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**6. AUTHOR(S)**
Yaakov Bar-Shalom

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
University of Connecticut U-1157
Storrs, CT 06269-1157

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**13. ABSTRACT** *(Maximum 200 words)*

The research effort reported here focused on the development of practical advanced algorithms for optimal processing of the information obtained from various remote sensing devices (radar, ESM or electro-optical) for surveillance and tracking targets. The processing consists of integration/filtering of the sensor data across time and fusion across sensors with the main goal being overcoming the inherent limitations of real-world sensors (accuracy and reliability) due to noise. which cause false alarms, and other factors, such as low observable (LQ) targets, which lead to low detection probability. We developed algorithms for: association and fusion of measurements from multiple, asynchronous heterogeneous sensors based on discrete mathematical optimization techniques (multidimensional matching/assignment techniques) for practical high density scenarios; target tracking for the case of multipath; phased array radar resource allocation for the case of unresolved targets; track formation of LO targets from EQ sensor (latd; radar waveform design for optimized tracking (i.e., system level) performance; track before detect approach for VLO targets with fluctuating amplitude; generalization of the CRLB iii the presence of false measurements to iion-Gaussian distribution; an efficient estimator (that meets the CRI⁻B) for acquisition by an ESA radar of a LQ TBM prior to reentry; SAM identification for timely countermeasures; bias estimation for multiple radars using targets of opportunity; exact incorporation of target classification into multidimensional assignment.

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# FINAL REPORT
Dec. 1, 1999 – Nov. 30, 2002

## ESTIMATION WITH MULTISENSOR FUSION

Yaakov Bar-Shalom, K.R. Pattipati and P.K. Willett
Univ. of Connecticut U-1157
Storrs CT 06269-1157
Phone 860-486-4823
Fax 860-486-5585
E-mail ybs@ee.uconn.edu

July 23, 2003

# ABSTRACT

The research effort reported here focused on the development of practical advanced algorithms for optimal processing of the information obtained from various remote sensing devices (radar, ESM or electro-optical) for surveillance and tracking targets. The processing consists of integration/filtering of the sensor data across time and fusion across sensors with the main goal being overcoming the inherent limitations of real-world sensors (accuracy and reliability) due to noise, which cause false alarms, and other factors, such as low observable (LO) targets, which lead to low detection probability. We developed algorithms for: association and fusion of measurements from multiple, asynchronous heterogeneous sensors based on discrete mathematical optimization techniques (multidimensional matching/assignment techniques) for practical high density scenarios; target tracking for the case of multipath; phased array radar resource allocation for the case of unresolved targets; track formation of LO targets from EO sensor data; radar waveform design for optimized tracking (i.e., system level) performance; track before detect approach for VLO targets with fluctuating amplitude; generalization of the CRLB in the presence of false measurements to non-Gaussian distribution; an efficient estimator (that meets the CRLB) for acquisition by an ESA radar of a LO TBM prior to reentry; SAM identification for timely countermeasures; bias estimation for multiple radars using targets of opportunity; exact incorporation of target classification into multidimensional assignment.

# 1 Objectives

The work reported herein deals with the development of practical advanced algorithms for optimal processing of the information obtained from various remote sensing devices (radar, ESM or electro-optical) for surveillance and tracking targets. The processing consists of integration/filtering of the sensor data across time and fusion across sensors with the main goal being overcoming the inherent limitations of real-world sensors (accuracy and reliability) due to noise — which cause false alarms — and other factors, such as low observable (LO) targets — which lead to low detection probability.

The following were the specific objectives of the research, with the corresponding publication number(s) in brackets:

1. Track detection for LO targets and the CRLB for target motion parameter estimates in clutter [210].

2. Incorporation of out-of-sequence measurements into a track without reordering and reprocessing the measurements [224,239,243,254,256].

