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ORIGINAL ARTICLE

Calibrating adaptive antenna arrays for high-integrity GPS

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Abstract A major challenge in using GPS guidance for aircraft final approach and landing is to reject interference that can jam reception of the GPS signals. Antenna arrays, which use space–time adaptive processing (STAP), significantly improve the signal to interference plus noise ratio, but at the possible expense of distorting the received signals, leading to timing biases that may degrade navigation performance. Rather than a sophisticated calibration approach to remove biases introduced by STAP, this paper demonstrates that a relatively compact calibration strategy can substantially reduce navigation biases, even under elevated interference conditions. Consequently, this paper develops an antenna bias calibration strategy for two classes of adaptive array algorithm and validates this method using both simulated and experimental data with operational hardware in the loop. A proof-of-concept system and an operational prototype are described, which implement the adaptive antenna algorithms and deterministic corrections. This investigation demonstrates that systems with adaptive antenna arrays can approach the accuracy and integrity requirements for automatic aircraft landing, and in particular for sea-based landing on board aircraft carriers, while simultaneously providing significant attenuation of interference. Evidence suggests that achieving these goals is possible with minimal restrictions on system hardware configuration—specifically, limitations on the permissible level of antenna anisotropy and the use of sufficient analog-to-digital converter resolution.

Keywords Space–time adaptive processing · GPS adaptive antennas · STAP

This work is respectfully dedicated to the memory of Dr. Herb Rauch, who passed away as this article was going to press.

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Introduction

The satellite-based global positioning system (GPS) is the premier technology for positioning, navigation, and timing. An important research area is to enable and to certify the use of GPS guidance for automatic aircraft landing, particularly under interference conditions. Four key guidance quality requirements for using GPS during automatic landing are accuracy, integrity, availability, and continuity (Rife et al. 2008). This paper focuses on adaptive antenna arrays to mitigate interference, which would otherwise limit availability and continuity. To gain these benefits without degrading accuracy or integrity, careful characterization and calibration of antenna biases are essential. The relationship between fundamental guidance quality requirements and the derived requirement for bias characterization and calibration are summarized in Fig. 1.

There is a broad range of interference mitigation techniques described in the GPS literature, including filtering and signal processing to reduce out-of-band and in-band interference power, automatic gain control to exploit quantization effects of the analog-to-digital conversion process, antenna designs that suppress low-elevation

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signals, and changes to the phase-lock and delay-lock loop filters to improve tracking robustness, including augmentation by inertial measurement units and vector processing in the delay-lock loop; see Spilker and Natali (1996) for further discussion. Controlled reception pattern antenna (CRPA) arrays are among the most aggressive antijam technologies, and it is believed that CRPA arrays implementing space–time adaptive processing (STAP) will be required to mitigate the elevated risk of radio frequency interference to aviation automatic landing (Peterson et al. 2005).

It is well understood that antenna gain and phase response nonlinearity contribute to biases in the tracking estimates of GPS code phase and carrier phase. These biases manifest as non-common mode navigation errors, in this context similar to ionospheric delays, satellite clock errors, multipath, etc. A CRPA array may introduce additional biases in the estimates of code phase and carrier phase, compounding those mechanisms that exist for fixed reception pattern antennas.

Two primary mechanisms that generate biases specific to CRPA arrays are electromagnetic mutual coupling and spatial and temporal filtering. Mutual coupling between the elements of the array changes the electromagnetic response of each antenna and causes biases by increasing the degree of frequency-dependant distortion in the received signals. Biases also are caused by the spatial and temporal weighting used to form the array output signal; incorporating temporal processing, in particular, exacerbates signal distortion and the biases due to that distortion (Compton 1988; Widrow and Stearns 1985).

As illustrated in Fig. 1, the major drawback of CRPA arrays is that they may introduce significant measurement biases that depend on signal arrival direction and which, in the case of STAP, are time varying since the array response continuously adapts to the signal and noise environment. These measurement biases have a direct impact on achieving accuracy and integrity requirements for sea-based automatic aircraft landing using GPS. Bias characterization for typical CRPA hardware and algorithms, as will be discussed subsequently in this article, indicates that bias magnitudes exceed the limits derived from accuracy and integrity requirements. In order both to mitigate interference and to reconcile all guidance quality requirements, bias calibration is essential.

