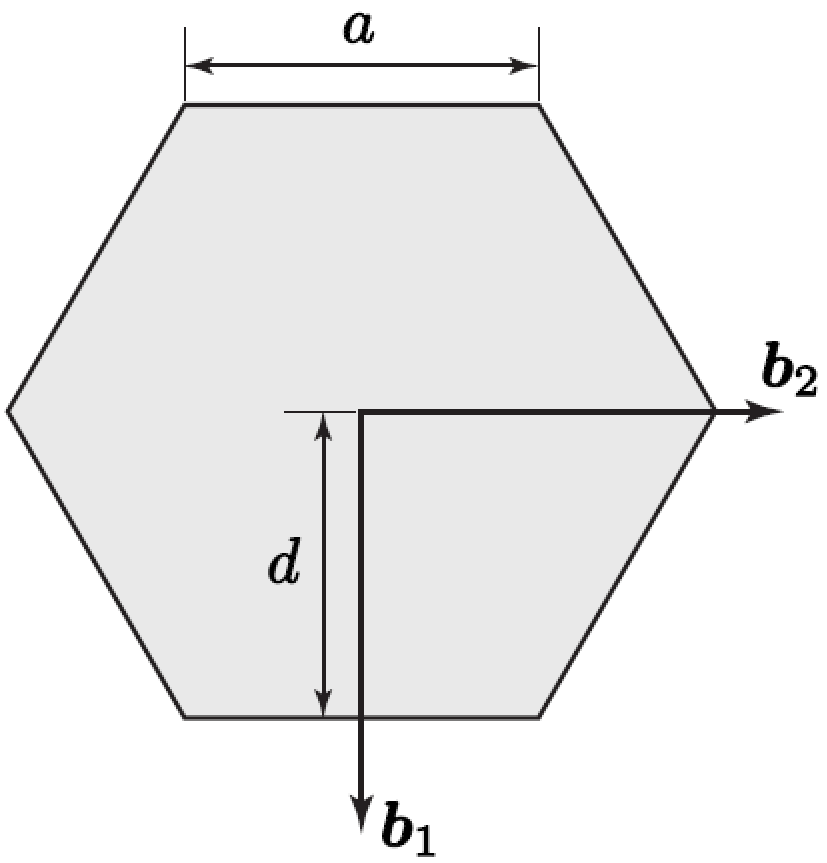
- Extended Kalman Filter (EKF)
  - Based upon linearized dynamics
  - Linear covariance (assumes Gaussian error distribution)
  - Observations update propagated mean and covariance

- 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)