3. Target track detection algorithms for LO maneuvering targets [225].

4. Angle extraction for unresolved targets in the same range cell of a radar [234].

5. Investigation of the relative performance of distributed and centralized trackers [237].

6. Altitude estimation from 2-D radars [238].

7. The CRLB in clutter [240,247].

8. Radar waveform selection [241,245].

9. Maneuvering target tracking with passive sensors [242].

10. Measurement scheduling in tracking [244].

11. Arrival angle extraction in the presence of sea surface multipath [246].

12. Multiple LO track initiation [248].

13. Tracking with multiple finite resolution sensors [249].

14. Tracking move-stop-move targets with a GMTI radar [250].

15. Use of particle filters in clutter [251].

16. Use of a monopulse radar for unresolved targets [252].

17. Comparison of nonlinear filters for passive tracking [253].

18. Multisensor management via the CRLB [255].

19. Benchmark problem for unresolved targets [257].

20. Use of LP for efficient fractional assignment in data association [258].

21. Track segment association [259].

22. Posterior CRLB in clutter [260].

23. Unresolved target measurement extraction [261,262].

24. Use of tracklets for distributed tracking [263].

25. Monopulse signal processing investigation [264].

26. Bias estimation for multiradar data fusion [265,269].

27. Intervisibility in hilly terrain [266].

28. Classification aided tracking [267].

29. Benchmark problem with unresolved targets [268].

30. Survey of PDA techniques [270].

31. Data association with unresolved measurements [271].

32. SAM identification with passive sensors [272].

33. Estimation text for a graduate course [B7].

# 2 Status of the Effort

1. We developed the ML-PDA algorithm for track detection for LO targets and the CRLB for target motion parameter estimates in clutter [210].

2. We derived the optimal as well as a practical suboptimal algorithm for the incorporation of out-of-sequence measurements into a track without reordering and reprocessing the measurements [224,239,243,254,256].

3. We developed a sliding variable-length window generalization of the ML-PDA estimation algorithm for track detection for LO maneuvering targets [225].

4. We developed a ML algorithm for azimuth and elevation angle extraction for unresolved targets in the same range cell of a radar [234].

5. We investigated the relative performance of a distributed and centralized trackers and obtained bounds on their performance difference [237].

6. An algorithm for altitude estimation from 2-D radars was obtained [238].

7. The CRLB for parameter estimation in clutter was derived [240,247].

8. Waveform selection for Doppler radars was investigated for best tracking performance [241,245].

9. An efficient algorithm (IMMPDAF) for maneuvering target tracking with passive sensors was presented [242].

10. Measurement scheduling in tracking was investigated for minimum MSE [244].

11. An algorithm for the most accurate elevation angle extraction in the presence of sea surface multipath was obtained [246].

12. Multiple LO track initiation with the MDL criterion was presented [248].

13. A data association algorithm for tracking with multiple finite resolution sensors was presented [249].

14. A new assignment algorithm was developed for tracking move-stop-move targets with GMTI radar [250].

15. The use of particle filters in clutter was investigated [251].

16. The azimuth-elevation correlation in a monopulse radar was presented [252].

17. The particle filter has been compared with the EKF for a passive tracking problem [253].

18. The CRLB has been used to allocate sensors in a field [255].

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19. The 4th Benchmark problem with unresolved targets sea multipath has been solved [257].

20. The use of LP for efficient fractional assignment in data association has been investigated [258].

21. A track segment association has been developed for an AEW problem [259].

22. The posterior CRLB in clutter has been rigorously derived [260].

23. A ML scheme for unresolved target measurement extraction was derived [261,262].

24. The usefulness of tracklets for distributed tracking was evaluated [263].

25. The crosscorrelation of angles from monopulse signal processing was investigated [264].

26. A ML algorithm for bias estimation for multiradar data fusion was developed [265,269].

27. The intervisibility in hilly terrain was evaluated [266].

28. Classification aided tracking with multidimensional assignment was rigorously derived [267].

29. The benchmark problem with unresolved targets was solved using the modified signal processing for angle extraction [268].

30. A survey of PDA techniques was carried out [270].

31. The MDL technique was used for data association with unresolved measurements [271].

32. An algorithm for SAM identification and time-to-go estimation with passive sensors was developed [272].

33. A new edition of a popular Estimation text has been published by a new publisher, primarily for academic use [B7].

# 3 Accomplishments and New Findings

1. The ML-PDA algorithm for track detection for LO targets has been shown to meet the CRLB in clutter down to SNR=4dB in a resolution cell, vs. the practical limit of 13dB in current systems [210].