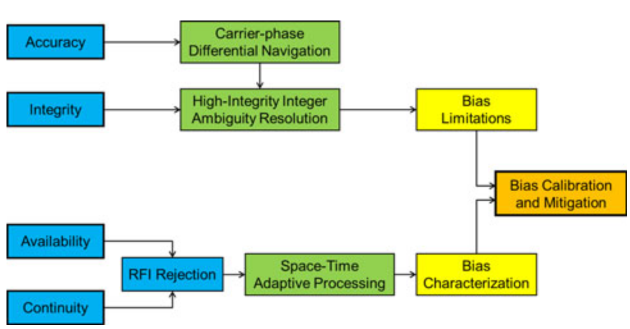


Fig. 1 Summary of accuracy, integrity, and interference rejection requirements and derived requirements for a GPS automatic landing system

Bias calibration is particularly challenging for STAP algorithms. When the antenna pattern is fixed or when the spatial and/or temporal filtering coefficients depend solely on incoming signal direction and frequency, then the biases likewise are fixed and can be calibrated and removed either by equalization filters or by measurement-domain compensation (Fante and Vaccaro 1998, 2000; Kim et al. 2004a). In contrast, adaptive spatial and/or temporal filtering reacts also to the sensed signal and interference environment, which causes the biases no longer to be deterministic. This nondeterministic behavior significantly complicates mitigation of STAP biases. STAP algorithms are nonetheless desirable, as these adaptive algorithms provide significantly greater attenuation of interference than that from single antenna and deterministic CRPA signal processing.

Existing solutions for calibrating the biases introduced by STAP algorithms are generally impractical to implement in operational systems. Among the solutions for mitigating navigation biases associated with adaptive antenna, arrays are frequency-domain antenna equalization (Kim et al. 2004b), constraints on the adaptive filter coefficients (Fante and Vaccaro 2000; Junqueira et al. 2000), and optimum adaptive filtering that considers the in situ manifolds of the receiving antenna array (O'Brien and Gupta 2008). The disadvantages of these approaches include signal processing complexity, sensitivity to measurement or antenna modeling imperfections, reduced interference rejection capability, and the requirement for detailed and precise antenna array characterization. In fact, most of the proposed approaches require in situ manifolds of the antenna over the bandwidth of the incident signals, depend on real-time access to the adaptive weights for equalization, or place extra constraints in the weighting algorithms. In contrast, the current approach is free of these limitations.

Although it has been believed that a sophisticated calibration approach would be necessary to remove biases introduced by STAP antenna arrays, this paper demonstrates that a relatively compact calibration strategy based on deterministic CRPAs can be used to reduce navigation biases substantially, even under elevated interference conditions. Specifically, a combination of simulation and experiment is used to demonstrate that the proposed bias calibration strategy can reduce GPS timing errors introduced by adaptive antenna array processing to levels sufficient to support the guidance quality requirements for sea-based automatic aircraft landing.

The remainder of this paper is organized as follows. The next section reviews STAP algorithms and their application to a GPS receiver. This is followed by characterization of code phase and carrier phase measurement biases and evaluation of a deterministic measurement-domain equalization technique. Next comes limited experimental verification of bias predictions and equalization performance. Finally, there is a description of a proof-of-concept system and an operational prototype, which would achieve the accuracy, integrity, availability, and continuity requirements for a GPS automatic aircraft landing system.

Adaptive spatial and temporal arrays

Adaptive directional antennas can point electronically to each GPS satellite while nulling some number of spatially distributed jammers. The characteristics of the antenna beam pattern are determined by a set of weighting coefficients that may be computed either deterministically or adaptively. This section describes two widely applied adaptive algorithms that were used in the current CRPA bias mitigation study.

Adaptive CRPA algorithms are perhaps most easily defined by contrasting them to deterministic CRPA algorithms. A deterministic CRPA increases gain in one or more look directions, depending upon the number of signals being tracked by the beamformer. An additional step of interference detection and localization can produce nullsteering constraints, which significantly reduce the array gain in the direction of undesired signals. However, in practice, this method of nullsteering has difficulties because performance falls off dramatically with only small errors in interference localization (Gromov 2002).