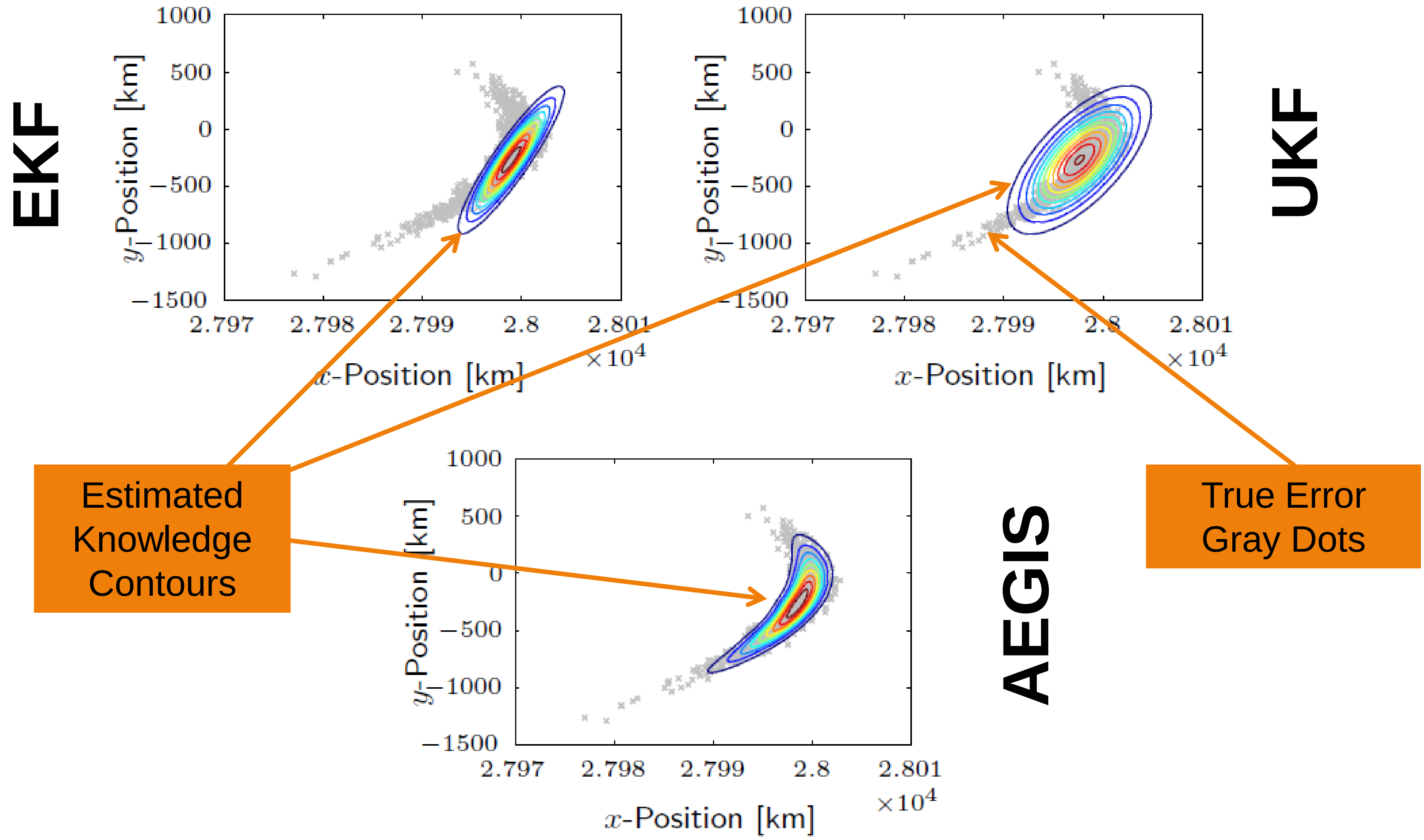
- Adaptive Entropy Gaussian Information Synthesis (AEGIS)
  - Non-linear dynamics
  - Does not assume a Gaussian error distribution, but error distribution is approximated by sum of individually weighted Gaussian components
  - Each Gaussian component is a UKF
  - Observations update each Gaussian component based upon Bayesian likelihoods

