THE JOURNAL OF NAVIGATION (2005), **58**, 419–432. © The Royal Institute of Navigation
doi:10.1017/S0373463305003346 Printed in the United Kingdom

Combating GNSS Interference with Advanced Inertial Integration

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There are many scenarios where an integrated INS/GNSS navigation system may be required to operate in a high interference or weak signal environment. The GPS receiver may exploit the inertial aiding by operating with narrow tracking loop bandwidths in order to increase interference resistance. However, where a low grade INS is used, wider bandwidths are desirable to calibrate the INS errors effectively. This is important for GPS tracking loop aiding and sole-means inertial navigation during jamming. To obtain both effective INS calibration and jamming resistance, an adaptive tightly-coupled (ATC) INS/GPS integration architecture has been developed. The ATC technique has been assessed by simulation, showing that it provides a significant anti-jam margin over an INS/GPS with fixed tracking bandwidths selected for INS calibration. Compared to the deep (or ultra-tightly-coupled) integration techniques currently under development, ATC is a low cost anti-jam integration technique as it does not require a complete re-design of the navigation architecture. When there is too much interference for any GNSS signals to be tracked, the INS provides sole-means navigation. Thus, it is important to optimise the calibration of the INS when GNSS signals are available. To this end, the effects of estimating higher order inertial instrument errors and satellite range biases within the INS/GPS integration filter have been assessed.

KEY WORDS

1. INS. 2. GPS. 3. GNSS. 4. Integrated Navigation.

1. INTRODUCTION. An inertial navigation system (INS) operates continuously (bar hardware faults) and provides a high bandwidth (>50 Hz) output with low short term noise. It also provides effective attitude, angular rate and acceleration measurements as well as position and velocity. However, the accuracy of an inertial navigation solution degrades with time as the noise and biases on the inertial instrument outputs are integrated through the navigation equations. For many applications, such as guided weapons, general aviation and road vehicle navigation, low cost inertial measurement units (IMU) are used. These IMU exhibit relatively large errors, causing a stand-alone navigation solution to decay rapidly. However, there is scope to calibrate these errors, enabling an aligned INS to provide a useful navigation solution stand-alone for a couple of minutes.

Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS), provide a high accuracy (~5 m) position solution that does not drift with time. The GNSS navigation solution is noisier than that of an INS, has a lower bandwidth (~1Hz) and does not normally include attitude. GPS and INS are thus complementary, so an integrated INS/GNSS navigation system combines the advantages of both technologies. The INS provides the core navigation solution, whilst the GNSS measurements are used to correct and calibrate the INS via an integration algorithm. INS/GPS is readily suited to traditional inertial navigation applications such as ships, aircraft and long-range missiles. However, as the cost of IMU and GPS hardware drops, the range of applications for INS/GPS technology is expanding. In particular, a major drop in the costs of IMUs over the next few years is likely as micro-electro-mechanical systems (MEMS) technology matures. Newer applications include road vehicles, trains, short-range guided weapons, unmanned air vehicles (UAVs) and personal navigation.

There are many scenarios where an integrated INS/GPS navigation system may be required to operate under low signal to noise conditions. These may be divided into three categories:

- Unintentional interference;
- Weak signal applications;
- Deliberate jamming.

Unintentional interference sources include broadcast television, mobile satellite services, ultra wideband communications, over-the-horizon radar and cellular telephones (Carroll, 2001). These present more of a problem to civil GPS users, who only have access to one frequency. The open-access GLONASS signals are on an adjacent frequency to the current open-access GPS signals, so are likely to be subject to the same interference sources. Once the second GPS civil signal and Galileo, which will broadcast open-access signals in two regions of the spectrum, are operational by around 2010, unintentional interference will cause less disruption as the GNSS services will only be interrupted when both frequency bands are subject to interference.

Where the GNSS signals are weak, the carrier power-to-noise densities within the GNSS receiver are similar to those in a jamming environment. Weak signal environments include inside buildings and urban areas with tall buildings and/or narrow streets. Applications such as personal navigation and asset tracking can require operation in these environments.

The deliberate jamming of GNSS signals is a major problem for many military applications. The work presented here is focused on guided weapons using low cost inertial sensors and GPS. However, it is also largely applicable to any INS/GNSS system incorporating a low grade IMU which has to contend with unintentional interference or weak signals. From the perspective of INS/GPS integration, jamming or interference levels may be divided into 3 categories:

- Low jamming, under which an INS/GPS navigation system can operate normally;
- Moderate jamming, under which an INS/GPS navigation system can operate effectively with modifications;
- High jamming, under which GPS signals cannot be tracked at all, so the calibrated INS must provide sole-means navigation.

The size of the jamming signal entering the GPS receiver can be reduced by using a controlled reception pattern antenna (CRPA) (e.g. Owen and Wells, 2001; Wells and Owen, 2002; Boasman and Briggs, 2002; Boasman *et al*, 2003) and/or radio frequency filtering techniques. However, these techniques only reduce the jamming to signal ratio; they do not eliminate the effects of jamming altogether. So, for example, a CRPA might reduce a high jamming environment to a moderate jamming environment.

