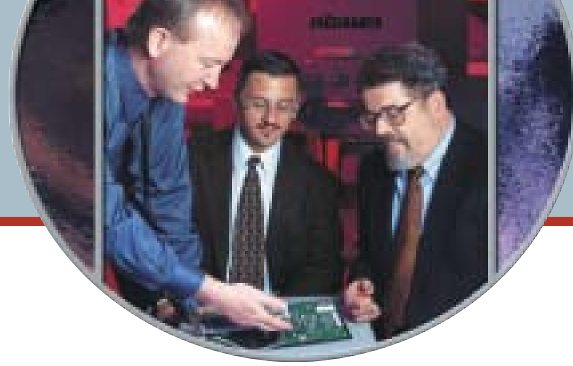
A High Antijam GPS-Based Navigator

Winner of Draper's 2000 Best Paper Award



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ABSTRACT

Current Global Positioning System (GPS)-based navigation system performance is marginal in high-interference environments in both civilian and military applications. This paper presents a new approach to solving these problems using a design that may be implemented at low cost in software in existing and future GPS receivers. The design approach includes GPS-only navigation capability, however, other sensors may be employed, such as inertial instruments (gyros and accelerometers), radars, and altimeters, etc. A multidimensional state is estimated recursively in real time using raw measurement data that include in-phase (I) and quadrature (Q) data from a bank of correlators and raw measurements from other sensors. The data are processed in a single processor that produces the desired navigation system outputs (e.g., position, velocity, time, and attitude). In addition, the GPS measurements may be used to calibrate correlated errors in the other sensors.

Traditional systems are not optimal at high jammer-to-signal (J/S) ratios as a consequence of modular design, the use of traditional fixed-gain or gain-scheduled tracking loops, and the use of artificial moding logic. In contrast, the approach described here employs a nonlinear filter that operates efficiently at all J/S levels. The design incorporates traditional code loop functions. Filter gains continuously adapt to changes in the J/S environment, and the error covariance propagation is driven directly by measurements to enhance robustness under high jamming conditions. Extended-range correlation may be optionally included to increase the code tracking loss-of-lock threshold under high jamming scenarios. Computational complexity is comparable to an extended Kalman filter.

The system has been tested via simulation and in the laboratory using a Nortel GPS simulator and Plessey receiver. Results indicate a consistent improvement in C/A code tracking of at least 15 dB in wideband antijam capability relative to traditional designs. This improvement can be traced to several factors: (1) elimination of moding logic, resulting in seamless operation at all J/S values; (2) continuous adaptive estimation of J/S using measurements from the full correlator bank; and (3) effective handling of measurement nonlinearities.

This technology is currently being developed for use in next-generation deeply integrated Inertial Navigation System (INS)/GPS navigation systems employing Microelectromechanical System (MEMS) sensors with a near-term goal of a single package consuming less than 3 W in a 3-in^3 volume.

INTRODUCTION

The problem of jamming mitigation in GPS-based navigation systems has been receiving greater attention recently, as the use of GPS proliferates and the ease of jamming has become more recognized. Rapid growth in the number of GPS receivers and applications is expected over the next 5 to 7 years, with an attendant reduction in unit price. The civil interference environment will likely increase due to a proliferation of telecommunications devices (mobile subscriber services, commercial spectrum crowding, pseudolites, etc.). Interference can also arise from active or passive intermodulation products of signals or local oscillators on the same platform as the GPS receiver or from radar signals in nearby frequency bands. However, the number and power of GPS signals may not increase significantly.[1] The expected interference environment may adversely affect the performance, continuity, and integrity of receiver operation in applications such as navigation, time transfer, precision aircraft landing, etc.[2] The National Research Council has recommended that the development and operational use of GPS receivers with enhanced antijam (A/J) capability be accelerated.[3] The transmitted GPS signal may be attenuated by trees, buildings, etc., resulting in reduced signal/noise ratio, even without jamming. This loss of signal results in an increase in effective J/S level.

Military receiver operation is at additional risk due to intentional jamming. A typical P(Y) receiver loses code lock at 54 dB J/S at the receiver input. A single 100-W jammer can cause loss of lock at a range of only 25 km. Jammers with several hundred watts of power are manufactured for $25 or less.[4] War fighting requirements for GPS receivers have been developed recently; the first requirement is to better protect user equipment access to the GPS signal through the addition of A/J technology.[5]

There are several methods for strengthening A/J resistance within a GPS-based navigator. These may be broadly divided into *precorrelation* and *postcorrelation* methods. The performance of precorrelation methods tends to be scenario and/or waveform-dependent. Precorrelation techniques include spatial processing, temporal processing, and spectral processing. Adaptive spatial processing methods, which require the use of multiple antenna elements and specialized processors, include null steering and beamforming, which can yield A/J improvements of 25 to 40 dB.[2] Adaptive spatial arrays are especially effective in a broadband Gaussian jamming

environment.[6],[7] Adaptive temporal processing methods include blanking and clipping of short-duty, high-power signals and acoustic wave filters. Transversal filtering of quasi-stable continuous wave (CW) signals (especially narrowband) can yield A/J improvements of 20 to 25 dB.[2] Amplitude domain processing[8] can yield A/J improvements of 15 to 45 dB under a variety of narrowband jamming environments. Adaptive spectral processing methods include digital excision filters and spectral amplitude domain processing.[8] These methods offer improvements of 25 to 30 dB in a variety of narrowband jamming environments, including pulsed, swept, and multiple CW. Of the above precorrelation methods, only spatial processing is effective against broadband Gaussian jammers. However, performance is limited by the number of jammers, and applications using spatial processing may also be limited due to cost and antenna size issues (number of elements).

