Office of Naval Research
Naval Fire Support Program

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

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Dahlgren, Virginia

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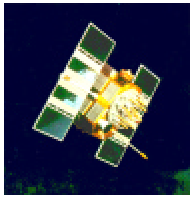
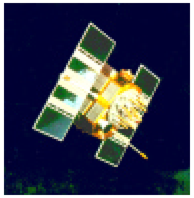
Acknowledgement



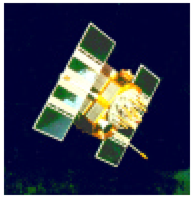
This Work was Performed as Part of the Naval Fire Support Project, Managed by Mr. S. Roger Horman (NSWCDD, T406). NFS is Funded by the Office of Naval Research's Air and Surface Weapons Technology Program. The ASWT Program is Managed by Mr. Gil Y. Graff (ONR 351).

What is this About?



- 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

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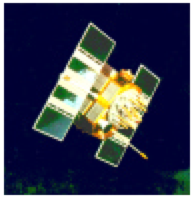
* Dr. Allan Evans and Dr. George Rogers of NSWC/Dahlgren are The Principal Investigators for Precision Tactical Targeting

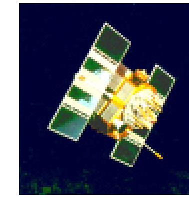
Background (Continued)



- **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**

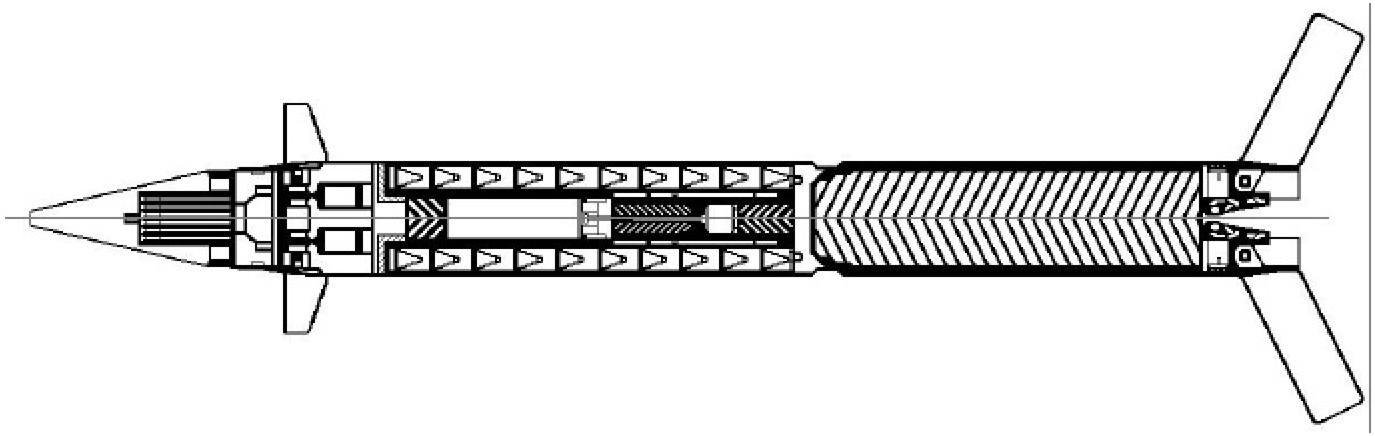
Approach



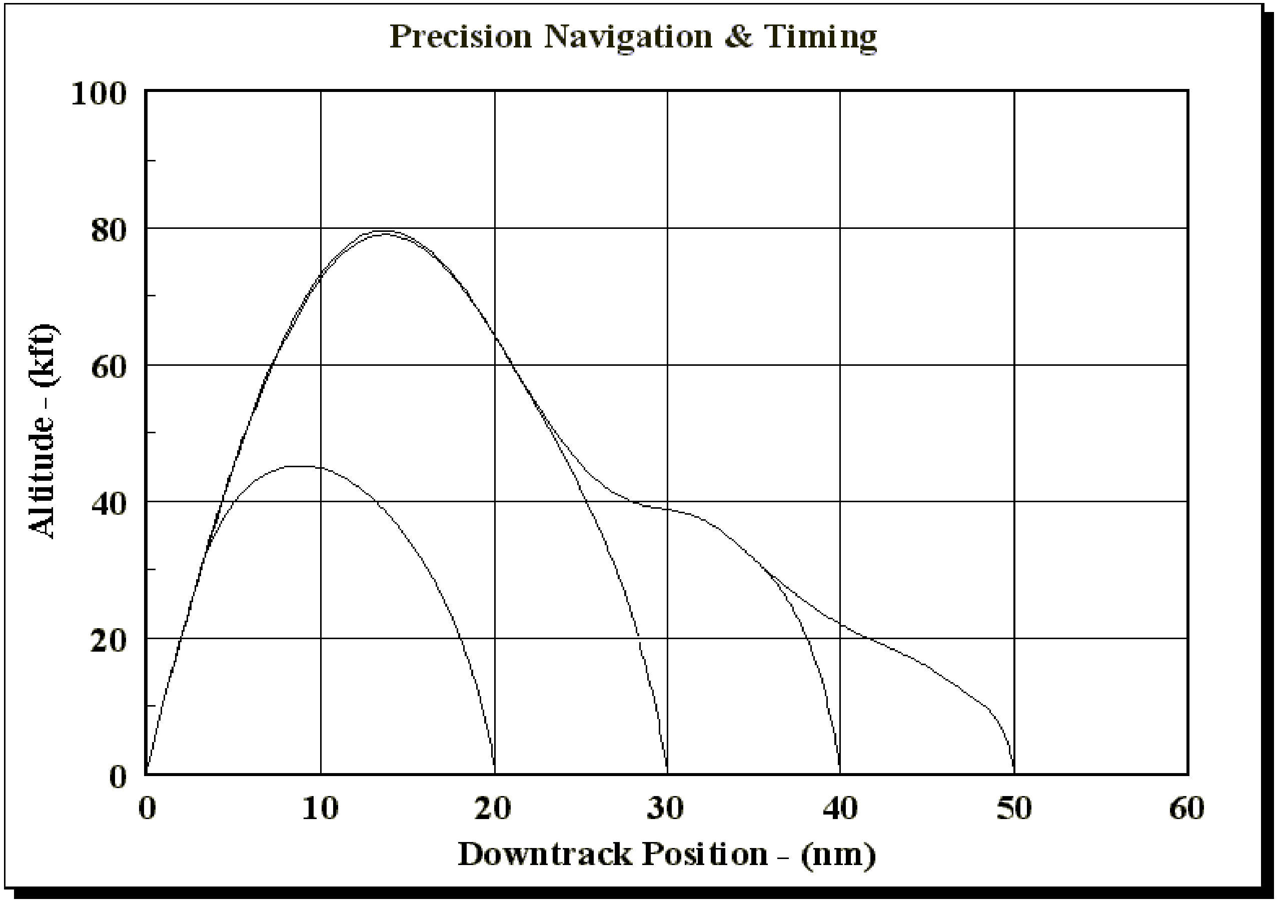
- Use Detailed GPS Receiver and Satellite Models, Modified to Reflect Various WADGPS System Errors
- Consider Several Levels of WADGPS Accuracy, PGM Receiver Quality and IMU Quality
- Use Current ERGM Airframe Characteristics as Test Bed. Evaluate for Short, Medium, and Long Range Trajectories
- Evaluate 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