To optimise the INS/GPS navigation performance of a guided weapon or UAV in a jamming environment, four steps must be taken:

- Optimise the alignment and calibration of the INS prior to launch;
- Ensure that the GPS receiver is tracking P(Y) code as soon as possible after launch;
- Implement INS/GPS integration algorithms that allow GPS calibration of the INS to continue under moderate jamming;
- Ensure that the continuing calibration of the INS during INS/GPS integration is as accurate as possible.

The first step is met by implementing optimised transfer alignment algorithms that provide the best possible calibration of the INS errors in the time available for alignment using the host aircraft's (or other launch vehicle's) INS/GPS as the reference. QinetiQ has recently developed a number of improvements to the 'rapid' transfer alignment technique, which require less host vehicle manoeuvring to attain a given accuracy (Groves, 2003; Groves and Haddock, 2001; Groves *et al*, 2002b). To ensure the receiver is tracking P(Y) code as quickly as possible, it must be acquired directly as C/A code is more vulnerable to countermeasures. This requires a number of measures:

- A download of ephemeris and satellite clock data prior to launch;
- Receiver clock calibration prior to launch;
- Position aiding from an INS or a trajectory prediction algorithm during acquisition;
- Use of massively parallel correlation techniques to search all of the phase and frequency offset combinations required for acquisition (e.g. Lee et al, 1999).

QinetiQ (then DERA) demonstrated direct P(Y) code acquisition on a gun-launched munition in 1999 (Groves *et al*, 2002a).

This paper focuses on the third and fourth steps, optimising INS/GPS navigation performance through anti-jam INS/GPS integration techniques and improving the INS calibration using extra Kalman filter states. This technology may be used in addition to a CRPA system to improve performance or in place of one to reduce costs. However, to ensure a robust navigation solution in all signal to noise environments, additional navigation sensors to INS and GNSS are required. For air applications, terrain referenced navigation (TRN) techniques, such as terrain contour navigation and Continuous Visual Navigation are suitable (Handley *et al*, 2003; McNeil *et al*, 2002; Groves *et al*, 2004a). For land applications, a magnetometer and a zero velocity sensor are useful.

Section 2 of this paper presents the theory of INS/GPS integration in a moderate jamming environment, including a description of QinetiQ's adaptive tightly-coupled (ATC) integration technique. Simulation results are presented in Section 3, comprising a validation of ATC and work on the effects of using different INS grades, transfer alignment and varying GPS environments. There follows a review of

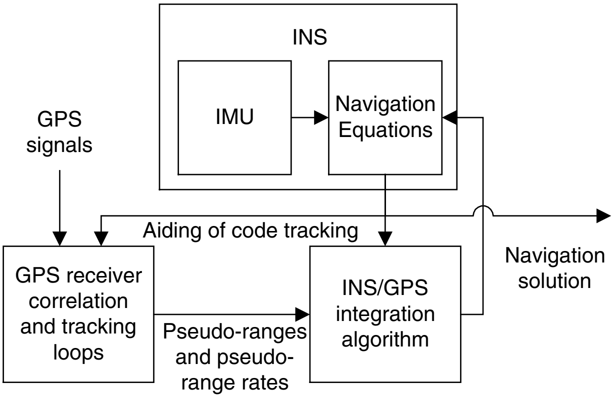

Figure 1. Closed-loop tightly-coupled INS/GPS integration architecture.

implementation issues (Section 4) and a comparison of ATC with deep (or ultra-tightly coupled) integration (Section 5). The paper concludes with work on estimating additional Kalman filter states (Section 6).

2. THEORY.

There are four main classes of INS/GPS integration architecture: uncoupled, loosely-coupled, tightly-coupled and deep. In all cases, the inertial navigation solution, with corrections applied by the integration algorithm, forms the overall navigation solution. This is because the INS operates continuously, whereas the GPS navigation solution is subject to interruption. Regardless of the integration architecture, the inertial navigation solution can be used to aid GPS code tracking where the signal to noise is insufficient for the carrier to be tracked. With a high grade INS, either the raw or corrected navigation solution may be used. With a low grade INS, such as those common in guided weapon systems, only the corrected solution is accurate enough.

In an uncoupled integration, the GPS position is simply used to reset the INS at regular intervals. Calibration of the INS errors is very limited and the reset is often triggered manually. This is generally only used in old systems where GPS has been retro-fitted.

In a loosely-coupled integration, the INS and GPS position and velocity are differenced to form the measurement input to a Kalman filter (e.g. Gelb, 1974), which estimates the INS errors. This technique may be used with any INS and any GPS receiver. However, the gain is limited by the need to account for time-correlated noise on the GPS navigation solution. Also, at least four GPS satellites must be tracked in order to provide the GPS navigation solution with which to calibrate the INS.

In a tightly-coupled integration, the GPS navigation filter is combined into the INS/GPS integration filter, which again is Kalman filter based. This takes as its GPS input the pseudo-range and pseudo-range rate measurements from the GPS antenna to each satellite, measured by the GPS receiver. Figure 1 depicts a closed-loop tightly-coupled INS/GPS integration architecture. In the closed-loop variant, the Kalman filter estimates of the INS errors are fed back to correct the inertial navigation equations function. In the open-loop variant, an independent INS navigation solution is maintained, which is corrected to form the integrated navigation solution. Where the inertial sensors are low quality, closed-loop INS correction is always used as there is no benefit in retaining an independent inertial navigation solution and continuous correction is needed to avoid linearisation errors within the Kalman filter. More details of the tightly-coupled INS/GPS Kalman filter are given in (Groves and Long, 2003a).

