AFRL-AFOSR-UK-TR-2023-0068

Multi-Fidelity Uncertainty Propagation to Track Maneuvering Spacecraft

Brandon Jones
UNIVERSITY OF TEXAS AT AUSTIN
110 INNER CAMPUS DR
AUSTIN, TX, 78712
USA

08/21/2023
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE 20230821	**2. REPORT TYPE** Final	**3. DATES COVERED** **START DATE** 20190901	**END DATE** 20230331

4. TITLE AND SUBTITLE
Multi-Fidelity Uncertainty Propagation to Track Maneuvering Spacecraft

5a. CONTRACT NUMBER	**5b. GRANT NUMBER** FA9550-19-1-0404	**5c. PROGRAM ELEMENT NUMBER** 61102F
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Brandon Jones

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF TEXAS AT AUSTIN 110 INNER CAMPUS DR AUSTIN, TX 78712 USA	**8. PERFORMING ORGANIZATION REPORT NUMBER**

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD UNIT 4515 APO AE 09421-4515	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/AFOSR IOE	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL-AFOSR-UK-TR-2023-0068

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Maneuvering spacecraft create difficulties in space object tracking and characterization, which is critical to identifying contentious behavior and risks. To maintain safety of operations and \ac{SSA}, we must understand how to infer maneuver capabilities for many targets via a minimal set of data. For the case of low-thrust propulsion systems, maneuvers prove difficult to detect when compared to their impulsive counterparts. Previous research focuses on trackers that maintain custody at the cost of estimating a maneuver (e.g., interacting multiplemodel filters) or assume perfect data association. The goal of this project is to improve robustness and maintain custody of maneuvering spacecraft in the context of both single- and multiple-target tracking. In space object tracking, the computation cost of the prediction step and the number of predictions is the primary driver of tractability. This work leverages a multi-fidelity propagation of the predicted state probability density function to enable tractable maneuver identification and estimation when considering multiple maneuver hypotheses. Specific objectives of this project focused on enhancing the multi-fidelity uncertainty
propagation technique for orbit determination and extending that approach to space object tracking.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT** SAR	**18. NUMBER OF PAGES** 9
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U		

19a. NAME OF RESPONSIBLE PERSON MICHAEL YAKES	**19b. PHONE NUMBER** *(Include area code)* 00000000

Standard Form 298 (Rev.5/2020)
Prescribed by ANSI Std. Z39.18

Air Force Office of Scientific Research (AFOSR) Agreement
FA9550-19-1-0404

FINAL Report

Multi-Fidelity Uncertainty Propagation to Track Maneuvering Spacecraft

PI: Brandon A. Jones, Assistant Professor, brandon.jones@utexas.edu,
+1-512-471-4743

The University of Texas at Austin, osp@austin.utexas.edu

Due: June 29, 2023
Period of Performance: September 1, 2021 - March 31, 2023 Duration:
Three years with seven-month no-cost extension

Program Officer: Michael Yakes

Report Abstract

Maneuvering spacecraft create difficulties in space object tracking and characterization, which is critical to identifying contentious behavior and risks. To maintain safety of operations and Space Situational Awareness (SSA), we must understand how to infer maneuver capabilities for many targets via a minimal set of data. For the case of low-thrust propulsion systems, maneuvers prove difficult to detect when compared to their impulsive counterparts. Previous research focuses on trackers that maintain custody at the cost of estimating a maneuver (e.g., interacting multiple-model filters) or assume perfect data association. The goal of this project is to improve robustness and maintain custody of maneuvering spacecraft in the context of both single- and multiple-target tracking. In space object tracking, the computation cost of the prediction step and the number of predictions is the primary driver of tractability. This work leverages a multi-fidelity propagation of the predicted state probability density function to enable tractable maneuver identification and estimation when considering multiple maneuver hypotheses. Specific objectives of this project focused on enhancing the multi-fidelity uncertainty propagation technique for orbit determination and extending that approach to space object tracking.

1 Accomplishments

1.1 Multi-Fidelity Propagator

The key enabling technology used for this work is multi-fidelity uncertainty propagation, i.e., using a combination of low- and high-fidelity propagators to propagate a probability density function representing knowledge of the state via equations of motion. Such approaches combine the computational efficiency of low-fidelity models with the accuracy of high-fidelity methods. In a previous collaboration between the PI and the Air Force Research Laboratory (AFRL), we developed a multi-fidelity propagator that, when compared to state-of-the-art methods, reduces computation time by an order of magnitude while producing a more accurate density (when compared to Monte Carlo). Even when not explicitly discussed, this propagator is used for prediction throughout this project. This density function represents our knowledge of solution uncertainty, and is often referred to as such.

