Assessment of Precision Guided Munition Terminal Accuracy Using Wide Area Differential GPS and Projected MEMS IMU Technology

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Demonstrate That a Set of Candidate Precision Guided Munitions (PGMs), Using Wide Area Differential GPS (WADGPS), Can Navigate and Guide to a Designated Target Location and Achieve Impact Errors on the Order of 1 Meter CEP.
Background

• Previous Investigations as Part of ONR’s Precision Tactical Targeting Program* Have Verified That a WADGPS/UAV Targeting System Can Achieve Target Location Errors (TLEs) of 1 Meter CEP Per Km of Standoff Range. Projected Extensions of This Technology Should Enable TLEs of One-tenth this Value

• A Closely Related Question is Whether PGMs, Also Using WADGPS, Can Achieve Impact Errors Against Designated Targets On the Order of 1 Meter CEP

• Combined Performance Would Allow PGMs to Physically Strike Many Naval Fire Support Targets

* Dr. Allan Evans and Dr. George Rogers of NSWC/Dahlgren are The Principal Investigators for Precision Tactical Targeting
• Successful Demonstration of 1 Meter CEP Accuracy for WADGPS-Guided PGMs, is a Precursor for Future Work in Which the Accuracy of the Integrated Targeting and Weapon System Will be Demonstrated.

• Secondary Objective is to Determine the Accuracy Drivers for the Targeting and PGM Systems, and to Define Affordable Design Changes that Allow 1 Meter CEP Errors on Target to be Achieved
Approach

• Use Detailed GPS Receiver and Satellite Models, Modified to Reflect Various WADGPS System Errors
• Consider Several Levels of WADGPS Accuracy, PGM Receiver Quality and IMU Quality
• Use Current ERGM Airframe Characteristics as Test Bed. Evaluate for Short, Medium, and Long Range Trajectories
• Evaluate Navigation Performance Using Detailed Model of Tightly Couples, GPS-Aided Navigation System (NAVSIM). NAVSIM is Legacy Model Successfully Utilized on Several Navy Development Programs
• Compute CEPs on Target for Various Ranges
• Use Existing Anti-Jam (AJ) Model to Assess PGM Impact Errors in Presence of Anticipated Jamming Levels
• Demonstrate that AJ Allows Graceful Degradation of CEPs in Jamming to Under a Few Meters
Candidate Airframe: Extended Range Guided Munition

- Long Range, GPS-Aided Precision Guided Munition
- Gun-Launched From Naval Warships to Provide Surface Fire Support
- Tightly-Coupled GPS/INS Navigation System
- Incorporates Advanced Anti-Jam Technology
- Allows Accurate Delivery of Submunition or Unitary Payloads on Target
- Under Development by Raytheon/TI Systems
- Naval Surface Warfare Center/Dahlgren is Technical Monitor
ERGM Trajectories

Precision Navigation & Timing

Altitude (kft) vs. Downtrack Position (nm)
GPS/INS Monte Carlo Navigation Simulation
GPS Receiver Model

- Tightly-Coupled 12-Channel Capability (All in View)
- Clock Bias, Drift, Aging; Pseudo Range, Δ-Range Noise
- Orbital Perturbation Model
- Independent $C/N_0$ Per Channel
- GPS Patch Antenna Gain Pattern (Body-fixed)
- Dynamic Modeling @ 10 Hz, Update @ 1 Hz
- Multiple Jammer Array (CW, Broadband)
- GPS Tracking Status (Each Channel)
- Dynamic Satellite Selection Capability
- Provision for Aiding Receiver Dynamics by INS
GPS/INS Navigation
Kalman Filter

- Tightly-Coupled GPS/INS Implementation
- Formulated in WGS-84 ECEF
- Propagate @ 10 Hz, Update @ 1 Hz
- Error States (17)
  - Position (3)
  - Velocity (3)
  - Attitude (3)
  - Accelerometer Bias (3)
  - Gyro Drift (3)
  - Clock Bias & Drift (2)
- Measurements
  - Pseudo Range (8)
  - Delta Range (8)
  - IMU ΔV, Δθ
- Dynamic Calibration of IMU Biases and Receiver Clock Errors
Tightly Coupled GPS/INS Implementation
Anti-Jam Modeling
ERGM Antenna Array

- GPS ANTENNAS (TOP & BOTTOM)
- HOJ ANTENNA
Interference Cancellation Concept

Canceller Gain:
\[ G_C = -\frac{G_S(f_c)}{G_J(f_c)} \]

GPS Interference Cancellation System
Antenna Geometry
(J/S)_{TOTAL} With and Without Jammer Cancellation