The final integration architecture is deep integration, also known as ultra-tightly-coupled. This combines the INS/GPS integration and GPS signal tracking functions into a single estimation algorithm and is discussed further in Section 4.

The response of a GPS receiver to different carrier power-to-noise densities depends on the code and carrier tracking loop bandwidths. However there is a trade-off between noise resistance and response to dynamics. Narrow bandwidth tracking loops are more resistant to noise, making them suitable for moderate jamming environments. Wide bandwidth tracking loops are more responsive to dynamics and provide more frequent statistically independent GPS measurements. Where a low grade INS is used, as in guided weapons, the wider bandwidths are needed to calibrate the INS errors effectively. This is important for GPS tracking loop aiding under moderate jamming and sole-means inertial navigation during high jamming. Thus, the tracking loop bandwidth requirements for GPS receivers in guided weapons are conflicting. The conflict can be resolved by adapting the tracking loop bandwidths to the receiver measured carrier power to noise density (C/N_0). When jamming is low, a default tuning is used which enables carrier tracking to remain in-lock. When the jamming is increased to near the carrier lock threshold, the bandwidths of both code and carrier tracking loops are progressively reduced to enable the higher jamming to be tolerated. This adaptation to jamming will reduce the tolerance to dynamics, so the tracking lock detection algorithms will have to account for dynamics as well as carrier power to noise density. When carrier tracking is lost, the corrected INS navigation solution can be used to aid the code tracking loop's response to dynamics. The INS can also be used to aid carrier tracking, but this has not been studied here as the time synchronisation and INS calibration requirements can be demanding.

Up to a point, the observability of INS error states by a Kalman filter increases with the iteration rate of the measurement update process. However, a basic assumption of Kalman filtering is that the measurement noise is time uncorrelated, whereas the tracking errors on GPS pseudo-range measurements are correlated over time of order 1 second. The pseudo-range rate measurements have a shorter correlation time. Where the interval between measurement updates is less than the tracking noise correlation time, the Kalman filter can become unstable unless the correlated tracking noise is accounted for in some way.

Where the tracking loop bandwidths are varied according to the carrier power to noise density, the pseudo-range and pseudo-range rate measurement correlation times will also vary, with narrower bandwidths giving longer correlation times. This presents a problem in selecting the integration Kalman filter update rate. A fast update rate can result in destabilisation of the Kalman filter under moderate jamming when the GPS receiver narrows its tracking bandwidths. Conversely, a slow update rate will reduce the rate of INS calibration where jamming is low, which can significantly impede the unaided INS performance when GPS signal tracking is lost. This is also a problem for INS/GPS systems that use fixed narrow bandwidth tracking loops to improve jamming resistance as discussed in Section 7 of (Groves and Long, 2003a).

A further complication arises when the Kalman filter corrected INS is used to aid GPS code tracking when carrier tracking is lost. If a fast Kalman filter update rate is used, positive feedback can occur: correlated tracking noise destabilises the Kalman filter, which corrupts the INS navigation solution, which in turn, can potentially take the GPS code tracking out of lock. To avoid this problem, the bandwidth of the Kalman filter's measurement update process should be less than that of the GPS tracking process.

To resolve these problems, QinetiQ has developed ATC INS/GPS integration (Groves, 2000). Using this method, the Kalman filter can be tuned for the low jamming scenario. Then, as the jamming increases and the GPS tracking loop bandwidths are reduced, the gain of the Kalman filter is effectively reduced by weighting the relevant elements of the assumed measurement noise covariance matrix, R, by the current tracking loop bandwidth divided by a threshold bandwidth. Where the bandwidth is above the threshold, no weighting is applied. This R matrix weighting is implemented independently for each satellite signal tracked and for pseudo-range and pseudo-range rate. More details are given in previous papers (Groves and Long, 2003a; 2003b), together with alternative implementations of ATC. This adaptive technique differs from that proposed by Mohamed and Schwarz (1999) and by Hide *et al* (2003) in that their technique adapts the Kalman filter according to measurement residual statistics, which introduces a lag of several seconds in the adaptation.

3. SIMULATION ASSESSMENT OF ATC.

An assessment of adaptive tightly-coupled integration has been conducted using the QinetiQ INS/GPS Integrated Navigation Simulation (QINS). QINS comprises kinematic and INS models, a GPS receiver and satellite model and a reconfigurable set of ATC INS/GPS integration algorithms. The GPS receiver and signal error models are essentially the same as those implemented in the QinetiQ Navigation Warfare Simulator (Gouldsworthy *et al*, 2002). The receiver model is iterated at the rate at which the correlator outputs are accumulated and 'dumped' to the discriminators. It comprises correlator and discriminator models, code and carrier tracking control functions and a receiver clock error model. The GPS constellation model is a simplified version that models circular orbits. For the runs discussed here, signals from 5 GPS satellites were tracked. Tracking lock was detected by comparing the measured carrier power to noise density, C/N_0 against a threshold. The INS error model was loosely based on a low grade (10°/hr specified drift) INS, the Boeing Digital Quartz Inertial Measurement Unit (DQI) (Boeing, 1997). Table 1 lists the inertial instrument errors simulated. An attitude initialisation error of about 2° per axis was also assumed. The INS modelling is discussed in more detail in (Groves and Long, 2003a).