1.2 Research Goals and Objectives

The goal of this project is to improve robustness and reduce computation time in multiple-model approaches for tracking maneuvering spacecraft. Specific research objectives from the proposal and our current approaches towards satisfying these objectives are:

- ***Objective #1: Detect and estimate low-thrust and impulsive spacecraft maneuvers.***
    - Status: Accomplished
- ***Objective #2: Develop a multi-fidelity approach to reduce computation time in a multiple-model tracker.***
    - Status: Accomplished
- ***Objective #3: Improve robustness and computational efficiency for joint maneuver detection, estimation, and data association.***
    - Status: Partially Accomplished

This project was initially funded under an intended collaboration between AFRL (through the Air Force Office of Scientific Research (AFOSR)) and the Defence Science and Technology Laboratory (DSTL) in the United Kingdom (UK) where each funding organization would support a local institution on a joint research project. In this project, the ultimate goal was to develop a multi-target tracker to maintain custody of spacecraft executing low-thrust, non-impulsive maneuvers. The UK team included in the original proposal was to focus on the maneuver estimation formulation (as part of a single-target estimation filter) while the University of Texas at Austin (UT) integrated it with the multi-fidelity propagator and its multi-target tracking tools. Ultimately, the UK team was not funded, which put the burden of developing a single-target tracking capability (Objective #1) on the UT team. Having a single-target tracking capability is a prerequisite for multi-target tracking. To that end, UT increased its emphasis on Obj. #1, which ultimately affected schedule and progress towards Obj. #3.

1.3 Project Accomplishments

As indicated in the goals and objectives, we have satisfied Objectives #1 and #2, and with progress towards Objectives #3. Accomplishments are broken up by objectives below. The objectives are presented in a different order below for clarity. References are to publications listed in Section 1.4.

1.3.1 Progress Toward Objective #2

To satisfy this objective, we extended on our previously developed multi-fidelity uncertainty propagation method to make it compatible with the orbit determination process. This was done for single- and multiple-model orbit determination with propagation via Gaussian mixture or particle-based approaches for uncertainty prediction [J1, J2]. When the observations of a space object are temporally sparse or uncertainty in the object's translation state is large (on the order of 100s of meters up to tens of kilometers), this new approach reduces the computation time required for prediction and estimation by one order of magnitude or more. In terms of the estimator's statistical performance, the output uncertainty in our new approach remained statistically consistent with or slightly larger than the true value based on a Monte Carlo analysis. To facilitate this accurate (or slightly pessimistic) assessment of uncertainty, we developed a new approximation of the propagation error with the multi-fidelity approach and included it as an additional noise process in the time update [J1]. Not including this can yield an optimistic error descriptor, i.e., higher than expected frequency of estimation errors larger than the filter-determined error statistics. With a tractable solution to non-Gaussian, single-model orbit determination problem, we demonstrated its efficacy for multiple-model filtering [C1]. This approach maintained tractability and again produced a statistically consistent solution. Based on these results, we satisfied Objective #2.

In work related to this objective, we improved the breadth of problems where the multi-fidelity approach to uncertainty quantification provides an improved solution. The computation time of the multi-fidelity approach is dominated by the runtime of the low-fidelity propagator embedded in the algorithm. Our early prototype used a numeric propagator, i.e., a Runge-Kutta algorithm, for the low-fidelity solution. This produced an approach most beneficial to the low-Earth orbit regime. By instead using a more efficient low-fidelity model based on Vinti theory, we reduced the computation time sufficiently to yield gains in performance up to geosynchronous orbits [C6]. Taking this further, we extended into the cislunar and lunar space [C2]. The approach of our existing methods did not produce immediate benefits for orbits in cislunar space, but we identified room for improvement with advancements in the low-fidelity model. In lunar space, performance gains are comparable to our low-Earth orbit scenarios since the Moon's gravity field requires up to 10^5 terms for accurate prediction.

- Related publications: J1, J2, C1, C2, C6

1.3.2 Progress Toward Objective #1

Satisfying this objective required significant portions of the project schedule. The technical challenge was expected, but the initial proposal was scoped for this to be the primary focus of the UK team for the first two years of the project. We identified that progress would be limited in Obj. #3 without first making progress on this part of the project. Hence, we devoted more time to this part of the work than initially proposed. Our work towards this objective followed three primary paths: (1) maintaining custody of a maneuvering spacecraft via multiple-model filtering (as proposed), (2) using methods of robust filtering to account for uncertainty in the prediction step while not affecting the algorithm's potential use in multi-target tracking, and (3) a Markov-Chain Monte Carlo (MCMC) approach that can account for the maneuver with very sparse measurements (over 19 hours between measurement collections).