40 NM Trajectory

Total (J/S) Without Interference Cancellation

Total (J/S) With Active Interference Cancellation
Error Budgets
Error Budgets

- Assumed Three Time-Phased Evolutions of WADGPS, Receiver & IMU Technology for Applications to Precision Guided Munitions:
  
  - CASE (1) Current Single Frequency Receiver with GPS Absolute Positioning & Current IMU (Reflects Current ERGM System)
  
  - CASE (2) Future Single Frequency Receiver with WADGPS Aiding & Near Term MEMS IMU
  
  - CASE (3) Future Dual Frequency Receiver with WADGPS Aiding & Far Term MEMS IMU

Note: Cases (2) and (3) Do Not Represent Capabilities of Current ERGM System (They are Considerably Better)
Error Budget Sources

- Near and Far Term Projections for MEMS IMU Errors Obtained from U.S. Army and DARPA Sources ♣♣

- Error Projections Consolidated Into Composite Near and Far Term Error Sets for Current Analysis

- Near & Far Term WADGPS Error Budgets Based on NSWCDD Compilation from Industry & Government Surveys ♥♥

♣♣ Vicki Lefevre, U.S. Army Aviation and Missile Research and Development Command, Redstone Arsenal, AL, personal communications, 29 May, 2001

Lt Col Greg Vansuch, DARPA/SPO, personal communications, 10 May, 2001

Micro Electro Mechanical Systems (MEMS) Inertial Measurement Unit
Near & Far Term Error Budget Estimates

(3-σ Value, per axis)

<table>
<thead>
<tr>
<th>Error</th>
<th>Current ERGM BAE IMU</th>
<th>Postulated Future MEMS Assumed in Reference [1]</th>
<th>Near Term Army MEMS</th>
<th>Far-Term Army MEMS</th>
<th>DARPA Target Goal MEMS</th>
<th>Composite Near Term MEMS</th>
<th>Composite Far Term MEMS</th>
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<tbody>
<tr>
<td>Gyro Drift (deg/hr)</td>
<td>(A) 300</td>
<td>(B) 300</td>
<td>(C) 60</td>
<td>(D) 3</td>
<td>(E) 3</td>
<td>(F) 60</td>
<td>(G) 3</td>
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<td>Gyro Scale Factor (ppm)</td>
<td>1200</td>
<td>1200</td>
<td>1050</td>
<td>300</td>
<td>600</td>
<td>1000</td>
<td>300</td>
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<td>Gyro Random Walk (deg/rt-hr)</td>
<td>0.6</td>
<td>0.06</td>
<td>0.9</td>
<td>0.36</td>
<td>0.3</td>
<td>0.6</td>
<td>0.3</td>
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<td>Gyro Misalignment (mrad)</td>
<td>1.2</td>
<td>1.2</td>
<td>2.1</td>
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<td>0.6</td>
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<td>Gyro G-Sensitivity (deg/hr/g)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1.5</td>
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<td>3</td>
<td>1.5</td>
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<td>Gyro G²-Sensitivity (deg/hr/g²)</td>
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<td>not specified</td>
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<td>Gyro Noise (deg/sec)</td>
<td>1.5</td>
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<td>not specified</td>
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<td>.75</td>
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<td>Accelerometer Bias (mg)</td>
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<td>15</td>
<td>12</td>
<td>3</td>
<td>1.5</td>
<td>12</td>
<td>2</td>
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<td>Accelerometer Scale Factor (ppm)</td>
<td>1200</td>
<td>1200</td>
<td>2100</td>
<td>900</td>
<td>900</td>
<td>1200</td>
<td>900</td>
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<tr>
<td>Accelerometer Random Walk (m/s)/√hr</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.15</td>
<td>0.3</td>
<td>0.36</td>
<td>0.15</td>
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<tr>
<td>Accelerometer Noise (mg)</td>
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</table>

Table 1. Near Term and Far Term MEMS IMU Error Estimates
## Assumed Current and WADGPS-Aided Navigation Errors