The performance of *postcorrelation* methods tends to be waveform-independent and offers the possibility of enhanced A/J capability against broadband Gaussian jammers. Postcorrelation methods include the addition of other sensors and enhanced signal processing. A common approach for real-time navigation applications is to add inertial sensors to form loosely coupled or tightly coupled architectures.[9]-[13] Inertial aiding allows bandwidth reduction in the code and carrier tracking loops to enhance A/J performance and also reduces navigation error buildup during periods when code or carrier tracking is lost. Application issues for this class of methods include cost vs accuracy and hardware integration complexity.

Signal processing techniques that attempt to mitigate the jamming problem through software and/or processor architecture modifications are attractive due to their inherent ease of implementation and low cost. They offer the potential of increasing immunity to broadband Gaussian jamming. Signal processing techniques that have been proposed include bandwidth reduction[12] and data wiping to, for example, increase coherent processing time beyond 20 ms.[14] Another proposed method[15] employs I and Q correlator outputs as inputs to a central processor that accounts for position and velocity error correlation among satellites. Navigation solutions are obtained using an extended Kalman filter.

We propose a new GPS signal processing technique that is different from those mentioned above, and that offers significant A/J improvement capability. Since this method is independent of the above methods, total navigation system A/J capability may be enhanced by cascading this method with any of the above techniques. The design may be implemented at low cost in software in existing and future GPS receivers. The approach includes GPS-only navigation capability, however, other sensors may be employed, such as inertial instruments (gyros and accelerometers), radars, and altimeters, etc. A multidimensional state is estimated recursively in real time using raw measurement data that include I and Q data from a bank of correlators and raw measurements from other sensors. The data are processed in a single processor that produces the desired navigation system outputs (e.g., position, velocity, time, and attitude). In addition, the GPS measurements may be used to calibrate correlated errors in the other sensors.

For simplicity, we consider only the code tracking problem here; extension to the carrier tracking problem has been developed, and results will be presented in the future.

Design Approach

Traditional GPS-based navigation systems are not optimal at high J/S ratios as a consequence of modular design, the use of traditional fixed-gain or gain-scheduled tracking loops, and the use of artificial moding logic. While current systems work well at low J/S levels, they suffer performance degradation at high J/S levels, due primarily to the presence of measurement nonlinearities and poorly known J/S values. The approach taken here is to formulate the problem directly as a navigation problem, in which the optimum (minimum-variance) solution is sought for each component of the multidimensional navigation state vector. By formulating the problem in this manner, the navigation algorithms flow directly from the assumed dynamical models, measurement models, and noise models. The solutions that are obtained are not based on the usual notions of tracking loops and operational modes (e.g., State 3, State 5, etc.). Rather, the solution employs a nonlinear filter that operates efficiently at all J/S levels and is a significant departure from traditional extended Kalman filter designs. The design incorporates traditional code tracking loop functions. Filter gains continuously adapt to changes in the J/S environment, and the error covariance propagation is driven directly by measurements to enhance robustness under high jamming conditions.

In the proposed system, individual satellite phase detectors and tracking loop filters are eliminated. Measurements from all available satellites are processed sequentially and independently, and correlation among the line-of-sight (LOS) distances to all satellites in view are fully accounted for. This minimizes problems associated with unmodeled satellite signal or ephemeris variations, and allows for full RAIM capability.

The proposed design offers several significant benefits at high J/S levels. The effects of measurement nonlinearities, which are significant at high J/S levels, are accounted for in an efficient manner. The estimator produces near-optimal state vector estimates, as well as estimates of the state error covariance matrix. The estimator operates in real time using recursive algorithms for both state vector and error covariance matrix estimation. The J/S levels are estimated adaptively in real time to facilitate seamless transitions between course tracking and tight tracking without the use of artificial moding.

Extended-range correlation may be included optionally to increase the code tracking loss-of-lock threshold under high jamming and high dynamic scenarios. If excessively high jamming levels are encountered (e.g., beyond 80 dB J/S at the receiver input for P(Y) code tracking), the GPS measurements may become so noisy that optimal weights given to the GPS measurements become negligible. In this situation, navigation error behavior is essentially governed by current velocity errors and the characteristics of any additional navigation sensors that are employed. Code tracking is maintained as long as the LOS delay error remains within the maximum allowed by the correlator bank. If there is a subsequent reduction in J/S so that the optimal weights become significant, optimum code tracking performance is maintained without the need for reacquisition. Detector shapes for each correlator depend on the correlator lag and rms LOS delay error.

