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UNFINISHED BUSINESS: GLARING ABSENCES from the ACHIEVEMENT LIST

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BIOGRAPHY

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ABSTRACT

Despite enormous advancements across multiple operations related to navigation, surprising deficiencies exist in some critical areas. Correction of those deficiencies would require

- no breakthroughs nor large investments, *but* changes in some ingrained habits.

Material to follow includes historical insights, status review, and suggested means of correction.

INTRODUCTION

This paper addresses questions and prescribes changes in the following areas:

- a more complete assessment of accuracy requirements: priority attached to *future* as well as *instantaneous* position imposes demands on knowledge of velocity and higher order dynamics.
- expansion of the item just mentioned as applied to collision avoidance – leading to an unflinching acknowledgement that capabilities of present and currently planned systems fail to deal adequately with expected changes for air traffic in 2-dimensions (runway incursion) and in 3-dimensional (TCAS limitations).
- absence of a standard integrity test algorithm (an issue that should have been settled long ago – and thus should be resolved before the need can become more urgent). The industry lacks both a standard FDE/FDI algorithm *and* a standard integrity test.
- the ironic situation that, while GPS has revolutionized both timing and navigation, crude methods are still customary for timing *of* navigation data in advanced systems.
- expansion of the last item to critique every operational system in DoD's inventory to date; at this late date the industry still lacks integrated avionics, integrated shipboard electronics, and integrated vetronics. Conglomeration of "boxes" from independent suppliers has not produced anything resembling integration.
- unpreparedness for widespread availability of MEMS; low-cost sensors will not automatically translate into low-cost IMUs. Other necessary steps are not being taken nor planned.

Impediments to progress in areas just identified are partly from habit, partly from incomplete understanding, and partly inherent in current business/procurement practices. There are technical solutions that have encountered resistance; nevertheless they are needed if these deficiencies are ever to be eliminated.

This paper will review each item in the order of the preceding listing, address questions as to how the industry arrived at its present state, and identify some possible solutions (with reasons why they have not been adopted), including some inherent differences between ramifications in military and commercial applications.

OLD POSITION OR NEW POSITION ?

("*It's the velocity, stupid!*")

The preponderance of this industry's work in defining navigation performance requirements has emphasized position. In the process important distinctions have been carefully pointed out between various error criteria (*e.g.*, absolute, relative, repeatable). Distinction is wisely made for separate error components (*e.g.*, vertical *vs* horizontal; along-track *vs* cross-track). Some velocity requirements have been cited as well – nevertheless operations often call for a specified level of accuracy in position without regard to *history* of position – which implies dynamics. It is suggested here that increased attention to dynamics is warranted in many applications since, quite often, the item of interest is not current but future position (*e.g.*, after flight time of a projectile for fire control; time to closest approach for collision avoidance). As an important step in the direction advocated, velocity accuracy requirements could be added where applicable. After several instances are cited here for illustration, this line of reasoning is followed for one of them (collision avoidance) to a logical conclusion. No originality is claimed; the aim here is perspective, not invention. To be sure, the need to augment requirements by considering dynamics is not universal. There are some applications wherein position is and always will be the overriding consideration. Surveying is an obvious example. Numerous counterexamples, though, can also be listed. Presence of an item in the following text does not imply that dynamics are being completely ignored in that item's development; rather, the cases included are useful for supporting the theme here position alone cannot generally provide full performance evaluation. The set of examples can begin with a hypothetical but demonstrative case of a low-Earth orbiter coming, for the first time, into view of three terrestrial observers. Suppose the three are

- widely separated so that trilateration with good geometry is feasible;
- well coordinated, in tight communication, and synchronized;
- in possession of scanning radars with extreme accuracy in range only; and
- time-shared to the extent that any object is observed only once per scan

Immediately upon processing of the three suddenly appearing range measurements, the space object's position is known to extreme accuracy *but*, since no orbit is yet established, there will be kilometers/second of velocity error. Almost instantly, then, the position accuracy will change from excellent to terrible.