2. The new practical suboptimal algorithm for the incorporation of out-of-sequence measurements into a track without reordering and reprocessing the measurements has been adopted in a phase 2 SBIR sponsored by AFRL at Alphatech [224,239,243,254,256]. SPAWAR is also using it in an internal project.

3. The new sliding variable-length window generalization of the ML-PDA estimation algorithm for track detection for LO maneuvering targets has significantly outperformed the MHT on real data from a NATO experiment [225].

4. The new ML algorithm for azimuth and elevation angle extraction for unresolved targets in the same range cell of a radar outperforms significantly the monopulse ratio based extractor [234].

5. The performance of a memoryless distributed tracker is only 5–15% worse in MSE than the centralized tracker's [237].

6. Altitude estimation from 2-D radars can be done for targets flying at constant altitude; the CRLB (best achievable accuracy) has been derived for this problem [238].

7. The CRLB in clutter can serve a realistic performance evaluation tool for tracking LO targets [240,247].

8. Waveform selection for Doppler radars can enhance tracking performance [241,245].

9. The algorithm for maneuvering target tracking with passive sensors that was presented can track low SNR targets down to 10dB while conventional algorithms require at least 18–20dB [242]. This has been transitioned to NUWC for System 53.

10. Appropriate measurement scheduling in tracking can reduce the estimation MSE [244].

11. Waveform selection for Doppler radars can improve the tracking performance; in particular, the upsweep LFM waveform was found to be the best [245].

12. The new ML algorithm for elevation angle extraction in the presence of sea surface multipath is much more accurate than the monopulse ratio based one [246].

13. Multiple LO track initiation can be done with the MDL criterion without the risk of "overfitting" [248].

14. The multiassignment data association algorithm can handle tracking with multiple finite resolution sensors [249].

15. The new assignment algorithm can successfully track move-stop-move targets with GMTI radar without track breaks [250].

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16. Particle filters can outperform the PDAF in some problems [251].

17. The azimuth and elevation measurement error correlation in a monopulse radar should be accounted for by the tracker [252].

18. The particle filter has a smaller probability of very large errors compared with the EKF for the passive tracking problem considered [253].

19. The CRLB is an effective means to allocate sensors in a field [255].

20. This is the first solution to date for the 4th Benchmark problem with unresolved targets sea multipath [257].

21. The LP can provide an efficient fractional assignment in data association [258].

22. The new algorithm for track segment association increases significantly the mean track life for the AEW problem considered [259].

23. The posterior CRLB in clutter is a fundamental result [260].

24. Separate angles can be extracted for unresolved targets from a single detection [261,262]. This has been transitioned to GTRI for their Hercules benchmark.

25. Tracklets have questionable usefulness for distributed tracking [263].

26. The crosscorrelation of angles from monopulse signal processing is significant and should be accounted for in tracking [264].

27. Bias estimation for multiple radars using targets of opportunity is feasible and will be used in BMD [265,269].

28. The intervisibility (sensor to target) in hilly terrain can be quantified probabilistically [266].

29. Classification aided tracking can improve the performance in multidimensional assignment [267].

30. The benchmark problem with unresolved targets required modified signal processing before its successful solution [268].

31. The PDA techniques are effective and affordable in numerous applications [270].

32. The MDL technique allows for effective data association with unresolved measurements avoiding overfitting [271].

33. SAM identification and time-to-go estimation is feasible with passive sensors and can be done in a timely manner [272].

34. The new edition of a popular Estimation text has already been adopted by several instructors at MIT, NPS, Cornell, Technion, George Mason, Taiwan, South Korea and other places [B7].

# 4  Personnel Supported

Faculty: Yaakov Bar-Shalom, K.R. Pattipati, P.K. Willett and T. Kirubarajan.

Graduate Students: A. Sinha (graduated), H. Chen (graduated), L. Lin, X. Lin, S. Yeom, X. Zhang, C. Gokberk (graduated).

# 5  Publications

*Published and/or accepted for publication during the report period*

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224.(J109) Y. Bar-Shalom, "Update with Out-of-Sequence Measurements in Tracking: Exact Solution", **IEEE Trans. Aerosp. Electronic Systems**, 38(3):, July 2002.

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236.  R. Niu, P. Willett and Y. Bar-Shalom, "Selection of the Radar Waveform from Tracking Considerations", **Proc. 2001 IEEE Radar Conf.**, Atlanta, GA, May 2001.

