Navigation Sensors and Systems in GNSS Degraded And Denied Environments

George T. Schmidt

IEEE Aerospace and Electronic Systems Society

Abstract---Position, velocity, and timing (PVT) signals from the Global Positioning System (GPS) are used throughout the world but the availability and reliability of these signals in all environments has become a subject of concern for both civilian and military applications. This presentation summarizes recent advances in navigation sensor technology, including GPS, inertial, and other navigation aids that address these concerns. Also addressed are developments in sensor integration technology with several examples described, including the Bluefin-21 system mechanization.

KEYWORDS: GNSS, GPS, Inertial sensors, Integration, Doppler velocity

1. Introduction to the issues

The Global Positioning System (GPS) is the most developed and widely used Global Navigation Satellite System (GNSS). GPS signals are used throughout the national infrastructure as in transportation (navigation), communications (timing), banking and finance (timing), and energy distribution (timing). Every day a new application of GPS signals is proposed. For example, in February 2012, the United States Congress passed the Federal Aviation Agency (FAA) Modernization and Reform Act which requires the FAA to develop a "comprehensive plan for safely accelerating the integration of civil UAVs into the national airspace system by 2015." Presumably those UAVs would be navigated using the unencrypted civilian L1 C/A signal of the GPS.

Shortly after the Act passed, a University of Texas "spoofing" demonstration was conducted at the request of the United States Department of Homeland Security and it was demonstrated that false GPS information could be introduced into a UAV onboard navigation system.[1] This demonstration certainly increased the concern over the use of UAVs in the national airspace and in safety of flight, in general, when using civil GPS. Then in 2013, the University of Texas team successfully took control of the GPS-based navigation system of a yacht in the Mediterranean Sea and steered the yacht hundreds of meters off its intended course again demonstrating "spoofing" should be a concern for civilian applications of GPS.[2] Spoofing is not a great concern for SAASM equipped military receivers using the encrypted P(Y) code.

For civilian applications it appears that one defense against spoofing is to provide an independent source(s) of navigation information. For example, long-range commercial aircraft, such as the B-787, already have several inertial navigation systems on-board which can be compared to the GPS indicated information. A possibly less costly approach would be to have receivers that can receive signals from all GNSS that are operating (GPS, BeiDou, GLONASS, Galileo, and/or others). With so many signals available, it is difficult to imagine how spoofing would be possible.

Another notable incident with L1 C/A GPS signals occurred when the Local-Area Augmentation System (LAAS) installed its first Ground-Based Augmentation System (GBAS) at Newark airport in November 2009.[3] Within the first days of its installation, radio-frequency interference (RFI) was found to be causing errors in GBAS processing. The source of the RFI could not be immediately determined. The FAA started an investigation involving detection and characterization of the RFI. After equipment was deployed on January 20, 2010, in one day more than 25 separate instances of RFI interference in the GPS L1 band were detected. Some of the RFI events were strong enough to result in the LAAS receiver loosing tracking of lower elevation GPS satellites. It was many months before the cause was determined to be from various kinds of "personal privacy" devices in vehicles moving along the New Jersey Turnpike adjacent to the airport. In 2010 the United States Federal Communications Commission Enforcement Bureau filed 21 actions against on-line retailers in 12 states for illegally marketing more than 215 models of wireless jammers nearly 80 of which could jam GPS signals, but such devices are likely still available.[4]

Military uses of GPS also include navigation and timing applications and interference in the GPS frequency bands is of great concern. The GPS signal on Earth (which has frequently been likened to a 25-watt light bulb shining on Earth from 12,500 miles away) is very weak (about 1.6 x 10^{-16} watts) by the time it reaches Earth. One measure of a receiver's ability to acquire and lock-on to the signal from a GPS satellite in the presence of background noise is the maximum ratio of the strength of the background noise, or jamming signal (J), to the strength of the signal from the satellite (S) at which the receiver can continue to process the GPS signal. That ratio, often called the jammer-to-signal (J/S) ratio, is significantly greater than one.

Using the Defense Advanced GPS Receiver (DAGR) as an example, the maximum J/S for acquiring the civilian L1 C/A GPS signal is 250.[5] For acquiring the P(Y) signal, the maximum J/S is much larger, up to 2500. Once the receiver has acquired the P(Y) signal, it can stay locked-on to it in the presence of jamming signals up to 12,600 times stronger than the GPS signal. However, a jammer near the receiver presents a danger to the receiver loosing lock on the GPS signal because the jammer need only be greater than approximately 2×10^{-12} watts. Personal protection devices and jammers can easily exceed that power level. Thus GPS may not be available in a jamming environment.

Attenuation of the GPS signal can be caused by trees, buildings, or antenna orientation, and result in reduced signal/noise ratio even without interference. This loss of signal can result in an increase in effective jammer/signal (J/S) level even without intentional jamming or interference. More sensitive GPS receivers might be required.[6] Pseudolites, beacons, and signals of opportunity might be used to create additional navigation information.[7] There are many situations that then require additional sensors to augment GPS or entire stand-alone navigation devices to integrate with GPS, such as inertial systems.[8,9] New integration techniques for using these sensors may be required.[10,11]

This paper will focus on describing GPS status and plans, deliberate interference, inertial systems, integration techniques, and system simulations.

2. GPS status and plans

The Department of Defense is always modernizing the GPS by purchasing new satellites and upgrading the systems that control them. Accuracies achievable by a GPS receiver are affected by the inaccuracies in the data sent to the satellites, in the data broadcast by the satellites, atmospheric effects, and other error sources. Military receivers routinely provide better than 3 meter accuracy using current satellites and are expected to provide better than 1 meter accuracy using Block IIIA and Block IIIB satellites in the future. The Block IIIC satellites will be equipped with high-speed satellite cross-links which will allow continuous data updates. As a result, those satellites will be able to provide more accurate data to receivers enabling a user's location to be determined within 0.15 m. These capabilities are some years away since a constellation of new satellites and new receivers must be deployed.[5] In addition, a new ground-based control system (OCX) must be developed that will allow these and other advanced functions to be controlled. Once achieved, these unprecedented accuracies will become addictive to users.

