Further Critical Perspectives on Certain Aspects of GPS Development and Use

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ABSTRACT

We seek to clarify a few problems associated with GPS use in order to propel their resolution by clearly elucidating the nature of these problems. We express our concerns about (1) certain aspects of prescribed GPS availability augmentation that currently calls for heavy supplemental reliance on (apparently risky) baro-altimeters, (2) the difficulty of ameliorating multipath effects in many civilian applications, (3) GPS's susceptibility to foliage attenuation as an L-band signal, (4) some evolving policy issues relating to agricultural use (and implied development support) of GPS, (5) Receiver Aided Integrity Monitoring (RAIM) validation (specifically its lack of official confirmation), and (6) anticipated obscuring cross effects of (RAIM) [a variant of Failure Detection in dynamical systems] with **heavy** (as contrasted with **light** or **medium**) integration with an INS as is otherwise recommended for use to achieve the greatest NAV accuracy. These topics, while controversial, cut across almost all applications and so elucidation should be viewed as a positive step forward.

INTRODUCTION

While GPS is being applied with great enthusiasm and is being heavily relied upon in many varied emerging military and civilian applications from surveying to transportation in its many forms, many existing problems associated with GPS had been merely alluded to in relatively subdued terms prior to [53] as only a whisper out of ear shot and generally treated as non-existent. The multitudinous benefits and positive consequences of GPS use have already received plenty of well-deserved publicity (verified by perusing current and back issues of *GPS World*). The following observations on controversial aspects of currently existing Global Positioning System (GPS) technology are made from the particular viewpoint of the present author's prior experience in INS failure detection [1]–[13] and behavior [14]–[19]; multisensor failure detection and reconfiguration [20]–[25, Sec. 2]; GPS testing [26]–[28]; and assorted GPS applications [29]. We express some concerns about certain aspects of prescribed GPS availability augmentation, handling of multipath effects, susceptibility to foliage attenuation, jamming and interference, some policy issues, RAIM validation, and anticipated cross effects with INS integration. Observations are made here from access to only open literature on these topics and the interpretation of results is our own. Many of these issues had originally been raised in [53] but some new disturbing aspects as well as many follow-on resolutions or mitigations are treated here within this same context as being new topics or aspects worthy of bringing up now. We also point out lucrative paths for solutions in our specialty area of Kalman filter estimation/tracking as it relates to GPS concerns.

AVAILABILITY AUGMENTATION?

"Category III landings" is the designation for instrument-only aircraft landings when visibility is severely limited or nonexistent. In order to extend GPS *availability* to 0.9999 for DoD applications and to 0.99999 for civilian FAA applications, respectively, it is now prescribed that airborne GPS applications should use an accurate baro-altimeter [30], [31] to augment GPS reception while ships with surface antennas (including U.S. submarines' AN/BRA-34) are encouraged to use the earth's geoid [32] (or, specifically, known height of antenna above the water level, with the water level *assumed* to be the geoid) to augment GPS reception, as needed. There appear to be problems with each of these strategies as discussed further below.

While modern day baro-altimeters are revealed to have good accuracy, Myron Kayton's and Walter R. Fried's textbook [33] characterizes baro-altimeters as exposing a vulnerability of frequently incurring Flight Technical Error (for example, occurring as ambient pressure changes with time and geographic location when the pilot or navigator neglects to reset the baro-altimeter to properly account for these changes) as a potential barrier or impediment to such critical reliance on baro-altimeters as a cornerstone to GPS availability. A manual correction is usually required. All of the following perspectives are from [33, pp. 462-3, Item 3]: Airport ground stations throughout the world broadcast local altimeter settings to aircraft. This setting is the barometric pressure at the station, reduced to sea level based on the standard temperature lapse rate. ⋯ The International Civil Aviation Organization (ICAO) has published an objective of 325 feet maximum flight technical error at 50,000 feet; however, measured errors of 225 feet (3σ) with maximum errors of 1,000 feet occur in civil operations. ⋯ At altitudes above 18,000 ft., all aircraft (re)set their altimeters to 29.92 inches of mercury. (The resulting pressure reading is called *pressure altitude* and the altimeter reading divided by 100 is called *flight level*.) This usage permits vertical separation to be maintained without frequent resetting of the altimeter to local conditions, but the **altimeter reading bears little relation to absolute altitude**. ⋯ Furthermore, in military operations and over water flights, local altimeter (reset) settings are not always available. ⋯ It is estimated that an assumed 1,500 ft. altitude error at 30,000 ft. ⋯. [33] also cites the independent references that supplied this fundamental information. A 1991 update [34, p. 168] confirms current practice is to now include a transition altitude (QNH) at and below which local setting must be used. Also see [35]. Our recommended three step method for properly assessing actual effect of using baro-altimeters to augment GPS would (1) start with the analytic solutions of [36] in terms of a system of two linear equations together with a range difference and pseudo-range equation and (2) modify it to accommodate a constant baro-pressure surface corresponding to a perceived altitude reading while removing one of the four GPS pseudo-ranges otherwise used, then (3) perturb the solution to ascertain the consequences of various uncertainties and biases (especially the ones just listed here for baro-altimeters).

To treat the ships's water level as being a geoid neglects certain realities such as high and low tides, weather and wind induced sea-state wave crests and troughs and consequent ship-motion effects (or relative effects of cable-towed antennas and the impaired ability to properly predict effective antenna phase center location during signal reception). Without such proposed GPS augmentation, large gaps will disrupt ideal 24 hour GPS coverage at certain locations within the Southern Hemisphere. It's no secret that purely GPS-derived position location is considerably far worst in altitude than in the horizontal. This fact drives the quest. An added worry is that the FAA was using the presence of airborne GPS, with advertised ideal 16 meter Spherical Error Probable (according to SS-US-200 GPS receiver spec), as motivation for reducing vertical separation from 1000 feet to merely 500 feet, especially worrisome during Air Traffic Controller (ATC) directed stack-ups by allowing greater capacity for existing congested airports without any other near term modifications. Furthermore, pilots are to eventually be able to prescribe their own flight plans and altitude (to help off-load the ATC's heavy burden). Use of a radar or laser altimeter should greatly help here and in Category III landings (although some pilots shy away from its use because of wide swings in the readings due to constantly varying terrain height underneath).