Approach (1) focused on the use of an Interacting Multiple Model (IMM) filter and was presented in [C1]. Prediction of each model used the multi-fidelity propagation, thereby keeping the filter tractable while not making assumptions of a Gaussian predicted density, i.e., a Gaussian transitional prior. When testing the prototype presented in [C1], we identified two shortcomings that motivated a change in approach: (i) the filter was sensitive to assumed possible models for the maneuver magnitude and direction, and (ii) it only improved filter consistency and not accuracy. Hence, we changed our approach to improve robustness.

For approach (2), we developed new estimation methods to track space object executing unknown, possibly long duration, maneuvers [IP1] based on multi-variate Laplacian process noise models. Laplacian models of process noise are robust to statistical outliers, i.e, unknown maneuvers, but admit no analytical solution in the uncertainty prediction problem. One of our major accomplishments for this objective is the development of two approaches: one numeric by structuring the importance-sampling density in a particle-based prediction and a second semi-analytic approach based on a Gaussian mixture approximation of the multivariate Laplace distribution.

We developed a new regularized particle filter to track maneuvering spacecraft that incorporates the multi-variate Laplace density. This new filter maintains tractability via manipulation of the proposal density in the importance sampling component of the estimator. When considering a Laplace distribution for the process noise model, we require many samples in the tails of the distribution for a maneuvering object to prevent particle impoverishment or depletion. To avoid this, we create a data-adaptive proposal density to promote consideration of rare events in the solution. This method produces more samples consistent with the dynamics of the maneuvers based on the available observations and is computational inexpensive. Since this is only done in the proposal density, we prevent bias in the filter through the importance sampling weight used in the filter. In our work, we analyzed the affect this approach has on the transitional prior and the orbit determination process. When there is no maneuver present in the true dynamics, our approach has no statistically significant difference to the Gaussian mixture filter's solution. When a maneuver is present, we showed that the new filter produces a statistically consistent solution after the filter's measurement update. The filter maintains this performance with unknown, and possibly time varying, low-thrust maneuver directions and magnitudes. In contrast, employing a Gaussian noise model fails to yield a consistent solution, and even diverges in some of our Monte Carlo cases. Additionally, since it does not use the measurement to manipulate the transitional prior (as is done in state-of-the-art optimal control-based methods), it does not affect the measurement likelihood function and is compatible with the multi-target tracking problem. Upon producing a single-target, non-Gaussian orbit determination approach that is robust to unknown maneuvers and is compatible with the multiple-target tracking problem, we deemed Obj. #1 to be satisfied.

To further improve tractability of our approach, we developed a new Gaussian Integral Filter (GIF). In this GIF, we use an approximation of a multi-variate Laplace distribution as a Gaussian mixture to develop a closed-form solution to the prediction step [PC1]. Unlike the previous filter that uses a re-definition of the importance-sampling distribution, this new method produces a semi-analytic solution to the prediction as a Gaussian mixture for practical implementation. This solution dictates the number of components required, which may be adapted to reflect requirements in tractability and accuracy without sacrificing the filter's compatibility with the multi-target tracking problem. This mixture refinement computation time is further reduced via the multi-fidelity propagation step. While not practical, the theory allows for generalizing the result to an infinite number of mixture components.

In [C5], we developed a novel integration of the multi-fidelity propagator with a Hamiltonian Monte Carlo-based approach to further improve robustness when observations are sparse (approach (3) above). We found that this method maintains a statistically consistent orbit determination solution with data gaps on the order of 19 hours or more. However, this approach does not produce a transitional prior and is incompatible with multi-target tracking. Long term, we envision the regularized particle filter or the GIF described above operating in a multi-target tracker that identifies when a maneuver likely occurs. Upon identifying these cases and producing the data association hypotheses of interest, this MCMC approach may be run as a secondary process that refines the solution and/or produces an estimate of the maneuver profile.

- Related publications: J2, IP1, PC1, C1, C5

1.3.3 Progress Toward Objective #3

The planned work for this objective was to incorporate the result of Obj. #1 in the Generalized Labeled Multi-Bernoulli (GLMB) multi-target tracker. The GLMB tracker requires a transitional prior free of manipulation to produce a measurement likelihood against which different data association hypotheses are ranked, i.e., a higher measurement likelihood corresponds to a hypothesis with a larger probability. While not completed as part of this project for the reasons stated previously, our long-term goal is to fully integrate the regularized particle filter developed in Obj. #1 with the GLMB, multi-target tracker to satisfy this objective.