Another significant improvement in GPS for military systems will be the introduction of the M-code in Block III, which is designed to be more secure and have better jamming resistance than the current Y code.[5] The system is being designed such that a higher power signal (+20 dBW over current signal levels) will be available for localized coverage over an area of operations to boost signal jamming resistance. This significant improvement (M-code spot beam) is scheduled for the Block IIIC phase of the GPS modernization process.[5] But unfortunately, GPS improvements take many years to plan, implement, and receive funding. Recently, there have been the initial stages of a debate over a redesign of the GPS constellation, which would have a dramatic impact on GPS Block III, whatever it might become.[12]

3. GPS interference issues

Representative jammers are shown in Fig. 1.[5] High power jammers are easy targets to find and to attack because of their large radiated power. Lower power jammers are hard to find. It is important to defend against them by improved anti-jam technologies within the receiver, by improving antenna, or by integrating with an inertial navigation system or other devices not subject to jamming. Proponents of high-accuracy inertial systems will generally argue that a high anti-jam GPS receiver is not required, while receiver proponents will argue that using a higher anti-jam receiver will substantially reduce inertial system accuracy requirements and cost. Both arguments depend entirely on the assumed mission and jamming scenario.

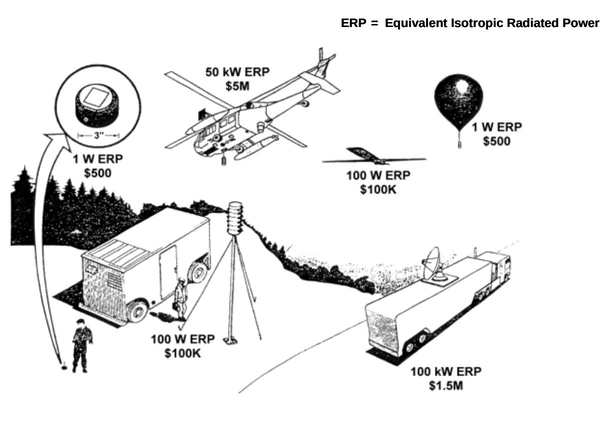

Fig. 1 Jammer possibilities.

What has generally become accepted is that the GPS is remarkably vulnerable to jamming during the C/A code acquisition phase where conventional receiver technology has only limited jammer tolerability (typically J/S - 27 dB).[13-15] A 1-W (ERP) jammer located at 100 km from the GPS antenna terminals could prevent acquisition of the C/A code in a very large urban area such as Beijing. Fig. 2 is very useful in determining trade-offs between required A/J margin and jammer power. A 1-W jammer is inexpensive and potentially the size of a hockey puck. So generally, a GPS receiver cannot be expected to acquire the C/A code in a hostile environment.

For military applications with older receivers, the C/A code could be acquired outside hostile territory and then the receiver would transition to P(Y) code lock, which has a higher level of jamming immunity. With modern receivers using multiple correlators, direct P(Y) acquisition can be achieved. A 1-kW (ERP) jammer at about 100 km would now be required to break inertially

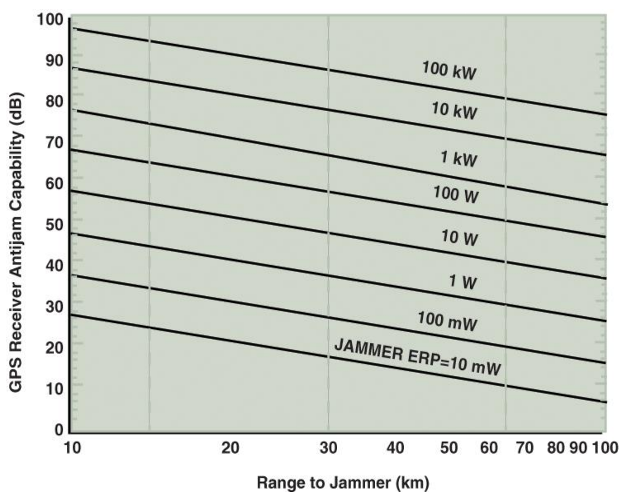

Fig. 2 GPS jamming calculations.

aided receiver P(Y) code lock at 54 to 57 dB. As the receiver approaches the jammer, jammer power levels of about 10 W would be effective in breaking P(Y) code lock at 10 km (see Fig. 3).

As will be shown later, the "deep integration" architecture for combining INS and GPS may allow for tracking GPS satellites up to 70 – 75 dB J/S, an improvement of 15 to 20 dB above conventional P(Y) code tracking of 54 to 57 dB. If future increases of 20 dB in broadcast satellite power using the M-code spot beam (M spot) are also achieved, nearly 40 dB of additional performance margin would be achieved, so a jammer of nearly 100 kW would be required to break P(Y) lock at 10 km.

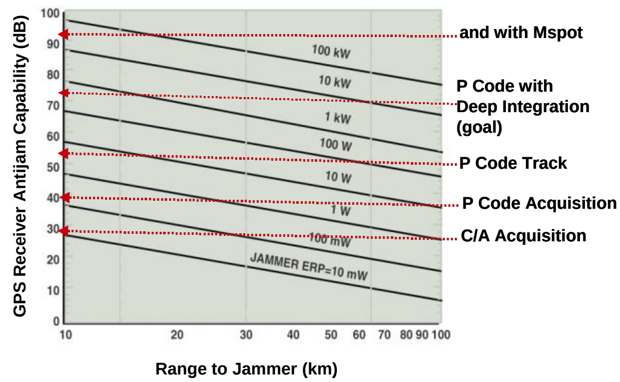

Fig. 3 Possible A/J capabilities.

Furthermore, new receiver technology with advanced algorithms and antenna technologies might also be incorporated into the system, further increasing its A/J capability significantly.[5,15] Filtering in the receiver can be effective against out-of-band signals. An adaptive nulling antenna can place deep nulls in the directions of several strong jammers. As a result, jamming power reaching the receiver is attenuated sharply. With this method, interference can be rejected by 20 to 50 dB or more as long as there is sufficient angular displacement between the GPS signal direction and that of the jammer.