STRUCTURAL PRELIMINARIES (from [26])

The *ideal* GPS L_1 carrier signal broadcast from the satellites can be represented mathematically as:

$$s(t) = A_p\, d(t)\, p(t)\, \sin\omega_c t + A_c\, d(t)\, c(t)\, \cos\omega_c t, \quad (1)$$

where

$$\begin{aligned} A_p &= \text{amplitude of the P(Y)} - \text{coded signal}, \\ A_c &= \text{amplitude of the C/A} - \text{coded signal}, \\ \omega_c &= L_1 \text{ carrier frequency}, \\ d(t) &= \text{GPS system data}, \\ p((t),\ c(t) &= P_2,\ C/A \text{ codes, respectively}, \end{aligned}$$

where t in the above is time. The primary purpose for the presence of the L_2 signal is to simultaneously avail a second signal at a distinctly different known frequency so that a dual frequency in vitro ionospheric delay calibration can be performed in GPS receivers (known as *User Equipment* or the *User Segment*). The L_2 carrier transmission broadcast from the satellites may contain either the P or C/A code, but generally not both simultaneously. The GPS data may be present or absent in the L_2 signal.

The L_1 and L_2 carriers (at approximately 1575.42 and 1227.6 MHz, respectively) are bi-phase-shift-key (BPSK) modulated by the two pseudo-random (PR) codes, also called *protected* (P) and *Clear/Acquisition* (C/A) in the earlier literature. These codes and their respective carriers L_1 and L_2 are derived coherently from a common satellite-based frequency standard or oscillator (as are L_3 and the proposed civil L_5 whose inclusion is still pending a yea or nay decision). The C/A code for each satellite is one of a sequence of Gold codes [38] which have been chosen to provide maximum mutual orthogonality among the satellite transmissions. These codes are 1023 bits long and have a period of 1 millisecond. Receivers that recover just the C/A code signal component are satisfactory for Users who do not require the more exacting navigation accuracy or jamming immunity provided to users of the P-code and, moreover, its presence is an aid to P-code (high performance) Users by helping them to bootstrap in acquiring the P-code.

The P-code is a high bit rate (10.23 mbps), long (267 days) code used for precision navigation applications and possessing more jamming resistance. Its length is subdivided into 37 different segments, spaced 7 days apart. By uniquely associating each segment with a particular transmitter, multiple access of different satellites is provided, due to the resulting mutual orthogonality between transmissions. At the end of one week, the code segments are restarted.

The frequency spectrum for the P-code component at L_1 has a characteristic $\sin x/x$ shape centered at the L_1 carrier frequency, with its first nulls separated by approximately $+-20$ MHz away from the center frequency as depicted in Fig. 1. This very wide width provides the essential jamming immunity of the GPS signal. Any interfering narrowband noise centered at the same L_1 carrier frequency will have its spectrum spread over this entire bandwidth according to the tenets of spread spectrum implementations—hence, its effective power is attenuated by 70 db. The characteristic form for the P-code autocorrelation function (i.e., the expectation $E[s(t)s(t+\tau)]$ in Eq. 1) is depicted in Fig. 2. It decays linearly from its peak value of 1 (corresponding to perfect alignment of code replicates) to the reciprocal of the code length when the misalignment reaches one P-code chip length.

From the elementary theory of random processes, knowledge of the correlation function corresponds to knowledge of the power spectrum, since the latter is the Fourier transform of the former, and there is a unique association. Any sequence that has a triangular autocorrelation function (implemented using a shift register as a sequence of shift and add operations), such as is exhibited here in Fig. 3, will have a corresponding power spectrum of the form $\left[\frac{\sin x}{x}\right]^2$ as depicted in Fig. 4. Observe that the first null of this $\left[\frac{\sin x}{x}\right]^2$ function is at the clock rate of the original shift register used to implement it. Inside the receiver, one can control the width of the internally generated $\left[\frac{\sin x}{x}\right]^2$ spectrum. To obtain a 10 MHz bandwidth, shift the internal PN generator at 10 MHz and the resulting first null will occur at 10 MHz. For a 1 MHz bandwidth, just shift the same PN generator at a 1 MHz clock rate. Sometimes there are practical limitations on just how high the clock rate can be set but it is variable.

The final signal component of Eq. 1 is the 50 bps digital data modulated message $d(t)$, which conveys space vehicle (SV) satellite and acquisition aiding information (i.e., ephemeris). The data message consists of 1500 bit frames, repeated every 30 seconds. Each frame contains telemetry and hand over words (HOW) generated by the satellite, plus satellite ephemeris and clock correction data uploaded by the ground-based monitoring stations (the GPS *Control Segment*). The HOW words contain a truncated representation of the regularly incremented satellite z-count, which enables a user to rapidly position his local P-code generator within his GPS receiver and acquire the P-code from the satellite.

The GPS signal impinging upon the user's receiver has undergone degradation and attenuation during transmission and is no longer ideal. The incident power has been reduced by propagation losses to a nominal level of -163 bB$_w$ at L_1, and incurs phase and frequency shifts as well due to differences in the positions and relative velocities of the satellite's and receiver's antennas. It may be further degraded or dispersed by multipath reflections in bouncing off of objects and additive interfering noise from transmission through the atmosphere and from the receiving electronics (thermal noise) used to boost the received signal up again to useful levels in order to extract the pertinent information that it contains.

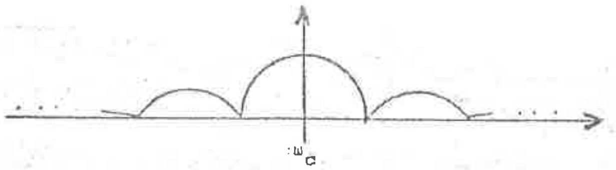

Figure 1. Frequency Spectrum of P-Code

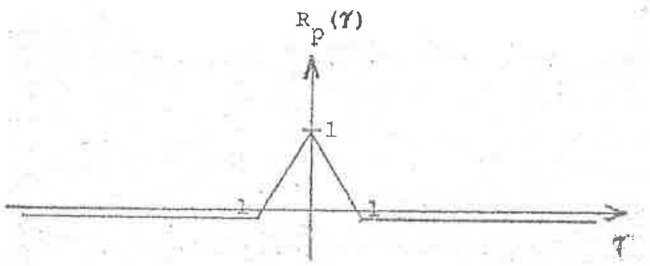

Figure 2. Corresponding Autocorrelation of P-Code

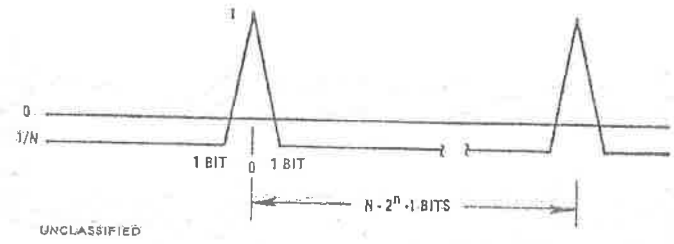

Figure 3. Autocorrelation Function of Maximal Linear Code

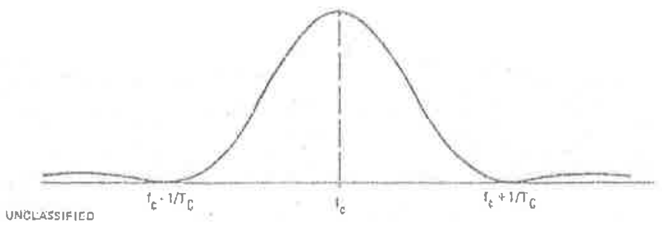

Figure 4. Frequency Spectrum of PN, T_c= Chip Width (the reciprocal of clock rate)

For example, the P-code signal component incident on the receiver antenna can be represented mathematically as:

$$s_r(t) = A_p\, d(t-\tau)\, p(t-\tau)\, \sin(\omega_c t + \theta) + n(t), \quad (2)$$

where

$$\begin{aligned} \tau &= \text{range time delay}, \\ \theta &= \text{corresponding phase delay } (-\omega_c\, \tau) \\ n(t) &= \text{interfering background noise}, \end{aligned}$$

but the magnitude level of A_p is less than it is in Eq. 1.