Adaptive algorithms automatically control sidelobes and steer nulls without the same sensitivity to small interference localization errors. Adaptive array processing increases SINR by using feedback to optimize some characteristic of the array output. Suppression of narrowband or continuous-wave interference can be achieved by adaptive spatial filtering. Greater interference rejection, particularly of multiple, high power, or wideband sources, can be realized by incorporating temporal filtering as well, for example with a tapped-delay line antenna array. In order to maximize availability and continuity, the best choice of weighting algorithm for the CRPA array is STAP, because it provides the greatest improvement in SINR.

The goal of any multielement antenna array is to combine received signals in such a way that the ratio of desirable to undesirable content at the array output is maximized. A composite array output signal $s(t)$ is produced by multiplying the signal vector, one sample per antenna element per sampling epoch, by the complex array weight vector, and then summing over the N antenna elements in the array:

$$s(t) = \sum_{j=1}^{N} s_j(t) \cdot w_j(t) = \mathbf{W}^T \mathbf{s}(t) \qquad (1)$$

For an array with temporal as well as spatial extent, signals from the current sampling epoch are added to the signal vector with their previous time neighbors in a first-in/first-out sense; summation then is over K time taps as well. Note that in the subsequent discussion, the explicit time dependence of the array weight coefficients $w_j(t)$ is omitted for clarity. The construction of (1) yields maximum constructive interference in the look direction(s) specified by the weight vector $\mathbf{W}$. Note, also that antenna anisotropy will change the array response and cause the optimal weight coefficients to differ from those calculated by purely geometrical considerations.

An adaptive antenna array uses feedback to optimize some performance index; this is illustrated in Fig. 2, and Compton (1988) may be consulted for further elaboration. "Adaptive" in this context means that the array gain pattern automatically adapts to the signal and noise environment, subject to user-specified constraints. The constraint or optimization criteria broadly can be classified either as maximizing the SINR at the array output or as minimizing the mean-square error (MSE) between the actual array output and the ideal array output. In both of these cases, the array weights adapt to maximize the desired signal and to reject interference.

For this investigation, both classes of adaptation scheme are studied. The MVDR (minimum variance distortionless response) array is in the SINR class of methods (Frost 1972; Applebaum 1976). This algorithm constrains to unity the array gain in a particular look direction while rejecting coherent interference down to the noise floor; the MVDR array also may have side constraints for nullsteering. The LMS (least-mean-square) beamformer is in the MSE class

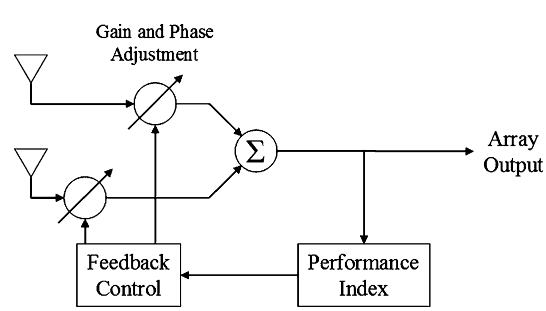


Fig. 2 Adaptive antenna array, after Compton (1988)

of methods (Widrow et al. 1967). This algorithm seeks a weight vector, which causes the array output to match a desired reference signal, while rejecting coherent interference present at the array input. For GPS, the LMS reference signal is the PRN spreading code sequence and the navigation data bits for adaptation that occurs prior to code wipe off and accumulation, or it is just the navigation data bit sequence for adaptation that follows code wipe off and accumulation. The steady-state weight vectors may be computed according to

$$\begin{aligned} \mathbf{W}_{\mathrm{MVDR}} &= \mu \mathbf{\Phi}^{-1}\mathbf{T}^{*} \quad \text{Applebaum/MVDR} \\ \mathbf{W}_{\mathrm{LMS}} &= \mathbf{\Phi}^{-1}\mathbf{S} \quad \text{Widrow/LMS} \end{aligned} \tag{2}$$

This notation comes from Compton (1988). Here $\mathbf{T}^{*}$ is the array steering vector, μ is a signal power scaling parameter, $\mathbf{S}$ is the reference correlation vector, and the signal covariance matrix $\mathbf{\Phi}$ is defined as the expected value of $\mathbf{X}^{*}\mathbf{X}^{T}$ where $\mathbf{X}$ is the measurement vector. In the interference-free case, meaning white noise only, $\mathbf{\Phi}$ is diagonal and the adaptive weight vector $\mathbf{W}$ is equal to the constraint vector scaled according to the gain of each antenna.