If A/J performance is increased significantly, then the jammer power must also be increased significantly to remain effective. In the terminal area of flight against a target, the jammer located at the target will eventually jam the receiver, and the vehicle will have to depend on inertial-only guidance or the use of a target sensor. Thus, it is important to ensure that accurate guidance and navigation capability is provided to meet military mission requirements against adversaries who are willing to invest in electronic countermeasures. This fact is true today and is expected to remain so in the foreseeable future. Fig. 4 summarizes some techniques that may be used.

- Lower Cost, High Accuracy IMUs
- Improve Signals in Space
  - Increased Accuracy
  - Mcode and Mspot
- Improved Receivers
  - Deep Integration with IMU
  - Anti-Spoof Techniques
  - Higher A/J Electronics
- Direct P(Y) Code Acquisition
  - Improved Aircraft Interface to Munitions
  - Miniature On-Board Clock
  - Multiple Correlators
- Higher Performance, Lower Cost Adaptive Antennas
  - Digital Beam-forming
  - Modern Algorithms

Fig. 4 Mitigation techniques in jamming.

4. Inertial navigation sensors and systems

Inertial navigation systems cannot be jammed. The major error sources in the inertial navigation system are due to gyro and accelerometer inertial sensor imperfections, incorrect navigation system initialization, and imperfections in the gravity model used in the computations. But, in nearly all inertial navigation systems, the largest errors are due to the inertial sensors.[16]

Whether the inertial sensor error is caused by internal mechanical imperfections, electronics errors, or other sources, the effect is to cause errors in the indicated outputs of these devices. For the gyros, the major errors are in measuring angular rates. For the accelerometers, the major errors are in measuring specific force. For both instruments, the two largest errors are usually a bias instability which is measured in deg/hr for gyro bias drift, or micro g for the accelerometer bias; and a scale-factor stability, which is usually measured in parts per million (ppm) of the sensed inertial quantity. The accuracy of the navigation system improves with decreasing inertial sensor errors. Unfortunately, system cost increases as the sensors are improved.

In most cases, an inertial navigation system equipped with gyros whose bias stability is 0.01 deg/hr will see its navigation error grow at a rate of 1-NM/hr of operation over several hours of a mission. For missions that are much shorter, gyro bias, accelerometer bias, initial INS alignment errors, and initial condition errors contribute to the resulting position errors.[17] The navigation performance requirements placed on the navigation system lead directly to the selection of specific inertial instrument performance in order to meet the mission requirements.

Fig. 5, "Current Gyro Technology Applications," gives a comprehensive view of the gyro bias and scale-factor stability requirements for various mission applications and what type of gyro is likely to be used in current applications. The gyro requirements assume there are no GPS updates available and that the mission requirements must be satisfied without GPS measurements.

Microelectromechanical system (MEMS) solid-state gyros have potentially significant cost, size, and weight advantages, which has resulted in a proliferation of the applications where such devices can be used in systems. While there are many conventional military applications, there are also many newer applications that will emerge with the low cost and very small size inherent in such sensors, particularly at the lower performance end of the spectrum.

In the near future, the MEMS and Interferometric Fiber-Optic (IFOG) technologies are expected to replace many of the current systems using Ring Laser Gyros (RLG) and mechanical instruments. However, one particular area where the RLG is expected to retain its superiority over the IFOG is in applications requiring extremely high scale-factor stability. The change to all-MEMS technology hinges primarily on MEMS gyro development. The performance of MEMS instruments is

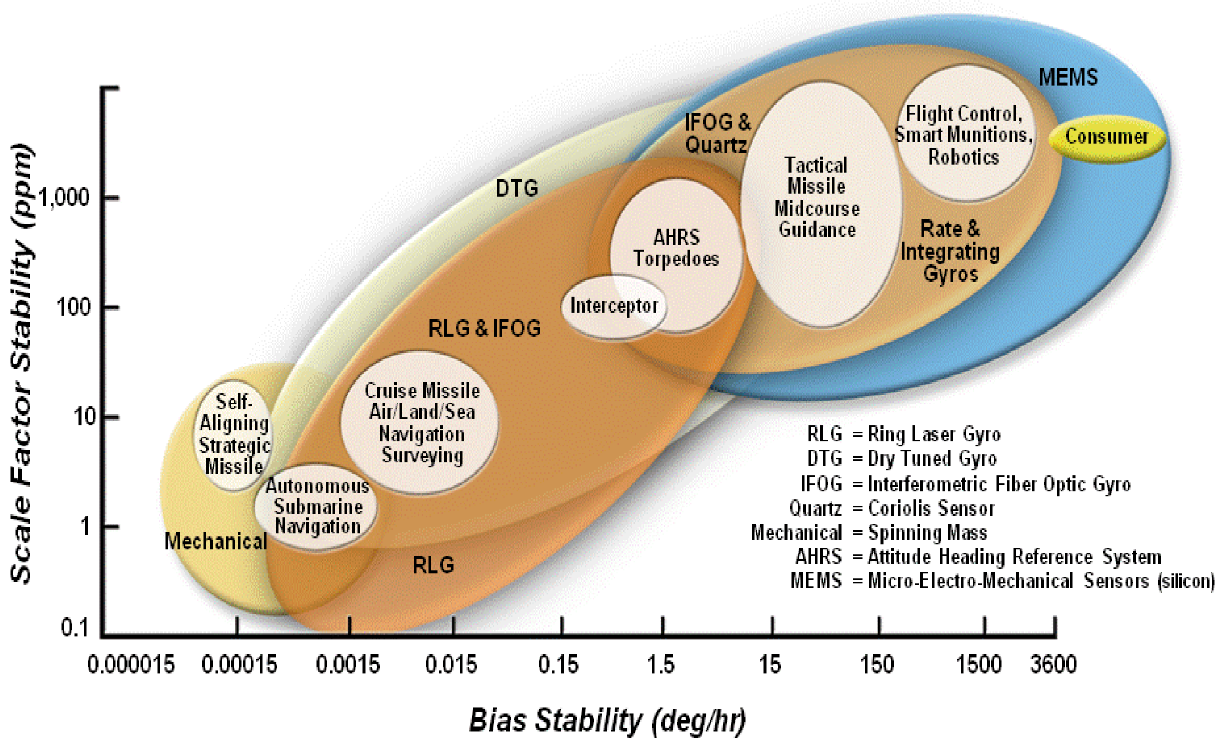

Figure 5. Current Gyro Technology Applications.