The tracking of the delay and carrier phase provides the desired GPS navigation information. The GPS receiver's estimate of τ in Eq. 2 (denoted here by $\hat{\tau}$) in essence provides the pseudo-range (PR) measurement for navigation purposes, while its estimate of θ (denoted here by $\hat{\theta}$) differenced over some pre-determined integration interval yields the delta range (DR) measurement. Due to the very high carrier frequency (and corresponding very short wavelength), $\hat{\theta}$ only provides an ambiguous measure of range, and so must be differenced over a relatively short time interval prior to use in navigation processing.

The GPS system data, once demodulated, enables use of the pseudo- and delta-range measurement for navigation purposes by availing the user with the required estimates of satellite position and clock error. Any GPS receiver must perform three basic functions:

1. tracking the above defined time delay τ associated with the P-code (or C/A-code) transmitted from the satellite,
2. tracking the phase delay θ associated with the carrier used for transmission,
3. tracking the 50 Hz data stream.

Just how any particular receiver accomplishes the above goals varies and is proprietary but representative designs are offered in [39] involving phase-locked-loops or delay-lock loops and generally has an associated high-level block diagram of the form of Fig. 5 (also see [54]).

The processing performed in any GPS receiver can be broadly partitioned into, first, front end processing, and then baseband processing. Immediately following the receiving antenna, the receiver front end consists, first, of a Radio Frequency (RF) filter which imposes some initial bandlimiting on the incoming noise

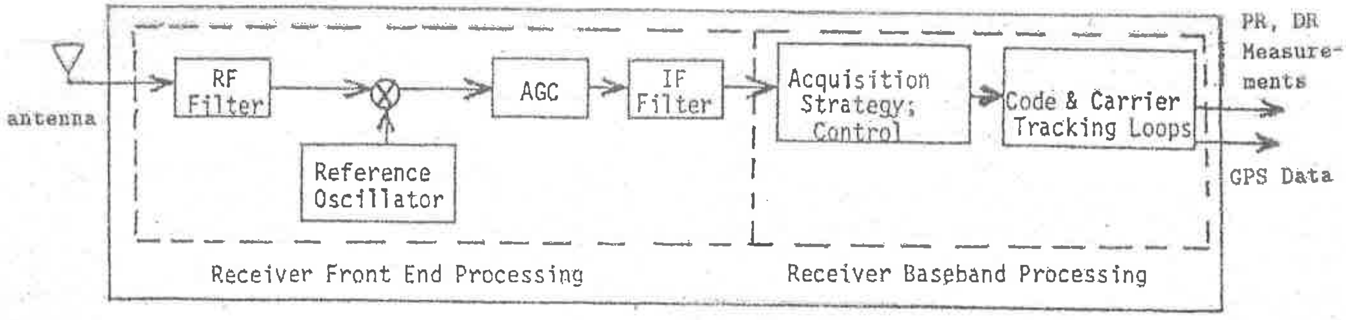

Figure 5. Block Diagram of Generic GPS Receiver

process, while leaving the desired signal almost unaffected. Next, the RF signal is multiplied by a locally generated known frequency (oscillator) to scale the signal to a lower common intermediate frequency (historically known as a superheterodyne) to which the subsequent processing is already compatible. The simple act of multiplying by a sinusoidal oscillator, as depicted in Fig. 5, is typically implemented over several stages within actual GPS receivers.

Following conversion to a common intermediate frequency (IF), it is followed by an Automatic Gain Control (AGC) device to accommodate wide swings in dynamic range of magnitudes without saturating or clipping off important aspects which are characteristic of the underlying signal of interest that are to be further explored. The AGC device or array of such devices are employed to normalize the range of the signal swings for baseband processing since the signal power level actively scales the effective gains of the baseband tracking loops. The AGC itself is a feedback controlled device which possesses its own unique characteristic dynamics, depending on how it is implemented, and its use allows certain critical baseband decision thresholds to be set at a fixed level under the assumption that the signal power is constant (because AGC forces it to be so). Finally, the IF filter improves the final bandlimiting of the noise processes and removes any anomalous harmonics introduced by prior front end stages.

The acquisition function is essentially a searching operation; once it declares the signal to be "found", then the tracking function can take over. Other receiver functions include monitoring indicators of goodness, such as measured signal-to-noise ratio level, and determining when the tracking has lost lock. A loss-of-lock indication will cause the receiver to attempt to re-acquire the signal (i.e., to enter an acquisition search mode again). Signal tracking at baseband is accomplished using one of several possible code and carrier tracking loop configurations, yielding the desired User GPS position, velocity, and time fix. Details abound on GPS receiver specifics in historical literature (e.g., [40], [54]) but configuration details of current commercial receivers are usually classified as being proprietary.

POTENTIAL WEAKNESSES

Multipath Concerns

While successful reception of four pseudo-ranges from different satellites selected to exhibit jointly adequate Geometric Dilution of Precision (GDOP) [less than 2.5] and individually good satellite elevation (e.g., a mask angle of no less than 10^o above the horizon [to avoid significant deleterious lens effects of oblique propagation through the atmosphere]) is theoretically sufficient for a GPS position fix under ideal circumstances. However, another important aspect enters the picture in practice.

A worry is the presence of *multipath*, which occurs when the desired satellite signals bounce off of other nearby objects before reaching the receiving antenna along with the ideal signal directly from the GPS satellite (a composite existing as the sum of several signals each of the form of Eq. 2 but with a different value of τ, which as a consequence clouds the receiver's estimate $\hat{\tau}$ of the true direct path signal). In some situations, the direct path signal is totally blocked and only the reflected signal arrives at the receiving antenna. This further aggravates the task of estimating the true τ. The bounced signal has a path length similar to that of the ideal signal and may be of comparable intensity, making proper discrimination difficult and therefore allowing corruption of the GPS position fix computation due to its presence.