For most of the runs presented here, it was assumed that transfer alignment was performed prior to launch of the weapon. Results from the QinetiQ Transfer Alignment Simulation (QTAS) (Groves, 2003; Groves *et al*, 2002b) were used to initialise the INS attitude and velocity errors and accelerometer and gyro static biases at the start of the INS/GPS simulation. A 'rapid' type transfer alignment over 2 minutes was performed incorporating a ±30° s-weave manoeuvre at 10 ms^{-2} lateral acceleration.

The INS/GPS Kalman filter estimated INS position, velocity and attitude errors; accelerometer and gyro static biases; and receiver clock offset and drift. Scale factor, cross-coupling and gyro g-dependent errors were modelled as correlated noise, with the dynamic biases accounted for as system noise on the corresponding static biases.

Table 1. 10°/hr slave INS inertial instrument errors (root mean square values are averaged over each component and expressed to 2 significant figures.)

Missile INS accelerometer error	rms value	Missile INS gyroscope error	rms value
Static biases	1500 μg	Static biases	10°/hr
Dynamic biases	150 μg	Dynamic biases	1°/hr
Dynamic biases correlation time	60 s	Dynamic biases correlation time	60 s
Scale factor errors	200 ppm	Scale factor errors	350 ppm
Cross-coupling errors	270 ppm	Cross-coupling errors	350 ppm
Random walk	60 μg/√Hz	G-dependent errors	1·0°/hr/g
Incremental quantisation	0·001 m/s	Random walk	1·8°/hr/√Hz
		Incremental quantisation	0·001°

Pseudo-range and pseudo-range rate measurements (where carrier was tracked) were processed at 1 Hz. A 600 s flight profile was used, comprising 30 s of straight and level flight, a pair of ±30° co-ordinated turns at 10 ms^{-2} lateral acceleration, 80 s of straight and level flight, a climb of 200 m over ∼4 s, then straight and level flight.

A series of simulations was conducted to optimise the tracking loop bandwidth adaptation within the ATC INS/GPS integrated navigation system under simulation. Best results were obtained by varying the tracking loop bandwidths as a quadratic function of C/N_0 between and upper and lower threshold (the maximum bandwidth applying above the upper threshold and the minimum below the lower threshold). Further simulations were conducted to determine the optimum C/N_0 thresholds for loss of code tracking lock, both for the adaptive and conventional tightly-coupled cases. If the threshold is set to high, noting that a higher carrier power to noise density corresponds to a lower jamming to signal ratio, then GPS measurements that could potentially aid the integrated navigation solution are rejected. Conversely, if the tracking lock threshold is set to low, false pseudo-range measurements can corrupt the navigation solution before loss of tracking lock is detected. The criterion selected was that the INS/GPS integrated navigation solution with GPS measurements accepted should never be worse than an unaided, but calibrated, inertial navigation solution after two minutes drift. With the 10°/hr INS, this was enumerated as the position error in any axis not exceeding 50 m for more than 30 s while GPS was tracked. Simulations were conducted at a range of jamming levels and tracking loss thresholds, with different noise seeds, to determine the thresholds which robustly met the criterion.

Figure 2 shows the position error of the integrated navigation solution with adapting GPS tracking loop bandwidths and ATC INS/GPS integration. For the first 250 s, the GPS jamming level was set at a constant 8 dB above the code tracking loss threshold (in J/S terms) for the conventional tightly-coupled configuration with fixed GPS tracking bandwidths. An 8 dB margin reduces the effective radius of an interference source by a factor of 2·5. After 250 s, the GPS jamming level was increased sharply to take the receiver out of tracking lock in order to assess the INS error calibration. Although the position errors are larger than for an INS/GPS system in a good signal to noise environment, the navigation performance is significantly better than that of a stand-alone calibrated INS, which is what a standard tightly-coupled system reverts to under that level of jamming. Note that some of the previously

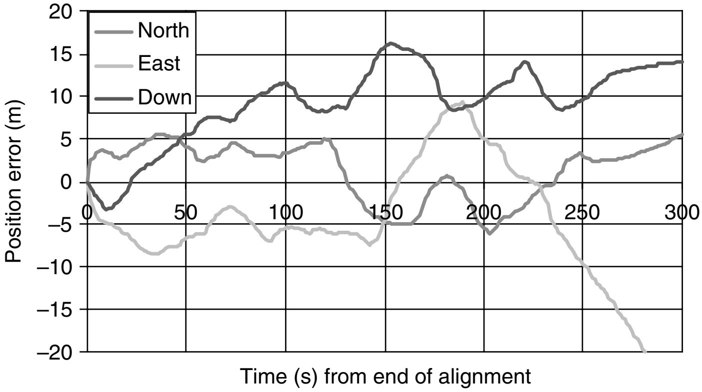

Figure 2. Position error of integrated navigation solution with adapting GPS receiver and ATC INS/GPS integration.

published results (Groves and Long, 2003a; 2003b) were based on over-optimistic estimate of inertially aided signal reacquisition performance.