continually improving, and they are currently being developed for many applications. Low cost can only be attained by leveraging off the consumer industry, which will provide the infrastructure for supplying the MEMS sensors in extremely large quantities (millions). The use of these techniques will result in low-cost, high-reliability, small-size, and lightweight inertial sensors and the systems into which they are integrated. The lower (tactical) performance end of the application spectrum will likely be dominated by micromechanical inertial sensors. The military market will push the development of these sensors for applications such as "competent" and "smart" munitions, aircraft and missile autopilots, short-time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, "smart skins" using embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale INS/GPS systems.

In the far future, the MEMS and integrated-optics systems technology may dominate the entire low- and medium-performance range. The rationale behind this projection is based on two premises. The first is that gains in performance in the MEMS devices will continue with similar progression to the orders-of-magnitude improvement that has already been accomplished in the last decades. That further improvements are likely is not unreasonable since the designers are beginning to understand the effect of geometry, size, and electronics on reliability and performance. Second, efforts have already demonstrated how to put all six sensors on one (or two) chips, which is the only way to reach a possible cost goal of less than $1000 per INS/GPS system. In addition, since many of the MEMS devices are vibrating structures with capacitive readout, this may restrict the performance gains. It is in this area that the integrated optics technology is most likely to be required to provide a true solid-state micromechanical gyro with optical readout. At this time, the technology to make a very small, accurate gyro does not exist, but advances in integrated optics are already under development in the communications industry.

A potentially promising technology, which is in its infancy stages, is inertial sensing based upon cold atom interferometry.[18,19] A typical atom de Broglie wavelength is many times smaller than an optical wavelength, and because atoms have mass and internal structure, cold atom interferometers are extremely sensitive. Accelerations, rotations, electromagnetic fields, and interactions with other atoms change the atom interferometric fringes. This means that atom interferometers could make the most accurate gyroscopes, accelerometers, gravity gradiometers, and precision clocks, by orders of magnitude. If this far-term technology can be developed, then it could result in a 2 to 5-meter/hr navigation system without GPS, in which the accelerometers are also measuring gravity gradients.

Figure 6, "Current Accelerometer Technology Applications," gives a comprehensive view of the accelerometer bias and scale-factor stability requirements for various mission applications and what type of accelerometer is likely to be used in current applications. The accelerometer requirements assume there are no GPS measurements available during the mission.

Current applications are still dominated by electromechanical sensors, not only because they are

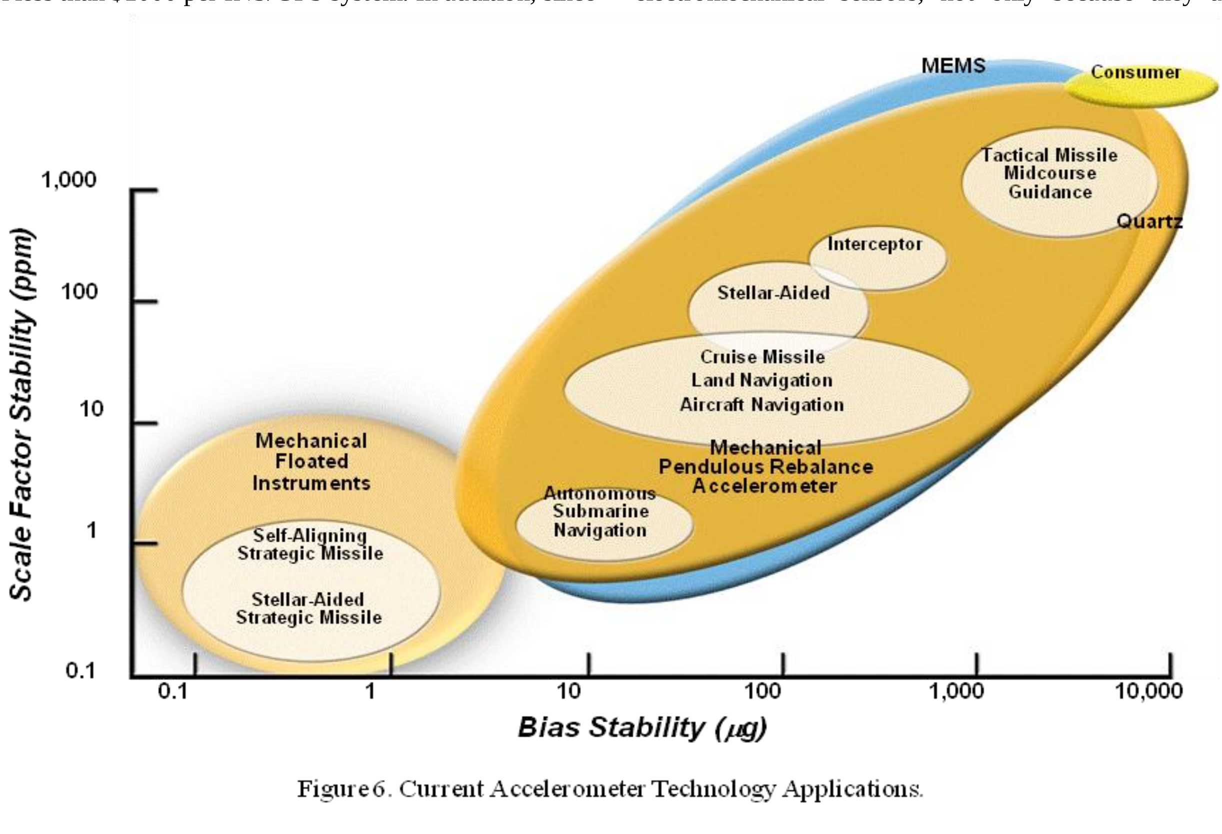

Figure 6. Current Accelerometer Technology Applications.

generally low-cost for the performance required, but also because no challenging alternative technology has succeeded, except for quartz resonators, which are used in the lower-grade tactical and commercial applications. MEMS accelerometers have impacted the consumer market.