This initial example, admittedly somewhat contrived, serves to introduce the discussion – not surprisingly, there are situations wherein an accuracy evaluation calls for a more detailed description than what could be expressed by position alone. To continue with a space-based scenario, the orbiter might later be approached by a spacecraft for rendezvous. Typically a sequence of trim adjustments will then be conducted, with the intent to reduce relative velocity between the two satellites to progressively smaller levels. Success of that operation obviously requires a final (at time of coupling initiation) relative speed value small enough so that both objects can withstand the soft-collision impact. This is clearly an operation for which velocity considerations are already thoroughly accounted for throughout the development. It is instructive to explore extrapolating that lesson from space to airborne operation. The airborne function closest to the preceding example is in-flight refueling, for which velocity considerations are again customarily taken into account throughout. Proceeding from control of soft collisions to prevention of hard collisions, however, the same attention to dynamics is not always evident. It is not unheard of, for example, to encounter suggestions as to how accurately positions must be known to avoid collisions. Decisions reached with criteria stated in that form are inevitably scenario-dependent and are highly likely to be, at least unconsciously, influenced by perceptions based on limited analysis and/or empirical evidence. To ensure safety under wide variations in conditions, those decisions will turn out to be conservative – unavoidably leading to wider-than-necessary spacings in many cases. Rather than immediate in-depth pursuit of collision avoidance a "bottom line" will first be stated here

> *correct evasions will be contingent on accurate knowledge of dynamics a large error in estimating velocity can hamper avoidance capability, contributing to a collision*

and further discussion of that topic is deferred until after additional considerations have been addressed.

The situation described as "position highly accurate now, highly *in*accurate immediately thereafter" – previously depicted for a suddenly visible space object – is reminiscent of a track file for an aircraft immediately upon radar lock-on. Position may be known to within a few meters at short range or, at 30 nmi range, to within 100 m. In some operations there is no reliable doppler information at acquisition time and, even if doppler data can be immediately available, it provides an indication of only the along-range component of velocity (*i.e.*, the component along the sightline to the tracked object). The cross-range component (*i.e.*, perpendicular to that sightline) could be Mach 1 East or Mach 1 West; either might be equally likely. Thus a 1000-fps error in velocity at acquisition is not at all far-fetched. Controls devised to maintain track files (*e.g.*, antenna steering; placement of gates to capture subsequent radar echoes from the same object) must initially cope with those unknowns, while driving the uncertainties down as rapidly as feasible. Success is critical, since failure to achieve these controls will result in loss of signal (*e.g.*, the antenna can fail to illuminate the object, or gates can be driven beyond the range and/or doppler cells holding the object's response).

Even after the uncertainties just mentioned are successfully reduced, while still in the presence of 3-dimensional maneuvering motion, continuous doppler gating requires repetitive refresh of velocity information. This is especially true at close range where, due to rapid changes in geometry, cross-range motion at one instant of time transitions into along-range motion later.

One application clearly requiring close attention to velocities: landing on an aircraft carrier demands close coordination of relative velocity throughout. Since coordination must obviously be continuous a still more general class of motions is pertinent. Ship's rotation, for example, must be noted before prescribing final aircraft maneuvers.

Another maritime example: ships nearing coastlines must restrict velocities to permissible levels by reason of shoals and traffic densities.

One of many military applications is fire control, wherein error in estimating cross-range target velocity directly produces a miss distance contribution on the order of

$(\textit{projectile flight time})$ x $(\textit{cross-range velocity error})$

and the projectile flight time itself is in error by amounts commensurate with along-range velocity estimation error; this produces another miss distance contribution of order

$(\textit{projectile flight time error})$ x $(\textit{cross-range velocity})$

The examples just cited are not exhaustive, but a sufficient variety has been described to make the point intended. In different ways for different applications, knowledge of dynamics can play an important operational role. It is further observed that velocity alone of course does not fully define dynamics. Arguments presented are readily extended to include higher-order or more general effects (*e.g.*, own-ship verticality, drifts, etc. for navigation; acceleration for tracking remote objects; rotations for coordinating relative motion between own-ship and another object such as an aircraft carrier). Wide dynamic variations characteristic of some applications have prompted the stipulation of additional performance requirements such as settling time for reduction of position, velocity, and/or verticality errors to specified allowable levels.