Where the GPS bandwidths are reduced to resist noise, the navigation system relies on the GPS-corrected inertial navigation solution to maintain code tracking lock in the short term under jamming, with the GPS measurements themselves applying corrections at a low gain. Therefore, a well calibrated INS at the point the jamming is encountered is essential to the success of anti-jam INS/GPS integration. If the INS drift is sufficient to take the GPS receiver out of tracking lock within the time constant of the reduced bandwidth tracking function, the anti-jam integration technique will not work. Consequently, for a guided weapon or UAV, it is essential that a full transfer alignment is performed prior to launch (Groves, 2003; Groves *et al* 2004b). Repeating the previous run with a non-transfer aligned 10°/hr INS, it was found that GPS code tracking lock was lost on all channels 25 to 35 s into the simulation and the navigation performance was essentially that of the raw, uncalibrated, INS.

Comparing different grades of INS, it was found that using a 1°/hr INS did not give significantly improved navigation performance over using the 10°/hr INS. However, performance with a 100°/hr INS was about a factor of two poorer when GPS was tracked and about a factor of five poorer after loss of GPS (Groves and Long, 2003a; 2003b). To determine the effect of the number of satellites tracked on ATC integrated navigation performance, simulations were run with four and seven satellites instead of five, noting that seven satellites was the number of satellites in view at 60° latitude with a 5° masking angle and 24 satellite constellation model. Tracking more satellites was found to improve navigation performance at jamming levels near to the maximum tolerable, but had less effect at more moderate levels.

4. IMPLEMENTATION ISSUES.

Clearly the primary criterion for implementing an adaptive tightly-coupled INS/GPS integrated navigation system is that the GPS receiver adapts its tracking loop bandwidths as a function of the carrier power to noise density (C/N_0). There are three ways of doing this:

- Explict adaptation of the tracking bandwidths as a function of the measured C/N_0;

- Allowing the tracking bandwidths or tracking function gains to be controlled by external software, implemented in the INS/GPS integration processor;
- Implicit adaptation of the bandwidths through use of automatic gain control on the analogue to digital converter without implementing normalised code or carrier discriminators.

Most GPS receivers do not vary their tracking loop bandwidths in response to interference at all. With GPS receiver tracking loops now implemented in software, modifying a receiver to adapt its tracking loop bandwidths is relatively straightforward, technically. However, there are commercial obstacles where the INS/GPS integrator is using a GPS receiver manufactured by another organisation. A number of GPS receivers are now being developed with accumulated correlator outputs and tracking control inputs enabling them to be used with an external signal tracking function. Tracking loop bandwidths do not form part of the standard GPS receiver output messages. However, this is not a major obstacle as the ATC integration algorithm can estimate the bandwidths from the C/N_0 measurements that are standard outputs.

Measurement of the carrier power to noise density can be very noisy at the jamming-to-signal levels at which adaptive tightly-coupled (and deep) integration must operate. This makes it difficult to set the tracking loop bandwidths correctly and determine tracking lock. Comparisons have been made between different C/N_0 measurement techniques (Groves, 2005) with the narrow to wide band power ratio (Van Dierendonck, 1996) found to be most effective. However, to obtain useful C/N_0 measurements near the limit of interference at which ATC operates, averaging times of order 25 s must be used.

When code tracking is lost on an individual channel, it is not necessary to perform a full acquisition process in order to recover the signal. This is because the integrated INS/GPS navigation solution, together with knowledge of the satellite position, enables the pseudo-range to be determined to a few tens of metres. For P(Y) code, this corresponds to a few code chips. Making use of the early, prompt and late correlators from non-tracking receiver channels, these may be searched simultaneously. This allows re-acquisition to proceed with long integration times, combating noise and enabling the acquisition algorithm to operate at marginal signal to noise levels (Groves and Long, 2005). For C/A code, the pseudo-range search region lies within a code chip, so extending the correlator spacing and/or using extended range correlation is the best method of recovering the signal.

In terms of the integration architecture, ATC requires only relatively minor modifications to a standard tightly-coupled INS/GPS integration algorithm. The impact on processor load is negligible. There is also no need to make major change to the interfaces between the different components of the integrated navigation solution. If the integration algorithm controls the tracking loop bandwidths, this can be done at a relatively low data rate, enabling spare capacity in the current control messages to be used. Thus, the adaptive tightly-coupled integration technique is ideally suited to mid-life upgrades of existing systems.

5. COMPARISON WITH DEEP INTEGRATION.

Deep INS/GPS integration (also known as ultra-tightly-coupled) combines GPS signal tracking and INS/GPS integration into a single estimation algorithm (Sennott and Senffner,

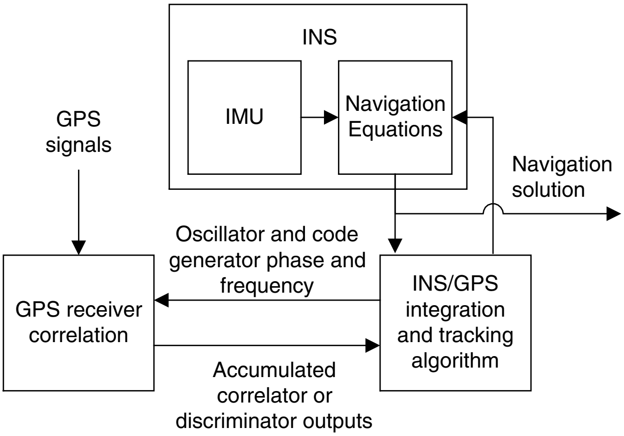

Figure 3. Deep INS/GPS integration architecture.