In the near-term, it is expected that the lower performance end of the accelerometer application spectrum will be dominated by micromechanical accelerometers. As in the case for gyros, the military market will push the development of these sensors for applications such as "competent" and "smart" munitions, aircraft and missile autopilots, short-time-of-flight tactical missile guidance, fire control systems, radar antenna motion compensation, "smart skins" using embedded inertial sensors, multiple intelligent small projectiles such as flechettes or even "bullets," and wafer-scale INS/GPS systems. Higher performance applications will continue to use mechanical accelerometers and possibly resonant accelerometers based on quartz or silicon. Quartz resonant accelerometers have proliferated widely into tactical and commercial (e.g., factory automation) applications. Silicon micromechanical resonator accelerometers are also being developed. Both of these technologies have possible performance improvements.

As in the case of gyro projections for the long term future, MEMS and integrated optics technology for accelerometers will dominate the entire low- and medium-performance range.

The rationale behind this projection is based on exactly the same premises as for the gyros. However, it is likely that the far-term accelerometer technology projections will be realized years sooner than the gyro.

As for total system cost projections, they are a function of inertial instrument technology and performance requirements. IFOG systems have the potential for far lower cost than laser gyro systems. MEMS/integrated optics systems offer the lowest cost in high volume production.

The ability of silicon-based MEMS devices to withstand high "g" forces has been demonstrated in a series of firings in artillery shells where the g forces reached over 6500 g. These small MEMS-based systems have provided proof-of-principle that highly integrated INS/GPS systems can be developed and led to a program where the goal was a system on the order of 3 in^3, or 2 in^3 for the INS alone.[20] The size goals were met but the performance goals are still being pursued. The current status of a typical MEMS INS is represented by the Honeywell HG1900 with a weight <1 lb., volume <20 cubic inches, power <3 watts, gyro bias of 1 to 30 ^{o}/hr, and gyro angle random walk of 0.1 $^o/\sqrt{hr}$. This system is in production. Another is the HG1930 which has a volume of <4 cubic inches, a gyro bias of 20^0/hr and a gyro random walk of 0.15 deg/$\sqrt{hr}$ (Fig. 7).[21] The volumes compare with tactical grade RLG and IFOG systems with a volume of about 34 in^3. Other manufactures also have MEMS systems. If performance improvements can be made, successful manufacturers will dominate the market.

Fig. 7 Honeywell MEMS IMUs.

5. INS/GPS Integration

Many military inertial navigation systems could be replaced with less accurate lower cost inertial systems if it were guaranteed that GPS would be continuously available to update the inertial system to limit its error growth. However, given the uncertainty in the continuous availability of GPS in most military scenarios, an alternate way to reduce the avionics system cost is to attack the cost issue directly by developing lower-cost inertial sensors while improving their accuracy and low noise levels, as previously described. The benefits and issues in using INS augmented with GPS updates, including a discussion of interference issues, have been presented in many references. Systems currently in use tend to be classified as either "the loosely coupled approach" or "the tightly coupled approach" (Figs. 8 and 9).[22] If other sensors (such as Doppler velocity or position fixes) are available, they are additional inputs to the Kalman filter.

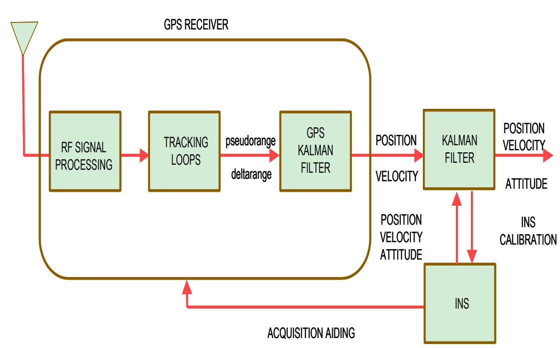

Fig. 8 Loosely-coupled approach.

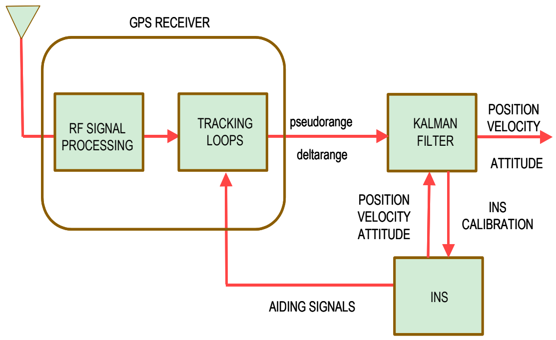

Fig. 9 Tightly-coupled approach.

The most recent research activity is a different approach called "deep integration" (Fig. 10).[23-26] In this approach, the problem is formulated directly as an estimation 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 are derived directly from the assumed dynamical models, measurement models, and noise models. The solution employs a nonlinear filter that operates efficiently at all jammer/signal (J/S) levels and is a significant departure from traditional extended Kalman filter designs. The navigator includes adaptive algorithms for estimating post-correlation signal and noise power using the full correlator bank. 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.

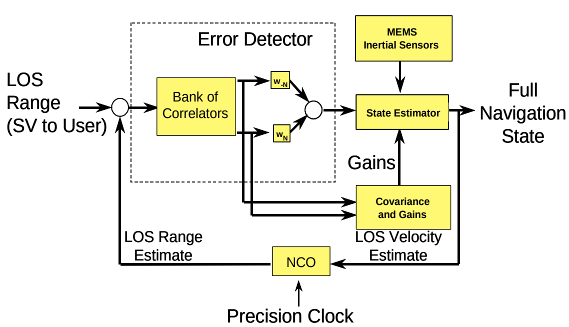

Fig. 10 INS/GPS deep integration.