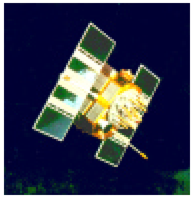
Candidate Airframe: Extended Range Guided Munition

- **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**



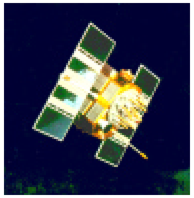
ERGM Trajectories





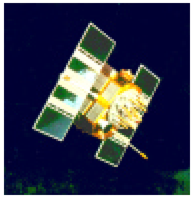
GPS/INS Monte Carlo Navigation Simulation

GPS Receiver Model



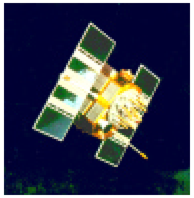
- **Tightly-Coupled 12-Channel Capability (All in View)**
- **Clock Bias, Drift, Aging; Pseudo Range, D-Range Noise**
- **Orbital Perturbation Model**
- **Independent C/N_O Per Channel**
- **GPS Patch Antenna Gain Pattern (Body-fixed)**
- **Dynamic Modeling @ 10 Hz, Update @ 1 Hz**
- **Multiple Jammer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

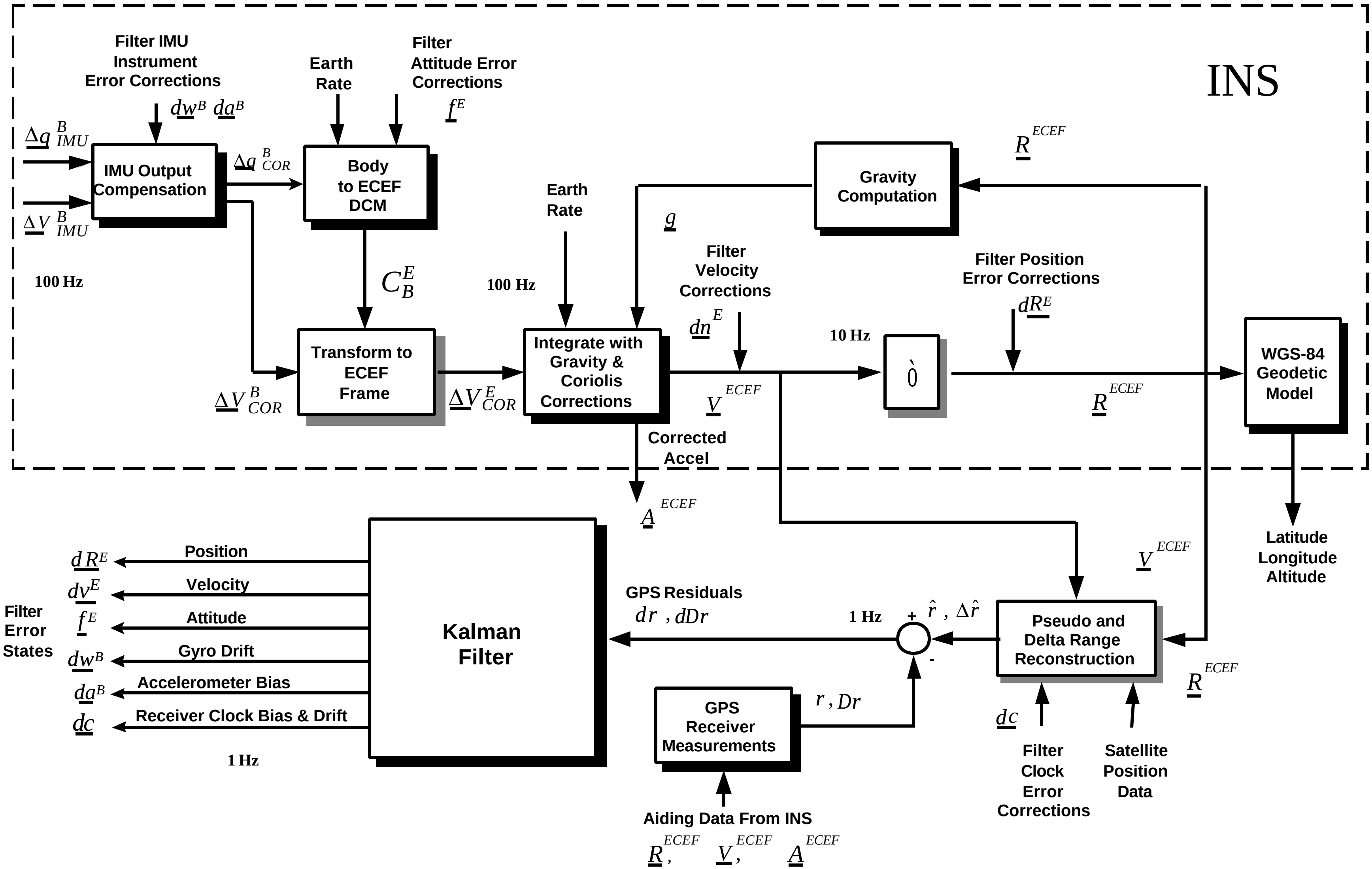
GPS/INS Navigation
Kalman Filter

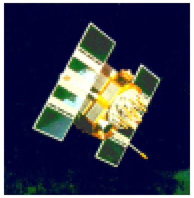


- **Tightly-Coupled GPS/INS Implementation**
- **Formulated in WGS-84 ECEF**
- **Propagate @ 10 Hz, Update @ 1 Hz**
- **Error States (17)**
  - **Position (3)**
  - **Velocity (3)**
  - **Attitude (3)**
  - **Accelerometer Bias (3)**
  - **Gyro Drift (3)**
  - **Clock Bias & Drift (2)**
- **Measurements**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