Spacecraft Model

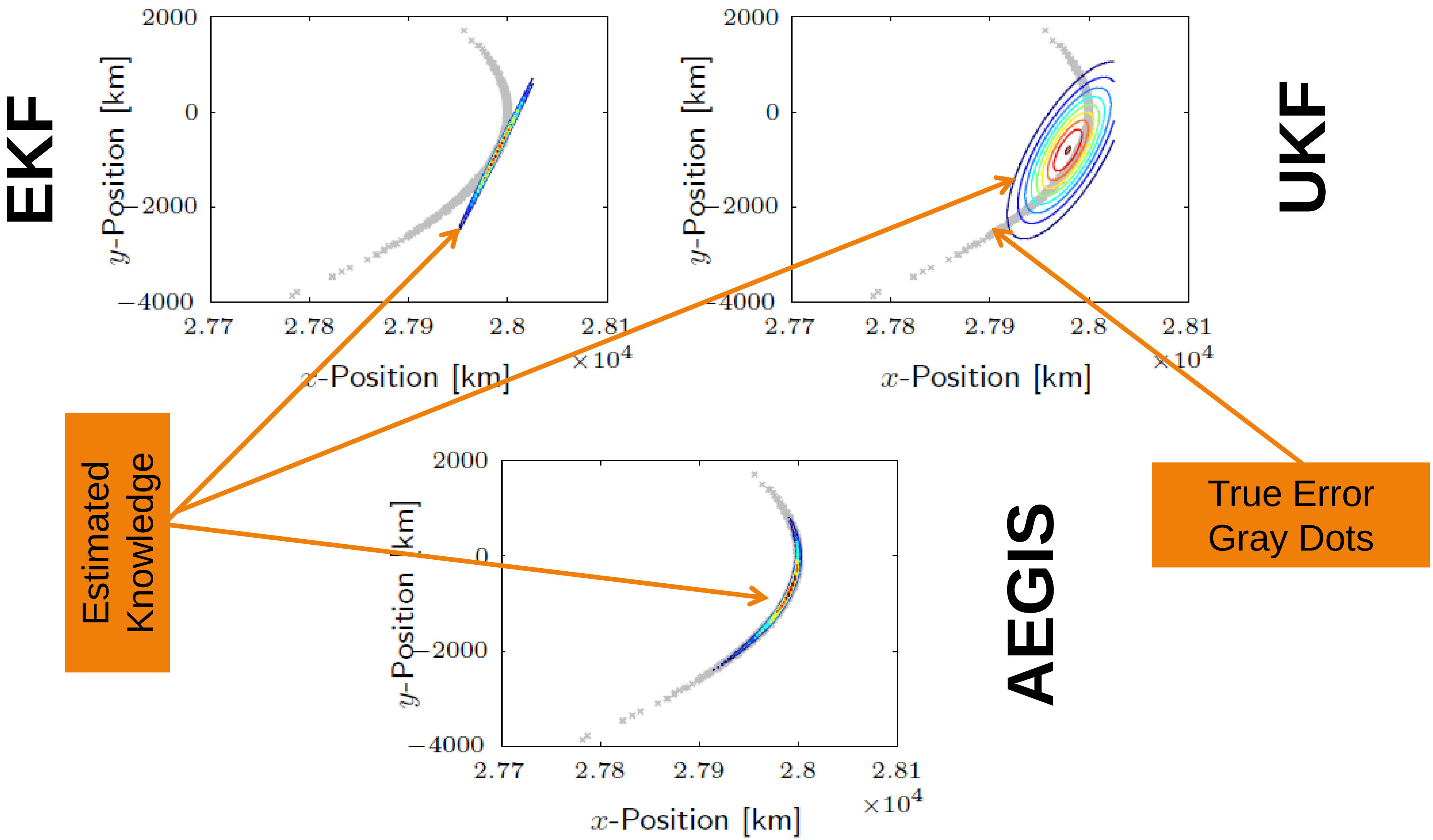




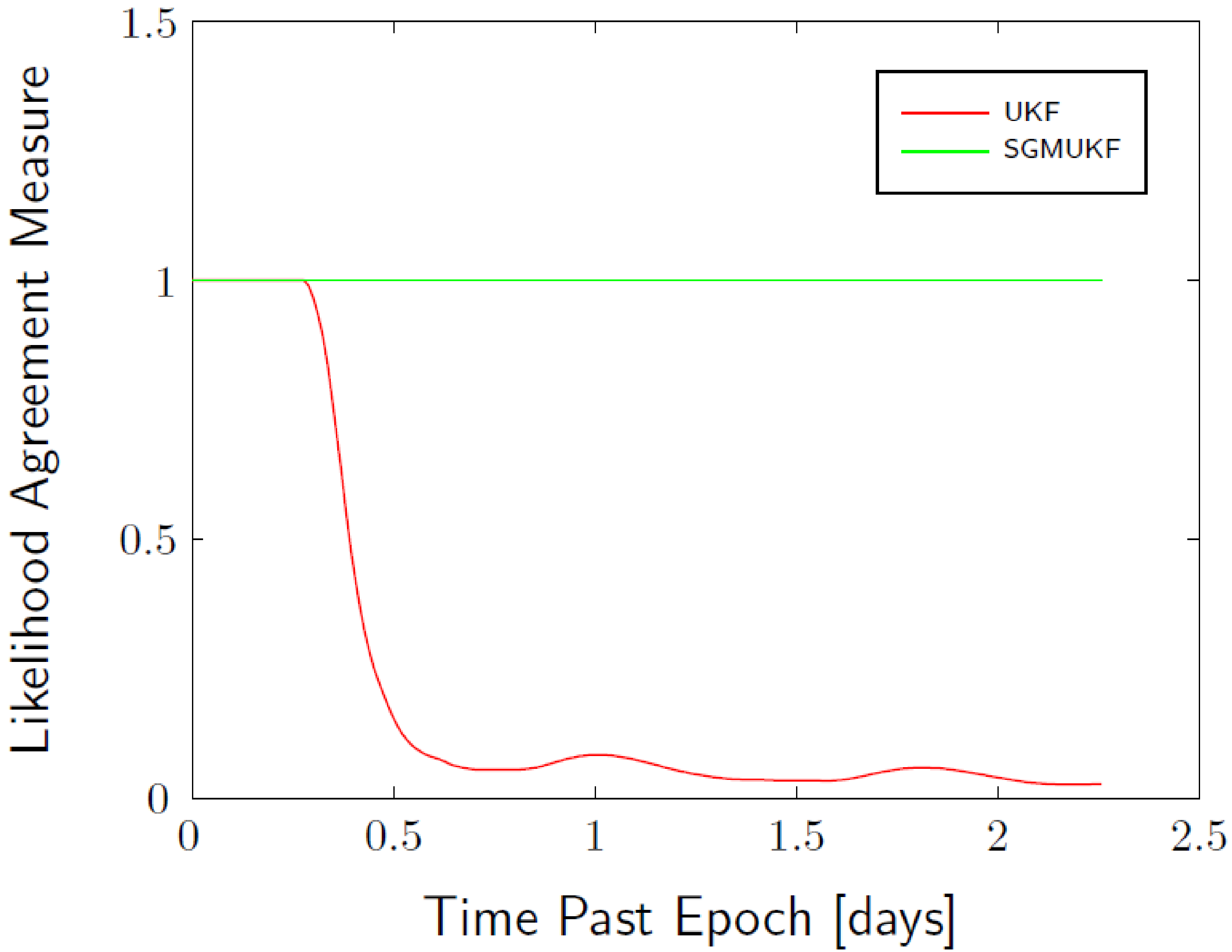
True vs Predicted SO Ambiguity for Various Strategies: 1 Rev Propagation