In this 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 distances to all satellites in view is fully accounted for. This minimizes problems associated with unmodeled satellite signal or ephemeris variations and allows for full Receiver Autonomous Integrity Monitoring (RAIM) capability.

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 70-75 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, such as an INS. 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 root-mean-square line-of-sight delay error.

Experiments have shown an improvement in code tracking of about 10 to 15 dB in wideband A/J capability for this architecture. Another 5 dB might be possible with data stripping to support extended predetection integration. Therefore, it would be expected that Deep Integration might be used in future implementations with a modest increase of software and hardware.

Honeywell and Rockwell Collins have created a joint venture, Integrated Guidance Systems LLC, to market and produce a series of deep integration guidance systems, Fig. 11. The IGS-202, for example, is G-hardened for artillery applications (15,750G), has a volume of 16.5 cubic inches, weighs< 1.25 lb, is based on the 1930G Honeywell MEMS IMU, and with deep integration and 2-channel digital nulling, the system supposedly has 80-90 dB J/S against a single jammer. The IGS-250 has a volume one-half of the IGS-202.[21]

Fig. 11 Integrated Guidance Systems INS/GPS.

6. Simulations

In this section two specific scenarios are simulated. The first is to show the significant payoff in performance when

Doppler velocity measurements are added to a GPS/INS system that is subjected to jamming.

The second scenario is to show the advantages of deep integration in a jamming scenario of a precision guided munition. Both scenarios are described in full detail in Ref.[22]

6.1 Helicopter Performance in Jammer Vicinity

This scenario is meant to depict a helicopter on a scouting mission with and without Doppler velocity aiding. The helicopter closely follows the terrain in order to avoid detection. The resulting flight profile has high levels of acceleration and jerk. The jamming scenario is as follows for this mission. GPS measurements were available until on-board estimates of IMU calibration and alignment had reached steady state. At that point, GPS was assumed to be jammed. The mission continued for another 19 minutes as shown in Fig. 12. It will be seen that velocity measurements make a considerable difference in performance.

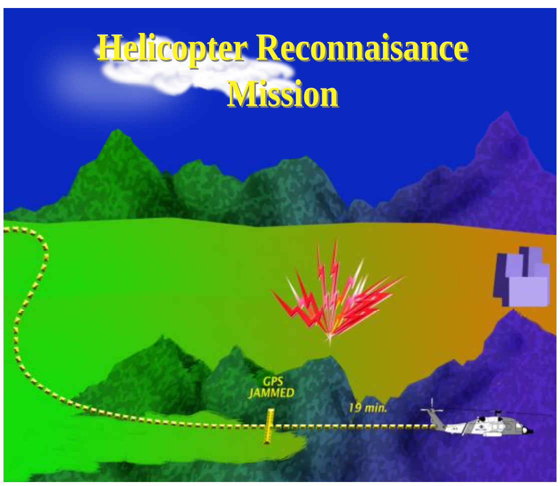

Fig. 12 Helicopter reconnaissance mission.

Near the end of the mission, the task of the helicopter is to define coordinates of a target at some distance (8 km) from its own position using an on-board sensor. The sensor is pointed using the inertial system. The error in target location coordinates is thus a combination of helicopter position error, plus the error due to INS misalignment pointing error multiplied by the range to the target.

Fig. 13 shows the errors in helicopter position and target location as a function of the errors in two tightly-coupled GPS/INS systems when no ground-speed Doppler measurements are included in the navigation solution. The INS system errors modeled are representative of either a 10-NM/hr or 1-NM/hr error growth rate inertial system. The pointing error is negligible in both INSs compared with the helicopter position error so that the target location error and the helicopter position errors are essentially the same. The target location errors for the 10-NM/hr and 1-NM/hr systems are thus 2760 and 192 meters, respectively.

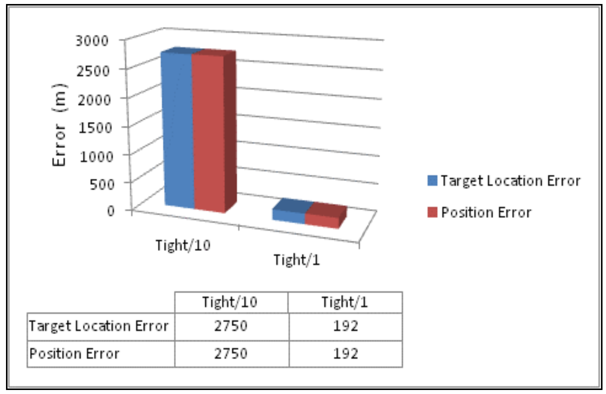

Fig. 13 Position errors 19 minutes after GPS loss.

Fig. 14 shows the errors when the navigation system is aided with ground-speed Doppler measurements. Dramatic results for both a 10-NM/hr and 1-NM/hr inertial system are shown in the figure. As expected, the Doppler ground-speed measurements slow the error growth that is seen with the unaided inertial system. The errors in these velocity measurements integrate into growing position errors so they are not equivalent to GPS, which provides position as well as velocity. But they provide much better results than the inertial instruments whose measurements must be integrated twice before yielding position. The improvement with the Doppler ground-speed sensor is clear. Note that when aided by these measurements, the performance of the 10-NM/hr system is nearly the same as that of the 1-NM/hr system, 21 and 14 meters, respectively. Because the helicopter position error is now so small, the pointing error begins to make a noticeable contribution to target location error, particularly in the 10-NM/hr INS where the position error is 17 m and the resultant target location error is 21 m.