For navigators using GPS only, navigation errors will be reduced significantly by using algorithms that approximate the minimum-variance solutions at high J/S. For navigators employing other sensors, a fully integrated system will allow simpler, smaller, cheaper hardware to be employed. Superior sensor calibration capability will reduce sensor performance requirements, allowing lower-cost sensors to be used.

Figure 1 shows the information flow between the principal elements of the navigation system. The data from each satellite in view are processed sequentially; the figure illustrates processing for a single satellite. The GPS receiver front end performs filtering, carrier wipe-off, and sampling to produce I/Q data. These data are processed by each correlator to produce the 50-Hz samples $I_{50}(j,k)$ and $Q_{50}(j,k)$ for the k^{th} correlator at the j^{th} time point. Square law detection and summation are then used to obtain $Z_k(n)$; currently, summation is over five samples so that $Z_k(n)$ is 10-Hz data. The processor uses inputs $Z_k(n)$ to calculate the navigation state estimate $\hat{x}(n)$. The state estimate is propagated to measurement update time using an assumed dynamical model. As shown in the figure (dashed lines), two types of sensors may be optionally added to the GPS-based navigator. Inertial sensor data may be incorporated during propagation to reduce the error bandwidth during periods of high dynamics and retard error growth if code lock is lost. If inertial sensors are used, the processor accepts raw sensor data (e.g., body-frame-specific force and angular rates for a strapdown configuration), and time-correlated sensor error states may be included in the navigation state vector to perform in-flight calibration of significant error sources. At measurement update time, the state is updated using the measurements $\{Z_k(n);\ k=-m,\ldots,m\}$ from $2m+1$ correlators, satellite ephemeris data, and (optionally) measurements from other sensors (e.g., radars, altimeters, etc.). The estimated time delay $\hat{\tau}_k(n)$, which is a function of the state estimate and satellite ephemeris, is fed to the code numerically-controlled oscillator (NCO), which controls correlator code phase, in order to maintain the mean code tracking error close to zero.

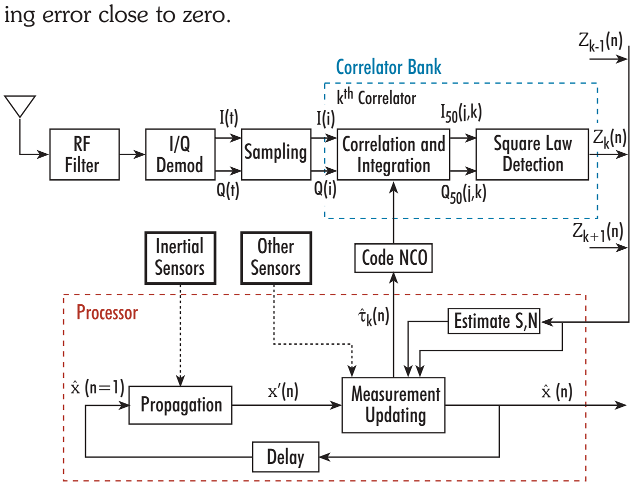

Figure 1. Code tracking information flow diagram for GPS-based navigator.

The navigator includes adaptive algorithms for estimating postcorrelation signal power (S) and noise power (N). Noise statistics are assumed to be the same for all correlators; although the 50-Hz noises are uncorrelated over time, the noise in adjacent correlators is correlated.

Analysis Results

Algorithm development and test was first carried out using a software-only simulation for L1 tracking only; extension to L1/L2 operation is straightforward. The navigator configuration included a full complement of strapdown inertial sensors, forming a *deeply integrated* INS/GPS system. The sensor error model used was representative of current MEMS sensor capability. Rms accelerometer errors were 1-milli-g bias stability, 100-ppm scale-factor stability, and 1 cm/s/√h random walk. Rms gyro errors were 10-deg/h bias stability and 0.03-deg/√h random walk. All stability errors were modeled as first-order Markov processes with a time constant of 5 min, which is representative of expected in-flight error characteristics.

A full 6-degree-of-freedom simulation was used with four satellites continuously in view. The navigation state vector consisted of position, velocity, inertial sensor stability errors, and user clock and clock rate. Clock errors were treated as biases. Satellite ephemeris errors were accounted for by including an unestimated range bias of 2 m, rms. It was assumed that the 50-Hz databit switching times were known.

The navigation algorithms are nonlinear. Thus, it was not possible to perform an accurate error covariance analysis based on linearization. As a consequence, the results in the sequel are based on Monte Carlo analysis. The principal criterion used to evaluate navigation performance was Circular Error Probable (CEP), which was calculated as the median horizontal error magnitude over the total number of Monte Carlo runs.