Tightly Coupled GPS/INS Implementation

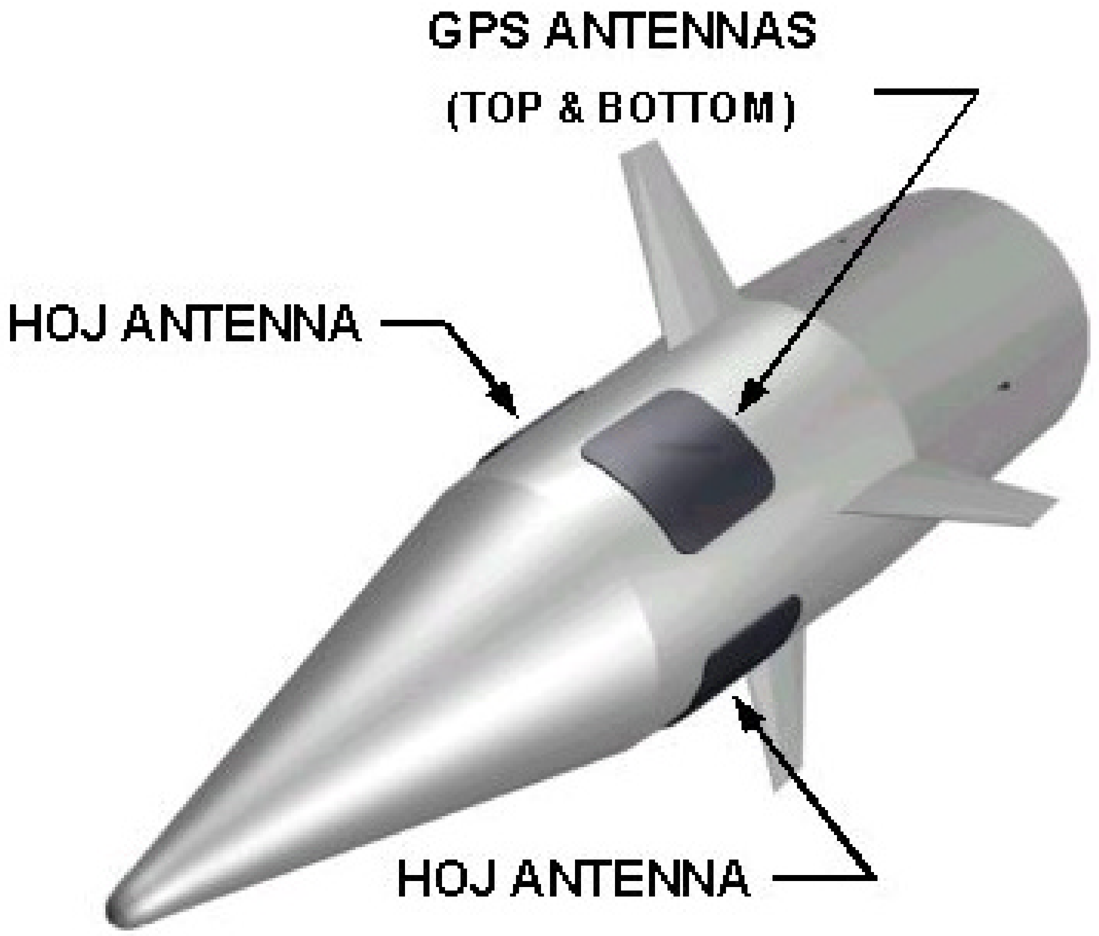




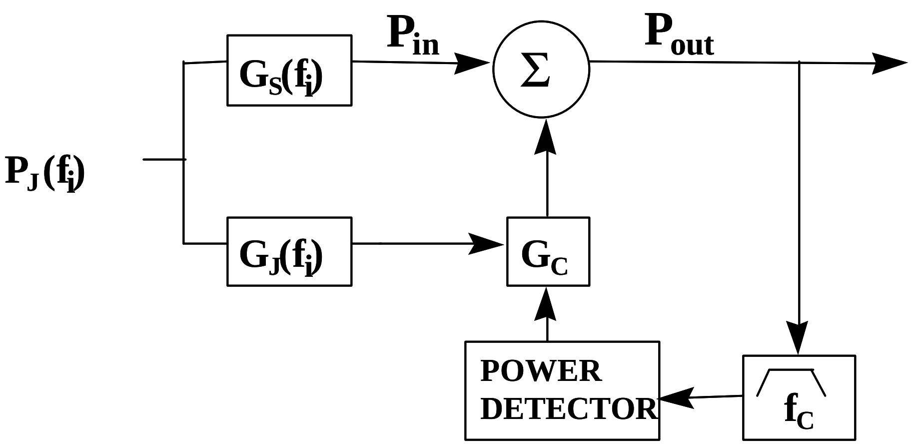


Anti-Jam Modeling

ERGM Antenna Array



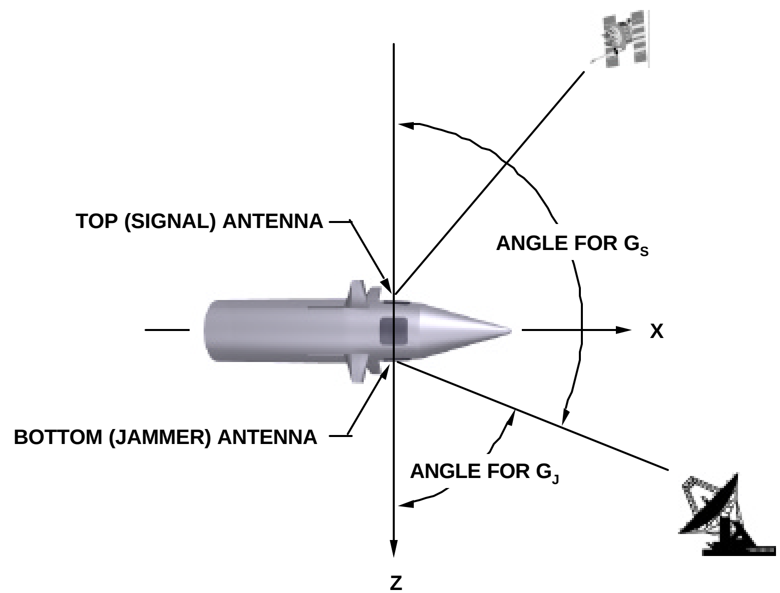
Interference Cancellation Concept



- Canceller Gain:

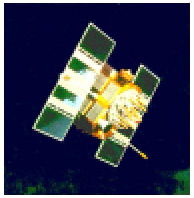
$$G_C = -G_S(f_c)/G_J(f_c)$$

Canceller Block Diagram

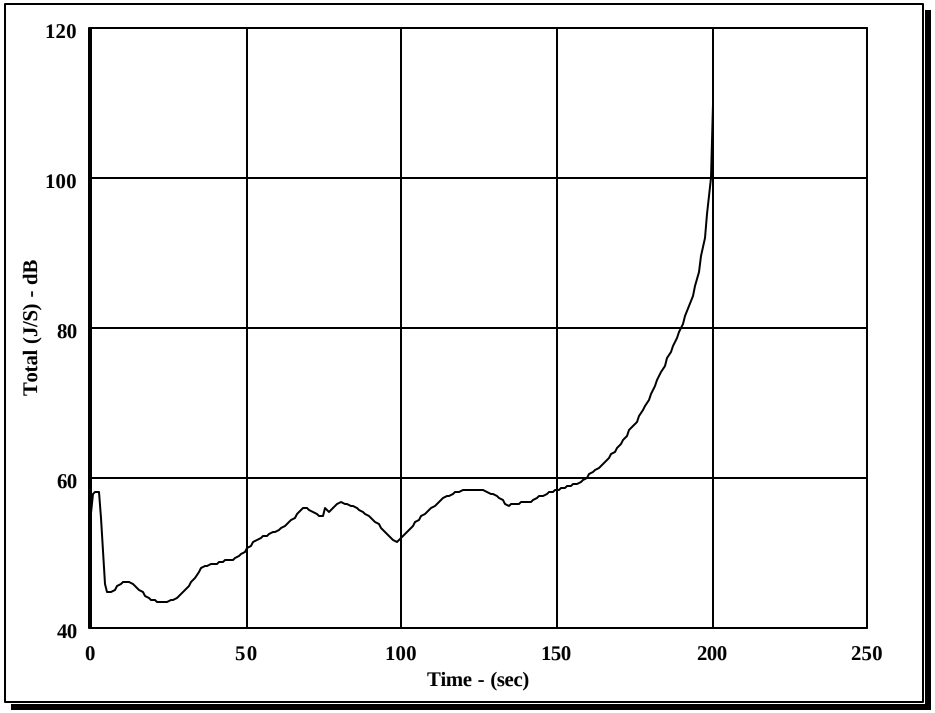


GPS Interference Cancellation System Antenna Geometry

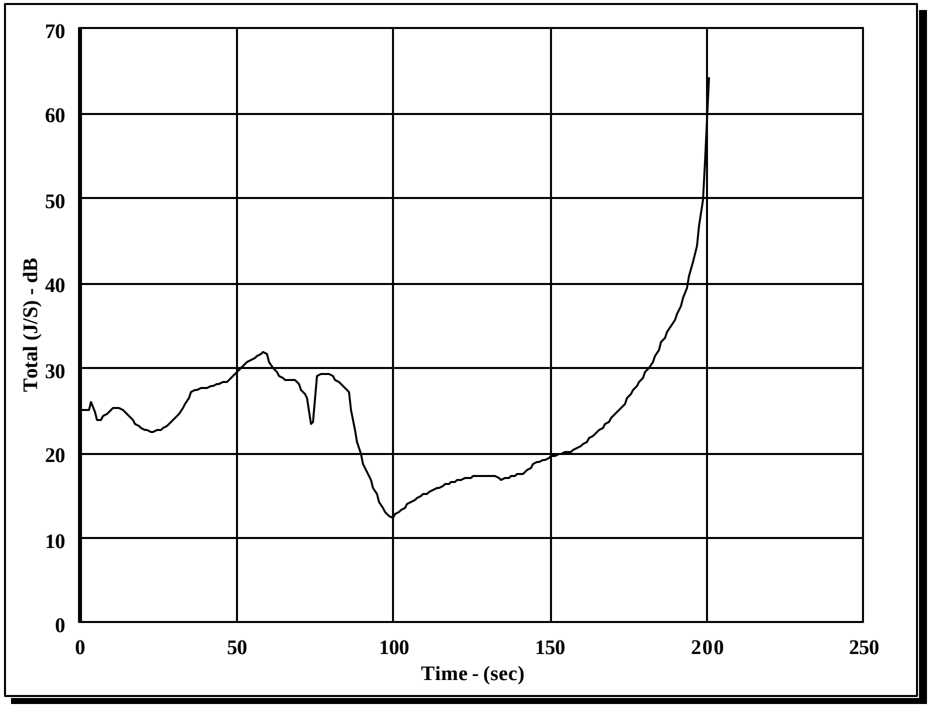
$(J/S)_{TOTAL}$ With and Without Jammer Cancellation



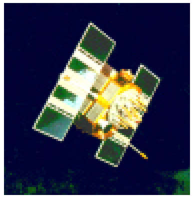
40 NM Trajectory



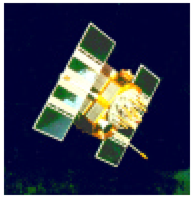
Total (J/S) Without Interference Cancellation



Total (J/S) With Active Interference Cancellation



Error Budgets

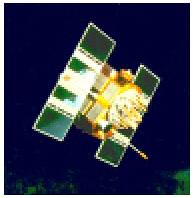


Error Budgets

- **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

♥♥ B. Larry Miller, Alan G. Evans, "NAVSIM Analysis of Future Missile Navigation Using WADGPS-Aided Receivers, NSWCDD Internal Memo, May 1, 2001

ASSUMED MEMS IMU NEAR & FAR TERM ERROR BUDGETS

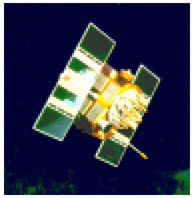
Micro Electro Mechanical Systems (MEMS) Inertial Measurement Unit
Near & Far Term Error Budget Estimates

(3-σ Value, per axis)

Error	Current ERGM BAE IMU	Postulated Future MEMS Assumed in Reference [1]	Near Term Army MEMS	Far-Term Army MEMS	DARPA Target Goal MEMS	Composite Near Term MEMS	Composite Far Term MEMS
	(A)	**(B)**	**(C)**	**(D)**	**(E)**	**(F)**	**(G)**
Gyro Drift (deg/hr)	300	300	60	3	3	60	3
Gyro Scale Factor (ppm)	1200	1200	1050	300	600	1000	300
Gyro Random Walk (deg/rt-hr)	0.6	0.06	0.9	0.36	0.3	0.6	0.3
Gyro Misalignment (mrad)	1.2	1.2	2.1	0.6	not specified	1.2	0.6
Gyro G-Sensitivity (deg/hr/g)	3	3	3	1.5	not specified	3	1.5