COLLISION AVOIDANCE

It is clear from the foregoing material that the role of dynamics is already taken into account in some operations but not in all, and often not in sufficient depth. To be specific, the discussion will now revisit, as promised earlier, prevention of collisions. Both TCAS applications (aircraft on a collision course while airborne) and runway incursions (aircraft on a collision course while on the ground) are addressed. To avoid constant digressions or qualifications a simplified terminology is adopted: all encounters will be between an aircraft (whether fixed wing or rotorcraft) and an "intruder" which may in fact be an intruding aircraft or, otherwise, anything from another airborne object to a truck or even a stationary object on a runway.

For collision avoidance it is admittedly useful to know an intruder's position but to "hit the nail on the head" the key issue is separation distance at the time of closest approach. To make that determination in a timely manner (sufficiently in advance of that closest approach time) requires knowledge of dynamics. Velocity plays a direct role in determining time-to-closest approach and projected miss distance at that time.

When a determination is made that projected distance will be less than a specified amount (*i.e.*, size of the aircraft or intruder, plus a safety margin exceeding the effects of estimation errors), guidance commands can be issued. In the airborne case ("TCAS" application, but with improved horizontal accuracy in the cross-range direction) those commands could include evasive turns. For prevention of an incursion (*e.g.*, involving two aircraft on crossing runways), guidance commands could direct one vehicle to speed up and the other to slow down.

It is noted that, whether in two-dimensional (incursion prevention) or three-dimensional (in-air collision avoidance) operation, closest approach time is *not* the familiar "time-to-go" (ratio of range to closing range rate). That characterization is applicable only to the restrictive case of a collision course. Recognition of that fact is evident in TCAS design wherein conservative adjustments ("DMOD") are introduced to allow for unknown cross-range motion at short distances. Again, with more complete knowledge of velocity (in the cross-range as well as along-range direction) the conservatism can be reduced without compromising safety.

Reasons for the absence of desirable features just described are understandable in light of chronology. Current plans for collision avoidance, for example, were developed long before GPS had an operational constellation and before there was much commitment to use it for commercial aviation. Since that time a way to determine velocity at high accuracy in all three dimensions, using GPS to the fullest extent of its capability and effectiveness, was devised and published in Ref [1]. Background and supporting analysis therein are followed by practical considerations pertinent to various operations, collision avoidance among them.

In view of recent events no serious proposal to use GPS should omit substitute data, especially in safety-critical operations. Here it is simply noted that, at most times in most places, enough GPS information will enable achievement of performance improvements in carrying out the function, while occasional unavailability of GPS can be backed up. For example, *the same benefits are available with raw data frem secondary surveillance radar (SSR) reports instead of GPS measurements.*

While one aspect of performance (accuracy) is emphasized here, dynamics could likewise affect other criteria. Integrity methods are applicable to velocity, and continuity during data blackout can be enhanced via dependable velocity histories.

At least in uncontrolled airspace it would be hard to discount benefits of improved situational awareness and conflict detection / resolution. Some envision future aircraft in free flight with evasive maneuvers in a horizontal rather than a vertical plane, via ADS-B in lieu of TCAS. Before adoption of that plan, however, certain issues remain to be resolved. This section concludes with informal deliberations from RTCA SC-186, with added interpretations from this author:

In most areas ADS-B is presently incapable of replacing radar. Also it is not realistic to require all aircraft (including GA and foreign carriers) to equip with ADS-B. Interference threats (jamming of GPS over wide areas, spoofing of ADS-B) must be overcome. Mixed equipages will not always be interoperable in transition periods. In controlled airspace, ADS-B devices must not flood ATC with deviate-from-course requests.

What's here: In-air decisions (changes in speed, altitude and direction), with no ATC involvement, are quite common in uncontrolled airspace, and – although not allowed by FAR – occur in controlled airspace as well. "Juking" for collision avoidance also occurs on occasion (although hazardous; evasive maneuvers should be limited to emergency conditions – despite absence of an *official* emergency characterization for TCAS).