Proposed calibration strategy

This section describes a proposed STAP antenna array bias compensation strategy based on a priori code phase and carrier phase calibration. Even though the GPS timing biases are not *exactly cancelled* with this suboptimal approach, we hypothesize that the resulting biases are sufficiently small to meet GPS automatic aircraft landing guidance quality requirements. The described strategy is evaluated in simulation in this section and using hardware in the loop in the following section.

Several methods for antenna calibration and bias compensation have been described previously in the GPS literature, and these methods, while too processing and memory intensive for practical hardware implementation at this time, do suggest a path forward with a carefully considered suboptimal strategy. Consider the example of antenna equalization by frequency domain filtering of the incoming satellite signals in order to undo distortion caused by each antenna's anisotropic gain and phase response. Since in practice, each antenna's response is a strong function of the incoming signal arrival direction, the equalization filters likewise are antenna and line-of-sight dependent. Consequently, antenna equalization requires not only a massive database of filter coefficients but also parallel equalization for each antenna in the array and for each GPS receiver tracking channel (Kim 2007). Furthermore, this filtering must be done at the sampling frequency or as a block processing operation on buffered samples. These considerations result in significant processing demands placed on the receiver.

An alternative method, called deterministic bias compensation, is more amenable to practical implementation. As described in De Lorenzo (2007), deterministic bias compensation applies precomputed code phase and carrier phase bias corrections to the GPS receiver tracking estimates. The corrections are defined as the code phase and carrier phase bias errors from their nominal non-biased values and are determined through a calibration procedure typically including some combination of software simulation, anechoic chamber characterization, and outdoor live signal testing. During operation, the code phase and carrier phase bias corrections can be stored in a lookup table and applied according to GPS satellite signal arrival direction. This method of bias compensation is performed at the tracking loop accumulator output frequency, typically on the order of 0.05–1 kHz, or at the update rate of the navigation filter, typically at 1–10 Hz, rather than at the sampling frequency, which may be 2–20+ MHz depending on signal bandwidth. Thus, deterministic bias compensation in the manner described here significantly reduces the computational burden on the receiver.

Though ease of implementation makes deterministic bias compensation attractive for practical hardware implementation, it previously had been believed that this calibration method would not reduce adaptive array biases to the level required for GPS automatic aircraft landing applications. In the *interference-free* limit, the MVDR and LMS steady-state weights are equal to the weights for the deterministic CRPA; therefore, deterministic corrections, in this circumstance, are exact to the limits of the calibration procedure. However, in the presence of interference, the weights no longer are deterministic and so the biases cannot be precisely calibrated a priori. The remainder of this paper will illustrate that the deviation from the *ideal* exact calibration/interference-free limit is sufficiently small to support sea-based automatic aircraft landing, even under elevated interference conditions.

Simulation-based characterization and results

This section applies GPS software receiver and adaptive antenna algorithms to simulated data in order to characterize the proposed calibration strategy in terms of two performance criteria: (1) magnitude of code phase and carrier phase biases and (2) C/N_0 improvement during interference scenarios. The effectiveness of bias compensation is quantified by comparing code phase and carrier phase errors for the adaptive antenna array to those same errors for the deterministic CRPA array, whose bias errors

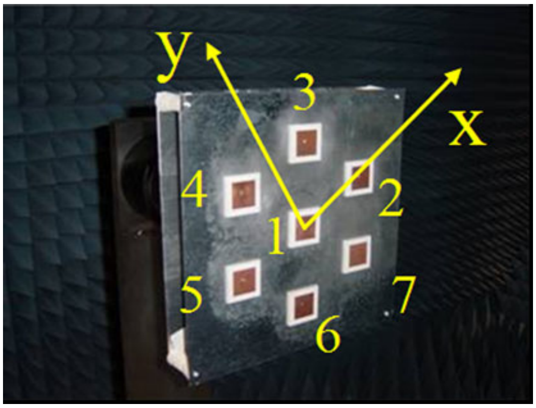


Fig. 3 Seven-element rectangular patch antenna array, in anechoic chamber during testing

are subject to precise a priori calibration. Interference rejection is quantified by comparing tracking output C/N_0 for the adaptive arrays to the tracking output C/N_0 for the deterministic CRPA in the same interference scenario. The following section extends this analysis to testing with hardware in the loop.