Gyro G^2-Sensitivity (deg/hr/g^2)	0.9	0.9	not specified	not specified	not specified	0.9	0.9
Gyro Noise (deg/sec)	1.5	1.5	not specified	not specified	not specified	1.5	.75
Accelerometer Bias (mg)	15	15	12	3	1.5	12	2
Accelerometer Scale Factor (ppm)	1200	1200	2100	900	900	1200	900
Accelerometer Random Walk (m/s)/√hr	0.36	0.36	0.36	0.15	0.3	0.36	0.15
Accelerometer Noise (mg)	15	3	not specified	not specified	not specified	15	7.5
Accelerometer Misalignment (mrad)	1.2	1.2	1.8	0.6	not specified	1.2	0.6

Table 1. Near Term and Far Term MEMS IMU Error Estimates

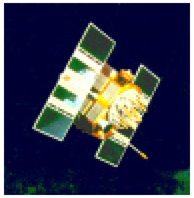
Assumed Current and WADGPS-Aided Navigation Errors



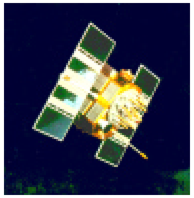
Modeled Error Parameter	Current Single-Frequency Receiver (Absolute Positioning)	Future Single-Frequency WADGPS-aided Receiver	Future Dual-Frequency WADGPS-aided Receiver
SV Clock and Group Delay Errors			
Range Bias (m)	2.0	0.1	0.1
Delta Range Bias (m)	0.005	0.001	0.001
Ephemeris Errors			
Radial (m)	2.0	0.1	0.1
Crosstrack (m)	6.0	0.3	0.3
Alongtrack (m)	10.0	0.5	0.5
Effective User Range Error (m)	5.0	0.1	0.1
PGM Receiver Errors			
Range Noise Including Multipath (m)	1.5	1.0	1.0
Delta Range Noise Including Multipath (m)	0.02	0.02	0.02
Atmospheric Delay Errors			
Residual Ionosphere (m)	5	0.6	0.3
Residual Troposphere (m)	2	0.5	0.5
Residual Ionosphere (% of Klobuchar model)	30	3	1
Residual Troposphere (% of Altshuler model)	10	5	5
Inertial Measurement Unit Errors	Current ERGM IMU (British Aerospace)	Future IMU (Draper MEMS)	Future IMU (Draper MEMS)