For GPS use in DoD airborne platforms where multipath is from other nearby metal parts, multipath is essentially eliminated by coating these surfaces with Radar Absorbent Material (denoted as a RAM treatment) so that anomalous reflections are attenuated to such a degree that only the ideal direct path GPS signals persevere. Similar control of the immediate environment is afforded in ship borne DoD installations as well. However, in dynamic mobile GPS usage within cities with sky scrapers and considerable variable metallic automobile, bus, and truck traffic, there is little in the way of instantaneous control that can be exerted to ameliorate the effect of multipath within these *urban canyons* other than count wheel revolutions (assuming no slipping has occurred on oil soaked streets in light rain) and that dimensions of template maps used for comparison are correct. Use of an INS isn't practical in this situation because of its expense. In long duration static survey applications with the GPS satellite constellation cycle period being every 12 hrs, repeatable sources of multipath reflections may be modeled and systematically compensated for after two or three epochs.

During the familiar TV commercial advertising use of GPS in automobiles, the mother declares to the taunting kids that she's not lost: "not THIS mom, not in THIS car!" How convenient that her destination was out in the boondocks away from fluctuating ever present traffic and building multipath (or interfering power lines). Only in this particular scenario would her GPS-assisted goal to arrive likely be met. She would also need to know the coordinates of her goal beforehand! How likely is that?

As reported in the *Boston Globe* in April 1997, these new automobile/GPS systems "may cause more problems than they solve, especially for new drivers who are easily confused and feel overwhelmed with information that is frequently worded ambiguously." Earlier devices with visual display screens later proved to be too distracting. Now instructions are provided orally to, say, "turn left at the next corner fifty yards ahead." What about the ambiguities posed by traffic circles and rotaries and simultaneous oblique intersections of more than two roads.

As also reported in the Sunday *Boston Globe* on p. A-18 on 27 Dec. 1998, under "Computer Points Auto into River", a German couple out for a late night drive in their new luxury car ended up in the water. The couple drove to a ferry crossing, which was not marked as such in their satellite-steered navigation system. The driver kept going straight expecting a bridge until his rude awakening "splash down".

One suggestion reported by the *Center for Transportation Studies* at Imperial College in London (based on research with 250 subjects who viewed videotaped scenes of driving different routes from the driver's perspective, accompanied by simulated GPS/map-based driving instructions) was that the information provided should contain more references to visible landmarks for driver corroboration rather than merely offering distances and directions about what next turn should occur at a specified street name or distance away.

How do symphony percussionist driving with GPS know that the current route is being blocked by construction (or by emergency vehicles) until he is able to make a direct first person visual assessment? How much time is lost in back tracking in most usual situations? Suppose the extent of the blockage is greater than anticipated and may possibly thwart several alternate routes too (such as occurs with large mud slides, or fires, or floods). Can these systems accommodate this yet?

Avoid Foliage-go to the desert, stay above tree-line, or avoid cover?

Just as L-band radars sometimes have difficulty penetrating some types of foliage [41], GPS is similarly stymied. GPS was widely hailed as a hero of sorts as an unfailing anchor in the shifting sands (devoid of definitive landmarks) as the most useful basis for navigation during the Gulf War (where, otherwise, U.S. intelligence maps were sorely out-of-date). Luckily there are few trees in the desert. Good GPS publicity has also recently accrued in the popular press from two incidents involving hikers lost in the White Mountains of New Hampshire (evidently above tree-line). Outfitting golf carts with GPS as a natural next step (followed by KVH Industries in producing Acutrack) also avoids reception through foliage since these carts are nominally on well-manicured meadows and don't normally drive through the woods except for brief excursions nearby and generally seek to avoid the water hazards (and their associated multipath reflections).

Wouldn't the above described scenarios be ideal for GPS manpacks; however, military use *sometimes re-*

quires GPS users to take cover. As long as troops with GPS manpacks avoid multipath from boulders and signal attenuation from overhanging foliage or being in valleys in close proximity to mountains [considerably exceeding a 10^o nominal mask] that effectively blocks reception of many more satellite signals, GPS manpack reception should be just dandy!

Bulletproof RAIM–shrouded in Kevlar?

While the original GPS receiver specs (SS-US-200) don't specifically mention required performance of Receiver Autonomous Integrity Monitoring (RAIM), this more recent topic is discussed in a series of MOP's [42] issued 11 years later (also see [43]). As of a 1990 NATO Agard NAV Conference in Ottawa, Canada, Honeywell (now GE) admitted that no prescribed specs were externally imposed upon its failure/fault detection strategy that it magnanimously included with its system. Current claims of effective RAIM performance are not cross-checked but are left to the integrity of the manufacturer.

It appears that no agency or independent tester monitors the manufacturer's integrity or RAIM performance. Could advertised bulletproof RAIM mean that it's literally shrouded in Kevlar? Let's trust marketing literature (especially on challenging aspects that are seldom cross-checked and are expensive to perform)!

Another complicating aspect is the various levels of integration of GPS with Inertial Navigation Systems (INS) as being either light, medium, or heavy. Earlier (1976) WPAFB studies of airborne INS failure detection [44] (also see [20]–[22]) indicate that some conventional spinning rotor INS failure modes or degradations are not uniquely distinguishable (e.g., heading error versus East gyro drift) and, moreover, when some serious degradations are present, they aren't observable until as much as 15 minutes after occurrence and even then only if a particular prescribed aircraft maneuver has been performed to reveal it.

Under the option of heavy GPS/INS integration (widely promoted as the way to obtain the most synergistic benefits between GPS and INS in concert), it would be expected that these concealing aspects of the INS would adversely taint otherwise ideal GPS RAIM decisions (e.g., INS is used to point the antennas, especially in the presence of enemy jamming or interference; however, if INS then incurs a large anomalous drift, antenna pointing is subsequently affected adversely, possibly delaying acquisition of new GPS satellite pseudo-range and consequently delaying the GPS fix used to update the INS). These and other issues [45] (cf., [9], [22]) remain to be further investigated [60], [71]–[73].

Other concerns regarding theoretical underpinnings of RAIM (or the lack thereof)

Our view is that Kalman filter-like (KF) algorithms have been successfully applied in many diverse scenarios and applications from own-craft navigation (which, in general, is relatively benign and linear for an Inertial Navigation System and somewhat nonlinear for GPS alone) to non-cooperative target tracking (which is more challenging by being very nonlinear if ballistic trajectories are involved). New developments continue to occur in Kalman filtering technology and in statistical estimation. Conventional Kalman filtering is applicable to only linear, possibly time-varying, systems with only additive white Gaussian noise [WGN] being present.