The measurements from all correlators were processed simultaneously, while the measurements from each satellite were processed sequentially. An ideal correlation function was assumed in the navigation algorithms, with $R_c(\tau) = 1 - |\tau|$ for $|\tau| \leq 1$ and $R_c(\tau) = 0$ for $|\tau| > 1$. A correlator spacing of 1/2 chip was used throughout. Two types of jammers were assumed: a wideband Gaussian jammer with a 20-MHz bandwidth and a narrowband jammer with a 1-kHz bandwidth. Jammer outputs were generated using a first-order Markov process driven by pseudorandom Gaussian noise.

In order to assess performance relative to traditional systems, a tightly coupled INS/GPS system was simulated. The simulation model assumed a GPS receiver capable of calculating pseudorange and delta range. The receiver outputs and the simulated MEMS sensor outputs were fed to a traditional INS/GPS integration filter. This filter was mechanized as a standard extended Kalman filter and used the same navigation state vector as the deeply integrated system. The receiver was velocity aided using the velocity components of the state vector estimate.

The tightly coupled receiver filter bandwidth was 0.1 Hz while in State 3 tracking. Code loop loss of lock was assumed to occur at J/S = 54 dB. Above this threshold, GPS data were not used, and free inertial navigation was assumed. It was assumed that a perfect estimate of J/S was available to the tightly coupled system receiver. A second-order phase-lock loop was used, with the transfer function (cf. Ref. [16])

$$H(\omega) = \frac{j2\zeta\omega_0\,\omega + \omega_0^2}{-\omega^2 + j2\zeta\omega_0\,\omega + \omega_0^2} \quad (1)$$

that represents the closed-loop response from input to the output estimate of input. The single-sided noise bandwidth of this filter is

$$B_L = \frac{\omega_0}{8\zeta}(4\zeta^2 + 1) \quad (2)$$

The damping ratio was $\zeta = 1/\sqrt{2}$ in all simulations.

The performance of the deeply integrated navigation system was evaluated for a Precision-Guided Munition (PGM) scenario in which the target was at a range of 63 nmi. The altitude profile is plotted in Figure 2. A single wideband Gaussian jammer was placed 10 km in front of the target in an attempt to simulate a worst-case scenario for a single jammer. This placement gives maximum J/S prior to final target approach with a resultant loss of navigation system performance just prior to target impact. The J/S history for a 100-W jammer is shown in Figure 3.

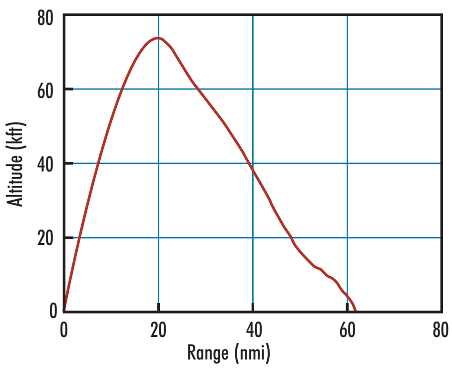

Figure 2. PGM altitude profile.

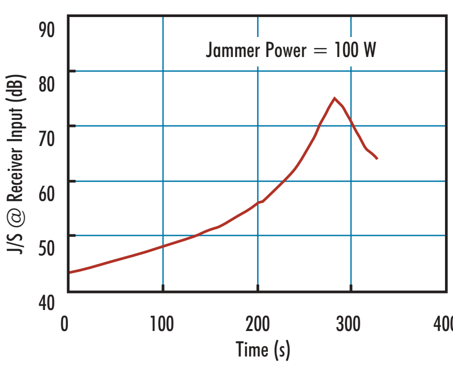

Figure 3. PGM scenario: J/S vs time.

Performance was evaluated by varying the jammer power from 1 W to 10 kW. A total of 25 Monte Carlo runs were made at each power level. Initial rms navigation errors were 10 m and 0.2 m/s per axis; initial rms clock errors were 10 m and 0.2 m/s. The CEP at target impact is plotted vs jammer power for wideband jamming in Figure 4 and for narrowband jamming in Figure 5. Comparing the results in the figures, it can be seen that the deeply integrated system offers significant improvement over the traditional tightly coupled system for both wideband and narrowband jamming. As an example, a 100-W wideband jammer results in an 11-m CEP for the deeply integrated system, compared with a 120-m CEP for the tightly coupled system. If the jammer power is reduced to 10 W, the CEP values are 2.6 m for the deeply integrated system and 71 m for the tightly coupled system.

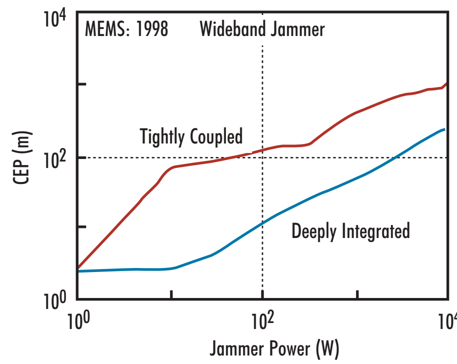

Figure 4. CEP vs jammer power: wideband jammer.