What's missing: Currently planned primary means for CA (ACAS/TCAS with visual acquisition and ground-based control) will obviously not apply to the vast majority of aircraft (no transponders). Even for the relatively few airliners equipped, CA directives will be deferred until late in an encounter {an intrinsic TCAS trait; cross-range information (unmeasured) is inferred only after sightlines rotate in azimuth – a close-range phenomenon}. Integrity violation probabilities are not yet quantified (*e.g.*, false *CLIMB* RA directive in approach with traffic above and voice jammed). Future ADS-B may provide some or all needed capability by enhancement or replacement of various ACAS/TCAS features - this would be preceded by considerable development work.

INTEGRITY TEST

This section reviews a well-known but unsolved problem. Occasionally a signal-in-space (SIS) is in error by an amount sufficient to cause danger. One ramification of the *G* in *GPS*: the danger can affect a large number of users, all in the same general region at the same time. RAIM provides a likely remedy but, from documented tests, not likely enough. Wherever consequences are extreme, the likelihood of occurrence must be extremely remote. On paper, they are. In reality, extensive tests performed on certified receivers missed integrity performance goals by orders of magnitude { Ref. [2] }. Years after those tests there still is no standard integrity algorithm, no integrity test standard, and no plan for either.

Ten years ago an attempt was made to tighten integrity test requirements. Ref. [3] was intended as a common-sense response to isolated but severe discrepancies, *e.g.*,

- there had been a history of cardinal-direction failure (zero-valued coordinates) in one receiver, and blind directions in another.
- missing from planned test requirements were (1) rejection for any catastrophic errors and (2) rigorous statistical confidence – likelihood that *apparent* probabilities deduced from observations disallow undue complacency regarding unknown *true* probabilities.
- simulated locations for planned tests used integer-valued coordinates; test results could be improved by rounding.
- test of pseudocode rather than operational software has always had obvious pitfalls.
- separation of alarm and detection testing is analogous to a *True/False* examination with a full set of *True* statements always known to follow a complete *False* set. Too easy.
- the first certified receiver is well known to have failed spectacularly in integrity performance.

Immediately it is acknowledged that correction of those early receiver problems is credible. That is not the issue here; there is no desire whatever to single out any source, supplier, group, nor organization for criticism. What *is* to be drawn from those experiences is inescapable historical proof of flightworthiness improperly bestowed – with proprietary rights accepted for algorithms and tests. Ref. [3] was intended to correct all of the issues just itemized from that time forward with special attention to obvious failures:

> "*Retest: if the equipment being tested fails , equipment must be modified to correct the problem before re-testing* ."

After this and all other intended requirements failed to gain acceptance, a doubt inevitably arose: aren't these problems sure to happen again? That doubt was prompted in part by Item 8 of Ref. [4] which reacted to the above requirement as follows:

> "*If a properly designed receiver fails the test, the manufacturer is required to modify or correct this receiver before retesting . This does not make sense: the receiver is, after all, designed properly, so what can the manufacturer `modify' or `correct'?* "

The self-evident flaw in this reasoning is, of course, that a receiver whose only outward indication is failure of a test is still automatically assumed to be properly designed.

Persistent doubts, expressed in Ref. [5] with answers offered by Ref. [6], are vindicated by Ref. [2]. Therein it is observed that receiver failure rates greater than 0.001/h exceeds SV MTBF requirement ($3.8x10^{-8}$/h) by ***over 4 orders of magnitude*** ! It is acknowledged that this does not constitute a valid one-to-one comparison. Still, regardless of precise interpretation, Ref. [2] states the unavoidable conclusion that receiver software problems clearly are far more prevalent than SIS failures. The vastness of the gap prompted a voicing of this question { Ref. [7] }

> "*Given the awareness of this situation as well as the existence of documentation providing an example of misinterpreted certification test procedures, what are the liability implications for FAA, for the airlines, for the airframe manufacturers, and for the equipment suppliers in the event of an accident?*"

The fact that no answer was recorded is also documented in Ref. [7].