True vs Predicted SO Ambiguity for Various Strategies: 3 Rev Propagation



Likelihood Agreement Measure: UKF and AEGIS PDFs vs Monte Carlo



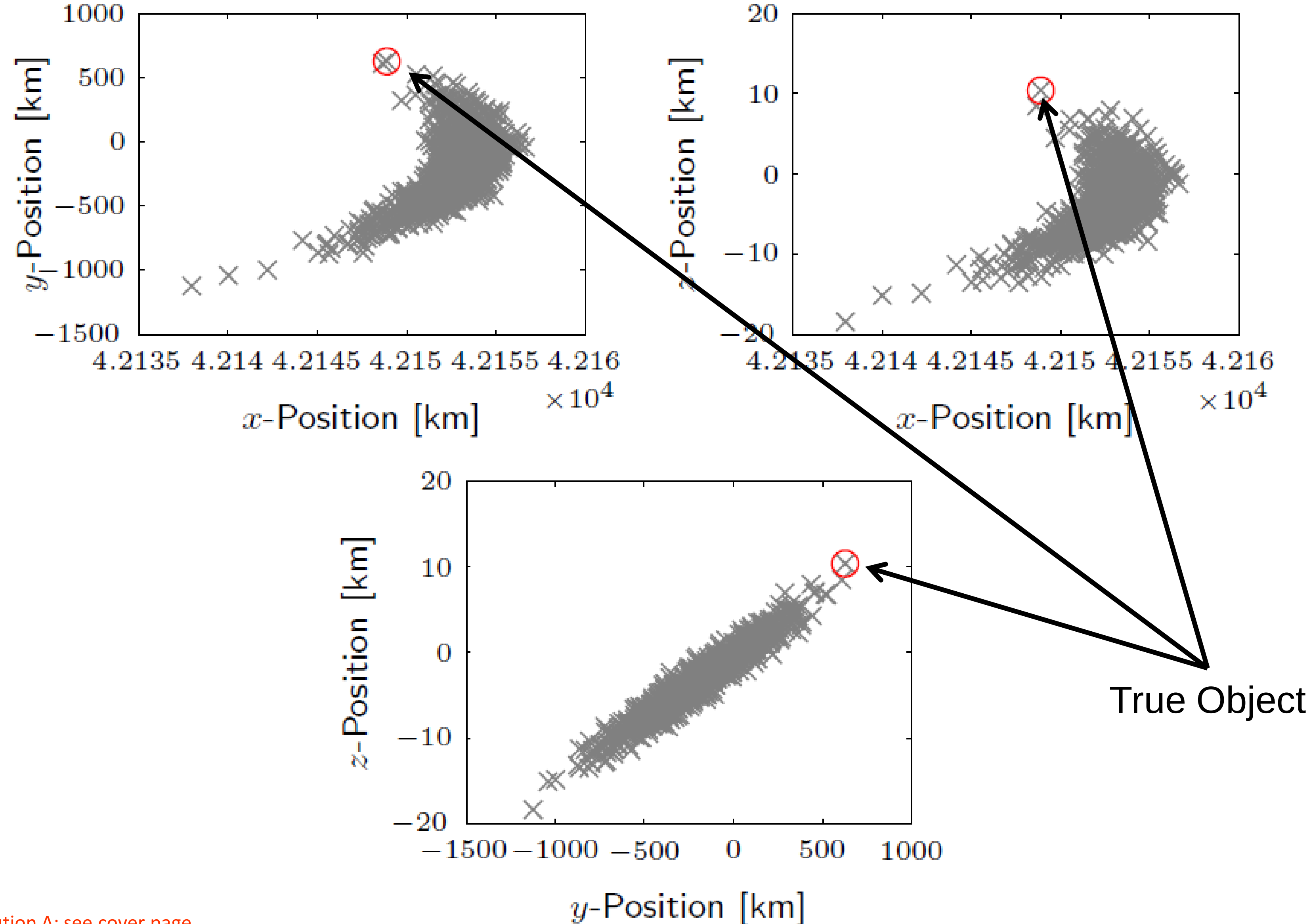
Propagation and Data Reduction Test