There are certain standard approaches that have been used to generalize use of a Kalman-like filter to more challenging nonlinear scenarios (like EKF, extended iterated EKF [83], interval EKF, Gaussian or Second Order filters, maximum likelihood nonlinear least squares batch [93], etc.). All these approximations are based on using more terms in the Taylor series expansion in an attempt to adequately approximate the nonlinearity near a specified operating point to a greater degree of accuracy) sometimes with success. I seek to at least alert the general navigation audience to some current issues and topics that are usually focused on only by nonlinear estimation specialist. In response, we emphasize the dichotomy of strong conclusions of "optimality and stability" guaranteed for a pure KF for exclusively pure linear systems with only additive GWN and how all bets are off otherwise. This issue was recently forced upon general navigation practitioners by James Chaffee et al at the ION National Technical Meeting in Jan 1997 when they dredged up underlying issues of Stochastic integrals (e.g., of Wiener, Ito, Stratonovich) arising in rigorous treatments of nonlinear estimation problems versus the conventional integrals for deterministic functions devoid of noise (e.g., of Riemann, Stieltjes, Cauchy, Lebesgue) [and we mention the ultimate unification resolution of both types as McShane integrals in the 1980's]. The bad "news" is that some evolving Receiver Autonomous Integrity Monitoring (RAIM) standards based on the expected "whiteness of KF residuals" have been challenged as being flawed. We perceive this as being somewhat of an extreme view (but not without some justification) and we hope that by trading-off complexity incurred vs. rigor provided, practicable answers will eventually be found by taking a more temperate stand. Additional refinements in statistical conclusions and tools that may be invoked (e.g., martingale inequalities and sample stability results of the late Frank Kozin [Brooklyn Poly], who inherited his approach from Clifton Samuels [Perdue/Howard] as did T.T. Soong [SUNY, Buffalo]) are a consequence of actually acknowledging the presence of stochastic integrals. RMS interpretations and "business as usual" if they are not. Moreover, [96] appears to be in the same tradition. Rather than being merely statistically well behaved on the average, each trial (sample function) has to be so.

We also alert the reader to other more exotic approaches to KF generalizations to nonlinear estimation for potential use in RAIM such as Gordon's particle filter [94], or use of a bank-of-Kalman-filters (McGill, 1965) or the use of "partitioned" Kalman filters, as advocated by Demitri Laniotis (1974) and subsequently by many others (e.g., R. Grover Brown, Wang Tang, Thomas Kurien, Peter Maybeck), with a variation incorporating a Markov chain with its "sojourn time" as an additional tunable parameter comprising the Interactive Multiple Model (IMM) filters (by Yaakov Bar-Shalom and his students X.-Rong Li, William Dale Blair, K.-C. Chang, Robert L. Popp, T. Kirubarjan, L. Yeddanapudi, by Raman Mehra, and by its originator, Henk A. P. Blom [Netherlands]).

For those considering using the MathWork's Simulink-to-C cross compiler to generate Interactive Multiple Model (IMM) C-code from Simulink block diagrams, a constraint that The MathWorks emphasized in their *Real Time Workshop* is that variations in the architecture, like having different state sizes, can't be accommodated by their tool via this technique. Yaakov Bar-Shalom's and Rong Li's IMM theory provides for varying state-sizes and even handles collapsing state sizes but constraints within this Real-Time Workshop tool stymie automatic code generation along these lines (while one can make the underlying matrix parameter values available for changing-after-the-fact at run-time but not the state size).

Another warning at the recent 4th ONR/GTRI Workshop on Target Tracking and Sensor Fusion in Monterey, CA on 15-16 May 2001 was that generating C-Code directly from MatLab using the cross-compiler only speeds run times up by a factor of two (rather than six or ten as The MathWorks claims). User also needs special DLL's (Dynamic Link Libraries) installed to use the results. Simulink-to-C doesn't need special DLL's with its C-output converted programs.

The efficiency of Matrix-X generated C-code over MatLab-generated C-code is fairly well known (since Integrated Systems had received a quality award for this product's usefulness from the U.S. government in the mid 1990's). A caution expressed at the ONR/GTRI Workshop was that the Matrix-X generated C-code was unreadable (being uncommented) but it's my belief that it's not really necessary that it be documented. It just needs to be right and run successfully and be transportable (and it is). The MathWorks now also sells Matrix-X (since April 2001).

Synonyms for partitioned filters are decoupled, decentralized, distributed, cascaded, federated, and multirate Kalman filters. Although discarded for some strenuous target tracking applications, in certain more benign navigation applications, "partitioning" is still a lucrative technique to "divide and conquer". A fairly recent critique by Larry Levy (JHU/APL) occurred at the 52nd Annual ION meeting in Cambridge in April 1997, where objections were "levied" against all forms of decentralized filters as being approximate at best and hard to properly evaluate, and a numerical bound on actual filter performance was postulated. While these charges are generally valid, a defense of decentralized filters in certain applications as being exact was offered in [25], where two additional upper and lower numerical bound refinements are offered on filter performance and a clarification is offered on the proper handling of performance evaluations using a truth model along with a lower order filter model (imposed or constrained for the practical purpose of reducing the computational burden and delay incurred during on- line real-time processing). We used our familiarity with both Kalman filter-based navigation and Kalman filter-based target tracking areas [11] to convey significant trends present in both such as advocating wide spread use of numerically stable Bierman squareroot filters for continuously operating Kalman-like filters. A new wrinkle of potential utility in RAIM algorithms is a new variant of Generalized Likelihood ratio (GLR). The failings of the original earlier version of GLR was warned about in [9]; however, this new GLR variant, originally developed by Lincoln Laboratory's Ed Kelley (and improved upon by Irving

Reed, M. Rangaswamy, J. R. Roman, J. H. Michaels, D. W. Davis), has already been proven to be more useful in radar applications than its predecessor namesake (see [91] for more insight). Its utility and full potential in failure detection remains to be seen (since it hasn't been tried yet).

Ed Kelly's GLR formulation was not the original GLR formulation for time segments of random processes which is how the clean problem has been historically posed (by Carl W. Helstrom, Harry L. Van Trees, Fred C. Schweppe, Jack K. Wolf, J. B. Thomas and E. Wong, W. B. Davenport and W. L. Root, I. Selin, Robert McAulay and Denlinger, A. S. Willsky and Hal L. Jones, Jack Liu from 1959 until 1976). However, Ed's GLR does appear to be a more tractable approximation to the original GLR formulation but ignores time interval (yet estimated covariance is obtained from samples over a time interval-but not necessarily the same time interval).

Recent (within the last three years) speech recognition work in AI Lab at MIT uses GLR in a non-standard manner to an advantage but without consideration of any decision threshold at all. They just look for relative spikes up that may occur in time as their clue that something interesting is occuring.