Though Ref. [3] was justifiably criticized for being incomplete, all test libraries advocated therein could have been finished long before now. Those standard interwoven pseudorandom sequences of blind tests, in fact, could still be generated, rigorously substantiated, and fully documented for open distribution. They could run much faster on today's computers – and provide a measure of safety not now available.

TIMING AND INTEGRATION

There is no need to reiterate here the vast but well-known benefits that GPS has brought to navigation, timing, and communications. It would thus seem quite logical to expect superbly time-tagged navigation data, promptly and accurately communicated throughout modern systems. Ironically that is not at all common, in even the latest avionics, vetronics, and shipboard electronics. In marked contrast to a unified time base, these systems are conglomerations of "boxes" from separate sources – each of which may have a time base independent of all others.

Ramifications of the situation just described are too far-reaching for throrough coverage here. Implications and various candidate solutions are discussed in Ref. [8]. The scope of those ramifications extends much further, actually impacting the overall effectiveness of an entire avionics suite (again, with equal applicability to vetronics and shipboard electronics). Since this is a dominant part of any addition to DoD's inventory there is enormous potential for cost reduction with no need for scientific breakthroughs {Ref. [9]}.

MEMS for NAVIGATION: WILL the INDUSTRY BE READY?

Dominant characteristics of MEMS sensors for inertial navigation invite a "good-news/bad-news" characterization, *i.e.*,

availability of low-cost units and abundant instances of high performance.

What's high performance isn't economical; what's economical isn't high performance.

Immediately this focuses attention on two corresponding issues:

low-cost sensors will not automatically translate into low-cost IMUs, and

IMUs with MEMS gyros will not enable extended coast operation any time soon.

Implications can be instantly clarified by raising a hypothetical event: Consider a surprise announcement today that MEMS gyros with some nominal drift rating (*e.g.*, 1 deg/h, 10 deg/h, 100 deg/h) could now be bought at very low unit cost (*e.g.*, $10. each, $1.,) in any lot size desired. What would be the impact tomorrow? Next month? Next year? In five years?
This author believes that the industry would be slow to capitalize on the advantage.

Reason for this assessment: the intended cost benefit could forever remain a mirage if sensors are the only ingredients changed. Outputs from those sensors must be handled in a way that (1) incurs negligible added cost and (2) provides levels of performance for applications commensurate with sensor quality ratings. The first item calls for standard interfaces and algorithms; the second requires clear guidelines for a dependable updating *modus operandi* – since updating is the *sine qua non* for achieving adequate performance in the absence of coast capability. Aside from a few exceptional applications (*e.g.*, submarine operation), the need for frequent updating is easily accommodated.

Some of the challenges implied by these realities have already been addressed and, if extant resources are accepted, even resolved. Others (certification, for example) are dealt with less easily. Since "less easily" is not synonymous with "impossible" there is an implicit opportunity accompanying this challenge. That opportunity, incidentally, arises *without* certification constraints in military applications – which in the presence of cost-cutting needs would seem to make preparation imperative for DoD.

Preparation in this context, then, involves more than the usual prescription of acceptance for interface and / or algorithmic standards. In military and commercial realms, different applications impose different requirements. As one example, RNP values (accuracy / integrity / continuity / availability) for civil aviation vary with flight phase. Military operations have still wider variations. At the very least, this clarifies dependencies wherein sets of tolerances will dictate what can or cannot be achieved in operation. That seems to call for cost / benefit analyses including parametric studies (deg / h, deg / *root*-h, sensor scale factors, mounting misalignments,) and – inescapably – specification of updating requirements (accuracy, data rates, etc.).

Hard? Yes, but if this were easy it might have been done already. The goal of this paper is to stimulate development of concepts for roadmaps to be followed, in order for MEMS to make a significant difference when widespread availability – in huge quantities at low cost – becomes a reality.