Antenna model

A hardware prototype antenna array fabricated at Stanford University was chosen as the model for the simulation portion of this study. This array, shown in Fig. 3, is a seven-element array of L-band single probe-fed right-hand circularly polarized rectangular patch antennas. The array was configured hexagonally with half wavelength (9.5 cm) baselines and has been well described in previous articles (Kim et al. 2004b; Kim 2007). Characterization of this array involved an extensive test program combining high-fidelity finite-element electromagnetic field simulations and anechoic chamber testing and precise gain, and phase response behavior was determined for a 220 MHz band about the GPS L1 center frequency of 1,575.42 MHz. Figure 4 shows the gain and phase response for the array center element, as a function of frequency, for signals received along 10 candidate line-of-sight arrival directions.

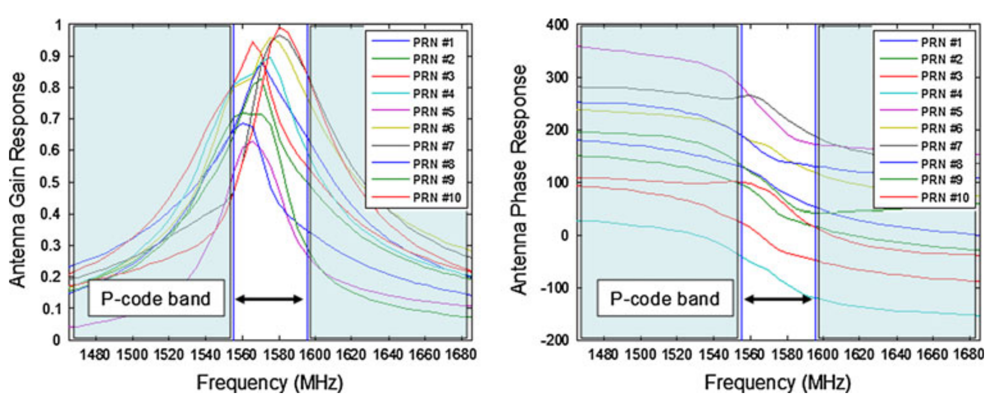
The antennas used in this simulation study were neither designed nor optimized to minimize signal distortion and biases. This means that the code phase and carrier phase biases are larger than would be expected for specially -optimized hardware. For example, specialized survey-grade antennas often will display calibrated biases of much less than 1 cm. Consequently, the results described in this article are conservative and implementing the adaptive algorithms and bias mitigation strategies from this investigation on optimized hardware likely would improve results.

Signal simulation

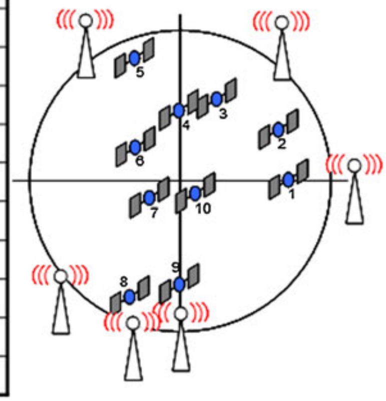
A software-based signal simulator generated synthetic inputs to the GPS receiver. The simulated input signals comprised both desired GPS signals and undesired radio frequency interference. GPS signals with a 10.23 Mchip/s spreading code chipping rate were incident on the array. This chipping rate was chosen not only to correspond to the requirements of a current generation military landing system but also to anticipate the needs of next generation civilian landing systems utilizing signals from modernized GPS satellites and other satellite navigation systems.

Interference from each of six on- or near-horizon wideband jammers was incident on the array to a maximum received J/S power ratio of 50 dB. The number and location of the interference sources, as shown in Fig. 5, were chosen to stress the spatial degrees of freedom of a 7-element antenna array. Greater J/S power ratios were not investigated since the purpose of this study was not to probe the absolute limits of CRPA antijam capabilities per se, but to reveal the C/N_0 advantages of GPS STAP algorithms and to quantify antenna- and algorithm-induced biases and compensation thereof. Increasing the J/S ratio is an area of future work to be undertaken in a follow-on simulation and experimental campaign with improved antennas, modified STAP algorithms, and additional anti-jam signal processing techniques as suggested later in this article.