I shared my perspective on old and new GLR's with Tony Filip (Lincoln Laboratory). Tony was also aware of the more expansive formulation as a decision based on a random process segment. Tony says that "radar is willing to tolerate the current GLR approximation in vogue to gain the tractability but gives up on the exactness of signal start time. The signal start time is critical in failure detection (and I suspect in target maneuver detection too) because that's when other systems are switched in and the system is reconfigured with redundant or warm standby components or by "analytical redundancy" (i.e., use of combination of other existing unfailed sensors-perhaps with further processing-to fill the void left by the failed sensor) to remedy the situation.

One Russian researcher (now in the U.S.), I. V. Nikiforov, continues to use the rigorous formulation and recently obtained tractable finite implementation results for even nonlinear detection situations [95]. Nikiforov has a prior book in English on this entire subject, published in about 1988. His notation and concepts can be challenging for engineers. He's a martingale, measure theory person (no sweat though) and he is rigorous. That's what it takes! Recall that the results in [1]–[8] were developed for fault detection in navigation systems and put on a platter for others to use (possibly for RAIM).

Interference–Is GPS's spread spectrum Gold Code resistant enough?

GPS signal acquisition is currently accomplished using *Coarse/Acquisition* (C/A) Code, a segment of a 1 MHz Gold Code sequence which repeats every 1 msec. While GPS receivers need only relatively simple hardware (consisting of correlator chips) to quickly acquire the GPS C/A Code, *it is much more vulnerable to enemy jamming and spoofing* than the 10 MHz *Precise* P(Y)-Code pseudo-random noise (PRN)[this is a paraphrased excerpt from Item AF97-135 of the DoD FY 1997 SBIR Program solicitation].

For resistance to wideband barrage jammers (the least sophisticated form of jamming) and possible anomalous interference, spread-spectrum techniques are usually invoked to spread out the incoming energy over the whole spectrum while correspondingly reducing its magnitude. GPS uses Gold Code of two different lengths for C/A-code and P-code match-up via correlator chips. Please see the next topic for further elaboration on consequences.

Historical Dropouts–making life easier for terrorists?

To date, there have been several reported anecdotal dropouts of GPS usage:

- At GPS-94 in Salt Lake City, Elizabeth Cannon, past chairman of the Institute of Navigation, reported loosing GPS signals during testing in Germany in the vicinity of a large radar;
- A commercial airline reported lost of GPS over St. Louis, MO in 1995. This was later traced to McDonnell-Douglas that was performing tests on the ground using satellite signal emulators;
- Observed GPS interference from the higher harmonics from TV broadcast stations in Italy (prompting MITRE to suggest imposing use of additional notch filters on those stations);
- In 1997, a Continental Airlines aircraft had a simultaneous GPS outage over France on all three of its receivers while relying exclusively on GPS as its sole means of NAV;
- In Dec. 1997, two GPS signal outages occurred over Albany, NY (due to tests at Rome AFB) [also see [65]

for more concerns relating to GPS vulnerability within 200 miles of a simple 4 watt jammer].

- (From Jane's Weapons:) there is a high powered Russian Strategic L-band Radar (in place since the '70's or early '80's) with signal frequency infringing on GPS frequencies (but so does our own AN/FPS-108 *Cobra Dane* in Shemya, Alaska at 1215-1250 MHz Narrowband and 1175-1375 MHz Wideband at 15.4 MW Peak power/920 kW average [from Eli Brookner's book]).

Even more upsetting is that in August 1997 at the Paris Air Show, the Russian firm, Aviaconversia, unveiled its 4 watt GPS jammer (range: 200 km) but at least there is [98] coming to the rescue.

While new equipment is being developed for airline security [46] to detect nitrogen-based explosives [47] and to identify potential terrorists that fit a particular profile, now terrorists of tomorrow (unconcerned with adhering to our administrative procedures or the Air Transportation Security Act of 1974 [Public Law 93-366 of 5 Aug. 1974] or the 1985 International Securities and Development Cooperation Act [Public Law 99-83 of 8 Aug. 1985] or with *playing fair* by only using metal guns) can pull an end-run and avoid the hassle by just jamming GPS with directional antennas (or worst, just trick it with slowly increasing intensity and avoid abrupt change to foil our detection of their faux signal in making GPS indicated position drift away from nominal behavior) yet terrorist can still remain covert. GPS usage is a prime candidate for electronic spoofing and electronic befuddlement. Using made-to-order cost effective commercially available GPS signal simulators, or duplicates of test *pseudolites* [55], already in place at some airports (perhaps its time to place more stringent controls on these devices, terrorists of tomorrow can now avoid the inconvenience of going to congested airports or standing in long lines, like real passengers do (or additional worries about providing fake packaging or encountering bomb-sniffing dogs). Unlike the situation with ELINT, they don't have to broadcast beforehand to give their position and malicious intentions away (and be snuffed out) and they can communicate with local human spotters in the airport via standard phone links to even pick out particular flights as having just departed and to signal that an electronic attack should now commence to affect that particular flight (and any other flights within range). We don't want to be a "how-to manual" here but merely seek to alert policy makers to these obvious vulnerabilities (that appear to be totally ignored).

As in seeking to stymie or block computer hackers from doing damage, just accumulating historical statistics of lack of prior occurrence likewise doesn't appear to be as effective a measure as actively anticipating possible future hostile moves and taking steps now to shore up any perceived vulnerabilities and thwart hostile actions. [In this modern era, widely publicized defense related innovations regarding unmanned drones, such as the vertical take-off and landing AEROBOT FS24-90 (165 lbs., 36 in. diameter, 30 in. height, 20-30 kt. cruise, with an enclosed fan for reduced visibility except from below or above, and capable of carrying a small explosive payload) [48, p. 31] and its ilk have increased the potential threat. There are also land- and sea-based drones to worry about but airborne ones have the fastest response times against a designated target and can still be located outside current practical limits of a guarded perimeter yet be called in quickly. A time to worry.]

Since the *Federal Radio Navigation Plan* is encouraging the phasing out of redundant Navigation sources in favor of total GPS reliance, it makes such terrorist goals more easily met since pilot sanity checks in comparison to other simultaneous navaids will no longer reveal (if no other simultaneous navaids exist) that GPS is under siege (to signal that primary GPS reliance should be suspended). Even if some GPS antennas are Controlled Reception Pattern Antennas (CRPA's), the number of jammers used could be selected to swamp its nulling capacity by exceeding its modest number of antenna elements. Nearby jammers also win the competition against actual GPS satellite signals that are broadcast from 10,000 nautical miles away. *Paladin Press* for "soldiers of fortune" also routinely prescribes use of coordinated synchronized blinking jammers to throw adaptive beamforming antennas into a "frenzy" by forcing them to stay within a constant state of flux or transition by blocking their attempt to settle into a steady-state condition where nulls are successfully placed on the jammer. This occurs because the blinking coordinated jammers appear to keep jumping around in space faster than the adaptive antennas' convergence rate (while pulsing is beneficial to terrorist by incorporating a duty-cycle that reduces the power requirements for jamming).