While UT focused on Obj. #1, we collaborated with researchers at the Universidad Carlos III de Madrid (UC3M) in Spain on an alternative method for maneuvering space object tracking with the GLMB tracker and a multi-fidelity prediction [C3, C4]. In this approach, statistical distributions of Control Distance Metrics (CDMs) are used to produce a transitional prior without affecting the measurement likelihood. The underlying distribution of the control distance metrics is based on historical data of similar missions and spacecraft. While the results are promising, future SSA requires a method that is robust to (i) errors in the underlying distribution, and (ii) considers maneuvers that are inconsistent with historical data. We developed an approach to remove the CDM distribution, but at the expense of runtime. This collaboration has continued beyond this project to determine if an alternative approach may be developed using a prescribed bound on the possible maneuvers.

- Related publications: C3, C4

1.4 Dissemination of Results

Below are the publications that cite AFOSR as a funding source. These are grouped by publication type. All have been mapped to this project's objectives as stated previously.

1.4.1 Journal (J) Publications

J1. Zucchelli, E. M., Delande, E. D., Jones, B. A., and Jah, M. K., "Multi-Fidelity Orbit Determination with Systematic Errors", *Journal of the Astronautical Sciences*, Vol. 68, pp. 695-727, 2021, 10.1007/s40295-021-00267-y.

J2. Yun, S., Zanetti, R., and Jones, B. A., "Kernel-based ensemble Gaussian mixture filtering for orbit determination with sparse data", *Advances in Space Research*, Vol. 69, No. 12, pp. 4179-4197, June, 2022, 10.1016/j.asr.2022.03.041.

At the time of this report's submission, we have one publication in preparation (IP) and about to be submitted. The first draft is complete and being iterated by the authors.

IP1. Zucchelli, and Jones, B. A., "Bayesian Low-Thrust Maneuvering Spacecraft Tracking via Rare Event Simulation" (working title), in preparation, 2023.

1.4.2 Peer-Reviewed Conference (PC) Publications

PC1. Zucchelli, E.M., and Jones, B.A., "A Gaussian Integral Filter with Multivariate Laplace Process Noise", 26th International Conference on Information Fusion, Charleston, SC, June 27-30, 2023.

1.4.3 Conference (C) Publications

C1. Zucchelli, E. M., McLaughlin, Z. R., and Jones, B. A., "Tracking Maneuvering Targets with Multi-Fidelity Interacting Multiple Model Filters", In *Proceedings of the 2020 Advanced Maui Optical and Space Surveillance Technologies Conference*, pp. 1-14, Wailea, Maui, HI, Sept. 16-18, 2020.

C2. Wolf, T., Zucchelli, E. M., and Jones, B. A., "Multi-Fidelity Uncertainty Propagation for Objects in Cislunar Space", In *AIAA SciTech 2022 Forum*, AIAA 2022-1774, San Diego, CA, Jan. 3-7, 2022, 10.2514/6.2022-1774.

C3. Escribano, G., Jones, B., Sanjurjo-Riva, M., Siminski, J., Pastor, A., and Escobar, D., "Data Association for Maneuvering Space Objects Considering Different Control Distance Metrics", In *Astrodynamics Specialist Conference*, Charlotte, NC, Aug. 7-11, 2022.

C4. Escribano, G., Jones, B.A., Sanjurjo-Rivo, M., Siminski, J., Pastor, A., and Escobar, D., "A GLMB Filter for Space Objects with Control Metric Based Maneuver Detection", in *2023 AAS/AIAA Space Flight Mechanics Meeting*, AAS 23-157 (13 pages), Austin, TX, Jan. 15-19, 2023.

C5. Zucchelli, E.M., and Jones, B.A., "Multi-Fidelity Hamiltonian Monte Carlo for Space Object Tracking with Sparse Data", in *2023 AAS/AIAA Space Flight Mechanics Meeting*, AAS 23-377 (14 pages), Austin, TX, Jan. 15-19, 2023.

C6. Wolf, T.N., and Jones, B.A., "Extending the Utility of Multi-Fidelity Space Object Uncertainty Quantification with Vinti Theory", in *2023 AAS/AIAA Space Flight Mechanics Meeting*, AAS 23-224 (17 pages), Austin, TX, Jan. 15-19, 2023.

1.4.4 Technical Presentations (Excluding AFOSR Reviews)

1. Jones, B.A., "UT-Austin SDA Efforts and Their Application to Cislunar Space", AFRL Cislunar Working Group Meeting, Albuquerque, NM, February 28, 2020.