Fig. 4 L-band patch antenna gain and phase response with respect to signal frequency and arrival direction



PRN	Azimuth	Elevation
1	0	40
2	30	30
3	60	40
4	90	50
5	120	20
6	150	60
7	210	70
8	240	20
9	270	30
10	300	80



RFI	Azimuth	Elevation
1	0	0
2	45	0
3	120	0
4	225	0
5	250	0
6	270	10

Fig. 5 The "standard constellation" of ten satellites as well as six near-horizon jammers

The satellite locations shown in Fig. 5 comprise a "standard constellation" chosen to maintain continuity with previous studies by the authors, and because, for the hardware prototype antennas in this study, the associated arrival directions yield the greatest degree of distortion on the received signals. Since the distortion is greatest for these arrival directions, it leads to extremes in the code phase and carrier phase biases, meaning that the simulation study results represent the worst-case outcome for this array.

Interference rejection performance

For the *interference-free* case, as shown in the upper part of Table 1, there is no C/N_0 performance benefit for the adaptive arrays compared to the deterministic beamforming CRPA, since each weight calculation method produces the same steady-state antenna weighting coefficients. In the presence of wideband interference, as shown in the lower part of Table 1, the adaptive arrays of anisotropic antennas show a clear C/N_0 advantage over the deterministic CRPA. The advantages of adaptive spatial processing are significant, with average increases in C/N_0 of 8.6 dB for LMS and 5.9 dB for MVDR, when compared to the deterministic CRPA. The benefits of adding temporal degrees of freedom by going from a single time tap to three and five time taps are greater still, with further average increases of 2.1 dB for both LMS and MVDR. Finally, where the deterministic CRPA tracks only eight satellites in the ten satellite simulated constellation and several satellites are approaching the limits of unaided carrier phase signal tracking capability, the adaptive arrays maintain lock on nine satellites with significantly greater carrier phase tracking margin. This result underscores the advantage of adaptive array processing, specifically automatic adaptive nullsteering, in maintaining lock on satellites with close angular separation to jammers.

Biases for an idealized receiving array

The adaptive weight computation algorithms investigated here introduce no code phase or carrier phase biases in the receiver's tracking output for the ideal case of isotropic antennas, as discussed by McGraw et al. (2004), O'Brien and Gupta (2008), and De Lorenzo (2007). This finding holds for spatial only processing as well as for space–time adaptive arrays based on MVDR and LMS, and in the interference-free case or in the presence of wideband interference. The significance of this result is that when the signals input to the array processing operation contain no distortion, either through optimized antenna design or following frequency domain antenna equalization, then the space–time adaptive algorithms investigated here introduce no code phase or carrier phase biases.

Bias mitigation performance

Table 1 shows the results, in terms of residual biases for the STAP algorithms, when using corrections determined via calibration of the multi-antenna deterministic CRPA. These results are for anisotropic antennas and interference-free conditions in the upper part of the table, and for the same antennas and six wideband jammers in the lower part of the table.

The preceding analysis used software simulation based on models of actual antenna hardware. This analysis indicates that during conditions of elevated interference, although navigation biases were reduced with a deterministic bias mitigation strategy, the residual biases exceed the limits required by aviation automatic landing. Therefore, combining the results for C/N_0 improvement in the presence of wideband jamming with the findings on post-compensation bias residuals yields the following conclusions: (a) for anisotropic antennas, *deterministic bias compensation* enables adaptive array processing when

Table 1 Deterministic compensation based on CRPA calibration; numerical model of antennas, synthetic signals, and jamming

Averages over 10 satellite constellation		Deterministic CRPA	LMS			MVDR		
Number of time taps		–	1	3	5	1	3	5
No Interference—nominal signal reception conditions								
C/N_o (dB-Hz)		45.7	45.7	45.9	45.8	45.7	45.9	45.7
Residual bias errors using 7-element CRPA calibration; average of absolute value	Code phase	–	0.05 m	0.04 m	0.04 m	0 m	0.03 m	0.07 m
	Carrier phase	–	10.0°	10.0°	10.0°	0.0°	0.1°	0.2°
Six wideband jammers each at $J/S = 50$ dB								
C/N_o (dB-Hz)		26.2	34.8	36.5	36.9	32.1	34.3	34.2
Residual bias errors using 7-element CRPA calibration; average of absolute value	Code phase	–	0.34 m	0.25 m	0.18 m	0.27 m	0.21 m	0.19 m
	Carrier phase	–	8.0°	8.5°	14.0°	2.1°	1.9°	5.7°

interference power is high and accuracy demands are relaxed and (b) when accuracy demands are strictest, it is most beneficial to implement *optimized antenna designs with minimal anisotropy* to fully exploit the interference rejection capabilities of the MVDR and LMS adaptive arrays.