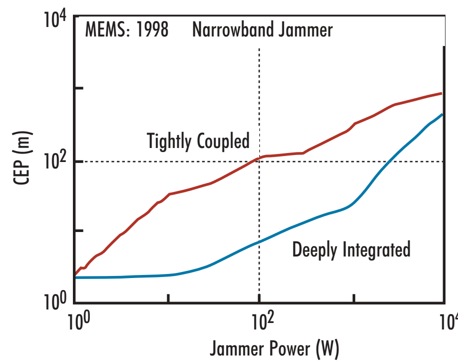

Figure 5. CEP vs jammer power: narrowband jammer.

A/J improvement capability may be quantified by comparing jammer power at a constant CEP value. The resulting improvement in A/J capability due to deep integration can be seen in Figure 6. For wideband jamming, improvements of at least 15 dB are seen for CEP values ranging from 6 to 120 m. For narrowband jamming, improvements of at least 15 dB are seen for CEP values ranging from 4 to 80 m. Improvement is seen to decrease as the CEP decreases below

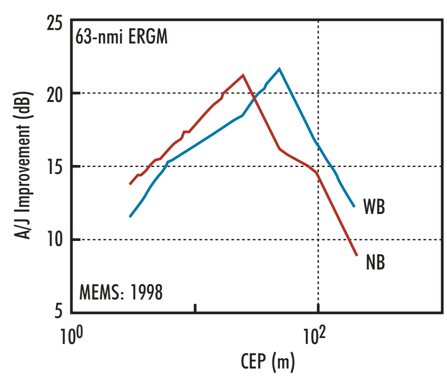

Figure 6. A/J improvement due to deep integration.

10 m. In this case, the decrease in CEP results from a decrease in jammer power, and the tightly coupled system tends to maintain lock with higher probability as the jammer power decreases. In the limit as the jammer power approaches zero, the tightly coupled system approaches efficient operation, and both systems give comparable performance. The improvement is also seen to decrease as the CEP increases beyond 100 m. In this case, the increase in CEP results from an increase in jammer power, and tracking quality of the deeply integrated system begins to degrade. In the limit as the jammer power increases without bound, the deeply integrated system can no longer maintain lock, and both systems are operating in a free inertial mode where the CEP is determined solely by initial navigation errors and inertial sensor errors.

Hardware Demonstration

A hardware-in-the-loop (HWIL) simulation was set up in order to test the deep integration algorithms in a realistic laboratory environment. A block diagram of the HWIL setup is shown in Figure 7. The hardware testbed included an IBM-compatible personal computer (PC), a commercial-off-the-shelf (COTS) GPS receiver, and a radio frequency (RF) signal GPS simulator. The receiver was a Plessey 12-channel Builder Kit for an IBM-compatible PC, operating on C/A code only (Figure 8). Full DOS-based receiver source code was provided with the Builder Kit, which provided well-documented C source code, software task management, user interfaces, and utility functions. The GPS signals and jamming inputs were provided by a Nortel simulator.

User vehicle flight profiles were generated externally and used as inputs to the GPS and interference (jammer) simulators. The profiles were also used to generate simulated inertial sensor error data. The combined GPS and jamming RF signals were provided to the GPS receiver hardware.

The deep integration algorithms were run on a Pentium II processor hosted within the computer. I and Q data were supplied to the computer by the receiver. Twelve correlator pairs were available within the receiver. Four pairs were used to supply data to the receiver software for acquisition, data bit synchronization, and almanac/ephemeris calculations. Eight pairs were available to the deep integration algorithms. Spacing between correlators was set to 1/2 chip. The deep integration algorithms generated feedback commands to the NCO located within the receiver. Navigation solutions were generated at a 10-Hz rate. The HWIL experiments were set up to evaluate LOS tracking errors with a single satellite under wideband jamming.

Tests were made to evaluate code tracking performance in the presence of constant jammer power. One example is shown in Figure 9, which was run over a period of 19 min. The upper left panel shows the residual LOS error, which is equivalent to the navigation error of an inertial-only navigation system. The residual LOS error reaches a value of 180 m by the end of the run, which is representative of a 2-nmi/h inertial system before in-flight calibration. J/S is maintained at 10 dB for the first 2.5 min, and then increased gradually to 60 dB, which is approximately 15 dB above loss of lock threshold for a typical C/A receiver. J/S is maintained at 60 dB for 12 min, and then gradually reduced to 10 dB and held at that value for the remaining 4.5 min. The true predicted (calculated in the filter) rms LOS tracking errors are shown in the two right panels. Position error magnitude is maintained below 40 m throughout the run, and is within the predicted rms values. Note the rapid response to both the increase and decrease in J/S. Velocity errors are less than 0.2 m/s throughout and are comparable to the predicted rms values. The results indicate an A/J improvement of at least 15 dB relative to typical C/A receivers.