Sources: (1) K. Kovach, "New User Equivalent Range Error (UERE) Budget for the Modernized Navstar Global Positioning System (GPS)," ION Tech. Mtg., Jan 2000.
(2) GPS JPO User Equipment UERE Budget, 1991
(3) B. Remondi, Private Communication, April 2001

Precision Navigation 6-DOF Flight Simulation Noise and Error Sources



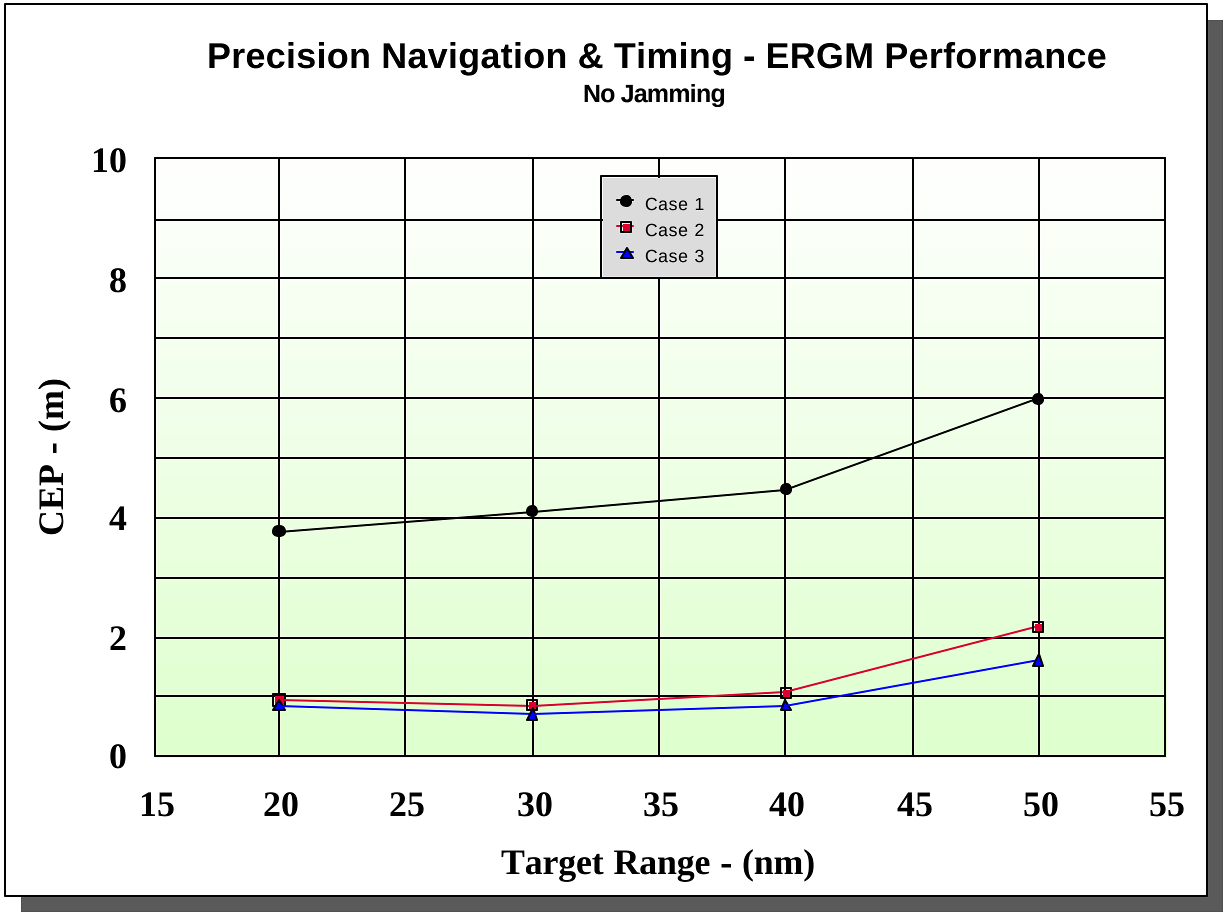
- Launch Angle Variation (Pitch, Yaw, and Roll)
- Launch Velocity Variation (Linear and Angular)
- Initial Tip Off Rates
- IMU Activation Delay Variation
- Accelerometer Errors
- Rate Gyro Errors
- INS Initialization Errors
- Motor Ignition Delay Variation
- Thrust Variations (Burn Time, Total Impulse)
- 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