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

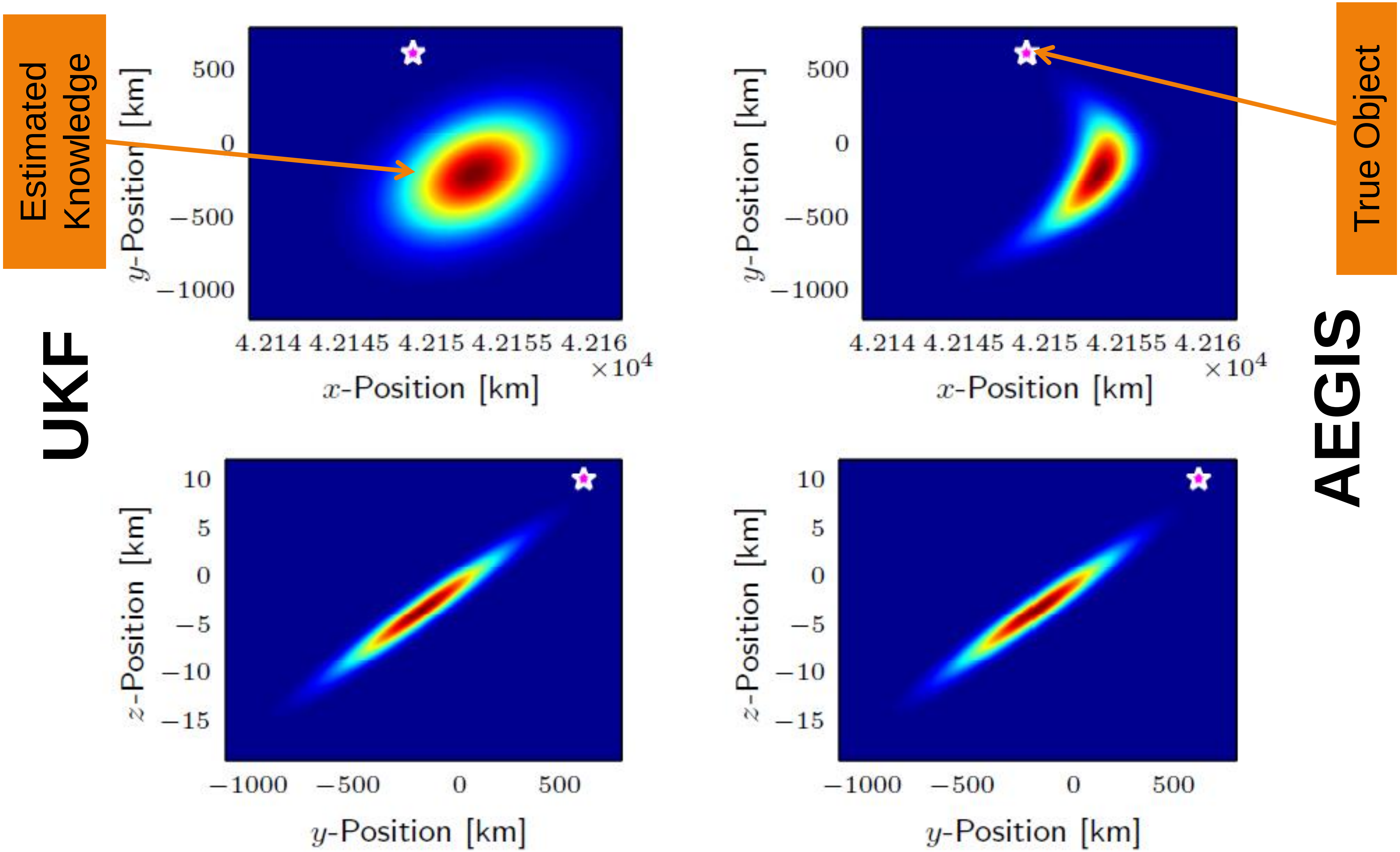
$$\phi = 20.708074^\circ\,, \quad \lambda = -156.257486^\circ\,, \quad \text{and} \quad h = 3060.74 \text{ m}$$