Tests were also run using the same 63-nmi PGM scenario used for the analysis. Results for a typical test are shown in Figure 10, using a single 100-W jammer located 10 km in front of the target. The residual LOS error grows to 115 m by the end of the run and is representative of an INS with biases of 10 deg/h and 1 milli-g before in-flight calibration. The J/S history shown in the bottom left panel is comparable to Figure 3. LOS tracking error histories are plotted in the two right panels. Position error magnitude is maintained within 10 m throughout the flight and is comparable to the rms error. Velocity error is generally less than 0.1 m/s, except for the brief 1-min period when J/S undergoes a rapid increase. Code track is maintained over the 5.5-min period, during which J/S exceeds the loss of lock threshold for a typical C/A receiver.

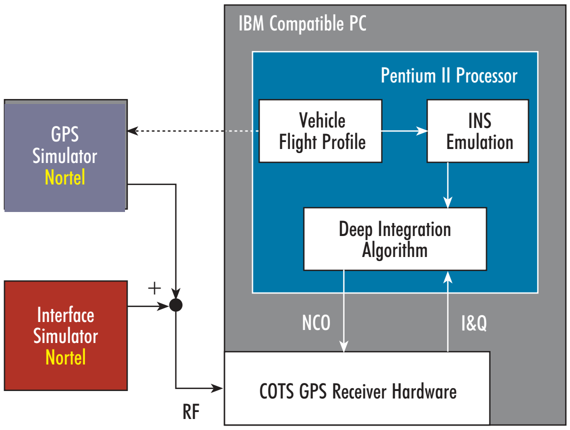

Figure 7. Hardware demonstration architecture.

Figure 8. Demonstration system.

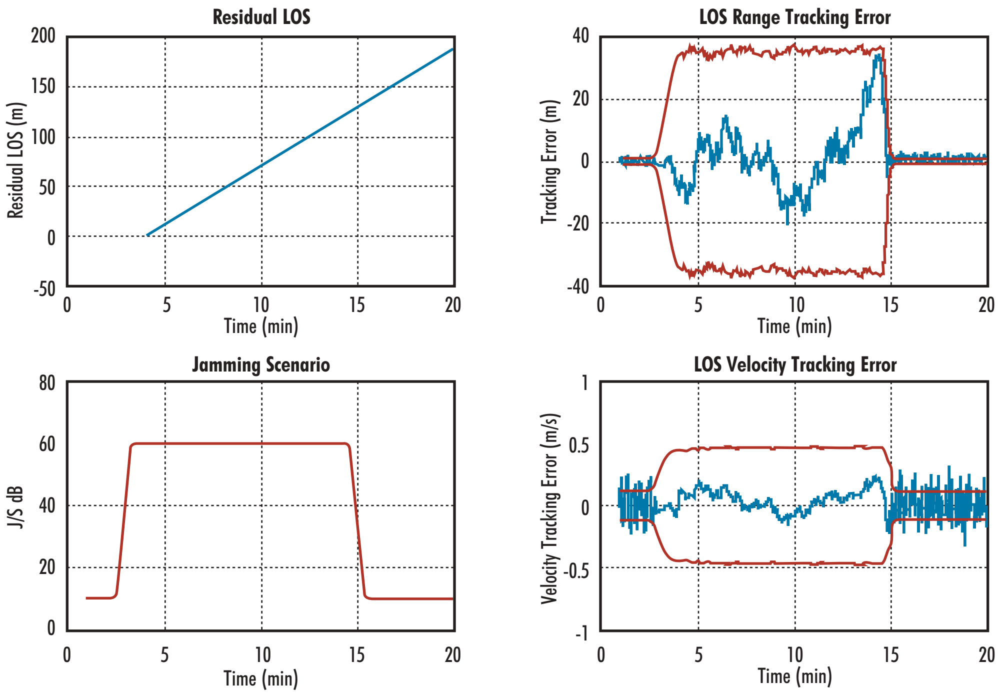

Figure 9. C/A code demonstration system performance: J/S = 60 dB.