2. Jones, B.A., "Improving Space Domain Awareness Through Advanced Methods of Uncertainty Quantification", Georgia Institute of Technology, Virtual Seminar, November 4, 2021.

3. Jones, B.A., "Improving Space Domain Awareness Through Advanced Methods of Uncertainty Quantification", Purdue University, West Lafayette, IN, September 1, 2022.

4. Jones, B.A., "Improving Space Domain Awareness Through Advanced Methods of Uncertainty Quantification", Numerical Analysis and Machine Learning Seminar Series, Univ. of Iowa, Virtual, December 6, 2022.

2 Impacts

2.1 Impacts to Space Situational Awareness (SSA)

Impacts from the completed technical objectives include:

- *Expected outcome for Objective #1:* Robust tracking of satellites capable of unknown low-thrust maneuvers produces critical object characterization and anomaly detection capabilities. We developed an approach to tracking spacecraft with unknown, possibly low-thrust, maneuvers with sparse data. This approach is fully compatible with multiple target trackers, which allows for its future use in data association. This will improve accuracy and statistical certainty when compared to the current state-of-the-art in SSA.
- *Expected outcome for Objective #2:* Hypothesis resolution is critical to situational awareness in any domain. A common approach leverages multiple models to determine the hypothesis (or hypotheses) most consistent with data available. For SSA with sparse observations, uncertainty prediction can be computationally demanding and is exacerbated when considering multiple hypotheses. This can limit the use of multiple-model methods or result in undesirable simplifying assumptions. This work mitigates the computational

challenge, thereby allowing for the development of capabilities for improved robustness and sparse measurements.

2.2 Research Awards and Milestones

The multi-fidelity uncertainty propagation and estimation tools developed in this work have been identified as a key capability in other follow-on efforts. The use of these new capabilities has or will have a direct impact on future projects. Funded efforts include:

- DARPA STTR – The Defense Advanced Research Agency (DARPA) funded Tau Technologies and UT in a Phase I and Phase II STTR for tracking mega-constellations in low-Earth orbit. A key concern with this problem is the increased computational complexity when scaling up the problem to many objects. The multi-fidelity propagator was a key enabling capability in that work. UT was awarded the additional six-month option period to continue this research and development.
- USSF UCRO – The United States Space Force and the Air Force Research Laboratory (via the Universities Space Research Association) awarded a grant for Rapid Initial Orbit Determination (RIOD) as part of its University Consortium Research Opportunity (UCRO) in April 2022. This work leverages the multi-fidelity propagator for rapid prediction of a sensor search space to quickly establish custody of a newly detected space object.

In addition to the impacts mentioned above, the following milestones were partially enabled by this grant.

- The PI, Brandon Jones, was promoted (assistant professor to associate professor with tenure) effective September 1, 2023.
- The graduate student funded through this effort, Enrico Zucchelli, is scheduled to defend his Ph.D. thesis in August, 2023. Tentative/working title is *Algorithms for Space Domain Awareness*. A majority of the thesis will cover the work described above.

REPORT DOCUMENTATION PAGE

1. REPORT DATE 06/29/2023	**2. REPORT TYPE** Final Report	**3. DATES COVERED** **START DATE** 09/01/2019	**END DATE** 03/31/2023

4. TITLE AND SUBTITLE
Multi-Fidelity Uncertainty Propagation to Track Maneuvering Spacecraft

5a. CONTRACT NUMBER FA9550-19-1-0404	**5b. GRANT NUMBER** FA9550-19-1-0404	**5c. PROGRAM ELEMENT NUMBER**
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

6. AUTHOR(S)
Brandon A. Jones, Assistant Professor, Department of Aerospace and Engineering Mechanics, The University of Texas at Austin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The University of Texas at Austin 3925 West Braker Lane, Building 156, Suite 3.340, MC: A9000 Austin, Texas, 78759-5316	**8. PERFORMING ORGANIZATION REPORT NUMBER** N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFRL - Air Force Office of Scientific Research 875 North Randolph Street, Suite 325 Arlington, TA 22203-1768	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFOSR	**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for Public Release; Distribution is Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This is the final report for this project. It includes a description of progress towards the project's objectives, a summary of accomplishments, and a description of technical and programmatic impacts of this work.

15. SUBJECT TERMS

astrodynamics; multi-fidelity methods; maneuvering spacecraft; multiple target tracking

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**
a. REPORT U	**b. ABSTRACT** U	**C. THIS PAGE** U	UU	9

19a. NAME OF RESPONSIBLE PERSON Brandon A. Jones	**19b. PHONE NUMBER** *(Include area code)* 512-471-4743