237.(J114) H. Chen, T. Kirubarajan and Y. Bar-Shalom, "Performance Limits of Track-to-Track Fusion vs. Centralized Estimation", **IEEE Trans. Aerosp. Electronic Systems**, 39(2):386–400, April 2003. Also presented at **4th ONR-GTRI Workshop on Tracking and Data Fusion**, Monterey, CA, May 2001. Also in **Proc. 4th Intn'l Conf. on Information Fusion**, pp. TUB1-25–TUB1-33, Montreal, QUE, August 2001.

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239.  M. Mallick, S. Coraluppi and Y. Bar-Shalom, "Comparison of Out-of-Sequence Measurement Algorithms in Multiplatform Target Tracking", **Proc. 4th Intn'l Conf. on Information Fusion**, pp. THB1-11–THB1-18, Montreal, QUE, August 2001.

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242.(J117) T. Kirubarajan, Y. Bar-Shalom, and D. Lerro, "Bearings-Only Tracking of Maneuvering Targets Using a Batch-Recursive Estimator", **IEEE Trans. Aerosp. Electronic Systems**, AES-37(3):770–780, July 2001.

243. Y. Bar-Shalom, M. Mallick, H. Chen and R. Washburn, "One-Step Solution for the General Out-of-Sequence Measurement Problem in Tracking", **Proc. 2002 IEEE Aerospace Conf.**, Big Sky, MT, March 2002.

244. X. Zhang, P. Willett and Y. Bar-Shalom, "Aspects of Measurement Scheduling in Tracking", **Proc. 2002 IEEE Aerospace Conf.**, Big Sky, MT, March 2002.

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250. L. Lin, T. Kirubarajan and Y. Bar-Shalom, "New Assignment Based Data Association for Tracking Move-Stop-Move Targets", **Proc. 5th Intn'l Conf. on Information Fusion**, Annapolis, MD, July 2002.

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254. M. Mallick and Y. Bar-Shalom, "Nonlinear Out-of-Sequence Measurement Filtering with Applications to GMTI Tracking", **Proc. SPIE Conf. Signal and Data Processing of Small Targets**, (Vol. 4728), Orlando, FL, April 2002.

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261. X. Zhang, P.K. Willett and Y. Bar-Shalom, "Monopulse Radar Detection and Localization of Multiple Targets via Joint Multiple Bin Processing", **Proc. 2003 IEEE Radar Conf.**, Huntsville, AL, May 2003.

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265. X. D. Lin, Y. Bar-Shalom and T. Kirubarajan, "Exact Multisensor Dynamic Bias Estimation with Local Tracks", **Proc. 6th Intn'l Conf. on Information Fusion**, Cairns, Australia, July 2003.

266. X. Zhang, P. K. Willett and Y. Bar-Shalom, "Target Intervisibility", **Proc. SPIE Conf. Signal and Data Processing of Small Targets** San Diego, CA, August 2003.

267. Y. Bar-Shalom, T. Kirubarajan, and C. Gokberk, "Tracking with Classification-Aided Multiframe Data Association", **Proc. Workshop on Multiple Hypothesis Tracking: A Tribute to Sam Blackman** , San Diego, CA, May 2003. Also in **Proc. SPIE Conf. Signal and Data Processing of Small Targets** San Diego, CA, August 2003.

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271. H. Chen, K.R. Pattipati, T. Kirubarajan and Y. Bar-Shalom, "General Data Association with Possibly Unresolved Measurements Using Linear Programming", **Proc. Workshop on Multiobject Tracking, Madison, WI, June 2003.**

272. L. Lin, T. Kirubarajan and Y. Bar-Shalom, "Identifying a Proportional Navigation Guidance Pursuer Using Angle-Only Measurements from an Evader", **Proc. SPIE Conf. Signal and Data Processing of Small Targets** San Diego, CA, August 2003.

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### Ph.D. dissertations

18. Huimin Chen, "Performance Evaluation for Multitarget Tracking Algorithms", April 2002. Postdoctoral fellow at Carnegie-Mellon Univ.

19. Abhijit Sinha, "Signal Processing and Tracking for Unresolved Targets", July 2002. Postdoctoral fellow at UConn.

# 6   Interactions/Transitions

An in-house course (5 days) was given at NUWC, Newport, RI in April-May 2002.