As MEMS developments continue, the cost-*vs*.-performance balance will change with time. Yesteryear's $5K, already far below the $100K often used in overdesigns today, could morph into much lower costs within a few years with MEMS. The mere existence of dramatic cost-slashing opportunities is expected to generate considerable pressure to exploit it. As already noted, however, low-cost sensors constitute a necessary but not sufficient condition for producing low-cost systems. The most immediate imperative is an update of the extant outdated standard for inertial navigation system (INS) data. Both velocity and attitude are presently truncated to 16 bits (there goes the error budget for many operations !), and the latter is expressed in terms of *angles* that *would* be there if a strapdown (*i.e.*, gimballess) system were *not* gimballess (!). As if that were not enough, there are singularities (Euler angles cannot be all-attitude, and the standard position expression includes longitude – meaningless at the poles). Also, while hybrid units are acceptable for display (groundspeed in knots, descent rate in feet per minute), they are far less practical for other purposes. Since the time of the extant standard's adoption, the scope of uses for inertial data has become vastly wider as well as more varied (nonuniform requirements for different operations). It is, however, a straightforward matter to generate position, velocity, and attitude from raw inertial sensor data {Ref. [10]} – so the whole problem can be solved by adopting a standard for outputs of an Inertial Measuring Unit (IMU) instead of the INS. That was the goal of Ref. [11].

Recommendation

An obvious first step is to define the requisite sensor time histories, along with the permissible forms for their expression. For a low-cost IMU that definition is quite straightforward. Raw data from the gyros and accelerometers are simply expressed in terms of values accumulated, within a chosen periodic time interval, for increments of rotation and of velocity in a sensor-referenced coordinate frame. At the discretion of the supplier they can be corrected or uncorrected, formatted according to any pattern (*e.g.*, fixed or floating point), independent of or subject to further preprocessing for calibration (*e.g.*, thermal), analog or digital at whatever data rates are specified.

The choices just described are of form, not of content. Since the nature of inertial instruments inherently implies a specific kind of information to be delivered (absolute motion, *i.e.*, with respect to a nonaccelerating frame), there is not much variation in what is measured. It is therefore possible to enable a systematic description of IMU output in terms of a standard repetitive data record, readily amenable to a standardized test. All that is needed for each IMU data record is a triad of rotation increments plus a triad of velocity increments, plus an instantaneous temperature. Thermal and any additional calibration coefficients can be provided in a header record. Already there are, not surprisingly, IMUs being sold with interfaces that conform to the description just given. It matches, moreover, the data record form used in a recent successful validation. Ref. [12] shows near-state-of-the-art performance obtained with an old uncalibrated low-cost ($5K) IMU updated at 1-Hz. Success of that fully documented approach is expected to influence the industry in the future, if only due to cost considerations.

To illustrate the extreme simplicity of this issue one data record, chosen from thousands of similar records in the test described, is shown here:

```
B 17  -.1442E-04  -.2844E-04   .5466E-05
                         .000993  -.001102  -.095550
```

The first character designates the algebraic sign of temperature w.r.t. a reference value, the integer is the departure of instantaneous from that reference temperature, the quantities in exponential form are incremental angles from the gyros, in radians, and the last three floating point values are incremental velocities from the accelerometers, in meters / sec.

Clearly it did not require a great deal of inventiveness to devise this scheme. There is not much ingenuity that can be introduced here to enhance performance; this isn't the kind of interfacing that calls for inventiveness (all ingenuity in this case should be directed at design of MEMS sensors themselves). As for the data records, acceptance of any form carrying the information shown above could provide the industry with a significant step toward preparation for MEMS.

If the industry cannot yet accept a standard of the type just described for all IMUs, the path could be cleared by separation of inertial nav applications into two main categories -

operations requiring coast capability, and
applications wherein frequent updates are available throughout.

There is no sharp line separating these categories but, as MEMS capabilities improve with time, parameter values (*e.g.*, duration of coast, accuracy and frequency of updates) can be redefined as needed. It might be reasonable, then, to consider a simple interface standard for raw data, applicable only to the frequent-update operation class. Since these constitute the majority of applications, the impact would be substantial. Even the choice of synchronous (described above) *vs*. asynchronous {described in Ref. [11]} can be resolved in that way; periodic data records are a special case of the more general (asynchronous) form.