<table>
<thead>
<tr>
<th>Modeled Error Parameter</th>
<th>Current Single-Frequency Receiver (Absolute Positioning)</th>
<th>Future Single-Frequency WADGPS-aided Receiver</th>
<th>Future Dual-Frequency WADGPS-aided Receiver</th>
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<tbody>
<tr>
<td><strong>SV Clock and Group Delay Errors</strong></td>
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<tr>
<td>Range Bias (m)</td>
<td>2.0</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Delta Range Bias (m)</td>
<td>0.005</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td><strong>Ephemeris Errors</strong></td>
<td></td>
<td></td>
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<tr>
<td>Radial (m)</td>
<td>2.0</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td>Crosstrack (m)</td>
<td>6.0</td>
<td>0.3</td>
<td>0.3</td>
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<tr>
<td>Alongtrack (m)</td>
<td>10.0</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Effective User Range Error (m)</td>
<td>5.0</td>
<td>0.1</td>
<td>0.1</td>
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<tr>
<td><strong>PGM Receiver Errors</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Range Noise Including Multipath (m)</td>
<td>1.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Delta Range Noise Including Multipath (m)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
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<tr>
<td><strong>Atmospheric Delay Errors</strong></td>
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<tr>
<td>Residual Ionosphere (m)</td>
<td>5</td>
<td>0.6</td>
<td>0.3</td>
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<tr>
<td>Residual Troposphere (m)</td>
<td>2</td>
<td>0.5</td>
<td>0.5</td>
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<tr>
<td>Residual Ionosphere (% of Klobuchar model)</td>
<td>30</td>
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<td>1</td>
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<tr>
<td>Residual Troposphere (% of Altshuler model)</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Inertial Measurement Unit Errors</strong></td>
<td>Current ERGM IMU (British Aerospace)</td>
<td>Future IMU (Draper MEMS)</td>
<td>Future IMU (Draper MEMS)</td>
</tr>
<tr>
<td></td>
<td>(2) GPS JPO User Equipment UERE Budget, 1991</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(3) B. Remondi, Private Communication, April 2001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Precision Navigation 6-DOF Flight Simulation
Noise and Error Sources

- Launch Angle Variation (Pitch, Yaw, and Roll)
- Launch Velocity Variation (Linear and Angular)
- Initial Tip Off Rates
- IMU Activation Delay Variation
- Accelerometer Errors
- Rate Gyro Errors
- INS Initialization Errors
- Motor Ignition Delay Variation
- Thrust Variations (Burn Time, Total Impulse)
- Thrust Misalignments
- Moment of Inertia Variations
- Atmospheric Variations
- Random Wind Model
- Aerodynamic Coefficient Uncertainty Model
- GPS Satellite Orbital Errors
- GPS Measurement Errors
- GPS Receiver Clock Bias and Drift
- GPS Random Time of Day at Launch
Preliminary Performance Results
PROJECTED ERGM WADGPS-AIDED NAVIGATION PERFORMANCE

NO TARGET LOCATION ERRORS • NO JAMMING

Case 1:
Current ERGM

Case 2:
Near Term MEMS
IMU + Single Freq.
WADGPS RCVR

Case 3:
Far Term MEMS
IMU + Dual Freq.
WADGPS RCVR

CEP VERSUS TARGET RANGE
PROJECTED ERGM WADGPS-AIDED NAVIGATION PERFORMANCE

NO TARGET LOCATION ERROR • SPEC JAMMING LEVELS AT TARGET ERGM ANTI-JAM ACTIVE

Case 1: Current ERGM

Case 2: Near Term MEMS IMU + Single Freq. WADGPS RCVR

Case 3: Far Term MEMS IMU + Dual Freq. WADGPS RCVR

CEP VERSUS TARGET RANGE
Precision Navigation & Timing
ERGM Performance - Clear Air - 40 nmi Trajectory

CUMULATIVE MISS DISTANCE DISTRIBUTION — 40 NM RANGE

NO JAMMING
CUMULATIVE MISS DISTANCE DISTRIBUTION — 40 NM RANGE

ERGM SPEC JAMMING • AJ SYSTEM ACTIVE

Precision Navigation & Timing
ERGM Spec Jamming Conditions - 40 nmi Trajectory

Cumulative Probability - (%)
Miss Distance - (m)
Summary


• Demonstrated Feasibility of Achieving PGM Positional Accuracies on Target Between 1-2 Meters CEP Out to 40 Nm in GPS Jamming.

• Performance Was Achieved By Using a Future Wide Area Differential GPS System, in Combination with Future Advanced Receiver and IMU Systems.

• Study Assumed Precise Target Location Information Based on Results from Navy’s Precision Tactical Targeting Program.

• Showed That an ERGM-Like Anti-Jam System Allows 1-2 Meter Accuracy to be Achieved in Presence of ERGM Broadband and CW Spec Jamming Levels at Target.

• Used Extended Range Guided Munition (ERGM) as Test Airframe for Initial WADGPS Evaluation. Future Efforts Will Consider a Range of Advanced PGM Concepts.

• Work Is Ongoing to Determine Accuracy Drivers for PGM Sub-Meter Positional Accuracy.