- 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.

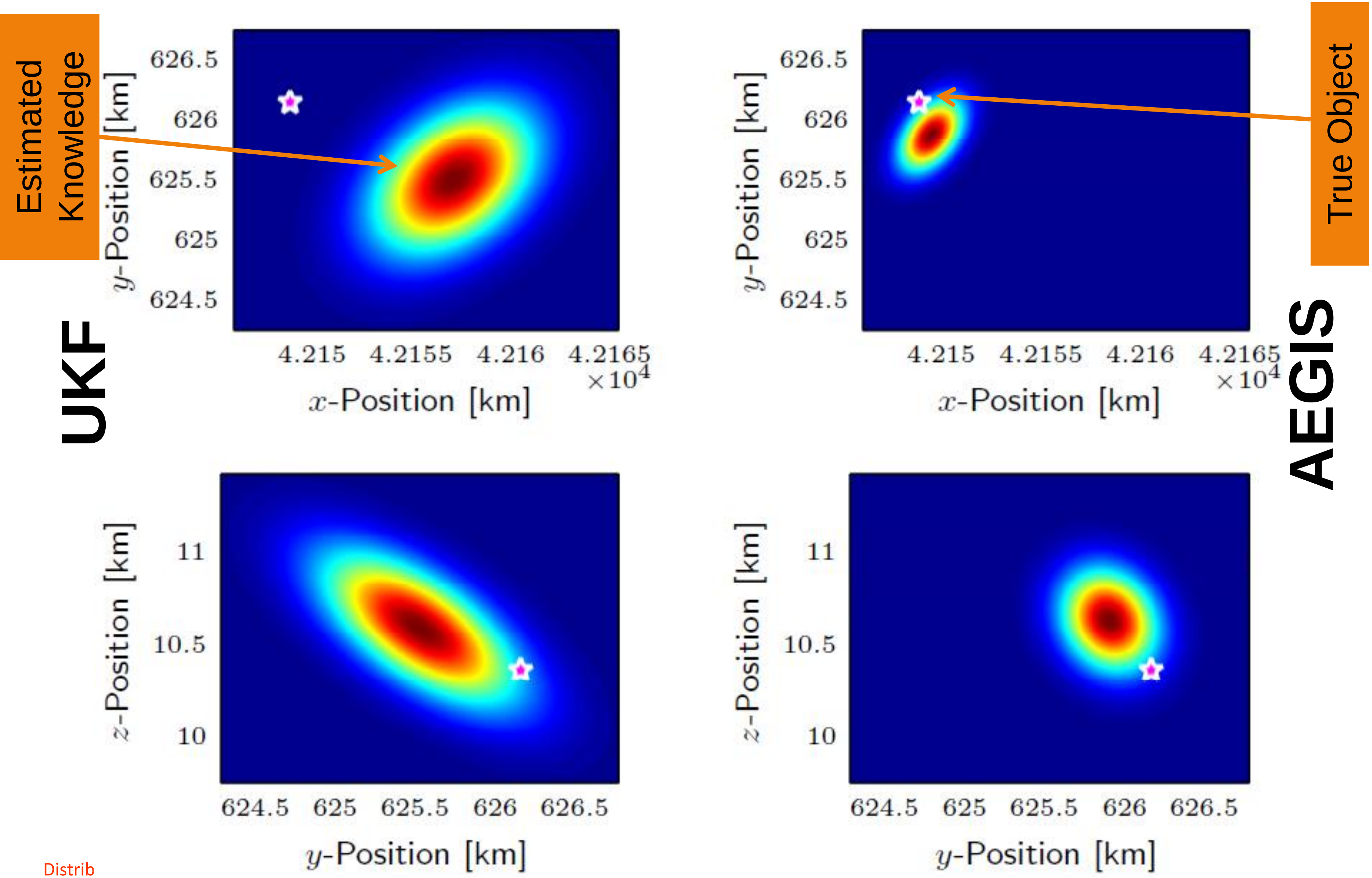
Selected Truth