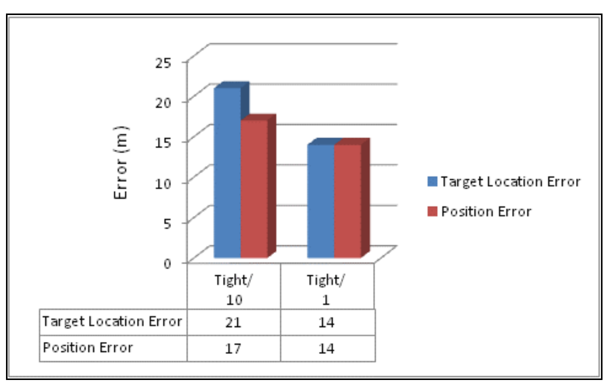

Fig. 14 Position errors with Doppler measurements.

6.2 Precision Guided Munition Scenario

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 NM. The altitude profile is plotted in Fig. 15.

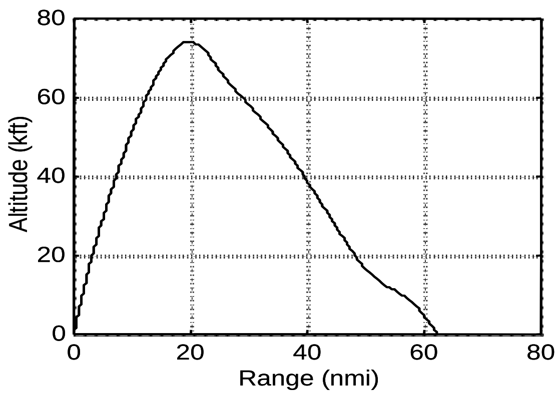

Fig. 15 Precision guided munition altitude profile.

A single wideband Gaussian jammer was placed 5 NM 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 Fig. 16.

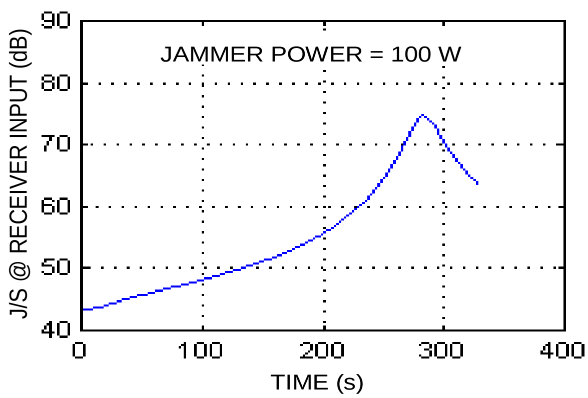

Fig. 16 PGM scenario: J/S versus time.

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 root-mean-square (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 Fig. 17. Comparing the results in the figure, it can be seen that the deeply integrated system offers significant improvement over the traditional tightly coupled system for wideband jamming. As an example, a 100-W wideband jammer results in a CEP of 11 m for the deeply integrated system, compared with a CEP of 120 m 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.

In the limit as the jammer power approaches zero, 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 the 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 process measurements, and both systems are operating in a free inertial mode where the CEP is determined solely by initial navigation errors and inertial sensor errors.

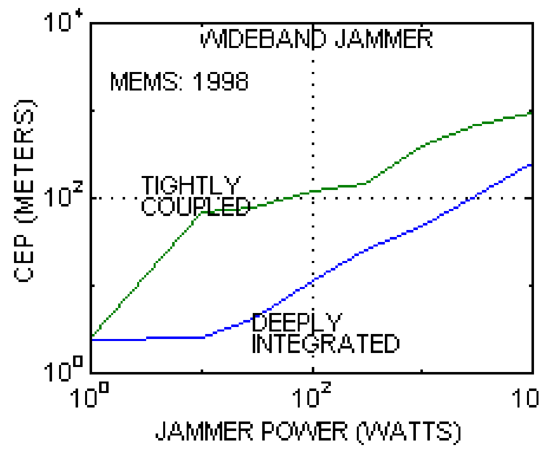

Fig. 17 CEP versus wideband jammer power.

7. Bluefin-11 example of environmental GPS denial

Bluefin-21 is a deep-diving submersible that has been used in the search for MH370. It is 5 m long, weighs 800 Kg, can travel at 7 kilometers/hr, has an endurance of 25 hours, and has a depth range of about 4,500 meters. The "21" refers to the vehicle diameter of 21 inches, which is the standard diameter of US torpedoes.[27]

The vehicle can be equipped with many different sensors such as side scan sonar, synthetic aperture sonar, multibeam echosounders, sub-bottom profiler, video camera, still camera, and other scientific sensors.

In order to achieve high navigation accuracy at great depths during the very long missions, a unique combination of devices is used. First, a military GPS P(Y) code receiver is used for navigation system initialization in conjunction with a RLG strapdown inertial navigation system that has a gyro bias turn-on to turn-on uncertainty of 0.005 deg/hr. A pressure sensor measures depth. The systems are operated in a loosely-coupled architecture. Of course, as soon as the vehicle submerges, GPS is unavailable and the vehicle must depend on its inertial navigation system to descend to the desired search area.

The vehicle has a Doppler Velocity Log (DVL) that is used in the Kalman filter once the DVL locks onto the bottom floor of the ocean. As was shown in the previous section, Doppler velocity has a very high payoff in maintaining navigation accuracy with an INS and no GPS.

However, the extremely long mission times also require search position accuracy beyond the capability of INS/Doppler alone. An Ultra Short Baseline Transponder (USBL) is used to provide position updates.[18] The surface USBL system calculates the absolute position of the Bluefin-21 (latitude and longitude) by sending and receiving an acoustic signal to and from the Bluefin-21. USBL measurements are better than 1% of the slant range. The vehicle position is then transmitted via an acoustic communication link allowing the Bluefin-21 to update its position estimate. Between USBL updates the Bluefin-21 navigates using its INS and DVL to meet mission requirements without GPS.

8. Conclusions

Recent progress in INS/GPS technology has accelerated the potential use of these integrated systems, while awareness has also increased concerning GPS vulnerabilities to interference. Many uses will be found for these new systems. In parallel, lower-cost inertial components will be developed and they will also have improved accuracy. Highly integrated A/J architectures for INS/GPS systems will become common, replacing avionics architectures based on functional black boxes where receivers and inertial systems are now treated as stand-alone systems.