Another step in the right direction could be systematic testing, including definition of dynamic path scenarios to be accepted throughout the industry. Equipment from different sources could then be compared on an equal footing. Ongoing improvements in performance can be difficult to track unless concrete steps are taken toward systematizing test capabilities. Given sensor output time histories in those scenarios, standardized tests could provide reliable evaluations according to a rationale that would be easy to substantiate. The practice would enable justification of supplier selection decisions on an objective basis.

While waiting for a response from industry, the simple input file format used for the successful tests just described may be submitted as a "de facto" draft standard interface for low-cost IMUs. If we are ever to realize low-cost inertial systems, steps of this type are clearly in order.

CONCLUSIONS

Despite huge improvements over a vast scope of operations, GPS capability has not yet been fully exploited in every applicable operation. Some functions, in fact, urgently need major improvements to remedy known inadequacies. This paper identifies those cases and advocates a course of action to be added or at least planned for the future.

Existing and future planned provisions for collision avoidance are deficient. In 2 dimensions (runway incursion prevention), most airports will not have ASDE – which is limited anyway by lack of identification tags with its data. For 3-D (in-air) operation, most aircraft will not have TCAS equipment – which is limited anyway by a dearth of timely cross-range information. GPS can supply all that is missing, by methods in Ref. [1].

Ref. [2] incontestably establishes a need for far better integrity testing of GPS receivers. Standards could eliminate or at least reduce a potential source of danger.

Much navigation information has only crude time-tagging. GPS could be used as a primary method. The need is pressing with high dynamics, where velocity and higher order information can rival in importance the ubiquitous position data.

With the wide scope of uses for navigation data in avionics, vetronics, and shipboard electronics, independent black boxes are highly impractical. After decades of digitization, anything resembling thorough integration of navigation systems remains an unfulfilled promise. That has contributed mightily to cost explosions.

The industry is not ready for MEMS. Even after low-cost inertial sensors are widely available, there will be no low-cost inertial navigation systems without change in direction. Proprietary inertial navigation interfaces and algorithms can easily be replaced with well-known techniques.

LESSONS from OTHER EXPERIENCES

Some of the conditions discussed here bring to mind an observation from a recent prophetic (pre-9/11/01) presentation by John Beukers {Ref. [13]}. An advanced complex civilization has difficulty acknowledging anything wrong. This seems especially applicable here; with so much success from GPS, it might seem that *everything* must therefore be right. The reality: *Not quite.*

This section can conclude by comparing two recent (and very different) situations involving identification of deficiencies. In the first case {Volpe Report; Ref. [14]}, admonishments have been taken seriously. For the second example, unfortunately, the title of Ref. [15] says it: not so.

APPENDIX: EXPLANATORY ADDENDUM

Topics addressed herein are discussed at length in references cited. For those unfamiliar with the issues, the ensuing clarifications will be helpful.

Collision avoidance . Double differencing of raw uncorrected GPS measurements has been used for years, with spectacularly successful results. By applying that to multiple vehicles (all of which can be in motion), dynamics can be determined in all directions with the same high accuracy typical in differential systems everywhere today. The only change is that all states (dynamic as well as location) are relative – precisely the information needed for this operation.

Integrity test . Imperfect data sets with known correct answers can be generated (by random number seed control) without foretelling which sequence is activated in any individual trial. Probability scaling can alleviate the dilemma of impracticality (too many trials needed) *vs*. low confidence (too few trials). Testing need not provide any more *nor any less* assurance than what would be suitable for flight.

Time tagging . In a common means of synchronizing data from asynchronous sources, each algorithm reexpresses every sample received from every module feeding it. Although expedient, that familiar method is crude and cumbersome; it could be retained only as backup to a refined GPS-based approach.

Integration . A supreme irony of the digital age is a multitude of expensive systems with severe nonessential performance limitations. Availability of raw data at output interfaces would enable vastly improved economy as well as capability. Bulleted items from background introductory material in Refs. [1] and [11] explain the extent.

Inertial navigation . Ref. [10] offers "cookbook" formulae for converting raw IMU data to attitude, position, and velocity. The itemization just cited from Ref. [11] can be satisfied thereby for IMUs.

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