There is an obvious battlefield counterpart to this unpleasant scenario for DoD applications as well. Enemy countermeasures against GPS would have a disruptive effect on everything else that hinges on it. A single atmospheric nuclear burst can thwart coordination of GPS dependent activities by "temporarily" blocking GPS reception [for as long as the atmosphere stays in flux with charged particles] without pinpoint destruction of the GPS satellites themselves in High Earth Orbit (HEO), an activity that would require a higher (and costlier) level of enemy technology. While electronics can be hardened against damage from an electromagnetic pulse (EMP), the atmospheric transmission medium can not.

Space-Time Adaptive Processing (STAP) to the rescue? But who is going to rescue STAP?

It has been asserted [66], [67], [68] that use of the same principles of Space-Time Adaptive Processing [69], [70] will thwart interference and jamming . However, they only treat or consider barrage or wideband white noise jammers, exclusively, as they defeat the jammers in simulations. They also consider only constant relatively high power jammers of this type. Jammers of mixed power levels are harder to defeat and, surprisingly, lower power jammers are more challenging to null out.

We alert the reader here to an apparent vulnerability in recent adaptive antenna processing that claims jammer resistance via lucrative new approaches to adaptive beamforming and/or null-steering but unfortunately presume only simplistic unsophisticated wideband barrage jammers as threats. When jammers are less cooperative by being statistically non-stationary (e.g., by exhibiting time-varying means or biases, by being synchronized blinking jammer pairs, or by varying the total power output with time), then statistics on the jammers can apparently no longer be successfully extracted from the time-averages (even over excessively long sampling and processing time intervals, even in post-processing mode using saved blocks of received data) because ergodicity of the covariance estimate is lost. As more systems uncritically embrace this STAP technology because of its analytic lure and beauty and potential in an unjammed environment, in my opinion, the entire defense infrastructure is becoming compromised and more susceptible and fragile unless someone speaks up. The technology of more stressing jammer threats predated (by at least a decade) in the open literature (of Paladin Press for soldiers of fortune and terrorists) the advent onto the scene of this analytically appealing theory for adaptive antenna array design and processing thus creating a situation that I find appalling for national defense readiness. This unpleasant situation arises or exists for abstracted, idealized STAP algorithms making use of the familiar $R^{-1}v$, where this necessary covariance estimate $R = R_1 + R_2 + R_3$ having constituent components due to thermal and environmental noise, clutter, and jammers, respectively. Without an ability to estimate R_3, the appropriate jammer nullings can no longer be activated successfully. Susceptible systems can apparently be revealed by in-situ tests with simple equipment. ELINT/SigInt can reveal this. Details are in [90].

More Bad News about Atmospheric Scintillation

Jack Klobuchar, a consultant on Atmospheric Scintillation, was session chairman on this scintillation topic at the national ION meeting in Cambridge two years ago. In the past at the AF Geophysical Laboratory/Phillips, he has worked extensively with Paul Fugere, a recognized expert in Power Spectral estimation, particularly with maximum entropy methods for geo-related phenomena.

These atmospheric scintillation issues also arose for early warning Radar at Raytheon within the last year or two. There is a neat article on it by Per Enge and other Stanford folks in *Navigation*, Vol. 47, No. 2, pp. 112-120, Summer 2000.

Raytheon recently hosted several specialist that had each devoted 30+ years of their lives to analyzing scintillation, only to find out that individual perspectives were vastly different. Sometimes the Total Electron Count rose as if there was a cause and effect relationship between this directly measurable quantity and consequential atmospheric scintillation. Other times, it is completely opposite. A situation that is very unsatisfying! Mission Research Corporation currently "holds the keys to the scintillation kingdom" for DoD.

It was revealed at the above meeting that about 18 specialist from around the U.S. had been using the same finite element (PDE) code developed for this application, PROPMOD, but were using it in drastically different ways to obtain models of cause and effect. Their goals were the same. Just how they were interpreting use of the software was different. There was an input parameter known as SSN (Sun Spot Number) that needed to be entered as input. It was known to be related to sun spot activity and some had entered the instantaneous value, others had entered a one week average, others a one month average. According to the user manual, the software developers had intended that it be a smoothed sun spot number, averaged over a year. Lincoln Laboratory uses a three month average with an instantaneous proxy number entered too [75]. Everything is apparently more ad hoc in this area than expected even for the experts. If they can't accurately predict the occurrence of scintillation, it can't be appropriately compensated for. Atmospheric scintillations fluxuate fairly rapidly. Instantaneous estimates can't have high fidelity if they use a year long average SSN. The scintillations also tend to form chaotic "clumps" over the earth's poles. Sometimes there are delay differences as a function of latitude of as much as 1.5 meters at L_1 frequency for stations separated by 12^o of geodetic latitude as measured on 19 Oct. 1998 [75]. These events move and persist over thousands of square miles at northern latitudes for significant time periods during times of heightened solar activity.

Naval Research Lab has extensive tabulations of atmospheric scintillation for low latitudes (where the communications satellites operate). Scintillations occur there too but have behavior that is more predictable and benign at low latitudes.

Legislated Agricultural GPS Use–the little guy's screwed again!

Although U.S. farmers are seldom "penny-wise and pound-foolish" unless it's forced on them, recent U.S. agricultural legislation has recently been passed making it mandatory for farmers to gauge their use of pesticides and fertilizer according to micro-managed need through use of GPS coordination with maps, possible (GPS-equipped) crop-duster aircraft, and explicit surveys of exactly where these chemicals or bio-substances are being applied. It is reasoned that in this way, it is less likely that excesses will occur thus saving money on these substances (by spreading it more parsimoniously) and, therefore, simultaneously satisfying Environmental Protection Agency (EPA) goals of reducing chemical and biological pollution or contamination of the environment. It is also claimed to be representative of state-of-the-art agricultural practices since farmers will later be able to coordinate crop yields to what precursor actions were taken earlier in the season (to establish a direct cause and effect relationship).

So far, this all sounds like "motherhood and the flag". The parallel reality is that any principal component analysis worth its salt relating to crop yield would surely identify the weather as being far and away the most significant factor affecting crop yield regardless of practices of fertilization and pest control. The financial plight of the average farmer has been discussed repeatedly in the last decade and has elucidated the squeeze the farmer experiences from having to acquire expensive equipment (to remain competitive), to market price fluctuations (due to Federal price support practices and relative to foreign imports), from occasional famine-inducing droughts (not to mention hurricanes, floods, and spring freezes). Yet farmers are now expected to further finance the high technology of GPS development/refinement or, more likely, pass these additional expenses on to the consumer: the American public (who must decide between purchasing these or less expensive foreign goods).