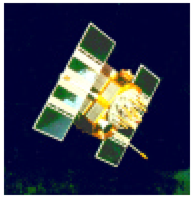
Case 1:
Current ERGM

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

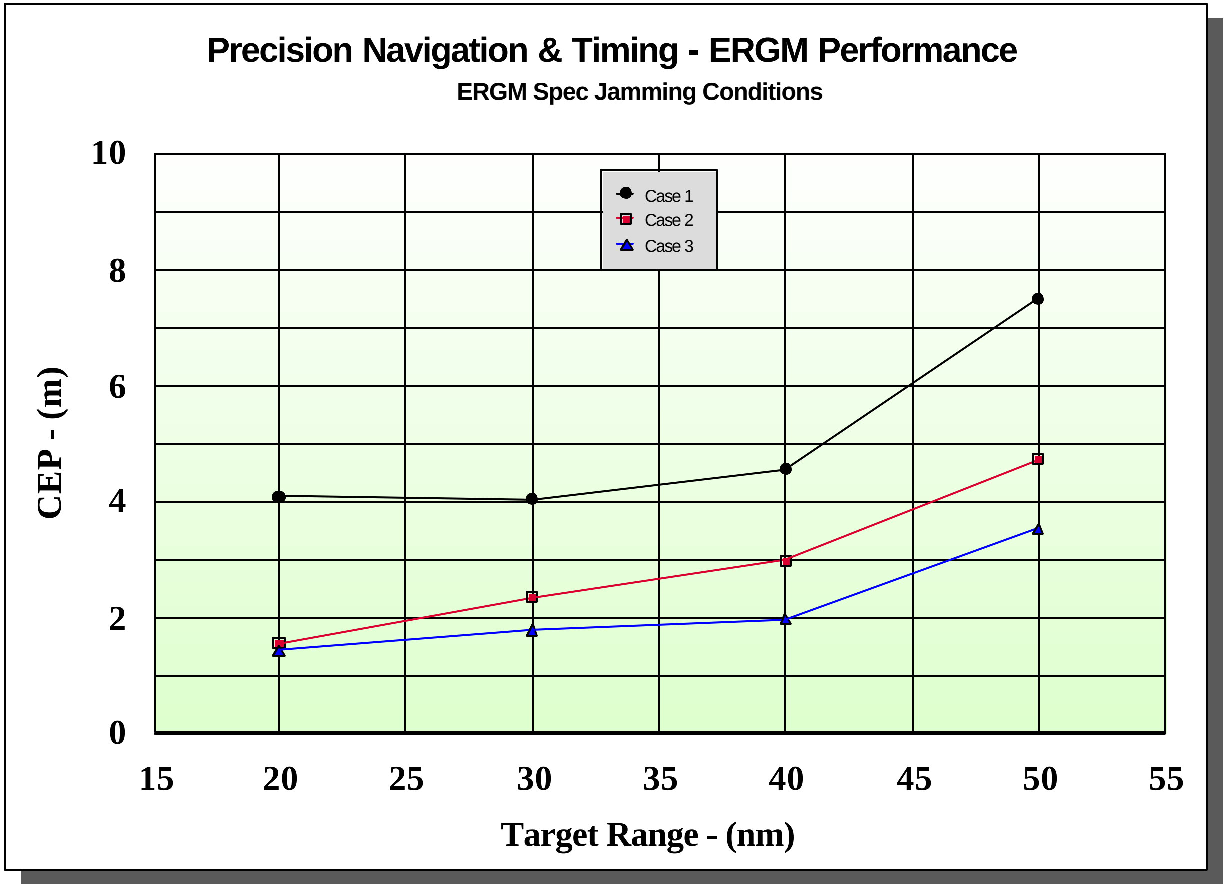
Case 3:
Far Term MEMS IMU + Dual Freq. WADGPS RCVR

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

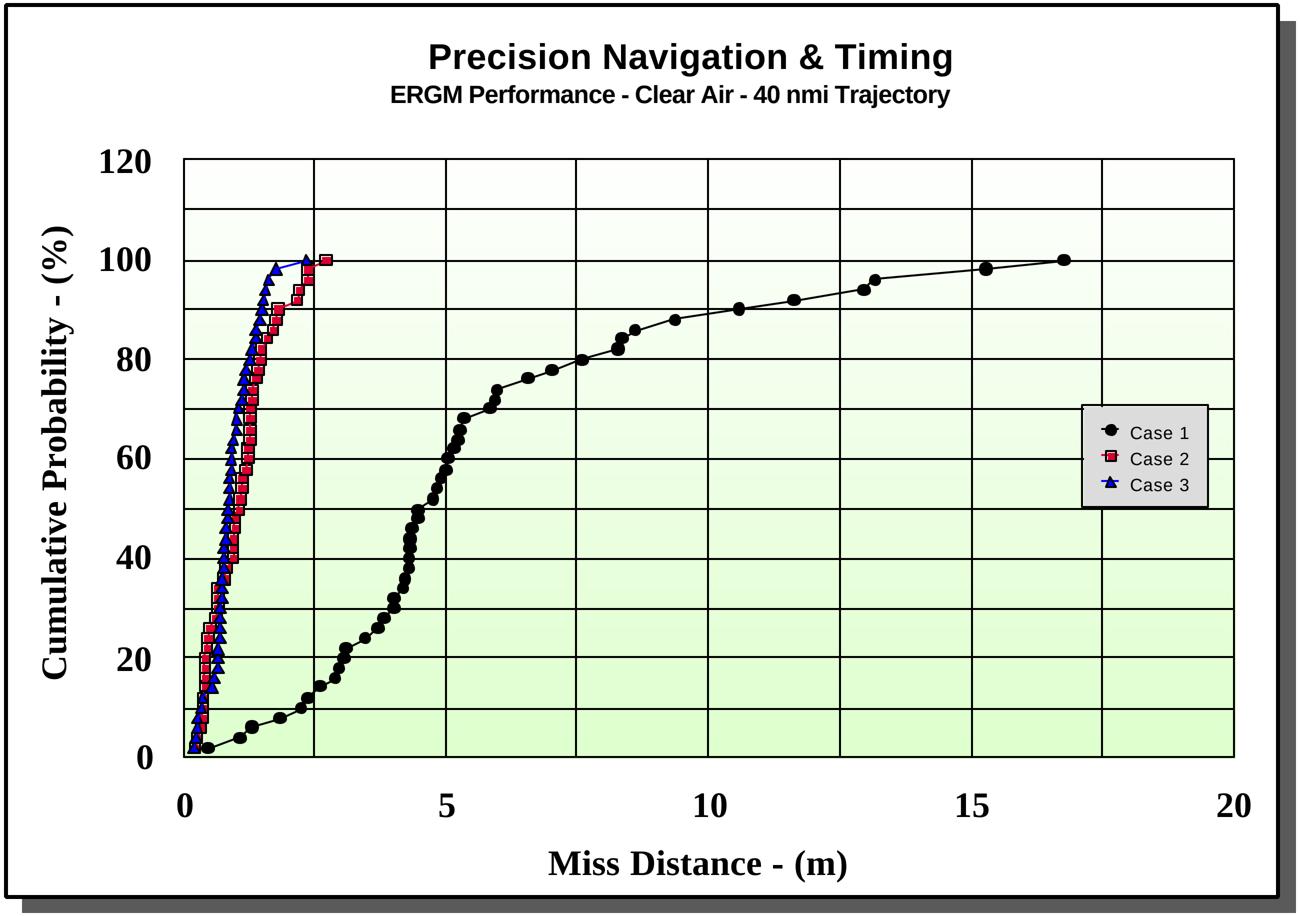
Case 2:
Near Term MEMS IMU + Single Freq. WADGPS RCVR