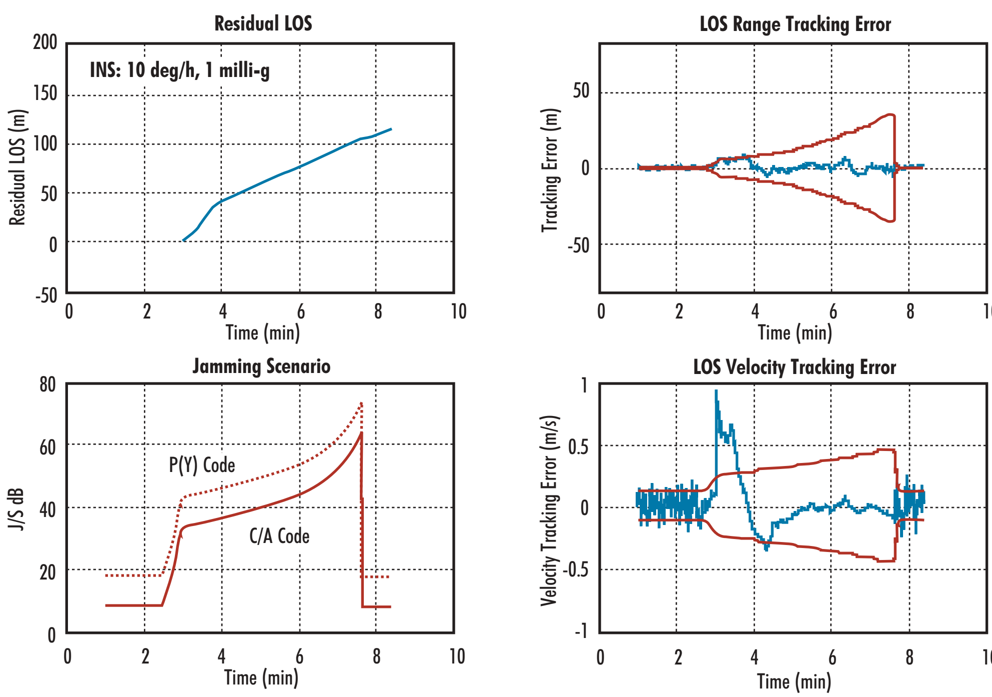

Figure 10. C/A code demonstration system performance: PGM scenario with a 100-W wideband jammer.

A shoot-shoot test was also performed in which the jammer is rendered inoperable, first by a PGM shell, and then the target is hit by a second shell. In this case, the J/S ratio drops suddenly as the second shell approaches the target. The results of a typical case are shown in Figure 11, in which the jammer is eliminated 1 min prior to target impact. The LOS position error magnitude is less than 10 m throughout and decreases to approximately 2 m over the final minute in response to the loss of jamming. The true position error is maintained well within the rms error over the entire flight. Note the rapid filter response to the jammer dropout, evidenced by the almost instantaneous reduction in the rms value. The velocity error amplitude is generally less than 0.2 m/s, except for a 1-min transient induced by the rapid increase in J/S near the beginning of flight. The predicted J/S history to achieve similar performance with P(Y) code processing is shown in the bottom left panel. The P(Y) curve is 10 dB above the C/A curve to reflect the approximate increase in A/J capability due to increased P(Y)-code processing gain.

Summary

In summary, the HWIL demonstration results indicate an improvement in code tracking of 15 to 20 dB in wideband A/J capability for the proposed deeply integrated INS/GPS system relative to traditional tightly-coupled designs. This degree of improvement is consistent with the predictions obtained from the analysis and software-only simulations under both wideband and narrowband jamming. The improvement can be traced to several factors: (1) elimination of moding logic, resulting in seamless operation at all values of J/S; (2) continuous adaptive estimation of J/S using measurements from the full correlator bank; and (3) effective handling of measurement nonlinearities.

Acknowledgments

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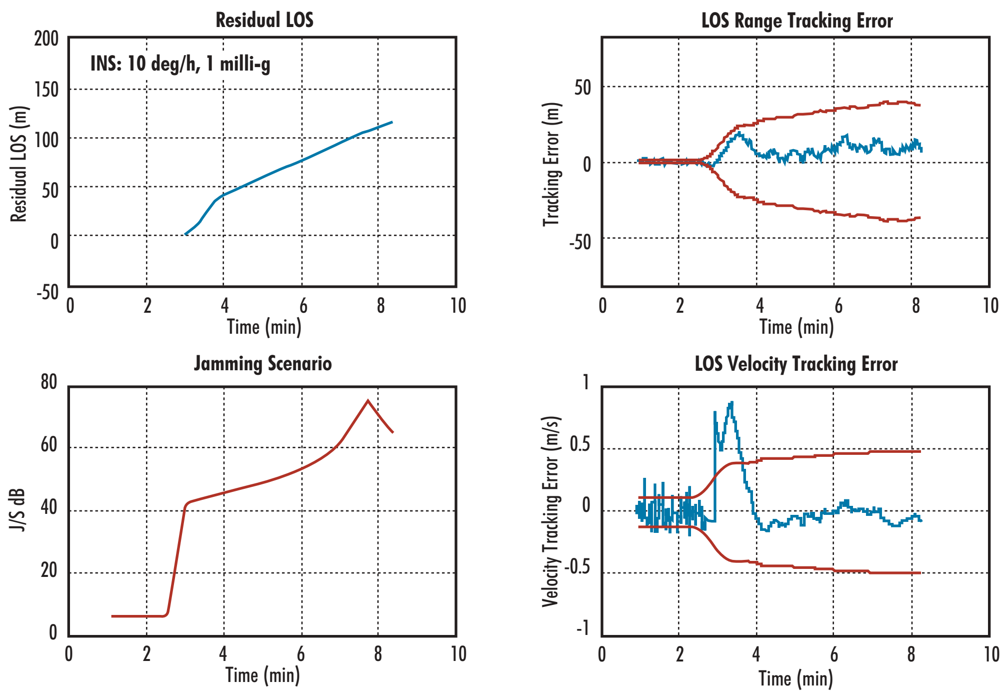

Figure 11. C/A code demonstration system performance: PGM scenario with a 100-W jammer: shoot-shoot option.