1997; Gustafson *et al*, 2002, Lukesh, 2002; Beser *et al*, 2002). Figure 3 illustrates this. As with the ATC technique, GPS tracking gains can be adjusted according to the measured carrier power to noise density. However, with deep integration, the INS/GPS integration function adapts implicitly rather than requiring an adjustment algorithm. The deep integration tracking function tracks a navigation solution and receiver clock errors rather than tracking separate phases and frequencies for each signal. Consequently, where more than four satellites are tracked, the signals input to the tracking function are used to estimate fewer quantities than for conventional signal tracking. So, for example, if eight satellites are tracked using vector tracking as opposed to individual tracking, it effectively reduces the tracking noise standard deviation by a factor of $\sqrt{2}$. As shown in (Groves and Long, 2003a; 2003b), the vector tracking inherent in deep integration brings an improvement in anti-jam margin of up to 2dB over that achievable with the ATC technique, depending on the number of satellites that can be tracked.

In tightly-coupled integration, there is a cascade between the tracking loops and integration filter. As discussed above, the integration filter's measurement update interval must be effectively limited to the time constant of the tracking loops to prevent time-correlated measurement noise from corrupting the state estimates. As a result, on each measurement update, the older data from the GPS correlation channels has been de-weighted by the tracking loops, effectively semi-discarding it. With deep integration, this cascade is eliminated, enabling all data from the correlation channels to be weighted optimally and bringing a further improvement in the anti-jam margin of the order of 3 dB. A 15 dB anti-jam margin over a conventional tightly-coupled integration (as opposed to ATC) has been reported in the open literature for deep integration without extended range correlation (Gustafson et al, 2002).

Deep integration requires a complete re-design of the navigation architecture. The integration filter outputs oscillator control commands to the GPS receiver and inputs either discriminator outputs or accumulated correlator outputs. None of these are included in the current GPS interface standards. They also require much higher repetition rates than the current messages. In addition, the GPS, the IMU and the integration and navigation processor(s) must all be tightly time synchronised, otherwise GPS tracking may be lost under high dynamics. The greater the level of dynamics expected, the more precise the timing must be. Timing must also be more precise for inertial aiding of carrier tracking within the deep integration architecture, than inertial aiding of code tracking. The only published demonstration to date of deep integration incorporating carrier aiding used a software GPS receiver, which allows GPS signals to be stored to compensate processing lags (Soloviev *et al*, 2004).

6. ADDITIONAL KALMAN FILTER STATES.

The baseline selection of states estimated by the INS/GPS Kalman filter is the position, velocity and attitude errors, accelerometer and gyro biases and receiver clock offset and drift, a total of 17. Transfer alignment performance can be improved by estimating higher order accelerometer and gyro errors as Kalman filter states (Groves, 2003). Therefore a study has been conducted to assess whether including some of these states is beneficial to INS/GPS integration. This is important where there is jamming or other interference as better INS calibration extends the time over which the corrected inertial navigation solution is sufficiently accurate to aid GPS code tracking and reduces the rate at which the navigation solution drifts when GPS is lost.

Up to 21 additional inertial instrument errors may be modelled as Kalman filter states within QINS. The accelerometer and gyro biases may be separated into separate static and dynamic states. The 'static' instrument biases remain constant from 'turn-on' to the end of a run, but change from run to run. The 'dynamic' instrument biases slowly vary over the course of a few minutes. These are modelled as first order Markov processes within the Kalman filter. 'Static' and 'dynamic' biases are sometimes known as 'turn on biases' and 'in-run bias variation', respectively. The other 15 states are the accelerometer and gyro scale factor and cross-coupling errors. The scale factor error is the error in the instrument output specific force or angular rate directly proportional to its true value. Cross-coupling errors model the x component of specific force or angular rate being sensed by the y and z axis instruments, and so on, as a result of the sensitive axes of the inertial instruments being not quite co-incident with the INS body frame axes. At first sight, there appear to be 6 gyro cross-coupling errors and 6 accelerometer cross-coupling errors. However 3 of these may be eliminated by suitable definition of the INS body frame. Here, the body z axis is defined as the sensitive axis of the z gyro, with the body y axis defined such that the sensitive axis of the y gyro is in the yz plane. This eliminates the x into y, x into z and y into z gyro cross-coupling errors, leaving 3 gyro and 6 accelerometer cross-coupling errors.

To determine the optimal state selection, a series of simulations was run with different combinations of states selected. Where scale factor and cross-coupling errors were not estimated, they were modelled as correlated system noise. Where dynamic bias states were not estimated, the in-run bias variation was accounted for by modelling system noise on the corresponding static bias states. In each case, no jamming was simulated for the first 300 s, then the jamming was increased to take the GPS receiver out of lock. This was followed by 120 s of sole-means inertial navigation. The Kalman filter indicated position uncertainty during sole-means navigation was used as the main measure of how well the INS had been calibrated. The 10°/hr INS model was used with no transfer alignment assumed at the start of the simulation. Three