EPILOGUE

While we have elucidated some areas of concern above, we remark that we have a high regard for GPS development and accomplishments to date and encourage its use and further refinement. Controversial aspects exist in almost all human endeavors not just GPS. Consider the Navy aluminum ship fiasco (burning and melting from fire at a relatively low temperature when they sustain battle damage), early *composite* fighter aircraft (that originally couldn't be repaired after sustaining flak damage except to slap steel plates over it and another comparable symmetrically plate placed elsewhere to counterbalance it [say good-bye to battles of attrition]; also being vulnerable to lightning strikes and Line Replaceable Unit cross-interference, otherwise entirely eliminated by metal enclosures), seeking to get NATO to agree to use of JTIDS in 1992 (when for the last 20+ years the USAF and Navy haven't yet been able to agree [not to mention the marines with their alternative PLRS version]), motivated by the lower cost of exclusive GPS attitude determination as essentially a radio receiver (GPS receiver) versus the higher cost for precision machined and aligned/calibrated gyros and accelerometers, use of interferometric techniques and multiple GPS antennas to obtain relatively coarse attitude determination (with a requirement to utilize an INS as part of the process) when *use of the INS alone suffices* (without multiple GPS antennas or a need for interferometry [however, the degree of accuracy attained in GPS attitude determination varies directly with the length of the baselines between participating antennas and depends critically on successfully using interferometry to infer attitude from GPS by precisely knowing the locations of the various participating antennas (vulnerable to thermal coefficient of expansion and baseline flexure); the candidate GPS antenna locations depicted in [52, Fig. 15] appear to ignore realities of persistent wing flutter and the associated large scale vibrations (displacing antenna locations) that are never completely suppressed even with active electro-constrictive damping] to provide a better (i.e., more accurate) attitude assessment constituting platform *pointing* accuracy, incident occuring during the GPS receiver Phase II DoD competition between Magnavox and Rockwell-Collins in the early 1980's where one contractor had software implemented in MelTran (a dialect of Fortran) while the other had software implemented in the Jovial dialect J73/I yet the DoD independently discontinued support of both computer languages midway through the competition without prior warning., a retiring general admitted in a 1997 *Aviation Week* that independently developed airborne radar and GPS assisted "smart bombs" interfer so that one or the other but not both can be used at a time (similar worries had been historically expressed about airborne ECM and combat radar), (departing from such time tested tenents of seeking to minimize electronic emmisions from convoys in order to reduce detection signature as a homing clue to the enemy and the potential use of GPS for passive radio silent aircraft return to the carrier) there is now CEC (where all the raw radar returns of all participating platforms are passed around to all present for reconstruction of prospective targets as seen from all perspectives) sending a glowing group message to the enemy emmisions detectors of "here I am", a good description appears in [74] of the difference between GPS-time and USNO Master Clock Time (yet the discussion drops the ball in describing GPS as having three orbital planes [as had been the plan twenty years ago] rather than the six orbital planes currently in use) but beware of [78] that advocates only 16 GPS satellites, the historical evidence of prior arms merchants later being on the receiving end of weapons that they developed and sold off [51, footnote] (an issue perhaps relevant to current ceasing or removal of GPS's Selective Availability [previously known as "denial of accuracy"] despite warnings to the contrary [77]), with multilayer Perceptron neural networks (useful only in feedforward applications but not in feedback control), and the *idealized* control strategy of *feedback linearization* [49], [88] (enough said).

These problems could have been averted or eliminated earlier if someone spoke up. In the case of GPS, some of the above mentioned problems are being worked on by the Mayflower Communications Company and the ERI Company and by [61]–[68], [79], [80] (for interference and jamming as discussed on p. 201 of June 1997 issue of *Aviation Week* and in the Proceedings of the 52nd Annual ION Meeting, June 1996) and by several investigators for multipath compensation (e.g., [50], [58], [69], [97]) and by Working Group 5 of RTCA Special Committee (SC)-159 for GPS fault detection and exclusion (FDE) [37], [43], [71]–[73]. The individuals and companies cited here are not exhaustive but merely explicit representatives of a more extensive ongoing effort.

In particular, a recent approach being developed by Dr. Basrur Rama Rao (MITRE) using GPS Microstrip Antenna Array for Multipath Mitigation follows: GPS Carrier Multipath is a major source of error in differential GPS that cannot be removed through signal processing in the receiver; it occurs from a variety of structural and ground reflections and is common to both land-based and airborne GPS systems. A new type of low profile, lightweight, two-element microstrip antenna array used in combination with a resistivity tapered ground plane for reducing multipath in GPS systems is being pursued. The concentric two-element array consists of an outer annular ring microstrip antenna enclosing a centrally located circular microstrip antenna. This antenna array is used as a polarization filter for adaptive cancelation of the cross polarized multipath signals; the function of the resistivity tapered ground plane is to reduce the back radiation lobes of the antenna by attenuating the signals that are either diffracted or reflected from the edges of the ground plane. This is encouraging! Other multipath mitigation initiatives have also recently been reported [50], [58], [97].

Even more upsetting are problems with GPS interference that had previously been down-played or pooh-poohed. The "chickens are finally coming home to roost" now as the outcome of independent tests say otherwise. Wideband communications are yet another worrisome source of interference to GPS [79], [80]. Moreover, I've found [90] that all STAP algorithms are extremely vulnerable to non-WGN jammers (as so many radar are hastening to convert to STAP capability exclusively). In my opinion, this is unacceptable from a defense readiness viewpoint. For radar, the solution appears to be use of mode switches to immediately abandon the better resolution of STAP when the presence of jamming attacks initially sensed and to return when such attacks cease.

ACKNOWLEDGMENTS

We became alerted to many of these aspects covered in this call-to-action editorial from practical experience and from realistic simulations [29] using **TK-MIP 2.0**, a product of **TeK Associates**, available commercially for performing Kalman filter analysis and simulation (and even actual on-line implementation via use of Data Acquisition Cards, or serial port input, and/or PCI) from an easy to use Graphical User Interface (GUI). On-line tutorials and extensive application examples are also available for **TK-MIP** including an on-line self-contained professional level textbook and short course complete with lectures, tests, corresponding answers, and a guest lecturer. This software runs on 80386 or later Personal Computer (PC) processor with hardware math co-processor chip under *Microsoft Windows 95/98/NT/ME/2000* (32-bit) operating systems.

TK-MIP is a software product for the PC (without MatLab) that we recently developed for teaching others about the theory and practice of KF simulation [81]–[93] and for actually implementing KF technology and its many variations on-line for linear and nonlinear estimation and tracking.

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