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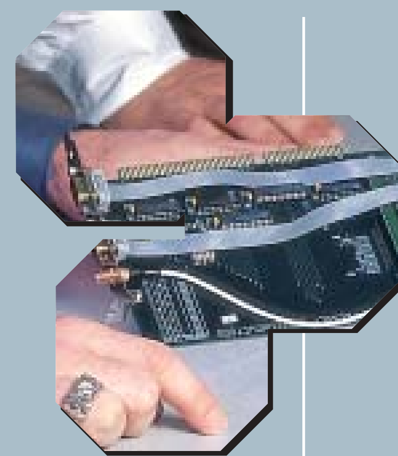

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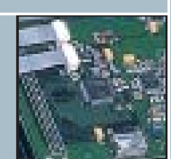

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is the Director of Systems Engineering at Draper Laboratory and one of the co-inventors of Draper's Deep Integration INS/GPS technique. He has been involved with the design of guidance, navigation, and control systems for over 25 years. Prior to his current position, he was Technical Director and Systems Engineer for guided projectile programs at Draper, including the Extended-Range Guided Munition Demonstration Program, the Competent Munition Advanced Technology Demonstration Program, and the Competent Munition Risk Reduction Program. Before that, he was the Group Leader of Advanced Control Systems at Draper, and coordinated Draper's work in robust control, learning control, neural networks, and image recognition. Previous work includes inertial navigation, GPS receiver design, INS/GPS integration, vehicle guidance law optimization, and a wide variety of control system design with application to missiles and space vehicles. Dr. Dowdle has also been involved with design and analysis of command, control, and communications (C^3) systems, including sensor-to-weapon issues. He has authored numerous papers and technical reports on the theory and application of multivariable control methods. Dr. Dowdle is a member of the honor societies Eta Kappa Nu, Tau Beta Pi, and Phi Kappa Phi. He is a past member of the Control Systems Society of the Institute of Electrical and Electronics Engineers (IEEE) and a former member of the American Institute of Aeronautics and Astronautics (AIAA) Technical Committee on Guidance, Navigation, and Control. He was the Technical Program Co-Chair for AIAA's 1997 Guidance, Navigation, and Control Conference. He received the University of Central Florida Alumni Association's 1988 Professional Achievement Award for Career Excellence, Draper's 1995 Annual Award for Best Technical Publication, and Draper's 1997 Distinguished Performance Award. Dr. Dowdle received a PhD in Electrical Engineering from the Massachusetts Institute of Technology (MIT) (1979) and an ME in Electrical Engineering (1976) and a BS in Engineering (1975) from the University of Central Florida.

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is a Principal Member of the Technical Staff at Draper. With a broad background in general engineering, physical sciences, and mathematics, he has been involved in applications of estimation and control optimization on the C-17 and Titan IV programs. His recent research efforts have comprised applications of control systems techniques to robotic manipulators. Specifically, he has investigated issues associated with the inverse kinematics of redundant manipulators and compliant control of manipulators tracking partially known surfaces. Dr. Flueckiger's education includes multivariable systems theory, robust control theory, system simulation, adaptive control theory, and system optimization. In addition, he has taught linear systems theory at the graduate level. Dr. Flueckiger holds a PhD in Electrical Engineering, an ScM in Applied Math from Brown University, and an ME and BS in Engineering from Harvey Mudd College.

Donald E. Gustafson degustafson@draper.com

is a Principal Member of the Technical Staff at Draper Laboratory. For the past 10 years, he has been principally responsible for the conceptual design of guidance and navigation systems for guided munitions using inertial and GPS sensors. Recently, he was responsible for the design of algorithms with high antijam capability in integrated GPS-based navigation systems. He developed methods for robotic vision, analyzed ground penetrating radar images for detection of buried waste, and developed algorithms for navigation in underground mines. From 1988 to 1991, he was with MIT Lincoln Laboratory where he worked on target detection and location techniques using distributed antenna arrays. From 1977 to 1988, he was Senior Vice President of Scientific Systems, Inc, which he co-founded, where he worked on automated interpretation of biomedical signals (EKG, EEG, EMG) and application of estimation theory to satellite meteorology, aircraft failure detection, and personnel forecasting. He developed system identification techniques for aircraft flutter suppression, personnel forecasting, plastic injection molding, and financial forecasting. From 1966 to 1977, he was with the MIT Instrumentation Laboratory (later Draper), where he worked principally on the Apollo Lunar Module navigation system and automated interpretation of electrocardiograms. He was co-recipient of the Draper Best Paper Award in 1995 and 2000, the 1999 Best Patent Award, and the 2000 Distinguished Performance Award for his work on antijam methods in GPS-based navigation. Dr. Gustafson has published more than 30 refereed papers in conference proceedings and archive journals. He received a PhD in Engineering from MIT.