Point for Analysis



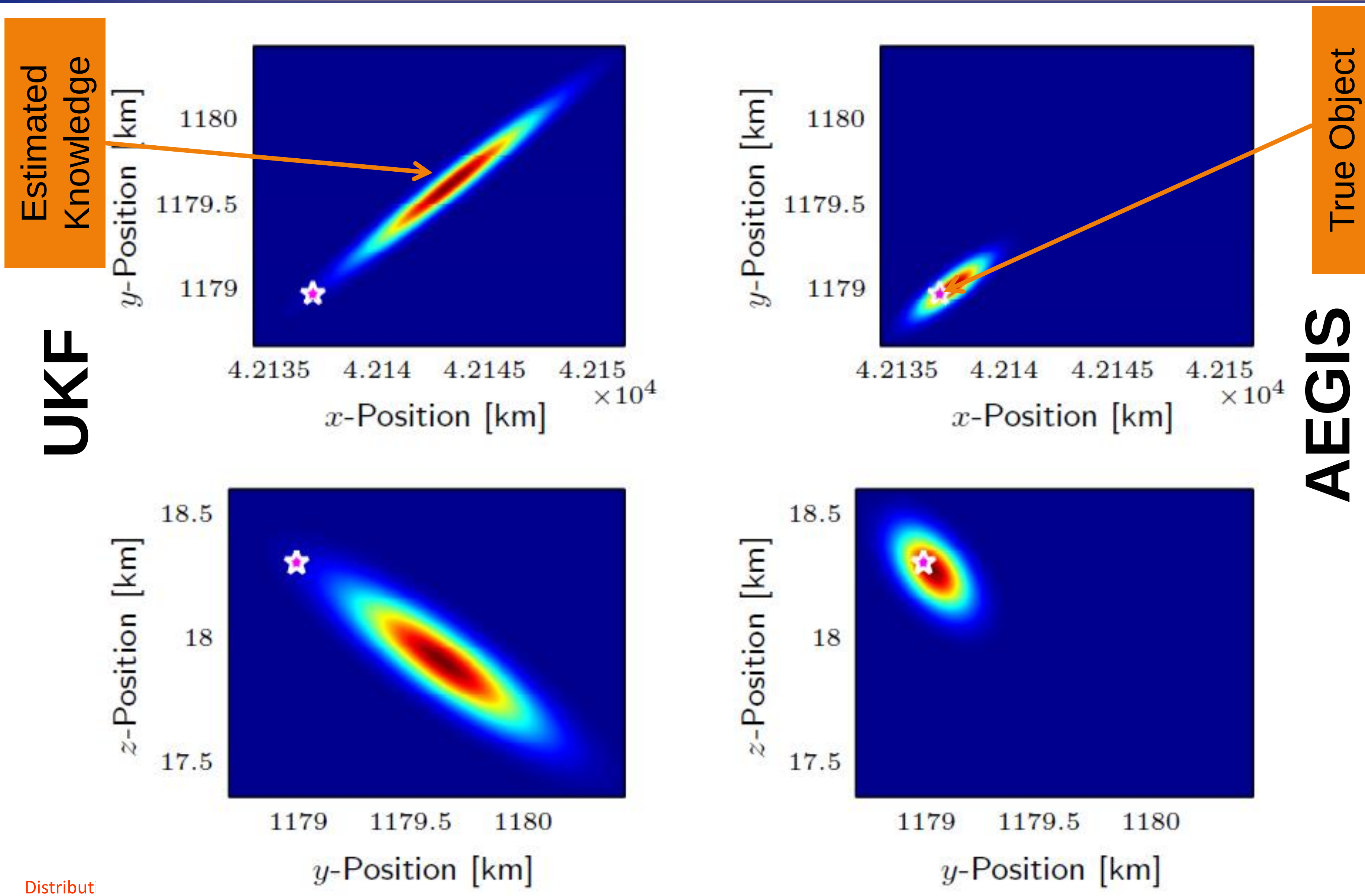
Estimated SO Ambiguity vs True SO: 1 Rev Propagation