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

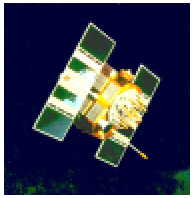
CEP VERSUS TARGET RANGE

CUMULATIVE MISS DISTANCE DISTRIBUTION — 40 NM RANGE

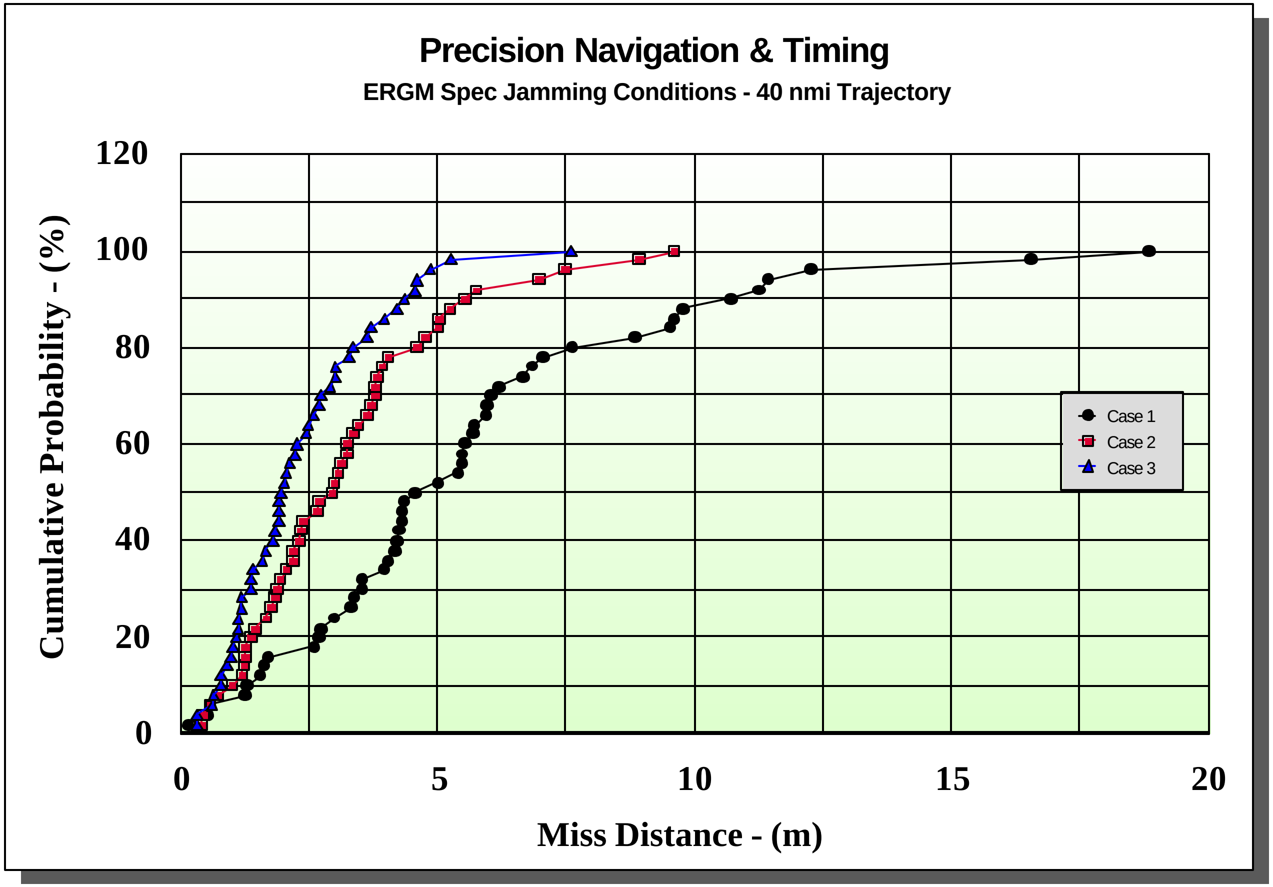
NO JAMMING



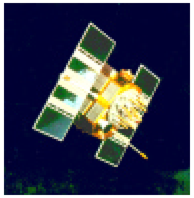
CUMULATIVE MISS DISTANCE DISTRIBUTION — 40 NM RANGE



ERGM SPEC JAMMING • AJ SYSTEM ACTIVE



Summary



- Closed Loop GPS-Aided Navigation and Guidance of a Precision Guided Munition (PGM) Was Evaluated for a Range of Current and Projected GPS/IMU Technologies.
- 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.