Experimental verification

This section describes limited experimental verification for bias characterization and mitigation with operational hardware in the loop. As mentioned previously, further experimental testing is the subject for follow-on analysis.

Quantification of code phase and carrier phase biases and evaluation of bias mitigation performance were carried with data from live open-air tests using a seven-element antenna array, custom analog hardware, and a dedicated data collection system (Backén and Akos 2006). Analog signal processing was performed by custom-designed front-end hardware downconversion and 2-bit analog-to-digital sampling. The mixing and the A/D conversion for all antenna channels were synchronized to a common clock. Residual antenna-to-antenna timing biases and cable delays were calibrated and removed during post-processing.

The data processed in this investigation were from a 10-min record collected in Sweden on November 7, 2006. The array of commercial off-the-shelf patch antennas had a clear view of the sky and there were 13 GPS satellites above the horizon, of which 10 were utilized in the subsequent analysis. As shown in Table 2, the average tracked C/N_0 was 47.3 dB Hz in single antenna mode and 53.9 dB Hz in 7 antenna CRPA array mode; the average increase of approximately 7 dB with respect to the single antenna system agrees well with simulation results and with theoretical array performance.

In addition to the baseline reception conditions described above, synthetic jamming was created during post-processing analysis. Three CW jammer signals were added to the antenna data records, phased to represent low-elevation transmitters and offset −1 kHz, 0 kHz, and +1 kHz from L1, with each jammer delivering a received J/S power ratio of 40 dB. Dynamic range considerations with the live signal records and the 2-bit A/D converter forestalled investigation at higher J/S levels.

The upper block of results in Table 2 shows bias characterization and mitigation from testing with hardware in

Table 2 Deterministic compensation based on CRPA calibration; seven-antenna receive array, live GPS data—Luleå, Sweden

Averages over 10 satellite constellation		Single antenna receiver	Deterministic CRPA	LMS w/1 time-tap	MVDR w/1 time-tap
No interference—nominal signal reception conditions					
C/N_o (dB-Hz)		47.3	53.9	54.0	53.1
Residual bias errors using 7-element CRPA calibration; average of absolute value	Code phase	–	–	0.29 m	0.17 m
	Carrier phase	–	–	7.0°	4.2°
Three narrowband jammers each at $J/S = 40$ dB					
C/N_o (dB-Hz)		N/A	32.7	49.8	42.9
Residual bias errors using 7-element CRPA calibration; average of absolute value	Code phase	–	–	0.45 m	1.66 m
	Carrier phase	–	–	24.6°	41.4°

the loop in the baseline signal reception conditions, while the lower block of results represents the synthetic jamming scenarios. The data in Table 2 show the code phase and carrier phase bias residuals for the MVDR and LMS adaptive antenna arrays relative to the multielement deterministic CPRA; the analysis method subtracts the code phase and carrier phase estimates while tracking with the adaptive arrays from the estimates while tracking with the deterministic CRPA. Note that this analysis method does not require *absolute* calibration, since it presumes that the code phase and carrier phase biases already would be known from calibration and removed via deterministic compensation, in a manner analogous to the results shown previously in Table 1.

For the antennas used in this study, post-compensation code phase and carrier phase biases using array processing are greater than the biases predicted from simulation. This discrepancy is troubling, and resolution is an area for further study. Primary reasons for the difference likely include (a) the use of real analog signal conditioning hardware and (b) antennas of different design than were specified in simulation.

Considerations for an operational prototype

The simulation analysis and experimental testing with hardware in the loop have demonstrated that a GPS receiver equipped with a multielement space–time adaptive antenna array can reject interference to increase availability and continuity but that it may suffer from code phase and carrier phase biases that impact accuracy and integrity. The unresolved issues that stand in the way of developing an operational prototype of this system are discussed next.

Considerations for interference rejection

In simulation, 4-bit analog-to-digital quantization was employed, which provided sufficient dynamic range to allow rejection of interference at *J*/*S* power ratios up to 50 dB when tracking signals processed by the 7-element adaptive antenna array. Hardware-based testing and simulations, which employed 2-bit A/D converters, showed limited ability to track signals at this *J*/*S* power ratio, although more moderate interference levels were not appreciably impacted. The obvious solution is to specify operational hardware with greater A/D resolution. We consider that many *more* than 4 bits of signal resolution will be required in order to effectively attenuate interference and overcome the bias errors associated with adaptive antenna arrays in an operational prototype.