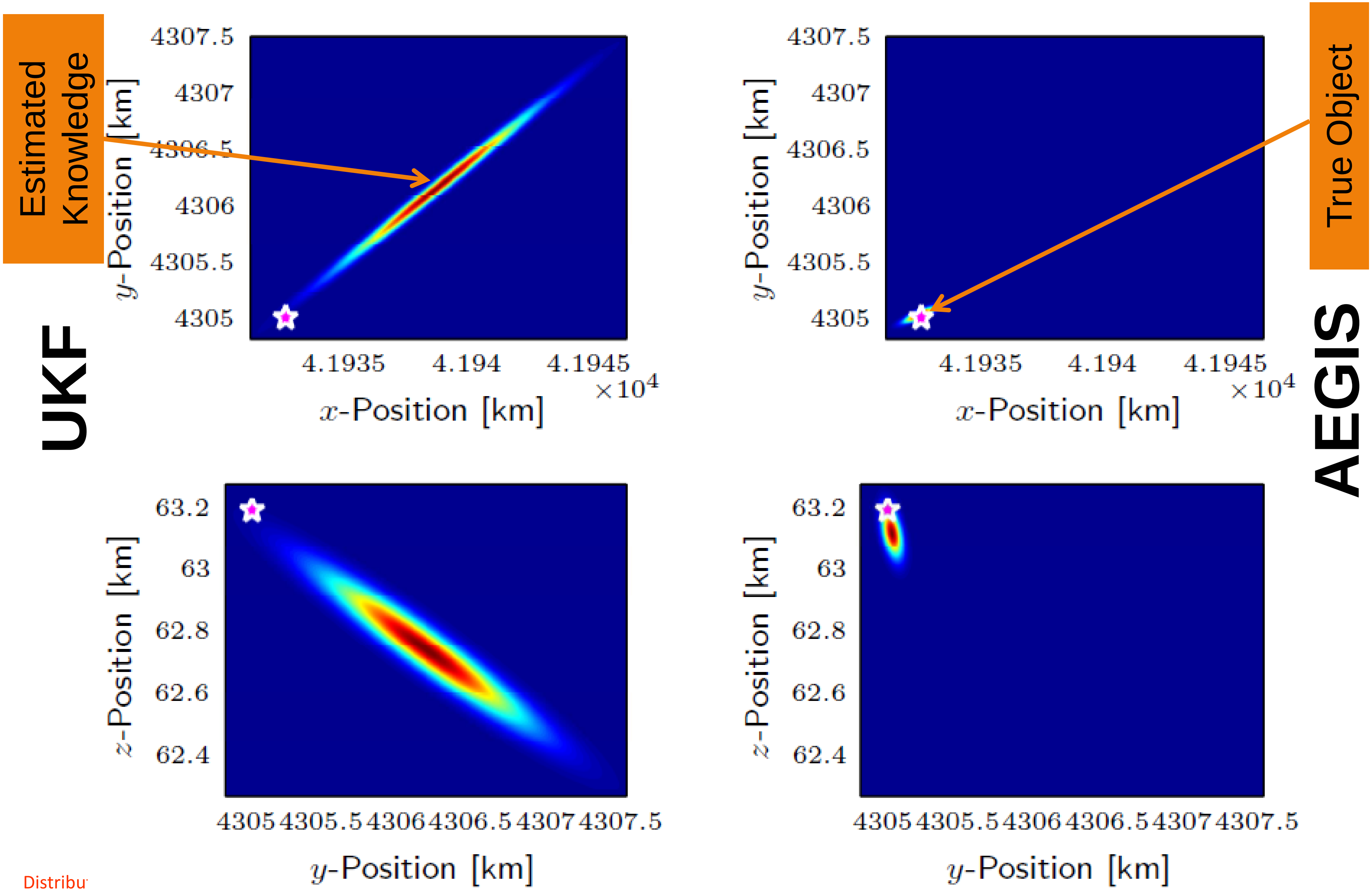
Estimated SO Ambiguity vs True SO After Measurement Update: 1 Measurement



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



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



Summarizing Statements

- **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**