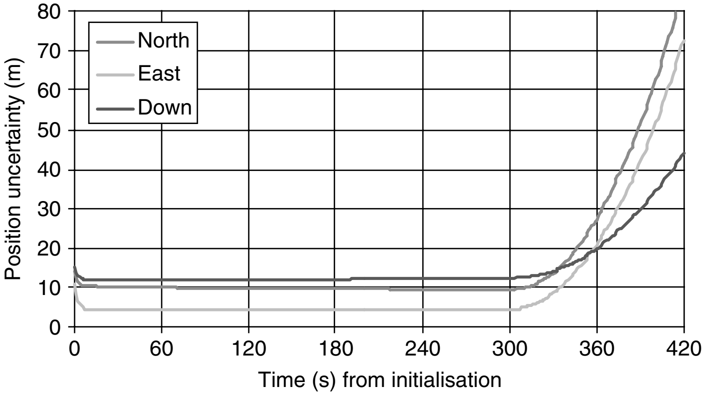

Figure 4. Position uncertainty with the baseline set of Kalman filter states estimated (no jamming for the first 300 s, then GPS jammed out).

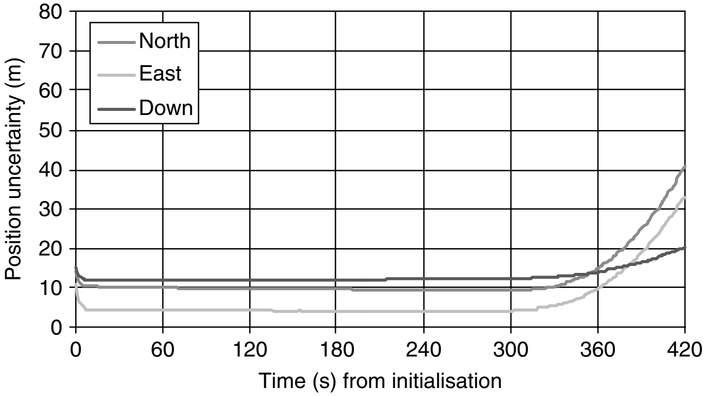

Figure 5. Position uncertainty with the optimal set of Kalman filter states estimated (no jamming for the first 300 s, then GPS jammed out).

different flight profiles were used: one with a stationary vehicle, one with the same manoeuvres as used in the adaptive integration tests and one with those manoeuvres performed twice. It was found that the best performance was obtained by adding the following Kalman filter states to the baseline selection:

- Accelerometer dynamic bias – z component;
- Accelerometer scale factor error – z component;
- Accelerometer cross-coupling errors – x into y, y into x, z into x and z into y components;
- Gyro dynamic biases – x and y components;
- Gyro scale factor errors – all components;
- Gyro cross-coupling errors – all components (y into x, z into x and z into y).

Figure 4 and Figure 5 show the position uncertainties with the baseline and optimal Kalman filter configurations, respectively, over the flight profile with the manoeuvres performed once. As can be seen, the addition of the extra Kalman filter states improved the position uncertainties during sole-means inertial navigation by a factor of about two and also brought a small improvement whilst GPS was tracking. The benefits of estimating the GPS range biases as Kalman filter states were also investigated. The range biases arise from ephemeris errors and residual satellite clock, ionosphere and troposphere errors. With 8 satellites tracked, it was found that estimating the range biases brought a small improvement in position accuracy whilst GPS was tracking, but had no significant effect on INS calibration.

7. CONCLUSIONS.

An adaptive tightly-coupled INS/GPS integration technique has been developed that enables GPS calibration of INS errors to continue under jamming levels significantly higher than tolerated by standard systems. At low jamming levels, it provides much better INS calibration than a fixed narrow bandwidth system. ATC has been assessed by simulation under a range of different conditions. It provides a similar anti-jam margin to those reported for deep integration, whilst requiring less processing power and fewer modifications to established interface standards. Thus ATC is an effective low-cost alternative anti-jam INS/GPS integration technique. In addition, the estimation of additional accelerometer and gyro errors, such as dynamic biases, scale factor and cross-coupling errors has been shown to improve the GPS calibration of low grade INS.

ACKNOWLEDGEMENTS

This work was funded by the Applied Research Programme of the UK Ministry of Defence. The authors would also like to thank colleague Martin Heath. This paper is based on a paper presented at NAV04, London, 9-11 November 2004. Parts of the paper were previously presented at the Institute of Navigation National Technical Meeting in Anaheim, California, USA, 22–24 January 2003 and GNSS 2003 in Graz, Austria (see references below).

REFERENCES

Beser, J., Alexander, S., Crane, R., Rounds, S., Wyman, J. and Baeder, B. (2002). Trunav: A Low-Cost Guidance/Navigation Unit Integrating a SAASM-Based GPS and MEMS IMU in a Deeply Coupled Mechanization. *Proceedings of ION GPS 2002*, Portland, OR.

Boasman, N. J. and Briggs, P. (2002). The Development of an Anechoic GPS Test Facility, *Proceedings of the ION 58th Annual Meeting and CIGTF 21st Guidance Test Symposium*, Albuquerque, NM.

Boasman, N. J., Briggs, P. and Stevenson, J. (2003). Testing INS/GPS/CRPA systems is a simulated jamming environment, *Proceedings of IAIN World Congress*, Berlin, Germany.

Boeing Defence UK (1997). DQI Digital Quartz Inertial Measurement Unit (Specification); Integrated GPS/INS – C-Migits II Users Guide.