The PI gave his IEEE AES Distinguished Lecture at Raytheon, Portsmouth, RI in June 2002.

Northrop-Grumman (Bethpage, NY) implemented our debiasing procedure for polar-to-Cartesian measurement conversion in the Navy E-2C AEW (Airborne Early Warning) system.

Northrop-Grumman is using one of our assignment algorithms for passive target localization from ESM (Electronic Support Measures) sensors.

The next generation air-to-ground surveillance systems from UAV (unmanned aerial vehicles), under development by DARPA, will use the VS-IMM (variable structure IMM) tracker developed in a recent Ph.D. dissertation at UConn.

Our image feature (target centroid) extraction and tracking algorithm has been implemented in the ARROW ABM (Antiballistic Missile) sponsored by BMDO (Ballistic Missile Defense Organization, now MDA). This system has reached operational capability.

ETC (Mystic, CT) implemented our algorithm for tracking a low SNR (Signal to Noise Ratio) maneuvering target with an active sonar. This has been transitioned to the USN Fleet.

Raytheon (Bedford, MA) has implemented a JPDA (Joint Probabilistic Data Association) tracker for their ASDE-X (Airport Surface Detection Equipment), ROTHR (Relocatable Over the Horizon Radar), GBR-P (Ground Based Radar Prototype for National Missile Defense) and in the THAAD (Theater High Altitude Antiballistic Defense).

The new Air Traffic Control tracking algorithm Raytheon developed for the FAA (as well as export) is based on the IMM estimator.

The French Navy is using the LO (Low Observable — low SNR) passive track detector named "The Magician", based on our ML-PDA algorithm, from extremely weak target signals.

BAE Systems (Nashua, NH) is using our ML-PDA algorithm for passive tracking for the Electronic Warfare system of the JSF (F-35).

ORINCON (San Diego, CA) adopted the VS-IMM for the next generation GMTI tracker.

Alphatech (Burlington, MA) adopted our tracker with out-of-sequence measurements for the GMTI tracker.

QinetiQ (formerly DERA, UK) developed an optimal passive sensor deployment policy for low SNR target tracking based on joint work with us, relying on our "information reduction factor" for a cluttered environment; They also used our unbiased conversion of radar measurements from sensor coordinates to Cartesian for enhanced accuracy tracking.

In Australia, the two new OTH radars in the Jindalee system (developed under the supervision of DSTO) are using the IMMPDAF as their tracking algorithm. The original Jindalee radar (at Alice Springs) developed by DSTO continues to operate successfully with a PDAF tracker.

# 7 New discoveries, inventions or patent disclosures

None

# 8 Honors/Awards

Yaakov Bar-Shalom:

- Fellow of IEEE

- Distinguished Lecturer of IEEE AES Society

- Member of the Connecticut Academy of Science and Engineering (2002)

- The PI has been appointed as Board of Trustees Distinguished Professor at UConn (2002).

- Reelected President of International Society of Information Fusion (ISIF) for 2002.

Keynote/Plenary Talks or IEEE Distinguished Lectures
K4. "Target Tracking and Fusion: How to Get the Most Out of Your Sensors", Keynote Talk at the **National Fusion Symposium**, San Diego, CA, June 2001.

K5. "Target Tracking and Data Fusion: How to Get the Most Out of Your Sensors", Plenary Talk at the **15th IFAC Symp. on Automatic Control in Space**, Bologna, Italy, Sept. 2001.

K6. "Target Tracking and Data Fusion: How to Get the Most Out of Your Sensors", NATO Lecture given to the Turkish Navy Res. Ctr., Sept. 2002.

K7. "Data Fusion in Tracking: Architectures and Performance", Plenary Talk at the **6th Intn'l Conf. on Information Fusion**, Cairns, Australia, July 2003.

K8. "Target Tracking and Data Fusion: How to Get the Most Out of Your Sensors", Keynote Talk at the **International Radar Symposium India**, Bangalore, India, Dec. 2003.

K.R. Pattipati:

- Fellow of IEEE

- Editor-in-Chief of IEEE Trans. on SMC

P.K. Willett:

- Fellow of IEEE

- Associate Editor of IEEE Trans. on AES