It is expected that the use of INS/GPS systems will proliferate and ultimately result in worldwide navigation accuracy better than 1 m, which will need to be maintained under all conditions. See Fig. 18 for possible examples.

Fig. 18 Examples of potential applications.

References

1. Shepard D, Bhatti J, Humphreys T. Drone Hack, GPS World, Aug. 2012: 30-33.
2. Divis D. GPS Spoofing Experiment Knocks Ship off Course, Inside GNSS, 31 Jul. 2013: 1-3.
3. Grabowski J. Personal Privacy Jammers, GPS World, Apr. 2012: 28-37.
4. Gibbons G. Editor. Online GPS Jammer Sales Draw Attention of FCC, ION Newsletter, Vol. 21(3), Fall 2011: 5.
5. Congressional Budget Office. The Global Positioning System for Military Users: Current Modernization Plans and Alternatives., Oct. 2011.
6. Lachapelle G. High Sensitivity GNSS Limitations in RF Perturbed Environments, NATO STO Lecture Series SET-197, Navigation Sensors and Systems in GNSS Degraded and Denied Environments, Oct. 2013.
7. Raquet J. Navigation using Pseudolites, Beacons, And Signals of Opportunity, NATO STO Lecture Series SET-197, Navigation Sensors and Systems in GNSS Degraded and Denied Environments, Oct. 2013.
8. Hopkins R, Barbour N. Contemporary and Emerging Inertial Sensor Technologies, NATO STO Lecture Series SET-197, Navigation Sensors and Systems in GNSS Degraded and Denied Environments, Oct. 2013.
9. Hopkins R, Gustafson D, Sherman P. Miniature Augmentation Sensors in GNSS Denied Navigation Applications, NATO STO Lecture Series SET-197, Navigation Sensors and Systems in GNSS Degraded and Denied Environments, Oct. 2013.
10. Veth M. Nonlinear Estimation Techniques for Navigation, NATO STO Lecture Series SET-197, Navigation Sensors and Systems in GNSS Degraded and Denied Environments, Oct. 2013.
11. Schmidt G, Phillips R. INS/GPS Integration Architectures, NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, Mar. 2011.
12. Divis D. Air Force Proposes Dramatic Redesign for GPS Constellation, Inside GNSS, May/June 2013: 20-24.
13. NAVSTAR-GPS Joint Program Office. NAVSTAR GPS User Equipment, Feb. 1991.
14. Mahmood S. Analysis of Differential Global Positioning System (DGPS) Techniques and GPS Jamming on Precision Guided Munition (PGM) Performance, NATO/AGARD MSP Meeting, Technologies for Precision Air Strike Operations in Rapid Reaction and Localized Conflict Scenarios, Seville, Spain, AGARD CP-576, June 1996.

15. Sklar J. GPS Capability Projections, Defense Science Board 1996 Summer Study Task Force on Tactics and Technology for 21st Century Military Superiority, Vol. 3, Oct. 1996: III.43-III.53.
16. Schmidt G. INS/GPS Technology Trends, NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, Mar. 2011.
17. Groves P. Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems, 2nd ed. Boston: Artech House, 2013: Chapters 5, 12, 18.
18. Kasevich M, Salomon C.-Editors. Special Issue: Quantum Mechanics for Space Applications: from Quantum Optics to Atom Optics and General Relativity, Applied Physics B, Vol. 84, Aug. 2006.
19. Zatezalo A, Vuletic V, Baker P, Poling T. Bose Einstein Interferometry and Its Applications to Precision Undersea Navigation, IEEE/ION PLANS 2008, Monterey, CA, 2008:940-950.
20. Barbour N, Hopkins R, Kourepenus A. Inertial Navigation Sensors and Inertial MEMS Systems and Applications, NATO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, Mar. 2011.
21. Honeywell, Inc., HG1900 MEMS IMU, DFOISR # 05-S-0725 and HG1930 MEMS IMU, DFOISR 05-S-0723; and Integrated Guidance Systems LLC, "IGS-2xx series, Deeply Integrated Guidance Family," on www.igsllc.com. Cited Apr. 9, 2010.
22. Schmidt G, Phillips R. INS/GPS Integration Architecture Performance Comparisons, NATO RTO Lecture Series, RTO-EN-SET-116, Low-Cost Navigation Sensors and Integration Technology, Mar. 2011.
23. Gustafson D, Dowdle J, Elwell J, Flueckiger K. A Nonlinear Code Tracking Filter for GPS-Based Navigation, IEEE Journal of Selected Topics in Signal Processing, Vol. 3(4), Aug. 2009: 627-638. Also, see U.S. Patent 6,331,835 B1, December 18, 2001.
24. Gustafson D, Dowdle J. Deeply Integrated Code Tracking: Comparative Performance Analysis, Institute of Navigation GPS/GNSS 2003, Portland, OR, 2003. Also Draper Laboratory Report P-4159.
25. Gustafson D, Dowdle J, Flueckiger K. A Deeply Integrated Adaptive GPS-Based Navigator with Extended Range Code Tracking, Draper Laboratory Report P-3791, Cambridge, MA, Jan 2000. Also, IEEE PLANS Conference, San Diego, CA, Mar. 2000.
26. Gustafson D, Dowdle J, Flueckiger K. A High Antijam GPS-Based Navigator, Draper Laboratory Report P-3776, Cambridge, MA, Jan. 2000. Also, Institute of Navigation National Technical Meeting, Anaheim, CA. 2000.
27. www.Bluefinrobotics.com (retrieved June 19, 2014).

George T. Schmidt is a Distinguished Lecturer and Vice President Member Services, IEEE Aerospace and Electronic Systems Society and an Avionics Consultant. He received his SB, SM, and ScD degrees from the Massachusetts Institute of Technology (MIT). He is an IEEE Life Fellow and an AIAA Fellow. His research interests are guidance, navigation, control, and dynamics.