Carroll, J. *et al* (2001). Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System. *John A Volpe National Transportation Systems Center report for US Department of Transportation.*

Gelb, A. (1974), Ed. *Applied Optimal Estimation*. The Massachusetts Institute of Technology Press, Boston, MA.

Gouldsworthy, S. N., Groves, P. D. and Wells, M. (2002). High-fidelity model development for navigation warfare simulation studies. *Proceedings of ION GPS 2002*, Portland, OR.

Groves, P. D. (2000). *Adaptive GPS and INS integration system*. International patent WO-01/04971 A1 (filed June 2000, granted in the USA 2005).

Groves, P. D. (2003). Optimising the Transfer Alignment of Weapon INS. *The Journal of Navigation*, **56** 323–335.

Groves, P. D. (2005). GPS signal to noise measurement in weak signal and high interference environments. *accepted for publication in Navigation*: *Journal of the Institute of Navigation*, **52**.

Groves, P. D. and Haddock, J. C. (2001). An All-purpose Rapid Transfer Alignment Algorithm Set. *Proceedings of the 2001 ION National Technical Meeting*, Long Beach, CA.

Groves, P. D., Handley, R. J., and Runnalls, A. R. (2004a). Optimising the Integration of Terrain Referenced Navigation with INS and GPS. *Proceedings of ION GNSS 2004*, Long Beach, CA.

Groves, P. D., Langrish, C. J. and Long, D. C. (2002a). Alignment and Integration of Weapon INS/GPS Navigation Systems. *Proceedings of NATO SET Symposium* '*Emerging Military Capabilities Enabled by Advances in Navigation Sensors*', Istanbul, Turkey.

Groves, P. D., Littlefield, C. A. and Long, D. C. (2004b). The need for transfer alignment in a GPS jamming environment and optimisation for MEMS IMUS. *Proceedings of ION GNSS 2004*, Long Beach, CA.

Groves, P. D. and Long, D. C. (2003a). Adaptive tightly-coupled, a low cost alternative anti-jam INS/GPS integration technique. *Proceedings of the 2003 ION National Technical Meeting*, Anaheim, CA.

Groves, P. D. and Long, D. C. (2003b). INS/GNSS Integration in a High Interference Environment. *Proceedings of GNSS 2003, The European Navigation Conference*, Graz, Austria.

Groves, P. D. and Long, D. C. (2005). Inertially-aided GPS signal re-acquisition in poor signal to noise environments and tracking maintenance through short signal outages. *submitted to ION GNSS 2005*, Long Beach, CA.

Groves, P. D., Wilson, G. G. and Mather, C. J. (2002b). Robust rapid transfer alignment with an INS/GPS reference. *Proceedings of the 2002 ION National Technical Meeting*, San Diego, CA.

Gustafson, D., Dowdle, J. and Flueckiger, K. (2000). A High Anti-Jam GPS-Based Navigator. *Proceedings of the 2000 ION National Technical Meeting*, Anaheim, CA.

Handley, R. J., Groves, P. D., McNeil, P. and Dack, L. (2003). Future Terrain Referenced Navigation Techniques exploiting Sensor Synergy. *Proceedings of GNSS 2003, The European Navigation Conference*, Graz, Austria.

Hide, C., Moore, T. and Smith, M. (2003). Adaptive Kalman Filtering for Low Cost INS/GPS. *The Journal of Navigation*, **56** 143–152.

Lee, W. C., Slimak, G. L., McGraw, G. A. and Kaspar, B. (1999). Fast, Low Energy GPS Navigation With Massively Parallel Correlator Array Technology. *Proceedings of the ION 55th Annual Meeting*, Boston, MA.

Lukesh, J. (2002). "Classic" Ultratight Integration Provides Truly Optimal Carrier Tracking Performance With C/A. *Proceedings of the 2002 ION National Technical Meeting*, San Diego, CA.

McNeil, P., Dack, L., Handley, R. (2002). Terrain Referenced Reversionary Navigation. *Proceedings of Royal Institute of Navigation NAV02* '*GNSS Vulnerability*', London, UK.

Mohamed, A. H. and Schwarz, K. P. (1999). Adaptive Kalman Filtering for INS/GPS. *Journal of Geodesy*, **73** 193–203. (1999).

Owen, J. I. R. and Wells, M. (2001). An Advanced Digital Antenna Control Unit for GPS. *Proceedings of the 2001 ION National Technical Meeting*, Long Beach, CA.

Sennott, J. and Senffner, D. (1997). A GPS Carrier Phase Processor for Real-Time High Dynamics Tracking. *Proceedings of ION 53rd Annual Meeting*.

Soloviev, A., Van Graas, F. and Gunawardena, Sanjeev. (2004). Implementation of Deeply Integrated GPS/Low-Cost IMU for Reacquisition and Tracking of Low CNR GPS Signals. *Proceedings of the 2004 ION National Technical Meeting*, San Diego, CA.

Van Dierendock, A. J. (1996). GPS Receivers. In *Global Positioning Systems: Theory and Applications Volume I (Ed: B W Parkinson, J J Spilker)*, AIAA, Washington DC.

Wells, M. and Owen, J. I. R. (2002). A Digital Adaptive Array Demonstrator for GPS. *Proceedings of NATO SET Symposium* '*Emerging Military Capabilities Enabled by Advances in Navigation Sensors*', Istanbul, Turkey.