Another consideration in an operational prototype is to employ additional methods of interference rejection to complement the capabilities of the adaptive array. The most promising of these methods include techniques such as frequency selective notch filters, time domain pulse blanking, automatic gain control to adjust the thresholds at which A/D quantization occurs, inertial aiding to allow reduction of tracking loop bandwidths and adaptive algorithm convergence speeds, and vector processing to take advantage of strong signals or signals well separated from jamming, either in spatial or frequency domains, to maintain lock on weak or jammed GPS signals.

Considerations for bias mitigation

The L-band patch antennas analyzed in simulation and tested with hardware in the loop displayed post-compensation biases that exceed the limits for aviation automatic landing. However, isotropic antennas do not exhibit code phase or carrier phase biases either in the interference-free or in the jammed case for the LMS and MVDR adaptive algorithms investigated here. Antennas that reduce the degree of signal distortion variability as a function of frequency and arrival direction, even if this reduction is not completely to the level of isotropic signal response, could be successful in reducing code phase and carrier phase biases below the level required for high integrity carrier phase integer resolution. Therefore, with a suitably optimized antenna design, STAP would be enabled for carrier phase differential navigation, allowing automatic aircraft landing while providing the benefits of interference rejection to the receiver.

Summary

This paper documents a continuing multiyear effort by Stanford University to enable high accuracy and high integrity GPS navigation with interference rejection provided by a space–time adaptive antenna array. For isotropic antennas and wideband interference, the MVDR and LMS space–time adaptive algorithms showed no navigation biases. For antenna simulation models and actual test hardware, navigation biases were *reduced* with a deterministic bias compensation strategy, although not always to the level dictated by aviation automatic landing requirements. However, the results suggest that for antennas of a suitably improved design, bias mitigation would be successful, enabling space–time adaptive processing in conjunction with carrier phase differential navigation. To achieve this ultimate goal, we recommend using a GPS receiver architecture that implements the features illustrated in Fig. 6, along with additional antijam capability and an improved hardware configuration. This is an area of active further research.

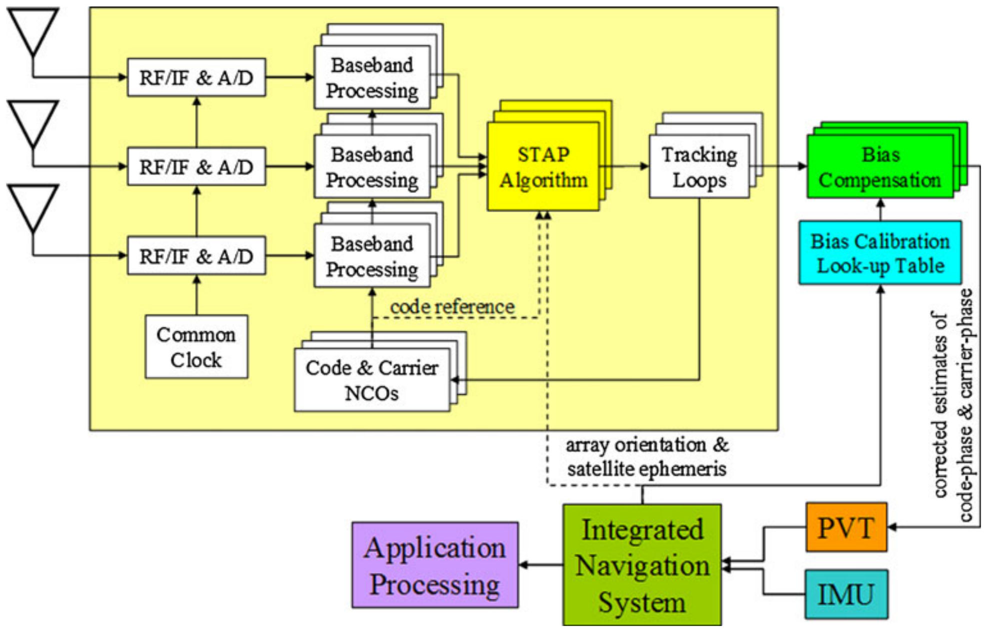


Fig. 6 Final GPS receiver architecture with STAP array processing and code phase and carrier phase bias compensation

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